DRAFT STANDARD OCEAN MAPPING PROTOCOL

Prepared by the

INTERAGENCY WORKING GROUP ON OCEAN AND COASTAL MAPPING

for the

NATIONAL OCEAN MAPPING, EXPLORATION, AND CHARACTERIZATION COUNCIL

About the National Ocean Mapping, Exploration, and Characterization Council

The Ocean Policy Committee (OPC) established the National Ocean Mapping, Exploration, and Characterization (NOMEC) Council in June 2020 pursuant to the *National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone*.[1] The purpose of the NOMEC Council is to coordinate Federal agency policy and actions needed to advance ocean mapping, exploration, and characterization, and to support collaboration with both non-Federal and non-governmental partners and stakeholders. The NOMEC Council develops and implements multi-disciplinary, collaborative, and coordinated approaches to mapping, exploring, and characterizing the Exclusive Economic Zone (EEZ) of the United States. The NOMEC Council reports to the Ocean Science and Technology Subcommittee (OST), which provides support and guidance for the NOMEC Council's work as appropriate. The OPC will provide strategic direction and facilitate interagency resolution of policy issues as appropriate.

About the Interagency Working Group on Ocean and Coastal Mapping

The Interagency Working Group on Ocean and Coastal Mapping (IWG-OCM) is a working group of the National Science and Technology Council (NSTC) Subcommittee on Ocean Science and Technology (SOST) and also reports to the OST Subcommittee of the OPC via the NOMEC Council. The SOST serves as the lead interagency entity for Federal coordination on ocean science and technology. The IWG-OCM was established in 2006 to "facilitate the coordination of ocean and coastal mapping activities and avoid duplicating mapping activities across the Federal sector as well as with State, industry, academic, and non-governmental mapping interests."[2] The IWG-OCM focus areas, which include U.S. coasts, Great Lakes, and oceans out to the limits of the U.S. EEZ and extended continental shelf, were established by the Ocean and Coastal Mapping Integration Act of 2009 (OCMIA). The IWG-OCM also represents the ocean and coastal mapping aspects of elevation on the Federal Geographic Data Committee's (FGDC's) 3D Nation Elevation Subcommittee.

About this Document

Pursuant to Objective 2.1 of the *Implementation Plan for the National Strategy for Ocean Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone*, this document is a standardized technical protocol for ocean and coastal mapping data that provides national standards and best practices to guide all ocean mappers in data acquisition, processing, and archiving. The goals of the document are to facilitate the widest access to, use of, and

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[1] https://www.noaa.gov/sites/default/files/2021-08/NOMEC%20Strategy.pdf

[2] https://iocm.noaa.gov/reports/OCM_Nat_Strat_Action_Plan_Version_1.pdf

integration of data; minimize duplication of effort; and maximize the efficient collection, processing, publishing, preserving, and stewardship of as much ocean and coastal mapping data as possible into publicly accessible archives, repositories, and databases.

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Abbreviations and Acronyms

(T) or nT	Tesla unit
ABGNSS	
ADCP	Acoustic Doppler current profilers
AGC	Automatic Gain Control
AI	Artificial intelligence
ASCII	American Standard Code for Information Interchange
ASPRS	American Society for Photogrammetry and Remote Sensing
AUV	Autonomous underwater vehicle
BIST	Built-In Self-Test
BOEM	Bureau of Ocean and Energy Management
BSWG	Backscatter Working Group
CO-OPS	Center for Operational Oceanographic Products and Services
CRS	Coordinate reference system
CTD	Conductivity-temperature-depth
CW	Continuous wave
DEM	Digital elevation model
DGPS	Differential Global Positioning System
DL	Deep learning
DPA	Defined Project Area
DSM	Digital surface model
EEZ	Exclusive Economic Zone
ERS	Ellipsoidally Referenced Survey
FE	Footprint extent
FGDC	Federal Geographic Data Committee
GeoHab	Marine Geological and Biological Habitat Mapping
GIS	Geographic Information System
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSF	Generic Sensor Format
GUID	Globally Unique Identifier
HRG	High-resolution geophysical
Hz	Hertz
I/O	Input/Output
IBM	International Business Machines
ICES	International Council for the Exploration of the Sea
IEEE	Institute of Electrical and Electronics Engineers
IHO	International Hydrographic Organization
IMU	Inertial measurement unit

ISO	International Organization for Standardization
ITRS	International Terrestrial Reference System
IWG-OCM	Interagency Working Group on Ocean and Coastal Mapping
JALBTCX	Joint Airborne Lidar Bathymetry Technical Center of Expertise
kHz	Kilohertz
Lidar	Light Detection and Ranging
MAC	Multibeam Advisory Committee
MBES	Multibeam Echosounder
MCS	Multichannel Seismic
min	Minute
ML	Machine learning
MMPA	Marine Mammal Protection Act
ms	Millisecond
MSL	Mean Sea Level
NCEI	National Centers for Environmental Information
NAD	North American Datum
NaN	Not a Number (a numerical value that is undefined or unrepresentable)
NAVD	North American Vertical Datum
NAVOCEANO	Naval Oceanographic Office
Nf	Nyquist frequency
NGS	National Geodetic Survey
NMAHS	Norwegian Mapping Authority Hydrographic Service
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NOMEC	National Ocean Mapping, Exploration, and Characterization
NRP	Navigation reference point
Nsr	Nyquist sampling rate
NVA	Non-vegetated Vertical Accuracy
OCS	Office of Coast Survey
OER	Office of Exploration and Research
QA/QC	Quality Assurance / Quality Control
RMS error	Root mean square error
ROV	Remotely operated vehicles
RTK	Real-time kinematic
RX	Receive antenna
SBES	Single Beam Echosounder
SBP	Sub-bottom profiler
SCS	Single-channel seismic
SEG	Society of Exploration Geophysicists
SL	Source level
SOMP	Standard Ocean Mapping Protocol
SOP	Standard Operating Procedure
SSS	Side scan sonar

SVP	Sound Velocity Profile
THU	Total horizontal uncertainty
TIN	Triangulated irregular network
TL	Transmission loss
TPU	Total propagated uncertainty
TS	Target strength
TVG	Time varied gain
TVU	Total vertical uncertainty
TX	Transmit antenna
uCTD	Underway-conductivity-temperature-depth
USACE	U.S. Army Corps of Engineers
USBL	Ultra-short baseline
USGS	United States Geological Survey
USV	Unmanned surface vehicles
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator
UXO	Unexploded ordnance
VVA	Vegetated Vertical Accuracy
WKT	Well-known text
XBT	Expendable bathythermograph

Standard Ocean Mapping Protocol Summary

Pursuant to Objective 2.1 of the Strategy and Implementation Plan in the *National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone,* this document is a standardized technical protocol for acquisition, processing, and archiving of ocean and coastal mapping data (NOMEC, 2020). The goals of the document are to facilitate the widest access to, use of, and integration of data; minimize duplication of effort; and maximize the efficient collection, processing, publishing, and stewardship of as much ocean and coastal mapping data as possible into publicly accessible archives, repositories, and databases. National data standards and best practices will be used, as required by the Geospatial Data Act of 2018 (FGDC, 2018).

Extending to the outer limits of the Exclusive Economic Zone (EEZ) and covering approximately 3.6 million square nautical miles, U.S. oceans, coasts, and Great Lakes waters comprise one of the largest areas of national seafloor in the world. As of January 2022, according to the *Progress Report of Unmapped U.S. Waters* released by the National Oceanic and Atmospheric Administration (NOAA), only 48% of U.S. waters have been mapped to at least 100-meter resolution (IWG-OCM, 2022). The remaining 52% of unmapped waters comprises data coarser than 100-meter resolution, estimated seafloor topography based on models, or higher-resolution mapping data that has not been shared for broader use.

Ocean mapping data are required to meet many Federal Government missions. Adhering to established standards when collecting, processing, and archiving mapping data expands its utility for multiple applications. To maximize the value of survey efforts, resources, data, and resulting map products, the Interagency Working Group on Ocean Exploration and Characterization (IWG-OEC) works with partners on mapping activities and data collection. Essential partners include States, Tribes, academia, private industry, non-profit organizations, and many others. Given the variety of mapping partners, a standardized protocol is needed to quickly and efficiently collect, process, and publish as much data as possible.

Data acquisition strategies usually include multi-tool systems—such as a combination of sub-bottom, side scan sonar (SSS), and bathymetric sonars—which promote survey efficiency and cost savings (relative to collecting each dataset individually) as well as allowing for a more comprehensive understanding of the survey area. Prior to commencing a geophysical investigation, investigators should communicate with stakeholders regarding collaboration and leverage assets. Collaboration can increase the field of the study, reduce cost, enhance survey capabilities and results, and develop future endeavors.

Personnel Safety

Marine surveys are inherently hazardous due to environmental conditions; deployment and recovery of rigging and systems over water; and towing of cables and equipment. Onboard hazards include electrical systems and movement of non-stabilized objects. The safety of the crew depends on extensive training, experience, and constant vigilance. Federal agencies have standards and guidelines for field activities and requirements for staffing of vessels and operational procedures (Yobbi et al., 1995). For example, the U.S. Department of Interior publishes handbooks on techniques for investigations in aquatic environments and other technical procedures (DOI, 1993; USGS, 1989). These resources are used to inform and ensure crew safety. Because maritime and aerial activities are innately dangerous, safety shall always be the primary consideration when conducting any operations. Data acquisition operations shall not be attempted unless conditions are deemed favorable and safe.

Environmental Compliance

The following chapters provide guidance on conducting a wide variety of data collection and field activities performed from crewed vessels and aircraft, as well as remotely operated or autonomous vehicles. Some of these activities require reviews for compliance with various relevant environmental statutes, including, but not limited to, the Endangered Species Act, Marine Mammal Protection Act, and National Environmental Policy Act. Adhering to the guidance in the following chapters does not guarantee compliance with the applicable environmental laws. Participants shall follow all environmental laws relevant to the performed field activities. Participants should also consult their agency-specific environmental compliance policies and procedures for guidance on how to meet these requirements.

Standard Ocean Mapping Protocol Chapters

The Standard Ocean Mapping Protocol (SOMP) is organized into the following seven chapters.

Chapter 1: Data Management covers methods for effective data management and stewardship, metadata records, and archive techniques, with the intent of promoting data accessibility and utility by a broad spectrum of users, including the public.

Chapter 2: Bathymetry focuses on procedures for the collection, processing, and delivery of bathymetric data, such as that acquired by sonar systems (multibeam, single beam, phase-discriminating) and light detection and ranging (lidar) systems. This chapter summarizes best practices for system setup, calibration, and maintenance; data resolution, range, and survey coverage; positioning and spatial reference; sound speed correction; tides and water levels; quality assurance/quality control (QA/QC) techniques, accuracy, and uncertainty; data processing and handling; and general gridded data specifications.

Chapter 3: Seabed and Lakebed Backscatter covers standard backscatter acquisition and processing methods, acoustic signal corrections, and image processing steps. This chapter describes backscatter, its existing challenges in data usage, protocols to apply, and information that should be documented during surveying and processing. The chapter advocates the Marine Geological and Biological Habitat Mapping (GeoHab) Backscatter Working Group (BSWG) publication *Backscatter Measurements by Seafloor-Mapping Sonar: Guidelines and Recommendations* (Lurton and Lamarche, 2015) as best practices.

Chapter 4: Water Column Sonar focuses on the collection, processing, and delivery of raw and interpreted backscatter from single beam echosounders (SBES) and multibeam echosounders (MBES). This chapter summarizes best practices for system configuration and calibration; operating frequencies and depth ranges; QA/QC techniques; analysis and interpretation of backscatter and derived products; and file formats.

Chapter 5: Side Scan Sonar concentrates on the collection, processing, and delivery of side scan sonar data. This chapter summarizes best practices for system configuration and calibration; general data acquisition parameters (e.g., range scales, frequencies, ping rates, survey speed); data resolution and survey coverage; positioning and spatial reference; target detection; QA/QC techniques, accuracy, and uncertainty; and data processing, mosaic generation, and derivation of products.

Chapter 6: Sub-bottom Profiling covers common system types and describes the standard operating procedure (SOP) for the use of single-channel acoustic systems that commonly operate in the 0.2 to 24 kilohertz (kHz) frequency range to remotely image seafloor surface morphology and near-surface stratigraphy. Topics include practical survey design; conventional acquisition procedures and parameters; data resolution; QA/QC techniques; processing protocols; data formats; and publication of sub-surface imaging data.

Chapter 7: Magnetometry focuses on general magnetic theory as it relates to anomaly detectability; factors that influence data quality; instrument selection, configuration, testing, and calibration; data sensitivity and coverage specifications; resolution/line spacing based on survey objectives; and data validation.

The SOMP leverages expertise in the field of ocean and coastal mapping across sectors (including government, industry, and academia), as well as existing mapping standards and procedures. This document will be updated by the IWG-OCM every 5 years to stay current with technological advancements.

For any questions about the SOMP or updated URLs, email nomec.execsec@noaa.gov.

Summary References

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Chapter 1: Data Management

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1.1 Introduction

The ocean mapping community has made significant progress in effective data stewardship over the last decade, yet it still lags behind other scientific communities in this area. Marine data collectors sometimes lack the awareness, resources, and/or expertise to fully implement best data management practices on their own, resulting in data being improperly documented, kept out of the public realm, and/or lost. More recently, the expense and difficulty of collecting data and the recognition that these data are used for multiple purposes have prompted efforts from funding agencies and data management communities to overcome these obstacles. The GO-FAIR Initiative, for example, is a stakeholder community that developed and promotes the FAIR Guiding Principles for scientific data management and stewardship to assist data holders in making their data Findable, Accessible, Interoperable, and Reusable (GO FAIR, n.d.). These principles apply to projects and datasets of any size and have been embraced by large international programs, such as the Integrated Ocean Observing System (NOAA IOOS, n.d.). Access to tools such as metadata editors and data packaging software have been developed to reduce data management barriers and help data collectors meet the requirements for data documentation, preservation, and access.

Using data standards (Appendix A) and metadata promotes data reusability, increases interpretability, clarifies ambiguous meanings, and reduces redundancy/duplication of efforts. This chapter provides overarching guidance and recommendations for effective data management and stewardship, specifically, the metadata and archival techniques necessary for data to be stored and maintained for access and understandability now and into the future by a broad spectrum of users, including the general public. This chapter does not address specific manufacturers or use cases.

1.2 Data Submission to Archives or Repositories

Submission of raw data and products to data archives or repositories is strongly encouraged to meet the data documentation, preservation, and access goals outlined above. ***Data repositories*** are either a space used to store records of continuing value or an institution focused on the care and storage of those records. Many universities, State, and Federal agencies host their own repositories.

In the United States, ***National Archives*** are data repositories owned and maintained by the Federal Government to meet the data preservation requirements of the National Archives and Records Administration (NARA). While Federal agency archives do not formally meet that definition, NOAA National Centers for Environmental Information (NCEI) does meet several definitions for the term and is referred to as both an archive and a repository. NCEI also adheres to the Open Archival Information System Reference Model (OAIS) (ISO Standard 14721) to ensure that data are independently understandable for long-term preservation (OAIS Reference Model, n.d.).

Although the guidelines presented in this chapter are widely used best practices that should be considered for all datasets, regardless of where they are stored, data providers should contact the appropriate repository or archive directly for specific submission requirements.

1.3 Minimum Data Submission Requirements for National Archives

Data must have accompanying metadata and be provided in the requested format(s) and folder structure (See Chapter 1.5 for NOAA NCEI example) before publication and archival. Also, processed data must be evaluated, and properly quality assured and controlled by a subject matter expert.

Data submitted to the NOAA NCEI Archive (NOAA NCEI, n.d. a) include:

- Data
  - See applicable chapters below (Chapters 2–7)
  - See Appendix C for formats by data type
- Metadata
  - See Chapter 1.4 for minimum metadata requirements
  - See Chapter 1.5 and Table 1.2 for recommended metadata fields for all data types outlined in Chapters 2–7
- Standardized folder structure
  - See Chapter 1.5.1 for NCEI example

1.4 Minimum Metadata Requirements

Data are often collected and processed using proprietary software, and calibration settings are instrument-dependent and vary with local and environmental conditions. Therefore, detailed documentation of specific settings and parameters in metadata records is critical to assess data for further processing and interpretation at any point in time. Standardization of metadata is accomplished by using a set of defined information or "attribute" fields arranged in a specific, machine-readable structure or "schema." This enables the organized storage of metadata records in searchable databases. Although different organizations employ or endorse different metadata schema (Appendix A), most require a common core set of attributes and are, to some extent, interoperable.

Repositories and archives maintained by U.S. Federal agencies, including NOAA, NCEI, United States Geological Survey (USGS), and other cooperative institutes, require that data submissions for the archives include geospatial metadata in a standard endorsed by the FGDC. FGDC-endorsed schemata include the Content Standard for Digital Geospatial Metadata and several International Organization for Standardization (ISO) geographic metadata standards such as ISO 19139/19115 and extensions (Appendix A).

These schemata contain mandatory and optional fields to document attributes, including information regarding the survey (e.g., dates of data collection, sensor(s) used, vessel and cruise names), data collection and processing steps, geographic reference, and contacts for lead participants:

- Descriptions of the ISO content and organization and guidance for writing metadata (NOAA NCEI, n.d. b; USGS, 2021).
- USGS and NOAA resources include metadata templates with guidance documents. Additionally, NOAA hosts an ISO Workbook (NOAA NODC, 2012).
- ISO Explorer (a web-based comprehensive explorer for ISO 19115 [ESIP, 2017] and 19115-2 [NOAA NGDC, 2020]) both act as implementation guides.

Table 1.1 lists and defines the minimum, or core, set of metadata attribute fields that are common across all data types in the SOMP and required for data submission to many data repositories and archives. These metadata attributes should be considered *prior to* data collection or processing to ensure that the information is documented before or at the time of collection/processing. Documenting metadata during the project is strongly encouraged as a best practice and facilitates a more accurate and detailed record. The following chapters will discuss additional required metadata fields specific to each data type.

All survey data, including raw and/or processed mapping data and supplementary data, any associated products, and metadata should be archived together in cruise- or mission-specific directories.

Raw and processed data file formats are currently dominated by industry-standard proprietary acquisition and processing software. Any data collected or processed using proprietary software should be provided in open file formats to the greatest extent possible (either instead of or in addition to the proprietary format). Maintaining proprietary formats allows for new processing techniques to be implemented and preservation of the whole, raw dataset. However, this practice can significantly increase data storage needs and effort (e.g., to convert files), so users should decide—prior to acquisition—what file formats will be preserved.

Supplemental data such as sound speed profiles, tides, vessel offsets, vessel track lines/navigation files, cruise reports, log/field notes, etc. are valuable information that provide context and help users fully understand the settings and environment in which the data were collected. Inclusion of all relevant information can aid in the most accurate analysis of the data. Supplemental data can be recorded in a variety of formats and are typically (and preferred) in non-proprietary formats (e.g., ascii, .csv, .pdf). Data products developed from the mapping data (e.g., mosaics, rasters, digital elevation models, maps) are also recorded in a variety of formats and are typically (and preferred as) open-file or easily accessible formats.

1.5 Recommended Core Metadata Fields for All Data Types

Table 1.1. Minimum metadata recommended for usability and archiving for all data themes.

A. General Information

Information Field	Example Text	Description
SurveyName	NF1309	Typically, “shipID, year, cruise number,” survey cruise ID/name.
VesselName	Nancy Foster	Name of survey vessel/ vessel name.
ChiefScientist	Transit or John Smith	Transit or chief scientist(s) and affiliation(s).
ChiefSciOrganization	USGS	Transit or agency(ies) / program(s) for which survey is conducted.
DeparturePort	US - Puerto Rico - San Juan	City, State for U.S. ports. City, country for international ports, vessel departure port(s).
ArrivalPort	US-SC-Charleston	City, State for U.S. ports. City, Country for international ports, vessel arrival port(s).
ShipOwner	NOAA	Entity that owns the survey vessel.
ProjectName	Corals in the Florida Keys	Specified project name or “Transit.”
Source	NOAA	Source organization of data being provided.

B. Reference

Information Field	Example Text	Description
Citation	NOAA (2010)	Bibliographic information to reference the resource. How should data be cited by the user? Ex: Cite as: NOAA (2010): Multibeam collection for M1907_NF_10: Multibeam data collected aboard Nancy Foster from 16-Mar-10 to 15-Apr-10, Charlotte Amalie, U.S. Virgin Islands to San Juan, Puerto Rico. NOAA National Centers for Environmental Information. [url], [access date].

C. Time

Information Field	Example Text	Description
StartDate	2013-09-10	Date only. YYYY-MM-DD, acquisition start date (ISO 8601).
EndDate	2014-10-28	Date only. YYYY-MM-DD, acquisition end date (ISO 8601).
StartTime	01:12:22	Time, as XX:XX:XX, hh:mm:ss, in UTC (Coordinated Universal Time), acquisition start time.
EndTime	17:30:10	Time, as XX:XX:XX, hh:mm:ss, in UTC, acquisition end time.

D. Location

Information Field	Example Text	Description
CoordinateSystem	Horizontal: WGS84 UTM Zones 17-20 Vertical: NAVD 88	Information about the spatial reference system used. Coordinate system/horizontal datum/vertical datum(s) used for raw and processed data. Describe processing steps used to shift coordinate system or datum, if different from raw data.
SpatialDomain	Longitude: -84.00 to -92.20 Latitude: 46.00 to 49.50	The geographic areal domain of the dataset, i.e., what geographic area does the dataset cover? Provide limits of dataset coverage in latitude and longitude values in the order of westernmost, easternmost, northernmost, and southernmost.
HorizontalDatum	WGS84	Information about the horizontal reference frame. If projected data, state projection zone.
VerticalDatum	MLLW	State information about the vertical coordinate reference system (CRS). A vertical datum is technically a surface of zero-elevation to which heights of various points are referred in order that those heights be in a consistent system. More broadly, a vertical datum is the entire system of the zero-elevation surface and methods of determining heights relative to that surface. Over the years, many different types of vertical datums have been used.

		The most dominant types today are tidal datums and geodetic datums.
SensorAltitude	n/a	Sensor altitude (if towed system).

E. Content

Information Field	Example Text	Description
Entity and Attribute Information	See SOMP Appendix C	Information about the physical parameters and other attributes contained in a resource. Details about the information content of the data sets, including the entity types, their attributes, and the domains from which attribute values may be assigned, and data fields defined.

F. Credit

Information Field	Example Text	Description
DataSetCredit	NOAA	Recognition of those who contributed to the dataset, cited authors, publishers. Who produced the dataset? Who are the originators of the data set?
Point of Contact	Nigel Smith	Contact information for an individual or organization that is knowledgeable about the data set, name, affiliation, email, phone. To whom should users address questions about the data?

G. Purpose

Information Field	Example Text	Description
Abstract	Text Summary	Brief narrative summary of the resource/dataset's contents. Abstract narrative should include information on general content and features; dataset applications: GIS, CAD, image, database; geographic coverage: country/city name; time period of content: begin and end date or single data; and special data characteristics or

		limitations. Description = abstract and purpose, a characterization of the data set, including its intended use and limitations. Brief narrative summary of the dataset's contents.
Purpose	Text Summary	Summary of the intentions for which the dataset was developed. Purpose includes objectives for creating the dataset and what the dataset is to support. Summary of the intentions for which the dataset was developed.

H. Sensors

Information Field	Example Text	Description
Acquisition	Info	Information about instruments, platforms, operations and other info of data acquisition? How were these data collected?
Navigation	DGPS or GPS	Equipment used in determining data positioning, including accuracy of system (e.g., the make/model). For example, Trimble R10 Integrated GNSS system RTK GPS - or Applanix POS MV GNSS-aided inertial positioning system.
Instrument	Reson 7125	Information about instruments, platforms, operations and other info of data acquisition? How were these data collected? Description of the instrument(s), and sensor(s). Vessel configuration, survey vessel dimensions (length, width, draft) and applied system offsets are critical and may or may not be documented in the raw data, depending on acquisition setup/software. What platforms were the instruments on? Ex: Geometrics G-882 Digital Cesium Marine Magnetometer

I. Processing

Information Field	Example Text	Description
ProcessingSteps	Text Summary	Paragraph describing processing performed on data, including software (and version) used, if any—list of process steps, details of data preparation, cleaning, transformation, etc.

J. Quality

Information Field	Example Text	Description
Data Quality Information	Info	Information about the quality and lineage (including processing steps and sources) of a resource such as attribute accuracy, logical consistency report, or completeness report. Describe any constraints that may have affected data quality during collection (e.g., sea state, software or hardware issues), scope, report, and lineage. How well have the observations been checked? How accurate are the geographic locations, heights or depths? Where are the gaps in the data? What is missing? How consistent are the relationships among the data? What is the quality of this data set?
Patch test & System Calibration	Step 1, Step 2…	Description of steps taken to ensure the system is calibrated including time and location of calibration. Complete listing of calibration corrections applied to data. Details of process used to refine system alignment / report. Include 'pre-' and 'post-calibration' settings for context and traceability to previous and later calibrations.
Settings	Sonar settings include	Description of settings used during data acquisition.

K. Distribution – Access – Handling

Information Field	Text Summary	Description
AccessConstraints	Yes or No	Are there legal restrictions on access or use of the data? Information about constraints on the use of the metadata and the resource it describes, the limitations, restrictions, or statements on the resource fitness for use, pertains to temporary data access restrictions, public, proprietary, sensitive, restricted…Additional notes: "Access Constraints" For "Proprietary" describe any components of the raw or processed data or mosaics that are proprietary (e.g., raw data files, processed data files, navigation files). It is recognized that backscatter raw and processed data file formats are currently dominated by industry-standard proprietary acquisition software, whereas the resulting mosaic or raster data are typically an open data format.
Distribution	Info	Information about the distributor of and options for obtaining the data set. Who distributes the data?
ResponsibleParty	Name	Who wrote the metadata?
DOI	DOI: 10.7289/V56T0JNC	Digital Object Identifier. If DOI is not provided, NCEI will create one upon request.
OutsideLink	http://www...	Web link to additional information regarding cruise, project, or funding. What are the URLs and other online resources associated with this data set?
Comments	Proprietary hold until Oct 1, 2014	General comments regarding the cruise or dataset, if any.

1.5.1 File Data Submission Folder Structure

One of the essential components of sound data management is an established filing (directory) structure. Established file plans demonstrate consistency and continuity in record keeping (Figure 1.1).

Figure 1.1. Data Type Folder Structure: an example of the folder structure from NCEI for submitting various data types.

compilations (grids, etc. from more than one cruise or instrument)
- nonpublic
- <dataset> (ex: data_type + provider)
  - documents
  - metatdata
  - ancillary
  - data

<platform>
- nonpublic
- <cruise>
  - documents (ex: cruise_report.pdf, gzip files individually for flexibility in adding files)
  - metadata (ex: <cruise>.xml, <dataset>.xml, gzip files individually for flexibility in adding files)
  - ancillary (ex: SVP.tar.gz, <dataset>_support.tar.gz, group files when appropriate)
  - **water column sonar**
    - level_00 (raw)
      - <dataset> (ex: cruise + instrument)
    - level_01 (processed)
      - <dataset> (ex: cruise + instrument + provider)
    - level_02 (products)
      - <dataset> (ex: cruise + instrument + provider)
  - **trackline** (includes single beam, magnetometer, sidescan, sub-bottom, and backscatter)
    - level_00 (raw)
      - <dataset> (ex: cruise + trackline)
    - level_01 (processed)
      - <dataset> (ex: cruise + trackline + provider)
        (nbp1508_trackoine_ldeo.tar.gz)
    - level_02 (products)
      - <dataset> (ex: cruise + trackline + provider)
  - **multibeam**
    - level_00 (raw)
      - <dataset> (ex: cruise + instrument)
    - level_01 (processed)
      - <dataset> (ex: cruise + instrument + provider)
    - level_02 (products)
      - <dataset> (ex: cruise + instrument + provider)

1.6 Dataset (Data Theme) – Data Management Protocol

The following are required metadata fields specific to each data type that should be provided in addition to the minimum requirements presented in Chapter 1.1 and Table 1.2.

1.6.1 Bathymetry Data Management

Single beam sonars ensonify the seafloor with a single narrow beam of sound typically directly below the vessel, whereas multibeam sonars ensonify the seafloor with a wide swath of sound, dividing the return from the seafloor into multiple beams across the wide swath. Multibeam sonars cover the space directly under the ship and out to each side and collect two types of data: seafloor depth and backscatter. The seafloor depth, or bathymetry, is computed by measuring the time it takes for the sound to leave the array, reflect from the seafloor, and return to the array. Multibeam and single beam bathymetry raw data (as collected) are recorded in the instrument's vendor-specific file format. Common file formats include, but are not limited to .all, .kmall, .imb, .s7k, .xse, and .raw.

The following subchapters and Chapter 2 identify additional information specific to bathymetry data that should also be included in a survey report and/or the metadata record. NCEI is the preferred destination for all bathymetric data and products to be included in the U.S. Bathymetry Gap Analysis (NOAA IOCM, n.d.) and to be made publicly discoverable and accessible. We encourage our partners, including those in government, industry, and academia, to collect/process bathymetry data using SOMP guidelines and submit it to NCEI.

1.6.1.1 Minimum Requirements for Bathymetry Data Stewardship and Discovery

At minimum, bathymetry data must include:

- Raw and/or processed data files and/or products in vendor-specific format (e.g., .all, .s7k, .xse). Processed data should be submitted in an open-source format such as .gsf
- Metadata should include all required fields (See Chapter 1.4 for details).
- Submissions should conform to NCEI guidance for archiving (See Section 1.6.1.2).
- Multibeam and single beam data submissions to the NCEI archive should be made by emailing mb.info@noaa.gov to alert a data manager of incoming data, set up the data submission, and/or ask any questions.
- When multibeam or single beam sonar data are to be submitted for archiving at NCEI, data providers should work with NCEI data managers to determine the best method for packaging data.
- One option to assist in data packaging is CruisePack (NOAA NCEI, n.d. c.), a standalone executable, to package sonar and any ancillary data. CruisePack generates consistent and complete metadata to document the data collection process and ensures that data submitted to NCEI are in a standardized format for automated incorporation into the archive.
- NCEI maintains raw multibeam (as collected) data files in the instrument's vendor-specific format (e.g., .all, .s7k, .xse). However, other supplemental data (sound speed profiles, tides, vessel offsets, cruise reports, etc.) and/or processed versions or products of the multibeam data are also accepted.

- Processed multibeam data shall be delivered in an MB-System processed format or another non-proprietary format. The majority of processed data in the multibeam bathymetry database are in MB-System, XYZ, or Generic Sensor Format (GSF) format.
- NCEI prefers single beam data to be in M77T format. Other acceptable formats for data or navigation products include GeoJSON, GeoCSV, or American Standard Code for Information Interchange (ASCII) CSV/tab-Delimited (with format documentation).
- NCEI ingests raw single beam data but requires associated navigation data in order for it to be discoverable via the Trackline Geophysical Data Viewer (NOAA NCEI, n.d. d.). Navigation information must either (1) be provided in a separate folder under the single beam folder structure, or (2) if multibeam bathymetry was collected during the cruise, the navigation data from the multibeam database may be used. If no navigation information is provided for raw single beam data, then the data will be archived but will remain undiscoverable through NCEI data discovery portals and only accessible upon request to trackline.info@noaa.gov.
- If data are intended to be regularly submitted to the NCEI archive in support of the NOMEC Strategy, please email mb.info@noaa.gov to discuss setting up a data submission agreement.
- For more detailed information, see the document "Submitting Marine Geophysical Data" (NOAA NGDC, n.d.).

1.6.2 Backscatter Data Management

Seafloor and lakebed backscatter are a measurement of the intensity of the sound echo generated by SSS, SBES, and MBES transducers that *reflect* from the targeted area of the seafloor or lakebed to the instrument's receiver. This process is explained in detail in the *Backscatter measurements by Seafloor-Mapping Sonar: Guidelines and Recommendations* report (Lurton and Lamarche, 2015), the definitive resource at this time for backscatter data acquisition and processing practices and in Chapter 3: Seafloor and Lakebed Backscatter; use of backscatter data in the water column is discussed in Chapter 4: Water Column Sonar.

Sonar instruments are typically used to acquire water depth measurements (i.e., bathymetry). However, they can also be calibrated to operate at frequencies optimal for recording backscatter or ***acoustic reflectivity data*** so that acoustic surveys can potentially yield information about bottom topography and composition contemporaneously.

Raw backscatter data files are processed to yield image mosaics of backscatter intensity indicating the seafloor or lakebed substrate's composition and texture. These images can then be interpreted and used to map aquatic geological and biological characteristics and habitats, as well as cultural heritage sites (e.g., shipwrecks) and other anthropogenic features (e.g., debris, disposal sites).

However, when raw backscatter (as collected) data files are recorded in the instrument manufacturer's proprietary file format, calibration settings may vary from survey to survey. Different software, settings, and methods are also used during image processing and mosaic generation, resulting in non-standard data collection and product generation practices. Given the variability in instruments, settings, and processing used in surveys and interpretation, Lurton and Lamarche (2015) make the following overall recommendations for data preservation and documentation:

- Data Format: preserve data in a "... format that allows [the user] to erase all previous corrections and to revert to the raw unprocessed signal… All processing steps should be described in this format." (p. 73)
- Metadata Requirements: include settings and corrections applied to the raw data, the backscatter data values assigned by the instrument manufacturer, and details of processing steps used to derive products. (p. 73-74)
- Interoperability and re-use of data: develop "... a nomenclature of processing levels of backscatter… [as] a means to better compare final processed products from various origins." (p. 172)

1.6.2.1 Minimum Requirements for Backscatter Data Stewardship and Discovery

At minimum, backscatter data must include:

- Raw and/or processed data files.
- Metadata (See Chapter 1.4 for details on required metadata fields).

1.6.2.2 Guidance for Archiving Backscatter Data with NCEI

- Backscatter data submissions to the NCEI archive should be made by emailing trackline.info@noaa.gov to alert a data manager of incoming data, set up the data submission, and/or ask any questions.
- When backscatter data are to be submitted for archiving at NCEI, data providers should work with NCEI data managers to determine the best method for packaging data.
- One option to assist in data packaging is CruisePack (NOAA NCEI, n.d. c.), a standalone executable, to package sonar and any ancillary data. CruisePack generates consistent and complete metadata to document the data collection process and ensures that data submitted to NCEI are in a standardized format for automated incorporation into the archive.
- For more detailed information, see the document "Submitting Marine Geophysical Data" (NOAA NGDC, n.d.).

1.6.3 Water Column Sonar Data Management

Water column sonar measures acoustic reflectance from scatterers in the ensonified volume, typically using a single beam or multibeam configuration. These instruments are used routinely to map fish schools and other mid-water marine organisms, assess biological abundance, characterize habitat, and map underwater gas seeps.

Most single-beam systems designed for fishery research are calibrated for target strength (TS) with established calibration procedures. Multibeam systems run through a 'normalization' process that can improve water column data (but they rarely receive full TS calibrations). In either case, the water column mapping range can extend from the transducer to the seafloor (if downward-looking) or to the water surface (if upward-looking); the range can also be limited within the water column by attenuation (related to operating parameters and water properties) and other effects, such as interference and synchronization.

The water column sonar raw (as collected) data files are recorded in the instrument's vendor-specific format. Common and historic file formats for single beam and multibeam, stationary and non-stationary water column sonar systems include, but are not limited to, .wcd, .raw., .ek5, .imb, .s7k, .01A, and .kmwcd.

The following subchapters identify information specific to all water column sonar data types that should be included in the metadata record.

1.6.3.1 Minimum Requirements for Water Column Sonar Data Stewardship and Discovery

- Ensure navigation datagrams are included in the water column sonar files; if vessel-based.
- Ensure time-synced position information is included as a separate document, if autonomous or not already embedded in the water column sonar files.
- Include absorption coefficients and other relevant calibration information (TS calibrations performed before/after data acquisition, file applied during acquisition, etc.).
- Other valuable data and metadata to include, if available:
    - International Hydrographic Organization (IHO) sea area.
    - Conductivity-temperature-depth (CTD) and underway Conductivity-Temperature-Depth (uCTD) profiles.
    - Sound speed profiles.

1.6.3.2 Guidance for Archiving Water Column Sonar Data with NCEI

- Water column sonar data submissions to the NCEI archive should be made by emailing wcd.info@noaa.gov to alert a data manager of incoming data, set up the data submission, and/or ask any questions.
- Data providers must use CruisePack (NOAA NCEI, n.d. c.), a standalone executable to package sonar and any ancillary data, when water column sonar data are submitted to NCEI archiving. CruisePack generates consistent and complete metadata to document the data collection process and ensures that data submitted to NCEI are in a standardized format for automated incorporation into the archive. NCEI will mint a digital object identifier for the sonar instrument on that cruise to provide a permanent citation for the datasets and facilitate proper attribution to the original data provider.
- To become a regular data provider to the NCEI archive in support of the NOMEC Strategy, please email wcd.info@noaa.gov to discuss setting up a data submission agreement.

- For more detailed information, see the “Submitting Marine Geophysical Data” document (NOAA NCEI. n.d. a.).

1.6.4 Sub-Bottom Data Management

The sub-bottom profiling (SBP) chapter of the SOMP describes the SOPs single channel [seismic] acoustic systems operating within the 0.2 to 24 kHz frequency range. These systems image the near-surface stratigraphy and seafloor morphology (< 100 m) in marine, lacustrine, and fluvial environments. Sub-bottom data are generally collected for shallow, geologic assessments and resource management.

Below are suggested SBP data management guidelines and specifications to be followed during data collection, processing, and archiving to ensure the data are transferable and perpetually accessible.

SBP raw data (as collected) are recorded in the instrument’s vendor-specific format. Common file formats include .jsf, .keb, and .ses. The industry-standard for seismic data is the SEG-Y Data Exchange format, an open standard maintained by the Society of Exploration Geophysicists (SEG). The latest revision, SEG-Y 2.0 (Hagelund and Levin, 2017), was released in January 2017.

The following chapter identifies additional information specific to SBP data to be included in the metadata record.

- Convert proprietary formats recorded during acquisition to SEG-Y for archiving. Proprietary formats should be retained as well, assuming that these formats will not be accessible into perpetuity. SEG-Y files should be archived uncompressed as compression algorithms may become unsupported over time.
- The 3200-byte textual file header should be encoded as EBCDIC or ASCII (UTF-8) character code and retain as much information as possible. At minimum, it should include SEG-Y revision level, date of acquisition, geographic location, line identification, signal sweep information, and recording format.
- The 400-byte binary file header should retain as much information as possible relevant to the SEG-Y file acquisition parameters; at minimum, it should include those fields designated as mandatory in the SEG-Y rev. 2.0 standard. It is highly recommended that additional information be retained, including sweep frequencies (start and stop in hertz (Hz)), sweep length in milliseconds (ms), sample interval (ms), and samples per trace to ensure adequate subsequent use of the data. If all traces in a data file are of equal length, set the fixed-length flag in the binary header to improve playback performance.
- The 240-byte trace header(s) should be populated using the SEG-Y standard. It is highly recommended that the source coordinates for each trace be included in the trace header, as well as recorded externally through the positioning device (e.g., Global Positioning System (GPS)). When archiving positioning data, such as including an explicitly defined coordinate referencing system with the International Association

of Oil and Gas Producers (IOGP) European Petroleum Survey Group (EPSG) Geodetic Parameter Dataset code (IOGP Geomatics Committee, n.d.), practice extreme care.

- Archive SEG-Y data with (1) minimal post-acquisition processing applied and (2) fully annotated data-file iterations with processing filters (e.g., AGC gain, bandpass, etc.).
- Collect SBP files using the acquisition system-provided formats, even if they are proprietary file types.
- Record swept-frequency data in both envelope and analytic (also known as full waveform) formats. Envelope data records are helpful in determining the "big picture", while full-waveform records are helpful in investigating finer details.
- Published SBP data should be archived and disseminated in SEG-Y format to facilitate accessibility and usability by the widest audience of users.

1.6.4.1 Minimum Requirements for Sub-Bottom Data Stewardship and Discovery

At minimum, SBP data must include:

- Raw and/or processed data files in SEG-Y format.
- Required metadata (See Chapter 1.4 for details on required metadata fields).

1.6.4.2 Guidance for Archiving with NCEI

- SBP data submissions to the NCEI should be made by emailing trackline.info@noaa.gov to alert a data manager of incoming data, set up the data submission, and/or ask any questions.
- When SBP data are to be submitted for archiving at NCEI, data providers should work with NCEI Data Managers to determine the best method for packaging data.
- NCEI encourages data providers to submit SBP data in SEG-Y format as NCEI relies on SEG-Y for extracting navigation necessary to generate track lines that display the location of the data in the Trackline Geophysical Data Viewer (NOAA NCEI, n.d. d.).
- Data submitted in unsupported formats will still be accepted but will not be discoverable through the web services provided at NCEI. These data are accessed from the archive upon request to trackline.info@noaa.gov.
- For more detailed information, see the document "Submitting Marine Geophysical Data" (NOAA NGDC, n.d.).

1.6.5 Side Scan Sonar Data Management

SSS collects a time series of backscatter, just like multibeam sonar does, except that there is no angular discrimination to the backscatter time series. This instrument is used to map seafloor geological and biological characteristics and habitats, as well as cultural heritage sites (e.g., shipwrecks) and other anthropogenic features (e.g., debris, disposal sites). SSS raw data (as collected) files are recorded in the instrument's vendor-specific format. Common file formats include, but are not limited to .xtf, .jsf., .hsx, and .gcf.

The following subchapters identify additional information specific to SSS data to include in the metadata record.

1.6.5.1 Minimum Requirements for Side Scan Sonar Data Stewardship and Discovery

At minimum, SSS data must include:

- Raw and/or processed data files in JSF or HSX format.
- Required metadata (See Chapter 1.4 for details on required metadata fields).

1.6.5.2 Guidance for Archiving with NCEI

- SSS data submissions to the NCEI should be made by emailing trackline.info@noaa.gov to alert a data manager of incoming data, set up the data submission, and/or ask any questions.
- When SSS data are to be submitted for archiving at NCEI, data providers will work with NCEI Data Managers to determine the best method for packaging data.
- NCEI ingests SSS data but requires associated navigation in order for it to be discoverable via the Trackline Geophysical Data Viewer (NOAA NCEI, n.d. d.). Navigation information must either (1) be provided in a separate folder under the side scan folder structure, or (2) if multibeam bathymetry was collected during the cruise, the navigation data from the multibeam database may be used. If no navigation is provided for SSS data, then the data will be archived but will remain undiscoverable through NCEI data discovery portals and only accessible upon request to trackline.info@noaa.gov.
- For more detailed information, see the document "Submitting Marine Geophysical Data" (NOAA NGDC, n.d.).

1.6.5.3 Side Scan Sonar Data Formats

- The raw and processed side scan sonar data (i.e., mosaics) should be archived to ensure data preservation to the fullest extent (i.e., no information is lost).
- Storage of side scan sonar images and mosaics is preferred to allow for a more thorough examination of data.

1.6.6 Magnetometry Data Management

A magnetometer is a passive instrument that detects variations in the Earth's magnetic field. This instrument has many applications, including structural geological mapping, energy and mineral exploration, archaeology, and munitions detection. Magnetic raw data (as collected) are time-series data. Common file formats include but are not limited to .csv and .txt. Present magnetic data in a format that can be imported and viewed in a Geographic Information System (GIS) platform.

The following chapter identifies additional information specific to be included with magnetometer data.

1.6.6.1 Magnetometer Protocol (Data Standard)

- For magnetometer time-series data to be useful and easily understood, consistency is important. Using the column headers in as described in Table 1.2 will aid data collectors and users in ensuring the utility of data:

Table 1.2. Minimum magnetometer data file headers necessary for magnetometer data records.

Column Header	Example	Description
Latitude	42.123456	Towfish location when magnetic reading was recorded. Latitude expressed to six decimal places. Locations in the Northern Hemisphere expressed in positive numbers. ISO 6709
Longitude	-80.123456	Towfish location when magnetic reading was recorded. Longitude expressed to six decimal places. Locations west of the prime meridian expressed in negative numbers. ISO 6709
Date	2022-01-02	Date, in year-month-day, in UTC Time, when the magnetic reading was recorded. ISO 8601
Time	09:13:23.05	Time, as hh:mm:ss.ss, in UTC, when the magnetic reading was recorded. ISO 8601
Reading	420145.07	Raw magnetic reading for the magnetic sensor. Multiple sensors should have separate columns for each sensor. Multi-sensor data should indicate from which sensor the reading was derived.
Altitude/Depth	10.3/-20.5	Sensor altitude or depth in meters. If both values were recorded separate into two columns. If multiple sensor data was recorded, include separate columns for each sensor.
Line	1	Survey dependent line name or number to denote all readings recorded sequentially on a particular line.

- See Appendix B for detailed data standards and structure.
- For effective processing, it is critical to capture time and date for correlation of the time-series data with other background field interference. Time and date should be recorded in two separate fields and use only UTC/date, not local time/date (Appendix A).
- Other metadata are especially useful in processing and interpreting magnetic data. For example, in data collected by multiple instrument gradiometer arrays, noting which instrument collected which sample will allow for refinement of an anomaly's location in geographic space: the instrument with the higher variance from the background field was closer at that precise moment to the ferromagnetic material causing the anomaly.

1.6.6.2 Minimum Requirements for Magnetometer Data Stewardship and Discovery

At minimum, magnetometer data must include:

- Raw and/or processed data files.
- Required metadata (See Chapter 1.4 for details on required metadata fields).
- Submissions should conform to NCEI guidance for archiving (See Section 1.6.6.3).
- Magnetometer data submissions to the NCEI should be made by emailing trackline.info@noaa.gov to alert a data manager of incoming data, set up the data submission, and/or ask any questions.
- When submitting magnetometer data for archive at NCEI, data providers should work with NCEI Data Managers to determine the best method for packaging data.
- For more detailed information, see the document "Submitting Marine Geophysical Data" (NOAA NGDC, n.d.).

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Chapter 2: Bathymetry

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2.1 Introduction

The SOMP bathymetry guidelines aim to provide a standard set of requirements to ensure that all seafloor mapping efforts advance the National Strategy to Map, Explore, and Characterize the U.S. EEZ. This chapter provides overarching guidance and recommendations for collecting mapping data from bathymetry with a focus on procedures for collecting, processing, and delivering bathymetry acquired by multibeam, single beam, phase-discriminating sonar, and lidar systems. It summarizes best practices for reporting positioning, system calibration and QA/QC techniques, coverage and resolution, uncertainty, tides and water levels, and general gridded data specifications. Various references were consulted for source material, including IHO S-44, the Office of Exploration and Research (OER) Deepwater Mapping Procedures Manual, the Office of Coast Survey (OCS) Specifications and Deliverables, Australian Multibeam Guidelines, and Norwegian Mapping Authority Hydrographic Service (NMAHS). This chapter does not address manufacturer-specific recommendations or recommendations about specific use cases.

2.2 Overview

Bathymetry is the measurement of water depths and is considered the underwater version of topography. Bathymetric maps are the fundamental first step in ocean mapping, exploration, and characterization operations. The applications of bathymetry are vast and include the study of underwater hazards like landslides and faults as well as important seafloor habitats like steep-sided trenches, canyons and seamounts, and channels cutting through abyssal plains. Bathymetry data are the backbone of nautical charts at all depths for the safety of surface navigation and subsurface vessels. It also plays essential roles in the delineation of international maritime boundaries, management of sediments for navigation, flood risk management, environmental stewardship, identification of offshore resources such as gas and oil reserves, tsunami inundation and storm surge modeling, and the safe planning and maintenance of submarine communication cables that transmit the vast majority of information around the globe.

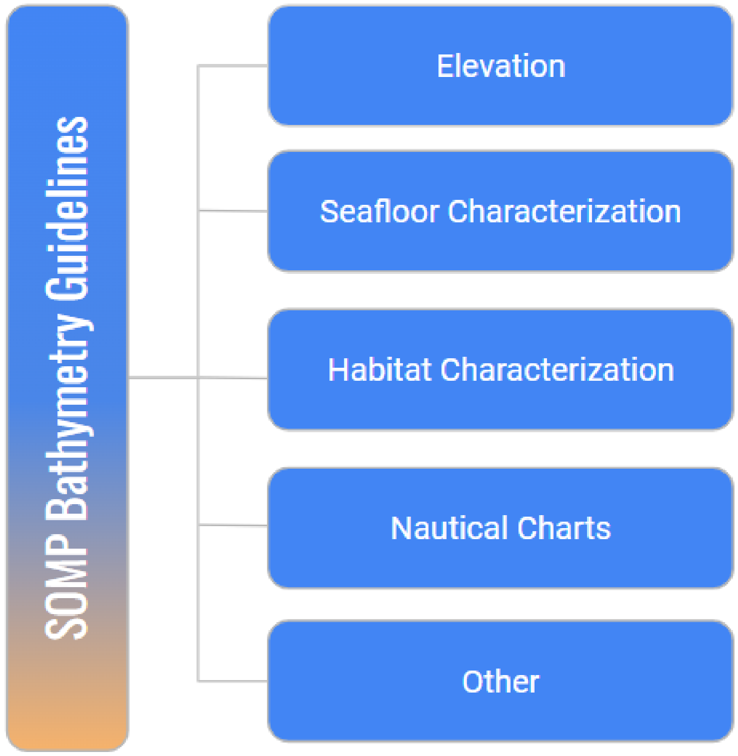

Figure 2.1. SOMP bathymetry guidelines chart: bathymetry guidelines cover elevation, seafloor characterization, habitat characterization, nautical charts, and other topics.

Bathymetry data are collected using multibeam, single beam, split-beam, interferometric sonars, and lidar systems. Different frequencies of bathymetric systems are optimal for different depths:

- Lower-frequency systems (~12 kHz) achieve efficient mapping coverage at full ocean depths, including the deepest parts of the ocean trenches;
- Mid-range frequency systems (~30 kHz) efficiently target water depths from 200–6000 m;
- High-frequency systems (~100–700 kHz) are most useful for depths less than 200 m; and
- Lidar is appropriate for relatively clear, shallow water with systems selected based on depth requirements (as deep as 80 m).

For this chapter, technical terms will follow the definitions in the IHO Hydrographic Dictionary (Hydrographic Dictionary Working Group, 2019).

2.3 Bathymetric Data Sources

The IHO Hydrographic Dictionary (document S-32) provides an authoritative definition for the following bathymetric data sources covered in the Bathymetry Chapter of the SOMP: Single Beam Echosounder (SBES), MBES, Interferometric Sonar, and lidar.

2.3.1 Single Beam Echosounder (SBES)

SBESs transmit and receive a sound pulse within a single, narrow, and (generally) downward-looking field of view to provide one bottom detection per ping cycle.

The types of SBES used vary across Federal agencies. Most mapping and surveying grade systems are dual-frequency, using both a high and a low frequency with beamwidths between 3–8 degrees for high frequency and 20–30 degrees for low frequency. Provided the magnitude of vessel roll and pitch is less than half of the sonar beamwidth, and the total heave is less than 0.5 m, these attitude characteristics will have little effect on sounding accuracy. If the system is not equipped with an attitude sensor to correct data for vessel motion, SBES should not be used when vessel roll and pitch angles exceed sonar beam width or total heave exceeds 0.5 m.

Most SBES systems output calculated depth values rather than the two-way travel time of each sonar ping, which requires configuration with a value for the speed of sound through the water column. It is recommended that field units configure SBES systems using a standard estimate for their given operating area, which must be preserved in the vessel configuration file of the metadata (e.g., 1500 m/s for the speed of sound in seawater). SBES data should then be corrected using full sound speed profiles acquired during the survey in post-processing.

2.3.2 Multibeam Echosounder (MBES)

MBES is a swath-sounding system in which the equipment emits a timed pulse of sound that is narrow in the fore-aft direction and wide in the across track direction. The reflected sound is received by several receivers arranged as an array; whereby signal processing algorithms are used for subsequent beamforming.

For each received beam, the time interval between transmission and reception of the reflected sound is converted into a range using a measured or predicted sound speed profile. System geometry, navigation, attitude data, and corrections for sound refraction are then used to convert each range and received beam angle into positions and depths on the seafloor.

2.3.3 Interferometric Sonar

Interferometric sonar is a swath-sounding system in which the equipment emits a timed pulse of sound that is narrow in the fore-aft direction and wide in the across-track direction, typically with one beam projected to each side of the sonar. The system rapidly samples the reflected sound following each emission. For each sample, the phase difference of the reflected sound arriving at two (or more) receivers located a known distance apart is measured and used to compute the acoustic angle of arrival. Also, the time difference between the emission and reception for each sample is converted to a range using a measured or predicted sound speed profile. System geometry, navigation, attitude data, and corrections for sound refraction are then used to convert each range and angle pair to positions and depths on the seafloor.

2.3.4 Lidar

Airborne lidar bathymetry is a technique for measuring the depths of moderately clear, nearshore coastal waters, lakes, and rivers from a low-altitude aircraft using a scanning, pulsed laser beam. The round-trip time-of-flight of each laser pulse to the water surface and seafloor is measured by receivers in the aircraft. With this information and the speed of light in air and water, accurate water depth can be calculated (Irish and Lillycrop, 1999). Topo-bathy lidar systems are airborne lidar bathymeters that produce topographic data for seamless data collection from land elevations near the shore, across the land-water interface, and into the water to depths as great as 80 m. The primary limitations on depth performance are airborne lidar system specifications and water clarity. Breaking waves that create white water and entrain sediment in the water column, turbidity plumes, kelp, and dark substrate may inhibit continuous data coverage.

2.4 General Protocols

2.4.1 Data Management

Management of bathymetric data is necessary for efficient use, future access, and validation of analytical and interpretative results. The raw and processed data should be archived to ensure data are preserved to the fullest extent.

See Chapter 1: Data Management for minimum bathymetric data requirements and management (e.g., recommended file formats, metadata, data archival).

2.4.1.1 Raw Data Acquisition

The following information should be associated with raw data (as collected):

- Sonar settings:
  - Operational frequency (report both frequencies if dual-frequency system)
  - Ping rate
  - Swath range
  - Gains or corrections (e.g., time varied gain [TVG])
- Attitude and positioning:
  - Specifications of the navigation system(s)
  - Accuracy
- Spatial reference of raw data (and navigation system, if different):
  - Coordinate system and horizontal datum

2.4.2 Sensor Installation Surveys

Surveying and documenting the alignment of mapping sensors is fundamental for establishing and maintaining high data quality. Sonar and lidar installations must be surveyed to establish the linear and angular offsets between sonar arrays or lidar sensor reference points, GPS/Global

Navigation Satellite System (GNSS) antennas, and motion sensors within a uniform mapping reference frame (typically oriented with the vessel, vehicle, or sensor platform). These surveys are conducted initially during the installation process and when any of this equipment has changed or is suspected of having changed (e.g., after dry dock or removal for factory calibration). It is crucial that these surveys are conducted with a high degree of precision and accuracy and are reported in a clear and standardized way that directly supports correct sensor configuration. The NSF-funded Multibeam Advisory Committee (MAC) Recommendations document best practices for Reporting Vessel Geometry and MBES System Offsets in a template (MAC, 2021).

2.4.3 Positioning

Positioning is the fundamental framework and starting point for every mapping operation. The position of any point is referenced using either geodetic coordinates defined by latitude, longitude, and ellipsoid height or Cartesian coordinates (x, y, z). The coordinate system should be specified in metadata and reporting documentation describing the survey.

Positions should reference a geodetic reference frame, which can be the realization of either a global (e.g., International Terrestrial Reference System [ITRS], WGS84) or a regional (e.g., ETRS89, NAD83) reference system.

Coordinates calculated through GNSS and the GPS contain inherent errors from signal transmission delays due to the atmosphere and must be corrected during bathymetric surveys by applying differential GPS (DGPS) correctors. Several manufacturers provide these data via subscription to DGPS receivers used in the offshore environment. Once the corrections are applied, inherent errors should be reduced to the sub-decimeter level.

The navigation system should continuously determine the position of the survey vessel. Uncertainty of the navigation system and QC methods should conform to the requirements defined by the IHO (IHO, 2020). Position fixes should be digitally logged continuously along the vessel track. Geodesy information should be present and consistent.

2.4.3.1 Geodetic Control

Horizontal control generally refers to the terrestrial network of geodetic marks that support two-dimensional mapping positioning and how field units position mapping data relative to a datum. Vertical control activities are conducted to support water level gauge installations, water level measurements, Ellipsoidally Referenced Survey (ERS), and vertical accuracy validation.

Positions should reference a geodetic reference frame, either a global (e.g., ITRS, WGS84) or a regional (e.g., ETRS89, NAD83) reference system. With frequent updates to geodetic reference systems, the epoch for surveys with low positioning uncertainty should be recorded. If horizontal positions reference a local horizontal datum, the name and epoch of the datum should be specified and tied to a realization of the ITRS or equivalent global geodetic reference frame (e.g., ITRS, WGS84, ETRS89, NAD83 realizations). The transformations between reference frames/epochs, especially for surveys with low uncertainty, should be considered.

2.4.3.2 Ellipsoidally Referenced Survey (ERS) Control

ERS is possible through GNSS-based sub-decimeter vertical control using a method of integer ambiguity resolution-enabled carrier-phase kinematic positioning. Differential and related carrier-phase methods based upon PPP kinematic GNSS methods are permitted from a real-time kinematic (RTK) service or via post-processing. Post-processed vertical control has the advantage of enhanced QC: quasi-independent forward- and reverse-time processing reduces the uncertainty in the vessel height solution otherwise present in RTK-based (forward-only) positioning.

The use of GPS over other GNSS (e.g., GLONASS) is preferred; however, if the availability of five or more GPS satellites is infrequent in a particular survey environment, a hybrid GPS-GNSS solution may be used. Inertially-aided systems help to ensure success in ERS regardless of the GNSS technique utilized; tightly-coupled inertial-aided GNSS is vital to overcome positioning problems associated with intermittent loss of individual satellite signals.

2.4.3.3 Tools

Software tools like Vertical Datum Transformation (VDatum; under development by NOAA's National Ocean Service [NOS]) convert elevation data from various sources into a standard reference system.

A standard reference system is vital because irregularities can occur when data products are created from different data sources. The capability of programs such as VDatum to transform and fuse various elevation data benefits coastal applications, including inundation modeling (e.g., storm surge, tsunami, sea level rise impacts), ecosystem management and coastal planning, hydrographic surveying, and ocean mapping using Kinematic GPS for vertical referencing, and shoreline delineation from lidar data.

VDatum coverage is accessible to the public and complete in all coastal regions of the continental United States (including the Great Lakes), Puerto Rico, and the U.S. Virgin Islands. In 2019 a Southeast Alaska regional model was added, and coverage will be developed for Hawaii, Alaska, and the Pacific U.S. territories once foundational geodetic and tidal data are established to allow for valid model construction.

In addition, current models are being revisited to include additional foundational geodetic and tidal data that will assist in improving transformational components of the VDatum models, assist refining and validating the uncertainty associated with models, and support a broader range of applications. The goal is to develop a VDatum utility throughout the country that will foster more effective sharing of elevation data and, eventually, link such data through national databases.

Vdatum is available online (NOAA, n.d. a.) as an API (NOAA, n.d. b.) and as downloadable software (NOAA, n.d. c.).

2.4.5 Resolution and Coverage Types

The following coverage and resolution recommendations are not intended to interfere with or supersede mission-specific requirements.

Bathymetric coverage is the mapped spatial extent of depth measurement based on the combination of the survey pattern and the area of detection of the bathymetric data source.

The NOMEC Council recognizes the IHO as a leading industry source and authoritative subject matter expert for bathymetry (IHO, 2022). The IHO is an intergovernmental organization that works to ensure all the world's seas, oceans, and navigable waters are surveyed and charted. The IHO coordinates national hydrographic offices' activities and sets standards to promote uniformity in nautical charts and documents. It issues survey best practices and provides guidelines to maximize the use of hydrographic information.

The SOMP identifies *the IHO Standards for Hydrographic Surveys*, S-44 Edition 6.0.0 as the leading source of standards and recommendations for hydrographic surveying and ocean mapping bathymetric data standards. This publication specifies minimum standards according to the intended use and encourages the use of IHO S-44 for purposes beyond the safety of navigation. It introduces the concept of a Specification Matrix in Chapter 7.5 of parameters and data types designed to cater to a range of needs (IHO, 2020).

Minimum bathymetry standards and feature detection requirements are defined in IHO S-44 Table 1 (IHO, 2020).

IHO S-44's Specification Matrix Chapter 7.6 provides a range of selectable criteria for bathymetric parameters and other data types collected (IHO, 2020). It allows flexibility and accommodation of new and emerging technologies and inclusion of hydrographic surveys conducted for purposes other than safety of navigation.

The following bathymetric data coverage types are recommended as minimum coverage standards: Complete or 100% Coverage, Set Line Spacing, and Trackline (transit and reconnaissance).

2.4.5.1 Complete or 100% Coverage

Complete or 100% Coverage: 100% bathymetric coverage implies that depth measurements are mapped to the horizontal and vertical standards specified in IHO S-44 Table 1, such that they provide a depiction of the vast majority of the bottom and can be considered as "full" bathymetric coverage (IHO, 2020).

Bathymetric coverage of less than 100% should follow a systematic survey pattern to maximize even distribution across the survey area. Additionally, the nature of the bottom (e.g., roughness, type) and the requirements for safety of surface navigation in the area must be taken into account early and often to determine whether bathymetric coverage should increase to meet the Complete Coverage requirements in the area.

2.4.5.2 Set Line Spacing

Set Line Spacing is recommended when acquiring bathymetric data in areas too shallow for efficient full-bottom coverage bathymetry and can be accomplished with single beam, multibeam, or lidar.

Nearshore environments are inherently dangerous, and the safety of personnel and equipment shall always be the primary objective and consideration when conducting shallow water operations. Field operations should not be attempted unless conditions are favorable.

2.4.5.3 Trackline Data Coverage/Transit Data

While the vessel is transiting, sonar data, including multibeam data, should be collected to maximize total geographic coverage and contribute to the goals of the NOMEC Strategy. The sonar data collection principles described in this chapter should be utilized during transit data collection.

When real time sound speed data collection is not possible, Sound Speed Manager, (freeware created and maintained by NOAA and the University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center) can be used to extract sound speed profiles from the World Ocean Atlas (and other sources), and send them automatically to the multibeam acquisition system to provide an approximate reference.

2.4.5.4 Crosslines

Crosslines are used to confirm internal consistency between survey lines and should be run orthogonally to the main scheme lines of a survey. Where practicable, conduct a crossline in each focused survey area; however, this may not be possible depending on the overall cruise or survey goals. At a minimum, one crossline per cruise should be conducted and should cross roughly the full range of depths found in the focus survey areas. If possible, the cross line should be run early in the survey to identify (and resolve) potential problems sooner rather than later. For lidar, fly crosslines for flight blocks that take longer than a day. Many software packages that process bathymetric data offer a crossline analysis tool and report sounding comparisons to the 95% confidence level for each IHO order specification.

2.4.5.5 Tides and Water Levels

Current and tidal information is essential for planning and performing coastal mapping operations where tidal levels may be tightly linked to positioning and the mapping system data quality. However, observing current and tidal levels is considered an integral part of coastal mapping operations when conducting bathymetric data acquisition operations in waters shallower than 200 meters or as specified as a project requirement.

Tidal data may be required for analysis for the future prediction of tidal heights and the production of Tide Tables, in which case observations should cover as long a period as possible and preferably not less than 30 days.

If wave or water clarity conditions prohibit seamless data collection across the land/water interface, collect topo-bathy lidar near low tide. Water clarity and wave conditions may change with tide level, so data may be collected at both high and low tide to achieve seamless data across the land/water interface.

2.4.5.6 Uncertainty Standards

Precise and accurate measurements are fundamental for quality bathymetric data. Synchronization of multiple sensors with the sonar system is essential for meaningful spatial data analysis. All measurements, however careful and scientific, are subject to some uncertainties. Uncertainty analysis of the survey systems and data must be conducted to meet accuracy and resolution standards and requirements. Position uncertainties must be expressed at the 95% confidence level and should be recorded together with the survey data.

The capability of the mapping system should be demonstrated by a total propagated uncertainty (TPU) calculation which may be separated into total horizontal uncertainty (THU) and total vertical uncertainty (TVU) components.

The SOMP recommendations for Uncertainty Standards are based on the IHO Standards for Hydrographic Surveys as outlined in Special Publication 44 (S-44), 6th Edition, which provides suggested minimum standards to follow. Uncertainty standards and methods should conform to the requirements as defined by the IHO (IHO, 2020).

2.5 Multibeam Protocols

2.5.1 System Geometry Review

Periodic reviews of the vessel/vehicle's sensor offset survey against the navigation/attitude and multibeam sensor configurations will ensure that all fields are interpreted correctly. Periodic review will catch unintended modifications introduced, for example, during software upgrades or by new users who may change installation parameters. If changes are found, assess recent data (since the last system geometry review) to identify when and why the change was made and determine whether data collected with the changed parameters need to be flagged or modified for downstream users. For example, incorrectly interpreted or modified waterline configuration leads to a bulk offset in bathymetry that must be documented (and corrected prior to further data collection).

2.5.2 Multibeam System Calibrations and Health Checks

To maintain maximum productivity and accuracy of data, the following system calibrations and health checks are recommended.

2.5.2.1 Inertial Motion Sensor Calibration

Following the manufacturer's service schedule is best practice to maintain up-to-date factory calibrations for the inertial motion sensor. For inertial motion systems providing GNSS-aided heading, an antenna baseline calibration should be conducted at least once annually, following any significant repair periods, or if a heading misalignment is suspected. Note any such calibrations in all documentation or metadata associated with the bathymetric dataset.

2.5.2.2 Multibeam Calibration Patch Test

Conduct a patch test at least once a year to resolve any angular misalignments of the multibeam or ancillary equipment (e.g., transducers, inertial motion sensor, antennas) or if any equipment is changed or disturbed. The patch test determines if there are any residual biases or errors in navigation timing, pitch, roll, and heading/yaw and resolves each bias individually in that order. The results of each test should be applied in the sonar acquisition software before data collection for the following test and should be documented in metadata.

Apply the results of the geometric calibration to the motion sensor installation angles configured in the data acquisition software. This approach is recommended for several reasons:

- The motion sensor typically has greater installation angle uncertainty than the transmit antenna (TX) and receive antenna (RX) arrays due to the relatively short baselines on the housing.
- The TX and RX array installation angle uncertainties are typically very low owing to the leveling processes carried out during installation and the long survey baselines (in the case of low-frequency, hull-mounted arrays).
- And perhaps most importantly, small installation biases cannot be determined independently for the TX or RX arrays from the calibration data.

While the motion sensor software is configured with motion sensor installation angles directly from the vessel survey, the multibeam calibration results are applied to the motion sensor installation angles within the multibeam acquisition software because they reflect the combined impact of these biases on the multibeam data, and only the multibeam data, as this calibration does not apply to other sensors on board.

If calibration results indicate a residual bias greater than 0.1 degree, conduct another calibration to verify the new angular offset values. Conduct the second calibration with the initial results applied in the acquisition software, using an iterative process to fine-tune and verify the installation angles. The accuracy of the results depends on the bathymetric features of the calibration area and the oceanographic conditions. Therefore, it is best to choose calibration areas where sound speed conditions are relatively stable, and sea states are mild throughout the tests. Although unlikely, if a new inertial motion system calibration (e.g., factory inertial measurement unit (IMU) calibration or antenna baseline calibration) during the field season results in new offsets, then it is recommended that a new patch test also be conducted to account for the new motion sensor configuration and performance.

If the angular offsets are applied in the multibeam acquisition software and accounted for during data acquisition, do not reapply them later in multibeam cleaning/processing software.

Any defined feature can be used for a patch test; a well-defined slope at approximately 10 to 20% or more grade will provide the best results. Wrecks can be used; however, it is recommended that the wreck be well defined to remove any ambiguity when processing the calibration data. Features in debris fields or other cluttered areas should be avoided because of likely ambiguity.

Navigation timing error and pitch tests can cover a wide range of depths, as long as swath coverage extends to at least ~45 degrees in the direction of overlapping coverage (the 'corridor' for assessing the alignment of soundings). Run the lines at different speeds, varying up to 5 knots, to delineate the along-track profiles when assessing time delay. Navigation timing error bias could also be determined from running lines over a distinct feature (i.e., shoal) on the bottom, as long as the feature is ensonified by the vertical (nadir) beam.

Conduct roll tests in depths where the multibeam can achieve full angular swath width (i.e., before 'roll-off' of the coverage-versus-depth curve) to accentuate the outer swath differences resulting from roll biases.

Determine heading (yaw) bias from two or more adjacent pairs of reciprocal survey lines, made on each side of a submerged object or feature (i.e., shoal), in relatively shallow water. Avoid features with sharp edges. Overlap adjacent swaths by 10–20% while covering the shoal and run lines at a 70 speed to ensure significant forward overlap.

Conduct system accuracy testing in an area similar in bottom profile and composition to the survey area and during relatively calm seas to limit excessive motion and ensure suitable bottom detection.

Example patch test procedure for each line set is shown in Figures 2.2, 2.3, and 2.4.

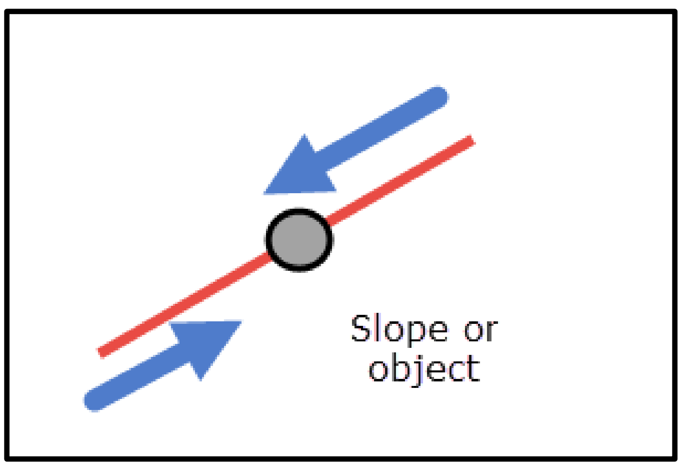

Figure 2.2. Pitch: run one line twice in opposite directions at the same speed over a steep, well-defined slope. Compare the nadir profiles of the swaths.

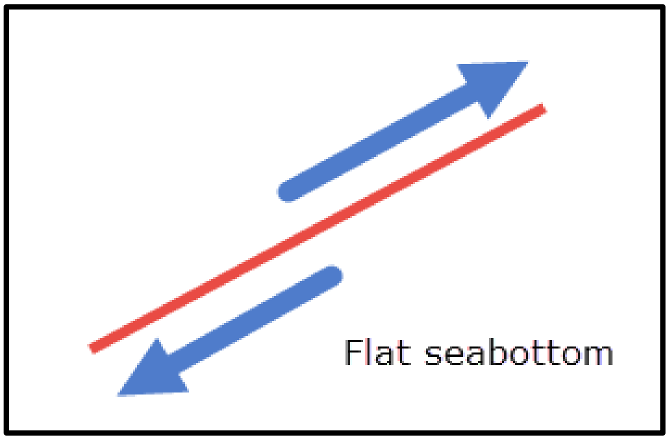

Figure 2.4. Roll: run the same line twice in opposite directions at the same speed over a flat seafloor area. Compare the across-track profiles of the swaths.

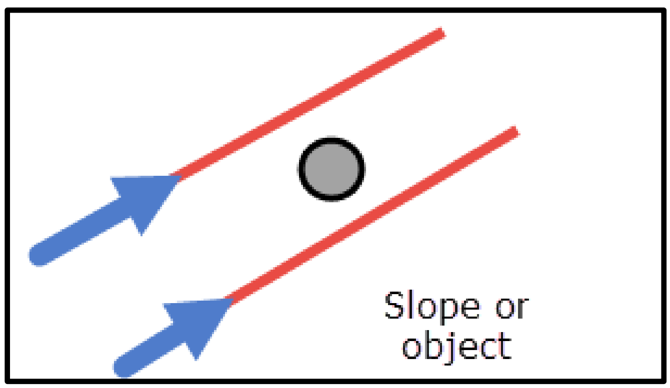

Figure 2.3. Heading/yaw: run two offset lines in the same direction and speed over a steep, well-defined slope, with the outer ⅓ of the two swaths overlapping. Compare the along-track profile midway between the two lines.

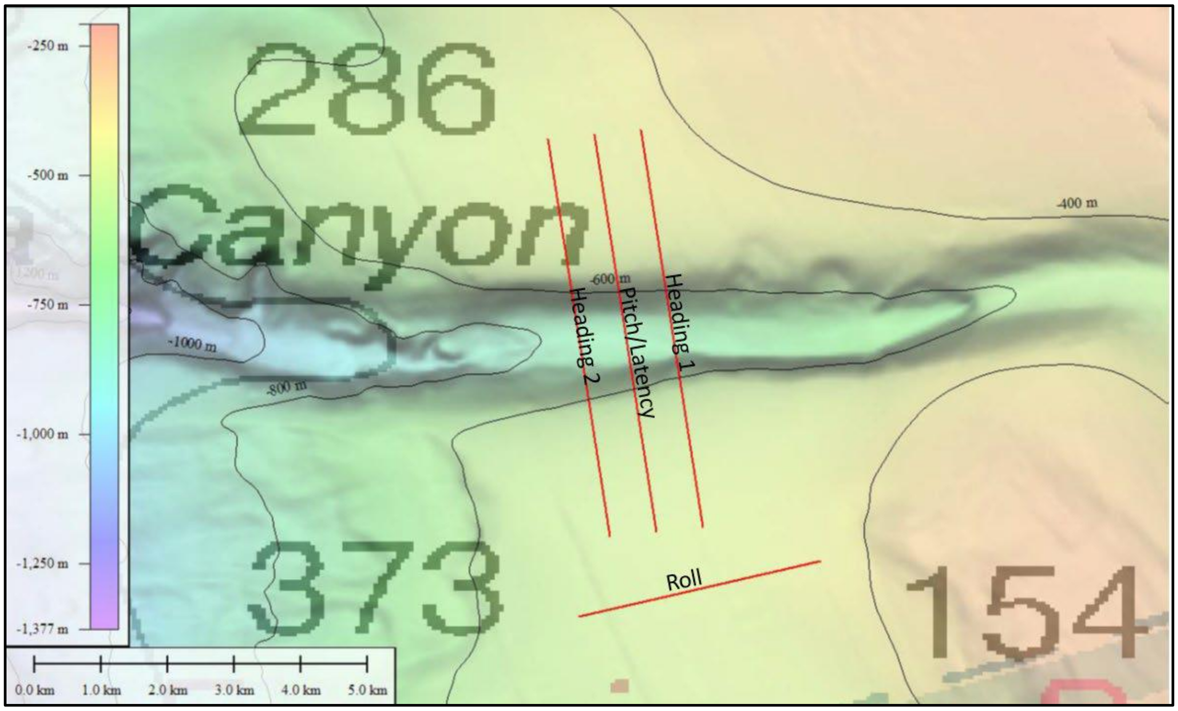

Figure 2.5. Sample patch test line plan: note the definition of slope for all biases except roll, which is on a flat area. Image source: Paul Johnson, NSF-funded Multibeam Advisory Committee (National Science Foundation).

The order in which these biases are determined may affect the accurate calibration of the multibeam system. Conduct the calibration tests in the following order with the hydrographer determining the biases in the following order: navigation timing error, pitch, roll, and heading (yaw).

There are several methods of achieving corrector values. One method is utilizing software that determines the values automatically (e.g., using cleaned data to provide offsets that minimize root mean square [RMS] RMS errors between test lines). Another method is to have three or more observers generate individual sets of values and use quantitative methods to develop a mean value for each corrector. Ideally, the final offsets are based on the agreement between automatic patch test tools and manual assessments by multiple observers. This process may be iterative, applying preliminary results and refining each test in the post-processing software until no further changes are warranted. Confirm offsets larger than 0.1 degrees with additional data collection (with preliminary results applied).

Final values derived from the patch test should be entered into the acquisition software and confirmed (without duplicating) in the processing suite.

2.5.2.3 Relative Backscatter Calibration

Use a relative backscatter calibration method to ensure consistency of the backscatter of a single system with different settings (Lurton et al., 2015). This method involves collecting multibeam data in a relatively flat, hard, and homogeneous seafloor region in a specific pattern consisting of reciprocal lines with various settings for pulse length and power applied. The results are then processed and can be applied during data collection or post-processing, depending on the particular multibeam system.

This procedure helps to normalize differences in backscatter values resulting from variable frequencies and pulse durations employed within sectors and among ping modes used during multibeam data acquisition. A successful relative backscatter calibration helps to produce a visually appealing backscatter mosaic image that displays the relative changes in backscatter that are representative of changes in the seafloor properties rather than changes in echosounder modes and transmit parameters.

2.5.2.4 Sound Speed Sensor Calibration

Sensors that determine sound speed should be calibrated according to the manufacturer's recommendation (typically annually). Calibration documentation provided by the manufacturer should accompany these data in the NOAA archive and any survey reports.

2.5.2.5 Multibeam Speed Noise Testing

Significant limitations on multibeam performance can stem from elevated noise levels due to hull design, engines, and other machinery; sea state; biofouling; electrical interference, etc. Periodically when possible, a series of tests should be run to track RX noise and RX spectrum to characterize the vessel's platform noise environment over a range of speeds or operating parameters (e.g., different engine lineups, if more than one is used during mapping operations).

Conduct these tests in calm to mild sea states, with low currents, and in the absence of rain and high winds to isolate the impacts of elevated sea states and weather on noise levels (which can be substantial). Pay attention to the vessel's orientation concerning swell, as pitching into a significant swell (or, in some cases, steering noise at oblique angles to the swell) can impact the results. Run separate tests to assess noise levels versus vessel heading relative to the prevailing swell, allowing surveyors to identify vessel orientations that may reduce noise levels and improve mapping data.

The noise floor can vary for each system; therefore, absolute noise thresholds are difficult to define across systems. The best indicator that the noise floor is too high is an apparent reduction in swath coverage and degradation of the data. Therefore, speed-noise tests are most valuable when compared to previous tests to monitor changes in the platform noise levels (e.g., due to engine lineup or other machinery alterations, especially pre- and post-shipyard), track the health of the system (e.g., RX element failure), and provide an early indication of potential performance reduction over time. The MAC provides guidance and software tools for collecting RX noise level data for Kongsberg systems, and other manufacturers may provide similar resources.

Multibeam assessment tools have been developed by the MAC (GitHub oceanmapping community, 2022).

2.5.2.6 Extinction Testing

Extinction testing is conducted annually or opportunistically on transits to determine the coverage achievable by the multibeam sonar across the full range of operational depths (i.e., from shallow water out to full extinction, if possible). This information is helpful for line planning and provides an early indication of performance degradation. Reductions in coverage can indicate increased vessel noise levels or other hardware issues, such as reduced transmission strength.

Repeating transit lines over a wide range of depths (e.g., transits in and out of a particular port on the same course) can provide a valuable comparison of swath coverage over the years. It is beneficial to collect pre- and post-shipyard data to ensure no changes in vessel noise that may limit swath coverage (or to document any improvement, such as from hull and transducer cleaning).

Several multibeam processing packages offer coverage assessment tools that can be used with cleaned data from various formats within a processing project. The MAC provides guidance and software tools for collecting and assessing swath coverage data with Kongsberg systems, and other manufacturers may provide similar resources.

Multibeam assessment tools have been developed by the MAC (GitHub oceanmapping community, 2022).

2.5.3 Hardware Maintenance

2.5.3.1 Transducer Face Cleaning

Heavy biofouling can impact transmit and receive levels and severely degrade the signal-to-noise ratio. Thus, the face of the transducers (both the transmit and receive arrays) and hull areas near the arrays should be visually inspected by scuba divers throughout the year for significant biofouling. Cleaning may be necessary multiple times per year and must be done per the manufacturer's recommendations to remove biofouling without damaging the transducer faces.

During every dry dock, the transducers should be cleaned and painted with anti-fouling paint, and the epoxy material adhering the transducers to the hull should be replaced as necessary to reduce the potential for cavitation due to non-smooth surfaces. It is critical that all transducer cleaning and painting steps strictly follow the manufacturer's procedures for preparation, paint type, and thickness of application. The mass of the paint on the transducer face directly impacts its frequency response; misapplication can severely degrade the adequate TX power and RX sensitivity, resulting in significantly reduced coverage and accuracy.

2.5.3.2 Impedance Testing

Most transducers have a useful life of roughly 10 years before showing performance degradation. Impedance testing, conducted by the sonar manufacturer, should be done throughout the system's life to monitor system health. The manufacturer can advise appropriate testing intervals.

Some systems offer self-testing functions that should be run routinely (e.g., before and after each survey) and may offer proxies for impedance testing. These are not substitutes for direct impedance analyses of individual transducer channels but may help to alert users to new element failures or general trends across an array. The MAC provides guidance and software tools for collecting and assessing Built-In Self-Tests (BISTs) for TX and RX Channels data with Kongsberg systems, and other manufacturers may provide similar resources (GitHub oceanmapping community, 2022).

2.5.4 Sound Speed Correction

2.5.4.1 Vertical Sound Speed Profiling

It is necessary to know the speed of sound through the water column to resolve the depth from the two-way travel time of the ping.

Range = [(Two way travel time)/2] x speed of sound

When profiling at oblique angles, variations in sound speed will also change the path of sound through the water, affecting not just the observed range but also the lateral position of the observed sounding; thus, sound speed profiles are essential for MBES. As the speed of sound varies depending on environmental conditions, it must be captured at frequent enough intervals to resolve the spatial and temporal variability of the area.

Sound speed profiles can be collected with various instruments, such as CTDs, expendable bathythermographs (XBT), XSVs, MVPs, and Remotely operated vehicles (ROV)-mounted sensors. Process profiles into a format that can be applied in the multibeam acquisition software; at a minimum, this can typically be done with software provided with the sound speed sensor or through profile processing tools in the multibeam acquisition software. More streamlined approaches for processing and monitoring sound speed are available with third-party software such as Sound Speed Manager (HydrOffice). HydrOffice, led by the University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center, with significant collaboration with NOAA and other agencies worldwide, provides open-source tools to support ocean mapping, including planning and processing sound speed profiles (HydrOffice, 2023).

2.5.4.2 Surface Sound Speed Measurement

Sound speed at the level of the transducer is a critical component for beam steering, and any error in the launch angle of the beams will propagate throughout the entire water column. Observe sound speed at the transducer and input to the sonar system in real-time for application (i.e., beamforming) during acquisition.

Monitor the surface sound speed in the acquisition software, with particular attention to differences from the most recent sound speed profile at that depth. Sound Speed Manager can monitor these changes and plan for new profiles, as well as confirm that the surface sound speed value is applied at the correct depth in the profile (thereby also confirming other parameters, such as waterline).

2.5.5 Tides and Water Levels

Personnel from NOAA's Center for Operational Products and Services (CO-OPS) are responsible for all planning of tide and water level requirements for NOAA's OCS hydrographic surveys. CO-OPS will analyze historical data and tidal characteristics for each project area; specify operational NOS control stations; specify general locations for subordinate water level stations to be installed and provide the tidal zoning (both preliminary and final) used during survey operations.

In deeper water surveys (>200 m), the tidal range is generally a tiny percentage of water depth; it is therefore considered negligible and the application of tidal correctors is optional. Document the application or non-application of tides in the survey/dataset documentation with the vertical datum specified as Mean Sea Level (MSL).

Whenever surveyed/predicted tides or water levels are used to reduce soundings to a datum, TVU calculations should incorporate the uncertainty of these time series. In most circumstances, observed values are preferred over predicted.

For detailed guidance and recommendations on time series water level data and associated water level reducers that can be applied to bathymetric soundings for correction to chart datum, refer to the NOAA Hydrographic Survey Specifications and Deliverables; Tides and Water Levels Requirements Chapter (NOAA OCS, 2022).

2.6 Lidar Protocols

These lidar protocols are derived from the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) Topo-Bathy Lidar Specification, currently under development by JALBTCX partner agencies U.S. Army Corps of Engineers (USACE), Naval Oceanographic Office (NAVOCEANO), NOAA, and USGS.

2.6.1 Collection Requirements

Although lidar collection parameters are highly dependent on the environment of the project area and numerous other factors, this chapter defines those collection requirements that must be met to achieve consistent topo-bathymetric lidar collection for IWG-OCM.

2.6.1.1 Collection Area

The collection area, or Defined Project Area (DPA), is defined by the area of interest, plus a buffer of 100 m. Data collection and deliverables are required for all production flight lines. The DPA should include any ground truth observations used to validate the accuracy of a survey.

2.6.1.2 Quality Level

Table 2.1 contains reasonable specifications for THU, TVU, sample density, and system depth performance. The cells highlighted in green are the typical acceptable level for each parameter to meet the requirements of the JALBTCX partner agencies (USACE, NAVOCEANO, NOAA, and

USGS). These specifications apply to bathymetric lidar data and bathymetric data collected as part of a topobathymetric lidar survey.

Table 2.1. Specification matrix for uncertainties of THU, TVU, sample density, and system depth performance for bathymetric data. All uncertainties are given at the 95% confidence level. For each bathymetric parameter, the matrix includes a range of values for parameter uncertainty. Cells outlined in black are minimum specification to meet interagency requirements.

A. Relationship of parameter values to standing Hydrographic Survey Orders established in the International Hydrographic Organization S-44 Standards for Hydrographic Surveys

		Range of Values						
Parameters	Depth THU (m)	20	10	5	2	1	0.5	0.25
	Depth THU (% of depth)	10	5	2	1	0.5	0.25	0.1
	Depth TVU "a"* (m)	1	0.5	0.3	0.25	0.2	0.15	0.1
	Depth TVU "b"* (m)	0.023	0.020	0.013	0.010	0.0075	0.0040	0.0020
	Sample Density (m^{-2})	0.04	0.25**	2	3	5	10	20

- IHO Order 2
- IHO Order 1a/b, Bathy QL 4b
- IHO Special Order, Bathy QL 0b/1b
- IHO Exclusive Order
- Both IHO Special Order, Bathy QL 0b/1b and IHO Exclusive Order

B. Relationship of parameter values to the Interagency Working Group on Ocean and Coastal Mapping Bathymetric Lidar Quality Levels

		Range of Values						
Parameters	Depth THU (m)	20	10	5	2	1	0.5	0.25
	Depth THU (% of depth)	10	5	2	1	0.5	0.25	0.1
	Depth TVU "a"* (m)	1	0.5	0.3	0.25	0.2	0.15	0.1
	Depth TVU "b"* (m)	0.023	0.020	0.013	0.010	0.0075	0.0040	0.0020
	Sample Density (m^{-2})	0.04	0.25**	2	3	5	10	20

- Bathy QL 0b/1b (1b has lower sample density)

- Bathy QL 2b/3b (3b has lower sample density)

- Bathy QL 4b

- Both Bathy QL 0b/1b and Bathy QL 2b/3b

- Both Bathy QL 2b/3b and Bathy QL 4b

THU = total horizontal uncertainty

*TVU = total vertical uncertainty ($\pm\sqrt{a^2 + (b * d)^2}$; a = portion of uncertainty that does not vary with depth; b = portion of uncertainty that varies with depth; d = depth)

** - Note that in optically deep water, bathymetric lidar systems produce data at lower sample density.

2.6.1.4 Multiple Returns

Data collection should be capable of multiple returns per measurement (pulse, waveform, or pixel) for the determination of water surface, seafloor, and midwater returns.

2.6.1.5 Data Voids

Data voids may result from operational or environmental conditions, including:

- Water clarity
- Turbidity plumes
- Bubbles and sediment entrained in the water column and surface foam from breaking waves
- Areas of low bottom reflectivity, such as mud or submerged aquatic vegetation
- Aircraft motion

Careful planning ensures complete data coverage.

2.6.1.6 Spatial Distribution and Regularity

Plan and execute collections to produce aggregate bathymetric point data that approach a uniform, regular lattice of points.

2.6.1.7 Collection Conditions

Consider the following collection conditions relative to survey intent:

- Cloud and fog between the aircraft and ground
- Snow and ice cover on land and water
- Extensive flooding or any other type of inundation
- Leaf-on or leaf-off vegetation condition
- High or low tides, water level, or river flow
- Submerged aquatic vegetation biomass

2.6.1.8 Depth Range

Depth performance of airborne lidar bathymeters varies based on system design factors such as laser power, optical element size, and receiver sensitivity. Estimated lidar system depth performance should be evaluated against desired depth range and expected water clarity in the project area to ensure the system selected is capable of meeting survey objectives. Consider minimum depth performance to ensure seamless coverage from land to water.

2.6.2 Data Processing and Handling

Elevations and depths should be reported in metric units.

2.6.2.1 Time of GPS Data

Record GPS data as Adjusted GPS Time (Standard [satellite] GPS time minus $1*10^9$) at a precision sufficient to allow unique timestamps for each pulse.

2.6.2.2 Datums

The CRS for latitude, longitude, and ellipsoid heights should be the North American Datum of 1983 (NAD 83) using the most recent adjustment published by the National Geodetic Survey (NGS) (currently NAD 83, epoch 2010.00, realization of 2011).

The vertical datum for orthometric heights should be the North American Vertical Datum (NAVD) of 1988 (NAVD 88). The geoid model used to convert between ellipsoid and orthometric heights should be the latest hybrid geoid model of NGS, supporting the latest realization of NAD 83 (currently [2017] GEOID model).

Use alternate vertical datums in areas where a current geoid model is unavailable, including Alaska, American Samoa, Commonwealth of the Northern Mariana Islands, Guam, Hawaii, Puerto Rico, U.S. Virgin Islands.

2.6.2.3 File and Point Source Identification

At the time of its creation and before further processing, each swath should be assigned a unique file source ID. Each point within the swath should be assigned a point source ID equal to the file source ID. The point source ID on each point shall be persisted unchanged throughout all processing and delivery.

2.6.2.4 Positional Accuracy Validation

Before the classification and development of derivative products from point data, the absolute and relative accuracy of the point data should be verified.

2.6.2.5 Relative Vertical Accuracy

Relative vertical accuracy refers to the internal geometric quality of a lidar dataset without regard to surveyed ground control.

2.6.2.6 Intraswath Precision (Smooth surface precision)

Intraswath precision should be assessed on large, flat, hard-surfaced, open areas (for example, parking lots or large rooftops) containing only single return lidar points and for the entire swath width.

2.6.2.7 Interswath (Overlap)

Interswath consistency should be assessed at multiple locations within swath overlap in non-vegetated areas of only single returns and with terrain slopes of less than 10 degrees for the following:

- Adjacent, overlapping parallel swaths
- Project swaths in opposing flight directions
- Crosslines
- Adjacent, overlapping flight blocks, i.e., lifts

2.6.2.8 Absolute Vertical Accuracy

The absolute vertical accuracy of the lidar data and the derived digital elevation model (DEM) should be assessed and reported under the American Society for Photogrammetry and Remote Sensing (ASPRS, 2014) for topographic data collected ancillary to bathymetry and wading depths.

Four absolute accuracy values shall be assessed and reported:

- Non-vegetated Vertical Accuracy (NVA) for the point data.
- Vegetated Vertical Accuracy (VVA) for the point data.
- NVA for the DEM.
- VVA for the DEM.

Assess NVA and VVA for the point data by comparing checkpoints to a triangulated irregular network (TIN) constructed from ground-classified lidar points.

Assess NVA and VVA for the DEM by comparing checkpoints to the final bare-Earth surface.

2.6.2.9 Point Classification

The minimum required classification scheme for lidar data is found in Table 2.2. All points within the minimum classification scheme that are not flagged as withheld should be classified appropriately.

2.6.2.10 Classification Consistency

Point classification should be consistent across the entire project, with no noticeable variations in the character, texture, tiles, swaths, lifts, or other non-natural division classification quality.

2.6.2.11 Intensity Values

Intensity values are required for each bottom return where water conditions allow.

2.6.2.12 Tiles

Establish and use a single non-overlapping project tiling scheme for all tiled deliverables. The tiling scheme should use the same CRS and units as the point data. The tile size shall be an integer multiple of the cell size for raster deliverables. Index the tiles in x and y to an integer multiple of the x and y dimensions of the tile. Edge-match the tiled deliverables seamlessly, without gaps, and conform to the project tiling scheme without added overlap.

2.6.2.13 Point Duplication

Do not duplicate lidar points (x, y, z, and timestamp) within the project. Near duplication (a group of points duplicated but with a slight but consistent spatial offset) will be regarded as duplication.

Table 2.2. Bathymetric/topographic lidar data classification scheme.

Code	Description
1*	Processed, but unclassified
2*	Bare-Earth ground
7	Low noise (low or high; manually identified, if necessary)
9	Water (topographic sensor)
17	Bridge deck
18	High noise (high manually identified, if necessary)
20	Ignored ground (typically breakline proximity)
21	Snow (if present and identifiable)
22	Temporal exclusion (topographic sensor) typically non-favored data in intertidal zones)
40*	Bathymetric Point, Submerged Topography (e.g., seafloor or riverbed)
41	Water Surface (sea/river/lake surface from bathymetric or topographic-bathymetric lidar; distinct from Point Class 9, which is used in topographic-only lidar and only designates "water," not "water surface")
42	Derived water surface (synthetic water surface location used in computing refraction at water surface)
43	Submerged object, not otherwise specified (e.g., wreck, rock, submerged piling)
44	IHO S-57 object, not otherwise specified
45	No-bottom-found (bathymetric lidar point for which no detectable bottom return was received)
64	Submerged Aquatic Vegetation
65	Denotes bathymetric bottom temporal changes from varying lifts, not utilized in bathymetric point class

2.6.3 Deliverables

Delivery is required for all ancillary products that support the processing of the lidar dataset, including, imagery and all metadata associated with those data.

2.6.3.1 Metadata

Product metadata files shall comply with ISO 19115-1:2014 Geographic information - Metadata - Part 1: Fundamentals.

Record the CRS, epoch, realization, geoid model, NGS model filenames, or information describing alternate vertical datum separation from ellipsoid in metadata.

2.6.3.2 Reports

Report deliverables shall include the following:

- A survey report detailing the collection of all ground survey data
- A lidar mapping report that describes:
  - Data acquisition and Processing
  - ABGNSS-inertial Processing
  - Point cloud creation
  - Geometric quality
  - Production

2.6.3.3 Classified Point Data

2.6.3.3.1 ASPRS LAS File Format

All point deliverables should be in LAS format, version 1.4-R15, using Point Data Record Format 6, 7, 8, 9, or 10. Data producers are encouraged to review the LAS specification version 1.4–R15 in detail (ASPRS, 2011). LAS files should conform to the following items:

- Include a unique identifier for the dataset in the LAS file(s) as a Globally Unique Identifier (GUID).
- Correct and properly formatted georeference information as Well-Known Text (WKT) (OGC, 2001) included in all LAS file headers.
- The encoding tag in the LAS header should be set properly. See LAS specification version 1.4–R15 (ASPRS, 2011) for additional information.
- Intensity values in 16-bits. See LAS specification version 1.4–R15 (ASPRS, 2011) for additional information.
- Tiled delivery, without overlap, using the project tiling scheme.
- Classification, as defined above, is at a minimum.

2.6.3.3.2 Use of the LAS Withheld Bit Flag

The withheld bit flag, as defined in LAS specification version 1.4–R15 (ASPRS, 2011), shall only be used to identify points that cannot be interpreted as valid surface returns. Examples include outliers, blunders, geometrically unreliable points, aerosol back-scatter, laser multi-path, airborne objects, and sensor anomalies. Preferred data delivery treatment is to exclude withheld points from delivered data.

2.6.3.4 Bathymetric Lidar Waveform

If collected, deliver bathymetric lidar waveforms. Deliver waveforms in:

- LAS deliverables using external auxiliary files with the extension ".wdp" to store waveform packet data. See LAS specification version 1.4–R15 (ASPRS, 2011) for additional information, or
- Alternate, well-documented, open-source formats, such as *.cpf

2.6.3.5 First-Return Surface (Raster Digital Surface Model)

Use lidar point data falling into the “processed but unclassified,” “bare earth,” and “bathymetric point, submerged topography” classes to generate the first-return digital surface model (DSM).

Generate the first-return DSM to the limits of the DPA in a 32-bit floating-point GeoTIFF raster format. GDAL version 2.4.0 shall be used to populate GeoTIFF keys and tags, or as otherwise agreed to in advance and specified in the Task Order. Deliver DEM data in the same coordinate reference system (CRS) and tiling scheme as the lidar data, with no edge artifacts or mismatches.

Georeference information should be delivered in or accompany each raster file, as appropriate for the file format. This information should include horizontal and vertical systems; the vertical system name should include the geoid model used to convert from ellipsoid heights to orthometric heights.

2.6.3.6 Bare-Earth Surface (Raster Digital Elevation Model)

Use lidar point data falling into the “bare earth” and “bathymetric point, submerged topography” classes to generate a bare-Earth DEM.

Generate the bare-Earth DEM to the limits of the DPA in a 32-bit floating-point GeoTIFF raster format. GDAL version 2.4.0 shall be used to populate GeoTIFF keys and tags or as otherwise agreed in advance and specified in the Task Order. Deliver DEM data in the same CRS and tiling scheme as the lidar data, with no edge artifacts or mismatches.

Georeference information shall be delivered in or accompany each raster file, as appropriate for the file format. This information shall include horizontal and vertical systems; the vertical system name shall include the geoid model used to convert from ellipsoid heights to orthometric heights.

Remove bridges; the bare-Earth surface below the bridge should be a continuous, logical interpolation of the apparent terrain lateral to the bridge deck. The bare-Earth interpolation shall begin at the junction of the bridge deck and approach structure where abutments are clearly visible.

Roads or other travel ways over culverts should remain intact on the surface.

2.6.3.7 Breaklines

Deliver breaklines used to enforce a logical terrain surface below a bridge.

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Chapter 3: Seabed and Lakebed Backscatter

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3.1 Introduction

Common standards for acquiring, processing, and reporting acoustic seafloor and lakefloor backscatter data have not been widely established. This chapter encourages advancement in standard backscatter acquisition and processing methods, acoustic signal corrections, and image processing steps. It describes backscatter, existing challenges in data usage, and applicable protocols.

Backscatter information assists in determining the characteristics and composition of the seabed/lakebed, sediment concentration levels in rivers or coastal waters, and classification of benthic habitats (Kist, 2017). Sonar systems engineered to collect backscatter record information about the physical acoustic properties of the seabed/lakebed by measuring the acoustic signal return—i.e., the angle and strength of the returning sound wave reflected from the seafloor/lakefloor—or suspended sediment. On a hard or rough seafloor, such as a rock outcrop or boulder field, there tends to be a more robust acoustic signal return than from a soft and smooth, transmissive seafloor like silt. Recording acoustic signal return 'strength' allows the backscatter data to be post-processed into mosaics, georeferenced, and displayed as a color or grayscale map. Examples of backscatter mosaics can be found in Schimel (2018) and online in the "NE Bathymetry and Backscatter Compilation" (Ward et al., 2020).

Analyzing backscatter is more complex than bathymetry because it requires many more parameters to be known or estimated, such as the loss and redistribution of acoustic energy or sensitivity of the specific sonar receiver. Coupled with this challenge, to use backscatter data effectively once recorded, a pragmatic and smart calibration technique needs to be established to get the best results. Modern multibeam systems can compensate for changes in signal strength and angle through better processing technology, and artificial intelligence (AI) should improve the post-processed interpretation of such 'corrected' backscatter returns. However, seafloor/lakefloor acoustic backscatter observations are too rarely calibrated or delivered without any specified standard. Geometric and radiometric corrections need to be applied so that individual surveys are internally consistent (John Hughes Clarke, University of New Hampshire, 2020).

GeoHab established the BSWG in 2015 (GeoHab, n.d.). The BSWG is composed of a multidisciplinary research consortium of internationally recognized experts in marine acoustics, geophysics, spatial analysis, and ocean environmental science. The BSWG undertook a robust process to develop guidelines that represent expert consensus, resulting in the publication of *Backscatter Measurements by Seafloor-Mapping Sonar: Guidelines and Recommendations* (Lurton and Lamarche, 2015), which presents techniques and procedures for the acquisition and processing of backscatter data. The NOMEC and SOMP writing team evaluated these guidelines and agreed they should serve as best practices for the SOMP/NOMEC implementation.

3.2 Guidelines

Utilize Chapter 1 Data Management and the GeoHab BSWG published *Backscatter Measurements by Seafloor-Mapping Sonar: Guidelines and Recommendations* (Lurton and Lamarche, 2015).

3.2.1 Data Management

Management of backscatter data is necessary for efficient use, future access, and validation of analytical and interpretative results. Raw and processed data (i.e., mosaics) should be archived.

For specific details and guidelines associated with minimum backscatter data requirements and management (such as recommended file formats, metadata, data archival, etc.), see the Backscatter Data Management subchapter of the SOMP Data Management Chapter.

3.2.2 Raw Data Acquisition

Below is essential information to be confirmed in the data files and/or survey report to increase usability:

- Vessel configuration
  - Survey vessel draft
  - Applied system offsets (e.g., measured offset between the IMU to transducers, IMU to navigation antennas, waterline from transducers, transducer static mount rotations)
- Sonar settings
  - Operational frequency
  - Pulse length: duration of the transmitted signal
  - Gains
    - Time varied gain (TVG): A correction applied to the received echo level to compensate for loss imposed by the distance between the target and the sonar system using the law for expected propagation loss, transposed into the time domain (Lurton and Lamarche, 2015).
    - Echo level: The intensity level of the acoustic wave backscattered and received by the sonar system; equal to the source level (SL) minus 2x the TL plus the TS (Lurton and Lamarche, 2015).
      - Raw – no TVG
    - Target Strength: the ratio between the intensity sent by the target back toward the transmitter and the incident intensity (Lurton and Lamarche, 2015).

        - The manufacturer's TVG applied for TL
      - Backscatter: Generation of a non-coherent echo of the acoustic wave in the same direction as the angle of incidence (Lurton and Lamarche, 2015). The measure of sound reflected by the seafloor and received by the sonar.
        - Manufacturer's TVG applied for TL and footprint extent (FE): Spatial resolution
      - Customized TVG applied for TL and FE/Other
      - Modeled TL and coefficient parameters
  - Transmission loss
      - Loss of intensity, as acoustic waves propagate, due to geometric spreading and absorption; a key parameter for acoustic systems as it constrains the amplitude of the signal received directly dependent on the signal-to-noise ratio (Lurton and Lamarche, 2015).
  - Sound speed profiles
  - Absorption profiles
  - Power settings
  - Cutoff angle across-track

*Note: If any settings are changed during the survey, document specific change(s) with timestamp(s).

- Data coverage should report:
  - Swath width versus trackline spacing
  - Percent of seafloor ensonified (e.g., 100%, 150%)
- If raw data are calibrated to a reference standard, the Level of Reference should be reported as:
  - No level reference considered
  - Level reference from the manufacturer (nominal value)
  - Relative reference level from calibration operation
  - Absolute reference Level from calibration operation
  - Other

3.2.3 Data Processing and Mosaic Generation

Below is essential information to be confirmed in the data files and/or survey report to increase usability:

- Processing steps
  - Describe data processing steps, including the application of sound speed, filters, and removal of erroneous soundings
  - Software and versions used

- Spatial reference
    - Coordinate system
    - Horizontal datum
    - Vertical datum
    - Describe processing used to shift coordinate system or datum, if different from raw data
    - Options as stated in *Backscatter measurements by seafloor-mapping sonars: Guidelines and Recommendations* (Lurton and Lamarche, 2015):
        - No geo-reference
        - Geographic reference (latitude, longitude)
        - Projected reference (Mercator, Universal Transverse Mercator [UTM], …)
        - Other
- Mosaicking settings
    - Order (1st, last, top, bottom, …)
    - Quality (angle, no specular, …)
    - Statistical (average, median, …)
    - Other
- Interpolation
    - No interpolation
    - Over NaN only
    - Averaging/smoothing
    - Other
- Visual representation
    - Grey level 0-255
    - dB value
    - Other
- Sound speed
- Tidal corrections
- Array directivity compensation
    - Definition: Directivity Function = The angular pattern describing the spatial spreading of the acoustical intensity radiated by a sound source or received by a hydrophone expressed in dB as log (base 10) of the intensity normalized by its maximum value (most often along the axis of the main lobe)
    - Options:
        - No directivity compensation
        - Compensation from a directivity pattern model (manufacturer)
        - Equalization from a statistical average modulation (user)
        - Customized model for directivity pattern (fitted to statistics)

        - Other
- Seafloor Incident Angle Compensation
    - Definition: Incidence angle = The angle of the sound ray path perpendicular to the target interface at the impact point. For a flat horizontal seafloor, it is the angle with the vertical; horizontal incidence is 90°, and vertical incidence (nadir) is 0°
    - Options:
        - Flat seafloor, no refraction by Sound Velocity Profile (SVP)
        - Flat seafloor, SVP refraction
        - Local across-track slope (derived from one ping), no SVP refraction
        - Local across-track slope (derived from one ping), SVP refraction
        - Local slope (from bathymetry, incl. along-track slope), no SVP refraction
        - Local slope (from bathymetry, incl. along-track slope), SVP refraction
        - Other
- Seafloor Angular compensation, options:
    - No BSAD compensation
    - BSAD Compensation from a theoretical model (e.g., Lambert's)
    - Compensation from the model with adaptive parameters (e.g., KM's specular)
    - Customized BSAD (model fitted to statistics)
    - Other
- Reference angle, options:
    - No reference angle
    - Vertical incidence
    - Fix angle at 45 degrees
    - Other

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3.4 Additional Resources

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Chapter 4: Water Column Sonar

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4.1 Introduction

From the ocean surface to the seafloor, the water column is the largest (by volume) and least explored biome on the planet (Webb et al., 2010), highlighting the need to collect sonar data throughout the water column. While the NOMEC Strategy defines “ocean mapping” as activities that provide comprehensive data and information needed to understand seafloor characteristics such as depth, topography, bottom type, sediment composition and distribution, and underlying geologic structure (NOMEC, 2020), water column acoustic data can be collected and stored in conjunction with seafloor mapping data. Due to the sparse historical data from the water column, water column sonar data should always be collected when feasible because this could provide much-needed baseline information for the future. The tragic explosion and oil spill from Deepwater Horizon is a case in point, where observations were made quickly after the disaster, but baseline data were sorely lacking (Joye, 2015).

Sonar data collected in the water column can provide information about multiple features from geological (e.g., benthic formations, and hydrocarbon seeps [Watkins and Worzel, 1978; Weber et al., 2012; Skarke et al., 2014]), to chemical/physical (e.g., temperature or salinity gradients), to biological (e.g., scattering layers, concentrations/aggregations of organisms [e.g., Benoit-Bird and Au, 2009]) (Figure 4.1; Colbo et al., 2014). Quantitative analysis of data collected using water column sonars can inform fisheries stock assessments (e.g., Stienessen et al., 2019) and basin-scale habitat modeling (McConnaughey and Syrjala, 2009); ecosystem-based management (Koslow, 2009); seabed classification (Cutter et al., 2014; Anderson et al., 2018); turbulent microstructure, internal waves, thermohaline staircases and the thermocline (Proni and Apel, 1975; Stranne et al., 2017, 2018); and spatiotemporal distribution of organisms (Benoit-Bird and Lawson, 2016).

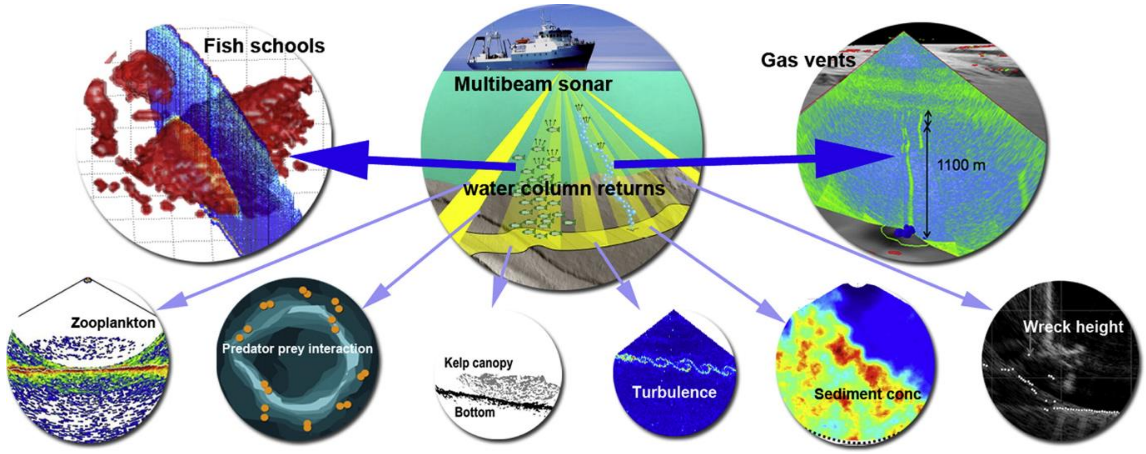

Figure 4.1. Water column sonars: scientists use data from water column sonars to address questions in fisheries, ecological interactions, and marine mammal and zooplankton research, as well as seeps and hydrothermal vents. (Image source: Colbo et al., 2014)

Water column sonar data can be collected using various tools and techniques. This chapter focuses on the detection, observation, and exploration of water column sonar data:

1. Logged during hydrographic survey or exploration mapping missions to investigate the water column
2. Collected during fisheries and ecosystem assessments using fishery sonars to map and characterize the seabed

Follow strict data calibration, acquisition, processing, and analysis protocols for enumeration and quantitative analysis of water column sonar data. This chapter provides information and guidelines on the type of sensors and platforms used for water column sonar data collection, recommended system parameters, calibration and QC techniques, data acquisition, and data interpretation and derived products. This chapter provides overarching guidance and recommendations for the collection of mapping data throughout the water column and will not address manufacturer-specific recommendations or specific use cases.

SOPs have been developed for specific use cases in fisheries and ecosystem assessments. Some example protocols and websites with further guidance are listed below:

- A General Guide for Deriving Abundance Estimates from Hydroacoustic Data (Cornell University & New York Sea Grant, n.d. a.)
- Fisheries Acoustics - A Practical Manual for Aquatic Biomass Estimation (FAO, 1983)
- NOAA OER Deepwater Exploration Mapping Procedures Manual (NOAA OER, 2020)
- Series of International Council for the Exploration of the Sea (ICES) Survey Protocols (SISP 9 - IPS): Manual for International Pelagic Surveys (IPS) (ICES, 2015)
- SOPs for Fisheries Acoustics Surveys in the Great Lakes (Parker-Stetter et. al., 2009)
- Understanding Our Ocean with Water Column Sonar Data (NOAA NCEI, 2021)

4.2 Instrumentation

Water column sonar data are collected primarily by acoustical systems that transmit sound into the water and then listen for echoes from targets in the water column. Anything in the water column with a density (kg m^{-3}) and/or sound speed (m s^{-1}) contrast to the surrounding water will scatter sound, and it is the sound that is scattered back to the acoustic system (i.e., "backscatter") that is recorded for analysis.

Echosounders form an electrical signal based on operational parameters that are often determined by the type of water column feature or organisms under study and the location of the survey. The most common parameters selected by the user are pulse duration, transmit interval, transmit power, and acoustic frequency (Table 4.1). There are two primary components of an echosounder, the transceiver and the transducer. The transducer converts the electrical signal from the transceiver into a transmitted acoustic pulse in the water, and vice versa, echoes arriving at the transducer are converted back into electrical signals received by the transceiver. The echosounder processes the electrical signal and outputs the digitized signal to a computer hard drive for analysis. It is important to remember that echosounders measure a voltage, and all analyses after that measurement are assessed using physical (i.e., physics of acoustics) and biological principles.

The different types of echosounders are defined by the type of pulse (e.g., frequency, bandwidth, and pulse form) generated and the type of transducer used. Narrow bandwidth echosounders transmit a continuous wave (CW) signal with a frequency range (bandwidth) that is usually defined as less than 10% (±5%) of the center frequency, whereas wide bandwidth (i.e., broadband) echosounders transmit signals with bandwidths greater than that. Broadband signals are typically linear frequency-modulated pulse forms known as "chirps," in which the transmitted signal's frequency ranges from the lowest to the highest frequencies chosen and sweeps from low to high (or vice versa) in a linear fashion. To use a musical analogy, narrowband signals are like tapping on one key of a piano keyboard, whereas broadband signals are like laying your forearm on a section of the keyboard and pressing keys from left to right ('upsweep') or right to left ('downsweep').

Transducers comprise several individual piezoelectric elements that vibrate when excited by a voltage. Transducers ultimately limit the bandwidth of the entire system; regardless of the electronic signal's bandwidth, the transducers will have a transmit and receive frequency range that provides efficient and reliable signals. The size and shape of the acoustic beam is determined by the arrangement and configuration of the elements and the frequency content of the input (or received) signal. The echosounder electronics are "matched" to a specific transducer to form a particular acoustic pulse configuration. There are two general classes of transducers: single beam and multibeam.

4.2.1 Single Beam Echosounder Systems (SBES)

Single beam echosounder systems (SBES) transmit a pulse of sound formed into a coherent beam (i.e., beamforming), often conical in shape (much like a flashlight beam), and upon reception, the entire beam is used to measure volume scattering. This is the fundamental function of water column sonars, and every echosounder, from the fish finders on recreational boats to depth sounders on commercial vessels, has this capability. In addition, some echosounders separate the beam into two, three, or four sectors. A two-sector system is called a "dual beam," and three or four-sector systems are called "split-beam" systems (Figure 4.2), where sometimes a split-beam is called split-aperture. These are all "single beams," and the sampling volume is based on the total beamwidth (Figure 4.2).

4.2.2 Multibeam Echosounder Systems (MBES)

In the most common applications for ocean mapping, MBES transmit a broad swath in the athwartship direction and narrow in the along-ship direction to ensonify a narrow slice of the water column and strip of the seabed with each ping cycle. MBES typically form hundreds of receive beams, closely spaced across the swath, and can report water column and seabed backscatter time series along the ray path for each. An MBES can form hundreds of beams, which are adjacent to each other. These beams can be arranged in many configurations, with swaths (bathymetric applications), two-dimensional arrays (fisheries sonars), and acoustic Doppler current profilers (ADCPs) being the most common arrangements, each with particular purposes and data products. Fishery MBES are a particular case of MBES designed specifically to sample the water column and behave like multiple SBES.

Advantages to multiple beams include greater sampling volume than single beam systems allowing you to see more of the water column; narrow beams (often 1–2°, versus 7–11° for SBES) for high spatial resolution; and electronically or mechanically steered beams to sample downwards or sideways at a prescribed angle from the sea surface. Disadvantages are that MBES requires a more complex transducer design, greater signal processing power, more complex electronics, more significant data storage resources than SBES and requires more physical space for installation on the platform when two transducer arrays are used.

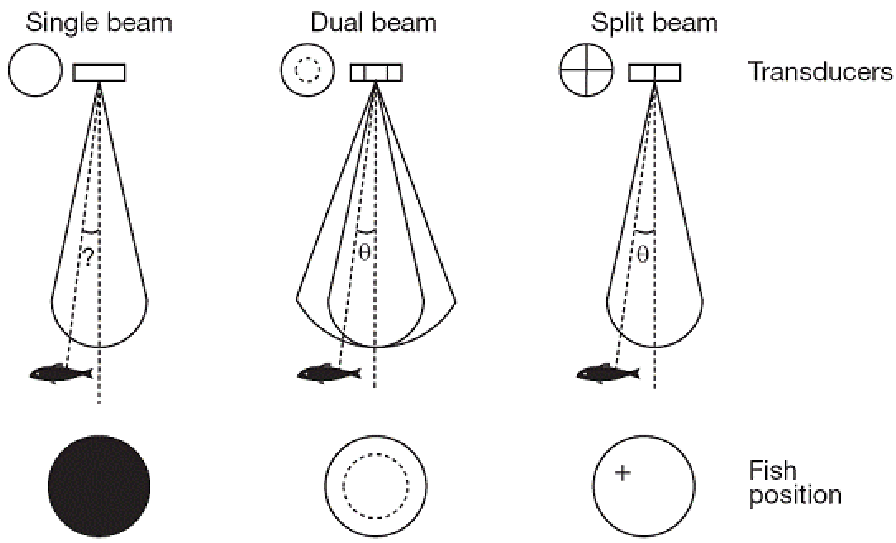

Figure 4.2. Transducer resolution and beam width: single beam, dual beam, and split beam (image source: Brandt [1996]; reproduced from the American Fisheries Society and Acoustics Unpacked [Cornell University & New York Sea Grant, n.d. b.]).

4.3 Platforms

Platforms situate the sonar systems where they are most useful while adhering to logistic and technological constraints. Surface vessels have been, and still are, the ubiquitous platform for sonar systems. Vessels can provide nearly unlimited electricity and data storage capabilities and accommodate onboard experts to evaluate data quality and intervene when quality degrades. However, vessel-based data collection can be limited by sea state; large overall costs to build, maintain, and staff vessels; and orientation of the echosounders on the sea surface. Alternative platforms have been developed to overcome these limitations, such as towed vehicles, ROVs, autonomous underwater vehicles (AUVs) and unmanned surface-vehicles (USVs), stationary moorings, net-mounted and even animal-mounted systems (e.g., Tournier et al., 2021) (Figure 4.3). All these alternatives have advantages and limitations compared with crewed vessels and as such, provide supplemental data but to date, do not supplant vessels as the primary platform for collecting acoustic data. Advantages include increased sampling over time and space, sampling in areas too dangerous for vessels and sampling close to boundaries such as the seabed, sea surface, and reefs. Limitations include increased required personnel to operate and maintain the platforms, the need for support vessels, and an increased likelihood of losing the platform.

4.4 System Parameters

The primary survey objective and selection or availability of acoustic systems dictates echosounder configuration. This chapter guides the collection of water column sonar data, whether the system’s primary purpose is to map the seafloor (e.g., hydrographic MBES for surveys of the seafloor) or the water column.

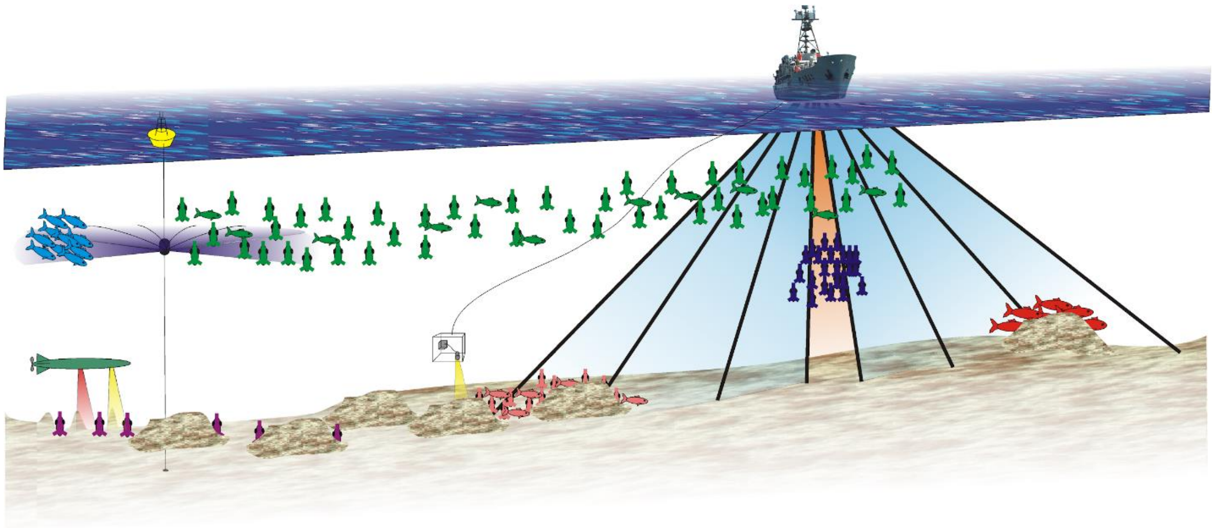

Figure 4.3. Ship-borne and alternative platform-deployed acoustical technologies for surveying fish in the pelagic and demersal regions: multibeam sonars, represented by the blue fan-shaped beams, significantly increase the sampling volume over single-beam echosounders (orange beam). Stationary transducers sample at one location over time, providing information on short-term to long-term behavior; these transducers are often attached to buoys for power and data storage and transmission. Autonomous underwater vehicles, towbodies, and remotely operated vehicles position acoustical and optical instrumentation near the features of interest. By decreasing the range to the feature, fewer extraneous targets and less sound absorption at higher frequencies improves detection and quantification of fish at boundary surfaces but at the cost of reduced sampling volumes. (Image source: Jech et al. 2007)

The frequency range and energy in the pulse of the sound transmitted by the echosounder influence range and resolution capabilities for detecting features in the water column and the seafloor’s depth. Higher frequencies are absorbed by the water more quickly than lower frequencies, generally resulting in a shorter-range capability. Water column features vary widely in density and sound speed (i.e., acoustic impedance) relative to the medium; therefore, expectations of the relative magnitude of acoustic backscatter, it’s range from the transducer, and background noise should be considered when selecting the appropriate frequency and system parameters (Table 4.1).

Table 4.1. Examples of typical range limits for detecting biological scatterers and the seafloor across a range of narrowband frequencies (assuming CW pulse forms) for echosounders.

Frequency (kHz)	Pulse Length (ms)	Biological Detection (m)	Bottom detection (m)
12	8	1500	10,000
18	4	1000	7,000
38	1	500	2800
70	1	300	1200
120	0.5 (1 for multi-frequency techniques)	200	500
200	0.5 (1 for multi-frequency)	100	200
400	0.25	75	200

Note: These values can vary by the operator to match survey requirements within the limitations of the echosounder system. In addition, broadband systems offer additional frequency and pulse characteristics but are not specified here.

The characteristics of the transmitted pulse can directly influence the detection of features above the background noise and signal attenuation. Generally, a longer pulse length carries more acoustic energy, and the returning backscatter can be easily differentiated from background noise and longer ranges. However, a longer pulse length in narrow frequency bandwidth (CW) can reduce the ability to resolve single targets (e.g., fish) in close vertical range or separate targets close to the seafloor. By contrast, for broadband or frequency modulated (FM) signals, the range resolution for similar target types is determined by the frequency bandwidth of the transmitted pulse (Lurton, 2002). Often, operators will select shorter pulse lengths in shallow water (0.2 ms pulse length is less than 200 m) to optimize range resolution and longer pulse lengths in deeper water (0.5 to 1.0 ms for greater than 200 m) to overcome signal loss and attenuation. When using multiple narrow bandwidth SBES with varying center frequencies, use equivalent pulse lengths to compare backscatter intensity across frequencies that may aid biological classification (Korneliussen et al., 2008).

4.5 System Calibration

4.5.1 Accounting for Water Column Sound Speed and Motion

Monitoring the sound speed in the water column is essential for accurate signal processing and data analysis, especially for MBES. MBES requires continuous measurement of the sound speed at the transducer, and all echosounder systems require periodic measurements of the entire water column, such as using a CTD profiler or an XBT. In addition, because the echosounder systems are located on platforms riding on or in the water, monitoring platform motion (e.g., heave, pitch, roll) is vital for SBES and critical for MBES calibration. These ancillary navigation and attitude systems must be appropriately configured with system offsets, calibrated, and synchronized to the echosounders, with data collected at appropriate rates.

4.5.2 Calibrating Single Beam Echosounders

Calibrating SBES systems accomplishes the primary goal of accounting for the variation in power, electrical, or mechanical loss in an echosounding system across platforms or environments. These results lead to surveys that provide comparable measures of the acoustic backscattering strength of water column features when using the same frequency and operating parameters.

Demer et al. (2015) reviews procedures for calibrating single, split-beam echosounders in detail. Scientific echosounders often have calibration routines built into the data acquisition and controlling software such as this:

Calibrate a single beam transducer using a standard target such as a metal sphere of copper or tungsten carbide, having known acoustic properties. Lower the sphere under the transducer to at least a 10-meter range positioned in the center of the transducer beam (or "on-axis") using one or many lines from the surface (Figure 4.4). Apply total system gain adjustments to achieve a TS matching the sphere's theoretical "on axis" value for the frequency, bandwidth, pulse length, pulse form, and environmental conditions (e.g., temperature, salinity, depth). Move the sphere through the transducer beam to characterize changes in perceived signal strength as the sphere moves off the central axis of the transducer.

The result is a model of the transducer beam pattern that can be applied to raw data to compensate for the backscatter or TS of an acoustic scatterer regardless of its angular position in the transducer beam.

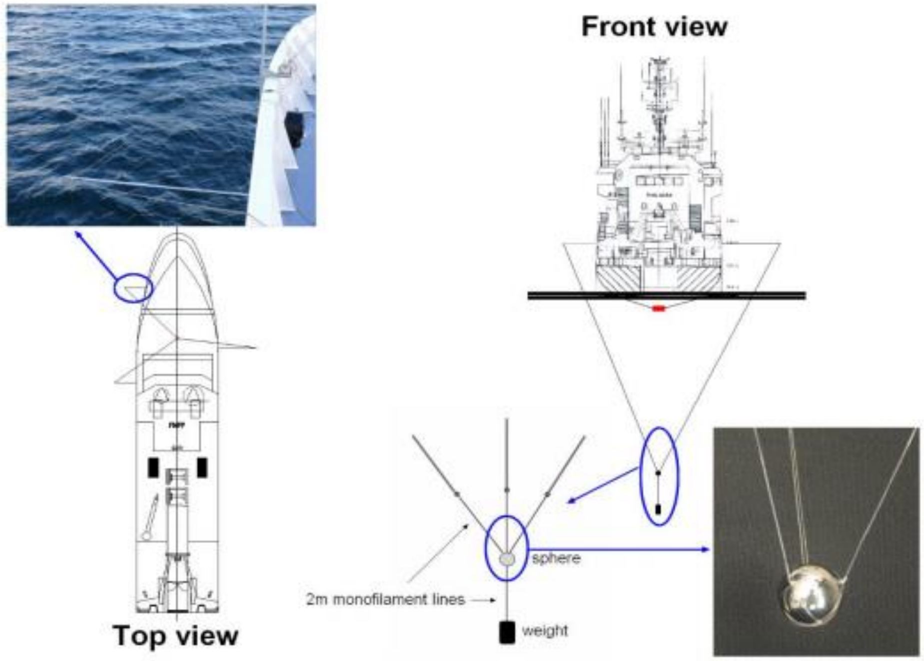

Figure 4.4. Transducer diagram: the calibration procedure for a single beam transducer with the standard calibration target (metal sphere) below a vessel and centered within the transducer beam (Image source: Demer et al. 2015).

4.5.3 Calibrating Multibeam Echosounders

Calibrations for hydrographic MBES include positional and motion calibration, and these practices are covered in the Bathymetry chapter of this protocol. Hydrographic and fishery MBES collect backscatter intensities in the water column. Calibrating the water column backscatter data from MBES with standard target methods allows for comparison across echosounder systems, platforms, and ocean basins. Methods for calibrating water column backscatter intensities for MBES is an active area of research. Demer et al. (2015) provide an overview of three calibration levels for MBES. Each calibration optimizes for a different objective. The levels are summarized here:

- **Level 1 multibeam calibration** accounts for specular reflection at normal incidence and decreasing intensity with increasing grazing angle. This is useful for monitoring fish and plankton at any angle away from the nadir.
- **Level 2 multibeam calibration** accounts for variation in backscatter between surveys due to environmental variation or the performance or settings of a system within platforms. This is important for comparing data from the same echosounder over time and ensuring that changes in backscatter, relative abundance, or biomass estimates are not due to changes in the acoustic system.

- **Level 3 multibeam calibration** permits the comparison of backscatter intensities across various echosounders and platforms. This is important for comparing data among echosounders, e.g., different platforms survey the same species.

Below are proposed protocols for multibeam water column backscatter calibration.

First, a standard calibration sphere, similar to that used for split-beam calibration, is moved through the multibeam to measure and normalize system gains across the beam footprints. The challenge in this example is to accurately position the sphere within the multibeam field of view, which tends to be very narrow in one direction. In research experiments, a calibrated SBES transducer is precisely positioned relative to the multibeam transducer and used to track the sphere location within the multibeam angle (Lanzoni and Weber, 2011). Alternatively, a split-beam echosounder measures backscatter intensity of the seabed at similar grazing angles as a MBES operating at equivalent frequencies (Ladroit et al., 2018).

A second MBES calibration approach uses a reference area of the seabed that is surveyed for backscatter intensity to compare MBES of similar operating frequencies (Weber et al., 2018). A challenge arises when extending these calibrations into the water column, as the water column targets do not have a constrained grazing angle (like the seafloor). Grazing angles of targets such as fish or other scattering objects may lead to significant variation in backscatter intensity, depending upon the angle of orientation relative to the transducer beam (Trenkel et al., 2008).

4.6 Quality Control

Criteria and thresholds of data quality can vary depending on the data application. The signal-to-noise ratio is often a guide for monitoring data quality, where “signal” is the component of the desired data, and “noise” is the unwanted component. For high signal-to-noise targets, such as fish species with a gas-filled swim bladder, set relatively high-volume backscatter thresholds to minimize scattering from other animals, such as zooplankton, squid, and jellyfish. Even a moderate level of noise is acceptable because of the strong signal. For low signal-to-noise targets such as krill, take more care to eliminate/minimize noise. Those in this threshold are more sensitive to noise.

Removing/minimizing the apparent noise during analyses of water column data is often referred to as “cleaning” the data (i.e., processing to highlight the ‘signal’). This involves removing the echoes from the seabed; transmitting pulse or ring-down of the transducer; wind- or cavitation-generated bubbles; false bottom echoes (aka “ghost” echoes); attenuated pings; and impulse, transient, and background noise from other sources, such as machinery (Jech and Schaber, ICES Cooperative Research Report 2021; Ryan et al., 2015; De Robertis and Higginbottom, 2007). The seabed and transmit pulse echoes are orders of magnitude greater than scattering by biological organisms, so they must be removed from analysis; otherwise, metrics such as abundance and biomass and spatial distribution can be severely affected. Most processing software packages have algorithms to detect the seabed echo and methods to eliminate it from analysis, but check the automated detections and correct any that are erroneous. For data close to the transducer, use a set depth or range above which data are ignored to eliminate the transmit pulse and near-field from the dataset. Set this depth consistently (for a given pulse length) throughout the survey but modify to encompass near-surface bubbles when they occur due to inclement weather (see Figure 4.5 for an example of near-surface bubbles).

Remove the other main types of noise (impulse, transient, and background) algorithmically from the data. Generic schemes for removing/minimizing these are given in Peña (2016) and Ryan et al. (2015). Figure 4.6 and Figure 4.7 provide visual examples of various types of noise, with Figure 4.7 and Figure 4.8 providing detailed examples of the data before and after cleaning using the techniques described in Ryan et al. (2015).

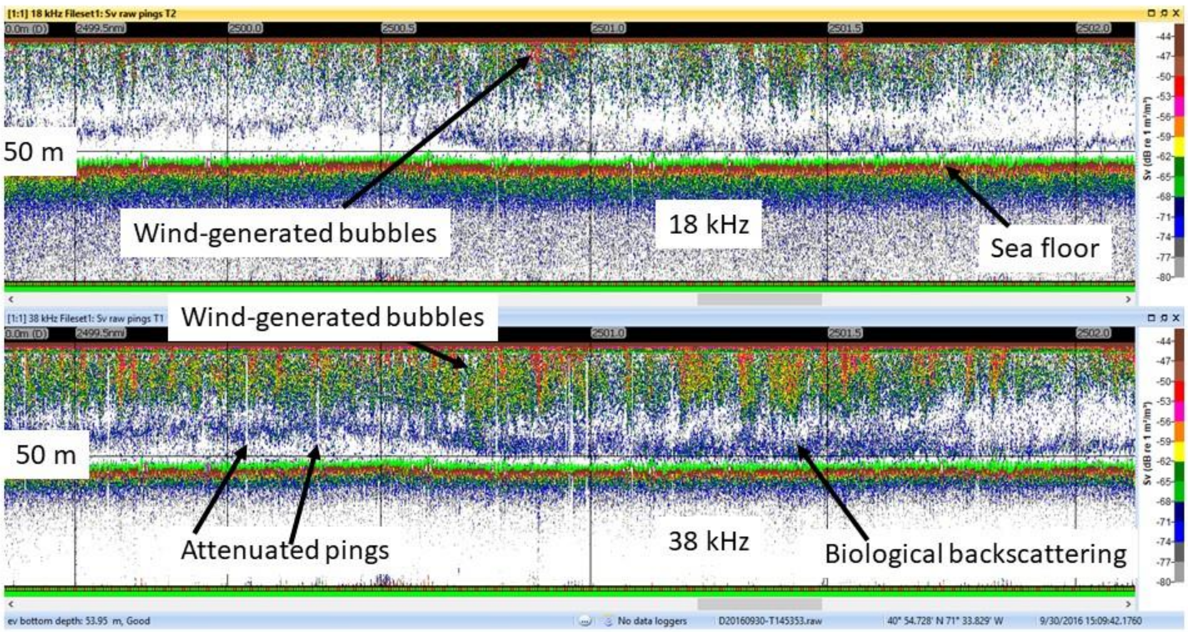

Figure 4.5. Wind-generated bubble echogram: 18 kHz (upper echogram) and 38 kHz (lower echogram) data collected on NOAA Ship HB Bigelow during 30 September 2016 showing wind-generated bubbles extending to about 40 meters depth and attenuated pings (vertical bands of empty scattering in the 38-kHz echogram). Data for this figure were collected using a Simrad ek60. (Image source: NOAA National Marine Fisheries Service)

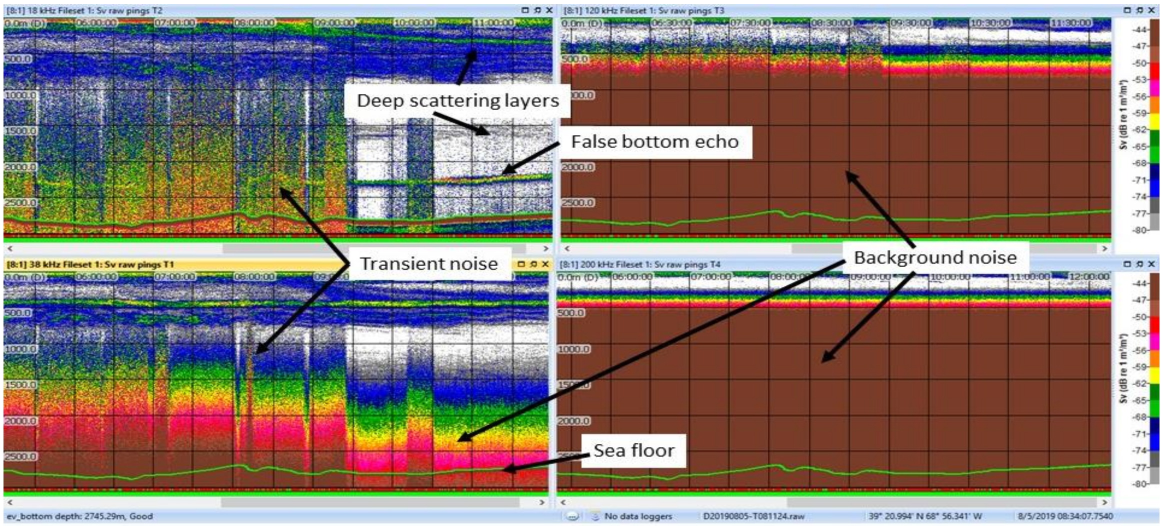

Figure 4.6. Transient and background noise echogram: 18 (upper left), 38 (lower left), 120 (upper right), and 200 (lower right) kHz data collected during 5 August 2019 showing transient and background noise, and a false-bottom echo (aka ghost echo). The portion of the echograms with less transient noise were collected during a midwater trawl haul. Data for this figure were collected using a Simrad ek60. (Image source: NOAA National Marine Fisheries Service)

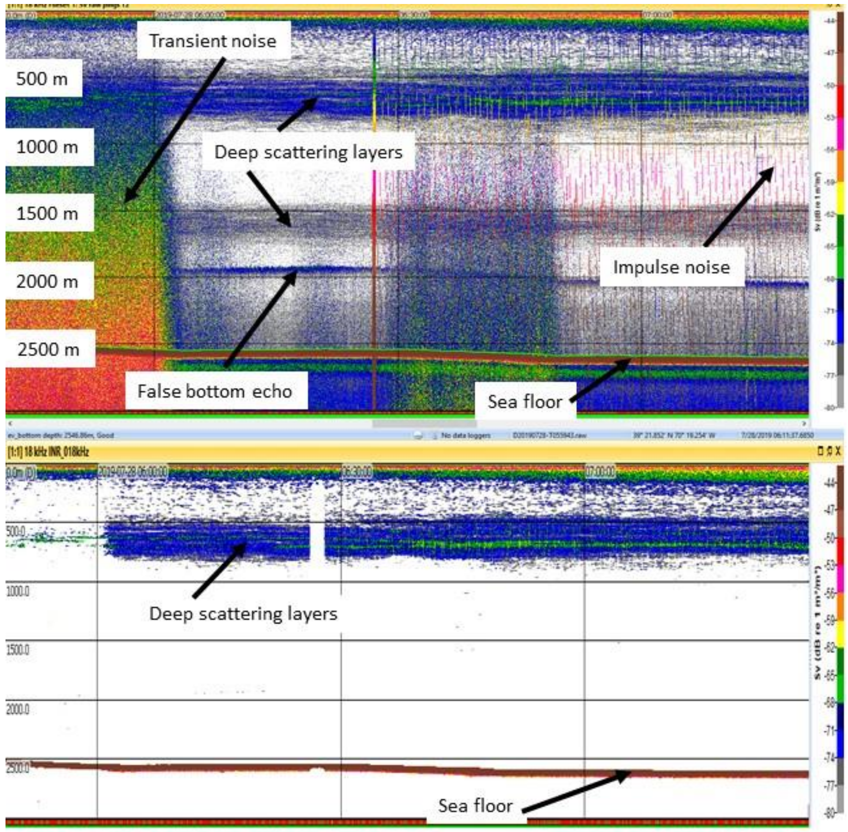

Figure 4.7. Echograms before and after noise reduction: 18 kHz data collected during 28 July 2019 showing impulse noise from a USBL acoustic system, a false-bottom echo, and transient noise due to increased vessel speed (upper echogram), and the same echogram after noise reduction using algorithms described in Ryan et al. (2015) (lower echogram). The portion of the upper echogram not infested with transient noise was collected during a NOAA midwater trawl haul. Data for this figure were collected using a Simrad ek60. (Image source: NOAA National Marine Fisheries Service)

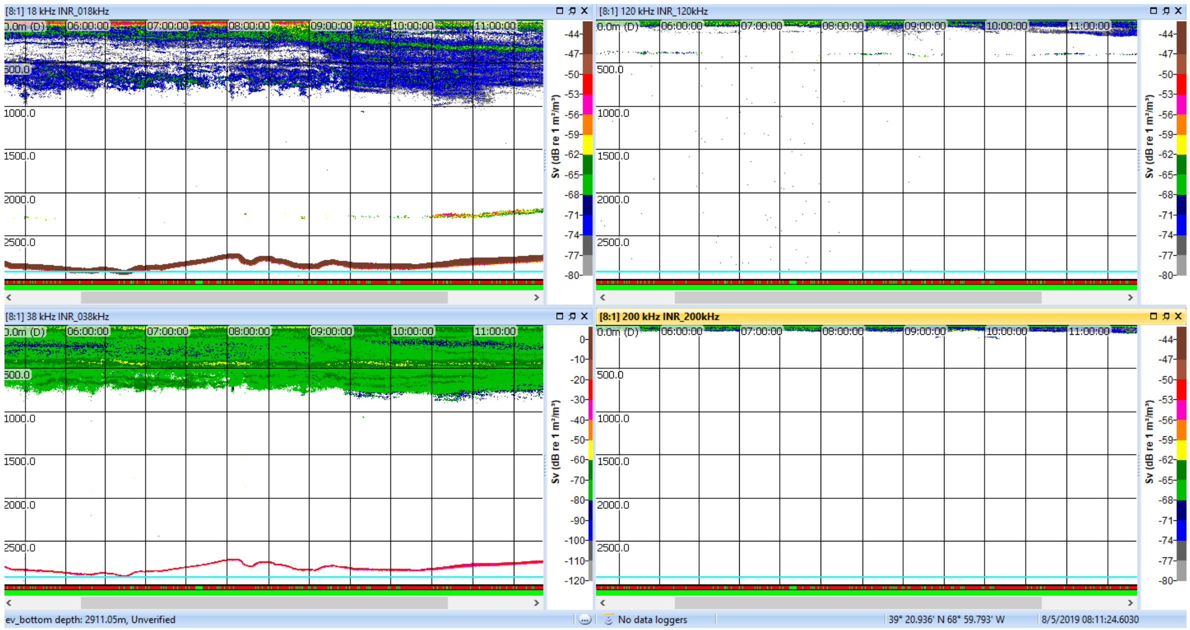

Figure 4.8. Removing transient and background noise: 18 (upper left), 38 (lower left), 120 (upper right), and 200 (lower right) kHz data collected during 5 August 2019 showing results of applying Ryan et al. (2015) algorithms to remove transient and background noise (compared to Figure 4.6). The 18 kHz echogram shows the remnants of the false-bottom echo, which could be removed using algorithms developed by Blackwell et al. (2019). Data for this figure were collected using a Simrad ek60. (Image source: NOAA National Marine Fisheries Service)

4.6.1 Vessel Speed

Vessel speed can affect data quality, primarily when the transducers are located on the hull and are susceptible to bubble sweep (i.e., bubbles entrained under the hull and transported across the transducer faces) or when transducer cables and echosounder electronics are sensitive to electronic or mechanical noise caused by increased load on engines and generators. Conduct these tests to measure noise levels at various vessel speeds. For these tests, place the echosounders into passive mode (no transmit, just reception) and vary the vessel speed (Figure 4.9). The influence of vessel speed can also be observed during active transmissions, especially in deep water (Figure 4.10). Higher vessel speeds result in higher transient noise. See Chapter 2.5.2.5 for additional information.

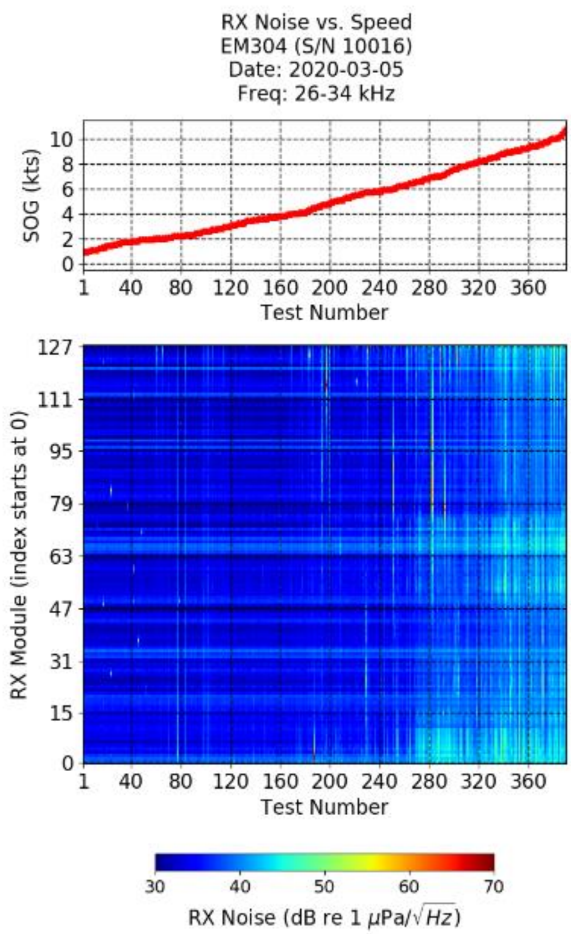

Figure 4.9. Speed vs. Noise: results of increasing vessel speed (top graph) on received noise (lower image) of the multibeam on NOAA Ship Okeanos Explorer. The warmer the colors, the higher the received noise. (Image source: Jerram et al., 2020)

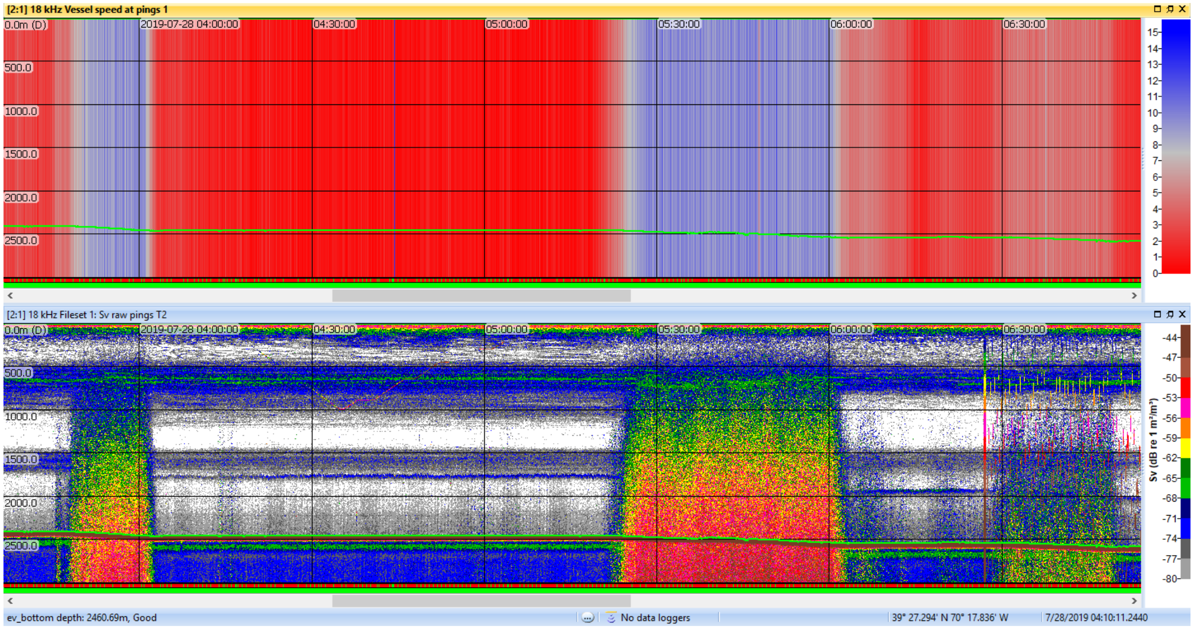

Figure 4.10. Influence of vessel speed on transient noise: 18-khz data (lower echogram) and corresponding vessel speed (upper image) collected during 28 July 2019 showing the influence of vessel speed on transient noise. The vessel speed color scale ranges from 0 kts (red) to 15 kts (blue). Data were collected using a Simrad ek60. See Figure 4.7 for description of acoustic scattering features. Higher vessel speeds have greater transient noise. (Image source: NOAA National Marine Fisheries)

4.6.2 Sonar Synchronization

Operating multiple echosounders or other acoustically transmitting sensors (e.g., ADCPs, Doppler speed loggers, fathometers, sub-bottom profilers [SBP], acoustic tracking systems) can cause errant signals to be detected as interference and noise on the water column systems (i.e., cross-talk). These signals bias backscatter measurements or produce misleading signals during analysis. In all cases, reporting and understanding the full complement of sensors operating during a mission is key to providing sufficient context for later data analysis and interpretation.

Many modern echosounders have built-in pulse synchronization options with customized settings to synchronize and control pulse transmission when multiple transducers are operating simultaneously. Pulse transmission (or 'ping timing') control software can advance or delay transmitted pulses to minimize or eliminate impacts of the cross-talk between systems (Figure 4.11). During hydrographic surveys, the MBES is often the primary sensor, and water column echosounders are secondary sensors. Synchronization systems provide ping trigger delays to the secondary echosounders to reduce noise, particularly transmissions from the secondary systems that may impact the derivation of seafloor depth or backscatter with the primary system (i.e., multibeam).

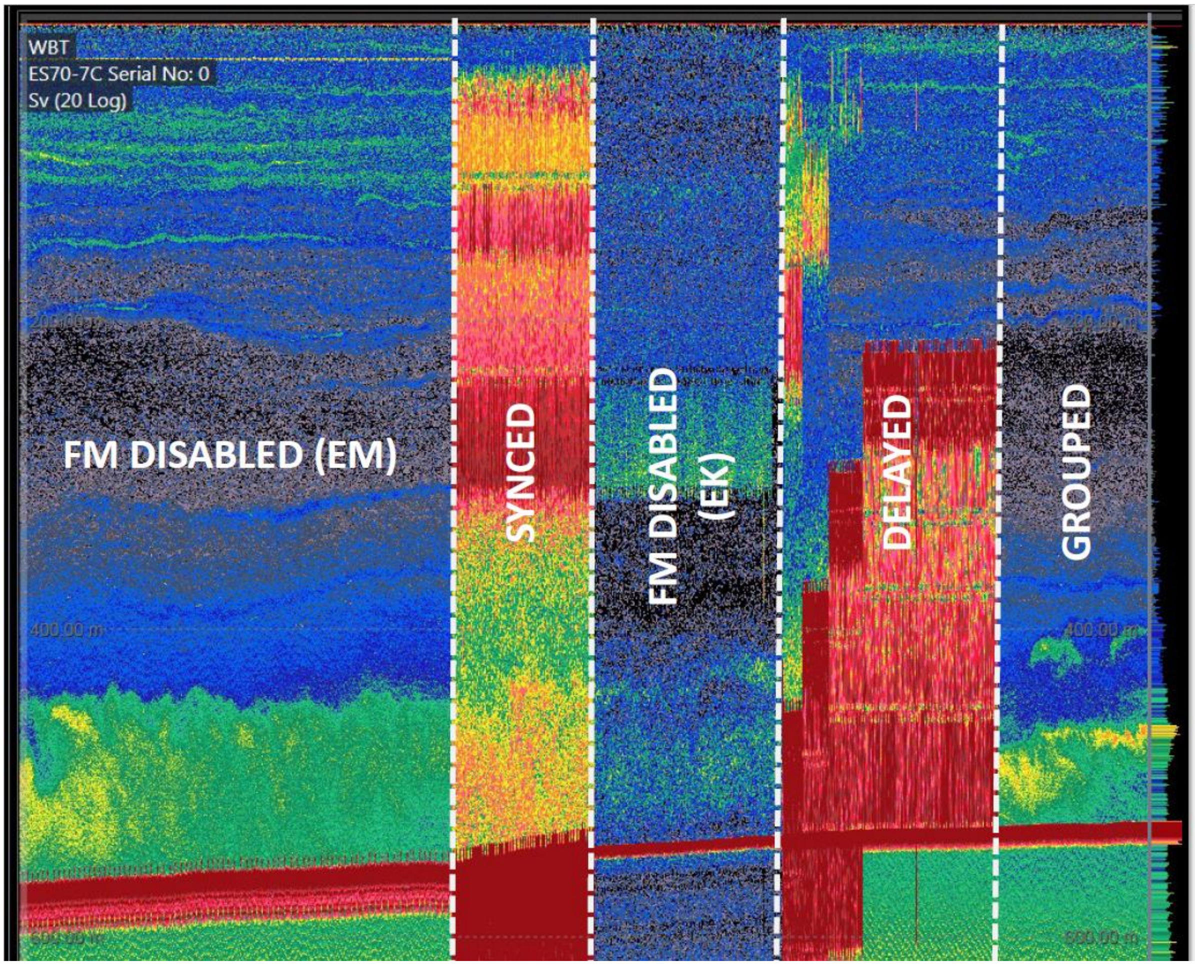

Figure 4.11. An image displaying examples of cross-talk between acoustic systems: for this example, NOAA Ship Okeanos Explorer had two systems (a multibeam and a 70 khz SBES) that were pinging at the same time. By delaying and synchronizing the ping rates of the two systems the interference between the systems changed. Data were collected using a Simrad ek80. (Image source: NOAA Office of Ocean Exploration and Research; Hoy, 2019)

Water column backscatter data from MBES can be viewed by ping as a “beam fan” (Figure 4.12) during data acquisition, analysis, and interpretation. The properties of the transmitted pulse in a hydrographic multibeam system result in some cross-talk across the detected beams. The seabed region facing the echosounder (i.e., typically near the nadir or directly beneath the system) provides a significant return strength (specular reflection). The strength of this return is apparent on the sidelobes of the multiple RX beams, causing a prominent arch of noise at the same range as the seabed (known as the nadir ring). The area between the arch (or nadir ring) and the seabed is often significant enough to occlude lower strength scatterers like fish (Figure 4.12) and limits the sampling volume for detecting water column features. While methods can be used to reduce the sidelobe effect (Bourguignon et al., 2009), the backscattering strength of targets below the side lobe effect will be biased. Some multibeam fishery systems use split-aperture techniques and beamforming to reduce side lobe interference across multiple beams. Noise can also be detected in multibeam data from asynchronous pulses from other acoustic sources, appearing as rings in the beam fan. These pulses can contribute to errant seabed soundings or biased backscatter signals in hydrographic data acquisition.

4.7 Data Formats

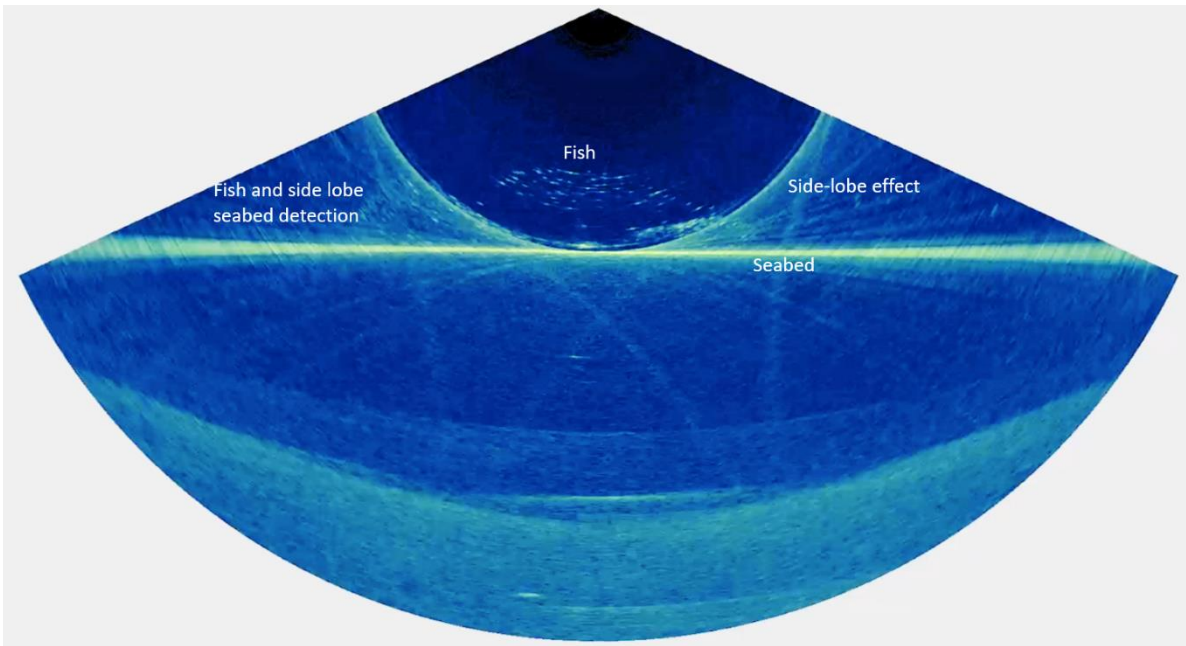

Figure 4.12. Fish detection in beam fans: example single ping "beam fan" from an MBES showing detections of the seabed, a school of fish in the water column, the side lobe seabed detection, and likely detection of a fish school within the seabed detected in the side lobes. (Image source: NOAA National Centers for Coastal Ocean Science)

The native format of water column sonar files is a proprietary binary format. Such file formats are not easily handled; however, a recent effort by the fisheries acoustics community resulted in the creation of netCDF4 files (Macaulay and Peña, 2018) upon the acquisition of an omnidirectional sonar (Peña et al., 2021). Developing an open-source data format was completed in collaboration with the academic community and sonar manufacturers. The scientific community continues to lead the way towards a change in data acquisition format. Through a standard file format, the data become more accessible to the scientific community and non-experts and better support FAIR (Findability, Accessibility, Interoperability, and Reusability) data standards (GitHub ices-eg/wg_WGFAST, 2022). Another benefit of open-source formats is alleviating the burden of navigating file format changes by the manufacturer. Further, netCDF and cloud-friendly formats, such as Zarr, facilitate the application of AI and scalable cloud processing, which are becoming increasingly necessary as data rates increase.

Water column sonar storage rates vary significantly across echosounder systems, operating frequency, depth or range, and transmitted pulse characteristics. For example, narrowband SBES surveying in 500 m water depth using a 1 ms pulse can provide 2 MB/min, whereas a broadband echosounder at the same frequency and pulse length can generate over 86 MB/min. MBES storage can exceed that of SBES by several orders of magnitude and multibeam data collection for only seabed sampling by two orders of magnitude (Rice and Greenway, 2017). A 200-400 kHz MBES sampling less than 50 m depths can generate data at 30 GB/hour, whereas a 200 kHz system sampling greater than 100 m depths will generate about 5 GB/hour (Figure 4.13). The decrease in data rates with depth is not continuous but instead related to a system's preconfigured settings that automatically increase the pulse length stepwise to optimize the signal to noise and resolution of depth detections. A longer pulse length requires coarser digital sampling of the returning pulse for storage.

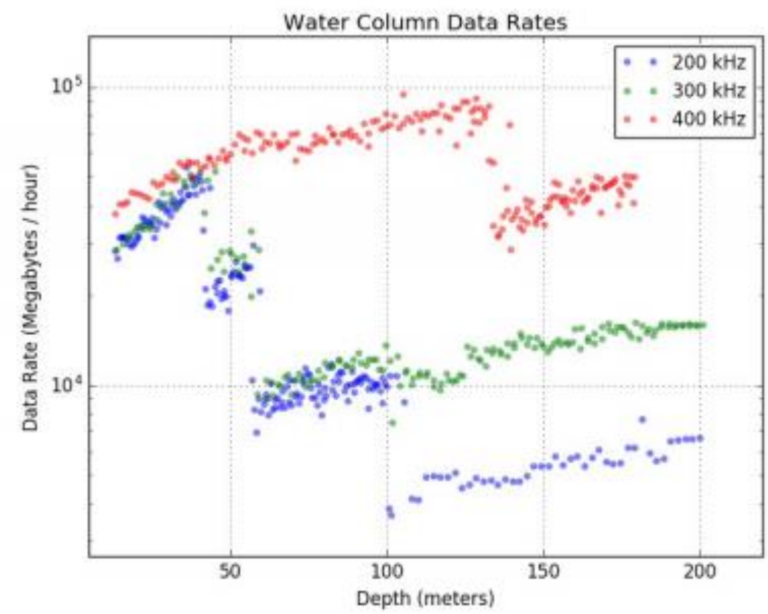

Figure 4.13. MBES frequencies and depths graph: example data rates for an MBES operating at three frequencies and varying depth ranges (Rice and Greenway, 2017).

4.8 Data Interpretation and Derived Products

Processing raw water column sonar files requires specialized software and/or expert knowledge of programming and the complexities of the sonar file structure. Software dedicated to processing these complex files is available commercially and in open-source formats. Echoview (Echoview Software, 2023) and Large Scale Survey System (MAREC, n.d.) are widely used commercial software with visualization and analytical capabilities. Fledermaus' Midwater Tool is another option focusing on the visualization of water column data (QPS, 2023). Open-source code bases have been developed by experts in the community and distributed for broader use. The deepwater fisheries acoustics team at New Zealand's National Institute of Water and Atmospheric Research has developed ESP3, a Matlab-based software package available as source code and compiled for the non-Matlab user (Ladroit et al., 2020). Python-based software packages called PyEcholab (GitHub CI-CMG/pyEcholab, 2022) and Echopype (Lee et al., 2020) were developed by scientists at NOAA National Marine Fisheries Alaska Fisheries Science Center and the University of Washington, respectively. Code bases in R are also available including EchoR developed by scientists at Institut Français de Recherche pour l'Exploitation de la Mer—French for French Research Institute for Exploitation of the Sea (Ifremer) (EchoR, 2022). These are just a few open-source repositories available to read and process water column sonar data. A more comprehensive list found on the ICES GitHub site will continue to be updated by the Working Group on Fisheries Acoustics, Science and Technology with community input (GitHub ices-eg/wg_WGFAST, 2022).

There has been an exponential growth in the volume of water column sonar data collected over the past decade attributed to collecting data on opportunistic sailings, increased numbers of sonar-integrated uncrewed vehicles, and new data-intensive sonar systems. Interpretation or classification of features in the water column has relied on manual assignment or statistical methods for classification based on geometric form or frequency-dependent backscatter response (Kloser et al., 2002; Korneliussen et al., 2008; De Robertis et al., 2010; Campanella and Taylor, 2016). Scientists' ability to continue relying on manual scrutiny or methods with limited automation to analyze the new volumes of data collected is quickly diminishing. The advancement of accessible AI tools in the last few years has opened many new possibilities for the application of machine learning (ML) and deep learning (DL) models, facilitated by cloud infrastructure and scalable compute engines, to complex scientific challenges (de La Beaujardière, 2019; Malde et al., 2020). The challenges faced in efficiently and effectively processing water column sonar data are well suited to ML/DL methods (Malde et al., 2020; Michaels et al., 2019).

Although cloud-based processing enables scientists to bring the processing to the data, note that processing routines designed for a single desktop will likely need to be altered to optimally and cost-effectively take advantage of a cloud environment. Some recent advances in the application of ML on water column sonar data include a comparison of different DL models to classify targets from underwater sonar data (Yue et al., 2017); the use of deep convolutional neural networks for acoustic target classification, precisely lesser sand eels *Ammodytes marinus* (Brautaset et al., 2020); water column pattern decomposition from stationary sonars using principal component analysis and nonnegative matrix factorization (Lee and Staneva, 2020); and the use of supervised learning to facilitate classification, specifically of the seabed (Sarr et al., 2021).

4.9 Data Management

The long-term stewardship and centralized access to historical, ongoing, and future water column sonar datasets are crucial to obtaining the most information and value from these essential data. The NOAA NCEI has established an archive dedicated to these data where the continually growing volume and diversity of archived data are globally accessible through the archive’s web-based map viewer and Amazon Web Services bucket (NCEI, 2021).

For specific details and guidelines on how and where to archive water column sonar data, please see the Water Column Sonar subchapter of the SOMP Data Management Chapter.

4.10 References

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Chapter 5: Side Scan Sonar

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5.1 Introduction

SSS are acoustic instruments that transmit two fan-shaped beams in a wide track across, a narrow track along the path, and one on either side. These are from the sonar's transducers to the seafloor and record the returns as a series of backscatter vs. time measurements. The sound is absorbed, reflected, and scattered to various degrees, depending on the seafloor's geological, geomorphic, and biological characteristics and anthropogenic features (e.g., shipwrecks, obstructions). For example, more sound is absorbed in soft sediment environments, whereas more sound is reflected in coarse sediment and rocky environments, by coral reefs and shellfish beds, and shipwrecks. The unique acoustic pattern indicative of a given seafloor feature is referred to as its "acoustic signature" and allows for the side scan data to be interpreted. Calculate the relief of seafloor features by measuring the shadow height in the side scan record. Tow SSS's at depth behind a vessel or operated from AUVs at a fixed altitude above the seafloor. Hull mounted options can be utilized, generally in shallower water.

SSS data have broad applicability, and surveys are conducted to meet project goals that range from seafloor characterization (e.g., benthic habitats, sediment, geologic and geomorphic features) to supplementing hydrographic surveys to meet object detection requirements (e.g., used in the region between regular MBES sounding lines for the additional indication of dangers and bathymetric irregularities).

This chapter focuses on collecting, processing, and delivering SSS data and will summarize best practices for acquisition standards and system set-up, range scales, frequencies and ping rates, coverage requirements, positioning, system calibration, QA/QC techniques, and how to derive products. This chapter provides overarching guidance and recommendations and will not address manufacturer-specific recommendations or recommendations concerning specific use cases.

5.1.1 Data Management

Management of SSS data is necessary for efficient use, future access, and validation of analytical and interpretative results. Archive the raw and processed data to ensure data are preserved to the fullest extent.

For specific details and guidelines associated with minimum SSS data requirements and management (such as recommended file formats, metadata, data archival, etc.), please see the Data Management chapter.

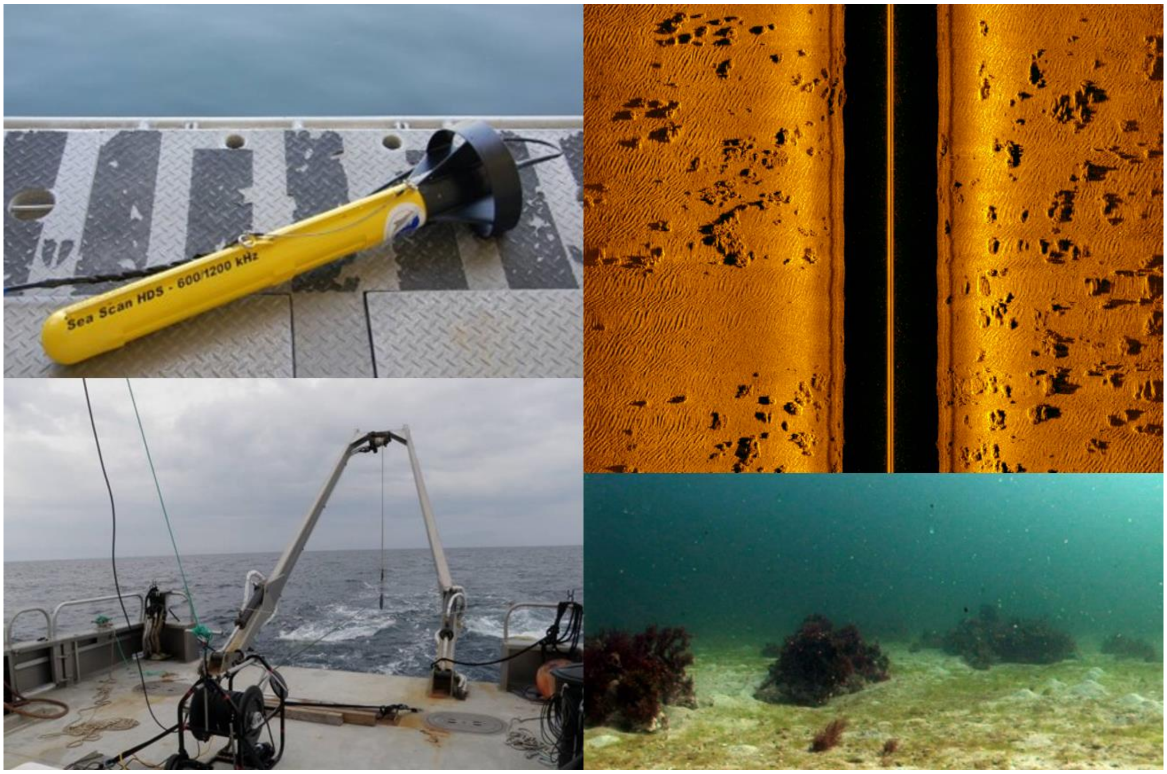

Figure 5.1. Side scan sonar examples: side scan towfish, typical towed deployment, raw sonar backscatter, and photograph of limestone reef at location of side scan imagery. Images courtesy of NOAA Fisheries.

5.1.2 Raw Data Acquisition

- Sonar settings
    - Operational frequency (report both frequencies if dual frequency system)
- Attitude and positioning
    - Specifications of the navigation system(s)
    - Accuracy
    - Installation information
        - Linear and angular offsets for installation on surface vessels or underwater vehicles
        - Towfish configuration and winch/cable information if towed
- Spatial reference
        - Coordinate system and horizontal datum References for raw echosounder data and navigation system, if different
    - Options as stated in the "Backscatter measurements by seafloor-mapping sonars: Guidelines and Recommendations" document (Lurton and Lamarche, 2015):

        - No geo-reference
        - Geographic reference (lat, long)
        - Projected reference (Mercator, UTM …)
        - Other

5.1.3 Data Processing and Mosaic Generation

- Processing steps
    - Describe data processing steps
    - Note application of gains (e.g., TVG, AVG), lookup tables (LUT), etc. to correct for water column returns, arrival angle, and refine contrast to produce a color-balanced image
    - Documentation of targets identified, if processed and available
- Spatial reference
    - Coordinate system and horizontal datum
    - Describe processing used to shift coordinate system or datum, if different from raw data
    - Options as stated in “Backscatter measurements by seafloor-mapping sonars: Guidelines and Recommendations” document (Lurton and Lamarche, 2015):
        - No geo-reference
        - Geographic reference (lat, long)
        - Projected reference (Mercator, UTM …)
        - Other
- Mosaicking settings
    - Order (top, bottom)
    - Statistical (average)
- Visual representation
    - E.g., Greyscale 0-255, gold scale 0-255, inverse gold scale 0-255

5.2 Target Detection

The specific settings used to acquire and process side scan data differ depending on project goals and the equipment and software used. It is recognized that defining a set of standard best protocols for the mapping community to follow is challenging. Instead, this chapter directs SSS operators and data processors to operate in such a manner that the data can detect a target (i.e., object or feature) of a particular dimension on the seafloor. In water depths less than or equal to 20 m, a target that measures 1-m x 1-m x 1-m (with the height measured from shadow length) should be detectable. In water depths greater than 20 m, a target should be detectable with a height (measured from shadow length) of at least 5% of the depth. The settings, software, and equipment needed to achieve these target detection standards are for the user to determine.

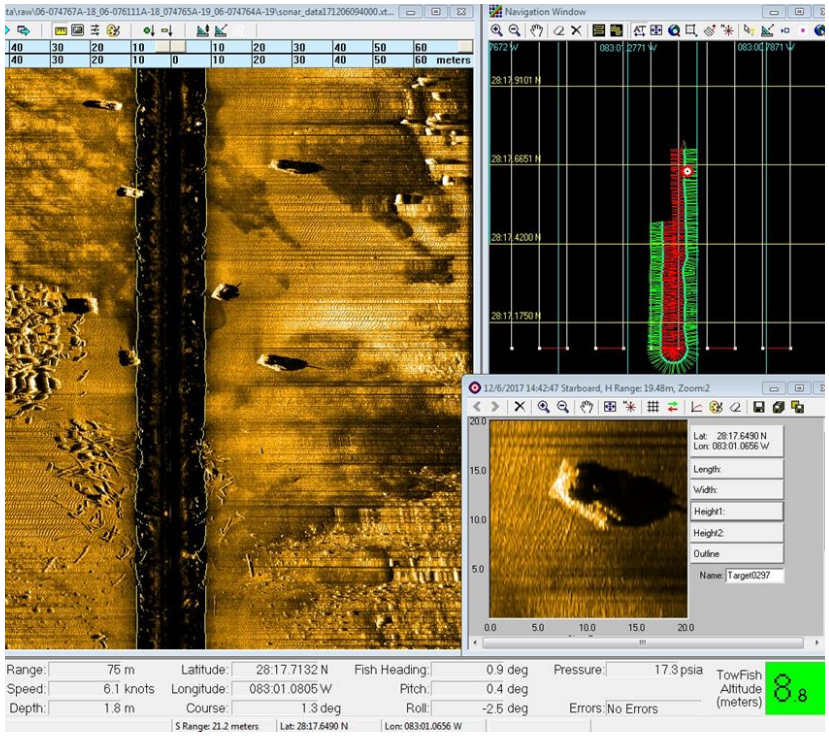

Figure 5.2. Side scan data collection: collection results over artificial reefs (military tanks). Image courtesy of Florida Fish and Wildlife Research Institute.

When a target is correlated to multibeam data acquired concurrently with SSS operations, determine the shallowest depth of the target from the multibeam data. Determine the shallowest depth measurement from a beam within 30 degrees of nadir unless multiple passes were made over the target. If the correlating sounding is sourced from one of the outer beams of the multibeam system, investigate the target further.

5.3 Coverage Requirements

SSS data coverage needs and range scale will vary based on specific program and project goals and equipment used. Coverage refers to the extent to which SSS swaths ensonify the seafloor with a received detection, that is, the band of the sea bottom, which is ensonified and recorded along a single vessel track line to the detection (e.g., -3 dB) limits. Range scale is the width of the seafloor ensonified on each side of the SSS towfish along a single vessel track line. The recommended percent of coverage is 125% or greater with 10% or greater overlap between each vessel trackline. This recommendation balances the desire for the seafloor to be fully ensonified (i.e., 100% coverage) and survey efficiency/wise expenditure of resources (i.e., minimal survey effort to achieve project goals). Note: If the project purpose is for navigation or object detection, then 125% coverage may not be adequate; refer to the NOAA Hydrographic Survey Specifications and Deliverables for additional guidance (NOAA OCS, n.d.).

5.4 Spatial Referencing

Provide survey coverage data as a geospatial dataset (e.g., .shp, .gdb) that includes the polygon feature class(es) of the location of the study site(s) surveyed and the line feature class(es) of the navigational cruise track lines of the survey vessel. If there is more than one study site, provide cruise track lines as a separate feature class per study site. Merge track line files to produce a single feature class if multiple line files were recorded for a given study site (e.g., based on the survey date, a subsection of the larger study site, or individual track lines).

Georeference geospatial data to the most current horizontal datum from the National Spatial Reference System. Projection information must be defined in the feature class so that the data project accurately when imported into GIS.

Geographic data must use the most recent adjustment and epoch of the North American Datum (NAD) of 1983 (currently NAD83(2011), Epoch 2010.00) in either (UTM; eastings/northings) with the zone specified or as geographic coordinates (latitude/longitude), and adequately documented. Note: Both horizontal and vertical datums will be replaced in 2022 by the North American Terrestrial Reference Frame of 2022 (NATRF2022), based on GPS/GNSS and a GRAV-D-based geoid (GEOID2022) (NOAA NGS, n.d.).

5.5 General Side Scan Data Acquisition Parameters

The following are standard acquisition parameters to use as a reference for guidance. Use specific settings to meet the target detection criteria defined above.

5.5.1 Frequency

The signal frequency varies across sonar systems, typically between 100 and 500 kHz for systems intended for object detection and seafloor characterization. There is a trade-off between lower and higher frequency systems. Lower frequencies will offer an increased maximum range scale (or swath width), whereas higher frequencies offer increased image fidelity and resolution.

5.5.2 Navigation/Positional Uncertainty/Accuracy

At a minimum, utilize a position and attitude system with one or more GNSS receivers and an IMU during a survey. A GNSS receiver acquires the vessel's position using GNSS satellites (i.e., GPS), and when using multiple receivers, it also provides heading information. Use the exact GNSS clock signal for positioning as the timing signal for the entire survey system. The IMU measures vessel attitude (i.e., roll, pitch, yaw, and heave) across all axes and rotations. These data, in conjunction with the positioning data and sound speed, allow data to be corrected to its true position on the seafloor. In integrated systems, the data from the IMU allows the vessel to maintain an accurate position, even in the event of a total loss of GNSS satellites for short durations such as operating under a bridge or other obstructions.

Horizontal accuracy will depend on the system configuration, investigation technique, water depth, and target density. However, the position of targets identified with side scan imagery must be sufficiently accurate to relocate the feature.

5.5.3 Survey Speed

Data collection speed should be such that an object 1-m x 1-m x 1-m would be independently ensonified a minimum of three times per pass. Typical survey speeds are 4-6 knots, though it could be faster, as survey equipment and conditions permit.

5.5.4 Horizontal Range

The achievable horizontal range of a SSS is a function of several parameters, including the sonar system's characteristics and tow/mount configuration, range scale in use, seafloor composition, and environmental factors (e.g., sea state, inclement weather, water column). If the effective range scale of the SSS is reduced due to external factors, then the range scale should be reduced accordingly to meet the target detection criteria and data coverage needs. For example, environmental changes may distort the outer half of the 100-m range scale. In this case, only 50-m of effective range could be claimed.

5.6 System Configuration

5.6.1 Towed System

A towed sonar system configuration can significantly reduce the effects of vessel motion and allow for adjustment of the operating height of the towfish above the seafloor to enable the optimum shadow, both of which improve data quality and resolution. However, the disadvantage of towed configurations is that they introduce uncertainty regarding the position of the towfish. This error has three components:

- An along-track component caused by uncertainty in how far the towfish is astern of the vessel. This error depends on the length of cable out, depth of towfish and vertical catenary of the cable (the last two also vary with the ship's speed);
- An across-track component, caused by deflection of the towfish by the tidal stream or current and by ship maneuvers;
- Errors in the position of the ship or boat, will be transferred to the towfish.

For towed sonar systems, measure static vessel offsets to the tow point. Calculate the actual towfish position using towfish depth and cable-out measurements. Determine towfish depth by a depth sensor installed in the towfish or calculated by subtracting the towfish height (determined by a separate echosounder installed in the towfish or the first return of each sonar ping) from the depth of water (determined from a vessel echosounder). If the sonar is equipped with a pressure sensor, test its accuracy annually and whenever the horizontal positioning accuracy of side scan targets is in doubt.

Cable out can be estimated visually from calibrated markings on the cable or measured with an electronic cable counter. Note: When measuring cable out, the cable zero mark is not at its connection to the towfish but the phase center of the sonar.

For most SSS operations, the optimum height of the towfish above the seafloor is 8 to 2% of the range scale in use. For any towfish height below 8% of the range scale in use, the effective scanning range is defined to equal 12.5 times the towfish height, provided adequate echoes have been received. During shallow water operations, the towfish may need to be flown very close to the surface with little tow-cable out which may introduce noise in the data from surface waves, and ship wake, and additional survey lines may need to be run to ensure coverage requirements are met. When the towfish height has exceeded 20% of the range scale, carefully examine the data as targets will display reduced shadow length to height.

In sufficiently shallow survey areas (perhaps <500 m), an ultra-short baseline (USBL) system can be used to more accurately position the towfish. Properly installed, calibrated, and processed USBL data can provide more accurate positioning than a simple cable-out determination of layback. In practice, USBL systems calculate the subsurface position of an object by combining acoustic range and bearing data from a vessel-mounted transceiver with attitude, heading, and location information from the vessel's navigation system. Equip the tracked object with an acoustic transponder or responder that communicates with the transceiver attached to the vessel. This technology does not require a transponder array to be deployed on the seabed before positioning can commence and is thus ideal for trackline surveys. The transceiver can be affixed to the vessel's hull or on a stable over-the-side pole with no inherent wobble at survey speed. Hull-mounted configurations require the transceiver to sit well below the vessel to avoid interference and multipath conditions. In nearly all cases, the calculated XYZ acoustic positions will require some degree of post-process smoothing before reinsertion into the raw sonar navigation packets before mosaicking.

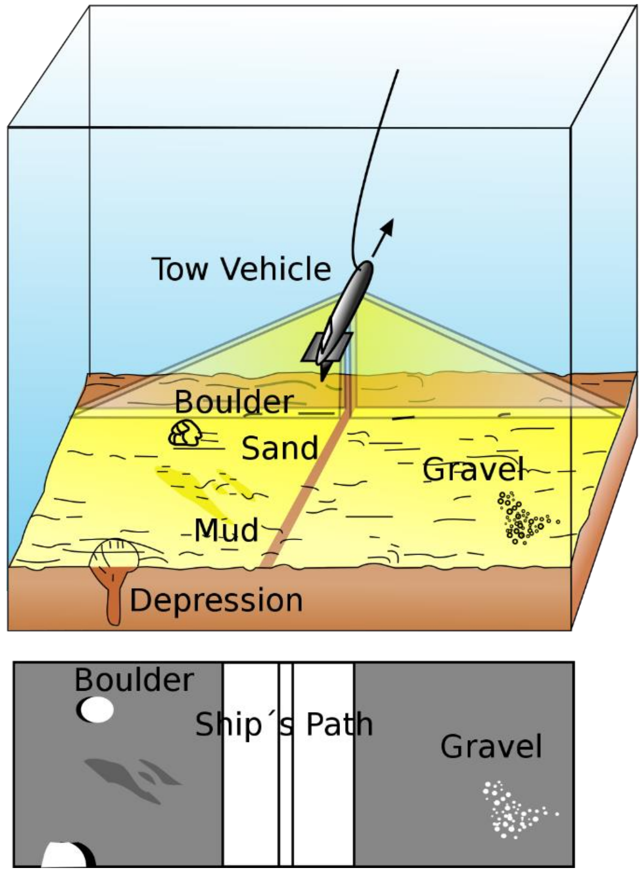

Figure 5.3. Schematic of a towed system: towed system and sonar beams (top) and data visualization (bottom) in which lines of data are interpreted as a "waterfall" image. Image courtesy of USGS.

5.6.2 Vessel-Mounted System

Hull-mounted or pole-mounted (bow or side) sonar system configurations allow for the position and orientation of the sonar to be accurately known, improving the positioning of detected features in the SSS data. Mounted systems are preferred in shallow waters or areas with potential or known hazards that pose challenges to surveying with a towed system. For example, mounted systems reduce the risk of entanglement in fishing gear and making contact with obstructions (e.g., boulders, wrecks). Mounted systems also increase the freedom of maneuverability of the survey vessel. Pole-mounted systems provide the benefit of adjustable and repeatable survey operations, and the systems are quick to set up. Pole-mounted systems are beneficial for mobile or 'fly-away' system configurations.

However, mounted configurations may introduce additional vessel motion effects on the data and potential interference from other vessel-mounted sensors. This method also may limit the operational extent of a given sonar system since it is attached to the vessel and unable to be operated at the optimum height above the seafloor.

For hull-mounted systems, position the sonar's phase center of the SSS during the vessel static offsets survey. The phase center of the sonar is considered to be at the fore and aft midpoint of the transducer and on the centerline in the athwart ship and vertical axes.

For pole-mounted systems, measure and confirm offsets annually. Use the benchmark closest to the pole mount as a reference point. The X, Y, and Z should be measured from the vessel's reference point. Some pole-mounted systems do not require traditional offset measurements because of their "plug and play" ability. In these setups, the antennas, IMU, and sonar are all integrated into the single boat setup, making the measurements of the vessel negligible.

For hull or pole-mounted SSS systems, position data are typically more accurate than a towed SSS system configuration, and operations in shallow waters can be conducted with less risk and increased safety and efficiency compared to towed systems. Range scale requirements for this configuration are based on a factor of water depth to be 8–15% towfish height of the operating range scale.

5.6.3 Documenting System Configuration

Measure and/or verify SSS system offsets before calibration. Depending upon whether the sonar configuration is hull-mounted or towed, requirements for offset measurements will vary.

At a minimum, vessel configuration and offset information should be presented as a text file (e.g., ASCII) or spreadsheet (e.g., .csv, .xlsx) AND a schematic file (e.g., .jpg, .bmp., .tiff). The files should contain details of survey vessel dimensions (length, width, draft) and offsets of survey instruments. Provide multiple files if using more than one vessel or configuration.

5.7 System Calibration

The SSS calibration test should consist of multiple passes (e.g., 10) on a known target. Image the target from various ranges and directions with survey speed, water depth, and weather representative of typical survey conditions. When possible and/or necessary to meet project goals, use an alternate system (e.g., MBES) to determine a high-accuracy absolute position of the target for comparison with SSS detected positions. Conduct this test across all range scales intended to be used for data acquisition.

Successful object detections should be used to compare the mean detected position with the absolute target position and to compute the approximate 95% confidence radius for the system. This radius should not exceed 5 meters for hull-mounted systems and 10 meters for towed systems.

Line plans are recommended for conducting a SSS calibration test (Figure 5.1). This plan balances ensonifications on the port and starboard channels, across the range scale, from different target aspects, and from different directions, assisting the hydrographer in differentiating systematic and random errors in detection and positioning.

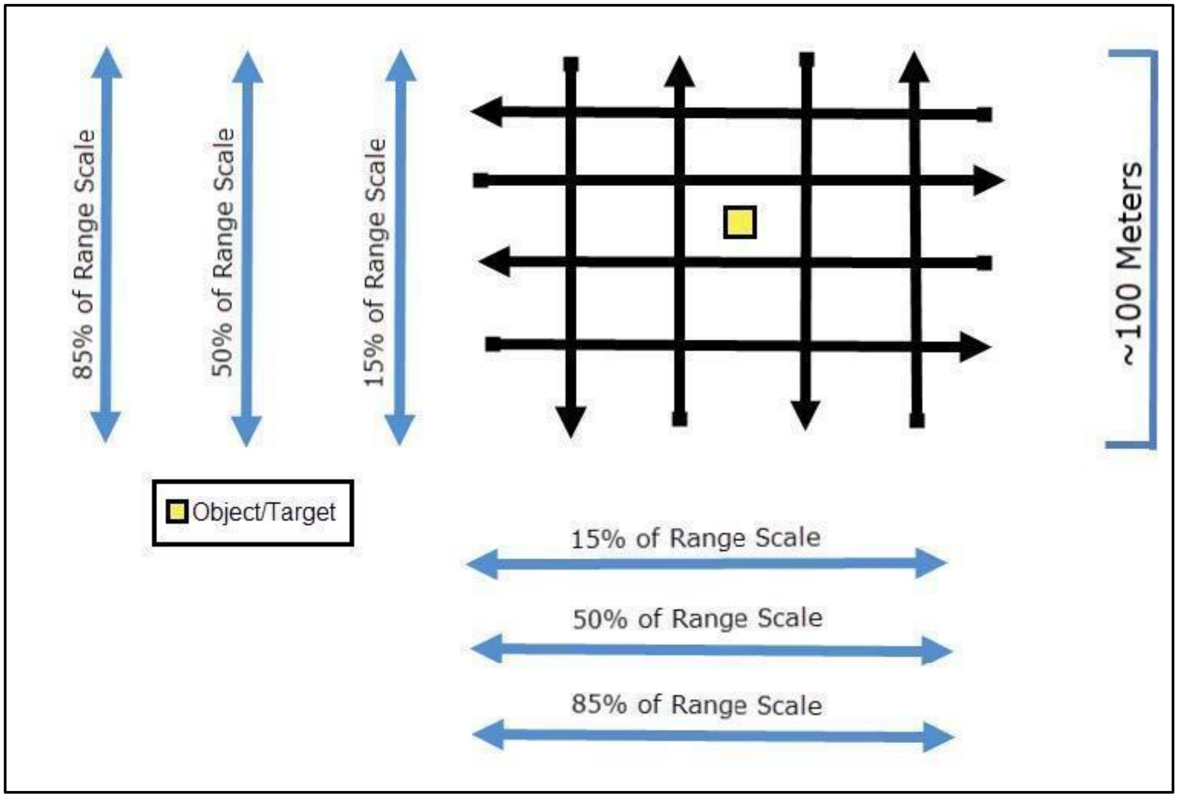

Figure 5.4. Side scan sonar calibration line plan: recommended line plan for SSS calibration testing.

5.8 Quality Control

5.8.1 Quality Assurance and Confidence Checks

Conduct confidence checks of the SSS system prior to a survey and at least once daily during a survey. Accompany these checks at the outer limits of the range scales being used based on a target near or on the bottom. Check each sonar channel (i.e., port and starboard channels) to verify proper system tuning and operation. Confidence checks can be made on any discrete object, offshore structure, or bottom feature convenient or incidental to the survey area. Targets can include wrecks, offshore structures, navigation buoy moorings, distinct trawl scours, or sand ripples. If a convenient or incidental target is unavailable, place a known target on or near the bottom and use it for confidence checks.

Make confidence checks during survey operations by noting the check target on the sonogram. Confidence checks are an integral part of the daily SSS operation and should be annotated, including the time of check, in the SSS acquisition and processing logs.

When an area is ensonified multiple times, examine and correlate targets between successive SSS coverages (i.e., compare the first 100% with the second 100% sonar coverage) or MBES data. Anomalous targets which appear consistently and correlate in each data record provide increased confidence that the acquisition system(s) is(are) working correctly and help to confirm the existence of these targets.

Before surveying with an SSS system that has been reconfigured or stored, perform a rub test. The test consists of manually rubbing each transducer on the towfish while the system is pinging and confirming the observed side scan return signal in the incoming data stream. A rub test failure indicates system errors such as incorrect gain or power settings, a faulty cable, or damaged transducers. Conduct this test swiftly while the towfish is out of the water and dry to avoid the possibility of electric shock. While testing, avoid running the system for an extended period while out of the water.

5.8.2 Environmental Influences

Environmental influences can impact the SSS record, including density differences between water masses, water mass separation and mixing due to tidal flows, surface mirroring (Lloyd Mirror Effect), and water column interference due to entrained air bubbles (e.g., from passing vessel prop wash or wave action), suspended sediment, and fish and other biologic organisms. These influences interfere with seafloor detection and affect the return signal, causing refraction and distortion in outer swath regions and degrading data quality.

In areas that experience a strong thermocline, sonar operators will need to lower the towfish below the thermocline so the signal will not be detectable to pass through the dense layer and the seabed. Sea state can also influence data collection and quality, especially for hull-mounted and pole-mounted systems operating in surface waters where air bubbles become entrained from wave action.

SSS records that include environmental influences affecting any portion of the swath and hinder the selection of contacts in the affected regions don't meet the requirement of 100% complete coverage and are considered a holiday. In such cases, reduce the swath range and reject the affected areas. Data should be reacquired so the acquired data meets the complete coverage requirement.

5.8.3 Operational Considerations

It is a good practice to tow the sonar parallel to the contours in areas characterized by relatively low gradients. However, when surveying in terrain with steep walls or submarine canyons, higher quality data are achieved by "flying" the towfish in a downslope direction to avoid the effect of achieving no acoustic return from the deep-side channel since the signal propagation will never reach the seabed to elicit a return echo.

5.9 Data Products

5.9.1 Mosaics

SSS data are compiled into mosaics of georeferenced sonar imagery. These products are often incorporated into GIS for analysis and visualization. Follow these mosaic protocols to enable the greatest use of the data:

- A single georeferenced raster file for each area of coverage in floating point GeoTIFF format or other standard image file format (e.g., JPEG2000).
- The projection information must be defined in the image (e.g., .GeoTIFF) or in an associated file (e.g., .tif with accompanying .twf file) so that the data project accurately when imported into GIS.
- SSS data presented as a continuous and comprehensive "map view" by "stitching" together adjacent individual track lines of processed data.
- Merge overlapping data to produce the best visual display; options include averaging and ordering by timestamp.
- Visual data products should use a color scheme standard in the industry (e.g., grayscale, inverse grayscale, gold scale).
- Tile mosaics, if necessary (e.g., for large study sites), to reduce file size and improve the visual layout of maps.
- SSS mosaics and waterfall images should represent data that have been processed to remove the central nadir region and at a color scale that enhances feature identification.

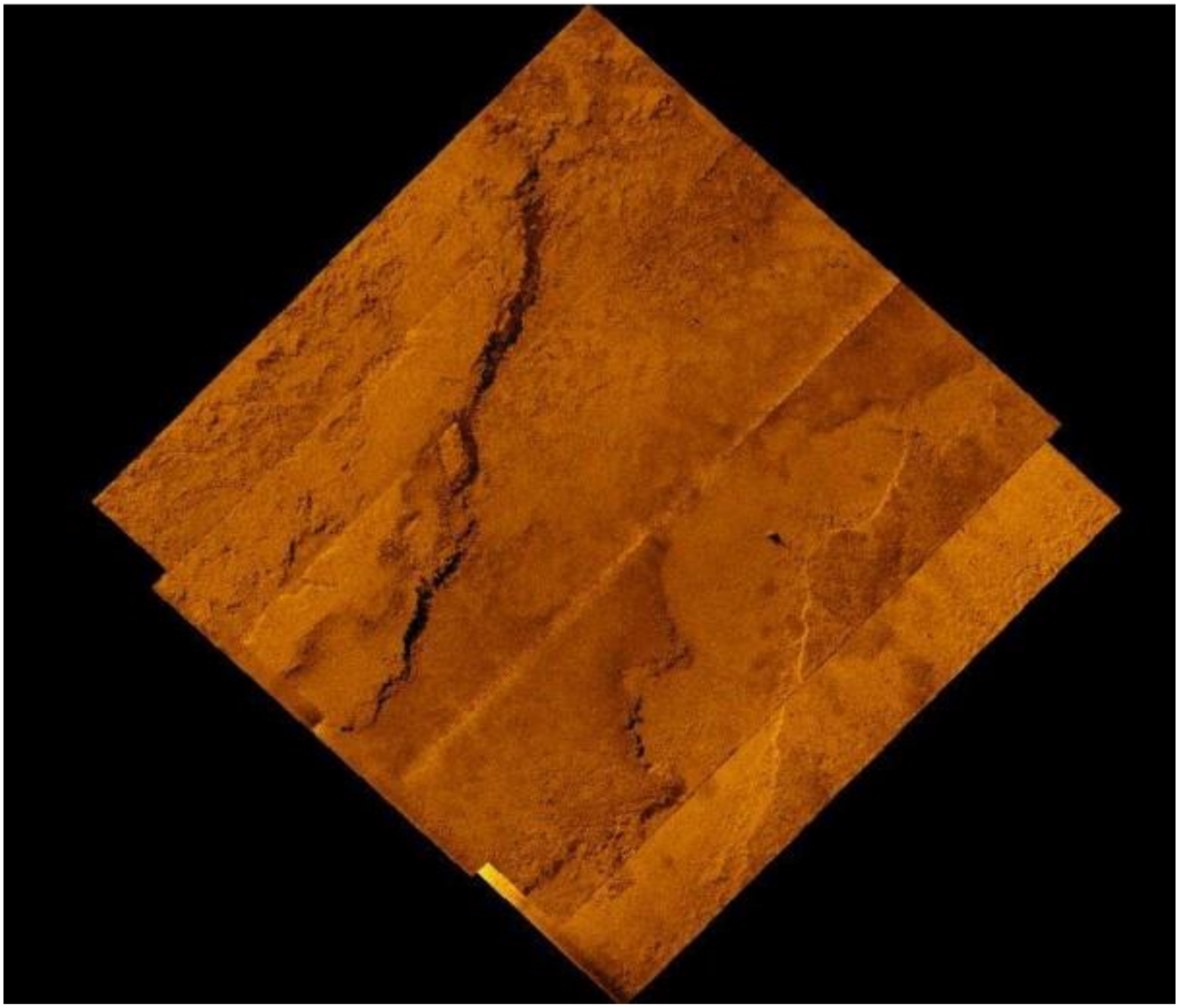

Figure 5.5. Geotiff mosaic of side scan sonar data collected with an AUV mounted system: imagery depicts several low-relief rocky reefs, a limestone ledge, and adjacent sand habitats. Image courtesy of NOAA Fisheries.

5.10 Data Management

Management of SSS data is necessary for efficient use, future access, and validation of analytical and interpretative results. Record SSS raw data files in the instrument's vendor-specific format. Common file formats include, but are not limited to .xtf, .jsf., .hsx, and .gcf. Archive the raw and processed data (i.e., mosaics) to ensure data are preserved to the fullest extent.

For specific details and guidelines associated with minimum SSS data requirements and management (such as recommended file formats, data archival, etc.), please see Chapter 1.

5.11 Other Resources

SOPs have been developed for SSS operations, and some example protocols and websites with further guidance are listed below:

- NOAA Hydrographic Survey Specifications and Deliverables (NOAA OCS, n.d.)
- NOAA Field Procedures Manual (NOAA OCS, n.d.)
- IHO S-44 Chapter 4 Seafloor Classification (IHO, n.d.)
- Procedures and Criteria for Evaluating Benthic Mapping Data (LaFrance, Curdts, and Stevens, 2019)

5.12 References

IHO. n.d. “Chapter 4: Seafloor Classification and Feature Detection.” https://iho.int/uploads/user/pubs/cb/c-13/english/C-13_Chapter_4.pdf.

LaFrance Bartley, M., T. Curdts, and S. Stevens. 2019. *Procedures and Criteria for Evaluating Benthic Mapping Data: A Northeast Coastal and Barrier Network Methods Document*. Natural Resource Report NPS/NCBN/NRR—2019/2050. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/DownloadFile/633175.

Lurton, X. and G. Lamarche. 2015. *Backscatter Measurements by Seafloor-Mapping Sonars: Guidelines and Recommendations*. https://geohab.org/wp-content/uploads/2018/09/BWSG-REPORT-MAY2015.pdf.

NOAA NGS. n.d. “New Datums.” National Geodetic Survey. https://www.ngs.noaa.gov/datums/newdatums/index.shtml

NOAA OCS. n.d. “Standards and Requirements.” https://nauticalcharts.noaa.gov/publications/standards-and-requirements.html.

Chapter 6: Sub-bottom Profiling

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6.1 Introduction

Sub-bottom (subseafloor) profiles are acquired using seismic-reflection techniques that provide a continuous vertical two-dimensional (2D) stratigraphic display along the survey ship's track. Interpretation and analysis of these profiles are used to map shallow (generally less than 200 m) stratigraphic and morphologic features. Sub-bottom systems use an acoustic source to transmit a sound wave directed downward. These systems work the same as bathymetric sensors but are of lower frequency so that the signal penetrates the seafloor where it responds to density or sound speed changes in the sub-bottom structure through an acoustic impedance. This acoustic impedance (z) of a material is defined by the product of sound velocity and density of the material. Some of the transmitted acoustic waves reflect where there is a contrast acoustic impedance of the material (e.g., water column and lithology). Some of the transmitted waves propagate through the seafloor and sediment. The depth of penetration of the acoustic energy below the seafloor and the sub-bottom depends on the power and frequency of the acoustic source and acoustic impedance of the substrate. Seafloor and sub-bottom reflections are received either by the acoustic source (transducer) or a separate receiver (hydrophone) and recorded digitally as amplitude and source to receiver time (two-way travel time). The change in reflectivity, and timing of the return signal, is processed through the topside hardware to produce a vertical, 2D profile of the subsurface physical environment as a series of amplitude changes over time and distance. Numerous publications that describe in detail the technique of 2D seismic data acquisition in the marine environment, for example Dondurur (2018).

This chapter describes SOPs for using one receiver (single-channel seismic (SCS)) within frequency bandwidths ranging from 0.2 kHz to 24 kHz. Sub-bottom systems can have a separate source and receiver, or the source (transducer) can also act as a receiver. The term sub-bottom often refers to systems where the source and receiver are the same components, or the source and receiver contained within a tow vehicle. In this chapter, we also use the term sub-bottom to describe systems with sources and receivers that are towed separately. These acoustic sources are often referred to as high-resolution geophysical (HRG) sources, typically used in shallow subseafloor imaging and have lower power and higher frequencies than implosive type systems (airguns). Airguns are more typically used with multichannel seismic (MCS) systems, which have multiple receivers offset by distance from acoustic sources. MCS systems are not addressed in this chapter due to the complexity of acquisition, processing, and survey-specific design. However, much of the SOP for SCS applies to MCS systems. Boomer and sparker sound sources are increasingly paired with multichannel streamers for very high-resolution continental shelf surveys, for example, 32 channels (groups) with group spacing as short as 1.5625 m. Many MCS systems processing methods apply to SCS processing, but there are many more methods available in MCS system processing primarily due to having multiple sources to receiver offsets for each shot.

This SOMP also does not describe the principles of seismic reflection or system design, instead, it focuses on common system types, practical survey design, conventional acquisition procedures, processing protocols, data formats, and publication.

Sub-bottom and seismic reflection systems are generally identified by the source/receiver configuration and by the method of the acoustic pulse. Systems use displacement to propagate a wave through the water (boomer, Bubble Gun, airgun), generate controlled broadband swept frequency waveform (chirp), or create an explosion (sparker) or implosion (water gun) in the water column (Mosher and Simpkin, 1999). Seismic reflection systems have separate towed sources and receivers. Boomer, Bubble Gun, and sparker systems imply having a separate receiver as part of the system. Sub-bottom systems have the source and receiver contained in the same tow-body (e.g., chirp systems) or have transducers that function as source and receiver, such as hull-mounted systems. Figure 6.1 shows examples of seismic-reflection profiles from various systems collected over the same terrain in Tampa Bay, Florida, U.S.A. The examples show the differences in signal penetration depth and vertical resolution. The comparisons are qualitative as each system has different source configurations that can produce different imaging results.

This chapter provides overarching guidance and recommendations for the collection of mapping data from the sub-bottom and will not address manufacturer-specific recommendations or recommendations concerning specific use cases.

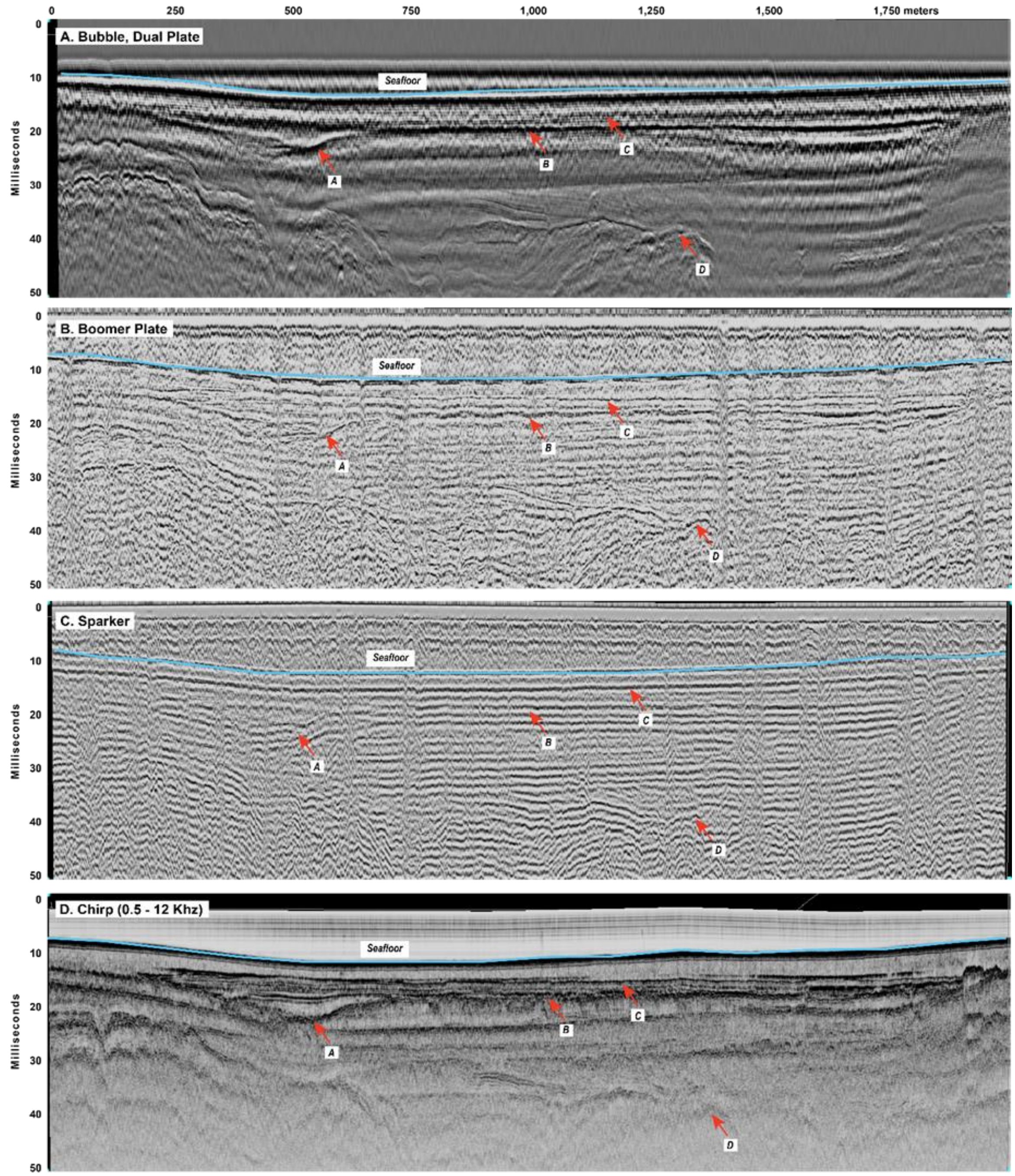

Figure 6.1. A qualitative comparison of seismic-reflection profiles: the profiles were acquired using (a) bubble pulse plate; (b) boomer plate; (c) sparker, and; (d) chirp systems. The profiles cover the same terrain and arrows A-D point to the same geologic features imaged in the subsurface. The uppermost reflector (seafloor) is also shown. Comparison of the profiles demonstrate the different penetration capability and vertical resolution between the systems.

6.2 Cruise Planning and Coordination

Data acquisition strategies usually include multi-tool systems, such as sub-bottom, seismic, SSS, and bathymetric systems to provide for efficient and affordable data acquisition. Prior to a geophysical investigation, communicate with stakeholders regarding collaboration and leveraging of assets. Collaboration can increase the field of study, reduce cost, and develop future endeavors.

With several useful technologies to deploy to complement the sub-bottom, acquire single beam bathymetry simultaneously as close to the seismic source as possible to provide accurate seafloor corrections during post-processing. Deep-towed sub-bottom systems should have a pressure sensor to record vehicle depth so the total water column depth can be determined. Water column depth = depth from the sea surface to the seafloor. A GPS, independent of the ship navigation, is necessary for spatial control, and the offset between the GPS receiver and the acoustic source should be measured (e.g., layback) before the survey. Water depth and positioning can be recorded within the seismic file header fields and/or independently. Data acquisition and spatial integration are performed at the topside unit using specially designed software. This software also calculates layback, which can be applied in post-processing. Offset corrections may not be necessary when the GPS antenna is fixed to a surface-towed system. The effectiveness of seismic data in accurate sub-bottom imaging is improved through ground truthing, sediment cores, or other investigative techniques (e.g., well logs) to validate the acoustic response of the stratigraphy. Cruise planning should consider existing core or log locations, or existing subsequent ground truthing. "Ground truthing" is verifying through direct measurements or sample collection that what we think is in a particular location is or is not. For example, if there may be seagrass on the seafloor at location X, conduct a benthic survey to take images and confirm whether the assumption is correct.

Survey platforms are optimized for navigation conditions and project budget constraints. Large vessels are desirable for open ocean surveys because they can accommodate 24-hour operations and accommodations for multiple watch crews. Smaller, day-boat operations are utilized for nearshore, shallow-water, and inland water areas. Autonomous vehicles can be used in a variety of conditions. Regardless of the environment, design survey lines straight as possible. The lines should be segmented to accommodate turns, obstructions, or shoreline features. Typically, the survey strategy consists of parallel lines (tracklines) with the spacing between lines determined by the desired stratigraphic resolution. These parallel tracklines must be crossed by tielines so there is a continuous sampling of the stratigraphy between lines that generates a typical survey grid pattern. Maintain consistent vessel speed along lines. Typical survey speed is 3–6 knots, depending on equipment type and oceanographic conditions, including current and waves. The towed systems are sensitive to wave conditions, and the quality of data can be compromised by adverse sea states. Rough sea conditions should be avoided for this type of survey. Waves can be accommodated somewhat by designing a survey into or with the wave direction; mitigate swells in the seismic record through post-processing.

Complete logging of the system configuration, weather and sea state, crew, file/line identification, data acquisition parameters, and equipment status is critical. This process begins before and throughout the survey, with descriptions of project intent, survey strategy, vessel and equipment, location, dates of acquisition, and point-of-contact entered into a central database or whatever media is available. This preserves cruise information for perpetuity and is the beginning of metadata development. As discussed in Chapter 1, if the data are to be archived in a global repository, the cruise information should align with the protocols of the repository (see NCEI for general use standards [NOAA NCEI, n.d. e.]). Additional guidance is provided in the Metadata chapter of this document.

6.3 Navigation

Accurate positioning of seismic data requires horizontally positioned traces with high precision. The ping, or shot, of the source is annotated with a geographic position, which is included in the trace header and/or external navigation file (along with any datum information). In older data that predates GPS positioning, interpolation between navigational fixes was required. Modern systems use DGPS with a high sampling rate to reduce interpolation. In coastal surveys, deploy RTK transmitters to improve resolution. As described in the following sub-bottom chapters, accurate layback measurements are necessary since the position is extrapolated from the DGPS antennas to the source and receiver positions. For surface-towed systems, mount a DGPS antennae directly on the source sled, with an FM transmitter to relay position back to the top-side processor.

6.4 System Types

Sub-bottom systems are defined by their sound source and source/receiver configuration. Depending on the application or goals of the survey, one system may be advantageous over another. Each system produces different power levels and frequency ranges. The following subchapters discuss the advantages of each system. See Mosher and Simpkin (1999) for examples of the system types. Chirp systems have the source and receiver in the same body or use the same transducer to transmit and receive. The chirp sound-pulse is spread across a user-specified bandwidth and pulse length. Other seismic reflection systems (e.g., boomer, sparker) separately tow source and streamer (receivers) and emit a broadband sound pulse that is centered around a peak frequency. Deep-towed boomer and sparker systems with attached single-channel streamers are more uncommon than surface-towed systems. The following chapter describes these systems.

6.4.1 Chirp

A chirp SBP is a hull-mounted or towed acoustic system that emits a frequency-modulated, or swept-frequency, pulse across a bandwidth generally between 0.5–24 kHz. Other configurations exist, but typical systems are configured to operate with bandwidths of 0.5–12 kHz, 2–16 kHz, and 4–24 kHz. The outgoing pulse of these systems is designed to various bandwidths and pulse lengths. The source signature is highly repeatable (Gutowski et al., 2002); as such, an advantage of chirp signal processing over single channel systems is that the signal is phase and amplitude-compensated in real time to filter out (match filter) the outgoing sonar component. This signal processing theoretically results in an artifact-free return signal representing the subsurface component's acoustic impedance (Shock et al., 1989). The resolution of chirp systems is the 10-centimeter range (Gutowski et al., 2002), with a maximum penetration of 75–100 m depending on the lithology. The signal's sampling frequency is around 20-25 kHz and, with a typical vessel speed of ~4 knots, the horizontal trace interval is about 1 m in shallow water. The return signal is a full waveform and contains the sinusoidal phase of the analytic signal (see Henkhart (2006) and Quinn et al. (1998) for examples). The chirp signal can be visualized with no phase information; just the instantaneous amplitude, or envelope signal, is displayed (Henkhart, 2006). The envelope record improves the contrast of the signal but removes phase information. Some systems retain the whole waveform of the signal and can be processed further to provide a higher resolution of fine-scale features in the subsurface (Saustrup et al., 2019; Baradello, 2014). Where possible, the full waveform, or analytic signal, should be extracted from proprietary formats and archived in SEG-Y. Collect and record raw sub-bottom data files by vendor-specific systems and save in proprietary formats. Convert the chirp envelope record to the SEG-Y file format during acquisition, and record the whole waveform and envelope traces in SEG-Y. Proprietary formats, such as EdgeTech's native JSF file format, stores both the analytic and envelope signals (EdgeTech, 2021).

6.4.2 Boomers (Including the Bubble Gun, or Bubble Pulser Variant)

Boomer systems utilize an electromagnetic source that takes an electrical discharge from a ship-based power supply to cause a circular plate to rapidly repel from a fixed flat spiral coil, generating an acoustic pulse with a frequency bandwidth of 0.2–6 kHz. Peak frequencies are on the order of 1 kHz (lower for Bubble Guns). A Bubble Gun operates similarly to a boomer plate, generating an impulse by rapidly compressing a fixed volume of air. Boomer and Bubble Gun plates are mounted on towed surface sleds and boomer plates can be mounted on a submerged tow body. Surface sleds are configured with 1 or 2–3 plates. Multiple plate configurations increase SL and directivity and are more commonly used with multichannel systems. Power inputs are set between 100–350 J/plate. Boomers and Bubble Guns produce an acoustic signal (fires) approximately every 0.5–1 s. They are often deployed with other higher frequency (higher resolution) chirp systems to provide deeper sub-bottom penetration.

6.4.3 Sparkers

Sparker systems operate by discharging an electrical pulse from a shipboard power supply using towed electrodes rapidly creating a vapor bubble that expands and then oscillates with amplitudes that decay with each bubble pulse, generating a broadband (50 Hz to 4 kHz) omnidirectional pulse of sound. The source signature is generally repeatable, less so than boomer signatures, but will vary with towed depth, seawater salinity, and electrode wear. Post-processing deconvolution is required to collapse the pulse and improve resolution. There are many types of towed sparkers, some sled-mounted, others just electrodes at the end of a high-voltage power cable. Input power can range from a few hundred J to over 10,000 J. Higher power sparker sources can penetrate several hundred meters into the sub-bottom. Because of the sparker's relatively high frequency compared to deep-penetration seismic air guns, sparker sources are used for high-resolution shallow imaging. Shot intervals range from two pulses/s in shallow water to several pulses/s in deep water.

6.4.4 Parametric Systems

The parametric sound source is a hybrid between the swept frequencies of the chirp and the single pulse from the displacement systems. This system uses the parametric effect, where two different high-frequency signals are emitted simultaneously. The two high-frequency sound waves interfere to generate a response signal at the intersection of the original beam, which is at a different frequency between the two original high-frequency signals (Mosher and Simpkin, 1999). The response is a low-frequency focused (shaped) beam that can be directed to the seafloor. This secondary signal is between 5–15 kHz (depending on primary frequencies) and has been used to image features up to 50 m below the seafloor (Schneider von Deimling et al., 2016; Wunderlich et al., 2005). Parametric-type systems are found on deep water vessels where low relief structures and a flat seafloor are primary targets. See Rostek et al. (1991) and Grant and Schreiber (1990) for test cases using this technology.

6.5 Seismic Data File Format

The conventional file format for seismic data acquisition and distribution is the SEG-Y format (SEG Technical Standards Committee, 2002). The SEG-Y file consists of ASCII and binary file headers containing acquisition parameters, binary trace data (and an optional extended textural header file). The headers and trace data have a consistent byte order and configuration (Tables 6.1 and 6.2), as outlined in the SEG Technical Standards Committee (2002). Numerous proprietary file formats were developed by equipment manufacturers (e.g., EdgeTech JSF, Sonar Equipment Services SES, or Knudsen KEB formats). Data logging in a proprietary format during acquisition should coincide with recording in the SEG-Y format or as soon as possible. Convert the proprietary format to 240-byte SEG-Y version 2 (rev. 2.0 specification). Populate the SEG-Y headers with the minimum values established in the SEG Technical Standards Committee (2002) and include as much information about the acquisition parameters as possible. The textural header can be used to describe values in the binary file and trace headers (e.g., sources X and Y are corrected for layback). Necessary header fields are in Table 6.1 and Table 6.2.

Table 6.1. Some important fields extracted from the binary header of the seg-y file. See SEG Technical Standards Committee (2002) for complete binary header specifications.

Description	Byte Position
Job identification number	3201 - 3204
Line number	3205 - 3208
Reel number	3209 - 3212
Traces per record	3213 - 3214
Sample rate (or interval)	3217 - 3218
Number of samples per trace	3221 - 3222
Data sample code (IBM or IEEE)	3225 - 3226
Sweep frequency at start (Hz)	3233 - 3234

Sweep frequency at end (Hz)	3235 - 3236
Sweep length (ms)	3237 - 3238
Sweep type (1 = linear)	3239 - 3240
Measurement system (1 = meters)	3255 - 3256
SEG-Y format revision number	3501

Table 6.2. Data values extracted from the standard trace header of the seg-y file.

Description	Byte Position	Value
Trace sequence number	1 - 4	Number of traces in file (integer)
Original field record number	9 - 12	Original field record number (integer)
Trace number within field record	13 - 16	Multi-receiver identifier
Trace identification code[1]	29 - 30	E.g., 1 = seismic data (integer)
Source/receiver offset[2]	37 - 40	Distance (meter)
Height scalar	69 - 70	Elevation adjustment (+/- scalar)
Coordinate scalar	71 - 72	Coordinates adjustment (+/- scalar)
Source X (source and receiver)[3]	73 - 76	Geographic or projected position (e.g., arcseconds)
Source Y (source and receiver)[3]	77 - 80	Geographic or projected position (e.g., arcseconds)
Delay recording time (ms)	109 – 110	+/- time between initial pulse and recording
Number of samples[4]	115 - 117	Vertical samples per trace (integer)
Sample interval (microseconds)	117 - 118	Sample rate (dt)
Year of recording	157 - 158	Gregorian 4 digit
Day of Year	159 - 160	Julian date
Hour of day	161 - 162	24-hour clock
Minute of hour	163 - 164	0 - 59
Second of minute	165 - 166	0 - 59
Time basis code	167 - 168	E.g., 1=Local, 2=GMT, 4=UTC

Note: See SEG technical standards committee (2002) for complete trace header specifications. 1 - Trace identification code is for time domain seismic data. 2 - Source receiver offset is in meters. 3 - Trace coordinates (SX and SY) can be in geographic or projected coordinates. 4 - number of samples per trace (ns) at sampling rate are required.

File names should indicate a survey line number and, if applicable, indicate whether there are multiple segments in a survey line. The naming convention should be consistent throughout the survey and described in the metadata and cruise documentation. Use other identifiers (e.g., date and/or time, cruise/project identification) in the filename. Some acquisition software can set up file name templates that will automate the naming of files. File names must contain the suffix indicative of the file format (indicate rev. one and newer SEG-Y files by a .sgy, .seg, or .segy suffix). Do not change file or line names post-acquisition to avoid unidentified duplicates throughout the acquisition to archiving workflow.

6.6 Acquisition

Describe towing and hull mount configuration in cruise logs and diagrams (Figure 6.2 and Figure 6.3) that indicate offsets from the navigation reference point (NRP), typically the GPS position. Describe fore, aft (layback), port, and starboard offsets and positive and negative conventions. If the tow vehicle is surface towed, the NRP may have zero offsets if the GPS antenna is on the vehicle. Layback needs to be measured by wire-angle and wire-out or other means (e.g., USBL) when the vehicle is towed below the surface water. Logs and SEG-Y textural headers (see SEG-Y discussion in Chapter 6.5) need to indicate if offset corrections from source to NRP are applied to coordinates in the SEG-Y header. Horizontal offset corrections can also be applied in post-processing. Describe the water depth of the source in logs and diagrams, and, if possible, recorded in the SEG-Y trace headers. For deep-towed vehicles, record pressure-depth data to the SEG-Y headers with enough precision (equal to sample rate) to apply static corrections during processing. Record the water depth below the source, preferably in the SEG-Y trace headers, if using bottom tracking during acquisition or other single or multibeam sonar. Tow depths can impact the data quality; multiples from the water surface obstructing primary reflections. In shallow water, avoid this by surface towing or towing the vehicle just below the prop wash or to the vessel’s side. In deep water, operate deep-towed vehicles closer to the seafloor to reduce the ensonified area and limit the need for migration in post-processing.

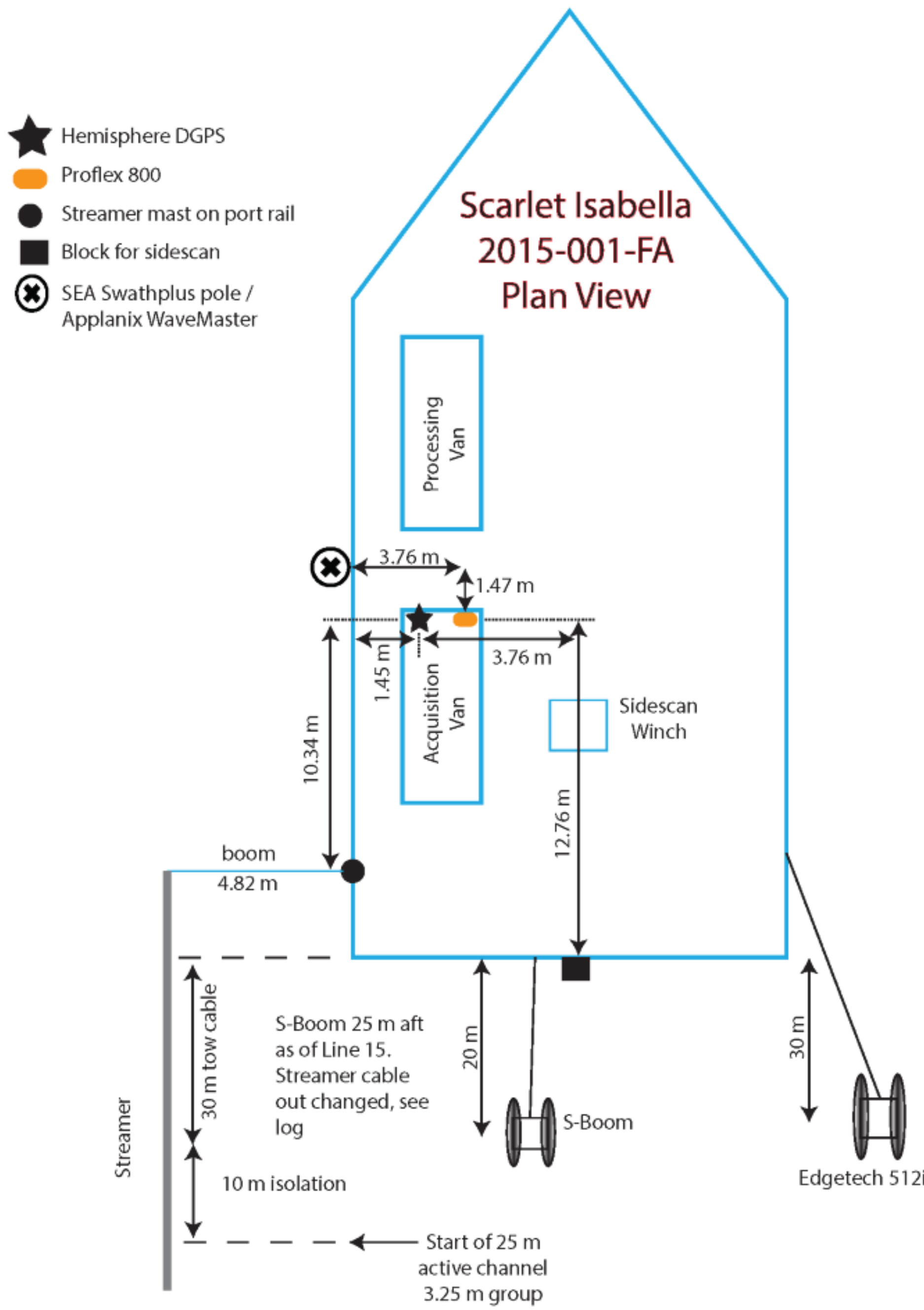

Figure 6.2. Geophysical towing configuration diagram for multiple acoustic tools and receivers: the offset measurements between GPS antennae, equipment tow points, and wire out. These offsets can be entered into the acquisition software to determine layback. Figure from USGS Geophysical Survey 2015-001-FA (Sweeney et al., 2015).

	A	B	C	D	E	F
1	FAN	2019-332-FA				
2	Date	08/09/19				
3	Location	Cedar Island, VA				
4	Vessel	R/V Sallenger				
5		**Personnel**	**Instruments**			
6	ET	*Chelsea Stalk / Jen Miselis*	Hypack/hysweep	2018		
7	Captain	*Andy Farmer*	DH-T50-P	sui 5.0.0.6		
8			POSmv WaveMaster II	POSview 9.91		
9			512i + SBB SLED	Discover 4.09		
10			Proflex 500-1 (SALL)			
11			Castaway 1			
12	**Day (DOY)**	**Time SOL (UTC) HHMM**	**SBB Hypack Line**	**Chirp Line**	**SVP**	**Comments/Targets**
13						
14	221	12:00				Depart City Dock with 512i
15		14:21			1	Arrive on site, S side of Line 1 Shore Parallel, Line File P2, CTD cast 1
16		14:26	0001_1425	0001_1425		SBB and Chirp line 1, Line File P2
17						Pulse: 0.7 - 12 Hz, L:20 ms, R: 4Hz; Writing to C/2019_233_CedarIsland location
18						SBB Settings: P:6, G:224
19		15:12				cool tidal channel in subsurface
20		16:11	0004_1610			Transit to and start of line 4 of the P1 Line File
21		16:18			2	SV cast at N End of survey AOI during transit to P1 line 4
22		16:24		0004_1624		Start of line 4 Chirp, Line file P1
23						
24						:. Conditions: Sunny, 91, No wind, seas very favorable.
25						
26		16:48	0050_1648	0050_1648		Start of most Northern Oblique Line (line 50), Line file P2_S (made in field to account for obliques working south.
27		17:10	0049_1709_0001	0049_1709_0001		Start of line 49, Shore Perp
28		17:31	0048_1731	0048_1731		Start of Oblique Line 48 headed offshore
29						SBB Settings changed to P: 10, G: 224
30						
31		17:51				Noticed the GPS receiver on the sled was randomly stating "Invalid" for mode in Hypack Survey. When Proflex File manager was checked, the same issue was occurring. At end of line 48, will stop session A, troubleshoot, and being Session B.
32		18:13				Began logging GPS session B file for SLED. After looking at rinex, there are no apparent indicators that the data is bad.
33		18:18	0047_1818	0047_1818		Start of line 47, headed inshore
34		18:39	0046_1839	0046_1839		Start of line 46 Oblique Headed offshore
35		18:42			3	slowed to idle to take cast
36		19:03	0045_1903	0045_1903		Start of line 45 heading inshore
37		19:30	0004_1930	0004_1903		Start of line 4, most inshore tie line, heading South.
38						Drop out at start of CHIRP line cause by prop wash
39		19:36				turning east to find more water
40		19:39				back on line - trying to keep in ~10' water depth

Figure 6.3. Acquisition log sample: the beginning of an acquisition log during USGS cruise 2019-332-FA collected in spreadsheet format. The log contains information about the cruise, equipment, personnel, location, svp, etc. Time annotated comments include trackline information, sea state, equipment issues, etc. From Forde et al. (2020).

Integrating motion sensors with tow-vehicles or pole-mounted systems allows for real-time heave (wave swell) correction. This improves heave correction by not smoothing real seafloor features.

6.6.1 Trace Data

Determine sample rates of the digital trace data based on the frequency content of the source signature. Some acquisition software will set this parameter from the trace data window and pulse lengths. Other software requires the user to determine parameters from suggested values.

The highest frequency that can be digitized is the Nyquist frequency (Nf) in Hz and the Nyquist sampling rate (Nsr) in samples/second, where

$$Nf=1/2Nsr \text{ or } Nsr=2Nf \text{ or } Nsi=1/Nsr,$$

when Nsi is the sample interval in seconds or

$$Nsi=1/2Nf.$$

For example, a chirp sub-bottom system with an upper frequency of 12,000 Hz has an Nsr of 24,000 samples/s or a Nyquist sample interval of 0.042 ms. When selecting the trace window and sample rates consider that file format limits the recording of 32,767 samples per trace.

Record (trace) length is selected to record the deepest reflector of interest, considering two-way travel time and seismic velocity. In deep water, delay recording time so as not to exceed the maximum number of samples per trace. Set a trace data window by applying a delay recording time if it is not desirable to record the water column. Record delay recording times in the SEG-Y trace header; times can be changed during acquisition to shift the trace data window. Some acquisition software can change the recording delay from automatic bottom tracking. Proceed with caution as spurious bottom picks result in undesirable data window shifts, such as not capturing the seafloor and sub-bottom reflections.

The trace data can be recorded in the SEG-Y file as standard integer and floating-point formats (International Business Machines [IBM] and Institute of Electrical and Electronics Engineers [IEEE]). To avoid clipping the trace data and promote capturing the full dynamic range of amplitudes, use floating point formats when disk capacities are not an issue.

6.6.2 Ping Rates

Ping rates (for chirp) or shot rates (for sparker and boomer) translate to the horizontal distance between traces depending on ship speed and the ping rate or pings/s. Water depth can constrain ping rates. Ping rates cannot exceed the delay recording time and trace length time. Some deep-water chirp systems put multiple pings in the water column, which effectively increases the ping rate. For inner-shelf chirp surveys, ping rates can be as high as eight pings/s. Boomers and sparkers fire shots around 0.5–1 s on an inner shelf survey. More extensive sparker surveys in deep water have shot intervals of several seconds. Because ping rates translate to horizontal resolution, obtain the highest possible rates depending on water depth and system limitations.

Chirp systems can control the amplitude (power), shape, length, and frequency pattern of the outgoing pulse. Select the power level to achieve the desired penetration without saturating high amplitude reflections, such as the seafloor reflector. Higher power settings in shallow water enhance artifacts and reverberation of the direct signal. The chirp pulse length can be controlled to enhance penetration and resolution. Longer pulse lengths (20 m or more) enhance penetration and minimize TL loss in deep water. Shorter pulse lengths (less than the water depth) achieve better resolution in shallow water and may be necessary to avoid outgoing pulse interference with the seafloor (Saustrup et al., 2019). For example, in 10 m water depth, a maximum 10 ms pulse length would be appropriate. With increasing water depth, longer pulse lengths of 30–40 ms provide more acoustic energy and less attenuation with depth. Polyvinylidene fluoride receivers are becoming more common in chirp systems and achieve better resolution (reduced footprint) with longer pulse lengths in shallow water. The swept frequency chirp pulse can be controlled to favor higher resolution with higher frequency bandwidths or skewed to lower frequency with deeper penetration results. Manufacturers provide a range of pulses or can provide custom pulses. Some acquisition software allows the user to design their pulses. Before starting a survey, pulse designs should be set to the desired results for the geology and survey goals. Maintain pulse settings for the survey to facilitate comparison between lines.

6.6.3 Power

Boomer and sparker systems can control amplitude (power). Sparkers control frequency depending on tow depth (shallow depth increases frequency). The Bubble Gun system is low power and does not control amplitude whereas the size of the plate controls the frequency. Shipboard power supplies can produce varying power levels for boomer and multiple boomer plates (50-1000 J). Multiple boomer or Bubble Gun plates increase SLs. Sparkers can take much higher power levels depending on size and specifications. More power results in deeper penetration but may also enhance artifacts (e.g., multiples) and reverberation. Power should be set lower in shallow water or where deeper penetration is not needed. Environmental regulations may limit the power levels of boomers and sparkers depending on water depths and other factors.

6.6.4 Gain

Gain is a time-varied scaling of the signal to enhance weak signals and compensate for signal attenuation. Do not make gain adjustments to the raw trace data during acquisition. Most acquisition software can apply display gains in real time and needs to be verified and logged before the survey. Check raw SEG-Y trace data as part of a QC plan.

6.6.5 Noise

Boomer and sparker systems use analog or digital hydrophones that receive seismic signals and ambient noise. It is best to eliminate noise in the acquisition process (e.g., power harmonic such as 60 Hz); high-pass filters may be effective in removing low-frequency noise. Noise that is higher frequency than the Nf can result in recording aliased noise that shows up as lower frequencies in the data. Apply a high-frequency cutoff filter before recording data. Parameters for an anti-alias filter, or the wideband recording filter, should be set to avoid cutting off low and high-frequency seismic reflections. The high cut is generally 80% of the Nf (Dondurur, 2018).

6.6.6 Storage

Modern hard disk drives have sufficient storage space and input/output (I/O) capability for most surveys. Typically, data are stored on an acquisition computer as the data are recorded and then copied to a backup device. In some surveys, the data are recorded directly to a network storage system that requires a robust network, testing, and consideration of I/O from other computers.

The raw data should be copied to a processing computer as a backup and post-processing. Raw data can be archived on Blu-ray discs.

Each straight trackline segment is a single file. A recording of the file should continue until there is a deviation of course (e.g., a turn), significant change in vessel speed (e.g., slowing down for environmental or hazard reasons), changes to acquisition parameters (e.g., changing pulse length), or equipment malfunction. However, long recording times of an individual file are not recommended as it statistically increases the chance of file corruption through software error or other environmental factors associated with seismic surveys (e.g,. loose cable connections, GPS failure). The length of the uninterrupted trackline ultimately determines file size, but care should be taken if the trackline becomes exceedingly long. To provide a comparison, a review of hundreds of chirp lines acquired by the USGS between 2007–2019 found that the most extensive seismic line, by far, contained 25,000 traces, and most lines were in the 3,000–10,000 trace range.

6.6.7 Tracklines

Some software acquisition systems can automatically end and start new lines at user-defined intervals; however, this capability is a carryover from bathymetric survey systems. To enforce complete and accurate logging of lines and ensure proper attention to data acquisition and quality, active management of trackline length is recommended over automated systems due to the previously mentioned limitations to trackline length.

6.7 Data Management

Seismic data management is necessary for efficient use, future access, and validation of analytical and interpretative results. For specific details and guidelines associated with SBP data management (such as file formats, data archival, etc.), please see Chapter 1.6.4.

6.8 Resolution

Seismic system type, source power, and resolution vary among systems. Source type and power are tailored to provide optimal results for the project's objectives. The most significant trade-off with seismic systems in near-surface (< 100 m) investigations is between sub-bottom penetration and vertical resolution. Higher power and lower frequency improves penetration (typically, single pulse systems resolve depths greater than 50 meters). Higher frequency moderated pulse systems (such as chirp) best serve shallow, high-resolution studies. Longer pulse lengths are desirable for penetration but can cause interference with signal return (Saustrup et al., 2019). Surface texture (e.g., high sand content, cementation) and features (e.g., shoals) also have a bearing on signal penetration, as does organic matter or gas content of the substrate. All of these factors must be considered in survey strategy plans, with the highest resolution designed for the desired target depth.

Technical specifications can be found in the literature that cites specific data resolution for sub-bottom profiling (e.g., NMAHS, 2017) and used as recommendations for specific goals. Since sub-bottom data can be used for many research, exploratory, and imaging (e.g., site assessment for infrastructure placement) purposes, data collection should occur at the highest resolution available to the equipment and environmental conditions. This ensures data suitable for most applications (*map once, use many times*).

Chirp systems provide continuous and high-resolution data on subsurface geological features within the uppermost 10–15 m of sediment. The SBP system should achieve a vertical bed separation resolution of at least 0.3 meters in the uppermost sediments, depending on the substrate. A medium penetration seismic system—such as a boomer, bubble pulser, or another low frequency system—can be used to provide information on a sedimentary structure that exceeds the depth limitations of chirp systems. The system should be capable of penetrating greater than 10 meters beyond any potential disturbance depth with a vertical resolution of at least 3 meters. The seismic source should deliver a simple, stable, and repeatable signature near minimum phase output with usable frequency content.

6.9 Quality Control

Apply basic QC to all SEG-Y files before processing the trace data. If data are recorded in a proprietary format, they need to be converted to SEG-Y format first. If multiple trace types exist, extract each trace type to SEG-Y format. Perform the following QC as a minimum:

- Open the file with software designed to read SEG-Y format. If there is a problem with SEG-Y headers or format, the file may not open. Scan all headers to make sure the values are correct. Ensure the mandatory header values (Table 6.1 and Table 6.2) are there.
- Plot header values to verify that there are no outliers or missing values. Plot navigation coordinates after conversion scalers. Ideally, plot coordinates with ping (shot) numbers on a GIS basemap.
- Plot the trace data. Some software can plot the trace data and evaluate headers simultaneously. Check amplitudes and polarity; full waveform chirp should be bipolar. Envelope traces should have all positive amplitudes. Check that trace length is sufficient for the survey goals. Check for avoidable acquisition noise issues (e.g., electrical noise).
- Spectral plots of the trace data (entire waveform for chirp) can help identify noise and help pick filter parameters in post-processing.
- If acquiring in deep water, check that the delay recording time and data windows are correct in the header. Check source depths and altitudes.

6.10 Processing

Processing of SCS chirp, boomer, and sparker data share common process steps that produce a process flow. Chirp processing is mainly limited to static corrections and gain adjustments because chirp data have a controlled frequency pulse, and the match filter process increases the signal to noise. Processing the full waveform chirp may require additional steps. Boomer and sparker data are complete waveforms but not controlled waveforms, so deconvolution should be applied to collapse the waveform to a spike. The data must be filtered to remove noise outside the main reflection frequencies.

A typical process flow:

- Static trace shift correction
    - Account for deep water recording delay
    - Account for source/receiver depth
    - Heave removal
    - Datum offset
- Noise suppression
    - Despike and noise burst removal
    - Bandpass and notch filters
    - Fxdecon
- Deconvolution (spiking)
- Poststack migration
- Gain
    - Time-varying gain
    - Automatic Gain Control (AGC)
- Navigation layback correction to update coordinate headers
- Export processed SEG-Y file with updated headers

Static corrections shift the trace data to a corrected vertical position. These static shifts include recording delay, correction for source/receiver depth, heave compensation, and corrections to a tidal or another datum. Recording delay should be in the SEG-Y trace headers. Source/receiver depths may be static or variable and recorded in trace headers. Heave compensation involves recording real-time bottom detections, depths from other sonars, or post-processing picks of the seafloor. The picks are filtered using values estimated from the predominant wave period at the time of surveying. The difference between original and smoothed picks is used to shift the traces. Heave filtering differs for boomer and sparker data because source and receiver are offset. Unless the source and receiver depths are measured independently, the best option for heave removal is real-time bottom detection during acquisition or picking the seafloor (after a bandpass filter is applied) and calculating the difference between the seafloor picks and a smoothed seafloor. Care must be taken, as this process has the potential to smooth out real seafloor features.

Some noise can be removed in acquisition with wideband recording filters (match filters for chirp), but noise can exist within the recorded data as coherent and random noise. Spectral analysis of the raw data (entire chirp waveform) can help identify noise and determine filter parameters. The following filters can be applied to increase the signal-to-noise ratio:

- Choose bandpass parameters to remove undesirable low and high frequencies.
- Notch filters remove discrete or a narrow band of frequencies such as 60 Hz powerline noise and associated harmonics, an example of coherent noise. Ideally, it is best to

preserve as much frequency content of the primary reflections as possible. Removal of lower frequency content will decrease penetration, and removal of high-frequency content will reduce the resolution. Another example of coherent noise is signals received from another HRG system operating simultaneously (cross talk). Minimize this during acquisition by controlling triggering.

- Despiking filters can remove relatively higher amplitude noise spikes in the traces. Multiple reflectors can be considered coherent noise.
- Predictive deconvolution may attenuate multiple reflections in SCS; however, this may result in degrading the data.
- Suppress random noise with stacking traces. MCS systems can increase signal to noise by stacking multiple channels for each shot. The matched filter in chirp processing increases the signal-to-noise.
- Coherency can be enhanced, and random noise in SCS reduced with trace mixing or taking a running average of amplitudes using a select number of traces. Stacking and trace mixing, if applied, should come after static corrections, coherent noise removal, and deconvolution.

Spiking or source signature deconvolution can be used to improve vertical resolution, compress the seismic wavelet (as in chirp match filtering), decrease ringing, and improve the amplitude spectrum. Deconvolution of SCS can be processed like a post-stack MCS system. Deconvolution on the full waveform chirp data may enhance vertical resolution if the match filter does not have ideal results. Deconvolution can create artifacts depending on the parameters used, so chirp systems need to be checked periodically to ensure the source signal has not degraded over time. Ideally, the source signature should be as close as possible to the match filter being used.

Gain recovery can be applied to compensate for spherical divergence, absorption, scattering, multiple reflections, and other factors that decrease reflection amplitudes with time from the source. Spherical divergence correction can balance amplitudes with depth. This method preserves the relative amplitudes in the data. A time gain function, where amplitudes are increased trace by trace by raising time to constant power, decreases amplitudes for early arrival times and increases amplitudes for later times but preserves the relative amplitudes. AGC applies a sliding window down each trace, and a mean or median scaler is calculated for the window, and applied, usually to the middle sample in the window. AGC results in better trace-by-trace balanced amplitudes but does not preserve relative amplitude within the trace.

Migration can move seafloor and subsurface reflection events to their accurate locations, increasing lateral resolution. Treat migration of SCS as if it were a post-stack MCS system. A disadvantage of post-stack migration is that relative amplitudes are altered. It is important to remove noise and artifacts as much as possible before the migration process.

MCS protocols are not discussed in this chapter. However, boomer and sparker sound sources are increasingly paired with multichannel streamers for very high-resolution continental shelf surveys; for example, 32 channels (groups) with group spacing as short as 1.5625 meters. Many MCS processing methods apply to SCS processing, but there are many more methods available in MCS processing primarily due to having multiple sources to receiver offsets for each shot.

Moveout and stacking alone increase signal-to-noise, and allow for more prestack processing options—such as multiple suppression, deconvolution, and de-ghosting. The cost-benefit of acquiring and processing MCS needs to be assessed depending on the survey's goals.

6.11 Archiving

For specific details and guidelines associated with data archiving, please see Chapter 1.6.4. Processed data must be evaluated, and fully QA/QC'd by a subject matter expert (see Chapter 6.9) before publication. Archive all datasets in cruise or mission-specific directories and include supplementary data such as producer organization and contact information, acquisition navigation (ASCII), acquisition log notes, and processing methods. Include notes on the format(s) used during data acquisition, equipment issues or malfunctions, and any processing steps applied to the data in the documentation.

Archiving of seismic data has advanced significantly in the past two decades. All marine seismic surveys—from past analog archives (for examples of digitizing analog datasets, see Bosse et al., 2017) to modern digital acquisition—need to be archived in online repositories so that the data can be accessed in perpetuity, as the geology does not change on human time scales and acquisition of data is expensive and may not be repeated. Examples of existing repositories include:

- National Archive of Marine Seismic Surveys (USGS, 2023)
- Lamont-Doherty Earth Observatory Seismic Reflection Field Data Center (LDEO, 2020)
- NOAA Marine Geology and Geophysics (NOAA NCEI, n.d. f.)
- National Science Foundation Marine Geoscience Data System (MGDS, n.d.)
- USGS Publications Warehouse (USGS, n.d. a.)
- USGS Coastal and Marine Geoscience Data System (USGS, n.d. b.)

Sharing scientific data leads to better collaboration, increases confidence in findings, expands our understanding of complex geologic systems, leads to new avenues of research, and saves on cost and energy. Proper data management and archiving of marine seismic data allows for efficient re-use of data for many purposes, and builds on existing collaborative efforts such as SeaSketch (SeaSketch, no date) and the NOAA Integrated Ocean and Coastal Mapping initiative (NOAA IOCM, no date), which highlights the slogan "Map Once, Use Many Times."

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Chapter 7: Magnetometry

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7.1 Introduction

Magnetometers detect variations in the Earth's magnetic field. Magnetometer data has many applications, such as structural geological mapping, energy and mineral exploration, archaeology, and munitions detection. Analysis of magnetometer data points to discrete anomalies on the seafloor and in shallow-buried contexts. This chapter focuses on general magnetic theory related to anomaly detectability, factors that influence data quality, instrument configuration and selection, platforms, coverage specifications, resolution/line spacing based on survey objectives, and validation. This chapter provides overarching guidance and recommendations for the collection of mapping data from magnetometers and does not address manufacturer-specific recommendations or recommendations concerning specific use cases.

7.2 General Magnetic Theory as it Relates to Anomaly Detectability

Earth's magnetic field is the sum of multiple contributing sources, which may generally be categorized by their origins (the vector sum of geological [Earth-based] sources, heliophysical [external, predominantly solar] sources, and ferromagnetic objects). The field is not static and varies in strength and direction as the north magnetic pole moves with time, and recent studies have shown that the Earth's magnetic field strength has fluctuated by about 9% from the global average in the last 200 years. The geomagnetic field results from the convection movement of the molten iron-rich outer core, driven by heat flow from the solid inner core, a process known as the geodynamo. The second category of contributing sources arises from the static magnetism of the Earth's crust. Ferromagnetic material existing on or below the crust, as well as the geological features of the crust itself (minerals with varying amounts of iron in their composition), alter the field. The third category of contributing sources arises from the interaction of the Sun's and Earth's magnetic fields and large-scale electrical currents in Earth's atmosphere. These include irregular, dynamic, and complex solar winds, Earth-directed geomagnetic storms, and typical solar diurnal variation arising from Earth's rotation under the influence of the Sun's ionizing radiation.

The geomagnetic field is a vector field, meaning it has a magnitude and a direction at every point in space. Often, only the magnitude of the geomagnetic field vector is measured, especially for geophysical surveys. The magnitude of the geomagnetic field is known as the total magnetic field (the total field).

In mapping the seafloor and the subsurface ocean environment using a marine magnetometer, researchers attempt to measure variations in Earth's total magnetic field in order to identify structures in the near-surface, such as discrete anthropomorphic anomalies (i.e., archaeological sites with high concentrations of ferromagnetic materials or perhaps unexploded ordnance [UXO]), as well as larger, deeper geological trends. Magnetic data is used to estimate the age and thickness of volcanic lava flows at mid-ocean ridges and ocean island hot spots and to explore for ferromagnetic minerals. The specific protocol for marine magnetic surveys depends on the intended purpose of the seafloor and subsurface ocean environment mapping. Generally, the smaller and more discrete the item being explored for, the narrower the survey line spacing and the lower the instrument altitude above the seafloor must be to have confidence in identification.

Marine magnetometers operate by measuring the total field as they move through the marine environment. These measurements are collected as time-series data along straight and parallel lines with the instrument kept at a constant altitude, close to the seafloor (½ the survey line spacing is an appropriate altitude). Collected time-series data may then be processed and viewed line-by-line or by plotting multiple lines and creating a contour map of the total field. Once mapped, the geographic location of objects causing magnetic anomalies from the total background field may be discerned. Magnetic anomalies are sensed perturbations of the background total field that signify contrasts in magnetic susceptibility, which is the ability of a substance to take on an induced magnetism caused by its immersion in Earth's magnetic field. The magnetic susceptibility of any substance on Earth is equivalent to the mass of its ferromagnetic components, or in other words, its iron content.

Near-surface ferromagnetic objects appear as individual magnetic dipoles, creating their local magnetic fields within the larger geomagnetic field. This dipole exists in two parts: induced and permanent. Every ferromagnetic object will create an induced dipole proportional to its mass, its magnetic susceptibility (a characteristic of the material making up the object), and the strength of the background geomagnetic field. This induced dipole will always be oriented with the background geomagnetic field.

An object's dipole is not dependent on the background field as it would remain even in the presence of no background field. As the object moves, the orientation of the permanent dipole changes with it. The addition of a permanent dipole is called magnetization, and it can happen in many ways, including during an object's formation (cooling from a molten state). An object can be demagnetized, meaning its permanent dipole can be removed, but not its induced dipole.

An object's observable dipole is a vector combination of its induced and permanent dipoles and appears as a single dipole to a magnetic surveyor.

The Earth itself appears as a large single dipole when viewed from far enough away (Figure 7.1 and Figure 7.2). The north and south magnetic poles vary approximately 11.5 degrees from the geographic north and south poles. The amplitude (height, or intensity/strength) of a ferromagnetic object's anomaly, its duration (length of time in the time-series data), and its shape contrasted against the expected background field can help surveyors understand what may have caused the anomaly sensed by the instrument.

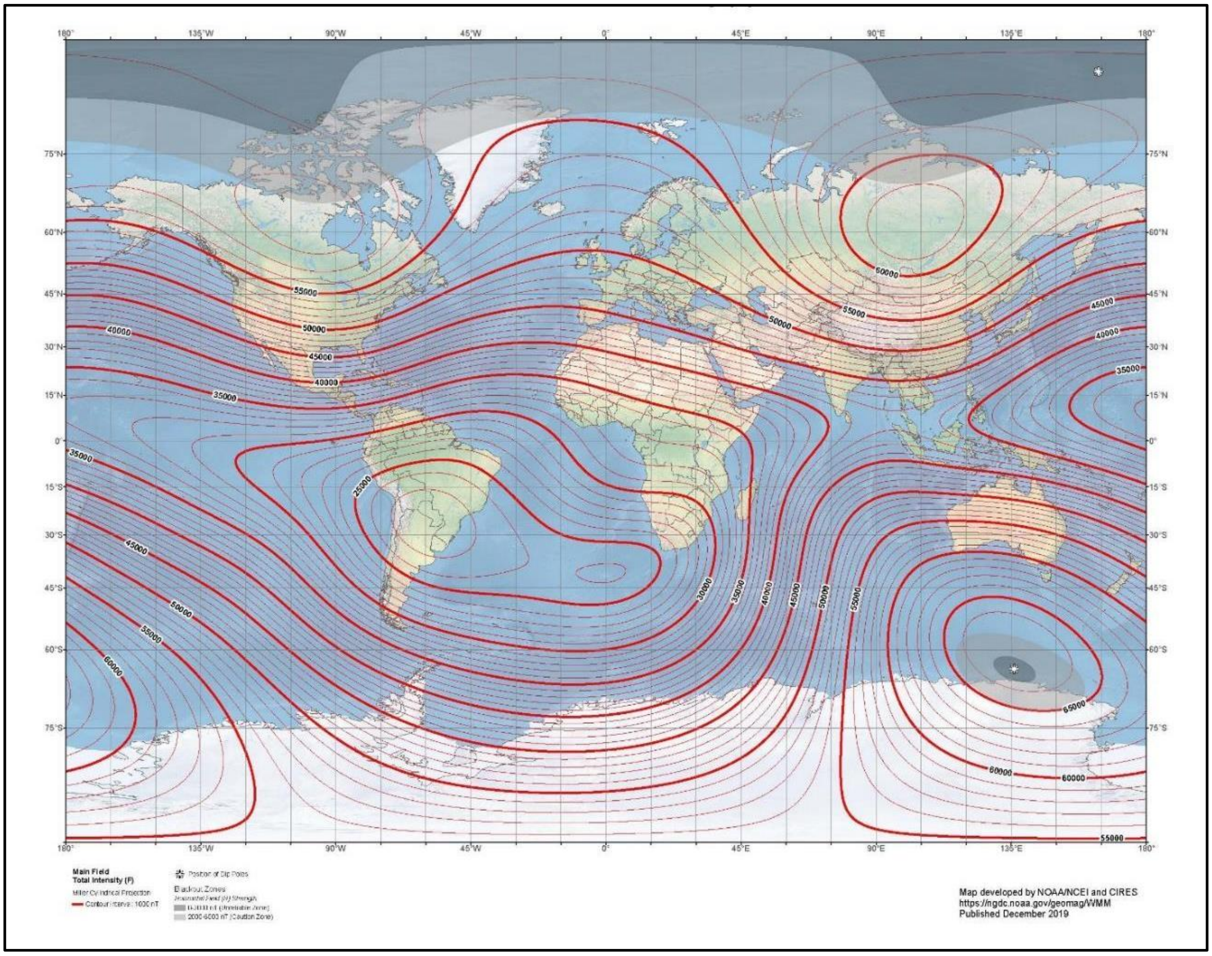

Figure 7.1. US/UK world magnetic model main field total intensity. Map developed by NOAA/NCEI and Cooperative Institute for Research in Environmental Sciences. Available at: https://www.ngdc.noaa.gov/geomag/wmm/data/wmm2020/wmm2020_f_boz_mill.pdf.

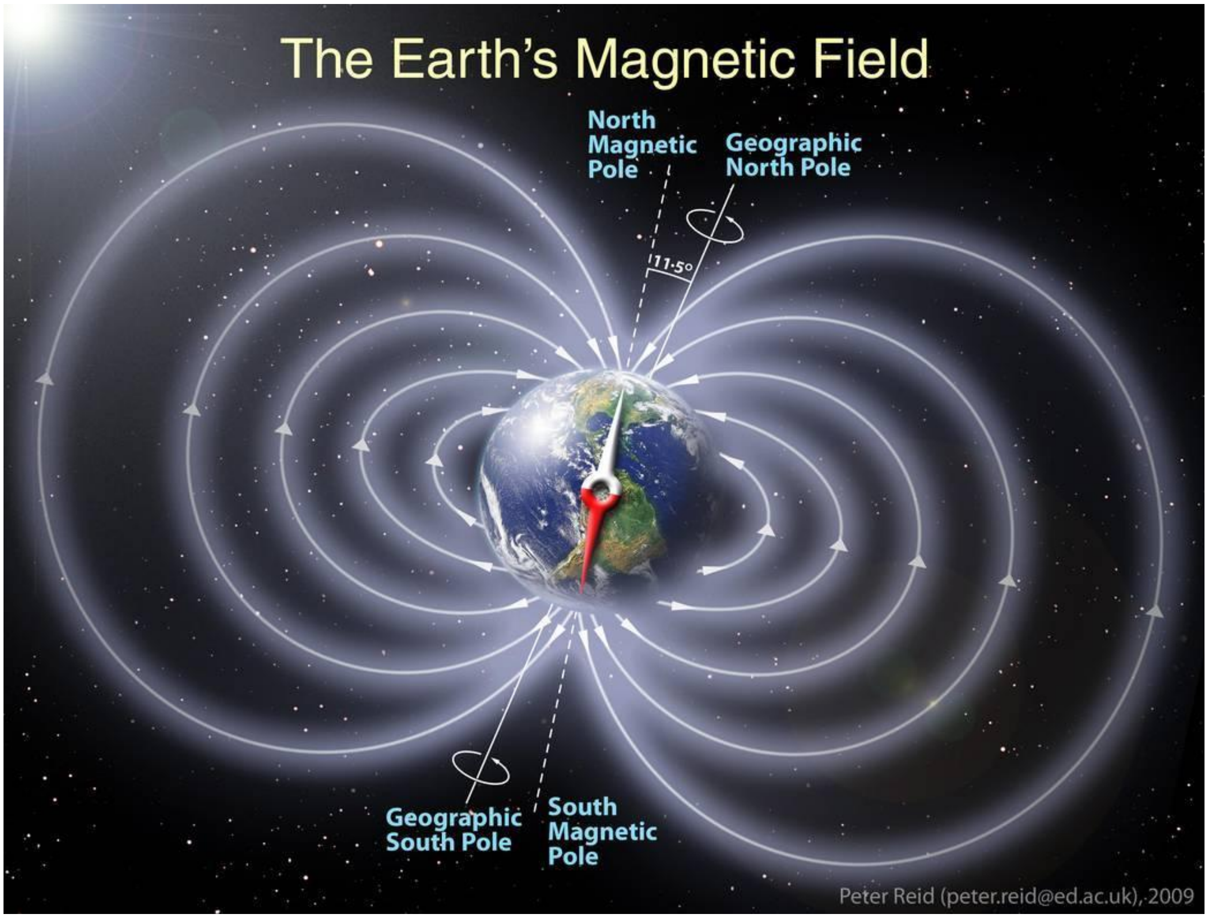

Figure 7.2. Earth's magnetic field: artist's rendering of Earth's magnetic field, including orientation of flux lines, north and south geographic poles, and north and south magnetic poles. Image by Peter Reid (2009); available at: https://www.nasa.gov/mission_pages/sunearth/news/gallery/earths-magneticfieldlines-dipole.html.

When a single track line is graphed as time-series data, anomalies present in graphically displayed magnetic data in three primary shapes: monopole, dipole, and multi-component.

Monopole anomalies result when a magnetometer intersects only one pole of a magnetic anomaly, and the other magnetic pole is far enough away to be unrecorded (Figure 7.3). Alternatively, an object's permanent magnetism and induced magnetism may align in such a way to minimize either the positive or negative expression of the total magnetic field. Monopoles can be either negative or positive concerning the background magnetic field.

Dipole anomalies result when a magnetometer intersects both the positive and negative portions of a ferromagnetic object's total magnetic field. As the sensor moves through the perturbation of the total field caused by the induced magnetism of the ferromagnetic material in the field, the sensor's reading registers as a coupled increase and decrease in amplitude. The dipole's orientation will depend upon the object's orientation, its permanent magnetic characteristics, and the latitude of the survey (i.e., its nearness to the poles versus the equator) because the strength and orientation of magnetic field lines comprising Earth's magnetic field vary according to how far from Earth's poles the survey is conducted.

Finally, multicomponent anomalies are simply a collection of monopole and dipole anomalies, all of whose vectors contribute to the cluster of readings in the data. In small anomaly detection, multicomponent anomalies typically point to multiple sources of ferromagnetic materials, all with their magnetism interacting with the total field, complicating the picture.

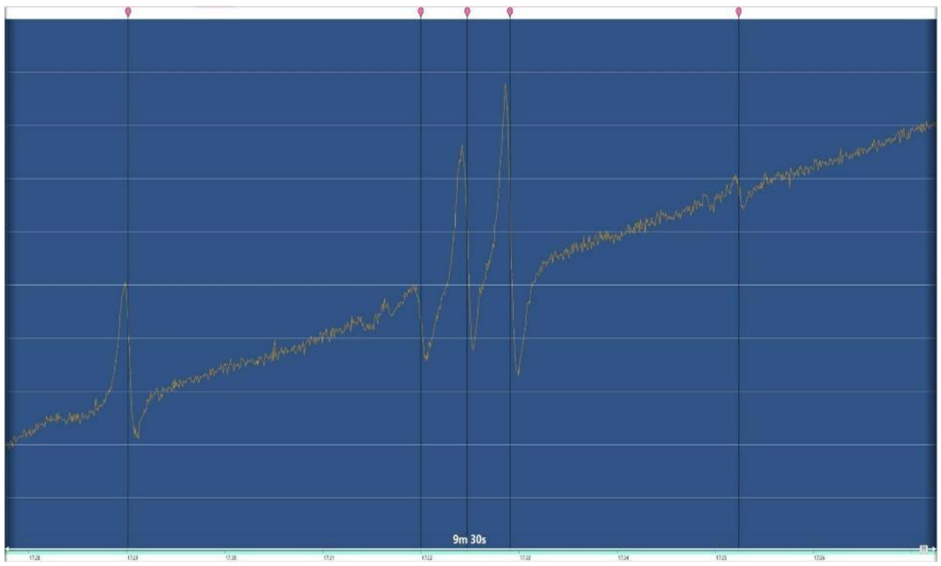

Figure 7.3. Magnetometer time-series data: marked anomalies over a 9m 30s period graphed on a 30 nanotesla (nT) scale. Graph from Matthew Lawrence, NOAA.

7.3 Factors that Influence Data Quality

7.3.1 Environmental Sources of Noise

Noise is defined as any influence on magnetic field readings that obscures the anomalies that surveyors seek to detect or reduces the accuracy of the local magnetic field recorded. It includes geomagnetic storms, diurnal variation, and ocean effect. If the survey's objective is to identify subsurface geology, then archaeological sites or UXO are also noise sources. Contrastingly, if the objective is to identify archaeological sites or UXO, then subsurface geology may be considered noise.

7.3.1.1 Diurnal Variation

At any given spot on the Earth's surface, the regional magnetic field varies throughout the day as the sun-facing side of the planet is influenced by the solar magnetic field. Diurnal variation also changes throughout the year as the Earth's position to the sun changes. Diurnal variation can cause magnetic field readings recorded in close spatial proximity to each other but temporally distant to have dramatically different magnetic field readings. For example, adjacent survey lines surveyed at significantly different times on the same day or different days can have very different average levels. One intuitive way to understand the effect of diurnal variation is to think of it as a ‘magnetic tide’ that has both the regular (daily) and random (storm-based) components to it, which can either raise or lower the overall total field values on an hourly or even minute-by-minute basis. See Chapter 7.9 for steps to correct for diurnal variation.

7.3.1.2 Geomagnetic Storms

Occasional solar activity events, such as solar flares, can cause substantial variations in the Earth’s field. These events can have a stronger amplitude than normal diurnal variations and will be present over a wider frequency range, meaning they can disrupt geophysical survey results. NOAA provides more information about geomagnetic storms (NOAA SWPC, 2023). Magnetic surveys should not be planned during forecasted geomagnetic storms because the noise generated by these effects will mask or distort the data signal and interfere with navigational accuracy for all instruments due to ionospheric scintillation. SpaceWeather.com provides forecast information for geomagnetic storms (Spaceweather.com, 2023). Solar activity broadly varies according to an 11-year solar cycle, with the likelihood of extreme geomagnetic storms occurring more frequently during specific periods. Awareness of geomagnetic storms is essential as they degrade the accuracy of GNSS and interfere with radio communication.

7.3.1.3 Ocean Effect

Dissolved salt in seawater makes it conductive, and movements of seawater will induce local magnetic fields. Ocean waves and swell create local fields that are not only detectable by a magnetometer, but can disrupt geophysical survey data, producing signals exceeding 10 nT at frequencies around 0.1 Hz. The effect is most pronounced in open ocean and tends to reduce or disappear in inshore protected areas. The effect is thoroughly described in Weaver (1965).

Ocean tides and currents have also been shown to produce magnetic variation (Tyler et al., 2003), but are slower in frequency, and are difficult to distinguish from diurnal variation. Utilizing tie lines (described below in Chapter 7.5.1) can help minimize the effects of this influence on survey data.

7.3.1.4 Subsurface Geology

Surveys seeking to detect near-surface ferromagnetic objects such as from anthropogenic sources may find that subsurface geology obscures the variations in the magnetic field the survey seeks to detect. In general, sedimentary rocks, especially carbonate rocks, tend to be less magnetic than igneous (basement) rocks, which typically have more iron content. Areas with a shallower depth-to-basement show more magnetic variation due to geological features and, most importantly, are closer to the high-frequency band of interest when detecting near-surface ferrous objects.

Additionally, the structure of the near-surface crust often contains fault lines, boundaries of dissimilar geologic materials, or erosional features, all of which can cause large-scale magnetic anomaly patterns if the rock is magnetic. These patterns can be used to study the structure and geologic history of the region but can also interfere with archaeological/UXO surveys.

7.3.2 Survey-Induced Sources of Noise

Magnetic data are most accurate when the magnetometer survey is conducted systematically with consistent towfish altitude, velocity, and line spacing. Changes in any of these factors may cause false anomalies as the sensor's orientation in the environment changes during the survey. Understanding the survey area's bathymetry and geology can significantly assist in avoiding survey-induced noise. When making accurate magnetic maps, it is vital to maintain a constant altitude above the seafloor or constant depth below the surface. Variations in altitude between adjacent survey lines are difficult to compensate for in data processing and can cause significant errors in the final map.

7.3.2.1 Surge Effects

Magnetometers record less accurate and more inconsistent total field readings when subject to repeated instrument oscillation from being towed close to the surface in rough seas or vessel wakes. Additionally, unwanted/unaccounted motion of the towed magnetometer can cause positional error, which either results in greater uncertainty in the location of anomaly sources or can distort the anomaly patterns, causing challenges in data interpretation. Correction for these effects is generally not possible in recorded data. A surveyor should modify instrument configuration and/or tow parameters to reduce this noise.

7.3.2.2 Survey Vessel Interference

Ensure a sufficient distance between the magnetometer sensor and the survey vessel or survey platform to prevent the sensor from recording magnetic field readings influenced by ferromagnetic materials used in the vessel's construction and magnetic rigging materials or the electromagnetic fields generated by the vessel or platform (i.e., ROV and AUV). Generally, 3–5 times the vessel's length is a common starting point for minimum sensor layback.

7.3.2.3 Power Supply Interference

Electrical generation systems that power a magnetometer create signal noise through electromagnetic field interference and insufficient electrical grounding. Grounding loops can cause detectable electrical currents that can interfere with magnetic data. These currents can cause active corrosion of the magnetic sensor and vessel. As with any towed marine electronic device, ground the magnetic sensor to the seawater at a single point and through a capacitor to prevent direct current flow.

7.3.2.4 Heading Error

The magnetometer sensor's orientation can cause varying magnetic signal readings to the local magnetic field. This type of error can be an inherent characteristic of the magnetic sensor or can be caused by the presence of magnetic material too close to the magnetic sensor or on the sensor itself, such as towing too close to the survey vessel. This can cause striped data patterns evidenced in adjacent survey lines that were transited in opposite directions, or errors in the dataset caused by small changes in the heading that are difficult to eliminate.

7.3.2.5 Dead Zones

Specific angular orientation of the sensor to the Earth's magnetic field can result in the sensor improperly reading the total magnetic field or causing actual gaps in the data. Not all magnetometers have dead zones; however, each instrument's user information will guide the surveyor on how to avoid this situation. Survey transect orientation and instrument configuration should be chosen to prevent the sensor from entering the particular angular region or "dead zone" while collecting data.

7.4 Instrument Configuration and Selection

7.4.1 Total Field Versus Other Types of Magnetometers

Magnetometers can be grouped into scalar (total field) or vector magnetometers. A scalar magnetometer measures only the magnitude of the magnetic field but can do so very accurately since it is insensitive to the motion of the sensor during a survey. Scalar magnetometers are the principal instrument used in marine surveys. Vector magnetometers measure the complete 3D magnetic field vector and are often used in laboratory or observatory settings where the instrument can remain stationary. Scalar magnetometers operate using quantum atomic principles such as nuclear magnetic resonance or electron spin resonance.

7.4.2 Platforms

7.4.2.1 Single Towed Instrument

The most common magnetometer configuration is a single instrument towed by a dedicated tow cable. The use of an altimeter is vital in determining the instrument's altitude. A depth sensor can also provide important positioning information but is not as effective for positioning the magnetometer sensor for optimal data collection.

7.4.2.2 Tandem Tow

Magnetometers can be mated with an SSS or other towed vehicle to simplify the deployment of the sensors, particularly at greater depths. AUVs and remotely operated towed vehicles offer increased position accuracy.

7.4.2.3 AUV/ROV/UAV Mounted

AUVs are configured to have integrated magnetometers and tow trailing magnetometers.

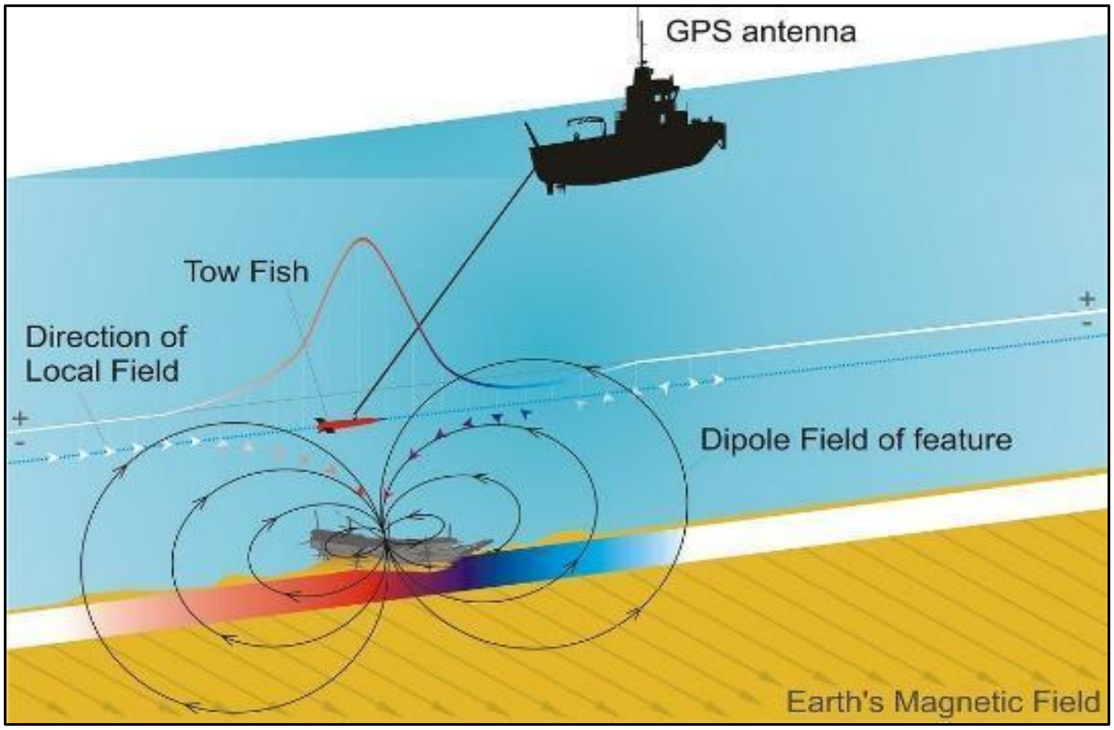

Figure 7.4. A towed magnetometer detecting a seabed-based object graphic: direction of local field and dipole field of feature illustrated.
https://www.assignmentpoint.com/science/geography/magnetic-survey.html

Electromagnetic interference from the vehicle's propulsion motors creates challenges with integrating magnetometers directly into AUVs. These issues are partially addressed by configurations that tow the magnetometer behind the AUV. Similar to the challenges faced with integrating magnetometers into AUVs, ROV-mounted magnetometers may be challenged by proximity to electric propulsion motors.

Aside from being unaffected by sea state, the most significant advantage of an AUV-towed magnetometer over a vessel-towed one is that AUVs can conduct very high-resolution surveys even at great depths due to their superior controls and inertial navigation systems. Vessel-towed high-resolution surveys become increasingly challenging as depth increases due to the required length of tow cable, resulting positional uncertainty, and other factors.

Uncrewed aerial vehicles (UAVs) are now able to carry specially-designed magnetometers. These systems can collect data in shallow water or impassable coastal terrain. Technological advances are leading to the development of smaller, more efficient, capable magnetometer sensors. These sensors can be more easily integrated into USVs, ROVs, AUVs, and UAVs.

7.4.2.4 Configuration

While single magnetometers are typical, two to four magnetometers can be grouped into different configurations to form gradiometers. Standard configurations that are commercially available include:

1) Two sensors, separated by a fixed distance and towed longitudinally. Longitudinal gradiometers created by linking sensors along a tow cable are used by geologists as the sensors can be placed farther apart, making the gradiometer more sensitive to distant magnetic sources.
2) Two sensors, held in a frame a fixed distance apart, are towed so that the sensors are either horizontally or vertically separated. Horizontal gradiometers are well suited to archaeological surveys.
3) Four sensors arranged at the ends of a cross offer independent horizontal, vertical, and longitudinal gradients of the ambient magnetic field. UXO surveys benefit from this sensor arrangement.

An essential feature of horizontal or four sensor gradiometers is their ability, through magnetic gradient data processing, to emphasize nearby magnetic sources and suppress the distant ones, resulting in improved data quality and a more focused survey effort. Depending upon the instrument's configuration, mathematical calculations with each sensor's simultaneous reading can remove noise caused by diurnal variation and more closely pinpoint the ferromagnetic source.

Utilizing two independently towed magnetometers separated by several meters can increase the data density (effectively decreasing the space between lines) without added vessel and crew time. Determining a gradient in this configuration is less precise because the distance between instruments cannot be precisely determined. For example, a planned survey with 20-m line spacing could tow 2 magnetometers 10 m apart to create 10 m line spacing effectively. This approach becomes increasingly more practical (compared to having a rigid frame) as the distance between magnetometers increases.

7.5 Sensitivity and Accuracy

Most commonly available total field magnetometers are sensitive enough to detect magnetic field variations in fractions of a nanotesla. The Tesla (T) is the SI unit for magnetic field strength. Magnetic survey units are typically billionths of a Tesla or nT. An obsolete term for this unit is *gamma.* Higher sampling rates may decrease sensitivity and accuracy.

7.5.1 Coverage Specifications

The smaller and more discrete the item being explored for, the narrower the survey line spacing must be to have confidence that it can be identified in the survey. The strength of the magnetic dipole created by a ferromagnetic object decreases rapidly with the cube of the distance from the object. To adequately plot and thus map the geographic location of anomalies, the magnetic field must be sampled consistently and at a high enough resolution to provide sufficient data for this purpose. Sufficient data density includes the distance between survey lines, altitude of the instrument off the seafloor, and rate of samples collected along each line, which is a function of vessel speed (towfish or AUV), divided by the sampling rate of the instrument.

Line spacing is simply the distance between survey lines, extending the entire survey area length. Altitude is the distance above the seafloor that the instrument is maintained. The optimum altitude for near-surface ferrous target investigation is one-half the survey line spacing. Surveying closer to the seafloor increases the signal from anomalies but does not improve the overall resolution of the final survey unless line spacing is also reduced because anomalies will be missed between survey lines. Smaller targets are likely to be missed when the survey is conducted farther from the seafloor. Because many survey areas contain large boulders, debris, and other obstacles that may damage or hang a towed instrument array, the survey altitude may need to be adjusted for practical purposes to avoid risking damage to or losing the instrument. It is preferable to have a consistent altitude than to have a constantly varying altitude to avoid obstacles.

The following examples illustrate the interplay between sensor altitude and line spacing for small UXO or archaeological object surveys. The smallest object to produce a one nT detectable anomaly (typical detection threshold for a very "quiet" location) in a survey with 6-meter altitude and 6-meter line spacing would have to be at least 5.9 kg (in ferrous content mass). If the local noise level necessitates that the minimum detectable anomaly threshold increases to 10 nT (typical for most locations), the most negligible detectable mass also increases to 59 kg. Since line spacing is usually greater than altitude in most surveys, this minimum mass increases even further. For a survey conducted with 20-meter line spacing and 6-meter altitude, and a worst-case scenario where the object is located between 2 survey lines, the minimum 1 nT anomaly detection would require a 22.7 kg object to create a 10 nT anomaly. At the same time, lowering the recommended altitude to 3–4 meters would increase the resulting anomaly by nearly 6–8 times (making it easier to detect); or correspondingly reduce the minimum detectable mass by two times if the anomaly threshold should remain the same), again making it far easier to detect. The main goal in equipping magnetometers with altimeters is to enable the operator to maintain a lower altitude, which significantly increases the chances of success for small-object surveys.

Finally, sample density is determined by dividing the instrument's speed of the instrument over the bottom by the rate at which the sensor is making magnetic field measurements. For example, for anomaly detection, the data sampling rate of the instrument should be greater than or equal to 4.0 Hz (or 4 cycles per second) with the vessel traveling no more than 4–5 knots to ensure sufficient data point density. Magnetic field readings should ideally be collected approximately every 0.5 meters and no more than 1 meter along a survey line (BEOM, 2020). Some recently developed magnetometers have the ability to sample at rates as fast as 1000 Hz, which is particularly helpful for high speed survey platforms such as UAVs. Surveyors have found that these sampling rates introduce interference at the 50/60 Hz frequency at which most electrical devices operate. Users should be aware of this interference and utilize a frequency filter when processing data.

In addition to acquiring data on equally spaced and parallel primary survey lines, surveyors should seek to record data on tie lines perpendicular to the primary survey lines at 500-m intervals. Tie lines provide another means for eliminating environmental noise caused by diurnal variation during data processing. Ideally, tie lines should be collected together as a set in close time. This will help reduce the effect of diurnal variation on the different tie lines and in turn, help the data analysis.

Other considerations that affect coverage include line orientation, sea state, the direction of the survey to avoid dead zones, ability to maintain a consistent altitude above the bottom, the rugosity of the seafloor topography, and ability to follow seafloor structures. For example, if the survey aims to identify a geologic feature, orienting the survey lines perpendicular to the feature may be more valuable than orienting north-south. Planning survey lines to be roughly parallel to the coast may make it easier to maintain constant altitude in areas where seafloor slopes significantly away from shore. Surveyors need to be aware that transiting planned lines going with the prevailing current may cause the magnetometer altitude to be different on adjacent lines running against the current. Inconsistent altitude caused by this situation may result in a striped data pattern similar to that caused by heading error. Adjust the tow cable length to maintain a consistent altitude. Ship information is essential in assessing and interpreting variance in altitude, and identifying variance from “porpoising” and tugging (which are effects of sea state) visible in data.

7.6 Resolution/Line Spacing Based on Survey Objectives

7.6.1 Unexploded Ordnance

For surveys whose primary objective is to identify UXO, enact survey line spacing of 5 m. The ferromagnetic mass of many discrete munitions of explosive concern is small and the additional effort to find these objects and safely remove them from a survey area warrants the additional survey time and cost. Survey altitude should be kept as low as possible; 2–3 m is ideal, and 3–4 m is adequate. A horizontal gradiometer with a typical sensor spacing of 1–3 m is especially useful in such surveys, as it eliminates the effects of diurnal variation and focuses on smaller near-surface sources.

7.6.2 Archaeological Survey

Survey line spacing for archaeological site detection should be driven by the need to sample the project or survey area (for example, survey to locate all archaeological resources within an area to be dredged) or by the intention of finding a particular object (for example, as in the search for a shipwreck that was likely lost in a particular area). When conducting a general survey for the purposes of sampling the project or survey area, survey line spacing should be no greater than 30 m with an altitude of no greater than 6 m. This initial search methodology is an example where the approach of towing two separate magnetometers separated by 5–10 m becomes exceptionally useful since it dramatically improves the chances of encountering something. Once a discrete anomaly is detected, perform a narrower line spacing survey around the anomaly in a “boxing” fashion. One-third to one-half of the original line spacing would be appropriate. A horizontal or vertical gradiometer with a typical sensor spacing of 1–3 m is especially useful in such surveys, as it eliminates the effects of diurnal variation and highlights smaller near-surface sources.

When conducting a survey targeting the identification of a particular archaeological site, a survey line spacing narrow enough to sense the expected ferromagnetic material of the wreck site is necessary. In some cases, such as when searching for ancient wooden-hulled shipwrecks containing small magnetic components, line spacing of 5 m with an altitude of no greater than 3–4 m may be necessary, or the wreck site could be missed by the survey entirely. Three m altitude would produce eight times the signal of a 6 m altitude and detect targets half the size. Wooden-hulled wreck sites with only a tiny quantity of ferrous material should be surveyed similarly to UXO sites—with the lowest practical altitude, to maximize the signal and overall resolution. See column "Mag Special Order" in Table 7.1 for survey parameters.

7.6.3 Geologic Mapping

For geologic mapping or mineral detection, perform surveys using wider survey line spacing than used for archaeological surveys, and interpolate the resulting data across longer distances. Suitable line spacing may be increased to 150 m, which is an example of a situation where a large-span gradiometer can be useful, such as a longitudinal gradiometer with a 50–150 m separation between sensors. It eliminates the effects of diurnal variation and focuses on deeper/more distant sources. See column "Mag Order 1" in Table 1 for survey parameters.

Table 7.1. Survey parameters delineated by the magnetic survey objective.

Survey Type	Mag Order 1 – only useful for geological surveys and may not be used for cultural surveys	Mag Special Order – useful for both geological, archaeological, and UXO surveys
Area description	General description of geologic features is desired (exploration)	Area characterized is critical
Magnetic field sensitivity	Should be 1.0 nano-Tesla [nT]) or less	Should be 1.0 nT or less
Background noise	Should not exceed a total of 3.0 nT peak to peak	Should not exceed a total of 3.0 nT peak to peak
Data sampling rate	1 Hz	Should be equal to or greater than one sample per meter of distance traveled along a survey line.. Higher survey speeds require higher sampling rates. 4 knots would require a minimum 2 Hz sampling rate.
Instrument altitude	One-half the survey line spacing.	Not to exceed 6 meters above the seafloor.

Tow speed	As fast as practical given instrument configuration.	Tow speed should not exceed sampling rate.
Timing	UTC	UTC
Positioning	+/- 10 meters	+/- 2 meters
Line spacing for feature/anomaly detection	150 meters	Not to exceed 30 meters with 500 meter tieline spacing.
Line spacing for anomaly search	N/A	Additional parallel lines at 10-15 meters to characterize anomaly, with additional perpendicular lines, with one line at least passing through the likely anomaly center.
Data quality	Low sea state, little noise/interference, no earth-directed geomagnetic storms, Kp less than 5.	Low sea state, little noise/interference, no earth-directed geomagnetic storms, Kp less than 5.

7.7 Validation

Before beginning a magnetometer survey, deploy the instrument for a short test to visually assess the incoming data in a graphical format. This ensures that magnetic field readings are not compromised by noise. Validation cannot be accomplished while the instrument is on the deck of the survey vessel due to the vessel's influence on the sensor. Deploy the magnetometer just below the surface or into the water column at an altitude sufficiently above the bottom to be outside the effect of potential seafloor anomalies. The instrument's layback should be well beyond the potential influence of the vessel. Depending upon its construction characteristics, the recommended layback distance is between three to five times the vessel's length. Layback from a steel-hulled vessel will need to be greater than a fiberglass hull. The surveyor reviews the data for a total magnetic field reading consistent with the average total field reading found at that geographic location. If present, signal noise as described above should be identifiable in graphically displayed data. The surveyor would then attempt to eliminate as much noise as possible. Digital filtering is not usually effective; noise elimination steps might include grounding equipment or changing the towbody to improve stability.

Further validation may be performed in seeking to find munitions of explosive concern. Detecting the anomalies created by these generally small items is particularly difficult. To ensure optimal instrument performance, surveyors may use test objects of similar characteristics to validate survey methodology and proper equipment function. The results of test data collection around the test targets can ensure that the magnetometer is detecting even the tiny anomalies at a certain distance from the test target. Similarly, surveyors seeking archaeological resources may find it appropriate to conduct a confidence check of their equipment. This consists of a defined trackline survey over a known archaeological resource to review the instrument's performance against an item of known characteristics.

Magnetometers equipped with a depth sensor must have that sensor zeroed to the water's surface before data collection to ensure proper readings. This requires a short (10-15 min.) adjustment period to achieve thermal equilibrium with local water temperature before depth calibration can be performed. Configure magnetometer acquisition software to interpret the depth sensor results for either fresh or saltwater. Adjust similar fresh/saltwater configuration settings for a magnetometer equipped with an altimeter.

7.8 Data Management

Management of magnetometer data is necessary for efficient use, future access, and validation of analytical and interpretative results. Archive the raw and processed data to ensure preservation of data to the fullest extent.

For specific details and guidelines associated with minimum magnetometer data requirements and management (recommended file formats, metadata, data archival, etc.), please see Chapters 1.1 through 1.6 and specifically Chapter 1.6.7 and the Chapter 1 appendices.

7.9 Processing

7.9.1 Filtering of Time-Series Data

Following data acquisition, use the acquisition software to graphically review the data to remove anomalous readings caused by intermittent noise. This noise generally is a few readings far beyond the range of surrounding readings and graphically presents as a spike in the data. At the surveyor's instruction, the acquisition software replaces anomalous readings with readings interpolated from the readings on either side of the spike in the time-series data.

7.9.2 Removal of Background Field

Removal of heliophysical (solar interaction with Earth's magnetic field) noise is a critical step toward ensuring proper data interpretation. Do this by subtracting time synchronized magnetic field readings from a base station, magnetic field observatory, or mathematical model of the Earth's magnetic field from the survey data. The formula is:

$$B(\text{corrected}) = B(\text{survey}) - B(\text{base station}) + \text{datum}$$

The datum is a constant number for the entire survey and is required to align the absolute value of B (corrected) with the approximate absolute value of the local field. This value is determined from the International Geomagnetic Reference Field model. Without the datum correction, the resulting B (corrected) is known as the residual field.

7.9.2.1 Base Stations and Magnetic Field Observatories

Dedicated base station magnetometers deployed as part of the survey methodology are the best way to record data to correct diurnal variation at the survey site. The base station should be deployed within the survey area or within a few km of the survey area. Some base station magnetometers can be deployed underwater with an acoustic release to retrieve the instrument. The greater the distance the base station is deployed from the survey area, the less effective its data are in correcting for diurnal variation. A base station sited a given distance on an east-west axis provides more usable data than one located the same distance away on a north-south axis.

It is essential to compare the base station's underlying geology to the geology in the survey area. For example, a base station sited over igneous rock will record substantially different magnetic field variation due to diurnal variation than the actual influence of diurnal variation's effect on a magnetometer surveying a limestone environment. The base station should be deployed in an area of low magnetic gradient away from sources of human interference such as industry or vehicular traffic.

The magnetic observatory data reporting network INTERMAGNET provides time-stamped geomagnetic field readings that can be used to correct for diurnal variation (GitHub Intermagnet, n.d.). Observatory data, even hundreds of km from the survey area, can be used as long as the observatory is located above geology similar to that found in the survey area. Surveyors should choose the observatory closest to their survey area. Unfortunately, few observatories in North America are adjacent to the coastline.

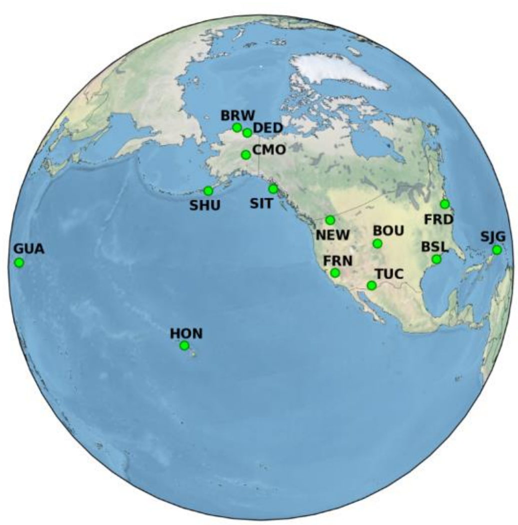

Figure 7.5. Magnetic observatories in the United States operated by USGS. https://www.usgs.gov/media/images/geomag-observatory.

7.9.2.2 Gradient

The magnetic gradient is the rate of change of the magnetic field through space. While the magnetic field created by a magnetic dipole decreases in magnitude with the cube of the distance from the dipole, the magnetic gradient created by the dipole will decrease even more rapidly to the fourth power of the distance. This makes the gradient very useful for distinguishing between small, nearby magnetic sources (such as ferrous objects) and large, distant sources, such as geological structures.

Although the total magnetic field is a scalar quantity, the gradient of the total field is a three-dimensional vector. The direction in which it is measured is vital. The gradient is most commonly measured by simultaneously measuring the entire field with two or more sensors, which must be synchronized and accurately positioned to each other. Some manufacturers have developed gradiometers with three or more magnetometers, each arranged in a tow vehicle with a specific orientation. These devices can measure all the vector components of the gradient and provide highly accurate locational information for anomaly sources. Gradiometers with three or more sensors can be used for archaeological surveys but are more likely to be employed for UXO detection. Use a four-sensor gradiometer of a specific configuration to directly measure the total magnetic gradient (also known as analytic signal), effectively bypassing much of the data processing and delivering the final product in real-time. The solar influence on the Earth's magnetosphere happens over a vast distance and does not significantly affect local magnetic gradients. For this reason, magnetic gradient data do not need correction for diurnal variation.

7.9.3 Anomalies

7.9.3.1 Anomaly Detection from Single Line Data

Surveyors seeking to locate discrete anomalies caused by archaeological resources or UXO often use graphical representations of single survey line data (also known as profiles) (Figure 7.3) to identify anomalies as a first step. Most magnetometer data acquisition software provides this data review option. To identify anomalies, the surveyor looks for high intensity, short duration changes to background magnetic field readings. The characteristics of the anomaly in this data display provides some information to characterize the anomaly's source, but it is not an effective means of precisely localizing the source object's location. GIS display of multiple line anomalies can give a better, two-dimensional approximation of a source position (Figure 7.6). Additional data sources, such as SSS records or high-resolution bathymetry combined with the line anomalies in a GIS, greatly assist with data analysis.

7.9.3.2 Anomaly Detection from Contoured Data

Magnetometer data visualization is best accomplished through contouring the recorded magnetic field readings following the removal of diurnal variation. See Figure 7.6 for an example. Since magnetometers only record the magnetic field readings at the sensor's location, you must interpolate data between readings along the survey line or between two lines. A process known as gridding is used to create a regularly spaced numerical matrix representing the data in two dimensions. The minimum curvature algorithm is the preferred interpolation process for magnetic data (Briggs, 1974). Machine contouring using minimum curvature gridded data provides a more accurate anomaly location represented by the most significant changes in the magnetic field.

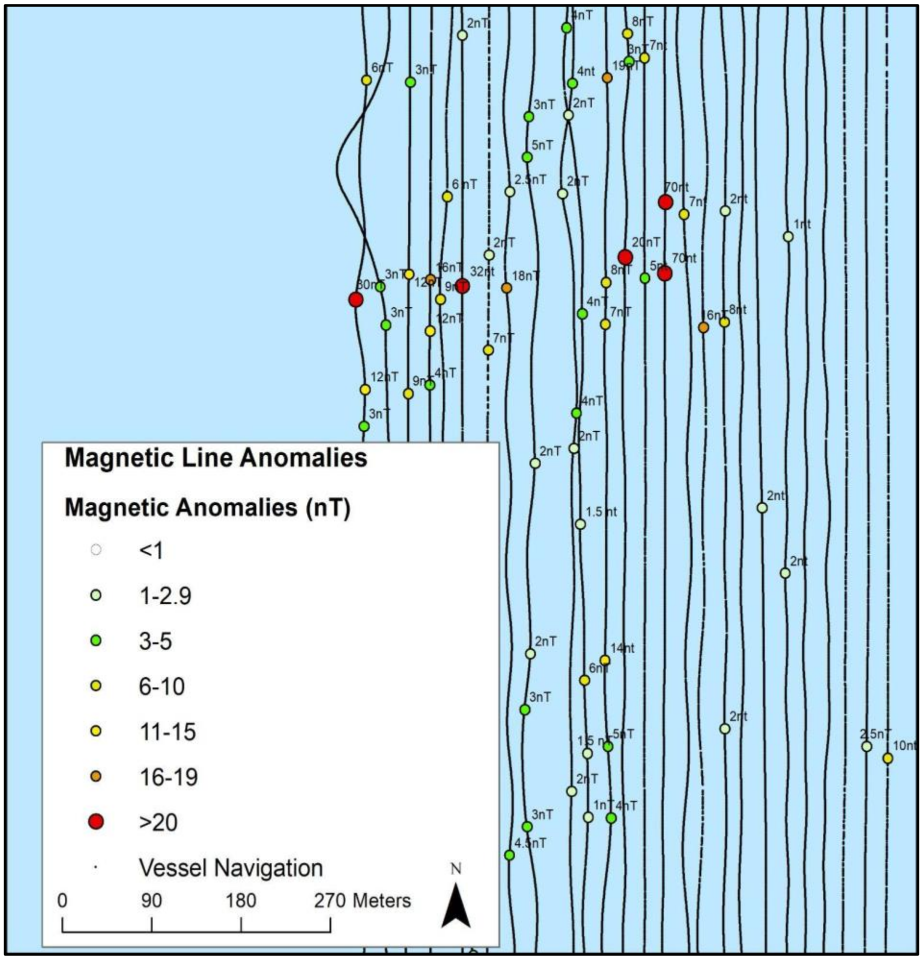

Figure 7.6. Line anomaly graphic: GIS display of line anomalies detected during an archaeological

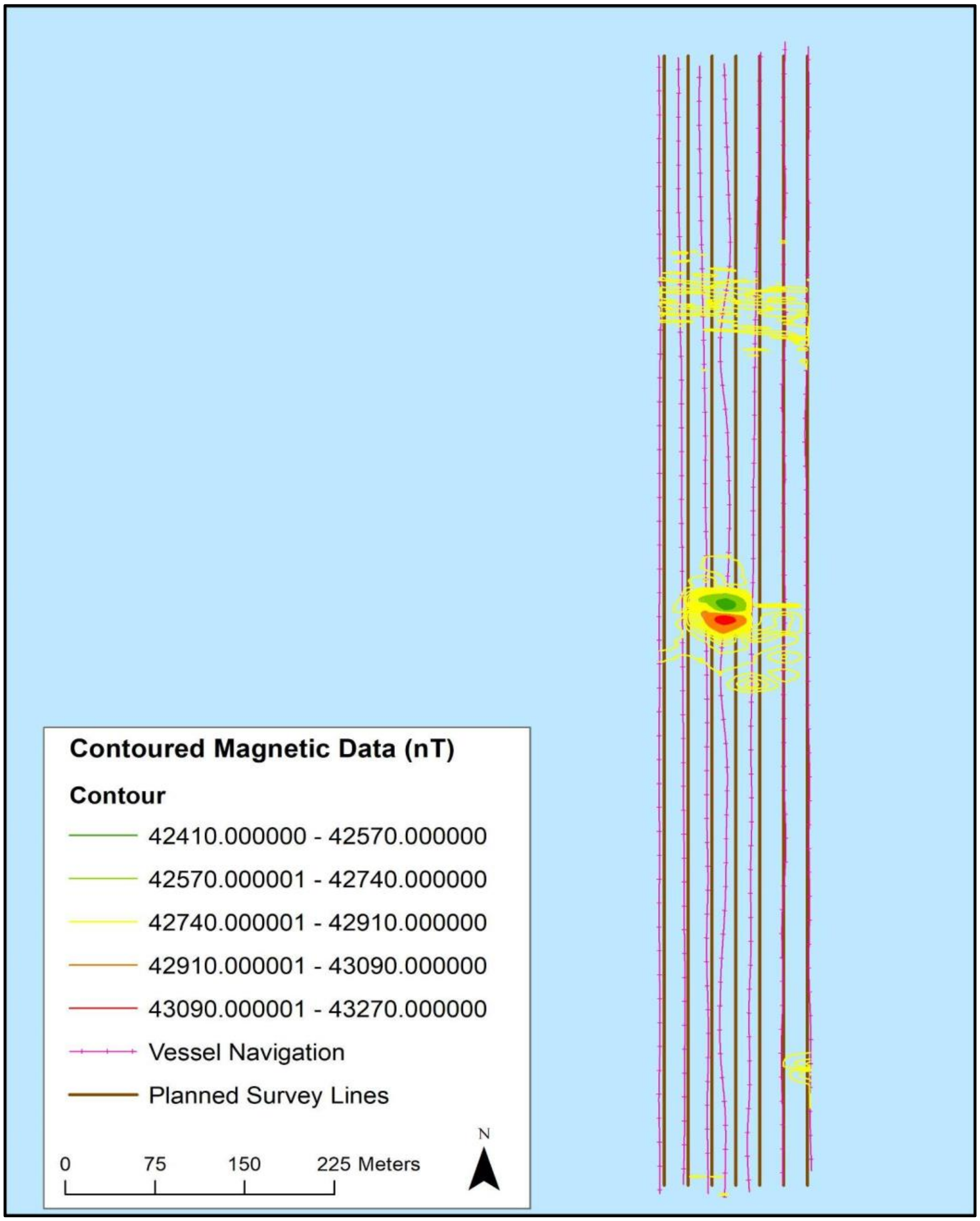

Figure 7.7. Contoured magnetic data: GIS display of contoured magnetic data from an archaeological survey focused on a buried wreck. Twenty-meter survey line spacing detected the wreck over several lines. The contoured data reveals the location of concentrated magnetic material. Image by Matthew Lawrence, NOAA.

7.10 References

BOEM. 2020. "Guidelines for Providing Archaeological and Historic Property Information: Pursuant to 30 CFR Part 585."

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Appendix A - Applicable Standards

The use of applicable standards is key to reusability, clarifies ambiguous meanings and their metadata can reduce redundancy and improve usability.

Applicable Data Standards (attribute, accuracy, quality, archive, exchange (transfer, syntax), service (distribution))

- International Organization for Standardization (ISO)
  - ISO 8601 (date and time)
  - ISO 6709 (latitude, longitude and depth)
  - Chapter 6 from IHO S-44 includes minimum metadata (https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.0.0_EN.pdf)
- American Standards Institute (ANSI)
  - ANSI INCITS 30-1997 (R2008) (date and time)
- Industry
  - SEG-Y (seismic)
- Federal
  - NIST FIPS PUB 4-2
  - FGDC Document Number FGDC-STD-007.5-2005 - Geospatial Positioning Accuracy Standards Part 5: Standards for Nautical Charting Hydrographic Survey

Applicable Data Guidelines / Protocols

- Industry
  - Lurton, X., Lamarche, G. 2015. *Backscatter measurements by seafloor-mapping sonars*. Guidelines and Recommendations. https://geohab.org/wp-content/uploads/2018/09/BWSG-REPORT-MAY2015.pdf.
- Academia
- Federal
  - BOEM. 27 May 2020. "Guidelines for Providing Archaeological and Historic Property Information: Pursuant to 30 CFR Part 585." https://www.boem.gov/sites/default/files/documents/about-boem/Archaeology%20and%20Historic%20Property%20Guidelines.pdf
  - U.S. Department of the Navy. n.d. "Naval History and Heritage Command Methods and Guidelines for Conducting Underwater Archaeological Fieldwork." https://www.history.navy.mil/research/underwater-archaeology/sites-and-projects/Guidelines.html.

Applicable FGDC-endorsed Metadata Standards

- INCITS 453 - 2009, Information technology - North American Profile of ISO 19115:2003 - Geographic information - Metadata Industry-standards
- Federal Geographic Data Committee. FGDC-STD-001-1998. Content Standard for Digital Geospatial Metadata (revised June 1998). Federal Geographic Data Committee. Washington, D.C
- ISO 19115-1:2014 Geographic information—Metadata—Part 1: Fundamentals
- ISO 19115-2:2009 Geographic information—Metadata—Part 2: Extensions for imagery and gridded data
- ISO 19139:2007 Geographic information—Metadata—XML schema implementation
- ISO 19157:2013 Geographic information—Data Quality
- ISO/TS 19157-2:2016 Geographic information—Data quality—Part 2: XML schema implementation
- ISO 19115-3:2016 Geographic information—Metadata—Part 3: XML schema implementation for fundamental concepts

Appendix B - Data Standard | Data Structure

Magnetometer Attributes

Name	Format (Data Type)	Definition	Applicable Standard(s)
Latitude	String (10)	Y coordinate (Latitude) of anomaly in original datum/projection; Latitude is a number preceded by a sign character: A plus sign (+) denotes northern hemisphere or the equator and a minus sign (-) denotes southern hemisphere; in Decimal Degrees to six decimal places; +/-DD.DDDDDD	FGDC-STD-001-1998; ISO 6709
Longitude	String (11)	X coordinate (Longitude) of anomaly in original datum/projection; Longitude is a number preceded by a sign character: A plus sign (+) denotes east longitude or the prime meridian and a minus sign (-) denotes west longitude or 180° meridian (opposite of the prime meridian); in Decimal Degrees to six decimal places +/-DDD.DDDDDD	FGDC-STD-001-1998; ISO 6709
Horizontal Datum	String (50)	Horizontal reference frame (e.g., NAD83, WGS-84, etc.) for water depth, Original horizontal datum and units (meters, feet, etc.) used during data acquisition	
Vertical Datum	String (50)	Vertical datum (e.g., MLLW, NAVD88, etc.) for water depth	
Coordinate System		Information about the spatial reference frame used. Geographic or Projected.	
Date		year-month-day; YYYY-MM-DD, exact date the reading was recorded, in UTC Time	ISO 8601
Time		hh:mm:ss; exact time the reading was recorded, in UTC	ISO 8601
Instrument	String (50)	Instrument type	
Raw Magnetic Readings (Amplitude) for each instrument,	Double (8)	Peak signal strength (gammas), where 1 gamma = 1 nano Tesla	

and indication of which instrument the reading is from			
Reference field used		Reference field used (if reporting anomaly data)	
Gradiometer Altitude	Double (8)	Definition: Sensor altitude meters, height of sensor (in meters) above the seabed	
Survey Line Number/Name	String (30)	Survey line ID number in which anomaly was recorded/observed	
Anomaly ID:	String (30)	Unique feature ID assigned during survey	
Comment	String (250)	Additional comments or recommendations (e.g., related to survey conditions, interpreted anomaly, notable uncertainties, etc.)	
Contractor | Company | Organization | Agency	String (50)	Name of contractor or agency that collected the data	
Duration	Double (8)	Along-track duration (in meters) of anomaly signal	
Magnetometer Type	String (50)	Specific type of scalar or vector magnetometer	
Project Name | Campaign Name	String (100)	Name of project/cruise/study	
Sensor Configuration	String (50)	Such as a single instrument total field magnetometer or multiple sensors in a gradiometer configuration	
Signal Type	String (2)	Anomaly signal type: M (unspecified monopole), M+ (positive monopole), M- (Negative Monopole), D (Dipole), MC (multi-component)	
Survey Number ID	String (100)	Specific numerical- or letter-based designation a contractor may give to an individual survey or reference in a survey report	