NOAA Technical Memorandum NOS CS 3

MULTIBEAM SONAR DATA ACQUISITION SYSTEMS: A SIMPLIFIED CONCEPTUAL MODEL

Silver Spring, Maryland
November 2003

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

The Office of Coast Survey (CS) is the Nation's only official chartmaker. As the oldest United States scientific organization, dating from 1807, this office has a long history. Today it promotes safe navigation by managing the National Oceanic and Atmospheric Administration's (NOAA) nautical chart and oceanographic data collection and information programs.

There are four components of CS:

The Coast Survey Development Laboratory develops new and efficient techniques to accomplish Coast Survey missions and to produce new and improved products and services for the maritime community and other coastal users.

The Marine Chart Division collects marine navigational data to construct and maintain nautical charts, Coast Pilots, and related marine products for the United States.

The Hydrographic Surveys Division directs programs for ship and shore-based hydrographic survey units and conducts general hydrographic survey operations.

The Navigation Services Division is the focal point for Coast Survey customer service activities, concentrating predominantly on charting issues, fast-response hydrographic surveys and Coast Pilot updates.

NOAA Technical Memorandum NOS CS 3

MULTIBEAM SONAR DATA ACQUISITION SYSTEMS: A SIMPLIFIED CONCEPTUAL MODEL

LCDR Jeff Brown, NOAA
LCDR Guy Noll, NOAA

October 2003

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT
OF COMMERCE
Donald Evans, Secretary

National Oceanic and
Atmospheric Administration
Conrad C. Lautenbacher, Jr.,
VADM USN (Ret.), Under Secretary

National Ocean Service
Richard Spinrad, Ph.D.
Assistant Administrator

Office of Coast Survey
Captain Roger L. Parsons

Coast Survey Development
Laboratory
Bruce B. Parker, Ph.D.

NOTICE

Table of Contents

Figures

Introduction

The purpose of this paper is to provide a conceptual framework of a multibeam sonar acquisition system from seafloor measurement to useable information. The framework considers the functional elements from sonar ping to data processing necessary to acquire multibeam sonar information referenced to earth-based coordinate systems.

Measuring water depth by timing a packet (pulse) of sound waves as they travel from a shipborne transmitter, reflect from the seabed, and travel back to a shipborne receiver is a technique that has been used for many years. The single-beam echo sounder, developed in the 1930's and still in wide use today, uses sound waves propagating vertically downward and returning vertically upwards to give the depth directly beneath the vessel. A series of lines with soundings taken at discrete intervals at a specified horizontal spacing constitutes a conventional survey of depths in an area. Conventional surveying with a single-beam echo sounder has the limitation that no quantitative depth information is obtained between survey lines or soundings.

Depth-measuring sonar systems (echo sounders) with multiple beams are now available. These systems employ multiple sound waves propagating at angles, which vary from vertical to nearly horizontal. The sound waves impact the seafloor in a pattern called a swath. The width of the swath may be equal to many times the water depth depending on the sonar design, water depth and bottom slope. Overlapping swath coverage makes it possible to obtain quantitative depth information for 100% of the bottom in the survey area.

Full seafloor coverage requires precise and accurate location of the soundings to avoid feature distortions and provide repeatability. Multibeam sonar sounding measurements must be corrected for the sound transmission characteristics of the water, adjusted for the vessel's motion during the sound transmission, and located in an earth-based reference system to create accurate and repeatable information. Integrating simultaneous measurements from sounding, position, and movement sensors into a common acquisition/processing stream allows useful information to be derived about the seafloor bathymetry and characteristics. In addition, planning of the survey and management of the large datasets produced are critical to conducting a successful mapping project.

The conceptual model encompasses sensor and information technology requirements to derive repeatable, accurate information from real-world observations of the seafloor. This model does not address the personnel skills or quality control procedures necessary for a successful mapping project.

A multibeam sonar acquisition system has seven conceptual subsystems. These are –

1. In-the-water measurements - sonar and sound velocity measurements
2. Transducer location derived from vessel location - horizontal positioning (GPS, other), vertical positioning (dynamic draft and tides information)
3. Transducer motion derived from vessel motion and attitude - heading, velocity, and heave, roll, pitch (HRP)
4. Survey control - line planning, line steering, coverage assurance
5. Data acquisition - acquisition hardware/software
6. Data management - data management/transfer system
7. Data processing - software to integrate and analyze the collected data

The first three subsystems pertain to the collection of real-world observations from a floating rigid-hull platform that is necessary to derive and locate seafloor measurements. Survey control organizes the collections and provides real-time feedback and direction for the operation of the platform. Data acquisition and management involve recording the observations, making them available for analysis and protecting them from loss.

Thus, a multibeam sonar acquisition system consists of many sensors and systems beyond the actual sonar. It is an integration of subsystems that sense, correct, collect, archive, and process the real-world observations of the seafloor. This document will provide a broad conceptual model for a multibeam sonar acquisition system.

In-the-Water Measurements

In-the-water measurements consist of the sonar sampling and measurements of the physical properties of the water column. The physical properties are used to determine sound velocity variations in the water column in order to mathematically correct the sonar sound pulse's path between the platform and the seafloor.

In-the-water measurements consist of three subsystems:

1. Multibeam echo sounder
2. Sea surface/transducer head sound velocity sampling
3. Water column sound velocity profile

A multibeam echo sounder system consists of a transducer array, transceiver unit, and operating/control unit. The system transmits sound pulses across a swath perpendicular to the vessel's heading. The return echoes are analyzed to determine the round-trip travel time to the seafloor and back (generally named "Two-Way Travel Time"). The travel time is used to calculate the distance from the sonar to the seafloor at the angle the pulse was transmitted. Some systems allow a small amount of return information around the mathematically determined bottom to be recorded. These samples, sometimes called snippets, can be analyzed to derive additional information, such as probable sediment type, from the sound pulse's interaction with the seafloor. Collection of return echo information for the entire water column is being implemented by some vendors, which will allow suspended targets to be recorded.

Mutibeam echo sounders are designed to balance many competing requirements. Horizontal and vertical resolution, depth range, acquisition speed, and swath coverage are some of the requirements that determine the design of a sounder. No sounder is optimum in all areas. Sounders are selected by vetting the various vendor systems against the project requirements, such as precision and accuracy, as well as the water depth and expected bathymetry of the area to be mapped. In general, the echo sounders are grouped into shallow water systems and deep water systems, with the boundary between the two at approximately 100 meters depth.

Sound velocity (SV) at the transducer array and its variation in the water column must be known to correct the sonar's sound pulse travel time. Ray trace calculations of the refraction (bending) of the pulse, using Snell's law, determine the location where the pulse impacted the seafloor. Without sound velocity correction, the echo sounder's data would contain large horizontal and vertical errors due to refraction. Multibeam echo sounders are more sensitive to refractive error than single beam sounders due to the acute incident angle of the sound waves on the interface between vertical layers of different water densities. Water column sound velocity is modeled by dividing the column into discrete layers with similar physical properties determined from a conductivity-temperature-depth (CTD) cast. CTD casts are taken periodically in the survey area. The project area drives the frequency of CTD casts. Tidal action, fresh water intake, and coastline irregularity impact the location and timing of the casts. New casts are needed whenever the temperature or density of the water column changes during survey operations.

Sound velocity at the transducer head is measured using a real-time sensor to calculate the sound velocity at the specific depth of the sonar continuously during sonar operation. The measurement is linked to the sonar transceiver to electronically steer (aim) the sound pulse during transmission from flat-faced sonar transducer designs.

Vessel Location

Vessel location, both horizontally and vertically, must be known at the time of the sound transmission and echo reception. The horizontal position is measured in relation to a geographic coordinate system. The vertical position is measured against the tidal or other vertical datum.

Horizontal position is generally obtained using the main frequency of the Global Positioning System (GPS). Differential corrections, broadcast from U.S. Coast Guard beacon sites, are applied to the GPS position to increase accuracy when possible. Temporary shore receivers are installed at geodetic reference marks to transmit corrections in areas where USCG coverage is not available, or for higher-accuracy dual-frequency observations. Uncorrected GPS position can be used if it meets the project requirements, although horizontal accuracy will be compromised. Hydrographic surveys for nautical charts of critical navigation areas require differential GPS positioning to meet horizontal error allowances.

Vertical location is determined relative to the local water-level datum, generally to the mean lower low water (MLLW) tidal datum. Vertical location is determined by applying zoned tidal corrections to the soundings computed from the multibeam swath. Tide predictions are used to determine initial correctors for preliminary processing of the soundings. Water-level observations acquired during mapping operations are used for the final corrections. The observations compensate for water-level variations (such as those induced by weather) from predicted tides. The observations are taken at long-term tide stations or at new tide gauges established specifically for the project, which are linked to the tidal datum by analysis of 19-year tidal epochs. Research is underway to relate the tidal datum to the ellipsoidal model used with GPS positioning. GPS elevation could then be used to determine a moving vessel's vertical position in relation to the seafloor in real-time. This research may allow tidal observations to be conducted independent of the mapping operations eliminating the need to operate tide stations during sonar data collection.

Draft (the portion of vessel below the water) variation due to vessel fuel and load changes, and settlement and squat of the hull caused by the vessel's movement through the water affects the vessel's vertical location as well. Together, these effects are known as dynamic draft. Dynamic draft's variation and its effect on the platform's operating characteristics must be taken into account to obtain precise and accurate seafloor information in near-coastal areas or when decimeter vertical accuracy is required. Linkage of the GPS ellipsoid to the water-level datum will make it easier to compensate for these effects using real-time kinematic (RTK) GPS observations to vertically position the transducer.

In sum, accurate and precise horizontal and vertical location of the depth requires accurate and precise location of the vessel during the sounding. Project objectives will determine the required accuracy and precision, the acceptable positioning systems, and the error sources that need to be taken into account. Instantaneous vessel location in four-dimensions, X, Y, Z, and Time, is the root of the calculations that relate the corrected sounding to the horizontal and vertical coordinate systems.

Vessel Motion and Attitude

Boats, ships, or anything else on or in the water are in constant motion. These movements alter the vessel's attitude, and thus the horizontal and vertical location of anything fixed to the vessel. The attitude of the vessel must be measured and corrected to millisecond accuracy to assure the precision of the soundings. The vessel movement can be decomposed into vertical, rotational, and horizontal components, namely heave, roll, pitch (HRP), and heading (See Figure 1). On smaller vessels, the accelerations caused by wave impacts (waves can move the vessel sideways) and vessel steerage (vessel heading fluxuates rapidly) in the horizontal plane affect the magnitude of the vertical and rotational components and should also be measured.

A reference point must be established on the platform at or near the center of motion. This point is normally designated with a granite monument or other fixed structure that has been surveyed and precisely located during a drydock. Offsets to GPS antennae, sonar transducers, heave, roll and pitch sensor (see Fig. 1), and gyro compasses are measured from this point, allowing each sensor's data to be adjusted to the common reference point.

The platform's movement in the horizontal plane is primarily specified by the heading and speed. Heading is the instantaneous fore-aft (longitudinal) orientation of the platform in relation to geographic North. Heading is directly related to the orientation of the sonar transducer, which is installed so that the swath is transmitted perpendicular to the vessel's longitudinal axis. Note that heading is equivalent to instantaneous vessel yaw (horizontal rotation of the vessel about the vertical axis).

Vessel Course Made Good (CMG), which is the movement through the geographic plane, is calculated from successive GPS positions. Vessel course impacts line steering but not individual soundings. Speed Made Good (SMG) is the rate of change of the vessel's position. It is usually determined from successive GPS positions. The number of pings impinging on a given sea floor area (ensonification) is a function of vessel SMG, water depth, sonar angular resolution, and sonar ping rate. The ensonification quantity subsequently determines the along-track (the direction of vessel movement) resolution of the soundings.

Heave is the instantaneous vertical change of the vessel's position. Roll is the angular rotation about the transducer's longitudinal axis. Pitch is rotation about the athwartship axis. Together, HRP and heading define the vessel's orientation in space and therefore the sonar's attitude at any given instance. Heave is measured to compensate for wave action effects on the vessel's vertical location. Roll is measured to determine the transducer array's center beam orientation relative to directly beneath the vessel (nadir). Generally, roll must be known at both sonar transmission and reception to within 0.05 degrees and 10 milliseconds to adequately determine geographic XYZ in shallow water. Pitch is measured to determine the orientation of the sonar echo's projection fore or aft relative to nadir. After the multibeam sonar itself, the sensor(s) used for heading, heave, roll, and pitch are typically the largest cost to the user. They are critical, however, because the sonar's attitude will affect the location of the sound striking the seafloor relative to the ship's fixed position.

Instantaneous heave, roll, and pitch (HRP) are measured by accelerometers aligned to sense specific degrees of movement. A single sensor unit usually provides heave, roll, and pitch measurements. Integrated units that combine HRP with heading, known as inertial reference units, are also available. Some also incorporate GPS receivers for positioning to create an inertial navigation system. The sensor unit is mounted at or near the vessel's center of motion to simplify application of corrections to the sonar observations.

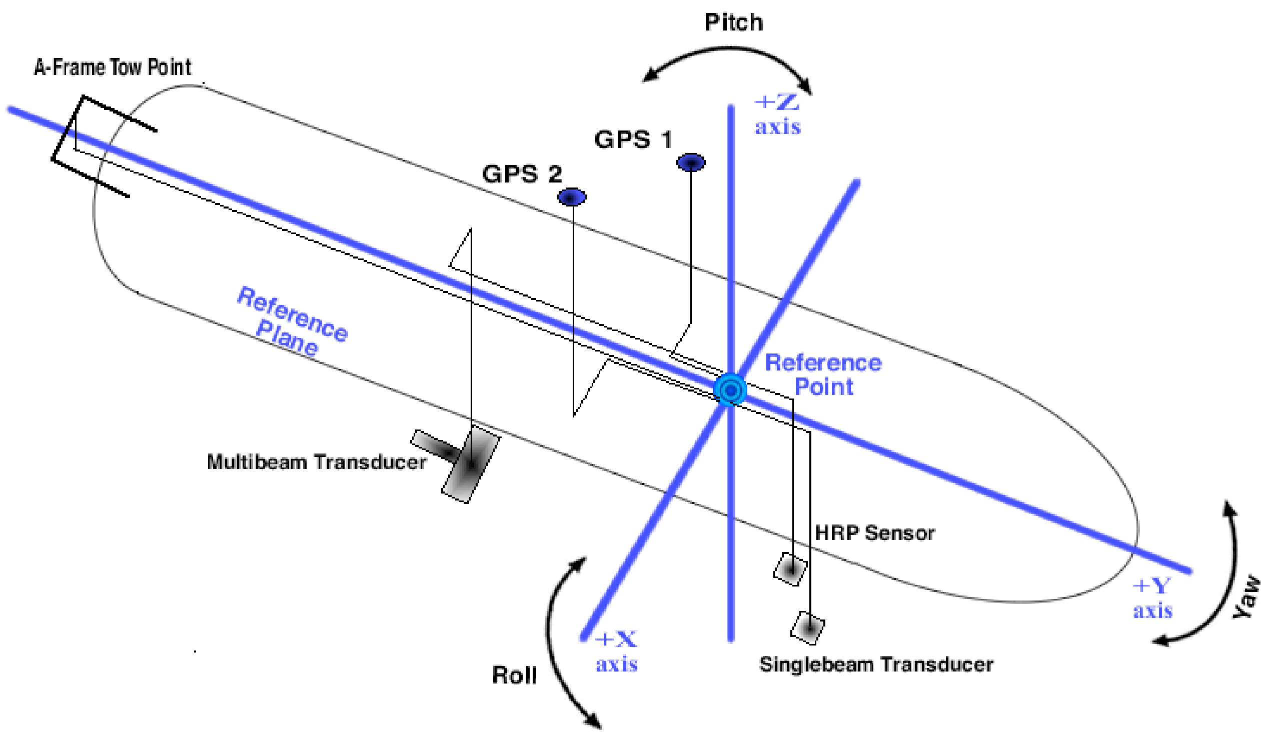

Figure 1. Diagram showing multibeam (MB) transducer, heave, roll, pitch (HRP) sensor, and positioning sensors (GPS) relationships to the motion reference point (RP). Heave, roll and pitch motions and axis conventions are also demonstrated. HF transducer represents a single-beam sonar. The multibeam (MB) transducer is offset to port in this diagram. One of the more difficult integration issues solved during installation and testing of multibeam sonar systems is alignment of the various components both physically and in terms of computational assumptions. Multibeam vendors, software companies, and sensor manufacturers do not use a standard set of axes nor rotational sign conventions. Multibeams installed aboard NOAA hydrographic ships have used the convention of X positive to starboard, Y positive forward, and Z positive up (easy to remember - "Heave Up"!). Roll rotation is positive when port side moves up, and pitch is positive when the bow moves up.

Survey Control

Multibeam sonar data is collected in a nominally straight line with a swath width of tens to hundreds of meters depending on depth. Mapping surveys require many lines of sonar sampling to cover an area. The efficient coverage of an area requires spatial planning of the sampling lines to ensure overlap and a method to direct the steering of the vessel. This is accomplished by using software to design the survey lines based on known depths, line overlap requirements, angular swath width, and other project requirements. The software should also provide real-time feedback of the vessel's path and location in relation to the planned survey line. The vessel's course can be adjusted based on the real-time feedback ensuring that the most efficient coverage is achieved. In the most advanced software packages, actual bathymetric coverage is computed in real-time, and the vessel can be steered to achieve the overlap desired. A composite image of all the lines (mosaic) created during processing will show coverage and is one way to assure that accurate corrections are applied.

Data Acquisition

Sound travel time, sound velocity, GPS position, tide data, HRP, vessel heading, and other sensor data must be acquired to calculate a seafloor depth. Each must be logged and associated in some organized fashion. Each must be time tagged to at least millisecond accuracy, so that the data can be synchronized in time. Ideally, this is accomplished using a master time signal from the GPS or a special clock aboard the vessel, but it can also be based on the data acquisition computer CPU timing. The time must be synchronized between all acquisition systems if more than one is used. Data logging is most easily accomplished using acquisition software to read the output of the sensors, time tag them, and write them in a file format useable by the processing software. Tidal observations and water column sound velocity profiles are usually collected independently. They must be managed to maintain their time and space association with the appropriate survey data for application during post-processing.

There are two competing philosophies for data acquisition systems; one based on integrating the information at the sonar, and the other based on integrating the information through a separately supported acquisition software package. Most sonar manufacturers provide software that can control the multibeam sonar system and log sensor data. However, an independent solution can help standardize the acquisition environment regardless of which sonar equipment is used.

Data Management

Data management is an often-overlooked element of an acquisition system. Multibeam sonar acquisition systems acquiring only basic seafloor depth can produce a data volume at a rate of one gigabyte per day. Advanced system features, such as snippets and water column information, will increase this data rate by factors of ten or a hundred. Simply stated, multibeam sonar acquisition systems create a lot of data very rapidly.

This large volume of data must be recorded and protected from loss in some logical management scheme. The scheme must provide high performance access to facilitate efficient processing and visualization of such large amounts of data. The data management scheme encompasses the data storage system and the network infrastructure to deliver the data to the processing workstations. Both must be designed to provide high-speed access to the data. The management scheme must also provide data protection in a manner that does not impact the 24/7 operations of mapping platforms. Tape backup can require significant downtime in order to archive the massive quantity of data. In general, data collection and processing is limited or must be stopped as the system performance or availability is affected by backup operations. New archival methods using disk mirroring and clustering can eliminate the backup downtime as well as provide real-time protection against system failure.

Data protection is sometimes considered a costly luxury. However, assuming a platform daily cost of $20K (small ship operation, with scientific party), the cost of an enterprise level storage system is equivalent to only 15 operating days, and pays for itself after one cruise. Another point to consider during the specification phase of data management is that the system should not only protect the entire data volume, but also simplify the overall data administration. Managing and backing-up the data can easily become a full-time job consuming a valuable bunk in the limited berthing on a ship. Consumer-level systems may not provide the speed, reliability, and ease of administration that a more expensive enterprise system does. The savings in purchase price may be quickly overrun by operational impacts of a poorly selected system.

Transferring gigabytes or terabytes of data must be considered carefully to reduce cost and maintain data protection. The transfer scheme must consider the cost and time it takes to create the archive, the offsite transfer method, and the cost and need to retain two valid copies of the data to prevent loss. In general, regular data transfers will be required to free the shipboard data storage for further data collection. Transfer of such large volumes of data requires significant planning to ensure data protection and the most efficient use of the shipboard storage.

In summary, data transfer technology is advancing, but the quantity of data produced by multibeam sonar acquisition systems is increasing rapidly as well. A data storage, protection, and transfer protocol must be devised during system specification to enable mission accomplishment. The protocol must be adequate for the data quantity, support redundant copies of the data, move the data rapidly to shore at the end of the cruise, and allow the shipboard system to be quickly cleared for reuse.

Data Processing

Data processing is both the beginning and ending of a multibeam sonar acquisition system. Knowledge of the data processing required to meet survey specifications will influence the in-the-water measurements taken, survey planning, ancillary sensor selection, and the data acquisition software used. The survey is planned, the environment is sampled, and the data are stored to enable certain specifications to be met. The data processing package, or pipeline, will then use these data to produce the desired end products or analyze them to derive information.

Most processing software packages have been developed to support specific missions, such as nautical charting, bottom typing, or the geological analysis of bathymetry. Some are designed to make comparisons between two surveys of the same area, while others are optimized to deliver information in near real time. The desired end products heavily influence the processing software selection, as well as the sensors and acquisition software used.

Examples of end products include, but are not limited to, digital terrain models, contour lines, hard copy plots of soundings, quasi-3 dimensional models, and GIS-ready data sets. Bottom type classification is a relatively new end product that is being actively investigated.