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Bathyswath-2 technical information

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Voids

Section	Notes
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List of modifications

Version	Date	Modifications	Pages	Writer	Checker
10.06	07/01/20	Table in section 7.3 & some reference errors corrected		JSS	
10.05	25/08/20	Review and update		MFG	
10.04	13/03/20	New graphic chart	71	FBY	
10.03	15/08/18	Merge versions, spelling & grammar check		MFG	
10.02	03/05/18	Occasional small corrections		MFG	
10.01	09/09/16	Housing weights and summary table added		MFG	
10.00	16/06/16	Bathyswath-2	78	DMA	MFG
9.03	04/04/16	Details of nadir region added		MFG	DMA
9.02	10/03/16	SU and DU details added		MFG	DMA
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9.00	04/08/15	Renumbered (was OD-5001) and revised		MFG	DMA
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7.04	01/07/13	Minor modifications	70	DMA	MFG
7.03	25/06/13	Revision of « high speed » section and general review	24-40	MFG	DMA
7.02	24/06/13	Add of section « surveying at high speed »	72	DMA	MFG
7.00	17/06/13	Bathyswath update	65	DMA	MFG
1.00	31/05/16	Initial document	65	DMA	MFG

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1 INTRODUCTION

1.1 REFERENCES

Ref. 1 "IHO Standards for Hydrographic Surveys, 5th edition, Special publication S-44", http://www.iho.int/iho_pubs/standard/S-44_5E.pdf

Ref. 2 ETD_2006_Bathyswath_OEM_Integration_Manual.pdf

1.2 GLOSSARY & ACRONYMS

ACRONYMS	DEFINITION
AGDS	Acoustic Ground Discrimination Systems
AUV	Autonomous Underwater Vehicle
COTS	Commercial off the Shelf
CW	Continuous Wave
DC	Direct current
DU	Deck Unit
DTM	Digital Terrain Model
FGPA	Field-Programmable Gate Array
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IHO	International Hydrographic Organization
INS	Inertial navigation system
LLWS	Lowest Low Water Springs
MBES	Multibeam Echosounder
MRU	Motion Reference Unit
NMEA	US National Marine Electronics Association (i.e. NMEA 0183 is a standard computer interface for marine equipment maintained by the NMEA)
OEM	Original Equipment Manufacturer
PDBS	Phase Differencing Bathymetric Systems
PRF	Ping (or Pulse) Repetition Frequency
PSM	Permanent Siltation Monitoring
QA	Quality Assurance
RIB	Rigid Inflatable Boat
ROV	Remotely Operated Vehicle
STD	Standard
SU	Subsea Unit
SVS	Sound Velocity Sensor
TEM	Transducer Electronic Module
TVG	Time-Varying Gain
USB	Universal Serial Bus
USV	Unmanned Surface Vehicle
UW	Underwater
UUV	Unmanned Underwater Vehicle (includes AUVs and ROVs)

1.3 SCOPE

This document describes the technical aspects of the Bathyswath-2 systems, their options, their components, and their performances.

2 OVERVIEW OF BATHYSWATH-2 SYSTEMS

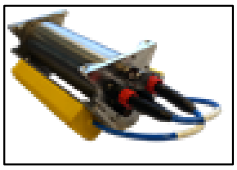
2.1 GENERAL

- Bathyswath-2 is a wide swath sonar system designed for surveying underwater surfaces. It provides high-density bathymetry and sidescan data.
- Bathyswath-2 is particularly adapted for shallow water areas because of its technology (Interferometry, Phase Differencing Bathymetric Systems)[1]
- Bathyswath-2 is delivered with its own data acquisition and processing software[2], it is also compatible with most third-party software
- Bathyswath-2 systems are developed and manufactured by ITER Systems in France (www.iter-systems.com)

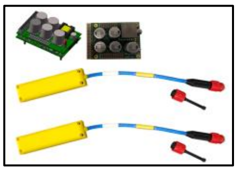
There are five versions of Bathyswath-2 systems:

- Bathyswath-2-STD (Standard): Standard version only including the sounder.

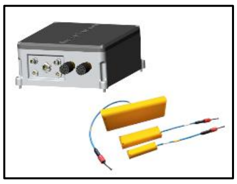
- Bathyswath-2-UW (Underwater): Integrated and underwater version (300 or 3000m depth rated) with the possibility to add inside the housing a sound velocity sensor and/or a motion sensor.



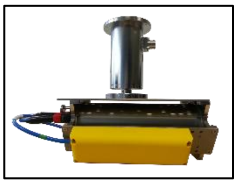
- Bathysath-2-OEM: Basic version for manufacturers or integrators that includes the electronics and the transducers.



- Bathyswath-2-Omega: Provides sonar control, GNSS positioning, INS motion compensation, sound velocity measurement, data acquisition and sonar processing and data acquisition in one compact package.

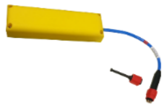


- Bathyswath-2-PSM: Fixed version, the Bathyswath-2 system is installed permanently at a fixed position underneath a pan rotator that covers an arc of a circle; Raw data are processed automatically on a local PC and/or uploaded on a server, a pdf report is issued after each acquisition.

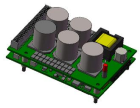


[1] Cf. section 3
[2] Unlimited license

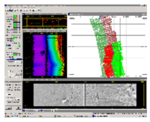
The main components of Bathyswath-2 systems are:



- One or more transducers, which transform an electrical signal into sound waves for transmission and vice versa in reception.



- A sonar electronics module, which we usually call the “TEM”, and which interfaces between the computer software installed on PCs and transducers, generating the acoustic pulses and amplifying the echoes.

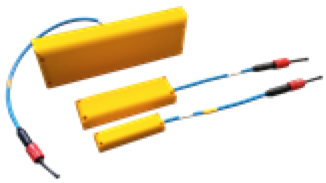


- Data acquisition[3] and processing software[4].

Add to that the secondary components such as housings, cables, power supplies, transducer mounts, etc ...

Bathyswath-2 systems use 3 frequencies, user choice[5] :

- 117 kHz
- 234 kHz
- 468 kHz



- The higher the frequency, the smaller the transducer, the shorter the range and the greater the resolution.
- Warm, silty water tends to absorb the sound a lot more than cool, clear water. In this case, it is often better to use a 234kHz system rather than a 468 one even in shallow waters where the required range is limited.

3 Also available for Linux
4 Bathyswath software works under Microsoft Windows
5 Bathyswath-2 electronics allows up to 3 transducers without being necessarily all the same frequency.

2.2 DESCRIPTION OF BATHYSWATH-2 SYSTEMS

2.2.1 Bathyswath-2-STD

Bathyswath-2-STD system is our standard version, it consists of:

- The Deck Unit (DU) in painted and anodized aluminium. It is waterproof to IP66 and includes the sonar electronics for 1, 2 or 3 transducers.
- One, two or three transducers (117, 234 or 468 kHz choice).
- One, two or three cable extensions for the transducers (1, 5, 10, 15 or 20m standard, other lengths on request).
- A V-bracket, to suit the transducer chosen. A larger version is available if you want to install a motion sensor and/or a sound velocity sensor underwater between the transducers.

To complete the bathymetric "package", you will also need the following ancillary devices:

- A GNSS receiver (e.g. GPS),
    - Provides position
    - Double antenna for heading
    - PPS pulses for system timing,
    - RTK (Rover) or satellite correction services (Omnistar, Atlas, etc.) or GSM for centimetric position.
- A sound velocity profiler and ideally a sound velocity sensor mounted near the transducers,
- A motion sensor for heave, pitch, and roll, e.g. INS (inertial navigation system)

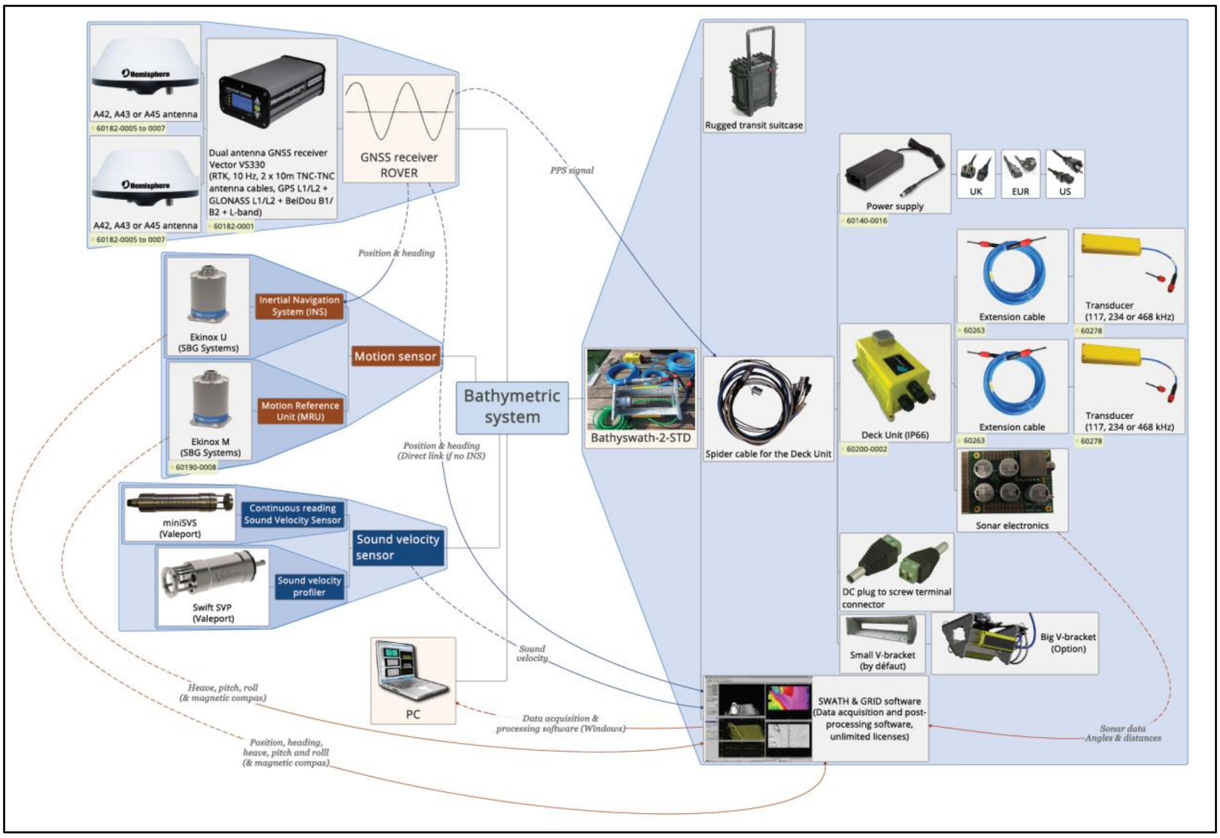


Figure 1_Example of Bathyswath-2-STD general arrangement

Figure 2_Bathyswath-2-STD with a big V-bracket

- Be careful not to choose too long cable extensions, that could obstruct the way on a small boat!

2.2.2 Bathyswath-2-UW

Bathyswath-2-UW system is our underwater and integrated version, it consists of:

- The Subsea Unit (SU) in titanium. It is waterproof to 300 (or optionally 3000m) and includes:
  - Sonar electronics for 1 or 2 transducers,
  - A communication and power board,
  - An optional INS or MRU (Ekinox A or E),
  - An optional Sound Velocity Sensor (miniSVS),
- One or two transducers (234 or 468 kHz),
- An umbilical (20m by default, longer or shorter on demand).

To complete the bathymetric package, you will also need the following ancillary devices:

- A GNSS receiver,
  - Double antenna for the heading value and PPS for the GPS time,
  - RTK (Rover) or satellite correction services (Omnistar, Atlas, etc.) or GSM for centimetric position,
- A sound velocity profiler for the speed of sound in the water column.

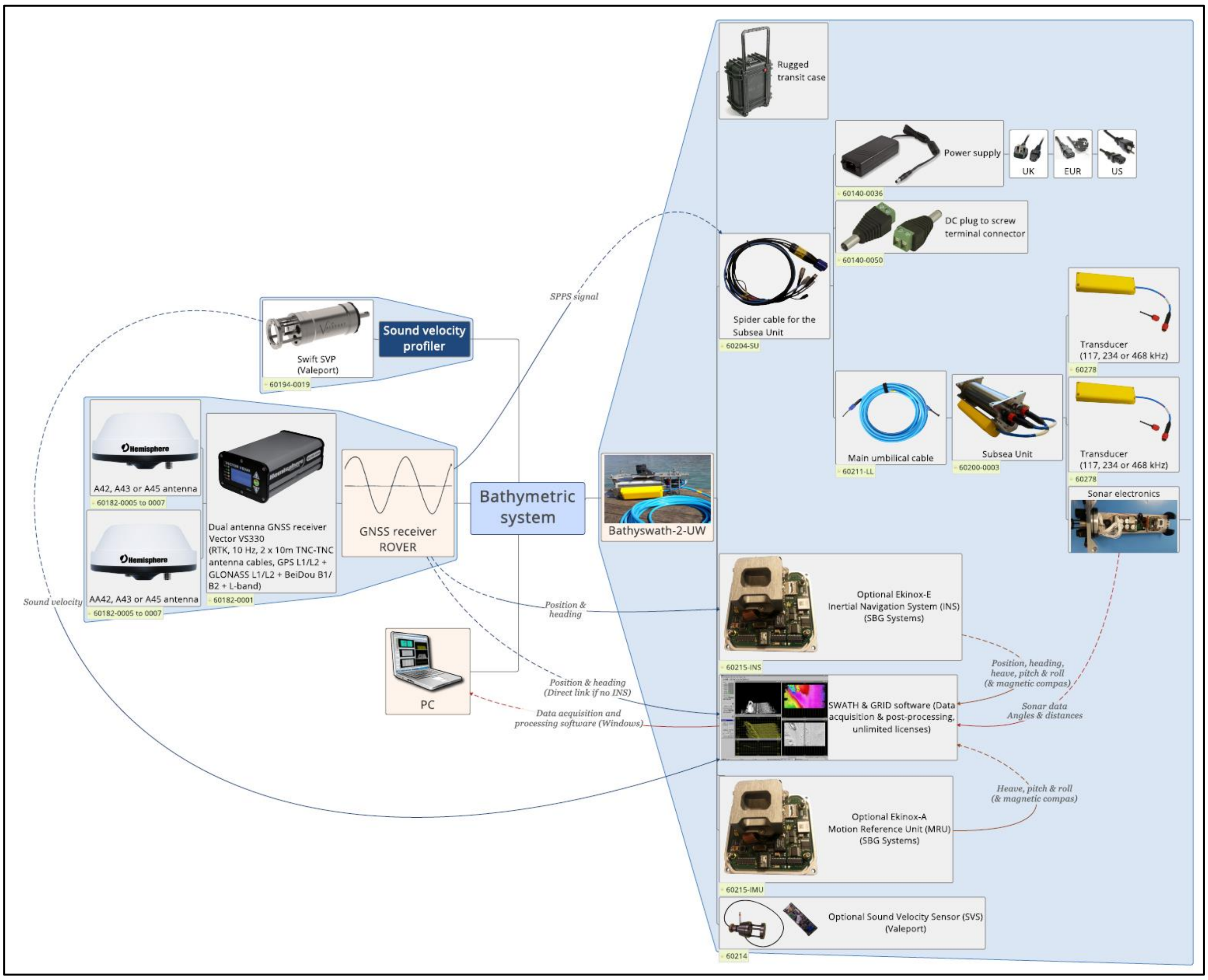


Figure 3_Example of Bathyswath-2-UW general arrangement

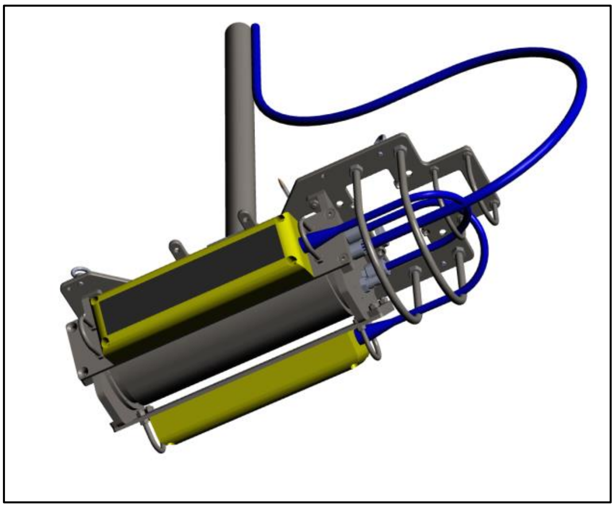


Figure 4_Bathyswath-2-UW

- Be careful not to choose a too long umbilical that could obstruct the way on a small boat!

2.2.3 Bathyswath-2-OEM

This is the simple, unpackaged version of Bathyswath-2. It is intended for the integration of the Bathyswath-2 electronics and transducers by manufacturers or integrators on their own systems.

A Bathyswath-2-OEM system consists of the following:

- A TEM (sonar electronics),
- One or two transducers,
- A test cable.

Key Bathyswath-2 qualities for integrators are:

- The small size[6],
- Low power consumption (less than 20W).

Refer to the OEM integration manual for more information (cf. Ref. 2).

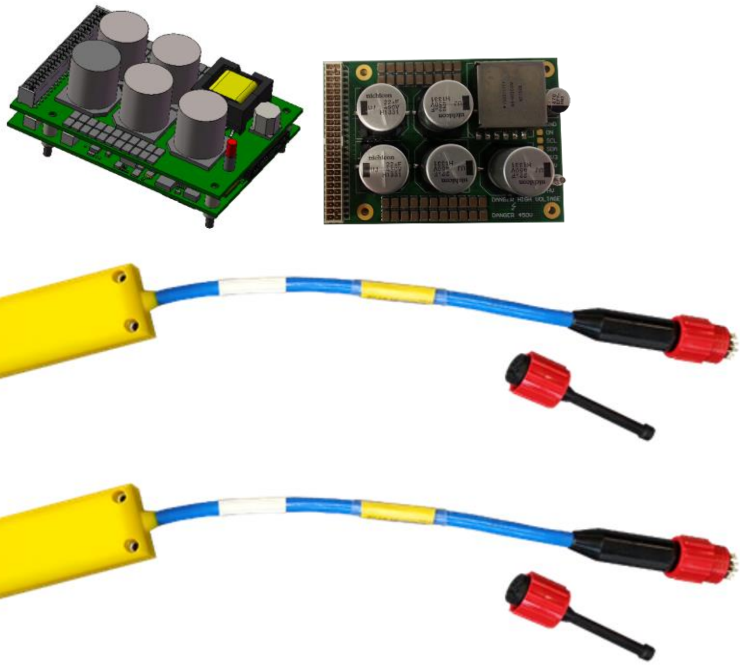


Figure 5_Package Bathyswath-2-OEM

Remember to tell us when you first ask if you want:

- The sounder electronics in your own housing,
- To have connectors at the end of the transducer tails[7].

[6] This is explained in more details below in the document
[7] Do not forget to specify the required length

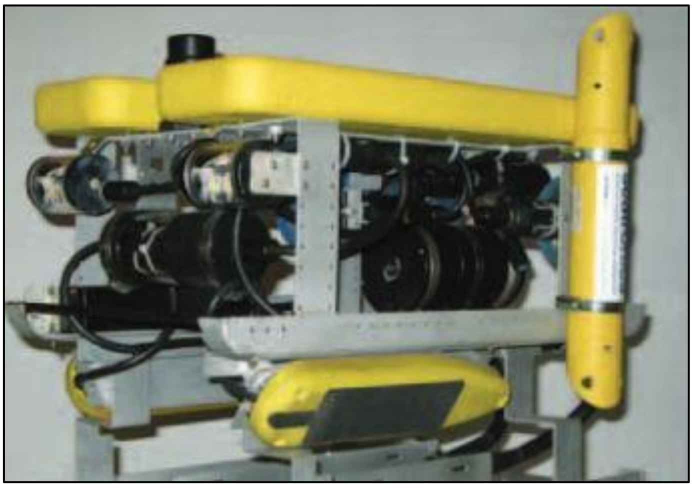


Figure 6_Bathswath installed on a ROV

Figure 7_Bathyswath on Gavia AUV

Figure 8_Bathyswath on Remus AUV

2.2.4 Bathyswath-2-Omega

This version includes the sonar electronics (TEM), GNSS positioning, INS motion compensation, sound velocity measurement, and data acquisition and sonar processing and data acquisition in one compact package.

The Omega deck unit contains:

- Optional motion sensor (4 possibilities),
- Optional dual-antenna GNSS receiver for heading and positioning (3 possibilities)
- Microcomputer for sonar data acquisition and processing
- Wi-Fi and 4G communications
- Power supply and communications board

Figure 9 Bathyswath-2-Omega Deck Unit

Bathyswath-2-Omega is perfect for small unmanned surface boats (USVs).
For use on manned boats, as the Omega Deck Unit contains the motion sensor, don't have the Deck Unit inside the boat and the transducers on an over-the-side pole. Instead, either mount the Omega Deck Unit on the top of the pole, or use Bathyswath-2-STD with a separate underwater motion sensor fixed next to the transducers.

2.2.5 Bathyswath-2-PSM

A Bathyswath-2-PSM system is installed permanently at a fixed position underneath a pan rotator which covers an arc of a circle. Raw data are processed automatically on a local PC and/or uploaded to a server. A pdf report is automatically issued after each acquisition, with no operator intervention needed.

Figure 10_Example of an installation on a water dam

Figure 11_Before and during the installation with divers

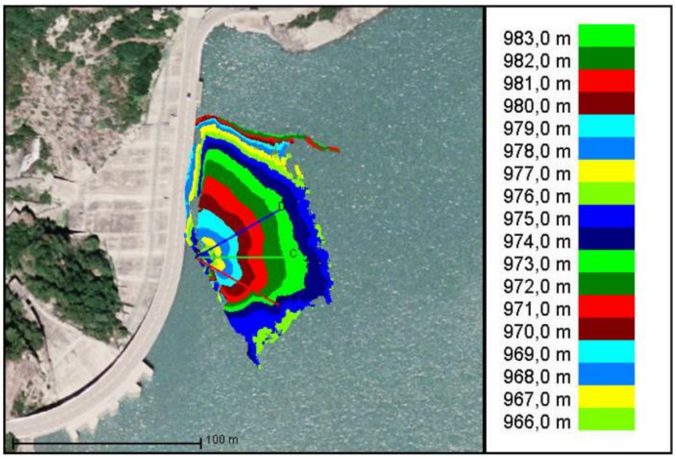


Figure 12_Extract from pdf survey report

2.3 DIMENSIONS AND WEIGHTS

2.3.1 Electronics interface units (Subsea Unit and Deck Unit)

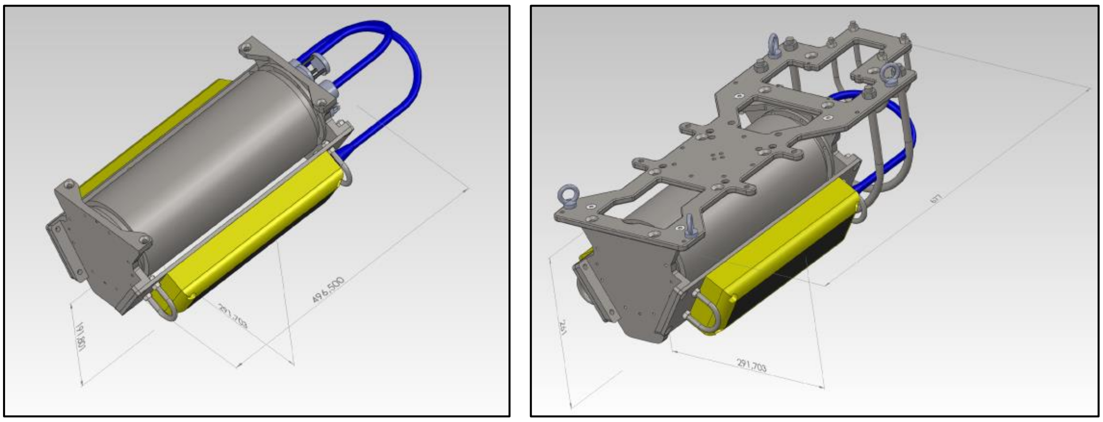


Figure 13_Bathyswath-2-UW_The Subsea Unit (SU) with or without the interface plate[8]

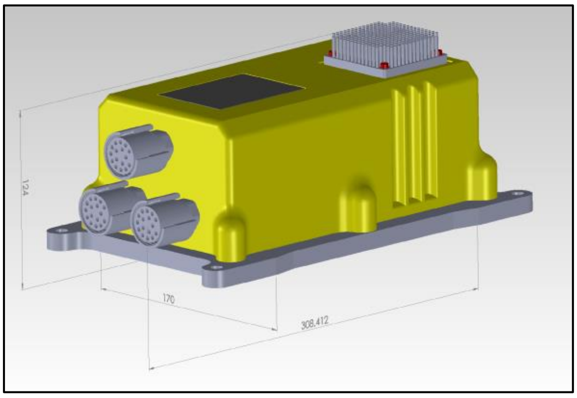


Figure 14_Bathyswath-2-STD Deck Unit (DU)[9]

[8] 496.5 x 291.7 x 191.8 mm or 677 x 291.7 x 261 mm
[9] 124 x 170 x 308.4 mm

2.3.2 Housing Dimensions and Weights

Housing	Length (mm)	Width (mm)	Depth (mm)	Weight in air (g)
Deck Unit	308.4	124	170	4200
Subsea Unit, stainless steel	496.5	291.7	191.8	26600
Titanium				15000[10]
Subsea Unit with Interface Plate	677	291.7	261	

Subsea Unit dimensions and weights are given with 234kHz transducers.

[10] To be confirmed

2.3.3 Mounting interface plates

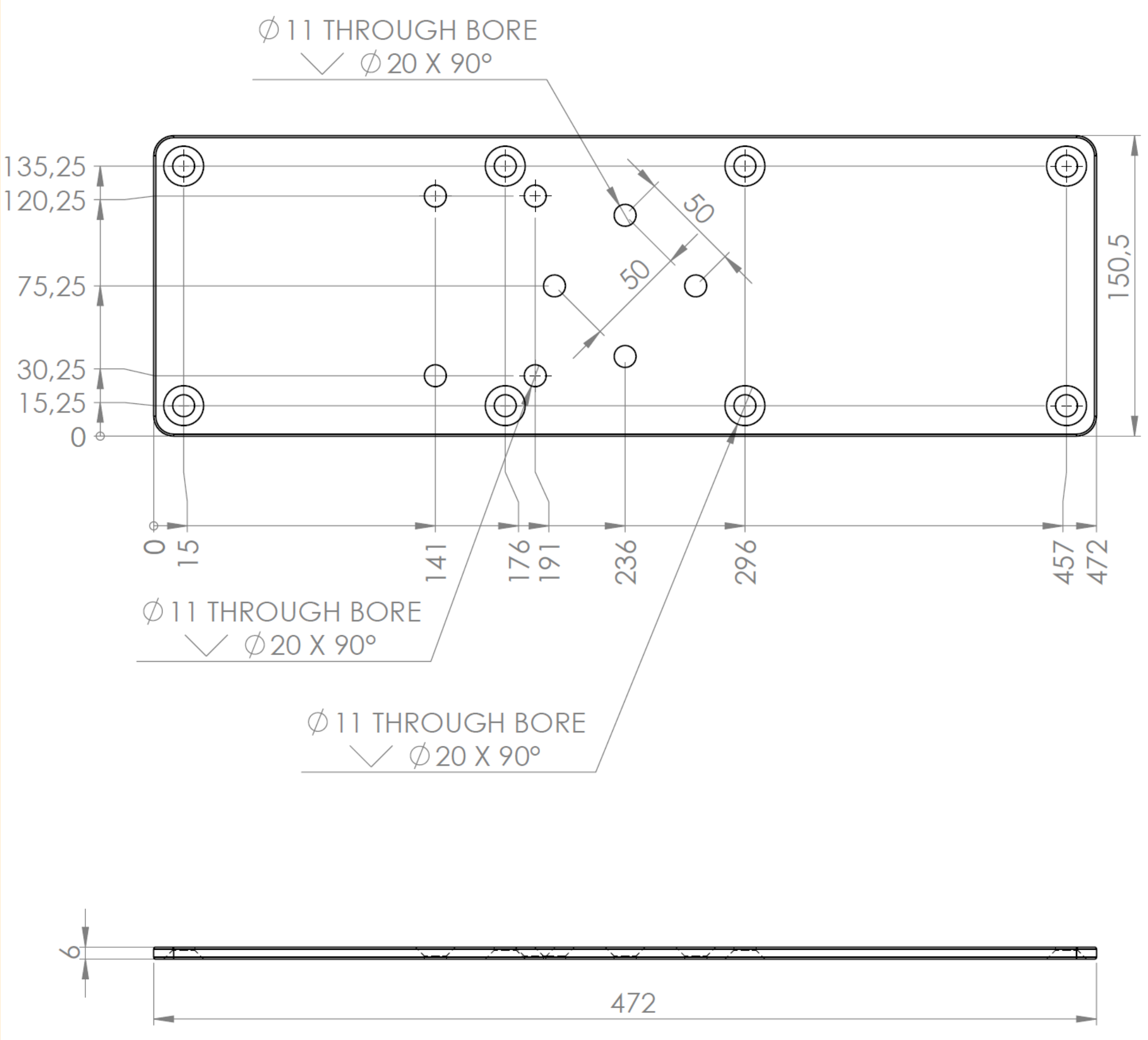


Figure 15_ Interface plate (P/N 60324) for the small V-bracket (Bathyswath-2-STD)

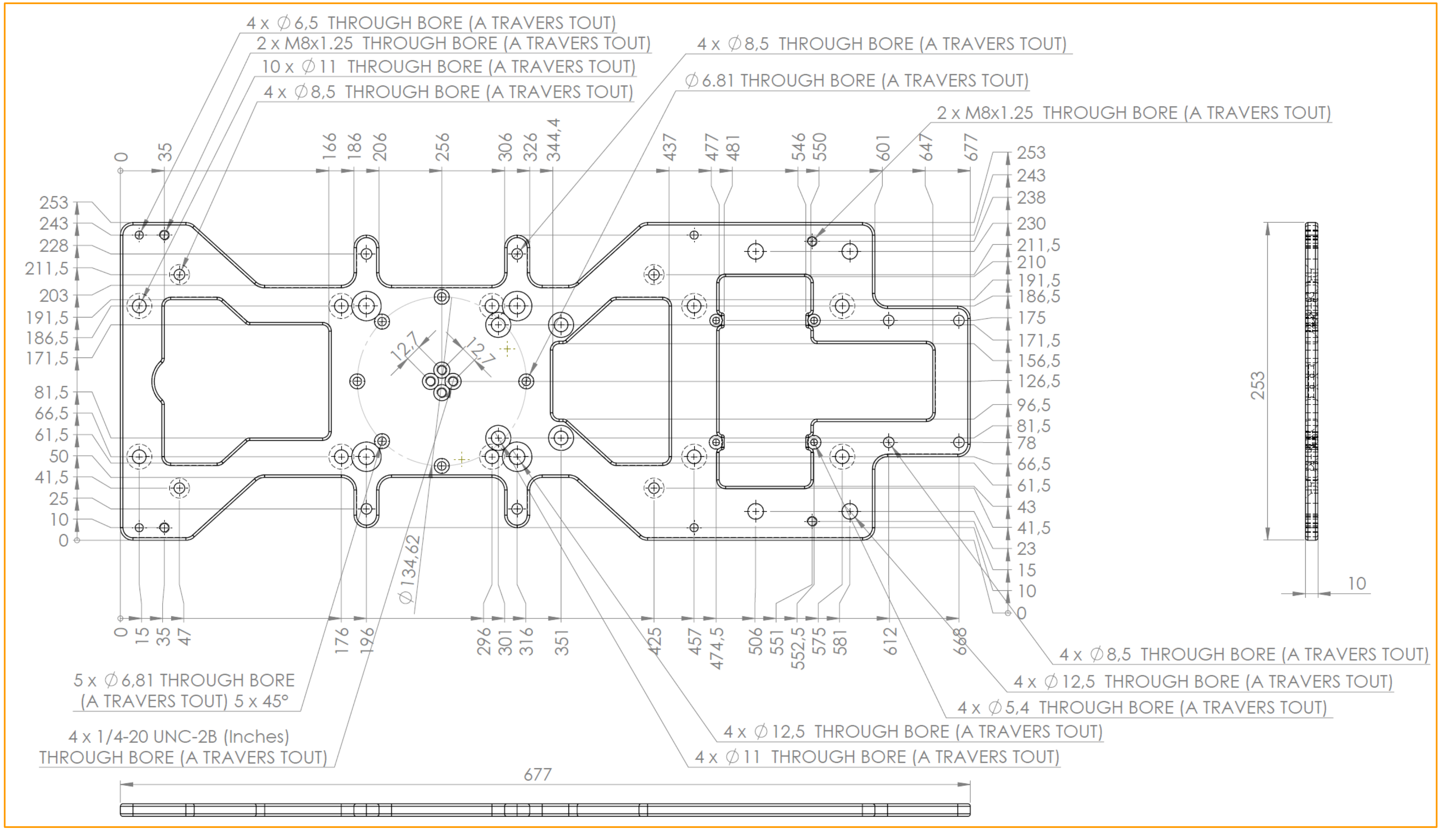


Figure 16_Interface plate (P/N 60318) for the Subsea Unit (Bathyswath-2-UW) or the big V-bracket (Bathyswath-2-STD)

2.3.4 Transducers

Transducer[11]	Length (mm)	Width (mm)	Thickness (mm)	Weight in air (g)
468 kHz	230 (+525)	60	40	902
234 kHz	340 (+525)	100	55	2487
117 kHz	550	200	70 (+1000)	9000

[11] The transducers are 1000m depth rated; It is possible to go to 2000, 4000 or 6000m with some modifications to the design but it will compromise the acoustics a little bit (some sensitivity lost on both transmit and receive)

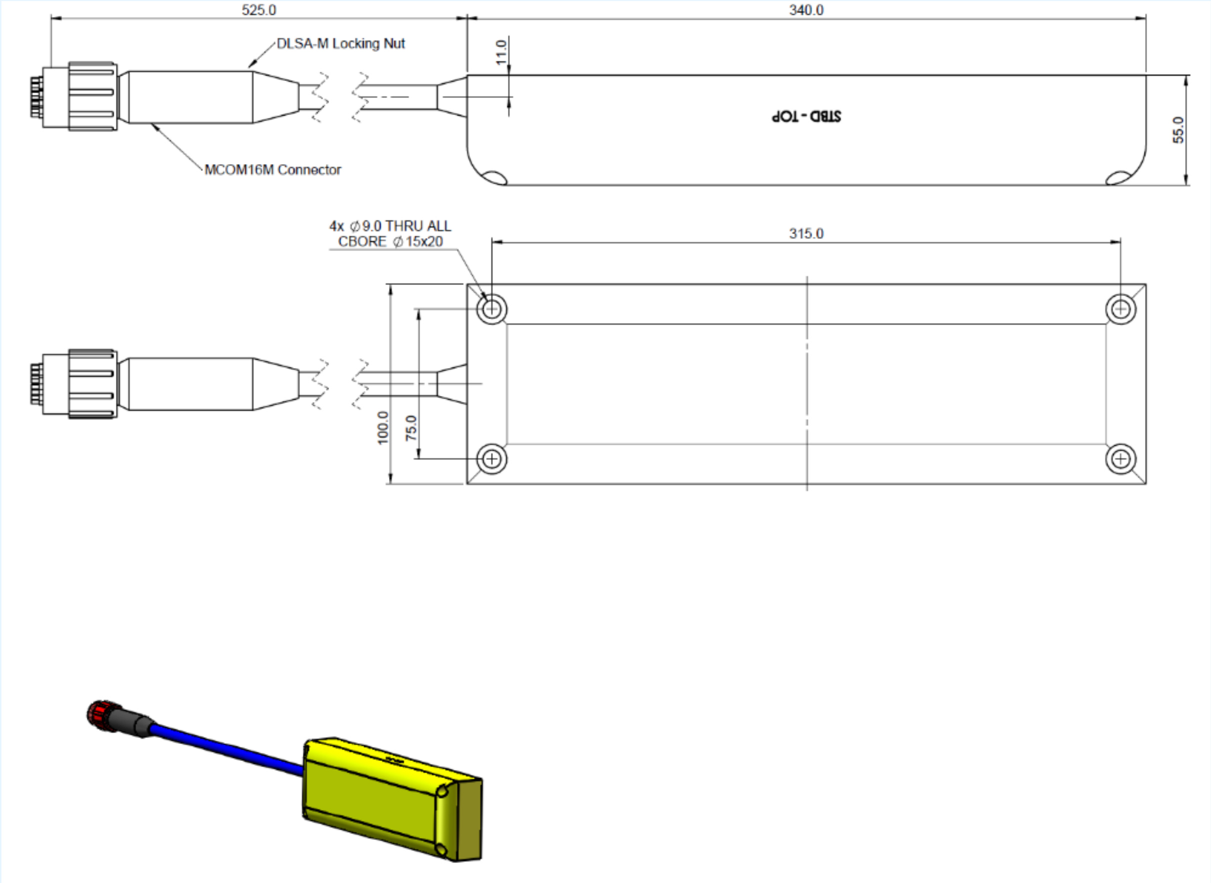


Figure 17_234 kHz transducer

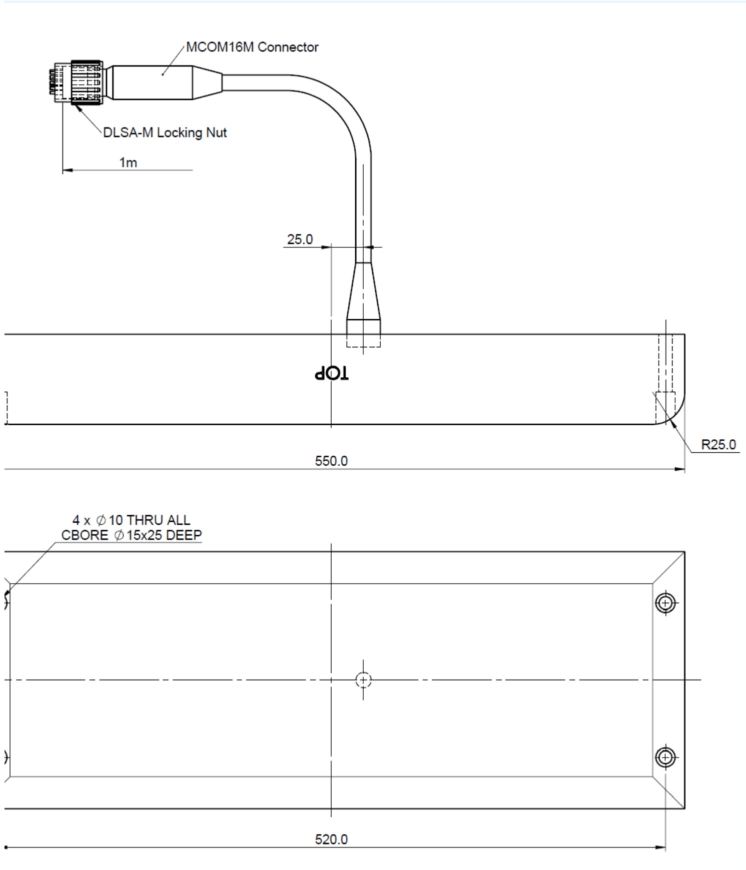


Figure 18_117 kHz transducer

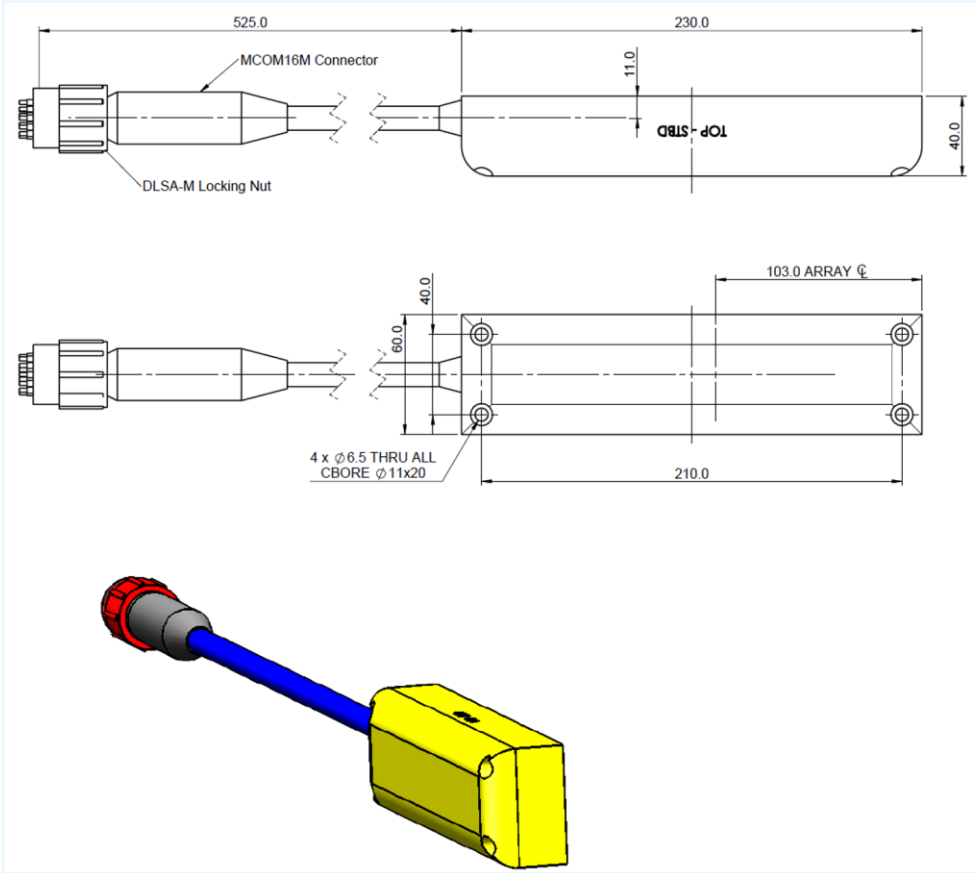


Figure 19_468 kHz transducer

2.4 LEVER ARMS

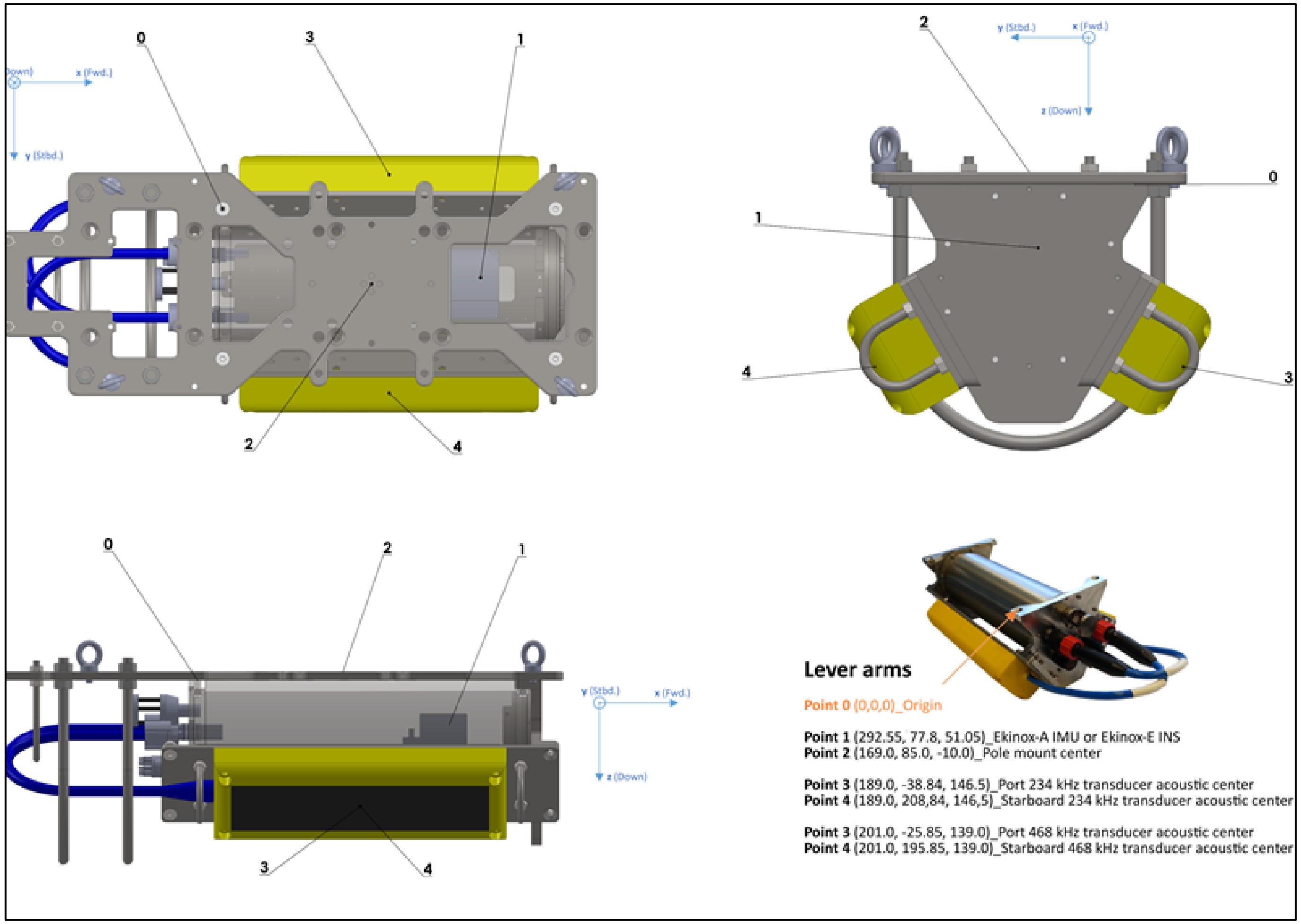


Figure 20_Lever arms with Bathyswath-2-UW

2.5 THE DIFFERENT TYPES OF INSTALLATIONS

2.5.1 Ship hull mount

This type of mount is specific to the user's boat; the V-bracket is not used. It is relatively complicated to implement since it requires significant work on the hull

Figure 21_Ship hull mount with a 1st generation Bathyswath transducer

2.5.2 Installation on the side

ITER Systems can supply on request a "low cost" mount consisting of 50 mm square tubes and COTS fixings. The systems can be moved to a safe stand-by position during high-speed transits.

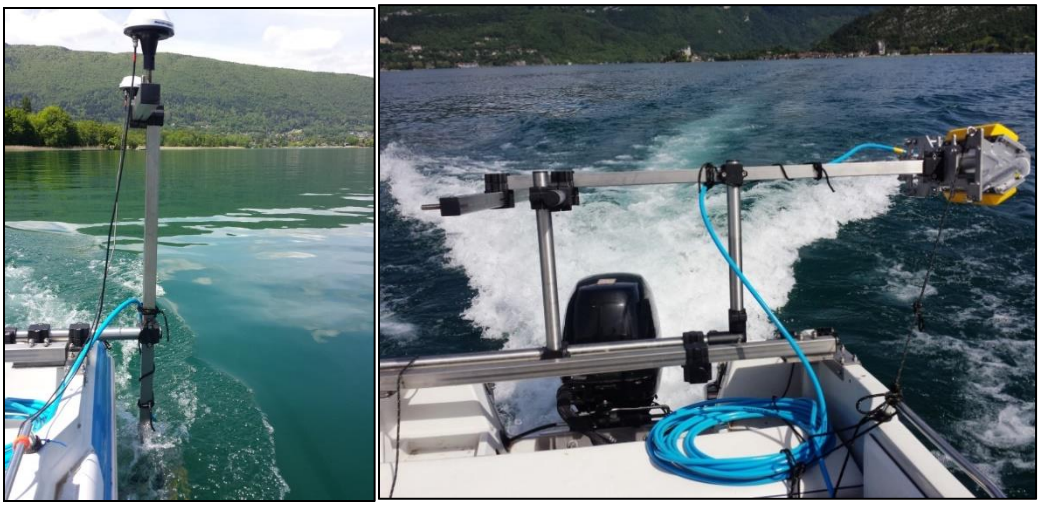


Figure 22_Bathyswath-2-UW side installation

2.5.3 Installation at the bow

This “universal” mount is tied in place with lorry straps, and is quick to deploy on almost any small to medium-sized boat, and requires no modification to the boat. It is therefore convenient when the sonar system must be used on several boats for short periods. However, it is not the best solution when Bathyswath is to be used on one boat, as it is less stable than a side mount or hull mount. It is more expensive than the “low cost” side mount.

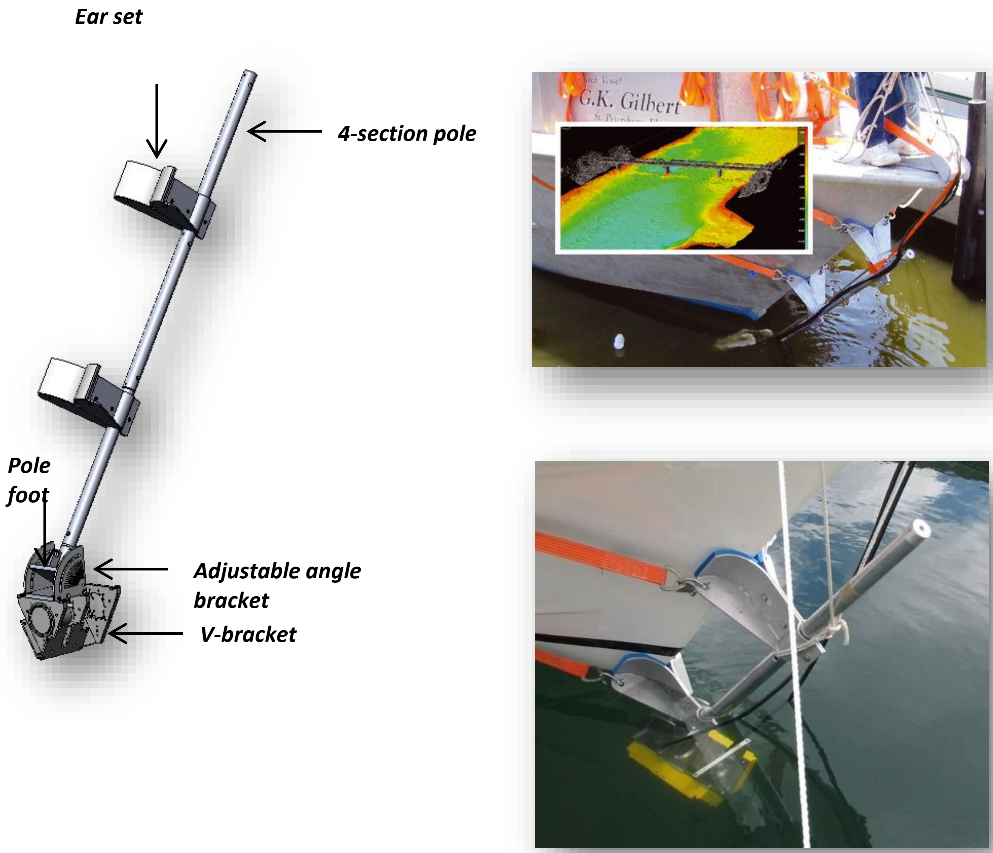


Figure 23_UnIversal bow mounting kit

2.5.4 Installation on a RIB or small boats

Bathyswath-2, thanks to its compactness, can be easily installed on all types of small boats.

ITER Systems can supply on demand a mounting installation that is adapted for RIBs. A wooden plate and 4 wedges in Delrin are installed across the boat and the pole mount can be brought outside the water during high speed transits.

Figure 24_Bathyswath-2-UW on a small RIB

2.5.5 Installation on a USV

Bathyswath-2, thanks to its compactness, can be easily installed on all types of unmanned surface vehicles (USVs) in STD, Omega, UW, or OEM versions, depending on the requirements.

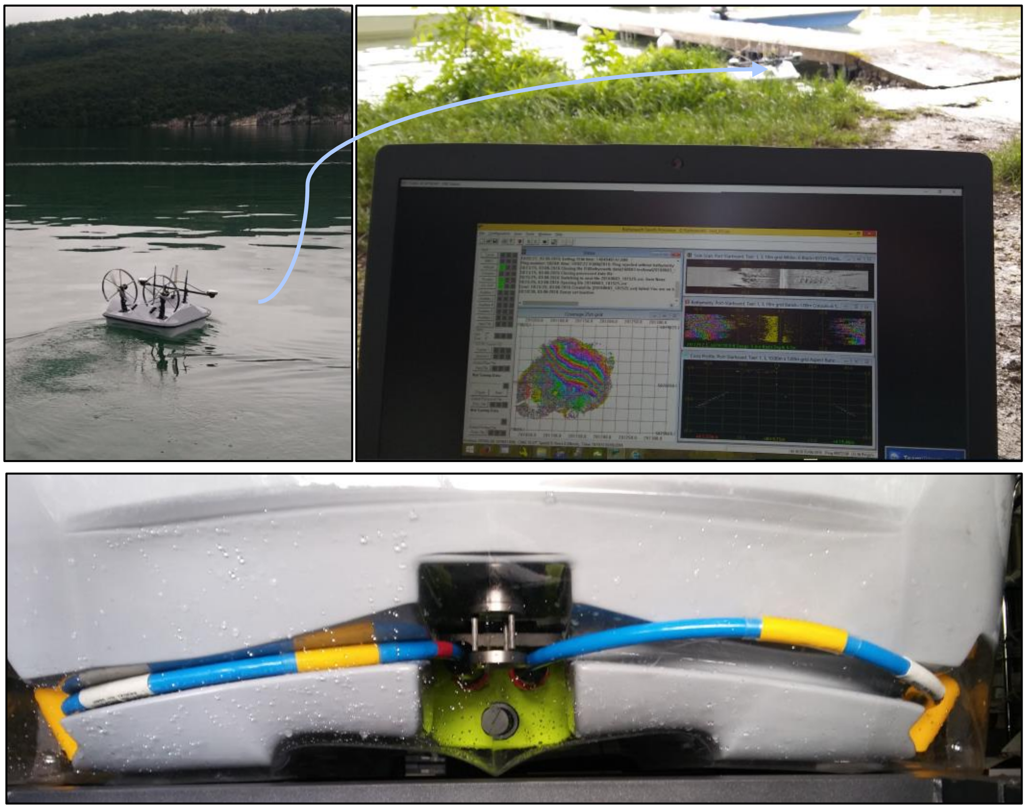


Figure 25_Bathyswath-2-STD on a USV

Figure 26_Bathyswath-2-STD on the ARC-boat USV

2.6 RUGGED TRANSIT SUITCASE

Bathyswath-2-UW and Bathyswath-2-STD systems are delivered in a rugged suitcase.

The customized high-density foam is compatible with both systems. An additional transit suitcase is required if the length of the transducer extension cables or the umbilical is too long.

Figure 27_Transit suitcase with Bathyswath-2-UW

Figure 28_Transit suitcase with Bathyswath-2-STD

2.7 SUMMARY

	Bathyswath-2-STD	Bathyswath-2-UW	Bathyswath-2-OEM
Transducers	1 to 3	1 or 2	1 to 3
Cable extensions	1 to 3	Option	Option
Transducer brackets	Yes	Yes	Option
IP66 Deck Unit	Yes	No	No
Subsea Unit (300m our 3000m)	No	Yes	No
Ekinox INS or IMU	No	Option	No
miniSVS Sound Velocity Sensor	No	Option	No
Umbilical	Option	Yes	No
Spider cable[12]	Yes	Yes	Option
Bathyswath-2 TEM	Yes	Yes	Yes
Bathyswath-2 interface board	Yes	No	Option
Rugged transit suitcase	Yes	Yes	No
Bathyswath software	Yes	Yes	Yes

Tableau 1_Summary of Bathyswath-2 systems

[12] For power, PPS and data

3 GENERAL PRINCIPLE OF OPERATION, ADVANTAGES OF BATHYSWATH

3.1 GENERAL PRINCIPLE OF OPERATION

A swath system is one that sends out sonar signals either side of the ship, in a beam that is wide in the vertical direction but narrow in the horizontal direction. These beams form a "footprint" on the seabed that is a narrow strip at right angles to the direction of travel. As the ship moves forwards, a ribbon-shaped swath of seabed measurements is built up.

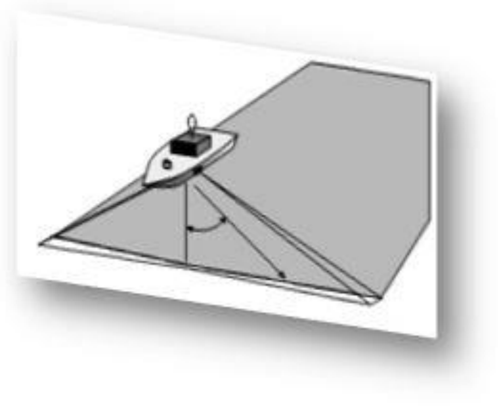
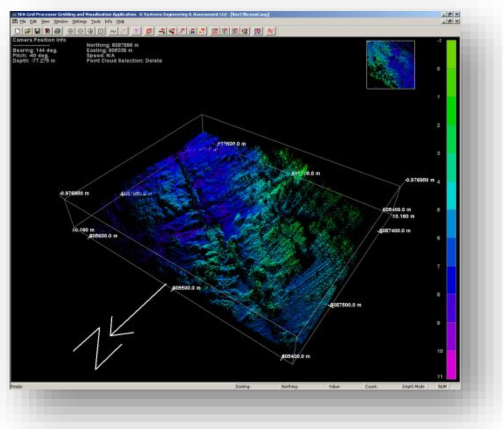


Figure 29 A swath

Bathyswath simultaneously measures two kinds of information: the distance and direction of the echoes from the seabed, and the strength of the signal.

The first is used to measure the depth of the seabed (bathymetry), and the second is used to provide a black-and-white image (sidescan).

For operation from the surface, the transducer(s) may be fixed to the hull of a survey vessel, or to a pole or other portable fixture. By measuring and recording the motion[13] and location of the transducers, the depth information is correctly located with respect to a survey grid system. Displays shown in real time allow the seabed to be inspected while the survey is underway. The post-processing software supplied with the system allows the data recorded during a survey to be processed into a continuous surface for charting in the form of a Digital Terrain Model (DTM).



Additional processing can provide bottom contour charts, individual depth soundings and 3-dimensional views of the data set (point clouds). In addition, the attributes of sonar reflectivity may be 'draped' onto these views or used to compute the bottom material encountered.

[13] Heading, heave, pitch and roll

3.2 INTERFEROMETRY

A “swath-sounding” sonar system is one that is used to measure the water depth in a line extending outwards from the sonar transducer. Such systems are generally arranged so that the line of depths, or “profile”, lies at right angles to the direction of motion of the transducer. A series of these profiles are known as a swath.

The term “interferometry” is generally used to describe swath-sounding sonar techniques that use the phase content of the sonar signal to measure the angle of a wave front returned from a sonar target. Systems using this technique are also known as Phase Differencing Bathymetric Systems, or PDBS. This technique may be contrasted with “beamforming” multi-beam echosounder sonars (MBES).

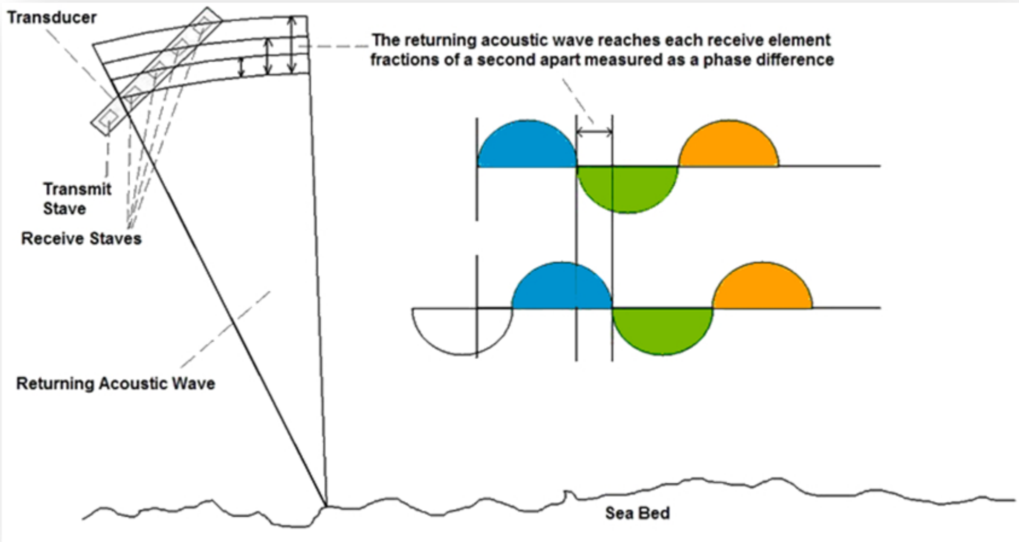


Figure 30_ Interferometry or as Phase Differencing Bathymetric Systems

These generate a set of receive beams, and look for an amplitude peak on each beam to detect the seabed (or other targets) across the swath. See below for a comparison between beamformers and Bathyswath.

Interferometers themselves fall into several categories. All these use similar transducer geometry: two or more horizontal arrays (or “staves”) arranged one above the other. Each array is equivalent to a “normal” sidescan array, producing a beam that is narrow in azimuth (that is, viewed from above), and wide in elevation (viewed from the side). One of these arrays is supplied with a pulse of electrical energy at the sonar frequency, producing a narrow “shell” of sound that moves outwards from the transducer.

Where this shell meets the seabed there is a small "ensonified" patch, which moves across the seabed as the sound travels outwards. The ensonified patch scatters sound energy in all directions. When this scattered sound is detected back at the interferometric transducers, the angle it makes with the transducer is measured. The range is calculated from the travel time there-and-back. The range and angle pair enables the location of the ensonified seabed patch to be known relative to the sonar transducer.

Bathyswath measures the phase of the measured signal at each of the transducer staves relative to a reference signal at the system's sonar frequency. The phase difference between the staves is derived by subtracting these phase measurements from each other. The phase is derived from a simple and robust electronic method, which directly provides a digital measurement of phase. The electronics are thus kept simple and therefore small and reliable. Wavefront angle is calculated from a simple formula relating phase and transducer spacing measured in wavelengths.

To measure the angle accurately, more than one pair of staves must be used. Narrow spacings give an unambiguous measurement of angle, but are more susceptible to noise and give poor resolution. Wide spacings give good resolution and noise immunity, but any one-phase measurement from them can decode to several elevation angles. To overcome these restrictions Bathyswath uses a range of spacings to obtain the best results. The combinations of spacings are used in a manner like that used by a mechanical Vernier measuring device.

3.3 ADVANTAGES OF BATHYSWATH

Bathyswath not only provides the benefits associated with other swath bathymetry sonars, but also it has several unique advantages, indicated below

3.3.1 Wide swath width and high productivity

Bathyswath measures depths across a wide track[14], giving high resolution. For instance, with a 234 kHz system and 100m average water depth, a survey at 3 knots[15] can easily cover 500m² per second.

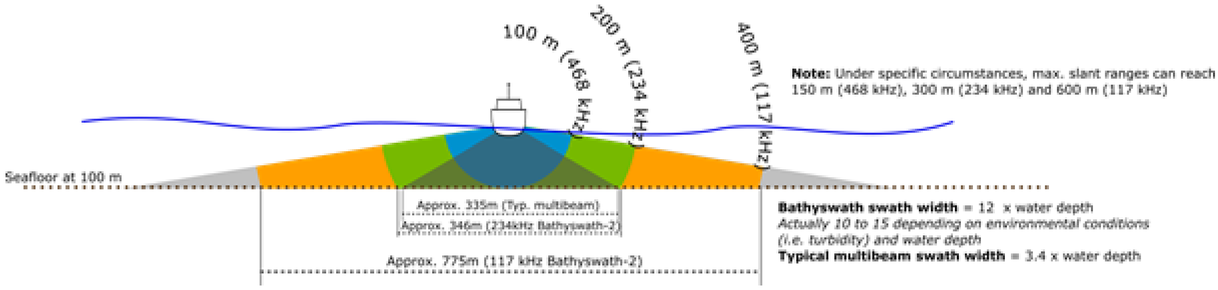


Figure 31_Swath width at 100 m water depth

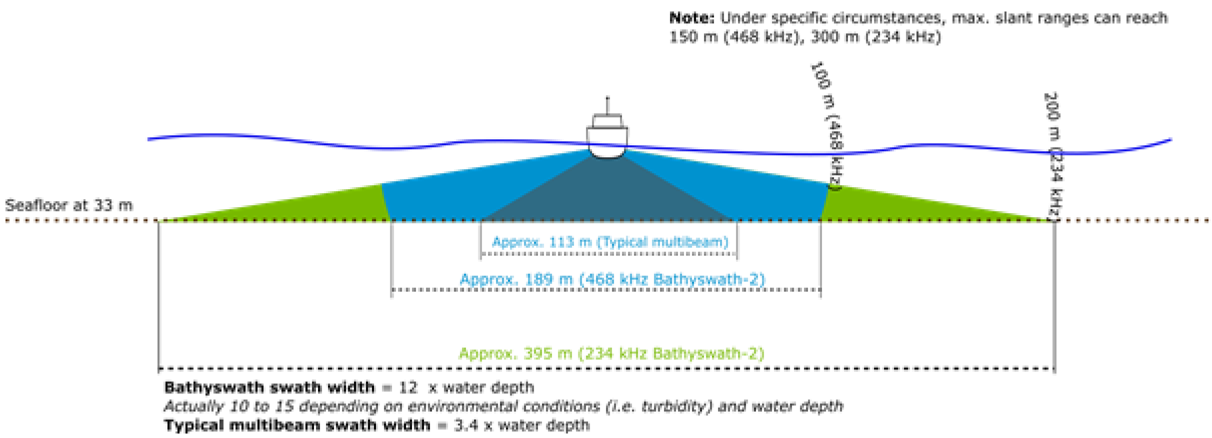


Figure 32_Swath width at 33m water depth

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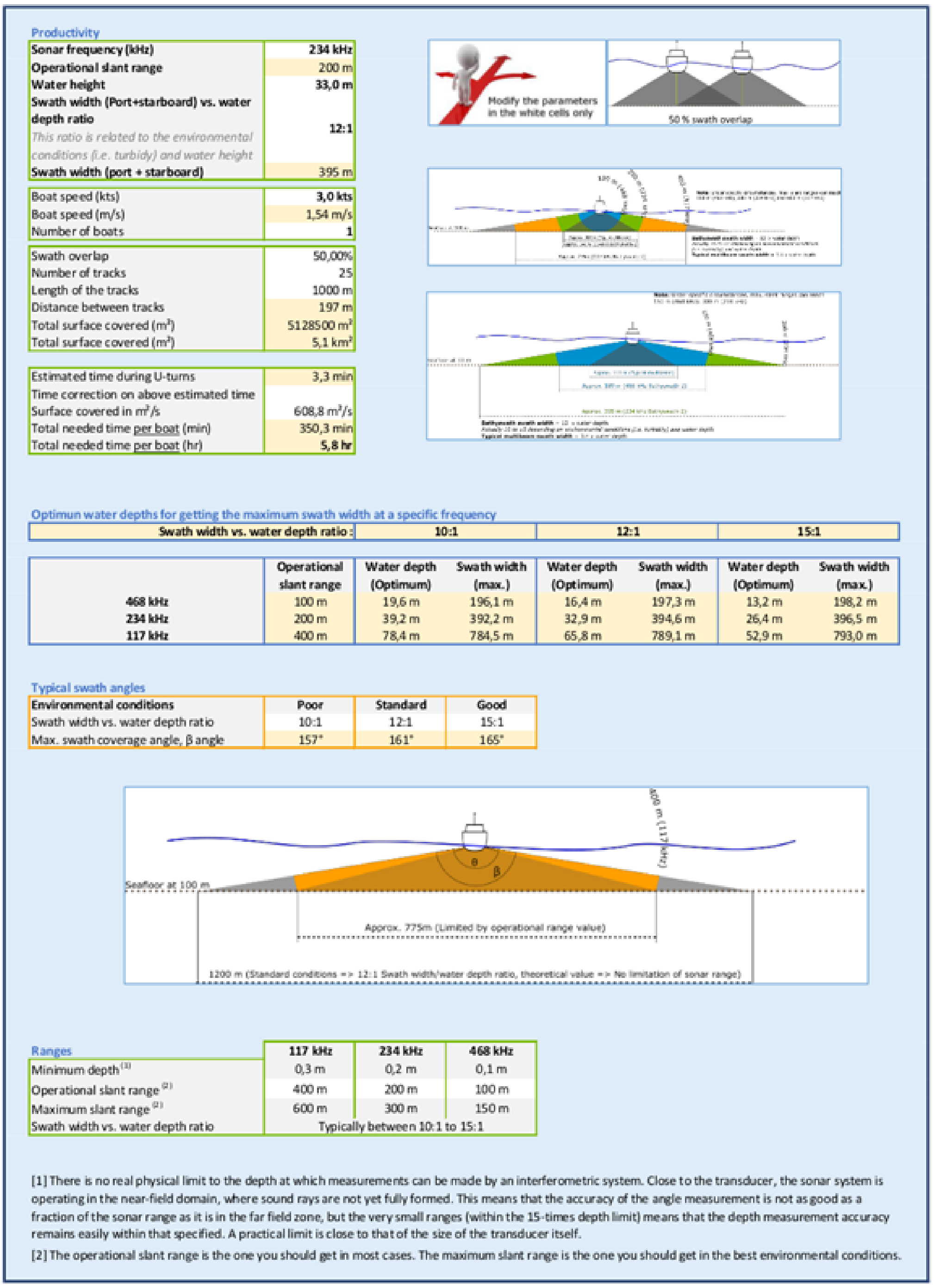
14 This allows to do the survey much faster than standard multibeam systems

15 Usual survey speed

The following productivity calculation worksheet shows that a 234 kHz Bathyswath system can survey a 5 square km area in 33m of water depth in roughly half a day including turns and 50 % overlap.



Productivity

Sonar frequency (kHz)	234 kHz
Operational slant range	200 m
Water height	33,0 m
Swath width (Port+starboard) vs. water depth ratio *This ratio is related to the environmental conditions (i.e. turbidy) and water height*	12:1
Swath width (port + starboard)	395 m
Boat speed (kts)	3,0 kts
Boat speed (m/s)	1,54 m/s
Number of boats	1
Swath overlap	50,00%
Number of tracks	25
Length of the tracks	1000 m
Distance between tracks	197 m
Total surface covered (m²)	5128500 m²
Total surface covered (m²)	5,1 km²
Estimated time during U-turns	3,3 min
Time correction on above estimated time	
Surface covered in m²/s	608,8 m²/s
Total needed time per boat (min)	350,3 min
Total needed time per boat (hr)	5,8 hr

Optimun water depths for getting the maximum swath width at a specific frequency

Swath width vs. water depth ratio :	Operational slant range	10:1 Water depth (Optimum)	10:1 Swath width (max.)	12:1 Water depth (Optimum)	12:1 Swath width (max.)	15:1 Water depth (Optimum)	15:1 Swath width (max.)
468 kHz	100 m	19,6 m	196,1 m	16,4 m	197,3 m	13,2 m	198,2 m
234 kHz	200 m	39,2 m	392,2 m	32,9 m	394,6 m	26,4 m	396,5 m
117 kHz	400 m	78,4 m	784,5 m	65,8 m	789,1 m	52,9 m	793,0 m

Typical swath angles

Environmental conditions	Poor	Standard	Good
Swath width vs. water depth ratio	10:1	12:1	15:1
Max. swath coverage angle, β angle	157°	161°	165°

Ranges	117 kHz	234 kHz	468 kHz
Minimum depth [1]	0,3 m	0,2 m	0,1 m
Operational slant range [2]	400 m	200 m	100 m
Maximum slant range [2]	600 m	300 m	150 m
Swath width vs. water depth ratio	Typically between 10:1 to 15:1		

[1] There is no real physical limit to the depth at which measurements can be made by an interferometric system. Close to the transducer, the sonar system is operating in the near-field domain, where sound rays are not yet fully formed. This means that the accuracy of the angle measurement is not as good as a fraction of the sonar range as it is in the far field zone, but the very small ranges (within the 15-times depth limit) means that the depth measurement accuracy remains easily within that specified. A practical limit is close to that of the size of the transducer itself.

[2] The operational slant range is the one you should get in most cases. The maximum slant range is the one you should get in the best environmental conditions.

Figure 33_Bathyswath productivity[16]

[16] The worksheet is available on Bathyswath website

3.3.2 Simultaneous pinging

Bathyswath provides the option to ping on both port and starboard transducers simultaneously, thus offering the ability to double the productivity and along-track coverage.

3.3.3 Portability

Bathyswath may be configured as a portable system, which means that it may be deployed from almost any vessel. This eliminates the need for expensive modifications to survey vessels, with the associated tying-up of capital investment in a single vessel, and allows the system to be transported anywhere in the world.

Bathyswath can be used with laptop computers, with electronic components weighing a few kilograms and taking power of less than 20 W.

Bathyswath-2-STD and -Omega can be transported by air in the operator's checked-in luggage, usually without needing to pay for excess baggage.

No special export licences (such as military "dual use") are needed.

3.3.4 High Resolution and Accuracy

Compared with beamforming swath sounding systems, Bathyswath takes many more depth measurements per hour, thus giving greater resolution and coverage, and allowing greater scope for statistical filtering of the measurements. Furthermore, the angle at which depths may be measured is not limited to a fixed arc, so that much wider coverage can be obtained in shallow water, even allowing measurements to be made of shoreline structures. A beamformer suffers from poor resolution at far range, where the footprint of its beams is very large due to the small strike angle with the seabed. Bathyswath avoids this problem, as the area of the energized patch of seabed does not increase dramatically as it moves away from the transducers.

3.3.5 Simultaneous Side Scan

Bathyswath produces high quality side scan data as well as bathymetry. The range of the side scan data is the same as that from sidescan-only systems.

The sidescan information helps with the interpretation and processing of bathymetric data, and the bathymetry enables the sidescan information to be correctly located on the seabed, avoiding the usual "flat seabed" approximation used in sidescan-only systems.

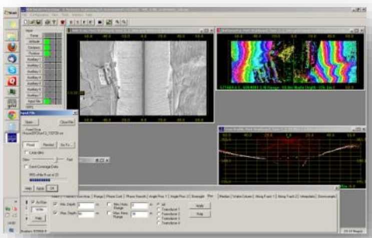


Figure 34 Bathyswath software screen showing simultaneous bathymetry and sidescan

3.3.6 Mid-water Objects and Structures

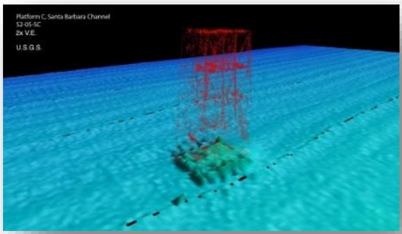


Figure 35_Mid-water structures (courtesy USGS)

Bathyswath can detect objects in mid-water and on the surface, as well as the bottom. The Bathyswath processing software allows such objects to be mapped and visualized in 3D. The high resolution of the system makes it ideal for this application. Measuring the amplitude of return as well as bathymetry allows small, hard, mid-water targets to be differentiated from “noise”.

3.3.7 Low Cost of Ownership

3.3.7.1 Hardware

The simplicity of the system results in a lower initial purchase price, high reliability, virtually zero maintenance and long service life. The compactness and ease of installation of the system also induce low costs of mobilization and demobilization.

3.3.7.2 Software

Each Bathyswath system comes with a software suite running on Windows and/or Linux for real time data acquisition and post processing. The license is unlimited.

3.4 MAIN INFORMATION REQUIRED BY THE SYSTEM

3.4.1 Motion sensors and position

Swath bathymetry requires that the full motion[17] of the platform be recorded. The essential parameters are roll, pitch, height, heading and position. Bathyswath is fully compatible with motion reference units (INS or MRU) from, amongst others, SBG-Systems, Trimble, SMC, Applanix, CodaOctopus, IXblue, Kongsberg, SBG Systems and TSS.

The position of the sonar sensor also needs to be measured. Bathyswath interfaces to a wide range of position sensors. Most such sensors are based on GNSS. Some sensor systems provide motion (attitude), heading and position as an integrated package.

Positioning information is accepted in both angular (latitude and longitude) format and grid projection (easting and northing). A range of conversion parameters and ellipsoids is available to the operator. A remote platform will often collect its own attitude and position data and pass it on to the Bathyswath system using an interface port.

Dual antenna GNSS receivers are recommended to give heading.

3.4.2 Speed of sound

Bathyswath provides interfaces to both a speed of sound profiler and a continuous reading speed of sound meter. The profiler is used by the surveyor at suitable intervals to measure speed of sound at intervals of depth. This is used by the system software to correct for refraction of the sound as it passes between layers of water with different sound speeds. The continuous reading meter is mounted near the sonar transducers. It ensures that the sound signals are correctly converted to measurements of angle. The profiler is essential, but the continuous reading meter is only necessary if the speed of sound at the surface changes strongly within the survey area.

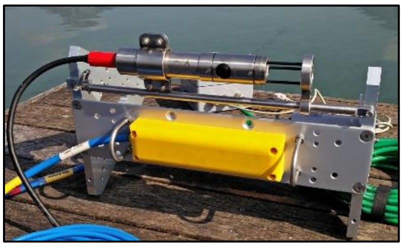


Figure 36_Continuous reading SVS[18]

Figure 37_Continuous reading SVS[19]

[17] Also known as attitude

[18] Bathyswath-2-STD configuration, miniSVS on a big V-bracket

[19] Bathyswath-2-UW configuration, miniSVS-OEM integrated in the Subsea Unit (SU)

3.4.3 Tide and vertical position

To relate the depths measured by the sonar system to a chart datum height, for example, LLWS (lowest low water springs) sea level, or position height datum (e.g. WGS-84) the height of the sensor needs to be measured in real time. Bathyswath supports two ways of doing this:

- Tide measurements: the height of the sensors relative to the water surface is measured, using measuring tape or equivalent methods, and entered as an offset in software. The height of the water surface relative to datum, against time, (i.e., a tide table) is recorded and entered into the processing software. This tide information can come either from recording or real-time tide sensors, or from published tide tables. For accurate work in inshore waters, more than one tide sensor is needed, including offshore tide buoys. The Bathyswath software can integrate between such multiple tide sensors in both position and time.
- GNSS (GPS) height measurements: if the positioning system can provide height information at the accuracy required by the users' application, then this information can be used in processing instead of tide. However, uncorrected GPS and differential GPS (DGPS) systems do not usually provide height to sufficient accuracy; a system such as real-time kinematic (RTK) correction or post-processed correction (PPK) is needed.

In either case, heave measurements from the motion sensor are merged with the height measurements in the Swath software.

3.5 OTHER FEATURES

3.5.1 Other sensors

Bathyswath provides interfaces to a range of other sensors and systems. These include:

- An arbitrary data stream, which is time-tagged and logged with the sonar data. The information in this stream can be extracted and used for the operator's own purposes during post-processing.
- Echosounders: data outputs from single-beam echosounders can be logged by the Bathyswath software. The depth information from the echosounder can be corrected for motion and position, and placed in the gridded depth model for comparison or inclusion with the swath data.
- Tide: on-line tide information can be logged and used for processing.

Acoustic pulse triggering is possible to and from other sonar systems, to minimize acoustic "cross-talk".

3.5.2 External control

Bathyswath can be controlled by external systems, either through an RS232 serial line or by TCP/IP or UDP/IP data packets. This is used in remote systems, such as USVs, AUVs and ROVs.

3.5.3 Standardised raw data output

In real-time, Bathyswath data is recorded in both a generic data format, and as 'end product' files. The latter file format is selected to suit the post-processing system chosen. The Processing/QA off-line software can export data in x,y,z and gridded digital terrain model (DTM) formats, and as depth-and-contour graphics. These outputs are available in common formats, including ASCII.

3.5.4 Patch test calibration

The system software includes support for automatic patch-test calibration, which uses data from overlapping survey lines to determine the precise mounting angles of the transducers, and other similar correction factors.

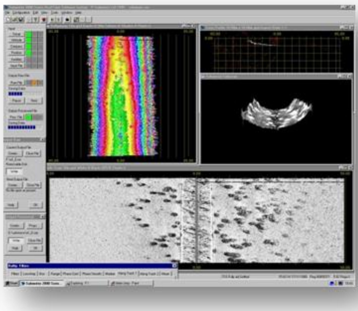
3.5.5 Sounding repetition rate

The user may set the rate at which soundings are taken, on-line. This has the effect of changing the range of the data collection. Swath width is approximately twice this range when using a twin transducer system. A 300m range corresponds to a ping repetition frequency (PRF) of around 2.5Hz (times per second). A 70m range gives a PRF of 10.7Hz. The time to gather a full swath at a given nominal range depends on the speed of sound. The operator can select the PRF required to maximize along-track coverage for the required swath width.

3.5.6 Wreck and object detection

The imaging function of Bathyswath allows the operator to detect and identify objects on the seabed, including wrecks. The use of sidescan and colour-coded swath bathymetry displayed coincidently is an extremely powerful tool for this task.

The links to commercial sidescan processors referred to above also provide the opportunity for extended capabilities in this area.



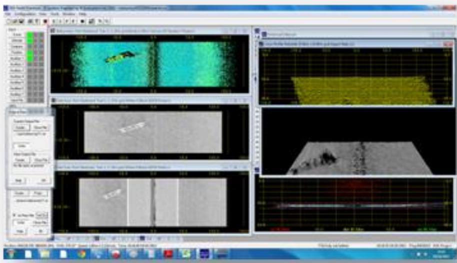


Figure 38_Detection of objects on the seafloor

3.5.7 Seafloor sediment classification

The combination of swath bathymetry and sidescan imaging helps the operator to classify the types of seabed being surveyed.

3.5.8 Integration with surface laser scanners

Bathyswath has been successfully integrated with laser scanning systems, with excellent results. Further information can be provided on request.

Figure 39_Livorno Castle Moat[20]

[20] Courtesy Codevintec (Italy), underwater data from Bathyswath and surface data from OPTECH ILRIS

4 SOFTWARE

4.1 INTRODUCTION

Bathyswath acquires, processes, and displays data whilst a survey is underway, using a program called “Swath Processor”. This also allows for control and set-up of the system, and gives error diagnostic information. The software stores data in two forms: ‘raw’ and ‘processed’. The raw data is exactly as it was acquired by the system, unfiltered and unprocessed. The processed data is filtered, and then written out in a file format that suits the post processing system being used.

Post processing software converts the data acquired in real-time into Digital Depth Models. These depth models are used to produce displays and plots of the surveyed area. Users may use Bathyswath post processing software, or a third-party program, to suit their application.

The Swath Processor program is used to provide the first pass of post-processing when using the Bathyswath software. It reads its own raw data files, and produces processed data files. The second pass of the post-processing converts the processed swath data files into Digital Terrain Models. This program is called “Grid Processor”. It also allows 3D visualization, filtering, data correction and calibration functions.

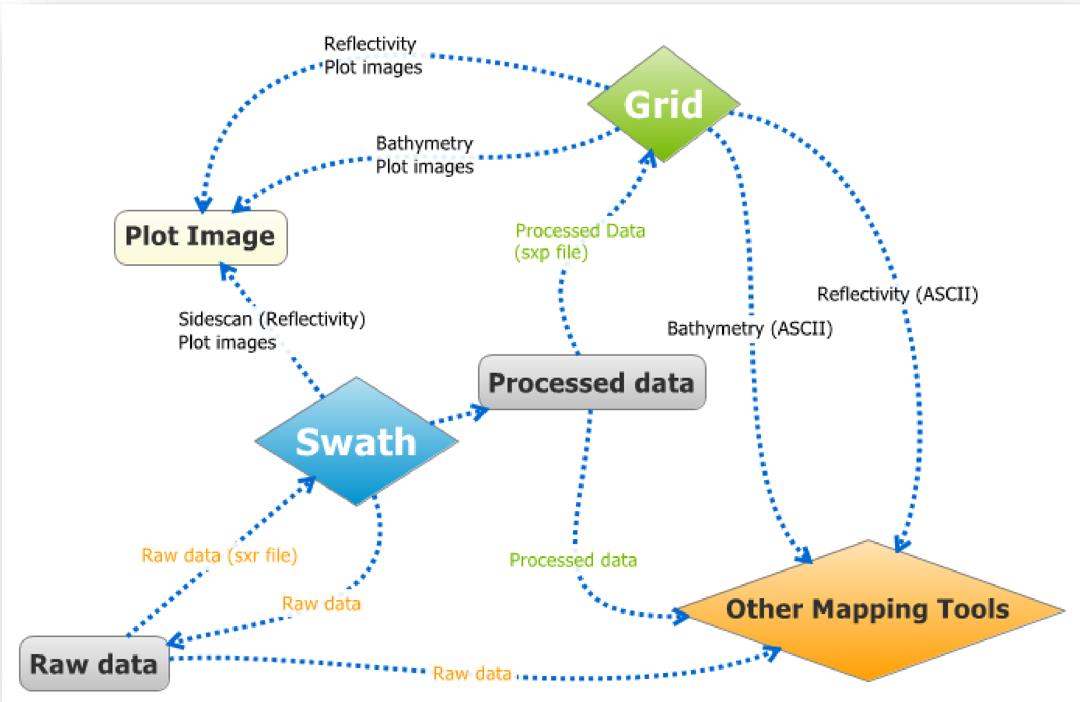


Figure 40_Bathyswath software tool flow

4.2 SWATH PROCESSOR DATA ACQUISITION SOFTWARE

Swath Processor runs on a PC and performs all the real-time functions. These include:

- Controlling the sonar electronics system,
- Acquiring data from the sonar electronics system,
- Acquiring data from the auxiliary systems,
- Storing all the raw data,
- Converting the raw data to depth, position, and amplitude [xyza], combining auxiliary data, such as motion, position, heading and speed of sound.
- Filtering the data to remove noise and unwanted targets,
- Displaying the data,
- Storing processed [xyza] data in a range of formats.

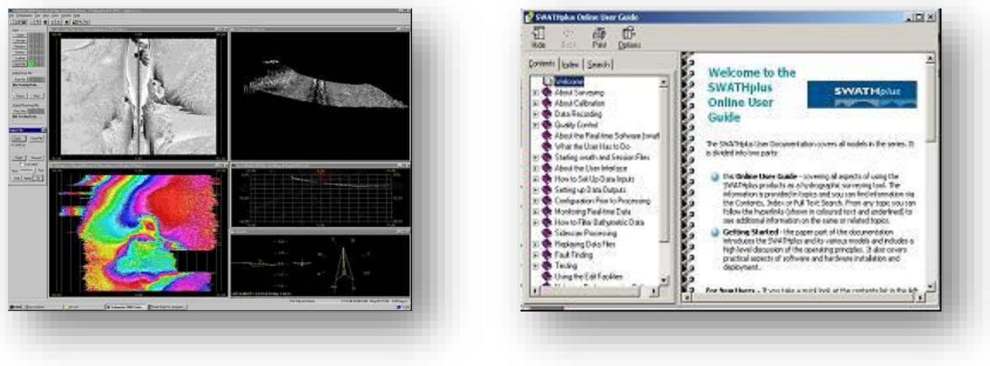


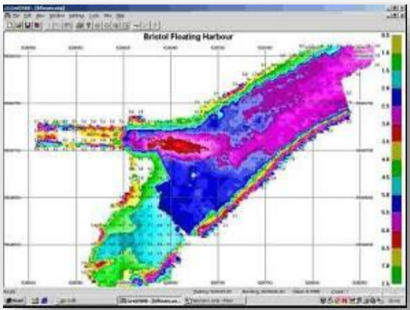
Figure 41_Swath Processor screen image and its online help facility

All these functions are controlled by the operator using parameters that are stored in a "session file". This allows the operator to store the parameters used on a particular project. In addition, the configuration parameters used to generate a particular processed data set are automatically stored in the processed data file. This feature is only available in the Bathyswath processed data file format. There is an extensive context-sensitive software help system to assist the user with all aspects of using the Bathyswath.

4.3 GRID PROCESSOR POST-PROCESSING SOFTWARE

The Grid Processor program runs off-line, either after the survey on the survey PC, or on a separate PC. It performs the following functions:

- Placing all the processed data (depth and amplitude) into a gridded digital terrain model (DTM).
- Displaying depth and amplitude for each node of the grid.
- Displaying statistical information about the depths in each node of the grid, including mean, standard deviation, range, and data count.
- The data for each ping and line of the survey are stored separately in the grid, allowing simple comparison of overlapping data sets.
- The data from overlapping survey lines is compared to provide automatic post processing calibration. This includes derivation of the roll offset between transducers. This calibration information is stored in the session file for subsequent re-processing of the raw data with Swath Processor.
- Filtering and removing the data in the grid, to enable the operator to quickly and easily clean and correct the processed data.
- 3D views of the data in the grid, allowing the operator to see the seabed in three dimensions and to "fly" across the seabed using the mouse or in pre-defined routes. The grid can be edited in the 3D mode, using the mouse to "lasso" points and groups of points that are not required, for example mid-water targets.



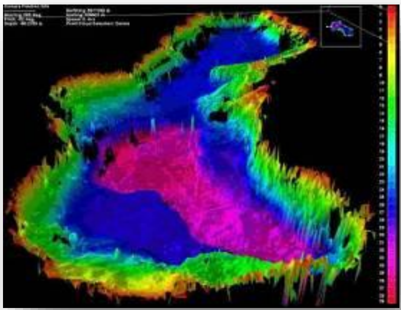


Figure 42_Grid Processor 2D & 3D displays

Grid data can be stored in "point cloud" format. In this mode, every data point from Swath Processor is retained in the grid. Although memory-intensive, this allows for high-resolution views. In this mode, the views are not restricted to a single surface, and so complex objects and mid-water targets can be imaged.

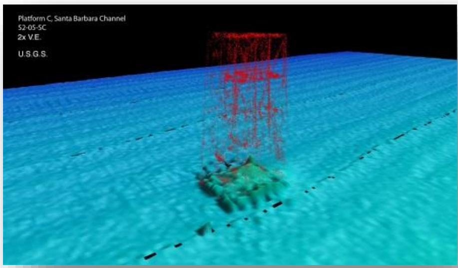


Figure 43_Data acquired in the water volume[21]

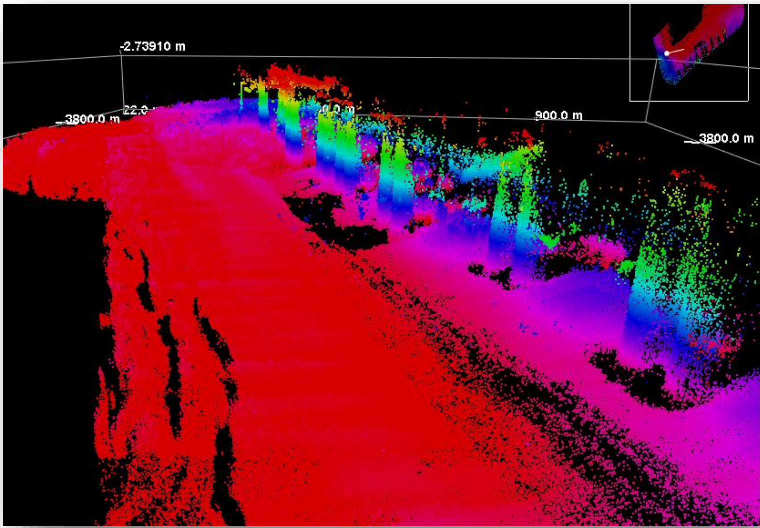


Figure 44_Piles of a jetty[22]

[21] USGS; United States Geological Survey
[22] Bathyswath-2-STD (468 kHz), India 2015

4.4 SWATHRT LINUX DATA ACQUISITION SOFTWARE

A data acquisition software package called swathRT is available for compilation on most operating systems, including Linux and Windows. It is much more “lightweight” than Swath Processor, and so is ideal for use on small unmanned and autonomous vehicles. It performs the following functions:

- Controlling the Bathyswath hardware
- Collecting raw data and storing it to disk or memory card
- Limited data processing, to provide the vehicle’s control systems with range and angle data if required
- Receiving commands from external control systems, using UDP packets
- Sending a subset of the data to external visualisation software (including Swath Processor) over a UDP link. This can be used, for example, to monitor the progress of a survey on a USV.

4.5 DATA PROCESSING TIME

Given an experienced operator and available secondary data, the processing time requirement for Bathyswath does not exceed 100% of acquisition time for a normal survey. At no stage in data manipulation is the raw data file modified. An audit file is available to quickly indicate which processing and calibration parameters have been applied to create the processed file.

4.6 DATA FORMATS

The Bathyswath data file format description is open and described in the Bathyswath File Formats document. In addition, source code fragments, example programs and technical advice are provided to developers and users who wish to exploit the Bathyswath data in their own software tools. Swath Processor can output in standard file formats, including ASCII, S7K, GSF and XTF.

4.7 SIDESCAN AMPLITUDE DATA

Sidescan sonar data is stored in the Bathyswath raw data before any normalization is applied. The sonar raw data includes the full time series of amplitudes and phases from each ping at a user selectable sample rate. All the data is recorded for each shot (i.e. everything from the trigger to the end of the swath) to allow for full reprocessing of the data. The system applies software normalization (TVG) to the data and displays the results (as well as recording the raw data) in real-time, and the sidescan can be replayed and reprocessed during post processing.

This feature, together with the angular measurements and auxiliary sensor data, allows the full sonar equation to be solved, thus permitting the acoustic properties of the seabed to be analysed for research and mapping purposes.

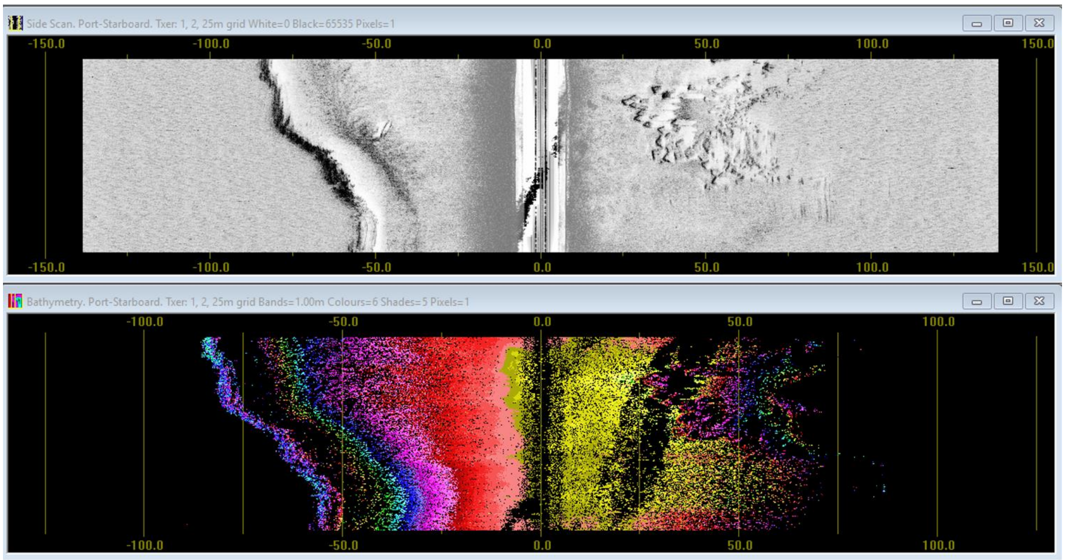


Figure 45_Bathyswath-2-STD (468 kHz) Concrete blocks at the entrance of the harbour[23]

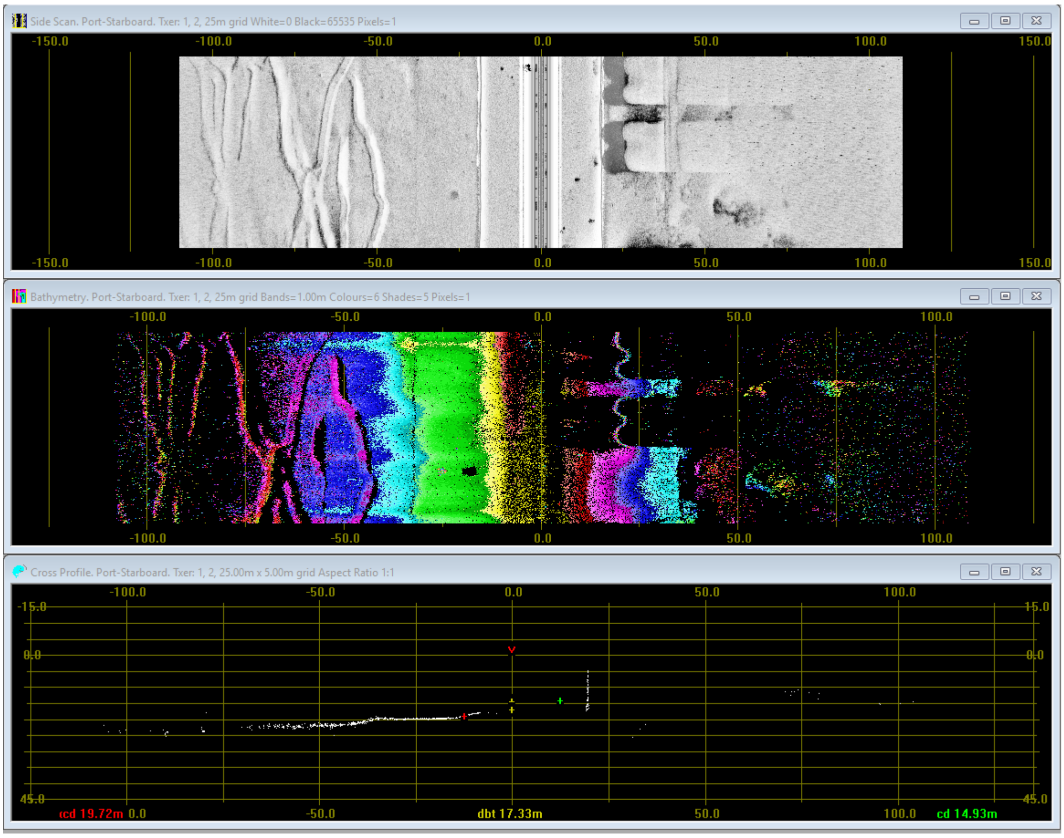


Figure 46_Traces on the seabed on port side and piles on starboard side[24]

[23] India, 2015
[24] India, 2015

4.8 OTHER SOFTWARE SYSTEMS

4.8.1 Third party software

The community of Bathyswath sonar users encompasses a very wide range of operational requirements. Although the Bathyswath software provides a comprehensive set of functions, it naturally cannot exactly match the needs of every one of these users. Therefore, Bathyswath has provided links to many of the industry-standard software packages available today. The following list gives some of the systems that have been used with Bathyswath sonars. The list of systems that are supported is growing. Most systems not on this list will also read in one or more of the standard file formats that the software provides.

Program	Developer	Notes
ARC	ESRI	GIS (Geographic Information System)
AutoCAD	Autodesk	Producing CAD-type plots. Integrate other survey data, such as coastlines obtained from land surveys.
CARIS HIPS & SIPS	CARIS	Comprehensive bathymetric, seafloor imagery and water column data processing software.
Cfloor	Cfloor	A long-standing bathymetry processing system.
EIVA	EIVA	Navigation and survey planning/ survey processing/ charting package.
Fledermaus	QPS	Interactive 3D geo-spatial processing and analysis tool
GeoSurvey	CodaOctopus	Sidescan processing and mosaicking software
HydroPro Navigation	Trimble	Navigation and survey planning/ survey processing/ charting package.
Hypack	Hypack	Navigation and survey planning/ survey processing/ charting package.
PDS	Teledyne	Originally designed for Reson sonars, PDS is now an excellent multi-purpose processing suite
Qimera	QPS	Navigation, positioning, and surveying package
SeeTrack	SeeByte	AUV mission planning and data processing tool
SonarWiz	Chesapeake Technologies	A complete sidescan data acquisition and survey management system. Includes seabed classification tools.
Surfer Pro	Golden Software	A low-cost utility with many very good display abilities.

Tableau 2_Third party software compatible with Bathyswath

4.8.2 Use of third-party software during data acquisition

Bathyswath can be used with "fully-functioned" third-party sonar processing and control systems, allowing the user to perform all data acquisition and processing functions in the third-party system. In this mode, the Bathyswath Swath Processor application acts as the interface to the Bathyswath hardware, and performs some initial processing and filtering before sending the data to the third-party process. The data that results from this process is as raw as possible whilst maintaining a consistent range-and-angle data format. This format is known as the "Parsed Data" format.

The user can elect to use the Swath Processor with minimal processing and displays, just passing the Parsed data to the third-party system or alongside the third-party system, with all displays enabled. Swath Processor and third-party applications can be run on the same computer, or on different computers, connected by Ethernet.

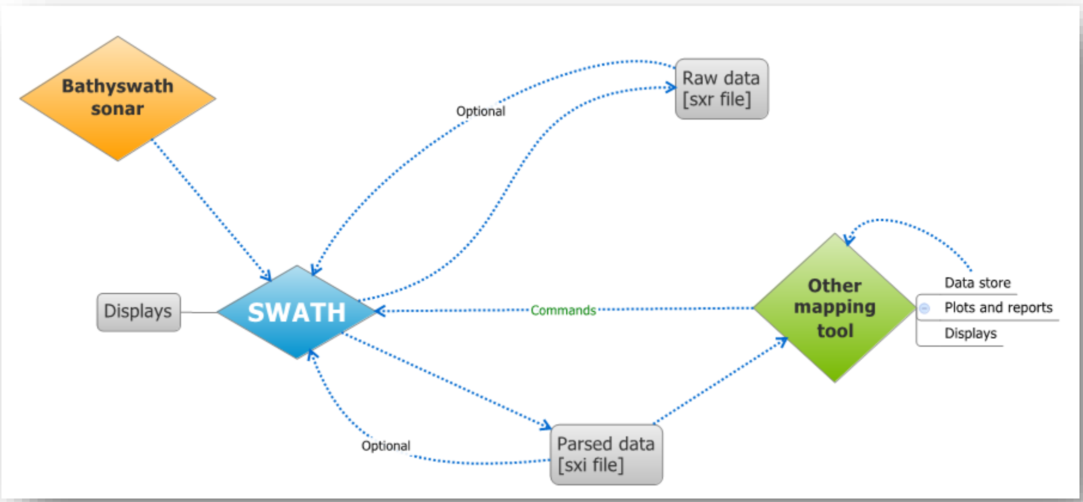


Figure 47_Third party software flow

4.9 NAVIGATION SOFTWARE

Bathyswath software provides a coverage chart, showing which areas have been covered in the survey. Tasks such as planning the survey route and giving the helmsman a display to steer from are provided by third-party software, integrated with the Bathyswath system.

4.10 SOFTWARE LICENSING

Bathyswath software (Swath Processor and Grid Processor) is freeware (free and unlimited license).

5 MANUALS, TRAINING AND SUPPORT

5.1 MANUALS

Each Bathyswath system is supplied with a full set of manuals, describing the use of the system for surveying applications, how to install and maintain it, and how to operate the software. The software includes an on-line, context-sensitive help tool.

5.2 TRAINING

Bathyswath team offers a training course. This generally takes place at the client's location. It takes about a week, and is a mixture of classroom training, surveying on the client's boat, and then processing back in the office. The idea is to get the customer's operators working with their own equipment in their own environment. An emphasis is placed on hands-on use of the system and software, including:

- Description of the system,
- Deployment,
- Real-time and post-processing software,
- Maintenance and troubleshooting.

5.3 SUPPORT

The warranty package that is included in the initial sale price includes replacement of faulty equipment and software upgrades. Major and minor software upgrades are distributed approximately every six months, although specific user issues may be addressed in interim releases. Extended maintenance arrangements are available and renewable on a yearly basis.

5.4 QUALITY AND CERTIFICATION

Bathyswath systems are provided with certificates of quality and calibration.

5.5 MAINTENANCE AND CALIBRATION

Bathyswath requires little maintenance and calibration. The transducers are extremely robust, and maintenance generally consists of a regular inspection for damage and fouling by marine life (cleaning if necessary).

The Bathyswath-2 TEM units use digital signal processing, which does not drift with time and so needs no calibration.

6 SYSTEM PERFORMANCE

This section describes the performance and capabilities of Bathyswath in various survey situations.

6.1 RANGES, SWATH WIDTHS & COVERAGE ANGLES

6.1.1 Grazing angle and spreading loss

Line spacing is the distance between adjacent survey lines. The spacing is determined by the sonar horizontal range expected at that depth, and the amount of overlap required. The horizontal range expected depends on the water depth under the sonar-head, as well as the seabed type and the sea state.

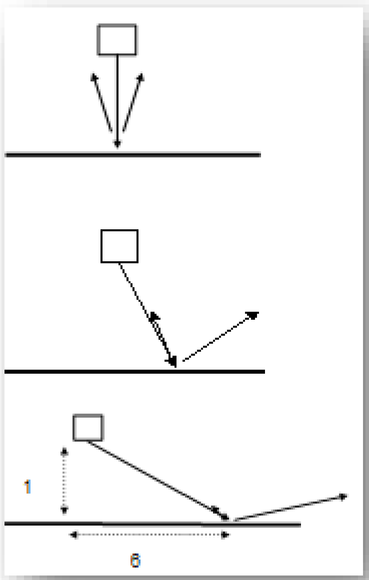


Figure 48_Grazing angle

The term "horizontal range" is used to describe the sonar coverage from one transducer. For a twin transducer configuration, the total swath width, from port edge to starboard edge, is therefore twice this range.

The horizontal range is limited by two factors: grazing angle and spreading loss. The grazing angle limit is related to the angle that the sound ‘beam’ makes with the seabed.

Directly under the transducers, sound is reflected directly, and there is little loss when sound is scattered by the seabed.

Moving away from the transducers, much of the sound is reflected away from the transducers, but enough sound is scattered back for the seabed to be properly detected.

At the grazing-angle limit, the sound makes a very small angle with the seabed. Most of the sound is reflected away, and the signal scattered back from the seabed is too small to be detected. The configuration of the Bathyswath transducers is similar to sidescan sonars: the swath width ends at the point where the backscattered signal is not sufficiently above noise to enable detection of the angle of the backscattered wave.

Backscattered acoustic signals from a seabed generally follow “Lambert’s Rule”; that is, the backscattered signal falls with the square of the cosine of the angle of incidence of the acoustic “ray”.

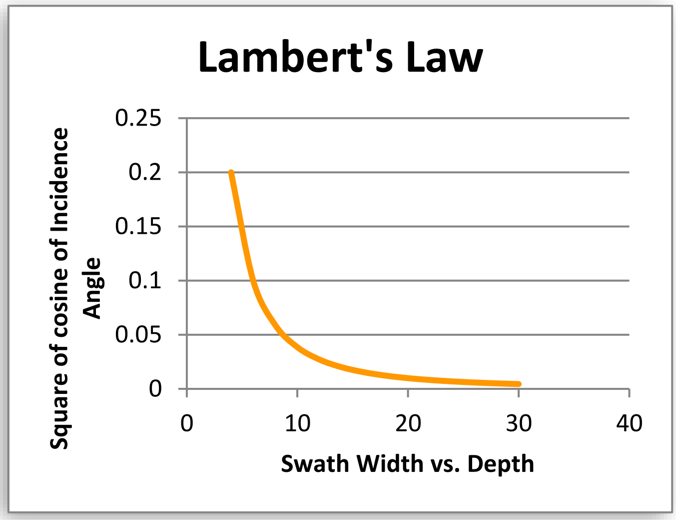


Figure 49_Lambert's law backscatter strength vs swath width

Plotting this rule, we can see that the Lambert's Law function is low at depth to swath width ratios above about 15:1.

In poor seabed conditions or turbid waters, this ratio can be reduced to about 10:1 or even less. Bottom types such as soft mud or peat can indeed reduce the expected range by as much as 30%. Sand, rock, and shingle all give good sonar backscattering.

The spreading loss limit is simply caused by the sound spreading outwards, and being absorbed by seawater. The rate of absorption is related to the frequency of the sonar signal. The spreading loss limit is thus determined by the distance from the transducers to the farthest point on the seabed (the slant range).

6.1.2 Ranges

	117 kHz	234 kHz	468 kHz
Minimum depth[25]	0.3 m	0.2 m	0.1 m
Operational slant range[26]	400 m	200 m	100 m
Maximum slant range [(2)]	600 m	300 m	150 m
Swath width vs. water depth ratio	Typically between 10:1 to 15:1		

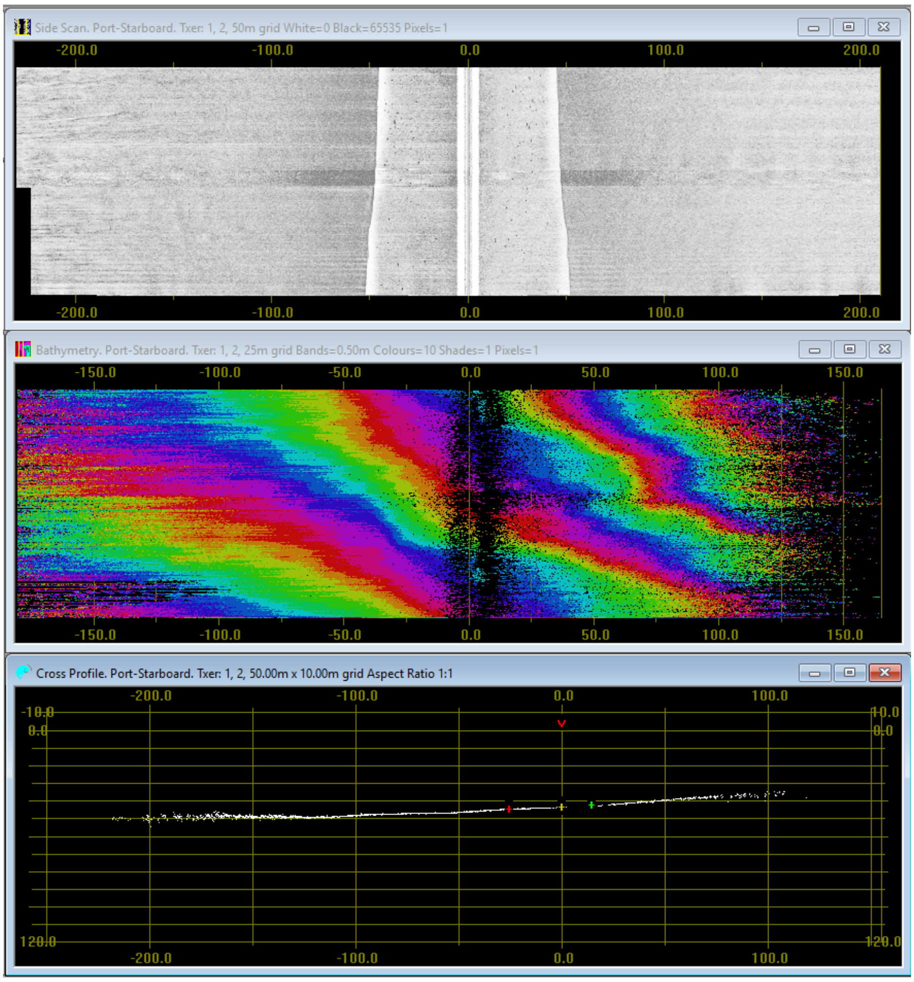


Figure 50_Bathyswath-2 (234 kHz) 200m range on port side in 44m water depth[27]

[25] There is no real physical limit to the depth at which measurements can be made by an interferometric system. Close to the transducer, the sonar system is operating in the near-field domain, where sound rays are not yet fully formed. This means that the accuracy of the angle measurement is not as good as a fraction of the sonar range as it is in the far field zone, but the very small ranges (within the 15-times depth limit) means that the depth measurement accuracy remains easily within that specified. A practical limit is close to that of the size of the transducer itself.

[26] The operational slant range is the one you should get in most cases. The maximum slant range is the one you should get in the best environmental conditions.

[27] Annecy lake, May 2016

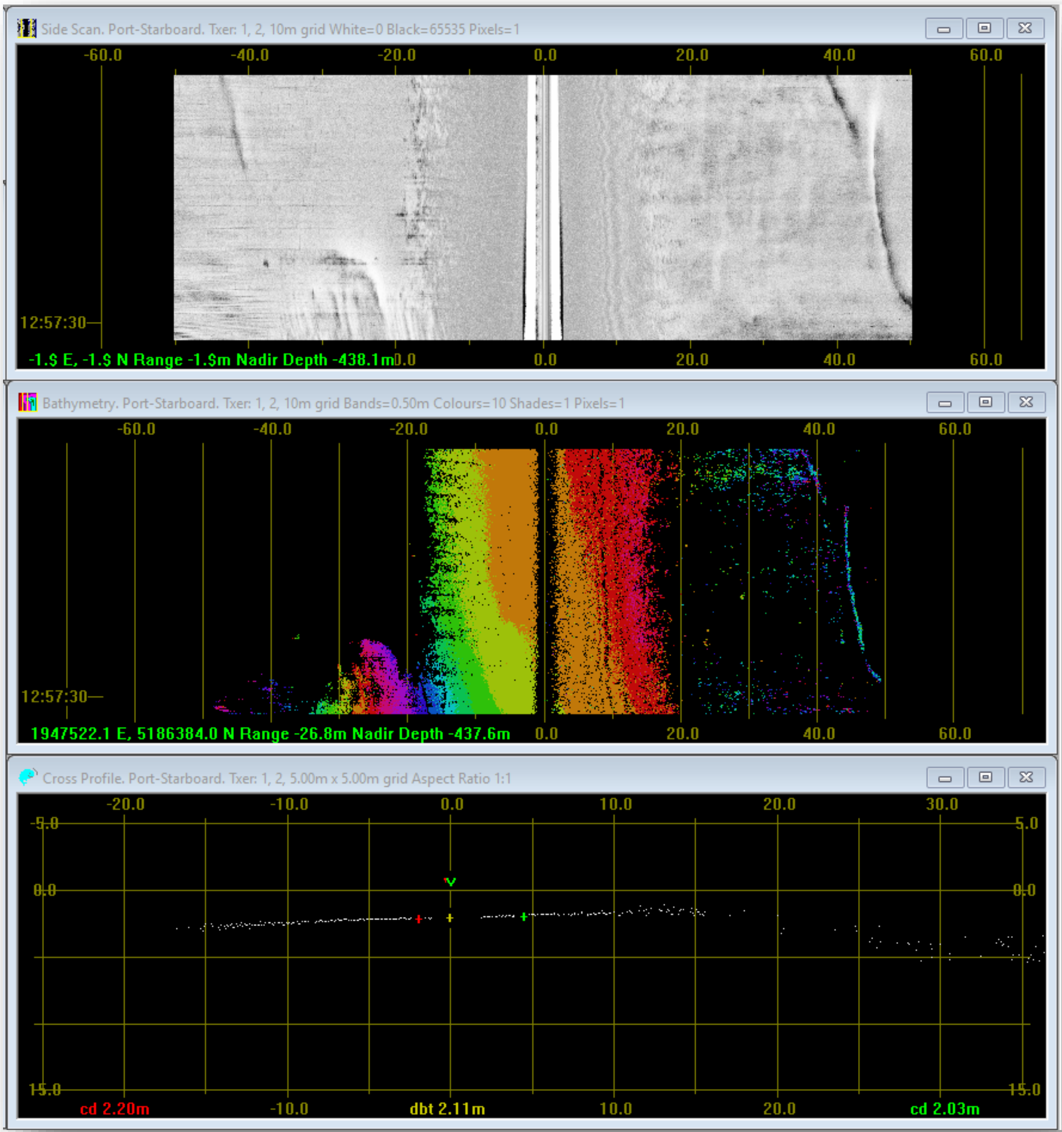


Figure 51_Bathyswath-2 (234 kHz) 30 m swath width in 2m water depth[28]

[28] Annecy lake, May 2016

6.1.3 Swath width and coverage angle

Environmental conditions	Poor	Standard	Good
Swath width vs. water depth ratio[29]	10:1	12:1	15:1[30]
Max. swath coverage angle, β angle	157°	161°	165°

Tableau 3_Swath angles

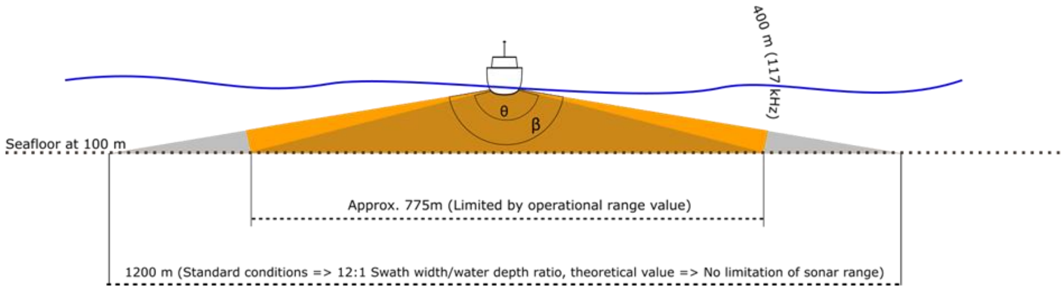


Figure 52_Coverage angle

The following table shows the optimum water depth for which the maximum swath coverage angle and width are reached without being limited by the operational sonar slant range.

Swath width vs. water depth ratio[31] :		**10:1 (Poor)**		**12:1 (standard)**		**15:1 (good)**	
	Operational slant range	Water depth (Optimum)	Swath width (max.)	Water depth (Optimum)	Swath width (max.)	Water depth (Optimum)	Swath width (max.)
468 kHz	100 m	19,6 m	196,1 m	16,4 m	197,3 m	13,2 m	198,2 m
234 kHz	200 m	39,2 m	392,2 m	32,9 m	394,6 m	26,4 m	396,5 m
117 kHz	400 m	78,4 m	784,5 m	65,8 m	789,1 m	52,9 m	793,0 m

Tableau 4_Optimum water depth for getting the max. swath width

[29] Theoretical value, not limited by sonar range (θ angle)
[30] In water depths of less than 10m, the ratio can exceed 20:1
[31] This ratio is related to the environmental conditions (i.e. turbidity) and water depth

6.2 ELEVATION ANGLE

Bathyswath is typically configured with two transducers, one facing port and the other starboard, and with both transducers pointing downwards at 30° from vertical (recommended). Each of the two transducers can, in principle, measure the angle of any sonar wavefront that approaches its front face, from -90° to +90° of its normal. If the two transducers were pointing horizontally, the angle of coverage would be a complete 360°.

The 30° elevation angle means that the top 30° is not covered on each of the port and starboard sides. In addition, the shape of the transducer beam in elevation means that the signal is weak for the last 20° of the -90° to +90° coverage. Therefore, we calculate the angular coverage range to be (360° - 2 x 30° - 2 x 20° =) 260°. This configuration also gives 20° overlap in the nadir region between coverage of the 2 transducers.

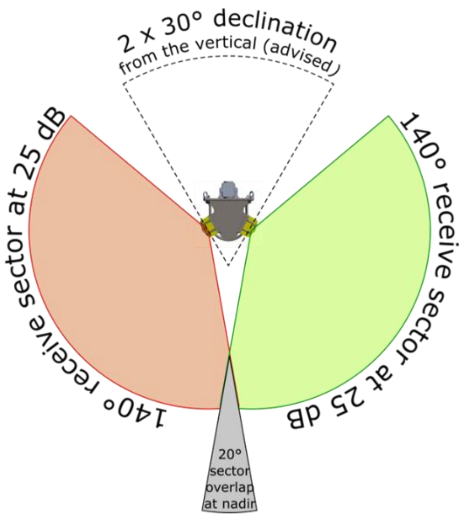


Figure 53_Elevation angle

6.3 ACCURACY AND RESOLUTION

6.3.1 Context

Consideration must also be given to the accuracy required from the survey. Bathyswath is essentially an angle-measuring instrument, so that depth accuracy reduces with horizontal range. The angular accuracy of both the Bathyswath sonar and commonly available MRUs is better than 0.05 degrees. The accuracy of the combined system is thus better than 0.1 degrees. The maximum range required for a given depth accuracy can easily be calculated. One accuracy specification is that of the International Hydrographic Organisation (IHO) S44 specification[32]. Bathyswath has been used, and quality checked, in surveys at all IHO S44 accuracy orders, including Special Order.

This section considers the accuracy and resolution of Bathyswath; these two parameters are closely related, and can be selected for, against each other, using statistical methods in data processing. It is derived from a model of the accuracy of Bathyswath, related to resolution. This model has been validated using data collected and published for the 2008 Shallow Survey conference. Bathyswath can output pulses down to 2 cycles (A single-wavelength pulse will not have enough transfer efficiency into the water), so the physical limit of measurement resolution is as per the following table.

[32] See Ref. 1

	117 kHz	234 kHz	468 kHz
Frequency[33]	117.1875 kHz	234.3750 kHz	468.7500 kHz
Divisor	*512 (or 2^9)*	*256 (or 2^8)*	*128 (or 2^7)*
Period	8.5533 µs	4.2666 µs	2.133 µs
$T=1.f^{-1}$			
Wavelength	12 mm	6 mm	3 mm
λ=c.T			
Resolution detection limit[34]	6 mm	3 mm	1.5 mm
½.λ – Half wavelength			
Minimum pulse time	17.06 µs	8.53 µs	4.26 µs
Min. pulse time = 2 cycles = 2.T			
Maximum pulse time	8553 µs	4266 µs	2133 µs
Max. pulse time = 1000 cycles = 1000.T			
Transmit pulse length[35]	17 to 8550 µs	8.5 to 4300 µs	4.3 to 2100 µs
Pulse length	2.5 cm	1.2 cm	0.6 cm
2. λ			
Measurement resolution limit[36]	1.2 cm	0.6 cm	0.3 cm
½ pulse length			
Resolution Across Track	7.5 cm	5cm	3cm
Beam Width, Azimuth	1.7°	1.1°	1.1°
Beam Width, Azimuth (2-way)	0.85°	0.55°	0.55°
Source level	224 dB	220 dB	222 dB
1µPa @ 1m			

Tableau 5_Accuracy and resolution

[33] Bathyswath is a single frequency (also known as Continuous Wave – CW) system; the sonar frequency is built into the electronics systems. The frequencies are derived by dividing a 60 MHz base frequency in powers of two (i.e. 60000 kHz / 2^9 = 117.1875 kHz)

[34] Any sonar system can detect objects that are larger than half of its wavelength. The limit to measurement resolution is determined by the sonar pulse $\Delta y = \frac{c.\tau}{2} \times \frac{1}{\cos\beta}$ where c is the speed of sound, τ is the pulse time, c.τ is the pulse length in meters, β is the grazing angle. In the best case, cosβ is 1

[35] The normal range is 2 to 300 cycles for the pulse length in the software but you can use the Advanced dialog to increase this range if needed

[36] These are theoretical values, but practically there is no way any sonar could tell the difference between a seabed at 20.000 m and another one at 20.003m.

6.3.2 Sampling

Bathyswath-2 range and angle data is sampled at 100kHz, but for longer ping ranges this is down-sampled by a variable factor up to 10.

6.3.3 Filtering, Accuracy and Resolution

Interferometric swath bathymetry systems give many data points per side, typically 2000 to 8000. However, the spread (standard deviation) of raw data points is usually greater than that of beam-forming multibeams, which typically produce 100 – 200 points per side.

Software filtering can be used to reduce this standard deviation to internationally acceptable survey limits. However, this filtering also reduces the resolution of the filtered data.

The International Hydrographic Organisation (IHO) Special Publication number 44[37], sets out standards for both accuracy (termed "uncertainty") and resolution. These are defined in a set of "Orders", of which "Special Order" is the most stringent, followed by Order 1.

Accuracy is specified in terms of the depth uncertainty to 95% confidence.

Resolution is specified in terms of the size of objects that must be detected, and the number of acceptable data points per square meter.

6.3.4 Beam Width, Azimuth

The beam width of the transmit and receive elements of Bathyswath, for the three sonar frequencies available, is given in "Beam Width, Azimuth" below. These figures are for both the transmit and receive elements. The effective width of the sonar "footprint" on the seabed is found by combining the "footprint" of both the transmit and receive staves, which is done by halving the beam width of the separate staves, to get a "two-way" azimuth angle.

	117 kHz	234 kHz	468 kHz
Beam Width, Azimuth	1.7°	1.1°	1.1°
Beam Width, Azimuth (2-way)	0.85°	0.55°	0.55°

Tableau 6_Azimuth Angle (Stave and 2-way Footprint)

6.3.5 Total propagated error

This analysis is concerned only with the depth error component of the sonar system. Other error components include position, attitude, heading and height relative to datum. The last of these is usually measured using GPS height or tide height, and is often the largest component. This discussion concerns itself only with the contribution of the interferometric sonar.

[37] See Ref. 1

6.3.6 Estimating depth uncertainty

This analysis uses Bathyswath sonar depth profiles extracted from the data sets that were submitted to the 2008 Shallow Water data set. Profiles are analysed at two Bathyswath frequencies: 468 and 234 kHz.

Depth error is first estimated by comparing raw data points with an averaged profile.

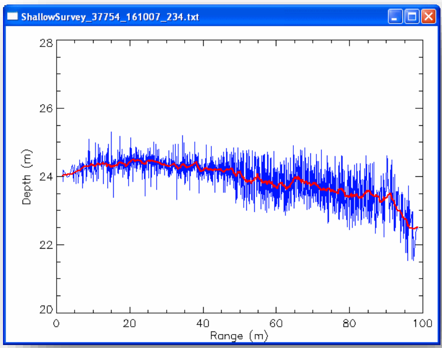


Figure 54_234 kHz profile

Blue: raw data, red: average

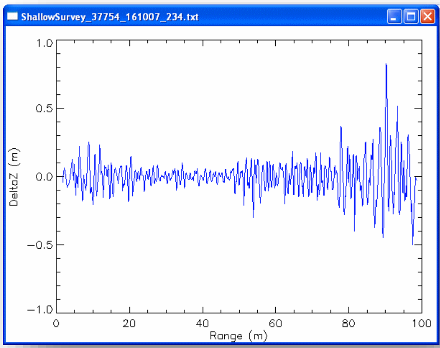


Figure 55_Estimated error on raw data

6.3.7 Data smoothing

The Bathyswath software includes a range of data filters. These include averaging filters, which smooth the data, thereby reducing the statistical spread (and thus the uncertainty) of the depth data, but at the expense of resolution.

This smoothing filtering is mathematically modelled using a Gaussian sliding window filter. The width of this window is selected to satisfy the S44 requirement for a given number of accepted data points per square meter. Both across-track (along the profile) and along-track (profile separation, from vessel speed and ping repetition frequency) are used. The smoothed points are converted to 95% uncertainty, using the statistical method recommended in IHO S44.

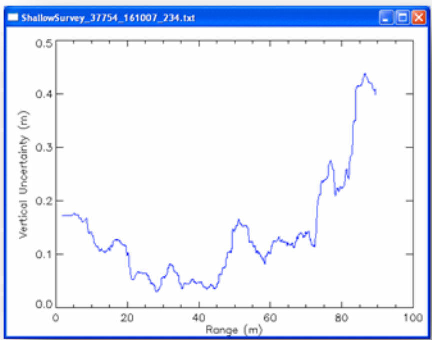


Figure 56_95% Uncertainty of smoothed data

6.3.8 Error modelling

The data smoothing procedure is repeated for several "pings" in the data set, and averaged by range. A mathematical model of phase error in Bathyswath is created, and validated against the observed uncertainty; see the blue line on the left:

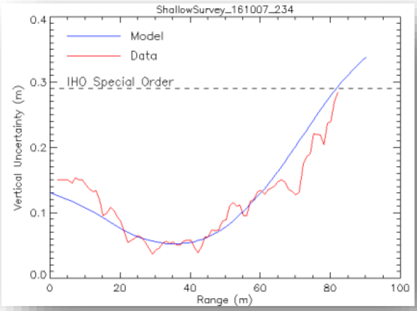


Figure 57_Data uncertainty at 234 kHz

The process is repeated for all three Bathyswath sonar frequencies:

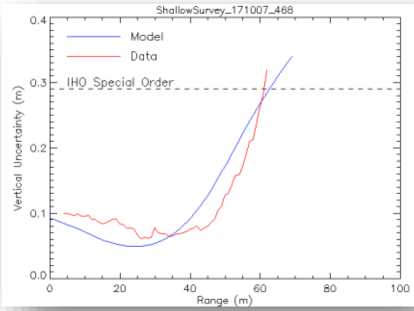


Figure 58_Data uncertainty at 468 kHz

Finally, the models are used to graph the maximum range (half swath width) at which the IHO S44 Special Order is met (Shapes are measured data):

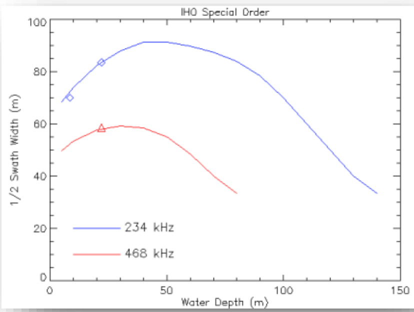


Figure 59_Horizontal range at which IHO S44 Special order is met

6.3.9 Data quality model

A data quality model, written in python, is available on request from ITER Systems. This computes and plots the standard deviation of depth measurements for a set of user-entered survey parameters. The model can be validated by simultaneously plotting the standard deviation extracted from real Bathyswath survey data.

6.3.10 Conclusion

Error modelling, validated with data from real Bathyswath surveys, shows that Bathyswath can provide survey depth accuracy within the requirements of IHO S44, Special Order, at good ranges. Longer ranges are achieved with the lower-accuracy Orders.

6.4 SURVEY PRODUCTIVITY

The time in which a given seabed area can be surveyed depends on the distance between the survey lines and the forward speed of the survey vessel.

6.4.1 Line spacing

The spacing between survey lines is determined by a combination of range limit and accuracy required. There must also be some overlap allowed to account for variations in the survey line followed. Otherwise, any small helmsman's errors will cause gaps in coverage of the seabed.

6.4.2 Pulse repetition frequency

The time taken for a ping cycle is that for a round trip from the transducers, to the farthest range, and back again. The speed of sound in water is about 1500 meters per second. For example, a 150-meter ping takes 0.2 seconds. This gives a pulse (or ping) repetition frequency (PRF) of 1 / 0.2 = 5 per second (or Hertz).

The software allows the nominal sonar range to be set in meters. The corresponding PRF is calculated in software and used in data acquisition.

6.4.3 Platform speed and along-track coverage

Bathyswath can provide total ensonification of the bottom at practical and efficient survey speeds.

The distance between pings along the track of the vessel is determined by the pulse repetition frequency (PRF) and platform speed. To minimize cross talk between the two sides, the system can be used with alternating sonar transmissions, port and starboard. Thus, in the alternating mode, this distance is doubled:

$$d = 2.v.PRF$$

where:

- d is along-track distance between pings, in meters.
- v is platform speed in meters per second[38].
- PRF is the pulse repetition frequency, in seconds.

Bathyswath also provides the option of firing both transducers simultaneously. This doubles the coverage rate, so that the along-track ping spacing reduces to speed x PRF. However, this mode should be used with caution in surveys with a requirement for high bathymetry accuracy, because some crosstalk between the channels can happen very occasionally. That is, the signals from one side can affect the other side. To avoid such crosstalk, the sonar frequency can be adjusted on up on one side and down on the other using the software settings.

Coverage is also determined by the width of the sonar beam. A narrower beam gives better resolution, but carries a greater risk of missing targets between beams. At 50 metres, the 234kHz and 468kHz beams cover 0.43m, and the 117kHz beam covers 0.74m.

Increasing the speed over the ground will reduce survey time, but will also reduce the along-track coverage. Five or six knots is generally a good compromise. At 5 knots, with a 100m range, giving 6.7 pings per second, each side is covered every 75cm along-track. At 10 knots, this spacing doubles. In the 5-knot example, ground is covered at 500 m^2/s, or 1.8 km^2/hr.

[38] Halving the speed in knots gives a good estimate

6.5 SURVEYING AT HIGH SPEED

6.5.1 Introduction

Some users have a requirement to survey at relatively high speeds, 8 knots or more. At excessive speeds, along-track coverage is reduced, and data density could fall below specification or the sidescan imagery might not fully cover the seabed. This section shows the options for meeting this specification with Bathyswath.

6.5.2 Data Density

Survey data specifications such as IHO S44[39] define a minimum detection resolution, which is often interpreted by hydrographic organisation in terms of sounding density. For example, S44 Special Order surveys require around 9 soundings per square metre, and Order 1a requires round 9 soundings in a 2x2 metre patch, so 2.25 soundings per square metre. Special Order is reserved for limited areas such as docksides, where high vessel speeds are not usually allowed. Therefore, we use the Order 1a requirement for this analysis. Bathyswath can provide S44 accuracy at around 3 soundings per metre across-track (see section 8.3), so it is necessary to achieve no fewer than (2.25 / 3 =) 0.75 pings per metre along-track. For typical 234 kHz Bathyswath swath widths (12 times water depth up to a maximum of 300 m), the speed at which Order 1a data density is just met can be calculated; this is 13 knots at depths below 25 metres.

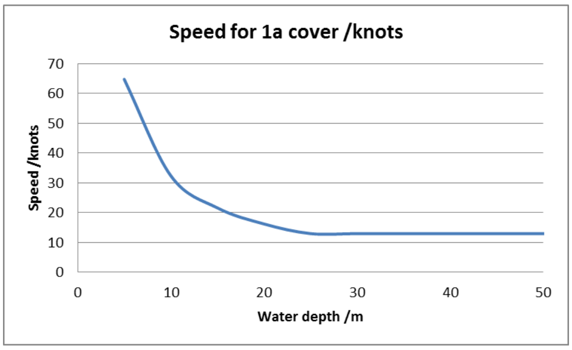


Figure 60_The speed in knots at which Order 1a data density is just met

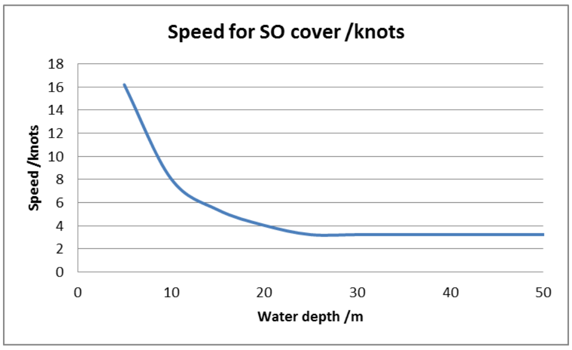


Figure 61_The speed in knots at which Special Order data density is just met

For Special Order data density, the maximum speed falls to 3.2 knots with 12 times water depth swath widths for depths below 25 m.

[39] See Ref. 1

To achieve Special Order data density at high speed in depths below 10 metres, the swath width must be reduced.

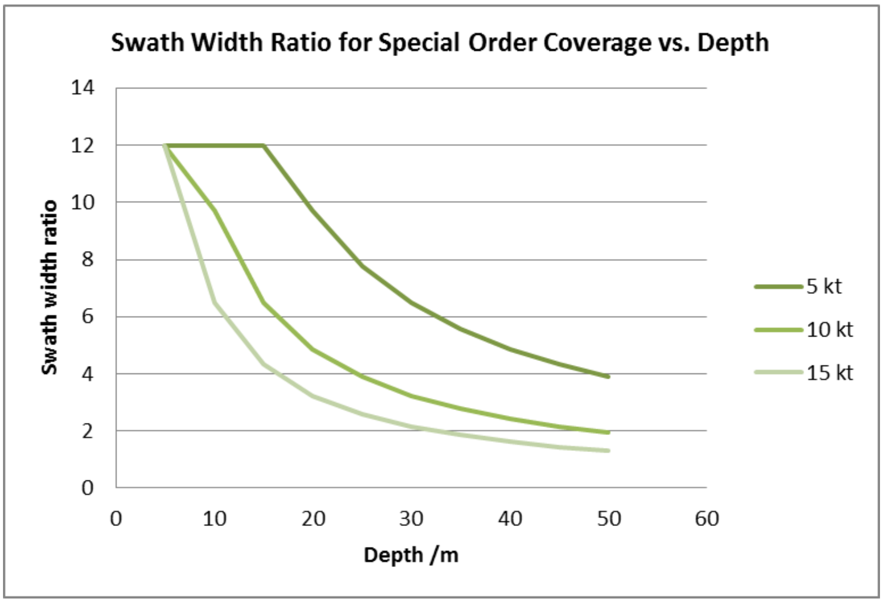


Figure 62_The swath width ratio at which Special Order data density is just met for various speeds

6.5.3 Complete Bottom Coverage

If it is necessary to find all sonar targets, no matter how small, then full bottom coverage is needed. This is determined by the area covered by the sonar beam on the seabed, called the "sonar footprint". A sonar beam is generally taken to extend to the angle at which the power at the centre of the beam falls to half its power, or 3 decibels (dB). For resolution purposes, a "two-way" angular resolution is quoted; see section 8.3.4 below. In this analysis we assume that detection of seabed targets of interest is achieved within the "one-way" azimuth angle.

The footprint is narrowest under the transducers, and widest at far range. Under the transducers it is wider in deeper water.

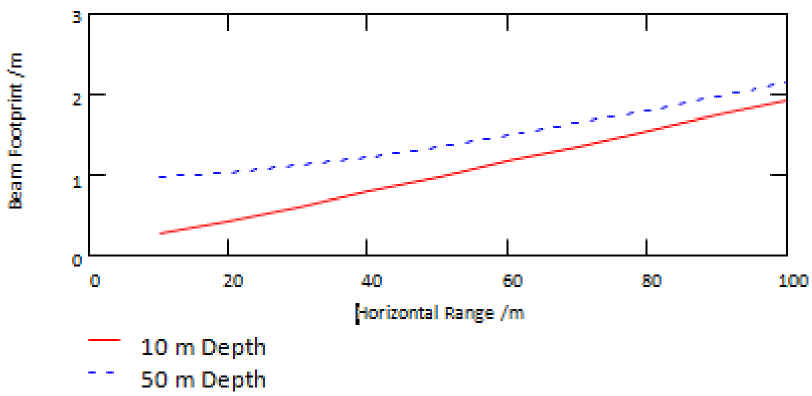


Figure 63_Beam Footprint vs. Horizontal Range, at 10m and 50m water depth

6.5.4 Maximum Speed for Full Coverage

The maximum speed for full coverage can be calculated for a given water depth using the ping rate for that depth, and the footprint of the beam below the vessel. The maximum speed is that at which the vessel moves forwards by the width of the footprint within the ping period. Bathyswath is usually operated in simultaneous ping mode, in which both transducers fire at the same time. This doubles the along-track coverage at a given forward speed compared to systems that work in alternating mode (port-starboard-port-starboard etc.).

This graph shows the maximum speed at which full coverage is achieved immediately below the boat, operating in simultaneous ping mode.

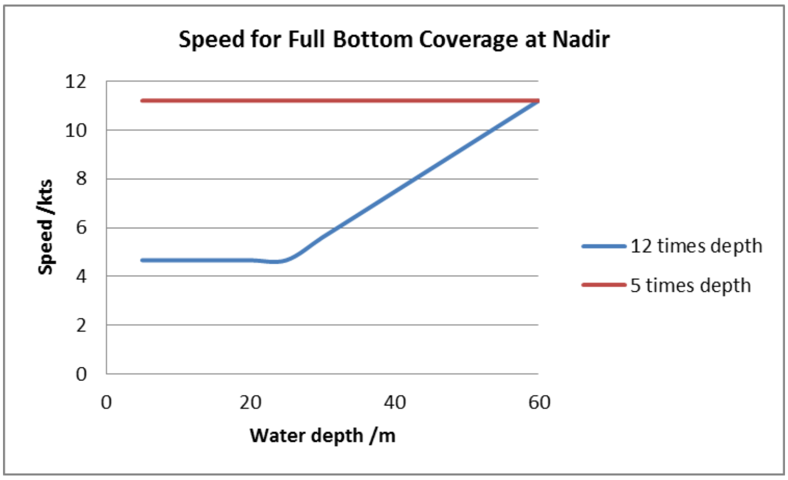


Figure 64_Max. speed for full coverage below boat

It can be seen from these graphs that full coverage under the boat can be achieved at ten knots water depth if:

- The swath widths are kept to five to six times water depth,
- The sonar is operated in simultaneous mode.

6.5.5 Sidescan Search Mode

Most sidescan systems are run with every other line spaced for 100% overlap, so that the nadir of each swath is covered by the far range of at least one adjacent line. Bathyswath can be run in this way to give higher bottom coverage with both bathymetry and sidescan.

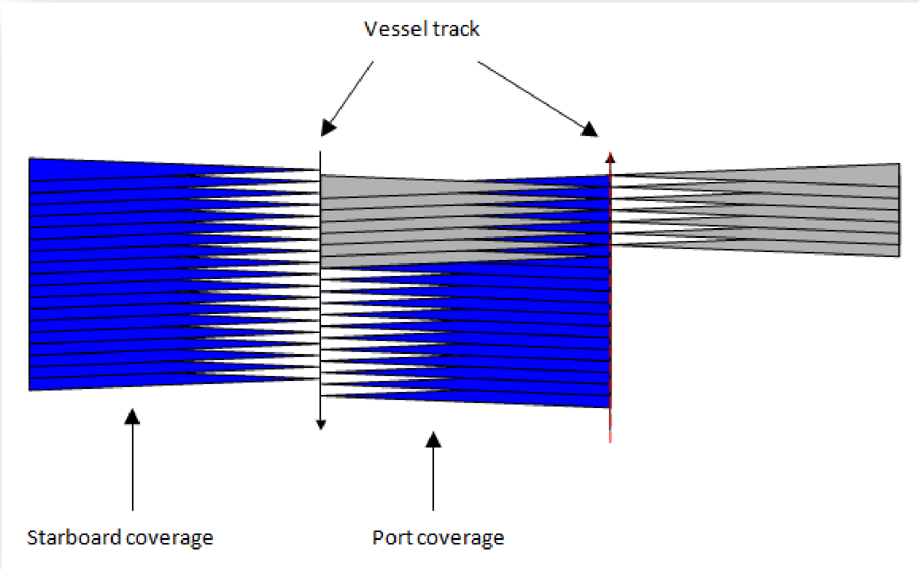


Figure 65_Side scan search mode

The maximum speed is given by the footprint at far range and the ping period: $v = \frac{f}{t}$

Where the footprint is a function of range and beam angle: $f = r.\tan\theta$ and time is a function of range and sound speed $t = \frac{2.r}{c_{sound}}$

… so the speed is independent of range, and for a beamwidth of 1.1° is 28 knots.

6.5.6 Conclusion

These calculations show that the Bathyswath sonars can easily provide both IHO S44 data density and 100% bottom coverage at relatively high survey speeds. Bottom coverage depends on the along-track and across-track beam patterns. Bathyswath provides very high data density across-track, so that coverage is complete in this dimension. The along-track coverage depends on ping rate, beam width, and speed of sound.

There are several options for obtaining 100% coverage:

- Operate the system with minimal overlap, limit swath widths to approximately seven times water depth, or,
- Operate the system with 100% overlap between adjacent survey lines. In this case, 100% coverage is obtained in 10 metres of water at 15 knots.
- Add a third, forward-facing transducer to boost data coverage in the nadir region.

There is a range of options lying between these solutions, so that the system can easily fit in with the operational practices of the user.

6.6 NEAR RANGE SEABED COVERAGE, THE NADIR REGION

6.6.1 The Nadir Region

The region of the seabed directly below the sonar transducers is called the “nadir region”.

This coverage of an interferometer is greatest at medium ranges from the transducers, and is least in the area close to the centre than at far range. There are several reasons for this reduced data density in the centre.

6.6.2 Measurement Geometry

An interferometer samples the angle to the seabed at regular intervals of time. Each angle and time pair is converted to a depth and horizontal range pair. Time is converted to range from the transducer (slant range) using the speed of sound, so regular time steps translate to regular range steps. However, regular steps in slant range do not produce regular steps in horizontal range. Horizontal range is a distance measured along the seabed, starting from a point immediately beneath the transducers.

A simple example illustrates this situation. Consider the system operating in a water depth **D**. The first depth measurement is taken immediately under the transducers. The next measurement is taken at a range step of **dR**. Simple trigonometry dictates that the horizontal range step, **dH1**, is much larger than **dR**. Now consider the situation further out along the profile, at some horizontal range **H**. Here, the horizontal range step **dH2** is much closer to the range step **dR**.

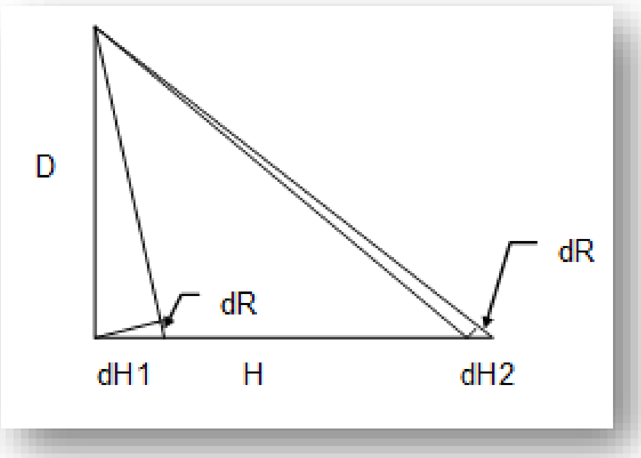


Figure 66_Measured geometry

6.6.3 Footprint of Transmit Beam

At the start of each ping, the sonar transmits a short pulse of sound. This pulse moves outwards at the speed of sound. Where the pulse hits the seabed, it returns an echo. The echo is picked up by the transducers and the angle of the returning signal is measured.

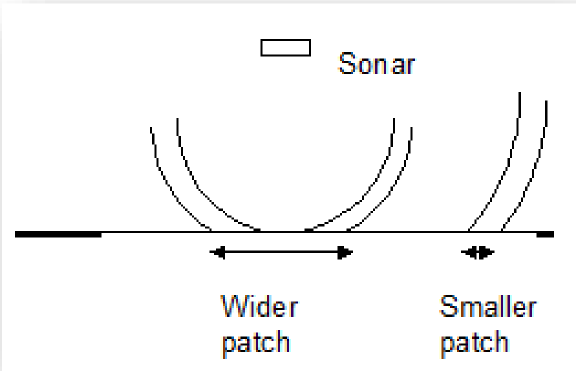


Figure 67_Footprint

At any one instant, the pulse of sound will be “illuminating” a patch of seabed. The size of this patch is determined by the length of the pulse and the geometry. Immediately below the transducers, this patch is at its greatest, and thus the resolution is lower than it is further out.

6.6.4 Amplifier Response

When the sound signal first hits the seabed, the size of the returned echo signal goes from a very low level to a very high one extremely quickly. This fast change in signal level presents a challenge to the amplifier designer. One important part of a successful interferometer like Bathyswath is thus the way in which the amplifier responds to these fast signal changes.

6.6.5 Filter Response

As explained above, an interferometer measures angles to the seabed as a set of samples separated in time, and thus in range. Before the sonar signal reaches the seabed, the angles measured will be discarded due to low signal levels, or random due to noise pick-up or returns from objects in the water. These random signals from the water-column must be discarded before the seabed depths can be recorded. Bathyswath uses a collection of user-settable filters to separate the seabed from objects in the water column.

6.6.6 Deep Water Response

The shape of the sonar transducer beam in elevation has been chosen to maximize the performance for most survey situations. In shallow to medium water depths, the direct reflection from the seabed directly under the transducers is very strong, and can cause the electronics to 'saturate'.

To reduce this, the sonar beam is shaped so that returns from this region are reduced in amplitude. However, at the limits of the depth capabilities of the system, this reduction can cause data-loss in the near-range area. Changing the transducer beam-angle so that the transducer normal makes a greater angle with the horizontal reduces this effect.

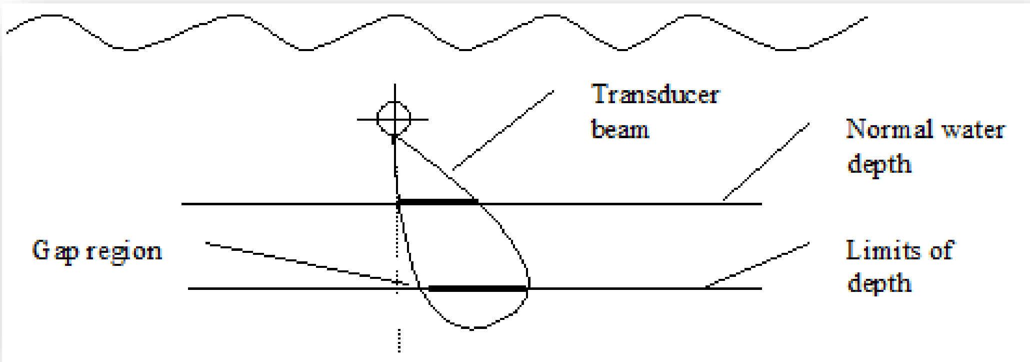


Figure 68_Deep water response

6.6.7 Coverage at Nadir

Most users find that the data coverage achieved in the nadir region is enough for their purposes. However, if very high data coverage is required at all parts of the survey, and if the sidescan component is also important, then a "sidescan survey" line pattern can be used (see section 6.5.5). Survey lines are run alternately at the sonar range and twice the sonar range, so that the nadir is "filled" from an adjacent swath in every case.

For example, here is a snapshot of the first ± 5m horizontal range of the waterfall view from a survey in India in 7 metres of water. Each coloured point is a depth sample.

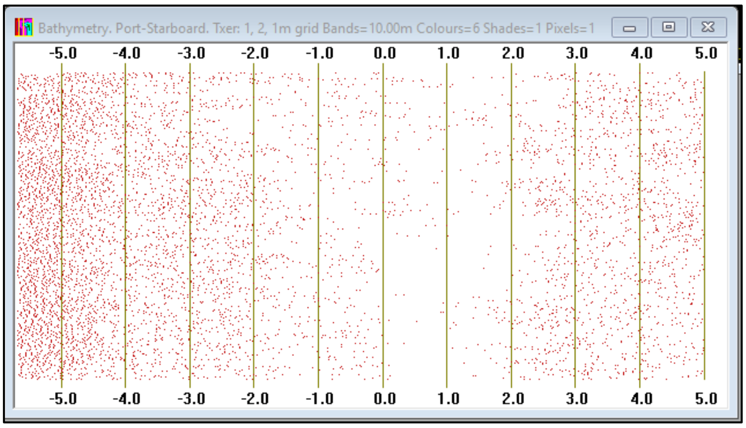


Figure 69_Nadir coverage, total of 60 depth samples in -5m to +5m for each ping[40]

Zooming in to ±3m horizontal range, we have:

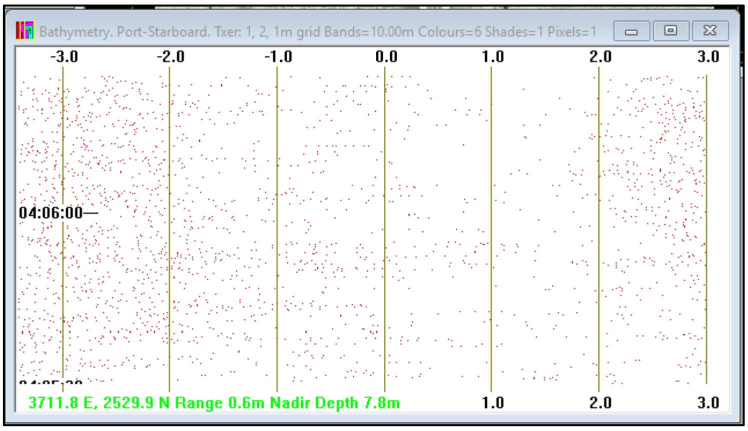


Figure 70_Nadir coverage, total of 11 to 20 depth samples in -1m to +1m metre for each ping[41]

For IHO S44, around 9 data points per square metre are required to meet the resolution requirement; that is usually assumed to be 3 per metre across track (along the ping), assuming 3 pings per metre (which depends on the ping rate and vessel speed). So, in this case, IHO S44 Special Order was met. In other cases, the first metre or two might be outside Special Order (but well within the requirement of Order 1a).

[40] So about 6 per metre

[41] So a minimum of 5 points per metre

6.6.8 Historical Nadir Coverage

Examining several survey projects done around the world with Bathyswath and measuring the range at which IHO S44 Special Order data density requirements are met, we can see the following relationship:

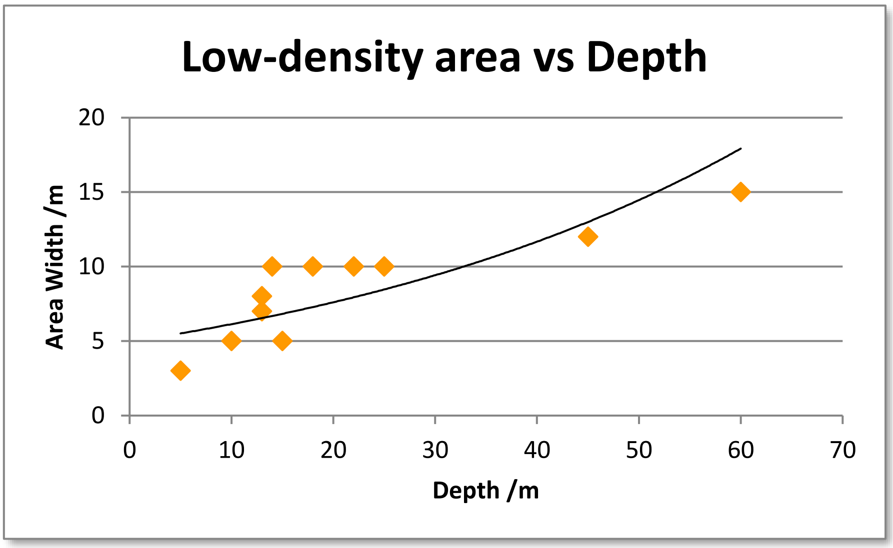


Figure 71_Low density area vs depth

The low-density region increases slowly with increasing depth. However, if we compute the angle that the low-density region covers, we can see that this angle decreases with depth:

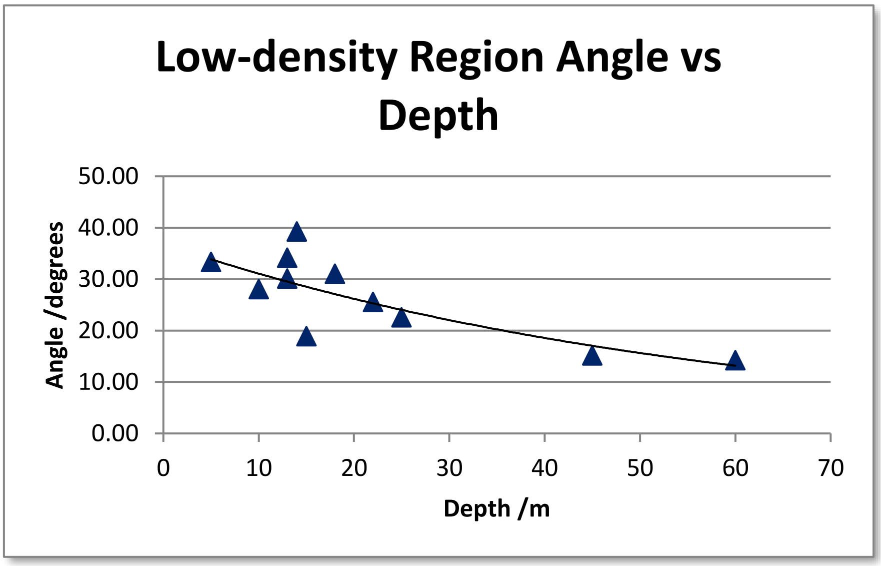


Figure 72_Gap angle vs depth

Also, note that Special Order is generally only used in very shallow water, less than around 10m. Furthermore, this data includes historical Bathyswath 1 and SWATHplus data; Bathyswath 2 has a higher data density, so the “nadir region” is smaller with Bathyswath-2.

6.7 ENVIRONMENTAL IMPACT MITIGATION

The standard Bathyswath systems use sonar frequencies above the limit of hearing of marine mammals.

The software provides a transmit soft-start scheme if required.

6.7.1 Source Levels

The transmit source levels of Bathyswath-2 at the three sonar frequencies are:

Transducer	**Source Level,** dB re1µPa@1m
468 kHz	236.1
234 kHz	233.5
117 kHz	225.5

6.8 MEDIA USAGE

Bathyswath samples a high density of data. It therefore stores data to disk at a high rate. When recording a full set of bathymetry and amplitude points at maximum resolution, the recording medium is filled up at a rate of 3.4 Mbytes per second. However, with the sample rates that the system uses for typical water depths, and operating on two channels, the data rate is 0.7Mb/s, which is 2.7Gbytes per hour. A 1 terabyte disk fills in 4.5 days at this rate.

7 COMPARISON BETWEEN INTERFEROMETERS AND BEAMFORMERS

7.1 DIFFERENT TOOLS

Interferometers and beam-forming multibeams are different tools in the surveyor's toolkit; each of them is the better choice for certain kinds of task. In general, interferometers are better for shallow water (less than 100 metres depth), where the wide swath width gets the survey done faster. Conversely, beamformers tend to have a greater depth range for the same size of sensor.

Some survey organisations use both kinds of instrument, and use them together or select the best one for each task.

7.2 RANGE AND ANGLE MEASUREMENT

Both interferometric multibeams and beamforming multibeams measure range and angle to a series of points on the seabed. A beamformer mathematically forms a set of "beams", and detects the range to the seabed in each beam. An interferometer measures the angle the incoming sound wave fronts in a time sequence of samples. Slant range is obtained from the time of the sample and speed of sound.

In summary, beamformers measure range for each of a set of angles, and interferometers measure angle for each of a set of ranges.

7.3 ADVANTAGES & DISADVANTAGES OF THE TECHNIQUES

Parameter / Function	Interferometer	Beamformer	Notes
Number of depth measurements	6000+	60-500	Depends on range
Range vs. water depth	10 - 20	3-5	Beamformer footprint becomes unacceptably large at far range.
Amplification / processing channels	4-5	60 +	In a harsh environment, simplicity is important
Outboard transducer electronics	Passive	Active	The outboard component of an interferometer is extremely robust, and cheaper to replace if damage does occur
Outboard transducer size and weight	350x160x60mm 5 kg (air)	120x190x450mm 16 kg (air)	Dimensions for a common portable beamformer. Many beamformers are much larger.
Horizontal resolution at range	Good	Poor	Beamformer footprint becomes unacceptably large at far range.
Angular coverage	260° (including 20° overlap)	90° - 180°	
Co-incident sidescan	True	Partial	An interferometer collects amplitude in the same way as its bathymetry: as a time-series.
Ability to resolve several targets at the same range	No	Yes	
Ability to resolve several targets at the same angle	Yes	No	
Profile data density	Increases with reducing grazing angle	Decreases with reducing grazing angle	In the first 5 m of horizontal range, a beamformer collects slightly more depth samples. Beyond that, an interferometer collects many more.

7.4 ADVANTAGES OF INTERFEROMETERS

7.4.1 Wide Swath Width

An interferometer produces a swath width of 10 to 15 times water depth, depending on sonar conditions. This advantage is particularly clear in shallow water (less than 30 m).

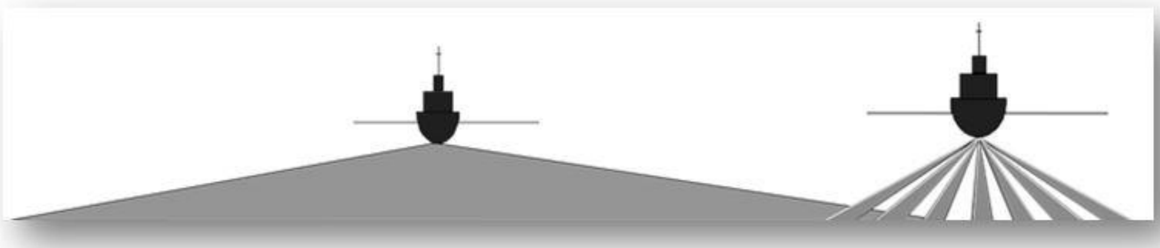


Figure 73_Interferometer (left) and beamformer (right)

7.4.2 Coverage

Bathyswath measures thousands of depths along every profile, across a very wide swath. Its coverage of the seabed is thus unparalleled.

7.4.3 Simplicity

A beamformer requires digitized signals from each of dozens of transducer elements, which must then be highly signal processed. This results in a requirement for many amplifiers, wires, connectors, and processors. These components must either be present in the wet end of the system, or highly complex cabling is required to pass through the hull of the platform. Such complexity must inevitably result in reliability problems.

In contrast, Bathyswath requires only three or four individual signal channels. The innovative use of electronic processing limits the requirement for many processors. Only the transducers need to be placed in the water, and these are entirely passive: they contain no electronic components at all other than the piezo-electric elements and are completely potted in plastic compound. They are thus extremely compact and robust.

7.4.4 Weight and Size

The simplicity of Bathyswath results in a lightweight, portable package with a small footprint and simple cable requirements.

7.4.5 Flexibility

Interferometric systems can similarly be configured to work from a range of platforms, and in a range of configurations.

7.5 MULTI-BEAM BEAMFORMERS

7.5.1 Effect of Beam Width at Far Range

Beamformers have a finite width of beam, detecting anything within this beam as signal. Their resolution is thus related to the width of beam. At far ranges, where the beams make a small angle with the seabed, horizontal resolution is poor. In contrast, Bathyswath produces a small pulse of sound and measures returns from this pulse across the seabed. The footprint of this pulse thus remains small, and the resolution of an interferometer remains good even at far range.

7.5.2 Angular Restrictions

Beamformers form a limited number of beams, in a limited angular sector. They therefore cannot survey up to the sea surface unless special mounts are used. In contrast, Bathyswath can survey a full 260° sector with 20° overlap in its standard configuration.

7.5.3 Lower Resolution

With less than a hundred depth measurements in each sonar cycle, it is often necessary for a beamformer to interpolate between measurements to simulate full coverage.

7.5.4 Roll Sensitivity

Beamformer profiles, being a much smaller percentage of water depth than an interferometer, are subject to large movements relative to vessel track. This can lead to unsurveyed areas at the swath edges if the survey vessel is subject to rolling motion from wave encounter.

8 EXAMPLES OF SURVEY PACKAGES

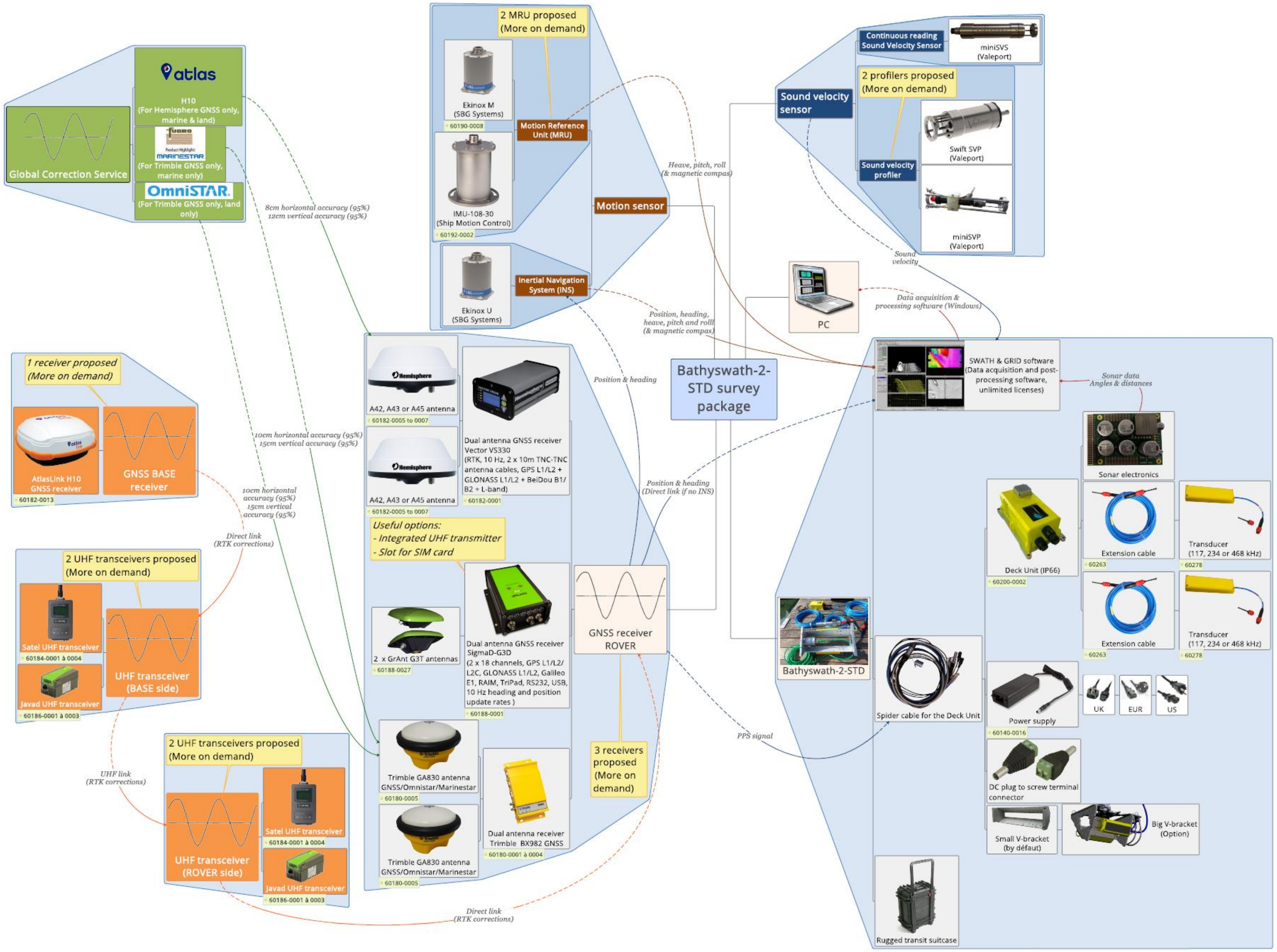


Figure 74_Example of Bathyswath-2-STD survey package[42]

[42] There are of course plenty of other configurations depending on end-user requirements