Marine Biodiversity Hub

National Environmental Science Programme

3. SEAFLOOR MAPPING FIELD MANUAL FOR MULTIBEAM SONAR

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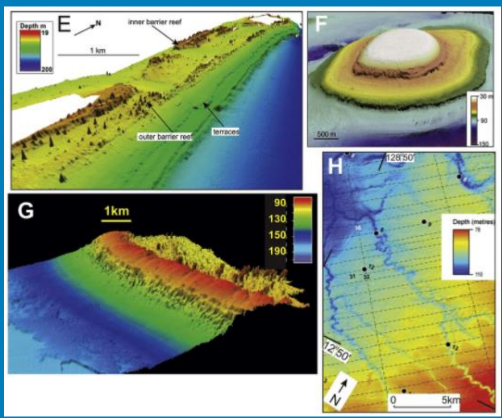

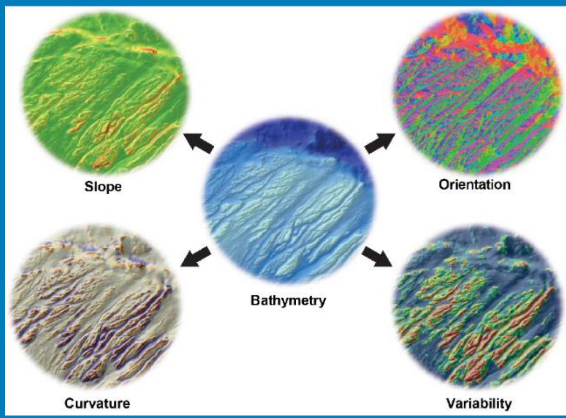

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3.1 Platform Description

Swath mapping systems use acoustic technology to collect data on the bathymetry (topography) and the backscatter (impedance) of the seafloor (Figure 3.1). These systems can either be mounted on a ship; autonomous underwater vehicle; remotely operated vehicle or a remote surface vehicle. They work by transmitting a sound pulse, called a ping, through a transducer at a specific frequency (or a range of frequencies simultaneously). This same ping is then recorded through a receiver placed very close to the transducer. The elapsed time that the ping takes to reach the seafloor and return to the receiver is used to measure the depth of the water. Certain attributes of the shape of the sound-wave are used to infer characteristics about the seafloor (geomorphology). Typical multibeam echo sounder (MBES) data products include bathymetry (seafloor depth) as well as backscatter intensity, which can provide a metric for seafloor "hardness" and will indicate the substrate type (Figure 3.1 a-d).

MBES have become one of the standard tools for geophysical surveying and mapping of the seafloor and have been used for a variety of scientific, safety at sea (hydrographic and military operations) and industrial applications. MBES can produce a spatially continuous acoustic image of the surface of the seafloor by generating a "swath" or "fan" of continuous data points, increasing the resolution of the resulting surfaces. This has revolutionized our ability to understand physical processes occurring at the seafloor, and the composition and distribution of substrate, which has in turn significantly improved our knowledge of seafloor ecosystems (McArthur et al. 2010, Lucieer and Lamarche 2011, Porter-Smith et al. 2012). Mapping of bathymetric morphology will delineate geological features that have relief (using the changes in seafloor depth information), however in regions where the relief is smaller than the minimum mapping unit (resolution of the grid cell is larger than the feature of interest) backscatter data can be used to assess the boundaries of the geology or sediment structure.

Australia's marine estate spans an incredible range of water depths; from the coast to 6000m+. Water depth has a very large influence on the acoustic survey acquisition, as it will dictate the resolution of the data (i.e., number of pings per unit area which will dictate the minimum pixel size) and the efficiency for surveying using MBES acoustics (i.e., swath width). While practices for employing the equipment have developed rapidly over the last few decades, there are a number of specific and common issues that need to be considered and detailed in a national standard operating field manual. This document has been developed in collaboration with Australia's *National Multibeam Guideline* written by the National Seabed Mapping Coordination working group which includes over 40 representatives from government departments, scientific institutions, universities and industry (see inset box).

> During the development of this manual, a broader assessment of multibeam survey standards by a national seabed mapping coordination working group was started. This program will provide guidelines for national standards of acquisition on and off the shelf, and improved data interoperability and access. This national working group guideline aims to be relevant for a wide range of purposes such as hydrographic mapping, marine infrastructure installation and planning, and baseline habitat mapping. It provides a more detailed description of the technical considerations of acquisition and international surveying standards, including details of operational procedures. Further details can be found in the *National Multibeam Guideline* to be available on www.ausseabed.gov.au by mid-2018.

In order to avoid duplication of details, this field manual will provide a procedure for specific planning, acquisition and processing steps relevant to marine monitoring. Where applicable, it will refer to the *National Multibeam Guideline* for further details of operational steps. It will also provide further specific details of pre- and post-surveying considerations required for marine monitoring activities when planning swath mapping surveys. This will include surveys required for both broad scale mapping to inform the development of habitat maps, and those being conducted as a component of monitoring. Further details of marine sampling platforms used to ground truth acoustic data, and to monitor of ecological indicators are presented in the accompanying NESP field manuals (Chapters 4-9).

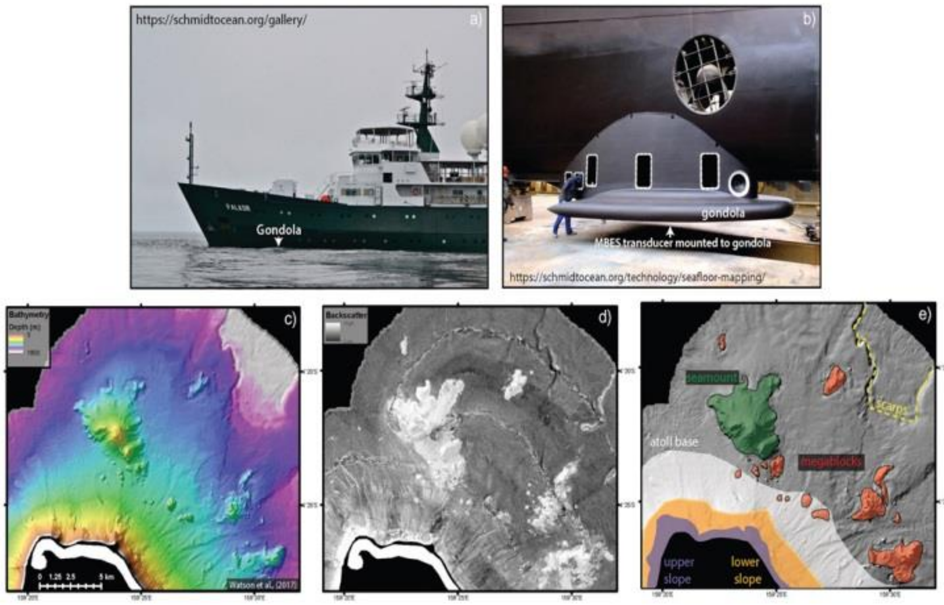

Figure 3.1. a) Multibeam transducer mounted on the hull of a ship in the (b) gondola. c) Multibeam acoustic bathymetry image c) coincident backscatter image and d) interpreted geomorphology map. (reference: Watson et al., 2017).

3.2 Scope

This manual refers to the use of multibeam or interferometric echosounders (referred herein as just multibeam or MBES) to conduct surveys of seafloor bathymetry and backscatter that can be used to derive maps of geomorphic features and habitats. It does not mandate use of a specific multibeam acoustic system (either an interferometric[3] or beamforming[4] multibeam). The examples given herein refer to Kongsberg systems merely as an exemplar of the procedure to be conducted. Similarities can be drawn from these examples to any particular MBES system being employed on the survey.

There are a number of multibeam echosounders that have been commonly used for surveying in Australian waters that would be suited to marine monitoring activities. It is important that the surveyor be mindful that there are differences in the way bathymetric measurements are made from both interferometric and beamforming multibeam echosounders, and these influence the scale and resolution of features being detected and the fidelity of the acoustic measurements (which is important for monitoring). The main difference is namely due to beam formers measuring range for each of a set of angles, and interferometers measuring angle for each of a set of ranges (Table 5). We have outlined the standard methods that are relevant to any of these systems to provide a framework to create a nationally consistent multibeam data archive for Australian marine and coastal waters.

This field manual details the specific planning, acquisition, processing and reporting considerations that are required to meet the seafloor surveying needs of monitoring programs. Although MBES can be used for water column data collection, these data are outside the scope of this standard operating procedural document in its current version (Version 0.1). This document provides guidance to organisations responsible for permitting and supporting research programs (e.g. Parks Australia) to collect multibeam data for monitoring programs (e.g. government research agencies, universities) to ensure consistency in acquisition and processing of multibeam acoustic data. This will increase the chance that data and spatial data products from different organisations and swath systems can be combined and reused into the future and become a valuable data asset for national research objectives; ongoing monitoring and planning. This manual is subset by four main phases of a seabed mapping survey as outlined in Figure 3.2:

1. Data acquisition;
2. Data processing;
3. Benthic classification (data interpretation),and
4. Accuracy assessment and reporting (including metadata management of spatial data products).

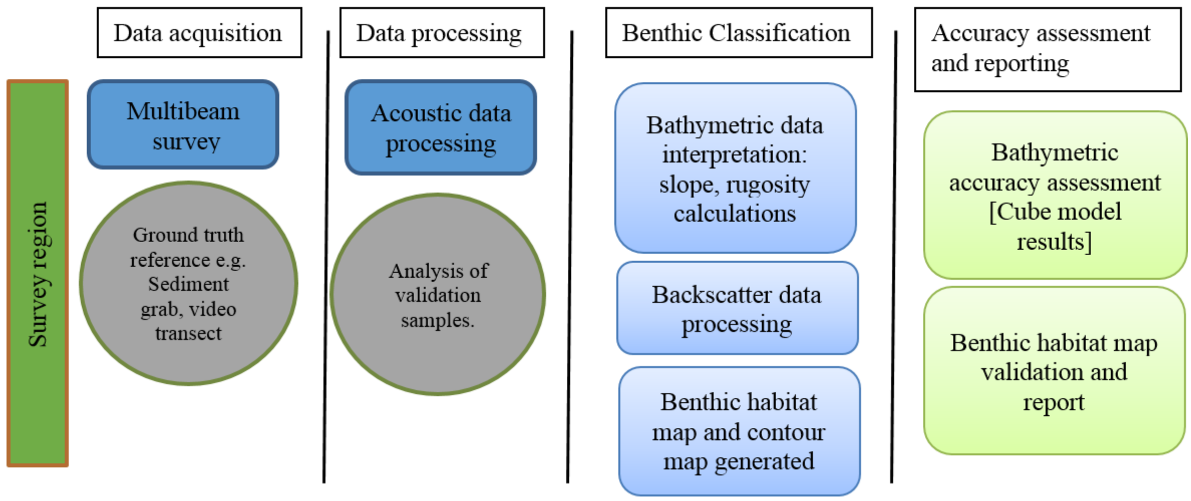

Figure 3.2. Workflow from MBES survey design to spatial data products and reporting

Table 3.1. Comparison of bathymetric systems (reference: Bathyswath.com)

Parameter / Function	Interferometric Multibeam	Beamforming Multibeam	Notes
Number of depth measurements	6000+	60-120	Depends on range
Range vs. water depth	10 - 20	3-5	Beam former 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 beam former. Many beam formers are much larger.
Horizontal resolution at range	Good	Poor	Beam former footprint becomes unacceptably large at far range.
Angular coverage	260°(including 20° overlap)	90°- 180° (or beyond 180° using a dual head system)	
Co-incident sidescan	True	Partial	An interferometer collects amplitude in the

			same way as its bathymetry: as a time-series.
Profile data density	Increases with reducing grazing angle	Decreases with reducing grazing angle	Higher complete profile data confidence with an interferometer.
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 beam former collects slightly more depth samples. Beyond that, an interferometer collects many more.
Capacity to acquire water column information?	Yes	Yes	Interferometric systems can identify targets in the water column but are unable to characterise them accurately due to lack of beam forming angles to locate the target.

3.3 Multibeam Acoustics for Marine Monitoring

The use of MBES for mapping and monitoring marine habitats has experienced a rapid increase since 2000 (Figure 3.3), and there is now a wealth of knowledge from which we can synthesise a 'best practices' document.

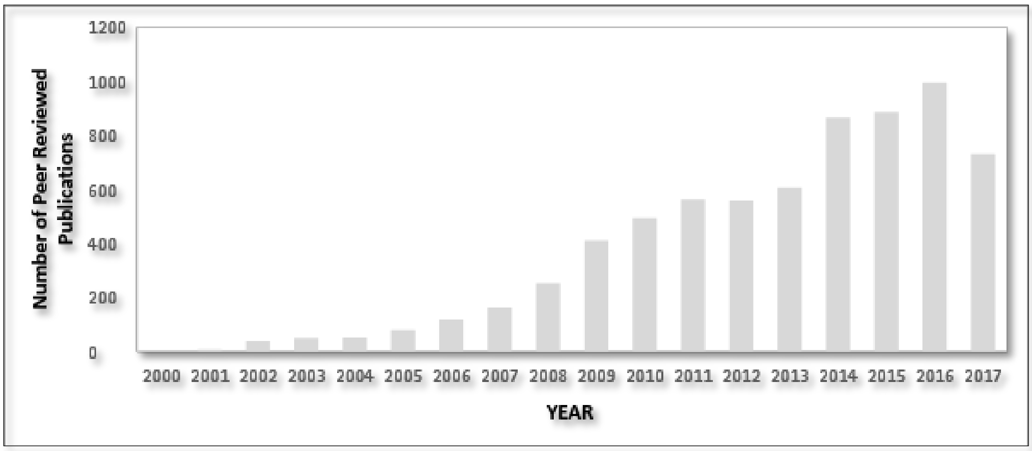

Figure 3.3. Annual total of peer reviewed papers featuring multibeam mapping for seafloor survey (Web of Science 2017-search words "multibeam seafloor habitat survey").

The **objectives** of multibeam acoustic surveys conducted by mapping programs are to collect seafloor data to identify, delineate and map biogenic, anthropogenic and geological features. This objective requires particular data to be collected that can a) chart the water depths creating a high resolution bathymetric map at an appropriate resolution in regards to the target habitat or feature and b) be able to differentiate boundaries between different substrate and/or habitat types.

To meet these objectives, there are two particular needs for mapping and surveying that can be defined as either baseline surveys or monitoring surveys (see Table 2). MBES can be used for both survey types, however, they have different acquisition and post-processing standards. A **baseline survey** is for exploratory purposes where data will be collected in a 'single pass operation'. This data is used to map the distribution of marine habitats at a particular spatial scale, and provide information necessary for more targeted field surveys using such tools as towed video, AUVs and stereo baited remote underwater video stations (BRUVs) (Lucieer et al. 2013, Monk et al. 2016). In contrast, a **monitoring survey** may have already identified target habitats or features (such as rocky outcrops) from previous broad scale or other hydrographic data that are to be monitored to assess change in distribution and extent (Rattray et al. 2009, McGonigle et al. 2010). This type of survey will require acoustic data to be collected at a higher resolution and with a greater degree of positional accuracy. Mapping for baseline survey and monitoring surveys will be dealt with separately throughout the manual, with their differences and the requirements that need to be considered to meet the aims of each survey type outlined in Figure 3.4.

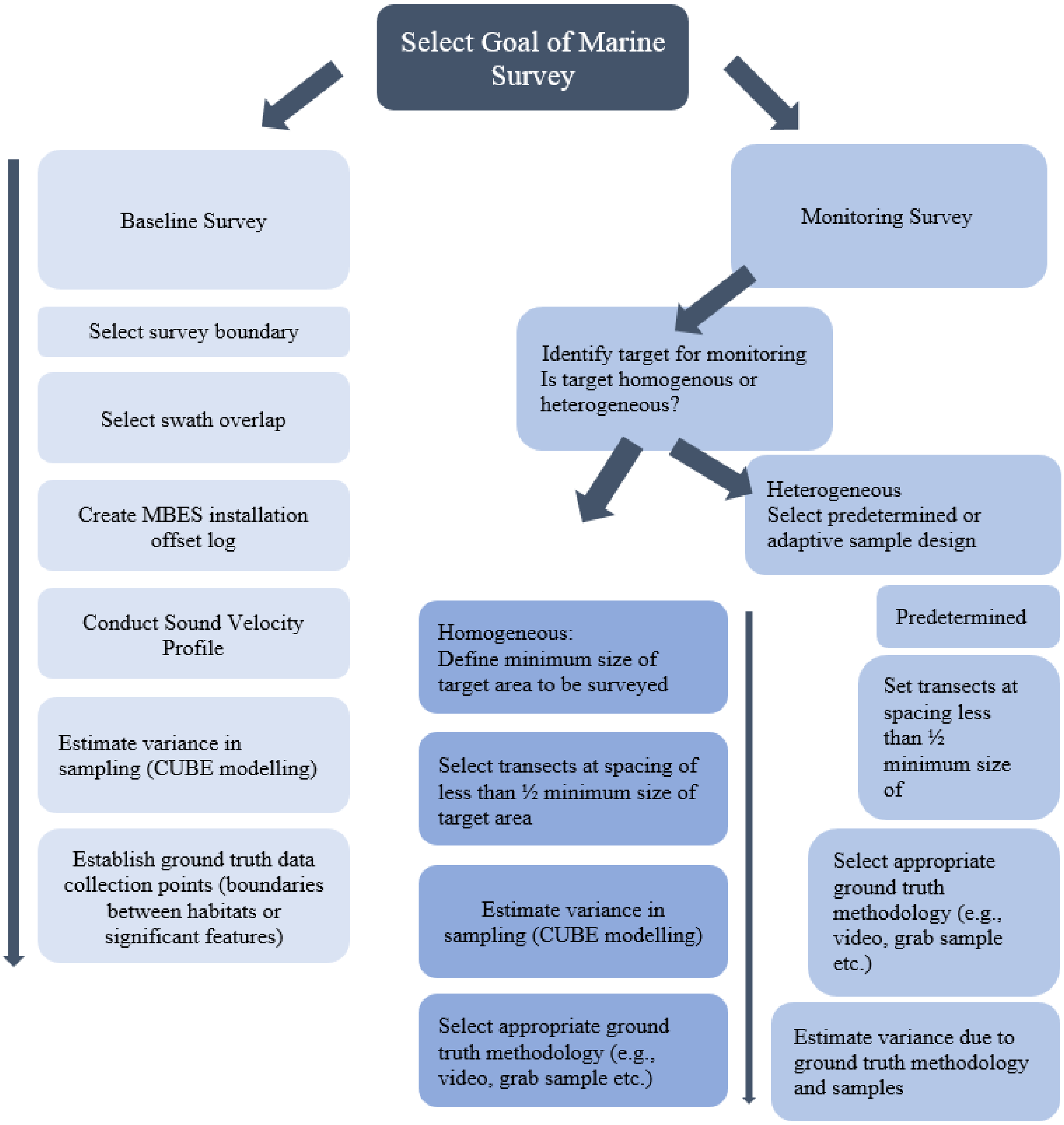

Figure 3.4. Decision tree for seabed classification survey design (adapted from Anderson et al. (2007)).

Table 3.2 Standard Operating Procedures identified according to survey purpose: Baseline or Monitoring

Specification	NESP Baseline	NESP Monitoring
Purpose	• Used to identify seafloor habitats and potential biodiversity hotspots. • Used for discovery purposes in regions that have had no baseline mapping conducted.	• Used to ensure spatio-temporal assessment of the seabed and habitat. The survey accuracy standard is very high to ensure reproducibility over time. • Used for repeat mapping and for targeting key habitats for monitoring purposes.
Pre survey preparation	• The coverage of the area to be surveyed (bounding box) with the datum and coordinate system clearly identified. • Establishment of line spacing • Determination of the system offsets and calibration area (patch test) area to be conducted as soon as practical and after system is completely set up ready for survey. The location and scheduling of the Sound Velocity Profiles	• In addition to baseline survey specifications: • Synthesis of all pre-existing survey data into survey region database • Identification of locations of seafloor targets to be monitored • Establishment of line spacing with min of 60% overlap.
Installation Offsets	• Provide Mobilisation Calibration Reports and logs	• Provide Mobilisation Calibration Reports and logs
Data Logging	• Bathy: Mandated • Seabed Backscatter: Mandated • Water column backscatter: Recommended (if available)	• Bathy: Mandated • Seabed Backscatter: Mandated • Water column backscatter: Mandated (if available)
Acquisition setting	• Mode: Equidistant mode where system allows • Minimise setting changes to optimise backscatter	• same
Sound Velocity Profiles	• Min of 1 per day, but should be monitored. • If sound speed at the transducer varies by > 2m/s another SVP should be collected	• Min of 2 per day (beginning and end of survey), but should be monitored. • If sound speed at the transducer varies by > 1m/s another SVP should be collected
Geodetic Parameters	• GDA2020. Horizontal accuracy: 5m + 5% of water depth. Vertical accuracy: 1% water depth	• GDA2020 -– Horizontal accuracy: absolute positioning to be at< 2 or less. Vertical accuracy: < 1m
Survey Speed	• Recommended 6 knots (or at survey speed appropriate to capture resolution required)	• Recommended 5 knots (or at survey speed appropriate to capture resolution required)
Mapping Coverage	• 100% Coverage with 30% overlap between survey lines of data with an 80% confidence level.	• 100% coverage with 60% overlap between survey lines of data with an 80% confidence level.
Resolution	• 1 m resolution in < 50m depth ; 5% of depth beyond 50 m	• 1 m resolution

Tides and GPS Tide	• Record GPS tides. All soundings shall be reduced to the ellipsoid.	• Record GPS tides. All soundings shall be reduced to the ellipsoid.
Point data attribution	• All data should be attributed with its uncertainty estimate at the 80% confidence level for both position and, if relevant, depth.	• All data should be attributed with its uncertainty estimate at the 95% confidence level for both position and, if relevant, depth.
Metadata and Reports	• Metadata report shall include heading and data deliverables outlined in this manual. Calibration Report and Report of Survey.	• Metadata report shall include heading and data deliverables outlined in this manual. Calibration Report and Report of Survey.
Archiving	• Australian Online Data Network (AODN) data portal. • National MBES Data Centre	• Australian Online Data Network (AODN) data portal. • National MBES Data Centre
Purpose	• Used to identify seafloor habitats and potential biodiversity hotspots. • Used for discovery purposes in regions that have had no baseline mapping conducted.	• Used to ensure spatio-temporal assessment of the seabed and habitat. The standard is very high to ensure reproducibility over time. • Used for repeat mapping and for targeting key habitats for monitoring purposes.
Pre survey preparation	• The coverage of the area to be surveyed (bounding box) with the datum and coordinate system clearly identified. • Establishment of line spacing • Determination of the system calibration (patch test) area to be conducted as soon as practical and after system is completely set up ready for survey. The location and scheduling of the Sound Velocity Profiles	• In addition to baseline survey specifications: • Synthesis of all pre-existing survey data into survey region file • Identification of seafloor targets for monitoring • Establishment of line spacing with min of 60% overlap.
Installation Offsets	• Provide Mobilisation Calibration Reports and logs	• Provide Mobilisation Calibration Reports and logs
Data Logging	• Bathy: Mandated • Seabed Backscatter: Mandated • Water column backscatter: Recommended	• Bathy: Mandated • Seabed Backscatter: Mandated • Water column backscatter: Mandated
Sound Velocity Profiles	• Min of 1 per day, but should be monitored. • If sound speed at the transducer varies by > 2m/s another SVP should be collected	• Min of 2 per day (beginning and end of survey), but should be monitored. • If sound speed at the transducer varies by > 2m/s another SVP should be collected
Geodetic Parameters	• 84ITRF with epoch reference. Horizontal accuracy: 5m + 5% of water depth. Vertical accuracy: 1% water depth	• 84ITRF with epoch reference -– Horizontal accuracy: absolute positioning to be at< 21 m or less. Vertical accuracy: < 1m
Survey Speed	• 6 knots	• 5 knots

Mapping Coverage	• 100% Coverage with 30% overlap between survey lines	• 100% coverage with 100% overlap between survey lines
Resolution	• 1 m resolution in < 50m depth ; 5% of depth beyond 50 m	• 1 m resolution (may require AUV or towed body in water depths >200 m)
Tides and GPS Tide	• Record GPS tides. All soundings shall be reduced to the ellipsoid.	• Record GPS tides. All soundings shall be reduced to the ellipsoid.
Point data attribution	• All data should be attributed with its uncertainty estimate at the 80% confidence level for both position and, if relevant, depth.	• All data should be attributed with its uncertainty estimate at the 95% confidence level for both position and, if relevant, depth.
Metadata and Reports	• Metadata report shall include heading and data deliverables outlined in this manual. Calibration Report and Report of Survey.	• Metadata report shall include heading and data deliverables outlined in this manual. Calibration Report and Report of Survey.
Archiving	• Australian Oecan Data Network (AODN) data portal. • National Data Centre	• Australian Ocean Data Network (AODN) data portal. • National Data Centre

3.4 Pre-Survey Preparations

There are a number of important factors that first need to be considered in order to ensure relevant areas are surveyed, time and costs can be accurately estimated, appropriate vessels and acquisition gear is used, and previous survey data is considered.

Firstly, it is important that all spatial data for the survey region must be sourced to gain a preliminary understanding of the seabed as this will influence several survey considerations. This information can be used to create a *survey plan*, which would include a summary of the following components:

- The coverage of the area to be surveyed (bounding box) with the datum and coordinate system clearly identified,
- Planned survey lines (direction and acquisition order of the survey lines),
- System calibration survey lines (patch test),
- Seafloor topography (features of interest) and slope, and
- The location and frequency of the Sound Velocity Profile (SVP).

Background spatial data might include electronic nautical charts from the Australian Hydrographic Office (AHO), aerial photos (in shallow water regions), LiDAR or satellite derived bathymetry data. It may also include previous maps of seabed habitats generated from single beam acoustic surveys or maps of sediment distribution from broad scale seafloor grab or dredge surveys. Information on seabed habitats can also be collected by analysing the distribution of other activities conducted within the survey region (for example, ancillary research such as fisheries surveys may be an indicator of habitat type).

The survey plan will aim to establish the range of water depths and seafloor complexity across the survey region. The range of water depths will define how many survey lines need to be conducted to ensure sufficient overlap between the acoustic swaths to ensure 100 % seafloor coverage (refer to Chapter 2 where coverage may relate to selected sampling sites). Where the water depth is relatively constant (such as on the outer continental shelf), the survey plan may provide adequate structure for accurate planning. In shallower waters, where the depths may change rapidly (or are unknown to the resolution of national satellite derived products) a comprehensive plan of survey lines may not be useful, as they will need to be modified as the bathymetric data is collected. In this case, a defined survey area boundary (polygon) with an initial survey line for calibration may be sufficient.

An essential component of the survey-planning phase is the need to obtain the relevant permits that may apply for sediment data collection which is common for MBES data validation, especially when conducted within marine parks. See Appendix B for a list of potential permits needed.

Following the establishment of the survey plan the logistical preparations for data acquisition can be conducted. These are outlined in the following sections and recorded in the vessel or field logbook over the duration of the survey and made available in the final reporting documentation.

3.5 Data Acquisition

3.5.1 Installation offsets

The spatial relationship between all of the sensors in an MBES system (GPS, transducer, motion reference unit etc.) with the vessel's frame of reference is paramount to obtaining high resolution and accurate data. The vessel's Central Reference Point (CRP) is determined upon each *new* installation of a MBES system and to best suit the vessels balance, and installation criteria (if the MBES is hull or pole mounted) (Edward and Martin 2015). The CRP is defined, as an example, within the Kongsberg operating systems Seapath software along with the installation offsets for the Global Navigation Satellite System and Motion Reference Unit. The offset of the MBES transducer is defined within the Kongsberg Seafloor Information System (SIS) software. Where possible the CRP should be defined at the MBES transducer directly. All installation offsets are required to be recorded and detailed within the survey report and processing log of the supplied raw data files.

To ensure that the depth charted is the true depth and not depth under keel, the vessel draft must be taken into consideration during data acquisition (likely at the start and end of a survey) to account for changes in draft due to foe example (fuel usage) although this will depend on the model of the vessel used for survey. Although this manual recommends that depths be provided in relation to the ellipsoid, to enable other users to reduce data to chart datum, vessel draft should be measured at the start and end of surveys and dynamic draft taken into consideration with measurements of the waterline conducted regularly. The vessel draft is recorded during a survey in the vessel log and/or entered in the acquisition system. For further information see section 2.4 of Australia's Multibeam Guideline (Version 0.1).

3.5.2 Data logging

During a survey with a MBES system there are a number of data products that should be recorded. These include:

1. Raw data: Always log raw proprietary format for all type of data (multibeam echosounder or ancillary systems). Raw positional data and motion datagrams are to be recorded at a rate of 1Hz and 100Hz respectively. These datagrams are logged to the raw sonar file.

2. Raw sonar data are recorded in the native/proprietary format of the multibeam system used (e.g. *.all for Kongsberg, *.s7k for Reson) and the ancillary data. Log complete backscatter i.e. beam intensity (RI and snippets or equivalent. Files are recorded for a duration of 30 minutes for shallow systems (< 150 m) and 120 minutes for deep systems (> 150 m) to account for computer processing speed.

3. Water column data [Recommended, if available]: Water column datagrams are logged to a separate file in proprietary format (e.g. *.wcd for Kongsberg). These files can take up a large amount of storage space (~ 10 times raw bathymetry), and the surveyor must ensure necessary disc space prior to collection.

4. File naming convention: It is important that the surveyor adhere to a consistent and acceptable naming convention that links to the metadata of the raw data format. Raw sonar files in proprietary format recorded by an acquisition software (e.g. SIS for Kongsberg) have the following naming convention.
   [Nnnn_yyyymmdd_hhmmss_Vesselname_system.Extension] [Survey line, year, month, day, hour, minute, second, vessel name, multibeam acoustic system. proprietary format extension (e.g.all for Kongsberg and s7k for Reson]. Survey lines are organised by Julian

day within the processing software but are acquired sequentially as line IDs throughout the survey. Where two separate systems are being operated at the same time on the same vessel, they can be distinguished by the system name of the MBES in the file name. If a new survey is to be created within the acquisition software during a survey the line number should be reset to the last number used +1.

5. Filters and settings: Both noise and spike filters should be monitored during the survey to ensure the data quality and integrity is maintained over the course of the survey. Beam spacing mode should be set to equidistant. It is very important that the pulse length should not be changed at any time during the survey so that all data are standardised.

6. Delayed heave: delayed heave datagrams are recorded by the acquisition computer and logged to files in the proprietary format.

3.5.3 Sound velocity profiles

A sound velocity profile (SVP) measures the speed of sound in water at different vertical levels in the water column and this data can be used to accurately form the beam of the sound. Some multibeam systems have a SVP sensor built onto the head of the transducer but for others that do not, it is important that a SVP sensor be deployed to collect this information.

Why are sound velocity profiles so important?
A MBES system emits a sound pulse in an arc out from the transducer. As the sounds contacts the seabed, it is reflected/backscattered back towards the transducer and received. Each backscattered pulse from each individual seabed point can be considered a discrete beam. The speed of the beam through the water column is governed by the water temperature and density. Because the water column, in most cases, is not evenly mixed, the speed of the pulse changes at different levels in the water column. At each change in speed, refraction or 'bending of the pulse path' occurs, unless the angle of incidence is equal to 90 degrees, as with a single beam echosounder. Refraction can happen many times throughout the pulse's path through the water column. Therefore, to enable best ray tracing possible and consequently depth conversion of each soundings, details of the water column sound profile are essential. Depending on the location of the survey and the conditions over the area (sea state, mixing regime, thermal layering etc.) of the survey, sound velocity profiles (SVP) should be conducted at the appropriate intervals or location. The SVP can be determined using one of the following four methods:

- Direct observation via deployment of a SVP measuring device (e.g. Valeport monitor)
- Calculation of SVP through deployment of an eXpendable Bathy Thermograph (XBT)
- Calculation of SVP using CTD (Conductivity/Temperature/Depth) data and applying the UNESCO formula (https://www.usna.edu/Users/physics/ejtuchol/documents/SP411/Chapter4.pdf) or;
- Calculation of SVP from Sea Surface Temperature and Climatology using SVP builder software (Sinquin et al. 2016).

How are SVPs applied to multibeam surveys?
A sound velocity profile (SVP) must be taken *within* the survey area at least once at the beginning of the survey and once at the end for monitoring surveys. In some areas, multiple SVPs should be taken. For example, profiles will vary due to freshwater inflows from rivers or currents from areas with different salinity e.g. proximity to an estuary. Surface sound speed variation may also be strongly affected also by solar warming. If variations can be expected, where and when the SVPs are to be taken must be carefully planned, and the survey line schedule adjusted to consider this.

Sound speed data is used in the following ways:

- correction for the fact that the transducer staves are the wrong spacing in wavelengths;
- correcting for the change in total sound path length because of the speed of sound variation, but ignoring refraction and;
- correcting for both refraction and sound path length.

Path length correction uses the speed of sound to determine the sonar path length from the time the ping is transmitted to the time it is received. The average speed of sound within the speed of sound profile is used for this, measured from the depth of the transducers to the depth of the seabed.

3.5.4 Geodetic parameters

The datum parameters entered into the acquisition software will use the Global Navigation Satellite System (GNSS) datum for example WGS84 (Table 3.2). Any datum shifts will need to be applied at the post processing stage. The use of differential GPS as a positioning system is required for all on-shelf and off-shelf multibeam acoustic data collection as we aim to resolve an absolute positional accuracy greater than 1 m. All positioning data should be provided as track plots (in x, y format) to enable interpretation of the vessel transits.

3.5.5 Survey speed

The speed of the vessel will have a direct impact on the density of soundings reaching the seafloor, the quality of the data (in the return signal) and to some degree determine the resolution of the final raster datasets (as it dictates the distance along track between pings). Depending on the type of vessel employed for the surveying, the survey speed must be kept constant and between 5-6 knots (11 – 14 km/h). The distance between pings along the track of the vessel is determined by the pulse repetition frequency (PRF) and ship speed; the faster the vessel, the fewer pulses ensonify the seafloor per distance along track. Aeration problems (bubble sweep) is a function of sea state but also of the heading with respect to the wave direction and the vessel speed. Aeration problems reduce the signal or the quality of the signal at the transducer head.

It is strongly advised that the surveyor creates a record of aeration problems versus sea state with respect to heading and vessel speed. This record will be helpful in ensuring that the survey is performed efficiently with a minimum of line rejections and corresponding reruns and infills. This should be recorded in the field log book.

3.5.6 Line spacing

Line spacing is the distance between adjacent survey lines. The best spacing between survey lines is determined by a combination of horizontal range limit (sonar coverage from one transducer) expected at that depth of water and the accuracy required from the survey (either baseline mapping or monitoring). The horizontal range expected depends on the water depth as well as the sea state, seabed type and the sonar frequency. If the surveyor is using two transducer heads, the total swath width from the port edge to the starboard edge is 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. At the grazing angle limit, the sound makes a very small angle with the seabed. Most of the sound at this point is reflected away and the signal scattered back from the seabed is too small to be detected.

Due to this loss of signal on the outer beams of the swath, some overlap in swath is required. A minimum of 30% overlap should take into account line keeping errors and where sea state is calm and create a 100% coverage of the seafloor. The type of survey being undertaken will determine the overlap with the highest quality requiring 100% overlap and the lowest quality requiring 30% overlap (Table 3.2).

The seafloor topography and the slope (gradient of the slope) is an important consideration for planning the survey lines. For MBES data collection, it is strongly advised to run the lines parallel to the seabed contours (along the slope, not up or down the slope). This is beneficial for keeping the coverage reasonably constant along the survey lines (as the swath width will vary with depth). It is also beneficial because less acoustic energy is reflected towards the transducer from steep slopes, causing poorer detections and the possibility of false detections in the sidelobes[5]. If survey lines must run up and down the slope, a reduction of vessel speed or reduction in swath width may be required to allow for the echo sounder to track the bottom continuously. Planned lines must be activated in this instance to ensure that gaps are not created between the survey lines as the swath coverage is reduced coming into shallow water and additional lines may need to be added.

For surveys where backscatter information is critical, the overlapping area should be increased (from 60% to 100%) to compensate for the high variability of individual backscatter intensities on the edges of the outer beam (Gavrilov & Parnum, 2010). For surveys where backscatter information is considered a secondary product, it is recommended that the overlapping be kept as minimal as practical (30% overlap).

3.5.7 Pulse length

The pulse length affects the amount of the transmitted acoustic energy into the water and the vertical resolution of the observed depth. Increasing pulse length enhances penetration through the water column but reduces vertical resolution. Kongsberg systems have limited, pre-defined options for pulse length which may be synonymous with other software packages. Therefore, the selection used may compromise the quality of backscatter data in order to meet the objectives of the survey.

Pulse length and sampling frequency must be considered as related to backscatter data. The sampling frequency of the system must be considered in order to hold the Nyquist-Shannon sampling theorem[6]. This enables the analogue signal to be reconstructed from the digital data (e.g. Kongsberg EM3002 systems recommended minimum pulse length of 100µsec or greater).

3.5.8 Tides and GPS tides

MBES data shall be corrected in real time for draft and tide variations as well as attitude input (roll, pitch, yaw and latency) via the vessel's Motion Reference Unit (MRU). All soundings shall be reduced to an ellipsoid with a minimum depth accuracy of 0.2% relative to water depth.

3.5.9 Data type

Bathymetry and backscatter datasets shall be processed and plotted onboard to monitor the coverage and data quality. This will allow for additional acoustic to be collected prior to the finalisation of the survey, in the event of data gaps between survey lines for example. Processing will be carried out to create full coverage bathymetric maps with contours, slope values and backscatter images. Onboard processed products shall include the following:

Bathymetry

- All raw bathymetric data is to be provided in proprietary format.
- Processed data is to be provided as a point cloud text file (or .csv) in UTM and depth (with depth value as negative) with uncertainties attached to each sounding.
- Processed data shall also be provided as gridded data in formats csv, ARC GIS Grid. ESRI ASCII *.asc format in UTM format.
- The requirement for gridding interval of MBES data is 1 m or better in shallow water (<100 m), 5 m in deeper water (100 – 200 m) and 10 m off the shelf (>200 m).
- Bathymetric charts shall be displayed with the smallest contour interval representative of the seafloor morphology.
- Any smoothing of contour lines is to be kept to a minimum.
- As a QA product, two images of the gridded processed bathymetry data should be provided with sun-illumination from two orthogonal directions and 5 times exaggeration

Backscatter

- All raw backscatter data is to be logged in proprietary format.
- Processed data is to be provided as a text file (or .csv) showing latitude, longitude and intensity (dB) (or provided in a format that is able to be converted to comma delimited csv files).
- Processed backscatter data is preferred as xyz ASCII comma delimited (XY in UTM zones; z in dB with 2 decimal places), and/or ESRI ASCII *.asc (values in dB) (Buchanan et al. 2013).

3.6 Data Processing

The data acquisition parameters are established to ensure that the data are fit for the purposes of benthic habitat mapping (i.e. baseline) and monitoring of Australia's waters. The post processing parameters and techniques, on the other hand, are generally optimised for a targeted purpose (and differ for a baseline or monitoring survey). There are a number of software packages available for processing MBES data and many of the software are in commercial proprietary to the specific multibeam system used for acquisition.

Regardless of the data processing software that is used (e.g. CARIS), the goal is for the minimum final products to be released at the completion of a field survey (summarised in Table 3.3):

- Bathymetric surface as both an x,z,y point surface and a raster x,y,z to the appropriate resolution requested (Table 3.2);
- Vessel transect log map to show the position of the vessel survey lines within the region;
- Map showing the location of field validation data (e.g. point map of where sediment grabs or video transects have been conducted etc) *[Recommended]*;
- Digital terrain models with hill-shading of the bathymetry from two orthogonal direction and 5 time exaggeration to easily identify artefacts of the dataset remaining, but also to identify key geomorphological features (including slope map) *[Recommended]*;
- Backscatter mosaic (both raw and processed) in geotiff format in the optimal resolution from the snippet and at 1 m from the average beam values;

- Water column backscatter (display of water column acoustic anomalies and x,y,z location of features detected in the water column) [*Recommended, if available*]; and
- 3D perspective videos of significant findings or seabed features (abrupt changes in relief, shipwrecks, canyon head steps etc.) *[Recommended]*.

3.6.1 Bathymetric data processing

Uncertainty related to the bathymetric (depth) measurements can be quantified and incorporated into a statistical model to derive the total propagated uncertainty (TPU) of the resulting bathymetric surfaces. A number of factors will influence this uncertainty including: draft setting of the transducer, incorrect sound velocity profiles, spatial variation in the sound velocity, temporal variation in the sound velocity, instrumental uncertainty (internal precision of the MBES unit) and motion (incorrect heave, pitch and roll corrections), settlement and squat of the vessel in the water and incorrect tidal corrections to name a few.

Where possible the CUBE (Combined Uncertainty and Bathymetry Estimator) should be used to calculate the TPU for the bathymetric surface as a measure of uncertainty in the survey. CUBE uses soundings and their associated uncertainty estimates as input and through spatial and uncertainty weighting, while also relying on the very high data density of multibeam data sets, outputs a bathymetry gridded surface and its associated uncertainty (error) surface. In addition, it tracks the statistical hypotheses for each depth point, and where there is more than one estimate, makes an attempt to determine which the most likely value is. This makes it a very powerful tool for identifying and removing outliers in the data. Once these have been removed from the data, CUBE is rerun to generate the final bathymetry and uncertainty surfaces. See "CUBE Bathymetric data Processing and Analysis (CHS February 2012)". The uncertainty surface is a quantification of the survey quality, which can be compared against specifications and used as input to the metadata for the survey (CHS 2013).

3.6.2 Backscatter data processing

A final compensated Geotiff mosaic of the acoustic backscatter for the survey region should be generated. We refer to the Lurton, X.; Lamarche, G. (2015) Backscatter measurements by seafloor-mapping sonars. Guidelines and Recommendations. Geohab Report. 150p, for optimal processing procedures for MBES backscatter image generation.

3.7 Data Interpretation

MBES bathymetric data will be processed to characterise and classify the seafloor in terms relevant to the distribution of benthic habitats and to help in the understanding of the spatial and temporal distribution of marine habitats. The combination of topography (bathymetry) and textural surfaces (backscatter) provide an excellent reference dataset for research and management of Australian marine seafloor habitats.

Geomorphological analysis can be used to classify the multibeam bathymetry data and define the extents of particular habitat types such as seagrass beds, rocky reef, and sand plains. We recommend the use of the national standardised benthic habitat classification nomenclature as documented by Seamap Australia (Butler et al. 2017). Importantly, this classification system includes other established and developing national classification schema such as CATAMI (Althaus et al. 2015) and Geoscience Australia's *Classification and Glossary of Seabed Geomorphology*.

The backscatter Geotiff can be interpreted into a sediment distribution and habitat map using one of two automated segmentation methods:

1. Image-based segmentation (e.g., using e-Cognition (www.ecognition.com)) where the image is segmented into regions of similar backscatter characteristics and using the bathymetric data to identify these boundaries and transition zone. These segments are then classified as surface features, backscatter intensity patterns of sediment/habitat distribution etc.
2. Signal based segmentation (e.g., using ENVI (www.esriaustralia.com.au/envi) where changes in the backscatter intensity, with increasing grazing angle from nadir, are analysed to classify the data.

Table 3.3 Expected data deliverables for a baseline mapping or monitoring survey to accompany metadata reporting

Deliverable item	Comment
Raw sonar data	Raw sonar data in native format as created directly from the native acquisition system of the multibeam system used. e.g. ***.all** for Kongsberg EM series, ***.s7k** for newer version of Reson SeaBat or ***.xtf** for the older one **Data format:** native format as produced by the acquisition system, except for the *.xtf **Datagram:** all logged automatically for Kongsberg EM series. For **Reson SeaBat**, datagrams with the following IDs are required: **1003, 1012, 1013, 7000, 7001, 7002, 7004, 7006, 7005, 7007, 7012, 7022, 7028, 7200, 7504** The water column data, recorded as separate files, for both Kongsberg and Reson are only required on special request in survey planning. For all other multibeam systems, it is required that raw data include SV profile, attitude, navigation, heading, raw bathymetry, **raw backscatter per beam** and if available **raw backscatter in time series** i.e. the equivalent seabed image or snippet style
Processed sonar data	Processed multibeam bathymetry data, including processed multibeam backscatter data, if requested **Preferred format:** Caris HIPS & SIPS project structure including processed **bathymetry surface** (see processed bathymetry grids below) (***.csar and XYZ**) and time series-generated **backscatter mosaic** (***.csar**) in **Fieldsheets** subfolder, processed **line** data & **geobar** in **HDCS_Data** subfolder, tide data used (***.tid**) in **Tide** folder, individual sound velocity profiles (***.csv**) used together with additional information on time and location of the cast in **SVP** subfolder. Backscatter mosaic and geobar are only required on request **Alternative format:** **Processed line:** SAIC GSF (*.gsf) if no other alternative
True Heave	Delayed, processed heave saved independently from raw sonar file, logged in 600-720 minutes period **Data format:** Applanix ATH or equivalent (Caris compatible)
Processed bathymetry grids	Processed multibeam bathymetry surface grid **Data format:** CSAR and xyz ASCII comma delimited (XY in specified UTM; z in negative metre at 2 decimal places) and/or ESRI ASCII *.asc (values in meter).
Processed backscatter mosaic	Processed multibeam time series-generated backscatter mosaic **Data format:** xyz ASCII comma delimited (XY in specified UTM; z in dB at 2 decimal places) and/or ESRI ASCII *.asc (values in dB).
Tide	Tide data used for tide correction (date, time and depth(m.mm)/pressure (dBar) **Data format:** Caris tide *.tid or ASCII *.csv
Sound velocity profile	Sound velocity casts used in SIS or equivalent acquisition system together **Data format:** ASCII *.csv
Log file (SVP cast)	SVP cast info (date, time, depth of cast and seafloor, location and line applied to) **Data format:** ASCII text
TPU/ CUBE related information	• XYZ of MRU to Transducers • XYZ of NAV to Transducers • Transducers mounting angles (if not horizontal) • Type of Navigation system • Type of MRU system • Sign conventions used to calculate XYZ (Down positive etc) **Data format:** ASCII text

3.8 Data Release

At the time of writing this manual, there is not currently a complete repository for multibeam data collected in Australian waters, although several agencies house some multibeam data (e.g. AHO, GA, IMOS, CSIRO), and several portals promote its accessibility and visualisation (e.g. seamapaustralia.org). Initiatives are underway for a single repository to be linked to appropriate visualisation platforms, and this is expected to be addressed in Version 2 of this field manual.

In the meantime following the steps listed below will ensure timely release of data and maximise data discoverability:

1. Create metadata record(s) describing the survey and data collection (for both raw and QA/QC data products). Minimum metadata requirements for multibeam data include the following:
   - Title of the survey region (e.g., AMP name and ID) and, if not a well-established region, its geographic boundary;
   - Surveyor's name and company;
   - Start and end dates of the survey;
   - Vessel name, type of vessel and MBES unit used, details regarding the positioning system, acquisition software, and operation parameters;
   - The number of lines recorded and corresponding number of kilometres; and
   - Summary of the main survey results (water depths, observed tidal range, sonar features of interest- anomalies, unusual targets etc.).
2. Publish metadata record(s) to the Australian Ocean Data Network (AODN) catalogue as soon as possible after metadata has been QC-d. This can be done in one of two ways:
   - If metadata from your agency is regularly harvested by the AODN, follow agency-specific protocols for metadata and data release.
   - Otherwise, metadata records can be created and submitted via the AODN Data Submission Tool at https://metadataentry.aodn.org.au/submit. Note that user registration is required, but this is free and immediate.
3. Generate interactive map imagery of the following derived data layers:
   - Location map with limits of the survey area;
   - Bathymetric map showing the depths, slope and bathymetric hill shading results;
   - Backscatter data map showing boundaries between habitat features;
   - Location of auxiliary data sampling (point features of sediment grabs) or transect lines of video surveys; and
   - Map showing the track plot of the vessel position, indicating the region of the patch test calibration.
4. Upload raw multibeam data files and all field logs generated during the survey to a secure, publicly accessible online repository (contact AODN if you require assistance in locating a suitable repository).

5. Add links to the location of raw data and derived map imagery to the previously published metadata record. Metadata accompanied by map imagery as described above may be additionally showcased through the Australian Ocean Data Network portal.
6. Produce a technical or post-survey report documenting the purpose of the survey, sampling locations, sampling equipment specifications etc. Provide links to this report in all associated metadata records *[Recommended]*.

3.9 Field Manual Maintenance

In accordance with the universal field manual maintenance protocol described in Chapter 1 of the Field Manual package, this manual will be updated in 2018 as Version 2. Updates will reflect user feedback and new developments (e.g. data discoverability and accessibility). Version 2 will also detail subsequent version control and maintenance.

The version control for Chapter 3 (field manual for MBES) is below:

Version Number	Description	Date
0	Submitted for review (NESP Marine Hub, GA, external reviewers as listed Appendix A.	22 Dec 2017
1	Publicly released on www.nespmarine.edu	28 Feb 2018
2	Relevant updates, including Data Release sections based on NESP, AODN, IMOS, GA, and CSIRO projects	Early 2019

3.10 References

Althaus, F., N. Hill, R. Ferrari, L. Edwards, R. Przeslawski, C. H. Schönberg, R. Stuart-Smith, N. Barrett, G. Edgar, and J. Colquhoun. 2015. A standardised vocabulary for identifying benthic biota and substrata from underwater imagery: the CATAMI classification scheme. PLoS ONE 10:e0141039.
Anderson, J. T., D. V. Holliday, R. Kloser, D. Reid, Y. Simard, C. Brown, R. Chapman, R. Coggan, R. Kieser, W. Michaels, A. Orlowski, J. Preston, J. Simmonds, and A. Stepnowski. 2007. Acoustic seabed classification of marine and physical and biological landscapes. Denmark.
Buchanan, C., M. Spinoccia, K. Picard, O. Wilson, M. J. Sexton, S. Hodgekin, R. Parums, and P. J. W. Siwabessy. 2013. Standard Operation Procedure for a Multibeam Survey: Acquisition & Processing., Geoscience Australia: Canberra.
Butler, C., V. Lucieer, P. Walsh, E. Flukes, and C. Johnson. 2017. Seamap Australia (Version 1.0) the development of a national marine classification scheme for the Australian continental shelf. University of Tasmania.
CHS. 2013. Canadian Survey Management Guidelines. Fisheries and Oceans Canada, Canada.
Edward, S., and T. Martin. 2015. Geophysical Surveying and Mapping (GSM): Shallow water multibeam surveying standard operating procedure. CSIRO.
Gavrilov, A. and I. Parnum. 2010. Fluctuations of seafloor backscatter data from multibeam sonar systems. IEEE Journal of Oceanic Engineering. 35 (2): pp. 209-219.
Lucieer, V., and G. Lamarche. 2011. Unsupervised fuzzy classification and object-based image analysis of multibeam data to map deep water substrates, Cook Strait, New Zealand. Continental Shelf Research 31:1236-1247.
Lucieer, V. L., N. Hill, N. S. Barrett, and S. Nichol. 2013. Do marine substrates 'look' and 'sound' the same? Supervised classification of multibeam acoustic data using autonomous underwater vehicle images. Estuarine, Coastal and Shelf Science 117:94-106.
McArthur, M. A., B. P. Brooke, R. Przeslawski, D. A. Ryan, V. L. Lucieer, S. Nichol, A. W. McCallum, C. Mellin, I. D. Cresswell, and L. C. Radke. 2010. On the use of abiotic surrogates to describe marine benthic biodiversity. Estuarine, Coastal and Shelf Science 88:21-32.
McGonigle, C., C. Brown, and R. Quinn. 2010. Insonification orientation and its relevance for image-based classification of multibeam sonar. Ices Journal of Marine Science 67:1010-1023.

Monk, J., N. S. Barrett, N. A. Hill, V. L. Lucieer, S. L. Nichol, P. J. W. Siwabessy, and S. B. Williams. 2016. Outcropping reef ledges drive patterns of epibenthic assemblage diversity on cross-shelf habitats. Biodiversity and Conservation 25:485-502.

Porter-Smith, R., V. D. Lyne, R. J. Kloser, and V. L. Lucieer. 2012. Catchment-based classification of Australia's continental slope canyons. Marine Geology 303-306:183-192.

Rattray, A., D. Ierodiaconou, L. Laurenson, S. Burq, and M. Reston. 2009. Hydro-acoustic remote sensing of benthic biological communities on the shallow South East Australian continental shelf. Estuarine, Coastal and Shelf Science 84:237-245.

Sinquin, J. M., C. Vrignaud, and G. Mathieu. 2016. DORIS Software: A tool to process sound velocity profiles. Hydro International, Online: https://www.hydro-international.com/content/article/new-tool-to-process-sound-velocity-profiles?output=pdf

Watson, S. J., Whittaker, J. M., Lucieer, V., Coffin, M. F., & Lamarche, G. 2017. Erosional and depositional processes on the submarine flanks of Ontong Java and Nukumanu atolls, western equatorial Pacific Ocean. *Marine Geology*, *392*, 122-139.

[3] An interferometric multibeam measures the angle of 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.

[4] A beamforming multibeam mathematically forms a set of “beams”, and detects the range to the seabed in each beam.

[5] The sidelobes are smaller beams that are away from the main beam. These sidelobes represent energy received in undesired directions which can never be completely eliminated.

[6] In the field of digital signal processing, the sampling theorem is a fundamental bridge between continuous-time signals (often called "analog signals") and discrete-time signals (often called "digital signals"). It establishes a sufficient condition for a sample rate that permits a discrete sequence of samples to capture all the information from a continuous-time signal of finite bandwidth.