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Geological seafloor mapping with backscatter data from a multibeam echo sounder

Maringeologisk bottenklassificering med backscatterdata från multistråleekolod

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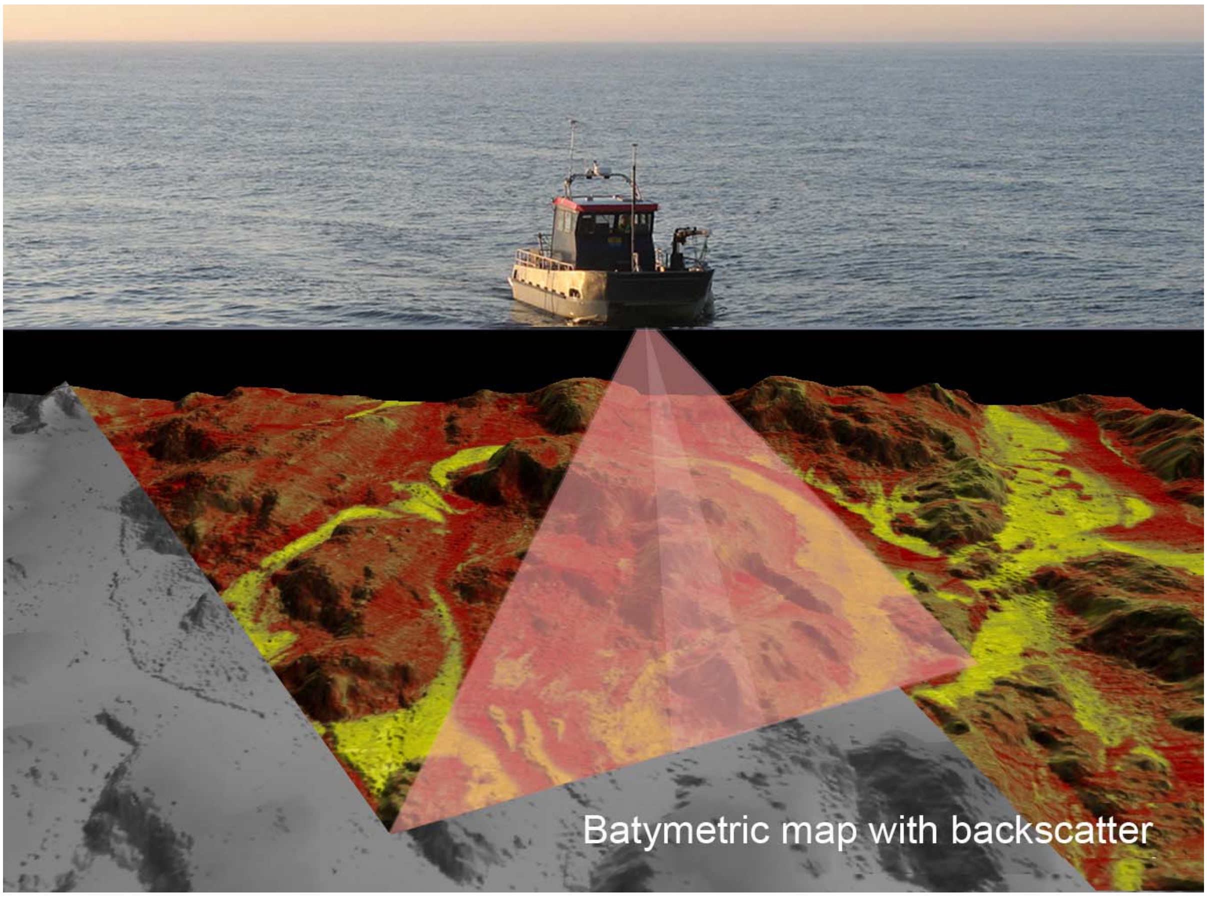
Gustav Kågesten


Batymetric map with backscatter

ABSTRACT

Geological seafloor mapping with backscatter data from a multibeam echo sounder

GUSTAV KÅGESTEN

This thesis examines and develops methods for using the amplitude strength of returning sound signals (backscatter) from a Simrad EM 3002 dual head multibeam echo sounder, in order to extract information about seabed sediments. It also shows ways of visualizing this information for users who are unfamiliar to this technique, and indicates how much information that is potentially possible to extract from backscatter data. The dual head version of the EM 3002 multibeam echo sounder is only a few years old and much research still remains how to best process and interpret data from this shallow-water mapping instrument, as the extreme gracing angles causes problems.

It was found that the bottom backscatter strength can be described primarily as a function of grain size for sand and finer sediments, and that surface shape and roughness play an important part for backscatter strength from coarser sediments and other hard surfaces like reefs and shipwrecks. Fine gravel reflected the strongest backscatter signal, while hard smooth surfaces like boulders and bedrock often return a considerably weaker backscatter signal, which corresponds to about the same interval as sediments with mean grain size 0,5-1 mm. To separate the two, surface shape and roughness have to be taken in to consideration together with backscatter data. One method to encompass surface shape and roughness into the analysis of seafloor sediments is to combine backscatter data with bathymetric data (depth data), another way is to use a statistical approach describing surface shape and roughness with the variations in backscatter strength. Both options were tested.

The results from this thesis were used to classify seafloor surface sediments into 5 geological classes on a series of shallows covering about 180 km^2 located in the southern part of the Gulf of Bothnia, targeted for big scale offshore wind power production. The classification was conducted using the statistical classification software Triton, backed up with groundtruthing, processed backscatter, side scan sonar and sub bottom profiler data. The accuracy was 91.3 %, based on sediment samples and films from the area. The results in this thesis were also used to locate soft sediments targeted for environmental pollution analyses.

KEYWORDS: Backscatter, multibeam, classification, grain size, roughness, environmental sampling, habitat mapping, biological modeling

Department of Earth Sciences, Gothenburg University
Box 460, SE- 405 30, Gothenburg, Sweden
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REFERAT

Maringeologisk bottenklassificering med backscatterdata från multistråleekolod

GUSTAV KÅGESTEN

Den här examensuppsatsen undersöker och utvecklar metoder för att använda styrkan i ljudekot (s.k. backscatter) från ett Simrad EM 3002 dubbelhuvud multistråleekolod, 300 kHz, för att få information om sedimenten på havsbotten. Den visar också hur man på olika sätt kan visualisera resultatet och göra informationen tillgänglig även för en ovan användare. Versionen av det använda ekolodet där två multistråleekolod kombineras för att öka täckningen i sidled är endast ett par år gammal och mycket forskning återstår för att på bästa sätt kunna processa och tolka backscatterdata optimalt. Lodet har möjlighet att mäta ända upp till vattenytan åt båda sidorna av mätbåten och den stora sidovinkeln skapar svårigheter i efterbehandlingen av insamlad data.

Undersökningen visar att den normaliserade backscattersignalens styrka från havsbotten kan relateras direkt till ytsedimentens kornstorlek för sand och finare sediment. För grövre sediment och andra hårda ytor som rev, berg och vrak, är även ytans grovhet samt form viktiga parametrar för hur mycket ljud som reflekteras tillbaka till ekolodet. Fint grus gav den starkaste backscattersignalen medan hårda jämna ytor gav tillbaka en betydligt svagare signal. Detta trots att dessa ytors reflektionsegenskaper är bättre än grusets. Backscattervärden från storblockig moränbotten låg i samma styrkeintervall (dB) som reflektionen från sediment med kornstorlek mellan 0,5 och 1 mm. För att kunna skilja dessa sediment åt bör man kombinera hårdhetsdata med djupdata eller med statistiska parametrar som standardavvikelse, vilket ger ett mått på bottenytans form och textur.

Resultaten från examensuppsatsen användes för att klassificera bottensedimenten i fem geologiska klasser från två stora grundområden i Gävlebukten i Södra Bottenhavet, där det projekteras för storskalig havsbaserad vindkraft. Den totala mätytan var 180 km^2. Klassningen gjordes med hjälp av statistiska parametrar i programmet Triton, i kombination med provtagningar, film och dykobsevationer från området, samt processad backscatter och djupdata, side-scan sonar och sedimentekolodsdata. Noggrannheten i klassningen var 91,3 %, baserat på provtagningar från området. Resultaten användes även för att lokalisera mjukbottnar för att kunna ta prover för analys av miljöföroreningar.

NYCKELORD: Backscatter, multibeam, klassificering, sediment, kornstorlek, miljöprovtagning, habitat, biologisk modellering

Institutionen för Geovetenskaper, Göteborgs Universitet
Box 460, SE-405 30, Göteborg
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PREFACE

This thesis encompasses 20 weeks of fulltime studies and finishes my master in Environmental and Aquatic Engineering, Uppsala University.

The project was made in cooperation with a marine environmental consulting company, Marin Miljöanalys AB, to which I owe many thanks. Especially to my colleges who were helpful and endured my company for over 70 field days on a small boat out on the big blue, and to my supervisor Martin Hörngren for taking time to help when he had no time at all. Once again it is proven that no laws of physics are superior to good old Murphy's…

I also want to thank my supervisor at Gothenburg University Earth Science Institute, professor Bengt Liljeblad, for help during the dark hours of writing. I also owe thanks to Kongsberg Maritime for their excellent support and to professor Mark Johnson for helping me with grain size analyses and letting me use the lab.

Last but not least… thank you, family and friends, who are always there with support in all sort of matters!

Just do it!

Göteborg, April 2008

Gustav Kågesten

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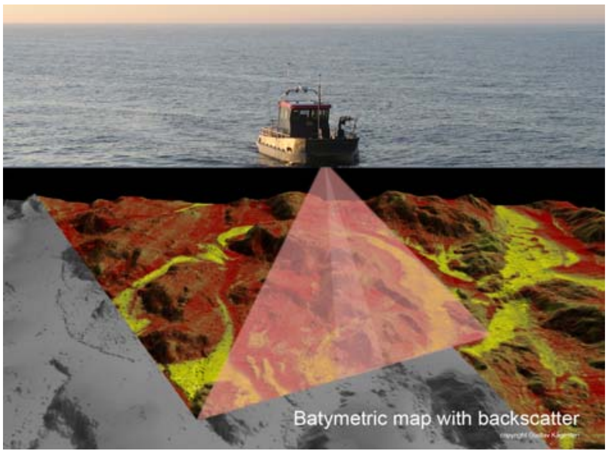
Maringeologisk kartläggning med multistråleekolod

– kastar ljus över okända bottenområdens geologi och biologi



Den snabba utvecklingen av avancerade multistråleekolod har skapat möjligheten att kartlägga sjö och havsbotten med väldigt hög precision och upplösning. Utöver noggranna djupkartor av botten och befintliga objekt kan man även få information om bottens hårdhet vilket öppnar möjligheten för en mängd användningsområden inom geologi, biologi och miljö. I bilden t.v. kan man se exakt var sanden ligger (gult) bland stråk av grus (mörkrött) och högar av blockig morän (gulrött).

Ett multistråleekolod skickar ut en stor mängd ljudpulser samtidigt där varje enskild ljudstråle kan liknas vid ett enkelstråligt ekolod, men med en väldigt fokuserad ljudpuls. Kombinationen av alla dessa ljudstrålar, som var och en täcker av en specifik vinkel under båten möjliggör kartläggning av en bred och högupplöst sektion av botten under mätfartyget. Traditionellt har multistråleekolodsdata endast används för att göra djupmätningar, men insamlad ekolodsdata innehåller även amplituden från varje eko. Amplituddata från de returnerade ljudpulserna kallas backscatterdata och går att använda till att bestämma vilken sammansättning bottens ytskikt har. Förenklat kan man säga att en svag signal (låg amplitud) indikerar en mjuk botten och en stark signal (hög amplitud) indikerar en hård botten .

Den returnerade ljudpulsen innehåller ekon både från vattenkolumnen (t.ex. fisk och plankton) och från botten. Formen och intensiteten på hela ekot kan därför analyseras på många olika sätt, beroende på vad man letar efter. Vanligtvis sparas endast data från den del av ekot som härstammar från botten, då man får enorma mängder data om man sparar rådata från hela ljudpulsen. Ett förenklat och vanligt sätt att spara backscatterdata är att beräkna ett medelvärde av den del av ekot som returnerats från havsbotten.

För att få fram en rättvis bild av havsbottens reflektionsegenskaper från multistråleekolodsdata måste styrkan på ljudsignalen från varje enskilt eko korrigeras för mängden energi som förloras på grund av absorption och spridning i vattenkolonnen, samt för den vinkel och träffyta som ljudpulsen har när den träffar botten. Rätt kompenserad och tolkad så ger resultaten från backscatterdata detaljerad information om sjö och havsbottnars struktur och hårdhet. Eftersom tekniken att behandla backscatterdata från multistråleekolod är relativt komplicerad och oprövad så finns det mycket kvar att utveckla, dessutom går hårdvara utvecklingen ständigt framåt och stället stora krav på nya mjukvaror.

Detta examensarbete syftar till att öka förståelsen av backscatterdata från multistråleekolod och är utfört i samarbete med Göteborgs Universitet och Marin miljöanalys AB. Under Sommaren 2007 kartlagde Marin Miljöanalys två stora grundbanksområden i Gävlebukten för WPD Scandinavia som planerar bygga två stora havsbaserade vindkraftsparker på utsjöbankarna Storgrundet och Finngrunden. Mätområdet täckte ca 180 km^2 och karterades med ett 300 kHz multistråleekolod, sidescansonar, sedimentekolod och magnetometer. Under arbetets gång togs även ett hundratal bottenprover och filmsekvenser över havsbotten.

Multistråleekolodet Simrad EM 3002D som användes är avsett för grunda vatten mellan 0 och 200 meters djup och kan kartlägga havsbotten med en täckning upp till 10 gånger vattendjupet med en upplösning på ca 10 cm. Med RTK korrektion av GPS signalen är mätfelet i höjdled endast ett par cm.

Insamlad backscatterdata från multistråleekolodet jämfördes med bottenprover, filmsekvenser och övrig sonardata från mätområdet för att kunna korrelera amplitudvärdet på den returnerade ljudsignalen med kornstorlek och struktur på bottens översta ytskikt. I resultatet finner man bland annat att mellansand och finare sediment som lera och silt kan beskrivas med en linjär funktion mellan amplitud och kornstorlek, där styrkan på den returnerade signalen minskar med kornstorleken. För grövre sediment ser förhållandet annorlunda ut. Fint grus visade sig returnera en starkare signal än grövre material som block och sten, troligtvis för att en del av ljudsignalen ofta speglades iväg bort från ekolodet på de hårda släta ytorna. För bottnar bestående av grövre material spelar alltså både ytans hårdhet samt dess ytstruktur en stor roll. Sand med kornstorlek mellan 0.5-1 mm visade sig ge samma amplitudvärde som större stenar och block, medan grus och småstenar returnerade den starkaste signalen tillbaka till ekolodet.

För att kunna skilja sedimenten åt användes därför en kombination av djupdata och backscatterdata (se bild ovan), där den blockiga moränen blir väl synlig i de batymetriska kartorna. Man kan även använda sig av statistiska metoder där amplitudvariationen (standardavvikelsen) är högre för bottnar med grov struktur som block och sten jämfört med en jämnare sandbotten. Automatklassificering baserad på en statistisk metod användes till att klassificera bottnarna på Storgrundet och Finngrunden i 5 geologiska klasser baserat på medel backscattervärde (dB) och standardavvikelse. Det klassificerade mätområdena användes sedan som input data i en GIS baserad biologisk bottenhabitat modell för området. Automatklassningen med backscatterdata från hela den 180 km^2 stora botten ytan stämde till 91 % jämfört med de bottenprover och filmer som togs slumpmässigt i området. Resultaten användes även för att lokalisera mjuka ler och siltbottnar för miljöprovtagning i de två planerade kabel korridorerna.

I Sjöfartsverkets arkiv finns redan stora mängder obehandlad bakcscatterdata från multistråleekolod över de svenska farvattnen insamlat under djupkarteringar. Korrekt tolkad kan denna information ge viktig kunskap om våra havsbottnar och kasta ljus över tidigare okända bottenområden. De detaljerade kartorna över bottens hårdhet kan bland annat användas för detaljerad kartläggning av bottenfauna och fiskbestånd som är beroende av specifika bottentyper. Denna information kan i sin tur hjälpa naturvårdverket och fiskeriverkat att skydda känsliga havsområden. Även för miljöprovtagningar av bottensedimenten är hårdhetskartor över botten till stor nytta då man enkelt kan placera sina provtagningar i de intressanta områdena med silt och lera (där miljögifterna lagras). Idag används ofta helt slumpmässiga provtagningsmetoder både för miljöprovtagningar och marinbiologiska kartläggningar. Utan detaljerad geologisk information om ytsedimenten är det lätt hänt att man använder sina resurser till att söka i fel områden och kanske missar de mest intressanta områdena helt och hållet. Ett annat möjligt användningsområde är detaljerad kartläggning av sandbottnar för att förebygga problem med förändrad sanddrift vid kustnära marina byggprojekt.

De potentiella användningsområdena för backscatterdata från multistråleekolod är många, den stora utmaningen ligger i att få biologer, geologer och miljöingenjörer att inse nyttan av denna förhållandevis nya teknik och applicerade den då den behövs!

INDEX

1. INTRODUCTION

The last unknown places on the planet are lurking in the depths of our great oceans. As technology is advancing so are our methods for ocean exploring. The ocean is subject for great and powerful commercial interests, fishing and oil and mining industries among many others. The rapid development put great demands on ocean mapping technology, not only to exploit the ocean but also in order to protect its sensitive echo-systems by protecting key areas from development and to create sustainable management plans for fisheries. By using different kind of sonar systems the ocean floor can be mapped with very high resolution. Hardware technology has come a long way and the bottleneck is often how to process and interpret the data correctly.

A powerful tool for ocean mapping is the use of multibeam echo sounders. Multibeam echo sounders send out a large number of sound pulses, making it possible to map a wide section of the seafloor underneath the surveying vessel. The collected depth data from each sounding also contains the amplitude strength from the returning sound pulse. This information is called backscatter data and reveals information about the context of the sea floor. In simplified terms: a weak return signal (low amplitude) indicates a soft bottom substrate and a strong return signal (high amplitude) indicates a hard bottom substrate. It is also possible to collect depth and backscatter data from the water column and extract information about plankton and fish populations. Much research remains of how to best process, visualize and interpret geological and biological information from these advanced sonar systems. However, as shown in this paper, there are already ranges of useful applications for this data, for engineers and marine scientists alike.

The data used in this thesis was collected while mapping two big offshore shallow areas in the bay of Gävle in the southern part of the Gulf of Bothnia, where offshore wind power plant parks are planned. The results of this thesis have been used to geologically classify the seafloor surface sediments on these shallows, using backscatter data from an EM 3002 dual head multibeam 300 kHz echo sounder, specialized for high resolution shallow water surveys. Another consulting company, Aquabiota, used the classified data as input data in a GIS based biological model for habitat mapping. The results were also used to locate soft sediment bottoms for environmental sediment sampling in the two planned cable corridors to the windmills.

1.1 AIMS AND OBJECTIVES

The aims of this study were:

1. To develop existing methods to process and analyze backscatter data in order to deliver geological classified maps of bottom sediments.
2. To find the most important factors that determine the returning signal strength (backscatter) for different beam angles and bottom substrates, and to find out how much information that can be extracted with this technology using the EM 3002D multibeam echo sounder.
3. To investigate applications for multibeam backscatter data in the future.

2. BACKGROUND AND THEORY

This chapter gives an introduction to single- and multibeam echo sounders and the physics involved. It also covers methods of processing backscatter data in order to represent the reflectivity properties of the seafloor. The last section of the chapter describes five geological classes that were identified with backscatter data and groundtruthing. These five classes where used for geological classification of the surface sediments in the survey area using statistical parameters derived from backscatter data.

2.1 HISTORICAL REVIEW

The oldest sea-mapping device recorded is the hand lead line. It consists of a lead weight on the end of a long rope with marked intervals to show the depth, first documented by the Ancient Egyptians (Australian Secretariat 2007). Later on early ocean explorers modified this devise so it could also collect sediment samples. The biggest problem with composing sea-maps in the old days was accurate positioning. Latitude is simply related to sun or star height and was used by the Vikings and many others, but to find out the longitude you have to have an accurate time in addition to astronomic measurements. It took until 1735 when an English clockmaker, John Harrison, managed to build a clock reliable and accurate enough to find out longitude at sea (NOAA 2007). The first survey vessel that truly took on ocean mapping was the HMS Challenger in 1872. During four years it conducted a 127,000 km journey around the world, penetrating deep into the worlds oceans, with the highest recorded depth over 8000 meters. At the same period of time Sir William Thomson invented a wire line sounding machine, later modified by Lieutenant Charles D. Sigsbee's to become the Sigsbee Sounding Machine. The machine was used on the coast survey steamer Blake to map the Gulf of Mexico in 1874-1875. The resulting bathymetric map of the Gulf of Mexico is the first accurate map of the deep ocean (USGS 2007).

The last decade have seen great development of acoustic seafloor mapping. After the disaster of Titanic in 1912 a German physicist named Alexander Behm tried to find a way to detect icebergs. Through his research he didn’t find a way of detecting icebergs but instead he discovered the technique of echo sounding to measure the depth of the sea, which was patented in 1913 (Wikepedia 2007). In the 1950s the first multibeam echo sounder techniques was developed by the US navy, using more then one sound pulse at the same time. The development of the multibeam echo sounders improved rapidly through the 80's and 90's (Fugro Pelagos 2003). Today there are very advanced sonar systems that employ accurate satellite positioning to help us produce bathymetric maps with down to a few cm precision with high spatial resolution.

2.2 SINGLE- AND MULTIBEAM ECHO SOUNDERS

Echo sounders measure water depth by sending acoustic pulses through a transducer. The acoustic signals are reflected at the sea floor and the transducer picks up the reflected echoes. The depth is calculated from the two-way-travel-time of the velocity of sound in water (~1500 m/s). As the vessel moves a single beam echo sounder repeatedly "ping" the seafloor with a sound pulse, producing a discrete print of depths beneath the ship. Due to the limited side vision of single beam echo sounders, you have to interpolate between the survey lines in order to produce a sea chart. Many sea charts today have been based on this kind of data.

A multibeam echo sounder consists of many transducers that send out multiple sound pulses (figure 1) covering a wide swath beneath the survey vessel. A multibeam echo sounder makes it possible to get 100% coverage of the survey area without having to interpolate between the survey lines. The number of beams, the beam opening angle and maximum incidence angles varies between different echo sounders. Zero degree incidence angle (referred to as normal incidence) is straight down under the boat. The use of beams with high incidence angles requires accurate calibration of the system with corrections for roll and heave motions and for the water column sound velocity profile.

2.2.1 Wordlist

Backscatter - Backscatter is the reflection of waves back to the direction they came from. The term backscatter data is used to describe the intensity of returning sound waves (dB).

Bathymetry - the underwater equivalent to topography. Bathymetric data is the same as depth data.

Groundtruthing - information about the seafloor sediments from sediment samples, UV films or dive observations.

Incidence angle - A sound beam with zero degree incidence angle (sometimes referred to as normal incidence) is directed straight down under the boat. A sound beam with 90 degrees incidence angle is directed horizontal to the surface perpendicular to the travel direction at either port or starboard side of the survey vessel.

Transducer - An echo sounder transducer converts electric energy into acoustic energy.

2.3 SOUND WAVE PHYSICS

A sound wave can be described as a small pressure change, which propagate outward from its source, and travel with different velocities depending on the density of the medium it travels in. For example the speed of sound in air is about 344 m/s at room temperature, and about four times faster in water, which is a much denser medium (Nordling and Österman 2006). The basic properties of a sound wave can be described by:

Amplitude (A) - signal strength or acoustic intensity, usually measured in decibels [dB], which is a logarithmic scale.

$$A = {}^{10}\log(I/I_0),\ I = \text{intensity}\ [W/m^2],\ I_0 = 10^{-12}\ W/m^2 \qquad (1)$$

Wavelength (λ) - changes with medium and frequency

Frequency (v) - or pitch, usually measured in Hertz, cycles per second [Hz]. The frequency remains constant as the wave propagates from its source. The normal hearing spectrum for the human ear is frequencies between 20 Hz and 20 kHz.

$$c = \lambda v,\ c = \text{wave speed}\ [m/s] \qquad (2)$$

2.3.1 Sound properties in water

In fresh water, sound travels at about 1497 m/s at 25 °C. The speed of sound in seawater increases with increasing pressure/depth (a change of 1km ~ 17m/s), temperature (a change of

1 °C ~ 4 m/s), and salinity (a change of 1‰ ~ 1 m/s) (Wikepedia 2007 b). Other factors affecting sound speed are negligible (Dushaw et al. 1993). As a sound wave travels through the interface between two water bodies with different sound velocity properties it will change its speed and also change its direction. Some part of the wave might also reflect back into the same medium. When the sound wave hits the seafloor some of the energy will be transmitted to the seafloor, some will be scattered and some will be reflected.

The relative amount of energy that is reflected verses transmitted as a sound pulse hits the seafloor is dependent on the frequency of the outgoing sound signal, the acoustic impedance contrast (defined by the density and velocity of sound difference between the seawater and the sea floor), the roughness of the sea floor and the angle at which the sound hits the sea floor (USGS 2007).

Big uniform surfaces are better reflectors of sound then rough surfaces with lots of different structures. Sound waves reflecting on rough surfaces often split into many small waves. Hard material will reflect the sound better then soft material, which absorbs the sound energy better.

2.4 BACKSCATTER DATA

Backscatter is the reflection of waves back to the direction they came from. By analyzing the amplitude of the returning sound wave it is possible to extract information about bottom structure and hardness, allowing for identification of bottom types. The bottom reflectivity properties depend on the hardness and the roughness of the seafloor surface. In simple terms a strong return signal indicates a hard surface (rocks, gravel), and a weak return signal indicates a soft surface (silt, mud).

2.4.1 Single beam backscatter

There are different ways of analyzing backscatter in order to identify sediment types. Single beam classification systems have been in use for many years, providing real time bottom classification for fisheries and many others. Single beam systems have the advantage of a constant incidence angle between the pings, and the relative small amount of data allows for detailed analyses of each acoustic return. Some systems use dual frequencies. The disadvantage is that seafloor coverage is limited by one beam and that the resolution is relatively low.

Two of the major commercial systems are RoxAnn classification system and the QTC classification system. The RoxAnn classification system identifies sediment types by analyzing the shape of the first echo return, indicating acoustic roughness, and the shape of the second echo return, being a measure of hardness of the seabed (Hamilton 2001). The second echo return is a sound wave that has reflected first at the bottom, then at the surface and back to the bottom again before returning to the echo sounder. The QTC-view system uses an empirical approach examining characteristics of the first echo return. The program then provides automatic classification of the bottom. The statistical classes obtained from the QTC view system generally have to be related to groundtruth for each bottom type in order to be related to specific sediment types (Hamilton 2001).

2.4.2 Multibeam backscatter

Multibeam backscatter has a much better coverage and level of detail then a single beam system, but is also more complicated to process. As the backscatter signal varies with beam geometry, water depth and bottom composition the data need to be compensated for the incidence angle of each beam in order to obtain relevant geological data about the seafloor (Intelmann, et al. 2004). The first step to process the backscatterdata is done by algorithms in the processor unit as the data is collected. The software roughly compensates the backscatter signal from beam geometry and water depth. To produce a good quality backscatter image further post processing is usually needed. Appendix 2 contains a summary of how Simrads multibeam echo sounder systems calculate backscatter values (BS) for each ping and beam to best represent seafloor acoustic reflectivity properties. The exact algorithms to calculate backscatter for the EM 3002D multibeam echo sounder, used in this survey, were not released by the manufacturer (Kongsberg).

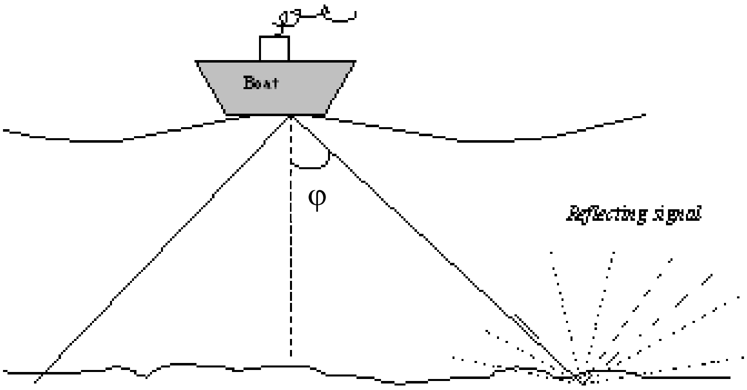


Figure 1. Sketch of multibeam measurements, showing the beam incidence angle and how the signal scatters as it hits the ocean floor. An unprocessed backscatter signal from a low incidence angle (φ) will generally be stronger then a signal from a high incidence angle.

Backscatter classification and statistical methods

The big number of sound pings per area unit obtained from a multibeam survey makes it difficult to analyze each signal with detail, as done when classifying single beam backscatter data (see 2.4.1). Instead it enables for a statistical comparison of individual pings in a grid, which can be used to create an acoustic statistical profile to identify different sediment types. Since the seafloor seldom is completely uniform and flat, the backscatter signal strength will show variations depending on the angle and roughness of the bottom. An irregular bottom will reflect the signal in many directions, and depending on the roughness and the frequency of the echo sounder some waves will be reflected away from the source and some will be reflected back. If you drop tennis balls onto a rocky riverbed they will bounce well but in all directions (high standard deviation), if you drop the balls on a sandy surface they will bounce less but come back to the direction they came from (low standard deviation). Sound waves will behave in a similar way.

There is a range of software available providing statistical classification systems for backscatter data. However, the complexity of the multibeam systems and the fast development of new hardware limit the software usable for the EM 3002 dual head multibeam echo sounder used in this project. The dual head system has only been on the market for a few years.

There are different approaches for statistical seafloor sediment classification. QTC Multiview classification software recognizes different bottom type, based on all surfaces that can be statistically distinguished from each other, and then letting the user put a name to each surface based on groundtruthing or previous knowledge of the area (Questertangent 2007). Triton classification software (also named Neptune C) used in this project let the user create its own classes based on backscatter data from known areas, then applying these classes to the whole data set (Kongsberg 2003). The class definitions are based on 5 statistical parameters extracted from the backscatter data. The statistical parameters in Triton are mean value, standard deviation, pace, contrast and quantile.

Mean value - mean backscatter value.

Standard deviation - is a measure of the deviation from the mean backscatter value.

Quantile - A common method for summarizing the distribution of a random variable. The median is the 0.5 quantile. The upper and lower quartiles are the 0.75 and 0.25 quantiles respectively. The quantile used in Triton is the 0.8 quantile.

Pace - The pace feature is a power spectrum representation of the backscattering strength, calculated through a Fourier transformation and a median filter.

Contrast - quantifying texture in an image, texture is related to the seafloor roughness. In Triton a gray level co-occurrence matrix is used for measuring the contrast

The parameters quantile and pace represents similar seafloor characteristics as mean backscatter value, and the parameter contrast resembles similar characteristics as standard deviation (figure 18).

2.5 GEOLOGICAL CLASSES

The backscatter data collected from the survey area (figure 2 and 3) were used to classify the surface sediments into 5 geological classes. The classified data were then used for GIS based biological modeling. The classes were chosen so they would best represent the geology in the survey area and what was visible on the backscatter data. The geological classes described below was used to classify the surface sediment in the Storgrundet survey area, see also Table 3. An adjustment of class 1 and 2 was done for Finngrunden survey area, adding small and mid sized rocks to class 2.

Class 1. Bedrock and moraine

This class describes a hard bottom type and the bottom structure is expected to be very coarse. The moraine was formed during the last ice age as the moving ice picked up material from the ground (i.e. bedrock and existing soil layers). The material was shaped by the eroding forces of the moving ice, and then deposited at the ice edge as the ice retracted. The resulting mix of blocks, rocks, gravel and soil is called moraine. The organic content of moraine is usually very low. In some areas erosion by waves and currents have affected moraine moving the finer sediments in the surface layers to areas of less water energy. The remaining moraine in these areas will mainly contain coarser material like blocks, rocks and gravel. Usually the coarser material is located on higher points in an area as these areas have been more exposed to erosion by waves.

Class 2. Gravel

This class describes, like class 1, a hard bottom but with finer bottom structure. It is expected to find this bottom type in regions with some shelter from waves and currents, but with enough water motions to keep finer sediments away. Commonly these areas are located on the fringes of more exposed structures.

Class 3. Sand
Sand bottoms are formed when waves and currents erode and sort the material, moving finer sediments to areas of less energy. Sand bottoms often show wavelike structures, which are formed when the water moves sand particles on the surface. Sand bottoms are something in-between hard and soft bottoms, and have a fine structure.

Class 4. Silt and clays
Glacial clays are characterized by high clay and silt content but have low organic content (<1%). Sporadic sand and gravel particles are often present. The clays have usually eroded in shallow areas and other areas affected by significant water motions. The surface is often covered with a thin layer of sand, gravel and sporadic rocks and blocks (figure16), deposited by the annual ice cover. The typical bottom structure for class 4 is a smooth fine bottom with sporadic interruptions of coarser material like blocks, rocks, gravel and sand.

Class 5. Muddy clay and unconsolidated sediments
This is an accumulation sedimentary bottom. These soft bottoms consist of sediments with high water to particle ratio in the bottom surface, and have a high organic content. The sediments bottoms are found in areas with very little water motions where fine material can be deposited. Typically this is deeper down. If there is environmental pollutions in an area it will most likely be found in these fine sediments as organic compounds and heavy metals bind only to very fine particles and organic material.

3. STUDY AREA

This chapter describes the study sites Storgrundet and Finngrunden, were two offshore wind power plant parks are planned. The chapter also includes a section with marine geology and a section with marine biology describing the geology and biology at Storgrundet and Finngrunden in general terms.

3.1 GEOGRAPHY

Storgrundet
Storgrundet is a 45 km^2 big shallow in the southern part of the Gulf of Bothnia, situated about 14 km from the mainland of Söderhamns municipality and about 4 km east of the island Storjungfrun. The depth varies between 2 and 41 meters.

The study area also covers a reference area, Hällgrund, for environmental consequence assessments, and a cable corridor from the mainland to Storgrundet (figure 2). The reference area measures 11 km^2, and the cable corridor is 12 km long, 250 m wide and has a maximum depth of 54 meters.

About 80 5 MW wind power plants are planned to be built on Storgrundet (WPD 2006 b).

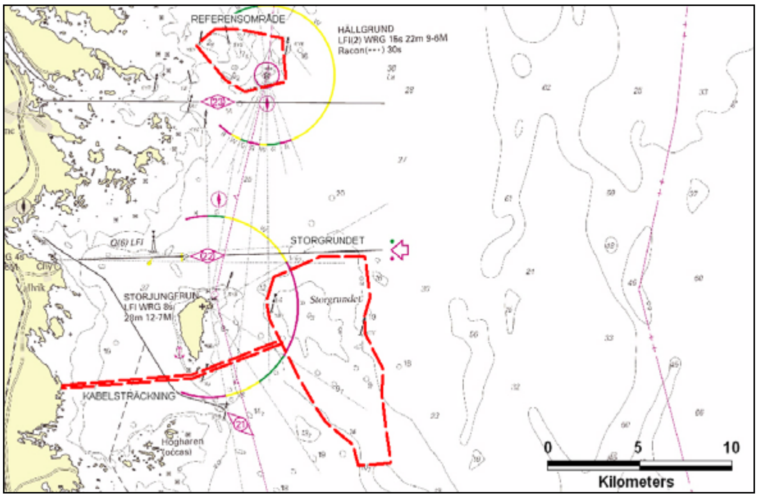


Figure 2. Map of the survey area on Storgrundet, and the planned cable corridor (Marin Miljöanalys 2007 a). The small area, Hällgrund, is a reference area for environmental consequence assessments. The total survey area covers 60 km^2.

Finngrunden

Finngrunden are a set of shallows in the southern part of the Gulf of Bothnia. The survey area (figure 3) consists of three shallows, the East bank, the West bank, a reference area for environmental consequence assessments, and a cable corridor to the mainland. The West bank is situated about 40 km northeast from Gävle, the survey area covers 73 km^2. The East bank is situated about 70 km northeast of Gävle, the survey area covers 33 km^2. The reference area is situated just north of the East and the West bank and covers 14 km^2. The cable corridor is 82 km long and 250 m wide, connecting the east bank, via the west bank with the mainland on two alternative legs. The depth on the shallows varies between 2 and 40 meters, and the maximum depth in the cable corridor is 64 meters. The shallows are situated just outside the Swedish territorial border, but inside Sweden’s economical zone.

The size and the location, far enough from the coast to not disturb the coastal population but close enough to make wind power production reasonable, makes Finngrunden suitable for big scale wind power production. The plan is to build 200 5 MW wind power plants with capacity of producing household electricity for 1,3 million people (WPD 2006 a).

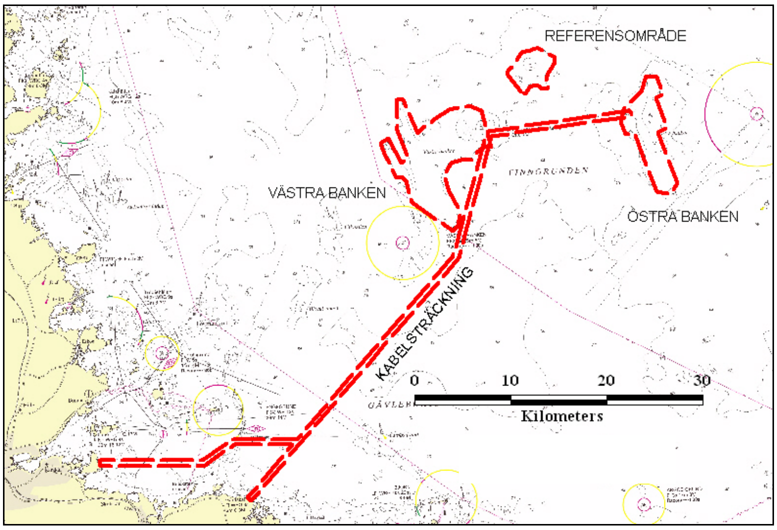


Figure 3. Map of the survey areas on Finngrunden and the planned cable corridor (Marin Miljöanalys 2007 b). The survey area on Finngrunden consists of the West bank, the East bank and a small shallow between the two used as a reference area for environmental consequence assessments. The total survey area covers 140 km^2.

3.3 GEOLOGY

Storgrundet is dominated by coarse moraine with boulders, gravel and sand. It is likely that both sedimentary and crystalline bedrock are present underneath the loose sediments (Marin Miljöanalys 2007 a). Finngrunden are also dominated by moraine, gravel and sand and the underlying bedrock, which is exposed at places, is sedimentary limestone (Marin Miljöanalys b). The moraine on Finngrunden consists generally of finer material, with fewer boulders and big rocks, compared with the moraine on Storgrundet. The sediments mainly consist of glacial material deposited during the last ice age. Both Finngrunden and Storgrundet are affected by drift ice during cold winters. The ice, which has been observed to be 6-7 meters thick at times, constantly move the bottom surface layer on the shallow areas (WPD 2006 a and b). The whole shallows show indications of powerful erosion by ice, currents and waves, which transport the material mainly towards the northwest. Previous marine geological measurements in the area has been conducted by SGU using single beam echo sounders, side scan sonar and seismic echo sounders. This data shows that the glacial deposits on top of the limestone bedrock has been transformed with the eroding water motions, moving the finer material like silt and clay to the deeper parts on the outskirts of the shallows, while the shallower parts consists of coarse material like stone blocks, rocks, gravel and sand (WPD 2006 a and b). Waves and currents have caused the sand and gravel to form of ripples and wave patterns on the bottom. The slopes on the edges of the shallows often consist of sand deposits. On greater depths (30-50m) finer sediments, like sand, silt and clays, are dominating. Some parts of the finer sediments have been covered with gravel, this feature occurs down to relatively large depths (Marin Miljöanalys 2007 a and b).

3.4 BIOLOGY

Due to ice cover wintertime and high erosion in the area, most algae are one-year species. As the salinity is low, varying between 4.5 and 5.5, most of the marine species are much smaller in these waters compared with areas of higher salinity. Observations from the East bank at Finngrunden by HydroGIS AB show that the vegetation is sparse (WPD 2006 a). Most of the macro algae are found on bigger blocks and rock surfaces down to 20 m depth. The dominating species in this area is the brown algae *Sphacelaria Arctica*. It grows on rocks along the edges of the shallows down to about 18 m depth. Areas with bigger macro algae, like different species of *Fucus*, have been observed on Finngrunden (Naturvårdsverket 2006). *Fucus* only occurs in sporadic patches as the ice and the sandy moraine bottom make long-term establishment difficult. Other species observed in the area are different red algae like *Polysiphonia Nigrescens* and *Hildenbrandia Rubra* and the brown algae *Pilayella Litoralis*.

Occurrences of benthic animals are also sparse on Finngrunden and Storgrundet. One of the typical species of mussel in this part of the Baltic Sea, *Macoma Baltica*, was mostly observed as dead shells on the bottom with few living specimens found. Crustaceans was found to be more common, like the *Mesidothea Entomon* occurring in plenty on bottoms with finer sediments then sand, and smaller crustaceans like *Gammarus sp., Idothea* and *Jaera sp.* Different species of fish have been observed, like the gulf herring *Clupea harengus*, and it is likely that the coarse moraine bottoms serve as quality playground with plenty of protection for eggs and juveniles (WPD 2006 a and b).

4. METHODS AND EQUIPMENT

This chapter describes how the sonar and groundtruthing data was collected, processed and analyzed. The data collected, i.e. multibeam bathymetry, side scan sonar, sub bottom profiler and groundtruthing data were brought together in a GIS program where all information about the seafloor was studied to understand how the backscatter data from the multibeam echo sounder was to be interpreted. There is also a detailed section how the backscatter data was normalized and classified. The processing of side scan sonar, multibeam bathymetry and sub bottom profiler data was done by Marin Miljöanalys AB.

4.1 SURVEYING

All data was collected from a small catamaran, Ranja, for technical specification see appendix 1.

Figure 4. Survey vessel Ranja

4.1.1 Positioning

An Aschtech Z surveyor RTK-DGPS system was used. The accuracy is 3 cm horizontal and 4 cm vertical. The coordinate system was WGS 84, which was converted into Swedish grid RT 90.

4.1.2 Bathymetry and backscatter

All multibeam data in this project was collected with a Simrad EM 3002D multibeam echo sounder. The system uses two angle mounted sonar heads (figure 6 a), producing a total of 508 individual beams with a maximum swath width of 200 degrees, 10 times water depth. The opening angle of each beam is 1,5 degrees and the pulse length is 150µs. The sound frequency can be set to 293, 300 or 307 kHz and the ping rate is up to 40 Hz. The EM 3002 uses dynamically focused beams and due to its electronic pitch compensation system and roll stabilized beams, the system has high resolution and accuracy even in foul weather. It is suited for detailed seafloor mapping and inspection with water depths between 0.5 and 150 meters (Kongsberg 2007). Data was collected with SIS Seafloor Information System. The procedure gave 100 % seafloor coverage within the survey area. Continues measurements with a Reason SVP15 sound velocity profiler corrected for temperature and salinity changes in the water column, and an Ixsea Octans III motion sensor corrected the multibeam data for roll and heave movements. Post processing of the bathymetric data was done in Caris Hips and Sips.

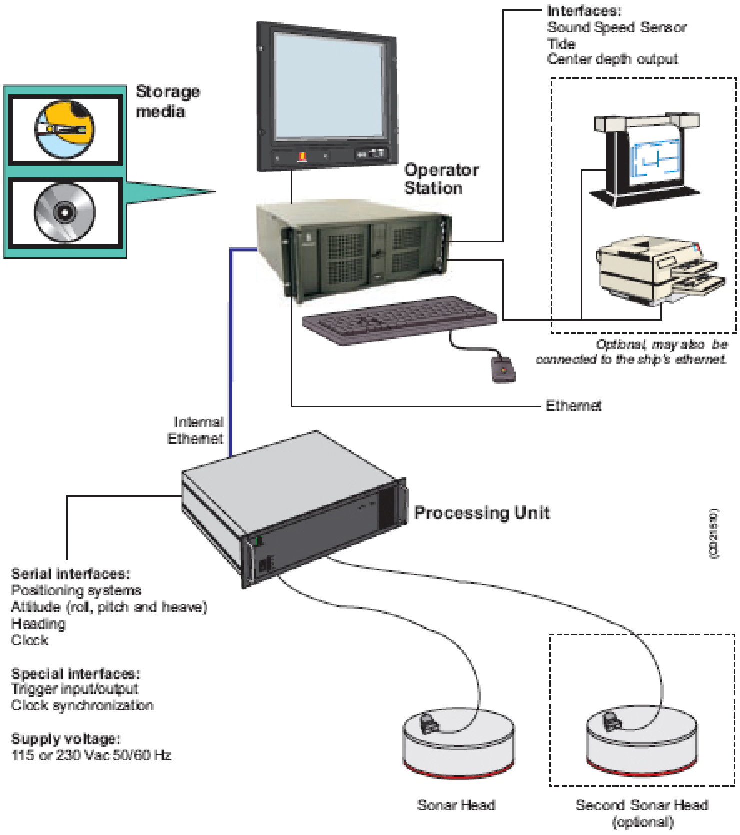


Figure 5. System layout, Seafloor Information System Multibeam EM 3002D

a) **b)**

Figure 6. a) Mounting the EM 3002D multibeam echo sounder on the survey vessel. b) Teledyne Benthos SIS1624 side scan sonar.

4.1.3 Side scan sonar

A Teledyne Benthos SIS1624, 100-400Hz, side scan sonar system was used for classification of sediments and to identify objects. The system produces high-resolution pictures of the bottom with a swath width of 50-300 m where bottom substrate, rocks and object can be identified. The side scan is towed behind the survey vessel, which makes it possible to adjust its height over the bottom to get the best image for object identification. Side scan sonar data are somewhat similar to backscatter data from a multibeam echo sounder as the side scan uses the amplitude from the returning sound signal. The procedure gave 100% coverage within the survey area.

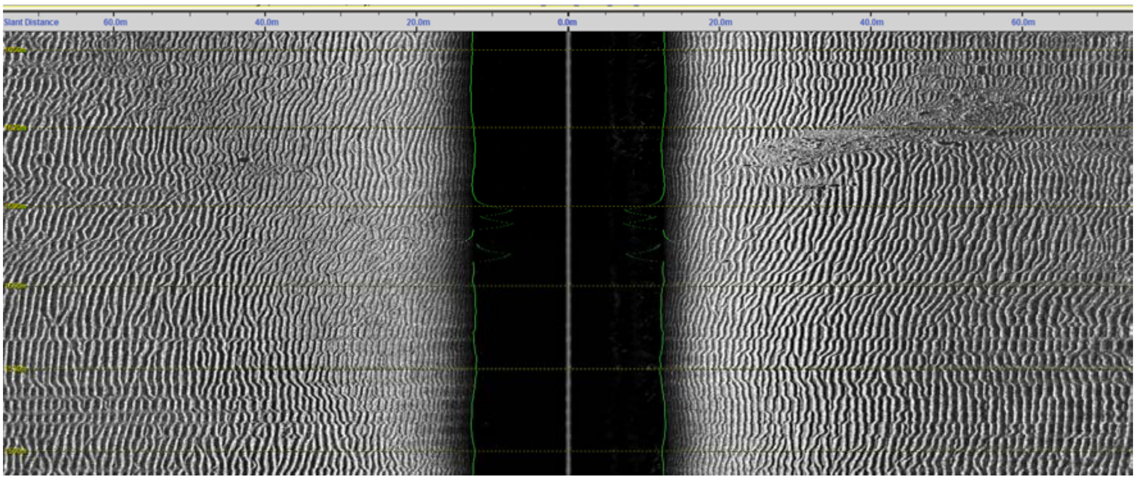


Figure 7. Side scan sonar image from Finngrunden with great sand ripples. The coverage is 150 meters.

4.1.4 Sub bottom profiler

A Teledyne Benthos CAP 6600 Chirp 2, 2-20 kHz was used to penetrate the bottom substrate and give information about sediment layers. Sub bottom profiler uses low frequency sound to penetrate the seafloor.

4.1.5 Groundtruth

Groundtruth information was collected from sediment samples and underwater films from both Storgrundet and Finngrunden. Storgrundet was the primary test area to correlate backscatter data with different seafloor sediment types. The locations for sediment sampling and under water filming on Storgrundet were chosen where specific bottom types were identified with backscatter data images, and at each site 2-3 sediment samples where collected. A few random sediment samples were collected at Hällgrund. The location of the sediment samples and seafloor filming sequences on Finngrunden where placed randomly all over the shallows, with exception of a few stations on the east bank which were selected for characteristics identified from backscatter and side scan sonar images.

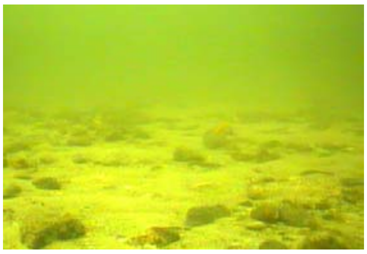
Sediment sampling

To collect the sediment samples on the shallows a van Veen grab sampler was used (figure 8 b). All samples were collected and stored for later identification of the sediment type, with exceptions of the fine sediment samples collected in the two planned cable corridors with a kayak sediment sampler (figure 8 a). The grain size distribution in these samples where estimated on site. The sediment samples from the cable corridors were sent to a lab for environmental analysis, which is not a part of this paper.

a) **b)**

Figure 8. a) Kayak sediment sampler. b) van Veen grab sampler

Video recording



Video image from UV camera

Under water video recordings on Storgrundet were conducted by drifting along transect lines, chosen so that they would cross between two or more different areas identified from backscatter data. Sediment samples where taken at the start and finish of the transect lines. On Finngrunden the video recordings of the seafloor where placed randomly over the shallows.

Diving

Diving took place at 3 dive sites on the shallow part of Storgrundet to try and locate exposed sedimentary bedrock. The boat laid anchor at each site and the diver searched an area of about 40 meter around the boat, taking notes of observed geology and biology.

4.2 POST-PROCESSING

4.2.1 Gain size analyses

8 sediment samples from Storgrundet, and 1 sediment sample from Hällgrundet, with gravel to fine sand where picked out for grain size distribution analysis. The samples where first washed in a wet sieve (0.075 mm), to determine the fine fraction, and then dried over night in an oven. The dry samples were run through a sieve set with ϕ intervals (mesh size 8mm, 4mm, 2mm, 1mm, 0.5mm, 0.25mm, 0.125mm and 0.71mm). All samples were put in a sieve shaker for 10 min. Each fraction for each sample was weighted. The grain size distribution and the mean grain size according to the Folk and Ward method were calculated for each sample using gradistat software (Simon et al. 2001).

4.2.2 Backscatter data processing

The data was processed to represent seafloor reflectivity properties independent of depth and incidence angle, and also to identify sediments using a statistical approach. The resulting data sets with normalized backscatter data were used as input values in all figures and tables based on mean backscatter data in this thesis. A statistical method was used to classify the backscatter data into 5 geological classes (table 1) based on statistical parameters (mean value, standard deviation, pace, contrast and quantile).

The processed backscatter data was further analyzed and visualized in the software Surfer, MapInfo and Global Mapper.

Backscatter normalization

The backscatter data is corrected for beam and depth dependence in the data logging process. Further processing to compensate the data for beam geometry and to produce mosaic backscatter images was done in Poseidon.

The Poseidon software gives you a number of choices, the most important ones are:

- Elimination of beams outside a certain incidence angle. Elimination of outer beams was conducted for most data sets when there was enough overlap.
- Grid size - the bigger grid size the lower resolution (1 meter pixels was used).
- Grid parameters -average, min or max grid value. A grid value is a representative of all values inside a grid. All options where tested, average value were used to produce the final data sets.
- Histogram corrections – an empirical method of correcting for beam geometry induced differences in backscatter strength. The histogram contains the mean values from each beam derived from all ping from the current and/or all previous data sets (Figure 9). By applying the histogram all beams that deviate from the mean beam value will be adjusted. As an example, if the mean backscatter value from beam 1 deviate 5 dB from the mean backscatter value based on all beams, all backscatter values from beam one will be adjusted 5 dB. The histogram method was used to produce the final data sets.

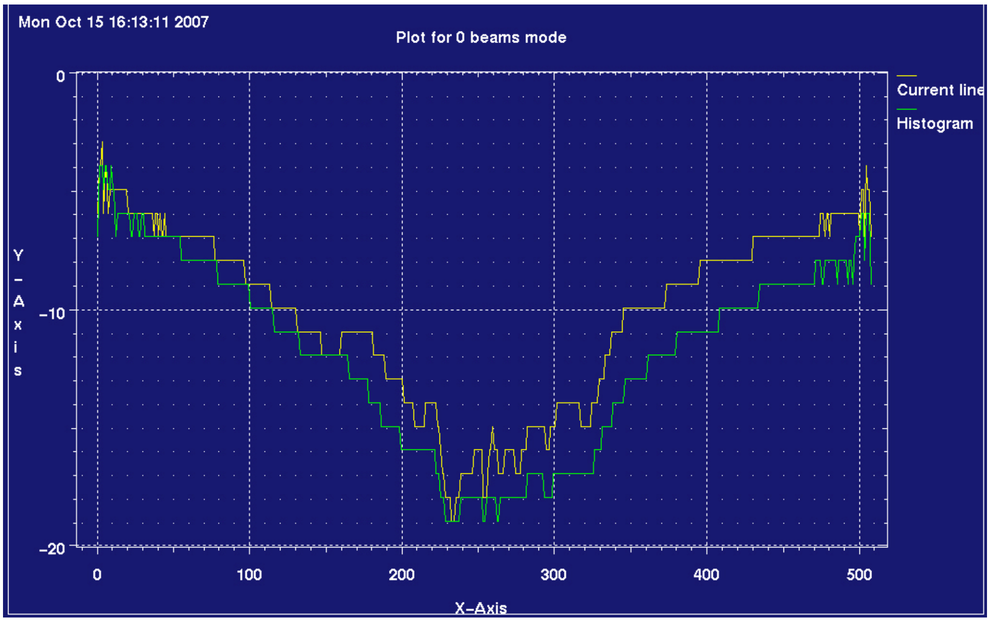


Figure 9. Histogram used for post processing backscatter data in Poseidon. The Y-axis display backscatter (dB) and the X-axis display beam number, normal incidence is around beam 250. The green line is based on all processed data, and the yellow line on the current survey line.

Statistical classification
Triton backscatter classification program consists of 3 parts: feature extraction (extracts statistical parameters from backscatter data), training section and classification section.

5 relevant classes where identified from groundtruthing and processed backscatter data. Triton was trained to recognize these 5 classes in the training module by selecting different regions containing data from these 5 specific bottom types. Also, for each class 3 individual classes were trained using data from the outer beams (high incidence angle, ~75-85 degrees), midrange beams (~45-65 degrees), and center beams (~0-30 degrees), to test how incidence angle affects mean backscatter value and standard deviation (figure 20-21).

The 5 classes where applied on all the data sets. The best result for Storgrundet study area (including Hällgrund and the cable corridor) was achieved by using 3 statistical parameters; mean value, standard deviation and contrast. On Finngrunden (incl. reference area and cable corridor) the statistical parameters used for seabed classification were pace, contrast and quantile (see section 2.4.2). The classified data sets where compared with groundtruthing, processed backscatter data, side scan sonar data and sub bottom profiler data for quality control and to be able to adjust the classes and statistical parameters when necessary.

Considerable efforts were made to find and correct for bugs in Triton and Poseidon, as dual head data caused various problems.

4.2.3 Data visualization

All the collected data, i.e. sediment samples and films, sidescan sonar images, sub bottom profiler information, bathymetry and backscatter data were brought together in two GIS programs, MapInfo and Global Mapper, for an overview of the information. The software Surfer was sometimes used for minor adjustments of the processed backscatter data.

Global Mapper - was used to convert ASCII files with backscatter data into various file formats and to change the projection from WGS 84 to Swedish grid RT 90. Global Mapper was also used to create all 3D images and images with backscatter data draped on bathymetric data.

MapInfo - was used to display graphic layers, like backscatter images, sidescan sonar images, bathymetric data and groundtruthing (i.e. sediment samples, films and dive observations).

Surfer – has a range of filter options, which can be used to smoothen the backscatter data set from incorrect soundings and deviations. Low pass filters were tested with some success but were not used in the final product.

5. RESULTS AND OBSERVATIONS

The results are divided into 2 main parts. The first part contains results and observations how normalized mean backscatter data changes with different bottom material and how you can classify bottoms combining mean backscatter data and bathymetric data. The second part contains result and observations from seafloor classification with backscatter data using statistical parameters like standard deviation and mean backscatter value.

Summary
Results from normalized backscatter data and groundtruthing shows that backscatter strength is mainly a function of grain size for sand and finer sediments, the finer sediment the weaker the backscatter signal. Backscatter signals from coarser materials, such as moraine gravel and boulders, is a function of both grain size and hardness and surface roughness and shape. The strongest backscatter signal was found to be reflected from a rough surface like gravel, which generally returns a stronger backscatter signal then boulders or other hard smooth surfaces. The implication of this is that a hard bottom with boulders might reflect the same mean backscatter signal as bottom with coarse sand (figure 14), and that using mean backscatter signal as the only parameter is not enough to separate the two. It was also found that that the backscatter signal from EM 3002D multibeam echo sounder penetrates poorly into the sediments and only reflects a thin surface layer of a few centimeters.

Two methods were tested to encompass bottom shape and roughness into the classification process; backscatter data combined with bathymetry (depth data), and statistical classification based on parameters like standard deviation, a measure of surface unevenness. It was found that by studying backscatter images draped on bathymetry (figure 10), it was possible to make detailed visual interpretations of the sediments, and to create visualizations of the seafloor containing both depth and geological information. For smaller areas this method gave the most detailed and accurate result. Statistical classification of backscatter data using Triton classification software also gave good results, but with less level of detail. Once the class training process was done the method was time efficient, and easy to apply on big data sets. The classified data are also easier to understand for users who are unfamiliar to multibeam backscatter data. Triton was used to define five geological classes using 5 statistical parameters, which were then applied on all survey data. The resulting classified data set were correct to 91.3 % compared with the groundtruth data (based on 89 sediment samples, 27 films and 3 dive observations from Storgrundet and Finngrunden).

It was found that beams with incidence angle >75° had a distinctly lower standard deviation and higher mean backscatter value compared with beams with incidence angle <70°.

5.1 BACKSCATTER DATA AND GROUNDTRUTHING

The sediment samples and under water films from Storgrundet showed that fine and medium sand returned a much weaker backscatter value compared with coarse sand and gravel bottoms (figure 10). The shift occurs somewhere between 0.5 mm and 1 mm mean grain size (figure 11)**.** The coarser samples (fine gravel and coarse sand) were less sorted than the finer samples (medium and fine sand). The sample size is too small to determine if sorting is a factor contributing to the big difference in sound absorption properties found in the narrow grain size interval between medium and very coarse sand (table 1). The groundtruth from Storgrundet indicate that gravel bottoms returns a stronger backscatter value then coarse moraine and bedrock bottoms (figure 10, 12, 13 and appendix 1). This hypothesis was strengthen by the 3 dive site observations on Storgrundet, which showed weaker backscatter values from coarse moraine with big boulders on the shallows compared with rocks and gravel deeper down (appendix 3, figure 27).

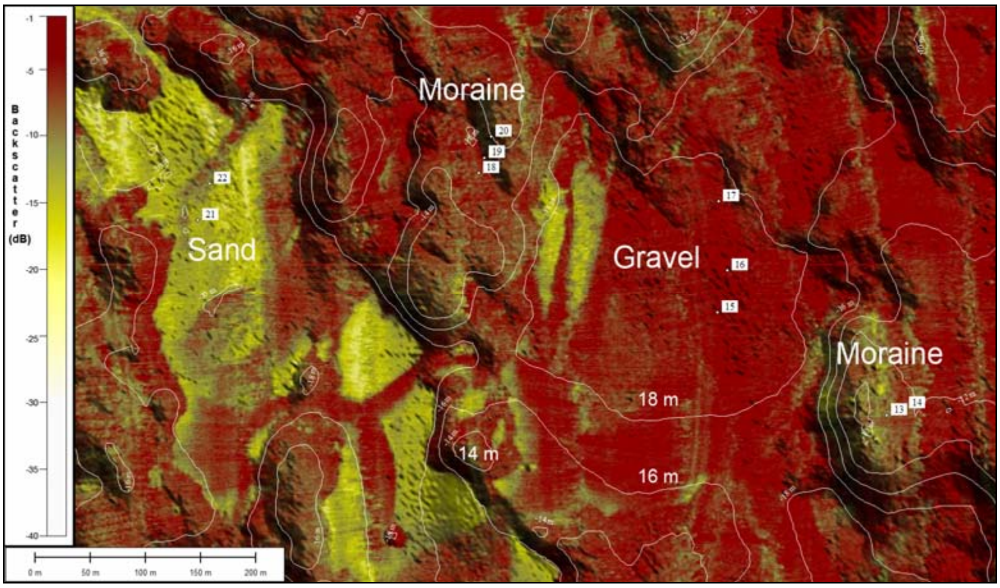


Figure 10. Sediment sample 13 to 22 from Storgrundet plotted on backscatter data draped on bathymetric data with 2m depth contour lines. Red shows a strong and yellows a weaker acoustic return (backscatter).

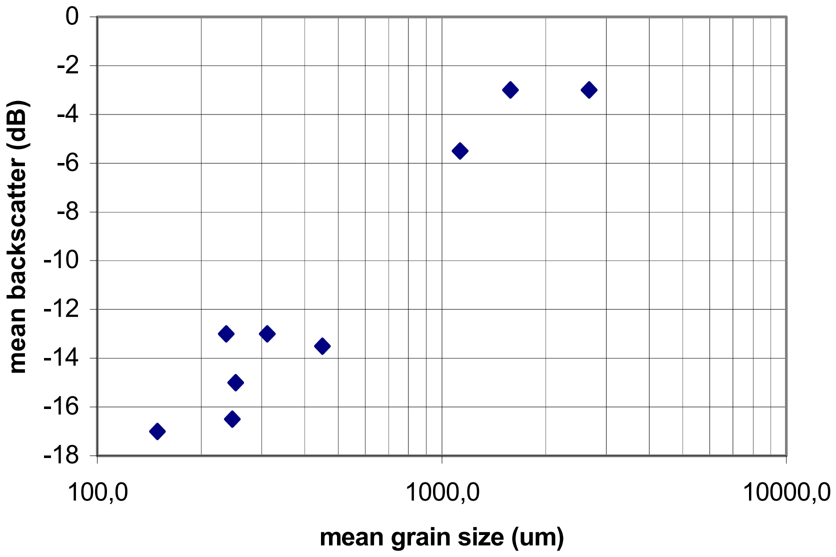


Figure 11. Mean grain size in sample plotted against mean backscatter value (table 1).

Table 1. Grain size distribution according to the Folk and Ward method from 8 sediment samples from Storgrundet and 1 from Hällgrund with corresponding mean backscatter value, arranged after mean grain size (figure 11).

Sample	Mean grain size (mm)	BS (dB)	Sorting (σ)	Sorting	Description
SG_16	2,674	-3	1,950	Poorly Sorted	Very Fine Gravel
SG_15	1,582	-3	2,091	Very Poorly Sorted	Very Coarse Sand
SG_8	1,131	-5,5	1,018	Poorly Sorted	Very Coarse Sand
SG_9	0,450	-13,5	0,523	Moderately Well Sorted	Medium Sand
SG_22	0,311	-13	0,786	Moderately Sorted	Medium Sand
SG_6	0,252	-15	0,467	Well Sorted	Medium Sand
SG_12	0,246	-16,5	0,480	Well Sorted	Fine Sand
SG_21	0,237	-13	0,637	Moderately Well Sorted	Fine Sand
HG_3	0,150	-17	0,824	Moderately Sorted	Fine Sand

Studies of the underwater films (Figure 13 and appendix 1) indicate that the observed variability in backscatter data also depends on external factors, which are not connected to bottom type. The variability in backscatter for flat uniform bottoms was about ± 2 dB for all sediment types. The films also showed that the transit zones between two different sediments are positioned with very good precision in the backscatter images (figure 12).

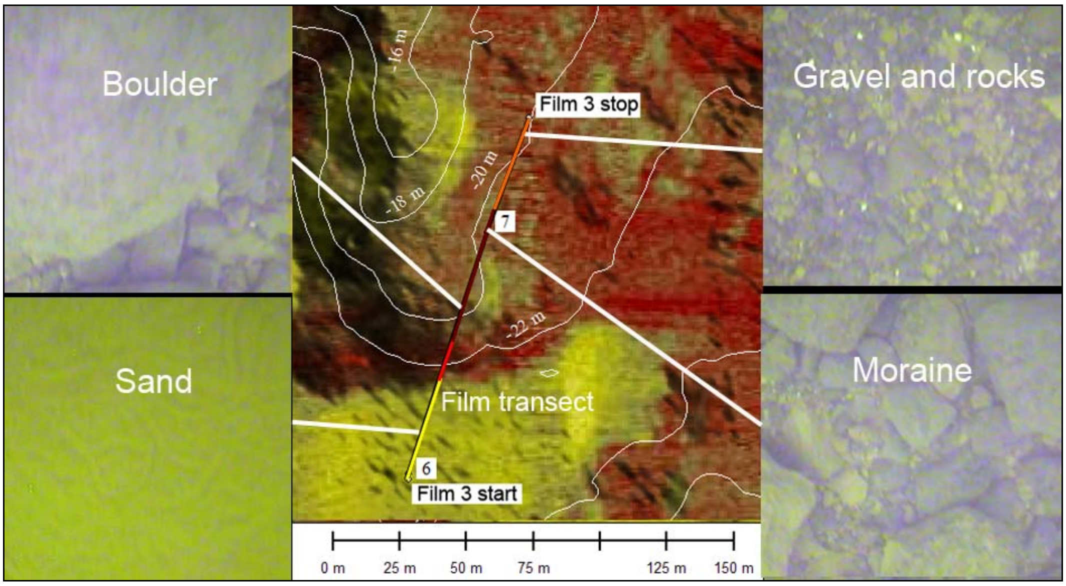


Figure 12. Backscatter image from Storgrundet draped on depth data showing film transect 3 (also shown in figure 13), and sediment sample 6 (sand) and 7 (fine moraine). The pictures show the different bottom types extracted from the film. Red shows a strong backscatter signal and yellows a weaker backscatter signal (dB).

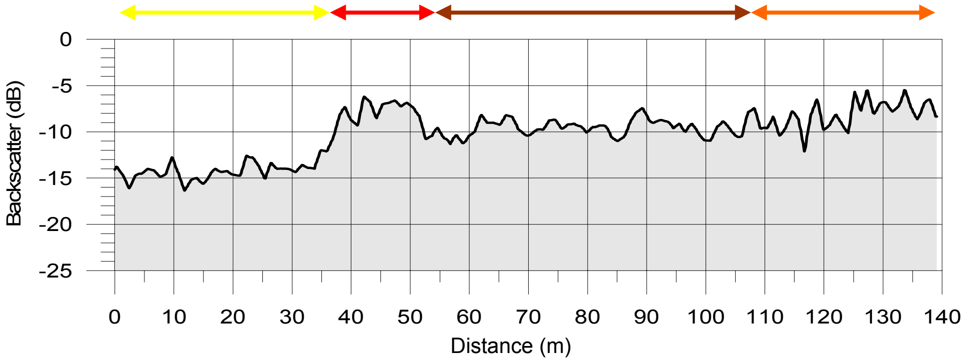


Figure 13. Backscatter profile from start to end point of film transect 3 (see figure 13). The film shows, left to right, sand with small shells (yellow), to fine moraine with gravel (red), to moraine with big boulders (dark red), to moraine with gravel (orange). Start depth 23 m, end depth 18 m.

The complete data set with groundtruth material from all survey areas on Storgrundet and Finngrunden plotted with mean backscatter value (dB) show that fine grain sizes (i.e. sand, silt and clay and muddy clay) can be separated by looking solemnly at mean backscatter value (figure 14 and table 2). Gravel has the highest mean backscatter value of all sediments encountered. From gravel to coarser sediments the mean backscatter starts to decrease with increasing grain size (figure 14), which is likely a function of both surface hardness and surface shape and roughness. A comparison between figure 11 and 14 shows that fine and coarse moraine corresponds to the same backscatter interval as sand with 1-0.5 mm grain size. Mean backscatter value alone is not sufficient to separate rocks and blocks from coarse sand.

All 6 classes shown in Figure 14 were statistically different from each other (two tailed paired t-test, 95% confidence interval) except for coarse moraine (class 6) and fine moraine (class 5). No relationship was found between processed backscatter and depth within each sediment type (appendix 3, figure 28).

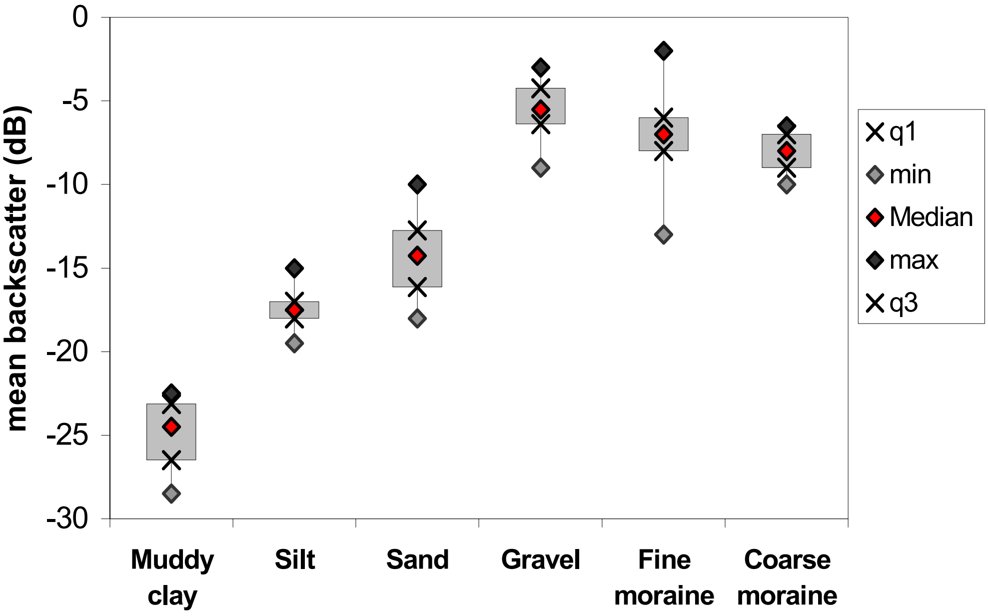
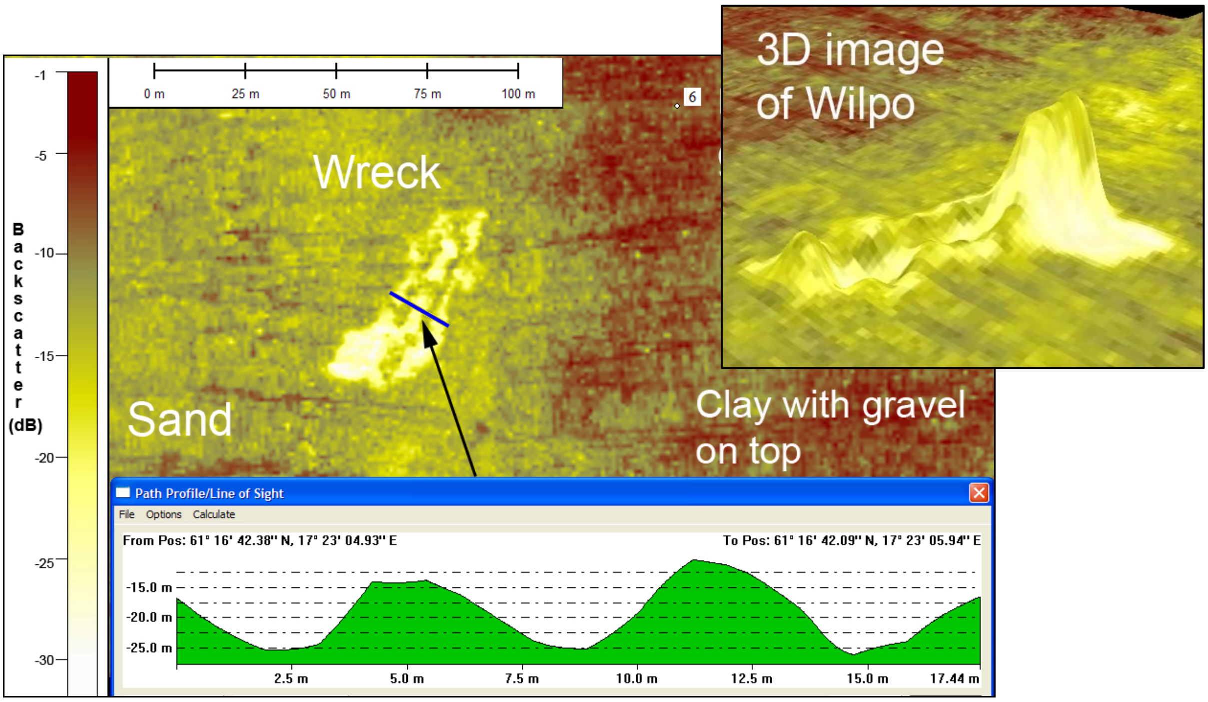


Figure 14. Box diagram with all relevant samples from Finngrunden and Storgrundet divided into 6 geological classes plotted with corresponding mean backscatter value from the EM 3002D multibeam echo sounder. Class 1 coarse moraine and bedrock, class 2 fine moraine, class 3 gravel, class 4 sand, class 5 sandy muddy silt, class 6 muddy clay and unconsolidated sediments. Two tailed paired t-tests between all classes showed that all classes where significantly different from each other with 95% conf interval except for coarse moraine and fine moraine (p-value = 0,195).

Table 2. All relevant samples from Storgrundet and Finngrunden divided into 6 classes. Class 1 coarse moraine and bedrock, class 2 fine moraine, class 3 gravel, class 4 sand, class 5 sandy muddy silt, class 6 muddy clay and unconsolidated sediments.

Classes	# of samples	Minimum BS (dB)	Maximum BS (dB)	**Mean BS (dB)**	Std. deviation
Coarse moraine	5	-6,5	-10,0	**-8,1**	1,4
Fine moraine	40	-2,0	-13,0	**-7,0**	2,0
Gravel	18	-3,0	-9,0	**-5,4**	1,5
Sand	20	-10,0	-18,0	**-14,1**	2,6
Silt	5	-15,0	-19,5	**-17,4**	1,6
Muddy clay	10	-22,5	-28,5	**-25,0**	2,2

As shown in figure 14 and from other observations there are strong indications that the backscattered signal from the 300 kHz multibeam echo sounder is weaker from hard, smooth surfaces, like bigger rocks and boulders compared with rough slightly softer surfaces like gravel. This theory is strengthened by observations from the wreck Wilpo found on Hällgrund (figure 15). According to a diver (Linder 2007) who has visited the wreck site, the wreck Wilpo, sunken around 1960 (Öiås 2007), has a steel hull and is in good condition. The surrounding bottom consists of sand. The backscatter values from Wilpo's steel hull vary between –11,5 and –25 dB, which correspond with backscatter values from sand to mud.



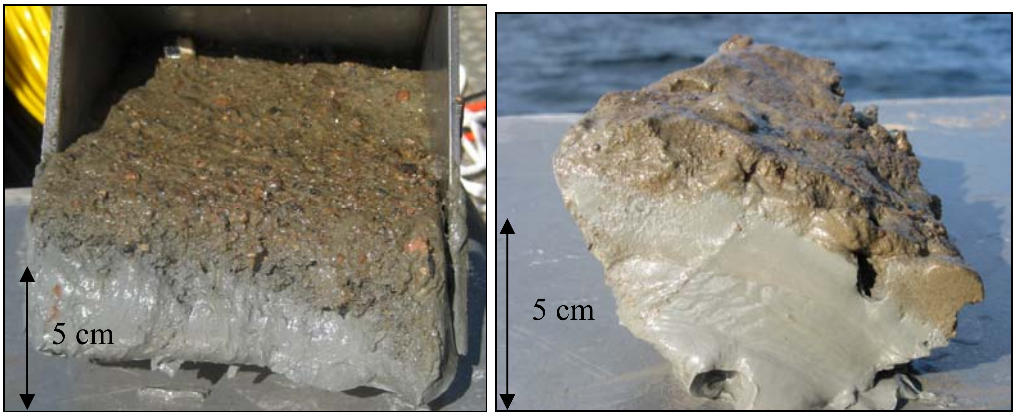
From Pos: 61° 16' 42.38'' N, 17° 23' 04.93'' E

To Pos: 61° 16' 42.09'' N, 17° 23' 05.94'' E

Figure 15. Backscatter image of the steel wreck Wilpo from Hällgrund. The depth is about 40 m. The profile shows the backscatter value from a cross section of the wreck, which ranges from –25 dB to –11 dB. The figure also shows sediment sample 6, containing clay covered with a thin layer of gravel on the surface (figure 16 b) and a 3D image of the wreck with backscatter data draped on bathymetric data.

Surface penetration

A number of samples from the van Veen grab sampler of soft clay bottoms covered with coarser material like sand and gravel shows that the 300 kHz high frequency acoustic signal from the EM 3002 multibeam echo sounder only reflects a very thin surface layer of 1-2 cm, and is seemingly not affected by the underlying sediment at all. The clay bottoms covered with a 1-2 cm thick layer of gravel and sand shown in figure 16 returns a backscatter signal, which corresponds only with the thin surface layer of sand and gravel. A total of 10 sediment samples were of the same character as the two shown in figure16, i.e. clay covered with a thin layer of sand, gravel and small rocks. The average backscatter value from these 10 samples was -7,95 dB.



a) b)

Figure 16. Van Veen grab sampler with one sample from Storgrundet (a) and sample 6 from Hällgrund (b). The underlying clay is covered with 1-2 cm with coarse sand/fine gravel. The corresponding backscatter value for sample 25 was –7 dB (depth 41 meters), and for sample 6 it was –9 dB (depth 42 meters). These backscatter values indicate a hard bottom, only clay would normally have a backscatter value around –20 dB.

5.2 SOFT SEDIMENT IDENTIFICATION

Backscatter data from Storgrundet cable corridor compared with 10 sediment samples with muddy unconsolidated sediments show that backscatter data can be used to identify soft sediments with very high precision. Figure 17 a. and 17 b. show two different ways of visualizing this information. Figure 17 a. is based on bathymetric data and a black and white backscatter image. Figure 17 b. show backscatter data with a fixed color scale based on the approximate mean backscatter values defined for each class as described in table 3. A classified image created with Triton statistical classification software shows the same soft sediment area but with less detail (figure 17 c). In all three images the soft sediments, which in this case were targeted for environmental analyses of sediments, are clearly visible.

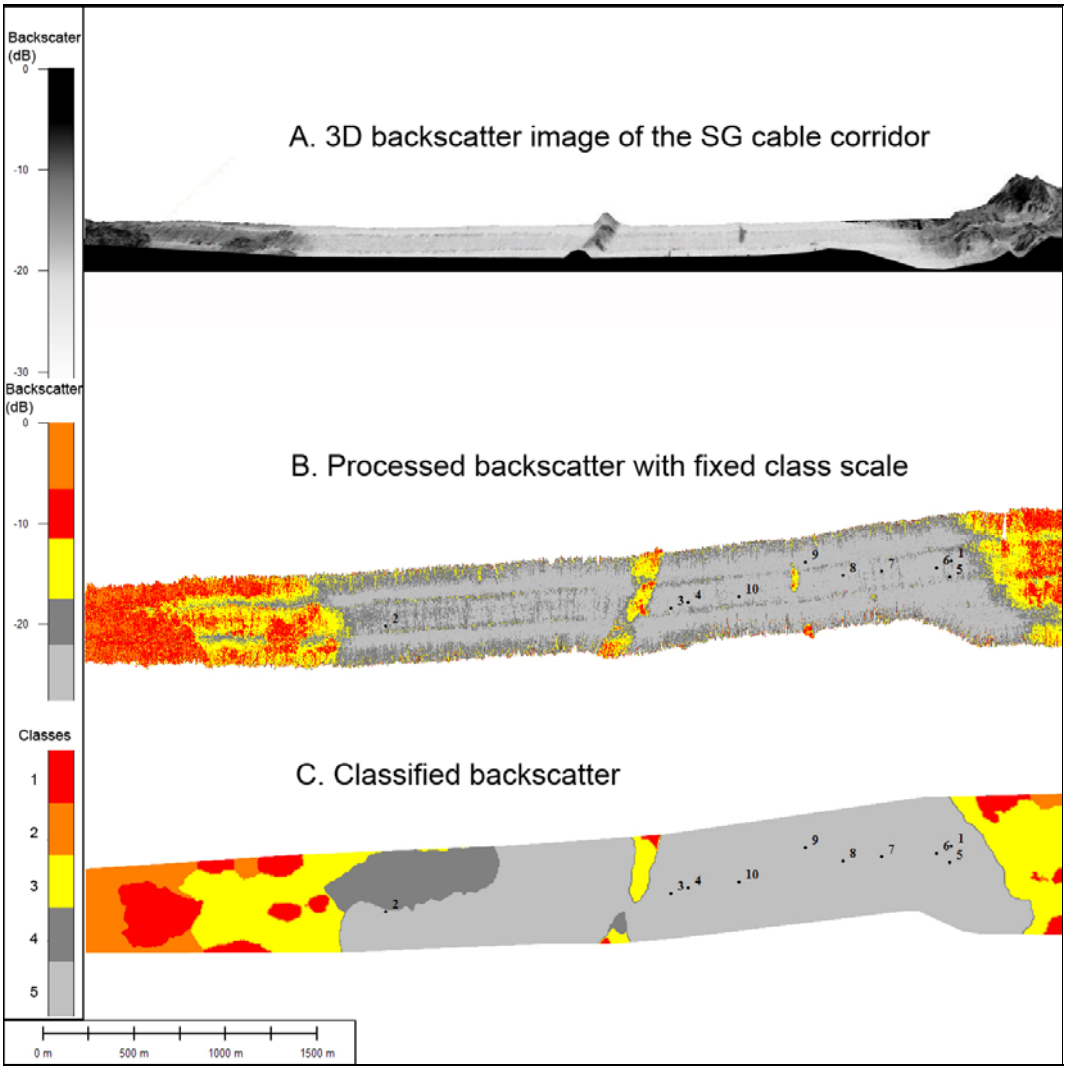


Figure 17. Backscatter images from a 4 km section of Storgrundet cable corridor with 10 sediment samples from unconsolidated muddy sediments. Image A show a mean backscatter image draped on depth data, where black is hard bottom and white is soft bottom. Image B shows the same section but with a fixed scale set after the classes defined in table 3. Image C is a classified image. The 5 classes are described in table 3 and the classification is based on the statistical parameters mean backscatter, standard deviation and contrast (figure 18). The depth is 5 to 54 meters.

5.3 STATISTICAL CLASSIFICATION

Statistical methods were used to classify the whole survey area of Storgrundet and Finngrunden into 5 geological classes. The statistical parameters standard deviation and contrast give a measure of surface shape and roughness, and helps to separate sediments where mean backscatter value alone is not enough. The five classes are described in table 3. The class definitions and the relating approximate mean backscatter values in table 3 are based on results and observations where backscatter could be related to sediment type.

Table 3. Description of the 5 geological classes used for statistical classification. The mean backscatter values for each class are approximate and depend on the post processing methods and the specific sediment types in an area.

Class	Color Code	Bottom Index	Reflection	Sound Dispersion	Geology	Back-scatter (dB)
1	Red	Hard	Very strong	Big	Bedrock and moraine	-6,5 - -11,5
2	Orange	Coarse	Strong	Average	Gravel	>-6,5
3	Yellow	Fine	Medium	Average	Sand	-11,5 - -18
4	Gray	Very fine	Weak	Small	Silt and clay	-18 - -22,5
5	Light gray	Soft	Very weak	Small	Muddy clay and un-consolidated sediment	< -22,5

5.3.1 Statistical classification of Storgrundet and Finngrunden

The classification software, Triton, was trained on areas where the sediment types were known to identify five sediment classes. These training areas were first identified using normalized mean backscatter, side scan sonar images and groundtruthing. The resulting statistical class definitions (figure18) indicate that backscatter signals from moraine and bedrock (class 1) have a higher standard deviation and contrast then the rest of the sediments. The difference in standard deviation is biggest between coarse moraine and gravel (class 2). It was found that the best classification result for Storgrundet survey area was achieved by combining three parameters; mean backscatter, standard deviation and contrast. For Finngrunden survey area the definition for class 2 was altered slightly to also encompass small to mid sized rocks, as the gravel bottoms on Finngrunden where often mixed with coarser material. The best result for Finngrunden was achieved using the statistical classification parameters contrast, pace and quantile.

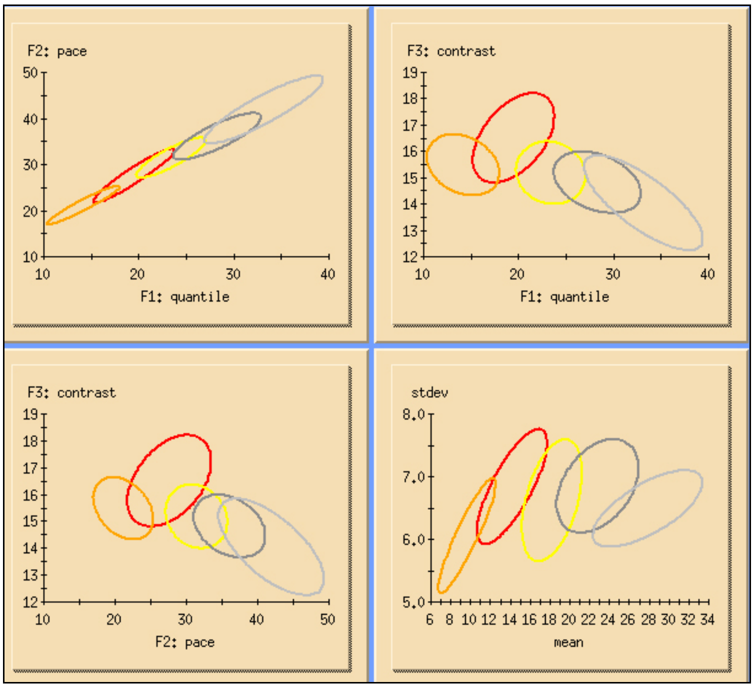


Figure 18. Backscatter class definitions for 5 seafloor sediment types, with 5 different statistical parameters (pace, contrast, quantile, mean and standard deviation). The classes are based on backscatter data (-dB) from all 508 beams. Class 1 moraine (red), class 2 gravel (orange), class 3 sand (yellow), class 4 silt (dark gray) and class 5 muddy clay (light gray).

There were considerable beam effects, showing deviations due to incidence angle, when the classification was based on 1-meter grids (i.e. each square meter is classified to represent one class). A better result, almost free of beam effects was obtained with classification based on 8-meter grids, however the resolution obtained was lower.

The final product with classified data from Finngrunden and Storgrundet was produced using 8-meter grids and a smoothing filter (figure 19). Based on the groundtruthing (89 sediment samples, 27 films and 3 dive observations) the classified backscatter data was correct to 91.3 %.

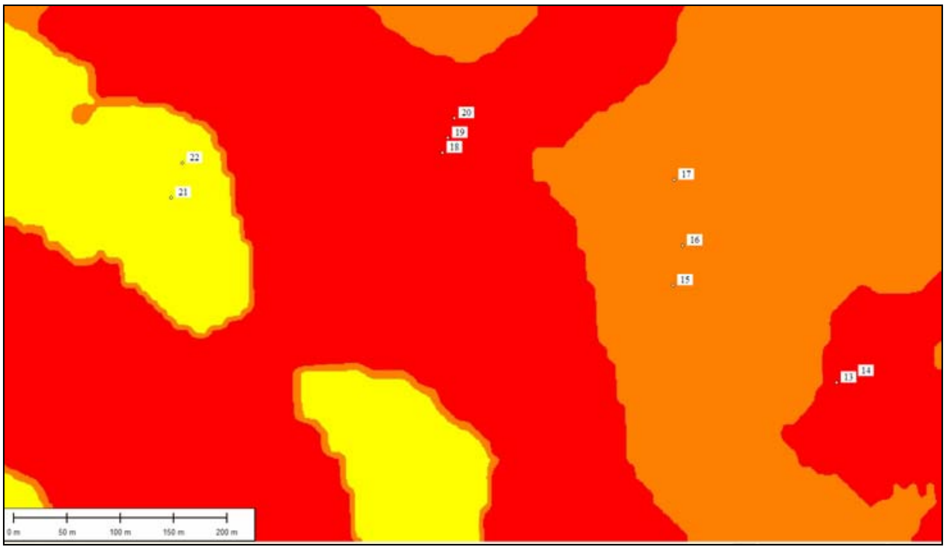


Figure 19. Classified backscatter data with sediment samples, showing the same area as in Figure 10. Class 1 moraine (red), class 2 gravel (orange) and class 3 sand (yellow). The sediment samples in this image all corresponds with the right class.

5.3.2 Beam angle limitations

Studies of how normalized mean backscatter and standard deviation change with incidence angle showed that there is a very distinct change for beam angles >~75°, where standard deviation is lower and mean backscatter is higher compared with lower incidence angles (figure 20).

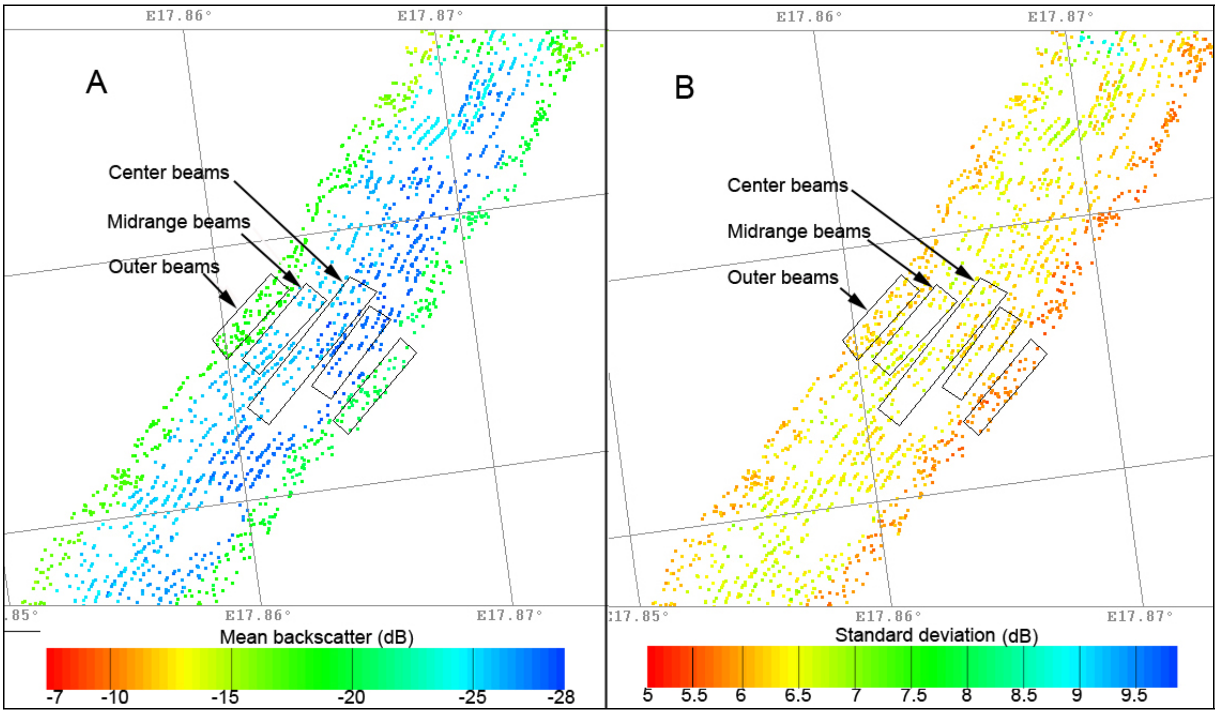
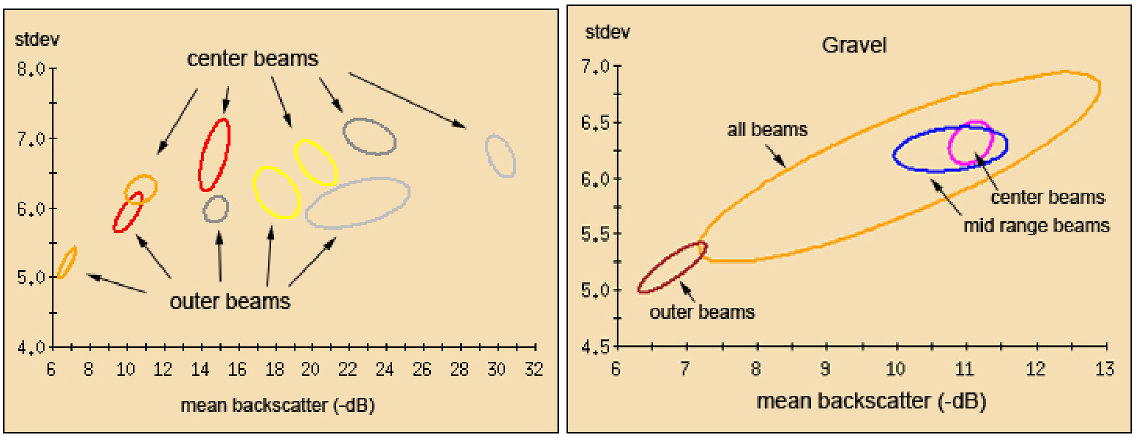


Figure 20. Triton class training module showing one EM 3002D echo sounder survey line from a silt bottom from Finngrunden cable corridor, average depth 55 meters. The squares in the figure defines different classes, in this case center, midrange and outer beams. a) Mean backscatter (dB), b) backscatter standard deviation. Notice how the standard deviation is lower, and the mean backscatter value is higher on the outer beams.

This observation was further investigated by training new classes in Triton based on center beams (0°-30°), mid range beams (45°-65°) and outer beams (75°-85°) for all five classes (table 3). The trend was the same for all classes; the outer beams had a higher mean backscatter value and lower standard deviation compared with values from midrange and center beams, which are not significantly different from each other (figure 21 and appendix 4). Figure 21 a shows the class definition based on mean value and standard deviation for outer and center beams from each sediment type. Notice how the moraine outer beam class overlaps the class definition for the gravel center beam class.

Figure 21 b and appendix 4 show that the center beams and the midrange beams have very similar class definition for all five sediment types, while the outer beams have lower standard deviation and a higher mean backscatter value. The result means that for angles up to about 70° it will be possible to make accurate class definitions.



a) *b)*

Figure 21. a) Class definition with backscatter mean value and standard deviation based on the center beams (0^o-25^o) and the outer beams ($>75^o$) for 5 geological classes (figure 20). Class 1 moraine (red), class 2 gravel (orange), class 3 sand (yellow), class 4 silt (dark gray) and class 5 muddy clay (light gray). b) Class definition for gravel based on all beams (0-85^o, orange), the center beams (0^o-30^o, pink), midrange beams (45^o-60^o, blue) and on the outer beams (75^o - 85^o, dark red).

5.4 NORMALIZATION PROBLEMS

Often backscatter and bathymetric data show some effect of ship track lines. This is mainly due to roll and heave motion (seen as cross track stripes in figure 22), incorrect sound velocity profiles (affecting not only bathymetric data but also backscatter data as seen in figure 17 b), and problems with normalization for incidence angle. On a few places the ship track lines were extra obvious (figure 22), showing higher backscatter values for every second line. As the survey vessel has measured in both directions this indicates that there is a difference in mean backscatters strength between the two sonar heads. Sonar head 1 uses 293 kHz and sonar head 2 uses 307 kHz sound frequency, which could be the reason for the observed effect. However, the difference between the two sonar heads was observed to occur quite sparsely and be limited to specific areas. This indicates there are several factors that could be involved, for example bottom composition and water depth.

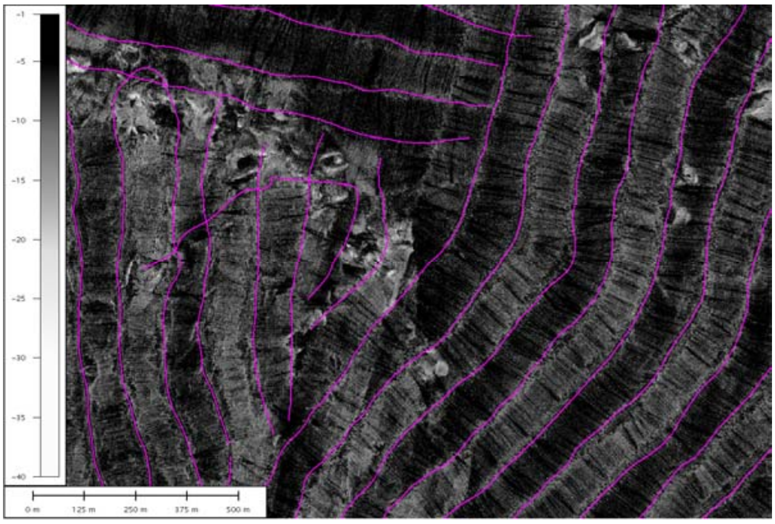


Figure 22. Backscatter image from Finngrunden reference area with ship track lines (purple). Black color represents high and white low backscatter values. Notice how every second line has weaker BS values, especially on the right side of the image. This could be due to the fact that the two sonar head operate at different frequencies 293 kHz and 307 kHz respectively. This picture also shows dead-ice-holes from the last ice age.

6. DISCUSSION

Backscatter and grain size

The results from section 5.1 show that for the EM 3002D echo sounder there is a linear relationship between bottom backscatter strength and sediment grain size for medium sand and finer sediments. The relationship can be used to identify soft sediments with very good accuracy if the backscatter signal is properly normalized to represent the reflective properties of the seafloor. It was found that gravel returns the strongest backscatter signal of all sediments encountered, including boulders and bedrock. This means that surface roughness and bottom shape must be taken in consideration in order to separate coarse sand and gravel from rocks, blocks and bedrock. The backscatter images from the wreck on Hällgrund (figure 15) indicate that a hard and smooth surface, in this case a ships steel hull, returns a much weaker signal then expected. This corresponds well with the observations that backscatter decreases in strength for grain sizes bigger then gravel. The reason for this behavior could be the short wave length (5 mm) and the narrow opening angle (1.5^o) of each transducer, producing a very focused high frequency sound pulse that can easily be deflected away from the survey vessel when reflecting on a hard smooth surface. A hard surface reflects the sound wave better then a soft surface but in order to result in a strong backscatter signal the sound wave has to be reflected back towards the source. Materials with a rough surface, like gravel, will scatter the sound pulse in many directions and is therefore more likely to reflect part of the signal towards the transducer. It seems like very coarse sand, gravel and pebbles have just the right mix of surface hardness and roughness to give a strong backscatter signal from a 300 kHz echo sounder. Sound frequency is likely to be of great importance for the reflective properties for different materials (Ryan and Flood 1996), and it is a well known fact that a lower frequency sound wave penetrates deeper into the bottom surface then a high frequency sound wave.

Another survey using 300 kHz multibeam echo sounder indicated that in sandy sediments, the median grain size, the seabed roughness, and the sorting of sediment can be combined to predict backscatter intensity with high significance, and that the relative importance of these variables varies between different sites (Collier and Brown 2005). The sorting statistics from table 1 has too few samples to support or reject this observation. The results shown in figure 14 and table 3 can be compared with a survey from Gullmarsfjorden using a 300 kHz Simrad EM 3000 multibeam echo sounder. That survey resulted in a similar relationship between grain size and backscatter strength, with the exception that there was no distinction made between gravel and coarser material, and the backscatter values from the survey were generally a few dB higher for each class compared with the classes in table 3 (Marin Mätteknik 2006).

It was observed during the post processing that the algorithms adjusting the backscatter value for incidence angle often over compensate for angular dependence. This could be due to the complex physics of how the original sound wave reflects on the surfaces structures of the sediments, often splitting up into many sound waves traveling in all directions. This could well be the reason that even for relatively flat bottoms a higher signal then expected reflects back towards the transducer from a high incidence angle compared with a low incidence angle.

Backscatter combined with bathymetry
The images with backscatter draped on bathymetric data, together with groundtruthing, are a very effective way of determining bottom composition. These images are relatively easy to understand for a viewer unfamiliar to backscatter data and leaves the user in better control of how the data have been processed, compared with advanced statistical classification programs. Co-registration of backscatter data and bathymetric data has been shown, among other applications, to be valuable for biological habitat assessments for quantitative rather then qualitative surveys (Lockhart et al. 2007).

The disadvantage with bottom classification based on mean backscatter data and bathymetry is that it is hard to make the classification process automatic, as grain size cannot be directly related to backscatter value for all sediment types without studying bathymetric data. Manual interpretations are time consuming to classify larger areas, but can be an efficient way of studying smaller areas, used for example for mudding planning in harbors. There is software, like the ARCGIS based Benthic Terrain Modeler (BTM) tool that can extract bottom rugosity and slope angle indexes from high-resolution bathymetric data. A combination of such an index and backscatter data could potentially provide an efficient automatic classification system.

Multibeam backscatter combined with other sonar systems
Information gathered from sub bottom profiler and side scan sonar data also provides valuable information together with backscatter data. An advantage with the hull mounted multibeam echo sounder compared with a towed side scan sonar system is that the correlation between backscatter data and bathymetric data is exact, although sand-wave patterns and other bottom structures such as rock outcrops and objects are more easily identified with side scan sonar. Sometimes a combination of the two was found to be efficient. For example sand wave patterns could easily be identified from side scan sonar, while the grain size could be identified from backscatter data. It has been found that for shallow water surveys a hull-mounted side scan sonar system works better together with the EM 3002D, then a towed side scan sonar system (Pøhner et.al. 2007). The high frequency (300 kHz) backscatter data was shown to penetrate only a couple of centimeters down into the sediments, therefore sub bottom profiler data can be a good complement to identify soft sediment that are covered with a thin layer of sand, gravel or small rocks.

Statistical classification
The results from the statistical classification in Triton show that with sufficient groundtruthing for class training and quality control it is an efficient and fast method of classifying large areas using only backscatter data. The accuracy with less then 9% error is reasonably good compared with previous surveys (Intelmann et. al. 2004). The class definitions (figure 18) reveal that there is a significant difference in standard deviation between gravel and moraine and bedrock, where gravel have a lower standard deviation then coarser sediments. This observation goes well in line with the theory that mixed and unsorted structures, like moraine surfaces, results in a higher variability in the backscatter data compared with flat surfaces like gravel and finer sediments (Gonidec et al. 2003).

A closer look at the class definitions as a function of incidence angle in figure 20 and figure 21 show that there is a drastic shift in both mean backscatter and standard deviation between incidence angles < ~70^{o} and incidence angles >~75^{o} for all 5 sediment types used for class training. The algorithms (see appendix 2) that normalize mean backscatter value for incidence angle dependence does not work well for the extreme incidence angles measured with the dual head system. The backscatter strength is overcompensated for high incidence angles resulting in too high backscatter value for beams with high incidence angle. It has been observed that for incidence angles between 20° and 70°, the backscatter data changes very little, while outside these angle the change is more drastic (Mulhearn 2000, Collier and Brown 2005).

The same shift that takes place for mean backscatter value for incidence angles > ~75° also take place for backscatter standard deviation for incidence angles >~75°. The difference is that standard deviation is lower for high incidence angles then for smaller incidence angles. No observation of this phenomenon was found in the literature. The explanation could be that a sound pulse from a very high incidence angle would become more dispersed compared with a sound pulses from lower incidence angles when it reflects the bottom. As a sound wave from a high incidence angle then represents a larger area, the variability between the sound pulses from the same area would likely be smaller, resulting in a low standard deviation.

The implication of the observation that statistical parameters change for high incidence angels is that angles bigger than ~70° is unsuitable to use for statistical classification. By excluding these angles it should be possible to get a very accurate classification result using automatic classification based on statistical parameters. This was confirmed from observations of a single head mulitbeam data set, combined with groundtruthing, from a previous survey in Lerkil on the Swedish west coast (Marin Miljöanalys unpublished data). The classification could be made with higher detail (grid size 1m) without unwanted beam effects, compared with classification using dual head data. To achieve a satisfactory result without eliminating high incidence angles from dual head data big grid sizes (>8 m) and an interpolation filter were used. This lowered the level of detail but on the whole the resulting classified data set from Storgrundet and Finngrunden still reflected the bottom composition with 91.3% accuracy based on the groundtruthing (89 sediment samples, 27 films and 3 dive observations) in the survey area.

Two statistical classification methods

In the Triton classification system the user has to have predefined classes, or train new classes for each survey site related to the encountered sediment types. Well-defined classes can be created if the user has enough ground truth information from each sediment type in the survey area. The classification process from there and on is relatively simple and fast. However it can be difficult and time consuming to gather the groundtruth material needed to create these classes. An alternative approach is the QTC Multiview Seabed Classification software, which automatically identifies areas that are statistically different from each other and then let the user put a name to these classes. Comparisons between these two methods have not been done within this project, but would be interesting to look into.

Accuracy and processing problems

The data sets with mean backscatter value and sediment type assume that the corresponding backscatter value reflects only the properties of the seabed. This is not completely correct. The quality of the backscatter data depends on the weather and ocean conditions when the data was collected, the skill of the surveying team, and how well the post processing has been conducted. All backscatter and bathymetric data showed some affect of ship track lines, mainly due to roll and heave motion, incorrect sound velocity profiles and problems with normalization for incidence angles. The backscatter variability due to external factors not connected to bottom composition was observed to be ± 2 dB, but varied between different data sets. The observations of backscatter variability was made by studying film transects.

All groundtruthing, except the samples from Finngrunden West bank, was located using high accuracy RTK-DGPS system with 3-4 cm precision. The real accuracy was lower as the exact location of the sampler or video camera also depends of the drift away from the boat, which can be up to 5-10 meters for deeper surveys on a windy day. Corrections where made for drifting when needed, but the exact offset could only be estimated leaving an error marginal of about ±5 meters on days with lots of waves and wind.

Another source of error is the classification of the groundtruth material. Many bottoms consist of a mix of different sediment types and can be hard to fit into one specific class. For example a sandy bottom mixed with rocks. The sediment samples collected may not represent the area very well. This is especially a problem for the mixed moraine substrates, where diving, films and photos were the best way to understand how the bottom really looked like.

A difference in backscatter strength of a few dB was observed between the two sonar heads for some survey lines (Figure 22). This indicates that there are one or several factors, linked to backscatter strength, which causes a difference between sonar head 1 and 2. There could be several explanations but the most obvious difference between the two is that sonar head 1 uses 293 kHz frequency sound and sonar head 2 uses 307 kHz frequency sound. As frequency is known to affect reflectivity properties (Ryan and Flood 1996), frequency could well be the reason. It is unclear if such a small difference really causes a measurable difference in backscatter strength, and how different sediment types affect this phenomenon. Further research is needed.

As significant differences were found (figure 14) between mean backscatter values and the different sediment types, errors due to processing problems and the methods of collecting data seem to be acceptable.

The biggest error in the automatic classification process was due to problems with high incidence angles >~75° for which standard deviation and mean backscatter values were shown to be very different compared with signals from lower incidence angle. The classification result was still acceptable with an accuracy of about 91 %. Bottom classification will always be an estimate as there are many surfaces that consist of a mix of two or several classes.

7. CONCLUSIONS

Detailed geological information can be extracted from backscatter data and be used for a range of services, even more so if backscatter is combined with bathymetric data. The combination of bathymetry and backscatter is also a powerful way of visualizing geological information for viewers unfamiliar to backscatter data.

For successful interpretation of backscatter data it is important to understand how the data varies with grain size and surface roughness as described in this paper. It is also important to know that the data only reflects a very thin surface layer. Literature studies showed that the relationship between bottom backscatter strength and grain size for high frequency multibeam echo sounders has been poorly examined in previous papers. It is likely that the relationship between grain size and backscatter strength change between different multibeam echo sounder systems since they often use different beam opening angle, pulse length and frequency.

Groundtruthing and measurements with side scan sonar and sub bottom profiler add important information to backscatter images.

Combining knowledge about backscatter strength related to sediment type with roughness and slope indexes extracted from bathymetric data could potentially provide very detailed geological information. Further research is needed.

Classification of sediments using statistical parameters like backscatter standard deviation and mean value is a powerful quantitative tool of classifying larger areas and users who are unfamiliar to backscatter interpretation can use the final product. There are problems using the full beam width from dual head multibeam data. The backscatter signal from extreme grazing angles needs to be better corrected for mean backscatter value but also for statistical parameters like standard deviation. Single head data is somewhat easier to use for statistical classification purposes. Classification combining statistical classes with detailed bathymetric data could provide good results. Further research is needed.

As backscatter data is collected together with bathymetric measurements, the information can be a valuable product in addition to bathymetric maps. Where multibeam data already exists, backscatter images can be produced to a very low cost compared with additional measurements with side scan sonar. When both side scan sonar and multibeam backscatter data are present they can be used as valuable complement to each other.

Examples of services for the EM 3002D multibeam backscatter data, which can be used with existing techniques:

- Identification of soft and hard bottoms for mudding projects and other building projects at sea, delivering co-registered maps with both bathymetric and backscatter information.
- Identification of bottom sediments with fine grain sizes which can potentially contain pollutions (i.e. mud and silt). Calculations can then be made to estimate the area which these sediment covers.
- Geological classification of surface sediments, which can be used for habitat assessments and many other applications

Possible services in the future:

- Even more detailed geological classification using both backscatter data statistics and roughness and slope indexes from bathymetric data.
- Mapping of macro algae coverage.
- Calculations of biological biomass, and fish and plankton distribution in the water column.

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APPENDIX 1

Technical specification R/V Ranja

<u>R/V Ranja</u>	
Type:	Catamaran hull, aluminium
Length:	7,70 m
Width:	3,60 m
Depth:	0,6 m
Weight:	3500 kg
Engine:	2x80 HK Yamaha Four Stroke
Fuel capacity:	100 L (+400 L extra tank)
Max speed:	25 knots
Survey speed:	4-7 knots
Equipment:	VHF, Radar, Echo sounder
<u>Hydrographic equipment</u>	
Multibeam echo sounder:	Kongsberg EM3002-D, 508 beams, 293, 300 and 307 kHz
Motion sensor/Gyro:	Ixsea Octans III
Positioning:	Aschtech Z-Surveyor, Network-RTK
Sound velocity profiler:	Reson SVP15, Valeport Mini SVS
<u>Geophysical equipment</u>	
Side Scan Sonar:	Teledyne Benthos SIS 1624, 100-400 kHz
Sub bottom profiler:	Teledyne Benthos CAP 6600 Chirp 2, 2-20 kHz
Magnetometer:	Geometrics G-882
<u>Sediment sampling</u>	
Environmental sampling:	KC, Kayak sampler
Surface sediment:	van Veen grab sampler
Bottom verification:	frame mounted UV-camera

APPENDIX 2

This appendix contains a technical description of how backscatter is normalized to represent seabed properties in the Simrad multibeam echo sounders.

The return signal strength from an echo sounder is defined by the equation:

$$U = SL - 2TL + BTS \qquad (3)$$

U = return signal strength [dB], SL = source level [dB re 1 μPa], TL = transmission loss [dB], BTS = bottom target strength [dB].

The source level (SL) is the amount of sound radiated by the source, measured as the intensity of the radiated sound at a distance of 1 meter from the source (Hammerstad 2005).

The transmission loss in the water column depends on two major factors:

- Spherical spreading of sound energy as it moves from its source: $TL_s = 20\log R$, R = range [m].
- Energy absorbed by the water: $TL_a = \alpha R$, α = absorption coefficient [dB/m].

The bottom target strength (BTS) depends on the reflective properties of the seabed but also on the bottom area that reflects the backscattered signal at any given time. Therefore it is common to define a bottom backscatter coefficient, BS [dB/m^2], as a measure of bottom reflectivity. The equations to best describe BTS changes with the incidence angle and also depends on the beam geometry, which can be described by the beam width (θ_x, θ_y) at normal incidence ($\varphi = 0$), and along track beam width (θ_x) and the transmit pulse length (τ) in all other directions.

$$BTS = BS + 10\log \theta_x \theta_y R^2 \text{ for } \varphi = 0 \qquad (4)$$

$$BTS = BS + 10\log c\tau/(2\sin\varphi)\ \theta_x R \text{ for } \varphi > 0 \qquad (5)$$

As the receivers in the multibeam echo sounders have limited dynamic range a time variable gain (TVG) is run during the ping to avoid overload, or having the echo buried in noise. The TVG will also flatten the beam sample amplitudes, which is beneficial for bottom detection (Hammerstad 2000).

The backscattering coefficient also varies with the incidence angle. Assuming a flat uniform bottom the assumption is that for incidence angles larger then 25 degrees the change follows Lamberts law, i.e.:

$$BS = BS_0 + 20\log(\cos\varphi),\ BS_0 = \text{mean backscatter coefficient} \qquad (6)$$

For incidence angle $0^\circ \leq \varphi < 25^\circ$ lamberts law doesn't apply as well, and another set of equations have been found to be a better approximation of mean backscatter coefficient. A simplified version is to calculate BS_N at 0° and BS_0 at 25° using (4) and (5), and assuming a linear change between the two. In the full model used in the Simrad multibeam echo sounders the trigonometric functions at φ 25° are replaced by $R=1.1R_1$, the full set of equations of this empirical approach are:

$$BTS = BS_N + 10\log\theta_x\theta_y R^2 \quad for R \leq R_I \tag{7}$$

$$BTS = BS_O - 5\log(R/R_I)^2[(R/R_I)^2 - 1] + 10\log\frac{c\tau}{2}\theta_x R \quad for\ R \geq 1.1R_I \tag{8}$$

$$BTS = BS_N + 3.162\sqrt{R/R_I - 1}(BS_O - BS_N) - 5\log(R/R_I)^2[(R/R_I)^2 - 1]$$
$$+10\log\frac{c\tau}{2}\theta_x R \quad for\ R_I < R < 1.1R_I \tag{9}$$

The crossover angle where Lambert law applies has been found to be quite variable depending on bottom type (Hammerstad 2000). The Simrad echo sounders uses a constant crossover angle of 25^o and the mean backscatter value will always be approximately, as it assumes a flat uniform bottom. Small deviation from Lambert law has been found (Gensane 1989), however these are neglected in the processing. Another paper, which aimed at finding a less empirical approach, the Jackson model, showed that backscatter values from grazing angels between 20^o and 70^o varies little due to angle. The BS values used for bottom classification from Simrads multibeam echo sounders are an average value of sample amplitude values.

In the post processing process it is theoretically possible to correct for the scattering area for non-uniform bottoms, however this option is not further investigated in this thesis.

Simplified seafloor backscatter can be described as the acoustic reflection loss at the seafloor [dB], with the equation:

$$BS = U - SL - 2TL - GT,\ GT = total\ gain \qquad (10)$$

APPENDIX 3

This appendix contains diving and UV film groundtruthing from Storgrundet related to mean backscatter, and also mean backscatter from sediment samples related to depth (figure 28).

Figure 23-26 shows backscatter profiles (1m grid, Poseidon) from start to end point of each film transect from Storgrundet. Figure 27 show mean backscatter draped on bathymetry from Storgrundet dive sites.

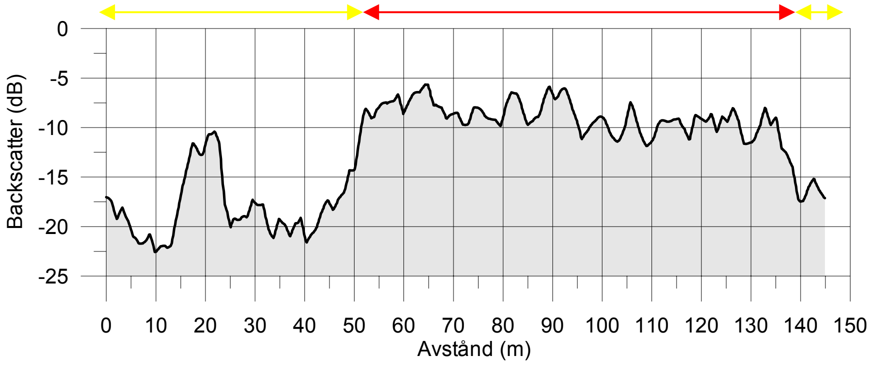

Figure 23. Backscatter profile from start to end point of film 1, Storgrundet. The film show sand/silt bottom (yellow) with a sharp transit to moraine (red). The average depth is 19 m.

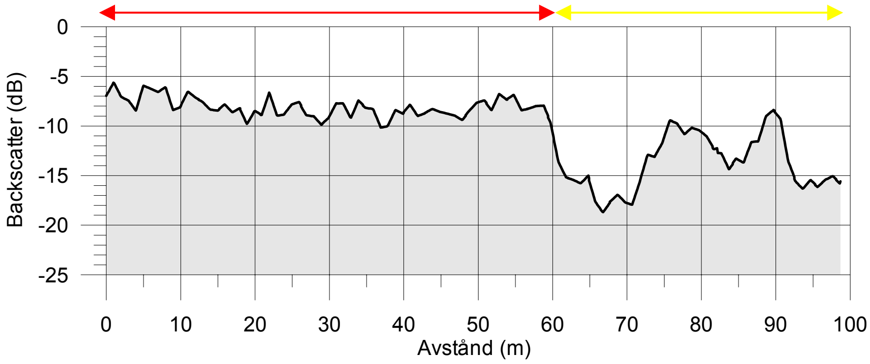

Figure 24. Backscatter profile from start to end point of film 2, Storgrundet. The film show moraine with small patches of sand (red), to sand with a few rocks (yellow), average depth 24 m.

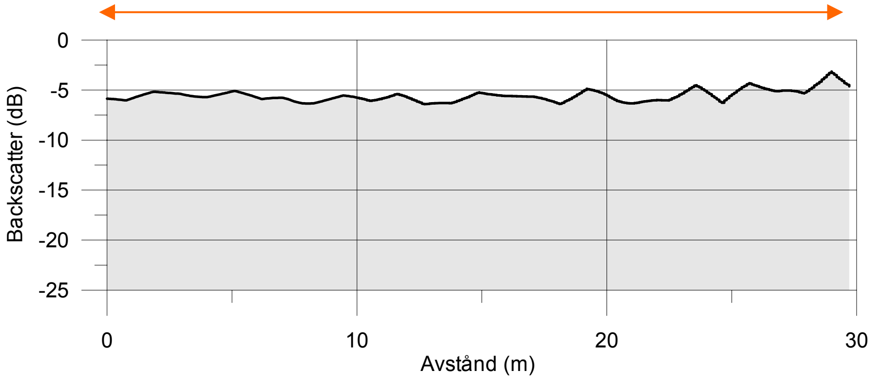

Figure 25. Backscatter profile from start to end point of film 4, Storgrundet. The film show gravel (orange) with some small shells and a few rocks, average depth 22 m.

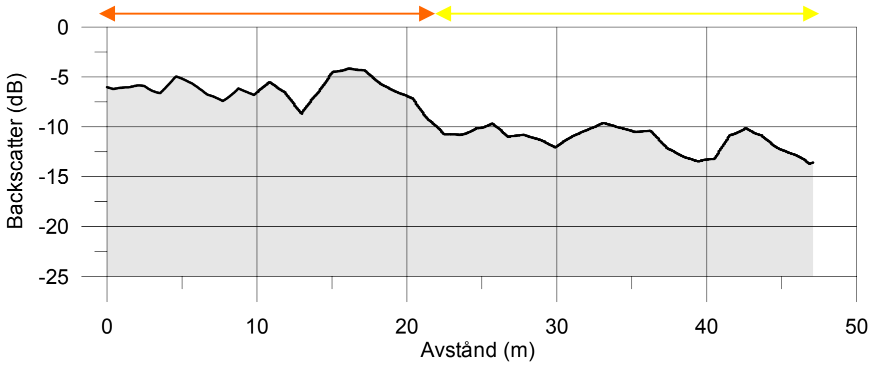

Figure 26. Backscatter profile from start to end point of film 5, Storgrundet. The film shows moraine and gravel (orange) to sand with some rocks and shells (yellow), average depth 21 m at start to 22 m at finish.

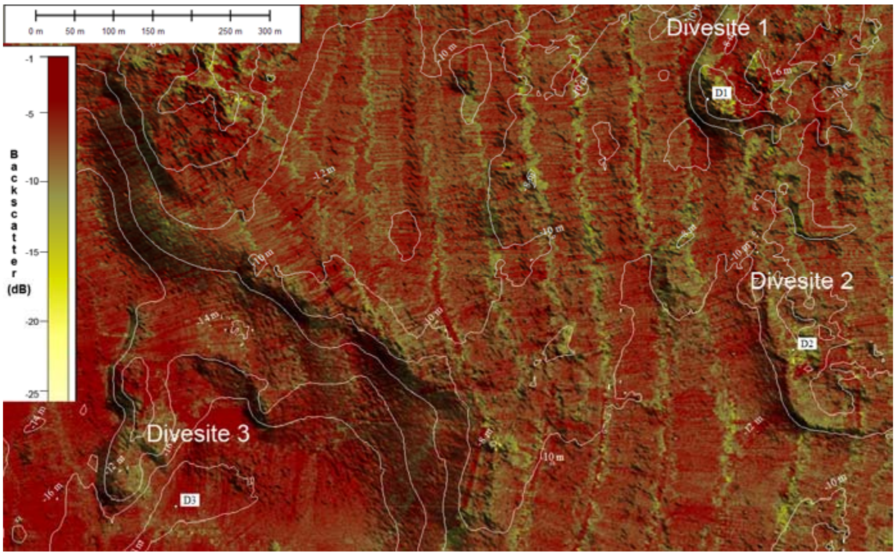

Figure 27. Mean backscatter draped on bathymetry with 3 dive sites from Storgrundet. The shallow part (3-6 meters) on site 1 and 2 consists mainly of boulders and bigger stones with some green algae growth, deeper down there was mainly smaller rocks and very spars vegetation (6-9 m). Dive site 3 had mid sized rocks on the shallow part (6-8 m) and small rocks and gravel on the deeper part (8-12 m) with very sparse algae growth.

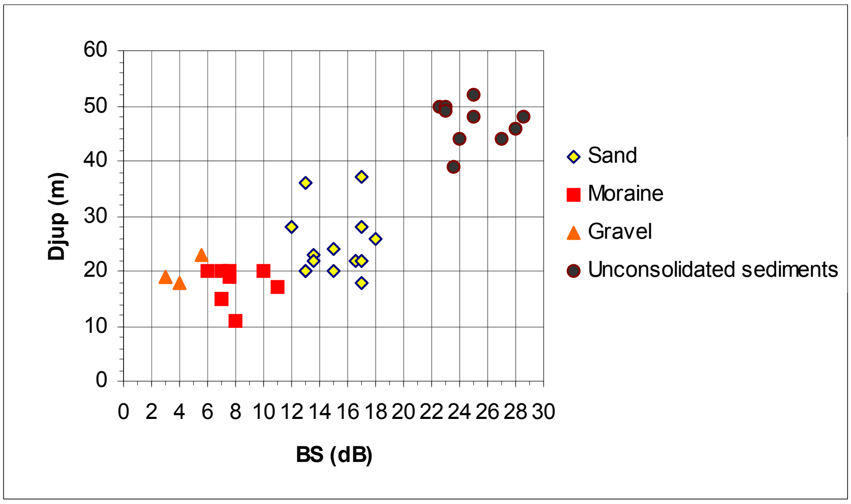

Figure 28. Backscatter value (dB) and depth (m) from sediment samples from Storgrundet, divided into 4 classes, moraine, gravel, sand and unconsolidated sediments.

APPENDIX 4

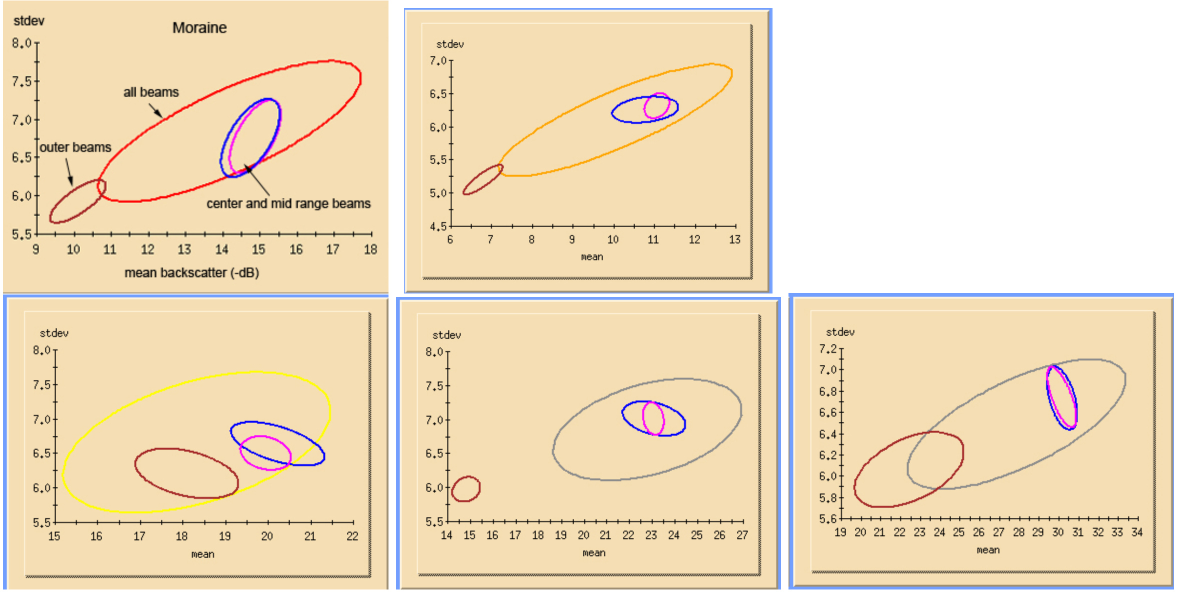

Figure 29. Class definition in Triton for 5 geological classes with mean backscatter (-dB) and standard deviation based all beams (0-85°, class color, see table 3), the center beams (0°-25°, pink), midrange beams (40°-60°, blue) and on the outer beams (>75°, dark red).