

ECHO*plus* Measurements in Hopavågen Bay, Norway

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Abstract

Rapid, remote, acoustic survey techniques are being increasingly used to study marine habitats. The techniques provide wide-area coverage of the seafloor and discrimination of bottom type when carefully calibrated to ground truth biology and sedimentology. One of these techniques involves the analysis of first and second echoes from the vessel's echo sounder using the ECHO*plus* Seabed Discrimination System. In order to test this acoustic system a survey was conducted in Hopavågen, a confined bay 80km west of Trondheim, on the coast of Norway. The principal objective of the survey was to assess the use of a single-beam acoustic technique for habitat mapping. The bay provides an ideal location for acoustic surveying with sheltered conditions, discrete biotope and sediment bottom types covering large areas with small topographic variations. In this paper we present a description of the ECHO*plus* hardware, digital signal processors (DSPs), and Hardness & Roughness algorithms and the results of calibration and surveying using the single-beam echo sounder. An acoustic map of bottom reflectance (hardness and roughness) was generated and compared to biological and sedimentological ground truth data obtained from grab, diver and video surveying. The results exhibit excellent correlation between acoustic bottom classed type and ground truth data.

Introduction

The increased use of coastal and near shore sites, for both industry and leisure activities, places ever greater pressure on the environment of these sites. If we are to ensure the sustainable development of the near shore, while maintaining the quality of life within it, new technologies must be adopted for rapid site evaluation and appraisal. In responding to the need to map and monitor near shore areas methodologies must be adopted that not only address the critical biological questions of life state and quality but are also cost-effective to use. What technologies should be adopted? What are the respective limitations and how should they be applied? Furthermore, what measures must be implemented to ensure that the technologies are being used correctly? An ongoing programme of investigation of acoustic techniques is being conducted at the University of St. Andrews and other institutes to address these issues. Each near shore area is unique and thus no one solution exists for mapping and monitoring all areas. It is essential therefore that a survey strategy is developed based on the managed and integrated use of a range of both new and old technologies.

Background

The echo sounder or single beam sonar has been used for a number of decades to measure bathymetry and also to record reflecting objects such as fish within the water column. More recently the acoustic amplitude variations have also been processed for seafloor classification (Chivers *et al.*, 1990; Foster-Smith *et al.*, 1999). An echo sounder consists of a sonar transducer used to both transmit and receive an acoustic energy pulse directly beneath the sonar. The energy pulse or acoustic wave travels from the sonar and is reflected or echoed from boundaries in its path. The intensity of reflection depends on the impedance ratio between water and the reflector and the angle that the reflector makes with the acoustic pulse. For example, a hard, flat seafloor will reflect more energy than a soft sea floor or one that is at an angle to the transmitted acoustic pulse. The sonar produces repeated pulses as it passes over the seafloor thus measuring a line track of data.

The range to the bottom and velocity of the acoustic pulse in the water determines the number of samples, or pings, off the bottom per second. There is a finite time that must be observed for the energy to travel to, and reflect off, the bottom - double for the second echo. The fidelity of recording changes on the bottom is determined by the ping rate with respect to the speed of boat over the bottom and the acoustic beam width. Thus for most surveys large areas of the bottom are covered with the echo sounder and there is significant averaging of data between each ping. Despite this, the echo sounder has been shown to produce high resolution, repeatable depth data along survey line tracks. However, because the echo sounder only produces information for targets directly beneath the sonar, it is necessary to extrapolate between survey line tracks in order to produce area coverage maps of the seafloor.

Physical Principles

The strength of acoustic energy returned from the seafloor with a single beam sonar has also been used to classify the bottom type. A number of methods have been proposed for this and include those by Jackson and Briggs (1992) who used the backscattered energy from the echo to infer bottom roughness. Orłowski (1984) used a method that integrated parts of the multiple echo signature from the seafloor to provide information on its characteristics. Burns *et al.* (1985) and Chivers *et al.* (1990) developed a classification system based on the first echo and the second echo or first multiple echo from the seafloor. Previously this information has been used to manufacture analogue systems to measure the seafloor characteristics. The ECHOplus sonar system is a development of this technique using digital technology based on the first return echo and second (multiple) return energy.

Figure 1 shows the voltage trace of typical echo sounder output for a single ping. Normally, this output is not available to the user because the system processes the data and stacks up a number of pings prior to display.

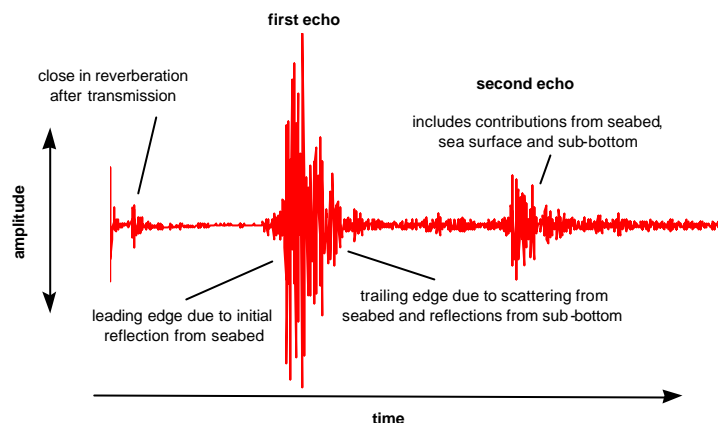


Figure 1 - Typical Echo Sounder Output

On the left is the tail end of the transmission, which may be reflections from close in structure or from entrained air bubbles beneath the transducer. In the middle is the first echo from the seabed. In general, this is composed of at least three components - the initial *reflection* from the seabed immediately beneath the transducer, *backscatter* from an area surrounding the point below the transducer and possibly reflections from the *sub-bottom*. On the right can be seen the second echo from the seabed which has undergone an additional trip to and from the sea surface. Although the arrival time of the second echo is approximately twice that of the first, the second echo is not just a scaled and delayed version of the first echo. It carries further information.

In outline ECHOplus uses:

- ?? Backscatter information from the first echo to characterise the seabed roughness,
- ?? Reflection information from the second echo to characterise seabed hardness.

Although not independent, roughness and hardness together do provide a reliable indicator for seabed discrimination. The scattering geometries, along with the analysis windows in the transducer response, are shown in Figure 2 below.

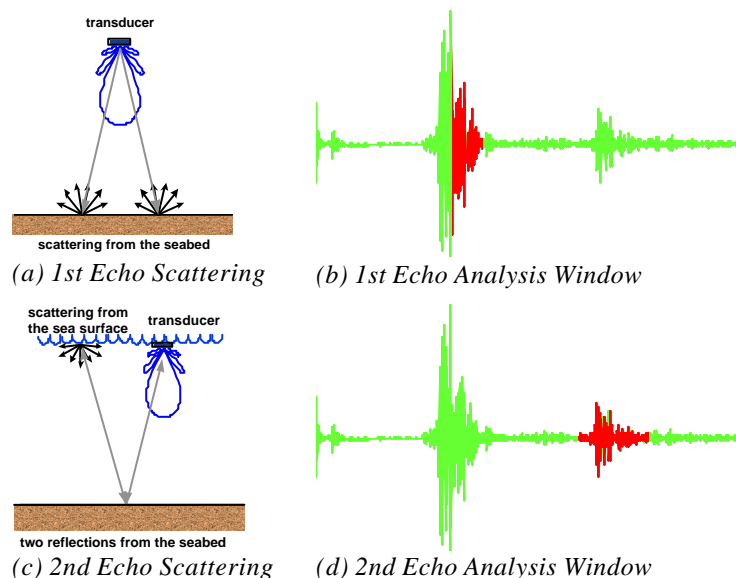


Figure 2 - Scattering Geometry and Echo Analysis Windows

An echo sounder transducer transmits over a broad range of angles. If the seabed were perfectly smooth all the energy transmitted normally to the seabed would return to the transducer and energy at other angles would be reflected away. The seabed is not completely flat and a fraction of the energy transmitted at other angles is returned to the transducer. This backscatter

mechanism is illustrated in Figure 2(a). The rougher the seabed, the more energy is scattered back to the transducer and the more energy appears in the analysis window.

To avoid contamination of the backscattered energy with energy that has been directly reflected from below the transducer only the tail of the first echo is used in the analysis as shown by the red window in Figure 2(b). The geometry of the window is such that the angles remain constant irrespective of depth.

The characteristics of the second echo are not as simple as the first and there are at least two theories for the underlying physical mechanisms.

In the simpler (Chivers *et al.*, 1990) theory the dominant ray paths for the second echo undergo two reflections at the seabed and a single scattering at the sea surface as shown in Figure 2(c). The amount of reflection is related to the difference in acoustic impedance between seawater and the sea bottom. Therefore, the harder the seafloor the more energy is reflected forward to the surface and back to the transducer and the more energy appears in the analysis window shown in red in Figure 2(d).

In the more advanced (Heald and Pace, 1996) theory the important observation is that because of the presence of the sea surface, the configuration is really a bistatic one with the transmitter and the receivers vertically displaced by twice the water depth. The impact of this is that the receiving transducer is in the near field scattering zone of the seabed and the scattered energy is therefore driven by the reflection and hence hardness properties of the seabed.

Both theories, however, support the concept that the harder the seabed the more energy appears in the analysis window. The ECHO $plus$ system exploits this principle and, in particular, makes use of this property to determine the analysis window parameters.

An alternative to using the second echo to determine the seafloor hardness would be to use the leading edge of the first echo (i.e. the reflected part). This is unsatisfactory on two counts:

- ?? The dynamic range would need to be much greater,
- ?? The pitch and roll of the vessel will move the reflection out of the beam.

The first point is a purely technological one. The second is, however, vitally important. As soon as the beam moves from the vertical the reflected energy from the beam centre is lost and the leading edge of the first echo will be attenuated accordingly. This problem does not affect the roughness determination, as the backscattered energy tends to remain constant under conditions of pitch and roll. As one side goes up the other goes down and the total energy in the analysis window is conserved.

ECHO $plus$ Implementation

The ECHO $plus$ implementation comprises two wideband, low-loss Analogue to Digital Converters (ADCs) and four fixed-point Digital Signal Processors (DSPs). The system architecture is summarised in Figure 3 below. The system processes two independent frequency echo sounder channels simultaneously and, therefore, two of the DSPs (A & B) are paired with the ADCs, one for each channel. The ADCs convert the transducer signals to a digital format, attenuated for the transmitted pulses and amplified for the received echoes, and then feed this data to the DSP for signal processing. The DSP software includes functions to detect the echo sounder, estimate the pulse characteristics, baseband and filter the received echoes and perform the first and second echo analysis. One DSP (C) is responsible for system control which monitors and schedules all system activities, performs the self-test, maintains the display and monitors the performance of the system. It also controls the RS232C serial link to the analysis

and archive PC. The final DSP (D) collects baseband data from the signal processing and prepares it for transmission over an industry standard IEEE1284 parallel link for analysis and recording.

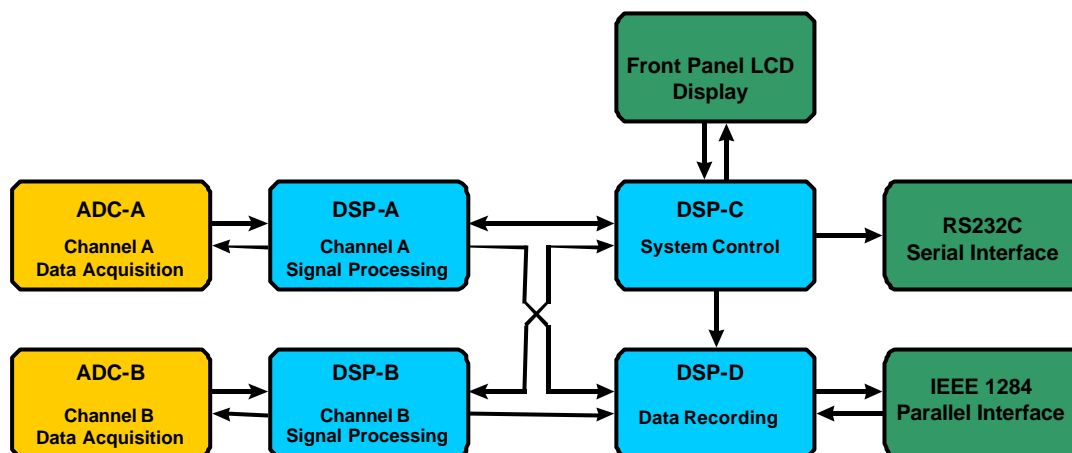


Figure 3 - ECHOplus System Architecture

ECHOplus has been specifically designed to address problems that have been experienced with recent surveys. When echo sounders have been used previously for seafloor classification the repeatability of measurements during a single survey, and between surveys using different sonars and acquisition survey vessels, has been poor. Numerous authors have noted a drift in instruments as temperature and humidity changes, the survey speed changes and a different response has also been noted from different sonars when used on different vessels (for example see Davies *et al.*, 1999). These issues have been addressed with ECHOplus which has compensation adjustments within the system for frequency variations, depth (signal strength losses), pulse length differences and power level fluctuations.

If no compensating action were taken the ECHOplus outputs would depend on depth as both the echo return levels and the total absorption losses are depth dependant. In order to compensate for the former a time varying gain is applied to the digitised voltages within the system. Because of the underlying geometry of the system, in particular the constant beam width of the transducer, this gain factor is a linear function of depth.

ECHOplus automatically detects and operates with any echo sounder within its operating range. There is no requirement for user intervention to tune the system to a particular frequency. This is achieved by using wideband low loss front-end analogue hardware together with frequency estimation software. The centre frequency of the transmitter is estimated directly from the pulse waveform and used to control the analogue data acquisition and the digital basebanding when listening to receive echoes. In order to minimise the processing load and data rate at the parallel recording port the received signal data is heterodyned down to DC. All subsequent signal processing is then identical for all types of echo sounder.

The frequency dependent differences in seabed acoustic properties should not be masked as they include valuable information. However, operating frequency affects the ECHOplus outputs in other ways unrelated to the nature of the seabed itself. In particular at high frequencies the absorption of seawater is high enough to be significant. To compensate for this the acoustic path length (which is different for the first and second echoes) is used along with the echo sounder frequency to generate a further correction to the output values. This cannot be compensated without knowing the depth and they are sensibly accounted for together. Additionally a compensation is made for the frequency response of the system itself.

The pulse amplitude is measured by the system on every transmission and the estimated amplitude is used to scale the outputs accordingly. ECHO**plus** measures the *electrical* power at the output of the echo sounder transmitter. This does not automatically relate to the *acoustic* power delivered by the transducer into the water column. Therefore, there are a number of sources of variation that cannot be compensated for including losses within the transducer cable, efficiency changes between different transducers and efficiency changes for the same transducer as a function of age. Apart from the final one, however, these will be constant for a particular installation.

The pulse length is measured and used to adjust the outputs accordingly. There are separate and independent corrections for roughness and hardness values. The measured pulse length is also used to tune the filtering process so that the signal to noise ratio and hence overall performance and reliability are optimised.

The corrections above are necessary to produce a self-consistent output. There are, however, other factors that may influence the output levels:

- ?? Beam pattern and direction,
- ?? Feed losses and impedance,
- ?? Transducer transmit and receive efficiencies,
- ?? Surface scatter.

ECHO**plus**, therefore, provides a reference calibration facility which is set by the user post installation. These factors can be compensated for either by using this reference calibration facility on ECHO**plus** or via a similar function in the analysis software, if it has this capability. None the less, procedures are recommended where repeat surveys are made over two or more areas of known sea floor in order to calibrate the amplitude response. Furthermore, it is recommended that when surveys are made of large areas using more than one sonar, or surveys are made over a number of years using different sonars and different survey vessels, calibration procedures are adopted for calibration using known reflectors.

Data Acquisition

Hopavågen bay lies approximately 80km west of Trondheim, Norway. The bay has a narrow and shallow exit to the main fjord through which the bay receives an 11% turnover in water volume during each tidal cycle. There is almost no freshwater recharge into the bay and thus it can be used for controlled marine ecology experiments. The bay is divided into two based on depth with a deeper northern half and a shallow southern shelf (see Figure 4 for a sun illuminated image). The central section of the bay is relatively devoid of marine ecology with fine-grained muds located in the deep northern half and a mixture of sand and silt on the shallow shelf. Around the bay margins rock outcrops and occasional boulder beds are colonised by horse mussels to a depth of approximately 8m.

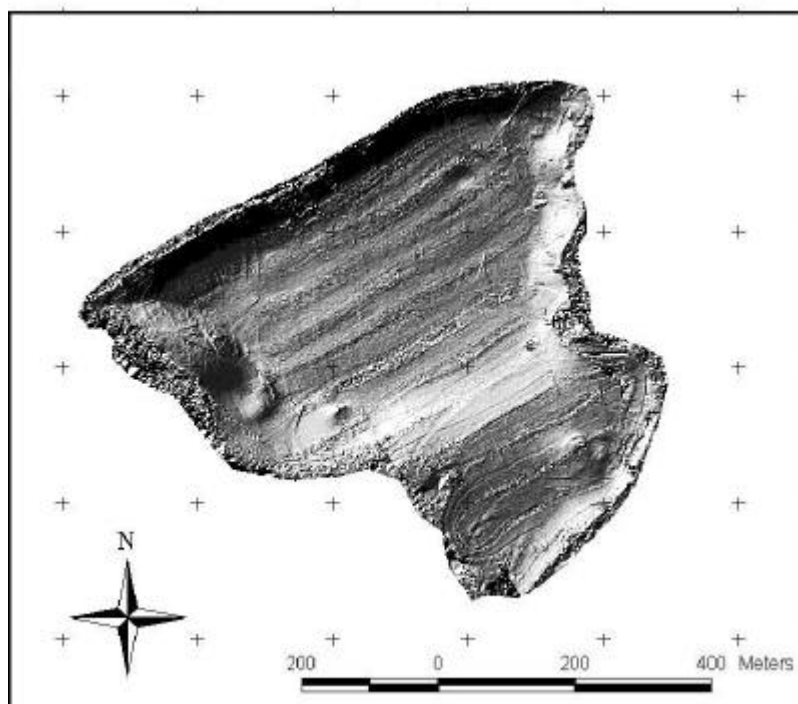


Figure 4 - Sun Illuminated Bathymetry from Hopavågen

The echo sounder sonar transducer was deployed as a side-mount beneath the keel line of the RV Calanus. A single channel 100kHz unit was chosen for this survey. The acoustic survey was conducted over couple of hours during a period of calm weather. A further day was required after the acoustic survey for the acquisition of ground truth data at 50 sites distributed across the bay. A Racal Skyfix DGPS was used to give full differential position during the survey and only showed occasional loss of differential signal near the sides of the bay where the valley profile increased. The bay has a maximum depth of 32m and a maximum line spacing of 75m was used. Tidal corrections were obtained from continuous logging profiles for the bay and speed of sound from CTD measurements. The ECHOplus acoustic discrimination information, from only a single channel, was recorded together with the navigation information on a dedicated computer.

Acoustic Data Processing

The final output of the ECHOplus survey was a depth chart and line plot of roughness and hardness for the seabed. The first step in processing the acoustic data is to edit for bad data from navigation errors, depth spikes and amplitude errors. These were expected when the survey boat was turning at the end of lines or slowing down to avoid obstacles in the bay. However, they represented less than 2% of the data. This editing included the application of running filters to the data that compared the values along track lines to indicate sudden unexpected jumps. A Cartesian plot of roughness against hardness was analysed using a density distribution to determine the grouping of data and to identify any further outliers that could have been generated by easily identified noise sources. This density distribution is shown as a colour contour plot in Figure 5. To obtain Figure 5 the raw data was further processed, by taking the square root, to improve its resolution at lower values. Three distinct groupings or high-density areas are evident from Figure 5, these are marked as A, B and C. Other smaller clusters are also evident. The area marked D, however, does not correspond to any particular cluster. It marks the location on Figure 5 that corresponded to areas identified by diver survey as being small, localised areas of bedrock close to the shore.

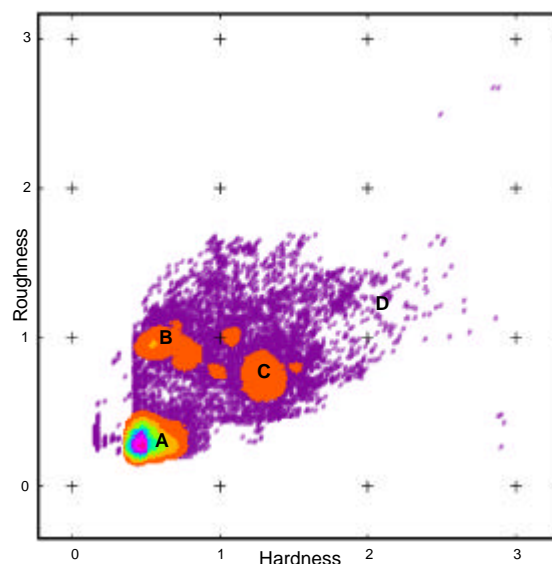


Figure 5 – Roughness vs. Hardness Density Plot showing Clusters for Acoustic Classification

It should be noted that although only three large zones of acoustic cluster were observed in the data this is a function of only having a limited data set over a small bay area. In general many more clusters might be observed in a scatterplot, such as Figure 5, when surveys are made of areas with a greater variation in seafloor. The peak values (with the same square-root processing as for Figure 5 above) for roughness and hardness of the groupings A to D are given in Table 1.

	Hardness	Roughness
Value of density peak A	0.4	0.3
Value of density peak B	0.6	1.0
Value of density peak C	1.3	0.8
Value of density peak D	2.1	1.2

Table 1 - Roughness and Hardness for Hopavågen Bay

In order to produce a map of bottom character over the whole of the bay the line data was extrapolated into a grid of values after which image processing procedures are applied to classify the data into zones based on their roughness and hardness values. This is shown in Figure 6 later. The final step in acoustic image classification is the prediction of likelihood of finding similar, or dissimilar, classified zones across the survey area and this work is ongoing.

Sediment analysis

Sediment samples were taken at 50 sites in the bay for grain size analysis in the laboratory. The sample sites were biased as no samples could be obtained using a grab sampler on the gravel with boulder sediment bottom type as the boulders prevented the grab sampler from catching material. The sediment was initially dried and then sorted using a 2mm grain size sieve. The remaining material was processed through a riffle box to obtain 3-10 grams of representative sample. This was analysed using a Coulter LS laser diffraction particle size analyser. Histograms of particle size were produced and the grain size was compared using a geographic information system to roughness and hardness values obtained from around the sample sites.

Four distinct grain size clusters were observed from the material sampled. Table 2 shows the results of analysing these samples and subdividing the data using the Udden-Wentworth size classification (Pettijohn *et al.*, 1972). Also presented on Table 2 are the acoustic values from

around the sample locations (these have been square rooted so they can be easily compared with Table 1). The fourth bottom type, namely coarse / very coarse sand (running to gravel and occasional boulders), along with an additional bottom type, identified as areas of rock outcrop but for which no ground truth was obtained, were observed by diver and video. Both these zones contained horse mussel communities. The acoustic classification and the classification based on grain size ranges identified similar roughness and hardness values for mud/silt locations and medium-coarse sand locations (classes A and C from Figure 5). However, no similar correspondence with ground truth grain size could be shown for class B. Analysis of the location of the data that comprise this cluster indicates that class B corresponds to the horse mussel communities to be found at several distinct sites around the edge of the bay. This cluster plotted samples predominantly around the inlet channel where a coarse shell bottom type was identified and over a significant area of rock outcrop. As noted above it was impossible to obtain ground truth from these sites. The presence of extensive horse mussel communities here has apparently had the effect of increasing the roughness values obtained for their locations.

It can be seen from Table 2 that both roughness and hardness are increasing monotonically with the change of seafloor from mud to the various classes of sand, from fine to coarse. Analysis of the data at point D in Figure 5 indicate that this trend continues into the gravel, rock and boulder regions that were not so well represented on this survey. This relationship provides a sound basis for the use of this technique in seafloor classification. It is to be expected that the relationship for other echo sounders with differing frequencies, beam patterns and installations will vary only in magnitude and not in general form (see the ECHOplus Implementation section earlier). For the purposes of this survey the data has been classed both acoustically and by grain size into a number of clusters or classes. However, there is often a continuum of grain size changes and thus acoustic classes between distinct zones. There are indications that the presence of biology on the sediment bottom has affected the simple relation between grain size and roughness / hardness in a systematic way. This could be a very important feature of the system and further work needs to be carried out to analyse its effects. Once again if the data set was larger this data range might be better represented within the classification scheme.

	Grainsize (μm)	Hardness	Roughness
Mud / silt	1.0 – 14.4	0.5	0.3
Fine sand	14.4 – 29.0	0.7	0.6
Medium-coarse sand	29.0 – 65.0	1.2	0.8
Coarse / very coarse sand	65.0 – 125.0	1.6	0.9

Table 2 - Grain Size with Roughness and Hardness values close to sample locations

Seafloor Classification

Unsupervised classification of the acoustic data was performed using an automatic classification scheme where natural breaks between clusters or ranges in acoustic return energy were used to subdivide the data into a number of classes. The results of this classification for both roughness and hardness are shown in Figure 6 below. The limited number of variables in this type of data does not usually lend itself to multidimensional clustering where a large range of bottom types are present however where only a few types are seen, and these types occur in discrete locations with sharp boundaries between the bottom types, the method is successful. Where there is a large degree of heterogeneity with respect to the footprint size of the echo sounder the acoustic data will necessarily represent a mixing of those seafloor characteristics present within the beam footprint. In Hopavågen there was a limited range of distinct bottom types and thus unsupervised classification of the acoustic data was successful in discriminating some of the different areas of bottom type where the acoustic signatures did not cross boundaries in bottom

type and it can be assumed that the whole of the acoustic beam is reflecting from a relatively flat area containing approximately the same material. Further work is now analysing various filtering options for assessing sample-acoustic locations that cross boundaries.

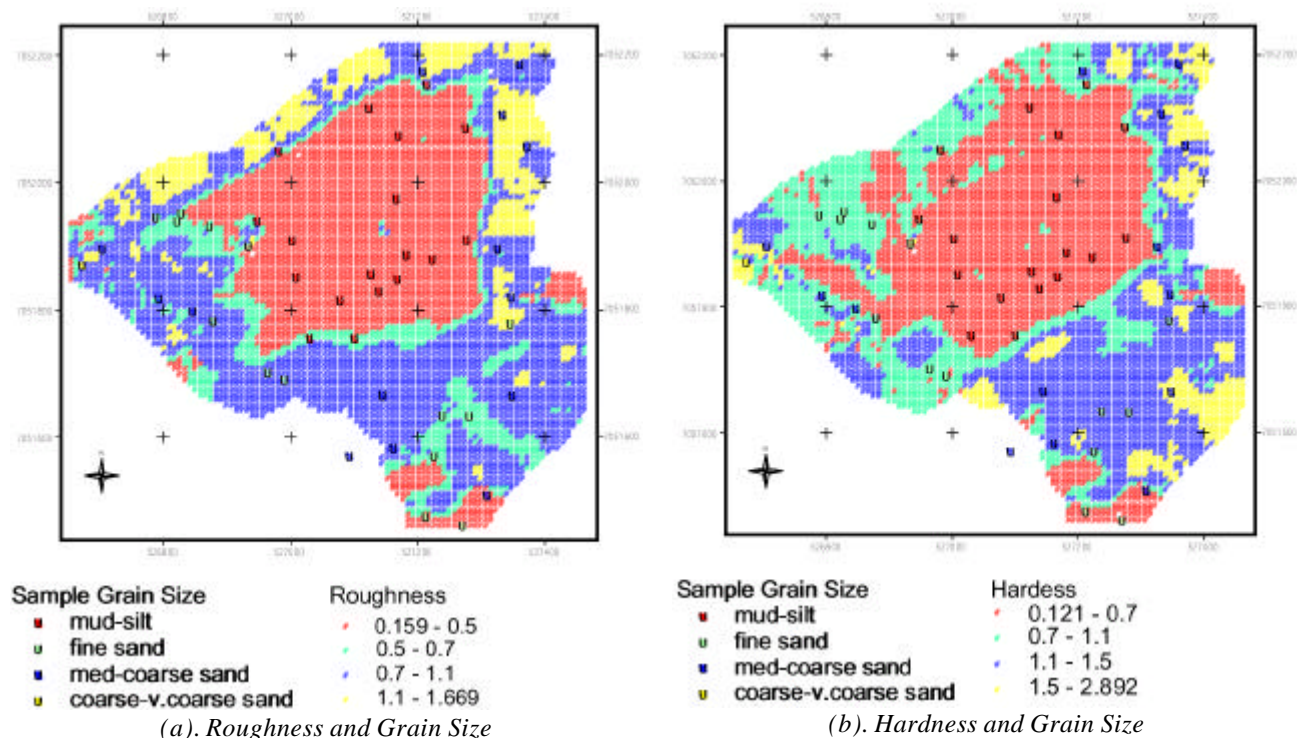


Figure 6 - ECHOplus output and Ground Truth

Acknowledgements

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