Review of standards and protocols for seabed habitat mapping

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MESH MAPPING EUROPEAN SEABED HABITATS

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MESH Programme

The MESH Programme, fully titled "Development of a framework for Mapping European Seabed Habitats" is a European Union INTERREG IIIB funded marine habitat mapping programme, developing international standards and protocols for seabed mapping. Led by the UK's Joint Nature Conservation Committee, it has focused on seabed areas within North-West Europe (NWE). The diverse habitats and biodiversity of the area are important food and energy resources, as well as essential ecosystem components of North West Europe.

Including all five Member States of the NWE European area (Table 1), the Programme aims to: compile existing habitat maps of the region, harmonized to the EUNIS classification system of the European Environment Agency; model areas where information is incomplete or inconsistent, to predict habitat distribution for unsampled areas and; detail international standards based on the best available expertise, to ensure the quality of future mapping programmes. This framework will be made available to National networks so they can continue to create, collate and improve habitat maps at a national level, contributing in turn to the compilation and aggregation of data at international level.

This report details the main seafloor mapping tools currently being used in seabed habitat mapping and may be considered a literature review of common practices. Many of the survey tools have been developed for engineering and hydrographic purposes and subsequently transposed to habitat mapping, giving rise to a wide range of methods of application. Techniques have been subdivided into Remote Sensing techniques (air and satellite borne sensors), Acoustic Systems (echo sounders), *In Situ* Sampling (grabs, trawls, dredges) and Video and Imaging techniques (photographic and video). This report is not intended as a finite list of technologies and their application, but represents the most significant approaches for mapping seafloor habitats in the waters of the North East Atlantic and North Sea.

For further information visit http://www.searchmesh.net/

Table 1. MESH partners.

Joint Nature Conservation Committee (JNCC)	United Kingdom
University of Gent	Belgium
Ifremer	France
Marine Institute	Ireland
IMARES (formerly Alterra-Texel)	Netherlands
TNO - Netherlands Organisation for Applied Scientific Research	Netherlands
Centre for Environment, Fisheries and Aquaculture Science (CEFAS)	United Kingdom
Agri-Food and Biosciences Institute (AFBI) (formerly DARD)	United Kingdom
Natural England (formerly English Nature)	United Kingdom
Envision Mapping Ltd	United Kingdom
National Museums and Galleries of Wales (NMGW)	United Kingdom
British Geological Survey (BGS)	United Kingdom

Belgium, France, Ireland, Netherlands and United Kingdom.

REMOTE SENSING TECHNIQUES

1 High Resolution Satellite Imagery

Steven Piel and Jacques Populus (Ifremer)

1 – General Principles of Operation

Satellites provide a means for looking at very large expanses of land within a very short time period. Satellite sensors create pictures of the Earth from space using electromagnetic radiation covering a range of frequencies, from radio waves to gamma rays. Electromagnetic radiation from the sun, or emitted from the satellite itself, hits objects on the Earth, and a portion of that radiation is reflected back to the satellite. Sensors on the satellite measure the wavelength and intensity of the reflected radiation. Different objects do not reflect radiation in the same way: clear water, for example, will reflect light differently than turbid water.

Satellite imaging is attractive because it can cover relatively large areas (spanning up to several thousand square kilometres) at relatively low cost. However, it is seldom possible to acquire satellite imagery under the appropriate conditions for effective benthic mapping (such as low-tide or calm sea state). Satellite imaging has proven useful above all in tropical, clear water environments for coral mapping.

Satellite multispectral instruments can create multiple images of a scene or object using light from different part of the spectrum. The imagery has been used very successfully to map vegetation of all types for many years, including tidal vegetation such as seaweed and saltmarshes. It is not as effective on sedimentary areas, where grain size and colour are not fully expressed within pixels of several tens of square metres. If the proper wavelengths are selected, multispectral images can be used to detect bathymetric features and benthic habitats (Meinesz *et al.*, 1991). Under optimal conditions, the nearshore shallow seafloor can be mapped using satellite multispectral imagery. This technique is especially useful for mapping shallow shelf areas where deposition, erosion, and growth of coral reefs can change the bottom topography over a period of a few years (Sabins, 1997). Water penetration increases with decreasing wavelengths (from infra-red to blue), so the blue-green wavelengths are likely to penetrate deepest in clear water.

Satellite data can be purchased from cloud-free archives, although this has proved impractical for obtaining low tide situations, or be specifically programmed for low tide windows, provided the system allows this. In Western Europe (Atlantic coast), the spring low tide occurs in conjunction with the orbiting satellites' overpass (between 10 and 12 AM UT). Therefore, potential low tide acquisitions can be identified by crossing the tide tables and the satellite ephemeris and requesting acquisitions at these times.

The main systems operating today and their overall capabilities are briefly described below.

2 – Variety of Systems Available

2.1 – Landsat Enhanced Thematic Mapper Plus (ETM+)

The Enhanced Thematic Mapper Plus (ETM+) is a multispectral scanning radiometer that is carried on board the Landsat 7 satellite. The sensor has provided nearly continuous acquisitions since July 1999, with a 16-day repeat cycle. The ETM+ instrument provides image data from eight spectral bands (Table 1–1). The spatial resolution is 30 metres for the visible and near-infrared (bands 1-5 and 7). Resolution for the panchromatic (band 8) is 15 metres, and the thermal infrared (band 6) is 60 metres. The approximate scene size is 172 x 183 kilometres, which makes Landsat advantageous in terms of price per pixel. However no satellite programming is possible and only recourse to archive data is available for Landsat, which makes obtaining a low tide image nothing short of a miracle. This is why Landsat has been little used in temperate areas where low tide is a key condition for tidal zone mapping, whereas it has been more widely used in tropical clear water coastal zones where tidal range is less.

Table 1–1. Landsat ETM+ spectral band characteristics (from http://landsat.gsfc.nasa.gov website).

Sensor	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8
ETM+	0.450 - 0.515 (µm)	0.525 - 0.605 (µm)	0.630 - 0.690 (µm)	0.775 - 0.900 (µm)	1.550 - 1.750 (µm)	10.40 - 12.50 (µm)	2.090 - 2.350 (µm)	0.520 - 0.900 (m)
Resolution	30 m	30 m	30 m	30 m	30 m	60 m	30 m	15 m

2.2 – Satellite d'Observation de la Terre (SPOT)

The SPOT programme was created by the French Centre National d'Etudes Spatiales (CNES) and has developed into an international programme with ground receiving stations and data distribution outlets in more than 30 countries.

Spot 5 current features (Table 1–2) are as follows:

- 10 metre full colour resolution;
- 2.5 and 5 metre "pseudo" colour resolution (impractical in the tidal zone, as it requires two overpasses);
- 60 x 60 km² image size;
- 2-3 day repeat cycle (at 45° latitude);
- Very efficient programming service allowing low tide shots;
- Regular delivery time of one week.

Table 1–2. SPOT instrument specifications (from http://spot5.cnes.fr website).

Satellite	Spot 1,2,3	Spot 4	Spot 5
High-resolution instrument (mapping)			
	2 HRV	2 HRVIR	2 HRG
Spectral bands	1 panchromatic (10 m) 3 Multispectral (20 m)	1 panchromatic (10m) 3 Multispectral (20m) 1 short-wave infrared 20 m)	1 panchromatic (2,5 or 5 m) 3 Multispectral (10m) 1 short-wave infrared (20 m)
Swath	2 x 60 km	2 x 60 km	2 x 60 km
Revisit interval	2-3 days	2-3 days	2-3 days
HRS instrument (stereoscopy)			
Spectral bands			1 panchromatic (10 m)
Swath			120 km; aft telescope-20°, forward telescope+20°
Revisit interval			26 days
VEGETATION instrument (low resolution)			
Spectral bands		4 spectral bands	4 spectral bands (1.1 km)
Swath		2200 km	2200 km
Revisit interval		Daily coverage of almost all the globe's landmasses	Daily coverage of almost all the globe's landmasses

2.3 – Compact High Resolution Imaging Spectrometer (CHRIS)

CHRIS is carried on the agile ESA satellite PROBA (Project for On-Board Autonomy) launched on an Indian launcher with IRS-P5. The exploitation of CHRIS data to be acquired as part of the PROBA mission will be organised by ESA's Earth Sciences Division in the framework of the Earth Observation Preparatory Programme. The PROBA instrument payload includes a Compact High Resolution Imaging Spectrometer (CHRIS), a radiation measurement sensor (SREM), a debris measurement sensor (DEBIE), high resolution and wide angle Earth pointing cameras, a star tracker and gyroscopes. Launched in October 2001, PROBA is a technology proving experiment to demonstrate the on-board autonomy of a generic platform suitable for small scientific or application missions. PROBA is equipped with an on-board memory of 1.2 Gbit, of which approximately 1 Gbit will be available for recording CHRIS data. An S-band ground station is located in Redu, Belgium. (http://www.rsacl.co.uk/chris/).

CHRIS provides spectral coverage from 400 to 1050 nm, up to 200 spectral bands in the visible range, (Table 1–3) with a minimum spectral sampling interval ranging from 1.25 to 11 nm and a ground sampling interval of 25m at nadir. The Sira Electro-Optics designed CHRIS instrument is the highest resolution Hyperspectral imager in space and is the only Hyperspectral imager in space designed by a non-US organisation. CHRIS builds up pictures of the Earth using a pushbroom scan and information from programmable groups of bands is captured and stored to form a datacube. With the right configuration of wavebands, it is possible to identify hidden targets, fields of illicit substances, mineral deposits and vegetation types, for instance. CHRIS has been optimised primarily to provide images of land areas, although its inherent programmability enables it to be used for coastal and other applications.

Table 1–3. CHRIS specifications and PROBA orbital characteristics (from http://www.chris-proba.org.uk/ and http://www.research.plymouth.ac.uk/ websites).

Compact High Resolution Imaging Spectrometer (CHRIS)	
Ground resolution	25 m (at nadir)
Image area	18.6km x 18.6km (748 x748 pixels)
Spectral bands	415 – 1050 nm
Measurements	Bi-directional reflectance distribution function (BRDF)
Project for On-Board Autonomy (PROBA)	
Mean altitudes	615 km (560 - 670)
Type of orbit	Near circular, polar, sun synchronous
Repeat cycle	approximately 7 days
Orbital period	96,94 minutes

CHRIS only acquires imagery on highly-selected test sites due to the small onboard memory and only two downlink ground stations. If a site has high priority, then consecutive imagery can be obtained for 3 days, but this would be followed by a gap of 5 or 6 days of orbit before data could be acquired again over that site. It should be mentioned that CHRIS is still in the experimental phase and not in wide use.

2.4 – Ikonos and QuickBird

Ikonos (1999) and QuickBird (2001) are the first commercial high-resolution satellites in the world. The usefulness of Ikonos imagery is being tested by NOAA (The National Oceanic and Atmospheric Administration) to accurately map coral reefs in the Pacific, in spite of the fact that it can only penetrate to a maximum depth of 30 m under ideal conditions. Their high resolution and short revisit rate (approximately 3 days, Table 1–4) make the images very valuable for shoreline mapping and coastal change detection at very local level. However, the effective programming capabilities needed to attain such a revisit rate remain to be assessed.

It should be mentioned that data from these new high-resolution satellites are not yet widely available owing to security and licensing issues and they are still very expensive. A

Table 1–4. Ikonos and QuickBird specifications (from http://www.geosys.fr/, http://www.spotimage.fr and http://www.digitalglobe.com/ websites).

System	Resolution (m)	Image size (km)	Revisit interval (day)
Ikonos (1999)			
Panchromatic	1	11 x 11	11 + programming
Multispectral	4	11 x 11	11 + programming
QuickBird (2001)			
Panchromatic	0.61	16.5 x 16.5	1 to 3.5 days *
Multispectral	2.44	16.5 x 16.5	1 to 3.5 days *

Multispectral - 4 bands (Blue, Green, Red and Near Infra-Red)
* The revisit rate for QuickBird is 1 to 3.5 days depending on the latitude at 70-cm resolution and maximum off-nadir angle.

3 – Review of Existing Standards and Protocols

3.1 – Data Acquisition

Satellite data acquisition has mostly been dealt with above. It depends on each sensor type and ground segment operationability. It is quite difficult to get figures for the ratio of result to shooting effort in terms of programmed acquisition, which are rarely publicised by satellite operators. It is sufficient to say that in some instances in Western Europe, several months were required to get a low–tide, cloud-free image. Moreover, going up the English Channel, the spring low tide progressively moves into phase opposition with the satellite overpass time. Therefore, spring low tide periods are impossible to target east of a line drawn from Portland Bill to Saint-Brieuc, which means that recourse to airborne surveys is needed.

When having to choose between several sensors, it seems, however, that there should be an optimum trade off between coverage and resolution (Figure 1–1 compares resolution of systems). In the past, the rather limited spatial resolution and the orbital cycle of the current suite of satellite sensors did not allow them to provide imagery often enough or with enough detail to be useful in most coastal zones. This is now changing with satellite constellations of side-looking sensors with much higher agility (e.g. the soon to come Pléiades system to replace the Spot series) which will be able to cover a much longer coastal stretch in a single overpass.

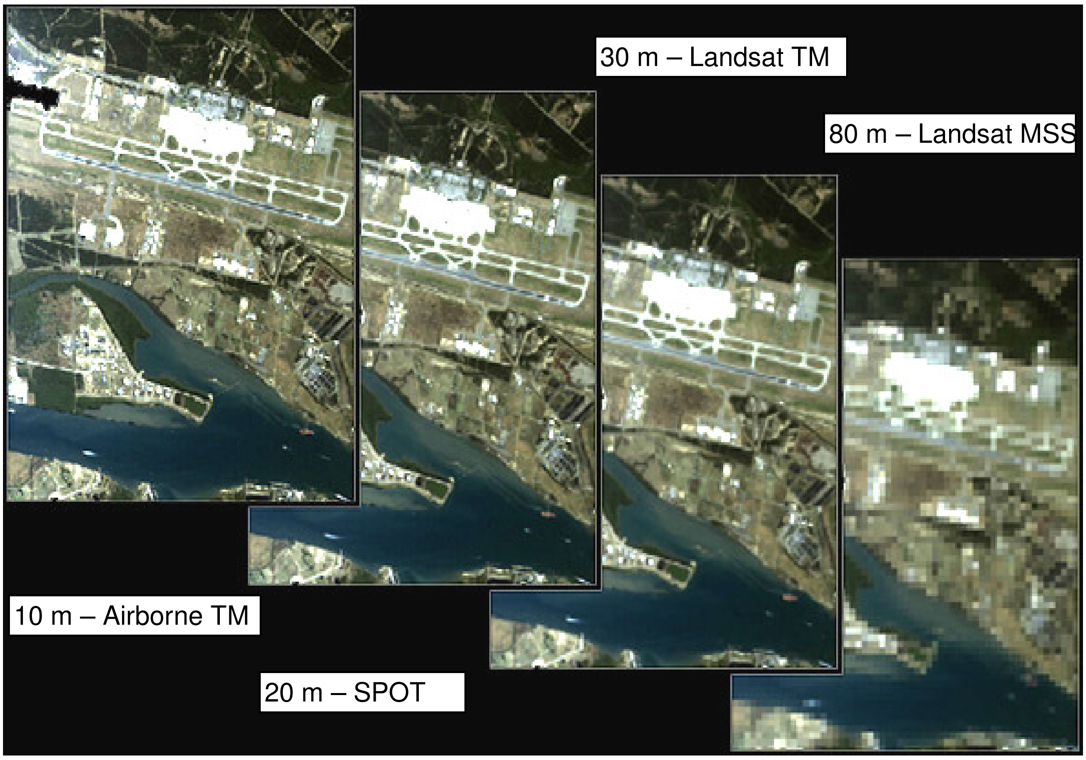

Figure 1–1. A comparison from various platforms (from http://www.airtargets.com.au/ website).

3.2 – Data Processing

In remote sensing, data processing means the operations necessary to bring the imagery into a state where it can be dispatched to interpreters. These operations are covered in "Progress in Phycological Research", volume 12, chapter 4 (Round and Chapman, 1997), as well in the "Remote Sensing Handbook for Tropical Coastal Management" (Green *et al.*, 2000). Basically two types of processing are concerned.

Geometric corrections are needed to geo-reference the imagery, i.e. to plot the data into a mapping system, ensuring registration with other data. These corrections are made necessary by the fact that both satellite and airborne platforms only deliver raw imagery. However, the viewing geometry and the platform attitude are both precisely known, making it possible to resample the imagery at a given mapping reference. Depending on the way these corrections are performed, any piece of satellite data can be assigned a position with accuracy to a decametre (while airborne data are currently accurate to a metre, see below). It is noteworthy however that despite an absolute position still closely dependant on pixel resolution, relative accuracy (i.e. the internal coherence of the imagery) is excellent in satellite imagery thanks to the stability of the space platform.

Radiometric corrections are required for any remotely sensed data, whether satellite or airborne, in order to retrieve highly defined quantity, the normalized measurement of backscatter called reflectance. Without going into too much detail, the intrinsic feature of a ground target when imaged by an electromagnetic system is its ground reflectance. This quantity, being unique to a given target, can be compared and monitored over time. However, most systems fall short in measuring reflectance in two aspects: a) they are too far from the target and only record "at-sensor radiance", so reaching ground reflectance will then require some additional effort; and b) the radiance itself is affected by atmospheric noise, i.e. the influence of the air column between the ground and the sensor. While some users are satisfied with the relative value (the radiance) allowing one-time classifications, others need to retrieve reflectance, as the only way to deal with multi-date studies. These corrections have been fully described by Green, *et al.* (2000). They are performed either by using invariants (stable targets whose reflectance is known once and for all) and regression or by using special software which takes the atmospheric content into account.

3.3 – Data Interpretation

There are several ways of processing remotely sensed data for habitat mapping. Processing is based on the fact that different types of habitats reflect radiation in different ways across the wavelengths, creating a "spectral signature" or in other terms, a colour quite comparable to that seen on an aerial photograph. The differentiation of various habitats will depend on how strongly their colours or spectral signatures differ in the imagery. Of course, resolution is a key aspect of any remote-sensing measurement. Too small a pixel may be worthless if the discriminating power of the spectral bands is not sufficient. This means very small pixels are of more value when dealing with human objects, whereas larger pixels are acceptable for natural targets which are often a continuum. However, some targets such as seagrass patches (which can reach a few dozen square metres in size) require high resolution while others (e.g. large, homogeneous tidal flats) do not.

Processing may also just be computer-assisted photo-interpretation; in this case, the interpreter uses the imagery to actually delineate contours. This is a time-consuming method but still the most powerful, as the interpreter makes full use of pixel information along with the neighbouring information contained in one or several sources of data (e.g. air photography and Lidar digital terrain model) available to him on a single software platform. It is advisable, though, to take advantage of the digital form of remotely sensed imagery (as even air photos can be scanned to a very fine grain) in order to adopt semi-automated or fully automated processes insofar as possible. Time savings are huge, while the loss in terms of information retrieval may be moderate.

Many descriptions of automated processing exist. Generally, it relies on statistical methods referred to as "supervised or unsupervised classification", depending on when and how ground truth data are incorporated into the procedure. It can also be based on the true physical properties (spectral signatures or reflectance in the various bands) of the targets. In all cases, and especially when processing relies on automated methods, validation is a key step that is unfortunately overlooked by many practitioners. Mumby (2000) gave an in-depth look at how validation should be performed and provided a relation between the amounts of field data incorporated versus mapping reliability.

Many authors deal with an entire coastal stretch and try to identify the various facies all at once, from the water line (or even below, in clear water) up to higher levels where salt marshes are found. One of the applications is for mapping shallow seabed features (and seagrass in particular) by using Landsat TM bands with the greatest water penetration, i.e. its blue and green bands (Rasib, 1997). Many studies have been done to map coral reefs using several classification techniques like linear regression, multiple linear regression, non-supervised classification or supervised classification (Liceaga-Correa *et al.*, 2002). Some studies (Call *et al.*, 2003; Palandro *et al.*, 2003; Liceaga-Correa *et al.*, 2002) successfully mapped some habitats, mainly seagrass meadows and coral reefs (with an overall accuracy ranging from 60 to 80 %), with the advantage of allowing a vast area to be mapped in a short time.

In Northwestern Europe, high resolution satellite imagery is not really suitable for identifying habitats under optimal benthic mapping conditions, as it lacks coverage. Nevertheless, a cloud-free Ikonos Multispectral (4 m resolution) image over the Eriskay region (Scotland, UK) could discriminate between typical shallow water habitat types (Malthus and Karpouzli, 2003). This image was first geo-corrected using 22 prominent ground control points on the imagery whose positions were determined to approximately ± 2 m in the field using a GPS. The data were then corrected to ground-based reflectance using the empirical line method, which has been shown to be an accurate method for atmospherically correcting high spatial resolution satellite imagery. After measuring broad-band blue attenuation and Photosynthetically Active Radiation (PAR), the water column correction was applied to produce an image of bottom reflectance. This empirical line method employed to atmospherically correct the imagery gave acceptable results for correcting such narrowly focused and localised datasets. However, the usefulness of the imagery for classification of bottom habitat on the basis of spectral differences alone was less obvious. This highlights the limitation of using just three visible and fairly broad bands to classify targets such as seagrass and algal species, which typically showed up as being relatively dark, with only subtle spectral differences. Further differentiation on the basis of spectral differences alone highlights the need for higher spectral resolution data, as a number of studies have shown (e.g. Mumby *et al.*, 2000).

For shallow waters, what has mostly hampered underwater seabed mapping has been the unknown depth, leading to misinterpretation of bottom types since water depth indeed affects the ability to measure bottom reflectance due to light attenuation. Most studies have been limited to mapping very shallow waters in tropical areas, i.e. corals, seagrass and sandy bottoms.

Multispectral satellite imagery has been used very successfully to map vegetation of all types for many years. If the proper wavelengths are selected, multispectral images can be used to detect bathymetric features and benthic habitats (Meinesz *et al.*, 1991). This technique is especially useful for mapping of shallow shelf areas where deposition, erosion, and growth of coral reefs can change bottom topography over the period of a few years (Sabins, 1997). Water penetration increases with decreasing wavelengths (from infra-red to blue), so the blue-green wavelengths will be likely to penetrate deepest in clear water.

As concerns tidal vegetation, a critical review of remote sensing for seaweed mapping can be found in "Progress in Phycological Research", volume 12, chapter 4 (Round and Chapman, 1997) that illustrates the possibility offered by satellite and airborne imagery to estimate intertidal vegetal cover (saltmarsh, seagrass, seaweeds, etc.) over large areas. This chapter concentrates on seaweed in the various forms found in nature (emergent, underwater or floating) and does not address the sedimentary domain. It deals mainly with passive remote sensing techniques. The main airborne and remote sensing sensors currently utilised for vegetation mapping are described. The acquisition conditions with regard to atmosphere and tide situations are examined. In particular, difficulties in timing satellite acquisition with respect to the tidal cycle are raised, concluding that aerial surveys are needed to get around this problem in some coastal areas.

Furthermore, more detailed image interpretation is obtained in two main ways: a) either by statistically classifying the images using training areas (i.e. pure targets initially identified in the field), b) or by referring to the spectral properties of the targets (also identified in the field with adequate instruments) and the subsequent use of specifically designed indices. To this end, typical reflectance spectra of intertidal algae ranging from 380 to 950 nm were measured in the field and their variation with respect to the substratum's humidity conditions was studied. A biomass inventory has also been drawn from the cover rating of some seaweed species or groups of species (Guillaumont *et al.*, 1997). Following these initial trials, coverage rates, biomass estimates and temporal evolution maps of fucoid seaweeds were produced in Brittany (Perrot *et al.*, 2003).

The review by Round and Chapman describes robust and easily reproducible methodologies for mapping seaweed coverage and provides indications of how the biomass can be determined with additional field sampling. It also reports on how seaweed types (mainly brown seaweed belts) can be categorised which requires remote sensing tools with slightly more sophisticated spectral equipment.

On salt marshes, several inventory studies were also conducted by classifying high resolution satellite imagery which had been proved capable of identifying several major types of haline vegetation. A common tool is the Normalized Difference Vegetation Index (NDVI), which reacts to the density of green matter. The NDVI is sensitive enough to clearly distinguish between e.g. dense Obione cover, tall gramineae and depressions with Salicornia or pioneering patches of Spartina (Populus *et al.*, 2001). Using NDVI, some studies (Guillaumont *et al.*, 1997) were able to clearly distinguish a gradient of density inside a seagrass ecosystem on the Ile d'Oléron (France).

Little is found in the literature on tidal sediments, which illustrates the difficulty in grasping the very subtle shades of colour that sediment types feature. Aerial photography is confronted with the same limitation. Karpouzli and Brown and Belgian have produced quite interesting demonstrations on the use of satellite imagery to map tidal flats. A recent evaluation of Spot 5 for coastal studies showed that with the regular 10-metre colour mode, quality and reliability of coastal inventories had increased. Several sedimentary facies could be identified, particularly up to three types of sand/mud mixtures. However, the imagery failed to bring out zones with boulders and cobbles.

4 – Current Usage

Spot imagery is widely used throughout the world for coastal mapping. It is currently in operational use in France in the Rebent project to monitor large seaweed belts, namely fucales and kelp. Comprehensive coverage of the north-Biscay, Brittany and eastern Channel coasts is planned, with a repeat cycle of six years, in order to monitor changes in seaweed coverage. The methods presented above are deemed robust enough to track changes within such a time period. It is anticipated that the next generation of high-resolution satellites (e.g. the Pleiades constellation or IRS) will have a full colour resolution of around 3 metres. Although improved, problems related satellite and low water conditions are likely to remain the main drawback in the future.

An additional means of working out water depth is radar technology, such as that developed by the Argoss system in the Netherlands (http://www.argoss.nl/projects/index.php?page=basrijkswaterstaat.html).

Argoss has developed the Bathymetry Assessment System (BAS) to construct depth maps from radar images and a limited number of echo soundings by numerical inversion of a two-dimensional model for the imaging mechanism. Some recent maps are presented which were made for Rijkswaterstaat. With the best ERS images, the BAS can produce high quality bathymetric maps in coastal waters with complex topography up to 30 m in depth. In simpler areas like shoals, radar image quality requirements are less stringent, especially when additional information from optical images is used. It will be shown that in such areas the BAS yields bathymetric maps with a quality that is comparable to that of traditional maps based on dense echo soundings alone. Rijkswaterstaat, responsible for coastal monitoring in the Netherlands, has started using the BAS in shallow areas like the Wadden Sea and Western Scheldt.

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2 Airborne Digital Imagery

Steven Piel and Jacques Populus (Ifremer)

1 – General Principles of Operation

This section deals with the main aircraft-deployed (planes, helicopters) electro-optical data acquisition techniques used to help in the fine scale physical characterisation of the seafloor. When applicable, these techniques can generally provide large coverage data on seafloor topography and/or benthic habitat conditions. They are widely used for mapping the tidal zone but also clear and shallow waters.

Although very high spatial resolution satellite data are now becoming available, as mentioned above, the lack of flexibility in the timing of data acquisition is still a limitation. The main advantages of airborne remote sensing for the coastal environment are its greater spatial resolution and the ability to obtain data at optimal times (e.g. with respect to weather conditions and the tidal cycle). Also, many airborne instruments have greater spectral resolution and programmable wavebands. The greater spatial resolution of airborne optical remote sensing has been useful for relatively limited site-specific areas but there are major problems with the geo-registration of airborne images, because of aircraft movements generating distortions that are difficult to correct. Nevertheless, successful examples have been provided by Bajjouk (1996) in France, Yates *et al.* (1996) in the UK, Borstad and Akenhead (1993) and Zacharias *et al.* (1992) in Canada.

Most of the airborne electro-optical techniques operate within the visible and near infrared portions of the spectrum (400 - 900 nm) that can penetrate water to certain depths (Table 2–1). Ten metres of clear ocean water can transmit almost 50% of the incident blue and green wavelengths (400-600 nm) and less than 10% of the red light (600-700 nm) (Sabins, 1997). They also sometimes have spectral bands in the mid-infrared that allow further distinction between vegetation types and other features.

Many private sector vendors are currently deploying airborne multispectral (MS) camera systems (table 1). These sensors are complex systems incorporating multiple cameras, different storage solutions, airborne inertial measurement units (IMU), Differential Global Positioning Units (DGPS), and specialised software for georeferencing, mosaicking, and colour balancing. These multispectral systems can collect stereo black and white, colour infrared, and true-colour imagery using a single pass at the customer-required ground resolution.

Table 2–1. Specifications for a few of the existing airborne multispectral systems (from CSC NOAA website: http://www.csc.noaa.gov).

Sensor	Sensor configuration	Spectral Resolution	CCD Array	Radiometric resolution
Z/I Imaging DMC	4 lenses (pan), 4 lenses (Multispectral)	4 MS bands (B,G,R, NIR) 1 band panchromatic	MS 3K X 2K PAN 7K X 4K	12 bit
LEICA ADS 40	Single lens with beam splitter	4 MS bands (B,G,R, NIR 1, optional NIR 2) 1 band panchromatic (visible range)	12K X 2–pushbroom sensor	8 bit
Geovantage GeoScanner	4-lens system	4 MS bands (B,G,R, NIR)	1.4K X 1K	8 bit
Applanix Emerge DSS	Single lens with beam splitter	3 MS bands (B,G,R) or (G,R,NIR)	4K X 4K	12 bit

Today, airborne multispectral camera systems are usually based on Charge Coupled Device (CCD) arrays and fall into two categories: frame sensors, which use square or rectangular CCD arrays (and have geometric characteristics similar to those of a film camera) and line sensors (“pushbrooms”) or scanners, which use linear CCD arrays and therefore have geometries similar to satellite sensors.

The main factors complicating multispectral mapping of coastal areas are clouds, narrow tide windows, atmospheric effects and the water column overlying submerged vegetation. Clouds can be avoided and imagery obtained during low tide windows by careful planning of aerial data acquisition. Cloud-free mosaics can usually be generated, even with 40% cloud cover. The other effects can generally be minimised or eliminated during image processing. In the case of CASI or other such instruments, multiple narrow bands and small pixel size are critical when the objective is to distinguish vegetation types in a heterogeneous environment (such as a marsh) and when mapping linear vegetation features (such as algae along a shoreline).

Airborne hyperspectral imaging is an emerging technology that has recently been used to classify benthic habitats in coastal zones. Hyperspectral sensors are remote sensing instruments that can collect up to several hundred spectral bands of data at a high spatial resolution. These sensors are generally mounted on light aircraft but can also be placed on satellite platforms. Data are collected at contiguous, narrowband wavelengths for a specifically defined portion of the electromagnetic spectrum (usually between 400 to 900 nm). In order to determine what the reflectance represents, the reflected spectral data obtained by the hyperspectral sensor is compared and matched to spectral data of known absorption features. While spatial resolution depends on the altitude of the aircraft and usually ranges between 1 and 20 m, the spectral bands measured and the bandwidths used can be programmed to meet user specifications and requirements.

Hyperspectral imaging also has its limitations. It has limited availability and may not be cost-effective. Also, because of its capacity to collect several hundred bands of data at high resolution, somewhat advanced software is needed to process and analyse these data.

2 – Variety of Systems Available

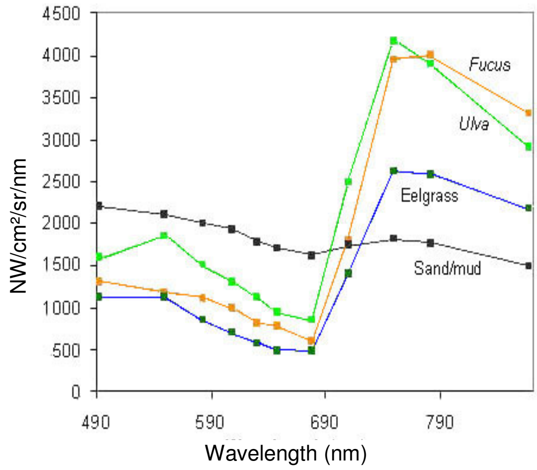
2.1 – Compact Airborne Spectrographic Imager (CASI)

The Compact Airborne Spectrographic Imager (CASI, manufactured by Itres Instruments Ltd. of Calgary, Canada) is a pushbroom sensor that simultaneously acquires data in up to 288 visible and near infra-red channels between 0.4 and 1.05 µm for the latest CASI-3 sensor. CASI has become a very widely used system over the last ten years and many references are available. Several studies showed that among the 288 spectral ranges, 11 non-continuous ones (Table 2–2) are designed to discriminate intertidal vegetation (Berry *et al*., 1997). Studies showed that some band sets could be used especially for intertidal habitat mapping (Thomson *et al*., 2003). In order to obtain ground truth data to base the habitat analysis of the imagery on, a ground level survey must be made. Pure beds of the target habitat classes can be identified in the imagery from GPS coordinates and from them, spectral signatures are generated for each of the classes (Figure 2–1).

Table 2–2. CASI bands used for intertidal discrimination purposes (from Berry *et al*., 1997).

Band	Wavelengths	Purpose
1	470-515 nm	Chlorophyll b absorption at 480 nm; Carotenoid reflectance peak at 500 nm; Penetration of clear water
2	540-560 nm	Green vegetation reflectance peak (eelgrass and green algae) Penetration of turbid water
3	575-590 nm	Brown algae absorption well
4	600-615 nm	First reflectance peak for brown algae
5	625-635 nm	Well between reflectance peaks for brown algae
6	640-655 nm	Second reflectance peak for brown algae, chlorophyll b; absorption at 650 nm (eelgrass)
7	670-690 nm	Absorption well for chlorophyll a (all vegetation)
8	704-714 nm	Red rise, near infrared reflectance for shallow submerged and floating vegetation, but avoiding 720 nm water vapour feature
9	743-755 nm	Near infrared reflectance for submerged and floating vegetation, but avoiding 762 nm water vapour feature
10	775-786 nm	Near infrared reflectance for emerged and marsh vegetation, substrate delineation
11	854-876 nm	

Figure 2–1. Spectral signatures for representative Prince Rupert Harbour habitat classes (Canada) (from http://web1.borstad.com/papers/rupertpaper.html. Mapping Intertidal Habitat in Prince Rupert Harbour, 1996).



While spatial resolution depends on the altitude of the aircraft, the spectral bands measured and the bandwidths used can all be programmed to meet the user's specifications and requirements. Such hyperspectral sensors can be important sources of diagnostic information about a specific target's absorption and reflection characteristics, effectively providing a spectral "fingerprint".

2.2 – Daedalus Airborne Thematic Mapper (ATM)

The ATM (Daedalus AADS1286 Multi-Spectral Scanner) is a scanner that records across a swath of 716 pixels (covering a wider angle than CASI) in 11 fixed wavebands (Table 2–3) covering visible, near, middle and thermal infrared. The scan mirror has three synchronised speeds (12.5, 25, and 50 Hz) to optimise the scan-rate to more closely match data acquisition and coverage over the ground at various altitudes, thus avoiding any under-sampling or too much over-sampling of the data in the along-track (flight-line) direction. An approximately 10% overlap of successive scans is normally used to avoid missing areas on the ground caused by changes in aircraft velocity or attitude. Actual pixel size (ground spatial resolution) will be dependent on the aircraft's flying altitude, since the ATM sensor has a fixed Instantaneous Field of View (IFOV) of 2.5mrad (~0.14°).

Table 2–3. Spectral bands available from the Daedalus ATM and current satellite systems (from Thomson *et al.*, 2003 and http://www.airtargets.com.au/).

Wavelengths (µm)	visible 420-450	450-520	520-600	605-625	630-690	695-750	near infrared 760-900	910-1050	middle infrared 1550-1750	2080-2350	thermal infrared 8500-13000
Daedalus 1286 ATM	1	2	3	4	5	6	7	8	9	10	11
SPOT satellite	- -	- -	PA (Panchromatic mode) XS1	XS2			- XS3	- -	- XS4	- -	- -
Landsat TM satellite	-	1	2	-	3	-	4	-	5	7	6

3 – Review of Existing Standards and Protocols

Many of the interpretation procedures for airborne digital imagery are similar to those of satellite imagery, as there is essentially no difference between since the two types of imagery are basically the same. Airborne imagery is similarly affected by the atmospheric content, unless flights are performed below 1,000 metres of altitude. As regards geometry, inertial systems and GPS have made such progress that imagery geo-referencing has now become commonplace. See the satellite section of this review and both references quoted there.

CASI image processing allowed dense and sparse habitat to be distinguished in the intertidal habitat-mapping programme of Hood Canal (Washington, USA). This programme collected 19-band CASI imagery during a spring low-tide series in 2000. After geocorrection and removal of downwelling light effects, they obtained a pixel size of 1.5 m to map two cover classes of seagrass (*Zostera marina*) and six other estuarine habitat classes. Both an unsupervised and a supervised classification have yielded good results except for oyster beds, which were difficult to separate from the wet sand-gravel-cobble class (Garono *et al*., 2004, Dekker *et al*., 2003).

CASI and Daedalus ATM data have also been used for intertidal sediment and salt marsh mapping in eastern England within the framework of the LOIS BOITA (Land-Ocean Interaction Study, Biological Influences On intertidal Areas) programme. Twelve classes of intertidal sediments and vegetation (Figure 2–2) were mapped with an approximately 70% correspondence with ground data (Thomson *et al*., 2003).

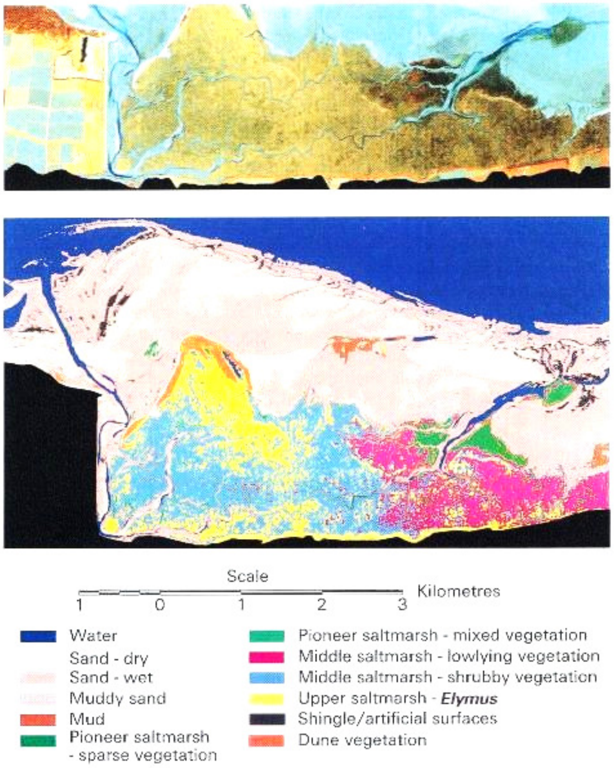


Figure 2–2. CASI image (above) and detailed class map with key (below) of the Wells to Stiffkey area of North Norfolk, UK (from Thomson *et al*., 2003).

Attempts to map intertidal vegetation with CASI in temperate regions were generally successful. The increase in the number of spectral bands and secondarily in spatial resolution (4-5 metres) compared to satellite imagery such as Spot enhanced the discrimination of several types of brown seaweed (Larsen *et al*., 1998). Bajjouk (1996) used an iterative scheme mostly based on seaweeds' spectral properties to identify the main types of fucoids and red seaweeds found in coastal Brittany.

Vegetation types that can be mapped generally include estuarine marsh species (willow, cattail, sedge and bulrush), intertidal algae (green and brown algae, including kelp), and eelgrass. The broad-scale substrates which can generally be identified are tidal flats, sand and cobble. Figure 2–3 is a CASI image of tidal deposits of *Ulva lactuca* in northern Brittany which was processed for biomass estimates.

Digital imagery has often been successfully used to classify tropical benthic habitats including coral reefs, seagrass, macroalgae (fleshy and turf), unconsolidated sediments, uncolonised hard-bottom and encrusting algae (Chauvaud *et al*., 1998; Warner *et al*., 2000; Goodman and Ustin, 2001).

A comprehensive review of surveying the coastal zone with CASI and interpreting its data is given by Brown *et al.* (2003) with focus on SACs (special areas of conservation).

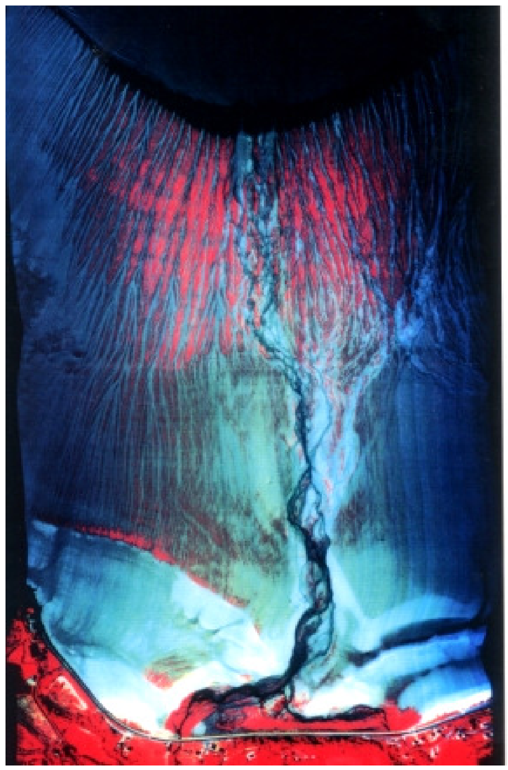


Figure 2–3. CASI imagery (colour infrared composite) of September 1993 showing green algae deposits in Saint-Michel-en-Grève, France.

4 – Provenance and Current Usage

Remote sensing digital imagery is at a crossroads, as the various techniques are tending to converge in terms of current capabilities. On one hand, satellite imagery is currently reaching metric resolutions in colour mode and improved platforms and ground segments are capable of delivering high quality homogeneous imagery in requested time windows, which makes it a strong competitor for airborne techniques. On the other hand, airborne cameras show very promising swath, resolution and sensitivity with the latest CDD arrays (12000 pixels) although they operate only in a few classical spectral bands (typically B,R,V and IR).

Formerly, elevation and planimetric data had to be acquired in two separate surveys which were a) a colour photography survey (having to choose between true colour and infrared colour) and b) a black and white photography survey for relief extraction by stereoscopy. Note that IRC (infra-red colour) surveys were very rare, as they only satisfied a small community dealing with vegetation. In terms of heights, obtaining vertical accuracy of 25 cm required photographs on a scale of 1/12000.

By flying today's cameras at the proper altitude (similar to conventional aerial photography, i.e. in a range of 2000-4000 metres), it is possible to achieve in a single flight a) pixel size of 25-50 cm, b) vertical accuracy of 25 cm obtained by stereoscopy either sideways with sufficient overlap between flight lines or in backward/forward mode and c) high rate of coverage.

Processing atmospheric effects, which is compulsory for such altitudes, has become commonplace. Besides, the 12 bit sensitivity of recent CCD arrays allows easier band matching for seamless mosaicking (edge effects being a well known complication of classic aerial photos). This improved sensitivity also allows more efficient automatic correlation in less textured areas, a key condition in order to keep vertical accuracy nominal overall. The associated DTM is then used to produce digital ortho-images.

As a result of these advances, multipurpose ortho-image mosaics with full four-band capability are now readily available for use by various practitioners as well as by the wider public. Costs are expected to be around 100 euros per km^2, which is a cheap alternative to other combinations of sensors (see CASI and LIDAR). However, the benthic community will have to accept vertical accuracy of only about 25 cm at best, which may be of limited value for some habitats such as macrophyte belts, for instance.

CASI-type hyperspectral instruments remain rare and highly specialised. Although apparently quite versatile, airborne systems will always suffer from a few inherent limitations, namely the need for very clear days (especially when a higher flight altitude is required) and the low geometric quality of the data which require considerable work to be produced in geo-registered mosaics.

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3 Aerial Photography

Steven Piel and Jacques Populus (Ifremer)

1 – General Principles of Operation and Data Processing

Aerial photography has been used for well over 100 years to help support a wide range of mapping applications. Though its use for land-based surveying and mapping applications is widespread, it is only in the last few decades that aerial photography has become a useful tool for certain broad-scale benthic habitat mapping applications. More recently, aerial photography has benefited from the huge progress made in computer technology, making it possible to digitise photographic prints down to their ground resolution (roughly 10 microns, typically 25 cm on the ground) and be easily handled on PCs. This has also made georeferencing of aerial photos a very common and easy task.

2 – Variety of Systems Available

Rather than a variety of systems, a variety of configurations is addressed here. Typically, aerial photography for broad scale coverage is acquired on a scale of around 1/25000. In France, for instance, full coverage of the coast at low tide was undertaken over the period from 2000-2001, with production of a 1/25000 ortho-mosaic. This type of product provided planimetric interpretation down to a scale of 1/10000. In this process, a DTM (Digital terrain model) was computed using analytical stereoscopic restitution of pairs of photos. Typical accuracies achieved in this kind of process were 2 metres horizontally, and 0.4-0.6 metre for the tidal zone or 1 to 1.2 metres vertically in respectively well textured (e.g. rocky) and smooth (e.g. tidal flats) areas.

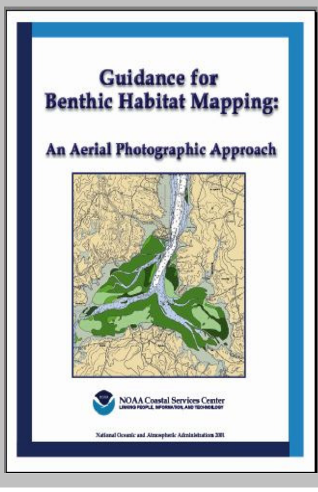
This type of survey is neither time- nor cost-effective, as it requires highly technical facilities in terms of the carrier and platform setup. Of course, it is more adapted to more local needs, as specific surveys can be tailored to any type of scale.

When more flexible and/or cheaper surveys are required (e.g. for mapping seagrass beds in summer at low tide), then using lighter carriers, such as ULMs or even UAV, may be envisaged. These carriers can be hired and lightweight professional cameras mounted on them at short notice when suitable conditions occur. Such photographs have several drawbacks: a) being shot from low altitude, they are small in size, though with very high definition, b) their verticality is only approximate and c) their location on the ground is unknown, which is critical in tidal zones where very few conspicuous marks are available. The way to deal with them is described below.

Box 3-1.
Technical guidance for data developers working to produce digital spatial data on benthic habitat. (Finkbeiner *et al.*, 2001).

This paper is deals more particularly with the field of aerial photos. The methods described in this document are designed to meet the following general objectives:

- Produce digital baseline data on the spatial extent and characteristics of benthic habitats.
- Produce synoptic data over estuary-sized study areas.
- Provide data that optimise the efficiency of further in-situ sampling.
- Provide data at a resolution that can contribute to environmental permitting processes.
- Produce data that support change detection over extensive areas.



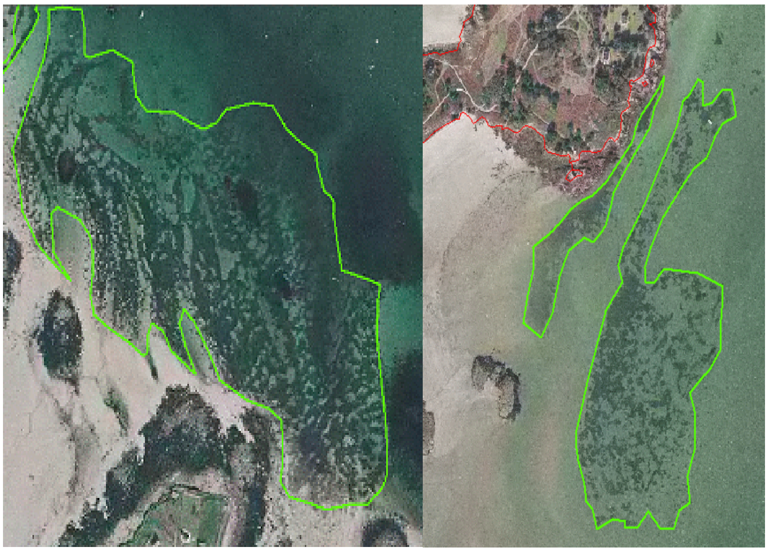
3 – Review of Existing Standards and Protocols

3.1 – Planimetric Interpretation

Many useful tips for aerial photography can be found in the Technical guidance for data developers working to produce digital spatial data on benthic habitat by Finkbeiner *et al.*, 2001.

Diverse benthic habitats have been successfully mapped using aerial photography. They include seagrass meadows (patchy or continuous), coral reefs, unconsolidated sediments, shellfish beds (oysters and mussels), hard-bottom areas, soft corals, macroalgal beds, and drifting algal accumulations. Aerial photographs can reveal the spatial extent and distribution of a habitat, habitat fragmentation (expressed as a percent bottom-cover value), and, in the case of submerged aquatic vegetation, qualitative measurements of biomass. Habitats or characteristics that are more difficult to map with aerial photography include low-biomass submerged aquatic vegetation, clam beds, bacterial mats, tube worms, habitat health, species composition and sediment texture. Though the depth of the photic zone will vary with water clarity and can reach 30 m in clear tropical water, it remains limited to roughly 10 metres in the temperate seas of Northwestern Europe.

In the framework of the French benthic network (REBENT), mapping of seagrass done along the Brittany coast showed that some habitats can be easily delineated using littoral orthophotography. Moreover, the study (Levêque, 2004) introduced a criterion of density (fragmentation rate) and one of quality (reliability rate) for each of the polygons digitised from the aerial photography (Figure 3–1).



RR: 1 ; FR: 1   RR: 1 ; FR: 2

Figure 3–1. Seagrass habitat mapping (Zostera marina), Aber Wrac'h (left), St- Jacut de la Mer (right), France (from Levêque, 2004). RR: Reliability rate; FR: Fragmentation rate (on a scale of 1 to 5).

Many studies can be mentioned, like the environmental monitoring programme developed to detect changes caused by building a 'fixed link' between Denmark and Sweden (Øresund). This work used aerial photography to study changes in seagrass communities during its construction. The scientists involved in the monitoring programme felt that aerial photo interpretation was a sufficiently sensitive tool to detect changes over time (http://www2.dmu.dk/rescoman/Airphoto/ap1validat.htm).

The advantages of aerial photography are the following:

- Photographs provide a visual assessment of relatively remote areas;
- They can be obtained at relatively low cost;
- Photographs can often be found from the present day back to the 1940's, providing insights into habitat change.
- The disadvantages are:
- Maximum water depths for bottom visibility are often <10 m (furthermore, few photos are taken under low-tide conditions);
- Sun glint and waves can render an image virtually useless and are a considerable nuisance for seamless mosaicking and interpretation;

- Often the time at which the images were acquired is not optimal for water clarity.

When photos are extracted from archives, additional drawbacks arise:

- The photography's coverage can be patchy – over both time and space;
- The photography was almost certainly acquired to map the land - not the water - and many areas of shallow water are missed;
- Mapping of highly dynamic habitats is complicated because the extent and condition of the habitat can change rapidly with the seasons and even storm events. The date of acquisition of the pre-existing images is often not consistent with important habitat fluctuations.

These reasons lead users to conduct ad hoc surveys in some instances. For reasons of cost-effectiveness they may be willing to adopt "in house" techniques such as using ULMs. When looking at either multi-date surveys or ULM-acquired, very high definition photography, attention must be given to potential geo-referencing hazards. It is advisable to rely wherever possible on a high quality archive ortho-photographic mosaic upon which specific subsequent imagery will be overlaid and rectified. This actually is the only way to deal with rectifying e.g. makeshift ULM-acquired photographs over tidal zones. Image registration can then be performed by image warping, using ground control points identified on both sources. This operation has been well described in the literature and is even currently available in image processing freeware.

3.2 – Stereoscopic Interpretation

Being primarily designed for elevation mapping and DTM (Digital terrain model) production by stereo-restitution, photogrammetry is also used to detect objects. This only concerns the tidal zone, as underwater stereoscopy is affected by water refraction. The advantage for the interpreter, with respect to classic planimetric studies, is the enhanced vision of the terrain provided by the third dimension and hence greater ability to delineate units which appear identical on the photo.

This entails time-consuming and costly processes (aero-triangulation, stereo preparation, etc.). After digitising the printouts, the two files are input to an analytical device that performs automatic correlation and provides 3D vision. The quality of the stereo-restitution depends greatly on the quality of the local correlation of the two photographs. Typically, for photos at 1/25000, accuracy of 40-60 cm can be expected on targets with enough texture to ensure proper aero-triangulation and correlation (basically, rocky units). Besides automatically computing a DTM, the 3D vision can be used by the interpreter to delineate homogeneous units and label them according to his knowledge of the terrain. Subtle breakpoints and slope changes can help the operator make up his mind in some tricky cases.

However, this technique is only available in the very few laboratories equipped with analytical stereo-plotters, which are primarily used for DTM production rather than photo-interpretation. It is therefore of quite limited use to the benthic habitat mapping community.

4 – Provenance and Current Usage

The aerial photographic technique is still widely used for habitat mapping in tidal and shallow water zones. Full intertidal mapping coverage of the Welsh coast was carried out in accordance with the CCW handbook for marine intertidal phase 1. Thanks to high resolution aerial photography, restitution was done at a very high scale of 1/5000 which shows very small units on the ground.

In Brittany, the Rebent programme made use of comprehensive photographic coverage performed in 2000-2002 in spring low tide conditions. The orthophoto layer was used as a) a geometric reference, its absolute positioning accuracy being 1 to 2 metres and b) an interpretation reference, as quite a number of targets could be identified in them. However it was felt that the production of the orthorectified mosaic suffered from many flaws and in many instances it was deemed preferable to use the original films, despite the amount of additional work necessary (scanning and geo-registration, absence of ortho-rectification). The initial films' quality could not be matched by the mosaic, and gave much deeper insight into subtle nuances. However, much care had to be taken to limit errors due to these images' inherently lower geometric quality.

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4 Lidar

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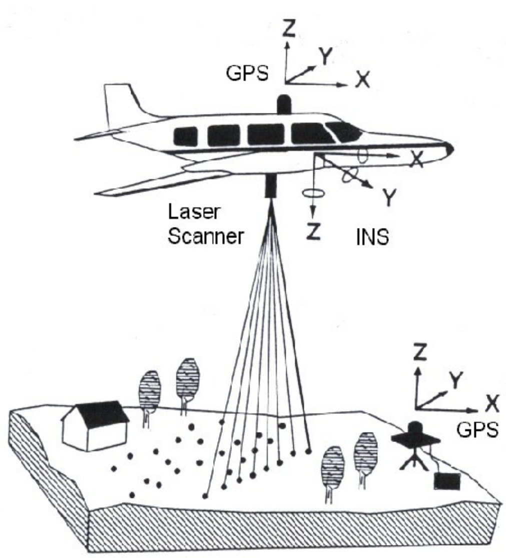
1 – General Principles of Operation and Data Processing

1.1 – General Facts about the Lidar Technique

Laser Induced and Ranging (LIDAR) is an airborne mapping technique which uses a laser to measure the distance between the aircraft and the ground. Since the 1970s the application of airborne LIDAR for topographic and bathymetric mapping has matured at a rapid pace, with the first commercial Lidar systems appearing in 1993. Much of this growth has directly followed advances in high speed digital and analogue electronics along with increases of several orders of magnitude in computer memory, storage capacity and processing speed.



The basic components of a Lidar system are a laser scanner and cooling system, a Global Positioning System (GPS) and an Inertial Navigation System (INS) (Figure 4–1). The laser scanner is mounted in an aircraft and emits infrared laser beams at a high frequency. The scanner records the difference in time between the emission of the laser pulses and the reception of the reflected signal. A mirror is mounted in front of the laser. The mirror rotates and causes the laser pulses to sweep at an angle, back and forth along a line. The position and orientation of the aircraft is determined using a phase differenced kinematic GPS. There is a GPS is in the aircraft and several ground stations (differential GPS) are located within the area to be mapped. The orientation of the aircraft is controlled and determined by the INS.

Figure 4–1. Lidar georeferencing system (from Earth Observation Magazine, Feb 1997 in http://www.personal.psu.edu website).

The principles of topographic and bathymetric Lidar mapping rely on the accurate round-trip travel time of a laser pulse transmitted from the Lidar system to a surface target. Travel times of the laser pulses from the aircraft to the ground are measured and recorded along with the position and orientation of the aircraft at the time of the transmission of each pulse. In operation, successive laser pulses are sequentially scanned across the water surface to produce, when combined with the aircraft's forward velocity, a swath of nearly evenly spaced soundings. Firing the laser at thousands of pulses per second and scanning the beam across the terrain using a scan mirror generates a dense distribution of ranges to the surface. After the flight, the vectors from the aircraft to the ground are combined with the aircraft position at the time of each measurement and the three dimensional X, Y and Z coordinates of each ground point are computed. Different approaches are used to resolve the return in time, including simple ranging to the first or last detected return, ranging to the first and last return, ranging to multiple returns, or digitising the entire backscatter return amplitude as a function of time.

A given system having a fixed frequency, dot spacing is a function of the flight altitude only. Since accuracy decreases with altitude (due to atmospheric content), the flight parameters will be dictated by the project requirements in terms of both accuracy and dot spacing. Another constraint in the case of visible light is the regulation of the particular laser for eye-safe range. Typical operating specifications permit flying speeds of 75 to 250 kilometres per hour, flying heights of 100 to 5000 metres, a scan angle up to 20 degrees and pulse rates of 2000 to 25,000 pulses per second. These parameters yield enough data points to create a highly accurate digital terrain model (DTM). Users of this technology have typically achieved accuracies of 15 centimetres RMS in terms of elevation on regular surfaces and half a metre for horizontal positions.

There are two main types of systems operating with different light frequencies (Figure 4–2): the first is the "topographic Lidar" with only one near-infrared (IR) wavelength, between 1047 and 1540 nm according to manufacturers, the other one is the ALB (Airborne Lidar Bathymetry) consisting basically of two rays at different wavelengths: blue-green (532 nm) and near-infrared. Usually ALB systems are also geared to survey in dual modes, i.e. topographic and hydrographic.

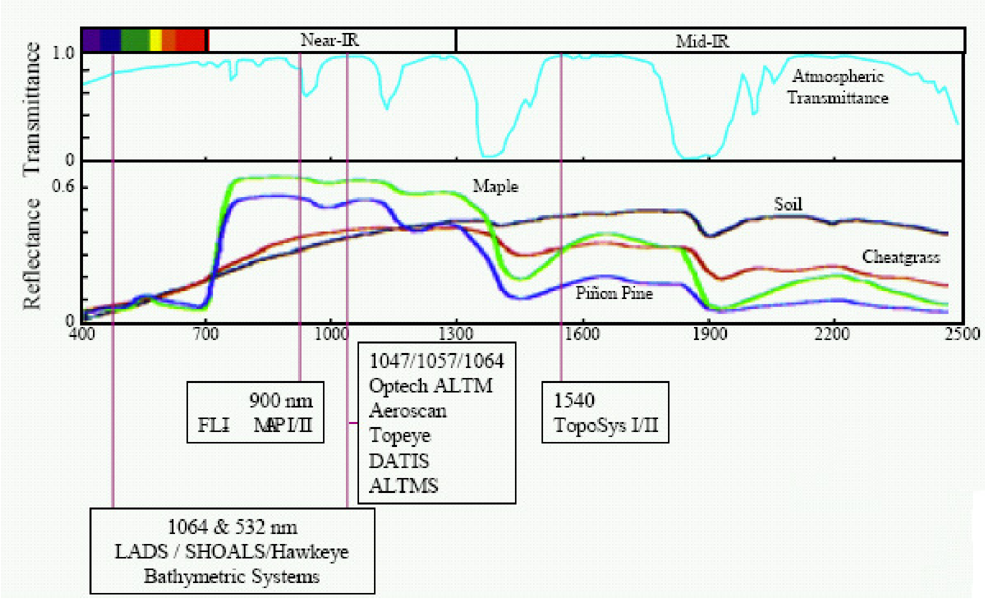


Figure 4–2. Wavelengths ranges for the different Lidar sensor systems (from Colorado State University website: http://www.cnr.colostate.edu).

1.2 – Topographic Lidar Description

The topographic Lidar emits pulses of light in the near infra-red (typically around 1 to 1.5 µm). The measurement of the time lapse between emission and return provides a way of knowing the distance between instrument and ground. Laser pulse backscatter return energy resolved in time provides a measure of the distance to vertically separated features, including canopy layers and the ground, where illuminated with laser energy. Ground resolution is typically metric while vertical resolution is about half a metre. In the coastal zone, only a few types of human built objects are erect, e.g. mussel poles or metal structures for oysters. A sufficient number of rays hit both the top of these structures and the ground below, producing two pulses which can be separated by the instrument gating. Water theoretically absorbs IR radiation; however, in reality the high sensitivity of the telemeter allows detection of surface returns even in slightly turbid waters. Vertical accuracy is expected to be better than 15 cm on regular terrain. However this value is degraded at higher altitudes and flying above 1,200 metres is not recommended.

1.3 – Airborne Laser Hydrography Assessment

Airborne laser hydrography systems accurately determine water depths by measuring the time of flight of two laser pulses at different wavelengths: one is backscattered by the sea surface, the other travels through the air-water interface to the bottom. An optical receiver on the aircraft detects the pulse reflections from both the seabed and the sea surface (Figure 4–3). The water depth is determined by the elapsed time between these two reflection/scattering events, after accounting for the system's operating geometry, propagation induced biases, wave height and tide effects. The horizontal coordinates of the soundings are determined from the aircraft position, altitude and attitude, the direction of the laser beam with respect to the aircraft and the measured water depth. The laser beams are swept in either an arc or a rectilinear scan across the direction of travel with a swath width typically half of the altitude. The surface sounding density can be varied from as little as 2 x 2 meters up to 5 x 5 m spacing and higher. The typical flying altitude is below 500 metres.

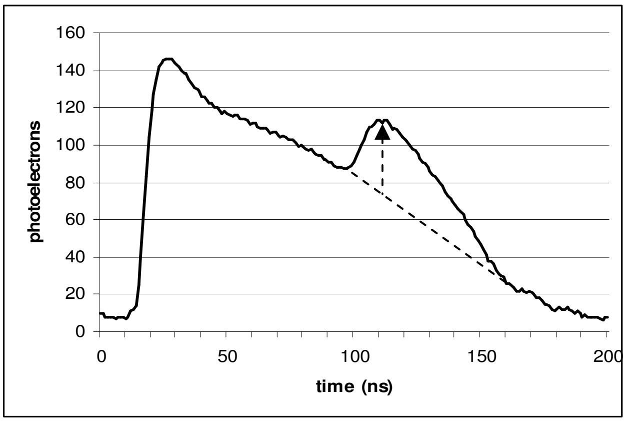


Figure 4–3. SHOALS green APD waveform and bottom peak signal (shown as arrow) (from Tuell, 2004).

Lidar bathymetric technology utilises the reflective and transmissive properties of water and the sea floor to enable measurement of water depth. When a light beam hits a column of water, part of the energy is reflected off the surface and the rest, unless absorbed by particles in the water, is transmitted through the column. As the light travels through the water column and reflects off the seafloor, scattering, absorption, and refraction all combine to limit the strength of the bottom return, and therefore the system's maximum extinction depth. This depth is a function of water clarity, and is generally about 2 to 3 times the Secchi depth (Smith, 2000). As shown in Figure 4–4, for turbid water, the extinction coefficient is smallest in the green part of the spectrum close to 0.6 nm. The presence of organic matter in the water tends to displace light penetration towards higher wavelengths.

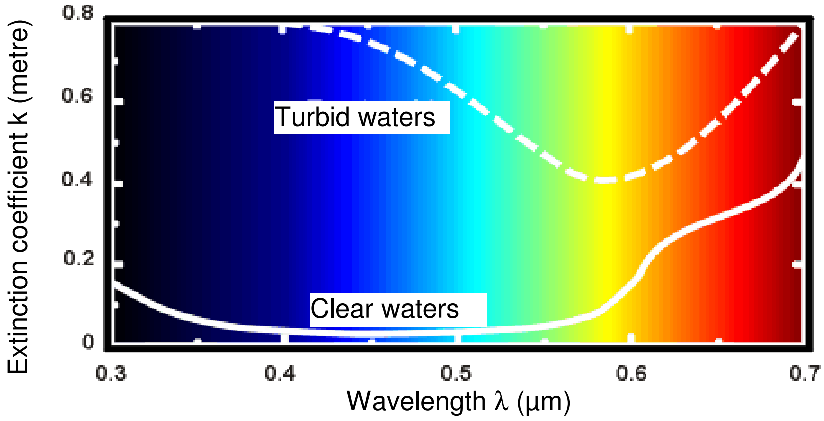


Figure 4–4. Evolution of the seawater extinction coefficient according to the wavelength (from http://isitv.univ-tln.fr/~lecalve/oceano/Figures/fig310.htm website).

Hydrographic Lidar can be used to complement acoustic survey techniques in several ways. While acoustic multibeam systems have revolutionised bathymetric data acquisition in medium and deep waters, they are generally much less effective in shallow water (less than 10 m below LAT). In contrast, Lidar systems have been specifically designed for use in such challenging environments and can provide uniform and dense data in even the shallowest water (Figure 4–5). Unlike multibeam systems, the Lidar's swath coverage is independent of the water depth. Because of its ability to achieve coverage rates several orders of magnitude higher than any of the acoustic methods, Lidar will likely be a cost-effective tool for surveying large and shallow areas with generally good water clarity. In very clear water it can be effective to depths of 50 m, but in turbid water it is only successful to depths of 2-3 times the Secchi disk. In general, Lidar systems will not be applicable in areas with chronic moderate to high turbidity. In areas where the turbidity may be variable over a wide range of values, it is critical to schedule Lidar operations during a period when the conditions are favourable, e.g. low discharge from coastal rivers and neap period.

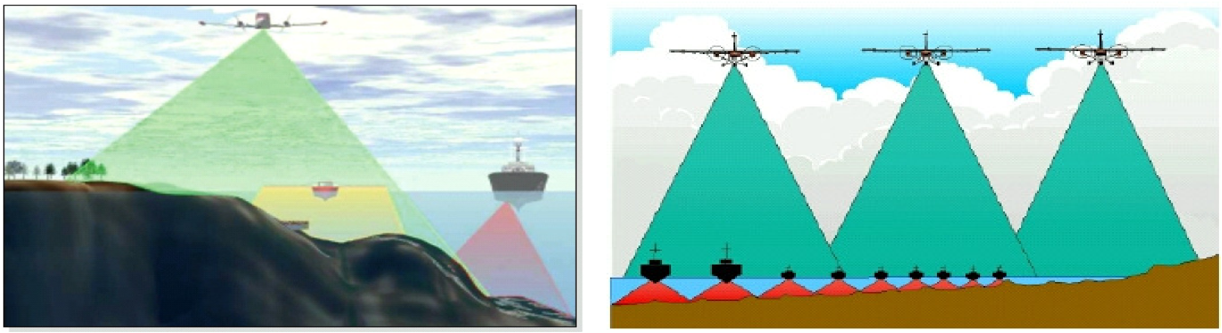


Figure 4–5. Depiction of Lidar and multi-beam sonar operation in shallow water to emphasise Lidar capabilities and efficiency (from Banic, 1998 and Guenther, 2000).

The advantages and constraints of ALB may be given as:

- The speed with which data can be collected for large areas provides a snapshot on a regional scale. Consecutive surveys can be compared to monitor changes in bathymetry and topography that occur over time, such as beach, cliff erosion and coral reef damage. ALB is ideally suited to undertake repeat surveys of mobile or critical seabed areas.
- Considering Lidar is non-intrusive, remote, shallow waters, rocky shorelines and coral reefs that present extreme hazards for survey vessels are easily surveyed without endangering the environment.
- A significant advantage of airborne laser bathymetry is its ability to work in dual mode, i.e. surveying very shallow water (< 10 m) across the shoreline and up onto land (topographic elevation). There is no degradation in vertical accuracy, no change in sounding density, and no adjustment in aircraft track to match the shoreline direction.
- Acquisition can be done by day or by night. The flight plan is similar to that of a classic aerial survey. A 40% overlap between flight lines must be ensured to provide proper geo-referencing. Of course, for tidal zone acquisitions, these flight lines must be positioned with respect to the varying water levels. Operation time is therefore reduced to a few hours around low water. Typically, the surface range covered per hour is between 20 and 30 km².
- One feature shared by all bathymetric Lidar systems is the need for non-turbid water conditions.
- DEMs need time and qualified people to process the Lidar data.

2 – Variety of Systems Available

2.1 – Airborne Laser Terrain Mapper (ALTM)

ALTM (Airborne Laser Terrain Mapper) is an Optech topographic Lidar system. The ALTM 1225 (Figure 4–1) with a frequency of 25 KHz at a maximum operating altitude above ground of 2000 m (Figure 4–6) can survey up to 80 km² per hour. The latest sensor, the ALTM 3100, offers area coverage rates as high as 100 kHz at 1100 m altitude and it can fly as high as 3,500 m with coverage rates as high as 33 kHz. Additional options include a 4k x 4k integrated metric frame digital camera for geo-referenced (x,y,z) colour or colour-IR images with sub-pixel accuracy.

Table 4–1. ALTM 1225 characteristics (from Optech website, http://www.optech.on.ca).

Aircraft altitude	1000 - 5000 ft
Aircraft velocity	85 - 110 knots
Swath width	approx. 2/3 Aircraft Altitude
Laser wavelength	1064 nm
Laser Pulse rate	25 KHz
Laser scan rate	20 Hz
Laser Scan angle	+/- 20 degrees
IMU frequency	50 Hz
Number of returns recorded	2
Laser footprint	10 - 20 cm

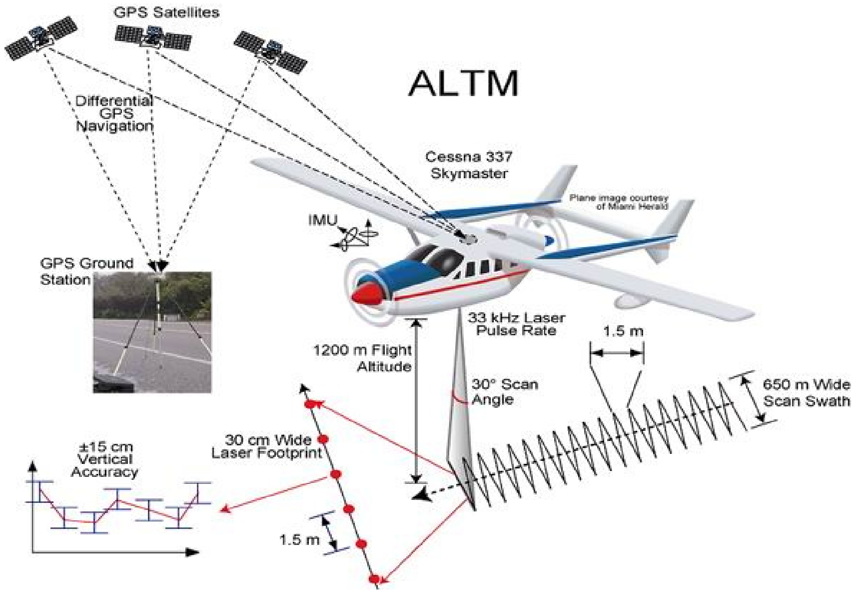


Figure 4–6. Schematic diagram showing ALTM data acquisition parameters to record topographic data (from http://ihrc.fiu.edu/lcr/research/airborne_laser_mapping/).

2.2 – Laser Airborne Depth Sounder (LADS)

The original LADS has been in routine survey operation with the Royal Australian Navy Hydrographic Service since February 1993, and has surveyed more than 75,000 sq km (22,000 sq nm) in 8 years of operation.

The manufacturer Tenix LADS Corporation now uses the new generation LADS called LADS Mk II (Table 4–2). The Airborne System (AS) is fitted into the Dash 8-202 aircraft, which flies 8-hour survey sorties. The AS comprises a solid state, 900 Hz pulsed Nd:YAG LASER mounted on a stabilised platform. Depth data is generated by firing laser pulses into the ocean and recording sea surface and seabed reflections. LADS Mk II normally surveys on a 5m x 5m rectilinear grid across a 240 metre swath during mainline sounding and higher sounding densities to 2m x 2m are available if required.

Table 4–2. Summary of LADS MkII's performance characteristics (from Tenix website: www.tenix.com).

Sounding Rate	900 Hz (3.24 million soundings/hour)
Area coverage	19 sq nm/hour (64 square kilometres/hour)
Sounding density	5m x 5m, 2m x 2m, 3m x 3m, 4m x 4m capability)
Swath width	240 m
Bathymetric depth range	- 70 m to - 0.5 m
Maximum topographic height	+ 50 m
Depth accuracy	S44 IHO Standard for Hydrographic Surveys Special Publication of 4th Edition 1998, Order 1
Position accuracy	5m CEP 95%
Data processing to data collection ratio	Better than 1:1
Output	Fairsheet plots and digital data in ASCII formats

2.3 – Hawk Eye Systems

In 1985, the Swedish Defence Research, FOI, was ordered by the Swedish government to develop a laser system for submarine hunting. FOI named the system FLASH and engaged Saab in Sweden, Feary in Australia and Optech in Canada as subcontractors. FOI made the system design and the control software based on own resources. Based on FLASH, Saab developed Hawk Eye. Saab is a subcontractor to Optech for the SHOALS system to US Navy. Saab has delivered Hawk Eye systems to the Swedish Navy, SMA (Swedish Maritime Administration) and Indonesia. SMA has employed a Hawk Eye system for a large share of their hydrographic surveys for many years.

Today, Swedish experts, Airborne Hydrography AB (AHAB), TopEye AB of Sweden and the United Kingdom Hydrographic Office are launching a joint venture called Admiralty Coastal Surveys. This new venture will enable the partners to develop Hawk Eye II - a Lidar system that can offer images of extremely high quality and definition in clear water depths of up to 30 m plus (the depth capability is 2.5-3 times the Secchi depth).

Hawk Eye II Laser Bathymetry and Topography System, LBTS, is an airborne system using laser technology for fast and accurate surveying of shallow waters, coastlines, shores, land and islands. At less than 200 kg, the compact and light design can be used by just one operator and pilot in any small aircraft. The Hawk Eye system includes ground equipment for mission planning and hydrographic/topographic processing, all at considerably less than the cost of multi-beam surveying.

The sounding density may be set at 0.1 – 10 m (this fulfils the IHO S44 requirements). The flight altitude can be varied between 100 and 1000 meters, and normal flight altitude is 200-300 m with a nadir angle of 15-20°. The minimum depth detection with Hawk Eye I (the previous system) was 0.3-0.4m. Hawk Eye II should have better discrimination due to shorter laser pulses, better receivers and better processing algorithms. The system is usually optimised around IHO Order 1 requirements. It may be possible to re-optimise around shallow depth detections for a particular task (according to Peter Hobson, Admiralty Coastal Surveys Managing Director, September 2004).

2.4 – Scanning Hydrographic Operational Airborne Laser Survey (SHOALS)

SHOALS is a successor to Optech's first airborne laser bathymetry system, the LARSEN 500, which was developed for the Canadian Hydrographic Service. The LARSEN 500 has been in operation since the mid-1980s on all three coasts of Canada and internationally in areas such as Indonesia, Barbados and the Middle East. It was used to produce the world's first nautical chart based on airborne laser data.

The SHOALS minimum depth capability was limited to about one metre. However, with the recent implementation of a special "shoreline depths" processing mode, SHOALS can now provide continuous topographic and bathymetric mapping through the shoreline from water onto land. Turbid water, weather-related phenomena and bottom structure can limit SHOALS depth determination. The typical maximum depth capability is 40-50 m in coastal waters and less than 20 m in more turbid inland waters. Heavy bottom vegetation and "fluid mud" may limit system performance as well.

The Lidar transceiver consists of a 200 Hz frequency-doubled Nd:YAG Laser which produces both green (532 nm, 3-5 mJ, 5-6 nsec) and infrared (1064 nm, > 5 mJ, 7-9 nsec) pulses. A two-axis, pitch/roll-corrected scanner is used to sweep the Laser beam pointing direction across the aircraft in order to produce a nearly-uniform distribution of laser spots on the water surface. In addition, the transceiver records laser energy return time series (waveforms) with four receivers. One receiver records the infrared energy reflected from the water surface (surface return) and two collect the blue-green energy reflected from the sea bottom (bottom return, Figure 3). A fourth receiver records Raman energy, at 645 nm, which results from excitation of water molecules at the sea surface by the blue-green laser energy. The Raman waveform and the infrared waveform yield direct ranging of the sea surface, while the two blue-green waveforms directly range the sea bottom from 0 m to 10 m and from 10 m to 60 m. The infrared waveform is also used to distinguish dry land from water. Additionally, one blue-green waveform is used to directly range topographic elevations.

The signals from each of the channels are pre-processed using a sophisticated analogue processing module and are digitised (for each Laser sounding) and recorded for use in off-line processing. All other required system parameters, as well as the scanner angles and the aircraft position and altitude, are also recorded for later processing. A down-look video system simultaneously records the area being surveyed below the aircraft. Global features of data delivered by SHOALS are given in Table 4–3.

Table 4–3. Nominal SHOALS System performance (from Cunningham *et al.,* 1998).

Parameter	Value	Notes
Measurement Rate	200 soundings/sec	
Altitude for data collection	200 – 400 m	
Sounding density	4 x 4 m	200 m altitude, 50 knots
	6 x 6 m	300 m altitude, 70 knots
	8 x 8 m	400 m altitude, 85 knots
Area coverage	3 nm^2/hr	200 m altitude, 50 knots
	> 6 nm^2/hr	300 m altitude, 70 knots
	> 10 nm^2/hr	400 m altitude, 85 knots
Maximum Depth Capability	> 3.0 (day)	K : diffuse attenuation coefficient (1/m)
$(Kd)_{max}$	> 4.0 (night)	d : bottom depth (m)
Maximum Depth Range	40 – 60 m	Depending on the water clarity
Minimum Depth Capability	0 – 1 m	Without the "shoreline depth" mode of operation allowing continuous measurement from subsurface bottoms to on-shore elevations.
Horizontal accuracy	± 4 m (DGPS)	1 standard deviation
	± 1.5 m (KGPS)	
Vertical accuracy	± 20 cm	1 standard deviation
Data processing ratio	1 : 1	

The SHOALS system also collects a directly downward-looking, geo-referenced video concurrently with the Lidar measurements. In addition to offering a visual record of the survey area, the video is frequently used to position coastal features such as navigation aids, piers and other objects of interest.

Finally, it is worth mentioning the Fish LIDAR Oceanic Experimental (FLOE) system that was built in the early ‘90s from the off-the-shelf components, where improvements were made to signal processing techniques used to discriminate fish returns from small particles in the water. The FLOE system penetrates depths up to 50 m. It has been used off the coast of California to survey anchovy and sardine (Figure 7), and more recently to measure plankton, squid, and marine mammals. Comparisons of LIDAR with acoustic data have been very encouraging, and these methods can produce similar results.

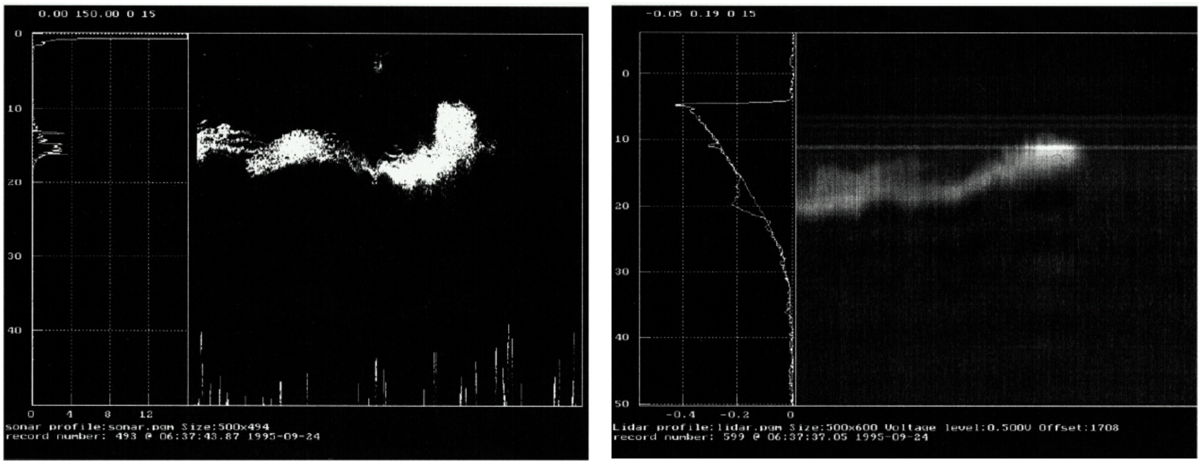


Figure 4–7. Comparison of synoptic acoustic and LIDAR signal-return data for the same school of sardines observed off the coast of southern California (from Brown *et al.*, 2002, in Churnside *et al.*, 2001, Remote sensing of capelin and other biological features in the North Pacific using LIDAR and video technology, ICES Journal of Marine Science, 59, 1120-1130).

3 – Review of Existing Standards and Protocols

Very few guidance documents can be found today about Lidar. Many papers in journals partly describe operations (mostly for topographic Lidar) and processing, however ROGs (Recommended Operating Guidelines) are still needed.

3.1 – Data Acquisition

Lidar airborne operations are quite similar to those of other airborne surveys, with a few particular features. Some surveying tips are given below:

- As it uses active light, the weather must be fair but clouds are no problem, provided they are located above the flight altitude with wind under 20 knots. Day or night-time periods can be used.
- Generally, the tide must be low, so windows centred on low tide time will be chosen. For tidal zone mapping, surveys should be made from 1 hour before to 1 hour after the spring low tide;
- For hydrographic Lidar, the neap tide low tide can ensure reasonably low water levels combined with reduced currents and sediment bottom removal.
- Flight lines should be made as long as possible to optimize survey duration, and organised so as to survey the shallower parts when the water level is lowest.
- From experience, state of the art coverage rates in complex shores are roughly 40 and 15 km² per hour for topographic and hydrographic surveys respectively, however the resolution of the latter is typically 2-3 times lower.

3.2 – Data Processing

Note: processing of hydrographic Lidar is not dealt with here.
Processing topographic Lidar data requires two major steps, which are a) quality checking of the raw data and b) building the data into a user-friendly DTM (Digital Terrain Model) for subsequent use along with terrain nature data. Some authors (Joinville, 2002, Daniels, 2000) give a good account of their procedure and guidance can be found there. However, operational documents fully describing these steps have not been produced yet. In short, quality checking mainly means checking three points: density, horizontal and vertical accuracy.

The data density requirement may not be fulfilled when the survey's navigation was not properly carried out, resulting in gaps between adjacent swaths or over water patches (as water theoretically absorbs the infrared radiation). The operators usually provide a density map along with the data files.

Accuracy is checked by way of high quality DGPS determination of reference surfaces. In practice, it is recommended that two of these references be surveyed per aircraft sortie, basically one at the start and the other at the end. Typically, these surfaces should be smooth and rather flat, so that horizontal inaccuracy has a limited influence on vertical accuracy. The best surfaces are playing grounds, with a large flat area surrounded by vertical objects (hedges, railings, posts). The validation is a two-step process. The horizontal positioning check should be carried out first: this is done by surveying a number (e.g. 30) of “vertical objects” in the field, namely by their footprints on the ground. After horizontal accuracy has been shown to be within the specified limits (i.e. 0.3 metres RMS for Lidar spots), the vertical check can be performed. A set of surveyed points distant from one another by more than the Lidar spot spacing (i.e. about 3 to 5 metres) is selected. Lidar spots no more than one metre away are then chosen and paired with the ground points. If there are enough of them, these pairs can then be processed statistically. The literature (Huising, 1998, Joinville 2002, Populus, 2003) shows that on bare, smooth and moderately sloped terrain, accuracy of better than 0.15 m RMS is achieved at all times with topographic Lidar. These Figures deteriorate with the terrain type, e.g. low-lying vegetation such as tidal marshes, and slope, as is the case in cliff type shorelines.

Lidar data are extremely voluminous, leading to (x,y,z) ascii files exceeding 20 Mo per km². Building gridded DTMs has the advantage of reducing this size by about two thirds. Besides, it is easier to handle raster files than point files under GIS. Usually, the latest pulse data are considered first, since they represent the ground. Unfortunately, they may also be generated by the top of some objects showing no double pulse (e.g. boats). In that case, only sophisticated filtering routines or visual inspection will allow them to be retrieved. The procedure to process topographic Lidar data into a DTM involves several steps: elimination of duplicates and outliers, identification of water surfaces, interpolation to adequate mesh sizes according to the users’ requirements.

As concerns the height reference, Lidar DTMs are initially expressed in a terrestrial system (WGS 84 or geoid level). Conversion to a tidal reference (LAT or Lowest astronomical tide) is only possible where precision tide data are known, so as to apply the shift between the LAT level and geoid level.

3.3 – Data Interpretation

For habitat mapping, two kinds of information are expected from Lidar range data, i.e. elevation and slope. Raster DTMs have to be displayed in such a way to aid orientation in the field. Slopes can also be computed and displayed. Specific height isolines are also useful (e.g. lower saltmarsh level). An example is shown below (Figure 4–8) of a Lidar DTM of one metre mesh size (initial spot spacing was about 1.5 metres) covering the Traict du Croisic, Loire-Atlantique, France. The colour spacing is every 25 cm. During field surveys, the elevation displayed on this map helped identify the main landforms and position the field sample locations (sediment and fauna). Interpretation was then done in conjunction with other data. The DTM was exploited jointly with aerial photos and samples for final habitat mapping.

The map below (Figure 4–9) shows LADS bathymetry merged with a topographic DTM (Digital Terrain Model) from part of Wembury Bay, UK, where both altitude references have been fitted to provide a seamless transition across the coastline.

A comprehensive review of surveying with Lidar and interpreting its data is given by Brown *et al*., 2002.

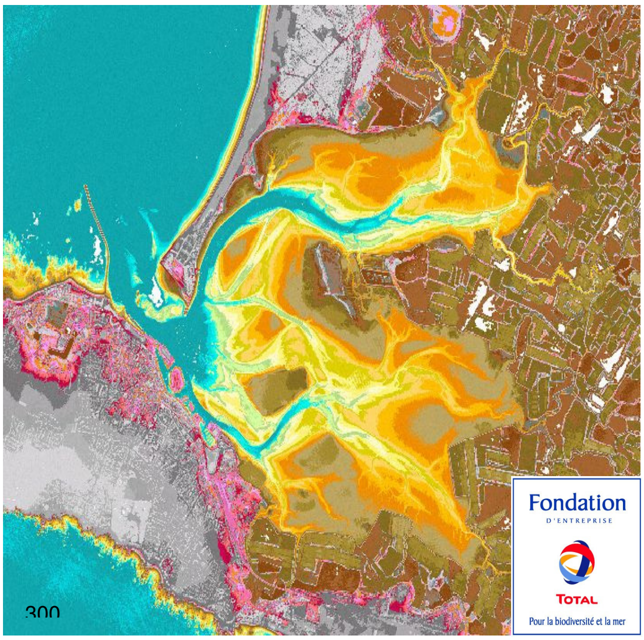
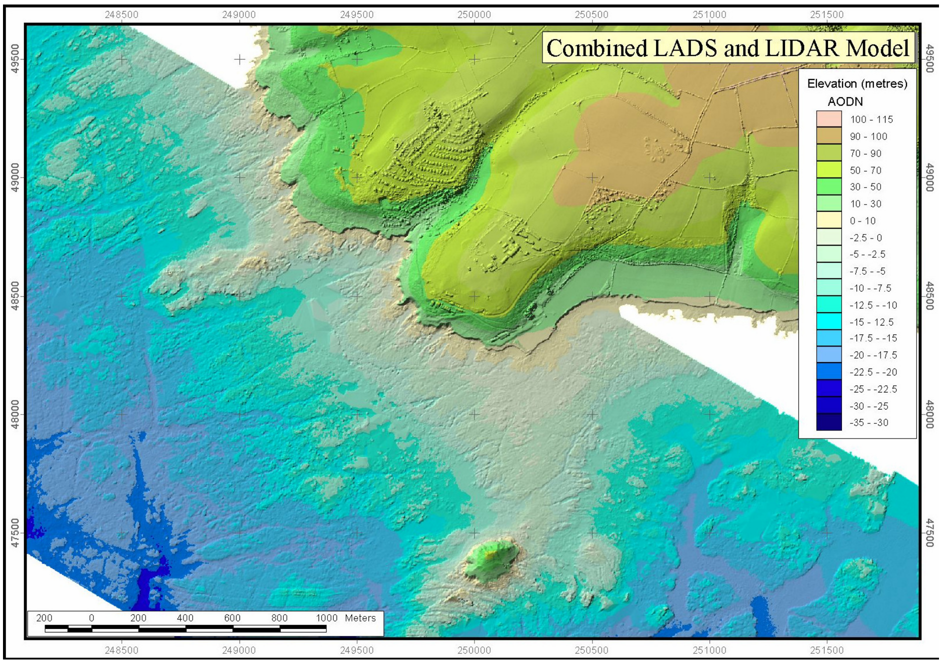


Figure 4–8. A topographic map of "Traicts du Croisic", Loire Atlantique, France at spring low tide (IFREMER).

Figure 4–9. Combined topographic and hydrographic Digital Elevation Model of Wembury Bay, UK (UK Environmental Agency).



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5 Planning Considerations for Remote Sensing of Benthic Habitats

Steven Piel and Jacques Populus (Ifremer)

In complex inshore areas, airborne techniques will likely be favoured for efficiently acquiring broad-scale survey data. For instance, aerial photography and/or hyperspectral imaging may be the best tools for identifying and delineating some habitats and topographic Lidar may be the most effective tool for generating high-resolution topography and bathymetry over broad, nearshore survey areas. Where applicable, aerial techniques will satisfy most of the data requirements and at a much more rapid area coverage rate than any boat survey. But acoustic or sampling operations by boat or by foot will be necessary to fill in coverage gaps or to generate ground-truth comparison data (Table 5–1 describes scales of surveying techniques).

However, these techniques will generally be of limited value in providing physical seafloor characterisation data in estuarine environments (i.e., one that is shallow, generally turbid and comprised primarily of soft and/or fine-grained sediments). In this case, though boat-deployed acoustic techniques have much slower survey coverage rates (especially in shallow waters), they are the only means of reliably acquiring the required broad-scale physical characterisation.

Although the identification of data requirements is often listed as a critical first step in the development of a plan to acquire benthic habitat data, in most cases the data acquisition tools available to meet the data needs in shallow waters will not vary a great deal between projects. For this discussion, it is assumed that a benthic habitat mapping project will entail some combination of broad-scale characterisation data and fine-scale sampling data. As addressed in more detail in the sections below, the selection of specific techniques within each of these two main categories will depend on the type of general environment, availability of existing data, variability of the habitat, habitat scales to be delineated, spatial extent to be covered and budgetary constraints. Ultimately, this section is intended to provide a general framework to select the most appropriate data acquisition techniques based on numerous project-specific considerations.

1 – Data Requirements versus Spatial Scales

Several of the planning decisions that need to be made regarding survey techniques will be based on the expected variability in the topography and habitat types likely to be encountered within the survey area. One of the key issues to address in this initial planning phase is how to balance the available resources between the broad-scale and fine-scale sampling effort. In general, if the topography and/or the composition of the seafloor are likely to vary significantly within a survey's data, then the broad-scale characterisation will be important to accurately delineate the extent of this variability. Follow-on fine-scale sampling operations will be used to selectively describe different habitats identified in the initial broad-scale characterisation. For any seafloor environment, the development of a comprehensive fine-scale sampling plan is necessary to establish a positive relationship between the benthic communities of interest and the physical seafloor habitat.

One of the fundamental concepts for understanding the distribution of benthic habitats is their variability over space and time, and it is important at the outset to note the distinction between three types of spatial scales, namely "habitat scale", “surveying scale” and “mapping scale”. Habitat scale is generally determined by the real extent of a distinct biological community or geological feature(s) of interest, regardless of any one sensor’s capability to detect and measure it and independently of a map's ability to display it. Surveying scale refers to the smallest object a given sensor can distinguish and is closely linked to its resolution. Mapping scale is defined as the relationship between the size of a feature (*i.e.*, habitat) on a map and its size in the real world.

For instance, a "seagrass habitat" could be described as occurring on a meso to macro scale, as seagrass often grows in large areas of coastal waters (e.g., thousands of square metres) and can therefore be delineated from aerial photographs in clear water (Finkbeiner *et al*., 2001). Seagrass can however, also occur in much smaller patches of a few square metres and/or in turbid waters. At micro scale, mapping seagrass distribution may require higher resolution than that available from airborne tools. Survey techniques like underwater photography or diver transects can effectively measure and map such microscale habitats.

If knowledge about seagrass habitat distribution is deemed essential, then survey techniques able to cope with such fine scale patchiness will have to be deployed, *i.e.* those with metric resolution. In this respect, Table 5–2 gives the ranges of sampling scales for a number of acoustic/optical sensors: a) high resolution satellite sensors (5-30 metres with high coverage and/or high acquisition revisit capabilities), b) a host of airborne sensors with limited coverage but very high resolution and high flexibility with regard to low tide constraints, c) acoustic sensors suitable to various depth ranges and d) “in situ” tools observing from short distance and sampling tools.

Table 5–1. Scales and methods for sampling coastal subtidal habitats (modified from Finkbeiner *et al.*, 2001).

Sampling scale	Method	Examples
1: 100,000 to 1: 30,000	Satellite sensors	SPOT, Landsat,
1: 30 000 to 1: 5,000	Airborne sensors	Aerial Video Imagery (AVI) and Aerial Photography (AP) Airborne Laser Bathymetry (LIDAR) which uses infrared and blue/green laser pulses to measure seafloor depth; possibly other information contained in backscatter characteristics such as schools of fish and bottom type Compact Airborne Spectral Imager (CASI): a Multispectral sensor that digitally records data along the flight path
1: 10,000 to 1: 10,000	Laser line scanner	Towed or airborne sensor capable of near video quality swath imaging of seafloor
1: 10,000 to 1: 1000	Hydro acoustic sensors and post-processors	Low frequency echo sounders for water depth and with post-processing of return backscatter for substrate characteristics Sidescan sonar can visualise seafloor morphology and seabed texture
1: 1000 to 1: 10	In situ visual or camera sampling	Free swimming or towed SCUBA Remotely Operated Vehicles (ROV) Drop or towed cameras
1: 100 to 1: 10	Removal sampling methods	In situ sampling by divers or ROVs Remote stationary sampling methods : grab or core samples

Table 5–2. Area of seafloor mapped (expressed as unit effort km²/h) versus resolution for different remote sensing systems (modified from Kenny *et al.,* 2000) and Diaz *et al* 2004)).

Technology	Area Mapped	Resolution (horizontal m)								Remarks (Example)
	$Km^2.h^{-1}$	10^3	10^2	10	1	0.1	10^{-2}	10^{-3}	$<10^{-3}$	
Remote Sensing, Satellite	>1000	X	X	X						Restricted to operational coverage and mainly shallow seas (Mumby and Alasdair, 2002)
Remote Sensing, Aircraft	>10			X	X					Generally restricted to water depths < 6 m (Moore *et al.*, 2000)
Laser Induced Detection And Ranging (LIDAR)	>10			X	X					Generation of high resolution terrestrial or underwater Digital Terrain Models (Populus, 2001)
Multi Beam Bathymetry	5		X	X	X	X				Allows the use of backscatter data to characterize substrata (Cutter *et al.*, 2003)
Side Scan Sonar	3.5		X	X	X	X	X			Size of surface coverage (swath) depends on the frequency used (Greene *et al.*, 1999)
Synthetic Aperture Sonar	3.0					X	X	X		Optimal operation at 50 - 100 <kHz
QTC-View, RoxAnn, EchoPlus	1.5		X	X	X	X				Substrate classification (Greenstreet et al., 1996)
High Resolution Sub-bottom Profiler	0.8	X	X	X	X	X				Narrow beam sub-surface coverage (Hovland et al., 2002)
Video Camera	0.2				X	X	X			Allows mega-epibenthos identification and provides ground truth for acoustic survey mapping technology. (Diaz *et al.*, 2003)
Grab/Core Samplers	0.003					X	X	X		Quantitative data on the macro and meiofauna requires additional analysis in a laboratory (Clarke *et al.*, 2002)
Sediment Profile Camera	<0.001						X	X		Sediment-water-interface inspections (Valente *et al.*, 1992)
X-ray photography	<0.001						X	X	X	High resolution geochemical and physical inspections (water content, density) (Schaffner *et al.*, 1987)

Table 5–3 further compares two major acoustic tools, multibeam sounders and sidescan sonars. For depths of less than 50 metres, sidescan sonars have quite higher resolution and a similar coverage rate to multibeam sounders. Below 50 metres, sounders provide increasingly efficient coverage, at the expense of resolution. Besides, since the sidescan sonar fish is towed at a constant depth, it cannot be used easily in shallow waters (under 10 metres). For the coastal fringe, small vessels equipped with hull-mounted acoustic systems are better adapted.

Table 5–3. Resolution and covered surface for a Multibeam Sounder and a Sidescan Sonar (from Kenny *et al*., 2000 in Ehrhold, 2003).

Depth (m)	**Multibeam Sounders EM1000 (12 knots)**			**Sidescan Sonar MS992 Simrad (4 knots)**		
	Range (m)	Max. coverage area (m)	Covered surface (km²/day)	Range (m)	Max. coverage area (m)	Covered surface (km²/day)
10	70	2.4	40	400	1	67
50	350	12	195	400	1	67
100	700	24	390	400	1	67

As regards the mapping scale, the example of seagrass bed mapping is quite meaningful. Due to their patchiness, effective mapping of seagrass beds may involve capturing contours at scales on the order of 1:5000 (survey scale), which means that the survey data must be compatible with this scale. However, rendering it along with larger sized targets such as macrophyte belts and tidal flats will be tricky: when the latter are captured and displayed on a 1:25000 scale map suitable for them, the former become dot-like and lose legibility. Mapping generalisation is then needed. This is a process that generates broad-scale maps from finer scales ones by merging these small entities with their surroundings. Generalisation will entail going upscale in the typology towards less detailed levels (e.g. the type of sediment supporting seagrass, in this case). In our example, to avoid losing the trace of seagrass entities on a scale of 1:25000, the cartographer will have to resort to some type of non-zonal representation.

2 – Temporal Scales

Seasonal or annual fluctuations in sunlight, water temperatures, and current velocity can significantly change the biomass extent of habitats. Consideration of potential temporal variations is particularly important when collecting and analysing baseline biological data, because accurate detection of changes over time requires comparing two or more data sets collected under similar, if not identical conditions. Calculating annual changes in seagrass cover or density, for example, depends on collecting data at the same time each year to reduce error due to seasonal fluctuations. The degree to which benthic habitats vary over time is strongly influenced by the physical oceanographic environment. For instance, benthic habitats in the intertidal zone can be expected to vary with greater frequency than habitats in deeper offshore waters. Time scales on the order of hours can be important in shallow estuaries. Also, extreme tidal events or floods can scour the bottom of a river or estuary and significantly alter the distribution of sediment and associated biological communities.

Airborne operations (or even satellite image acquisition programming) must be carefully planned in many respects. For airborne imagery, besides seeking low tide situations, the season should be chosen with respect to plant phenology and light conditions as well as the period of the day. In the case of hydrographic Lidar, the right period of the year should be chosen in terms of river runoff and the weather conditions prevailing a few days before the survey monitored, so as to avoid high turbidity levels.

The time allowed for mapping a survey site depends on the length of shore to be surveyed in the season. According to the Countryside Council for Wales (Wyn *et al*., 2000), a target of 100 km per survey team (two surveyors) per season has been established to enable the project to be completed within the agreed time-frame. For the four years that the survey has been running, each team has covered on average 0.6km per hour, (0.17km²/hr), or 2.4km/tide (0.68km²/tide), assuming four hours of survey per tide.

This Figure varies considerably with the characteristics of the shore and whether the surveyors are on foot or in a boat (Table 5–4).

Table 5–4. The effect of shore type on survey speed (rough guide) (from Wyn *et al.*, 2000).

Shore type	Survey Method	Survey Time Hours (4 h/tide)	Site Length km	Site Area km²	Km/h	km²/h
Sandy shore	foot	8	8.2	3.64	1.025	0.5
Bedrock cliff	boat	3	5.1	0.11	1.7	0.04
Sandy mud inlet	foot	8	4	2.23	0.5	0.3
Thick mud estuary	boat and foot	15	33.5	4.3	2.2	0.3
Muddy gravel inlet	foot	8	4.3	0.81	0.5	0.1
Complex mixed shore	foot	8.5	7	0.65	0.8	0.08
Complex bedrock platform	foot	7	3.6	0.6	0.5	0.08
Complex shelving bedrock	boat and foot	9	13	0.52	1.4	0.06

The length of coastline that can be covered each day depends on:

- whether access is by foot or by boat;
- type of access when on foot;
- weather conditions
- shore type, and
- level of survey detail required for a particular stretch of coast.

3 – Ground Truthing Techniques to Validate Remote Sensing Data

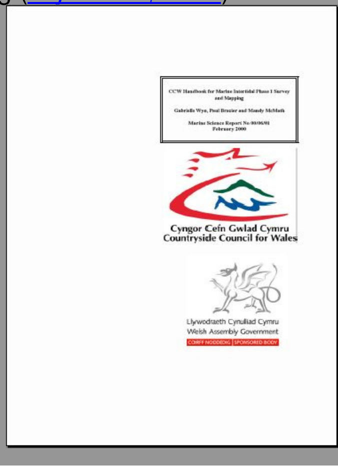
Field surveys are critical to any successful remote sensing approach. Owing to the difficulties of mapping submerged habitat imposed by the intervening water column, field surveys are even more critical to creating accurate underwater benthic data. Field surveys provide critical opportunities for educating image analysts, verifying the accuracy of data, deploying ancillary technologies to assist in the mapping and documenting more detailed habitat character and conditions. Field surveys are often however, one of the more costly components of a project. For this reason, efficiency in conducting field operations is especially important. Field activities typically fall into one of two general categories, signature development and accuracy assessment, the former occurring primarily at the beginning or during a project and the latter at the end of any remote sensing project. Regardless of whether field verification is for signature development or final accuracy assessment, many of the methods for recording site information and the logistics associated with fieldwork will be the same.

The recurring method consists in establishing an error matrix by crossing the ground-truth data and data which has been deduced from the classification or extrapolated. Ground methods used for validation consist in selecting at random points on a mesh or transects. A wide variety of techniques exist for measuring these, including destructive and non-destructive approaches. These methods are fully covered in the Remote sensing handbook (Mumby, 2000) which underlines the fact that non-destructive methods allow repeated monitoring, are less harmful to the environment and are generally faster to implement than destructive methods. It also emphasises the importance of getting a great number of samples in a given survey period. This means a wider area can be surveyed and/or greater replication achieved at each site (which in turn, improves the precision of population estimates and the statistical power of analyses). Generally speaking, replicate measurements are strongly advised to ensure good ground-truth data. This is the case for the seabed core sampling instrument used by the Monterey Bay Aquarium Research Institute (Figure 5–1).

Box 5-1.
CCW Handbook for Marine Intertidal Phase 1 Survey and Mapping (Wyn *et al.*, 2000)

This handbook from Countryside Council for Wales provides information on the distribution and extent of habitats and communities on the shore.

It describes the methodology used for Intertidal surveys;
it provides the method for surveying rocky and sediment shores from the splash zone down to the lower shore;
the standard recording protocol in the field and;
the means by which the data are stored and presented.



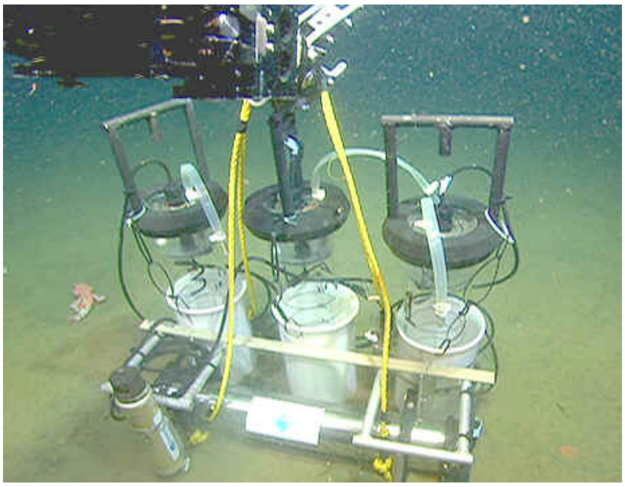


Figure 5–1. Benthic mooring on the seafloor (from Monterey Bay Aquarium Research Institute (MBARI: http://www.mbari.org/muse/).

In order to precisely locate training sites in the imagery, some benthic surveys such as the Hood Canal survey, Washington, U.S.A. Garono *et al.* (2004) used tarps (quadrants within 6 m x 6 m). The position of each tarp was then measured with a DGPS and field teams placed training sites within 10-100 of ground-control points (GCP) tarps (Figure 5–2). Those training sites should be placed in representative intertidal habitat types, relatively monotypic patches representing varying proportions of seagrass or other habitat types. On-ground reflectance spectra from selected, monotypic habitat strata were measured at the time of the CASI flight using a hand-held radiometer. Five replicate measurements were taken for each habitat stratum under ambient light conditions. Then the spectral data collected with the hand-held radiometer were used to select CASI band combinations for supervised classification.

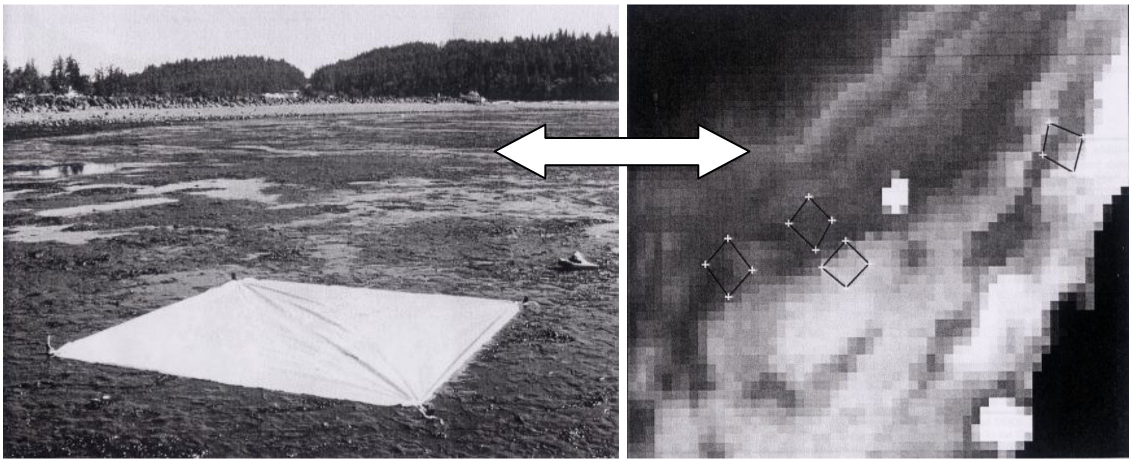


Figure 5–2. Example of a GCP tarp (white) visible in the CASI imagery and four training sites (from Garono *et al.,* 2004).

Because benthic field verification can occasionally involve operating electronic equipment from small craft, planning for environmental and other conditions is especially important. The following sections present some of the issues to be considered for field visit planning, logistics, and equipment.

4 – Positioning systems

Because it is reliable, accurate, and easy to use, the Global Positioning System (GPS) has become the prevailing accurate position control during most field survey operations. It is widely used throughout the surveying industry and has essentially revolutionised the profession. Instead of the labour – and equipment – intensive methods (microwave, optical, etc.) formerly needed for obtaining survey-quality position control, the use of differential GPS (DGPS) enables a navigator or surveyor to obtain comparable (or in many cases better) positioning accuracy without having to establish any local control stations. Although GPS coverage can be impacted by vertical obstructions (e.g., buildings, tree canopies, cliffs, etc.), there are few marine applications (such as narrow estuarine rivers, perhaps) where GPS would not be the overwhelming choice for position control.

In addition to providing accurate horizontal positions, kinematic GPS (KGPS) processing also can be used to provide accurate vertical tracking data. The vertical tracking applications require the use of dual-frequency GPS receivers and generally entail establishing a separate GPS base-station over a local vertical reference point; in some cases, data from a continuous operating reference station may be able to provide the GPS base station data. If the accurate data is required in real-time (known as a real-time kinematic or RTK application), then a reliable radio link must also be established between the base station and the survey platform. Though the accurate vertical-tracking DGPS application is far more complex and costly to implement than standard horizontal-tracking DGPS, the technique has proven beneficial in instances (e.g., dredge monitoring and navigation hazard surveys) where vertical accuracy was critical and the true tidal (or water-level) impacts at the survey platform were difficult to measure from shore-based monitoring stations. (Waddington, 2003).

The development of a European strategy for global satellite navigation emerged in 1998 as Galileo and is now well on track. The fully deployed Galileo system will consist of 30 satellites, 27 operational + 3 active spares), positioned in three circular Medium Earth Orbits (MEO) at an altitude of 23 616 km above the Earth and at an inclination of 56 degrees with respect to the equatorial plane. It will be interoperable with the other two satellite navigation systems – GPS and GLONASS. However, by offering dual frequencies as standard service, real time positioning will be possible down to the metre range. It will guarantee availability of the service under all but the most extreme circumstances and will inform users within seconds of failure of a satellite.

5 – Planning Considerations

5.1 – Weather

Check the local weather forecast and conditions for the day of fieldwork. A boat with shelter can extend the amount of fieldwork and the life of the equipment, by protecting it from harsh weather, direct sunlight, or humidity. It is also important to determine the desired navigational track for the fieldwork. The conditions offshore may be extremely different from conditions within a protected bay. It is extremely important to recognise that conditions may change daily and that fieldwork may be cancelled or postponed.

5.2 – Tides

Using bathymetry maps or local expertise, determine if the areas to be visited are only accessible during high or low tide. This will reduce the number of boat groundings and decrease the amount of time spent at each study site. A nautical chart and/or sound local knowledge are highly recommended.

5.3 – Turbidity

Many observations can be made by swimming, snorkelling, scuba diving or using a towed video camera. The field team may find it advantageous to conduct verification activities when phytoplankton blooms are not in season, or after periods of heavy wind or rain, in order to decrease the amount of time required to adequately characterise the site.

5.4 – Phenology

Field observations are best made as close as possible to the date of photo acquisition to facilitate comparison between data recorded in the field and signatures observed on the imagery. If this is not possible, the field team may find it advantageous to conduct fieldwork during the same month that the photography was acquired to reduce the error from observations made during the growing and non-growing season of vegetation. Thus, if the photography was acquired in June, when submerged aquatic vegetation (SAV) has the highest biomass, and the fieldwork were to be conducted in January when biomass is at its lowest, the differences in observation would likely be due to the differences in the phenology.

5.5 – Field Equipment

Below are lists of minimal and additional equipment (according to the NOAA Coastal Services Center) for field verification. The primary concern in obtaining field information, regardless of the equipment used, is to record observations with locational certainty.

Minimum Equipment:

- Differential GPS and aerial photographs;
- Equipment for observation, which varies depending on depth, weather, and clarity of water (may range from wading, to scuba, to underwater tow video systems);
- Method for recording location and observations;
- 8-magnification Lupe lens;
- Clipboard (for holding photos or maps).

Additional Equipment:

- Laptop computer (weatherised and/or protected from elements) to record field observations;
- Fieldwork software package that collects and displays GPS points while storing collected field information in a functional and queryable database;
- GPS hook-up to computer for real-time observation of navigational track and collected data points;
- Relevant ancillary data sets (bathymetric data, historic coverage and current coverage);
- Scanned and rectified aerial photographs;
- Snorkel equipment;
- Scuba equipment;
- Underwater video or still camera with display monitor to view deep or highly turbid habitats and/or to use during foul weather;
- Depth finder;
- Viewing tube/bucket for surface observations;
- Electrical power supply for the equipment. In some cases, much of the equipment can be run from the boat battery. Care must be taken, however, to avoid drawing down batteries required for starting the boat engines.

6 – Synergy between Lidar and Remote Sensing Imagery

Considering the high scale needed to deal with intertidal and shallow water habitats, reducing biological sampling is of paramount importance. This requires producing a map of both ground elevation and texture onto which biological sample data will be incorporated to deliver the final habitat map. Some attempts have already been made to integrate height and texture data, respectively collected by Lidar (but also sometimes by stereoscopy of aerial photos) and by remote sensing imagery. A few of these initiatives are described below.

CASI and LIDAR, for example, can be fit together on the same inertial system of an aircraft. A comprehensive review of both techniques used in synergy is given by Brown *et al.* (2003). The swaths of the two instruments are quite similar 20° incidence), hence ensuring the same coverage. For instance, for a flight altitude of 1000 metres and a swath of 700 metres, current high-frequency ALTMs will yield a density of one dot per 3 m² and first generation CASI (512 pixels) will yield a 1.5 metre pixel. New generation CASI (1300 + pixels) can even reach a 0.5 metre pixel. This combination is quite efficient in terms of coverage, i.e. roughly 50 km² per hour. The resulting DTM is of the highest quality (accuracy better than 15 cm RMS), as are the ortho-rectified CASI images produced with it. Such high resolution (permitting a scale of 1/5000) may be overly accurate for some needs and a higher acquisition altitude could be sought, if the user is willing to give priority to the coverage rate rather than to vertical accuracy.

According to Brown's studies (Brown, 2004 and Brown, 2003, when a DSM (Digital Surface Model) and slope are used in addition to CASI data, the saltmarsh classification accuracy is significantly increased by 8.5% (Table 5–5). Note: the neural network used in his study is the Multi Layer Perceptron (MLP). The basic unit of the MLP is the node, which sums its inputs and performs a function on the summed input.

Table 5–5. Confusion matrix for CASI and Lidar MLP classification ($^{+}$ Accuracy defined by producer) (from Brown, 2004).

		Ground data							
		Water	Mud	Algae	Pioneer	Atlantic 1	Atlantic 2	Terrestrial	User's Accuracy
Classified data	Water	48	0	0	0	0	0	0	1.00
	Mud	0	38	0	0	0	0	0	1.00
	Algae	3	13	42	0	0	0	8	0.64
	Pioneer	0	0	5	51	6	0	0	0.82
	Atlantic 1	0	0	2	2	47	0	0	0.92
	Atlantic 2	0	0	1	0	0	49	0	0.98
	Terrestrial	0	0	0	0	0	2	45	0.96
	Accuracy^{+}	0.94	0.75	0.84	0.96	0.89	0.96	0.85	–

Several examples of combined used of height data provided by Lidar and aerial photography can be found in the literature. It is quite easy to merge geo-referenced pictures between a Lidar DTM map and coastal orthophotography (Figure 5–3). This makes it possible to digitise the main channels (the deepest ones) by crossing the DTM with the very conspicuous network of channels on the ortho-image. In fact, each image brings its own information and combined interpretation is enhanced.

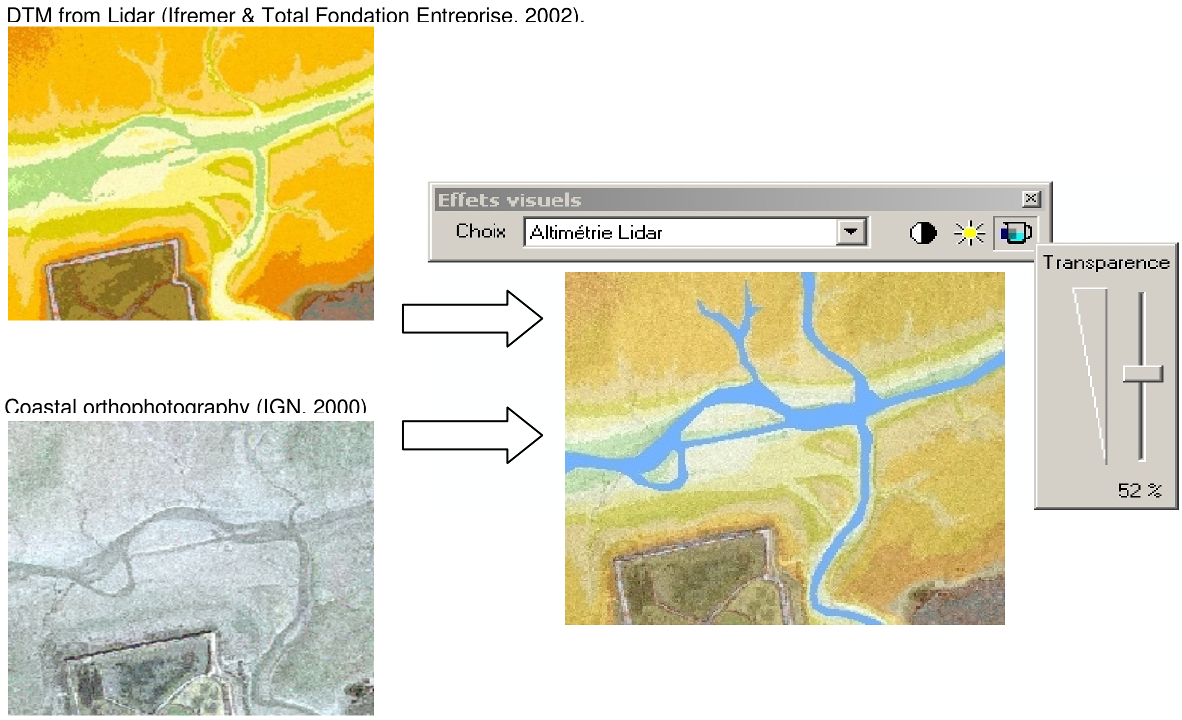


Figure 5–3. GIS digitisation of channels by crossing raster data (from Piel, 2004).

A particular example concerns intertidal seaweed mapping. Seaweed development and distribution are, to a certain extent, a function of their frequency of inundation rather than their strict elevation. This frequency varies with the tidal amplitude. To apply a single formula all along the coast, elevations have to be converted into annual immersion times (water heights over the course of a year). This can be done by inverting the tidal curve for each homogeneous tidal zone (as defined by Hydrographic Offices). In Figure 5–4, the red line represents the isoline of 10% annual immersion. This limit provides a very fine-drawn boundary between medium schorre (*Spartina maritima*) and higher schorre (*Obione portulacoides*). Slope and orientation are the second most relevant factors for habitat distribution. After the statistics per ground unit have been refined for each method, a predictive approach should be explored by combining elevation, slope and orientation, along with the texture contained in the orthophotographs, to model the presence of the various classes. The results should then be assessed against ground truth.

Figure 5–4. The 10% line of annual immersion corresponding to a particular schorre type transition (from REBENT, IFREMER DEL/AO, 2004).

Current efforts are also underway to integrate a hyperspectral imager into the hydrographic Lidar SHOALS-1000T, and to develop the sensor fusion algorithms and software which will enable the system to conduct shallow-water benthic habitat mapping, environmental monitoring and coral reef mapping. The new sensor will be called SHOALS-1000TH (Topographic and Hyperspectral). This could be an interesting breakthrough, since remote sensing of underwater features has always been hampered by the lack of reliable high resolution data in coastal waters.

7 – Cost Considerations

Satellite imagery is the most cost-effective method for producing habitat maps with coarse descriptive resolution (e.g. broad thematic units such corals, sand, rock, seagrass and algae). Using a case study mapping coarse-level coastal habitats of the Caicos Bank, it appears that SPOT XS is the most cost-effective satellite sensor for mapping sites whose size does not exceed 60 km in any direction (i.e. falls within a single SPOT scene). For larger areas, Landsat TM is the most cost-effective and accurate sensor among the satellite sensors tested (Mumby *et al*., 2000). However this should be tempered by each satellite's ability to cope with the low tide constraint that prevails in e.g. Mesh temperate regions.

Detailed habitat mapping should be undertaken using digital airborne scanners or interpretation of colour aerial photography. In a single survey (a few hours), an aircraft can cover a study area that would require a week or more for a vessel, this being particularly true in shallow and difficult to access coastal areas. Aircraft provide access to shallow water regions and bottom type features are observed in situ without disturbing the biological structures (Brown, 2002). The relative cost-effectiveness of these methods is more difficult to ascertain however, because quotes are case-specific. While the acquisition of digital airborne imagery such as CASI is more expensive than the acquisition of colour aerial photography, its high cost must be offset against the huge amount of time required to create maps from aerial photograph interpretation (API). If habitat maps are needed urgently aerial photography interpretation (API) might take too long and therefore be inappropriate. For small areas of, say, a few dozen km², a map could be created within a few days using CASI but might take almost twice that time to create using API. Further, as the survey area increases, the cost of API is likely to rise much faster than the cost of a digital airborne scanner survey, making API progressively less cost-effective. In cases where the costs of API and digital airborne scanners are similar, the latter should be favoured because they are likely to yield more accurate results than API I (Mumby *et al*., 2000).

As for combined use of Lidar and digital imagery, current costs per km² are around 400 euros, for quite high resolution (metric). Digital cameras offering imagery plus elevation obtained by a single aircraft pass and front/rear looking stereoscopy) well below that price have been announced, but this remains to be confirmed.

Table 5–6, gives an overview of several combined tools for tidal and subtidal zones and assesses three key features: cost, coverage and resolution.

Table 5–6. Comparative table of combined subtidal and intertidal means (modified from Ehrhold, 2003).

Depth range		Combined Means	Cost	Coverage area	Resolution
Subtidal area	10-50 m	MBS + SSS + AGDS + FD	++++++	++++	++++
		SSS + AGDS + FD	+++++	++++	++++
		MBS + AGDS + FD	++++	+++	+++
		AGDS + FD	++	++	++
		FD	+	+	+
	0 -10 m (shallow)	MBS + SSS + AGDS + FD	++++++	++++	++++
		MBS + AGDS + FD	++++	+++	+++
		AGDS + FD	++	++	++
		FD	+	+	+
		SPOT 5 + LIDAR •	+++	++++	++
		NCAD/DC + LIDAR •	+++	+++	+++
Intertidal area	>0 m (up to tidal range)	LIDAR	+++++	+++	++++
		NCAD/DC	++++	+++	++++
		IRAF + LIDAR + FD	++++	+++	+++++
		NCAF + LIDAR + FD	++++	+++	+++++
		DC/CASI + LIDAR + FD	+++++	++	++++

MBS : Multibeam Sounder ; SSS : Sidescan Sonar ; AGDS : Acoustic Ground Discrimination Systems ; FD : Fieldwork Data (from sampling, corers, underwater photography, towed video or diving) ; NCAD : Natural Colour Aerial Photography ; DC : Digital Camera ; IRAF : Infrared Colour Aerial Photography
• anticipated

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6 Sea Bottom Topography with Navigation Radar

Jan Kleijweg (TNO-FEL)

1 – General Principles of Operation

Microwave Remote Sensing is a valuable tool in obtaining information on the processes taking place at the sea surface. The mayor advantage of microwaves above other windows in the electromagnetic spectrum is that microwaves are not hindered by weather and give information around the clock. Early in 1980 the potential of imaging space borne microwave sensors was demonstrated. A large number of phenomena including wind, waves, internal waves, fronts, slicks and bottom topography can be observed.

Information on seabed topography is of vital importance for shipping, fishery, and all kinds of off-shore activities. Traditional methods for obtaining this information use ship borne echo sounders, however these methods are time consuming and costly.

In radar images, changes in sea surface roughness owing to bottom topography are mainly affected by wave-current interactions. The hydro-meteo conditions under which bottom topography can be observed are both as high as possible surface current as a wind speed of between 2 and 4 Bft. Besides this, the signal to clutter ratio to monitor these phenomena is low.

These specific hydro-meteo conditions combined with the low orbit cycles (max. every 3 days) of radar remote sensing satellites makes space borne less attractive for operational use for sea bottom topography mapping.

That navigation radar's are capable to monitor sea bottom topography is quit new An example is given in Figure 6–1. In contrast with space-borne radar's these systems are able to monitor a particular area around the clock. This ability makes navigation radar attractive for operational use of sea bottom topography mapping. Further investigations are needed to demonstrate the performance.

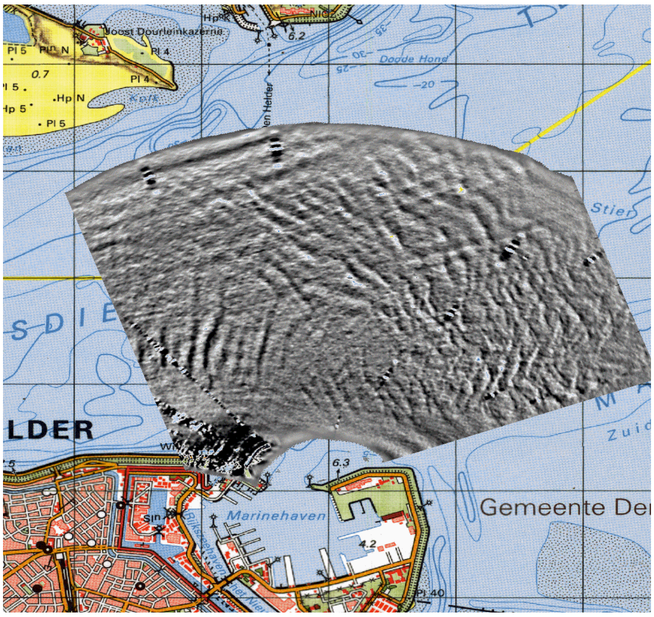

Figure 6–1. *S*ea bottom topography in de "Wadden Sea" the North of the Netherlands. The wind was approximately 10m/sec. Water depth was between 5 and 20 m and total observation/ processing time was 2 minutes. The area is about 4 by 2km.

7 Sidescan Sonar

Ceri James (BGS)

1 – Principles of Operation and Data Processing

Sidescan sonar is based on the same acoustic principles as the single beam echo sounder and the multibeam echo sounder. All three have **transducers** which comprise:

- a **transmitter** which emits a sound pulse into the water column down to the sea bed
- a **receiver** which picks up the reflected sound from the sea bed as a vibration which is converted into a digital or analogue signal and recorded on a survey vessel

Both the single beam echo sounder and the multibeam echo sounder measure the time elapsed between transmitting and receiving pulses and these calculations provide the primary input for the water depth data and sea bed morphology images and sections provided by these sounders. Sidescan sonars do not measure the time elapsed between transmitting and receiving pulses, they measure the strength of the reflected acoustic sound at the receiver. Their output provides photo like images of the sea bed.

Sidescan sonars normally comprise two transducers mounted on either side of torpedo shaped towfish (Figure 7–1) which is attached to a survey vessel by a cable. Data is transmitted along the cable from the towfish, which also contributes to controlling the depth at which the towfish flies above the sea bed (Figure 7–2).

Sidescan sonars are characterised by a beam which is narrow in the horizontal plane and wide in the vertical plane. This creates a narrow acoustic sweep across the sea bed at right angles to the track of the towfish. The range of the sweep is governed by the velocity of sound in water. The longer the range set by the operator the longer it takes for a sound pulse to travel out and back to the towfish. Because a sidescan has two transducers, the sweep coverage of each towfish is double the range i.e. a typical sidescan set to survey at a range of 150 m will produce a sweep of 300 m across its track.

Figure 7–1. Sidescan sonar towfish on deck of survey vessel Sidescan is a Klein 5000 (©NERC/ BGS).

Sidescan sonars are commonly available with frequencies ranging from about 50 kHz to 500 kHz. Lower frequencies provide a longer range with lower resolution whilst the higher frequencies have a higher resolution but a shorter range. Higher frequencies have shorter pulse lengths and therefore can resolve smaller objects on the sea bed.

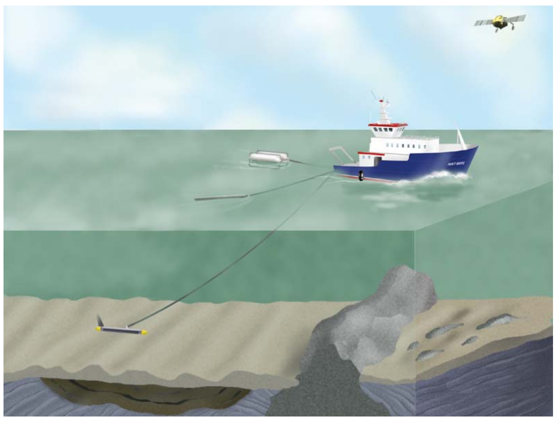

Figure 7–2. Sidescan sonar towfish in survey position (©NERC/ BGS/ NMW). (Note: surface tow boomer and its hydrophone, which can be run at same time as sidescan, also shown at sea surface).

There are also great differences for sidescan sonars between across track resolution and along track resolution. For example at 100 m range from the towfish, a sidescan may have an across track resolution of < 5cm, this may be up to 50 times better than the along track resolution. The along track resolution is therefore a limiting factor in sidescan resolution; this is governed by the horizontal beam angle. A sidescan sonar beam with a horizontal beam angle of 1° would be 1.75 m wide at 100 m range and unable to resolve objects smaller than this. Towing speed is also an issue; to attain the best quality image this should be limited to 3 to 5 knots. Another important operational parameter in terms of sonar coverage and resolution is the altitude of the towfish above the sea bed. Because resolution decreases across the range it is important to fly the towfish relatively close to the sea bed to minimise the water column coverage and maximise the sea bed coverage on the sidescan record (Figure 3). A common towfish altitude is to aim for a height above the sea bed set at about 10% of the range e.g. 15 m for a range set at 150 m. For greater detail and resolution in the near field of the record the towfish may go down to 5% of the range. However, for mosaicing purposes the height could increase to 20% of the range. In setting a towfish altitude care is obviously required to ensure the towfish does not hit the sea bed and will fly over any large features such as sand waves, wrecks and rock shoals.

The image recorded on a sidescan record portrays the intensity and variation of the sound returned from the sea bed to the receiver. In the pre-digital age when all data was simply recorded straight on to paper the stronger the signal the darker the image burnt on the paper. Areas of shadow to the sonar beam behind positive features or within negative features on the sea bed appear as white, blank zones. This produces a negative like image (Figure 7–3). With modern digital systems the polarity can be reversed to produce a positive image; colour tones as well as monochrome can also be displayed with digital systems.

The sound received and recorded by a sidescan sonar system is a function of two primary mechanisms which enable sound to return from the sea bed. These are:

- Reflection. Direct returns of sound bouncing back off features on the sea bed such as rock outcrops, sand waves and wrecks.
- Backscatter. This is a diffuse and weaker process based on the interaction of sound energy with the ambient texture and character of the sea bed. The intensity of the backscattered sound is a function of bottom roughness and angle of incidence.

The rougher the sea bed, the stronger the backscatter, the darker the tone on a sidescan record. Gravels, rock pavements, shell beds and accumulations, and some glacial sediment will produce good backscatter. The shallower the angle of incidence, the weaker the backscatter. This is a limiting factor in setting the range of a sidescan because angle of incidence decreases with increasing range.

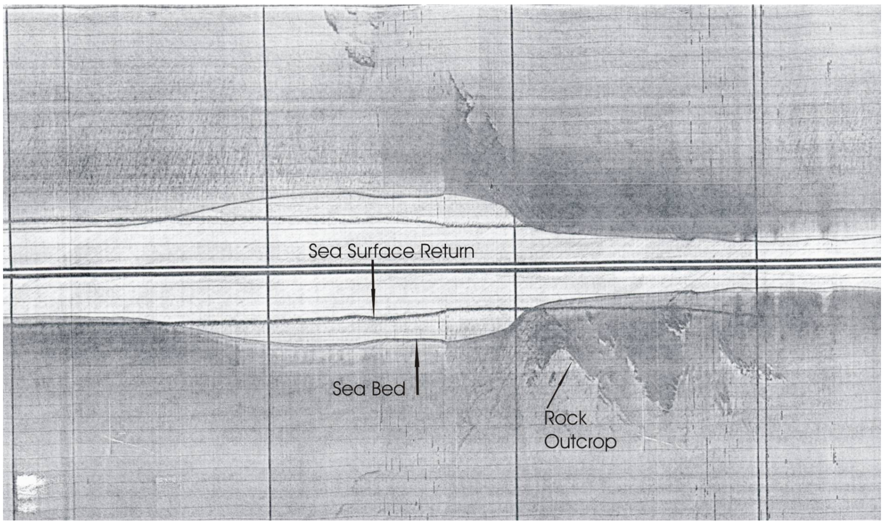

Figure 7–3. Sidescan paper record with range of 150 m from analogue sidescan sonar (late 1970's) (©NERC/ BGS).

Backscatter is also recorded by multibeam echo sounders and has been used on a number of sea bed mapping projects to complement the normal multibeam sea bed morphology images. However, they do not yet appear to match the quality and resolution of records obtained by modern digital sidescan sonars.

2 – Sidescan Systems

Up until about 1985 sidescan sonar systems were completely analogue with no acoustic or data processing. Recording was directly on paper. From the mid 1980's systems appeared with analogue to digital processors but still with analogue fish and cable and no acoustic processing; there was some limited data processing which enabled water column removal and slant range correction. They allowed recording on magnetic tape as well as on paper. Many of these systems are still in use. However, these systems and the growth of cheap computing power stimulated the development of software and hardware manufacturers such as CODA (UK), Triton (USA) and Elics (Fr) which provided integrated processing and recording of sidescan sonar data and allowed interpretation, mapping and mosaicing of sidescan data (Figure 7–4).

The early 90's saw the development of fully digital sidescan sonars; these include CHIRP systems. All have digital fish, cable and processors. This produced enhanced signal and data quality and improvements in data processing and interpretation tools. Recording became fully digital, with paper recording a secondary option. However, these are still single beam systems and the problems inherent in along track resolution are still applicable; survey speeds are still required to run at < 5 knots. This is an issue if these sidescan sonars are run simultaneously with multibeam systems. Survey speeds for multibeams are generally 7 or 8 knots, running at sidescan sonar speeds of <5 knots will reduce the normal survey area coverage of a multibeam.

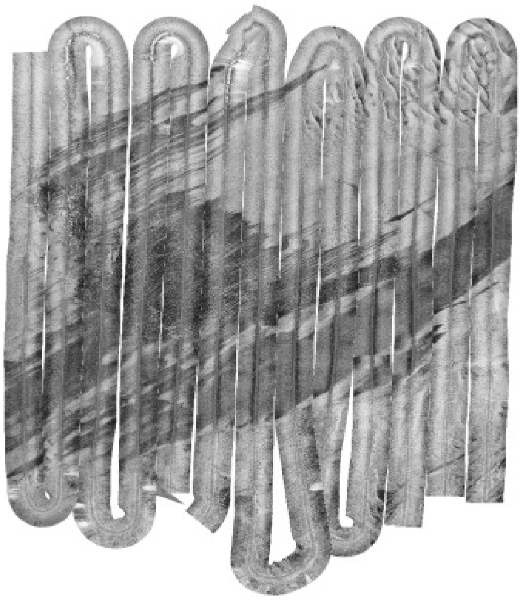

Figure 7–4. Mosaic of sidescan survey lines (©CEFAS).

To try and overcome these problems a number of sidescan manufacturers have designed systems which can be run at multibeam echo sounder speeds. They improve along track resolution by producing multiple sound pulses (Edgetech MPX) or multiple beams (Klein 5000). Both these systems have recently been deployed in a habitat mapping survey in the UK running simultaneously with a multibeam system (James and others, 2004). The survey outputs were very good, producing excellent resolution out to a range of 150m running at speeds of 7 knots in difficult weather conditions up to Force 5. (Figure 7–5).

Data recording, storage and processing is an issue with digital sidescan systems. Processing power, communication hardware, software and hard disk storage for shipboard recording, and post-processing and archiving must be planned to meet the data rates generated. For example, the multipulse and multibeam sidescan sonars produce 500Mb to 1Gb of data in one hour of survey. Fortunately the price of digital storage is relatively cheap with portable hard drives of 250 Gb or more readily available.

Figure 7–5. Mosaic of Klein 5000 sidescan data (900 m wide) (©NERC/ BGS).

Georeferencing of towed sidescan system data is a limiting factor in its utility. Normal practise is to record the cable out distance to the towfish with reference to the GPS antenna on the survey vessel. This distance, known as the layback, is also computed with reference to the depth of the towfish. Modern digital systems process the layback and GPS data to calculate the position of the towfish. They work on the assumption that the towfish is running directly in line behind the vessel. This may not be the case in areas with strong currents or swells.

Ultra short baseline systems (UBS) can be used to accurately position towfish. These comprise a transponder in or at the towfish and a transceiver on the survey vessel. The transceiver is referenced to the survey vessel GPS enabling the towfish to be positioned accurately. UBS systems are relatively expensive to deploy and may need specialist installation on survey vessels, adding to survey costs. They are not commonly deployed for regional small scale sidescan surveys, which is the most likely type of survey for habitat mapping.

Compared to multibeam echo sounders (MBES) where each ping is individually georeferenced, sidescan systems are at a disadvantage in terms of georeferencing recorded features to metre scale accuracy. However, they are relatively easy to deploy compared to multibeam systems, they do not require as much calibration and engineering to fit on to vessels of opportunity and because they are towed systems they are able to maintain a measurable elevation above the sea bed which means they can maintain a constant range of sweep and consistent data quality in varying depths of water. This is particularly useful in shallow water of < 20 m, where MBES systems with their fixed beams are at a disadvantage and cannot cover as much of the sea bed as sidescan systems. Sidescan systems because they are towed do not require tidal corrections, unlike MBES which are fixed to a floating survey vessel.

The Natura 2000 Marine Monitoring Handbook contains a section on procedural guidelines for sidescan sonar (PG 1.4) at http://www.jncc.gov.uk/marine/mmh/Pg%201-4.pdf . Some of these are also updated in Kenny and others (2003). Fish and Carr (1990) also provide a useful guide. There are numerous reports, papers and websites (listed at end of report), which describe the principles and operation of sidescan sonar. Manufacturers websites are good sources of information; some such as Klein Associates, http://www.l-3klein.com are particularly useful with practical and clear advice on operations and basic principles.

3 – Review of Existing Standards and Protocols

Sidescan sonar has been used for survey and mapping of the sea bed for over 30 years. As described in the previous section the equipment, methodologies, software and output have evolved and developed over time. Target detection for military purposes and wrecks has been a primary driver in improving standards and resolution and there are IHO standards (S44 and S57) with regard to hydrographic surveys which can be downloaded from the IHO website http://www.iho.shom.fr/

There appears to have been no attempt during this period to produce international standards or protocols for mapping the sea bed with sidescan sonar. Numerous geological surveys have produced sea bed maps which have been based on sidescan sonar interpretations to characterise the physical nature of the sea bed in terms of its sediment, bedforms and rock outcrops. These have used standard geological classifications such as Folk or Wentworth for sediment, and mapped rock using national systems based on age or lithology. These are applicable to habitat mapping.

3.1 – Data Acquisition

Data acquisition using modern digital sidescan systems follow standard procedures based on the operating criteria outlined by the manufacturer of the sidescan. Data is normally recorded through the sidescan manufacturers own software or through third party software such as CODA or Triton Elics. The type of sidescan specified for any survey must take into account the nature of the sea bed, water depth and sea conditions and the area to be covered. The size of the survey vessel would also have a bearing on the choice of sidescan. A small lightweight towfish, such as C-MAX, would be applicable for a small boat.

Complete coverage of the sea bed to enable full mosaics to be produced is the ultimate goal in terms of survey design. However, this may not always be possible, for example, because of funding.

Therefore a grid approach may be adopted with lines parallel and at right angles to the principal physical grain of the sea bed. The grain could be due to channels, sand banks or rock outcrop. Line spacing of the grid should enable capture of the shape and nature of the principal features on the sea bed and its ambient character. The line spacing should also allow extrapolation of interpretation between lines.

In some areas a parallel corridor approach may be adopted rather than a square grid. For example, where there are strong rectilinear currents and unidirectional swells and waves. Surveying across these would be difficult and uncomfortable and also would compromise the quality of the survey data. The corridor approach is also useful in areas of sand waves where collecting survey data at right angles to the principal crest direction provides more relevant data on the nature of the sea bed than survey lines drawn parallel to the principal crest direction. The corridor approach may also enable adjacent line spacing to produce mosaic corridors of sidescan (Figure 5 and 6) to gain an understanding of the relationship between primary and secondary bedforms and an indication of sediment transport and dynamics.

3.2 – Data Processing

The processing of digital sidescan data is normally undertaken using proprietary software from vendors such as CODA Octopus and Triton Elics. The procedures adopted produce true scale images which can be interpreted as individual lines or as mosaics of survey lines (Figure 4 to 7). The processing includes signal manipulation using time variable gain (TVG), slant range correction and removal of the water column. An important element of processing is ensuring co-registration of adjacent survey lines so that linear features such as sand wave crest join across survey lines. It is also important to maintain a consistent backscatter response both along and between survey lines so that variations in backscatter are due to changes in sea bed character and not changes in TVG setting by the operator.

Although much of the processing is a digital process, it is not fully automatic. The operator controls and interferes and by their action can enhance or diminish features on the record. The finished sidescan record is therefore a qualitative, manipulated output, certainly in terms of the backscatter response of the ambient sea bed. The form of features such as bedforms and rock outcrops, or any features which are a response to reflected sound rather than backscatter should not be lost in this process. The cost of this type of software is of the order of €10,000 to €25,000 (2005 prices).

Commercially organisations and a number of academic and research organisations e.g. TNO, have developed software for image processing for sidescan (Figure 7–6). Some of these are based on MATLAB routines (http://www.mathworks.com/matlabcentral)

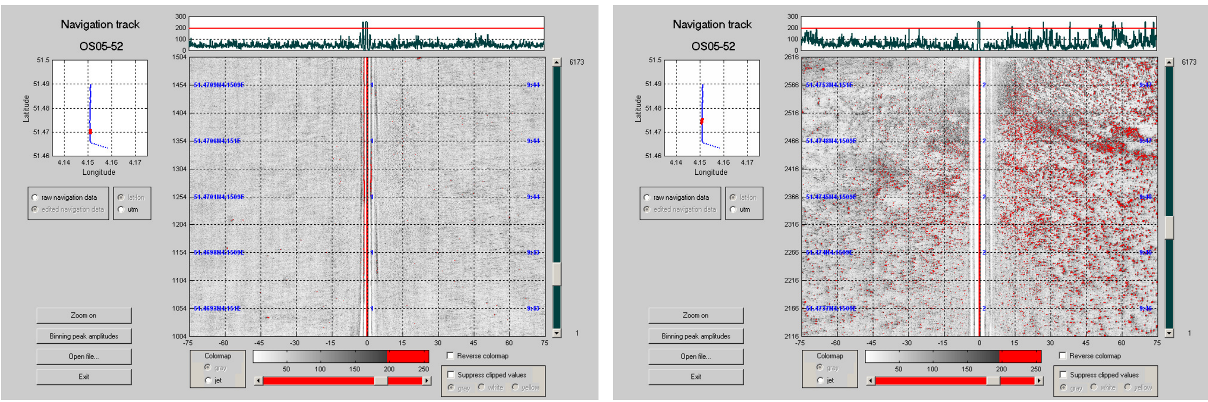

Figure 7–6. Sidescan images from Eastern Scheldt Estuary, Netherlands (©TNO). Right image – Oyster (*Crassostrea gigas*) bank creating strong backscatter. Illustrated with processed colour coding. Left image – smooth sea bed with low backscatter.

3.3 – Data Interpretation

Sidescan sonar since its inception, has been used world wide as a survey tool by a variety of users including oil and gas, hydrography, engineering, marine resources, military, universities and geological surveys. The wealth of users and applications has meant there is no standard method of data interpretation that is relevant to all users.

The nature of the sidescan sonar record with its capacity to image positive and negative features as tones of dark and light and its ability through backscatter to indicate the character of the sea bed has meant its adoption as a primary instrument for mapping sediments, bedforms and rock outcrops. It is also relevant to sediment transport and dynamics.

Belderson and others, (1972) showed, from its early development, its value in mapping the sea bed. Their pioneering work on bedform interpretation from sidescan records produced a hierarchy of bedforms which is applicable to Shelf seas mapping (Stride, 1982). A bedform classification system for sidescan sonar interpretation was also developed in BGS in the 1980's for the publication of some BGS 1:250,000 maps (BGS, 1990). Classification systems based on sidescan sonar interpretations have also been developed in France (Augris and others, 1995).

For habitat mapping, sidescan sonar should be deployed within a suite of complimentary survey methods including multibeam echo sounders to provide a georeferenced morphology over which high-resolution sidescan mosaics can be draped. This enables the dynamic relationship between bedforms and other physical features to be assessed in 3D (Figure 7–7). Acoustic ground discrimination systems (AGDS) based on proprietary systems such as QTC and RoxAnn are also important complimentary sources of information based on single beam and multibeam echo sounder.

Sub-bottom reflection data has a significant contribution to make by indicating the nature of the sediment and geology beneath the sea bed. These may be exerting an important control on the character of the sea bed displayed on sidescan sonar. Video and camera surveys are also vital in confirming sidescan interpretations. Physical sampling with grabs, cores and trawls is also essential for biological and grain size analysis and ground truthing

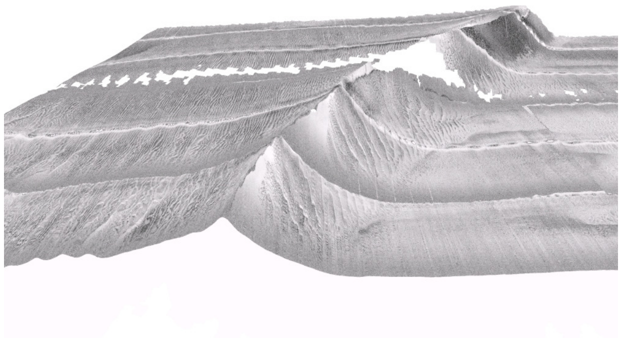

Figure 7–7. Klein 5000 sidescan mosaic draped over multibeam 3D surface (©NERC/ BGS).

A multidisciplinary approach is essential in producing habitat maps with sidescan sonar providing an important element in terms of coverage, quality and resolution.

3.4 – Provenance and Current Usage

Although multibeam echo sounders are becoming more common as survey instruments of choice, the photographic like image and resolution of digital sidescan sonar does provide a dimension in terms of the nature and character of the sea bed which cannot yet be matched by most multibeams (Figure 7–8). When backscatter quality from multibeams approaches that of sidescan then the latter may become redundant. Sidescan systems remain an important tool however, and if USB systems could be integrated into sidescan systems at a competitive price then this would address much of the georeferencing issue.

There is a considerable historical and current investment in sidescan technology and systems, and there is a large and extensive historical archive of sidescan data in many European countries which could be utilised for habitat mapping.

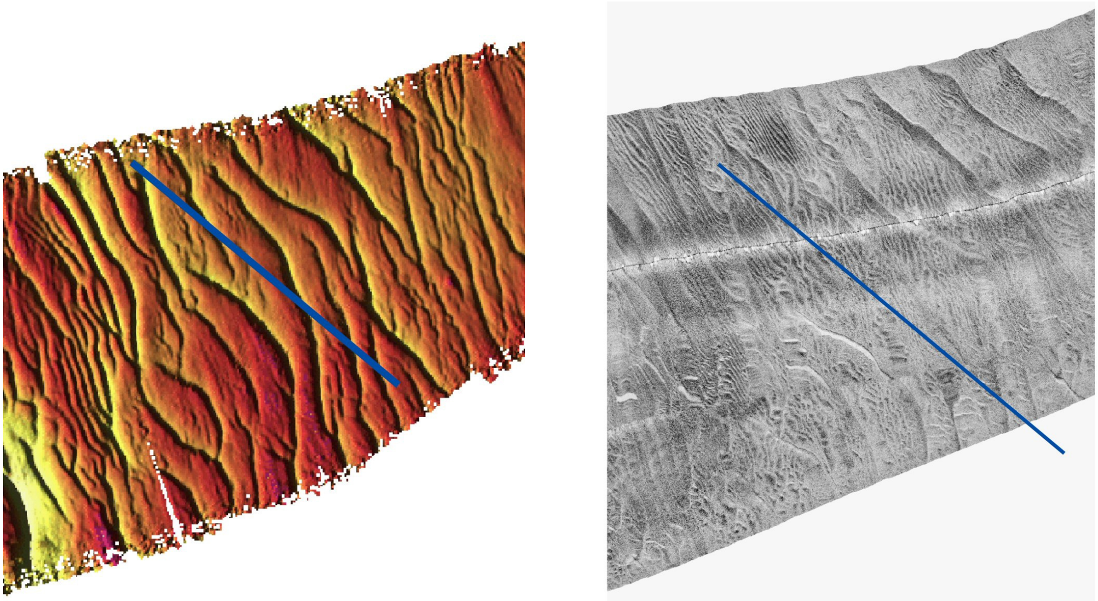

Figure 7–8. Comparison of multibeam (left) and sidescan image (right). The primary waves are 1 m high. (©NERC/ BGS).

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Stride, A.H., (1982). Offshore Tidal Sands. Chapman and Hall, London, 222 pp

Web Sites

Cardiff University, Analysis of data from Multibeam and Sidescan Sonars, by Neil Mitchell, Royal Society University Research Fellow. http://www.ocean.cardiff.ac.uk/people/neil/sonar/sonar.html.

Department of Geology San Jose State University, Mapping the Seafloor, by Don Reed. http://geosun1.sjsu.edu/105d/exped4/10.html.

Institute for Marine Acoustics, Sonar Primer, Measuring with Sound, by John P. Fish. http://www.marine-group.com/SonarPrimer/SideScanSonar.htm.

Klein Sonar, Side Scan Sonar System Description. http://www.l-3klein.com.

NOAA Ocean Explorer, Submarine Ring of Fire, Seafloor Mapping by Bob Embley. http://www.oceanexplorer.noaa.gov/explorations/03fire/background/mapping/mapping.html.

Office of Coast Survey, Research and Development, Hydrographic Systems and Technology Programs http://chartmaker.ncd.noaa.gov/csdl/htp/sonar.htm.

Office of Coast Survey, Side Scan and Multibeam Sonar. http://chartmaker.ncd.noaa.gov/hsd/wrecks.html.

USGS Coastal and Marine Geology Program, Seafloor Mapping Technology - Data Acquisition. http://woodshole.er.usgs.gov/operations/sfmapping/dataacq.htm.

USGS Pacific Sea-Floor Mapping, Mapping Info Page. http://walrus.wr.usgs.gov/pacmaps/map_info.html.

8 Multibeam Echo Sounders

Jonathan White and Veronique Jegat (Marine Institute)
Vera Van Lancker, Samual Deleu (Ghent University) and Koen Vanstaen (CEFAS)

1 – General Principles of Operation and Data Processing

Multibeam echo sounders (MBES) determine depth by accurately measuring the angles of emission, reception and two-way travel time for a pulse of sound energy from the emitting instrument (transducer) to the seabed and back. MBES systems can achieve full bottom coverage with beam swath widths of 4 to 7 times the depth of water being surveyed (Figure 8–1). They are sometimes called beamformers or true multibeam systems, opposed to interferometric swath systems.

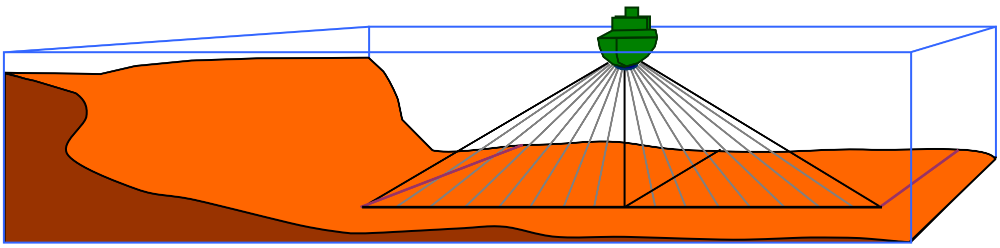


Figure 8–1. Multibeam swath coverage. (After Geological Survey of Canada).

A narrow fan of acoustic energy pulses are emitted into the water in a given direction, perpendicular to the main axis of the boat, from an array of transducers. When these pulses hit the seabed, they are reflected back as an echo, and detected by an array of receivers. In a signal processing technique called beamforming, the receivers divide the echoes of the signal into a set of acoustic channels (or beams), defined by their direction of arrival to the receivers. These receivers can be seen as underwater microphones, called hydrophones. The travel time and orientation of each beam gives the location of the seabed patch hit (the foot print) relative to the receiver. The geographic position and depth of the centre of each patch or sounding, can then be calculated from the geographic position of the vessel and measurements of the speed of sound (sound velocity) through the water column. For each cycle of transmission/reception (ping), a series of soundings are obtained from the fan of emitted beams and this is often referred to as the swath.

Following data collection, processing is undertaken. This includes offset correction, attitude correction, tidal offset and cleaning of erroneous echoes present as outliers in the data. The soundings can then be built into a Digital Terrain Model (DTM) for 3D viewing of the sea floor, creation of sun-illuminated imagery and contour maps.

MBES can also measure the amount of acoustic backscatter from the seabed for each acoustic beam. Backscatter information is perfectly co-located with the seabed bathymetry information and makes MBES unique in the ability to simultaneously collect bathymetry and backscatter information in a single survey. Only part of the acoustic signal emitted will be reflected back to the receiver from the sea floor, part may be transmitted into the sediment and part scattered in a different direction by the seafloor. The way the seafloor interferes with the acoustic signal and the returned echo can be used to characterise the seafloor material. The transmission and scattering will depend on the frequency of the MBES, the angle of incidence and the type of sediment – its density and porosity (Figure 8–2).

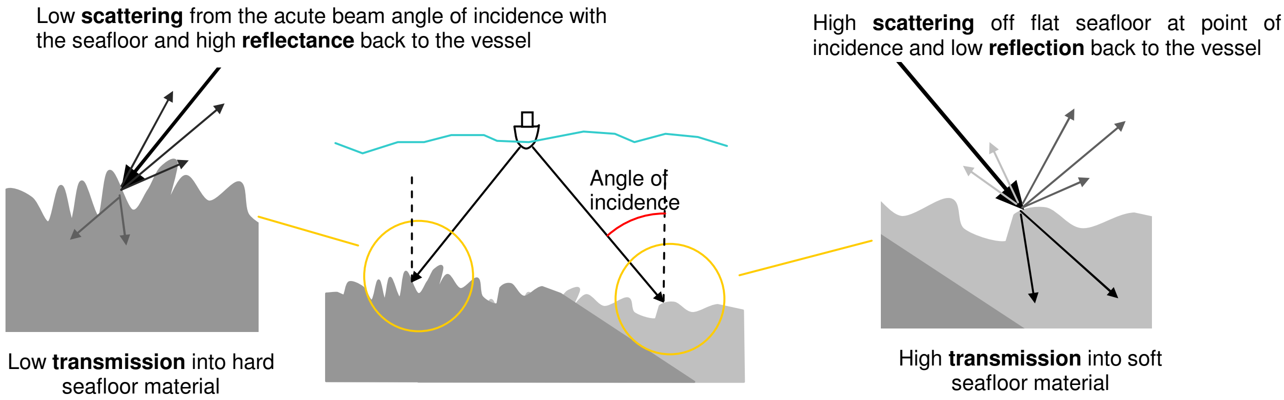


Figure 8–2. Reflection, transmission and scattering of the acoustic signal. (After L3 Communications SeaBeam Instruments, (2000).

The backscatter value (per beam or per full swath depending on the system) is calculated from the intensity of the returned signal with corrections for echo sounder and seabed geometry. Backscatter images can be built in the same process as sidescan sonar mosaics (Figure 8–3). These images map the different acoustic characteristic of the seafloor, which may be used as a tool for characterising seabed material when accompanied with ground truthing from grab samples, seafloor photography, video or as input to acoustic classification software.

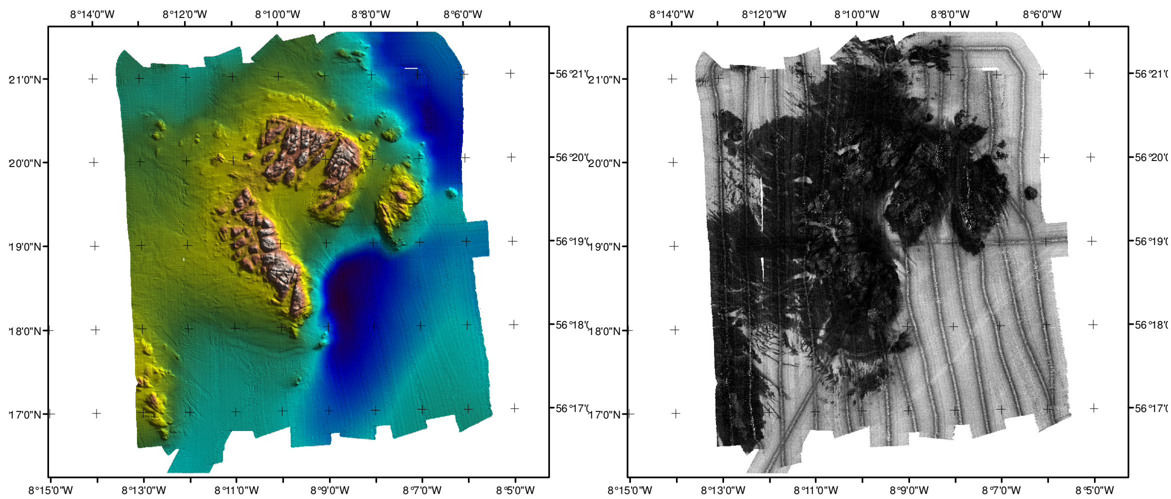


Figure 8–3. MBES shaded relief and accompanying geo-referenced backscatter image (Marine Institute).

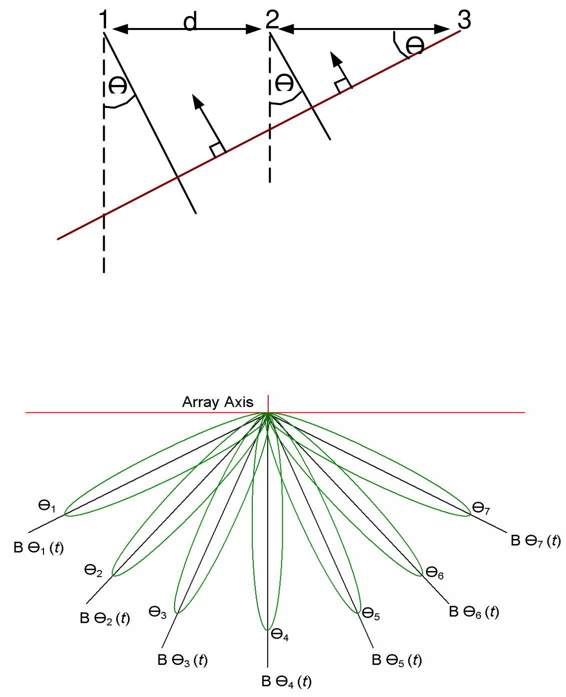
2 – Technical Details

2. 1 – Transducer Design and Geometry

The acoustic signal is emitted and received by transducers - piezoelectric elements able to convert electricity to pressure waves and vice versa. Projectors and hydrophones respectively transform electrical energy into acoustic energy and acoustic energy to electrical energy.

The geometry and size of the transducer will control the shape of the acoustic signal that is transmitted – the beam width, wavelength and frequency. The longer the transducer, the narrower the beam width can be achieved. To overcome manufacturing problems associated with constructing very long individual transducers, transducers can be built into arrays, with which constructive interference can be used to form the acoustic signals. Such an array of projectors enables a narrow beam of sound to be the generated, capable of insonifing a small patch of seafloor. Similarly, an array of hydrophones is used to receive narrow beams of sound.

By applying a set of time delays to the hydrophone readings and by summing them, a set of “virtual” arrays are created, pointed in any chosen direction. This process is called beam forming and allows sweeping of the seabed without any mechanical movement of the array. (For a more detailed explanation of the mathematics involved in beam forming see Figure 8–4 and Box 8–1).



Box 8–1.

The projectors/hydrophones are aligned in two flat linear arrays. The direction of emission/reception is narrow in the array’s long axis. In this design, the projector array will create a narrow fan acoustic signal. A linear receiver can however, only receive information from one direction and so the beam steering technique is used to allow it to receive from any of a number of given directions.

The principle of beam steering is based on the formula that wave fronts arriving from an angle θ from the nadir (the point vertically beneath the transducer), will reach each individual hydrophone with a time delay equal to $T_N \equiv (N \times \sin\vartheta)/c$ where N is the transducer number, ϑ the hydrophone spacing, θ the angle of incidence and c the sound speed at the transducer head ().

Figure 8–4. Beam steering technique (After L3 Communications SeaBeam Instruments, 2000).

In practice, the transmitter and receiver instruments are set up in a Mills Cross configuration (Figure 8–5). The transmitter (projector) creates a transverse narrow insonified strip narrow in fore and aft direction (~0.5 to 2°) and wide in the port and starboard direction (~120 - 150°). The receiver (hydrophone) is set up perpendicular to the transmitter, so that the strips of seafloor insonified by the transmitter are intercepted by the strips observed by the hydrophone. For each hydrophone, the transmission time (travel time) is recorded as well. The position of each observed strip is then accurately deduced from the travel time and angle of reception.

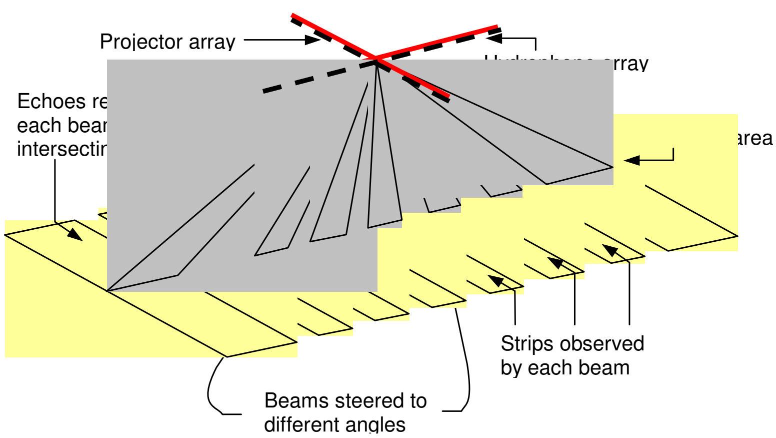


Figure 8–5. Mills Cross configuration using two linear arrays. (After L3 Communications SeaBeam Instruments, 2000).

As higher frequencies can be used when surveying seafloors in shallow water, it is not necessary to use a long linear array of projectors to create a narrow beam of sound at emission. At reception, the hydrophones can be positioned in a semi-circular array and grouped in sub-sets with directivity to receive the returning acoustic signal – a process also called beam forming. In this way no electronic beam steering is required, however, some constructors use the beam steering technique for the outer beams to increase the swath coverage and to allow some freedom to adjust the coverage depending on the applications. An example of shallow water semi-circular hydrophone array is the Kongsberg Simrad EM1002 (Figure 8–6).

A single antenna can be used to transmit and receive (for example the Kongsberg Simrad EM1002). Other systems use a linear transmitter array and circular receiver (for instance the Seabat 8101). A semi-circular solution may be a preferable solution owing to size and portability and the array being less sensitive to sound velocity variations, with no or little beam steering, however, price, availability, water depth and resolution will need consideration.

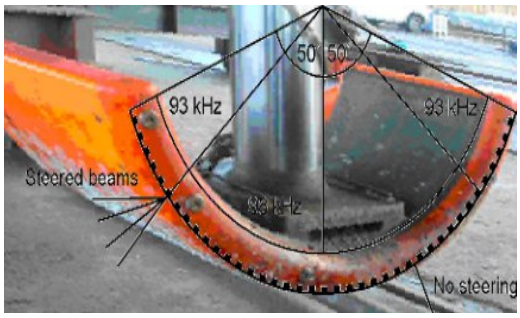


Figure 8–6. EM1002 circular antenna, beam steering used for outer beams. Photograph of the hull mounted instrument on the R.V Celtic Voyager.

Spatial scale: Shallow versus deep water survey systems

Acoustic energy emitted from multibeam echo sounder transducers will undergo spreading and absorption as it propagates through the water column. This propagation loss will limit the range the acoustic energy may penetrate the water column with high frequency energy being absorbed at a higher rate than low frequencies and limiting their use to shallow waters. Lower frequencies have longer wavelengths and will be able to penetrate to deeper seafloor depths. On this basis MBES systems may be divided into three major categories depending on their operating frequencies, Deepwater, Shallow and High-resolution systems (Table 8–1).

Table 8–1. Examples of these in commercial systems (Adapted from Lurton, 2002).

Categories:			**Examples:**			
	Types of waters	Depth ranges	Multibeam system	Frequency	Maximum depth	Resolution
Deepwater	Deep ocean and continental shelves	1000's of metres	Kongsberg Simrad EM120	12 kHz	11,000 m	1.5 - 7.5 m
Shallow water	Continental shelves	10's to 100's of metres	Kongsberg Simrad EM1002 Reson Seabat 8101	95 kHz 240 kHz	1,000 m 500 m	0.15 - 1.50 m 1.5 - 15.0 cm
High-resolution	Local shallow water studies	10's of metres	Reson Seabat 8125	455 kHz	120 m	1.0 - 20.0 cm

When undertaking a multibeam survey the water depths of the survey area are a major determinant in choosing the survey system to be used, as operating frequency of the echo sounder must be lower in deeper water. Accompanying this is the increasing footprint size with water depth, reducing the spatial resolution of the system and its ability to distinguish between closely spaced features (Figure 8–7).

The resolution of the system will define the minimum difference in depth that can be detected by the system and be implicit in the choice of system. Deep water, low frequency systems will have a longer wavelength than shallow water high frequency systems, and consequentially will have a lower resolution (Table 8–1). Therefore low-frequencies (deep water) are not suited to detect small topographic features or objects. Shallow water multibeam systems can be mounted on ROV (Remotely Operated Vehicle) platforms to achieve high resolution in deep water. Although it is essential to select the best tool for the application, i.e. the highest frequency possible for the depths encountered in the area, the decision of which system to use will be a compromise between spatial resolution, signal resolution and swath coverage across the seabed, together with the systems and funds available.

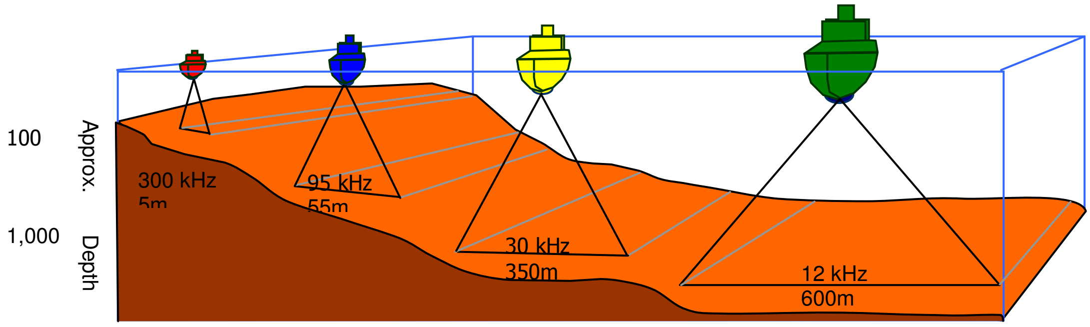


Figure 8–7. The size of the multibeam acoustic footprint at the seabed surface in relation to water depth and associated operating frequencies (After Geological Survey of Canada).

1.2 – Calibrations and Georeferencing of Multibeam Data

Multibeam echosounders are an advanced survey instrument and require regular calibration to obtain high quality data. It is critical to measure movements of the ship accurately and understand the velocity structure of the water column to georeference the sounding footprint on the seafloor. This is done by dimensional surveys, patch tests and sound velocity corrections.

Dimensional survey and patch test

To understand the movement all instruments undergo during surveys it is essential to know the offset distances between the GPS antenna, Motion Reference Unit (MRU) and transducer units precisely. This is done by land surveying techniques, using a surveyors level when the ship is in dry dock.

The measurements can be confirmed in the field by a "patch test" – surveying of patches of seafloor at different angles and speeds and analysing differences in the resultant data. This is a well documented procedure which is often detailed in the operators manual. Patch tests will identify and enable correction of positioning time delays (latency) and pitch, heading and roll offsets. This is best performed by sailing calibration survey lines over an inclined area of seafloor, such as a coastal slope or large sand wave. Each sensor must be individually calibrated on a routine basis, usually stipulated by the manufacturer. Gyro-compasses and motion sensors can be calibrated on the quay side through comparison with land based instruments, while tide gauges need to be routinely returned to the manufacturer for calibration, usually in a pressure chamber.

New system installations and calibrations should to be undertaken with an engineer from the manufacturer. It is advisable to collect two perpendicular lines at the start or end of a survey as a calibration check and control without going through a full calibration of the system.

Sound velocity corrections

The speed at which sound travels through the water column (sound velocity profile) must be known to convert the travel times of acoustic waves into distances. Sound velocity commonly ranges from 1400 to 1570 ms^{-1} (Figure 8–8) approximately four times the speed of sound through air. This is a function of water density, which is affected by water temperature, salinity and pressure and therefore varies with the depth. This parameter has a significant effect upon the calculation of the distance between the seabed and the transducer, and positioning of the footprint of each beam. Additionally, acoustic waves are refracted when the water density, and hence sound velocity, changes in just the same way that light is bent when looking through a glass of water (the Snell-Descartes law of refraction). Outer beams show more distortion than central beams owing to the longer distances travelled and larger slope angles. Refraction effects occur extensively where waters are stratified in to layers with steps in temperature and salinity resulting from freshwater inputs (in estuaries) or insolation in the summer, especially in lakes.

Sound velocity profiles are measured using a sound velocity profiler (SVP) or conductivity, temperature and depth profiler (CTD) (Figure 8–8). During a survey, profiles should be recorded at regular intervals, dependent upon the water body being surveyed and it's degree of mixing. A sound velocity sensor is also often mounted near the transducer face, which is especially important when using beam steering.

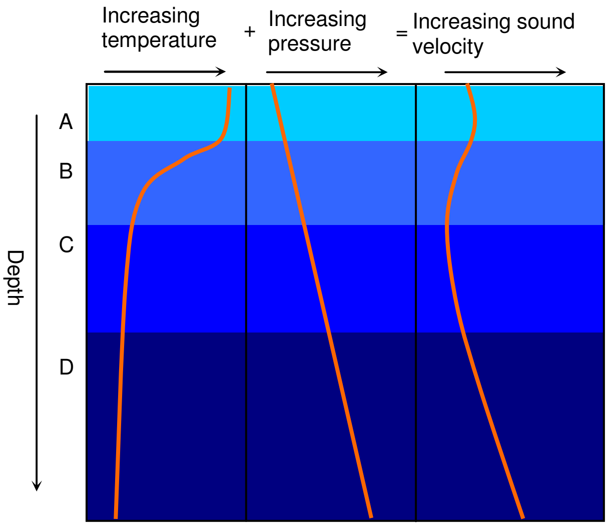


Figure 8–8. A typical sound velocity profile (after Thurman, 1997) and sound velocity profile instrument.

Georeferencing

The multibeam echosounder essentially measures the angle and travel time of each sounding insonifiying a patch of seafloor. These measures must be further processed to obtain geo-referenced soundings:

- The angle must be compensated for the motion of the boat (heave, pitch, roll and yaw) using a Motion Reference Unit (MRU) (examples include Applanix POS M/V, Seatex MRU5 and iXSea Octans)
- The sound velocity profile of the water column in the survey area must be loaded in the system during acquisition or post-processing to calculate corrected distances (see above).
- The heading of the ship from gyroscopic compass must be applied to orientate the swath of soundings relative to the true North.
- At each ping, the accurate position of the ship must be obtained using Differential Geographic Positioning System (DGPS) or real-time kinematic GPS (RTK-GPS). Knowing the location of each transducer head relative to the GPS antenna, the horizontal position of each sounding can be calculated This is measured using a draft sensor or tape.
- Finally, soundings must be corrected for tidal height and reduced to a standard vertical datum (e.g. Chart Datum, Lowest Astronomical Tide (LAT), etc. (Figure 8–9)). Soundings can be de-tided using in-situ tidal measurements from a tide gauge(s) or by using predicted tidal heights. Often a combination is used.

Operations

In most cases, multibeam transducers are fixed to a vessel's hull (Figure 8–10), especially in the case of deep water systems. For shallow water applications the size of many transducer heads is such that they can be mounted on a retractable arm over the side of the vessel or on an ROV.

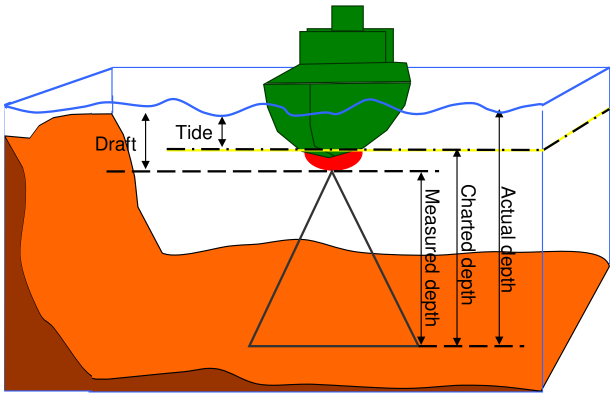


Figure 8–9. Vertical corrections applied to the multibeam measurements.

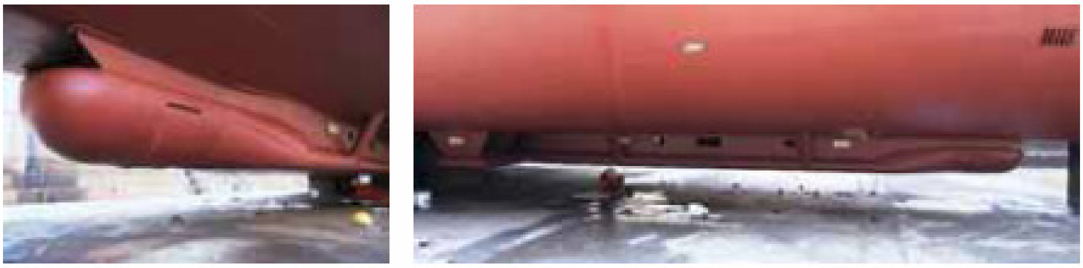


Figure 8–10. Hull mounted gondola © GSI.

Data collection is digital, with transducers linked to a computer that controls the signal emission (energy, swath angles, etc.), runs electronic filters and stores received signals. Processing of raw data into both images and measurements is also performed on computer. Adequate computer storage space needs to be allocated prior to the start of the survey to ensure recording and backup of data on a line-by-line basis. Unlike sidescan sonar or sub-bottom profiles, it is not common practice to print out data during its acquisition. The acquisition software should have a waterfall display for quick online quality control. It is preferable (when practical) for data processing to be performed on-board, in near real-time, so any acquisition problems can be quickly detected and corrected.

3 – Data Acquisition

3.1 – Survey Planning

The time requirements for surveying an area are primarily dictated by the water depths in question, with shallower areas taking longer to survey owing to smaller footprint size (Figure 8–11). For survey planning one must first gather as much available information as possible on the bathymetry, from admiralty charts, previous surveys, GEBCO (General Bathymetric Chart of the Oceans) etc. Knowledge of oceanographic characteristics can also be useful, for planning locations of sound velocity measurements, tide gauge deployment and calibrations.

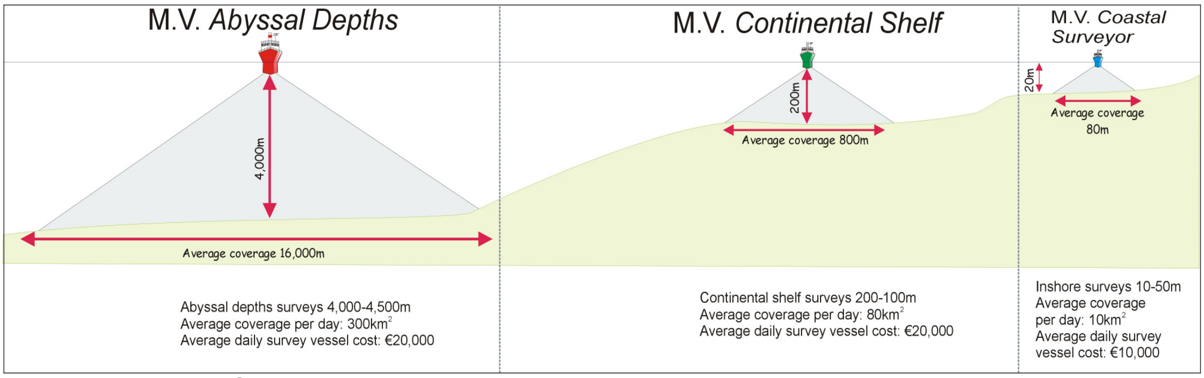


Figure 8–11. MBES swath coverage relative to water depth.

Surveys tend to be conducted in accordance to set standards, such as the International Hydrographic Organization (IHO) standard S44 and those of Land Information New Zealand (LINZ). The purpose of the survey and its depth, as defined in the chosen standard will dictate the required degree of overlap of the survey lines in order to conform to the standard. In general, for full coverage of an area to create a complete DTM, a 20% overlap of adjoining survey lines is required. This is to allow for loss of data from outer beams owing to sharp features on the seafloor or poor weather conditions making their positioning uncertain. Survey lines are planned in parallel for a “swath by swath” survey, preferably along the bathymetric contours to minimize changes in the size of the swath and related changes in system settings or in a direction suitable for the steering of the vessel in case of complex shore lines, heavy currents or swell.

The vessel speed will be dependent upon the depths encountered, as time for the acoustic signal to complete a return journey through the water column must be allowed. Approximately 3 to 4 knots is appropriate for water depths more than 1000m, 8-9 knots in shallow waters, less than 200m. The required survey accuracy will also influence vessel speed; reducing speed to 3 knots in shallow waters will be needed to achieve positional accuracy of less than 1m.

International hydrographic standards such as LINZ or IHO S44 also require regular crosslines to be acquired in order to assess data quality. This practice is not strictly necessary for surveys with no navigational charting purpose, however, it is a good practice to acquire at least one crossline over a surveyed area as an end of survey check (Figure 8–12). Box 8–2 gives a simple example of estimating the time for a given survey.

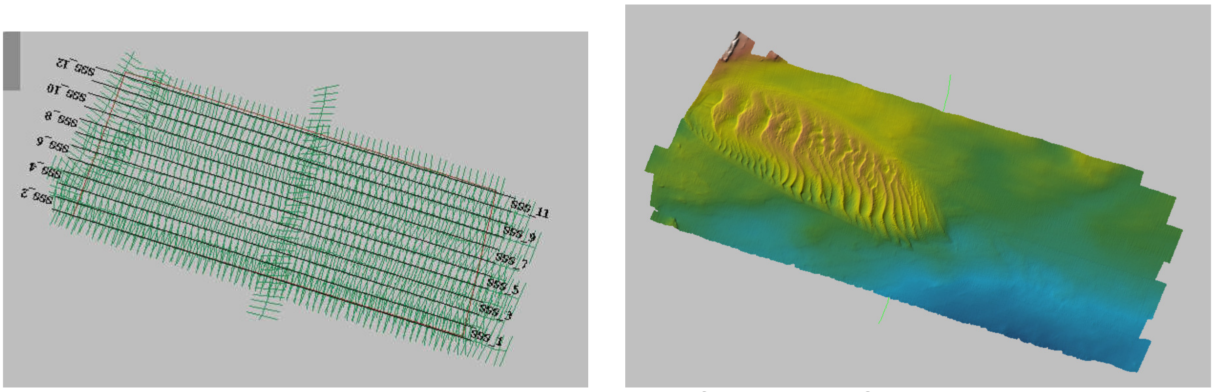


Figure 8–12. Example of multibeam survey lines in North Channel Irish Sea (Marine Institute – MESH_05_01 survey).

Box 8–2. Example of time budget calculation:

Area: 10x10km, 100m depth in relatively flat area, 100% coverage, 20% overlap
Multibeam swath at 100m depth: 400m
Line spacing: 320m
Number of lines: 10km/320m = 32 lines + 1 crossline
Time to run the lines at 8 knots: 33 * (10km/8 knots) = 20.6 hr
Total time, including turns of 5 minutes: 20.6 hr + 33*5 min = 23.3 hr
Include 10% more to account for SVP profiles and weather down time: 25.8 hr

3.2 – Survey Settings

Depending on the multibeam manufacturer and acquisition software, the operator can have access to very different type of settings.

The primary settings are:

- Beam spacing: modes of equidistant, equiangular or in-between. To obtain a regular grid of soundings, it is preferable to choose equidistant.
- Coverage: fixed port/starboard angles or fixed port/starboard distances.
- Gain settings: should be kept constant for backscatter applications.
- Filtering: filtering options differ widely from one system to another. Usually data are filtered, or flagged as rejected, depending on the strength or direction of the returned acoustic echoes.
- Offsets: positions of the sensors (transducer, navigation antenna, motion sensor) relative to a common reference frame. The mounting of sensor and high accuracy surveying in of them are made in dry dock for hull mounted systems or in the case of a pole mounted system deployed over the side of a vessel, relative locations are precisely measured during their installation.

Data processing

Multibeam data processing consists of three main steps: correction of soundings, cleaning and check of soundings and visualisation of the soundings.

Preliminaries
Often the acquisition software will record data in a format different to that read by the processing software. Raw data may therefore need to undergo a transformation, conversion or importation process from acquisition at the sensors (multibeam, motion sensor, tidal data etc.) to processing software formats.

Corrections
Tidal information must be incorporated at the post processing stage, to correct all sounding depths to a standard water level. Draft readings and sound velocity corrections can also be applied at this stage or re-applied to correct for erroneous settings made during acquisition.

Data cleaning / checking
Data cleaning and checking will apply to vessel navigation and attitude data, as well as the depth soundings. The process begins with a visual inspection of vessel navigation and attitude data to identify and remove any invalid measurements by the navigation or MRU instruments.

The suppression of erroneous depths caused by fish, noise or air in the water column can be performed manually or automatically through various filters. Erroneous soundings are also called outliers or spikes. Manual cleaning can be performed through several interfaces depending on the software manufacturer. The most common incorporate visualisation of the data ping-by-ping on a line-by-line basis (also called a waterfall display) or on a subset of data in a 2D or 3D view (Figure 8–13 and Figure 8–14). These interfaces are very useful for checking the quality of the data and can reveal problems in the acquisition settings such as neighbouring lines not matching and abnormal swath shape.

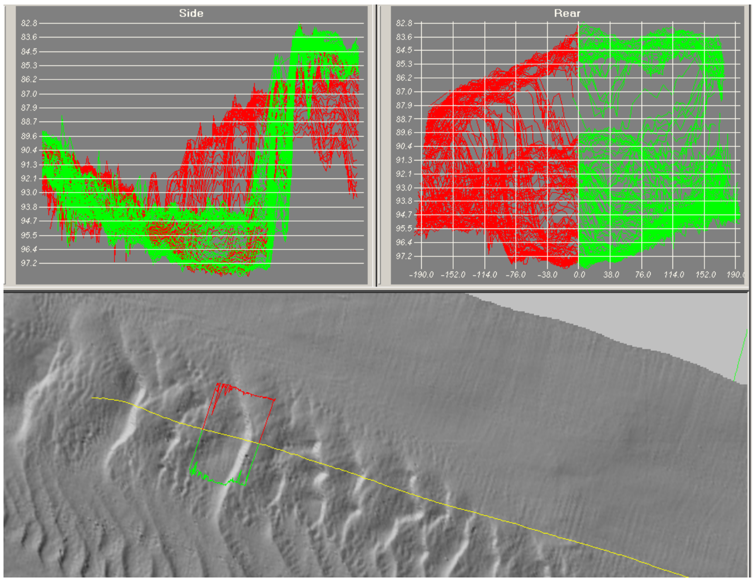


Figure 8–13. Example of ping by ping data cleaning (screen caption of the “Swath Editor” in CARIS HIPS software). (Marine Institute – MESH_05_01 survey).

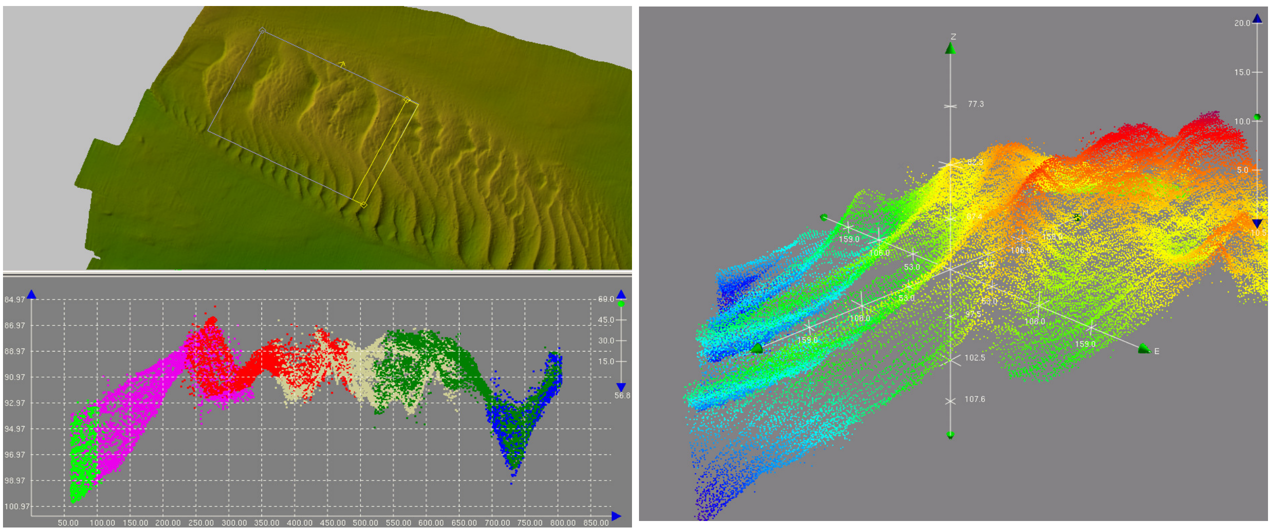


Figure 8–14. Example of view by subset of data, both 2D and 3D views (screen capture of the “Subset Editor” in CARIS HIPS software) (Marine Institute – MESH_05_01 survey).

Filtering methods are numerous. They can be as simple as setting a minimum/maximum depth threshold, swath reduction (outer beams are usually the noisiest) or employ more advanced algorithms. Most recent has been the development of CUBE (Combined Uncertainty Bathymetric Estimator), a method that statistically calculates the most likely depth at a point on a surface. The correction of measurements over wrecks and similar objects should be performed with care, if at all, owing to their irregular topographies, angles and shapes, apparently erroneous soundings may be real. Manual processing and checking will be necessary regardless of the degree of sophistication of automated methods, highlighted in the afore mentioned case of wrecks, to assure the efficiency of any applied filters, ensure data quality, to check and finalize processing.

Data visualisation

The outcome of data processing are cleaned soundings (x,y,z records and backscatter), which can be used for visualisation of the bathymetric data. Two main types of digital terrain models (DTMs) can be built from those points.

- A Triangular Irregular Network (TIN): where the soundings are the vertices of triangular cells. This type of DTM gives an image of the seafloor with actual depths value, usually used for safety of navigation application.
- A Regular Network: a grid of square cells where the depth of each node is an averaged depth of the neighbouring soundings. This type of DTM gives a smoother image and is more usually found in geophysical analysis.

For further analyses, DTMs can be visualised in 3D fly-through software and used to build contour maps (Figure 8–15).

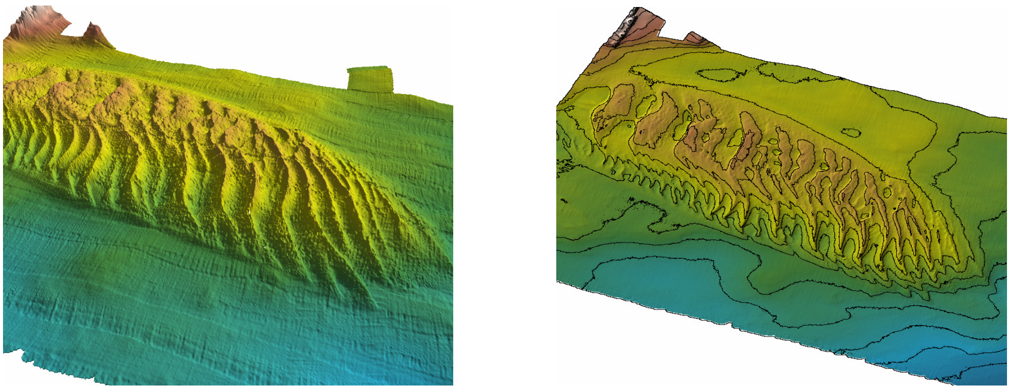
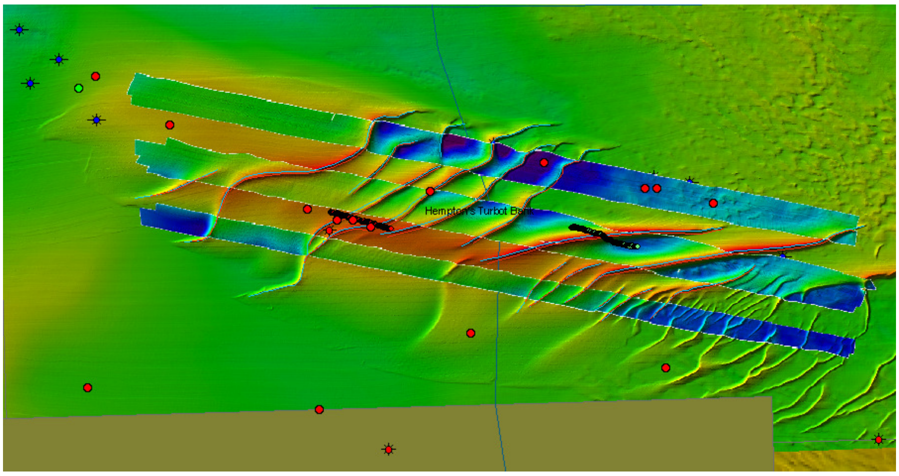


Figure 8–15. Example of 3D DTM view and contours (North Channel Irish Sea, Marine Institute – MESH_05_01 survey).

Images with geographical information (the “geotiff” format for example) may also be created and imported into a Geographic Information System (GIS). Each pixel of the image is attributed with an averaged depth value and colour coded in accordance. Most of the software packages offer an option to add a shaded relief effect, which gives a better render of the seabed morphology. Figure 8–16 illustrates the DTM from habitat mapping surveys performed on the MESH priority area of the Hemptons Turbot Bank, presented in ArcMap GIS from ESRI.

Figure 8–16. Hemptons Turbot bank, multibeam images from 2004 and 2005 (stripes) overlaid with sample locations (red dots), video trawls (black dots) and digitised sand wave crests (blue lines) – screen capture in ESRI ArcMap (Marine Institute - CE_04_02 and MESH_05_01 surveys).



4 – Backscatter Data

When available, the backscatter information is logged in the proprietary format of the multibeam software. There are typically two standard types of format:

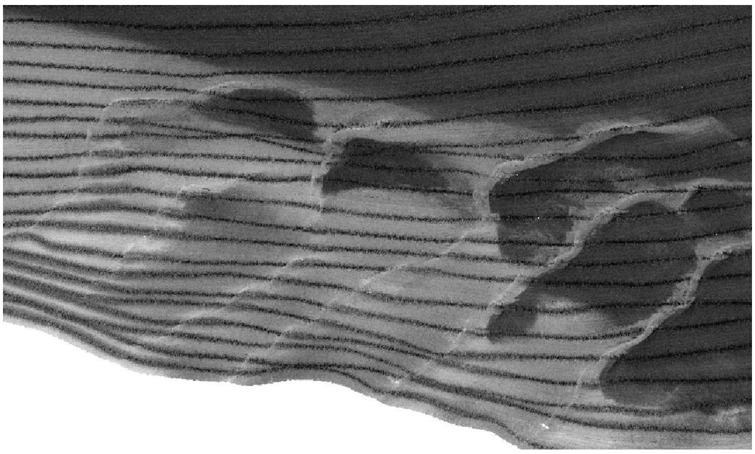
- One backscatter value per beam,
- Full echo record (also known as snippet) per beam.

During acquisition of multibeam data, special care should be taken when the backscatter data are to be used for further analysis. Changes in gain will result in changes in backscatter strength in the final mosaic and should therefore be avoided if possible. Any changes in gain should be recorded in the survey log. Some systems may automatically change gain levels when acquiring data in a fixed coverage mode and should therefore be avoided at any time when multibeam backscatter data it to be used.

Multibeam backscatter data can be mosaiced in the same was as data from sidescan sonar. For this purpose, the beam-averaged data format is of little interest as the imagery obtained from it is very blurred, owing to the low resolution (merely hundreds of points per swath). The full echo record may be processed as a sidescan sonar record to create high resolution images from the full echo record (Figure 8–17).

Processing requirements are limited as most of the beam pattern and Time-Varying Gain (TVG) corrections are performed internally during data acquisition. Bathymetry data processing is simply used to update the backscatter information to remove invalidated beams before the mosaic process. For better results, the backscatter information must be corrected for beam pattern, seabed slope or frequency-dependent angular artefacts (owing to the geometry of the multibeam system), this is usually performed internally during acquisition but some software packages allow for post-processing corrections.

Figure 8–17. Backscatter mosaic of Hemptons Turbot bank, summer 2004 survey.



Multibeam backscatter can be further processed in specialist software for seabed classification purposes (e.g. QTC MultiView or Kongsberg Triton). The classification is the segmentation of the mosaic image into classes of similar acoustic backscatter characteristics.

For habitat mapping, the backscatter model obtained can be used as a tool to optimise ground truthing, by identifying acoustically distinct regions for sampling and hence reduce the number of samples required. Results from the samples such as particle size analysis (PSA) may then be added to the model to produce a comprehensive sediment map.

5 – Evaluation of Multibeam Echosounders for Habitat Mapping Purposes

Multibeam systems are ideal for bathymetric surveys providing full coverage of the sea bottom, compared with single-beam echo sounders, which return only coverage directly beneath the hull. As such, the high-resolution bathymetric maps and DTMs obtained through multibeam surveys are invaluable for habitat mapping purposes as they visualise seafloor morphology and by repetitive survey, its change. They also provide information on possible obstructions, so ensuring the safe deployment of underwater systems such as video cameras and ROVs.

Backscatter information is also a very valuable interpretative tool for mapping the acoustic properties of seafloor sediments and dynamics with harder bottoms reflecting more energy than soft bottom, sediments that have recently moved absorbing more energy than static sediment, bare rock reflecting more energy than that covered in a turf of growth. Backscatter maps can provide a tool for planning sediment sampling locations and programmes. Expert backscatter interpretation or automated classification algorithms enable the delineation of areas with similar acoustic backscatter properties and may be a guide to identifying seabed habitats.

Unlike sidescan sonar, the positioning of soundings from MBES is very accurate. While MBES backscatter images do not achieve the resolution and quality of sidescan sonar mosaics, they do not suffer the nadir effect to the same degree as sidescan, which stripes images.

The large insonified swath (4 to 7 times the water depth) and speed of survey make MBES efficient surveying tools. Systems permanently hull mounted on a vessel are available for any survey undertaken with the vessel, without incurring additional equipment costs, however, user familiarity in their operation is essential to ensure data collection, correction and processing are appropriately implemented.

5.1 – Varieties of Systems Available

Numerous multibeam systems are commercially available. The main constructors are Kongsberg Simrad, Reson, L3 Communications (Elac-Nautic) and Atlas Hydrographic (Table 8–2).

Table 8–2. Examples of existing multibeam systems (note that this is not a full list of manufactures or systems).

System	Constructor	Depth Range / Max Swath Width
EM3000	Kongsberg Simrad	Single: 1-150m / 5x depth Dual: 1-150m / 10x depth
Seabat 8101	Reson	0.5-300m / 7.4xdepth
Sea Beam 1180	L-3 Communications Elac Nautic	300m / 8.3x depth
Atlas Fansweep 20/100	Atlas Hydrographic	1-600m / 12x depth
EM 1002	Kongsberg Simrad	EM 1002S: 2-600m / 7.4x depth EM 1002: 2-1000m / 7.4x depth
Seabat 8160	Reson	10-2500m / 3x depth
EM120	Kongsberg Simrad	20-11,000m / 5.5x depth

The quality of these systems are quite similar although performance will vary depending upon the depth for which the system was designed, the type of seafloor surveyed and the survey vessel upon which they are mounted. Prior to purchase, it is advisable to request sea trial data of the systems under consideration from manufacturers for comparison. It is of cause essential to choose a system suitable for the intended purpose (depth and resolution) as discussed in section 2.b above, and therefore imperative that present and future requirements are clearly determined.

Combined prices for hardware and software are usually offered by most manufacturers, incorporating engineering skills for installation, surveying and calibration. Rental of equipment, installation and operation personal may also be an appropriate option from time and financial perspectives, especially in the case of mobile pole mounted and ROV surveys.

6 – Review of Existing Standards and Protocols

6.1 – Acquisition and Processing

Existing documents
A number of standards and protocols exist for Hydrographic surveys (Table 8–3). The International Hydrographic Organisation (IHO) standards are probably the best known and most commonly used standards in Hydrographic surveying but were not specifically developed for multibeam surveys. The Land Information New Zealand (LINZ) standards were designed for multibeam surveying and are therefore probably the most relevant, detailing the procedure for performing multibeam surveys to hydrographic standards. The LINZ specifications also discuss the requirements for backscatter mapping using MBES.

Hydrographic standards will often exceed the need for habitat mapping purposes and therefore serve as a highly rigorous reference set of habitat surveying standards and protocols. For example, IHO S44 specifies a maximum line spacing of 25m or 3 times water depth. In a water depth of 20m this will require a maximum line spacing of 60m, while many MBES systems will achieve a seafloor swath of more than 100m in this water depth, creating a 40% overlap between lines. For habitat mapping purposes one may therefore choose to reduce the overlap by increasing the line spacing, so increasing the seafloor coverage achievable in a given survey time, yet maintaining 100% sea floor coverage.

Specialist Software
Sonar manufacturers usually produce their own specialised acquisition and processing software, available as combined or separated products. Table 8–4 gives a list of existing software.

Table 8–3. Existing standards of multibeam data acquisition and processing.

Title	Company / Agency	Application	Comments
LINZ Land Information New Zealand	Land Information New Zealand.	Hydrographic surveys and backscatter requirements.	Survey requirements applicable to habitat mapping. The defined accuracy minimums of the standard, if adhered to during a habitat survey, would more than provide for the needs of the application.
IHO S44 International Hydrographic Organisation Special Publication 44 Standards for Hydrographic Surveys.	International Hydrographic Organisation.	Hydrographic surveys.	Survey requirements applicable to habitat mapping. The defined accuracy minimums of the standard, if adhered to during a habitat survey, would more than provide for the needs of the application.
IHO S57 ZOC International Hydrographic Organisation Special Publication 57 Transfer Standard for Digital Hydrographic Data – Zones of Confidence principle.	International Hydrographic Organisation.	Hydrographic surveys.	Survey requirements applicable to habitat mapping. The defined accuracy minimums of the standard, if adhered to during a habitat survey, would more than provide for the needs of the application.

Table 8–3 (Continued). Existing standards of multibeam data acquisition and processing.

Title	Company / Agency	Application	Comments
National Standard Contract and Specification For Surveying Services Standard Technical Specification: Section Xa – Hydrographic surveys of river channels and other water areas using swathe bathymetry	Environment Agency (UK)	Hydrographic surveys.	Survey requirements applicable to habitat mapping. The defined accuracy minimums of the standard, if adhered to during a habitat survey, would more than provide for the needs of the application.
Hydrographic Work Flow – From Planning to Products.	[1] Naval Oceanographic office. [2] Science Applications International Corporation. [3] Interactive visualization Systems Inc.	Hydrographic surveys data management and processing.	Hydrographic survey planning. Applicable to Habitat Mapping. Doug Croning[1] Mel Broadus[1] Barbara Reed[1] Shannon Byrne[2] Walter Simmons[2] Linday Gee[3]
NOS Hydrographic Surveys Specifications and Deliverables.	National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS).	Hydrographic surveys.	Standard for data delivery of NOS data to NOAA. Could be adapted for data exchange standards.

Table 8–4. List of existing software.

Software	Constructor	Usage	Website
HIPS and SIPS	CARIS Ltd.	Data processing and visualization Supports a wide range of multibeam systems.	http://www.caris.com/products/software.cfm/prodID/1
HYSWEEP	Hypack Inc.	Data acquisition and processing.	http://www.hypack.com/hysweep.asp
CARAIBES	Ifremer.	Data acquisition and processing.	http://www.ifremer.fr/fleet/equipements_sc/logiciels_embarques/caraibes/index.html
Fledermaus	IVS Ltd.	Data post-processing and visualization.	http://www.ivs3d.com/products/fledermaus/
Merlin	Kongsberg Simrad.	Data acquisition for Kongsberg Simrad systems only. UNIX based.	http://www.km.kongsberg.com/
SIS		Data acquisition for Kongsberg Simrad systems only. Windows based.	http://www.km.kongsberg.com/
Neptune		Data processing for Kongsberg Simrad data only. UNIX based.	http://www.km.kongsberg.com/
Poseidon		Multibeam backscatter processing and mosaicing.	http://www.km.kongsberg.com/
Triton		Multibeam backscatter seabed classification software. UNIX based.	http://www.km.kongsberg.com/
MB Systems	Lamont-Doherty Earth Observatory of Columbia University (L-DEO) Monterey Bay Aquarium Research Institute (MBARI).	Data processing and visualization. Supports a wide range of multibeam systems. UNIX based. Free.	http://www.ldeo.columbia.edu/res/pi/MB-System/MB-System.intro.html
QINSy	Quality Positioning Services BV (QPS)	Data acquisition and processing	http://www.qps.nl/Eng/Pages/QINSy.asp
QTC Multiview	Quester Tangent.	Multibeam backscatter seabed classification software.	http://marine.questertangent.com/m_mv.html
PDS2000	Reson nl.	Data acquisition and processing.	http://www.reson.nl/PDS2000.htm
Isis MB-Logger BathyPro	Triton Imaging Inc.	Data acquisition and processing.	http://www.tritonimaginginc.com/site/products_index/index.htm

6.2 – Data Interpretation

The seabed topography and acoustic seabed backscatter derived from multibeam echosounders are useful parameters in habitat mapping studies. Multibeam echosounders cannot however, alone identify or define seabed habitats and will always require ground-truthing. Without ground-truthing multibeam data will only be able to provide information on the seabed character and morphology and not on the biological habitat. Once the seabed signatures of acoustically distinct regions have been ground-truthed a habitat map may be derived from the multibeam echosounder data.

6.3 – Multibeam Bathymetry

Multibeam bathymetry provides information on the seabed bathymetry and morphology. This allows to visualise, identify, study and measure seabed features, but does not allow to study differences in seabed nature (Figure 8–18).

Standard data processing and interpretation involves building a DTM, which can be visualized in various software packages, such as Fledermaus (http://www.ivs3d.com) or the Generic Mapping Tools, GMT (http://gmt.soest.hawaii.edu/). DTMs can also be imported into Geographic Information Systems (GIS), like Arc View (ESRI), where they can be visualised and integrated with other survey data, for instance ground truthing data such as grab samples and video tows, to study spatial relationships and correlations, as well as further advanced processing and analysis such as calculation of Bathymetric Position Index (BPI) (Figure 8–19).

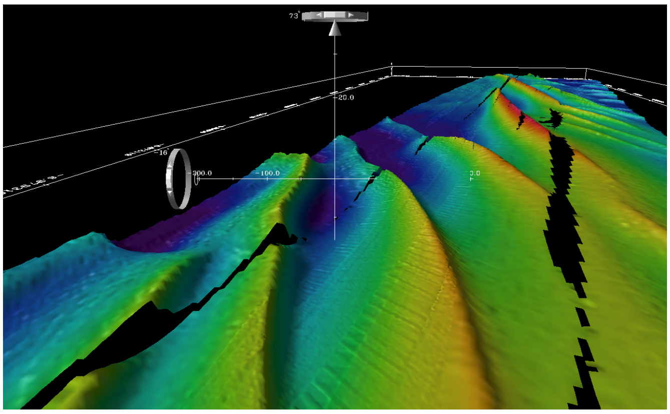


Figure 8–18. Fledermaus image of Hemptons Turbot Bank sand waves. Looking east northeast (73˚) from a perspective of 16˚. Vertical scale is exaggerated by a factor of 6. Scale is in metres.

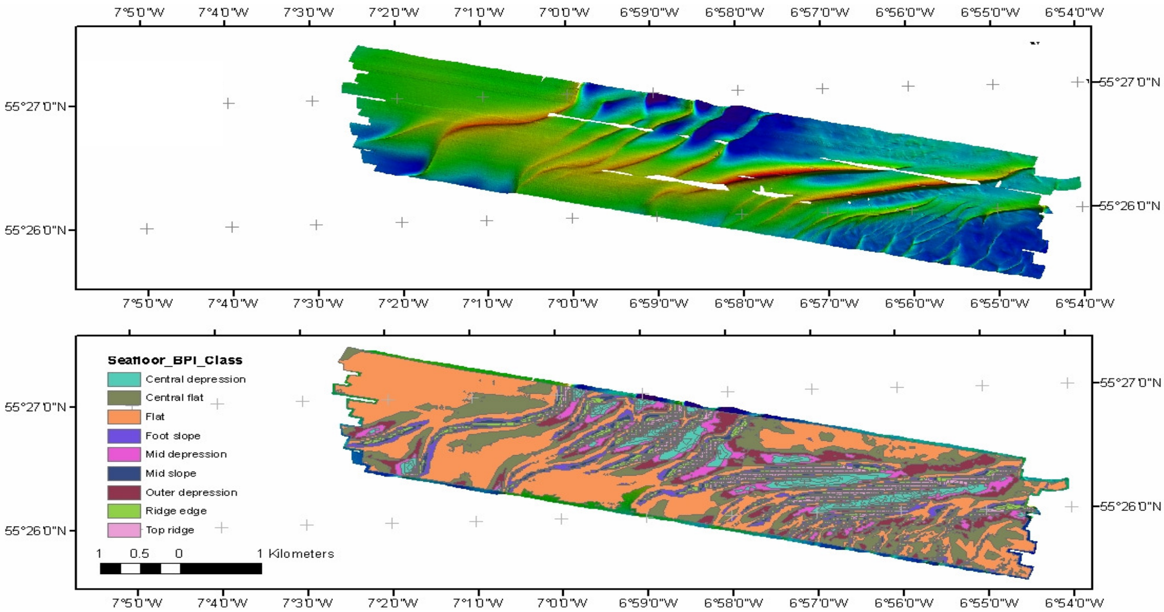


Figure 8–19. Bathymetric Position Index classification from DTM for Hemptons Turbot Bank (bottom) with shaded relief (top).

Multibeam bathymetry has been used globally for a wide range of applications and industries such as hydrographic, oil and gas, engineering, marine resources, military, geologic and habitat surveys, etc. The wealth of users and applications has meant that no specific standards or protocols exist for the interpretation of multibeam bathymetric information. The interpretation will very much rely on the habitat mapping experience of the personnel.

6.4 – Multibeam Backscatter

Multibeam backscatter provides information on the nature of the seabed and is a valuable data layer for habitat mapping purposes. Interpretation of multibeam backscatter for habitat classification is largely related to the ability to identify acoustic distinct regions, indicative of seafloor roughness and hardness. Areas may be demarked by eye from this (Figure 8–20) and interpretation is similar to the interpretation of sidescan sonar data.

Interpretation can be aided by automated seafloor classification techniques of the multibeam backscatter. Several software tools exist of which Kongsberg Simrads Triton and QTC Multiview are the most commonly used commercial packages.

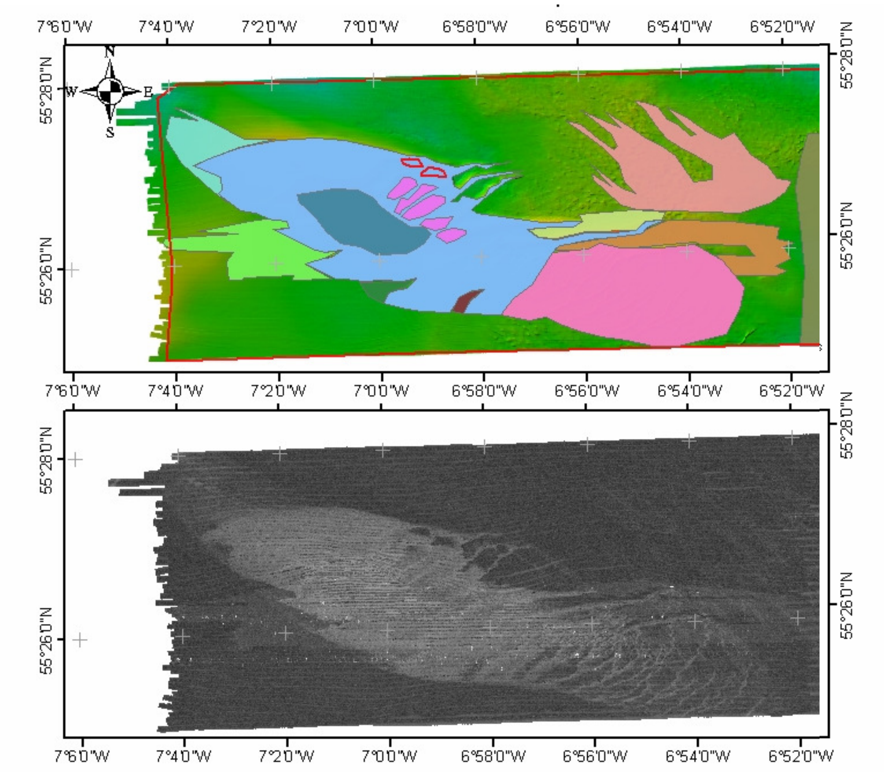


Figure 8–20. An example of multibeam backscatter (bottom) demarcation (top) by eye, from Hemptons Turbot Bank.

Existing documents

Several reports have been published where multibeam bathymetry and/or backscatter was used to study seabed habitats. Such published reports can form a guideline in the absence of formal standards and protocols for multibeam data interpretation (Table 8–5).

Table 8–5. Existing literature on multibeam data interpretation.

Author(s)	Title	Company/Agency	Application	Comments
Noji, T.T., S.A. Snow-Cotter, B.J. Todd, M.C. Tyrrell, and P.C. Valentine	Gulf of Maine Mapping Initiative: A Framework for Ocean Management	Gulf of Maine Council on the Marine Environment (US/CA)	Habitat Mapping, environment	Excellent information on joint habitat mapping strategy between the USA and Canada
V. Kostylev[1] B. Todd[2] G. Fader[2] R. Courtney[2] G. Cameron[3] R. Pickrill[2]	Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and seafloor photographs	[1] EcoVector [2] Geological Survey of Canada (Atlantic) [3] Cameron Geoscience Research	Habitat Mapping	Excellent study on sea floor habitat mapping integrating multibeam bathymetry data with associated geoscientific information
Unknown	Summary View of Multibeam Survey Technique	NOAA	Habitat Mapping	Good slide summarizing the use of multibeam data for habitat mapping purpose

7 – Provenance and Current Usage

Since the late 1970s, multibeam echo sounders have become one of the most used bathymetric systems for survey companies, telecom companies, government agencies, harbours authorities and universities the world over. Dramatic progress and development in computer technologies has helped this advance, increasing data processing speed and storage capacities.

More recently advances in data management systems and GIS have enabled better and easier use of collected data for cartography, data comparison and correlation with other sources of information. The latest improvements are now in the 3D visualization of the seafloor, useful for data processing and control (Fledermaus, CARIS HIPS), navigation (GeoNav3D, work from the Center for Coastal and Ocean Mapping, UNH) and automated backscatter classification (for example QTC and Triton).

For the above reasons multibeam echosounders have proved to be a useful tool in habitat mapping applications. There have been many applications of the technology around the world, with large initiatives being undertaken in Canada, the USA and Ireland, with small scale projects being undertaken in many parts of the world.

The General Bathymetric Chart of the Oceans (GEBCO) maintains a list of vessels equipped with multibeam echo sounding equipment, documenting the vessels country of registration, the operator, the system installed and the year of installation (http://www.ngdc.noaa.gov/mgg/gebco/swathmapping030423.pdf). A searchable online data base version is maintained on the International Research Vessel web pages at: http://www.researchvessels.org/swathdb/default.asp?SwathOrder=Sorter%5FSystemandSwathDir=ASCandSwathPage=1.

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Center for Coastal and Ocean Mapping / Joint Hydrographic Center, http://www.ccom-jhc.unh.edu

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Multibeam Sonar Theory of Operation, L3 Communications Seabeam Instrument for Monteray Bay Acquirium Research Institute (MBARI), 2000, http://www.mbari.org/data/mbsystem/formatdoc/

Summary View of Multibeam Survey Technique, NOAA Coastal Services Center Benthic Habitat Mapping http://www.csc.noaa.gov/benthic/mapping/techniques/pdf/qf_mbeam.pdf

9 Interferometric sonar systems

Jonathan White and Veronique Jegat (Marine Institute)

1 – General Principles of Operation and Data Processing

1.1 – Principles

Interferometric systems measure bathymetry and co-located Sidescan Sonar imagery, which can be co-plotted (Gostnell, 2005). Similarly to Beamforming Multibeam Echo Sounders (MBES), an interferometric multibeam echo sounder (also called phase measuring wide swath sonar) determines depth by measuring the angle and travel time of an echoed, emitted pulse of sound energy. Both systems can achieve full bottom coverage, with interferometric systems achieving swath widths of up to 15 times the depth of water (horizontal range of 7 and ½ times water depth to each side of the vessel) opposed to swaths of 4 times water depth of MBES.

The difference between beamformer and interferometric systems is in the determination of the travel time and angle of the received pulse. Beamformers have only one receiver array, where a single travel time is determined for each angle interval. Interferometers have two or more receiver arrays in a vertical arrangement between which an angle is determined for each travel time interval, while the acoustic signal is produced in a similar manner to a sidescan sonar plus (Bates and Byham, 2001).

It has been report that while the technique of interferometry has been around for some time and the name is in common usage, the technique to which it is commonly applied has evolved into “phase comparison swath bathymetry/multibeam” (SEA (Group) Ltd.) or “phase measuring bathymetric sonars” (GeoAcoustics Ltd.). These techniques use the phase content of the sonar signal to measure the angle of wave front returned from a sonar target. The sound wave is emitted from a single transducer (projector array) down and out to the sides of the vessel; narrow in the fore and aft direction (~1.5°) and wide in the port – starboard direction (~120°). The phase of returning echoes are detected by the 2 or more receiving transducers mounted one above the other from which the difference in phase is used to calculate angles and travel distances of the returning sound pulses (Green,1998). The corresponding horizontal distance from directly below the vessel out to the position at which the sound pulses were reflected is then calculated based upon Pythagoras’ Theorem (Figure 9–1).

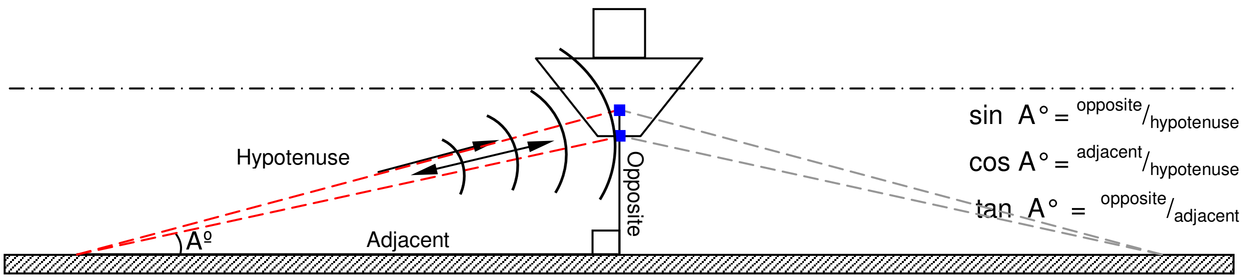

Figure 9–1. The operating principal of interferometric sonar systems. Returning sound waves, emitted from a single emitting transducer, are detected by receiving transducers mounted directly one above the other. The difference in phase of the returning wave, as it passes the two receivers is used to calculate incident angles, from which depth may be derived *via* the principle of Pythagoras’ theorem.

Angle of origin may in fact be calculated in a number of ways, most of which are similar to the approach of Denbigh (1989):

$\theta = \alpha_n - \alpha_{n+1}$, where:

α = atan (I / Q),
n = interferometric receive element
I = in-phase1 component
Q = quadrature1 component
(After Gostnell, 2005).

Interferometers fall in to several categories, all of which use similar transducer geometry with two or more horizontal arrays arranged one above the other. Each array is similar to a standard sidescan array, producing a narrow beam that is wide in elevation. Different approaches use different methods to measure the angle of the returning wave front:

The addition of two signals produces amplitude patterns varying in strength, from which the angle of the wave front can be calculated by detecting only the minimum or maximum values and determining the angles at which they cross. This method produces only a few depth values along a profile and can be extended by using the gradient of the amplitude patterns to produce phase measurements.

A time series of amplitude measurements can be recorded at each receiving transducer and a phase shift derived by finding the time shift with the best correlation between the two. This approach has limitations; the resolution is restrained by the size of the time series bins, Correlations may be hampered by noise in the data and returning sound waves.

Direct measurement of the phase at the receiving transducers relative to a reference signal. In order to ensure accurate measurement of the angle accuracy more than one pair of receiving transducers are required. Wide spacing of these ensures accurate measurement, however, this system is susceptible to noise and poor resolution, while narrow spacing gives good resolution and little interference from noise, it results in any one-phase measurement decoding to several elevation angles.

Owing to the nature of the sonar wave front as it spreads and the returning signal, the density of recorded data is noticeably larger than that from beamforming (multibeam) sonars, for which data density is dependent upon the number of beams formed and data bin sizes of processed data. This data density characteristic of interferometric sonar needs to be taken into consideration when determining computing needs; processing and storage capacities.

As interferometry relies upon the difference in phase of a returning signal at two separate sensors to determine depth it is more sensitive to amplitude, and therefore capable of producing detailed amplitude images (backscatter). This is an integral component of the product from this technique and is of the detail of normalised sidescan sonar imagery. In habitat studies bathymetry and co-located amplitude values (backscatter) is valuable for habitat appraisal and classification when used with *in-situ* ground truthing (Bates and Byham, 2001).

New processing techniques to the field are improving the resolution of data collected with interferometric devices. Synthetic Aperture Sonar (SAS) can improve the detection and resolution of angular objects and areas by summation of many sonar returns from an object received at different locations, using a receiver with a broad beam width (Banks *et al.,* 2001). The synthetic aperture relates to the image processing approach where the focusing aperture is “synthetically” created through the recalculating summation of the many returns.

1.2 – Evaluation

Interferometric systems can provide high resolution soundings over a wide swath. The width of the swath relative to water depth make it an attractive choice for gathering depth data and sidescan sonar imagery from shallow areas – in 4 m of water, swath can be near to 50 m width (Gostnell, 2005). From these soundings, high resolution 3D images of the seafloor can be produced to analyse the seabed characteristics and texture. According to Blacquiere and van Woerde (1998), however, these systems are not ideal if complex underwater structures have to be visualized (for instance harbour walls and wrecks); the imagery produced can be graphically flawed as light and dark banding of the interferometry can remain across the data making depiction of the seabed difficult. For more simple situations (relative flat seafloor), interferometry is very well suited and good results have been achieved. These systems are also very attractive because of their low cost, ease of deployment and high resolution. Interferometric systems are efficient in very shallow waters (≤40 m) (GeoAcoustics Ltd.) where beamformers are more limited, providing larger swath coverage.

Accuracies of interferometric systems will evolve with use and developing technology. Hogarth 2002) after assessing all sources of error achieved repeatability of surveys with centimetre accuracy. Green (1998) considered the technique to have reached a mature state, being an accepted alternative to beamforming multibeam, with differences in data being advantageous to some applications (Table 9–1), though even in the intervening period there has been notable development.

Table 9–1. Advantages and Disadvantages of Interferometric systems compared with beam based systems. (After Green, 1998).

Advantages	Disadvantages
High resolution, useful in detecting small targets in shallow water. Wider swath width, especially advantageous in shallow water. Integrated sidescan and bathymetry output. Ability to differentiate several targets at the same angle - useful when targets are to be resolved in the water column.	High data rates require a powerful processing system. Some man made targets such as dock walls can suffer from range ambiguity, which can require targets to be re-surveyed at a different range. Water column targets need filtering during data processing. Coverage of the nadir is not as high as at more horizontal areas.

Mallace (2002) in his comparison of Reson 8125 and 8101 beamforming multibeams, GeoSwath interferometric system and Atlas Fansweep 20 hybrid beam forming/interferometric system concluded that while the interferometry produced digital terrain models giving a good guide line of seabed topography they were nosier and less accurate than the beamforming systems. GeoAcoustics publicity material of their GeoSwath systems however, itemises survey results of high resolution and low cost, while Bates and Byham (2001) found bathymetric resolution limitations over steep seafloor slopes, though effective results over gentle slopes and semi-quantitative information of bottom type. A recognised limitation to interferometry is termed the "shifting footprint effect", which results from receivers acquiring simultaneous echoes from slightly different locations on the seabed, resulting in degradation of the signal coherence and of the measured phase difference (Lurton, 2000). This geometrical effect is inherent, and while it cannot be prevented, it can be minimised reports Lurton, though compensation receives for time shift due to the target observation tilt angle.

Gostnell, Yoos and Brodst (2006) undertook evaluation testing of three "phase differencing bathymetric sonar (PDBS)" interferometrics systems (GeoAcoustics GeoSwath, SEA SWATHplus, and Teledyne Benthos C3D) in shallow waters between 40 and 7m in depth. They concluded that "the technology appears capable of resolving ~1m^3 sonar targets on the seafloor and sloped and vertical features up to, or slightly above, the draft of the instrument." As with other comparison studies, the technique was also shown to provide higher coverage efficiency, by up to twice that achievable in shallow waters shoaler than 10m, than multibeam echosounders.

More comparison of interferometric technique with single and multibeam are listed by SEA (Group) Ltd. (http://www.sea.co.uk/swathplus.aspx?nav=products), but this information may be biased.

1.3 – Operations

Interferometric transducer units tend to be small (less then 40 cm^2), enabling them to be mounted on a retractable pole over the side of a vessel (Figure 9–2 to Figure 9–4). Units can easily be installed as temporary additions to almost any size vessel (Figure 9–5) or on an ROV (Figure 9–6). Water depths surveyed are typically between 30 and 200 m, with accuracies in the range of 0.1 m to 0.5 m. Time to survey an area of 1 km^2 in 30 m of water using the SWATHplus instrument are estimated at around 25 minutes, including time turning between lines. Data collection is electronic with transducers linked to a PC controlling signal emission, storing received signals and processes raw data into both images and measurements.

Figure 9–2. SWATHplus sonar head and mounting bracket.

Figure 9–3. Sonar head, mounting brackets and pole.

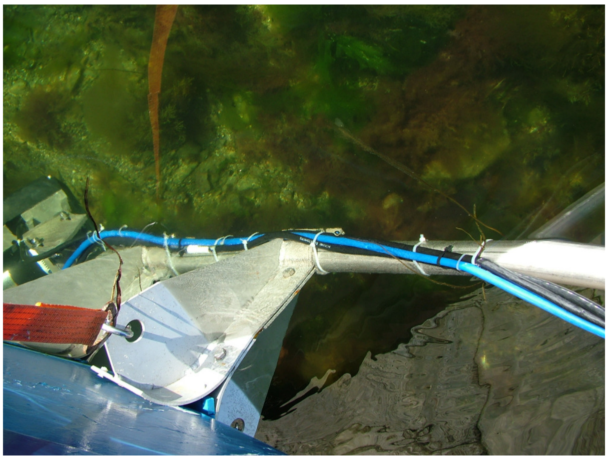

Figure 9–4. Sonar head mounted on the bow of the vessel.

Figure 9–5. Deployment vessel, showing mounting straps across the bow.

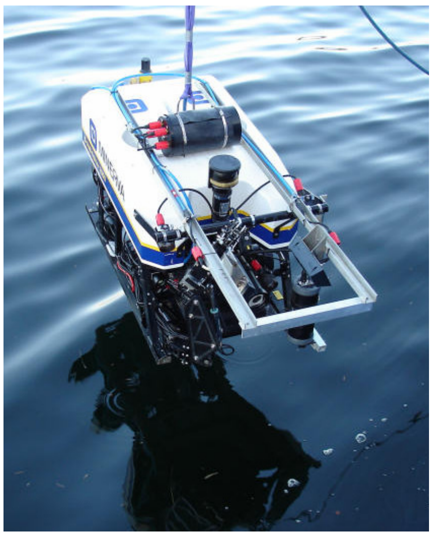

Figure 9–6. GeoAcoustics GeoSwath Plus wide swath sonar mounted on a Minerva Sub-fighter ROV (sonar electronics bottle is on top and transducers on the front frame) for surveying cold water corals mounds on the Tautra ridge off Trondheim, Norway.
(http://www.GeoAcoustics.com).

1.4 – Georeferencing

The raw measures of the interferometric system are the angle and associated travel time of each patch of seafloor insonified (sounding). These measures must be further processed to obtain geo-referenced soundings:

- The angle must be compensated for pitch, roll, heave and yaw motions of the survey vessel.
- Based on the angle and a sound velocity profile, the path followed by the sound pulse can be traced (ray tracing). For each emission/reception cycle (ping), the result is an accurate location of the soundings relative to the receiving transducer.
- The heading of the ship obtained from gyroscopic compass must be applied to orient the swath of sounding to the actual North.
- At each ping, the accurate position of the ship must be obtained from DGPS
- The location of each transducer head relative to the DGPS antenna.
- The depth of the sounding must be further reduced from the heave and draft at the time of measure.
- Finally the depth must be reduced from tide, and be therefore each sounding related to a standardised vertical datum (Lowest Astronomical Tide (LAT) or Mean Sea Surface (MSS)).

Therefore, additional equipment required for conducting interferometric surveys includes:

- Motion Reference Unit (MRU) for measuring heave, pitch and roll.
- Sound Velocity Profiler (SVP) or Conductivity, Temperature and Depth Profile (CTD) to measure the change in sound velocity through the water column.
- Sound Velocity Sensor at the transducer face, used for beam steering.
- Gyroscopic Compass for heading data.
- Differential Global Positioning System (DGPS) for horizontal position.
- Draft sensor or tape.
- Tide gauge(s) for measuring the tide level throughout the survey, critical for coastal surveys. These can be shore mounted and bottom mounted instruments. Depending upon the survey location accurate tidal models may be available.
- A Sound Velocity Sensor for measuring real time sound velocity at the transducer face may be advisable and an Altimeter for quality assurance.

1.5 – Calibrations

The alignment of the sensors (GPS antenna, MRU and transducers) must be accurately known to geo-reference correctly the soundings. This is done by land surveying techniques and patch tests – surveying of patches of seafloor at different angles and speeds and analysing the changes. For interferometric system, the assessment of the alignment of the two receivers is very critical, as it will have a high effect on the accuracy of the measured angles.

Each sensor must be individually calibrated on a routine basis, usually stipulated by the manufacturer. For example, gyro compasses and motion sensors can be calibrated on the quay side through comparison with land based instruments, while tide gauges need to be routinely returned to the manufacturer for calibration usually in a pressure chamber.

2 – Varieties of System Available

Table 9–2 summarizes information of standardly available interferometric systems. Van Oord ACZ BV performed swath multibeam trials in 2004 demonstrating that GeoSwath Plus is compliant with the standards of IHO S44 Special Order and S57 ZOC A1. No information was found on the SWATHplus system on this matter.

Table 9–2. Commercial Interferometric systems.

System	Constructor	Wavelength	Max. Depth	Width (Approximated)
SWATHplus (fka Submetrix)	Systems Engineering and Assessment Ltd. (SEA)	117 kHz 234 kHz 468 kHz	200 m 120 m 80 m	1000 m 500 m 250 m
GeoSwath Plus	GeoAcoustics Ltd.	125 kHz 250 kHz 500 KHz	200 m 100 m	600 m 300 m

3 – Review of Existing Standards and Protocols

3.1 – Data Acquisition

No agency or survey industry seems to have published specific documentation of standards or protocol for interferometric multibeam surveys. Standards for (beamformer) multibeams apply (see specific technical document). Manufacturer's documentation (Table 9–3) is probably the most appropriate for defining a generalized operating procedure.

Table 9–3. Existing literature on data acquisition using interferometric multibeam.

Title	Author	Company/Agency	Application	Comments
Shallow Water Surveys Using the GeoAcoustics GeoSwath	Peter Hogarth	GeoAcoustics Ltd.	General bathymetric surveys	Good information on survey setup and calibration.
Bathymetric Sidescan Techniques for Near Shore Surveying	Dr. C.R. Bates[1] P.W. Byham[2]	[1] University of St Andrews UK, [2] Submetrix Ltd. (Now Sea Ltd.)	Near shore surveying	Practical example of survey with Submetrix (SWATHplus). Could be merged
Hydrographic Work Flow – From Planning to Products	Doug Croning[1] Mel Broadus[1] Barbara Reed[1] Shannon Byrne[2] Walter Simmons[2] Lindsay Gee[3]	[1] Naval Oceanographic office [2] Science Applications International Corporation [3] Interactive visualization Systems Inc.	Hydrographic surveys	Hydrographic survey planning. Applicable to Habitat Mapping with adaptations

3.2 – Data Processing

Literature dealing with processing of Interferometric data is listed in Table 9–4.

Table 9–4. Existing literature on the processing of interferometric data.

Title	Author	Company/Agency	Application	Comments
Shallow Water Surveys Using the GeoAcoustics GeoSwath	Peter Hogarth	GeoAcoustics Ltd.	General bathymetric surveys	Good information on survey setup and calibration. Valid for GeoSwath systems only, would need to be generalized.
The Sea-Floor Mapping Facility at US Geological Survey	R.E. Deusser W.C. Schwab J.F. Denny	US Geological Survey	General data processing	USGS data acquisition and processing method. Could apply to habitat mapping with reviewing

Specialist Software
Manufacturers usually also produce specialized acquisition and processing software (as combined or separated products). Table 9–5 lists existing software and their approximate costs. Processing data takes less than half the time of the acquisition though this it will vary depending on the area of survey and sea state at the time of acquisition.

Table 9–5. List of existing software and indicative prices (will vary with contract and quantities purchased).

Software	Constructor	Costs	Description
GeoSwathPlus	GeoAcoustics Ltd.	~ €91,000 ~ €12,000	Full system (GeoSwath and GeoSwath Plus). GeoTexture (seabed discrimination)
SWATHplus processing software	Sea Ltd.	~ €73,000	Full system 234kHz (computer, hardware, software for acquisition SWATH SEA and processing SWATH GRID). For commercial survey, the software licence is limited to 2 sits. No limitation for educational research.
HIPS and SIPS	CARIS Ltd.	~ €20,000	Processing and visualization. Supports a wide range of multibeam systems.
MB Systems	Lamont-Doherty Earth Observatory of Columbia University (L-DEO) Monterey Bay Aquarium Research Institute (MBARI)	Free	UNIX based. Data processing and visualization.. Supports a wide range of multibeam systems.

3.3 – Data Interpretation

Generalities
The standard data interpretation involves building a DTM (Digital Terrain Model) from the soundings. Interferometric multibeam data has a high data density though with relatively high standard deviation compared with beamformers. So building a binned DTM will give an excellent result (accuracies of 6cm at the 95% confidence level for GeoSwath).

These DTMs can be visualized in various software, such as Fledermaus (http://www.ivs3d.com/products/fledermaus/) or the Generic Mapping Tools, GMT, (http://gmt.soest.hawaii.edu/). DTMs can also be imported into Geographic Information Systems (GIS), like ArcView from ESRI for further mapping and interpretation. For example sediment sample locations can be mapped and overlaid with the bathymetric information to check for correlations.

Existing documents
Few specific documents exist for the interpretation of interferometric data (Table 9–6). The interpretation of traditional (beamformer) multibeam can however, be applied.

Table 9–6. Existing literature on interferometric multibeam data interpretation.

Title	Author(s)	Company/Agency	Application	Comments
USGS Shallow Water Mapping Surveys using an Interferometric Sonar System	Jane F. Denny William Danforth	U.S. Geological Survey	Geophysical survey Habitat mapping	Excellent exposé from the USGS methods of using the interferometric SEA system and its use in complement to Side Scan.
Gulf of Maine Mapping Initiative: A Framework for Ocean Management	Noji, T.T., S.A. Snow-Cotter, B.J. Todd, M.C. Tyrrell, and P.C. Valentine	Gulf of Maine Council on the Marine Environment (US/CA)	Habitat Mapping, environment	Excellent information on common habitat mapping strategy between the USA and Canada. Interferometric systems are mentioned but not the main topic of the document.
Summary View of Multibeam Survey Technique	Unknown	NOAA	Habitat Mapping	Good slide summarizing the use of multibeam (interferometer or beamformer) data for habitat mapping purpose

4 – Provenance and Current Usage

The use of interferometric systems for shallow water bathymetric surveys has been increasing for the last 10 years, with systems from SWATHplus and GeoAcoustics Ltd. being used widely globally (USA, UK, Spain, France, Greece, China, Australia, New Zealand, Indonesia, Singapore, Taiwan, Argentina), and for a wide range of applications including port and harbour surveys, hydrographic surveys, river surveys, dredging and habitat mapping.

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Web Sites

SEA (Group) Ltd.: http://www.sea.co.uk/

GeoAcoustics Ltd.: http://www.GeoAcoustics.com/

10 Acoustic Ground Discrimination Interpreted With Ground Truthing

Bob Foster-Smith (Envision Ltd.)

1 – General Principles of Operation and Data Processing

This report is adapted from the Procedural Guidelines to be found in the Natura 2000 Marine Monitoring Handbook (Foster-Smith *et al*., 2001) (available at http://www.jncc.gov.uk/marine/mmh/Pg%201-3.pdf) which is based on more extensive technical reports that can be found on the Envision web site at www.envision.uk.com. More information is required about QTC and information may be obtainable through www.questertangent.com.

2 – General Principles of the Technique

Acoustic ground discrimination systems (AGDS) are based on single beam echo sounders and are designed to detect different substrata by their acoustic reflectance properties. An echo sounder generates a short pulse of sound at a single frequency that travels through the water and rebounds off the seabed (Urick, 1983; Mitson, 1983).The echo is detected by the transducer which converts the acoustic energy into an electrical signal that is displayed on a screen. The transducer shapes the pulse of sound into an approximate cone directed towards the sea floor. The area ensonified (analogous to the term 'illuminated') by the echo sounder directly under the vessel is approximately circular, although sounders produce many side-lobes that make the footprint a more complex shape in practice. The area depends upon the diverging beam angle (angle of the apex of the cone of sound), depth and topography of the sea floor.

Sound waves travelling in the centre of this cone will hit the seabed first (assuming the seabed is level) and depth is measured from time taken for this returning sound energy to be detected by the transducer. The strength of the echo and the way it decays with time produces a complex signal whose shape depends to a large degree on the nature of the sea floor and this is the basis upon which echo sounders have been used for sea floor classification (Orlowski, 1984; Burns *et al.,* 1985; Jackson and Briggs, 1992; Keeton and Burle, 1996). The extent to which sound is absorbed or reflected by the sea floor depends upon the hardness of the seabed: Hard surfaces produce strong echoes whilst soft surfaces (and this may include rock substrata that are acoustically softened by overgrowth of biota) results in a weak signal. The sound energy that spreads away from the centre of the cone produces a weaker echo. This wave energy takes slightly longer to reach the seabed because of the extra distance travelled and this time lag increases with increasing angular distance away from vertical axis of the transmission pulse. Rough surfaces will produce an echo that decays slowly since sound spreading some distance from the vertical may reflect off inclined surfaces angled towards the transducer (a property termed 'backscatter') whilst flat surfaces will reflect sound away from the transducer. The decaying echo may also contain an element that depends on the reflectance of sound from subsurface features. This is particularly the case for low frequency sounders where there is greater penetration through soft surface sediment. The shape of this returning pulse or first return forms the basis for AGDS systems that map acoustic seabed properties to physical seabed properties

Additionally, there may be multiple echoes as the returning sound energy bounces off the water surface and rebounds from the sea floor a second (or third) time. The significance of the second echo (first multiple echo) for ground discrimination is debatable, but it has been considered to be more sensitive to hardness than the initial reflectance of the first echo (Chivers *et al.,* 1990; Heald and Pace, 1996).

The beam characteristics vary between transducers and AGDS work best with those with a relatively wide beam angle (15^{o} or greater) and side lobes which have greater scope for measurement of roughness than narrow-beam hydrographic sounders. Thus, depth measurement may not be particularly accurate.

3 – Using AGDS

3.1 – Equipment

It is likely that each AGDS will have its own echosounder, although they can be adapted to different sounders. AGDS may be a permanent fixture on a research or fishing vessel and hard-wired into the ship's echosounder. If AGDS are to be deployed from vessels of opportunity then portable systems with dedicated sounders are required. Vessel suitable for work should have adequate cabin space for electronic equipment. Small vessels are adequate for sheltered inshore waters, although AGDS can perform well in quite rough conditions. The usual method is to mount the transducer on a pole strapped to the side or the bow of the boat in a manner that prevents any movement or vibration of the pole.

The choice of frequency and power will depend upon the working depths expected. Some systems are set up for working optimally between certain depths and, for example, a RoxAnn system set for working between 3-30m may return invalid readings much below 30m. Many sounders increase power as the depth range selected increases. Power greatly affects the outputs of the AGDS and even if the AGDS is capable of operating with a variety of power outputs, the system should be kept on one power setting for the survey. However, some sounders also automatically change power with depth; a feature that may not appear in the operating manual of the sounder! People using AGDS should check with the sounder manufacturer on this aspect. Lower frequencies may also penetrate deeper into the seabed (depending on substrate) and give different returns when compared to higher frequencies.

3.2 – Data Output

AGDS output digital values of sea floor reflectance properties, including depth. The data can be recorded for every ping (e.g., QTC™) or at intervals that can be set by the operator (usually every 1-5 seconds). Depending on which software is used to record AGDS output, data may be averaged over set intervals (e.g., Microplot™) or the closest actual data return at the interval time recorded (e.g., RoxPlot™). Being based on a single beam sounder, these measurements are taken from the area ensonified by the sounder directly under the vessel as it tracks over the survey area. Thus the data take the form of a series of point records along the vessel's tracks tagged with position and time. AGDS result in relatively small amounts of data which are easily stored on hard drives, CDs or standard storage devices.

3.3 – Spatial Scale and Coverage

Since the operation of AGDS depends upon measurement of the integrated backscatter from each pulse, the resolution of the data is ultimately limited by the size of the footprint of the sounder, which is a function of depth and beam angle. In normal operation at moderate depths (less than 30m) a maximum spatial resolution of 25m might be achieved.
However, a more critical limit to resolution is in practise set by the distance between adjacent tracks. It is unlikely that vessels would be able to steer parallel tracks closer than 25m with 50m being a more usual minimum track spacing. Track spacing greater than 500m is not recommended. As a consequence of the above, along-track resolution is higher than across-track resolution. If the track data are interpolated to create a pseudo-complete coverage (see below) then the overall resolution is a compromise between along-track and cross-track resolutions.

3.4 – Standardisation (calibration)

Note that 'calibration' can mean interpretation of values in terms of sediment type. It is taken to mean establishing data standardisation in this Section. AGDS systems can be quite variable with the output dependant upon a wide range of factors, such as ship speed, tide, weather conditions, turbidity and depth (even though depth corrections are applied). Some ground types give variable responses depending upon the direction a vessel travels over seabed features. For these reasons, it is important to standardise data from day to day and even during the day. There is some debate about the best way to carry out standardisation: (a) keep tracks parallel and compare adjacent tracks; (b) run some tracks across main tracks; (c) run tracks over a known area with clearly defined ground types at the start and finish of every day's survey; (d) overlap some tracks from one day to the next.

3.5 – Capability and Limitations

Uncertainty may be high with AGDS surveys, but the adoption of realistic objectives for a survey can reduce uncertainty to acceptable levels. AGDS measure acoustic properties of the sea floor and do not directly measure sediment or biological characteristics. These must be interpreted from the acoustic data through the use of field sampling (such as videography, diver observations, physical sampling using grabs etc). As with all remote sensing systems, the extent to which AGDS can discriminate between biotopes (e.g. physical habitats and their associated benthic communities) is dependant on the spatial distribution and degree of difference between adjacent biotopes. For example, it might be expected that AGDS will be able to detect the difference between a limited number of discrete biotopes with clearly defined faunistic/habitat boundaries, whereas a large number of subtly different biotopes that merge into each other will be poorly discriminated using these systems.

With this in mind suitable objectives for AGDS surveys include:

- Very broad scale survey of large areas to map the approximate distribution and extent of a limited range of broadly defined habitats (no more than 15). This type of survey is useful for gathering information in areas where there is little available data and broad scale survey has been the most common use of AGDS.
- The selection of suitable sites for more detailed survey. AGDS surveys can identify areas where there is a greater likelihood of finding a particular habitat of interest and thus reducing subsequent survey effort and cost.
- Rapid repeat survey of a small number of broadly defined habitats to assess gross change over time. Although uncertainty will undermine the significance of apparent changes between similar habitats, it must be remembered that gross changes can and do occur.
- The survey of a small number of distinct habitats. Whilst this might be useful for monitoring changes in boundary, this specific application for monitoring may be very limited.
- To complement swathe acoustic surveys (e.g. bathymetric sidescan or multibeam sonar) by providing additional discriminatory power in areas that are difficult to interpret from bathymetric or backscatter images. Note that in most situations AGDS can be operated at the same time as swathe systems.

AGDS are of limited use where repeat surveys are required to assess small and subtle changes in habitat composition.

3.6 – Georeferencing

AGDS data are tagged with time (from either the computer or GPS) and position. It is best to be self reliant if vessels of opportunity are used to avoid problems of interference between different electrical components and to be able to position the GPS antennae above the transducer as far as is possible to minimise heading errors.

3.7 – Specific Processing Prior to Interpretation

The purposes of this stage are (1) to check that the data are of sufficient quality for further analysis and the removal of data that are considered dubious (e.g. erroneous positional data, depth spikes), (2) to explore the nature of the data, check for dependencies between variables that might compromise analysis if not properly considered, and transform data if required, (3) to check for patterns of spatial correlation in the data that need to be considered when deciding the most appropriate route for further analysis (e.g. variogram analysis prior to data interpolation), (4) to standardise data prior to amalgamation of different data sets or to facilitate comparison between data sets, (5) adjust depth data to chart datum and, (6) to derive other attributes that might be useful for interpretation (e.g., variability, slope).

3.8 – Varieties of System Available

Two proprietary AGDSs have been used extensively for surveying biotopes – *RoxAnn™* (SonaVision, Aberdeen) and *QTC-View™* (Questor Tangent Corp – Sidney BC Canada). *Echo Plus ™* (SEA Ltd, Bath) is a third system new on the market that is a dual frequency, digital system similar in principle to *RoxAnn*. In addition, SonaVision have recently developed a 'swathe' version of RoxAnn with seven beams known as *RoxSwath.* This is essentially seven separate transducers with number 4 set vertically and 3-1 set at increasing angles to port and 5-7 to starboard and should not be confused with other swath systems.

The *RoxAnn* system uses analogue signal processing hardware to select two elements from the echo and measure signal strength (in millivolts) integrated over the time (Burns *et al.,* 1985; Chivers *et al.,* 1990). The first selected segment of the echo is the decaying echo after the initial peak. This measure of time/strength of the decaying echo is termed 'Echo 1' (or 'E1') and is taken to be a measure of roughness of the ground. The beam width of the sounder is important for E1 since a wide beam will give greater scope for measuring signal decay away from the perpendicular than a narrow beam. For this reason it is recommended that AGDS operate with a sounder of moderate beam width (15° – 25°). The second segment is the whole of the first multiple echo and is measured by the *RoxAnn* processor as 'Echo 2' (or 'E2').

The two paired variables (E1 and E2) can be displayed on a Cartesian XY plot, and this is the basis of the *RoxAnn* real-time display as used in the data logging and display systems *Microplot™* and *RoxMap™*. Rectangular areas on the Cartesian plot can be marked out so that records lying within that section of the plot can be colour-coded and displayed on the track plot.

QTC View operates in a very different way to *RoxAnn*. The echo is converted from analogue to digital form and is then subjected to analysis using a large number of algorithms for wave-form analysis (Collins *et al.,* 1996; Collins and McConnaghey, 1998). The *QTC* choice of algorithms and the way they are applied to the echo is considered commercially sensitive. However, the second echo is not used. The system can be run in one of two settings; 1) supervised or 2) unsupervised mode.

1) In the supervised mode the system is designed to be calibrated (ground-truthed) by positioning the vessel over known ground types and a sample dataset collected. The exercise is repeated for different ground types and the combined datasets subjected to principle components analysis. The data are displayed on a three-dimensional plot of the first three principal components, termed '*Q space*'. The *Q* space is then divided up into regions that relate to the ground type classes by forming a catalogue. This catalogue can then be applied to subsequent survey data collected at the site to classify the tracks in real time. If new ground types are covered further ground truthing is necessary.

2) The unsupervised mode offers greater flexibility without the use of calibration. The signal is subjected to the same algorithms within the *QTC View* system, but all variables are logged for later principle components analysis to be applied to the complete dataset. The software package *QTC Impact* is then used to identify 'natural' clusters which are acoustically different, within the dataset, which can then be attributed to ground types as dictated by the field sample data. The clusters can be further split by running *Impact* again. This process of finding 'natural' clusters is termed 'unsupervised classification' and is covered in greater detail later under the section on classification procedures.

4 – Review of Existing Standards and Protocols

The above introduction is taken from the Natura 2000 Marine Monitoring handbook. This was specifically written for habitat mapping and was based on the experience of two groups: CEFAS and SeaMap (now Envision Mapping) with extensive knowledge of broadscale habitat mapping. This guideline included sections on data acquisition, data processing and data interpretation.

This document formed the basis of workshop on AGDS to test and compare the way RoxAnn is used by various workers (Brown *et al.,* 2003; 2005). It is worth quoting the conclusions and recommendations of the workshop in full as a critique of the guidelines:

- The JNCC Marine Monitoring Handbook (Foster-Smith *et al.*, 2001) is, on the whole, comprehensive and sufficiently detailed for the purpose of AGDS surveys in marine SACs or other regions of conservation interest. A degree of flexibility needs to be retained to allow for informed decision making by the surveyor as conditions and requirements are often very different between survey sites.
- The need to ensure high levels of positional accuracy when collecting both AGDS data and ground-truthing data should be strengthened within the JNCC Marine Monitoring Handbook guidelines, particularly when using towed or drop down video systems in relatively deep water.

- Whilst it is not possible to be prescriptive as to the minimum number of ground-truthing data points collected during a survey as this is greatly affected by the degree of homogeneity of the seabed and can vary dramatically from one survey area to the next, it should be highlighted within the JNCC Marine Monitoring Handbook guidelines that increasing the number of ground-truthing stations will strengthen accuracy of the final habitat map and improve the ability to assess the accuracy of such maps.
- AGDS data analysis is a vast subject and many routes can be taken through the process of data interpretation. Different research/survey teams within the UK adopt different approaches and there was insufficient breadth of experience amongst the research teams who participated in the current workshop to compare and contrast a range of approaches. The JNCC Marine Monitoring Handbook (Foster-Smith *et al.,* 2001a) provides an outline to this subject area, and in light of developing methodologies and ideas within this field the guidelines as they stand are sufficiently detailed and allow for a degree of flexibility.
- AGDS systems should not be the only system used when accurate mapping of seabed features is required. Swathe systems are recommended for such applications when a high degree of precision is required for mapping distinct seabed features or boundaries between different acoustically distinct habitats. In such situations AGDS can be used as a complementary system, and can usually be operated along side swathe systems to provide valuable additional data which can often help when interpreting the swathe acoustic data.
- When mapping seabed habitats using acoustic techniques it is crucial that the resolution of the map is linked to what can be discriminated acoustically.

The remainder of this Section comments on the Guidelines and adds some detail where this is considered essential for the appropriate use of AGDS techniques.

4.1 – Data Acquisition

The guidelines set out to provide a comprehensive account of mobilisation of equipment, survey design (including suitable ground truthing techniques).

Planning the survey

The Guidelines discuss the need for a flexible approach to survey design with respect to complexity of coastlines and heterogeneity of the ground. Although a series of regularly spaced parallel tracks may be desirable for consistency in analysis, the need to concentrate survey effort where most needed in the limited time available may dictate a nested survey design, where some sectors of the survey area will be more intensively tracked than others. The decision about tracking intensity may need to be made on survey, especially if poor weather reduces available survey time.

What is lacking is guidance on track spacing with regard to the desired scale and resolution of the survey. This is discussed in more detail by Foster-Smith *et al.* (2000) in relation to survey design incorporating other survey techniques.

Choice of field sampling technique

The Guidelines emphasise the role of video as a suitable tool for ground truthing AGDS broadscale surveys. Videography, it points out, is ideal for biotopes that are primarily characterised by their epifauna and flora, it is also useful for determining surface features of sediment (sand waves, shell fragments and evidence of bioturbation or biogenic sand reefs). Thus, video is almost universally applicable to surveys except where visibility is likely to be extremely poor. Sidescan sonar can also be used as a ground truthing tool in addition to visual/direct sampling techniques, and areas of habitat type recognised from the traces can be used to interpret AGDS data.

There is little discussion on the scale of video observation and how this matches the resolution of AGDS surveys. This is an important issue that probably crosses the various sampling/remote sensing techniques and (as with the issues raised above) might be addressed in a cross-cutting section on survey design using multiple techniques.

Selecting field sample sites

The emphasis of the Envision approach to interpretation is through the use of post-survey image processing techniques (see below). However, the Guidelines point out that AGDS have been designed to give real-time discrimination between habitats and that this facility is very useful for gaining knowledge of the distribution of biotopes during the survey which is necessary for designing stratified field sampling. The following points should be considered when selecting field sampling sites:

- The full range of acoustic ground types should be sampled (E1/E2-space for *RoxAnn* or Q-space for *QTC-View*).
- The samples should cover the geographic range of the survey.
- There should be at least 5 samples for each of the main habitat or biotopes. Even if the surveyor may feel that a particular ground type can be very confidently predicted (e.g., kelp forest in shallow water on hard ground) these habitats should still be sampled a minimum number of times. Failure to do this will compromise subsequent analysis.
- However, survey effort may be focused on particular biotopes if real-time prediction of these biotopes is low.
- Sites should be selected in areas where the acoustic data is consistent along tracks, rather than in areas where the along track data is changeable. This will alleviate problems of wrongly attributing acoustic values to particular biotopes due to positional uncertainty.
- Field samples should lie on AGDS tracks so that they can be associated with real data rather than interpolated acoustic values.

4.2 – Data Processing

The Guidelines are focussed primarily on either E1 and E2 for *RoxAnn* or the Q values (eigenvalues) for *QTC-View*. The assumption is that interpretation will follow the image processing route. Thus, most of the data processing recommended can be done in spreadsheets (e.g., Excel) and other packages that might be used for data exploration, such as Surfer and MapInfo.

The following procedures are recommended:

- Depths are tidally adjusted to chart datum by applying corrections calculated from a tidal prediction program, for instance using the simplified harmonic method produced by the UK Hydrographic Office (e.g., Total Tide™) . The corrections are applied at time intervals of 5 minutes. The Guidelines stress the importance of 5 minute intervals for the construction of digital elevation models since greater intervals (e.g., 30 minutes) results in obvious steps in the final DEM. However, there is no discussion on the merits of using AGDS for this purpose and the limitations of resolution in detecting seabed topographic features. Interpolation required for DEM construction may result in excessive smoothing and steps between adjacent tracks which compromise the DEMs. AGDS are probably not the best tool for critical DEMs, but can be used to create smoothed, very coarse resolution DEMs where no other data are available.
- The Guidelines suggest that macros can be designed for the automatic filtering of data to flag data associated with low boat speed or erratic positions and depths. It does not elaborate on these and this might be addressed. Also, much filtering can also be done using visualisation in GIS (particularly using non-earth projections of data). The problem with macros is that the sensitivity set for detection of spurious jumps in values will vary over the survey area (small jumps in homogeneous areas may be artefacts, but real in heterogeneous areas). Analysts may prefer to plot tracks in non-earth coordinates (e.g., track point sequence against depth which will create a continuous depth profile along the tracks) and select jumps by eye.
- The Guidelines give useful advice on visualisation of data for quality assurance using various scatter plot techniques. However, there is no guidance on how to decide if data are 'outlying' and what should be done with these data. It should be pointed out much more clearly that no data should be permanently discarded and that all editing and removal of dubious data should be carried out on copies. All amalgamations should also be tagged with survey details so that data provenance can be checked if problems occur in later stages of data processing and interpretation.
- Useful variogram techniques are discussed: This is a graphical technique for showing the spatial correlation between data. It shows how the similarity between values decreases as distance between points increases. The variogram illustrates the overall pattern of spatial correlation for the whole dataset and not local variation. It does not show very broad scale spatial trends or local variations in spatial correlation. The variogram shows:-
- Noise (the variance within the minimum sampling distance): this should not be too large in relation to the maximum variance of the data set. If it is, then the variability within the minimum point-to-point distance is so high that one point is independent of its near neighbours – in other words, no spatial patterns will be seen and interpolation is impossible.

- The range (the lag distance where the sill is considered to have been reached): The range gives the maximum distance where some spatial correlation might be expected to be present. Whilst interpolation is possible over distances represented by the range, the interpolated data are not likely to be much better than the local average. Thus, it is better to choose a search radius which is equivalent to half the sill variance.

4.3 – Data Interpretation

The Procedural Guidelines does point out that data analysis is a vast subject and many routes can be taken through the process of data interpretation. However, although a passing reference is made to the editing of track data in real-time, the Guidelines concentrate on the use of post-survey image processing if biotope maps based on the interpretation of AGDS data are to be produced. More recent advances have been made by Questor Tangent in the analysis of QTC data.

Software requirements
Image processing: *ERDAS Imagine*™ and *IDRISI*™ are both suitable packages for classification.
Geographic information systems: *ArcGIS™* and *MapInfo™* are standard GIS packages.

Interpolation: point-to-area conversion
Although the Procedural Guidelines warns the reader about the validity of interpolation, there is the overall assumption that interpolation of point track data is desirable and that these data (depth, roughness, hardness and Q values) are treated as continuous variables and not as point categorical data. These assumptions need to be challenged: Firstly, it may be more accurate to keep the data in the form of points and, secondly, if interpolation is required, it may be more appropriate to use some method suitable for categorical data, such as nearest neighbour. The relative merits of these different approaches need elaborating. The reader is referred to Burroughs and McDonnell (1998) for a detailed discussion of this subject.

There are undoubted benefits to interpolation, not least being the cosmetic appearance of the final map product. Perhaps one of the most compelling reasons for interpolation is that it opens up the use of proprietary image processing software for further analysis (Sotheran *et al.,* 1997). A grid of interpolated values can be treated as a digital image where each grid node becomes a centroid of a pixel. However, a more scientifically justifiable reason for interpolation is based on spatial modelling and a thorough understanding of the nature of the data. If interpolation is used, then it is important to realise that the outcome may be sensitive to the method used (e.g., distance weighted or Kriging) and parameters set (e.g., search radius, search method and number of points taken into consideration). The Procedural Guidelines makes a brief reference to these issues but they deserve a more thorough discussion since many workers may follow methods used by previous groups without being fully aware of the assumptions made or the effect of the default options on final maps. For example, interpolation can have the effect of 'smoothing' variables to the extent that calculated values between adjacent tracks with widely differing values will be an average between the tracks: such values may not actually occur in reality. This may result in 'sand' being predicted between 'mud' and 'rock'. Analysts should be on the guard for these effects.

Specific software for carrying out the recommended analytical techniques are: *Surfer™*, *VerticalMapper™* and *Geostatistical Analyst* in *ArcGIS™* will perform interpolation and variogram analysis.

4.4 – Interpretation

Many forms of acoustic remote sensing detect sea bed features directly. Sidescan sonar produces a 'black and white' image from which sand ripples and other features can be discerned by eye. Swath bathymetric systems likewise can detect fine scale topographic features. AGDS, on the other hand, measures reflectance properties and the presence of seabed sediment types and biota must be inferred from the relationship between these features and the acoustic measurements. There are many ways in which AGDS data might be classified using the ground truth data ranging from univariate or bivariate analysis of continuous variables (e.g., silt content of sediments) to multivariate classification techniques. (N.B., the inferential methods are discussed under the heading of 'Classification' in the Procedural Guidelines).

4.5 – Classification

Many approaches to classification have been adopted such as calibration the use of and unsupervised classification (Kaiser and Spencer 1996; Kaiser *et al*., 1998; Greenstreet *et al.,* 1997). However, the technique used routinely by Envision Mapping is supervised classification using *Idrisi 32* (Eastman, 1997).

Calibration
The simplest form of classification is an extension of the real-time calibration as used in Microplot. E1/E2 space is divided up into rectangular (or other shaped) areas whose dimensions can be modified by experience. Forms of calibration have been used by many workers (Murphy *et al*., 1995; Magorrian *et al*., 1995; Greenstreet *et al*., 1997; Caddel, 1998).

Univariate/bivariate plots
Univariate or bivariate statistics have been used by Pinn and Robertson (1998), Kaiser *et al.* (1998), and Hull and Nunny (1999). Variables, such as silt content, species counts etc, can be plotted against E1 or E2 and the acoustic variables used to predict the variable. This can be extended to E1/E2 plots by plotting contours of silt content (for example) and then classifying track data by the contour plot. This approach can be applied to categorical data (e.g., biotopes) if the frequency of their occurrence is plotted in E1/E2-space and the results contoured as above.

Correlation and regression
There is no reference made in the Procedural Guidelines to the use of correlation analysis, regression modelling and other similar statistical techniques in analysis of dependencies of variables (such as sediment grain size or habitat category) on measured acoustic responses.

Unsupervised classification
Detecting ‘natural’ clusters in data and then assigning biotopes to these clusters is the basis behind unsupervised classification.

RoxAnn
RoxAnn data can be clustered, but there are not many variables available for multidimensional clustering. Clusters may appear in small data sets, but as the range of biotopes increases, the data begins to resemble a ‘cloud’ without clear nodes, and the division of the data cloud therefore becomes somewhat arbitrary. Unsupervised classification is most useful as a guide to the collection of ground samples. Once this information is available, supervised classification is preferable.

QTC
QTC View and *QTC Impact* do use clustering although the raw parametric data is hidden from the analysts due to commercial confidentiality. The three Q values are plotted in Q space, and natural clusters of points within the 3-dimensional plot are identified and classified statistically under direction of the analyst. The decision to split and merge clusters is assisted by provision of statistical information of each cluster.

Supervised classification
Supervised classification of the images is quite straightforward for *RoxAnn* data, assuming that the variables (which are standardised from 0-255) are independent. Although there are a number of classifiers, maximum likelihood (which incorporates information about the covariance between variables as well as their variance to calculate the probability of a set of pixel values of belonging to each habitat class) is universally acclaimed as the most satisfactory (Bailey and Gatrell 1995; Wilkie and Finn 1996; Eastman 1997). It is a very convenient route for analysis since it is well supported by proprietary software and it gives good results. This method of classification can also be applied to QTC data, using the three Q values and depth in the classification procedure.

Comparison of methods
There is insufficient discussion in the Procedural Guidelines on the appropriate use of the various analytical approaches, although Foster-Smith *et al*. (2000) does compare unsupervised and supervised classification techniques. It is likely that no one approach will suffice for all needs and circumstances and this is an area that requires much greater discussion with a presentation of case studies.

4.6 – Bathymetric Models

In addition to the above products, the construction of 3-D bathymetric models are very useful for visualising the topography of the survey area and, if biotope maps are draped over the model, the relationship between bathymetry, topographic features and biotope distribution. These models can be created in the image processing packages and also in *Surfer™* and *Vertical Mapper™*. Some extra precautions need to be taken with the bathymetric data for successful modelling. The model is very susceptible to spurious depth records and they need to be carefully edited. Shore lines should also be digitised and the points given a nominal height value and incorporated into the model. Interpolation procedures may need to be specifically tailored to the creation of the model in that more averaging of the data may be required to smooth the model than is the case for image processing (i.e., weaker distance weighting coupled with a larger search radius).

4.7 – Accuracy Testing

Interpretation is sensitive to the way in which it is carried out and the resulting maps have varying degrees of success in predicting habitats. Accuracy measurement is an essential accompaniment to interpretation, but it is often a mistake to conclude that AGDS techniques have failed if poor accuracies are obtained. Also, it must be remembered that a similarly critical assessment of the subjective interpretation of sidescan images is often not attempted, taken as an indication of failure of AGDS techniques. There is a good basis for discussion of accuracy measures in both the Procedural Guidelines and Foster-Smith and Sotheran (2003).

There are many ways that performance of the biotope mapping process can be assessed and the following questions form useful points for consideration:-

- How internally consistent are the biotope maps with the ground samples used for classification?
- How well do maps predict biotopes as assessed against an external ground sample data set?
- How dependent is performance on survey design, particularly survey intensity? Where (in terms of confusion between biotopes and location within survey area) is uncertainty most acute?
- How consistent is the interpretation of different AGDS data sets for the same area?

Error matrices for the basis of many accuracy measurements and these are discussed in detail. However, other statistical measures (such as correlation coefficients) are not referred to.

The Procedural Guidelines also stress that misclassification of the field data can undermine data interpretation and is a major source of uncertainty in interpretation. This is particularly important for interpretation of acoustic data since it is likely that the field records will be summarised as biotope classes for the purposes of data analysis. The reader should refer to the relevant procedural guideline to ensure that the appropriate measures are taken to minimise misclassification

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11 Seabed Imaging Using Existing 3D Marine Exploration Seismic Data Sets

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1 – General Principles of Operation and Data Processing

The emergence of 3D seismic acquisition as a tool for regional reconnaissance, as well as field development since the 1990s, has resulted in near complete data coverage of several hydrocarbon provinces worldwide. The availability of such data sets has resulted in their application to problems other than hydrocarbon exploration, their primary purpose. One application has been the production of a mosaic of seabed relief images for geohazard and geotechnical assessment.

The application of 3D seismic to geohazard and geotechnical studies, especially in deep water, has become common. Long *et al.* (2004), Steffens *et al.* (2004), Cook *et al.* (2002) and Austin (2004) provide examples of such studies ranging from places as far a field as the Gulf of Mexico, the Faroe-Shetland Channel and offshore Indonesia. These studies often cover large areas, e.g. the 3D seismic coverage of the Faroe-Shetland Basin is approximately 30,000 km^2. There are two reasons for this. Firstly, 3D seismic surveys are expensive, so utilising them for secondary targets makes economic sense. Secondly, in deep water (>500 m) the image quality is comparable to, if not better than, swath systems.

Due to the high spatial sampling of 3D seismic data (12.5 m grid sizes are common) the level of detail observed in the seabed relief image is remarkable. The detail combined with the large aerial coverage provides a valuable resource to scientists interested in the morphology of the seabed.

3D seismic is acquired using a specialist survey vessel that tows several hydrophone streamers and one or two airgun arrays. The streamers are often many kilometres in length with 12.5 m recording elements. After firing of the airgun array, the pressure waves reflected from the seabed and deeper layers within the sedimentary basin are recorded digitally over a preset time window with a regular sampling rate. The high spatial sampling of 3D seismic data (12.5 m grid) requires accurate navigation; so differential GPS is used as well as telemetry to locate the true positions of individual recording elements. The output of each element of each streamer is digitally recorded as separate channels.

The collected data undergoes extensive processing to (a) enhance primary reflection energy and attenuate random and coherent noise; (b) move primary reflections to their proper spatial location (Yilmaz 2001). The final result is a data volume consisting of vertical time series traces located at a regular surface grid. Interpretation of the data volume is performed on an interpretation workstation where individual reflections are tracked to produce a regular surface.

There are a number of limitations in using 3D seismic to investigate seabed habitats. These are:

- All seismic surveys are designed for optimal imaging of structure at particular target depth ranges, typically 3-6 km. In certain circumstances, such as shallow water depths (<300 m) and hard water bottom conditions this may result in poor or non-existent primary seabed events, (Bulat, 2004; 2005).

- Because the earth is a dispersive medium, propagation of an elastic pressure wave through it will progressively attenuate higher frequencies more rapidly than low frequencies. This fundamental property obliges a survey intended for imaging the structure of sedimentary basins to use sources with peak frequencies of the order of 30-50 Hz, as the higher frequencies are simply absorbed by the earth, little or no reflection energy with high frequencies will reach the recording system. These are much lower frequencies than typically employed for swath bathymetry. The observed seabed event on all seismic data is a composite event based on the interaction of all acoustic impedance contrasts within a quarter of the dominant wavelength of the source impulse (Widess 1973). Because of the increased wavelength of the source (approximately 50 m) the seabed event on 3D seismic is a composite of the acoustic impedance contrasts over 12.5 m. Generally, the water-sediment interface provides by far the largest contrast within this interval, but locally, other contrasts within this interval may be large enough to make a contribution. An example is provided in Bulat (2005) where 3D seismic in a part of the Faroe-Shetland Channel shows open linear gullies at the seabed, but TOBI data over the same area shows them to be partially in-filled with fine-grained loose sands. The 3D seismic preferentially images the partially buried topography rather than the true seabed.

- Sampling theory dictates that features with dimensions less than twice the grid spacing will not be coherently imaged. The grid spacing of the 3D survey, typically 12.5 m although 25 m is not uncommon, limits the size of observable seabed features to 25 m and 50 m across respectively.

2 – Varieties of System Available

3D exploration seismic is extremely expensive to collect and to process to the interpretation volume phase. Consequently, there are only a few contractors available with the necessary equipment and expertise.

However a range of processing techniques are available utilising software such as ERMapper to create 3D images from the first return data.

3 – Review of Existing Standards and Protocols

There are no known standards or protocols for this technique.

3.1 – Data Acquisition

3D marine seismic acquisition is an extremely complex and costly undertaking. Yilmaz (2001) provides a good overview of the technologies employed. Here we are concerned with utilising existing seismic data volumes, not in primary data acquisition. However, we need to understand the data acquisition geometry as this may impact on the suitability of the resulting data for these purposes (Bulat, 2003; (2005). Acquisition geometry is an important factor for the quality of the seabed event in water depths less than 300 m. If the target depth of the survey was deep (>3-4 km) and the seabed conditions are hard, then the design of the survey may preclude recording a clear seabed return due to contamination by the seabed refraction event.

3.2 – Data Processing

The processing of 3D marine seismic data is also complex and costly. The primary aims are to (a) enhance primary reflections (b) attenuate random and coherent noise (c) properly locate the primary reflections in space. Yilmaz (2001) provides a detailed description of the principles and practice of seismic data processing. Processing is an iterative process and often takes many months effort by a team of processors in collaboration with customer representatives to achieve a final seismic data volume.

Here we are concerned with utilising existing processed data. Consequently, we are unable to influence data processing decisions. However, we do need to understand what they were for the interpretation phase (Bulat, 2005). Again, target depth will constrain the processing of the whole volume. For example, a very deep target might just as accurately be imaged with lower temporal and spatial sampling because of the loss of higher frequencies when seismic energy is transmitted through the earth. It also has the benefit of reducing processing costs markedly. However, it will degrade the resolution of shallower horizons such as the seabed event. Some Oil Companies engaged in deep-water plays now routinely identify the near-seabed as a secondary target (Austin 2004). In such cases at least two data volumes are generated, a high-resolution version for geotechnical evaluation and an exploration version for imaging deeper reflections.

Seismic data volumes are usually provided as SEG-Y (a standard exchange format) data tapes, or as proprietary format volumes for particular Seismic interpretation software such as Landmark Graphics Corporation's SeisWorks. Loading of SEG-Y data can influence the quality of the seabed horizon. Seismic amplitudes are usually recorded and processed as 32 bit real numbers with a numerical range over many orders of magnitude. However, until very recently it was common practice to clip seismic amplitudes during data loading to save disc space and to provide sufficient dynamic range for smaller reflections. As the seabed is often the largest amplitude event in the volume and it was commonly clipped. This procedure produces terracing artefacts on the final horizon. Seismic horizons are generated by propagating seed points throughout a volume using automatic tracking software into adjacent traces. The automatic tracking software reconstructs the seismic signal shape from a set of adjacent time samples so that the position of the horizon in time can be accurately interpolated. Where the reconstruction is impossible, such as when amplitudes of several adjacent samples have been clipped, the software is forced to snap to the nearest sample, often 4ms. This effect can be prevented, by loading the SEGY data without amplitude clipping.

Once a seismic horizon has been picked, it will commonly be necessary to remove miss-picks and to interpolate across small gaps in the horizon, depending on the quality of the underlying seismic data. The horizon can then be exported to other visualisation programs, such as ER-Mapper where horizons may be patched into a mosaic; depth converted and shaded relief images generated.

3.3 – Data Interpretation

An important step in interpreting the final shaded relief images is to identify data artefacts. The most common artefacts seen on seabed images are terracing, survey footprint and survey edge effects.

Seabed images ocCASIonally exhibit a pronounced step-like topography, much like river terraces that coincide with the sample rate of the data and slavishly follow the two-way time or depth contours. Such terracing destroys the visual continuity and texture of the horizon (Bulat and Long 2001) and is due to amplitude clipping of the data volume during loading as discussed above. Where the data has been provided as SEGY it is easy enough to prevent. However, it is not uncommon for seismic volumes to be provided as pre-loaded SeisWorks or other projects where the amplitudes have been clipped.

Survey footprint is systematic noise associated with acquisition direction. It is often observed on 3D seismic surveys (Marfurt *et al.,* 1998). In seabed images this manifests itself as linear corrugations that are broadly parallel to the line acquisition direction. Survey footprint reflects the survey direction and changes in conditions; tide, water velocity, hydrophone position between lines. In the Faroe Shetland Channel most of the surveys were acquired the same acquisition direction. By generating an ER-Mapper shaded relief image illuminated along the acquisition direction the impact of the noise has been minimised (Bulat and Long 2001, Long *et al.,* 2004). Attempts have been made to attenuate footprint anomalies on the picked horizon. These procedures can be very effective over certain features such as the Afen slide (Bulat 2003). The approach has built-in assumptions however, that will not be universally valid.

Survey boundaries are commonly observed. These arise due to slight differences in acquisition and processing of individual surveys. Another factor is the lack of continuous measurements of acoustic water velocity estimates during the acquisition of the 3D seismic, which results in inaccurate depth conversion. These abrupt changes in overall level do not significantly degrade a shaded relief image of the seabed, which shows us the relative relief i.e. morphology. But obviously it does detract from using these data to make an accurate bathymetry map.

The observed seabed event on all seismic data is a composite event based on the interaction of all acoustic impedance contrasts within a quarter of the dominant wavelength of the source impulse (Widess 1973). Due to the need to image reflections from deep levels within sedimentary basins low source frequencies are commonly used. Consequently, because of the increased dominant wavelength of the source (approximately 50m) the seabed event on 3D seismic is a composite of the acoustic impedance contrasts over 12.5m. Generally, the water-sediment interface provides the by far the largest contrast within this interval, but locally, other contrasts within this interval may be large enough to make a contribution. An example is provided in Bulat (2005) where 3D seismic in a part of the Faroe-Shetland Channel shows open linear gullies at the seabed, but TOBI sidescan data over the same area shows them to be partially in-filled with fine-grained loose sands. The 3D seismic preferentially images the partially buried topography rather than the true seabed. When contrasted with higher frequency datasets such as TOBI images and swath bathymetry it becomes possible to obtain clues regarding the physical properties of the seabed and near seabed sediments. Identifying shallowly buried topographies may prove useful in providing a geological context for seabed habitat. For example, the partially in-filled channels cited above may contain locally thicker sandy deposits than on the adjacent shelf. This may prove a significant factor in aiding recognition of subtle variations in seabed habitat that might be observed with higher frequency data sets.

Although shaded relief images reveal many morphological details of the seabed and have a strong visual appeal; they have the disadvantage that the pattern of shade and light is as much a function of the illumination parameters as it is of the topography. Thus mapping the exact position of troughs and highs requires a different approach. By calculating local dip azimuth and magnitude from the depth converted horizons a unique map identifying topographic features can be made. Such derived products are more influenced by footprint artefacts.

4 – Provenance and Current Usage

This technique was developed originally for geohazard assessment and site investigation studies relating to hydrocarbon exploration wells or production platforms. However because of the extensive datasets potentially available (the FSC image cover 30,000 km^2) they have been exploited for regional assessments of seabed conditions. This has included being used as part of Environmental Impact Assessments (EIA), a requirement for an exploration well permit (J. Hartley pers comm.). The data has been used for landscape assessment in marine archaeology (Simon Fitch per comm., 2004).

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12 Sub-Bottom Acoustic Profiling

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1 – General Principles of Operation and Data Processing

Sub-bottom Acoustic Profiling is the industry standard technique for the collection of data concerning shallow geological and sedimentary conditions. Sub-bottom profilers are generally towed systems, which emit an acoustic signal vertically downward through the water column, subsequently propagating into the underlying geology. Acoustic energy is reflected from the interface between sedimentary layers, due to contrasts in acoustic impedance. Acoustic impedance (Z) is density times velocity, the velocity at which acoustic energy travels through the sediment ($Z = \rho v$). The reflected energy is detected and recorded as a function of the two-way travel time, by the sub-bottom profiler to build an image of the shallow geological conditions. The resulting profile gives invaluable insight into the nature of the sub-bottom: structure, thickness, sediment deposition conditions, debris and natural hazards. In some cases, the composition can be estimated.

Acoustic Profiling involves the use of a source, or set of sources, for the acoustic signal and a receiver (or set of receivers) to pick up the acoustic signal after it has travelled through the sub-surface. Normally, but not necessarily, the source(s) and receiver(s) are mounted in a tow fish, a vehicle to be towed in or on the water by a ship.

The tow fish produces a signal at a set time interval such as 125 or 500 m. This interval is known as the firing or shot interval. Each received signal is recorded on paper or otherwise, normally printed adjacent to the previous one, thus making reflective layers visible as line-ups of high amplitudes. Profiler records are usually made along straight sailing tracks.

Sub-bottom Acoustic Profiling, in the sense of this review, should not be confused with other types of Acoustic Profiling such as bathymetry measurements using Echo Sounders or Swath Bathymetry measurements which do not penetrate the sea bottom. Other types of Acoustic Profiling involve instruments like the Side Scan Sonar in which a signal is transmitted to either side of the tow fish and is reflected and scattered at the sea floor. These instruments, like the bathymetric sounders, also use high frequencies (several 100 kHz) which do not penetrate the sea floor (Figure 12–1).

In the low frequency range (around 100 Hz and lower) acoustic measurements for the assessment of the geology of the sub-surface can also be made. These types of measurements involve an array of sound sources and usually several hydrophone arrays, towed behind one or more ships. The hydrophone arrays can be up to several kilometres long. These measurements are made by and for the hydrocarbon industry and are not considered here.

The signal produced by the source of a Sub-bottom Acoustic Profiler is a brief audible sound. This sound –or signal- carries a set of audible frequencies, usually around 3 kHz. These frequencies allow penetration of the sea bottom. The amount of penetration depends, amongst others, on the acoustic frequency, f, and on the type of sediment through which the signal travels. For example: a 10 W, 3.5 kHz signal can penetrate about 15 to 20 m in medium coarse sand and about 70 m in soft mud. The vertical resolution depends, amongst others, also on frequency, although there is no exact relationship between these properties. For the sake of simplicity it is sufficient to say that as resolution increases, penetration decreases, and vice versa. Resolution is the ability of a system to separate closely spaced objects, if a system has a resolution capability of 20 cm, then it is capable of resolving an object or a sedimentary unit greater than or equal to 20 cm thick. For short signals containing a band of frequencies, the vertical resolution is ¼ of the wavelength λ; the thinnest bed or layer that can be detected is about $\frac{1}{4}\lambda$ ($f = v/\lambda$), f is the frequency which contributes most to the signal.

The signals can be (*a*) of short duration with a single frequency (such as 0.5 ms, 3.5 kHz), (*b*) of short duration with a broad band of frequencies (such as 5 ms, 0.3 – 2 kHz), (*c*) long, swept frequency-modulated signal (such as 40 ms long, swept from 1 to 8 kHz), also known as Chirp systems or *(d*) dual frequency signal (with frequencies such as 35 and 45 kHz, also known as parametric systems). In each of the profilers, the duration and frequencies of the emitted signal are set either by switches or by the controller software or both. Short, broad-banded signals produced by, for instance- Boomers and Sparkers, usually show in the frequency domain a dominant frequency, i.e. the frequency which contributes most to the signal.

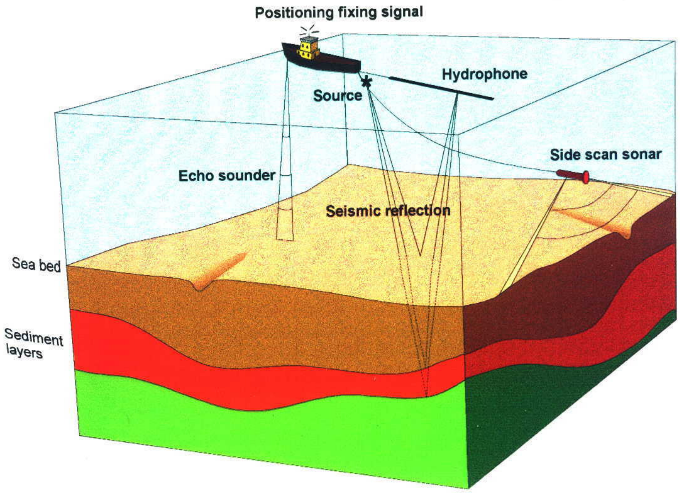

Figure 12–1. Various types of acoustic profiling performed at sea.

Chirp Profilers penetrate the sub-surface better and have a better vertical resolution than the single-frequency profilers of equal power output. This is because (simply stated) the low-end of the sweep lets the signal penetrate deeper. The vertical resolution is equal to the inverse of the frequency bandwidth. (See for instance http://www.edgetech.com). For parametric systems the penetration depends on the difference between the two frequencies. (See for instance http://www.km.kongsberg.com http://www.innomar.com).

The horizontal resolution depends on the directivity of the source and receiver, frequently denoted by the aperture angle or beam width, and on the in-line shot interval.

Many, if not all, manufacturers give requirements and protocols for the deployment and usage of their systems. Some, like Egdetech, one of the manufacturers of Sub-Bottom Chirp Profilers, provide the user also with protocols for the testing and calibration of their system. Frequently, though, these protocols are provided when buying or renting the systems and are not published on their web sites.

Whereas the echo sounder (using frequencies of 12 kHz and over) is used in Acoustic Ground Discrimination Systems (AGDS), such as RoxAnn and QTC (see www.jncc.gov.uk/marine/mmh/MMH_0601.pdf), Sub-bottom Acoustic Profilers can also be used for this purpose (see for instance www.egdetech.com). Sometimes, software provided with the Profilers can produce the reflection strength along a reflecting surface, either by indicating the surface on-screen or by an automated reflector tracker. The calibration protocol of Edgetech is designed precisely to do that, so that the reflection strength of the sea bottom (extracted from the data by a sea bottom-reflection tracker) gives a reliable indication of the type of sediment or habitat. As always, groundtruthing by taking bottom samples is important for calibration.

The acoustic source and receiver is usually mounted in a tow fish which is towed behind the ship. Sometimes towing at the side of the ship is better. This can depend on whether and where the ship has an A-frame or a crane. Some systems are usually hull-mounted. This has the advantage that surveying can be done at greater speeds. For towed systems, the maximum towing speed is usually 3 to 5 knots. This is because higher tow speeds induce more noise and more drag on the towing cable.

The acoustic systems always come with a deck-unit, which should be placed in a dry area, away from rain and spray. All systems can write output to paper and almost all also include some form of digital storage. This storage can be anything like tape cartridges (DAT, Exabyte, DLT, etc) and disks (magnetic, optical, CD, DVD, etc.).

Most systems store the data in one of the standard formats published by the Society of Exploration Geophysicists (SEG) (see www.seg.org), mostly in SEG-Y format. This is because most industry-standard seismic processing software can read SEG-Y files readily. The SEG-Y format is designed for tape storage and storage on disk is done in tape-image formats, for instance TIFF format, which is an encapsulated format preserving the lengths of each shot. However, encapsulated formats are not common; normally an image format on disk blindly has each shot written to disk without any indication of its length. Such formats rely heavily on the length indicated by a designated item in the shot header. Many systems can also store the data in an in-house format. In such cases, the in-house format is used for storing the data while shooting (in 'real time') and the SEG-Y format is used when re-formatting the data off-line.

Most systems include software to do some basic processing. With systems like Chirp Profilers, the software is quite sophisticated for the long, swept wavelet should be filtered to a short, Klauder-like wavelet in order to visualize the sub-surface. Many systems do frequency (band-pass) filtering to get rid of frequencies picked up at the receivers which lie outside the band of frequencies emitted by the source. Some also do processing steps such as heave compensation (correcting for the up-and-down motion of the tow fish), horizontal stacking (adding the output of two, three or more adjacent shots). It should be noted that these last processing steps can also be performed by analogue instruments.

Acoustic Profiler systems can input navigational data from some navigation system (normally a dGPS system) and have the data stored together with the acoustic data. For instance the SEG-Y format has designated places in the shot header for source and receiver positions (if the source and the receiver are mounted in a tow fish, these positions would be equal). Many, if not all, can have the offset, the distance from the tow fish to the GPS antenna, manually input, so that the corrected positions are stored.

The EU-euroseismic database contains information on Acoustic Profiling data (Sub-Bottom Profiling, single- and multi-channel, Side Scan Sonar, etc.) held at European institutes at <www.eu-seased.net>.

2 – Varieties of System Available

There are a great variety of commercially available systems designed to operate in a wide variety of water depths. Traditionally these systems are designed to operate in water depths less than 1000m. However, there are now a great variety of deep tow systems capable of operating at depths up to and beyond 2000m.

Acoustic Profilers include the single frequency and chirp profilers mentioned above, of which many systems exist (see www.edgetech.com, www.km.kongsberg.com, www.innomar.com, www.titonimaginginc.com, www.GeoAcoustics.com, www.meridata.fi and many others). Acoustic profilers also include systems in which the source and receiver are separate, such as a Sparker or a Boomer as a source and a single channel hydrophone streamer as a receiver. These systems usually can be set at a higher power output than the others. The hydrophone streamer is normally towed a few meters behind the source. The main frequency in the emitted signal lies around 1 kHz, allowing a penetration of 100 m or more and the vertical resolution is around 1 m or worse. Generally speaking, a Sparker can be set at higher levels of output power than a Boomer can. A typical Boomer signal of 300 J would have frequencies of 1 to 7 kHz, a penetration of 20 m in sand and a resolution of about 50 cm. A typical Sparker signal of 1000 J would have a dominant frequency around 600 Hz, a penetration of 150 m and a vertical resolution of 2 m.

A hydrophone streamer consists of a tow cable, stretch sections and an active section. The stretch and active sections are oil-filled flexible hoses of equal thickness. The active section has hydrophones in it, spaced evenly, for instance every 30 cm. The length is for instance 12 m for the active section containing 40 hydrophones.

Multi-channel streamers are basically the same, they have more active sections. Multi-channel data allows more sophisticated processing of the data. For instance, the signal-to-noise ratio can become higher, velocity information on the sedimentary units can be extracted, etc.

Boomer and Sparker systems can be found at, for instance, www.GeoAcoustics.com.

3 – Review of Existing Standards and Protocols

3.1 – Data Acquisition

Standards and protocols on the usage and deployment of Sub-Bottom Acoustic Profilers are provided with the systems when buying or renting them. For habitat mapping calibration of the emitted signal is essential. This calibration is described by the manufacturer, in some cases. Again, these procedures are provided with the system. Apart from these procedures, groundtruthing by conventional sampling methods remains essential too. If no such procedures are available, then measurement of the repeatability of the signal in terms of power output and wavelet shape should be performed. If the repeatability is excellent, groundtruthing can be sufficient to do habitat mapping. If, on the other hand, the repeatability is poor, habitat mapping cannot be done.

Shock *et al*, 1989 show why the Chirp Sub-Bottom Profiler is well suited for quantitative sediment analysis. This is because the Chirp signal produces high resolution acoustic profiles with no ringing or side lobes. Together with the high repeatability, good estimates of acoustic attenuation through the sediment and reflection coefficients of the sea bottom can be produced. The parametric systems of Kongsberg and Innomar are also claimed to be side lobe-free by their manufacturers.

Standards on tape formats (and the image format on disk) can be found at www.seg.org.

Procedural guidelines for dGPS positioning (Guideline PG 6-1) from the Marine Monitoring Handbook http://www.jncc.gov.uk/marine/mmh/MMH_0601.pdf are useful as general guidelines for surveying. Standards of format of disk files containing positional data can be found at www.seg.org and at www.oilandgas.org.uk/ukooa.

Further survey design requirements are straight-forward. The in-line density of shot points is much greater than the cross-line density. This means that the distance between the sailing lines should be less than half the smallest size of an area where the property under investigation is constant. This could mean that many lines would have to be shot, much more than feasible. In such cases a trade-off between requirements of horizontal, cross-line resolution and available survey time will have to be made. At the very least the technique will be able to identify large-scale habitat units

Having the tow fish far away from the ship, or having a multi-channel streamer behind the ship, would require some care not to have too much feathering by sea currents, i.e. drifting of the equipment sideways and away from the sailing line. Amongst the procedures provided by the manufacturer, the maximum wave height is also given. Down-time due to bad weather should be taken into account when considering the time of renting/using the ship.

Generally, Acoustic Sub-Bottom Profiler systems are more expensive to buy or hire than echosounders are. The tow fish is usually the most expensive part. Costs for buying a complete system (deck-unit, tow fish, cables, software, etc) are on the order of € 90,000 to 110,000. The lower end of this range is for instance the Chirp system of Edgetech, the high end is the DelphSeismic Plus system of Triton Elics. For these prices one buys a complete system with software to process and interpret the data. Other systems, being less complete (for instance lacking interpretation software), are less expensive. Hiring systems cost on order of 1 or a few percent of the purchase-price per day, say a few € 100 per day.

The tow fish produces a signal at a set time interval such as 125 or 500 ms. This interval is known as the firing or shot interval. Each received signal is recorded on paper or otherwise, normally printed adjacent to the previous one, thus making reflective layers visible as line-ups of high amplitudes. Profiler records are usually made along straight sailing tracks. Covering an area is usually achieved by sailing lines in parallel or in a grid of parallel and perpendicular lines. A firing interval of, say, 250 ms at a speed of 4 knots, gives a shot interval of 0.5 m, so the in-line density of shots is far greater than the cross-line density, which is the amount of tracks per unit of length measured perpendicular to the sailing line.

3.2 – Data Processing

Some processing steps which help to improve the visibility of reflectors on paper or on screen are provided by the manufacturer. These include a.o. frequency band filtering, heave compensation, horizontal stacking, Automatic Gain Control, etc. Some, see www.titonimaginginc.com, also provide a wavelet shaping filter, multiple filtering, etc.

For multi-channel data, a vast variety of processing can be done by using standard processing tools developed for the hydrocarbon industry. ProMAX is a well-established software package and can be found at www.lgc.com. This type of software is also suited to do single-channel processing such as the ones mentioned above. Automatic heave compensation is an exception to this rule. If this software is not provided by the manufacturer, it may have to be bought/leased separately or as a part of another software package. At www.woodshole.er.usgs.gov/operations/sfmapping/seissoftware.htm a concise overview of software is given. Free downloadable manuals of software are for instance available at www.iris.edu/manuals/manuals.htm. Other software packages can be found at www.pgs.com, www.cgg.com, etc.
The extraction of the reflection coefficient of the sea bottom reflection can give information on the type of sediment, see Figure 12–2. The reflection coefficient depends on the acoustic impedance contrast at the interface. The acoustic impedance is Z = ρv, or density times velocity.

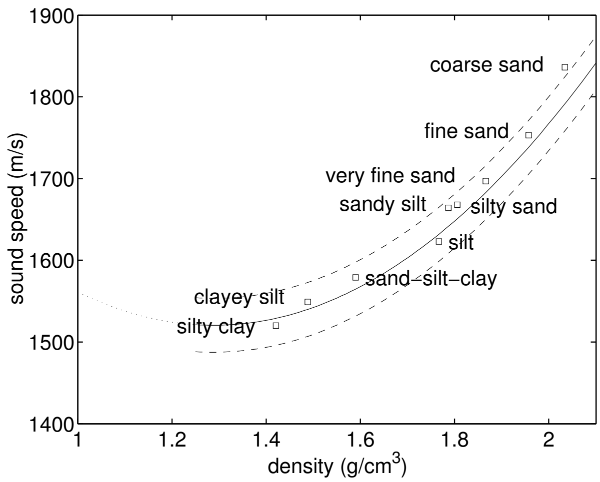

Figure 12–2. Empirical relation (solid line) through measured values (blocks) of sound speed versus density. From Hamilton, 1980, see also Hamilton, 1982.

Removing the effect that the tide has on the elevation of the ship and tow fish (de-tiding) is normally not done during the acquisition phase, though monitoring the tide using a tide gauge and/or modelling the tide can provide the data to do it after the survey.

Potential data products are: digital vertical profiles of the subsurface, cartography of the different acoustic facies, contour maps of the depth of the basis of each acoustic facies unit, facies descriptions, thickness maps of each acoustic facies, volume calculations, identification of anomalies in the seismic dataset that could have implications on habitat occurrences, identification of potentially existing infrastructure and/or objects (i.e. pipelines, buried wrecks).

3.3 – Data Interpretation

Although modern seismic sections often bear striking resemblance to stratigraphic cross sections, the geophysical limitations should not be forgotten!

Consider the four fundamental factors that are closely related:

- Penetration
- Resolution
- Signal-to-noise ratio
- Contrast in physical properties

Not every wave shape variation has a geological meaning or represents a buried feature. Geophysical interpretation of the acoustic profiles should always be performed with the greatest care. Many pitfalls must be recognized before an attempt at geological interpretation can be made.

For a good interpretation of the results are ideally correlated within the context of existing seismic knowledge databases. The estimation of the nature of the acoustic facies is normally based on a correlation of the seismic results with existing coring and sedimentological information.

The interpretation of data for geological purposes can be done by various software packages such as Seisworks (see www.lgc.com) or Petrel (see www.sis.slb.com) to name a few. Triton-Elics (see www.titonimaginginc.com) provides the acoustic acquisition system with an interpretation tool. These tools can be used to interpret structural features, but can also be used to extract acoustic parameters of the sedimentary units, providing information on the sediment properties and habitat. Sea floor mapping software is increasingly included into interpretation tools (see www.titonimaginginc.com).

Buying processing and interpretation software can cost anything from €10,000 and more. Usually the software can be bought in separate modules, so according to one's wishes the price can higher or lower. For non-profit organisations, the price is usually halved.

4 – Provenance and Current Usage

Acoustic Sub-Bottom Profiling has been an industry standard technique for decades for establishing the shallow geology beneath the sea floor. The information readily available in profiler records provides the interpreter a quantitative assessment of the structural and sedimentological setting of the subsurface. From this, together with samples from corings, the paleo-environment in which the sedimentary layers were deposited can be determined.

Sub-Bottom Profiling is, therefore - especially when combined with sea floor classification systems, side scan sonar surveys and swath bathymetry - well suited for (paleo-) habitat studies. Though Chirp technology can well be used for insights into habitats (Shock *et al.*, 1989), Sub-Bottom Profiling has not the same amount of success as depth sounders (used by RoxAnn, for instance). This is mainly due to the fact that the reflection coefficient alone may not be sufficient to distinguish between as many different types of sea bottom as RoxAnn can.

New developments will include synergy of software for sea floor mapping with 3D interpretation. Also, multi-channel surveys will provide sediment classification of sub-bottom units in the near future. TNO in the Netherlands is currently working towards that goal. If the Chirp signal is well calibrated, tracking another reflector beneath the sea bottom will provide the reflection strength of that reflector, thus indicating the reflection coefficient of this reflector. Edgetech provides software to do this. In this way, an estimate of sedimentary properties of an unit underlying the upper-most unit, will be feasible.

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IN SITU SAMPLING TECHNIQUES

13 Diver Surveys

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1 – General Principles of Operation and Data Processing

Divers (both scuba and snorkelling) can be employed in a wide variety of ways in order to gather data on the subtidal environment, and such work has been undertaken extensively since the advent of SCUBA diving. Health and Safety considerations regarding the physiological effects of diving and the limits of air tank capacities impose significant restrictions upon time spent underwater and maximum working depth. In the UK although the maximum depth to which air divers can work is 50 m, the limit is instead the amount of decompression planned. In-water decompression of more than 20 minutes duration cannot be completed without a chamber on site (irrespective of depth). The use of alternative breathing gases (such as Nitrox and Trimix) can extend the depth and/or duration of dives for marine survey. Nitrox in particular is routinely used in scientific diving. Any form of diving entails exposure to physical hazards (e.g. decompression illness or DCI), and as a result the conduct of professional diving operations is strictly controlled by legislation. Within the UK, the Health and Safety Executive enforce standard training and operational requirements for scientists diving at work. Therefore, most scientific diving in the UK is generally undertaken at depths less than or equal to 30m, and is particularly suited to the infralittoral and upper circalittoral zones. Below such depths remote methods of benthic surveying are readily utilised, such as towed/drop-down video systems, ROVs, trawls, dredges, grabs and corers.

Divers are able to move over significant distances of seabed (over 100 m) per dive, and may facilitate surveying at a number of scales, from detailed observation of quadrats to broader scale visual assessments over transects. As such, diver surveys can generate qualitative, semi-quantitative and fully quantitative datasets. Divers are able to access all types of substratum, from rocky reefs to sedimentary plains, with the only limiting factors being those addressed above and the sites tidal currents / exposure regime and visibility. In addition to direct observation methods, divers may also use a number of tools for sample collection or recording, such as push-cores, cameras and videos. Such tools may be used in isolation or as a hierarchical suite of survey approaches.

The impact of trained scientific divers upon the marine environment is minimal, with the exception of destructive sampling techniques (such as push-cores or suction sampling) and anchoring of dive boats.

The following overview is modified and compiled from a number of procedural guidelines in the Marine Monitoring Handbook (JNCC: Davies *et al*., 2001), specifically Holt and Sanderson (2001), Murray (2001), Brazier (2001) and Bullimore (2001). Equipment specifications are examples only, and other authors may provide alternatives.

1.1 – Transect Surveying Techniques

Transect surveys are used to gather data to describe biotopes/habitats and their composition (through species abundances and sediment descriptions). By using stratified sampling, a number of transects can provide an inventory of the biotopes within a given area.

Transect start positions are taken using diver entry dGPS coordinates, and a direction is specified to lay the transect. Checklists of species and abundance scales are used along with writing boards. Reference specimens are collected and where possible a stills camera/video is used to supplement written records. The transect equipment consists of a 50 m tape measure, with an attached 3 m plastic pole (such that 1.5 m of the pole falls either side of the transect tape). The survey is completed by gradually rolling out the tape using the pole, and recording species and abundances in situ. This will ultimately cover 3 m x 50 m (150 m^2) of seafloor. Divers will have to decide where one biotope ends and the next one begins, which is based upon the rule of a 5 m^2 minimum area for a biotope. Upon completion of the transect, the pole and line are sent to the surface using a 25 kg lifting bag.

Data gathered is transferred to a standard recording form, and then to an electronic database. This can then be integrated into a GIS to present results spatially. The data can be analysed using descriptive, univariate and multivariate statistics (usually after transformation).

1.2 – Quadrat Sampling Techniques

Quadrats are generally used for the quantitative assessment of biodiversity for a particular feature occurring within a site. In particular, this method is suited to assessing the quality of a particular habitat/biotope rather than as a method for attaining an inventory of biotopes for a given area. It may also be used as part of a long-term monitoring strategy, with the advantage of a very high degree of spatial precision possible when using permanently marked quadrat locations – to ensure that the same location is being sampled at each survey. The use of quadrats relies upon background data for the area of interest being available (often from a pilot study) in order to identify representative areas for further investigation using quadrats, and to develop species-list /*pro-formas* to aid the quadrat surveys. Quadrats can either be randomly placed on the seafloor, located along a transect, or permanently located on the seabed (either directly using site markers or with the use of acoustic pingers). Quadrats are versatile in terms of shape and size, and can easily be tailored to suit a whole range of community types. They are usually sub-divided into smaller grid-squares to aid the assessment of epibiota abundance and densities. Abundance can be assessed using either direct counts of individuals or colonies, or through percentage cover. The frequency of the grid squares in the quadrat is important, as using finer divisions on the quadrat mean that the resultant counts are more similar to percentage cover. There are existing recommendations as to where counts or percentage cover should be used. Direct observation of abundance may be supplemented by photographic records (either stills or video) of the quadrat or quadrat sub-squares, which can be processed in the laboratory. The positioning of quadrats may be noted in relation to diver entry and exit positions, or through the use of diver-positioned acoustic transponders. Where repeat monitoring is desired, quadrat positions may require permanent marking (as discussed above).

Similarly to transect data, the species abundances recorded from quadrats may be transferred onto standard recording forms and electronic databases, prior to statistical treatment.

1.3 – Diver Operated Cores

Diver-operated push-cores are designed for use in sedimentary environments for identification of habitats/biotopes and an assessment of their quality in terms of species richness and abundance. 11cm and 5cm cylindrical corers are used, with the former for collecting a sample that will be subjected to faunal analysis, and the latter for collecting a sample for particle size analysis. Sample sites are determined from previous or background research in the area. Locations are based on diver entry positions, as recorded using dGPS. Cores may be taken around the deployed shotline or at pre-determined distances along a transect. In addition to taking the cores, divers make qualitative notes regarding the surrounding sediment, such as surface relief, firmness, stability and sorting. Additional notes regarding evidence of bioturbation, any epifauna present and sediment features such as ripples or surface silt/flocculent are beneficial. On return to the survey vessel samples are checked for adequacy and notes made to describe the sample. The faunal samples are then sieved using gentle puddling, and preserved in buffered formalin. Once sufficient time has elapsed to ensure preservation is effected the samples are washed and stored in ethanol. Faunal samples are sorted and infauna identified to the highest taxonomic level practical, while particle size analysis is completed for the separate (but associated) sediment samples.

Many analysis procedures are available for data obtained through cores, and this topic is treated widely in scientific literature. Univariate and multivariate statistical techniques are applicable depending on the objectives of the study.

1.4 – Quantitative Photographic Sampling

This method is a variation of the quadrat sampling method, and may be used to assess community composition, including species and abundances. The use of reference frames and fixed focus settings ensures accurate fields of view to facilitate generation of quantitative data. The use of stereophotography is encouraged in order to improve species identification, and reduces the masking effect of smaller canopy-forming species. Photographs may be projected on screens, viewed through a microscope or scanned and viewed using computer software. Using computer software, contrast and brightness can be adjusted to improve the identification of species. Grids can be overlaid to facilitate counting of organisms or percentage cover estimates through point sampling. Once species and abundance data has been generated, the data is stored within an electronic database and may be subjected to complete statistical treatment (see above), depending upon the study requirements. A new development in this area is the application of digital imaging techniques. For example, digital images (both photographic stills and video footage) along a transect can be combined to form a mosaic which may be georeferenced and overlain upon other existing spatial data. Percentage cover, direct counts etc. may then be facilitated using image processing techniques (see Videography reviews).The use of stereo video techniques to estimate volumes of conspicuous erect epibiota (e.g. sponges and seafans) are also under development (University of Cork; Rohan Holt pers. comm.).

Methods of attaining species abundances from quadrats, and from various line intercept transect and belt transect survey techniques, are widely discussed within scientific literature (e.g. Bohnsack, 1979; Brown *et al*., 2004). For habitat mapping, full coverage methods are deemed most appropriate (Holt and Sanderson, 2001). For further discussion comparing transect and quadrat techniques, please refer to Lessios (1996) for a succinct overview.

2 – Data Acquisition

The following documents provide adequate procedural detail regarding diver survey methods, which could be applied to habitat mapping:

Holt, R. and Sanderson, W. (2001). Procedural guideline no. 3-3: In situ survey of subtidal (epibiota) biotopes and species using diving techniques. In: Natura 2000 Marine Monitoring Handbook. UK Marine SACs Project. Editors: Davies, J. *et al.,* Joint Nature Conservation Committee, Peterborough, UK.

Murray, E. (2001). Procedural guideline no. 3-7: In situ quantitative survey of subtidal epibiota using quadrat sampling techniques. In: Natura 2000 Marine Monitoring Handbook. UK Marine SACs Project. Editors: Davies, J. *et al.,* Joint Nature Conservation Committee, Peterborough, UK.

Brazier, P. (2001). Procedural guideline no. 3-8: Quantitative sampling of subtidal sediment biotopes and species using diver-operated cores. In: Natura 2000 Marine Monitoring Handbook. UK Marine SACs Project. Editors: Davies, J. *et al.,* Joint Nature Conservation Committee, Peterborough, UK.

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Kroglund, T., Oug, E. and Walday, M. (2002). Water quality- Guidelines for marine biological investigations of littoral and sublittoral hard bottom. Norwegian Standard 9424.
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OSPAR (1997), Kroglund *et al.* (2002), ISO (2004) and Jan *et al.* (1994) address both transect and quadrat methods of surveying the benthos, in particular with respect to hard substratum. OSPAR (1997), Kroglund *et al* (2002) and ISO (2004) treat transect methods as a semi-quantitative approach to sampling, and discuss the use of a semi-quantitative species abundance scale, such as the SACFOR scale provided by Hiscock (1996). Hiscock (1996) details the use of a semi-quantitative survey over an extended area not necessarily spatially limited by transect or quadrat, such that all conspicuous species of a habitat are recorded. It is often considered however, that some effort-limitation should be undertaken in order to make surveys comparable (Holt and Sanderson, 2001). Each of the documents above addresses the sampling strategy and appropriateness of each technique. All guidelines refer to the appropriate health and safety governing body for details of diving restrictions and codes of conduct.

ISO (2004) and Kroglund *et al.* (2002) identify the use of diver surveys in a number of different survey aims, such as overview/pilot surveys, the description of environmental conditions/baseline surveys and trend monitoring of hard substrate epifauna. Fully quantitative but time-consuming methods such as the use of quadrats are required only in trend monitoring. Although these guidelines make no specific mention of habitat mapping, the techniques detailed are readily applicable to such studies, in particular those detailed for baseline surveys such as belt transect methods. ISO (2004) largely reproduces the information provided by Kroglund *et al.* (2002) and it is recommended that these guidelines be used as a backbone for standards and protocols regarding the use of diving in habitat mapping. These guidelines, along with Hiscock (1996) and OSPAR (1997), additionally include advice on defining the position of sampling/survey stations, recording of survey information ('metadata') and information on data treatment and storage. However, the precise guidelines for transect and quadrat surveys could be relaxed for habitat mapping purposes, allowing further flexibility in survey design (Hiscock, 1996).

Holt and Sanderson (2001), whose guidelines are developed from Hiscock (1996), provide the only recent example of guidelines for diver surveys that are specifically designed to survey biotopes and habitats. However, the other protocols addressed above which allow the assessment of species abundances may also be used for this purpose. Holt and Sanderson (2001) provide good detail on the logistics of data acquisition, with particular regard to health and safety considerations and conditions that specifically affect divers. These are the only guidelines that mention the use of a stratified random survey design based upon ground-types identified from hydrographic charts, acoustic ground discrimination systems (AGDS) or sidescan sonar survey maps. This is particularly important in the use of divers for habitat mapping. Additionally, some discussion is provided of defining biotopes in situ through the consideration of minimum areas. These guidelines are applicable to all substrate types, rather than specifically dealing with hard seabed. It is suggested that Holt and Sanderson's (2001) guidelines are combined with the ISO (2004) working document.

Murray (2001) provides additional detail on quadrat sampling methods with further consideration of diver-specific issues such as training on deployment of equipment, positioning of quadrats and methods of counting species. These guidelines build upon those provided by ISO (2004) and others detailed above. Such a method is used to provide a detailed, quantitative inventory of the characterising species of a habitat or biotope, and as such would provide baseline information for monitoring. The use of quadrat sampling as a method of ground-truthing remotely sensed data is not recommended, as this would be too time consuming and provide insufficient spatial coverage. However, the information derived from quadrat sampling can provide critical information on the description and characterisation of the mapped habitats, and may form an important additional layer of information. It is recommended that quadrat sampling details are at least appended to future guidelines for diver surveys in habitat mapping.

Brazier (2001) and Hiscock (1996) provide the only guidelines that specifically address the use of divers to survey soft substratum. This method relies upon the use of diver-operated cores, and follows a similar methodology to the use of grabs in soft sediments in terms of the material collected and the subsequent storage and analysis of this material. The use of cores provides quantitative data that can be used for the identification of soft sediment habitats and biotopes, which rely upon infaunal characterising species. The guidelines do not address methods of survey stratification or their application to habitat mapping. Data generated by these techniques may provide ground-truthing for remotely sensed data, especially the site descriptions that accompany the core samples. In soft sediment environments, divers can only sample a relatively small area in comparison to remotely operated grabs, but may still provide valuable information regarding sediment features, bedforms and epifauna of the surrounding area, which may be highly relevant to ground-truthing remotely sensed data. It is recommended that this guideline is added to the guidelines of transect and quadrat methods, but with additional information on its use in habitat mapping.

Divers are capable of undertaking a number of measurements in addition to assessing species abundances, which are often impossible using remote methods. In particular, assessments of habitat heterogeneity and habitat complexity, in addition to notes regarding bedforms and sediment characteristics, may be of particular use in habitat mapping and ground-truthing of remotely sensed data. Methods of assessing habitat heterogeneity and habitat complexity in the littoral environment, and to a certain extent the sublittoral, are documented in scientific literature. The guidelines for Selected Ecological Studies in Mediterranean Marine Reserves detail such measurements (Charton *et al.* (2000). Hiscock (1996) also details a number of additional observations that should be made at a survey site, as provided in the MNCR Phase 2 recording forms. It is recommended that these additional measurements are detailed in future guidelines for the use of diver surveys in habitat mapping.

Quality assurance of species abundance estimates, through counts or percentage cover, should be undertaken and is detailed in all guidelines above. OSPAR (1997) and Holt and Sanderson (2001) suggest that such estimates are calibrated, or 'backed-up' through the use of photo documentation. OSPAR (1997), Kroglund *et al.* (2002) and ISO (2004) emphasise the importance of gathering a reference collection of species where possible. Pre-survey training and expertise is highlighted by Holt and Sanderson (2001), Murray (2001) and Jan *et al.* (1994). Holt and Sanderson (2001) suggest that biotope designations are carefully re-examined by an experienced operator to ensure that all possibilities have been examined and the classification is correct. Such quality assurance procedures should be incorporated into future guidelines.

Bullimore (2001) addresses the specific use of photographic techniques for recording species abundances. This complements the guidelines for quadrat surveying but may also be used for transect-style surveys. The advantage of this method over in situ recording of species abundances is that a permanent record is created that can be re-examined and resulting species abundances can be verified by multiple workers. Additionally, such images provide a useful illustration of habitat types (Hiscock, 1996). It is suggested that these guidelines are at least appended to any guidelines in which quadrat or transect surveying is addressed.

3 – Data Processing

Each of the guidelines discussed above provides some discussion on data processing. All guidelines detail methods of calculating species abundances from counts or percentage cover estimates. A comparison of various methods of deriving species abundances using quadrats is provided in Lindenbaum *et al.* (2002).

Kroglund *et al.* (2002) and ISO (2004) suggest that species and their abundances are recorded for each survey station and a diversity index computed. Such data should be stored electronically in a database that is suitable for further statistical treatment. Holt and Sanderson (2001) recommend that all data gathered in the field is transferred to standard recording forms and then entered into an electronic database. One such database used widely within the UK countryside agencies is Marine Recorder. It allows the recording of sample data along with associated survey metadata. Its structure also allows data to be disseminated, if required, onto the National Biodiversity Network (NBN) Gateway (www.SearchNBN.net). Databases can be used to produce summary statistics and graphical data representations which may be of value to visualise large and complex datasets (Jan *et al.*, 1994). Where species abundance data has been semi-quantitatively recorded (for instance using the SACFOR scale), no further data analysis can take place. However, where species counts or cover has been provided, such data may be further analysed (see next section).

Where photographic methods have been used (for instance photoquadrats, see Bullimore, 2001), the required species abundances must now be extracted. This can be undertaken using an overlain grid to facilitate counting of species or cover estimates, and such a grid may be overlain on a slide projector or digitally using image processing software such as Adobe Photoshop (which costs around £500 for a full software license). If photographic film has been used rather than a digital system, the slides require scanning to convert them into digital format for manipulation and backing-up through a computer. A slide scanner can cost upwards of £400. Where video footage has been collected, there must be consideration of whether field of view can be established, enabling transect analyses to be undertaken for species abundances/densities. Where field of view cannot be accurately determined, species-time methods of analysis may be used to derive species relative abundances (see review of towed video techniques). All species abundances should be transferred to an electronic database, as for in situ estimates (see above). It is recommended that a brief appendix or footnote is included in future guidelines referring to video analysis methods.

Core samples require considerable laboratory time to process, both for the identification, enumeration and storage of infauna and particle size analysis (see Brazier, 2001). The resulting data is usually of high quality with fully-quantitative species abundance estimates, which are entered into a database for further statistical manipulation.

Of particular importance to habitat mapping is the georeferencing of data. This is not addressed directly by any of the guidelines given above, and requires attention in future guidelines. Site position is recorded as metadata (see above) and this can provide information for georeferencing of species abundance data. Ideally, the transect position, and its spatial coverage, is required for use in habitat mapping. Diver entry position is generally recorded using a GPS receiver, and the orientation and length of transect can be drawn into a geographical information system (GIS) (this assumes that transects are started at the diver entry point. Alternatively surface marker buoys can be used- see below). Georeferencing of quadrats is more problematic, as multiple spatially-dispersed quadrats may be completed within one dive. If divers carry a surface marker buoy, this can be tracked using a boats GPS, so that whenever the buoy appears stationary and position is recorded that ought to relate to the quadrat. There may be some lay-back between the surface buoy and the diver, particularly in deeper water and strong currents, but this can be allowed for by corrections or by spatially buffering the position. Technological advances have enabled the development of acoustic diver tracking devices (as often used in the oil industry). Such ultra short baseline (USBL) acoustic reference systems allow accurate positions to be recorded throughout the dive, which can be used to derive sample positions (transects, quadrats or cores). In the database containing species abundances data, the georeferencing information is also added. A final step in data processing is the presentation of such data within a GIS, in which the georeferencing database fields can be used to display ‘XY’data. This allows a spatial visualisation of the data, which can be overlaid upon other datasets (e.g. those from acoustic methods such as multibeam sonar bathymetries). This step is not detailed in any standards or protocols reviewed, and requires addressing in future guidelines.

Time estimates for the processing of in situ data do not exist per se, and do not include the georeferencing or GIS presentation of data. Estimates for the processing of photographic data in order to extract species abundances is given as ‘several hours per image’ (Bullimore, 2001) depending on level of detail required. Estimates for the processing of core samples range from less than one hour to greater than one working day per sample (Brazier, 2001). Again, these estimates do not include database development, georeferencing or GIS integration. From the authors experience (e.g. Mitchell, 2004) one hour of diving data gathered from transect surveys takes between 2 and 6 hours of processing, depending on whether in situ species abundances are recorded alone, or whether photographic methods are used, and also on whether fully quantitative data must be extracted. Time estimates require updating to address specific processing required for habitat mapping in future guidelines.

4 – Data Interpretation

Data interpretation for use in habitat mapping involves the designation of habitats and/or biotopes to survey sites. There are a number of methods of interpreting such data, which are highly dependent upon the habitat classification scheme being used. The organisation of semi-quantitative data into biotopes (from the Marine Habitat Classification System for Britain and Ireland; (Connor *et al.*, 2004) is detailed in Holt and Sanderson (2001), and spatial scale considerations are also addressed here, with a minimum possible biotope area being $5m^2$. Data interpretation for biotopes is also addressed by Murray (2001), but otherwise is not addressed in any other guidelines.

Most of the diving methods described above generate either quantitative or semi-quantitative species abundance data that are usually supplemented by notes on substratum. The species abundances may be used to identify characterising species which are often listed by habitat classification schemes, while substratum types underpin habitat classification. Where quantitative data has been derived from diver surveys it is amenable to statistical investigation, which may aid classification into habitats. In such cases the statistical approaches followed may be similar to those used for any biological sample data, such as that gathered from grab samples. Details for such analysis are provided in many guidelines, such as ISO/FDIS 16665, ICES BEWG (2004), Schratzberger and Boyd (2002) and Thomas (2001). With respect to diver-gathered data, statistical analysis is well-examined by Murray (2001) and Brazier (2001). It is recommended that details of statistical treatment of quantitative data be at least appended to diver survey guidelines, where the derivation of quantitative data has already been addressed.

There appears to be little available information in guideline format that relates to how the results of statistical treatment of quantitative data may be interpreted into habitat classes. The use of characterising species, as determined through analyses such as SIMPER, may facilitate classification and multivariate analysis such as dendrograms and MDS (multidimensional scaling) plots may enable identification of discrete habitats. This subject area requires attention in future guidelines, however it is dependent upon what habitat classification scheme is being used.

Assignment of habitats/biotopes is crucial to quality assurance, and should be completed by experienced personnel familiar with the study area, with a good working knowledge of the range of potential habitats available in the region. Preferably, another suitably-qualified worker should verify the attributed habitat types. This point is addressed by Holt and Sanderson (2001). When an observed habitat/biotope does not quite fit within a national habitat classification description, the creation of local descriptions can be useful.

Where possible, any additional data should be used to aid the assignment of habitat classes. For example, if grab samples have been collected in close proximity to diver surveys on what appears to be acoustically-similar ground, particle size data should be used to help determine substratum. If previous diver surveys have been completed in the vicinity for other purposes, species lists generated by these should form a background for the *pro-forma* lists used for the habitat mapping diver surveys. Additional survey data such as that collected using MNCR Phase 2 recording forms (Hiscock, 1996; Holt and Sanderson, 2001) is also very useful in assigning biotopes and habitats. Exploiting available data for use in habitat classification is not currently addressed in existing guidelines.

Diver surveys provide as much detail as it possible to gather about a habitat or biotope, albeit spatially restricted, and as such are capable of discriminating and identifying habitats and biotopes to EUNIS levels 5 and 6.

5 – Provenance and Current Usage

Diver survey techniques are used extensively throughout the world to study the marine benthos. In particular, much scientific literature published regarding coral reef studies describes the use of quantitative and semi-quantitative diver surveys (e.g. Hodgson, 1999). In temperate waters, divers have been used in monitoring programmes, which usually focus upon a single assemblage or species (e.g. Lindenbaum *et al.*, 2002; Goni *et al.*, 2000; pers. obs.). Many studies have utilised diving in order to map the distribution of a species of interest (e.g. Goni *et al.*, 2000; Bates *et al.*, 2004c; Mitchell and Collins, 2005) and in this sense has been used routinely to map specific habitats. Diving is rarely used however, in studies of the broad spatial distribution of all habitats within a given area. The following are rare examples of where diving has been used as a ground-truthing methodology in habitat mapping:

Bates *et al.* (2004a,b,c) used SCUBA divers to complete MNCR Phase 2 surveys (see above) of biotope depth zones as ground-truthing of acoustic remote sensing in potential and candidate Special Areas of Conservation in Scotland. In this case, in situ recording was supplemented by video footage. Bates *et al.* (2004b,c) used divers to take cores in shallow sedimentary environments for analysis of infauna and particle size analysis to aid identification of soft sediment biotopes.

Mitchell (2004) used video recordings taken by SCUBA divers to derive data enabling the description of habitats and identification of biotopes in Strangford Lough, in conjunction with in situ notes transcribed onto MNCR Phase 2 recording forms. Diver entry positions were spatially buffered to georeference the data.

Bates *et al*. (2004b) used snorkel divers to take video and make notes of substrate and species to ground-truth shallow areas in the Sound of Barra, Scotland, that had been surveyed using bathymetric sidescan sonar and AGDS.

Spatial mapping of *Zostera* beds using divers has been carried out in several locations; notably in the Skomer Marine Nature Reserve, Studland Bay and more recently in Galway Bay, where divers used DPVs (Diver Propulsion Vehicles) to map seagrass beds over many kilometres (Rohan Holt, pers comm.)

There are no critical studies specifically addressing the effectiveness of diver surveys in habitat mapping, particularly its role in ground-truthing. Such research would be recommended due to the inherent scale issues when merging a fine scale method such as diver surveys with broader scale methods such as acoustic remote-sensing. Such scale and georeferencing issues require addressing when considering diver survey best practise for use in ground-truthing of remotely sensed data. These considerations apply to all methods of ground-truthing (Foster-Smith *et al.,* 2000).

6 – Summary of Future Guideline Recommendations

ISO (2004) largely reproduces the information provided by Kroglund *et al.* (2002) and it is recommended that these guidelines be used as a backbone for standards and protocols regarding the use of diving in habitat mapping.

1 It is suggested that Holt and Sanderson's (2001) guidelines are combined with the ISO (2004) working document.
2 It is recommended that quadrat sampling method details (e.g. from Murray, 2001) are at least appended to future guidelines for diver surveys in habitat mapping.
3 It is recommended that push-core guidelines (e.g. from Brazier, 2001) are added to the guidelines with additional information on its application in habitat mapping.
4 It is recommended that additional *in situ* measurements and notes that may aid habitat identification are detailed in future guidelines (e.g. substrate type, bedforms, habitat complexity, surface relief, slope)
5 Quality assurance procedures should be incorporated into future guidelines (e.g. backing-up of data, photo documentation, adequate metadata records and reference collections of species).
6 Guidelines for the use of photographic techniques should be at least appended to any future guidelines in which quadrat or transect surveying is addressed.
7 It is recommended that a brief appendix or footnote is included in future guidelines referring to video analysis methods.
8 Georeferencing of transects, quadrats or push-cores requires addressing in detail in future guidelines.
9 Database development, in particular the linking of species abundance data with georeferencing information, should be addressed in future guidelines. Such databases also allow the accurate recording of metadata, which is often lacking or poorly recorded.
10 Standards for the recording of survey metadata should be included in future guidelines.
11 Guidelines should provide details on incorporating diver survey data into a GIS such that it can be overlaid upon existing datasets.
12 The existing estimates of diver survey processing times require updating to reflect the georeferencing and GIS development requirements, and should also be incorporated into the discussion of different semi-quantitative and quantitative data acquisition options.
13 It is recommended that details of statistical treatment of quantitative data be at least appended to diver survey guidelines.
14 Some discussion should be provided on how the results of statistical treatment of quantitative data may be interpreted into habitat classes, in addition to how semi-quantitative data should be used to determine habitats.
15 Guidelines should provide advice on combining existing data and additional qualitative notes made during surveys with quantitative or semi-quantitative species abundance data to aid habitat interpretations.

There are no studies specifically addressing the effectiveness of diver surveys in habitat mapping, particularly its role in ground-truthing. This requires future research.

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14 Particle Size Analysis (granulometry) of Sediment Samples

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1 – General Principles of Operation and Data Processing

The physical properties of the substratum are an important feature in habitat classification, because the substrate provides the conditions for the behaviour of zoobenthos. For example, coarse sediment beds are particularly suitable for encrustation of organisms, but not for digging, whereas mud beds promote bioturbation, but lack stability as a platform. The characteristics of the sediment bed also reflect the physical processes acting on it and grain-size analysis is an important tool in classifying sedimentary environments. Coarse sediments are typical of high-energy hydrodynamic conditions, whereas muds are characteristic of low-energy conditions. Therefore, in habitat mapping, the physical properties of soft sediment beds are described by the particle size of samples collected from the sea bed. The advantage of this technique is that it produces an actual measurement of the seabed properties and that it can be carried out on the same samples taken to study the composition of the zoobenthos. Therefore, it produces a direct link between the observed zoobenthos composition and the properties of its substratum. The limitation of the technique is that it relies on samples of only a small portion of the sea floor, so that it is unknown whether the samples are representative of the general conditions. Both spatial and vertical variation of the sea bed can be large especially in shallow marine environments, because of the presence of migrating bedforms, such as sand waves and megaripples, and bed stratification caused by changing meteorological conditions. Sampling strategies with several closely spaced stations to monitor spatial variability are therefore recommended, and when sampling campaigns are accompanied by an acoustic survey (multibeam or sidescan sonar) to monitor small-scale spatial variability of the sea bed, it is best to position the samples based on an interpretation of these data sets.

Samples of the seabed are collected aboard a ship with gravity coring and grab sampling instrumentation operated from a crane. In the case of gravity coring a cylindrical or box-shaped apparatus with a weight on top is driven into the sea bed, secured, and pulled aboard. This way an undisturbed sample of the top 0.3 to 1.0 m of the sea bed is collected. With grab sampling the top 20 cm of the sea bed is scraped and collected in a shovel type device. Alternatively, seabed samples may be obtained from the top parts of longer core samples, obtained using vibracoring or flush techniques. The depth of penetration depends on equipment type, method of deployment, weather conditions and sediment type. Gravity corers may collect non-representative samples if a bow-wave is created ahead of the equipment thereby disturbing loose seabed sediments prior to coring. The core and grab samples are kept in storage in warehouse facilities. The EU-seased database contains information on seafloor samples held at European institutes at www.eu-seased.net. Samples of a few hundred grams up to several kilograms are taken from the top 20 cm of the cores or from the grabs and transferred through a sieve to separate coarse and fine fractions. The coarse and fine fractions are weighed and the fine fraction (generally < 2 mm) is collected for detailed laboratory analyses.

In the laboratory, the size (e.g., diameter) of a population of grains is measured using sieve and gravity settling techniques or, more common in modern facilities, an automated grain-size analyzer. Instrument calibration involves three types of standards (Syvitski *et al*., 1991):

1) Those that test instrument accuracy and precision, such as standards consisting of samples of spherical beads in a sequence with ascending narrowly defined diameters, or a sequence of samples of particles with a known specific density;
2) Those that test for size equivalency, such as spherical glass beads,
3) Those that test for the accuracy of measurements on multimodal or poorly sorted distributions, or low-sphericity, such as natural sediment samples.

These standards are available from the instrument manufacturers (1) and/or the European Reference Materials (1, 2, 3) (ERM, website http://www.erm-crm.org/ermcrm). Data processing and interpretation occurs through calculation of moment measures and other grain-size parameters that describe the relevant characteristics of the frequency distribution, such as mean grain-size, sorting, and percent mud. These grain-size parameters then form physical environmental variables in statistical multivariate analysis that are used to define the habitats. In the characterization of habitats the numerical grain-size parameters of the substratum are converted to descriptive terms, such as very fine sand, or coarse gravel. Numeric laboratory results are stored in digital databases.

Existing grain-size data were usually collected for other purposes than habitat characterization, e.g. for sand extraction studies. Some of the data is stored, or will be stored, in Web databases, such as the Seafloor Sediment Grainsize Database of the US National Geophysical Data Center http://www.ngdc.noaa.gov/mgg/geology/size.html. The spatial scale of the data depends on the sample spacing, which is generally in the 100 m – 10 km range. Habitat maps based on the grain-size properties of the substratum can be generated by point gridding and contour plotting of relevant parameters (e.g., Andrews, 2003). When using existing datasets it is important that the different methods used to measure the grain-size distributions are calibrated to reflect the same grain-size characteristic. In view of the present and future use of accurate automated particle sizers it seems logical to convert older datasets to values reflecting modern measurements, but so far no standard or agreement has been put forward. Georeferencing of the data is achieved during data acquisition on board the ship. Sampling and coring positions are planned prior to data acquisition. Modern vessels are equipped with Dynamic Position systems operating using dGPS, which allow precise positioning of the ship according to the predefined coordinates.

2 – Varieties of System Available

Several different laboratory techniques exist for particle size analysis. These techniques use different grain properties to describe the size of grains. Therefore results may vary for the same sample depending on the technique used (Syvitski *et al.*, 1991).

Examples of differing definitions of particle size (Pettijohn *et al.*, 1987):

- *Sieve diameter* – width of the minimum square aperture through which the particle will pass
- *Stokes' diameter* – diameter of a free-falling particle in laminar flow
- *Projected area diameter* – diameter of a circle having the same area as the projected area of the particle in random orientation
- *Volume diameter* – diameter of a sphere having the same volume as the particle

The preferred technique used depends on the particle-size range of the sediment (Table 14–1). Sometimes more than one technique needs to be used. A review of conventional and modern automated techniques is provided by McCave and Syvitski (1991).

Table 14–1. Preferred particle-size techniques for different grain-sizes.

Class	Gravel	Sand	Silt	Clay
Size	> 2 mm	0.063 - 2 mm	4 – 63 µm	< 4 µm
Preferred Technique	Sieve, Caliper	Laser Particle Sizer, Coulter Counter, Sieve, Settling Tube, (SediGraph)	Laser Particle Sizer, Coulter Counter, (Sieve), SediGraph, Hydrometer, Settling Tube, Pipette	Coulter Counter, SediGraph, Hydrometer, Pipette

Traditionally, the sand fraction (63 to 2000 µm) is analyzed with a different technique than the mud fraction (< 63 µm). Conventional techniques are sieve and pipette analyses, whereby the sand fraction is sieved and mud is analyzed by gravity settling in glass cylinders. The grain property measured through pipette analysis is the Stokes' grain diameter which is the diameter of a glass sphere settling with the same velocity as the grains under consideration. At given time intervals a sample is collected from a certain depth in the cylinder, dried, and weighed to determine the weight percentage of a certain grain-size class. Other methods based on gravity settling are the hydrometer method and the settling tube. The specific density of a suspension can be measured at set time intervals using a weight with graduated stem (hydrometer), which is freely floating in the suspension. Settling tubes measure the fall duration of particles in a long cylinder (> 1 m high, 15-25 cm wide) of turbid-free water. Sediment accumulates on a pan suspended below a digital balance and weight change is recorded through time.

In the last fifteen years automated equipment, such as X-ray sedigraphs, coulter counters and laser particle size analyzers have become state-of-the-art techniques used by many laboratories. The choice of automated particle-analyzer depends on the application of the grain-size distributions. X-ray sedigraphs are useful in studies of mud settling, however caution is in place, when organic matter is present, because it may distort the calculations from X-ray results to grain-size distributions. The sedigraph method is based on X-ray attenuation by the particles in suspension. Laser-particle sizers measure the scatter from grains falling in front of a laser, whereas a coulter counter measures the conductivity of an electrolyte when grains are transferred through an aperture (e.g., Syvitski *et al.*, 1991). Different aperture tubes (coulter counter) and laser beams are used depending on a grain-size estimate of the samples and different operators may make different choices. The particle size measured by laser analysis is the projected area diameter of an equivalent sphere, whereas the particle size measured by coulter counter is the volume diameter. The advantage of automated techniques is their precision and speed. One drawback of most automated particle sizers, however, is that gravel can not be analyzed. Sieving is used in determining the grain-size of the gravel fraction, for which settling, coulter counter and laser particle size analyses are not an option, because they can't handle particle sizes > 2 mm. This limitation introduces a potential problem with gravely seafloor sediments, because it requires that frequency distributions from two techniques, which measure different grain-size properties need to be merged.

Many studies have been conducted dealing with the comparison of the results of one technique to another, especially since the introduction of the automated particle sizers, when new data needed comparison to older datasets produced through conventional techniques. McCave *et al.* (1986), Shillabeer *et al.* (1992), and Konert and Vandenberghe (1997) compared the results of laser particle size analysis to conventional pipette and sieve analyses. Wen *et al.* (2002) compared laser particle size analyses to sieve-hydrometer analyses. Although laser particle sizers produce a different result than the conventional sieve-Stokes' settling combinations, their precision and speed is by far superior. With the introduction of faster computers the grain-size models calculated from the measured light scattering spectra have also become more accurate. The remaining discrepancies with conventional techniques are caused by the differences in grain-size properties that are measured and depend on the shapes of the mineral grains, which vary per sediment type and per size class. For example, clay minerals have a platy shape, whereas dune sand may consist of spherical quartz grains. The diameter of a platelet has a different relation to the volume of the grain than a perfect sphere and deviations in grain shape from the perfect sphere also affect the hydrodynamics of gravity settling.

3 – Review of Existing Standards and Protocols

3.1 – Data Acquisition

Procedural guidelines for Grab Sampling (Guideline PG 3-9) and dGPS (Guideline PG 6-1) from the Marine Monitoring Handbook http://www.jncc.gov.uk/marine/mmh/MMH_0601.pdf are useful as general guidelines for sampling of the sea bed. For this handbook a procedural guideline for particle size analysis is in preparation (Guideline PG 2-4). Also useful are the Puget Sound Protocols and Guidelines on marine sampling available at
http://www.psat.wa.gov/Publications/protocols/protocol.html.

In <position.pdf> strategies and guidelines for station positioning are given, including the use of dGPS. The document <field.pdf> discusses marine sampling of sediment, water column and tissue. The document <sed_conv.pdf> discusses sample and storage requirements and analytical procedures on sediment samples, including sieving and pipette analysis. The issue of sample size and outsized clasts in coarse-grained sediments is not addressed and needs consideration. One large clast in a sample can considerably influence the weight percentages in a size distribution and for an accurate representation of coarse particles large sample sizes are necessary. Depending on the application, this aspect of coarse size distributions is treated differently and it is necessary to define some standard practice in habitat sampling and classification to produce comparable results. For example, in coarse gravely areas, Goff *et al*. (2004) collected 500 g to 1000 g of material over two or three subsamples so that the coarse fraction could be estimated accurately, but Brown *et al*. (2001) took 500 ml subsamples from grabs for particle size analysis. A similar issue is that of shell fragments. Sometimes an estimate of biogenic carbonate in the > 2 mm fraction is made and used for correction of the clastic gravel fraction.

For muds and sands, 100g is sufficient material for particle-size tests to be representative. With gravel size particles however, larger quantities are required for representative results to be obtained (Table 14–2).

Table 14–2. Minimal sample sizes necessary for particle size analysies based on maximum grain size (From Head, (1980); based on BS 1377:1975 Section 1.5.4.2).

Maximum size of material present in substantial proportion	Minimum mass of sample to be taken for seiving
2.0 mm	100 g
6.3 mm	200 g
10.0 mm	500 g
14.0 mm	1 kg
20.0 mm	2 kg
28.0 mm	6 kg
37.5 mm	15 kg
50.0 mm	35 kg
63.0 mm	50 kg

As a general rule a sample mass 200 times of the mass of the largest particle is suggested. This has an impact on the type of equipment chosen for sampling.

Procedural guidelines on laboratory techniques and requirements of the equipment are presented by the International Organization for Standardization (ISO):

ISO 3310 (1990-2000) Test sieves -- Technical requirements and testing, ISO 11277 (1998) Determination of particle size distribution in mineral soil material -- Method by sieving and sedimentation, ISO 13320 (1999) Particle size analysis -- Laser diffraction methods -- Part 1: General principles, ISO 13319 (2000) Determination of particle size distributions -- Electrical sensing zone method, ISO 13317-2 (2001) Determination of particle size distribution by gravitational liquid sedimentation methods -- Part 2: Fixed pipette method, available from: http://www.iso.org/iso/en/prods-services/ISOstore/store.html. Costs are up to CHF 200 per ISO description.

In marine studies samples are usually not pretreated to remove organic matter or biogenic carbonate. Sampling and analyses for sand extraction purposes does not require an accurate representation of the mud fraction, as long as the total mud content is not too high. For habitat classification studies, however, accurate mud contents may be more important. Dispersing agents such as sodium hexametaphosphate (commercially known as Calgon) are commonly used. Standard pretreatment with acid and hydrogen peroxide significantly influences the results of the analysis and raises the mud content due to the breakdown of aggregates. It is recommended that laboratory procedures are applied to conform to international standards; however, the procedures should be practical in marine studies of the sea bed. It is therefore recommended that the existing guidelines are adjusted so that they are applicable to habitat studies.

3.2 – Data Processing

Particle size data may be represented in two different scales:

1. linear grain-diameter scale in mm and µm
2. logarithmic phi-scale

The relation between the scales is expressed as $\varphi = -\log_2 S$, where S is the grain diameter in mm.

Frequency distributions are used to provide graphic representations of individual samples (Figure 14–1). Quarter phi-units are best used to estimate the characteristics of a grain-size distribution. Multimodality can be an important characteristic of sediments, which may be hidden if the size intervals are too small. Cumulative frequency distributions were popular before the computer era, because they have the advantage that median grain-size (D50: 50% of grains smaller than this grain-size) can be determined graphically.

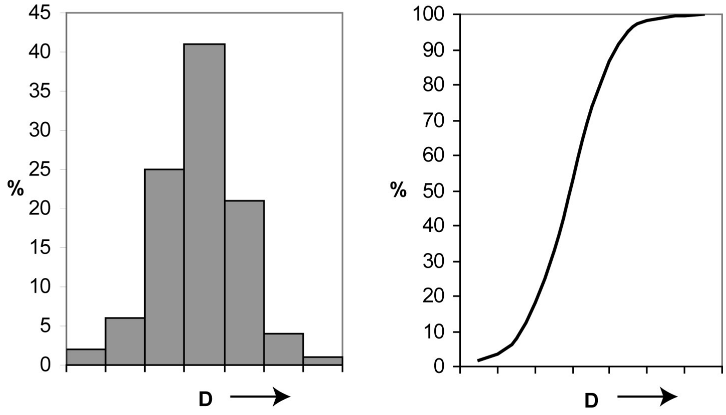

Figure 14–1. Representation of grain-size distribution as frequency distribution (a) and cumulative frequency distribution (b).

When large numbers of samples are classified or compared, it is more appropriate to use Folk (1954) or Shephard (1954) ternary diagrams (Figure 14–2 and Figure 14–3) or to calculate parameters that characterize the grain-size distribution with a few variables, e.g. moment measures, such as mean and standard deviation. Note that the Folk and Shephard diagrams result in different sediment classifications, especially with the coarser grain-sizes (see Poppe *et al.*, 2000). Guidelines are available from the International Organization for Standardization: ISO 9276-1 (1998) Representation of results of particle size analysis -- Part 1: Graphical representation (cost CHF 61,00), and ISO 9276-2 (2001) Representation of results of particle size analysis -- Part 2: Calculation of average particle sizes/diameters and moments from particle size distributions (cost CHF 67,00). Sometimes only moment parameters are stored in digital databases, e.g., median grain-size (D50). Storage of frequency distribution in quarter-phi intervals is preferred however, as it is easier to recalculate different datasets to the same moment measures.

For the conversion of numerical data to descriptive terms the following classification tables are most commonly used in studies of sedimentary environments: Udden-Wentworth (Udden, 1914, Wentworth, 1922; Table 14–3), or the modified Udden-Wentworth scale of Friedman and Sanders (1978). The basic difference between the two is that the Friedman and Sanders (1978) scale is more detailed and that it has the silt-clay boundary at 2 µm instead of 4 µm in the original Udden-Wentworth scale.

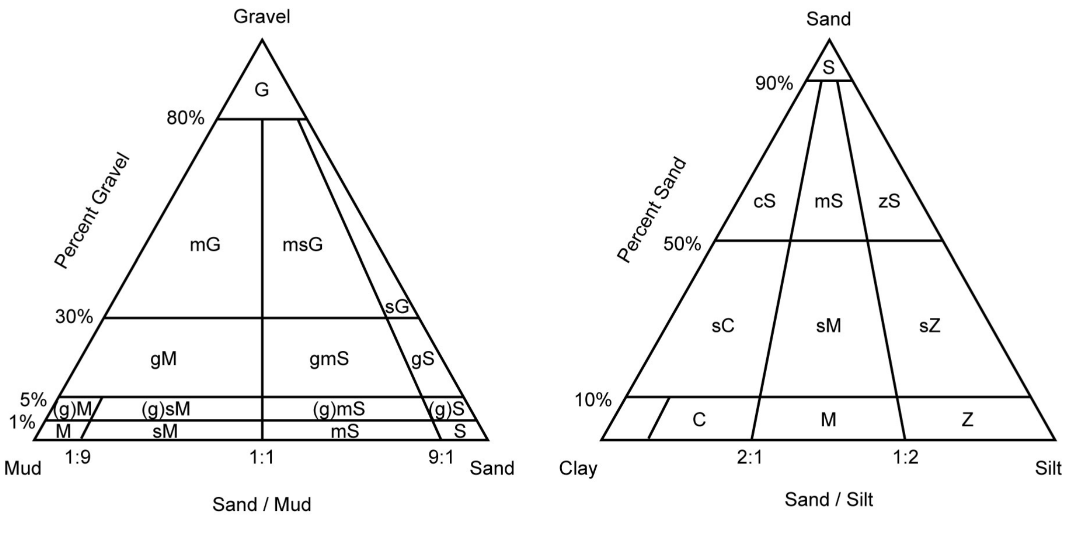

Figure 14–2. Grain-size classification according to Folk (1954).

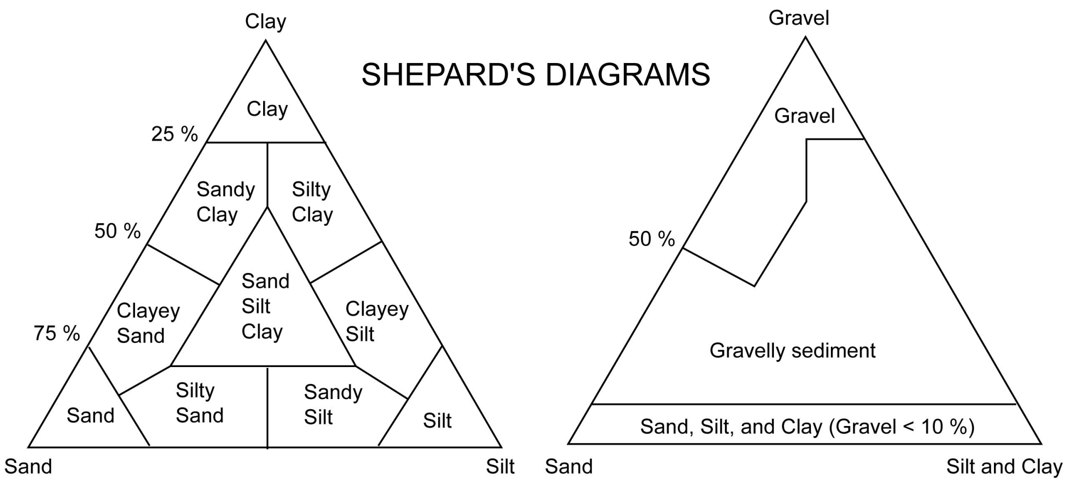

Figure 14–3. Grain-size classification according to Shepard (1954).

Table 14–3. Grain-size classification according to Udden-Wentworth scale (1922).

Millimeters (mm)		Micrometers (µm)	Phi (φ)	Wentworth size class	
	4096		-12.0		
				Boulder	Gravel
	256		-8.0		
				Cobble	Gravel
	64		-6.0		
				Pebble	Gravel
	4		-2.0		
				Granule	Gravel
	2.00		-1.0		
				Very coarse sand	Sand
	1.00		0.0		
				Coarse sand	Sand
1/2	0.50	500	1.0		
				Medium sand	Sand
1/4	0.25	250	2.0		
				Fine sand	Sand
1/8	0.125	125	3.0		
				Very fine sand	Sand
1/16	0.0625	63	4.0		
				Coarse silt	Silt
1/32	0.031	31	5.0		
				Medium silt	Silt
1/64	0.0156	15.6	6.0		
				Fine silt	Silt
1/128	0.0078	7.8	7.0		
				Very fine silt	Silt
1/256	0.0039	3.9	8.0		
				Clay	Mud
	0.00006	0.06	14.0		

Grain-size analyses can be used as a tool in classifying sedimentary environments (e.g., Folk and Ward, 1957; Friedman, 1979). The grain-size of sediments is controlled by provenance, transport history and depositional conditions. Four types of parameters are used to describe grain-size distributions: 1) the average size; 2) the spread around the average; 3) the symmetry of the distribution, the presence of coarse or fine tails; 4) the shape of the modes in the curve: peaked or flat. These parameters can be graphically determined or calculated with mathematical procedures. GRADISTAT (Blott and Pye, 2001) is a software routine running on MS Excel, and is available free of charge from the authors. It can be downloaded at http://www.interscience.wiley.com/jpages/0197-9337/sites.html or http://www3.interscience.wiley.com/cgi-bin/jabout/2388/OtherResources.html. With this package mean, mode, sorting, skewness, D50 and other statistics can be calculated using arithmetical, geometrical, and logarithmic relations based on moment measures and Folk and Ward (1957) graphical methods. With this computer program statistical parameters for several hundreds of samples per hour can be calculated. A relatively new approach in classifying grain-size distributions is by end member modelling (Prins and Weltje, 1999). The modelling algorithms are aimed at construction of physical mixing models that express the input data as mixtures of a limited number of end members, often expressed as separate modes in multimodal grain-size distributions.

3.3 – Data Interpretation

Grain-size distributions of soft-sediment shelf environments are governed by sediment supply, the nature of the substrate, the local influences of tidal currents and waves, and biological processes. It is important to note that the link between benthos and environment works both ways. In soft sediment beds burrowing and trapping of sediment by benthos affect the grain-size distribution of the sea bed. On the other hand, grain-size properties of the substrates impose limitations on, or provide opportunities for animal behaviour. Moreover, the grain-size distributions of the substrate also reflect the benthic hydrodynamic conditions, which simultaneously affect the composition of the benthic communities, as well as sediment transport and deposition. The grain-size distributions of sediment samples are used in two ways in habitat studies:

- In habitat classification for environmental characterization of sediments that contain benthos;
- In habitat mapping for groundtruthing of acoustic backscatter classification.

These two applications use different aspects of the grain-size distributions.

Environmental classification of habitats is based on multivariate analyses of biotic and physical factors (using e.g., TWINSPAN, ANOSIM, PRIMER, or BIOSTAT). Important grain-size parameters are percent mud, and median grain-size (D50) of the sand fraction. Muddy sediments usually occur in areas sheltered from waves with weak bottom currents. Muds are transported in suspension in slow moving currents and accumulate through gravity settling when current speeds decline. Fine and medium sands are transported as bedload by bottom currents. Under shallow marine conditions coarse sands and gravels are usually the product of winnowing of fines by wave action or bottom currents, since currents are usually not strong enough to transport these coarse particles, unless during catastrophic events. Mixed muds, sands, and gravels provide evidence of periodically changing conditions, or extreme events.

Habitat mapping is usually carried out using acoustic techniques, such as multibeam and side-scan sonar in combination with seafloor sampling for groundtruthing purposes (e.g., Andrews, 2003). The acoustic surveys provide habitat information in 100% coverage, and the backscatter signals can be used to deduce physical properties of the sea floor. The choice of useful parameters to describe the physical properties of the sea bed using grain-size analyses is not straightforward (Goff *et al.*, 2000). The mean or median grain-size in a frequency distribution is not diagnostic of the population of grains, but only indicates where the mode is. For calibration of acoustic backscatter signals it is important to characterize the entire grain-size distribution, so more than one parameter should be used. Using the mean, sorting, and the percentage coarse and fine fraction, describing the tails of the distribution is a valuable approach (e.g., Knebel *et al.*, 1999; Brown *et al.*, 2001; Goff *et al.*, 2000; 2004).

4 – Provenance and Current Usage

The Udden-Wentworth Scale is the most widely used in sediment classification. Folk (1954) and Shepard (1954) diagrams have been used over the past 40-50 years in seafloor sediment mapping, for different applications, such as e.g. sand extraction. However, grain-size parameters of the substratum used in habitat classification are variable. Some use grain-size range, mean grain-size and percentage mud. Mud is usually defined according to Folk (1954) as the fraction < 63 μm. Examples of substratum characterization using grain-size parameters are presented in the EUNIS Habitat Classification Categories: http://eunis.eea.eu.int/habitats-code-browser.jsp?habCode=A#factsheet and The Marine Habitat Classification For Britain And Ireland Version 04.05 by Connor *et al.* (2004) available online at: http://www.jncc.gov.uk/marine/biotopes/intro/download_V0405.htm. Connor *et al.* (2004) use a grain-size characterization of sediment types with each class representing two divisions on the Wentworth scale (Wentworth, 1922) (Table 14–4).

Table 14–4. Wentworth scale (Wentworth, 1922).

Description	Grain-size class
Boulders	Very large (>1024 mm), large (512-1024 mm), small (256-512 mm)
Cobbles	64-256 mm
Pebbles	16-64 mm
Gravel	4-16 mm
Coarse sand	1-4 mm
Medium sand	0.25-1 mm
Fine sand	0.063 - 0.25 mm
Mud	<0.063 mm (the silt/clay fraction)

Note that this differs in a crucial area from the nomenclature of the Wentworth scale, as shown in Table 14–4. The description "coarse sand" here covers "very coarse sand" and "granule" grade on the Wentworth scale and not "coarse sand". The description "medium sand" here covers "medium sand" and "coarse sand" on the Wentworth scale. The description "fine sand" here covers "very fine sand" and "fine sand" on the Wentworth scale. This deviating classification may create confusion and should be avoided.

This grain-size classification is adequate enough to make a crude estimate of the characteristics of the substrate, but it does not provide detailed quantitative information useful when determining the sedimentological environmental conditions. At present in habitat classification the full potential of grain-size measurements as environmental variables may not have been reached and more interdisciplinary research with both biologists and earth scientists is recommended. Moment measures, or median grain-sizes (D50) are commonly determined to be used as an independent physical parameter to characterize the environmental conditions. The drawback of using these conventional grain-size parameters is that they are not applicable to multimodal grain-size distributions. A next step in using granulometry as a habitat proxy is the use of complete grain-size distributions rather than single grain-size parameters in data classification and interpolation (Gruijters *et al*., 2005).

4.1 – End-member Modelling

In the field of sedimentology the analyses of numerical particle size data in terms of environmental interpretations of sediment types has made great progress in recent years. Especially the recognition that multimodal grain-size distributions reflect the results of different sedimentary processes acting in the environment simultaneously is of great importance (Prins and Weltje, 1999). Spatial variation in grain-size distributions is the result of combinations of sedimentary processes acting at variable time-averaged intensities at different locations. The resulting grain-size distributions of sediment samples are the sum of the impact of all these processes. In shallow marine environments the dominant processes are fine-grained sediment rain-out from turbid plumes carrying suspended sediment supplied by rivers and coastal erosion, and redistribution of coarse-grained sediment by tidal currents and waves. The grain-size distributions of the sediments can be characterized by bi-linear mixtures of the end-member grain-size distributions produced by these processes (Figure 14–4). Using end-member modelling techniques the relative contributions of several end-member populations to the actual grain-size distribution can be estimated. Since the end-member populations are directly linked to environmental conditions the relative importance of processes such as bottom current strength and rates of sediment rain-out from turbid plumes can be estimated (Figure 14–4). These parameters are potentially important physical characteristics of the habitat. The use of end-member modeling of grain-size distribution in habitat studies has not yet been tested, but it is a novel approach that has produced good results in geological studies.

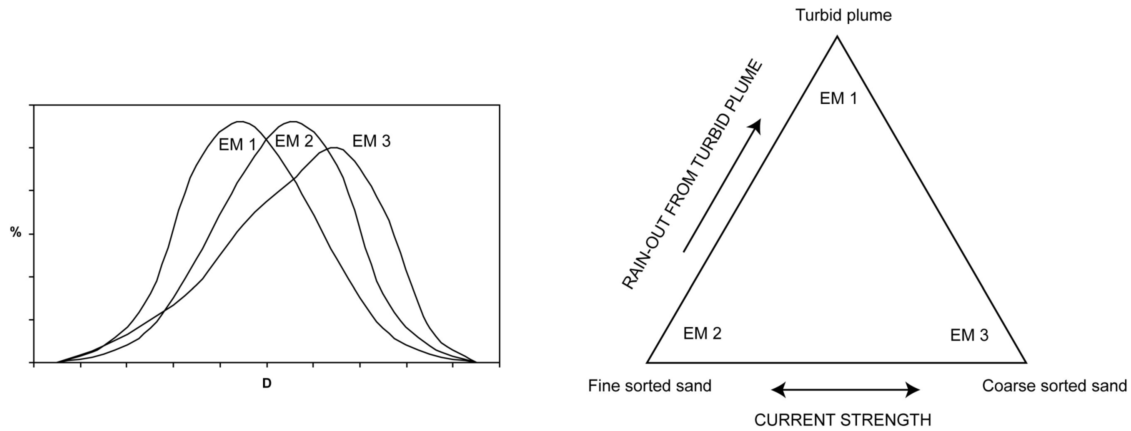

Figure 14–4. Example of end-member separation and interpretation of a shallow marine sediment. Left: Separate curves of three end-members extracted from a single grain-size distribution. Right: ternary diagram with interpretation of the three end-member model.

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US Geological Survey Open-File Report 00-358. http://pubs.usgs.gov/of/of00-358/text/chapter1.htm

STANDARDS

BS1377:1975 Methods of test for soils for civil engineering purposes. British Standards Institute London

ISO11277:1998 Soil quality -- Determination of particle size distribution in mineral soil material -- Method by sieving and sedimentation

15 Trawls and Dredges

Samantha Vize and Roger Coggan (CEFAS)

1 – General Principles of Operation and Sample Processing

Trawls and dredges are destructive sampling gears towed over substrata to sample epibenthic macrofauna. They are normally deployed from the stern of a vessel and towed for short distances to obtain representative samples. The duration and speed of tow depends on the nature of the substratum and the gear being used. Typically, small trawls and dredges are towed at 1-2 knots (either under power or while drifting, Holme and McIntyre, 1971) but speeds of up to 4 knots may be used for larger otter trawls targeting demersal fish species. To ensure good ground contact, the gears are usually towed on a length of warp equivalent to 3 times the water depth.

Trawls are designed to skim over the surface of the seabed. They come in many sizes, and different designs target different elements of the benthic fauna. Trawls can be rigged with different types of ground-gear to enhance their sampling efficiency or selectivity. Typically, beam trawls are fitted with 'tickler chains' in front of the foot-rope which help to dislodge or disturb fauna, increasing sampling efficiency. On otter trawls, different types of foot-rope are used to suit the roughness of the ground and prevent it snagging on the seabed. Where the ground is clear ('clean'), such as on mud or sand, the foot-rope comprises a plain length of rope weighted with light chain. As the ground gets progressively rougher, a foot-rope comprising rubber rollers, steel bobbins or 'rock-hopper' gear (rubber disks ~ 50 cm diameter) is used to keep it slightly elevated above the seabed. Although efficient in sampling most demersal fish and larger motile invertebrates, such gears do not efficiently sample the smaller and sessile epifauna. The choice of gear therefore depends on the type of sample required. The gape of the meshes used in the trawl net and cod-end liner largely determine the minimum size of organism retained by a trawl.

Dredges are designed to dig into and sift the sediments. They also come in many sizes and designs but basically comprise a rigid steel frame fitted with a chain and/or mesh bag. They are most frequently used to sample or harvest bivalve shellfish such as scallops, oysters and clams. The leading edge of the dredge often has a heavy chain, an inclined flat bar, or a toothed bar designed to dig into or scrape the substratum to remove molluscs. Again, the size of mesh determines the size-selectivity of the gear. For both trawls and dredges, the choice of gear must be matched by the choice of vessel, ensuring there is sufficient power to tow the gear through the water and to handle tow cables, otterboards and frames etc (Ross, 1997).

2 – Georeferencing and General Information

The design of the trawl or dredge and the conditions under which it is used will all influence the outcome of a sampling session, so it is important to record relevant general information (meta-data) such as the date, vessel name, environmental conditions (e.g. sea state, wind speed and direction, state of tide), gear specification (e.g. width and height of trawl, type of ground gear, mesh sizes, door types, tow speed, warp out, etc), water depth, time and duration of tow etc. (Rumorh, 1999; Southern California Bight Field Methods Committee, 2002).

It is also imperative that a geographical reference position is assigned to a trawl. The duration of a tow is normally considered to be from the time the winch is locked (after the gear has been shot) to the time when hauling begins. Positions are nowadays recorded using a Global Positioning System (GPS, accurate to within 10–15 m) or a differential GPS (d-GPS, accurate to within 1–5 m). For short or straight-line tows, only the start and finish positions are usually recorded, but for longer or curve-line tows the GPS position can be recorded continuously to log the actual track of the tow. As well as giving a georeferenced position, this enables the distance covered by the tow to be calculated (for use in quantitative analysis). As the vessel's GPS records the position of the GPS antenna and the trawl is towed some distance behind this, a systematic 'layback' error is introduced that should be corrected. Layback can be estimated simply using Pythagoras' theory and many GPS systems allow a constant layback error value to be entered to provide the required correction. Failing this, the correction should be applied during post-processing of the positional data. Alternatively, the trawl or dredge can be fitted with a short baseline transponder and an acoustic tracking system is then used to correct positional data fed from the vessel's GPS. Examples of these systems include Trackpoint II (from ORE International) and HiPAP (High Precision Acoustic Positioning, from Konsberg Maritime).

The assumption that the gear starts sampling at the nominal beginning of the tow and stops sampling at the nominal finish of the tow is usually erroneous, as is the assumption that the gear remains in contact with the seabed for the entire duration of the tow. Time-depth recorders attached to light, 2 metre beam trawls have shown an error of up to ~200% between the actual and the assumed contact times (Coggan, pers. obs.) which has great implications for any quantitative analysis (e.g. faunal density). These assumptions are rarely challenged, but could be overcome by mechanical devices, such as odometer wheels, or by routine use of time-depth recorder (e.g. 'Microloggers') or acoustic tracking systems, which also provide real-time depth data.

NB. The ICES Study Group on Acoustic Seabed Classification is scheduled to produce a Co-operative Research Report in 2005 covering the capabilities of a variety of acoustic remote sensing systems including sidescan, multibeam and AGDS (Anderson, pers. comm.). The authors understand that a chapter by Craig Brown and David Limpenny will give guidelines on the use of appropriate ground-truthing methods, and this will include sections on sampling by trawls and dredges.

3 – Sample Processing

Trawl and dredge samples can be processed in a semi-quantitative or quantitative manner. In the former, the taxa are identified and scored as present/absent, or their abundance recorded on a categorical scale, such as the SACFOR scale (Superabundant, Abundant, Common, Frequent, OcCASIonal, Rare) used in the UK Marine Nature Conservation Review (Hiscock, 1996). In the latter, the volume of the catch is recorded, the taxa identified and enumerated, and their density estimated by 'swept area' calculation. Samples are commonly processed on deck. If washing is required this is normally done over a 5 mm or a sieve of at least the same minimum mesh size as that of the sampling gear (Cooper and Boyd, 2002). If washing is not required the sample is processed on a sorting table. Taxa are identified as precisely as possible and individuals that can not be identified are preserved for later examination in the laboratory. It is also common practice to preserve a reference collection from each sample so that the identification can be verified post-hoc (for Quality Assurance purposes). Species abundance and/or biomass data are usually recorded on field record sheets and transferred to spreadsheets or databases at a later date. Algal and colonial species such as Porifera, Hydrozoa and Bryozoa can be recorded using the SACFOR scale (above) but are sometimes only noted as being 'Present'.

If samples are large, or if certain taxa are very numerous, sub-sampling techniques are commonly used to speed up the sample processing. A common sub-sampling strategy is to thoroughly sort and enumerate a measured portion of the catch, and then estimate the actual numbers in the total catch by application of an appropriate scaling factor (known as 'raising' the data). The fundamental assumption of this strategy is that the sub-sample is representative of the whole catch, and this assumption is usually false. Rare species are not representatively sampled by taking a portion of the catch, so their abundance can be significantly underestimated, or in the worst cases their presence might not be recorded at all. An alternative and more reliable sub-sampling strategy is to sort the entire sample (to ensure a full census of the less common species) and to sub-sample only the highly numerous taxa.

For the top-down approach to habitat mapping (i.e. applying an *a priori* hierarchical classification system such as EUNIS), it is not always necessary to identify specimens to species level as many habitats classes can be assigned on the basis of higher taxonomic levels (Genus, Family, Order) alone. Greater taxonomic precision is required for identifying biotopes and assigning the lower levels of the hierarchy. Even here however, biotopes are commonly defined by a few characterising species, so there would appear to be a great deal of redundancy in the data collected by quantitative processing of trawl and dredge samples. Habitat class could be assigned with a similar degree of confidence on the basis of a far more rudimentary examination of the sample, and the time and effort saved put to more effective use by increasing the sampling frequency (i.e. taking more replicate samples to assess gross variability of habitats in the area).

4 – Variety of Systems Available

4.1 – Trawls

Agassiz Trawl

The Agassiz trawl (Figure 15–1)is essentially a double-sided beam trawl, designed for use in deep waters where it is difficult to control which way up the trawl lands on the seabed (Holme and McIntyre, 1971). Agassiz trawls are most often used to sample mega and macro epibenthos. They come in several sizes from about 1.5 to 3 metres wide and are towed of speeds of 1 – 3 knots. (See Holme and McIntyre, 1971).

Figure 15–1. Agassiz Trawl.
(Image source:http://www.kmf.gu.se)

Otter Trawls

Otter trawls (Figure 15–2) are used to sample demersal fish and motile invertebrates; epifaunal catch is largely incidental. An otter trawl consists of a conical or funnel-shaped net leading into a bag or codend in which the fish and epifauna are retained. Otter trawls derive their name from the otterboards, or doors, which act as paravanes to hold open the mouth of the net when towed. The trawl net can be attached directly to the otterboards or can be extended laterally by panels of netting (wings) at its opening and long cables (sweeps) which help to herd mobile individuals into the mouth of the net. Nets can range in size from a few metres to 180 metres depending on the target species and the nature of the substratum. Otterboards range in size from 5 – 9 square meters and can weigh between 1400 and 3000 kg. During towing, the otterboards and the sweeps create clouds of sediment that help to herd the mobile fauna into the path of the approaching net. Normal towing speed is 2.5 knots.

Floats are attached to the head-rope to keep the mouth of the net open. The footrope along the bottom of the net mouth is weighted with chains. The footrope can be modified to suit the benthic habitat being sampled i.e. a clean rope is generally used for soft and unobstructed sediments such as muds and sands; however rollers, bobbins or rock-hopper gear are used for habitats ranging from cobbles to large boulders in order to prevent the nets from snagging.

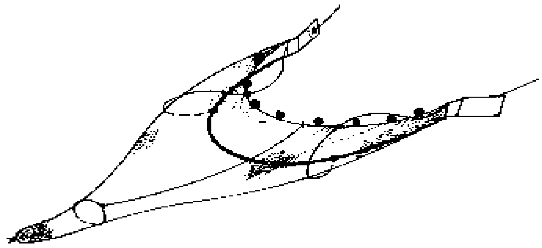

Figure 15–2. Otter Trawel. (image source: http://www.umit.maine.edu/trawling/gear.htm)

Beam Trawls

Beam trawls (Figure 15–3) are most often used to sample epifauna in a "semi-quantitative" or qualitative manner (see Holme and McIntyre, 1971). They are designed to sample at or just above the surface of the seabed, and due to the relatively large area that can be covered in one deployment they are useful for collecting larger, rarer or more motile species. Similar in design to otter trawls, but the net mouth is held open laterally by a rigid frame or a horizontal beam commonly 2 or 4 metres in length, instead of otter boards. The footrope along the bottom of the net mouth is often weighted with a chain. Beam trawls usually have up to 3 tickler chains. Chain mats can be attached to prevent large rocks and cobbles from entering the nets (Jennings *et al.*, 1999). Demersal fish species, commercial shellfish, and megafaunal and large-bodied epifaunal invertebrates are better sampled with a 4m beam trawl; whereas small-bodied epifauna and small, juvenile fish are better sampled with a 2m beam trawl. Tow speed and duration is usually ~4 knots for ≤ 30 minutes for a 4m beam trawl and ~1 knot for ≤ 15 minutes for a 2m beam trawl.

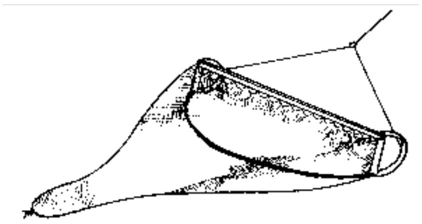

Figure 15–3. Beam Trawls. (Image source:http://www.umit.maine.edu/trawling/gear.htm)

4.2 – Dredges

Anchor Dredge
Developed by Forster (1953), this is most often used for sampling sandy deposits, though can be used for sampling firmer, coarser sediments (Holme and McIntyre, 1971). It consists of a rectangular metal box; open at both ends, with fixed or hinged wishbone towing arms attached. The anterior opening ranges from 0.3 - 0.5 m wide and 0.2 to 0.3 m deep. Collecting bag is usually canvas or net and can be several metres long. The collecting bag has been removed in a modified version by CEFAS to make the gear more robust, and the metal box has a sealed metal plate at its base and an anterior opening of 0.5 m wide and 0.2 m deep. (See Figures 6.7 – 6.9 Holme and McIntyre, 1971 and Brown *et al*. (2002; http://www.cefas.co.uk/publications/files/02dpl001.pdf).

The name of this dredge is derived from the manner in which the dredge is shot and hauled, thus collecting a discrete sample from a single point. The dredge can be deployed over the side or stern of the vessel and after sufficient warp is paid out (three to five times the water depth), the warp is secured. The dredge penetrates the sediment under the weight of the drifting vessel. On larger vessels, there is a tendency for the dredge to drag if insufficient length of warp has been paid out. Therefore uncertainty in its mode of sample collection, i.e. instantaneous or gradual, means that the resulting data should be treated as semi-quantitative in nature. Advantages of this gear are that due to being fitted with double-sided cutting plates, it can fall either side up and will still collect a sample, and its small size makes it relatively easy to hand and deploy.

Rallier du Baty Dredge
Designed to work in a range of substrata from sands to cobbles the Rallier du Baty Dredge has been widely used in the English Channel and the Celtic Sea (e.g. Cabioch, 1968). The dredge consists of a heavy-duty metal ring (40 – 60 cm diameter), attached to a central towing arm. An open-ended collecting bag is attached to the ring, with the trailing end tied to prevent loss of material during sampling. The collecting bag consists of an inner bag of the desired mesh size (typically 0.5 or 1 mm) protected by an outer, coarser-mesh bag, which is, in turn, enclosed by a heavy duty apron of fishing net to reduce chafing. The warp is attached to the metal ring, with a weak link between the towing bridle and the central towing arm of the dredge, which is designed to break if the dredge becomes obstructed.

The dredge is deployed over the stern or the side of the vessel, with the warp length of three to five times the water depth. Contact with the seabed can be judged by the vibration of the warp whilst towing. Towing speed is approximately 1.5 knots, for 5-10 minutes. The circular ring allows the dredge to roll laterally as it is towed across the seabed, as such the dredge is less prone to snag on obstructions and it can continue to sample over uneven topography. Samples collected by this method should be treated as, at best, 'semi-quantitative' in nature due to the difficulty in determining whether the sample contents are evenly or erratically accumulated over the length of the tow. (See Brown *et al*. (2002; http://www.cefas.co.uk/publications/files/02dpl001.pdf).

Naturalist's Dredge
Invented in the late 1700's by Danish scientist O. F. Müller and slso known as a rectangular dredge, this is used for sampling on rocks or when the nature of the seabed is unknown. The rectangular steel frame is designed to scrape epifauna from rock surfaces or collect stones. Owing to the lack of penetration the dredge has on the seabed, it will not sample the sediments unless they are soft mud. Towing arms are attached to the frame along with a collecting net which is usually about half as deep as wide, with mesh varying according to target species (Holme and McIntyre, 1971). The dredge opening ranges from 0.5 – 1.5 m in width. (See Figure A.1 Holme and McIntyre, 1971).

Rock Dredge
Used for dredging over rough or rocky ground, this versatile dredge (Figure 15–4) will even collect surface scrapings from bedrock (Holme and McIntyre, 1971). It consists of a heavy-duty metal frame rim 0.6 m wide and 0.4 m deep, to which towing arms are attached and a dredge bag made of metal rings or wire grommets. A finer-mesh bag may be attached inside the outer chain-link bag enabling the dredge to collect finer material. On deck, the trailing end of the dredge is mechanically lifted to release the sample contents. The robust nature of this dredge has resulted in the use of this gear in

areas where little is known about the nature of the substratum, or where sampling conditions may be difficult due to rough and course substrata. The advantages of this dredge are that it will still collect a sample whatever side the dredge falls. As with other dredges, the data generated should be treated, at best, as 'semi-quantitative'. (See Figure 6.5 Holme and McIntyre, 1971; Brown *et al*., 2002; http://www.cefas.co.uk/publications/files/02dpl001.pdf).

Figure 15–4. Rock Dredge.

Oyster/Scallop Dredges e.g. Newhaven scallop dredge
These are designed for catching bivalves in commercial quantities and may be damaged if towed over bedrock or through large boulder fields. The design is essentially a metal frame, the bottom edge of which is fitted with scraper bars, blades or rake-like teeth to dig into the substratum to dislodge oysters and deflect scallops and clams into trawl bag. The bag is constructed of interlaced alternate large and small iron rings on the lower surface and heavy gauge nylon mesh on their upper surfaces. The size of the ring openings functions much in the same manner as mesh openings in trawl nets. The mouth of each dredge is approximately 80 cm wide and bears about 10 teeth up to 7 cm in length. (See Figure 6.6 Holme and McIntyre, 1971; Brown *et al*., 2002; http://www.cefas.co.uk/publications/files/02dpl001.pdf).

A number of these dredges can be attached to a robust metal frame to which large rubber rollers are fixed at each end (Figure 15–5). Single dredges can weigh up to 90 kg; where as a team of 3 dredges on a beam can weigh up to 400 kg. Dredges are usually deployed over the stern or side of the vessel and towed for a pre-determined time, usually 10 – 15 minutes at a speed of approximately 2.5 knots. The dredge must be deployed the correct way up. Samples collected using the scallop dredge should be treated as at best 'semi-quantitative' in nature. The robust design means that the gear is suitable for use over coarse unconsolidated substrata, and it is often used to test the suitability of the seabed prior to deployment of less robust gear such as the beam trawl. The gear is very heavy however and multiple dredges require large vessels. The sampling efficiency is also variable under poor weather conditions.

Figure 15–5. Three Oyster/ Scallop Dredges (Image source: CEFAS).

Triple D Dredge
The Deep Digging Dredge or "Triple D" dredge (Figure 15–6) developed by the NIOZ was designed for sampling larger and infrequently occurring infauna and epifaunal species. The prototype (Bergman and van Santbrink, 1994) was 2 m long, 1.5 m wide, and 1.5 m high and weighed about 600 kg. The dredge consisted of a pair of broad runners connected by a stainless steel cage (mesh size 0.7 cm) mounted 5 cm above the seabed and was equipped with a fixed cutting blade designed to slice a strip out of the seabed (approximately 150 m length, 0.2 m width and 0.1 m depth). A later modification had a hinged cutting blade operated by compressed air, increased the sampling depth to 0.14 m and enabled a haul of a preset length, independent of vessel movement during deployment and retrieval.

Figure 15–6. The Tripple D Dredge (Image source: http://www.pml.ac.uk/biomare/site.htm).

Epibenthic Sled
The Aquarieve III epibenthic sled was originally designed by Thouzeau and Vine (1991) and used for epifauna studies on scallop grounds on the Georges Bank. The sled has a sampling blade, 0.34 m wide cutting 2-3 cm into the sediment. A steel collection box has regularly spaced holes (1 cm diameter) so most of the sediment passes through. Paired odometer wheels measure the towing distance, which can be viewed on ship. The sled is towed at an approximately speed of 1 knot. At the end of a prescribed tow length, the sled door can be electronically activated to close and the sled is then retrieved. A colour video camera can be mounted onto the sled to record its sampling performance. The disadvantages of this gear are the 1 tonne weight of the sled and the specialised cables and electronic devices require a large research vessel. In addition, captured organisms are highly likely to be damaged. However, since the area of the seabed sampled can be determined with a relatively high degree of accuracy, samples can be viewed as ‘quantitative’. (see Figures 6.26 and 6.27 Holme and McIntyre, 1971).

5 – Review of existing standards and protocols

5.1 – Data acquisition

This section on data acquisition relates to the obtaining and processing of samples to derive species x samples data matrices. We present a brief summary of existing documents containing guidelines, standards and protocols relevant to sampling using trawls and dredges.

In an attempt to standardize the methods employed to survey benthic habitats, Rumorh (1999) provides comprehensive recommendations for sampling soft bottom macrofauna within sediments ranging from mud to sands. Within these recommendations reference is made to remote sampling techniques such as trawls and dredges. Rumorh (1999) suggests a number of protocols as standard practice for soft bottom epifaunal studies, with recommendations given on the standard gear to use and gear specifications. Procedures are given for treatment and preservation of samples and determination of biomass, along with recommended sieve sizes etc.

Comprehensive procedural guidelines on the use of the Global Positioning System (GPS) are outlined in Ince *et al*. (2001), which are suitable for positional recording of trawls and dredges in habitat mapping surveys. The guidelines include overviews of GPS and d-GPS, advantages and disadvantages of equipment, co-ordinate reference systems and accuracy testing etc.

Comprehensive procedural guidelines on sampling sublittoral sediment biotopes and species using remote-operated grabs are outlined in Thomas (2001). Within these guidelines there are a number of sections that are relevant to sampling using trawls and dredges such as: on-board processing, laboratory methods (i.e. preservation and storage of faunal samples), and sorting, identification and biomass analysis, safe working practices and general rules to be observed when working on boats, and an equipment check-list for sampling infauna and epifauna. Reference to beam trawling with respect to sampling benthic and demersal fish populations on sediments is given by Wilding *et al*. (2001).

Cooper and Rees (2002) review 23 standard operating procedures (SOPs) submitted by participants of the UK’s National Marine Biological Analytical Quality Control scheme (NMBAQC). The SOPs cover both field sampling methodology and laboratory analysis and contains detailed examination of individual SOPs for trawl sampling, laboratory analysis of benthic macrofauna and sampling sub-tidal sediments. The report makes an important point that current SOPs offer little or no advice with respect to sub-sampling of trawl catches and that “….there is a clear need for more guidance on approaches to sub-sampling of trawl catches”. The report also gives conclusions and recommendations considered to be the most important for improving the quality and comparability for data produced by different laboratories.

Southern California Bight Field Methods Committee (2002) produced a field operations manual for marine monitoring in Southern California (see http://www.sccwrp.org/tools/methods.htm). The manual provides some useful, though brief, information on general safety at sea consideration, benthic sampling methods and trawl sampling methods.

The UK National Marine Monitoring Programme (NMMP) "Green Book" (Marine Pollution Monitoring Management Group, (2003) provides procedural guidelines for the collection, processing and analysis of subtidal macrobenthic samples. Although specifically focusing on grab sampling, the guidelines are, in many parts, relevant to processing samples collected by trawls or dredges.

Guidelines produced for the conduct of benthic studies at aggregate dredging sites (Boyd, 2002) (see http://www.cefas.co.uk/publications/files/02dpl001.pdf) contain comprehensive information on standards and protocols for qualitative and semi-quantitative methods of sampling benthic macrofauna using trawls and dredges (and grabs), processing the samples and analysing the resulting data. Quality assurance standards and survey design are also addressed. The operation, application and limitations of a variety of trawls, dredges and grabs are compared. These guidelines are highly relevant to the application of these techniques in seabed habitat mapping.

The ICES Benthos Ecology Working Group (BEWG) is currently drafting a working document on guidelines for the study of the epibenthos of subtidal environments. These guidelines will include sections pertaining to destructive sampling methods such as trawls and dredges, and methods for processing epibenthic samples. Although written with a view to guiding the conduct of monitoring surveys, the guidelines are likely to include standards and protocols that may be relevant, in full or in part, to the use of trawls and dredges in seabed mapping studies.

5.2 – Data processing

Quality Assurance/Quality Control
Accurate identification of specimens is crucial for any analysis to be valid. Taxonomic competence of personnel must be ensured through training workshops and other regular meetings to verify uniformity of work. Quality assurance and quality control procedures must also be implemented to ensure the accuracy of specimen identifications among personnel and to ensure that high standards are maintained.

The UK's National Marine Biological Analytical Quality Control Scheme (NMBAQC) was established in 1994 to monitor and set up marine biological data quality standards for benthic faunal studies, particularly with regard to the National Marine Monitoring Programme (NMMP). The NMBAQC scheme is a programme whereby macro-invertebrate samples, sediment samples and invertebrate specimens are exchanged between approximately 30 laboratories throughout the UK for ring tests. Further details are available at http://www.nmbaqcs.org/.

General guidelines have been prepared by the ICES/OSPAR Steering Group on Quality Assurance of Biological Measurements in the Northeast Atlantic (SGQAE), for the setting up of quality systems, with the emphasis on marine biological monitoring (see Rees, 2004).

Taxonomic coding systems
A number of hierarchical taxonomic coding systems have been developed to standardise the identification of taxa. However, like any hierarchical system, problems arise when species are revised/re-classified and Latin names change. This has lead to the development of coding systems where each taxon is assigned a unique serial number that does not change in the event of any taxonomic revisions. One such example is the Integrated Taxonomic Information System (ITIS) that uses non-intelligent Taxonomic Serial Numbers (TSNs) (see below).

National Oceanographic Data Centre Taxonomic Codes

(http://www.nodc.noaa.gov/General/CDR-detdesc/taxonomic-v8.html)
In 1977, the National Oceanographic Data Centre published the first edition of the NODC Taxonomic Code containing approximately 16,000 records. A second and third edition were released in 1978 and 1981 respectively. The last hard copy edition was published in 1984, with subsequent releases available only in digital format such as version 7.0, containing approximately 206,000 records. Up to 1996, the NODC Taxonomic Code was the largest, most flexible, and widely used of the various coding schemes which adapted the Linnaean system of biological nomenclature to modern methods of data storage and retrieval. The code comprised a 12-digit numeral that 'intelligently' encoded 6 taxonomic levels (Phylum, Class, Order, Family, Genus, Species) with two numerals each (e.g. 211305090217). Released in

1996, version 8.0 of the NODC Taxonomic Code was the final version of this 'intelligent' coding system, and introduced the new non-intelligent Taxonomic Serial Numbers (TSNs) used in the Integrated Taxonomic Information System (ITIS).

ITIS assumed responsibility for assigning new TSN codes and for verifying accepted scientific names and synonyms in the late 1990's. ITIS is supported by a partnership of U.S. and international organisations, including the National Oceanic and Atmospheric Administration (NOAA) and the National Oceanographic Data Centre (NODC) (see http://www.itis.usda.gov/). ITIS contains nearly 300,000 entries for terrestrial, marine, and freshwater species from all biological kingdoms. Although focusing on North American species, it also includes worldwide treatment of selected groups of fishes, birds, reptiles, molluscs, corals, and other groups.

Marine Conservation Society Species Directory (UK)

The first edition of The Species Directory of Marine Fauna and Flora of the British Isles and Surrounding Seas was released in 1987 (Howson, 1987). Revision of the directory lead to the release of a second version of the code, incompatible with the first (Howson and Picton, 1997), available in paper and CD-ROM format. The directory is divided into chapters each covering a different phylum or major taxonomic group. The MCS code is an alphanumeric code (e.g. ZG0442, W1943) in which the letters identify the phylum and the numbers relate to a serial list of taxa within that phylum. The main part of the directory comprises three columns, the first giving the MCS code, the second giving the class, family, order, genus or species name and the third detailing synonyms in common use, and notes on taxonomy, status, distribution and habitat.

UNESCO/IOC Register of Marine Organisms (http://www2.eti.uva.nl/database/urmo/default.html)

The UNESCO-IOC Register of Marine Organisms (URMO) is a large and growing dataset that is being built up and maintained by Jacob van der Land at the National Museum of Natural History, Leiden, the Netherlands. Access to completed data sets will be provided by the Expert Centre for Taxonomic Identification (ETI) such as such as ETI's World Biodiversity Database (http://www.eti.uva.nl/). The register contains a number of 'global species databases' for exclusively marine taxa.

Species 2000 (http://www.sp2000.org/)

Species 2000 is a "Federation" of database organisations with the aim to create an array of participant global species databases covering each of the major groups of organisms and each using a consistent taxonomic system.

Encyclopaedia Taxonomica (Netherlands)

(http://www/taxonomics.com/Taxonomica2/Introduction.asp)

The aim of the Encyclopaedia Taxonomica is to become a place to find information, communicate and exchange knowledge with people working in biology. At the end of 2003, TCN code lists (TaxonCode Netherlands) were completed and are provided on The Encyclopaedia Taxonomica; these will set the standard in the Netherlands for the coding of species.

AlgaeBase (http://www.algaebase.org)

AlgaeBase was developed at the Martin Ryan Institute, National University of Ireland, Galway) with support from the Higher Education Authority (Irish Department of Education and Science) and from the European Union. It aims to include all organisms regarded as algae, including the Cyanophyta (or Cyanobacteria). Primarily AlgaeBase is a taxonomic database of information on algae that includes freshwater, marine (seaweeds) and terrestrial algae, including uses and many pictures.

6 – Data Interpretation

6.1 – Univariate analyses

A priori assumptions can often be made when viewing community data sets, for example there may be replicates from a number of different sites and/or times. A pre-requisite to interpreting community differences between sites is that the differences can be shown to be statistically significant. Simple discriminant analyses can be applied when species abundance (or biomass) data has been reduced to univariate indices, such as Species Richness (*S*), Shannon-Wiener diversity index (*H'*), Margalef's index (*d*) and Pielou's evenness index (*J'*) (Magurran, 1988). The existence of replicate samples from each of the groups (sites/times etc.) allows formal statistical treatment by analysis of variance (ANOVA) and *t*-tests using the indices.

6.2 – Multivariate analyses

Several software packages are available that address multivariate analyses of community data, including PRIMER, TWINSPAN, DECORANA and CANOCO. PRIMER (Primer-E Ltd, Plymouth) is currently the most widely used.

PRIMER

PRIMER (Plymouth Routines In Multivariate Ecological Research) was developed at the Plymouth Marine Laboratory. PRIMER version 5.0 consists of a wide range of univariate, graphical and multivariate routines for analysing the species/samples abundance (or biomass) matrices that arise in biological monitoring of environmental impact and more fundamental studies in community ecology, together with associated environmental data. PRIMER version 6.0 has recently been released.

The basic routines of the package cover: hierarchical clustering into sample (or species) groups (CLUSTER); ordination by non-metric multidimensional scaling (MDS) and principal components (PCA) to summarise patterns in species composition and environmental variables; permutation-based hypothesis testing (ANOSIM), an analogue of univariate ANOVA which tests for differences between groups of (multivariate) samples from different times, locations, experimental treatments etc; comparative (Mantel-type) tests on similarity matrices (RELATE); standard diversity indices; dominance plots; species abundance distributions, etc. (Clarke and Warwick, 1994 and 2001; Clarke and Gorley, 2001). PRIMER also has two routines that are highly beneficial for habitat mapping projects. The SIMPER procedure identifies the species that contribute most to the average Bray-Curtis dissimilarity between (and/or within) groups of samples, while the BIO-ENV procedure selects environmental variables that "best explain" the patterns in the community data.

TWINSPAN – Two Way Indicator Species Analysis

TWINSPAN is a FORTRAN program for two-way indicator species analysis for classifying species and samples, producing an ordered two-way table of their occurrence (Hill 1979a, b). The process of classification is hierarchical; samples are successively divided into categories, and species are then divided into categories on the basis of the sample classification. TWINSPAN, like DECORANA, has been widely used by ecologists and has the potential to be particularly useful in habitat mapping projects.

DECORANA – Detrended Corresponence Analysis

DECORANA is a program for ordinating multivariate species data, and will perform correspondence analysis and detrended correspondence analysis (Hill, 1979a).

CANOCO - Canonical Correspondence Analysis

CANOCO is an extension of DECORANA (Hill, 1979b). It includes the indirect techniques of principal components analysis (PCA), (detrended) correspondence analysis and principal coordinates analysis and also the direct techniques of weighted averaging, canonical correspondence analysis, canonical varieties analysis (= linear discriminant analysis) and redundancy analysis (ter Braak, 1986 and 1988). CANOCO can also test whether species are related to measured environmental variables using a Monte Carlo permutations test (ter Braak, 1988).

7 – Provenance and Current usage

Trawls and dredges are long-established and widely used sampling techniques. In the context of habitat mapping they are most frequently used to ground-truth remote sensing techniques. Due to the difficulty in determining whether the sample contents are evenly or erratically accumulated over the length and duration of a tow, samples collected by trawls and dredges should be treated as qualitative or at best, 'semi-quantitative' in nature. They are effective methods for determining which epibenthic megafauna characterise particular areas of seabed. When using trawls and dredges for habitat mapping projects, it is beneficial to carry out a 'pilot' survey to determine what sort of sampling design needs to be applied in order to record the variety and spatial extent of habitats in the area to be mapped.

Most of the data analysis programmes considered here are also well established and in common use. However their application is mostly focused on establishing change within marine communities. Their application to habitat mapping is less certain.

8 – Recommendations

8.1 – Acquiring and processing samples

The majority of standards and protocols reviewed here relate to obtaining samples for investigative or monitoring purposes. None specifically address the purpose of habitat mapping, although the requirement to obtain and process samples is unlikely to be significantly different. However, the precision with which fauna are identified and enumerated may vary according to the level of habitat classification required (e.g. EUNIS Level 4 - fairly imprecise, but Level 6 - fairly precise). The available guidelines need to be adapted to indicate how thoroughly an area should be sampled, and how thoroughly the samples should be processed, in order to validate the attribution of habitat classes at each of the EUNIS levels.

8.2 – Data processing

Accurate identification of taxa is a pre-requisite to accurate identification of habitats, so suitable quality control measures need to be considered to ensure harmony between data suppliers in terms of their taxonomic identification.

The variety of standards and protocols available for encoding taxonomic data presents the potential for a great deal of incompatibility between data sets submitted to a central repository by multiple institutes/projects. An acceptable common standard should be sought for future use. The unique Taxonomic Serial Number type of system would appear to be the most 'future-proof', as the coding does not change if/when the descriptive taxonomy is revised.

8.3 – Data interpretation

Unlike spot sampling techniques (e.g. grabs), a single trawl or dredge tow may cover a number of habitat types, integrating the epibenthos from the various habitats into a single sample. Great caution therefore needs to be exercised in the interpretation of the data. Based on results of prior acoustic surveys, trawl and dredge sampling can target acoustically distinct areas. However, the assumption that such acoustically distinct areas represent homogeneous habitats must be questioned. An acoustically distinct area may contain several habitats, and certain habitat types may straddle the boundary between several acoustically distinct areas (issues of 'specificity' and 'fidelity'). A great deal of investigation needs to be directed towards correlating epifaunal assemblages with the physical nature of sediments and subsequently populating Levels 4, 5 and 6 of the EUNIS classification system with new habitat/biotope descriptors.

Data analysis programmes (PRIMER etc.) are frequently used to assist/inform interpretation. In terms of habitat mapping, procedures such as cluster analysis and BIOENV may be highly instrumental in determining significantly different community types and thereby help to define new habitat categories, particularly for the deeper water habitats which are currently not well differentiated by the EUNIS system. Consideration should be given as to how such analyses can best be used in this application. MESH should be mindful of the danger that this could lead to the generation of highly specious habitat types (for instance a single Level 4 category being split into ten or more Level 5 categories) which may be a hindrance rather than a help to the mapping process. Likewise, routines that investigate the similarity/dissimilarity between samples (or samples and models) would appear to have great potential for use in a habitat matching application (i.e. matching the data you may have collected from a sample site with one of a range of habitat types for which you have model data sets), and consideration should be given as to how these can be best applied in this context. One of the advantages of such a 'statistical' approach to analysis is that it can also provide confidence measures which can be used to provide some 'confidence rating' with the interpretation.

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16 Geotechnical Measurements

Fiona Fitzpatrick (Marine Institute) and Dave Long (BGS)

The intrinsic characteristic of sediment is partly controlled by the physical and chemical properties of the particles and partly by the bulk sediment character, including grain size distribution, sorting, grain orientation, grain arrangement, porosity and the degree of cementation. These bulk properties are controlled by the depositional environment and history of transportation, which can be identified by applying a series of routine repeatable measurements and observations. Geologists, hydrogeologists, civil engineers and biologists employ Geotechnical measurements and subsequently, a variety of techniques and classifications have emerged. Listing all the methodology and result interpretation is beyond the scope of this review and attempts are made to concentrate on the most repeatable and commonly utilised techniques, drawing from a combination of marine geological and engineering methodologies. Although operating descriptions are given of the various systems, it is ultimately the responsibility of the user that the system is used in accordance with the manufacturers' operating methodology.

1 – Introduction and bulk sediment properties

Sediment descriptions are achieved in two parts, (a) the direct observation of a sediment and character description and, (b) by measurements. It is also necessary to classify sediments (please see the section on Granulometry). Essentially, sediments can generally be classified into four groups:

- Residual sediments form in place by direct weathering.
- Transported sediments have been deposited in their current location by natural processes.
- Non-indurated (*i.e.* lithified) rocks, which are technically sediments, exemplified by some Tertiary or Cretaceous sands (Keuper Marl, Oxford Clay, etc.).
- Dumped sediments, or sediment bodies created by man.

Sediments are not solid mass, but aggregates of solids with voids, which can be either filled with liquid or air. Sediments can also exist in four states: *(i)* solid, *(ii)* semi solid, *(iii)* plastic and, *(iv)* liquid, all dependent on water content, or pore water pressure. The strength of sediment therefore depends on the strength of the minerals composing the aggregates and the strength of the forces holding the aggregates together. The response of sediment to the environment or changes in the environment depends on many factors, many of which cannot be quantified within the structure of this document. Simplistically, two factors must be considered, cohesion and friction.

1.1 – Cohesion

Cohesion is defined as the intermolecular attractive force acting between two adjacent sections of substance holding soil particles together, as oppose to compression. **Adhesion** is the attractive force between two dissimilar substances. Considering attractive forces act over relatively short distances, the importance of cohesion is greater for clay size particles; hence the term cohesive as applied to sediments with a large proportion of clay components compared to cohensionless sands.

1.2 – Angle of internal friction

Frictional forces are derived from the resistance of the grains to sliding past each other, resistance to grain crushing or rearrangement of the grains and a resistance to volume change (or dilatency). A stationary sediment has a weight (N) which, generates an equal and opposite reaction (R). When directed force (H) is applied to the soil, R must readjust. The triangle of forces, represents in magnitude and direction, the relationships between N, H, and R and the angle (Ǿ). When Ǿ has reached its maximum possible value, movement occurs. This is the angle of internal friction or the angle of internal yield and is used to resolve shear stress. The angle is controlled by a combination of grain size, shape, packing arrangement and surface texture of the grains. Sands have an angle of internal friction between 26-46° and clayey soils, closer to 13°.

1.3 – Compressive strength

The load bearing capacity of the four sediment states is defined as the compressive strength[1] of the threshold of minimum directed pressure before deformation occurs. Deformation is a manifestation of the fluctuation of pore water pressure (i.e. volume) and can result in compression (consolidation), liquefaction or cohesivity.

The compressive strength of fine sediments is primarily a function of mineral composition, particle size and the degree of compaction. Generally, the strength of a soil increases with particle size, particle alignment and compaction. Secondarily, the rate of the load and degree of confinement of the soil; which relates to vibration and sediment thickness, respectively, also affect compressive strength.

1.4 – Angle of repose

In unconfined unconstrained and unconsolidated sediments, the angle of rest is known as the *angle of repose* (Φ_r) and is typically several degrees lower than the angle of internal friction. Average angles of repose of unconsolidated dry sands are typically 32-34°, which can increase as the sands become saturated.

1.5 – Deformability and elasticity

The deformability and elasticity of sediments is important for understanding their behaviour under stress (e.g. on tidal flats or within the wave base). When **stress** is applied to a body, it responds by exhibiting **strain** (a change in unit length). **Young's Modulus** defines the ration of applied stress to the resulting strain. Generally, strain increases with stress until the **yield stress** or **plastic limit** is reached, at which point the material ruptures.

Poisson's ratio of stress-strain behaviour must also be taken into account, which takes into account that when a material is subject to compression it may experience a decrease in length in one direction, but an increase in length perpendicular to the applied stress. Poisson's ratio is the non-dimensional ratio of the strains in each of the two directions. In sediments, the stress-strain behaviour is governed by a combination of moisture content, temperature, pore fluid pressure, chemistry, rate of loading and the pervious stress history.

1.6 – Voids ratio and porosity

The voids ratio (e) is defined as the ratio of volume of voids (V_v) to the volume of solids (V_s):

$e = V_v/V_s$ expressed as a pure number or decimal and can exceed 1 1.1

The porosity (n) of a sediment is defined as the ratio of the pore volume (Vv) to the bulk volume (V) and is expressed as a percentage

$$n = V_v/V = V_v/(V_v + V_s) \quad 1.2$$

The relationship between voids ration and porosity is given as:

$$n = e/(1 + e) \text{ and } e = n/(1 - n) \quad 1.3$$

1.7 – Grain orientation and packing arrangement

Grain packing has a strong influence on the critical threshold to move a grain and on the porosity and voids ratio; the tighter the packing arrangements the greater the shear strength required to initiate movement.

[1] Compressive strength is generally measured in units of kPa, where 1kpa = 0.01kgcm[2]

1.8 – Moisture content

Moisture content (*w*) is defined as the mass of water that can be removed from sediment by heating and is expressed as a percentage of the dry mass:

$$w = \text{loss of moisture /dry mass} \times 100\% \quad (1.4)$$

Note: this differs from water content (loss of moisture/total mass x 100%) that is sometimes used (often US))

1.9 – Permeability

Permeability of sediment differs from porosity and reflects the interconnection of pore spaces. It is defined as the ability to discharge fluids under a hydraulic gradient and is controlled by Darcy's Law which states:

$$q = Aki \quad (1.5)$$

which, relates the volume of flow per unit time (normally 1 second), (*q*) to the cross sectional area (*A*) of a sample, the coefficient of permeability (*k*) and the hydraulic gradient (*i*).

1.10 – Shear strength

The dynamic response of a material to applied stress is given by the Mohr-Coulomb equation:

$$\tau_f = C + \sigma \tan \Phi_i \quad (1.6)$$

where: τ_f is the shear stress at failure, C is the cohesion due to the presence of clays (Pa), Φ_i is the angle of internal friction and σ is the normal shear stress (Pa). The shear strength of cohesionless sediment under loading is affected by a series of factors, including particle size distribution, moisture content and whether the sediment has been preloaded or previously dried out.

The shear strength of water saturated muddy sediments decreases rapidly as a function of water content. The erosion shear strength (τe) of a cohesive sediment bed is related to dry density and erosion of the bed can only occur if the constant fluid bed shear stress (τb) exceeds (τe).

2 – Description of the sediment

Field description of sediment is an important part of sediment identification and understanding the transportation processes. In terms of marine habitat mapping this may be achievable by examination of the exposure on the intertidal zone, or by diver in the subtidal zone or a variety of remotely sensed techniques, such as still photography, video transects or even backscatter or sidescan sonar. The physical morphology and juxtaposition of adjacent sediment types often gives a good indication of the provenance, transportation and depositional processes. As general rules, if it is possible, the sediment should be described in context of the **body** or **unit**, separating or subsampling various sediment layers within the sediment body. Additionally, the presence and extent of post depositional weathering must be described, often evidenced by columnar or crumb partings in silts and clays or by weakened state or concentric layering in coarser sediments or gravel. The colour of weathering should be noted. The position and thickness of any redox (blackened) layers should be measured. The following paragraphs detail measurements and techniques used to describe the sediment mass.

2.1 – Measurement of colour

The colour of soil is made up of an achromatic background of white, pure grey or black and a chromatic component. Colour is an important component as it often reflects mineralogy or the condition of the sediment and may reflect the source rock (lithochromatic).

Considering the human eye can distinguish over 10 million surface colours, description is subjective and therefore sediment colours are most conveniently measured by comparison with a colour chart, which allows allocation of a specific colour ID based on simple comparison of a sample against a colour chart. The Munsell system of colour notation is the most sophisticated and widely used of several methods of colour quantification. It employs three coordinates, hue, value, and chroma, which make up an approximately spherical colour solid and are combined to form a numerical notation for each colour. Hue is equivalent to the dominant wavelength of reflected light. The Munsell system comprises 100 hues, which are arranged into ten families, comprising five principle hues: red (R), yellow (Y), green (G) blue (B) and purple (P) and five intermediate hues: yellow-red (YR), green yellow (GY), blue-green (BG), purple-blue (PB) and red-purple (RP), with the principle hue denoted first. The hue family is then divided into 10 categories and classified according to the intensity of the principle hue, for example 10YR denotes full yellow and 0YR red dominating, with 5YR in the middle of the range. The letter N denotes achromatic hues.

Value is measured in terms of luminosity (or brightness ~ proportion of black and white) and is classified according to a notation between 0 (black) and 10 (white), with Value 5 representing grey, e.g. 10YR 5/.

Chroma represents the degree of saturation (strength intensity, proportion of pure colour and neutral grey) and is indicated as a notation between 0 and 20, e.g. 10YR 4/4.
It is also necessary to clearly describe stains. Stains can be caused by particle coatings of weathering residues (oxides, leaching, etc) and describe the nature of the stain – linear (streaks), uniform, patchy, etc. The depth of the stain or leaching must also be noted.

Method:
A sub sample should be decanted or extracted from the storage bag and placed under the holes in the Munsell soil colour charts. All protective films must be removed prior to viewing and the light conditions noted. All attempts must be made to classify samples in daylight. Should the sediment be mottled – classification should follow the visual estimations of Hodgson 1974. As discussed above, the colour value depends on the reflectance of the material, which varies inversely with particle size. To classify speckled sediment, a technique often used is to squint through eyelashes when carrying out the comparison.

It should be noted that moisture greatly affects colour and that the colour will change as the sample dries out. Chemical reactions such as oxidation can affect samples causing changes of colour.

2.2 Bedding and discontinuities

The scale of the bedding depends on a combination of transportation forces and sediment sources. The most frequently employed method (of determining scale of bedding) is based on physical measurement, and it is recommended that the BS 5930 (1981) classification be utilised. If layers cannot be measured, the sediment can be described as interbedded or interlaminated.

Discontinuities are present in semi consolidated, semi cemented or cohesive sediment types (e.g. clays) and are exemplified by bedding plane partings, joints, fissures or shear planes. It is important to note major shear planes, attitude, orientation and continuity. The spacing of discontinuities can also be measured and logged (Table 16–1).

Table 16–1. Scale of bedding and discontinuity spacing BS 5930 (1981).

Bedding	Discontinuities	Mean spacing (mm)
Very thickly bedded	Very widely spaced	>2,000
Thickly bedded	Widely spaced	2,000 to 600
Medium bedded	Medium spaced	600 to 200
Thinly bedded	Closely spaced	200 to 60
Very thinly bedded	Very closely spaced	60 to 20
Thickly laminated	Extremely closely spaced	20 to 6
Thinly laminated		<6

2.3 Grain texture

The most important component of sediment is probably the grain. The **shape** and **size**, with the compositional component is vital to the understanding of the sediment dynamics. With larger grain sizes **sphericity** and **roundness** is classically classified utilising callipers measuring the orthogonal long, intermediate and short axes.

Grain size

Grain size is probably the most important sediment property to qualify when analysing sediments. With the coarse to fine sands, size is defined by the measure of the group of particles rather than the individual sizes employed for larger sizes. A comprehensive discussion on the analysis of grain size is given in the section devoted to Granulometry of this review.

Shape

The shape of particles can be measured in terms of form, roundness and surface texture. Particle grains are unusually spherical in form and tend to represent triaxial ellipsoids and have a long orthogonal axis, D_a, a short D_c and intermediate D_b axis. The nominal diameter D_n, is the diameter of a sphere having the same volume and weight as the grain. For ellipsoidal particles $D_n = (D_a.D_b.D_c)^{1/3}$ and it is found that on average, $D_n \approx D_b$.

The **Corely shape factor**, S, is recommended as a measure for shape and is defined using the three axial diameters:

$$S = D_c/\sqrt{D_a D_b}$$

Roundness

Roundness, and its inverse, angularity, refer to the outline of a grain and is a measure of the sharpness or roundness of the corners of a sedimentary particle. Roundness is defined as the average radius of the corners and edges divided by the radius of the maximum inscribed circles (Figure 16–1). Roundness is determined by comparing the sand grains with a visual comparison chart and as a descriptive roundness.

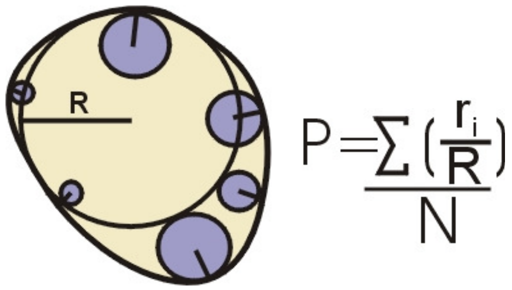

Figure 16–1. Roundness: the average radius of curvature of corners (ri) to that of the largest inscribing circle (R). (©Marine Institute reproduced with permission).

Form

Form refers to attributes involving the three dimensional morphology: *i.e.* the variations in proportion of the three axes that define the geometric shape and generally a visual estimate, rather than actual measurements are employed. Although various measures are used, the most popular is the Zing diagram (Figure 16–2), which requires a plot of the ratio of the axes (short: intermediate) *vs.* (intermediate to long). These four shape terms are most commonly used to describe pebble to boulder size particles.

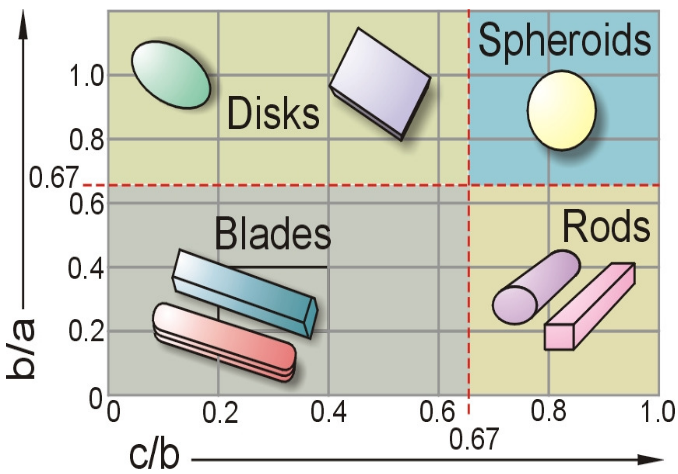

Figure 16–2. Zing diagram showing form (modified after Zing 1954 ©Marine Institute, reproduced with permission).

Sphericity

The parameter of form or shape can also be described in terms of sphericity and refers to the equal dimension measure of the ellipsoid and is defined as the cube root of the volume of the particle divided by the volume of the circumscribing sphere. Sphericity can be described as high or low, for example is the sediment particle elongated (one dimension longer than the other two), flattened or sheet-like (one dimension much smaller than the other two dimensions), or is it spherical (its three dimensions roughly the same length) (Figure 16–3). Sphericity should not be confused with roundness, which describes angularity.

2.4 – Sorting

The degree of sorting of sediment is important in the context of mixing and sediment transport. The most commonly used sorting classification was devised by Compton (1962) for sandstones, but works equally well on unconsolidated sediments. The classification divides the degree of sorting into 5 categories and is used by direct visual comparison (Figure 16–4).

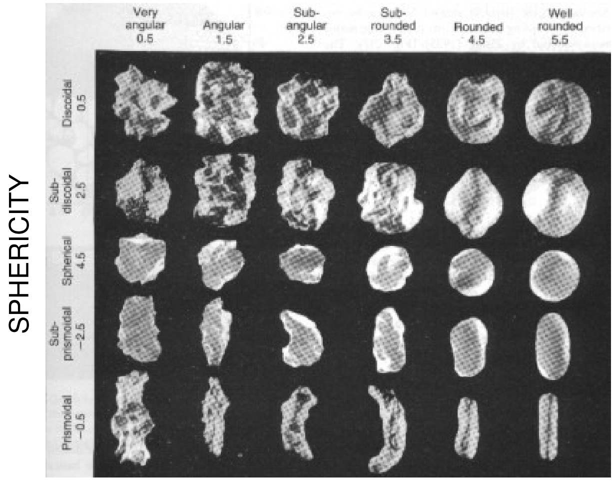

Figure 16–3. Descriptive roundness and sphericity chart for sand and gravel (Powers 1982).

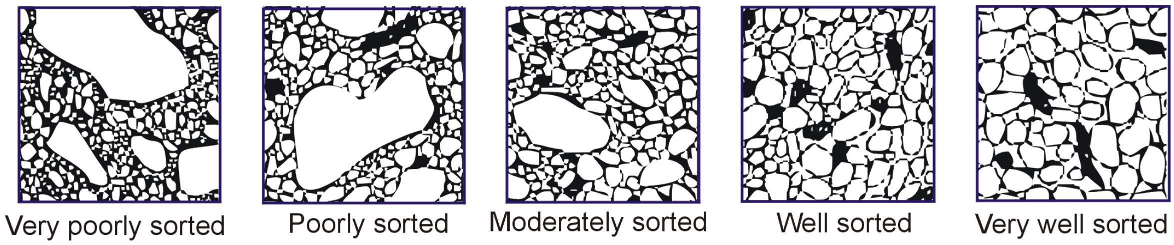

Figure 16–4. Degrees of sorting (after Compton 1962 ©Marine Institute, reproduced with permission). This visual assessment can be compared with sorting coefficient determined from the granulometry.

2.5 – Procedures for sample description

All representative sub samples, core samples will be conducted in accordance with standard sedimentological practices. It is important to note all observations – even if it appears trivial at the time – it may give more information later. Photograph or video each sample, making sure a scale bar is present with a number identifier. If in any doubt – do not discard sediment. Please note the following:

- Sediment colour (Munsell colour chart – use in daylight only).
- Size - classified according to the Friedman and Saunders 1978
- Grain size classification.
- Degree of sorting (use Compton 1962).
- Clean washed – poorly washed.
- Degree of roundness/sphericity (use Powers 1982).
- Fabric, microfabric.
- Gravel Shape (Zing 1935) and classification.
- The faunal content to be described and identified (or drawn with scales or a subsample retained).
- Shelly hash – size, roundness, colour (presence of organics), epibionts.
- Percentage minerals to shell, identify major minerals, i.e. % glauconite.
- Smell, gas bubbles.
- In grabs note any surface ripples (height and wavelength).
- In the descriptions, use the modified Shell/AAPG mnemonics and abbreviations (Table 16–2).

Table 16–2. AAPG Mnemonics.

BEDDING	
hom/homog	homogeneous
lam	laminated/laminae
mass	massive
mm-bd	millimetre bedding/lamination
cm-bd	centimetre bedding/lamination
dm-bd	decimetre bedding
m-bd	metre bedding

TEXTURE	
Grain Sorting	
(srt)	poorly sorted
srt	moderately sorted
srt	well sorted
Grain Sphericity	
(ang)	subangular
Ang	angular
(rnd)	sub-rounded
rnd	rounded
rnd	well-rounded
cly	cly
Classification	
vf/f	very fine sand
f	fine sand
m	medium sand
c/crs	coarse sand
vc/vcrs	very coarse sand
VfPl	very fine pebbles (4-2mm)
Fp	fine pebbles (8-4mm)
MPl	medium pebbles (16-8mm)
CPl	coarse pebbles (32-16mm)
VcP	very coarse P(64-32mm)
sC/sCbl	small cobbles (12.8-6.4cm)
lC/lCbl	large cobbles (25.6-12.8cm)

COLOUR	
blk	black
blu	blue
brn	brown
dk	dark
grn	green
gry	grey
lt	light
olv	olive
orng	orange
red	red
wht	white
yell	yellow

GENERAL DESCRIPTORS	
AA	As described Above
abd	abundant
arg	argillaceous
artic	articulated
auth	authigenic
bio/biocl	bioclastic
bkn	broken
calc	calcareous
cly	clayey
Carb	carbonaceous
Cmt	cemented
Co	cohesive
Coq	coquinoid
Comm	comminuted
Conc	concretionary
Disartic	Disarticulated
decr	decrease
g/s	grainsize
Fiss	fissile
Flk	flaky
frag/s	fragmented/fragments
Fri	friable
Foss	fossiliferous
Hd	hard
Hkly	hackly
Incr	increase
inf	infill/infilling
liq	liquid
mic	micaceous
nod	nodular
occ	ocCASIonal
org	organic
ph/phos	phosphatic
por	porous
s	sandy
sat	saturated
scatt	scattered
sh	shelly
si	siliceous
tr	trace
u/c	unconformity
hyphen	range
( )	slightly/poorly
underscor	very/well

ROCK TYPES	
Sedimentary / Sediments	
BIO	bioclastic
BIRDSEED	rnd srt crsS-vfPbl
CLY	clay
COQ	coquina
GRAV	gravel
DOL	dolomite
JASP	jasper
LST	limestone
MICROSPH	microsphorite (phos. mudstone)
MUD	mud
PH/PHOS	undifferentiated phosphorite/microsphorite
PP	phos pellets (rnd-rnd wht, brn and blk S)
S	sand
SST	sandstone
SHL	shale
SLT	silt
Metamorphic	
QZT	quartzite
PHY	phyllite
SCH	schist
GNS	gneiss

MINERALS	
AP	apatite
BIOT	biotite
CAR	carnelian
CHL	chlorite
EP	epidote
FS	feldspar
FE	fe oxides
GT	garnet
GLC	glauconite
HE	heamatite
IL	ilmenite
MT	magnetite
MUSC	muscovite
MI	mica (undifferentiated)
SP	sphene
PYR	pyrite
PX	pyroxene
QZ/vQZ	quartz/vein quartz
RU	rutile
zircon	
ZR/ZIR	

FOSSILS/ORGANICS			
BRA	brachiopods	GAS	gastropods
BAR	barnacles	LIG	lignite
BIV	bivalves	OST	ostracods
BRY	bryozoans	ROT	rotalids
COR	corals	SH	shell
ECH	echinoids	SS	sponge spicules
FP	faecal pellets	Sp	species
FB	fish bones	WD	wood
FOR	foraminiferids	WT	worm tubes

GEOTECHNICAL	
VS	Very soft
S	Soft
F	Firm
St	Stiff
V.St	Very stiff
H	Hard
Fb	friable

3 – Measurement techniques

The following paragraphs discuss measurement techniques for the bulk properties of sediment and their application.

3.1 – Dry, wet bulk density and moisture content measurements

Measurements of bulk density are best obtained by homogenising a sub-sample of the sediment and a known volume weighed. The sample is then dried at 105 °C for 24 hours and re weighed. The sample should be allowed to cool down before weighing. Ideally the cooling should be 24 hrs in a dessicator. Density measurements are given then as:

$$\text{Wet Bulk Density} = \frac{\text{Mass of Wet sediment}}{\text{Volume of Wet sediment}} \quad (g/cm^3) \text{ or } Mg/m^3 \qquad 3.1$$

$$\text{Dry Bulk Density } (\rho) = \frac{\text{Mass of Dry sediment}}{\text{Volume of Wet sediment}} \quad (g/cm^3) \qquad 3.2$$

The moisture content can be defined using the results obtained by measurements of density. This measurement is used as an index to express the degree of consolidation of the sediment. Generally, moisture content increases as bulk density decreases.

$$\text{Moisture Content} = \frac{\text{Mass of water in sediment}}{\text{Mass of dry sediment}} \quad (\%) \qquad 3.3$$

3.2 – Organic content

The organic content of sediment can be measured in two ways, by weight loss on ignition or ingestion. Dried samples are initial ground in a mortar and pestle and 2 g weighed into a pre-fired crucible and placed in a muffle furnace. The sediment is then combusted at 300 °C for three hours. The crucibles are then removed and cooled in a dessicator. Once cool, the samples are reweighed and the total organic percentage determined. A maximum temperature of 300 °C should be used so as not to ignite or desiccate and inorganic hydrous minerals, such as single layer clays. It is recommended that control samples are re-combusted after cooling to ensure weight loss is completed. British Standards (BS1377) indicates a temperature of 800 °C to breakdown and drive off all carbon, however for the reasons given above this is only suitable for sandy sediments with little or no clay or chalky material (Head, 1978).

Alternatively, particularly for fine sediments, the organic content can be measured by loss on ingestion. It is recommended that *c.* 10 g of sediment is washed in a bath of 10% hydrogen peroxide for at least 24 hours. The sample should then be thoroughly rinsed in distilled or fresh water and excess fluid pipetted off. The sample should then be dried in a 70 °C oven for 24 hours and the residue reweighed in order to determine the total organic percentage. It is again recommended that control samples are re-ingested to ensure all organic material has been removed. However, hydrogen peroxide has only a limited action on undecomposed plant remains such as roots and fibres (Head, 1978).

3.3 – Calcium carbonate content

The calcium carbonate or shelly fraction of estuarine and tidal sediments has proven to be an accurate indicator of residual transport paths of sediments. Shelly fractions can also be used to determine the age of mobile sediment and the different components used to determine provenance. Once dry sieving is completed, the fractions on each sieve are recombined into whole Φ units and subsampled by standard methods. The visible large shell fragments can be removed manually and the remains treated with a 10 % Hydrochloric acid solution for 24 hours in order to digest the shelly content. After the reaction has ceased, the sediments can be rinsed on a 63 µm sieve with freshwater and transferred to an oven for drying. Standard drying measures should be employed, 24 hours at 70 °C and the residue reweighed to establish the shelly content.

The total carbonate content of predominantly silty samples can be established by ignition. Sediments are washed and dried in an oven for 24 hours at 70 °C. Once dry, the samples are disaggregated with a mortar and pestle and 2 g weighed into pre-fired crucibles. The sediment is then transferred to a muffle furnace and combusted to 950 °C for three hours. Samples should be left to cool in the furnace for 24 hours and then reweighed to determine the weight of the ashed sediment. Again, this gives a measure of the carbonate content without igniting the clay or hydrous mineral components.

3.4 – Atterberg limits

Fine-grained soils are classified on the basis of plasticity and compressibility, which is a function of strength and settlement characteristics. The cohesion of sediment is controlled in part by moisture and salt content and composition. The Atterberg Limits provide a laboratory measurement of cohesion and include measurement of the Plastic Limit and Liquid Limit. Subtracting the plastic limit from the liquid limit yields the plasticity index (Table 16–3).

The plastic limit (PL) is defined as point at which the moisture content has reached a point where the sediment changes from a semi-solid to a plastic like consistency (shear strength ~170 kPa). As moisture content increases, the material remains plastic until it passes the Liquid Limit (LL) where the consistency changes to semi liquid (shear strength ~1.7 kPa). The upper and lower limits of the plastic range (that is, the liquid and plastic limits) are called the Atterberg limits. A large liquid limit indicates high compressibility and high shrink swell tendencies and a large plasticity index indicates low shear strength.

Method

A subsample of sediment is reserved for Atterberg limit measurements – usually 300 g is sufficient. The sediment must not be allowed to dry before the tests commenced. The sediment must then be screened through a 425 mm sieve, <452 mm portion used for this test.

The **plastic limit** is measured by rolling the moistened sediment into 3 mm diameter worms. The worm is then remolded and rolled out again to the same diameter. Each time the sediment is rolled out it will lose some moisture. The plastic limit occurs when the soil can no longer be rolled out into a 3mm worm without the soil crumbling. At this point the water content is determined and recorded as the plastic limit.

1) Using the palm of your hand, roll a small specimen of the sediment on the glass plate to form a thread 3mm approximately 80-90 strokes (forward and back = 1 stroke) is a good rate.
2) Attempt to roll the sediment to 3 mm diameter. If the thread breaks larger than 3 mm, add a small amount of water, mix thoroughly and try again. If the thread breaks smaller than 3 mm, remove some water by kneading in your hands and try again.
3) Roll the soil to 3 mm. diameter if it does not break, knead it in your hands and try again. If it falls apart, delaminates as a tube, or forms small barrels, move to the next step.
4) Place the entire thread in a moisture content can and close the cover.

Repeat steps 2 and 3 for two more trials. Add ALL the threads to the same moisture content can. Determine the moisture content (3.1)

The **liquid limit** test also begins with damped sediment. The sediment is smeared onto a small brass bowl (Casagrande), and then a standard grooving tool is used to create a 2 mm wide groove down the centre of the soil smear. The bowl is then raised 10 mm and dropped at a rate to two drops per second. The number of blows required to close 13 mm of the groove's length is recorded, along with the moisture content of the soil. The remaining soil is then allowed to dry somewhat and then the above process is repeated two more times, providing two more pairs of moisture content and blows required to close 13 mm of the groove. By linear interpolation between these three pairs of data the liquid limit is defined as the water content corresponding to 25 blows.

Table 16–3. Atterberg limits.

Plastic Limit	Liquid limits
	Number of drops
Container (g)	Container (g)
Container and wet sample (g)	Container and wet sample (g)(g)(g)
Container and dry sample (g)	Container and dry sample (g)
Dry sample (g)	Dry sample (g)
Water content %	Water content %
PL	LL
Plasticity Index	= LL - PL

3.5 – Measurement of Unconfined Compressive strength

Pocket penetrometer
The pocket penetrometer is lightweight and a commonly used instrument for measuring the unconfined compressive strength of fine grained cohesive sediments. In use the penetrometer is slowly into the sediment until the penetration mark of the plunger reaches the level of the soil surface. The action of pushing the penetrometer into the sediment compresses an internal spring and a pointer, which moves along the scale, indicates the maximum amount of compression. The scale is calibrated to read unconfined compressive strength directly. Note that often the units are given in kgf/cm^2 and have to be divided by 10 (or 9.81) to give the result in MPa. 1 kg force (kgf) = 9.81, where 1 kgf is produced when a mass of 1 kg is acted upon by acceleration due to gravity of 9.81 m/s^2. Generally, pocket penetrometers measure unconfined compressive strengths between 0.05 to 0.45 MPa.

Several tips may be included with the system *e.g.* Pocket Geotester, which has tips of 1/4”, 10 mm, 15 mm, 20 mm and 25 mm with the inner and outer dial showing calibrations for the metric and inch tips in both kg/sq.cm or Tsf. It is recommended that when testing sandy sediments, which have internal friction, but little cohesion, that 20 or 25 mm tips are used. Research has shown that in sands, force readings indicate friction angles. It is also recommended that smaller, 10 and 15mm tips are used for clayey soils that have cohesion, but little angle of internal friction and the force can be equated with cohesion values.

The penetrometer must not be used in sediments containing gravel or ocCASIonal pebbles. Care must be taken to measure undisturbed surfaces.

Shear vane (TVST)
The TVST is recommended for the rapid determination of shear strength of cohesive soils either in the field or the laboratory. It permits the determination of a large number of strength values with different orientation of failure planes. It is simple to use with sample trimming eliminated. All that is needed is a reasonably flat surface 25 mm in diameter. (The head for the softest sediments is nearer 50 mm diameter, and it is advisable to have a surface capable of taking two test so that an average value can be calculated).

The shear strength of cohesive soil is dependent upon many factors including rate of loading, progressive failure, orientation of the failure plane and pore water migration during testing. The vane shear tester does not eliminate the effects of any of these variables. However, it does give repeatable values in homogeneous clay and extensive laboratory testing indicates excellent agreement between the unconfined compression test and the shear tester. The smallest division on the dial is 0.05 kg/cm^2, (5kPa) permitting visual interpretation to the nearest 0.01 kg/cm^2 (1 kPA). Three vanes are usually provided. They have ranges of 1.0, 0.2, and 2.5 kg/cm^2

In use the vane is inserted into the sediment and the torsion head slowly rotated until failure occurs. The maximum shear strength is then read from the index pointer on the dial of the instrument head. In many versions of the vane, the value must be multiplied by 2 to obtain the unconfined compressive strength.

The Vane Shear Tester and Pocket Penetrometer indicate respectively shear strength under nil load and unconfined compression strength. Taking these two results in a Mohr diagram, the shear test shows an axes-origin-centred circle whose radius is equal to the measured value. The penetrometer test circle passes through the axes origin with its diameter corresponding to the measured value. The tangential line common to the two circles is the critical straight line representing the Coulomb statement for the tested soil.

The simultaneous use of the shear tester and penetrometer allows rapid evaluation of the degree of the internal friction of soil in shear strength, or to determine if the soil is essentially cohesive (Figure 16–5).

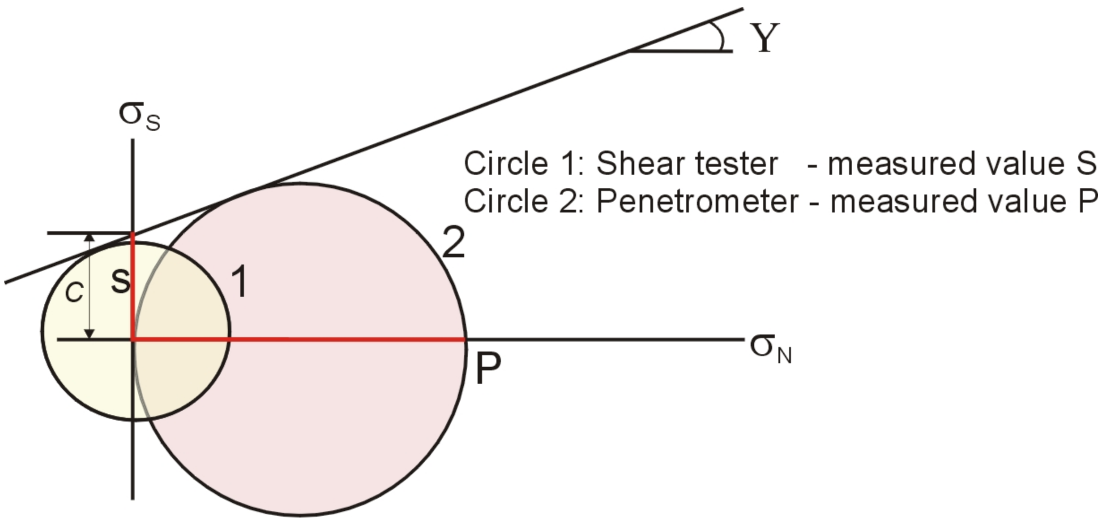

Figure 16–5. Measurements of shear strength comparisons with a penetrometer or shear tester (©Marine Institute, reproduced with permission).

Classification of Unconfined Compressive Strength

Although a number of field tests for strength exist. It is recommended that, in absence of a penetrometer or shear vane, the Australian Mineral Foundation test (1973) is employed (Table 16–4). The test is entirely tactile in operation and, although very simple, gives easily comparable results.

Table 16–4. Australian Mineral Foundation test.

Term	Abbreviation	Unconfined Compressive Strength (Qu) kPa	Tactile test	Standard Penetration Test (blows per 300 mm (N))
Very Soft	VS	<25	Easily penetrated 5cm by fist	2
Soft	S	25-50	Easily penetrated 5cm by thumb	2 to 4
Firm	F	50-100	Can be penetrated 5cm by thumb with moderate effort	4 to 8
Stiff	St	100-200	Readily indented by thumb but penetrated only with great effort	8 to 15
Very Stiff	V.St.	200-400	Readily indented by thumb nail	15 to 30
Hard	H	>400	Indented with difficulty by thumb nail	30 and over
Friable	Fb		Crumbles or powders when scraped by thumb nail	

3.6 – Critical Bed Shear Stress

The critical bed shear stress (τ_{ce}) for erosion of the bed composed of predominantly silt can be estimated from the dry density (ρ) of the sampled sediment, as a guide for the strength and compaction of the sediment, where:

$$\tau_{ce}=0.0012\ (\rho^{1.2})\ \text{N/m}^2$$

3.7 – Permeability

Permeability in the field is measured by a **permeameter**. This can be either a constant head or falling head type (define difference). The coefficient of permeability, k, is then calculated using the equation:

$$k = \eta q l / A(P_1 - P_o)$$

where, η is the viscosity of the fluid, *q* is the volume of fluid passing through the specimen in 1 second, *l* is the length of the test specimen, *A* is the cross-sectional areas of the specimen perpendicular to the flow, P_1 is the absolute pressure at the point of entrance to the specimen (*i.e.* atmospheric pressure) and P_o is the absolute pressure at the point of exit from the specimen (normally atmospheric pressure).

Useful measurements

1 N = 1 kg x 9.81 or 1 kg force
1 kN/m^2 = 1 kPa
1 N/m^2 = 1 Pa
1 kgf = 9.81 N
1 kgf/cm^2 = approx. 100 kPa (rounded) or 98,066.50 Pa
1 kgf/m^2 = 9.81 Pa *i.e.* 1 N/m^2
1 TSF[2] = 1 kg/cm^2

[2] Ton per square foot

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ISO/TS 17892-3:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 3: Determination of particle density -- Pycnometer method.

ISO/TS 17892-4:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 4: Determination of particle size distribution

ISO/TS 17892-5:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 5: Incremental loading oedometer test.

ISO/TS 17892-7:2004 Geotechnical investigation and testing -- Laboratory testing of soil -Part 7: Unconfined compression test on fine-grained soils.

ISO/TS 17892-6:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 6: Fall cone test.

ISO/TS 17892-8:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 8: Unconsolidated undrained triaxial test.

ISO/TS 17892-9:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 9: Consolidated triaxial compression tests on water-saturated soils.

ISO/TS 17892-10:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 10: Direct shear tests.

ISO/TS 17892-11:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 11: Determination of permeability by constant and falling head.

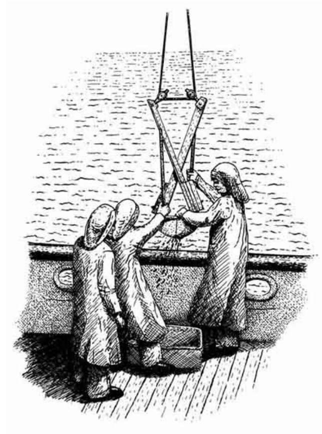
ISO/TS 17892-12:2004 Geotechnical investigation and testing -- Laboratory testing of soil -- Part 12: Determination of Atterberg limits.

ASTM D4318-05 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils

ASTM D2216-05 Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.

17 Grab Sampling

Andrew S. Y. Mackie (NMW), Roger Coggan (Cefas) and Sytze van-Heteren (TNO)



The benthic macroinfaunal invertebrates are considered a useful group to study in species assemblage mapping and environmental monitoring studies. This is because the majority of species are essentially sedentary and their natural distributions usually show good relationships with their sedimentary habitat and depth. Their responses to environmental change can easily be measured. They are an integral part of marine food webs and can be an important source of food for certain commercially exploited fish and invertebrates. More practically, the taxonomic literature on the worms, crustaceans, molluscs and echinoderms that are the main components of the macrofauna is generally good. Finally, the 'soft-bottom' benthos can be readily sampled by grabs, dredges and trawls.

This review considers the use of grabs in quantitative assessments of seabed habitats, and concentrates on four types, namely the van Veen, Smith-McIntyre, Day and Hamon grabs. (Qualitative sampling by dredges and trawls is dealt with in a sister review, Vize and Coggan 2006).

1 – General Principles of Operation and Sample Processing

Grabs are used to obtain quantitative samples of infaunal invertebrates and the substrates in which they live. If sufficient samples are taken, statistical variability among species, abundance and biomass can be investigated, providing a powerful means to compare samples from different places and different times. Grabs should be capable of repeatedly taking samples of a constant standard area – nowadays commonly 0.1 m^2, though smaller (0.05 m^2) and larger (0.2 m^2) devices can be used. They should adequately sample the infauna contained below the area covered.

An ideal sampler would routinely collected undisturbed sediment to a depth of 20 cm or more to capture all the infauna, including the larger, deep-dwelling, animals. The nearest device available is a large spade corer, such as the Reineck box corer (Reineck 1958, 1963; Farris and Crezee 1976) that can sample sediment to about 45 cm. However, such corers are large, heavy and require relatively large vessels to deploy them. Smaller sampling devices are therefore something of a compromise.

Most of the smaller and most abundant infaunal species are present in the upper layers (5-10 cm) of the sediment. For this reason, a minimum volume of 5 litres sediment collected (equivalent to a sampling depth of 5 cm for a Van Veen grab) is regularly cited in sampling procedures (Kingston 1988, Riddle 1989b, Rumohr 1999).

2 – Requirements for a Quantitative Benthic Sampler

Mackie (1981) summarised the basic requirements for a quantitative benthic sampler. The sampler should have:

- A minimum of working parts and be corrosion resistant.
- Be sturdy enough to withstand repeated deck handling and bottom impact.
- A bulk or weight that allows safe operation.
- The correct orientation on the seabed for sample collection.
- A trigger release mechanism to ensure actuation on the seabed at the proper time.
- A constant sample area.
- Adequate penetration of the sediment to capture the animals present.
- A low resistance to water on descent to minimise pressure-wave effects on surface-layer animals.
- Easy retrieval with no loss of sample.
- Easy removal of sample and quick redeployment capability.

3 – Overview of Current Grab Operation

The Smith-McIntyre, Day and Hamon grabs are all set in pyramidal frames (Figure 17–1). These give the grabs increased stability on the seabed, ensure correct orientation of the grab buckets, permit easy addition of supplementary weights and aid safe manual handling on deck. The 'standard' Van Veen grab lacks a frame and is more prone to incorrect orientation or toppling. A new modified grab (Mackie in prep, Mackie and Darbyshire 2001) has L-shaped bars attached to each bucket and its arm, effectively creating a frame. This L-frame Van Veen (Figure 17–2) is stable on the seabed and safer to manhandle and empty on retrieval.

Figure 17–1. Hamon grab (University of Wales, Bangor).

There are great similarities in the deployment of all the grabs currently in use. Each is lowered (0.5-2.0 $m.s^{-1}$) vertically by wire via a winch and A-frame, jib or crane over the stern or side of the vessel. Although the grab is often lowered at constant speed, it may be allowed to free-fall for the last 5 m or so, to aid initial penetration (van Veen grab), or conversely, lowered more slowly to reduce the 'bow-wave' effect (Smith-McIntyre, Day and Hamon grabs). A release mechanism is activated when the grab reaches the seabed and a sample is taken as the wire is hauled in. It is essential that the wire remains as vertical as possible on deployment and retrieval, otherwise the grab may by pulled to one side ('grab-drift') and only a partial (or no) sample may be collected (Kingston 1988, Riddle 1984).

Figure 17–2. L-frame Van Veen grab, set ready for deployment (NMW).

The 'bow-wave' effect displaces the often light or flocculent surface layer of many sediments, which can reduce the catch efficiency for small surface invertebrates – particularly microcrustaceans or surface-dwelling polychaetes (Smith and McIntyre 1954, Word 1976, Andersin and Sandler 1981). The incorporation of mesh screens in the top surface of the grab buckets (Fig. 3) can reduce this effect, allowing water to flow through the buckets during descent. The amount of mesh on the tops of grabs varies from 0-83% (e.g., Wigley 1967; Andersin and Sandler 1981). Rumohr (1990, 1999) recommended a minimum of 60%. Often, the mesh is itself covered by moveable flaps that act as one-way valves, allowing a through-flow of water on descent, but not on retrieval (Figure 17–3). Many grab designs also include sealable doors in to top of the grab buckets to allow inspection or sub-sampling of the undisturbed sample before the grab is emptied. Orton (1925) recognised that on final closure, the grab buckets can squeeze out lateral jets of water. This can be reduced by the use of mesh screens, or prevented by side guards (a feature of the Ponar grab; Powers and Robertson 1967), but these have rarely been used in marine surveys (Birkett 1958).

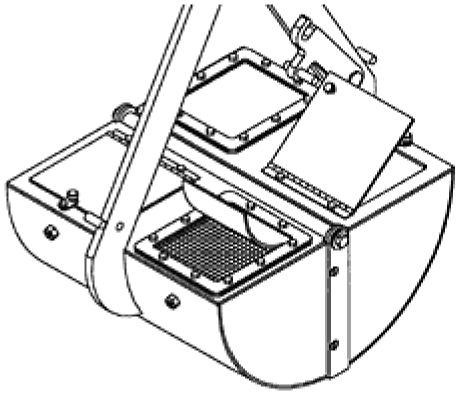


Figure 17–3. Mesh screens with valve-flaps, and inspection doors on the upper surface of a Van Veen grab.

All the grabs under consideration have the facility to add or remove weights to aid or limit penetrations according to the type of sediment being sampled. On soft muddy sediments an excessively heavy grab will sink too far in and may not collect a representative sample. Conversely, on hard packed fine sand or coarse gravelly sediments, extra weight is required to keep the apparatus firmly in contact with the seabed. This weight acts against the initial gentle upward pull of the warp that causes the grab to close. Insufficient weight can lead to 'warp-heave', a slight raising of the grab above the seabed while it closes, reducing digging performance and sample size. Care is needed to add supplementary weights in a balanced way to minimise the risk of toppling the device.

All designs are subject to certain factors that affect their performance. Riddle (1984) carried out extensive experiments into all aspects of grab efficiency, in laboratory and field situations. Kingston (1988) recognised five disadvantages associated with grabs activated or closed by the wire (warp). In addition to the warp heave, drift, initial penetration and the bow-wave effects mentioned above, the vertical movement of the ship in a swell can cause the grab to lose contact with the seabed ('grab-bounce').

All grabs have some form of trigger-release mechanism to hold the jaw(s) open as the grab descends. The trigger is normally activated on contact with the seabed. Where the mechanism relies on tension to be kept in the warp (Van Veen, and Hamon grabs), over-rapid deployment can cause the warp to become slack, allowing the trigger to fire during descent. Where the mechanism relies on mechanical friction and is physically triggered by contact with the seabed (Day and Smith-McIntyre grabs) 'grab-bounce' may cause the trigger to fire early, or it may not fire at all if the sediment is soft or there is insufficient weight on the grab to overcome the friction. Weather conditions have a marked influence on triggering success, with failure rates increasing dramatically when sea conditions are greater than Beaufort force 5-6 (Riddle 1984, Kingston 1988, Kingston and Riddle 1989). Obviously, any large stones or shells that obstruct the closure of the jaws will cause the grab to fail. Even small obstructions can prevent full closure and lead to the sample being fully or partly washed out of the bucket as the grab is retrieved through the water column.

In general, the 'lighter' Van Veen, Smith-McIntyre and Day grabs can be used from smaller vessels. A minimum vessel length of 10-12 m is usually sufficient to ensure enough deck space for operations and sample processing. The Hamon grab usually requires a larger vessel, on account of its greater weight (300-600 kg) and size.

The size and number of samples taken depends largely upon the aims of the study (Green 1979; Riddle 1989a). Spatial and temporal replication must be carefully considered (Green 1979; Van der Meer 1997; Armonies 2000; Underwood and Chapman 2005). For a general grab sampling survey designed to map the invertebrate assemblages of an area of seabed, a single 0.1m^2 sample per station may be adequate (Cuff and Coleman 1979; but see also Green 1980, Cuff 1980). In other broad-scale studies (e.g., Mackie *et al.,* 1995), at least two replicates have been taken to 'even' out the influence of any anomalous samples.

In order to investigate animal-sediment relationships, samples of the sediment must be taken for particle size analysis (i.e. PSA / granulometry – see review by S. Passchier, this volume). Some studies collect sediment samples (approx 250 – 500 ml) from each grab used for faunal analysis. While this ensures that the sediment and faunal analyses relate to the same sample, this procedure can attract criticism from those who consider that it renders the sample semi-quantitative. Other studies take a specific replicate at each sampling station, for the sole purpose of granulometric analysis. However, this can attract the criticism that at heterogeneous stations, the sample used for PSA may differ significantly in its granulometry from the sample(s) taken for faunal analysis, leading to erroneous conclusions regarding the nature of animal-sediment relationships.

3.1 – Georeferencing and General Information

The increasing accuracy and precision of positioning technology (dGPS), coupled with the fine detail now obtainable from remote sensing techniques such as multibeam sonar, has led to more rigorous recording of individual grab positions (see Rees *et al.,* 1994). The grab is typically deployed from a location on the vessel that is some distance from the dGPS antenna, and this is often accounted for on larger vessels by recording/measuring the positional 'offset'. Sometimes this fixed offset can be applied within the position recording software to automatically correct for the positional error. Occasionally, an acoustic tracking device is attached to the grab to record the exact sampling position, but this is not yet common practice

The cruise plan and sampling logging system are usually agreed between the skipper and the scientist-in-charge before sampling begins. A test deployment of the grab is often made to ensure the gear and all recording systems are working properly. Metadata is recorded for each of the grabs to be used (e.g., type, design, modifications, weights etc) and for each sample taken. Sea-state and weather conditions are also commonly recorded.

For sample acquisitions, common meta-data collected includes: date, time of deployment and retrieval of grab (alternatively time when the grabs hits the seabed), latitude, longitude, depth of water, depth of sample (e.g. in Day grab), sample volume (e.g. in for Hamon grab), visual sample status (valid/invalid sample) and visual sample assessment (e.g. the type, colour and smell of the sediment, the presence of shells, obvious faunal species and anthropogenic debris/litter). For sample processing, the meta-data commonly records the purpose of the sample (i.e. for faunal or sediment analysis) and the size of the mesh through which the sample is sieved (1mm, 0.5mm).

Each processed sample is labelled with sufficient information to record its unique identity. For example, MH0307/23B could mean “Milford Haven, July 2003 survey, Station 23, sample B”. Sample label writing can be minimised by pre-printing the standard survey information on waterproof labels, leaving only the station number and replicate to be added. When samples are separated into different sieved fractions (2 mm, 1mm, 0.5 mm), this is also recorded on the sample label (e.g. “2 mm, 4/5” could mean “2 mm sieve fraction, container 4 of a total of 5). Any fauna removed from the sample for individual fixation/preservation (e.g. scale-worms which are easily damaged) are similarly labelled.

3.2 – Sample Processing

Sample processing is usually a 2-phase process. On the vessel, samples are sieved to remove the finer sediment, thus reducing the volume of material that has to be preserved and taken ashore. In the shore laboratory, the fauna are separated from the remaining sediment, identified, enumerated and weighed.

For practical purposes the fauna of marine sediments are subdivided into three broad size-classes: meiofauna, macrofauna and megafauna. The separation of these groups is not well-defined and the size-distributions of the categories overlap. The meiofauna are generally considered to include animals passing through a 0.5 mm mesh sieve. Depending upon the meiofaunal taxon under investigation sieve meshes down to 30-40 µm may be used (McIntyre, 1969, McIntyre and Warwick, 1984). The macrofauna are usually considered to include those taxa retained on a 0.5 mm sieve, though in some situations larger or smaller meshes may be deemed necessary (e.g. see Bachelet, 1990). The megafaunal are very large animals that can be picked by hand. For studies of the shelf benthos, the standard sieve used has a minimum mesh size of 0.5 or 1.0 mm diameter. The latter is used largely for practical cost- and time-related reasons (Kingston and Riddle, 1989) as benthic macrofaunal processing can be very labour-intensive activity. Sieves with larger pore sizes (e.g. 2 mm, 5 mm) may be used above the standard sieve in order to separate mixed grade sediments into different size fractions, for more manageable processing on ship and in the laboratory.

As grabs are retrieved on board, they are landed onto some kind of supporting frame where the collecting bucket or buckets can safely be opened (Figure 17–4). On most samplers, the success of the grab can be assessed by viewing the collected material through the inspection doors in the top surface of the grab (Figure 17–3). Samples are rejected if they do not meet certain pre-determined criteria, for example if the grab has leaked, if the surface of the sample is unduly disturbed, or if the volume is less than an acceptable minimum (commonly set a 5 litres, see Rumohr, 1999, Southern California Bight Field Methods Committee, 2002: Figure 3).

Once on deck, the sample is usually washed over sieves to remove the finer material. A variety of sieve rigs are available, from large-scale washing baths (Eleftheriou and Moore, 2005; Figure 5.21) or tables (Rumohr, 1999: Figure 3), large trays (Figure 17–4), small hoppers (Eleftheriou and Moore, 2005: Figure. 5.19), sample tub–cradle–chute systems (Proctor *et al.*, 2003: slide 42) to automated sieving devices like the Wilson Auto-Siever (http://www.tresanton.co.uk/wilson.shtml). A large metal ‘elutriator’ fitted with many spray nozzles (Figure 17–5) may be used as an alternative to the standard sieving methods, but these devices are not common.

Whichever apparatus is used, copious amounts of sea-water and an abundance of large diameter sieves (e.g. 45 cm) are necessary for efficient elutriation. The crucial point of the sieving exercise is to extract the delicate invertebrate animals from the sediment in the best possible condition, as intact, well-preserved, animals are much easier to identify in the laboratory. Sample washing must therefore be a gentle rather than aggressive process.

Figure 17–4. Washing and sieving grab samples.

Figure 17–5. Elutriation machine (University of Wales Bangor/Ivor Rees).

Once sieved, the different sample fractions are fixed using 8-12% formaldehyde (equivalent to 20-30% formalin) in seawater. This is two to three times the commonly recommended strength of formalin, but is necessary for adequate fixing of large volumes of sediment, which may also contain cryptic or tube-dwelling species. The addition of a stain (usually Rose Bengal) to dye the fauna greatly aids the final processing. If the samples are to remain in formalin for some time, a buffer is usually added (hexamethylene tetramine or borax) to protect the shells of small bivalves while the samples await laboratory sorting (Rumohr, 1999). In the laboratory, samples are thoroughly washed in freshwater to remove the formalin, and the animals picked from the remaining sediment and preserved in 80% alcohol (with 2% propylene glycol added to reduce dehydration of the tissue).

4 – Variety of Systems Available

A number of useful reviews of grab samplers have been published (Thorson, 1957; Holme, 1964, 1971; Hopkins 1964; Eleftheriou and Holme 1984; Kingston 1988, 2001, Rumohr, 1999; Eleftheriou and Moore, 2005). Good bibliographies are provided by Eleftheriou and Holme (1984), Elliott *et al.* (1993) and Eleftheriou and Moore, (2005). The following descriptions outline the construction and use of the four types of grab considered in this review.

4.1 – Van Veen Grab (van Veen 1933, 1936)

See Figure 17–2 and Figure 17–3 (above), Eleftheriou and Moore 2005: Figure 5.11; Rumohr, 1999: Figure 1.

The Van Veen grab comprises two quarter-circle buckets joined at a central pivot (Figure 17–3), each bucket having an overlapping arm. The arms may be long (Fig. 2) or short and are used to close the grab in a scissor-like movement. The arms are moved by chain or wire attached directly to their ends, or by a continuous warp threaded through pulleys on then end of each arm (as in Figure 17–2). The grab is used worldwide and particularly in Europe and North America.

Typically, the Van Veen grab lacks a frame, though The National Museum of Wales have successfully operated several L-framed versions since 1997 (Mackie, in prep.; Figure. 2). The frame is attached to each arm, allowing easier handling and helping to prevent the grab from toppling onto its side when it lands on the seabed. This L-frame grab has about 30 % mesh area on the upper side of the buckets and also benefits from a bucket shaped for more efficient digging (Mackie, 1981: Riddle, 1984, 1989b). In the USA and Canada a variant (referred to variously as the Young Van Veen, Young grab, Ted Young grab) has relatively short arms and is set in the circular base of a ‘pyramidal’ frame. There are also variants with two grabs, side by side, in the same frame. The term ‘modified Van Veen’ used in various methods manuals and protocols (see below) does not refer to a single grab type. These publications however, usually contain a drawing, photograph or reference that can permit identification of the design

The Van Veen grab is relatively light, weighing 45-50 kg for a 0.1 m^2 version, though lighter and smaller (e.g. 0.05 m^2) models are sometimes used on very soft substrata. The grabs can be weighted by adding lead to the arms, usually immediately above the buckets, though weights in excess of 100 kg tend to make the grabs top-heavy and more prone to toppling. Mackie (in prep.) found that when the grab was used on compacted mud, a small amount of weight was required on each arm to ensure proper firing of the trigger-release mechanism.

The long-arm, continuous-warp version has the best digging efficiency compared to chain-rigged Van Veens, Day grabs and Smith-McIntyre grabs (Riddle, 1984, 1989b) tested on fine-medium sand. A 59 kg grab collected about 11 litres in tank tests. This is slightly more than the volume collected by heavier L-frame grabs in the field. Grabs of about 90-95 kg work reasonably well on harder bottoms and very well on most sands and all muddy sediments.

The bucket shape of most Van Veen grabs means that the grab cannot fit in the hole it digs. On harder substrates, this causes the grab to lift slightly on closing and decreases the volume of sediment collected. The modified shape of the buckets in the L-frame Van Veen, and the novel Kingston Hydrostatic grab (Kingston 1988), removes this problem. The former has an initial penetration capability of 6.5cm, a maximum bite depth of 17 cm and can collect up to ~13 litres of material.

4.2 – Smith-McIntyre grab (Smith and McIntyre 1954)

See Eleftheriou and Holme, 1984: Figure 6.15; Eleftheriou and Moore, 2005; Figure 5.12.

The Smith-McIntyre grab (Figure 17–6) comprises two quarter-circle buckets mounted within a pyramidal frame (Fig. 6), giving greater stability to the grab compared to the Van Veen design. The buckets are connected to a central spring mechanism, which is compressed prior to deployment and released when two pressure plates hit the seabed, causing the buckets to be thrust into the sediment. On retrieval, warps attached to lever arms on each bucket cause them to close together, capturing a sample. The grab is popular worldwide but, due to the dangers presented with cocking the spring mechanism, the simpler Day grab is often preferred.

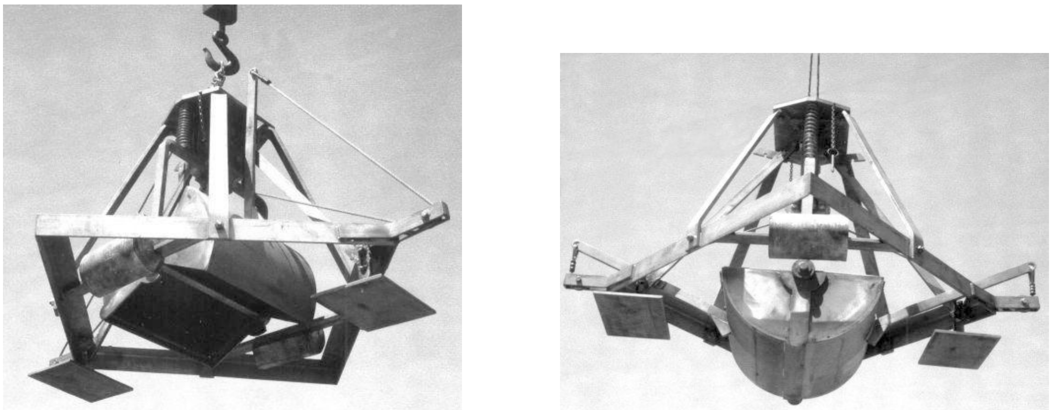


Figure 17–6. Smith-McIntyre grab, ready for deployment (left) and on retrieval (right) © 2003 Kahl Scientific Instrument Corp., All Rights Reserved).

The Smith-McIntyre grab weighs 65-70 kg for a 0.1 m^2 version. Typically, additional weights up to ~90 kg are added during normal operation The triggering of the spring mechanism may induce an upward movement of the frame on harder ground, reducing sampling efficiency, but this can be countered by using extra weight. Bite profiles are semicircular and the 0.1 m^2 version retains about 6 litres of sediment, (Riddle, 1984, 1989b).

4.3 – Day grab (Day 1978)

See Eleftheriou and Holme 1984: Figure 6.16; Brown *et al.*, 2002: Figures 7 and 8; Eleftheriou and Moore 2005; Figure 5.13.

The Day grab (Figure 17–7) comprises two quarter-circle buckets mounted in a pyramidal frame having an 80-90 cm square base (0.1m^2 version). Each bucket has a short stub-arm (centre of Figure 7) from which warps lead through the top of the fame, via pulleys on the base of the frame. The stub-arms also have a U-shaped lug on their inner surface, in which a trigger bar sits to hold the buckets open. At each end of the trigger bar, a downward extension ends in a horizontal plate that hangs a few centimetres below the base of the frame and cause the trigger bar to be lifted out of the U-shaped lugs when the grab is lowered to the seabed. Hauling on the warp then causes the buckets to close and collect a sample.

Figure 17–7. Day grab prepared for deployment. Photo: Cefas.

Eagle *et al.* (1979) modified the flaps on the upper surface of the buckets, changing the position of their hinges from the central axis to the outer upper edges of the grab. When the grab is retrieved, these flaps can be opened, allowing access to measure the depth of material retained and to take sub-samples, if required. Sturdy metal flaps are common, as simple rubber flaps can result in sample loss if the grab sinks too deeply into muddy sediments.

A typical 0.1 m^2 Day grab weighs about 60-70 kg. As with other grabs, weights can be added to the frame as required. Commonly, in excess of 100 kg is used in normal operation, though Proudfoot *et al.* (2003) give 200 kg as the maximum weight. Insufficient weight can lead to the frame being pushed upwards as the buckets are drawn into the sediment, reducing the effective bite depth. Riddle (1984, 1989b) found bite profiles to be semicircular and about 7.4 l was collected on the test sediment. Brown *et al.* (2002) reported a maximum bite depth of 14 cm.

The sturdy design, simple mechanism and ability to access the undisturbed surface of the sample make the Day grab a popular device for sampling marine benthos. It does not however, work well on hard, coarse, substrata.

4.4 – Hamon grab (Oele 1978)

See Eleftheriou and Holme 1984: Figure 6.17; Brown *et al.*, 2002: Figures 4 and 6; Eleftheriou and Moore, 2005; Figure 5.14.

Unlike the other grabs considered here, the Hamon grab has a single large scoop-like bucket. This is fixed to the end of a long arm and mounted in a large pyramidal frame with a square/rectangular base (Figure 17–8 and Figure 17–9). The pivot point lies a little way along the arm and not at the top of the bucket, as with the preceding grabs. A hook-like trigger nearer the free end of the arm engages with the frame base and holds the grab open under tension from the warp. On arrival at the seabed, the tension is released, and the hook disengages. On hauling, the warp runs through two pulleys, causing the lifting arm to rotate through 90°, driving the sampling bucket (scoop) through the sediment and closing it against a rubber-covered stop plate.

Figure 17–8. Hamon grab being deployed Photo: Craig Brown/Cefas.

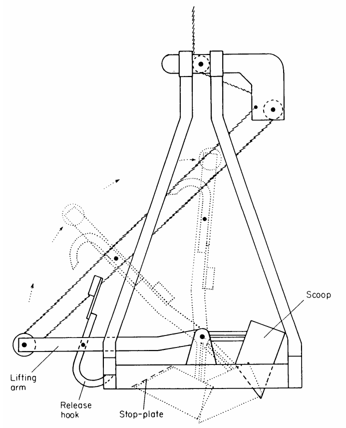


Figure 17–9. Hamon grab schematic Plate taken from Eleftheriou and Holme (1984).

The grab was originally designed for collecting material from hard, coarse substrata off the Dutch coast. The original design was very large and took samples covering an area up to about 0.29 m^2. Subsequent use and modification have led to the production of the more manageable 0.1 m^2 version, which is the officially recommended sampler for UK studies in areas of aggregate extraction (Brown *et al.*, 2002). The adoption of the grab in the UK in the early 1990s (e.g. Kenny and Rees 1996) led to a number of design modifications by Cefas (Kenny, pers. comm., Limpenny, pers. comm.). Apart from the introduction and testing of the smaller model, adjustments concerning the weighting of the grab and the use of a longer toothed bar on the underside, have led to a grab with better sample reproducibility and efficiency. The grab works very well on most coarse grounds, although cobbles are understandably difficult to sample (Marine Ecological Surveys, per.s comm.; pers. obs.).

The 0.1 m^2 Hamon grab weighs about 300 kg and the addition of weight to the frame (Figure 17–8) can take this to around 600 kg. Insufficient weighting can cause the grab to 'walk', sliding the frame along the sediment in the opposite direction to the movement of the sampling bucket. Some foreshortening of the sample area will occur if the pivot of the grab is raised by 'warp-heave'.

In normal operation, the 0.1m^2 grab provides samples of 10 – 12 litres (Limpenny, pers. comm). The stop plate can be fitted with an inspection hatch, but accessing the sample is difficult. The motion of the scoop through the sediment tends to mix the sample, so the Hamon grab is not used in studies that require the undisturbed surface of the sample to be viewed or sub-sampled. Failure to take a sample is unusual, compared to grabs designs that use two opposing jaws, but can be caused by stones being wedged between the scoop and stop-plate (Limpenny, pers. comm., pers. obs.).

5 – Review of Existing Standards and Protocols

There are a number of publications on standards and protocols relating to the use of grabs to acquire good benthic data. This review includes information from UK, Europe and North American sources. Some of the standards and protocols were developed for use in specific types of study (e.g. sewage dumping grounds, aggregate extraction), others relate to specific types of grab, and some are based on personal experience. Some have more universal application than others, with a few reflecting relatively local 'historical' procedures that are to be maintained to ensure long-term compatibility of temporal datasets. Whatever the rationale behind the different accounts, all include useful information.

This review focuses primarily on faunal sampling using grab devices. For a consideration of sediment sampling using grabs, the reader is directed to the separate review of particle size analysis (granulometry) by Passchier (this volume).

5.1 – Data Acquisition

The following text provides short summaries of a number of notable publications. They are arranged chronologically, European studies followed by those from North America.

European sources

ICES soft-bottom macrofaunal sampling publication

Sometimes referred to as the 'ICES Green Book'. Rumohr (1990) produced a guide to the collection and treatment of benthic samples. A new edition of this valuable publication was produced more recently (Rumohr, 1999) to incorporate the results of ICES/HELCOM quality assurance workshops (ICES, 1996) into the recommendations. It considers, *inter alia*, sampling strategy and equipment, sample processing and quality assurance.

For grabs, Rumohr noted that there was *no unequivocal evidence that any one grab performs consistently better than its counterparts, in all conditions*. He concluded that the use of all standard designs (Van Veen, Smith-McIntyre and Day grabs) be continued.

The 'Yellow Book'

So-called because of its yellow cover, this work (Rees *et al.*, 1990) was produced as a guide for those involved in sampling UK sewage sludge dumping sites. It is one of the first UK guides to comprehensively examine all aspects relevant to a specific macrofaunal monitoring programme, from the initial planning to archiving and publication. A useful flow diagram presents the decisions that need to be made regarding any benthic sampling programme, and recommendations made concerning the specification of grab samplers and the processing of the resulting samples.

JAMP benthic sampling guidelines

The OSPAR Joint Assessment and Monitoring Programme (JAMP) sets out the rationale, objectives for quantitative benthic sampling, and the sampling, analysis, data and quality assurance requirements (OSPAR 1997). Technical Annex 2 concerns the soft-bottom macrofauna. Some of the advice is specific (field data recording), but most is general and reference is made to other publications for the detail (ICES 1994, Rees *et al.,* 1991, Rumohr 1990).

SAC Marine Monitoring Handbook

Thomas (2001) provides a 'Procedural Guideline' for quantitative sampling of sublittoral sediment biotopes and species using grab samplers. The work is geared towards standardising practices for studies relating to Special Areas of Conservation (SACs), and would be relevant to seabed habitat mapping. The advice given is clear and practical, with the pros and cons of different equipment, their use in the field, shipboard sample processing, laboratory work, quality control and safety all being discussed. The appendices include equipment checklists, safe working practices on boats, plus deployment procedures for the Day and Hamon grabs.

CEFAS marine aggregate area sampling guidelines

Although produced to help standardise benthic work in aggregate-related work, this comprehensive work (Boyd 2002) presents clear, well-laid out information relevant to other studies — including seabed mapping. The chapters cover all aspects of survey from planning through to the reporting stage. Techniques covered include grab sampling and sedimentology. A useful table summarising the specifications, and pros and cons of the different benthic samplers is presented. A standard operating procedure (SOP) for the Hamon grab is presented and covers everything connected with using this apparatus and processing samples obtained from it.

Standard Operating Procedures (SOPs) Review

Cooper and Rees (2002) examined 23 standard operating procedures (SOPs) submitted by 6 organisations participating the UK's National Marine Biological Analytical Quality Control scheme (NMBAQC). This is an excellent publication covering all aspects of field and laboratory work, including grab sampling and processing. The review assesses all the procedures and gives a set of recommendations for raising quality standards.

The Green Book

Produced by the UK Marine Pollution Monitoring and Management Group (2003), the "Green Book" provides procedural guidelines for the collection, processing and analysis of a variety of environmental samples. The guidelines are designed to enable the fulfilment of the UK's commitments to a number of local, national (e.g. National Marine Monitoring Programme) and international (e.g. European Community, OSPAR, JAMP) programmes and agreements. Appendix 1 (6 pages) concerns quantitative sublittoral macrobenthic sampling. It details the requirements relative to sampling strategy, precision of site positioning, type of grab (0.1 m^2 Day or Van Veen), collection procedures, sample processing and data analysis.

Humber Benthic Field Methods Workshop Proceedings

In 1997, an important workshop on benthic field methods took place at Hull University (Proudfoot *et al.,* 2003). This workshop – attended by representatives from 11 benthic laboratories – yielded a wealth of information on the all aspects of benthic work and a best practice protocol for the use of 0.1 m^2 grabs. Procedures in other available guidelines – the "Yellow Book" (Rees *et al.*, 1990) and ICES 'Green Book' (Rumohr 1990) – were reviewed and commented upon prior to the production of a set of proposed UKNMBAQC field methods. The appendices give detailed standard operating procedures for the Day, Hamon and Van Veen grabs.

ICES/OSPAR Quality Assurance publication

Aimed at ensuring quality standards in a variety of biological studies, this important publication (Rees, 2004) also contains a wealth of information on macrozoobenthos, sampling design, and field surveys, and laboratory work. Annex 5 details good practice in relation to benthic macrofaunal sampling and analysis and contains some pertinent points aimed at achieving consistency: e.g. Sampling devices (grabs, corers, etc.) must be used on a long-term basis; gear changes have to be accompanied by intercalibration and a period of parallel sampling.

Methods for the Study of Marine Benthos

Eleftheriou and Moore (2005), in the third edition of this standard work, detail the current situation concerning macrofaunal sampling by trawl, sledge, corer and other methods. Previous editions are Holme and McIntyre (1971) and Holme and McIntyre (1984). The book covers all aspects of benthic sampling and is a core publication for all involved in seabed study. Three key chapters relating to benthic grab sampling are: Chapter 1 - Design and analysis in benthic surveys (Underwood and Chapman); Chapter 5 - Macrofaunal techniques (Eleftheriou and Moore) and Chapter 7 - Deep-sea benthic sampling (Gage and Bett).

International Standard ISO/DIS 16665

These guidelines for quantitative sampling of the benthos were developed over a number of years by the European Committee for Standardization (CEN) ISO Technical Committee 147/5 and were recently published (ISO 16665: 2005). The guidelines have been formulated with reference to many of the foregoing publications (e.g. Eleftheriou and Holme 1984; Rees *et al.,* 1990; Rumohr 1999; Proudfoot *et al.*, 2003) and coverage is therefore comprehensive.

North American sources

Puget Sound benthic sampling protocols

These protocols (Tetra Tech, 1987) originated from a 1985 workshop and a series of reviews written by representatives of most of the organisations involved in Puget Sound benthic work. The prime aim of the publication was to standardise the methodology, creating compatible data sets and enabling the creation of an inclusive Puget Sound database.

The publication considered nine elements that needed to be addressed for standardisation. These are listed below, along with the most prevalent choice among the organisations involved in the Sound:

- Sampler — modified Van Veen
- Sample area — 0.1 m2
- Replication — 4 or 5 samples per station
- Sieve mesh — 1.0 mm
- Sieving location — on vessel
- Relaxant use — no
- Stain use — Rose Bengal
- Taxonomic level — species
- Sampling season — variable

If a 0.5 mm sieve was used it was recommended that 1.0 and 0.5 mm sieve fractions be obtained. Further, should identifications only be carried out at a higher-level (e.g. class), material should be archived to allow future species-level analysis. Minimal acceptable sampler penetration was graded according to substrate, ranging from 4-5 cm in coarse sand to ≥10 cm in muddy sediment.

Macrofaunal sample processing is described in precise detail and templates are provided for sampling logs, infaunal 'chain of custody' sheets, and tracking the progress of infaunal laboratory processing. Requirements for quality control of sorting and identification are also given.

New Brunswick Marine and Estuarine Biodiversity Monitoring Protocols

Pohle and Thomas (1997) describe these protocols in the form of a comprehensive and well-referenced review. Extensive information is supplied on all aspects of benthic work from sampling to data analysis.

Later, Pohle (1999) gave detailed protocols for sampling the infauna and other faunal groups. Experts and student volunteers were used to test the protocols at specific sites. Protocols were written in a logical step-by-step manner taking the participants through all the stages from the personnel and equipment required through to specimen identification and verification. A 0.04m2 Ponar grab was used.

US EPA benthic manuals

There are a number of publications by the US Environmental Protection Agency that provide information concerning benthic sampling.

Section 3 in Strobel *et al.* (1995) gives an account of laboratory methods for macrobenthic community assessment. By contrast, section 6 of the Field Operations Manual of the National Coastal Assessment (Strobel and Heitmuller, 2001) provides a thorough account of field sediment sampling. A step-by-step protocol is given for the operation of a 0.04 m^2 Young grab and processing for benthic fauna, sediments and contaminants.

Southern California Bight Operations Manual

The field operations manual of the Southern California Bight Field Methods Committee (2002) was produced as a guidance document aimed at achieving consistency in the methods and procedures used by over 60 organisations. The manual gives concise, but pertinent advice on all aspects of field sampling for a range of techniques including grabs and trawls. A 0.1 m^2 Van Veen grab and a tandem Van Veen (both chain rigged) are described as is the operation of the grabs and the processing of samples.

An interesting difference from other manuals is the recommendation that relaxants (Epsom Salts or propylene phenoxytol) be routinely used. From personal experience, such treatment must be carried out with great caution. Different animals react in different ways to such chemicals and all will have different response times. The danger is that some will be over-relaxed and in poor condition when finally fixed. A safer alternative is to selectively relax particularly fragile forms, though this is only possible for larger animals removed during the sieving process.

Chesapeake Bay Quality Assurance Project Plan

This publication (Versar, 2002) describes the standard operating procedures relevant to all aspects of long-term monitoring in Chesapeake Bay since 1984. High quality data throughout was highlighted to ensure the required standards of accuracy were achieved. Much of the text is written relative to the responsibilities of the various staff involved.

5.2 – Quality Control and Quality Assurance

Quality control and assurance are important elements in acquiring faunal data from grab samples. In their thorough review of Standard Operating Procedures, Cooper and Rees (2002) recommended that:

… individual laboratories examine each stage of a procedure and, where there is the potential for variation in the quality of output, decide upon acceptable boundaries. Where a specific level of accuracy or precision is required then this should be stated and a Quality Control procedure established to ensure that standards are met. At the very least, the quality control procedure should document the standard attained. By highlighting the quality of the data it is possible to ensure that it is not used in an inappropriate way.

Rees (2004) sets out the guidelines for quality assurance recommended by the ICES/OSPAR Steering

Group on Quality Assurance of Biological Measurements in the Northeast Atlantic (SGQAE), which covers sampling design, field surveys, and laboratory work. Annex 5 details good practice in relation to benthic macrofaunal sampling and analysis.

The accurate identification of specimens is crucial for any analysis to be valid. The taxonomic competence of personnel is not usually assured by a recognised qualification, rather through training workshops. In the UK, approximately 30 laboratories participate in the National Marine Biological Analytical Quality Control Scheme (NMBAQC), which formally tests faunal identification of batches of material circulated to the laboratories.

Within a laboratory it is common practice for a proportion of samples processed by an individual to be cross-checked by a fellow worker to ensure that all fauna have been picked from the sample and the taxa correctly identified. Many laboratories also seek to provide quality assurance by sending a proportion of samples for external checking and verification. They may also send entire reference/validation collections for external scrutiny.

5.3 – Data Processing

The raw data obtained by acoustic sampling techniques requires extensive processing before it can be analysed and interpreted, but this is not the case for the raw faunal data obtained by grab sampling. Data are usually provided in the form of species-by-sample tables, which record the abundance and biomass of the observed taxa. Prior to analysis, data processing is usually limited to two specific procedures aimed at standardising the data:

5.4 – Standardisation of the area sampled

When working with infaunal data (i.e. that derived from grab or core samples), it is convention to express faunal density (or biomass) in terms of numbers (or weight) *per unit area of the seabed* (**not** per unit volume of sediment). The area of seabed sampled by any grabbing device should be known. Most grabs in common usage (see the examples above) sample an area of $0.1m^2$, so it is a simple calculation to convert the data to numbers (or biomass) per square metre.

5.5 – Standardising taxonomy, including data truncation

The field of taxonomy is continually advancing and there can be many changes made to taxonomic nomenclature. Consequently, it is common for a study to use a recognised species checklist drawn from the taxonomic literature at a set point in time (e.g. Howson and Picton, 1997). It is important that all studies declare which taxonomic literature has been used in making faunal identifications. When faunal data are brought together from disperate studies there can be a requirement to harmonise the taxonomy across the different data sets.

Where different studies have identified fauna to different taxonomic levels, a process of data truncation may be required to harmonise the data prior to analysis. For instance, if one study has identified taxa to species level, but another has only identified taxa to genus level, then the data from the first study must be truncated to genus level before the two data sets can be pooled.

Often, a taxonomic coding system will be used to aid data manipulation and analysis, giving each taxon a specific number or letter code. Some systems are hierarchical, giving related taxa the same root code (e.g. NODC Taxomomic Codes). Such systems frequently undergo revision to keep up to date with revisions in taxonomy, and this can lead to incompatibilities between different versions of the same coding system. An alternative approach is to use a non-hierarchical structure, assigning each taxon a permanent serial number that does not change in line with any taxonomic revisions. This is the basis of the Taxonomic Serial Number (TSN) used by the Integrated Taxonomic Information System (ITIS). A variety of common coding systems have been considered by Vize and Coggan (2006) in their review of trawling and dredging techniques (this publication).

6 – Provenance and Current usage

Quantitative grab sampling as we know it today can be traced back to the pioneering work of the Danish C. G. J. Petersen in the early 1900s (Petersen, 1914, 1918; Petersen and Boysen Jensen, 1911). The early Petersen grab was soon superseded by the Van Veen grab, which was shown to be a superior device and is still in common use. (In 2002, the American Society for Testing and Materials withdrew its *Standard Practice Guide* for the Petersen grab.) The Smith-McIntye grab became popular in the 1950s and '60s and is used worldwide to the present day. However, in northern Europe, the similarly framed Day grab (Day 1978) is preferred on account of its simpler mechanism and greater reliability. In recent years, the commercial extraction of gravel from the seabed has led to an increased interest in the fauna supported by harder unconsolidated sediments, to which the twin-bucket van Veen, Smith-McIntyre and Day grabs are not well suited. Consequently, the single bucket Hamon grab has recently come to prominence and is widely used for sampling gravel and sand substrates. As pointed out by Eleftheriou and McIntyre (2005: preface) there has been little change in macrofaunal sampling methodology in 20 years. The L-framed Van Veen described herein (and Mackie, in prep.) is arguably the only recent development of note.

7 – Conclusions and Recommendations

7.1 – The Sampler

The actual grab design employed can vary considerably between countries, particularly between Europe and the USA. This is likely to remain the case for historical reasons – a particular grab is often specified in long-term monitoring studies for reasons of consistency as much as anything. For habitat mapping studies it would be beneficial to limit the variety of grabs used as this would promote consistency across studies and minimise data artefacts that may be attributable to the use of different grab designs.

All of the most commonly used European samplers have strengths and weaknesses, and each can excel in a particular application. Consequently it would be inappropriate to recommend any one type of grab as a 'standard' for habitat mapping studies. Instead, guidance should be given on the selection of grabs, so they are matched to the type of substrate to be sampled.

The van Veen grab is arguably the most versatile, being suitable for use on all substrates except hard-packed gravels and cobbles, and from all sizes of vessel. However, the lack of a supporting frame makes it more prone to failure than other designs. The Day grab is compact and has a similar versatility regarding ease of deployment, though it has more limitations on softer and harder sediments. The Hamon grab is suitable for both sand and gravel substrates, but should not be used to sample muds, on account of its great weight, which can cause the grab to sink deeply into soft muds. When setting out to sample unknown grounds, it would be advisable to take a Hamon grab and one of the twin-bucket designs (van Veen, Day or Smith McIntyre grab).

One problem with assessing grabs is the variety evident within each design. Different examples of the same grab type may differ in their characteristics, so it is recommended that more information (meta-data) is routinely recorded about the design and rigging of the grab (e.g. area of seabed sampled, shape of buckets, maximum possible penetration, modifications to the frame, meshes used on top-plates, rigging and the amount of weight used). It is also recommended that metadata relating to each sample is fully recorded, including position co-ordinates, time and depth of sampling, sea conditions, the volume of the sample and its nature (e.g. sediment type from visual inspection). In addition, each sample should be photographed prior to processing to provide a permanent record of the appearance of the sample. Although habitat mapping is less reliant on fully quantitative data than monitoring studies, these types of metadata are important in assessing whether apparent faunal differences between samples (and /or habitats) are real or simply reflect the use of different sampling devices.

There is still a need for cross-comparisons within and between grab types concerning bite profile, volume of sediment collected and faunal capture efficiency. Such a comparison may be beyond the scope of the present project.

7.2 – Standards and Protocols

This review has shown that there are many existing standards and protocols relating to the use of grabs and the processing of the resulting samples. Several are designed for environmental monitoring or surveillance reasons – for example concerning sewage sludge dumping, aggregate extraction or point source discharges. Some are retained for historical reasons; that is providing consistency in sampling over long time periods, and may be local, national or international in their application. Most contain some information that is, or should be, universal. Referring future habitat mapping studies to the plethora of available documents would likely lead to a great deal of confusion and ambiguity in precisely how grab sampling techniques should be applied for habitat mapping. Therefore, it is recommended that specific guidance should be developed by the MESH project.

Existing protocols detail a variety of sampling strategies. As each is developed for a particular purpose, it is not surprising that they differ in their recommendations relating to the number of sampling stations and sample replication. Consequently, this is another area of guidance that will need to be provided specific to habitat mapping studies. Whereas protocols for environmental studies are designed to obtain numerical data to a desired statistical precision, this is not a fundamental requirement for benthic habitat mapping, where the major interest lies in describing species assemblages over a particular spatial area. While it is certainly feasible to produce detailed fine resolution maps of benthic faunal assemblages from intense surveys involving many stations with a high number of replicates, this is neither pragmatic nor cost-efficient. When applied to habitat mapping, grab sampling will most frequently be employed as a method of 'ground- truthing' acoustic surveys, sampling within different seabed facies (distinct sediments and bedforms) to ascertain the nature and variety of faunal assemblages that they support. Given limited resources (time and money) it would be preferable to increase the number of sampling points ('stations') and reduce the number of replicates per station. Specific guidance will need to be developed on sampling strategies and the minimum requirement for ground-truth sampling.

Standards and protocols relating to sample processing seem to have become more firmly established in the past decade, in response to the growing emphasis on monitoring studies where consistency in methodology is of utmost importance. Such protocols would appear to be suitable for use in habitat mapping studies, without major revision. For the purpose of standardising procedures across future mapping studies, it is recommended that existing protocols should be drawn together in a single guidance document.

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VIDEO AND IMAGERING TECHNIQUES

18 Sediment Profile Imagery

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1 – General Principles of Operation

Sediment Profile Imagery (SPI) or REMOTS (Remote Ecological Monitoring Of The Seafloor) is a method for the rapid surveying or monitoring of marine sediments. The SPI camera works like an inverted periscope providing cross sectional images of the sediment surface and underlying profile.

The system consists of a camera mounted above a wedge-shaped prism with a Plexiglas faceplate and an internal light provided by a flash strobe (Figure 18–1). The back of the prism has a mirror mounted at a 45-degree angle to reflect the profile of the sediment-water interface up to the camera. The prism is filled with distilled water, and because the object to be photographed is directly against the faceplate, turbidity of the seawater is never a limiting factor. The sediment profile camera can either be diver held or remotely operated from a research vessel.

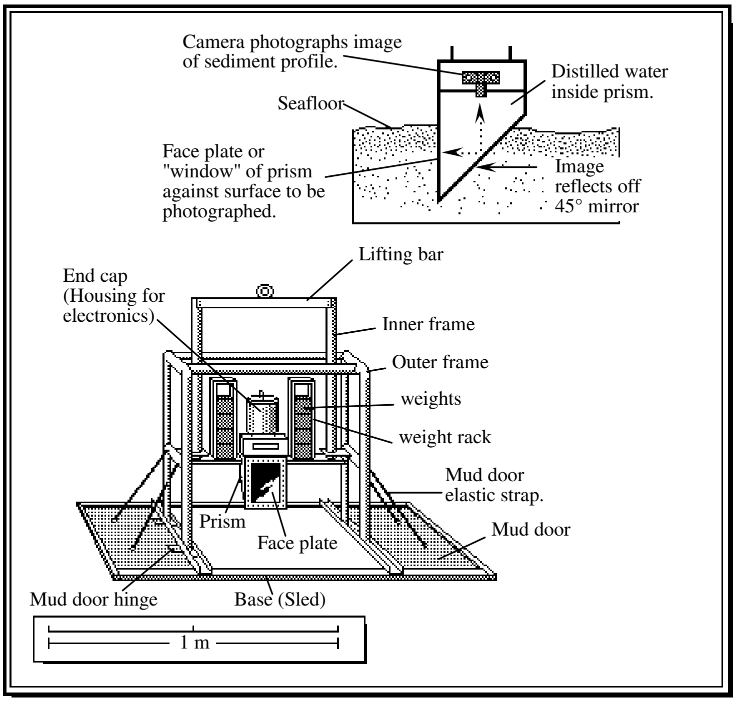

Figure 18–1. Diagram of an SPI camera (source: Aqua-Fact International).

Boat operated systems consist of a camera, mounted on a support frame, that can be moved up and down by producing tension or slack on the winch wire. As the camera is lowered, tension on the winch wire keeps the prism in the 'up' position until the frame hits the bottom (Figure 18–2). At this point the tension on the winch wire is reduced causing the inner frame to move to the 'down' position, penetrating the undisturbed sediment-water interface. On impact with the bottom, a trigger activates a time delay on the camera shutter release and a photograph is taken after the prism comes to rest.

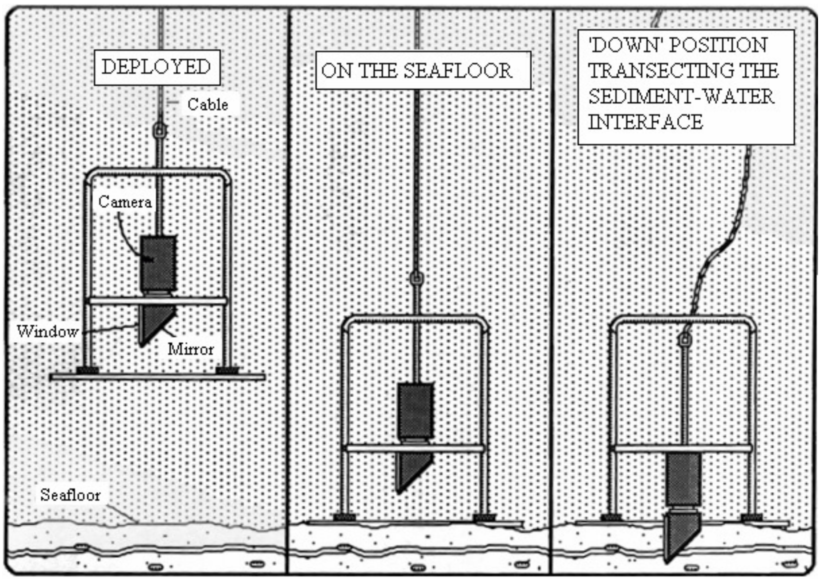

Figure 18–2. SPI camera deployment on the seafloor (source: Aqua-Fact International).

The images acquired from the SPI camera can be rapidly analysed (five minutes per sample) by computerised image analysis software. From this over 20 physical, chemical and biological parameters can be quantified, including: sediment grain size, prism penetration, surface pelletal layer, sediment surface relief, mud clasts, redox area, depth of current and relict redox boundaries, methane gas vesicles, apparent faunal dominants, voids, burrows, surface features (e.g. worm tubes, epifauna, shell), dredged material, microbial aggregations, and successional stage (see Table 1). From this information the benthic habitat can be characterised using indices such as the Organism-Sediment Index (OSI) or Benthic Habitat Quality Index (BHQ) (see 'Data Interpretation' below). A review of the history of development and application of SPI cameras is given in Solan *et al.* (2003).

The main limitation of SPI is its small 'footprint'. It is difficult to relate a single sample to an entire habitat; therefore a series of samples is usually obtained at each station by 'hopping' the system across the seabed and using a number of sampling stations to cover the area under investigation. SPI also only works on soft sediments (mud or muddy sand) without subsurface obstructions, and is often used in combination with other sampling techniques (e.g. grabs or trawls) or as a tool for ground-truthing remote sensing techniques (e.g. acoustic techniques).

2 – Varieties of Systems Available

There is little variety in basic SPI systems available as they all operate as described above. However, some have been fitted with time-lapse cameras to collect time-series images from a single deployment, and some with coring devices to provide physical samples of the sediment. Few companies in Europe offer SPI technology on a commercial basis, one of these being Aqua-Fact International (www.aquafact.ie). Among academia, the Ocean Lab at Aberdeen University is currently working on the development of a multi-wavelength (SPI) camera capable of still and time-lapse digital imaging of invertebrate infaunal bioturbation, and an appropriate image analysis routine for post-hoc interrogation (Coastal Ocean Benthic Observatory project (COBO): http://www.oceanlab.abdn.ac.uk/research/grants.shtml).

3 – Review of Existing Standards and Protocols

3.1 – Data Acquisition

There are two main current sources for information on SPI set-up, deployment and image acquisition. The Marine Monitoring Handbook gives a general description of survey designs with advice on number of replicates and desired sediment penetration (http://www.jncc.gov.uk/marine/mmh/Pg%202-2.pdf). R.J. Diaz and Daughters go into a more detailed description of how they deploy SPI and acquire images (http://www.courses.vcu.edu/ENG-esh/diaz/diaz_services.htm). Other information on specific sampling designs can be found in the following papers: Diaz *et al.* (2003); Karakassis *et al.* (2002); Rosenberg *et al.* (2003); Nilson and Rosenberg, (1997 and 2003); O'Connor *et al.* (1989; and Smith *et al.* (2003).

A further source for information on SPI will be the proceedings of the Sediment Profile Imagery Colloquium of Experts (SPICE) conference 2004 (http://mri.nuigalway.ie/spice/spice/spiceindex.htm) which included as one of its aims the outlining of methodologies in experimental design of sampling programmes, image acquisition, image analysis and data analysis.

At present none of the above documents provide thorough enough standards and protocols relating to the use of SPI to acquire data. A merging of several of these sources needs to be used to write a definitive protocol for the future use of SPI in habitat mapping. It is understood that guidelines on standards and protocols relating to SPI may be included in the proceeding of the SPICE conference mentioned above.

3.2 – Data Processing

Image analysis is the main form of data processing used for SPI; this involves the digitisation and enhancement of images to be then visually evaluated by a human operator or by a dedicated image analysis system (Figure 3 shows an example of an SPI image). As previously stated, SPI can be used to quantify over 20 physical, chemical and biological parameters. The usual parameters quantified are the sediment type measured from the upper 5cm sediment layer; prism penetration depth, which gives an indication of relative sediment compaction; sediment boundary roughness, which indicates the degree of physical disturbance or biotic activity at the sediment water boundary; sediment apparent redox potential discontinuity depth (ARPD, see Figure 18–3), which assesses the depth of oxygenated sediment on the bottom; and infaunal successional status which qualifies the type of animals living in the bottom. Other additional parameters such as the presence of mud clasts, epifauna, infaunal burrows and tubes, outgassing of sediments (due to production of hydrogen sulphide and ammonia as by-products of anaerobic metabolism) are usually also measured. A timescale for the analysis of images compared to time taken to collect is approximately 1 hour sampling to 1-2 hours processing.

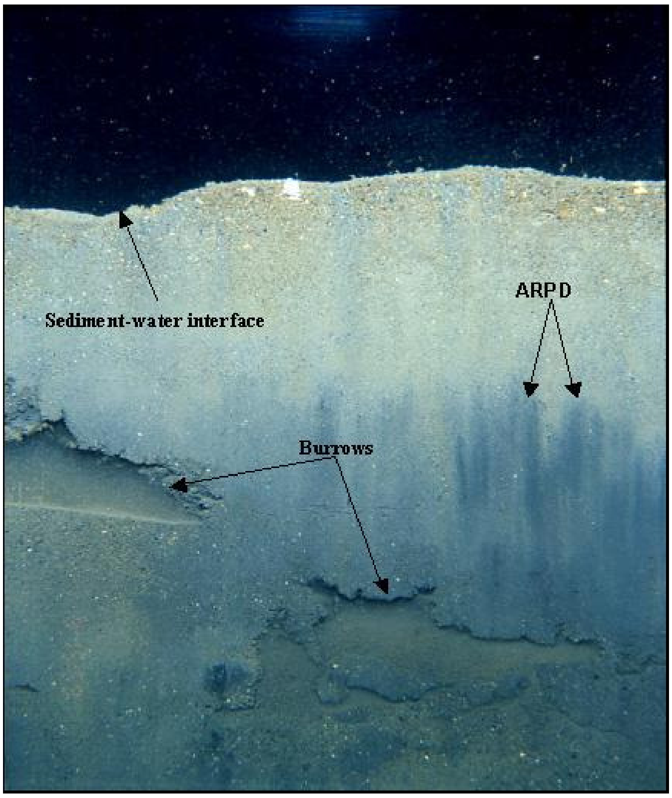

Figure 18–3. SPI image showing several sediment features (source: CEFAS).

The main sources of information on the analysis of SPI images are; the Marine Monitoring Handbook (http://www.jncc.gov.uk/marine/mmh/Pg%202-2.pdf), which gives a brief overview on SPI analysis; R.J. Diaz and Daughters (http://www.courses.vcu.edu/ENG-esh/diaz/diaz_services.htm), which gives a detailed description of the image analysis process used by the company; Aqua-Fact image analysis information (available on request, info@aquafact.ie), which also gives a detailed description of the process used by the company. Ghita *et al.* (2004) give specific information on an image analysis software package that can perform automatic identification of oxidised sediment and also the identification of other features such as burrows and voids. Birchenough *et al* (submitted), Nilsson and Rosenberg (1997, 2003), and Rosenberg *et al.* (2003) also give brief descriptions of the process used to analyse images.

There is no definitive source for the analysis of SPI images that is appropriate for habitat mapping, but a merging of some of the above sources would give a good general protocol. As mentioned previously, a further source should come from the proceedings of the SPICE conference 2004 which aimed to produce guidelines for best practice and standardisation of SPI analysis, including a ring test: - circulating images among users to compare and contrast their interpretations (http://mri.nuigalway.ie/spice/spice/spiceindex.htm).

3.3 – Data Interpretation

Data acquired from SPI analysis can be used to make observations of sediment-organism relationships and to quantify the quality of the benthic habitat. In relation to the EUNIS scale SPI data should be able to determine habitats up to biotopes (level 5) or sub-biotopes (level 6). Benthic habitat quality can be calculated using two different indices, the Organism-Sediment Index (OSI; Rhoads and Germano, 1986) and the Benthic Habitat Quality index (BHQ; Nilsson and Rosenberg, 1997).

The Organism-Sediment Index (OSI) defines benthic habitats by evaluating apparent redox potential discontinuity (ARPD, see Figure 3) layer, successional stage of macrofauna, the presence of reduced sediment at the sediment-water interface that would indicate current or recent low dissolved oxygen conditions (**Table 18–1**). The OSI has a range of –10 to +11; the lowest value is for highly disturbed and degraded habitats whereas the highest value is for areas with very deep oxygen penetration, mature stage 3 communities, and no methane gas bubbles at depth.

The Benthic Habitat Quality index (BHQ) is based on a quantitative determination of the relative densities of surface and subsurface organisms. The index assigns points based on the type and extent of signatures left by animals in the sediment. High scores are assigned to features that correlate with considerable bioturbation (Figure 18–4 and Table 18–2).

Table 18–1. Method of calculating the Organism-Sediment Index (OSI) value (source: Aqua-Fact International).

A. CHOOSE ONE VALUE:		
	Mean ARPD Depth	Index Value
	0.00 cm	0
	>0 - 0.75cm	1
	0.75 - 1.50cm	2
	1.51 - 2.25cm	3
	2.26 - 3.00cm	4
	3.01 - 3.75cm	5
	>3.75cm	6
B. CHOOSE ONE VALUE:		
	Successional Stage	Index Value
	Azoic	-4
	Stage 1	1
	Stage 1-2	2
	Stage 2	3
	Stage 2-3	4
	Stage 3	5
	Secondary Succession	
	Stage 1 on 2	5
	Stage 2 on 3	5
C. CHOOSE ONE OR BOTH IF APPROPRIATE:		
	Chemical Parameters	Index Value
	Methane Present	-2
	No/Low Dissolved Oxygen	-4
ORGANISM-SEDIMENT INDEX =	Total of above subset indices (A+B+C)	

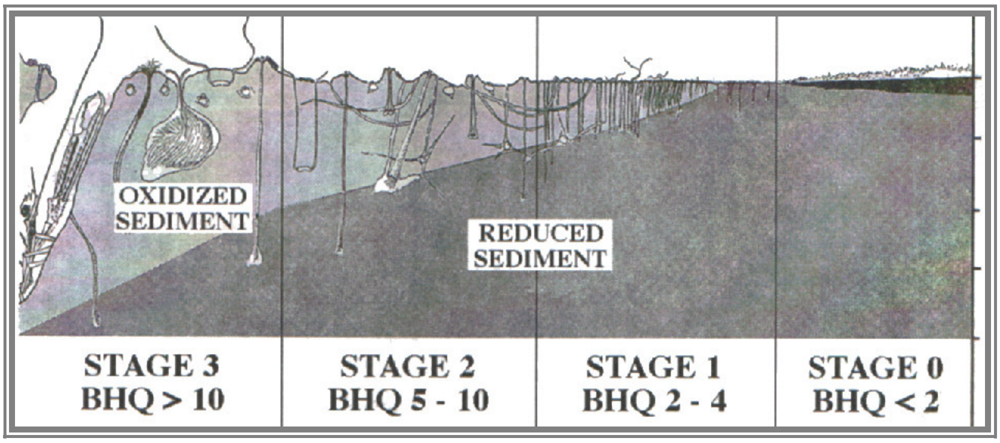

Figure 18–4. The distribution of benthic infaunal successional stages along a gradient of increased environmental disturbance from left to right and the associated Benthic Habitat Quality index (source: Nilsson and Rosenberg, 1997).

Table 18–2. Calculation of the Benthic Habitat Quality (BHQ) index from the sediment profile images. BHQ = $\Sigma A + \Sigma B + C$, where *A* is surface structures, *B* subsurface structures and C mean sediment depth of the apparent redox potential discontinuity (ARPD). The BHQ value varies between 0 and 15 and corresponds to the different successional stages depicted in Figure 4 (source: Nilsson and Rosenberg, 1997).

A	Surface Structures	Faecal pellets	1
		Tubes ≤ 2 mm in diameter	1
		or Tubes > 2mm in diameter	2
		Feeding pit or mound	2
B	Subsurface Structures	Infauna	1
		Burrows 1-3	1
		or Burrows # > 3	2
		Oxic Void at ≤ 5 cm depth	1
		or Oxic Void at > 5 cm depth	2
C	Mean Depth of ARPD	0 cm	0
		0.1 cm – 1.0 cmc	1
		1.1 cm – 2.0 cm	2
		2.1 cm – 3.5 cm	3
		3.6 cm – 5.0 cm	4
		5 cm	5

Specific examples of SPI data interpretation can be found in the following papers: Birchenough *et al* (submitted), Diaz *et al*. (2003), Karakassis *et al*. (2002), Nilsson and Rosenberg (2003), Rosenberg *et al*. (2003) and Smith *et al*. (2003).

3.4 – Provenance and Current Usage

SPI was first developed in the early 1970's by a group of US scientists led by Dr Don Rhoads, for application in paleoecology and sedimentation (Rhoads, 2004). Since its early beginnings SPI has been successfully applied for many different applications around the world. These have included:

- Sediment quality surveys and identification of pollution 'hot spots'
- Dredged material disposal site studies
- Sewage sludge disposal site studies
- Assessment of low dissolved oxygen

- Aquaculture impact assessment
- Oil platform impact assessment
- Industrial discharge impact assessment
- Verification of data collected by acoustic techniques such as side-scan

Some specific examples of application include; the use of SPI to determine the effects of trawling on benthic habitats (Nilsson and Rosenberg, 2003; Rosenberg *et al*, 2003; Smith *et al*., 2003), fish farm impacts (Karakassis *et al*., 2002; O'Connor *et al*., 1989), assessing macrobenthic communities at dredge disposal sites (Birchenough *et al*, submitted) and using SPI for time-lapse analysis of animal-sediment relationships (Solan and Kennedy, 2002).

SPI is a useful tool for habitat mapping as it compliments many traditional and new techniques and it was concluded by Rhoads *et al.* (1981) that it is a cost effective and informative reconnaissance tool to aid in the design of benthic sampling programs. SPI is unique in providing in-situ sediment profiles and, therefore, can be regarded as a survey tool in its own right and also as a method of ground-truthing remote sensing techniques, such as sidescan sonar.

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19 Remote Video techniques

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This second edition of the review of video techniques merges the original separate reviews on drop cameras, towed video sledges and Remote Operated Vehicles (ROVs), consolidating common elements that relate to all the techniques, such as positioning/georeferencing and the analysis of the video record.

1 – Introduction

Video imaging of any type is an extremely valuable tool in habitat/seabed mapping, providing fundamental information on (and a permanent record of) the physical nature of the seabed (e.g. substrate type, impacted vs. non-impacted), and a direct appreciation of the disposition of biota among the substrates. Habitat types may be recognised and assigned almost immediately by suitably trained and experienced observers, and there can be far less reliance on complex data processing and analysis required in some other sampling methods (e.g. acoustic surveys ground-truthed by grab samples).

Video techniques have two main applications in habitat mapping. Firstly they can be used as primary survey techniques in their own right, to explore and investigate previously unsurveyed areas of seabed. Secondly, they can be used as a method for ground-truthing surveys undertaken using remote sensing techniques, such as sidescan and multibeam sonar. Here, the video techniques are used to target specific features (e.g. rock outcrops, sand banks etc) or to further investigate areas of apparent acoustic uniformity that may comprise several different habitats (e.g. boulder and cobble reefs lying in expansive areas of 'gravel'). Depending on their specific purpose, video surveys can be designed to be purely descriptive, semi-quantitative or fully quantitative.

Images recorded by video can be used to:
- provide information on the types of sediment and their associated epifaunal communities with a view to characterising and identifying the habitat type, and
- detect and locate boundaries between various habitats.

The extent to which these objectives can be achieved depends on several factors, including:
- the equipment selected
- the survey strategy (or design)
- the methods employed in analysing the video record

A further, critical step is the adequate geo-referencing of information such that it can be used to produce a habitat map. All of these matters will be considered in this review, which aims to identify existing standards and protocols that can be adapted or adopted in habitat mapping and to highlight areas of deficiency that can be addressed within the MESH project.

2 – General Principles of Operation and Data Processing

Video techniques tend to fall into a hierarchy of sophistication, starting with passive drop cameras that are hung over the side of a vessel, progressing to bespoke designed platforms that are towed behind a vessel and finishing with piloted, 'robotic' devices such as ROVs. In general, the set up of the video system is common to all techniques. The platform (cage, sled or ROV) provides a sturdy mounting frame for the video camera, which is connected to a deck control unit via an umbilical cable. The umbilical feeds power to the camera and lighting system and returns the video signal to a recording unit on deck. Here, a video overlay is applied, using a proprietary system such as TrakView®, to record a data stream onto the video image, commonly giving fixed metadata relevant to the station (e.g. data and station details) and real-time data such as GPS output giving time and position (Figure 19–1). A photographic camera is frequently used in tandem with the video camera to provide high-resolution 'still' images of the seabed, usually for quantitative analysis. More advanced video cameras now have a built-in digital stills camera. The stills camera is either triggered by the operator from a deck control unit, or automatically by a pre-set timer. Photographs can be time stamped to allow their position to be determined by cross-referencing with a GPS log, but care must be taken to synchronise the camera clock with that of the GPS. Alternatively, as the video image records the tell-tale flare of the flashgun each time the stills camera is triggered, time/position data for a series of still images can be gleaned from the video overlay data when the video record is reviewed.

Figure 19–1. Example of a section of video record illustrating video overlay showing station metadata (top line; date and station details) and real-time data giving GPS position (middle line) and time stamp (lower line). Other data on the image relates to the lens aperture and zoom. Note also the scale bar in the bottom left corner.

Camera angles vary according to the system used. On drop-cameras, the video camera invariably points directly downwards (vertical), but in towed systems it may be angled slightly forwards (oblique, e.g. between the front edge of the sledge runners), allowing for some anticipation of the seabed about to be encountered. While it may be argued that vertical mounting produces a more quantifiable image in terms of measurable area, experience suggests that taxonomic identification is more reliable using an oblique view, as this increases the period for which organisms are captured in the field of view. A common configuration on towed systems is to have an obliquely mounted video camera and a vertically mounted stills camera. On manually fired stills cameras, this improves the success rate of capturing points of interest as they pass below the platform. In ROVs, the camera angle can often be adjusted in real-time from the deck control unit, as this aids piloting and navigation. Stills cameras are frequently mounted to give the same field of view as the ROV's video camera, ensuring synchronisation of video and stills images.

Various methods exist for calibrating the field of view of the camera, a necessary step for any form of quantitative analysis relating the number or coverage of organisms to the area of seabed observed. Calibration must be carried out underwater (not on deck) as the difference in refractive index between air and water will significantly alter the field of view. Simple solutions involved fixing a scale object (e.g. graduated ruler) in view of the camera, but these were only applicable to situations where the scale object could be placed on or very close to the seabed (e.g. fixed to the runners of a video sledge, as in Figure 1 or held in the manipulator arm of an ROV). For video sledges, another method was to record a test deployment (to just a few metres depth), with a large square grid (10 cm spacings) tied flat between the sledge runners. When viewed on the video monitor this appeared as a trapezoidal grid (due to perspective), and could be traced directly onto the monitor to provide a reference scale (Atkinson, pers. comm.). One generic method involving a laser-spot system appeared applicable to all video techniques. In its simplest form, a pair of parallel laser beams was projected in front of the camera, scaling being derived from the known distance between the laser spots. More advanced forms used four spots to represent the corners of a virtual quadrat. For obliquely mounted cameras, the perspective of the quadrat would change from a square to a trapezoid, but the area within the quadrat could be calculated using simple trigonometry. The most advanced forms had five or six spots, but these were usually only required in applications where the geometry of an object was of interest.

The umbilical cable is a critical part of the system, and may be a limiting factor, having a fixed length and a fixed capacity to deliver power to the platform (video, lighting and propulsion unit, if present). Power supply can be taken from the support vessel or provided by a generator. On specialist vessels, a load-bearing umbilical spooled on a dedicated winch is used for deploying and/or towing the platform. However, in many cases, the umbilical is not load bearing, so is strapped to the towing wire (or rope) while the system is being deployed. In ROVs, such wires are usually only needed during deployment and recovery.

The support vessel itself is also an important consideration, and must be suited to the size of system in use, which can range from a small hand-held camera to something that would fill several container lorries. Vessels should preferably have a dry area / wheelhouse in which the TV monitors, recording equipment and control units can be safely operated. Tow speeds of 0.75 knots (speed-over-ground) or less are recommended for optimum video analysis, so it is essential to have an experienced skipper and a vessel capable of maintaining steerage at low speeds. The wide range of systems available means that video techniques can be applied to a wide range of circumstances, covering estuarine, nearshore and offshore habitats. It is possibly the only method, apart from SCUBA diving, that can be applied to underwater caves.

2.1 – Spatial Scales Covered

For drop-cameras, the maximum field of view is approximately 5 m^2 and decreases to ~0.2 m^2 when the frame reaches the seabed. The system can be used in a 'spot-sampling' mode by hopping the frame across the seabed to give close-up shots of the sediment surface, or in a 'drift-dive' mode where the frame is held a few metres off the seabed to give wider angle shots while the support vessel drifts.

In towed video systems the field of view is commonly between 1 and 5 metres width and tow distances may be anything from 50 metres to several kilometres. Species density data can be calculated if the transect width and length are known. Alternatively, species-time counts can be used to assess relative abundance if accurate measures of the field of view are not practical. In addition, video freeze-frames or still photographs may be treated as point quadrats.

2.2 – Types of Data Collected and Storage

Unlike many other remote sensing techniques, video methods do not record data *per se*. The visual image is recorded direct to a storage medium, which from many years has been magnetic video tape (VHS, SVHS or Hi8). With the advent of digital video cameras, recording has been to digital tape or some form of disk (DVD or hard-drive). Video tapes are frequently copied to DVDs as these can be played back through a computer and image capture / movie editing software used to take 'freeze-frames', which are saved as an electronic image file (e.g. TIFF or JPEG). Consideration should be given to the longevity of the media to which images are recorded as both video tape and DVDs will degrade with time, so suitable archive copies should be made.

Photographic stills are usually recorded using digital cameras or conventional slide film. The images are downloaded direct to a computer, or scanned-in using a proprietary film scanner. The images can then be manipulated within image processing software packages, such as Adobe Photoshop, to increase contrast or brightness. In such packages, grids can be overlain to facilitate counting of organisms or percentage cover estimates. Images are usually copied to CD or network drives for permanent storage.

It is good practice to record relevant metadata at the time of acquisition, showing when, where and how the images were collected. Records can be kept on paper, spreadsheet or database and are important for cataloguing and georeferencing the material (see section 5 on georeferencing).

2.3 – Processing

Unlike other remote sampling methods, video techniques deliver direct visual information, so there is no requirement for data processing to clean the data and correct for known errors, as is required with multibeam acoustic data. Rather, video techniques are more analogous to direct sampling techniques (e.g. grabs and trawls), supplying samples that need to be processed to provide derived data, which is subsequently analysed. Consequently, the standards and protocols that apply to video techniques concern the acquisition of samples, the methods of processing those samples to derive data, and the ways in which that data is analysed or interpreted. Each of these will be considered in sections 4 and 6 below.

The information that can be extracted from underwater images is highly dependent on water clarity and the speed of the camera over ground. In general, post-processing of video footage only permits quantification of larger specimens of the epibiota (megafauna and some macrofauna), as smaller organisms cannot be seen with sufficient clarity to allow identification (Guidelines for the study of the epibiota of subtidal environments: Working Document (ICES BEWG)). The possibility of accurate species identification, and the size of epibiota that can be identified, is enhanced by slow (<1 knot) towing in clear water, and this must be considered when comparing data between tows. Where possible, notes should be made on the clarity of the video footage and the 'actual' rather than 'expected' field of view. It has been demonstrated (Smith *et al* 2003) that the direct identification and quantification of a range of burrowing organisms can be made through observation of burrows structures

3 – Varieties of System Available

The examples listed below are intended to illustrate generic types of gear and no endorsement of any particular product is implied.

3.1 – Drop Cameras

The term 'drop-cameras' is used here specifically to describe passive camera systems that are dangled over the side of a vessel, as distinct from being towed or propelled. The camera is commonly mounted in a protective frame, looking downwards, and is lowered over the side of a boat to obtain images of the seabed. The systems can be used in a 'spot-sampling' mode (a single observation), or as a bed-hop camera, hopping the frame across the seabed to give several close-up shots of the sediment surface. Alternatively, a haphazard transect can be sampled by deploying the device from a drifting vessel.

Several small cameras are suitable for mounting on other pieces of sampling gear, such as grabs or corers to give a visual record of the seabed at the point of sampling. They are typically compact, lightweight and inexpensive. The example in Figure 19–2 is the Crystal Cam®, designed and developed by Inuktun of Canada. The camera head is encased in transparent epoxy giving and rated to a depth of 300 m.
Source: Inuktun Services Ltd, Canada

Figure 19–2. Crystal Cam®. (http://www.inuktun.com/crystal_cam.htm accessed 3/3/06)

Next in the range are medium size cameras, without protective frames. Some are designed for the 'sports' marked (SCUBA diving and fishing) to locate sites of interest. Those for scientific use are frequently more robust (and costly) and often have integrated or integral lighting systems. Many have a fixed horizontal view and are intended for inspection of sub-sea structures (such as oil rigs), but those with a vertical, downward view are most applicable to seabed mapping. The example in Figure 19–3 is the DV1 Dropcam, from JW Fishers (UK).

Figure 19–3. Source: JW Fishers Mfg, USA. http://www.jwfishers.com

The FlySpy (Sub-Atlantic, UK) can achieve a full 360 degrees field of view by means of a continuous pan and 180-degree tilting ability. A flywheel system cancels out torque when starting and stopping panning, providing a wobble-free picture. Low light mono or colour cameras can be fitted together with dimmable lighting. Various control console options are available and the camera is rated to 150 metres.

Medium sized drop-cameras are frequently mounted in a protective cage, which can house a camera, a lighting system and a laser-scaling device. Usually made from stainless steel, the cages can be weighted to provide additional stability (Figure 19–5).

Figure 19–4. Source: Sub-Atlantic Ltd, UK (http://www.sub-atlantic.co.uk accessed 14/11/04)

Research institutes with access to engineering workshops often design and make their own drop-camera frames. This is an example of a large frame used by CEFAS. It requires a crane or davit to launch, so can only be used on larger vessels. Small or large video and stills cameras are clamped to the metal plate in the centre of the frame, which can be adjusted to alter the plane of view. The cage will also accommodate a lighting system. The high degree of protection offered to the camera and lighting gear means it can be used on rough grounds.

Figure 19–5. SV-DRCAGE drop camera cage. (Photo courtesy of Shark Marine technologies Inc http://www.sea-viewdiving.com/diving_equipment/cameras/svdrpcage.htm).

Provenance and Current usage

Drop-cameras have been largely superseded by towed video devices, ROVs and AUVs. However these can involve a great deal of expense, and drop-cameras still have a 'niche' as reliable and affordable means of collecting video records. They are generally easy to handle and can be deployed quickly. They have particular application on rough grounds, where a sledge cannot be used, and also in high-energy environments that are not accessible to most ROVs (e.g. Cole *et al.*, 2001).

Figure 19–6. Cefas (©) Drop frame camera

3.2 – Towed Platforms

Video Sledges

A sledge is usually constructed as a frame of aluminium or stainless steel tubing, with some form of runners that are in contact with the seabed. Sledge design in the UK and Ireland has been heavily based upon that of Shand and Priestly (1999), which has proved very successful (Figure 19–7). The sledge is fitted with floats or buoyancy tank on top to help maintain an upright position during deployment. A buoy is attached to an appropriate length of rope (at least twice the operational water depth), which is attached at the rear of the sledge to aid retrieval in the event of entanglement, and to provide a drag force, which reduces the yaw of the sledge. The system has been modified by various institutes to accommodate more advanced camera and lighting systems as the technology has developed.

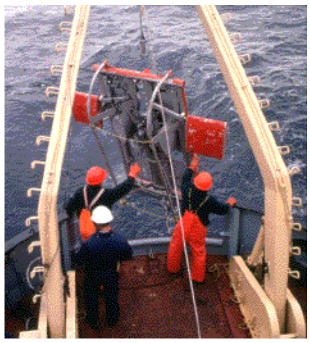
Figure 19–7. Examples of video sledge used in the UK, based on the design of Shand and Priestly (1999). The system on the right has a dedicated load-bearing umbilical tow wire. In the other systems, the tow wire and umbilical are separate.

The camera is mounted on an adjustable plate, looking down between the sledge runners or slightly forwards. A standard configuration includes a colour video camera and a 35 mm stills camera, with the latter pointing slightly behind the video, allowing the video to be used as a remote 'viewfinder' for the stills. Some modern video cameras have a built-in high definition digital stills camera, which can be electronically downloaded when the sledge returns to the deck. Such a combination camera can be mounted on a pan-and-tilt mechanism to give added flexibility to the system. Video lights and flash strobe are positioned by trial and error to provide optimum illumination of the areas in view.

As more sophisticated 'stereo' system is known from CSIRO in Australia (right). This large camera continuously records the seabed from stereo video cameras, and takes digital still pictures at a rate of one every five seconds. Images are transferred to computer via fibre optic cable, enabling them to be catalogued according to their geographical position. The system can also take under way measurements of the water column including light, temperature, salinity and turbidity.

Figure 19–8 Stereo video system. (http://www.marine.csiro.au/media/04releases/26apr04.html accessed 14/11/04. Source: CSIRO © Copyright CSIRO Australia).

Towed bodies flown above seafloor



Some other towed devices that do not contact the seabed have been used in habitat mapping, and examples are given below. These are distinct from 'drop-down' cameras that are deployed from a stationary or drifting vessel.

Schneider *et al.* (1987) describe the BRUTIV system (Bottom Referenced Underwater Towed Instrument Vehicle, Figure 19–9) which is towed 3 m above the seabed and takes colour photographs at 10s intervals. Images are analysed to give information on sediment type, and fauna are enumerated and classified into taxonomic groups (identifiable fauna, > 2 cm in diameter).

Figure 19–9. BRUTIV system. (Source: Department of Fisheries and Oceans Canada: http://www.mar.dfo-mpo.gc.ca/science/review/1996/Gordon/Gordon_e.html accessed 3/3/06).

TOWCAM (Figure 19–10) is a towed body system that collects continuous composite colour video imagery of the seabed over transects many kilometres in length (Gordon *et al.,* 2004). Towed at a speed of 2-4 knots, it relies on a combination of dead weight and adjustable wings to control altitude, which is usually kept at 2-4m above the seabed. A Trackpoint II transponder is attached to the towed body to determine exact location of imagery over the seabed. Video imagery and navigation data are recorded on DVCAM digital tape for later analysis..

Figure 19–10. TOWCAM. (Source: Department of Fisheries and Oceans Canada. URL: http://www.dfo-mpo.gc.ca/science/Story/trawling_e.htm accessed 3/3/06).

Baker *et al.* (1999) describe a towed automatically compensated observation system (TACOS). A depressor weight and drag chain are used to stabilise the platform, and altitude is maintained via a pressure sensor control that keeps the depressor weight about 5m off the seabed. A weak-link in the drag chain prevents the system becoming snagged or entangled. A laser-spot system is used to provide a reference scale. A schematic diagram of the deployment set-up can be found at http://www.aims.gov.au/pages/research/video-sensing/papers/barker/fig1.html (accessed 11/3/2006)

Figure 19–11. TACOS. (Source: Alaska Fisheries Science Center/National Marine Fisheries Service. http://www.afsc.noaa.gov/race/groundfish/habitat/tacos_seguampass.htm accessed 3/3/06).

Norris *et al.* (1997) studied seagrass beds using a downward facing camera mounted on a 45 kg towfish. A computer integrated a dGPS data stream with the video signal, and an 'average' field of view was used in data analysis.

Hybrid systems
Gordon *et al.* (1997) and Rowell *et al.* (1997) report the use of a backward pointing camera mounted at the front of an Aquareve III Epibenthic sledge. This provided information on the undisturbed nature of the substrata as it passed into the mouth of the sledge.

Sotheran *et al.* (2004) give a comprehensive report on field trials of a small drop-down video system that can also be towed short distances while the support vessel (a small inflatable) drifts across a site of interest.

Provenance and Current usage for towed systems
Towed video systems have been used frequently in studies of the marine benthos since the 1970s (see Machan and Fedra, 1975; Holmes and Barrett, 1977). Since the early 1990s when acoustic remote sensing techniques were first used in habitat mapping, towed video sledges have been a popular method of ground-truthing acoustic data (e.g. Magorrian *et al*., 1995; Sotheran and Walton, 1997; Robertson and Pinn, 1999). Their appropriateness for this task has been discussed by a number of authors (e.g. Foster-Smith *et al*., 1999; Foster-Smith *et al.,* 2000; Sanderson *et al*., 2001), especially with respect to positional accuracy and potential damage to fragile species where repeat tows are considered.

Currently, towed video systems are used extensively throughout the world. They are regularly used in stock assessment studies for the shellfish *Nephrops norvegicus* and *Pecten maximus* (Richard Briggs, DARD, Northern Ireland; Colm Lordan, Marine Institute, Ireland; Ian Tuck, Fisheries Research Services, Scotland; Gerry Sutton, University College of Cork, Ireland. *pers. comm.*), and are frequently used along with drop-down video in habitat mapping studies (e.g. Brown *et al*., 2005;

Roberts *et al.*, 2004; Mitchell and Service, 2004). Towed body systems are used extensively for continental shelf mapping in Canada (Bedford Institute of Oceanography; Donald Gordon, *pers. comm.*) and Australia (e.g. Barker *et al.*, 1999). Sledge systems have also been used in studies of the impacts of demersal trawling and in coral monitoring (Chris Smith, Institute of Marine Biology, Crete, *pers. comm.*). In the deep sea, a towed body video system (WASP- Wide Angle Survey Photography) is used by the UK National Oceanography Centre to depths of 6000m for quantitative studies of deep-sea benthos and integration with geological data.

3.3 – Remote Operated Vehicles (ROVs)

ROVs are deployed over the side or stern of a vessel and operated whilst the ship is stationary (either at anchor or holding a fixed position) or moving slowly (either drifting or tracking the path of the vehicle). They are not towed behind a vessel as this compromises safety and operability. The major driver in the development of ROVs has been the offshore petrochemical industry where they are used for underwater inspection and manipulation (intervention), in place of commercial divers. A wide range of ROVs is available on the commercial market, falling broadly into three categories defined by their size and functionality, namely observation vehicles, light work-class vehicles and heavy work-class vehicles. Cost, complexity and maintenance requirements tend to increase exponentially as size increases. A general review of ROVs is available at http://www.rov.org/info.cfm

Mini and micro class ROVs

The "Mini" and "Micro" class ROVs are very small in size, weighing around 15 kg and the "Micro" class usually less than 3 kg (Figure 19–12). A single person can deploy and operate these systems from a small vessel, making them very useful in many applications. As they are inexpensive, they make a good alternative to diver-based surveys.

Figure 19–12. Mini ROV. Source: Loxus Technologies, Finland: http://www.loxus.com/fin/tuotteet2.htm

Observation/inspection class ROVs

Typically, ROVs in this class are light and easily manhandled (Figure 19–13). The minimum instrumentation is usually a video camera, providing the operator with real-time visual images of the any area under inspection (e.g. rock-face, pipeline etc). They may also carry basic sonar instrumentation to aid navigation in low visibility, and a rudimentary, single function manipulator arm (an opening/closing claw). Cameras may be fixed, or have some pan/tilt functions.

Figure 19–13. Observation/ Inspection class ROVs Sources: ISR–Lisbon ; R. Coggan: http://damiao.isr.ist.utl.pt/vislab/NARVAL/rov.htm

Light work class ROVs
These are medium sized ROVs with greater instrumentation payload (Figure 19–14) (several cameras, plus environmental sensors), more advanced piloting/navigation capability (e.g. auto-piloting features, navigation tracking system) and a multi-function manipulator arm (grab, rotate, bend) capable of 'light intervention' work (e.g. picking up objects for inspection).

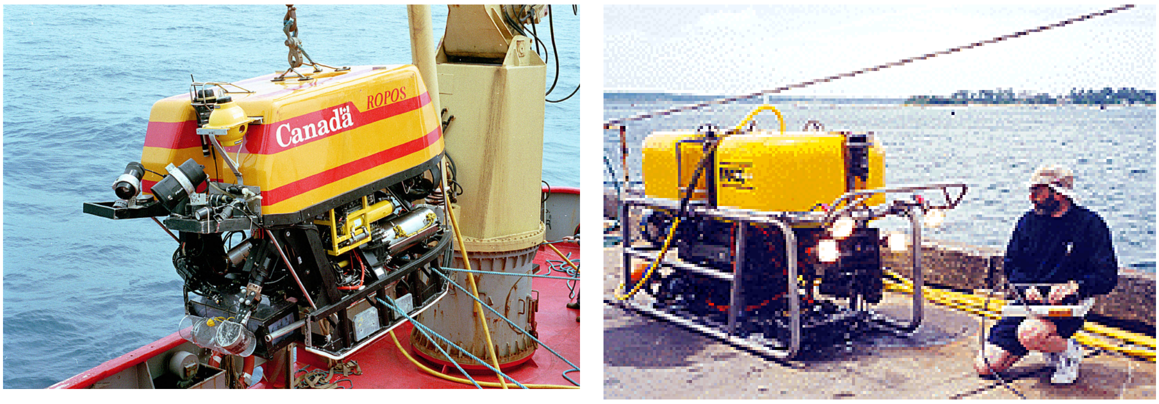


Figure 19–14. Light work class ROVs (Source: Department of Fisheries and Oceans Canada: http://newport.pmel.noaa.gov/nemo_cruise98/technology.html accessed Nov '04 and Max Rover © Hellenic Centre for Marine Research: http://www.hcmr.gr/greek_site/institutes/support/rovs.html accessed Nov '04).

Heavy work class / intervention ROVs
These are large ROVs (Figure 19–15) that can be likened to under-water robots, with a high payload capability, including cameras, sensors and sophisticated manipulator arms (approx. 7 function) capable of 'heavy intervention' work (i.e. underwater engineering, deploying and operating sediment sampling devices such as cores and probes).

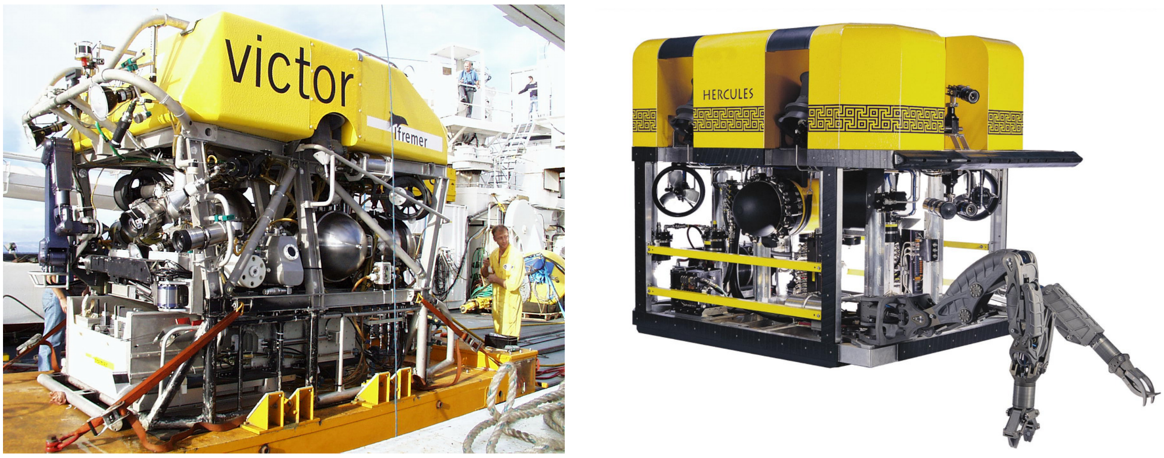


Figure 19–15. Heavy work class ROVs. (Sources: ©Ifremer/M. Bonnefoy; Subsea 7 (UK) http://www.sut.org.uk/urg_uris/website/ROVs_Page3.htm and http://www.pal.uni-erlangen.de/field/).

Provenance and Current usage for ROVs
ROVs do not currently have widespread use for seabed mapping in Europe, but are more established in the USA (e.g. Karpov *et al.,* 2005; Amend *et al.*, 2001; Veisze and Karpov, 1999). This is due, in part, to their availability and cost, as well as the requirements for maintenance and specialist technicians. The major technical hurdles in their development have been overcome and reliable systems are now available. The main developmental phase now lies in software systems for analysing the video record and integrating it with other sample data (acoustic or ground-truth

sampling). Large ROV systems (light and heavy work class vehicles) tend only to be available in large national institutes. Smaller institutes are restricted (by cost) to own or hire smaller systems.

4 – Review of Existing Standards and Protocols

4.1 – Acquiring Samples (Video Footage and Stills Images)

The basic set-up is illustrated in the two schematic diagrams in Figure 19–16. This review encountered a number of survey strategies, which fell into four generic types, some of which are specific to the equipment used. These were:

- Spot surveys, commonly used with drop-cameras or ROVs to investigate a particular point or small area of seabed, from a vessel at anchor or holding a fixed position.
- Drift surveys, commonly used with drop-cameras or ROVs to investigate a limited area of seabed in exploratory surveys from a drifting vessel.
- Towed transects, most frequently used to cover pre-determined transect lines with gear such as video sledges or demersal platforms towed behind the survey vessel.
- Piloted transects, only used by ROVs, to follow a pre-laid transect marker (e.g. rope) or predetermined course (only ROVs with advanced navigational capabilities), with the support vessel navigating/following behind the ROV.

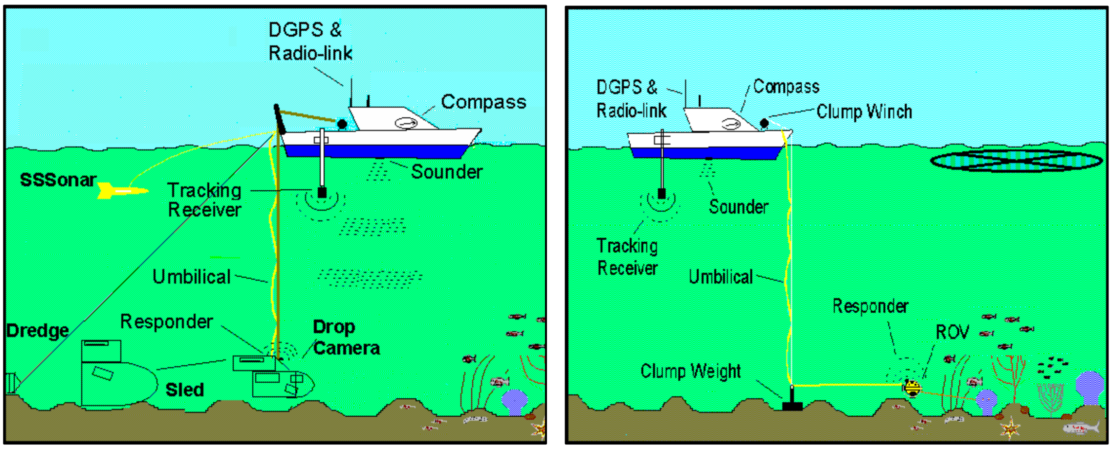


Figure 19–16. Drop Camera (left) and ROV operations. (Images courtesy of Roland Pitcher, CSIRO, Pitcher *et al.* 2001).

It was common practice to record a brief title or 'header' shot at the beginning of the video or stills sequence to capture metadata relating to the survey (e.g. data, survey and site details etc). The relevant information was written onto a suitable surface (e.g. a white board) and recorded by the gear (video or stills camera) prior to deployment.

Details on the general practical use of remote underwater camera systems, specific data media requirements and best practise in the use of imaging techniques are provided by the Guidelines for the Study of the Epibiota of Subtidal Environments (Working Document- ICES BEWG, 2004). The document also deals with the conversion of photographic film to digital images, and their subsequent analysis. Several other documents also consider the safe curation of video and photographic material. The making of back-up copies is addressed in Service and Golding (2001), while the storage of digital video data and the possibilities of play-back through both TV monitors and computers are discussed in Sotheran and Foster-Smith (2004). Most digital cameras now come complete with software that enables editing and/or play-back via computer, and many computers already have software that can be used for play-back purposes (e.g. Windows Media Player).

The International Organisation for Standardisation (ISO) working document "Water quality – Guidance for quantitative sampling and sample processing of marine soft-bottom macrofauna" presents guidelines for general survey documentation, field logs, and defining survey stations. It is recommended that such guidelines be incorporated into the protocols for survey using remote video and stills cameras.

Quantitative analysis of video images collected by remote camera systems can be problematical due to the variable perspective of the image caused by the mobility of the camera platform and adjustability (pan, tilt, zoom) of the camera. Without any form of visible reference scale, it is not possible to determine the scale and extent of the image or of features (e.g. species) within it. This problem has been largely overcome by the development of laser scaling devices (e.g. Barry and Baxter, 1992; Pilgrim *et al*., 2000) which employ two or more parallel laser beams set a fixed distance apart to provide visible reference points in the video image. Such devices are well established and can be fitted to any camera system. The manufacturers supply protocols for their use and it is unlikely that these will require further development for application to habitat mapping.

4.2 – Drop Cameras

The most complete source of protocols for the use of drop-cameras found during this review was Sotheran *et al.* (2004). This describes the development and use of a small drop-camera system suitable for deployment from inflatable boats for the purpose of identifying biotopes of populations of conspicuous species. Although drop-camera systems were used in a number of studies in North America, no detailed documents relating to standards and protocols were found. Australian studies cited in a national workshop on video sensing in 2000 gave some details of protocols for acquiring data, but these tended to be study-specific (see http://www.aims.gov.au/pages/research/video-sensing/index.html).

To enable comparisons of data collected by different groups and agencies at different temporal and spatial scales standardised methods need to be developed ("Standard Operating Practices") for the collection of data for different habitats. Additionally standardising database management and the way in which raw and numerical data is stored and accessed is crucial.

The workshop highlighted that there is a lot more to successfully using video than most participants realised. Consequently an "Idiots Guide to Fisheries Videography" should be developed and maintained on a webpage accessible to all Australian fisheries researchers (Source: http://www.aims.gov.au/pages/research/video-sensing/report/report_frames.html accessed on 15 Nov 2004).

It should be possible to adapt the protocols detailed in Sotheran *et al.* (2004) and Holt *et al.* (2001) to cover a number of different types of drop-video system for the task of habitat mapping. The greatest hurdle might be in deciding exactly what should be mapped (habitats, biotopes, species abundance, species diversity) as this will have great bearing on the way in which the systems are operated.

4.3 – Towed Platforms

The following documents provide sufficient technical detail for the use of towed video systems, including the equipment required, set-up (both of towed system and deck systems), deployment and survey vessel requirements:

- A procedural guideline for *in-situ* survey of sublittoral epibiota using towed sledge video and still photography (Service and Golding, 2001).
- A procedural guideline for identifying biotopes using video recordings. (Sotheran and Foster-Smith, 2004).
- Doyle (2004) and Shand and Priestly (1999) provide additional detail on equipment set-up and deployment of the towed sledge system specified by Service and Golding (2001).

Additional detail to that of Service and Golding (2001) is provided by Sotheran and Foster-Smith (2004) regarding survey strategies with respect to baseline mapping and biotope/habitat inventories. Both of these procedural guidelines are appropriate for use in habitat mapping studies, and make specific reference to such research. A merging of these two documents, which relate to a large-framed towed sledge and smaller drop-down/ towed systems respectively, would be recommended such that they are more generically applicable and explain the differences between drop-down video approaches and towed video approaches.

Survey design considerations are explored by the CEFAS/DTLR Guidelines for the conduct of benthic studies at aggregate dredging sites, specifically the chapter by Rees and Boyd (2002). In addition, these guidelines present an overview of survey approaches and recommended guidelines for the deployment of camera systems (Brown *et al.*, 2002). Survey approaches are also explained and discussed with respect to underwater video use by Barry and Baxter (1992).

It is recommended that the MESH guidelines include further detail on survey design considerations for using towed video systems, in particular discussing scale issues and survey stratification. It is common practice (Sotheran and Walton, 1997; Foster-Smith *et al.*, 2000; Mitchell and Service, 2004) that existing acoustic/geophysical data is used to aid stratification of video survey effort, through the classification of acoustic data into 'ground-type' classes. For statistical reasons, a number of 'replicate' tows are considered to be best practise within each 'ground-type'. How the number of replicates are decided and where such video tows should be placed within each ground-type for ground-truthing purposes is a matter for ongoing research, as such survey design / statistical considerations have enormous implications for the confidence of the resulting habitat maps.

Procedural guidelines for the set-up and deployment of an alternative towed video system, the towed automatically compensating observation system (TACOS) described above, are detailed in Barker *et al.* (1999). This document does not however, address in detail survey design for use in habitat mapping studies.

4.4 – Remote Operated Vehicles

The manner in which video data is acquired depends on the purpose of the surveys and is formally laid out in the survey design. There are two generic survey designs, namely a descriptive (or semi-quantitative) design and a quantitative design. These have been adequately described by David Donnan in a draft of Procedural Guideline 3-4 of the Marine Monitoring Handbook (Davies *et al.* (2001) entitled 'Descriptive and quantitative surveys using remote operated vehicles'. As this document is not yet available, the relevant extract is reproduced below (with permission of the author). Note that further discussion is made of quantitative analysis techniques in section 6 below.

Descriptive ROV survey

For descriptive or semi-quantitative ROV surveys the standard MNCR phase II methodology may be followed (Donnan, 1997), using the SACFOR scale to record the abundance of species identified (Hiscock, 1996). In order to assist the standardisation of results it is necessary to establish a route and list of habitats which surveyors can use on future/repeat surveys being carried out within a monitoring programme. Consequently, a detailed site description will be required during the baseline survey. The route specification may include information such as, 'launch ROV at point xx^{o}N yy^{o}W, at 30m bcd, follow a course of 180° over sand to base of boulder slope at 20 m bcd. Ascend boulder slope to surface'. A minimum search time to be spent on each biotope could be specified.

Quantitative ROV survey

There are two principal approaches to the quantitative use of ROVs which will be appropriate for SAC monitoring. These involve the enumeration of selected target species within: a) a known area or distance - transects, or; b) a period of time - species-time counts. Papers by Barry and Baxter (1992) and Michalopoulos *et al.* (1992) provide a detailed discussion of the main considerations and constraints, both statistical and logistical, which apply to these techniques.

Transects

Using an ROV to generate a sequence of video to be analysed using standard transect methodology which will allow measurements of density within known-sized areas (Krebs, 1989). Either strip or line transects may be employed but the accuracy of both techniques depends upon reliable information concerning the dimensions of the field of view and the distance travelled over the bottom (Barry and Baxter, 1992). This is a potential problem with the kind of low cost ROV that is likely to be employed in SAC monitoring as the variations in ROV altitude, pitch and roll will result in video frames of unequal and unknown size. The solutions to this difficulty range in complexity and cost from laser range-finding/measurement (Tusting and Davis, 1992) to simple rods held in front of the ROV (Bergstrom *et al.*, 1987). Alternatively, a suitably marked transect line may be deployed where it is feasible to do so. This line provides a visual datum for both the length of transect and taking measurements and can greatly assist the standardisation of dives (Donnan ., in prep). This latter technique is, generally, most useful over sediments or where the seabed is even enough to lay the transect easily. The length of transect and marked intervals will vary according to site specific requirements and the target species involved. The transect should be rigged with a heavy shot at either end, each with a marker buoy. A further benefit is that the position and bearing of the transect can be fixed by the survey vessel dGPS. Depending on the target species involved, counts can be made of organisms touching the transect or organisms within a pre-determined distance of the line.

Species-Time Counts

This technique may be used to determine relative abundance of species where it is too deep, or the substrate is too rugged to deploy a marked line or fly a straight transect. It also overcomes the difficulties in relation to transects mentioned above, when the size of the video frame is unknown. Michalopoulos *et al.* (1992) report the use of a species-time census procedure giving density estimates not significantly different to a strip transect. The surveyor scores the occurrence of species over a number of segments of video from a ROV dive, each segment of equal time. From these scores a relative abundance can be calculated.

In the south-eastern USA, the Coastal Ecology and Conservation Research Group of the United States Geological Survey (USGS) has used ROVs on the continental shelf of the Gulf of Mexico to assess community structure of fish and epifaunal assemblages (largely driven by the requirement to assess Essential Fish Habitat). At each site, twelve replicate video transects were recorded (2 minutes duration), and 30 replicate still-images (for assessing percentage cover). The position of replicate samples was randomised, using randomly selected bearings for each video transect and random timings along each transect for the stills images.
(Source *http://cars.er.usgs.gov/coastaleco/Cruise-Rept-NEGOM-TM-2003-01/methods/methods.html* accessed on 12 Nov 2004).

Another focus of ROV work on the Pacific coast of the USA is the Oregon Department of Fish and Wildlife Marine Habitat Project, which has successfully developed survey techniques using small ROVs in their Rocky Reef Assessment programme, over a period of approximately 5 years (Amend *et al*., 2001; Fox *et al*., 2000; Merems, 2003). Amend *et al.* (2001) provide detailed description of their survey and assessment procedures and protocols and note that "*ROV sampling protocols are in an ongoing evolution*" and "*The challenges we have faced over the last two years in accepting this technology as a research tool have mostly been overcome. While operations are by no means a simple process, they have become facilitated by experience*." The ROV surveys are guided by the output of acoustic surveys that have mapped the reefs (Merems, 2003), using straight-line transects across the reef to ground-truth the sonar map, collect fish abundance data and investigate community diversity. Transects are typically ~350 m long and provide ~30 minutes of video record. The entire footage is previewed to assess sections of suitable quality for quantitative analysis, and these sections 'sub-sampled' at periodic time intervals to assess faunal densities. Periods where the ROV is rested on the seabed (e.g. for close inspection or changing the video tape) are excluded from such analysis.

The Oregon Department of Fish and Wildlife have been working with the California Department of Fish and Game to develop standardised sampling techniques for small ROVs. Some of this work, where ROVs have been used in monitoring studies of the Santa Barbara Channel Islands Marine Protected Areas, has now been published at: http://www.dfg.ca.gov/mrd/fir/dss.html#ROV_CI. Survey design was based on random stratified sampling, with survey lines (~3 km long) running parallel to prevailing depth contours and ≥20 m apart (Karpov *et al*, 2005). Prior knowledge from acoustic and ROV surveys was used to exclude areas of sand from the survey, as the objective was to assess fish populations on rocky reefs. The ROV was equipped with forward and downward looking cameras (each with a laser-spot system) and a ranging sonar and flown at an average 0.5 m above the seabed at speeds of 0.5 to 1.0 metres per second. Deployment included the use of a 136 kg 'clump' weight, suspended ~5 metres off the seabed, to prevent excess drag on the umbilical. Scientific papers reporting the design and precision of the surveys are currently in preparation (Karpov, pers. comm.).

5 – Spatial Positioning and Georeferencing of Information

A multiplicity of data standards exists with respect to recording, expressing and displaying point locations on the globe. Three major variables are involved, namely the datum on which measurements are made (there are literally hundreds, e.g. world geodetic survey 1984, WGS-84), the way the coordinates are expressed (e.g. latitude/longitude, eastings/northings) and the projection on which those positions are displayed (common variants are the Universal Transverse Mercator, UTM, and Ordnance Survey of Great Britain, OSGB, grid). Although converting between different datums or projections is usually possible, it would be beneficial to adopt a standard (e.g. WGS-84/UTM) and to ensure that the geodetic parameters of the data set are always recorded in the positional metadata. These matters are discussed succinctly by Kvitek *et al.* (1999). A standard should also be adopted for the expression of Time to avoid confusions that arise from logging local time. The most suitable standard for Europe would appear to be the Universal Time Constant (UTC) also known as Greenwich Mean Time (GMT).

The position of a remote camera system (either towed, drop-down or ROV) and any data derived from footage collected by the system can be obtained in a number of ways, with varying associated accuracies:

The position of the support vessel, as determined from a differential Global Positioning System (dGPS), can be used as an approximation for the position of the remote camera system. This is particularly applicable for drop-down camera systems, and when tidal currents are weak. A spatial buffer zone may be used to indicate visually (e.g. within a geographical information system (GIS)) that the position is not precise, with the size of the buffer relating directly to the degree of positional uncertainty.

A 'corrected' position can be derived by applying a calculated 'layback' to the support vessel's dGPS position. This is particularly applicable to towed camera systems. The layback is calculated by simple trigonometry using information on the length of cable deployed, the angle of the towing wire and the water depth. Tidal strength and direction also need to be considered, as these may laterally displace the towed gear from the ship's track. The 'corrected' position will be subject to moderate degree of uncertainty, which can be represented visually by using a spatial buffer (see above).

When displayed in a GIS, the video track can be 'registered' against known seabed features. The approximate position of the camera is plotted (using the ship's position) and subsequently corrected so that features seen in the video record (e.g. rocky reefs) are spatially aligned with the corresponding features that have been accurately geo-located by other means (e.g. high resolution bathymetry from multibeam sonar). This method is somewhat subjective and imprecise, but is useful for correcting gross positional errors.

Acoustic tracking systems can be fitted to the remote camera system, providing information on its range, bearing and heading relative to the support vessel. The true position of the camera can be derived in real-time by applying this information to the dGPS positions of the vessel. These Ultra-Short BaseLine (USBL) systems provide far greater accuracy and precision than the other methods described above. Common examples are the LXT Tracker and Track Point II systems (O.R.E. Inc.) and HiPAP (High Precision Acoustic Positioning; Kongsberg Simrad). They are widely used on ROVs for vehicle navigation, but are equally applicable for use on towed and drop-down camera systems, particularly in deeper waters where layback is likely to be considerable with an associated increase in positional uncertainty. However, it should be noted that in practice USBL systems will frequently not function well when the target is directly beneath the ship's transducer as is often the case with drop-down systems. As tracking systems are now relatively inexpensive they should be considered essential equipment for habitat mapping surveys. The systems are well established, with protocols for their use provided by the manufacturers. It is unlikely that these will require further development for application to habitat mapping.

All of the above methods for deriving the position of remote camera systems are dependent on the quality of the GPS data, so measures should be taken during surveys to ensure this quality is maintained (i.e. activating the differential lock for the vessel's GPS and monitoring the GPS signal). Guidelines on positioning using dGPS are given by Ince *et al.* (2001). Whenever possible, an estimate/indication of positional accuracy should be recorded, as this is an important consideration in determining the accuracy and confidence of the derived habitat maps.

The use of acoustic tracking devices on ROVs is well documented in habitat mapping: Amend *et al.* (2001) give details of the Track Point II system used for ROV surveys of rocky reefs in Oregon, USA. Veisze and Karpov (1999) also give extensive details of a system for geopositioning an ROV and the subsequent use of that data in a GIS to locate frame-grabbed images and their associated habitat/species data. It is sometimes standard practice to allow an ROV equipped with acoustic tracking systems to periodically sit on the seabed for a short while (> 30 seconds) to collect a time-series of positional data from a fixed point, thus enabling calculation of a standard deviation error in the recorded dGPS position.

In some survey designs there was not a requirement to precisely locate the remote camera. Here, the equipment was deployed inside a pre-defined, georeferenced polygon to make an inventory of habitats that occurred there, and no attempt was made to map habitat or biotope boundaries within the existing polygon.

Automated real-time mapping of habitat boundaries by ROVs has recently been developed under the SUMARE project (http://www.mumm.ac.be/SUMARE/). The focus of the project was to develop intelligent autopiloting capabilities for their AUV ('MAUVE') and ROV ('PHANTOM') platforms using optical or acoustic sensors and pattern recognition algorithms. This has resulted in their ability to track and map bathymetric contours or habitat boundaries. As an emerging technology, this project is perhaps the most accessible (civilian) source for standards and protocols relevant to the use of such systems for marine environmental monitoring. The project completed in 2003 and project documents are available from the website, including details of the 'ROV configuration with adaptive sensing and guidance'.

Video footage and stills images should be time and date stamped, as this information can be cross-referenced to the time stamp in the GPS data to aid geo-referencing. Positional data streams can be imprinted onto video footage using a proprietary data-overlay system such as TrakView®. Alternatively, recent technological developments have enabled the positional data to be recorded on the video's audio track, which can then be 'replayed' using dedicated software (e.g. CamNav Mapper (http://www.blueglen.com/prod_camnav_single.htm)). This has the advantage that parts of the video image are not masked or obscured by the data overlay. Equivalent systems for recording positional data on (or with) still photographs were not encountered in this review. If the camera was fired by an operator activating a trigger, then the time and position of each firing was recorded manually on a log-sheet. If the camera was triggered by an auto-timing device, the position of each shot could be derived by cross-referencing the time-stamp to the GPS record. Alternatively, when a stills and video camera were used in combination, a tell-tale flare of the camera flash appeared on the video record, allowing the position of the stills image to be read from the data overlay when the video record was reviewed.

Once the video and photographic images have been analysed and interpreted (see next section) the resulting information needs to be mapped. This is achieved by linking the data derived from the interpretation with positional data (usually in a database), and displaying it in a GIS. A variety of methods are available for representing both point and transect data, using shapefiles with habitat attributes and applying dynamic segmentation techniques, which are clearly presented by Nasby-Lucas *et al.* (2002). Further details on presenting data in a GIS are available from any relevant software manufacturers (e.g. ESRI).

6 – Video Analysis and Interpretation

The manner in which the images are analysed and interpreted is dependant on a number of factors, including the image quality and the purpose and design of the survey. It is imperative that the required outcome of the analysis and interpretation is fully considered prior to conducting the survey to ensure the material collected is fit-for-purpose and will satisfy the needs of qualitative, semi-quantitative or fully quantitative analysis. Analysis and interpretation consider both the biological and physical characteristics observed in the images. The presence of a scale object within the field of view provides an immediate appreciation of the scale of the image and is often an important contributing factor in the correct assessment of sediment type (e.g. in discriminating gravel, pebble and cobble) and species identification.

6.1 – Analysis

Video and photographic data can be subjected to a number of levels of analysis, depending on the initial survey design and the level of information required from the analysis. Qualitative analysis usually involves just a visual interpretation of the material, accompanied by some degree of faunal identification. Although it can be achieved quickly and may appear 'simple', it relies heavily on the experience of the observer, and can therefore be highly subjective. Habitats can be identified to

EUNIS levels 3 and 4, and boundaries between habitats can be identified, by sight, on transect surveys. Qualitative analysis is frequently a pre-cursor to any from of quantitative analysis.

A relatively rapid method of semi-quantitative analysis is scoring the relative abundance of species on a categorical scale. In the UK, the SACFOR scale (superabundant, abundant, common, frequent, ocCASIonal, rare) is often used (Sotheran and Foster-Smith, 2004), having been initially developed by Hiscock (1996) for the UK Marine Nature Conservation Review (see: http://www.jncc.gov.uk/page-2684). When combined with substratum descriptions, this type of analysis is appropriate to the application of local and national habitat classification schemes (usually down to EUNIS level 5).

Photographic stills or video 'freeze-frames' may be treated as point quadrats and subjected to species counts or percentage cover estimates, providing fully quantitative data. The image is often overlain with a physical or digitally generated grid to facilitate counting or estimates of cover (Service and Golding, 2001; ICES BEWG, 2004). Where the field of view can be calculated, the method can be used to derive measures of absolute species density.

There are several established approaches for quantitative analysis of video footage collected by a transect survey. These all require the length of the transect to be known or calculated (either through the use of an odometer or from the positional data record). Where the field of view remains constant (e.g. from a towed video sledge) and visibility is good, direct counts are made of all the organisms encountered over a known distance to derive measures of absolute density. Where visibility is poor, a line-transect method may be used (Bergstedt and Anderson, 1990), dividing the image into a number of corridors and making species counts for each corridor. Visibility is assumed to be best in the central corridor, and counts made here are taken to be error-free. As visibility is progressively reduced in the outer corridors, counts made here are adjusted by a relevant factor to account for animals that may have been obscured by the low visibility.

Where field of view is constantly changing (through changes in topography, altitude of the camera or visibility) and cannot be easily determined, species-time methods may be used to quantify the visual data, counting the number of each species encountered in a fixed time to derive estimates of relative abundance. Service and Golding (2001) address the species-time methods in detail, and both transect methods and species-time methods are described briefly in the ICES BEWG Guidelines. Published, peer-reviewed literature provides further details regarding these techniques, and importantly describes which technique is appropriate given different survey methods and conditions (e.g. Michalopoulos *et al.,* 1992; Bergstedt and Anderson, 1990; Kimmel, 1985; Malatesta *et al.,* 1992).

In the south-eastern USA, the Coastal Ecology and Conservation Research Group of the United States Geological Survey (USGS) has used ROVs on the continental shelf of the Gulf of Mexico to assess community structure of fish and epifaunal assemblages (largely driven by the requirement to assess Essential Fish Habitat). They detail their protocols for video and stills analysis (especially from reef areas) as follows:

Video Tape Analysis
All fish observed during the 2-minute transects will be tabulated and identified (to species when possible). Sessile epifauna greater than 2 cm in height (e.g., gorgonians, sponges, black corals, crinoids) and intercepted by the bottom of the video frame during each transect will also be tabulated. Epifauna will be identified to lowest possible taxa, and grouped into functional categories (i.e., see fans, branching corals). Additionally, the presence/absence of encrusting algae, cup coral colonies, and discarded longline was scored on 15 second intervals during each transect. Navigational logging of the ROV position with the Hypak Max system will be used to determine the approximate length of each transect. Average density (individuals/m^2), of both fish and epifauna, will be determined.

Still Photo Analysis
Epifaunal percent cover will be determined from the digital still photographs. Using the Point Count Program originally developed for the Florida Keys Coral Reef Monitoring Program, random points are overlaid on top of each photograph and the taxa that are intercepted by a point recorded. Percent cover is subsequently determined. Analysis of images collected during the TM-2002-01 cruise indicated no significant difference between the percent cover estimates derived using twenty versus

forty, sixty, eighty, or one hundred random points (Paired T-test, P>0.05). Therefore, twenty points were used for all analyses."
(Source: http://cars.er.usgs.gov/coastaleco/Cruise-Rept-NEGOM-TM-2003-01/methods/methods.html accessed on 12 Nov 2004).

Video footage is relatively simple to acquire, so large amounts can be accumulated, even on small survey. As processing time can be extensive, it is often not practical to derive quantitative species data for all this footage, so sub-sampling may be necessary within each video record. The precise method of sub-sampling may depend on the survey objectives, but where the data will be subjected to statistical analysis, consideration should be given to how sub-sampling will affect the resulting data quality. For instance it will be important to ensure a representative number of species have been encountered and to maintain sample independence (e.g. removing effects of spatial autocorrelation). In the case of habitat mapping, the requirement to identify and locate habitat boundaries will also have a bearing on the methods used for analysis and sub-sampling.

The Oregon Department of Fish and Wildlife use long (>30 minute) ROV transects when surveying rocky reefs. The entire footage is previewed to determine sections of suitable quality for quantitative analysis, and these sections 'sub-sampled' at periodic time intervals to assess faunal densities. Frame-by-frame advance allows detailed identification of organisms, measurements, and habitat interpretation. Amend *et al.* (2001) also detail their methods for estimating the surface area of the seafloor sampled in the video (required to calculate faunal densities) and how they cleanse and process navigational data to geo-locate their observations.

6.2 – Automated Processing/ Analysis

An alternative method to direct identification and manual enumeration of epibiota on video freeze-frames or stills images is to utilise image processing software. This can auto-classify an image on the basis of 'training sites' identified by the operator. The training site highlights a known species or taxon, and the software selects other parts of the same image having the same pixel values (or signature properties) and then calculates the total area covered by that taxon. This works well for certain species/taxa/conditions and may be a rapid and effective way of accurately calculating percentage cover. Scion software is an example of such a system (http://www.scioncorp.com/).

Pitcher *et al*. (2001) have developed a semi-automated processing for analysing images collected for the purpose of counting and measuring fish. This could be adapted for analysing epibenthic megafauna and so be relevant to habitat mapping.

Automated methods of video analysis and interpretation were also considered at an Australian national workshop on video sensing held in 2000 (see URL: http://www.aims.gov.au/pages/research/video-sensing/index.html), but the application related mostly to quantitative surveys assessing gross faunal coverage (rather than identifying habitats) or to counting large organisms such as fish (Harvey and Cappo, 2001).

Owing to the time and cost involved in developing automated analysis of video records such an approach is probably beyond the scope of most habitat mapping studies. Human interpretation will probably always be superior for extracting data relevant to identifying seabed habitats, so developing our own capabilities in habitat recognition and classification is likely to be more productive than developing automated video analysis methods.

7 – Data Storage

The analysis of video and photographic images results in data of many different formats. For example, geo-referenced images can be associated with numeric records of species abundances, and qualitative or semi-quantitative comments on substratum type, bedforms etc. Relational databases are an ideal way of recording such associations and an example database structure is given in Figure 19–17.

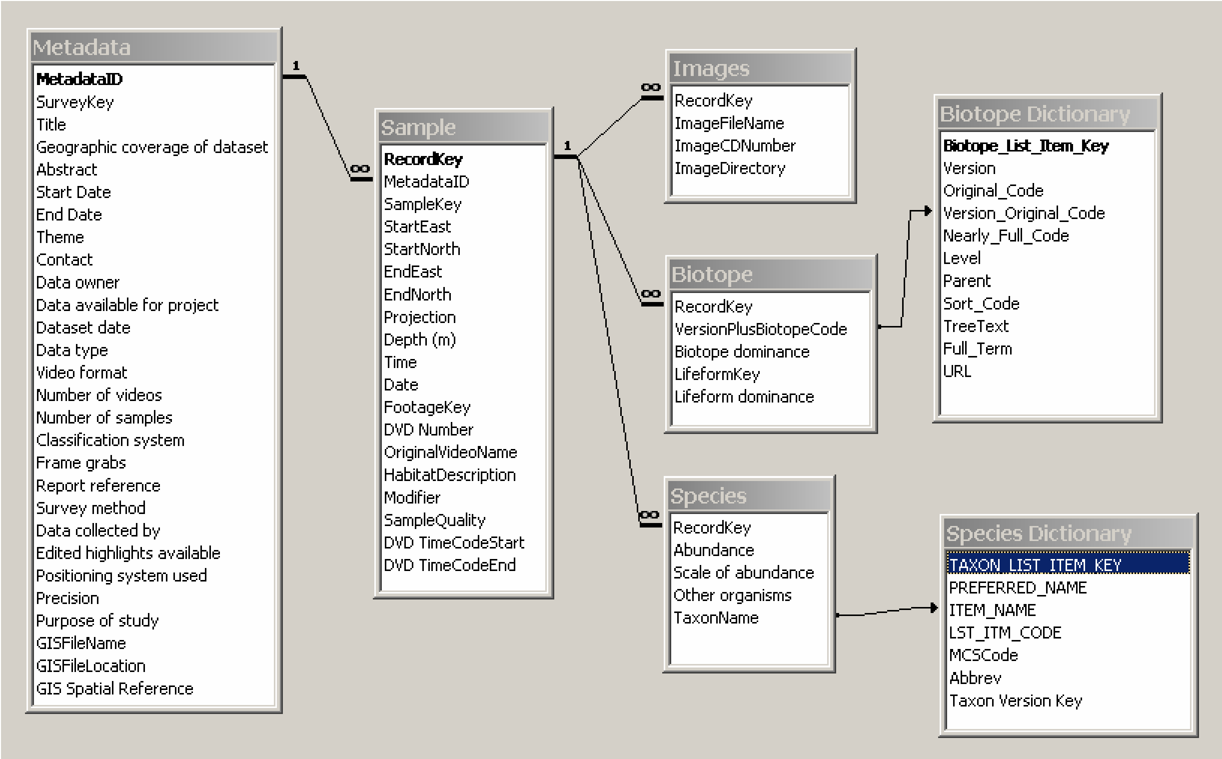


Figure 19–17. Relationship diagram of example Access database used to store video sample data.

A GIS is often the most convenient way of visualising the information held in such databases, allowing the data to be viewed in relation to other pertinent information. For habitat mapping, the overlaying of such data on top of images depicting seabed bathymetry or sonar backscatter can be a powerful aid to interpretation, complementing the other methods detailed below.

8 – Data Interpretation

The interpretation of video-derived data into habitats is governed principally by the approach to classification. A top-down approach imposes an existing classification scheme on the data, while a bottom-up approach allows the classification to be derived from the (statistical) analysis of the data. A data-driven, bottom-up approach necessitates the use of exploratory, multivariate, statistics to enable the data to 'speak for itself' and guide classification into habitats. Such a method is relevant perhaps for looking at ecologically-functional local habitats and for habitat modelling, but is critically dependent on video data being of a high statistical quality and/or a large sample size. A top-down approach to habitat classification, where data is fitted to an existing classification scheme, necessitates the extraction of characterising species and key physical parameters such as dominant substrates from video-derived datasets.

Where quantitative data has been derived from the video footage it is amenable to statistical investigation, which may aid classification into habitats for both top-down and bottom-up classification approaches. In such cases, the statistical approaches followed may be similar to those used for any biological sample data, such as that gathered from grab samples. Multivariate ordination and cluster analysis were applied to species time data derived from video by Magorrian and Service (1998). Details for such analysis are provided in many guidelines, such as ISO/FDIS 16665, Schratzberger and Boyd (2002), ICES BEWG (2004) and Thomas (2001). It is recommended that such details are at least appended to towed video use guidelines, where the derivation of quantitative data has already been addressed.

There appears to be little available information in guideline format that relates to how the results of statistical treatment of quantitative data may be interpreted into habitat classes. Multivariate data analysis such as dendrograms and MDS (multidimensional scaling) plots may enable identification of discrete habitats. The use of characterising species, as determined through analyses such as SIMPER (similarity percentages; Clarke and Gorley, (2001), may facilitate classification of community clusters identified from multivariate statistical routines such as MDS and ANOSIM (analysis of similarities; Clarke and Gorley, (2001). This subject area requires some attention in future guidelines, however it is heavily dependent upon whether a top-down or bottom-up habitat classification approach is being used to interpret data, and, if top-down, which habitat classification scheme is being used.

Assignment of habitats is crucial to quality assurance, and ought to be completed by experienced personnel familiar with the study area, with a good working knowledge of the range of potential habitats available in the region. The attributed habitat types should be verified by another suitably qualified worker (Sotheran and Foster-Smith, 2004).

The organisation of semi-quantitative data into biotopes (from the UK MNCR classification) is detailed in Holt *et al.* (2001) and Sotheran and Foster-Smith (2004). Spatial scale considerations are also addressed here. In general, the recommendations set out by Holt *et al.* (2001) for processing video records using a top-down classification approach and semi-quantitative data are appropriate for the purposes of many habitat mapping studies, and could be adopted with minor revision.

Where possible, any additional data ought to be used to aid the assignment of habitats. For example, if grab samples have been collected in close proximity to parts of the video tows on what appears to be acoustically-similar ground, particle size data should be used to help determine substratum (for example, it may be difficult to distinguish fine sand from muds on video). If diver surveys have been completed in the same area, this data may also aid identification of some species viewed on the video. Such combining of available data is not currently addressed in existing guidelines.

The recent advent of accurate positional labelling of video sequences obtained by underwater video techniques has enabled some high-tech presentation of the material. One such method is in video mosaicing, where Ifremer have two notable products. The first is the MATISSE system (Mosaicing Advanced Technologies Integrated in a Single Software Environment) which produces geo-referenced video mosaics of the seabed from a vertical, downward looking camera (Information at: http://www.cesos.ntnu.no/~jouffroy/Publications/Vincent-2003.pdf). The second is a visualisation software package 'Adelie' (details at http://www.ifremer.fr/fleet/systemes_sm/adelie/fiche-adelie151-uk.pdf) which performs georeferencing and mosaicing functions on video obtained by any underwater vehicle, and enables interactive mapping/analysis of that video within ArcView GIS. This is a state-of-the-art tool providing a one-stop-shop for the processing, analysis and mapping of underwater video. Other software available to spatially reference video includes Blue Glen Technologies CamNav Mapper (http://www.blueglen.com/prod_camnav_single.htm) and RAVEN View (http://www.observera.com/ravenview.html) software. These presentation methods may facilitate data interpretation for habitat classification.

Another high-tech visualisation method is SeeTrak, which enables visualisation, analysis and data fusion (the meaningful integration of information provided by disparate sources) of acoustic and video data. Developed in conjunction with the AMASON research project (Advanced MApping with SONar and Video: http://www.ece.eps.hw.ac.uk/~amason/), the software is marketed by SeeByte Ltd (Scotland, UK). Promotional material indicates a military/defence application, but the system may have applications in habitat mapping due to its ability to allow in-combination interpretation of multiple remotely sensed data sets.

From existing studies where towed video systems have been used for habitat mapping, it appears that it is possible to identify habitats from such footage to EUNIS habitat classification level 5. However, more frequently habitats have been classified to level 4. From the author's experience the use of high resolution photographic stills taken at regular intervals significantly aids interpretation of video footage and permits classification to a higher EUNIS level.

8.1 – Estimated Data Processing Times

As a rule of thumb, the most simple analysis of video records takes approximately 2 to 3 times the actual duration of the video record. The method of analysis can vary greatly however, depending on the purpose of the survey, and so more time is required (possibly up to 10 x duration of record). Simple exploratory surveys may just record the range of habitat types observed, whereas monitoring surveys may require quantitative species assessments or counts to be made of specific objects or features (e.g. burrow entrances being counted in *Nephrops* stock assessment surveys).

Estimates of processing time should also include the time required to process navigational data (prior to, or in parallel with the video processing) and to subsequently geo-reference the observational data (see above). Finally, time should be allowed for entering data into a suitable database and display of information in a GIS.

9 – Overall Evaluation of Existing Standards and Protocols

The guidelines that are specific to the use of remote video systems cover the importance of georeferencing adequately, however these guidelines do not cover the analysis of video or photographic data in much detail, with limited information on the different options available and where each option is suitable. It is recommended that guidelines incorporate semi-quantitative and the various quantitative data analysis approaches addressed above. A decision tree as to which approach is suitable (dependent on purpose of survey/habitat map) should be developed to facilitate analysis. It is generally recommended that where resources allow quantitative data should be extracted from photographic/video footage, which may then be treated in a number of ways for data interpretation, including full statistical analysis. Quantitative data can always be re-classed into semi-quantitative abundance classes to simplify further analysis where necessary.

There does not appear to be a single document source that adequately details standards and protocols for the various methods of processing and interpreting video data for the purpose of habitat mapping. However, there are several sources that deal with processing the data acquired by different video survey strategies (as detailed above). These would appear adequate for habitat mapping purposes but need to be augmented with guidelines which stipulate how thorough the processing needs to be in order to categorise habitats at each of the hierarchical levels of the EUNIS system (classification system adopted for the MESH project). If the aim of the processing is to identify Level 6 habitat categories, this will require far more detailed processing of the video than if the aim was to identify habitats to Level 4 categories, with obvious cost/time implications. In terms of producing timely, tangible results, it may be beneficial to undertake a rapid processing first (say to Level 4) so that a coarse interpretation is almost immediately available for plotting, and follow this with a more thorough processing at a later date to provide greater detail. We must not lose sight of the fact that we are attempting to map habitats, and this may require far less intensive processing and analysis than would a quantitative monitoring survey, depending upon the proposed use of the resulting habitat map.

10 – Common Recommendations

There is a reasonable resource of existing standards and protocols that require adapting for the purpose of seabed habitat mapping and thoroughly testing before 'Guidelines' documents can be produced. As part of the MESH project, a web-based habitat signatures catalogue is in preparation which will include examples of video images for a range of EUNIS (and additional) habitat types, in order to help facilitate and harmonise standardised video interpretation. As with other visual techniques, confidence of interpretation should be high.

It appears there could be a massive potential for over-processing video records in an attempt to gain quantitative data that, in the context of habitat mapping, may provide little marginal benefit over semi-quantitative of qualitative analysis.

A merging of the guidelines provided by Service and Golding (2001) and Sotheran and Foster-Smith (2004), which relate to a large-framed towed sledge and smaller drop-down / towed system respectively, would be recommended such that the guidelines are more generically applicable. Differences between towed and drop-down systems should be addressed.

Further details on survey design considerations for using towed video systems should be included in future guidelines, in particular discussing scale issues and survey stratification with respect to use in ground-truthing remotely sensed data and implications for confidence of resulting habitat maps.

Guidelines should include data media considerations (including adequate backing-up of data, which is a particular issue with imaging techniques) and field log-keeping.

Guidelines should incorporate both semi-quantitative and various quantitative approaches to video footage analysis. A decision tree as to which approach is suitable ought to be developed to facilitate analysis.

Database development, in particular the linking of species abundance data with geo-referencing information, ought to be addressed in future guidelines.

Guidelines should provide details on incorporating video-derived data into a GIS such that it can be overlaid upon existing datasets.

The existing estimates of video footage processing times require updating to reflect the geo-referencing and GIS development requirements, and should also be incorporated into the discussion of the different semi-quantitative and quantitative data analysis options.

It is recommended that details of statistical treatment of species abundance data are at least appended to towed video use guidelines.

Some discussion should be provided on how the results of statistical treatment of quantitative video data may be interpreted into habitat classes, looking at both top-down and bottom-up habitat classification approaches.

The guidelines ought to provide advice on integrating existing data with video-derived data to aid habitat interpretations.

It would be of great benefit to undertake a cost-benefit analysis of the various levels of processing video footage with respect to the resulting quality and type of habitat map.

It would be a useful exercise to indicate where quantitative data is required to discriminate between two habitat types, and where semi-quantitative or qualitative data would suffice.

A decision-tree should be developed to guide users in which video data analysis approach would be suitable depending on purpose of survey and how habitats are to be classified.

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