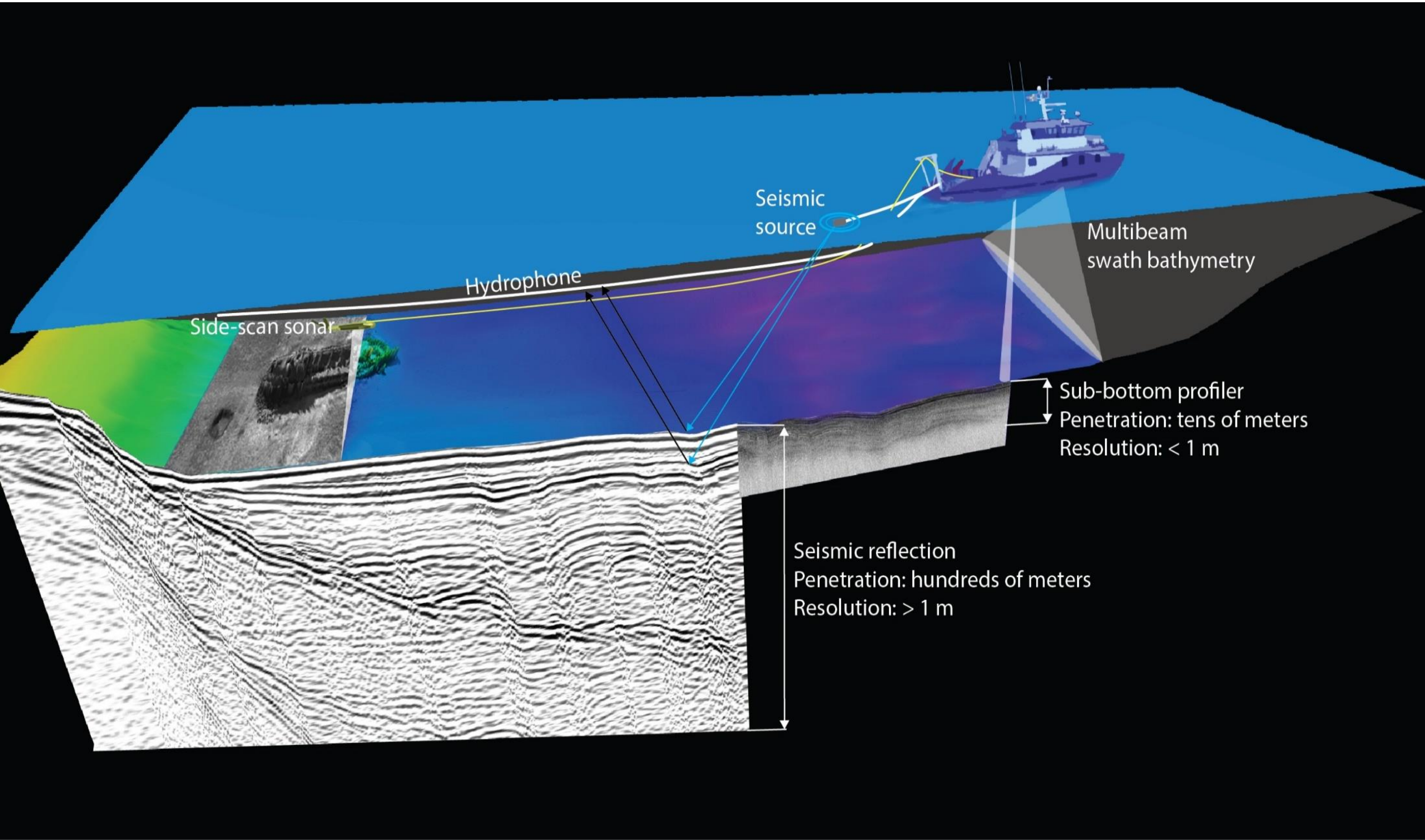
Marine geophysics, 7.5 hp

Moment 4

Lecture 2: ***High resolution acoustic seafloor and sub-bottom mapping methods***

Stockholm University



Moment 4

Lecture 2: *High-resolution acoustic mapping methods*

Reading: Chapter 3, pages 31-60 in *Marine Geophysics* by E.J.W. Jones and *Mapping submarine glacial landforms using acoustic methods* by Jakobsson *et al.* provided as a PDF.

This lecture complements the book by providing additional information on acoustic high-resolution mapping methods, specifically with respect to multibeam bathymetry since that field has evolved substantially over the last decade. Section 3.5 "MULTI-BEAM SWATH SOUNDING" in Chapter 3 of the course book should therefore be viewed as providing a historical snapshot on the state of the multibeam field at the end of the 1990s. The capacity of multibeam sonars has since improved substantially. For example, it is now standard to employ several hundreds of beams rather than the numbers presented in Chapter 3. This Lecture 2 of Moment 4 and the provided PDF of Jakobsson et al. (2016) comprise the information you should learn before the exam of this course regarding multibeam bathymetric mapping.

Moment 4

Continuation…….

Chapter 3 in the course book presents only a few data examples and does not include many photos of installed mapping system on vessels. For this reason there are numerous data examples included in this lecture, most acquired by the Marine Geology division at the Department of Geological Sciences, Stockholm University. In addition, several photos of installed mapping systems in vessels are included. The course book does not contain a dedicated section on errors and artifacts that may occur in acoustic mapping data. Instead, this is brought up along with that the various methods are presented. In this course we dedicate the following Lecture 3 to errors and artifacts since they unfortunately play a major role when the acquired geophysical mapping information is to be interpreted geologically.

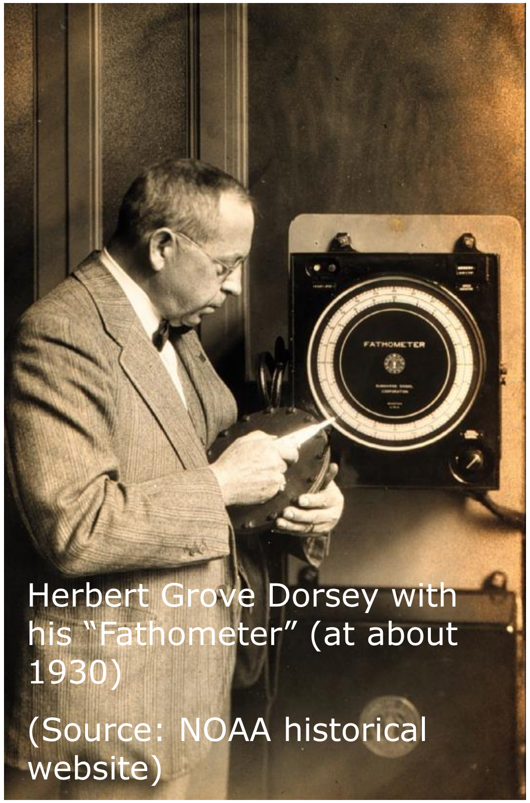
Acoustic mapping systems covered in this lecture

The mapping systems are here presented in the same order as they are described in the chapter *Mapping submarine glacial landforms using acoustic methods* by Jakobsson et al. (2016) provided as a PDF. These mappings systems are presented:

1. Single-beam echo sounder (SBES)
2. Side-scan sonar
3. Multibeam echo sounder (MBES)
4. Sub-bottom profilers
5. Chirp sonar
6. Parametric echo sounders

1. Single-beam echo sounder (SBES)

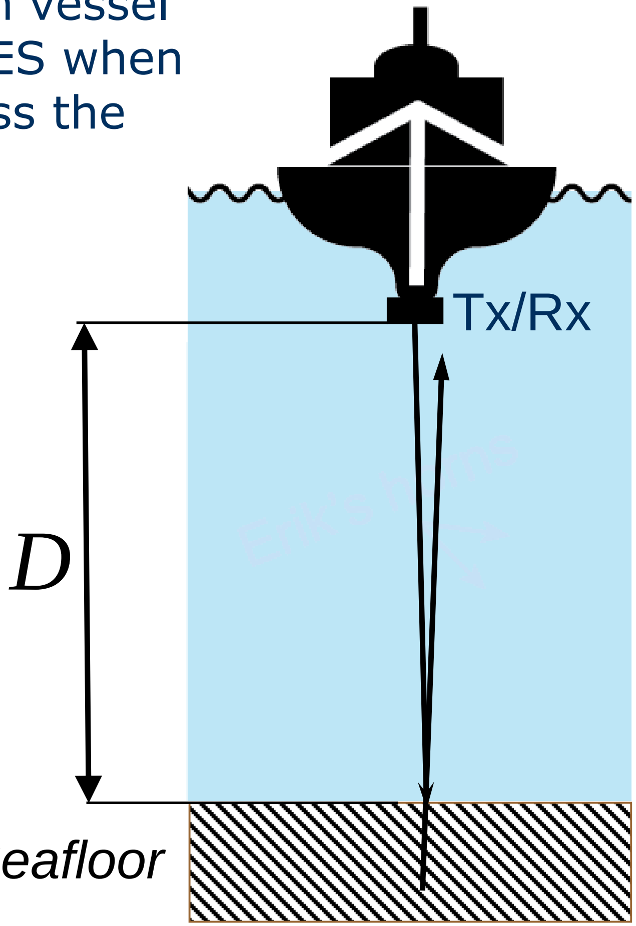
The illustration showing the principles of a single beam echo sounder (SBES) is here repeated from lecture 1. The SBES was invented in the 1920s. Between 1925 and 1927 the German research vessel *Meteor* was the first to systematically use SBES when completing 14 echo bathymetric profiles across the South Atlantic.

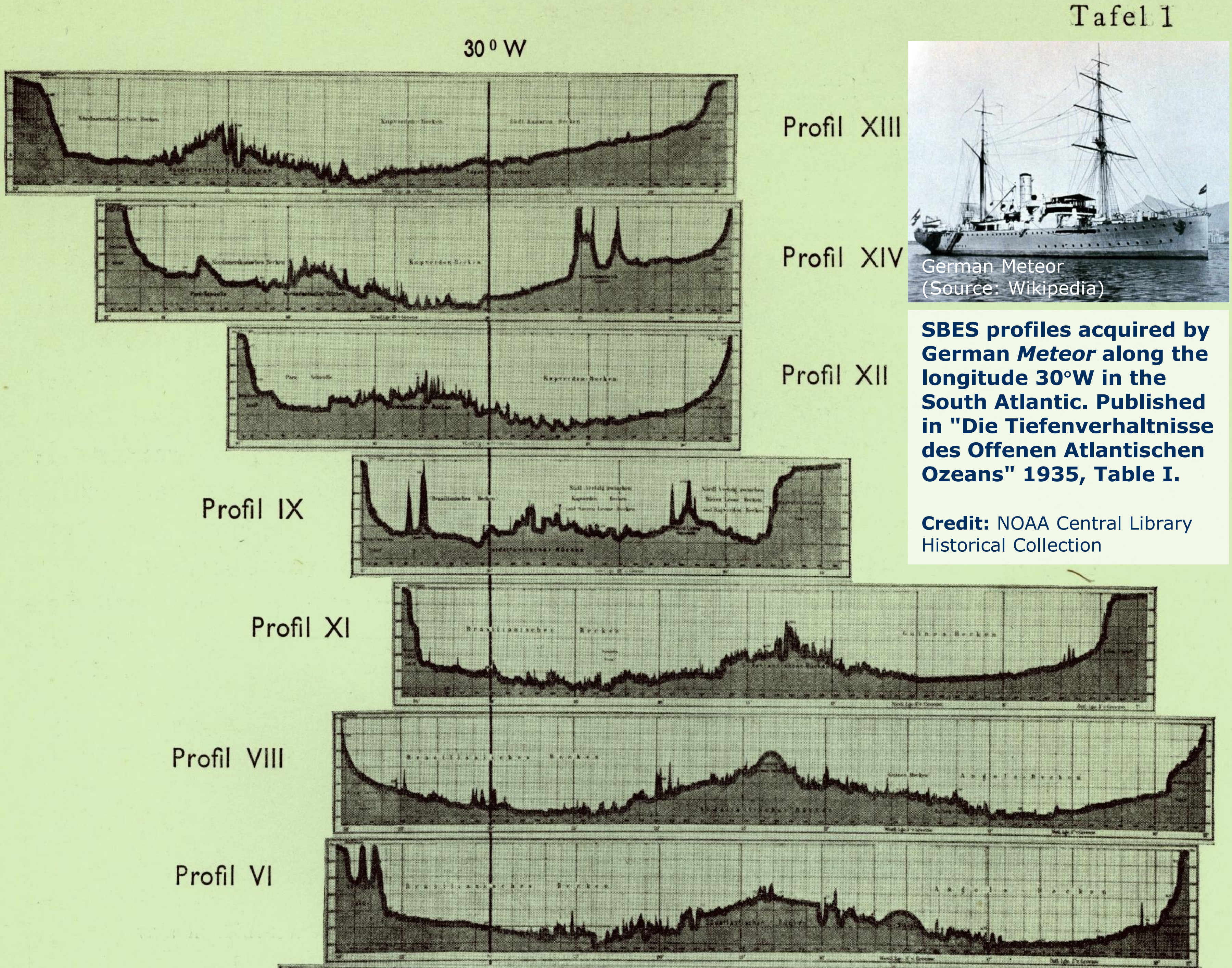


Herbert Grove Dorsey with his "Fathometer" (at about 1930)

(Source: NOAA historical website)

$$\boxed{D = v \times \frac{twt}{2}}$$





German Meteor
(Source: Wikipedia)

SBES profiles acquired by German *Meteor* along the longitude 30°W in the South Atlantic. Published in "Die Tiefenverhaltnisse des Offenen Atlantischen Ozeans" 1935, Table I.

Credit: NOAA Central Library Historical Collection

SBES frequencies

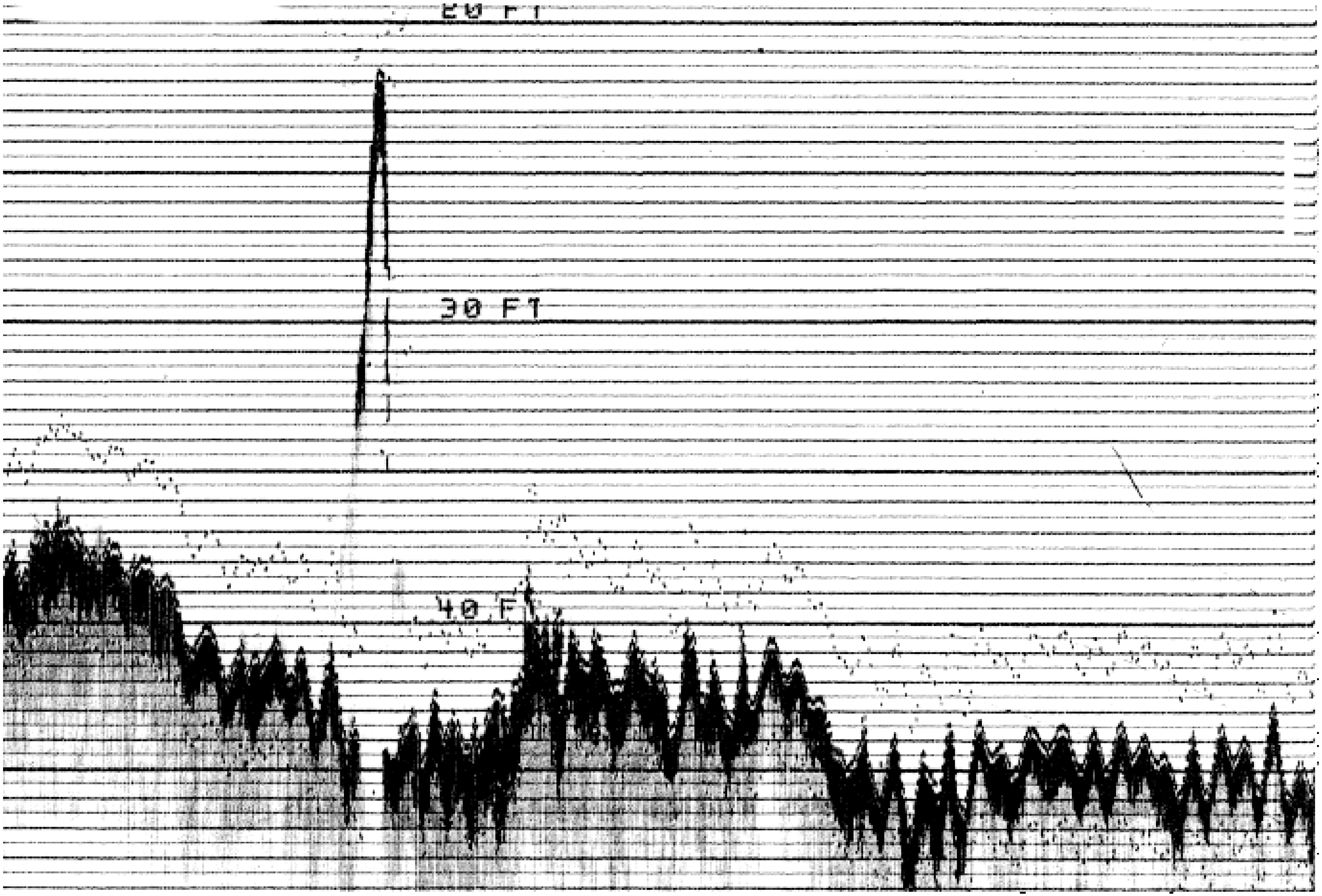
The standard conventional SBES is designed to acquire bathymetric (depth) information only and not to penetrate the seafloor sediments. For this reason, frequencies >20 kHz are commonly used. However, for the several thousand meter deep world ocean lower frequencies are needed for the acoustic pulse to be able to reach the seafloor (see table of approximate sonar ranges below). A bottom detection algorithm is used to pick the seafloor echo. However, it should be noted that several sub-bottom profilers are just SBES operating with lower frequencies that permit the acoustic pulse to penetrate into the seafloor sediments.

A SBES for acquisition of bathymetry typically transmits a short sound pulse (lengths of about 0.1-1 ms) vertically down from a transducer with a typically 5-15° wide circular aperture.

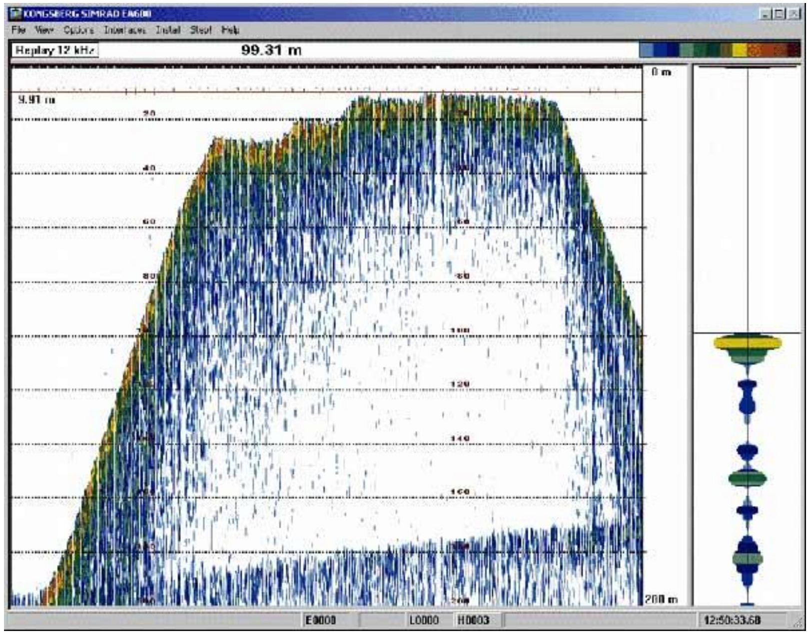
Common frequencies for different sonar ranges (IHO 2005).

Depth (range, m)	**Frequency (kHz)**	**Wavelength (cm)**
<100	>200	<0.75
100-1500	50 - 200	3 - 0.75
>1500 m	12 - 50	12.5 - 3

SBES ”bathymetric profile” from older system where a paper recorder with an electro-sensitive paper was used to register the incoming signals (echoes).



Modern SBES systems are not using paper printers as the main data recording mechanism, which was the case for the first systems. Instead the data are stored directly in digital form. However, some SBES still includes a paper recorder in addition to storing the data digitally.



Screen shot from the interface of a Kongsberg EA600 SBES
(Screenshot from Kongsberg)

Teledyne Odom Hydrographic Echotrac MK III dual-frequency SBES with a thermal paper recorder included.
(Photo from Teledyne)

Slope correction of recorded depth data

The fact that the SBES beam has a width causes some problems when mapping slopes (Chapter 3, page 35-36 in course book). The illustration below clearly shows this problem. When the seafloor is inclined, the dip from the sounder (ϕ_0) is less than the true dip (θ_0). Because the r_1 section of the beam returns before z_1 as it simply is a shorter distance. See equations 3.1 to 3.5 (Chapter 3, pages 35-36) how a dipping seafloor is corrected for.

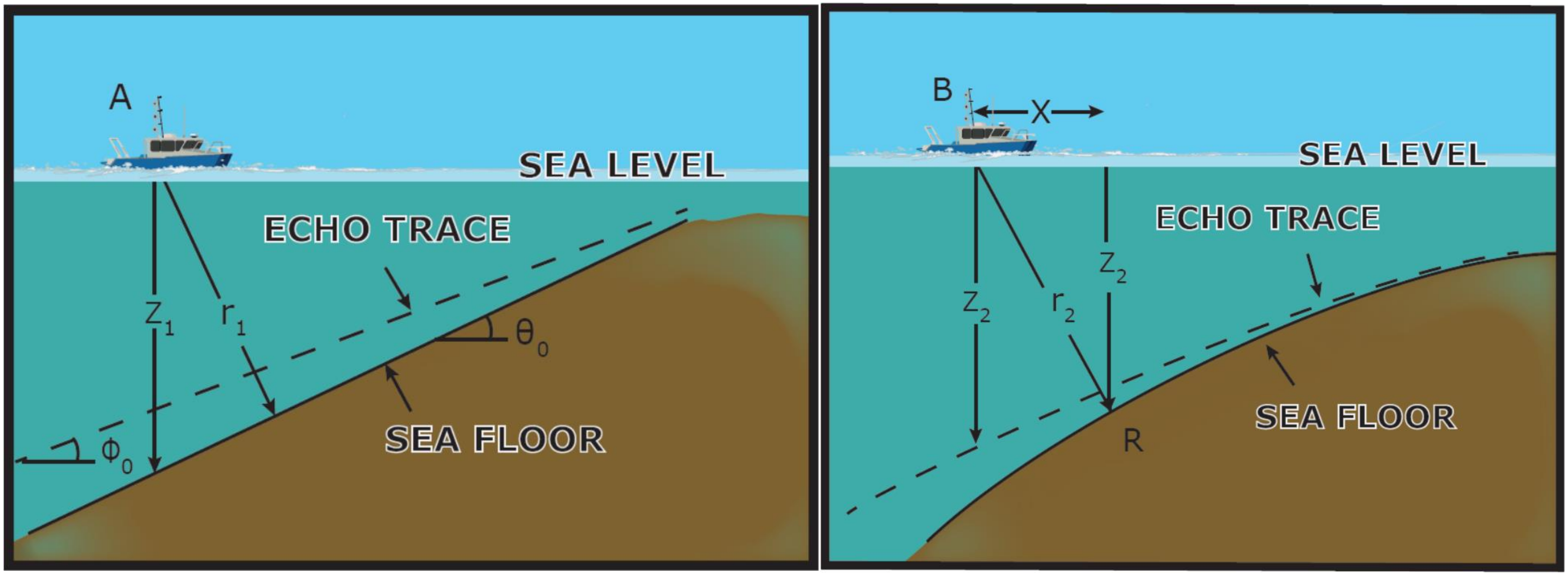


Illustration of mapping of a sloping seafloor. A) Uniform dip. B) Variable dip. (Modification of Fig. 3.7, page 37 in course book).

Sound speed correction

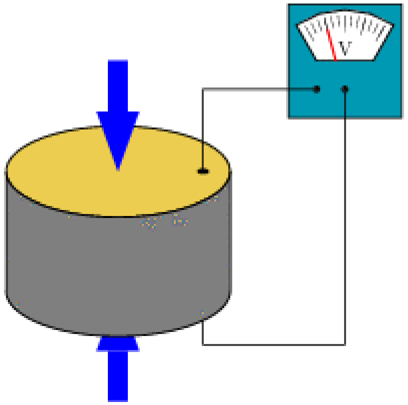
When a SBES is displaying depth of the seafloor it is based on the recorded two-way-travel (twt) of the acoustic pulse. Displayed depths are based on an assigned sound speed. The default setting is commonly 1500 m/s. However, a proper harmonic mean should preferably be calculated based on a sound speed profile acquired using a SVP (Sound Velocity Profiler) or based on calculations from temperature, salinity and depth acquired with a CTD (Conductivity, Temperature, Depth) probe. This topic has been covered in the lecture “Speed of sound in the ocean”.

Historically, echo soundings from the world ocean were corrected using tables consisting of regions with estimations of mean sound velocity-depth profiles. Such tables were first published by Matthews (1939) and later by Carter (1980). This is further described in Chapter 3 of the course book.

How does a echo sounder transducer work?

Most modern echo sounders are based on using piezoelectricity.

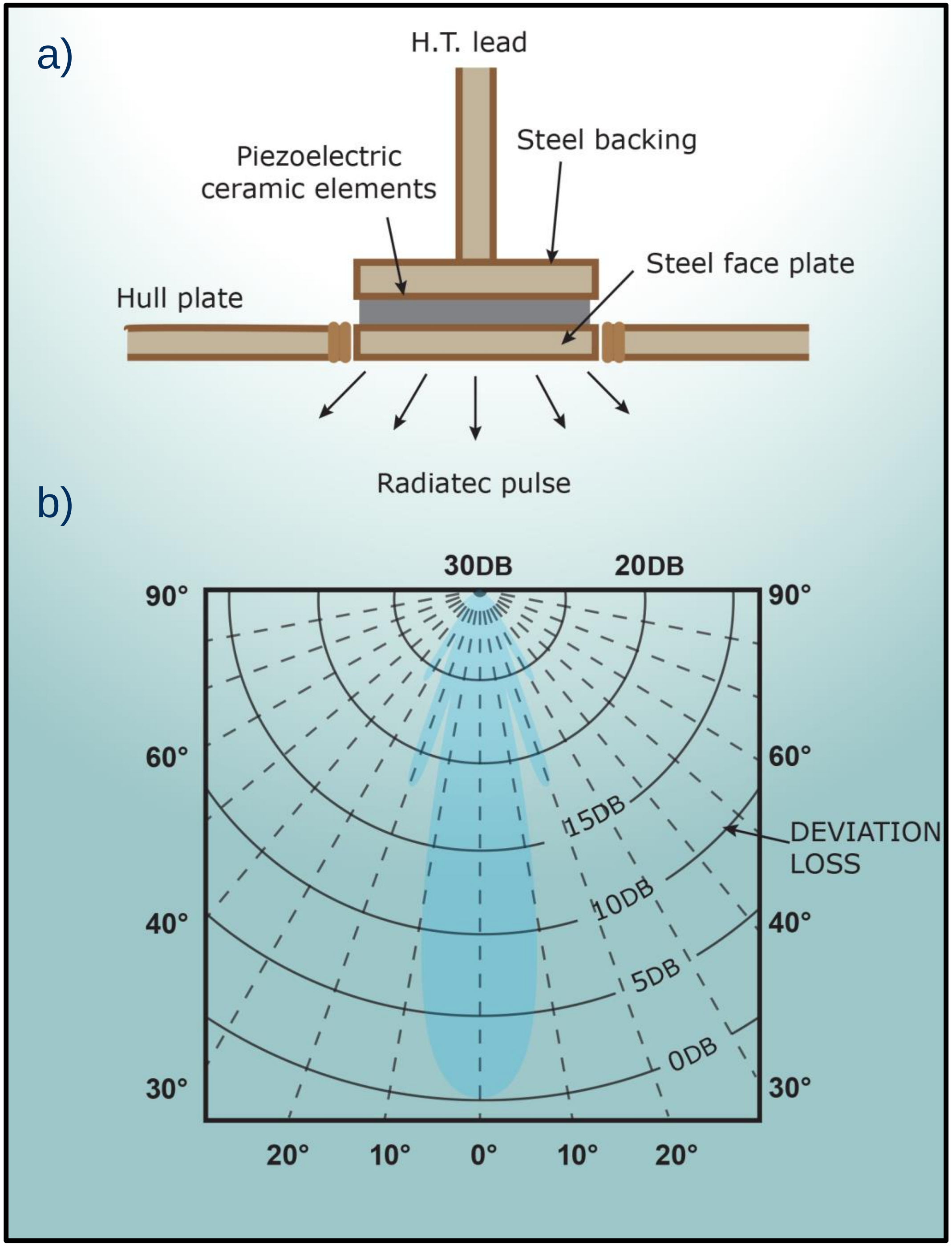
Piezoelectricity is the ability of some materials such as crystals and certain ceramics, including bone to generate an electric potential when the material is applied to mechanical stress. The effect is reversible, so that an electrical potential will yield a stress in the material.



From Wikipedia

Transducer materials

During World War II the transducer material was often nickel. The ceramic material barium titanite was discovered to be piezoelectric in 1946. Lead zirconate titanite was found to be better a decade later. Modern sonar commonly make use of piezoelectric ceramics.



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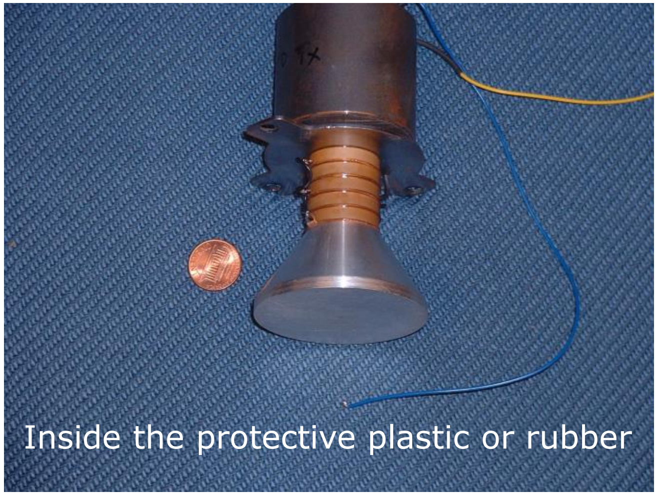
a) Illustration of an echo sounder transducer (Figure 3.4. modified from Jones, 1999).
b) The directive pattern of a transducer assumed to be circular with a diameter of five times the wavelength of the transmitted sound pulse with a certain frequency. (See Chapter 3, page 35)

The shape of the transmitted beam is controlled by the geometry of the transducer.

Transducers

Image courtesy:
Kongsberg Maritime

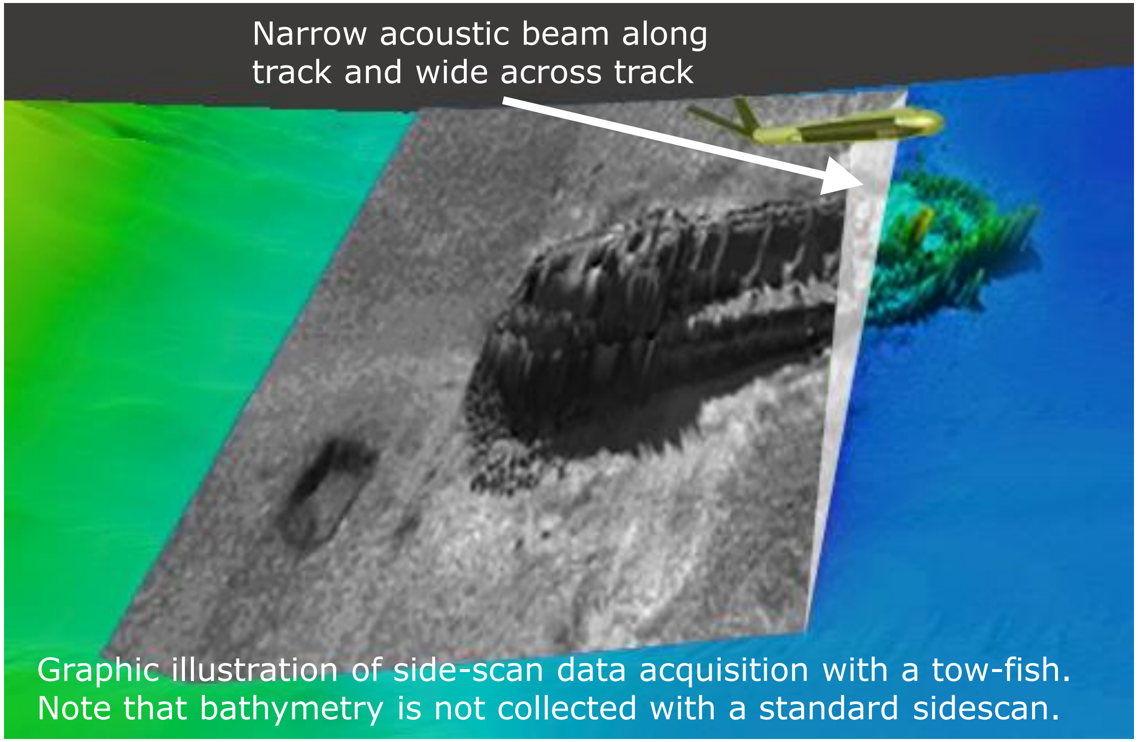


Inside the protective plastic or rubber

Transducers comes in different shapes and sized. SBES usually have circular transducers. Larger transducers are required for lower frequencies. The ceramic elements are covered by plastic material for protection.

2. Side-scan sonar

The standard side-scan is sending out two sound beams from a tow-fish, one to each side. Each beam is as wide as possible across track, and as narrow as possible along track. The along track beam is usually <1° and is transmitted at oblique angles of the tow-fish.



Narrow acoustic beam along track and wide across track

Graphic illustration of side-scan data acquisition with a tow-fish. Note that bathymetry is not collected with a standard sidescan.

A thin stripe is mapped by each transmitted ping using a very short pulse allowing for the detection of small objects. A high frequency (>500 kHz) side-scan sonar is in theory capable of mapping cm-scale objects.

The history of the side-scan sonar is briefly presented in the course material (see PDF, Jakobsson et al. 2016) and will not be further addressed in this lecture.

Schematic diagram of the beam pattern of a side-scan

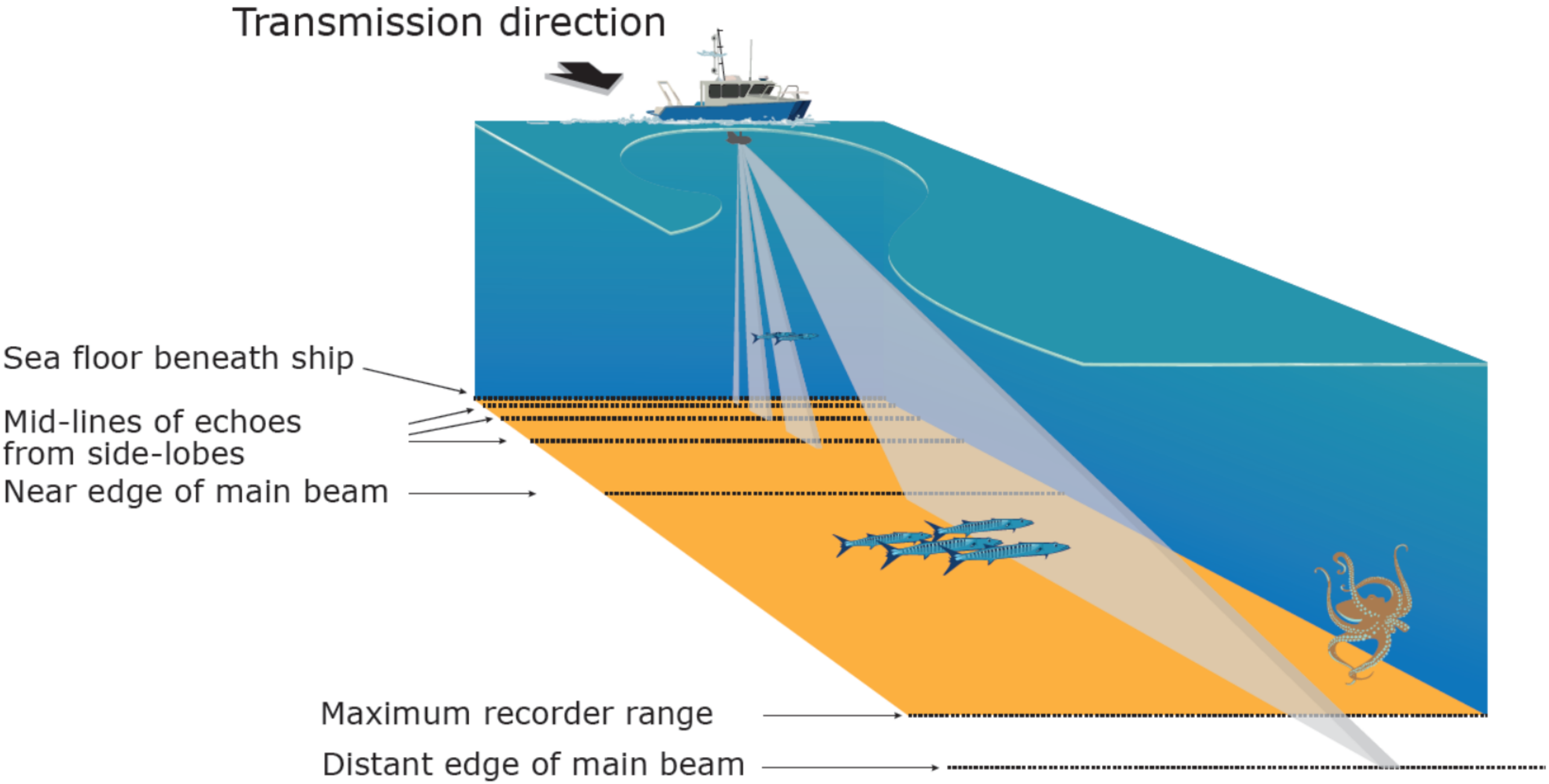


Illustration is a modification of Figure 3.11 in Chapter 3 of the course book

Side-scan examples

The course book is including more information on the side-scan sonar than on the MBES. For this reason, only a few main points to consider are listed here before some side-scan data examples are shown.

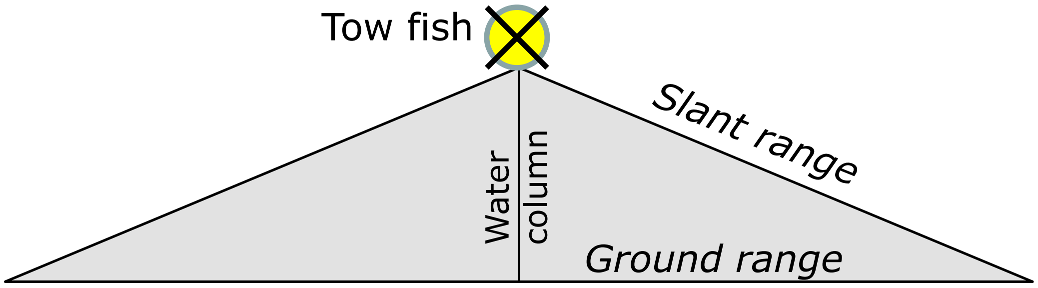
1. A side-scan records time-series of [a]backscatter intensities of the transmitted pulse after it has been echoed back from the seafloor.
2. The low incident angle of the transmitted beam implies that up-sticking objects cast shadows behind, specifically far out from nadir (the center of the tow fish). The shadow effect is also seen in pits, but then on the reversed side. The shadow effect increases the ability to detect objects. The length of the shadows can be used to infer object height from the seafloor.
3. The entire times series is geo-registered on the seafloor. The geo-registering process involves slant range correction (see next slide). This is different compared to a MBES where many individual beams are formed, which are individually geo-registered.

[a] Backscatter is amount of energy that is reflected back after that the transmitted pulse echoed back from the seafloor or any objects on it.

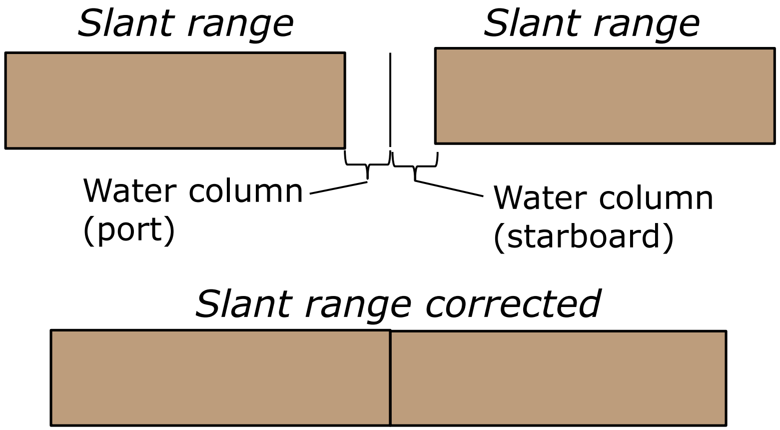
Slant range correction and object heights

The side-scan record must be corrected for the so called "slant range" before a geo-registered mosaic can be created.

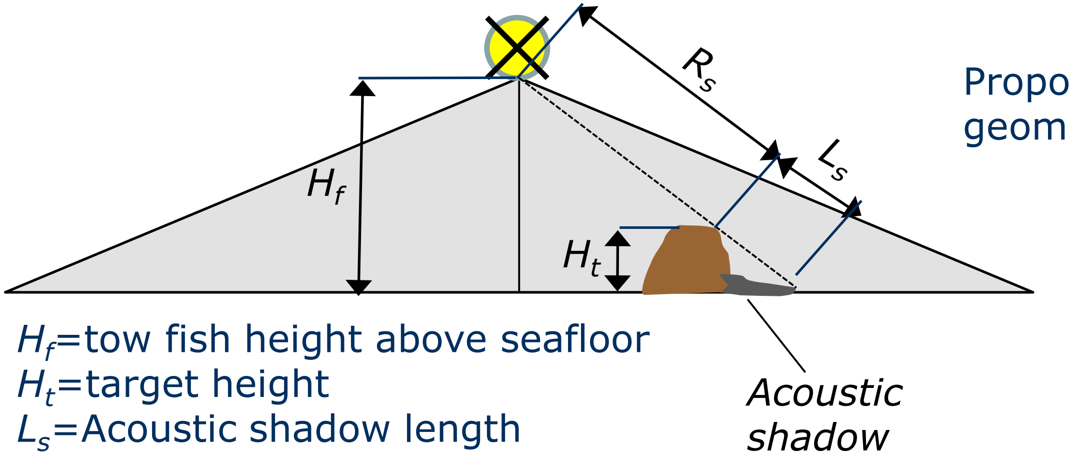
Side-scan geometry and slant range:



Side-scan image from above:



Estimating target height:



H_f=tow fish height above seafloor
H_t=target height
L_s=Acoustic shadow length
R_s=slant range to target
R_s+L_s=Slant range to end of shadow

Proportionality between two geometrical triangles gives:

$$\frac{H_t}{L_s} = \frac{H_f}{R_s + L_s}$$

..implying that the target height H_t can be written as:

$$\boxed{H_t = \frac{H_f \times L_s}{R_s + L_s}}$$

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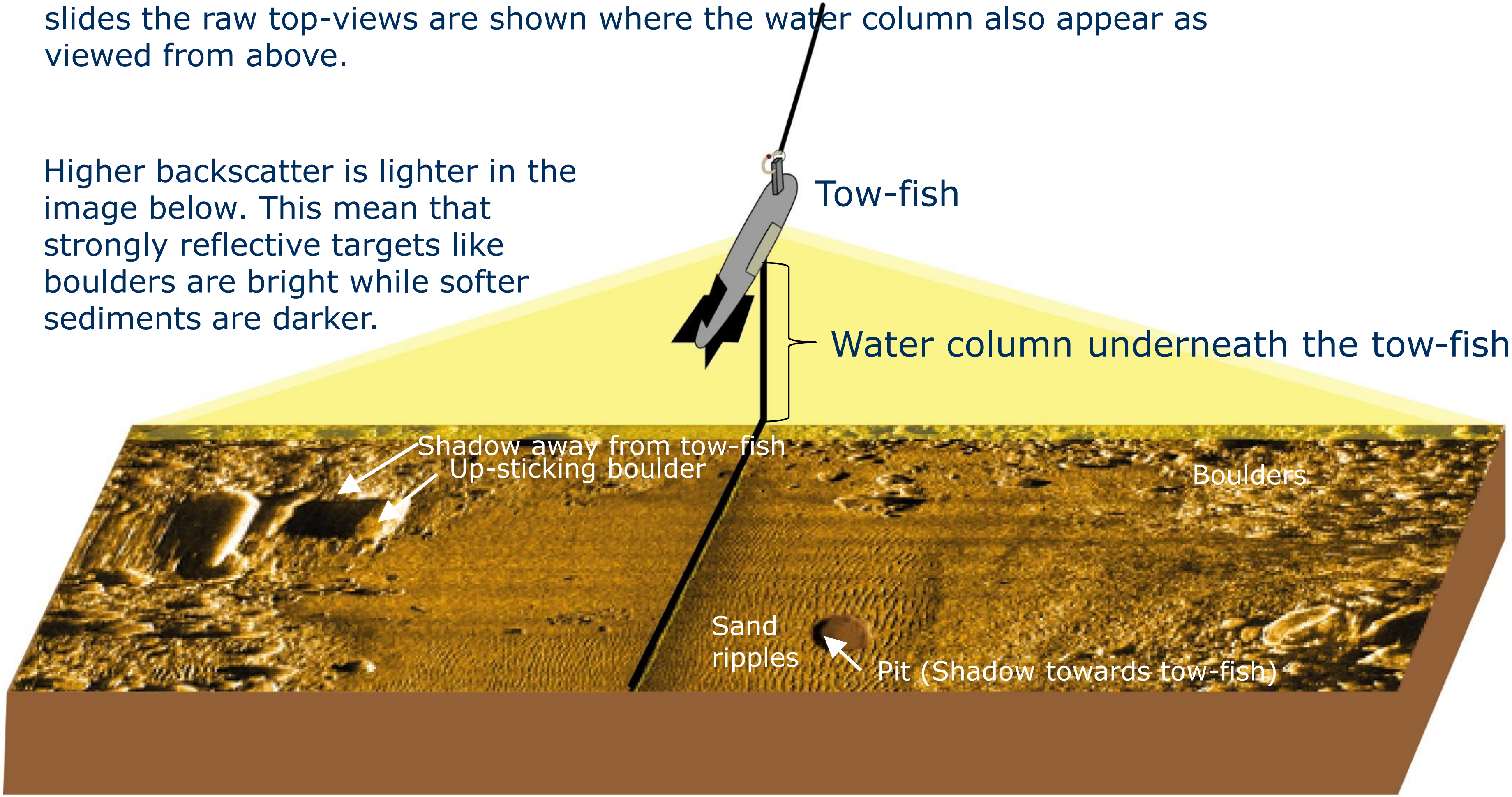
Schematic illustration of side-scan collection of seafloor imagery.

Note that this view shows how the acoustic beams are mapping the seafloor. On the following slides the raw top-views are shown where the water column also appear as viewed from above.

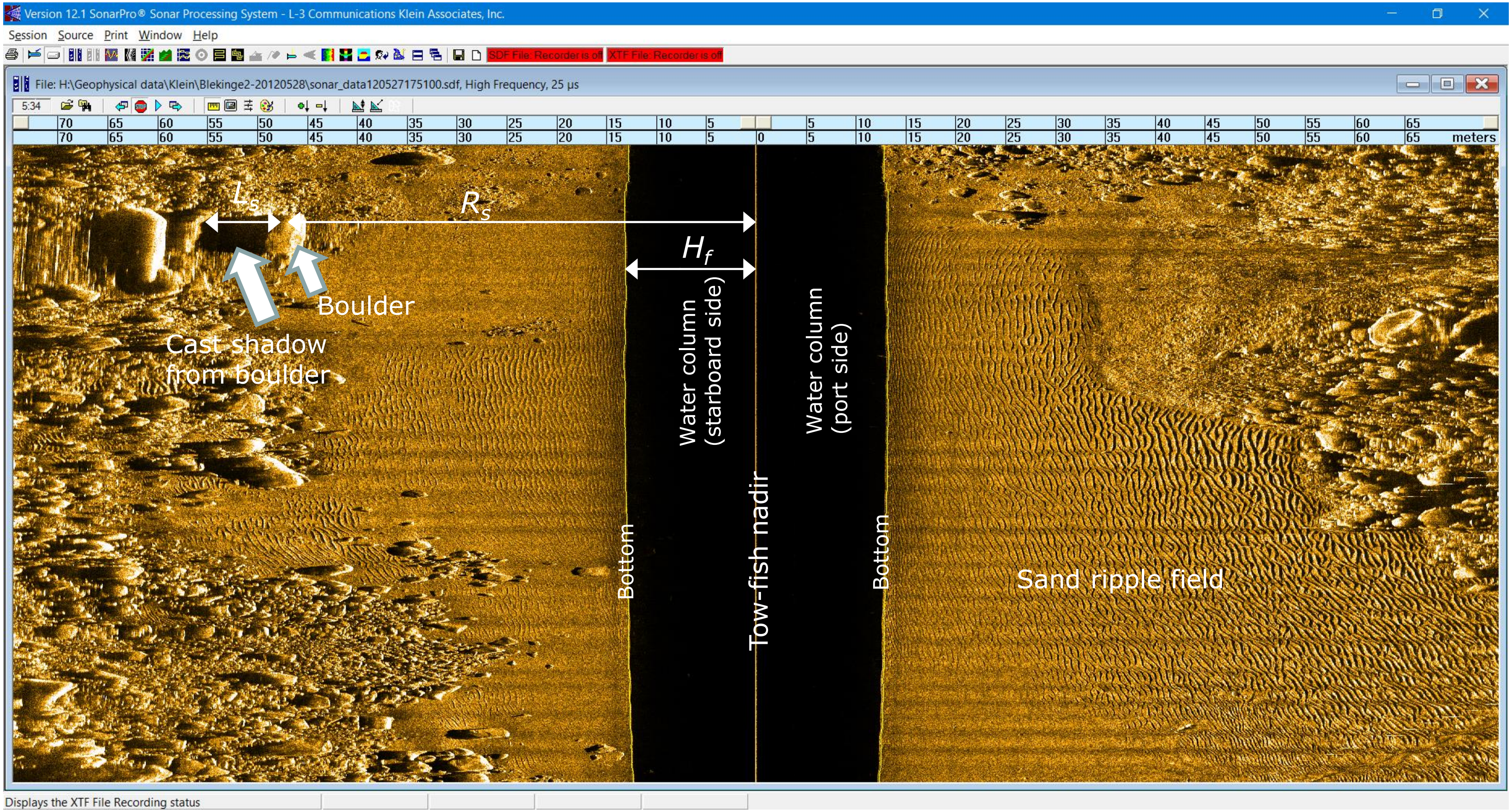
Higher backscatter is lighter in the image below. This mean that strongly reflective targets like boulders are bright while softer sediments are darker.



Stockholm University side-scan
Klein 3000, 100/500 kHz

Example of side-scan imagery

The image below is not slant range corrected. The range display in meters is based on a sound speed of 1500 m/s. The data is from southern Sweden. Boulders are igneous rocks from the local bedrock.



Version 12.1 SonarPro® Sonar Processing System - L-3 Communications Klein Associates, Inc.

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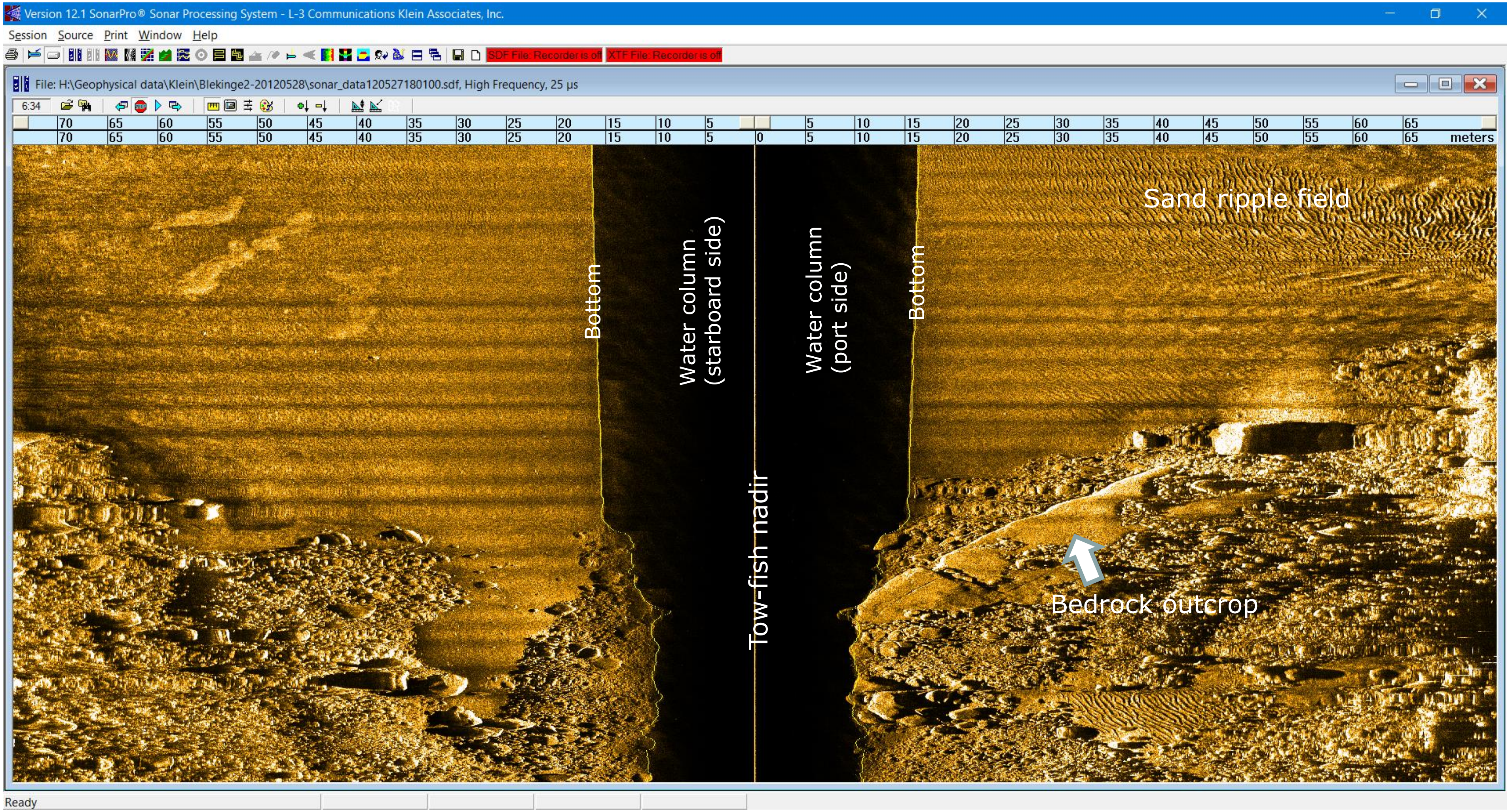
Displays the XTF File Recording status

Stockholm University side-scan Klein 3000, 100/500 kHz

Example of side-scan imagery

The image below is not slant range corrected. The range display in meters is based on a sound speed of 1500 m/s. The data is from southern Sweden. Boulders are igneous rocks from the local bedrock.

Stockholm University



Version 12.1 SonarPro® Sonar Processing System - L-3 Communications Klein Associates, Inc.

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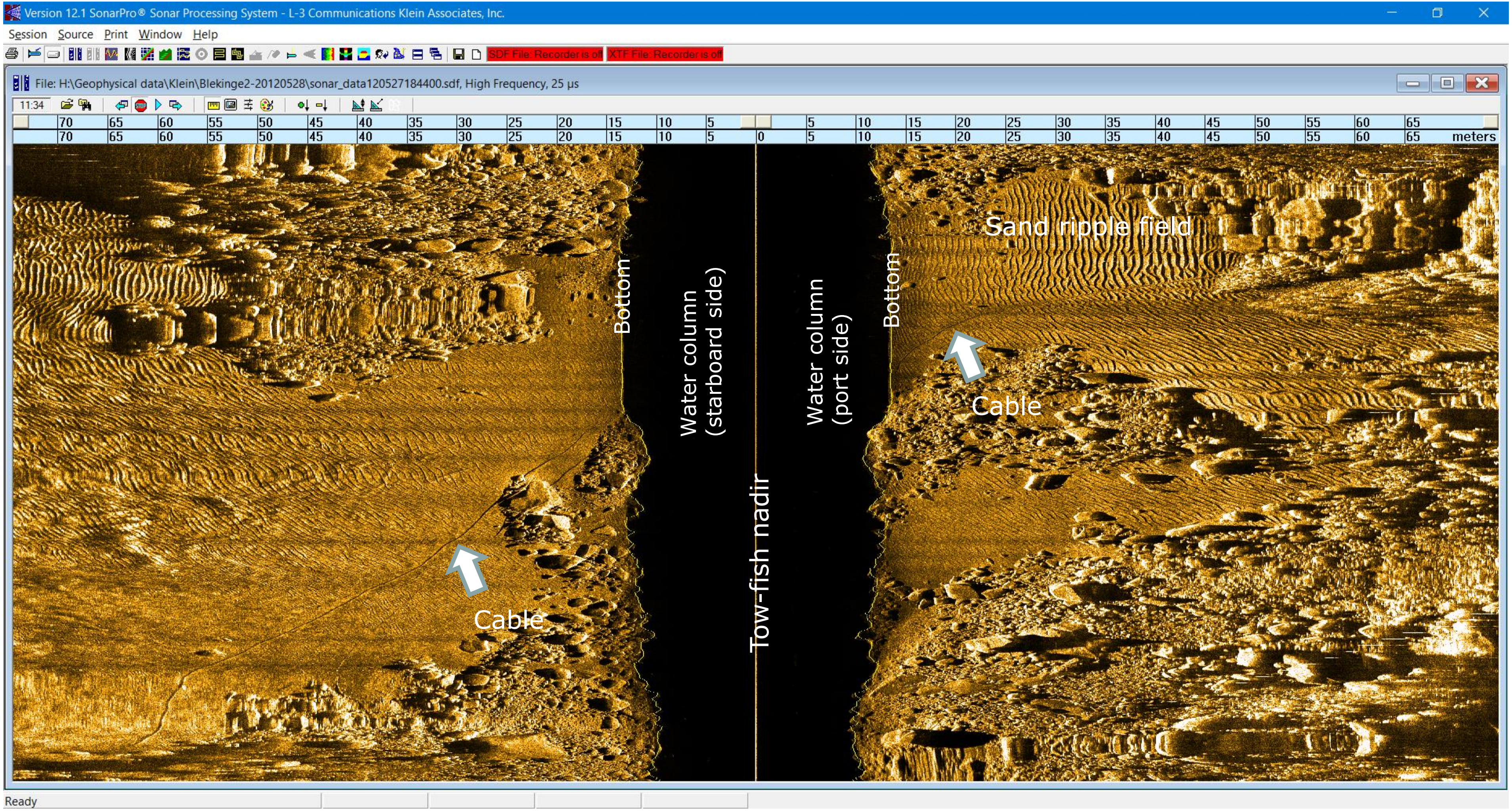
Example of side-scan imagery

Stockholm University side-scan Klein 3000, 100/500 kHz

The image below is not slant range corrected. The range display in meters is based on a sound speed of 1500 m/s. The data is from southern Sweden. Boulders are igneous rocks from the local bedrock.



Version 12.1 SonarPro® Sonar Processing System - L-3 Communications Klein Associates, Inc.

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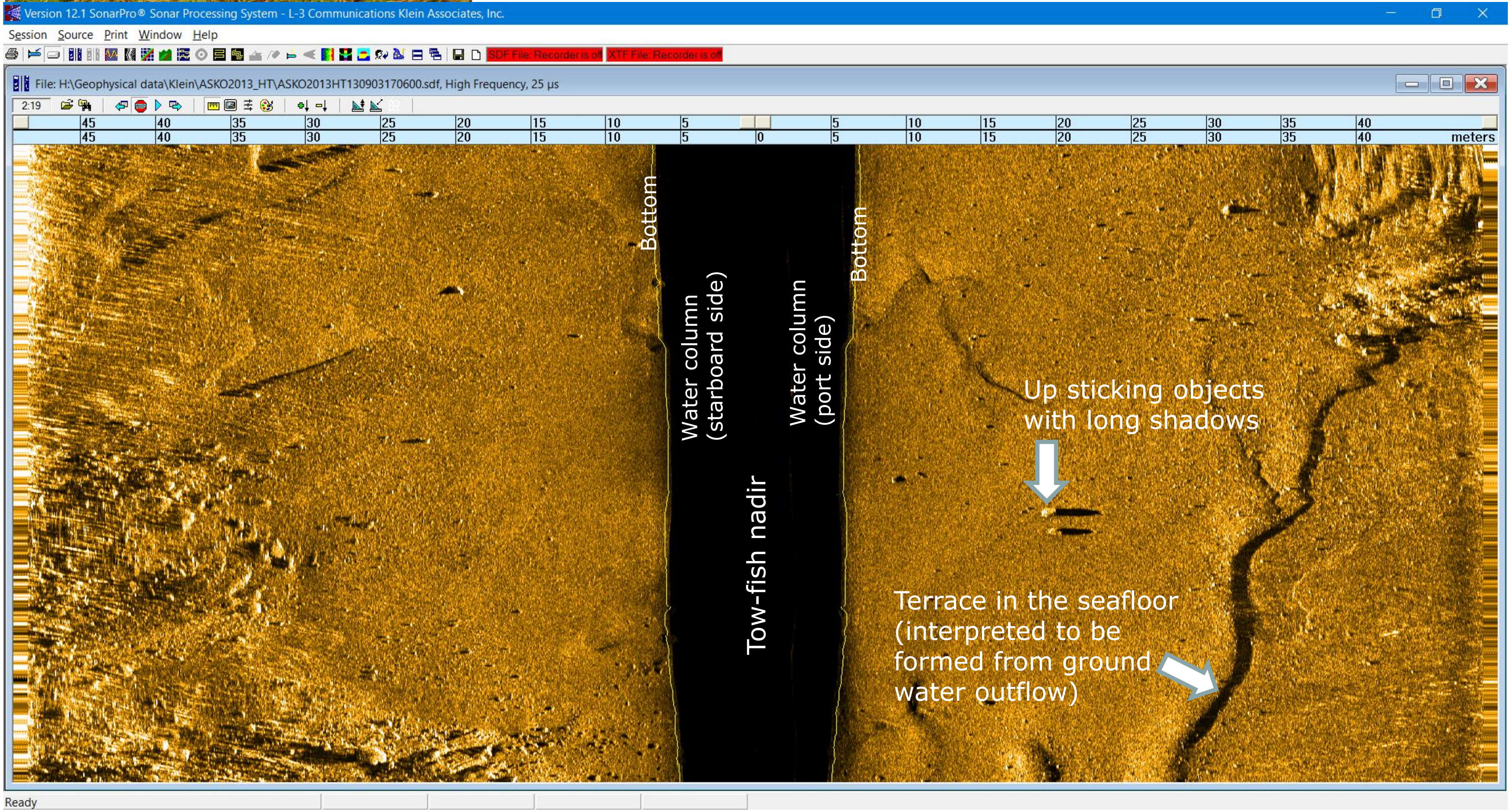
Ready

Stockholm University side-scan
Klein 3000, 100/500 kHz

Example of side-scan imagery

The image below is not slant range corrected. The range display in meters is based on a sound speed of 1500 m/s. The image is from east of Askö, Stockholm Archipelago. Terraces in the seafloor are clearly seen. These are shown later in this lecture in multibeam bathymetry.

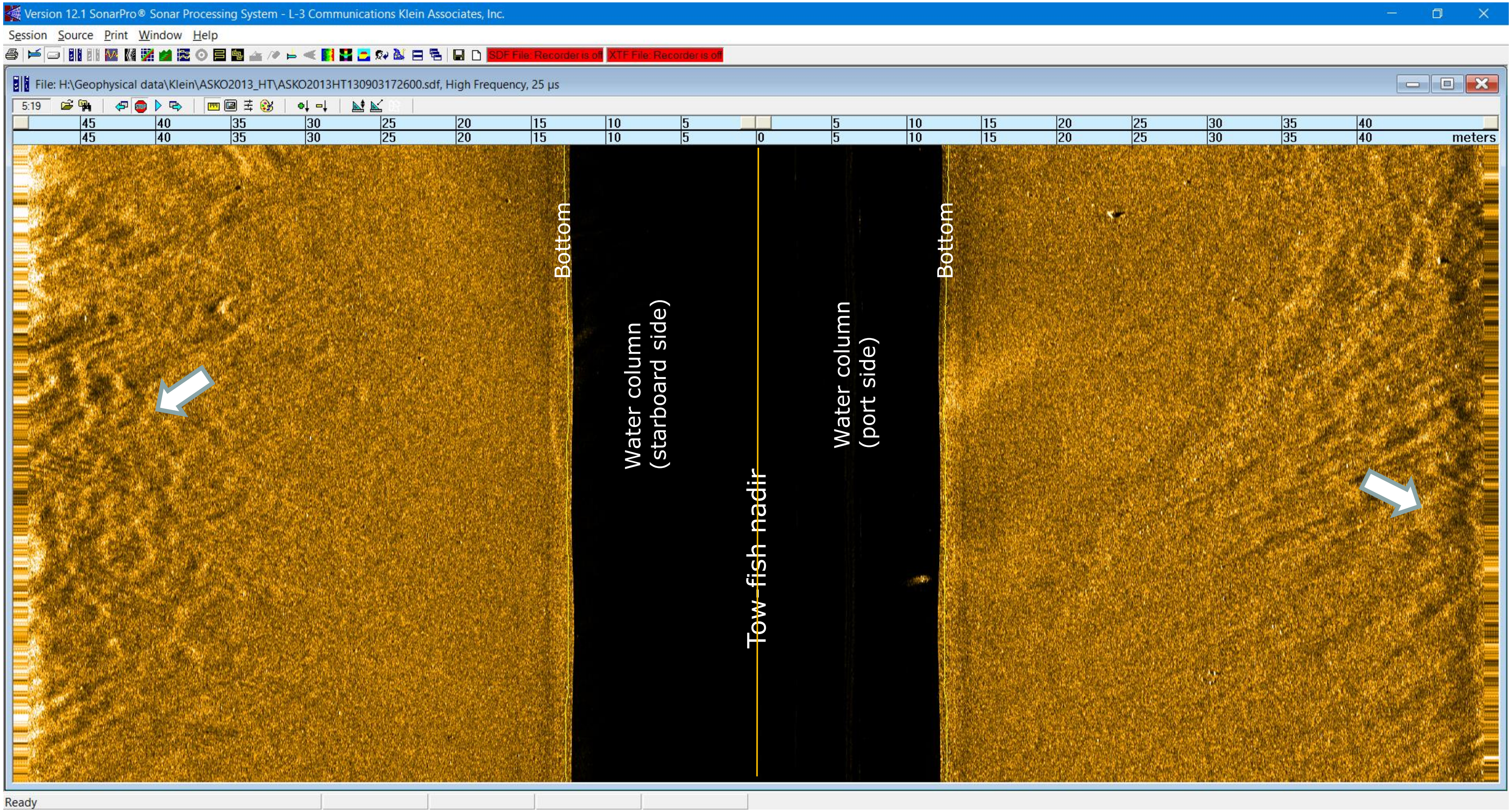


Stockholm University side-scan
Klein 3000, 100/500 kHz

Example of side-scan imagery

The image below is not slant range corrected. The range display in meters is based on a sound speed of 1500 m/s. The image is from east of Askö, Stockholm Archipelago. Artifacts from refractions are seen. These are caused by layers in the water column causing strong variations in sound speed.

Stockholm University



Version 12.1 SonarPro® Sonar Processing System - L-3 Communications Klein Associates, Inc.

SDF File: Recorder is off

XTF File: Recorder is off

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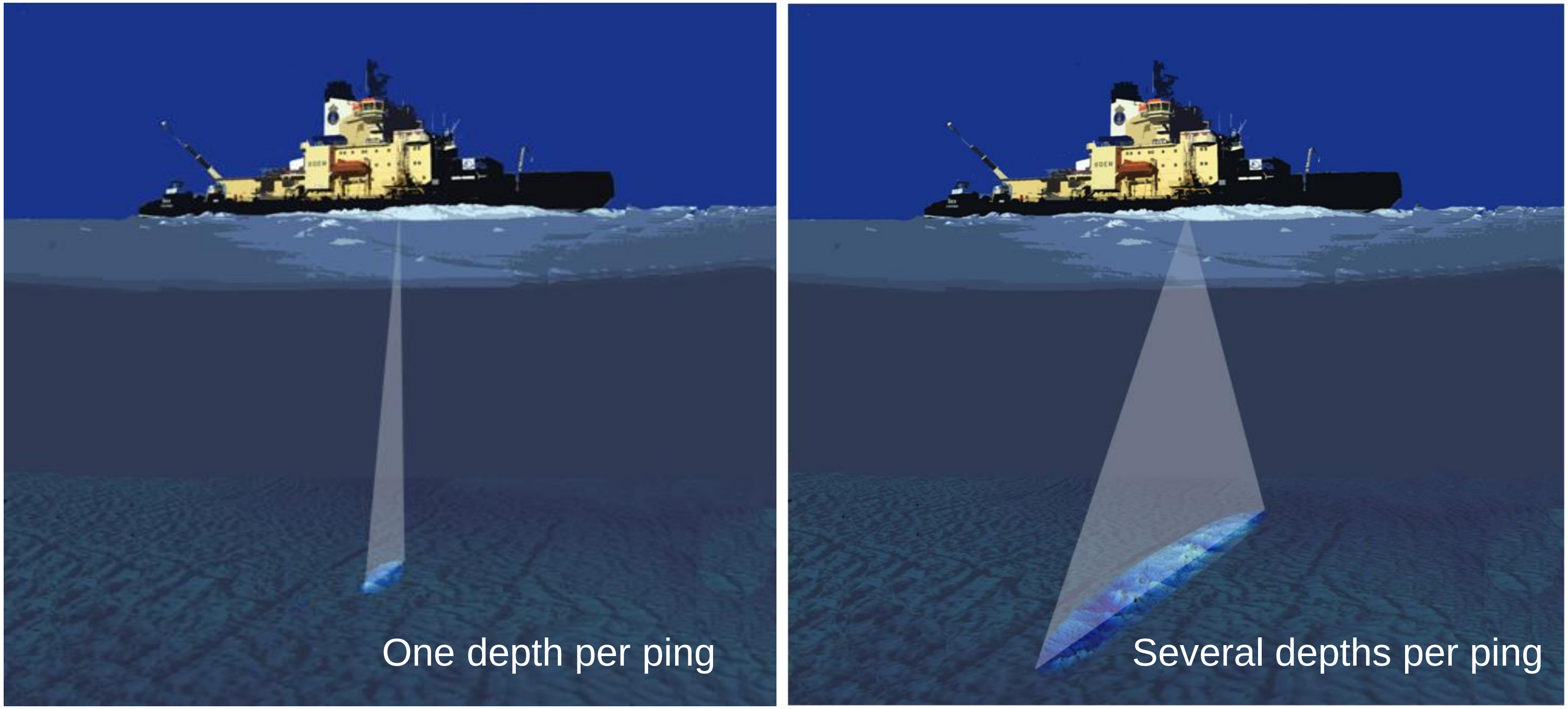
Ready

3. Multibeam echo sounder (MBES)

Illustration of the conceptual difference between a Single Beam Echo Sounder (SBES) and a Multibeam Echo Sounder (MBES)



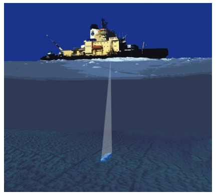
The history of the MBES is briefly presented in the course material (see PDF, Jakobsson et al. 2016) and will not be further addressed in this lecture.

Comparison, single versus multibeam

1. A multibeam operates with several echo beams while a single beam with one

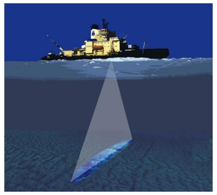
2. A multibeam has narrower beams than a single beam

3. Compensation is carried out for:



In a single beam:

- *sound velocity in the water column*
- *Tide*
- *Heave (not always)*



In a multibeam :

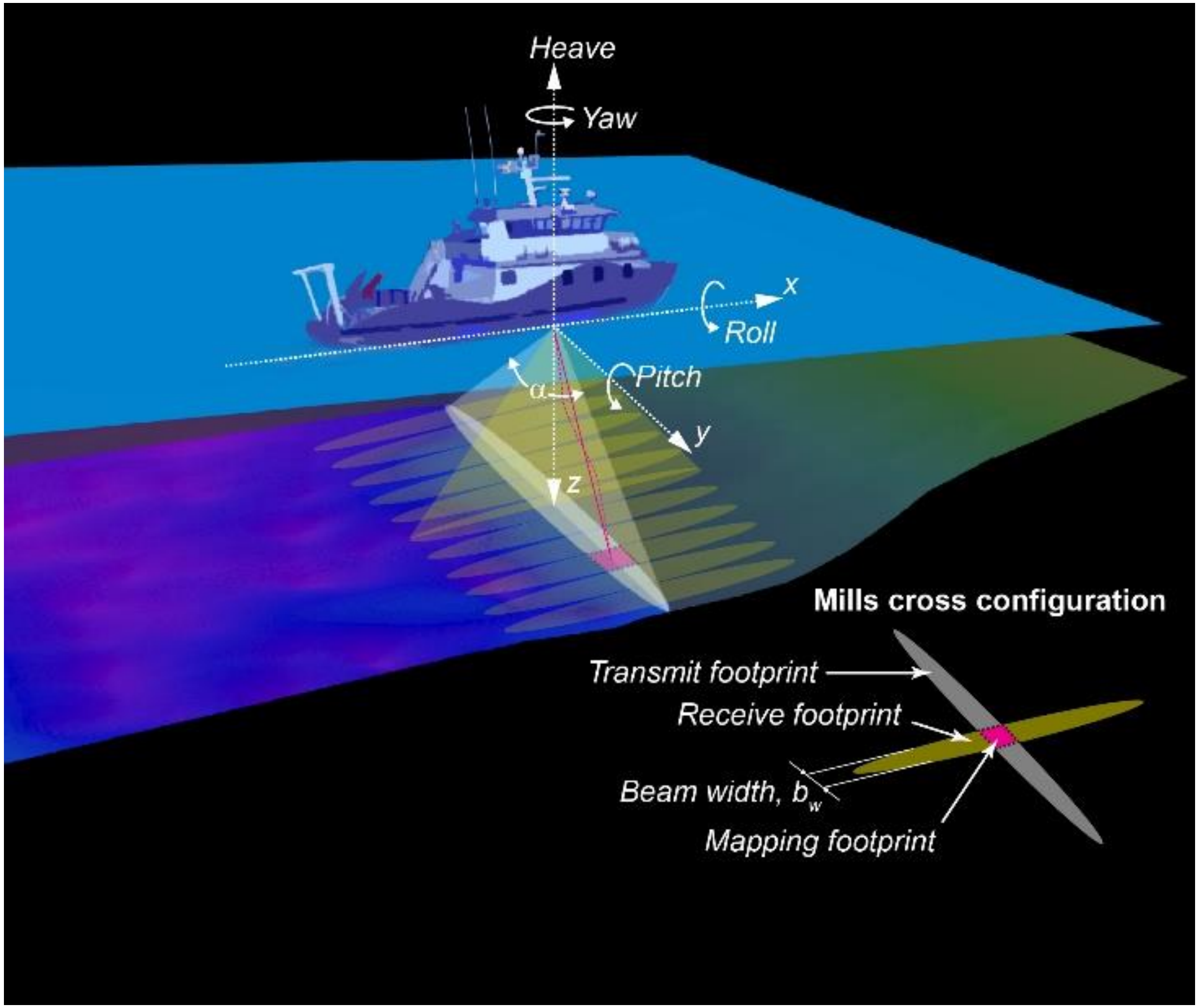
- *sound velocity in water column*
- *tide*
- *heave*
- *roll*
- *pitch*
- *heading*
- *time*

Multibeam concept

The signal is sent out from an along keel transmit transducer array. This results in a across strip ensonification of the seafloor (white stripe).
An along keel strip of the seafloor is listened at (yellow stripe) with an across keel receiver transducer array.

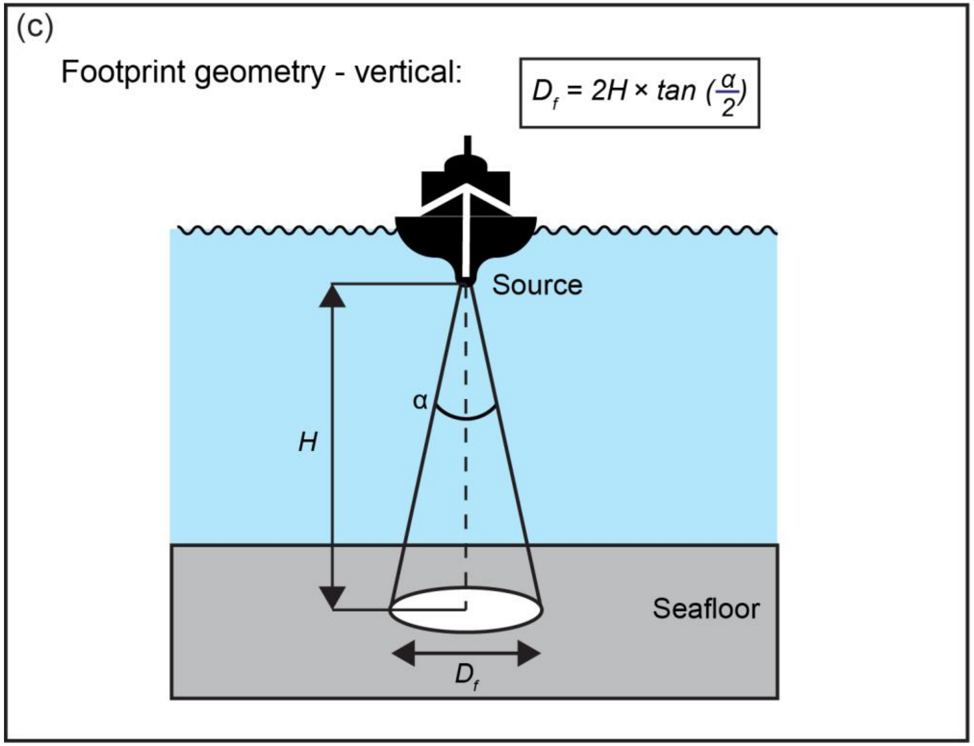
The intersection of transmit and receive **footprints** constitutes the area of one **beam**. This is the systems footprint. The configuration of using a along keel transmit array and across keel receive array is called **Mills cross or Mills T**.

Swath width (α) is typically between 130° and 150 ° in modern MBES. This determines the coverage of the system. Because sound speed is not constant, refraction causes the beam to be bent. This is corrected for with a sound speed profile. Ships motions (heave, yaw, roll, pitch) as well as heading must be corrected for. This is done using a so called motion sensor.



Multibeam resolution

The resolution of a multibeam sonar is determined by the foot print following from the same concept as explained previously for a single beam system:



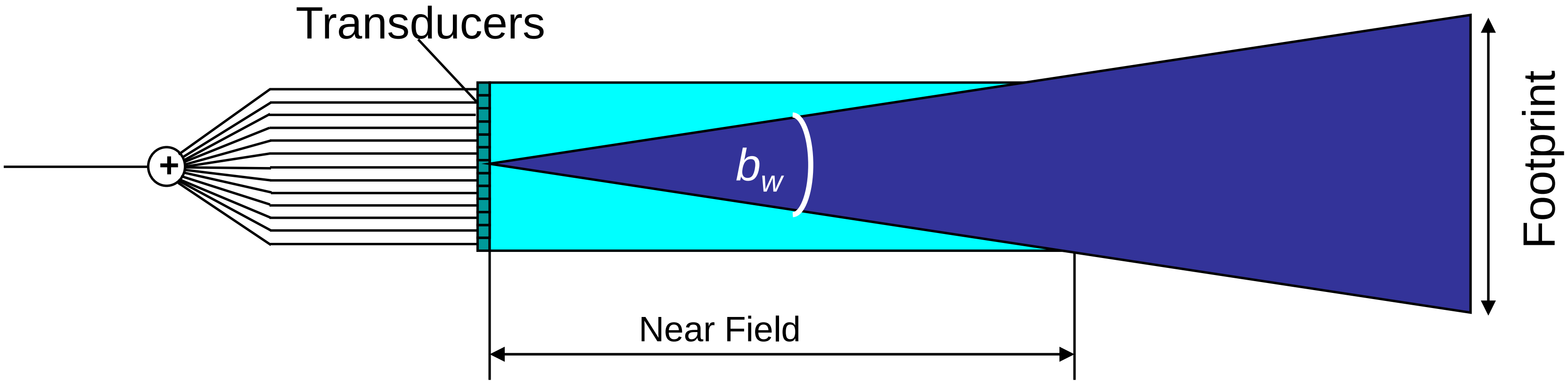
The length of the transducer array (l) and applied frequency (f) determines how narrow a beam can be produced. The longer transducer array and higher frequency, the narrower beamwitdh (b_w):

$$b_w \approx \frac{100000}{lf}$$

Note that in the single beam example above, beam width is the same as α

Schematic illustration of transducer array

Many connected transducer elements are connected to create one array acting as one transducer for transmission or receiving



The more transducers that are connected in an array, the narrower beam is possible to construct, implying higher resolution.

$$b_w \approx \frac{100000}{lf}$$

MBES frequencies

MBES frequencies are generally in the same range as SBES and the depth range versus frequency table by IHO (2005), repeated from one of the earlier slides in this lecture below, is also applicable here. A typical deep water multibeam system capable of mapping the deepest spot on earth (the Challenger Deep, c. 10 994 m) is 12 kHz while a high resolution shallow water system optimal for <100 m water depth is >200 kHz.

Common frequencies for different sonar ranges (IHO 2005).

Depth (range, m)	**Frequency (kHz)**	**Wavelength (cm)**
<100	>200	<0.75
100-1500	50 - 200	3 - 0.75
>1500 m	12 - 50	12.5 - 3

Overview of Stockholm University sonar systems installed in research vessels

IB Oden
Ship length: 109 m
Multibeam:
KM EM122, 1°x1°, 12 kHz
(Depth range: 20-11000 m)

Sub-bottom profiler:
KM SBP120, 3°x3°, 2-7 kHz

Midwater split beam:
KM EK60, 18 kHz

(KM=Kongsberg Maritime)

RV Skidbladner
Ship length: 6.4 m
Multibeam:
KM EM2040, 1°x1°, 200-400 kHz
(Depth range: 0.5-550 m)

Sub-bottom profiler:
EA 600, 15 kHz

RV Electra
Ship length: 24.5 m
Multibeam:
KM EM2040, 0.4°x7°, 200-400 kHz
(Depth range: 0.5-550 m)

Sub-bottom profiler:
Topas PS40, 24ch, parametric, 35-45 kHz/1-10 kHz

Midwater split beam:
EK 80, 70/200 kHz

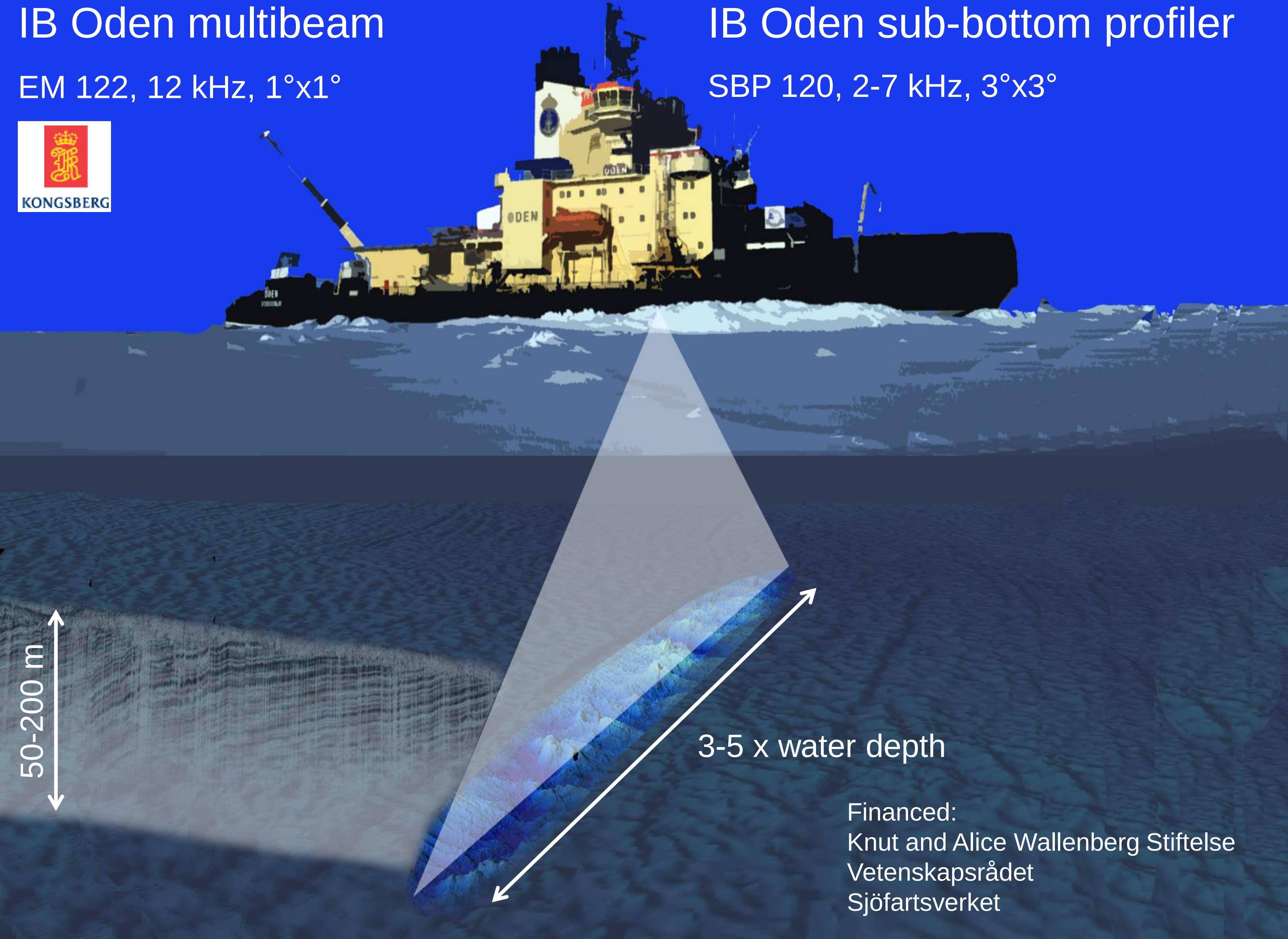
Acoustic Doppler Current Profiler (ADCP):
Teledyne Workhorse Mariner, 600 kHz
(range up to 165 m)

IB Oden multibeam

EM 122, 12 kHz, 1°x1°

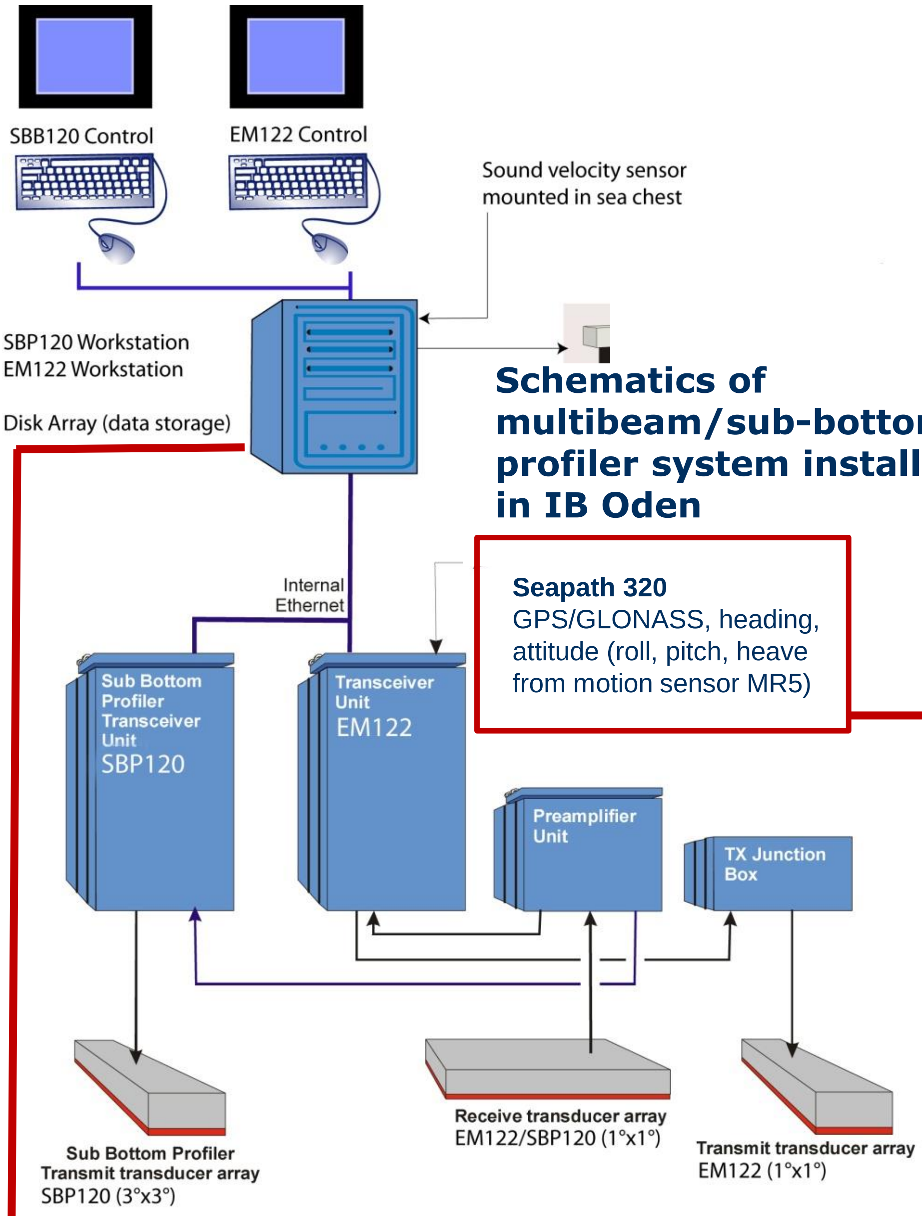
IB Oden sub-bottom profiler

SBP 120, 2-7 kHz, 3°x3°



Financed:
Knut and Alice Wallenberg Stiftelse
Vetenskapsrådet
Sjöfartsverket

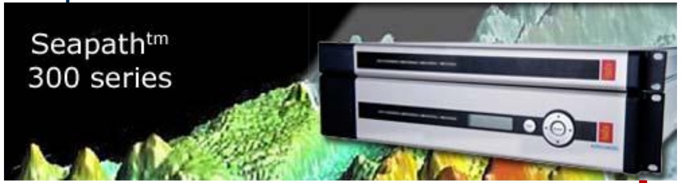
Schematics of multibeam/sub-bottom profiler system installed in IB Oden



Seapath 320
GPS/GLONASS, heading, attitude (roll, pitch, heave from motion sensor MR5)

Operation area on bridge

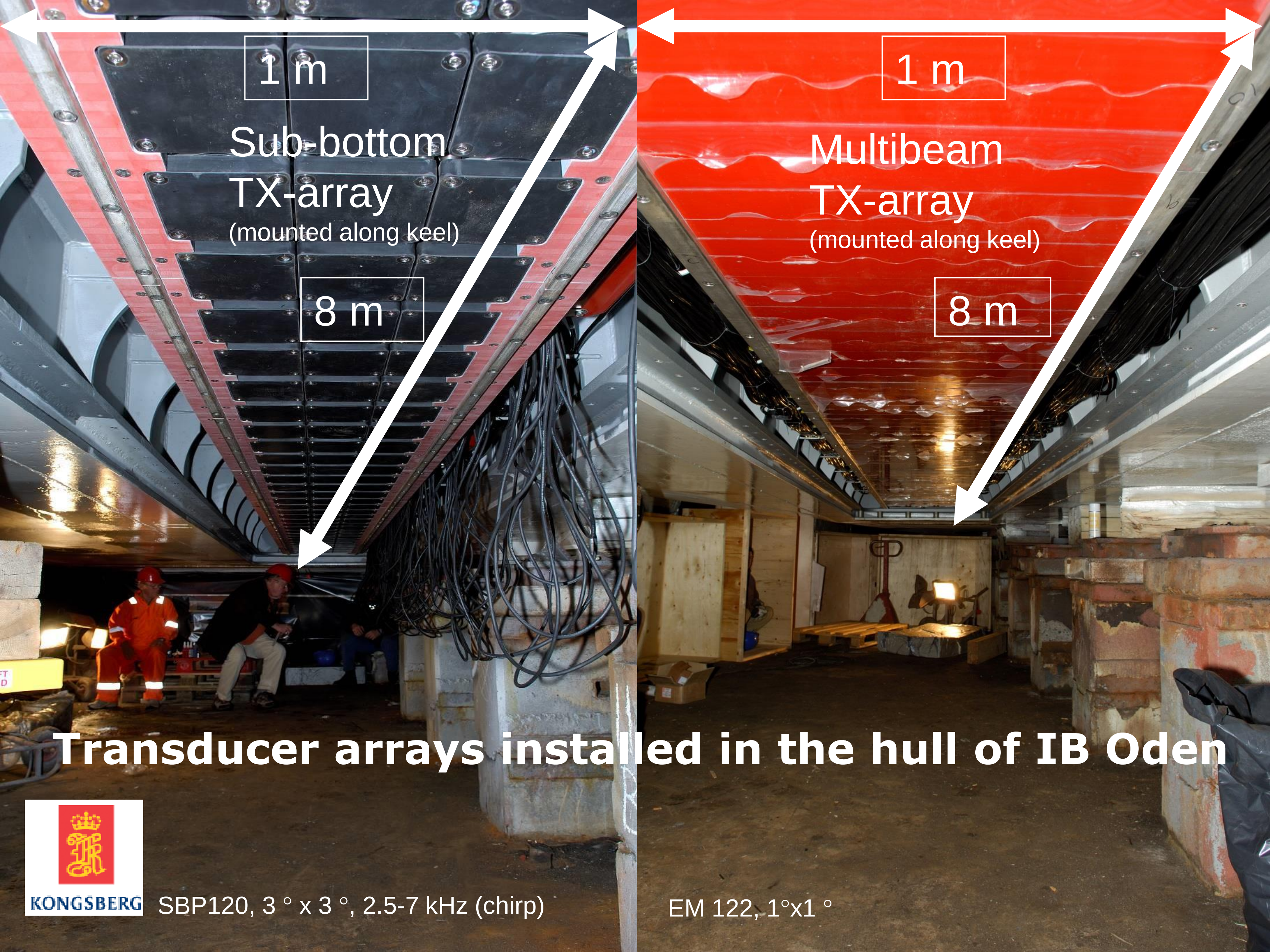
Seapath 320 GPS/GLONASS L1/L2



MRU 5: Motion reference unit (Calibrated 2013)

A sound velocity sensor is installed in the sea chest to take continuous sound velocity readings near the transducers.

Transducer arrays installed in the hull of IB Oden



KONGSBERG

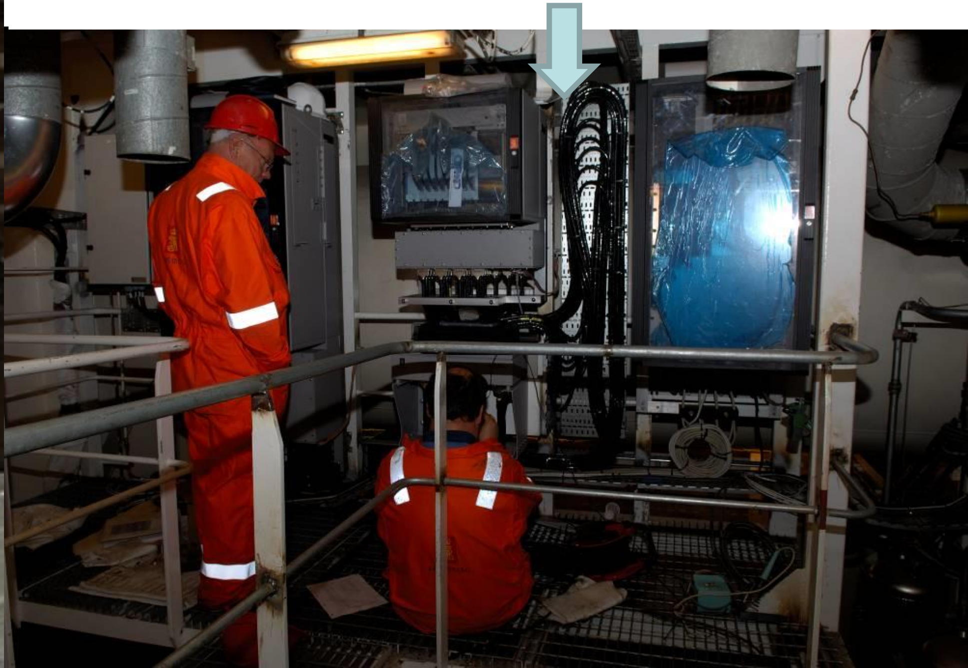
SBP120, 3 ° x 3 °, 2.5-7 kHz (chirp)

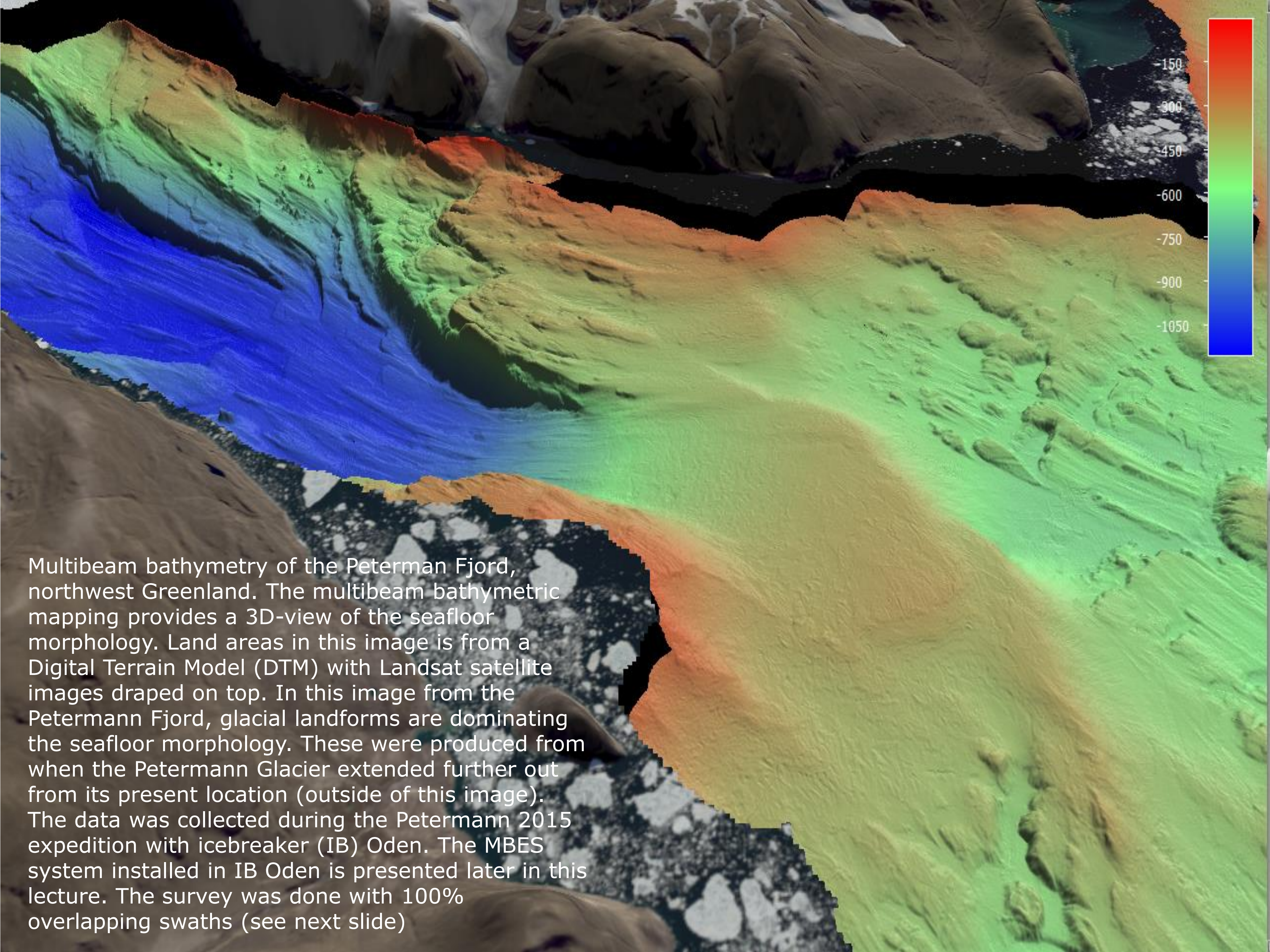
EM 122, 1°x1 °

Multibeam/Sub-bottom RX-array (mounted across keel)

Ice protection windows mounted in front of transducers for operation in ice. These are made of polyurethane and reinforced with titanium.

Transceivers

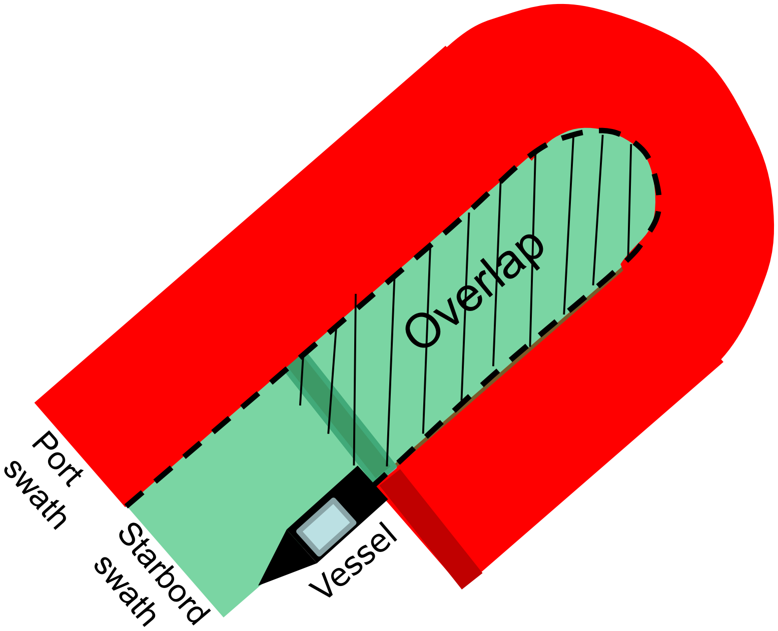




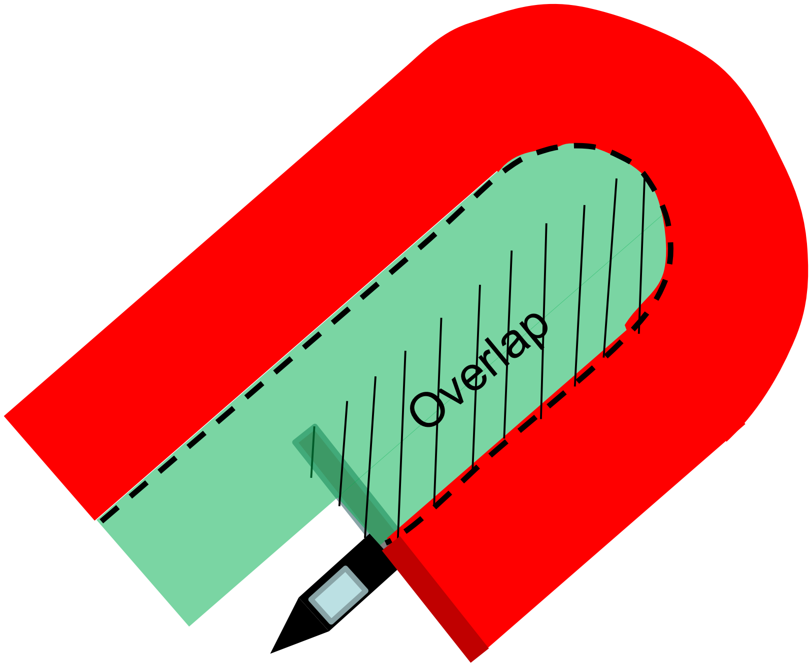
Multibeam bathymetry of the Peterman Fjord, northwest Greenland. The multibeam bathymetric mapping provides a 3D-view of the seafloor morphology. Land areas in this image is from a Digital Terrain Model (DTM) with Landsat satellite images draped on top. In this image from the Petermann Fjord, glacial landforms are dominating the seafloor morphology. These were produced from when the Petermann Glacier extended further out from its present location (outside of this image). The data was collected during the Petermann 2015 expedition with icebreaker (IB) Oden. The MBES system installed in IB Oden is presented later in this lecture. The survey was done with 100% overlapping swaths (see next slide)

Multibeam survey patterns

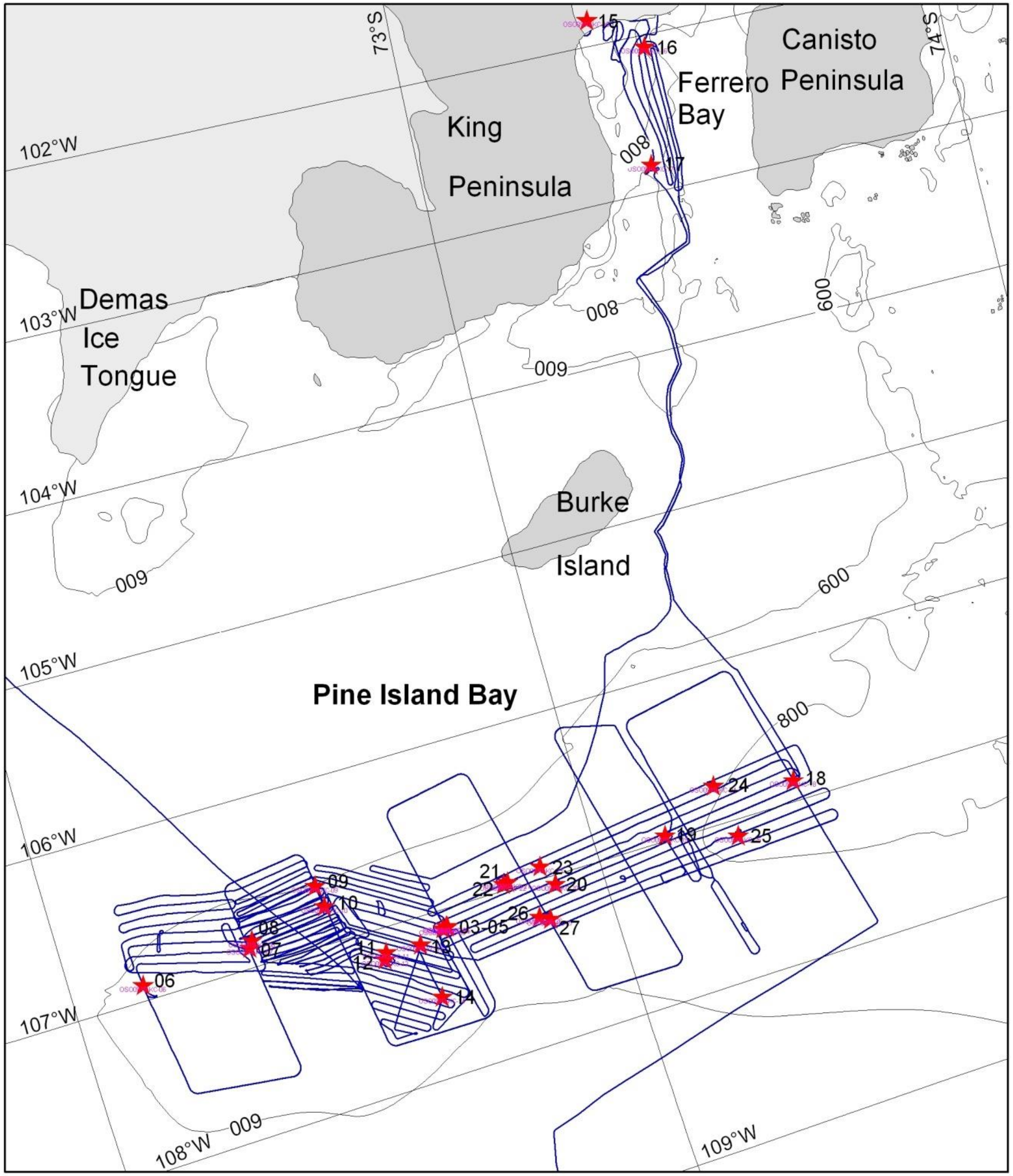
Multibeam surveys are preferably carried out along systematic survey patterns. For high quality multibeam surveys, the track lines are usually run so that the multibeam swath coverage of the seafloor overlaps 100% with the neighboring track. This is commonly referred to as 100% overlap. This pattern ensures full coverage of the seafloor and makes data cleaning easier.



100% overlapping swaths

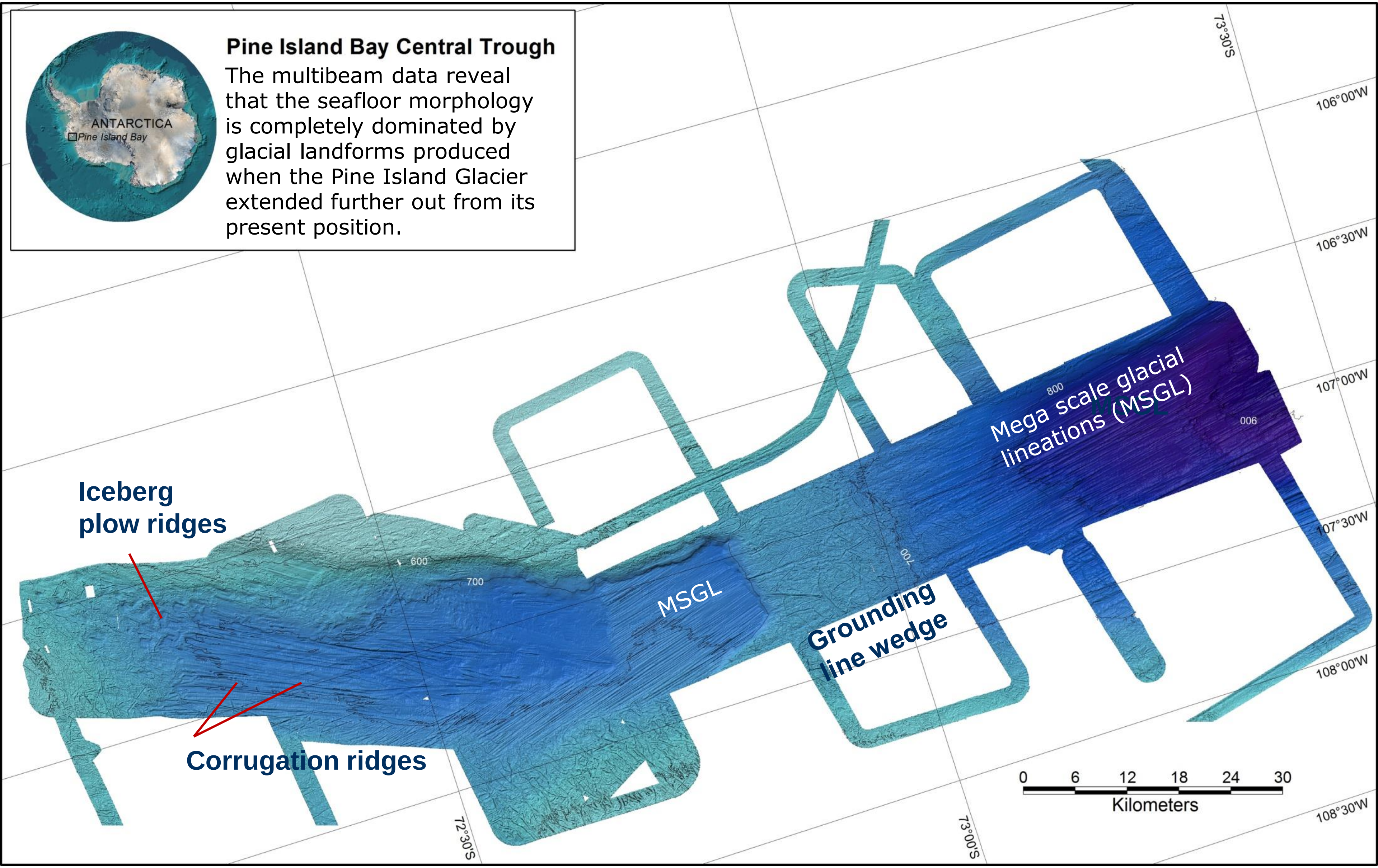


50% overlapping swaths



Trackline showing survey in ice-free conditions in Pine Island Bay, West Antarctica. The survey was here made with 100% overlapping swaths. This resulted in a high-quality dataset. The stars show sediment cores retrieved to ground truth the geophysical mapping.

Multibeam bathymetry from Pine Island Bay

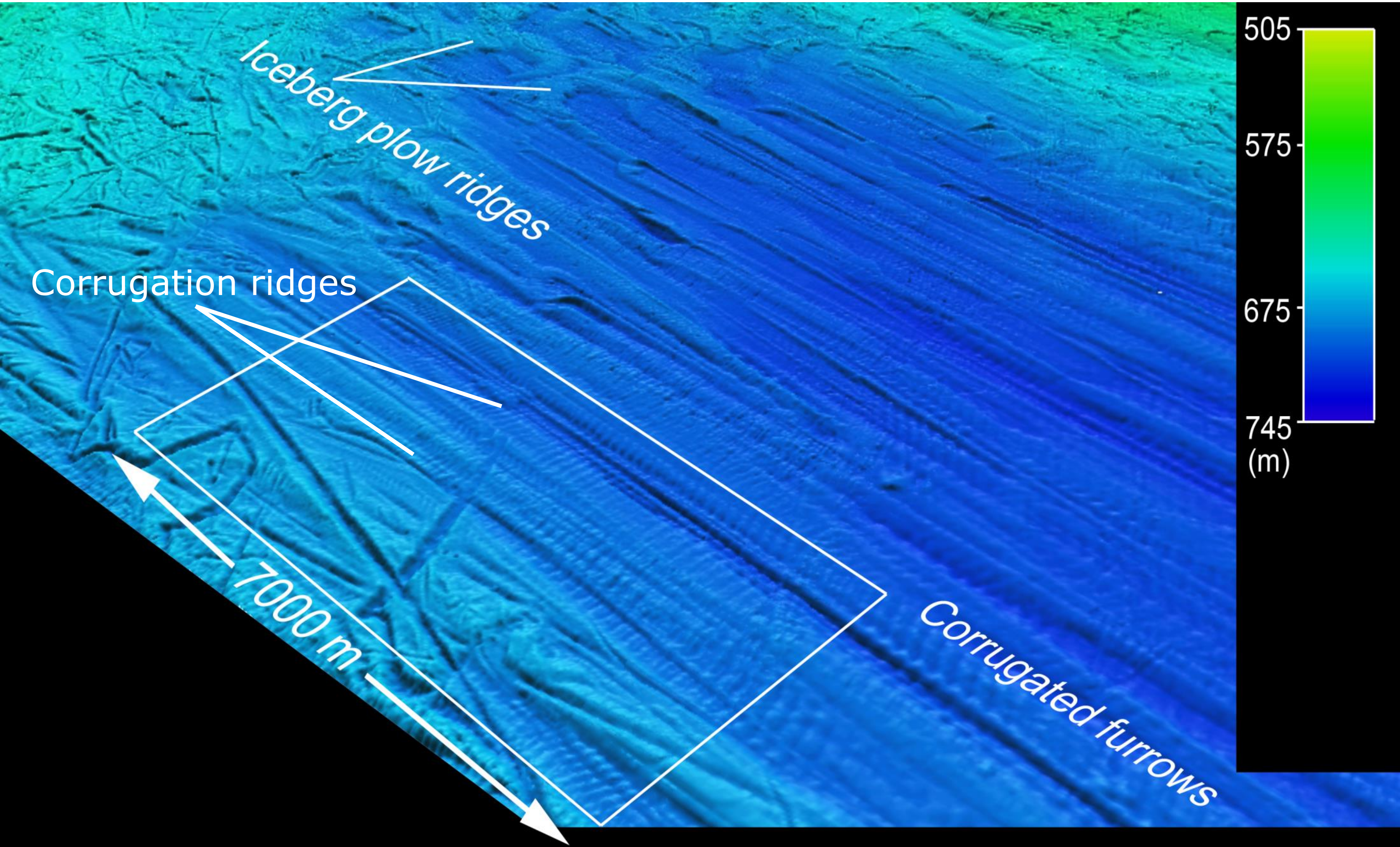


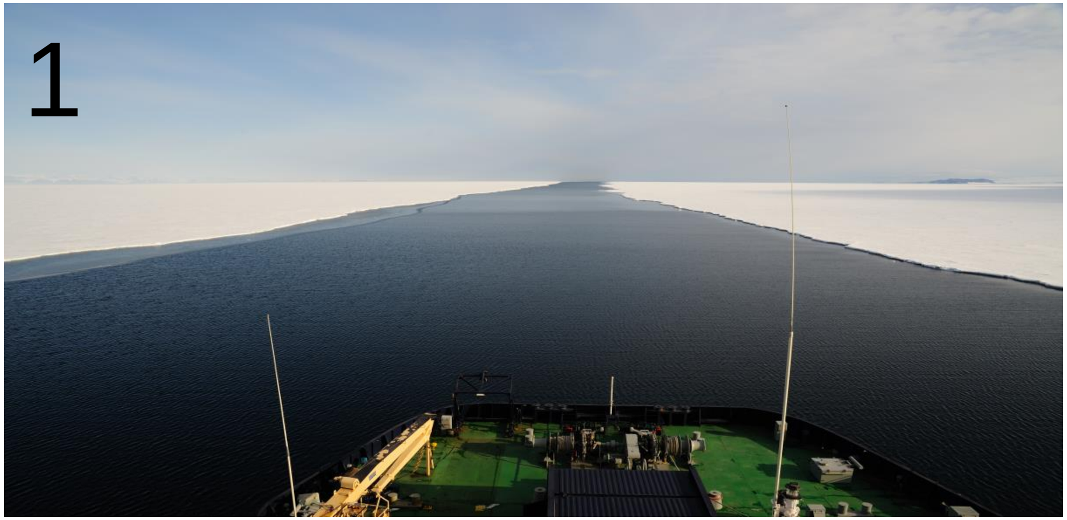
Pine Island Bay Central Trough

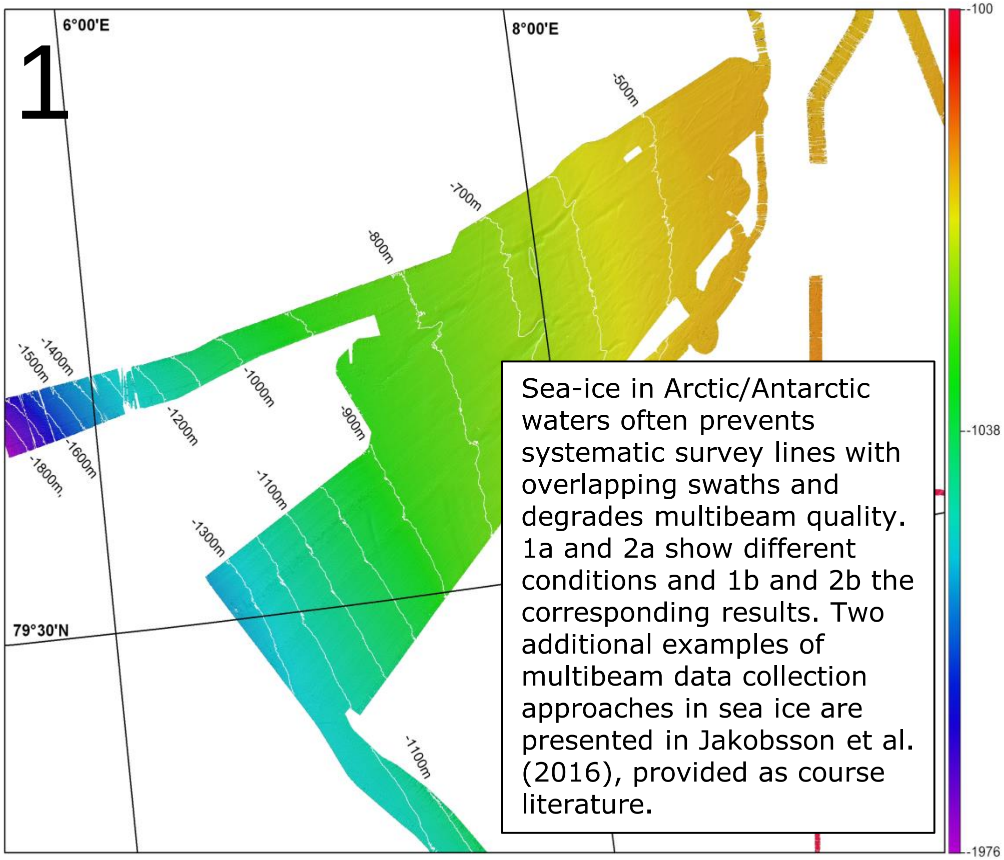
The multibeam data reveal that the seafloor morphology is completely dominated by glacial landforms produced when the Pine Island Glacier extended further out from its present position.

Multibeam bathymetry from Pine Island Bay

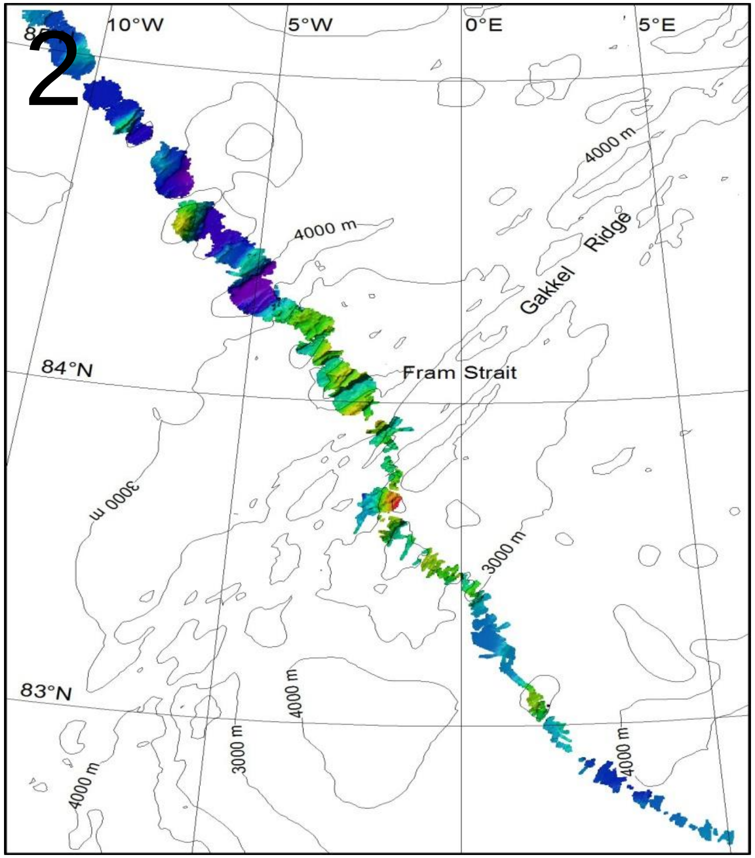
Zoom in showing some glacial landforms revealed by the multibeam bathymetry.
The glacial landforms are explained in the case study lecture in Moment 8.







Sea-ice in Arctic/Antarctic waters often prevents systematic survey lines with overlapping swaths and degrades multibeam quality. 1a and 2a show different conditions and 1b and 2b the corresponding results. Two additional examples of multibeam data collection approaches in sea ice are presented in Jakobsson et al. (2016), provided as course literature.



RV Skidbladner

Equipment:

Multibeam: KM EM2040, 200/300/400 kHz, 1°x1°

Sub-bottom profiler: KM EA600, 15 kHz

Boat:

Arronet 20 CS, 6.4 m

150 HP, Honda outboard, gasoline

Navigation

Seapath 330+ (GPS/GLONASS, RTK capacity)

Motion sensor: MR5+

Vessel equipment.

Garmin AES, 7012 nav-plotter, VHF radio

GSD 22 echo sounder, 50/200 kHz

Multibeam setup on RV Skidbladner

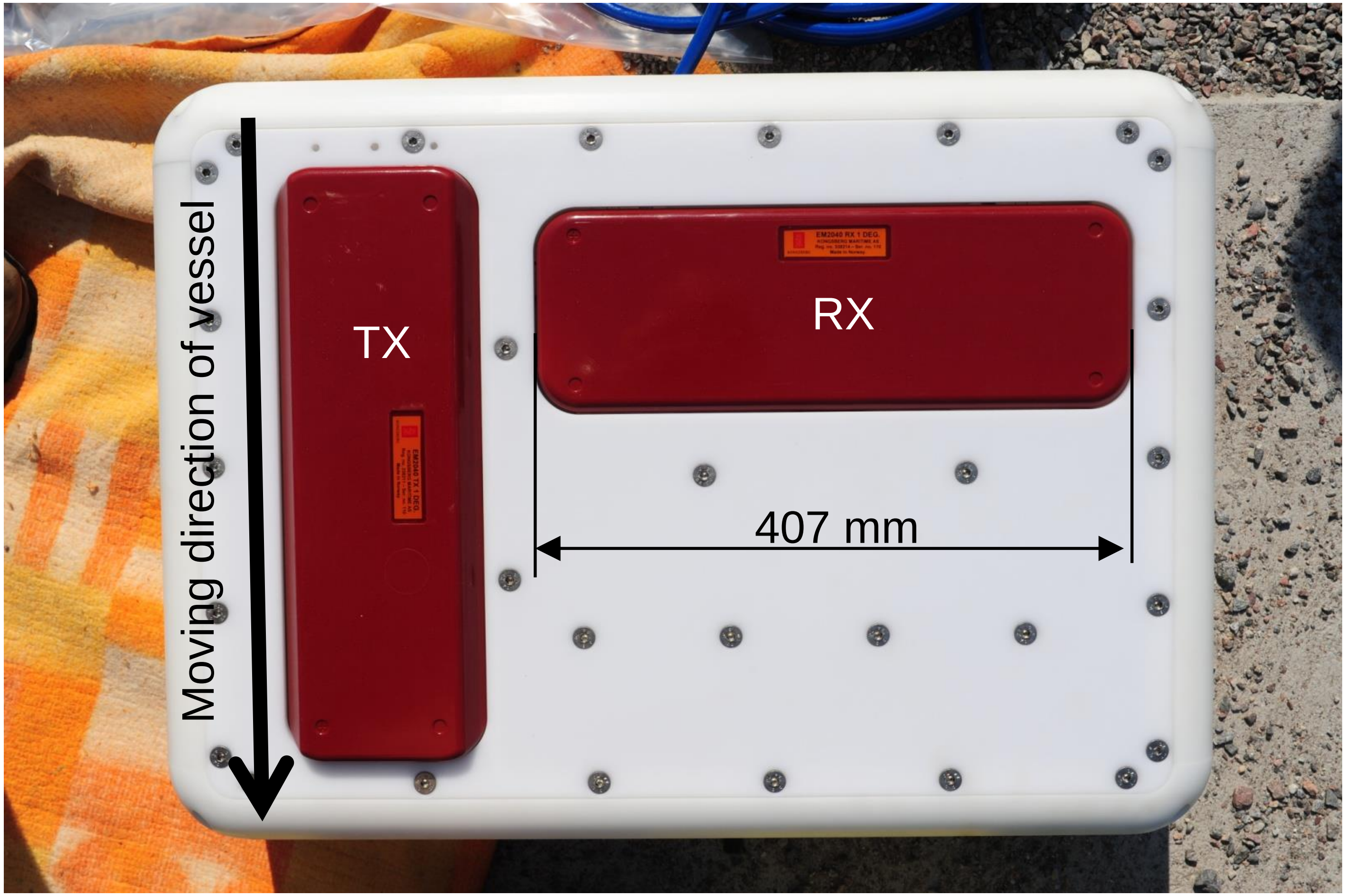
GPS antennas for the Seapath 320+ navigational system. A minimum of two antennas are required to be mounted with an offset in order to derive heading.

Sound velocity sensor mounted for continuous recording near the transducers. (Valeport MiniSVS)

Motion sensor (Seatex MRU 5+) mounted in waterproof bottle

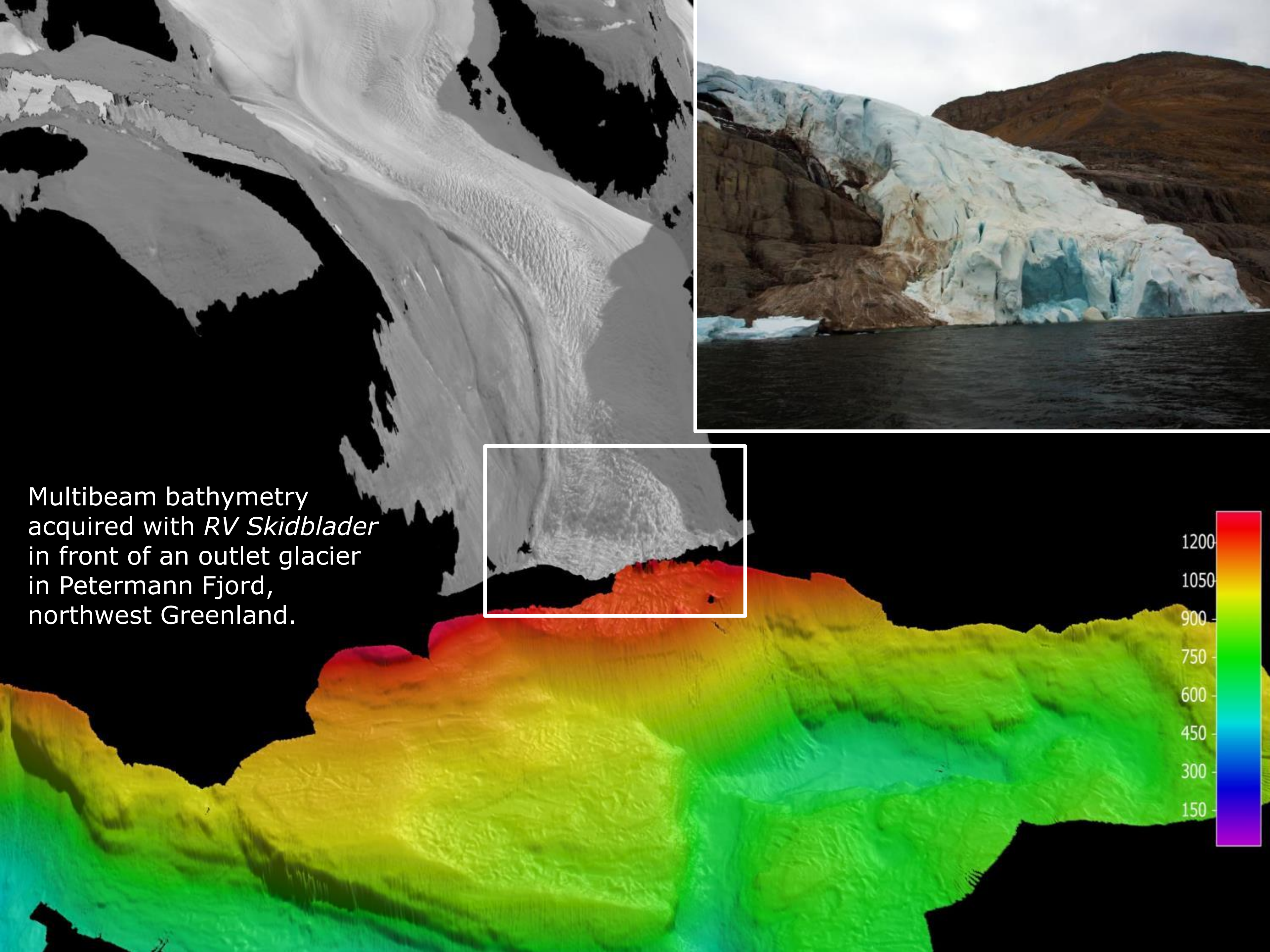
Multibeam transducers mounted in plastic casing (see next slide)

EM2040 1°x1° setup

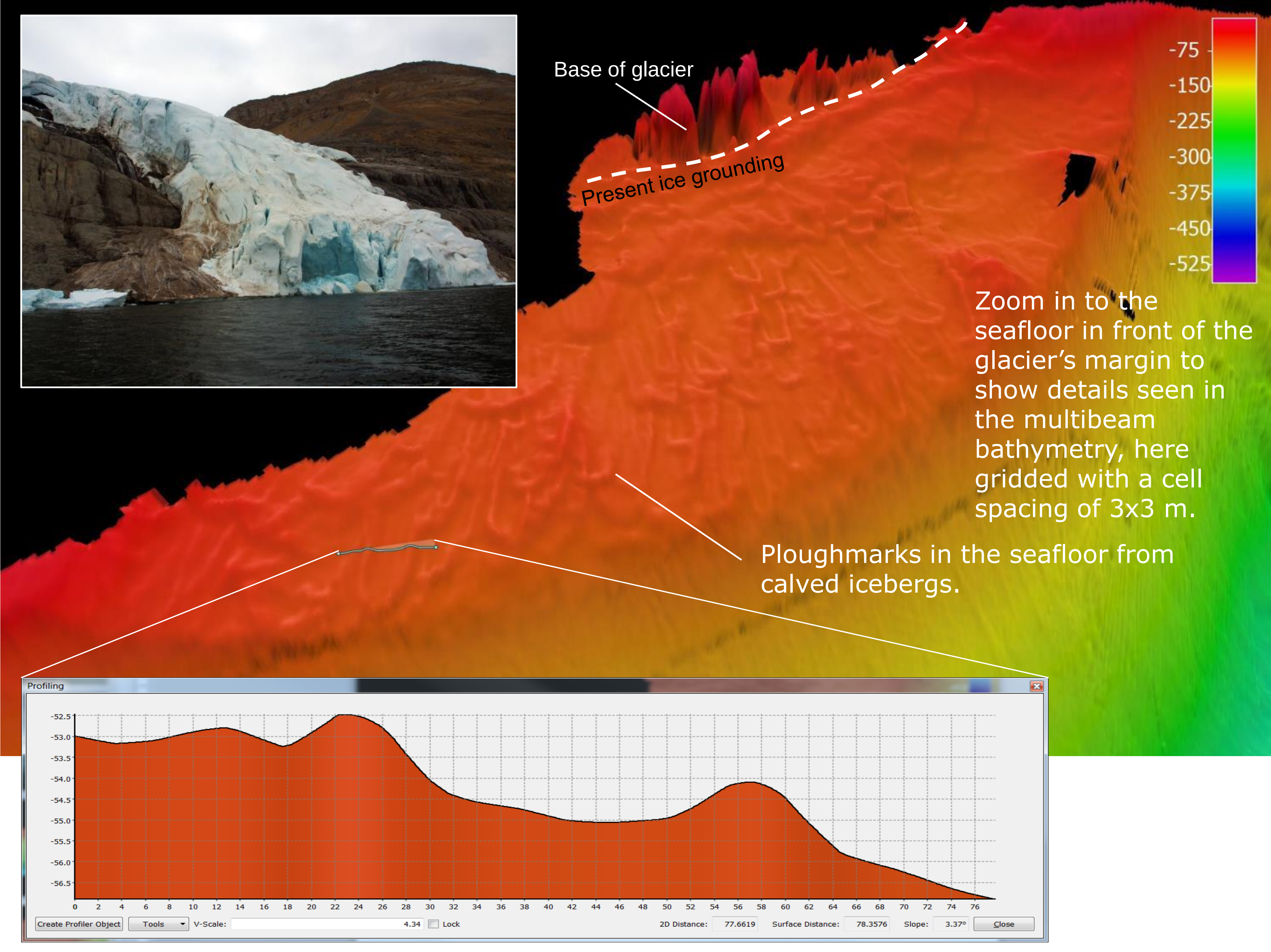


Frequencies: 200/300/400 kHz

1° beam width applies for 300 kHz suggesting that the effective length is more close to 333 mm



Multibeam bathymetry acquired with *RV Skidblader* in front of an outlet glacier in Petermann Fjord, northwest Greenland.



V-Scale: 4.34 ☐ Lock

2D Distance: 77.6619

Surface Distance: 78.3576

Slope: 3.37°

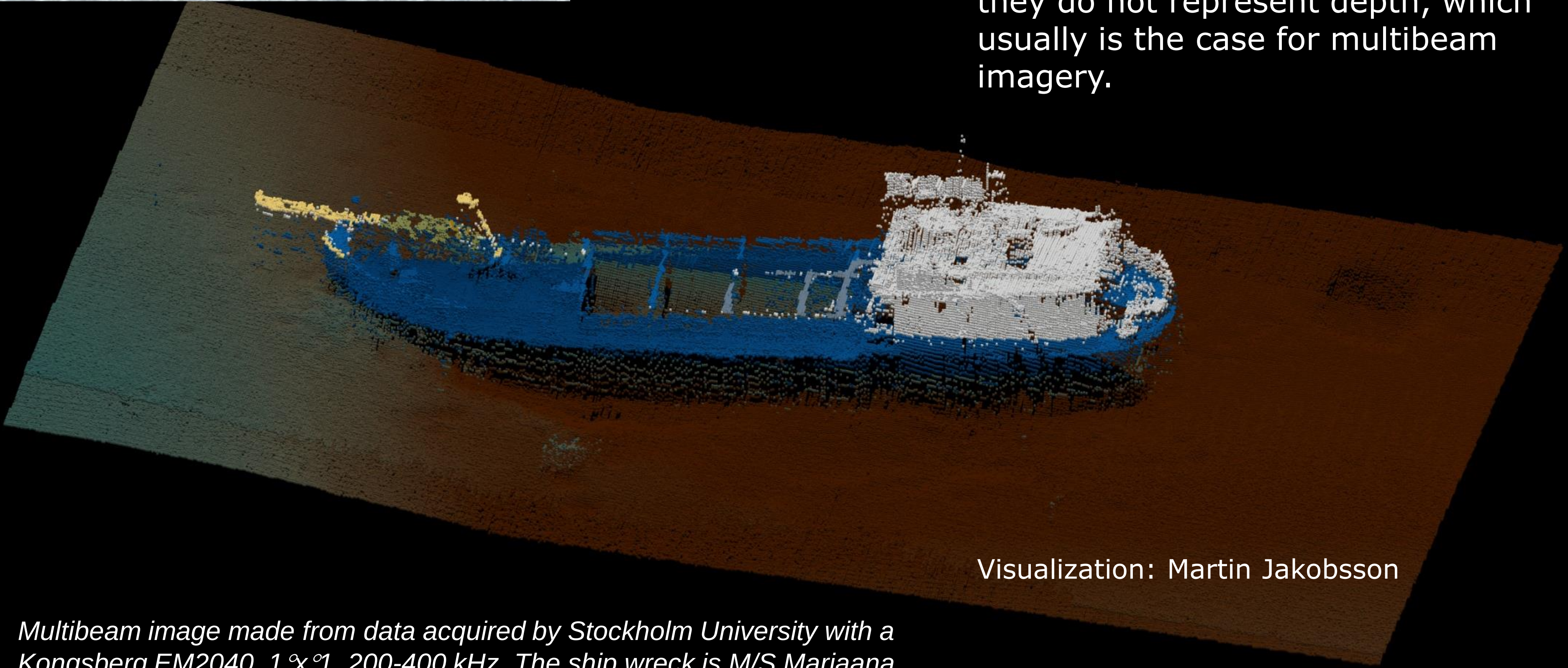
Zoom in to the seafloor in front of the glacier's margin to show details seen in the multibeam bathymetry, here gridded with a cell spacing of 3x3 m.

Ploughmarks in the seafloor from calved icebergs.

EM 2040 multibeam bathymetry from shallow waters

Sister ship: Rospiggen

Note that the colors are assigned to resemble the ship’s colors. Hence they do not represent depth, which usually is the case for multibeam imagery.



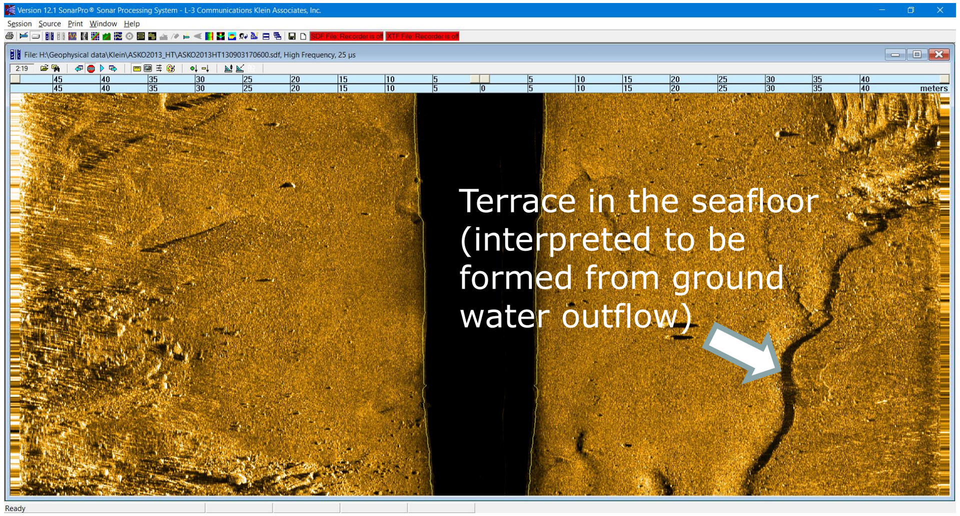
Visualization: Martin Jakobsson

Multibeam image made from data acquired by Stockholm University with a Kongsberg EM2040, 1°x°1, 200-400 kHz. The ship wreck is M/S Marjaana who was built for Underås Sandtag AB in 1944 and was first called *Underås Sandtag II.* The ship was used to carry sand to be used for concrete. It sunk 1969 in Lake Mälaren, Sweden, after collision with ice.

Ground water formed features in the seafloor east of Askö, southern Stockholm Archipelago

In the following slides terraces and depressions in the seafloor are seen in multibeam bathymetry. These same features were previously shown in side-scan imagery. They are interpreted to be formed from escaping ground water in the seafloor. The features are described in:

Jakobsson, M., O'Regan, M., Gyllencreutz, R., and Flodén, T., 2016. Seafloor terraces and semi-circular depressions related to groundwater discharge in Stockholm Archipelago, Baltic Sea. In Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K. & Hogan, K. A. (eds) 2016. Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient. Geological Society, London, Memoirs, 46, 1–2, http://doi.org/10.1144/M46.43



Version 12.1 SonarPro® Sonar Processing System - L-3 Communications Klein Associates, Inc.

SDF File: Recorder is off

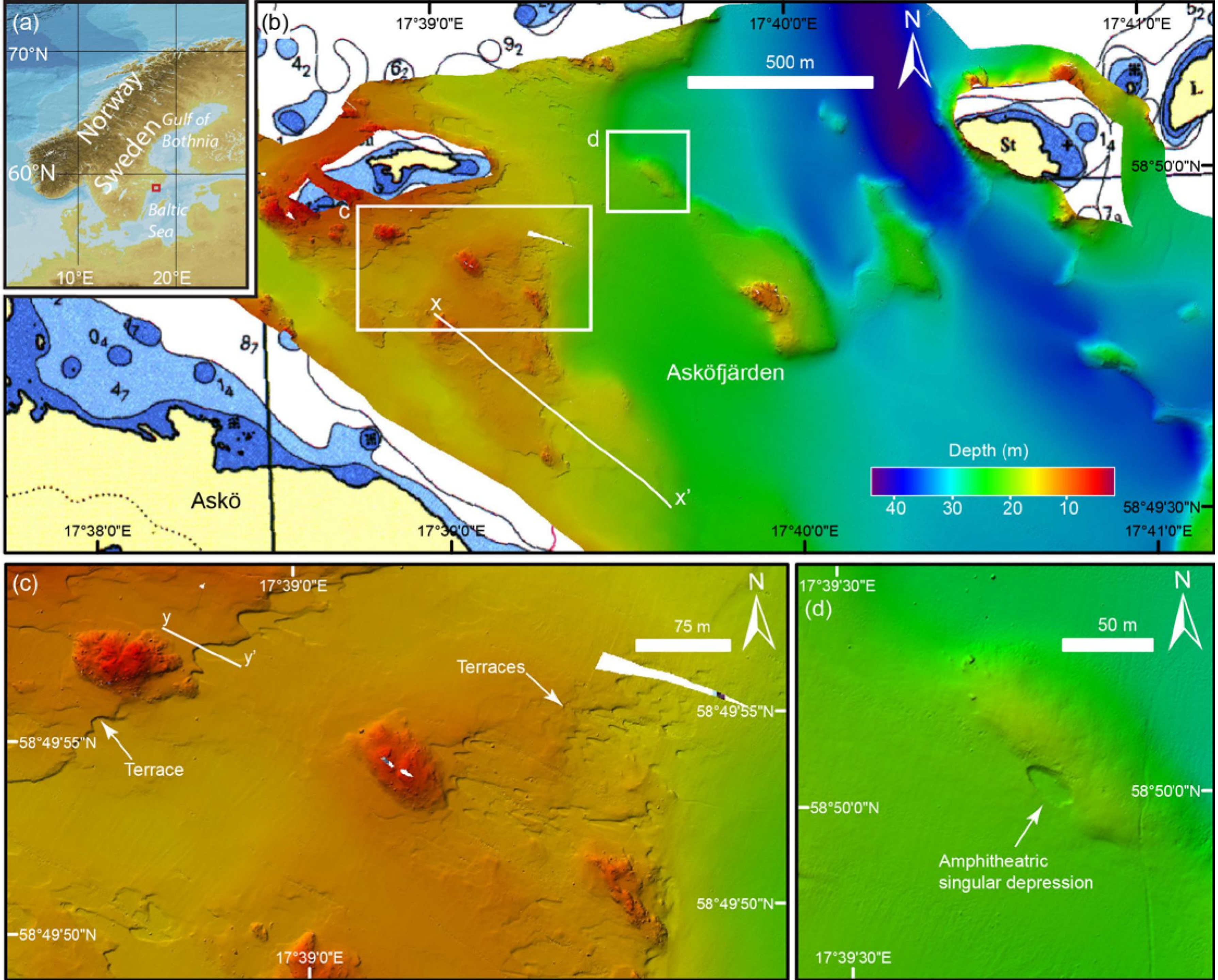
XTF File: Recorder is off

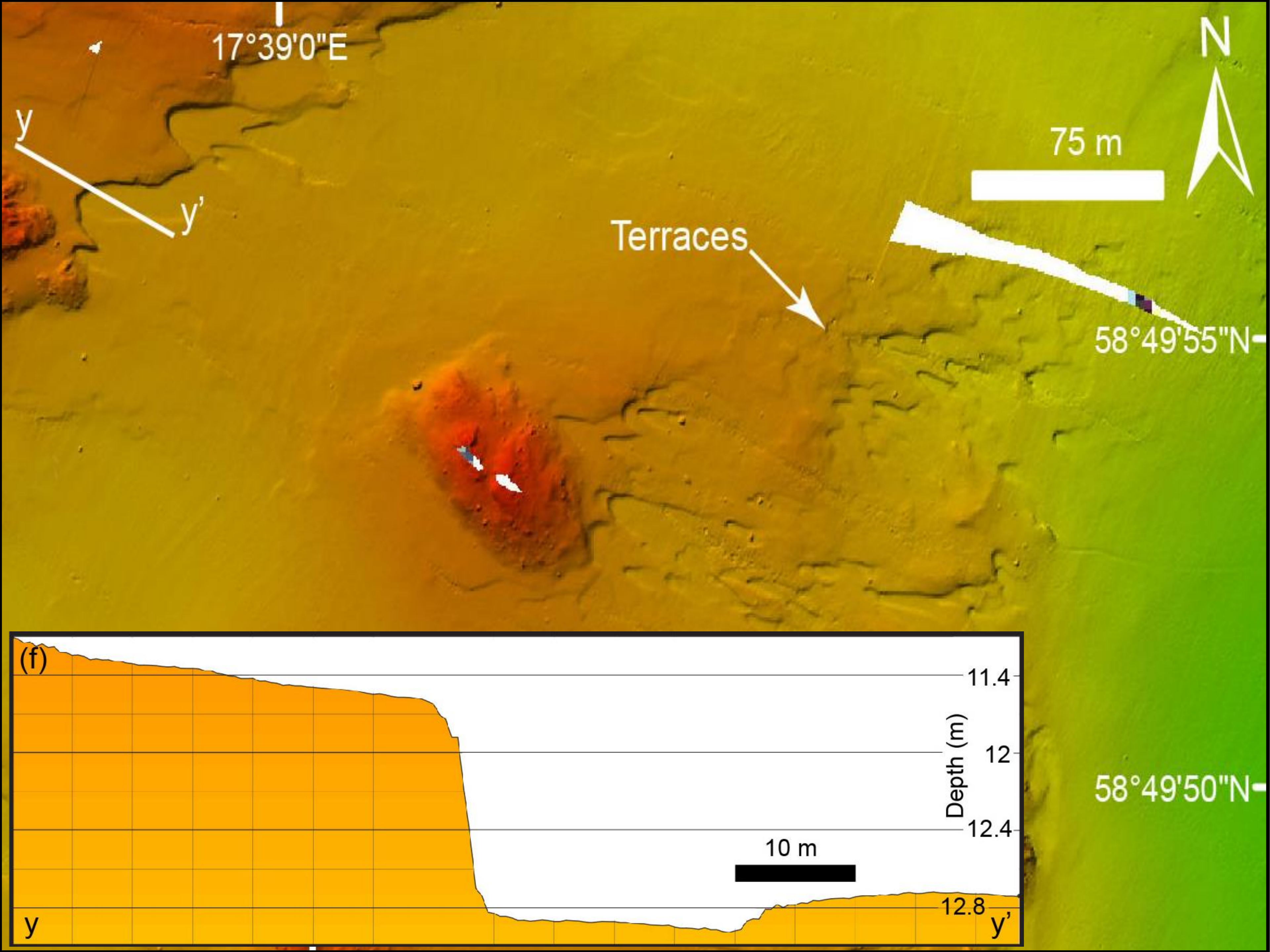
File: H:\Geophysical data\Klein\ASKO2013_HT\ASKO2013HT130903170600.sdf, High Frequency, 25 µs

Ready

Terrace in the seafloor (interpreted to be formed from ground water outflow)

Previously shown side-scan image


(a)
70°N
60°N
10°E
20°E
Norway
Sweden
Gulf of Bothnia
Baltic Sea
(b)
17°39'0"E
17°40'0"E
17°41'0"E
17°38'0"E
17°30'0"E
58°50'0"N
58°49'30"N
500 m
N
d
c
x
x'
Askö
Asköfjärden
St
L
Depth (m)
40
30
20
10
(c)
17°39'0"E
58°49'55"N
58°49'50"N
75 m
N
y
y'
Terraces
Terrace
(d)
17°39'30"E
58°50'0"N
50 m
N
Amphitheatric singular depression


17°39'0"E
y
y'
75 m
N
Terraces
58°49'55"N
58°49'50"N
(f)
11.4
12
12.4
12.8
Depth (m)
10 m
y
y'

RV Electra

Equipment:

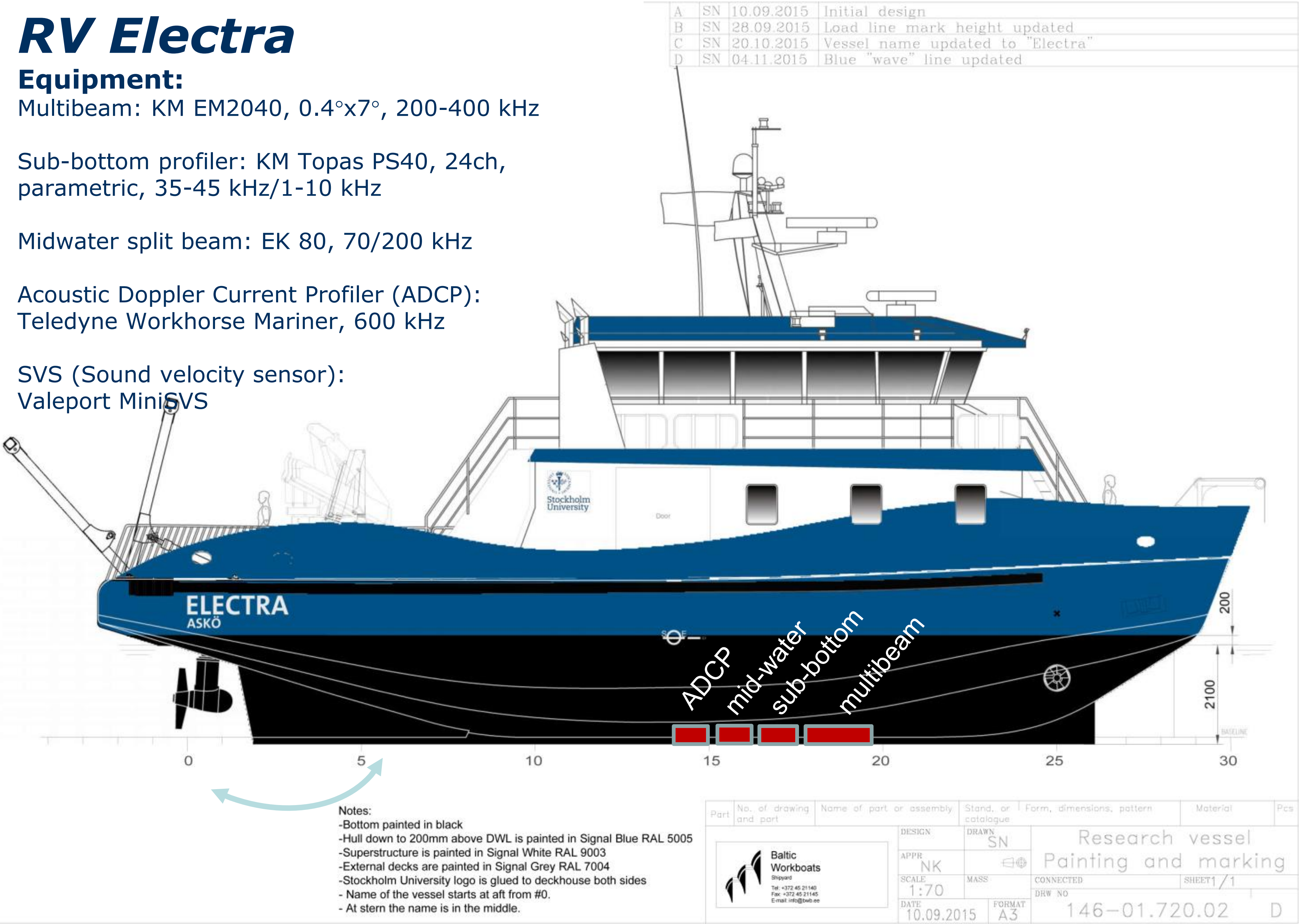
Multibeam: KM EM2040, 0.4°x7°, 200-400 kHz

Sub-bottom profiler: KM Topas PS40, 24ch, parametric, 35-45 kHz/1-10 kHz

Midwater split beam: EK 80, 70/200 kHz

Acoustic Doppler Current Profiler (ADCP): Teledyne Workhorse Mariner, 600 kHz

SVS (Sound velocity sensor): Valeport MiniSVS



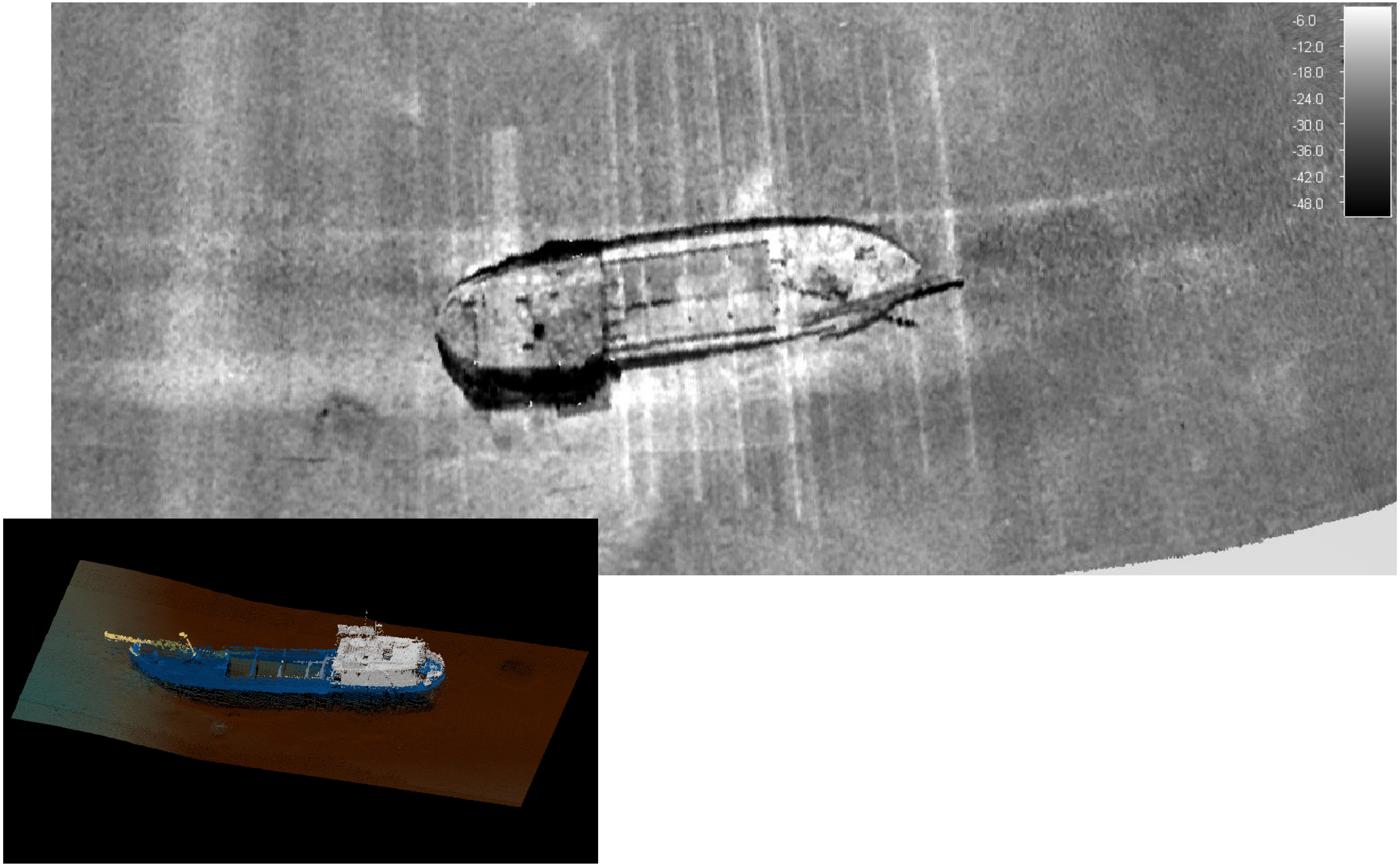
A	SN	10.09.2015	Initial design
B	SN	28.09.2015	Load line mark height updated
C	SN	20.10.2015	Vessel name updated to "Electra"
D	SN	04.11.2015	Blue "wave" line updated

Notes:
-Bottom painted in black
-Hull down to 200mm above DWL is painted in Signal Blue RAL 5005
-Superstructure is painted in Signal White RAL 9003
-External decks are painted in Signal Grey RAL 7004
-Stockholm University logo is glued to deckhouse both sides
- Name of the vessel starts at aft from #0.
- At stern the name is in the middle.

Multibeam backscatter

- The amplitude strength from an echoed signal is referred to as **backscatter**
- The backscatter strength is dependant on bottom sediment type (mud, sand, gravel, rocks etc), bottom roughness, gas, sound pulse incident angle
- The difference between side-scan and multibeam backscatter is that each amplitude strength value in a multibeam is tied to a depth value and has a **precise geo-registration**.
- The acoustic backscatter registered by side-scan sonars is commonly logged as **time series of intensity values**. One such time series is recorded for each channel, port and starboard. There is no depth information with the time series.

Backscatter mosaic of the wreck Marjaana in southern Mälaren



MBES in summary:

Accurate multibeam bathymetric mapping requires knowledge of:

1. **the sound velocity of the water column and at the transducers**
2. **the vessel's horizontal position (navigation)**
3. **the water level during survey and its relation to vertical datums**
4. **the time**
5. **the motion of the ship (roll, pitch, yaw, heave)**
6. **the precise geometric configurations of all incorporated sensors**

Modern multibeam systems also records:

1. **Backscatter information**
2. **Water column imagery**

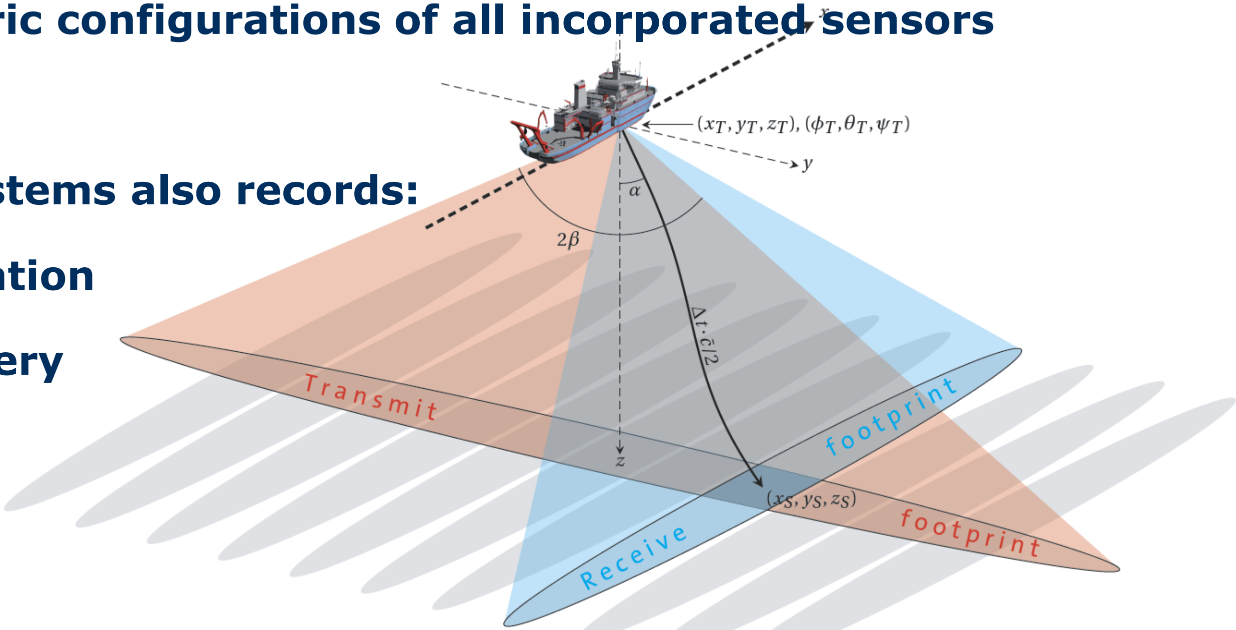
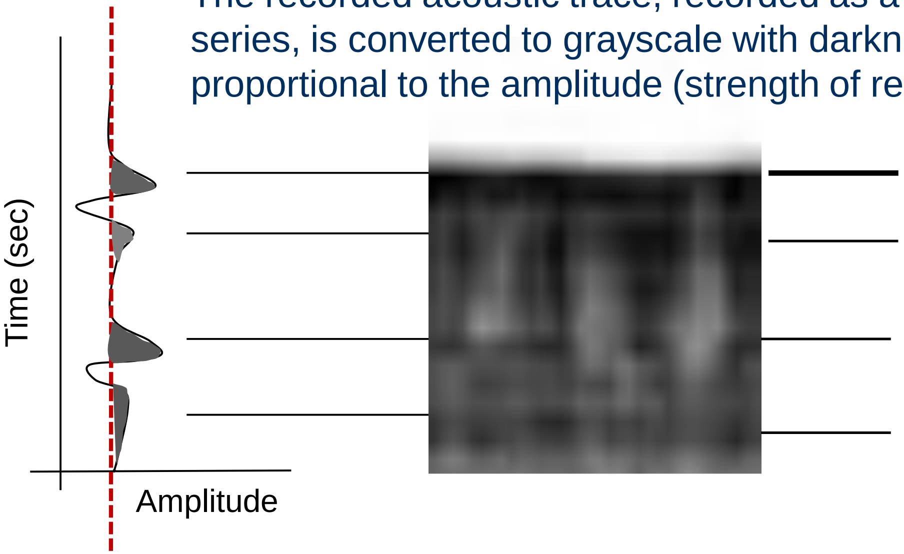


Image from Benjamin Hell's PhD Thesis 2011, Stockholm University

4. Sub-bottom profilers

The sub-bottom profiler is an echo sounder designed to image the upper sediment stratigraphy. The operational principle is the same as for a bathymetric SBES with the main difference in that the output-energy is high enough in order to allow the pulse to penetrate the sediments. Reflections occur at any impedance contrast within the sediment stratigraphy (see Moment 4, Lecture 1). The frequencies used for conventional sub-bottom profilers ranges from about 20 kHz to 0.5 kHz. Sub-bottom information may be achieved with frequencies even higher than 20 kHz in soft sediments.

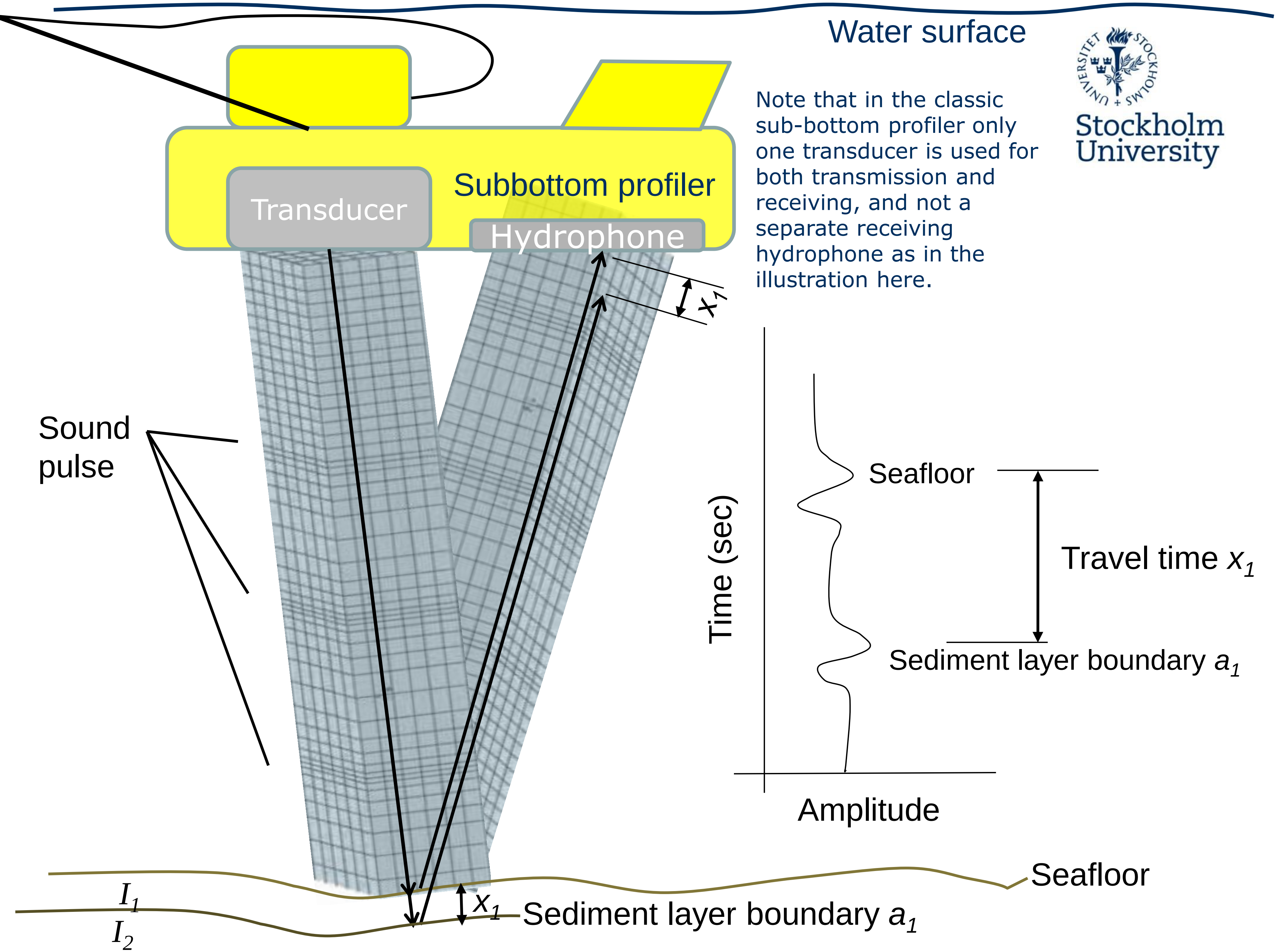


The recorded acoustic trace, recorded as a time series, is converted to grayscale with darkness proportional to the amplitude (strength of reflection)

Bottom reflection

Each reflection is caused by an impedance contrast in the sediment stratigraphy.

Stockholm University

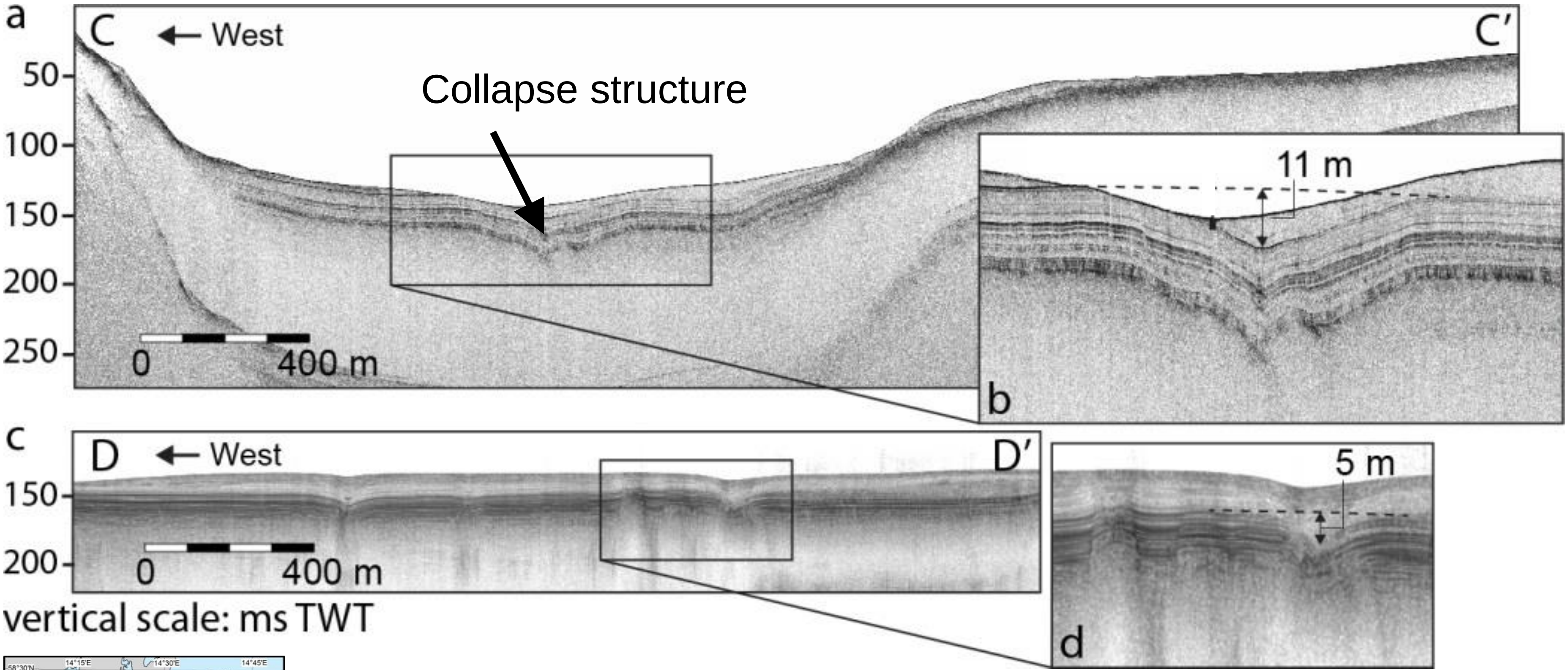


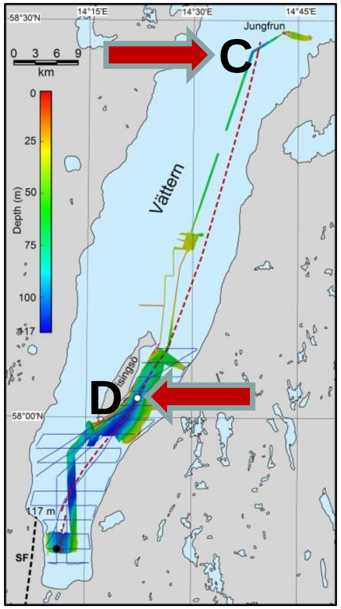
Note that in the classic sub-bottom profiler only one transducer is used for both transmission and receiving, and not a separate receiving hydrophone as in the illustration here.

Different speed of sound in different materials cause reflections

Examples of approximate sound speeds:

- Air (0°C): 331 m/s
- Air (20°C): 343 m/s
- Methane (60000 kPa, 25.15 °C): 1000 m/s
- Fresh water (0°C): 1402 m/s)
- Fresh water (20°C): 1482 m/s)
- Sea water (3.5% salinity, 20°C): 1522 m/s)
- Clay ~1480->1500 m/s
- Sand ~1700-1800 m/s
- Wood (oak): 3850 m/s
- Granite >5000 m/s





Sub-bottom profiles from Lake Vättern acquired with the EA 600 and a 15 kHz transducer mounted on *RV Skidbladner*. The profiles revealed collapse structures seen in glacial and post-glacial clay interpreted to be cause by an earth quake 11 500 years ago.

5. Chirp sonar

The chirp sonar is a specific kind of sub-bottom profiler. The Chirp (named after the “chirp” of a bird) sonar transmits a frequency-modulated (FM) pulse that sweeps through a frequency range of several kHz. The frequency range is commonly between 500 Hz and 24 kHz and pulse lengths of are commonly 10-50 ms. The length can thus be made up to hundreds of times longer than for conventional SBESs, which allows much more energy to be transmitted in each pulse. Penetration up to about 200 m in sub-bottom sediments can be achieved with powerful Chirp sonars. The reason for that the pulse can be made so long without loosing resolution is that the FM pulse is compressed using matched filtering. This implies that the returning chirp signal is correlated in the time domain with a stored copy of the outgoing pulse, which collapses the pulse to a short duration wavelet:

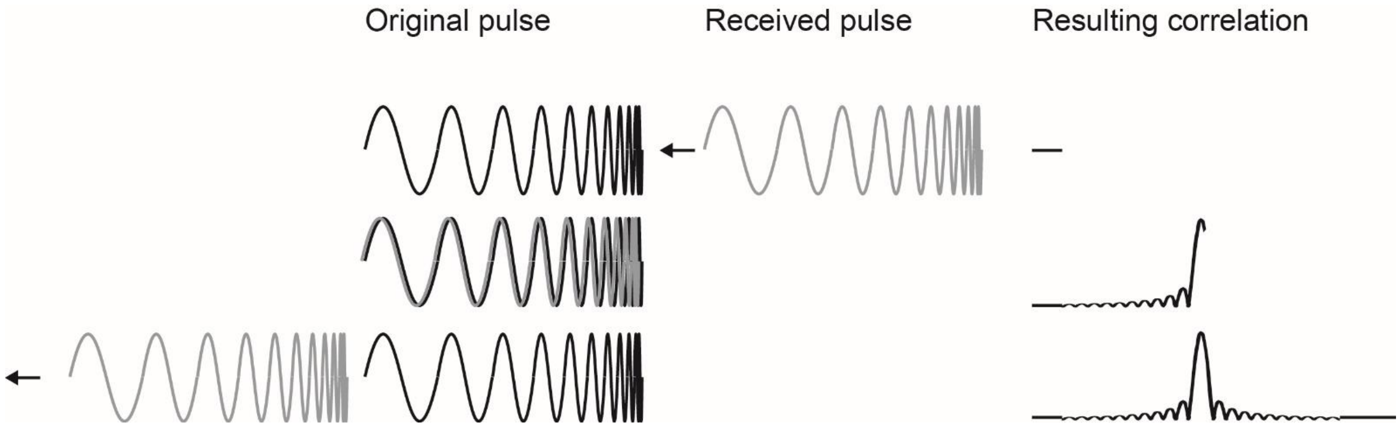


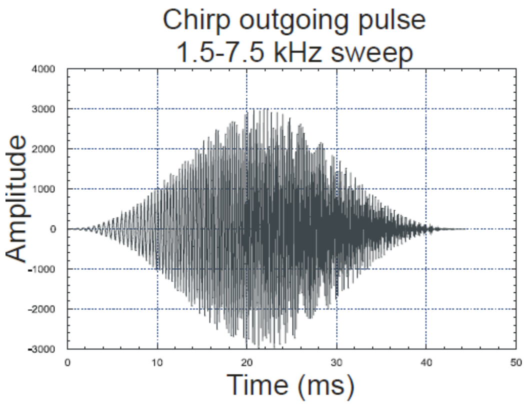
Figure 6 from Jakobsson et al (2016), provided as a PDF

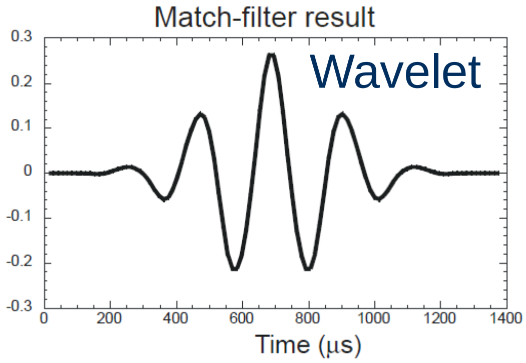
Resolution of a chirp

One limitation of the conventional echo sounder used as sub-bottom profiler can be summarized in: Shorter pulse gives better vertical resolution, but less energy transmitted. This is because vertical resolution is given by the Raleigh criterion: 1/4λ (at best theoretically), but more realistically 1/2λ.

Chirp sweeps out a signal from x Hz to y Hz. The difference between the starting frequency and the end is called the bandwidth.

The matched filtering collapses the received long chirp pulse to a short duration wavelet.


Chirp outgoing pulse
1.5-7.5 kHz sweep


Match-filter result

Vertical resolution is estimated by:

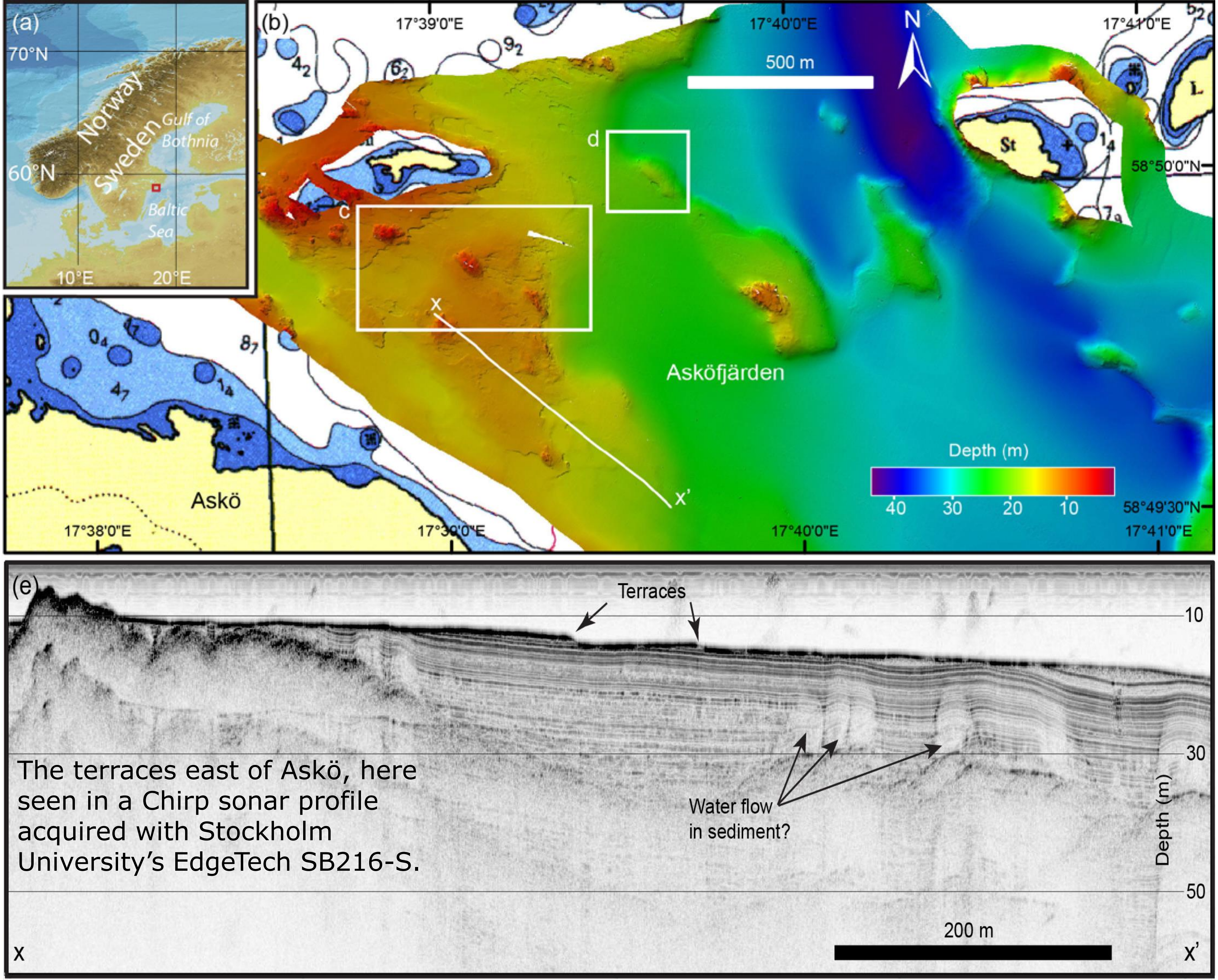
$$\boxed{R_v = \frac{v}{B\times 2}}$$

B=Bandwidth
R_v=Vertical resolution
v= sound velocity in sediments

Chirp sonar examples

Stockholm University’s Chirp sonar: EdgeTech SB-216S, capacity of chirping within the range of 2-16 kHz.

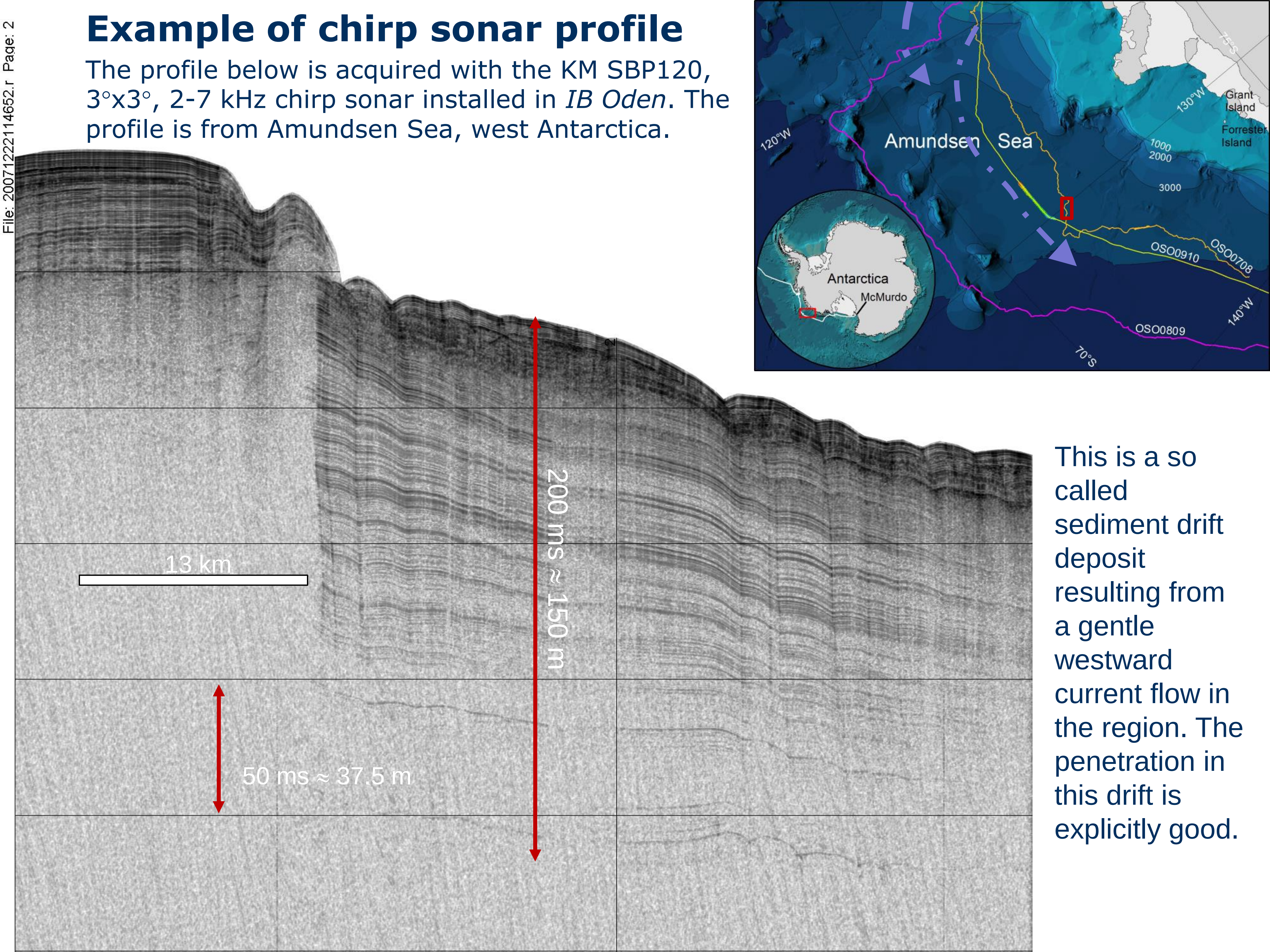
Using the rule of thumb presented in the previous slide and an assumed sediment sound velocity of 1500 m/s, the vertical resolution with a 2-16 kHz pulse (14 kHz bandwidth) is about 21 cm. The signal can penetrate up to ~80 m in clay



The terraces east of Askö, here seen in a Chirp sonar profile acquired with Stockholm University’s EdgeTech SB216-S.

Example of chirp sonar profile

The profile below is acquired with the KM SBP120, 3°x3°, 2-7 kHz chirp sonar installed in *IB Oden*. The profile is from Amundsen Sea, west Antarctica.



This is a so called sediment drift deposit resulting from a gentle westward current flow in the region. The penetration in this drift is explicitly good.

6. Parametric echo sounders

The peaks of transmitted sound pulses will travel slightly faster than the troughs for the physical reason that the compressibility of water is not linear. The pulse eventually takes a saw-tooth appearance instead of the original sinusoidal shape. This effect of distortion is used in a so called parametric sub-bottom profiler as it implies a non-linear mixing of two signals of different frequencies.

The parametric echo sounder transmits two sound pulses with high intensity simultaneously at two frequencies separated by a desired frequency value. The interference of these two signals will, due to non-linear mixing of the saw-tooth pulses, generate secondary frequencies where one is equal to the sum and another is equal to the difference between the original frequencies. While the sum secondary frequency will be very high and is quickly attenuated, the difference frequency will be low and penetrate the sediment stratigraphy providing sub-bottom information. The resolution of a parametric echo sounder can be estimated in the same way as for a Chirp sonar profiler by treating the difference secondary frequency as the bandwidth.