Deep Seafloor Mapping Systems—A Review

Robert C. Tyce

Graduate School of Oceanography
University of Rhode Island
Narragansett, Rhode Island

ABSTRACT

During the last decade a new set of deep seafloor mapping systems have been introduced to the oceanographic community which have substantially changed the way deep ocean surveys are conducted. For the first time large areas of the deep seafloor can be completely investigated with detailed sonar imagery and bathymetry. Improvements in digital computer processing make possible real-time mapping displays aboard ship from these sophisticated new systems. This paper reviews the history and characteristics of nine of the principal non-military deep seafloor mapping systems presently in use, covering a range of instruments from very high resolution systems towed near the seafloor to long-range, hull-mounted sonars.

INTRODUCTION

While surface-ship echo sounders have been the principal source of seafloor mapping data for many years, for most of that time they provided only sparse sampling of oceanic depths. This resulted in maps with limited detail and often more interpretation than actual data. Early oceanographers thought that ". . . the sea-bed extends for wide spaces in long undulations and gentle slopes. . .".[1] With the development of deeply towed echo sounders and side-looking sonars in the 1960's as well as growing evidence for the theory of plate tectonics, the tremendous diversity of seafloor terrain became apparent. Detailed mapping then became essential to understanding seafloor processes. With the advent during the past decade of new wide-aperture mapping systems, as well as the computer technology to accomodate the large digital data sets they produce, seafloor sonar mapping has truly matured. For the first time we have the capability to contemplate surveys with complete coverage of large areas of the seafloor, such as the U.S. Exclusive Economic Zone (EEZ), which totals nearly 12 million square kilometers. Programs were recently begun by the U.S. Geological Survey (USGS) and the National Oceanographic and Atmospheric Administration (NOAA) to completely survey the EEZ with sonar imagery and detailed swatch bathymetry.

This paper reviews the capabilities of the principal non-military deep sea sonar mapping systems presently in use. The nine systems discussed are of varying complexities, designed for various objectives. They include short-range, high-resolution systems towed near the seafloor as well as surface-towed and hull-mounted systems of reduced resolution. They include imaging as well as bathymetric sonars, since both are in widespread use, and increasing use of both types together is to be expected.

HISTORICAL BACKGROUND

The first use of echo sounding for ocean depth measurement occurred before 1920.[2] Obviously superior to the lead line, the echo sounder has since become the principal contributor to maps of the seafloor. It was not until the last decade, however, that deep seafloor mapping truly came of age, with the introduction of several new swath mapping sonar systems to the oceanographic community. Although we are discussing non-military applications of sonar technology, it is appropriate to note that most recent sonar mapping innovations trace their origins to Office of Naval Research (ONR)-funded programs in the 1960's. Beginning with a Navy sponsored summer study held at Woods Hole Oceanographic Institution (WHOI) in 1956,[3] several programs were conceived which would result in the development of pivotal new survey systems; including the Deep Tow near bottom survey system, the research submerisble *Alvin*, and the millitary swath mapping predecessor to Sea Beam.

The Navy's initial interest was in detailed seafloor bathymetry and associated physical properties, particularly as they related to sonar design. With the loss of the submarine *Thresher* in 1963, an additional need for deep water search capability became apparent. This led to the first deeply-towed, side-looking sonar system as part of the Scripps Institution of Oceanography's (SIO) Deep Tow system in 1965.[3]

The first side-looking sonar was actually developed in 1960 at the Institute of Oceanographic Sciences (IOS) in England for use in shallow water.[4] Scaling these results for deep water, this same group produced the first Geological Long Range Inclined ASDIC (GLORIA) side-looking sonar system for deep ocean geological surveying in 1969.[5] Designed to be towed at 50 m depth, GLORIA was 10 m long, 1.75 m wide, weighed 6 tonnes in air, and transmitted a 50 kw FM pulse of acoustic power every 30 seconds. This gave a swath to one side of 22 km. GLORIA was a sophisticated system, requiring transducer array phasing to compensate for vehicle yaw due to the long time delays between transmission. GLORIA's main weakness lay in the difficulties associated with handling such a bulky vehicle. This led to the development of the GLORIA II vehicle in the late 1970s.[6]

In 1964 General Instrument Corporation (GIC) introduced a Narrow Beam Echo Sounder (NBES) for detailed bathymetric work in deep water, and ten of these systems were subsequently installed on Navy and NOAA ships. The NBES system uses a side-looking, sonar-like transmit array mounted along the keel of the ship to project a beam $2\frac{2}{3}^\circ$ by 54°. Rather than receiving on this transducer as in the other sonars discussed here, a second array is mounted perpendicular to the transmit array and 16 perpendicular beams $2\frac{2}{3}^\circ$ by 20° are formed electronically. The received signal then comes from the intersection of the two transducer beam patterns, being a narrow $2\frac{2}{3}$ by $2\frac{2}{3}^\circ$ beam. A vertical reference gyroscope is necessary to stabilize the transmitted beam and to determine vertical for the received beams. For the NBES system a single stabilized vertical beam was formed electronically, then digitized as well as displayed as a bottom profile on a graphic recorder.

As the result of military experience with multibeam swath bathymetry and greater availability of digital computers, GIC realized that more than just the vertical beam of the NBES system could be used for bathymetric mapping. Thus, in 1976 digital computer processing and control hardware were added to the NBES sonar hardware to produce Sea Beam, which processes all 16 beams into a swath of bathymetric measurements $42\frac{2}{3}^\circ$ wide, or about 0.8 times the depth.[7] This produced a system capable of providing completely filled swaths of detailed depth measurements. The Sea Beam was originally developed for the Royal Australian Navy. However the first operational Sea Beam system was installed on the French research vessel *Jean Charcot* in 1977, where programs to provide real-time bathymetric mapping were developed, and the potential of Sea Beam became apparent.[8] Because they made complete coverage of large areas possible, these systems were well received, and a dozen became operational worldwide by 1986, with five in the U.S. For shallow water applications, a companion system to Sea Beam called Hydro Chart was also developed by GIC for NOAA in the 1970s.[7] In 1986 this system was updated for the Japanese, resulting in two operational shallow water multibeams. This system, also known as the Bathymetric Swath Survey System (BSSS), has an operating frequency of 36 kHz and 21 beams of 5°, for a swath equal to about 2.5 times the water depth in depths down to about 500m.[9,10]

During the 1970s, developmental work was also being done by the Deep Tow group on various side-looking sonar improvements. One of the first of these was a higher frequency, focused transducer system designed to improve along-track resolution. While successful, this system was not extensively utilized due to its electronic complexity. Later work involved phase comparison between pairs of transducers to determine echo arrival angles, which was suggested by a forward-looking bottom profiler system previously developed at SIO for the Navy's Deep Submergence Rescue Vehicle program. This system was only occasionally used due to the considerable data collection and processing burden it placed on the available minicomputers. Recent improvements in computers have lessened, but not removed, this burden.[11]

During the 1970s commercial interest in the deep ocean grew considerably, with oil companies moving to deeper water and several international organizations forming for the purpose of mining manganese nodules in the deep sea. As a result, commercial development was begun on several new deeply towed survey systems which would be introduced in the 1980's, including systems by International Submarine Technology (IST), EG&G, EDO Western and Klein Associates.[12,13]

Development of the IST SeaMARC I system was completed in 1980, with private support, as part of the first detailed search for the *Titanic,* conducted that year by scientists from Lamont-Doherty Geological Observatory (LDGO) and SIO.[14] Subsequent search efforts to locate the *Titanic* utilized both SeaMARC I and Deep Tow, but were hampered by bad weather and limited station time. In 1985 two new systems were used in the final successful search for the *Titanic;* the Navy-supported ARGO system from the Woods Hole Oceanographic Institution (WHOI), and the French SAR system from the Institute Français de Recherche pour l'Exploitation de la Mer (IFREMER).[15,16]

In the early 1980s a new shallow towed IST system (SeaMARC II) was also developed, with support from the Hawaii Institute for Geophysics (HIG) and the Office of Naval Research. This system provides both swath bathymetry and side-looking sonar imagery in the same towed vehicle, utilizing the same multiple transducer, phase comparison techniques employed by the SIO Deep Tow group.[17,18,19]

SIDE-LOOKING SONARS

Conventional ships' echo sounders are relatively simple devices, often consisting of a single wide angle transducer, a single power amplifier to provide a sinusoidal pulse of sound energy, and a single receiver (using the same transducer) to display the echo profile on an analog graphic recorder. The modern mapping systems discussed here are in actuality all side-looking sonars, as they use long narrow transducer arrays to project a sonar beam which is wide across the track but very narrow ($<3^\circ$) in the direction of travel (Figure 1). They also tend to consist of much more complicated electronics for echo processing, requiring time-varying gain (tvg) for dynamic range compression and often including computerized digital recording and processing systems. The Sea Beam system, for example, has 60 transducers, more than 100 amplifiers, a vertical reference gyroscope, and a small room full of electronics and computers in order to produce real-time maps of the seafloor. Depending on how these systems process the returning echo, they can be grouped into (1) wide beam, (2) split beam, and (3) multibeam systems.

Wide beam systems represent conventional side-looking sonar imaging technology, utilizing the same transducer array to both transmit and receive a single narrow beam to each side of the vehicle. Essentially all such systems are towed systems, in order to (a) minimize the processing complications introduced by the pitch and roll experienced by surface ships, (b) to minimize the impact of refraction of sound near the sea surface, or (c) to increase resolution by operating near the bottom. These systems produce swath imagery, though the systems are often equipped with more conventional echo sounding profilers or lower-frequency subbottom profilers. The GLORIA II, SeaMARC I, EG&G 990, EDO 4075, ARGO/Klein and SAR systems are all of this type. In its simplest, analog form, this swath image represents a time history of seafloor acoustic backscatter amplitude, displayed one line at a time on a grey-scale graphic recorder. The result is a distorted image which roughly approximates acoustic backscatter as a function of distance to the side of the vehicle in one dimension, and distance along the vehicle's track in the other. More sophisticated systems will process the displays in an attempt to remove the water column, to correct for cross-track (slant range) distortion, to equalize cross- and along-track distances, and to remove echo variations due to transducer directionality and incidence angle. To make these sophisticated corrections requires measurement of vehicle altitude, and is usually accomplished after the signals have been converted to digital form for computer processing.

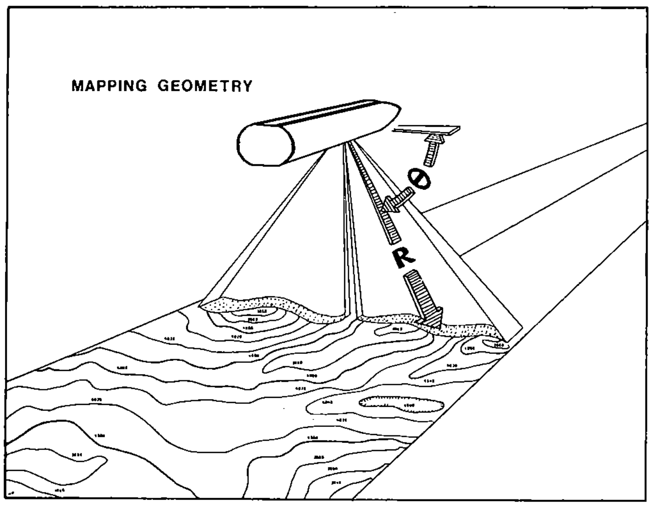


Figure 1. *Mapping geometry for side-looking sonar imagery and swath bathymetry from deep seafloor mapping systems, with slant range R, and angle of incidence (90° - grazing angle) indicated.*

Split-beam side-looking sonar systems utilize two or three closely spaced receiving transducers mounted parallel to the transmitting array in order to determine the arrival angle of the received echo. The result is effectively a stereo measurement of the acoustic return. By measuring echo delay time and angle, these systems can determine bottom depth to about 3% of altitude in addition to producing swath imagery. To do so requires a very considerable amount of data processing. The Deep Tow and SeaMARC II systems have both utilized this approach.

Multibeam systems utilize a large array of receiving transducers mounted perpendicular to the transmitting array in order to form the received echoes into a number of beam directions. Data are then usually processed to determine bottom depth within each beam rather than acoustic imagery. Sea Beam is of this type (as is Hydro Chart, its shallow water analog), utilizing 40 transducers to form 16 beams with depth resolution of 1 m, and measurement accuracy of better than 1% of depth. While primarily used for high-resolution swath bathymetry, these systems have also been used to produce swath imagery from their side-looking sonar returns. These systems are generally hull mounted, in part due to the dimensional constraints of two perpendicular transducer arrays.

Performance Limitations

The basic parameters of interest with side-looking sonars are range and resolution and, in general, one is achieved at the expense of the other. The controlling factors are transmitted energy and bandwidth, background noise, sound absorption, and angular dependence of acoustic backscatter from the seafloor. Range is primarily controlled by sound absorption in the ocean, which increases as frequency squared. Background noise is a secondary factor which generally decreases with frequency (5-6 dB/octave) up to about 100 kHz, where it begins to increase at a similar rate. For ranges on the order of 4 km (the average depth of the ocean), 12 kHz produces near optimal signal-to-noise ratios, and is the most common deep ocean echo sounder frequency. When absorption is not limiting, then the angular dependence of backscatter from the seafloor will generally determine maximum range (except when operating near the sea surface, where downward refraction of sound sometimes limits range), since the echo signal level diminishes rapidly as the grazing angle between the vehicle and seafloor decreases at longer range. As a general rule this tends to limit swath widths of these systems to about 10 times the vehicle altitude. Thus a vehicle at 100 m above the bottom might be able to survey a swath 1 km wide. Table 1 shows that this swath width is achieved by systems operating between 59 and 190 kHz. A vehicle 6 km above the seafloor might be able to survey a swath 60 km wide, provided the operating frequency were low enough for absorption not to be limiting. For GLORIA II this means an operating frequency of 6 to 7 kHz, with an FM transmit pulse being used to increase transmitted energy without reducing resolution.

Resolution across track is generally determined by the transmit pulse length (t), except for frequency modulated (FM) pulse systems such as GLORIA II and SAR, where the resolution is determined by the bandwidth (BW) of the frequency modulation. The sonar will transmit a short pressure signal which might be a pressure pulse as in Klein sonars, a sinusoidal (CW) pulse at a fixed frequency as in most of the sonars described here, or a frequency modulated (FM) pulse as in the GLORIA II and SAR systems. Since theory tells us that the bandwidth of any pulse is at least 1/t, resolution of non-FM systems can also

Table 1
Deep Ocean Sonar Survey System Characteristics

System	Gloria II	Sea MARC II	Sea Beam	Sea MARC I	E G & G 990	EDO 4075	ARGO/Klein	Deep Tow	SAR
Frequency (kHz)	6.2/6.8 (FM)	11/12 (CW)	12.158 (CW)	27/30 (CW)	59 (CW)	100 (CW)	100 (PULSE)	110 (CW)	170/190 (FM)
Introduction	1977	1982	1975	1980	1980	1980	1985	1962	1984
Pulse length	2, 4 sec	.25 – 10 ms	7 ms	.15–3.2 ms	0.1–0.5 ms	0.1 ms	0.1 ms	.1–.4 ms	
Pulse rep.(sec)	20–40	1–16	1–22	0.5 – 4	0.2 – 1	0.1 – 1	0.3	.1 – 1	1
Bandwidth (kHz)	.1	.1 – 4	.14	.31 – 6.7	2 – 10	10	10	2.5 – 10	2.5
Beamwidth (deg)	2.5 x 30	2 x 40	2.7 x 2.7	1.7 x 50	1.2 x 40	1 x 25	1 x 40	.75 x 60	0.5 x 80
Array length	5.33 m	3.8 m	2.8 x 2.8 m	1.5 m	1.2 m	0.9 m	0.8 m	1.2 m	0.9 m
Vehicle Length	7.75 m	5.5 m	Hull mount	3 m	1.7 m	4.9 m	4.3 m	2 m	5 m
Weight (metric)	2 tonnes	2 tonnes		1.5 tonnes	0.1 tonnes	0.5 tonnes	2.3 tonnes	1.0 tonnes	2.3 tonnes
Stabilization	Heading	all axes	all axes	Heading					
Data type	Digital	Digital	Digital	Digital	Digital	Analog	Analog	Analog	Digital
Cameras							TV & Still	TV & Still	
Other sensors				subbot+mag	subbot+temp	subbottom	navigation	many	Subbottom
Tow depth	30–60 m	50–100 m	Hull mount	to 7 km	to 6 km	to 5 km	to 6 km	to 7.5 km	to 6 km
Water depths	> 10 km	> 10 km	> 10 km	7 km	6 km	5 km	6 km	7.5 km	6 km
Tow Altitude				25–1250 m	10–200 m	10–100 m	10–50 m	10–150 m	10–200 m
Cross Track res.	30 m	5 m	14–233 m	0.5–2.5 m	.3 – 1.3 m	.1–.4 m	.1–.4 m	.1–.3 m	0.3 m
Along track res.	218 m	175 m	233 m	0.7–37 m	.2–4.2 m	.2–1.7 m	.2–.9 m	.1–2.0 m	.1–1.7 m
Bathy accuracy		150 m (3%)	10–50 m						
Swath width	14–60 km	1 – 10 km	0.8 depth	1 – 5 km	0.2–1 km	0.1–0.8 km	0.1–0.7 km	0.1–1.5 km	1.5 km
Survey speed	10 kts	8 kts	15 kts	2 kts	2 kts	2 kts	1 kt	1–2 kts	1.5–2 kts
Number in use	2	1	12	1	25	4	1/6	1	1
Coverage @ 5 km (sq. km / day)	26,686 imagery	3,558/3,558 image/bathy	2,669 bathymetry	444 imagery	89 imagery	71 imagery	31 imagery	133 imagery	133 imagery
Coverage @.5 km (sq. km / day)	2,224 imagery	2,224 / 756 image/bathy	(BSSS) 834 bathymetry	444 imagery	89 imagery	71 imagery	31 imagery	133 imagery	133 imagery

be said to be determined by bandwidth. The range resolution in meters is basically one-half the velocity of sound divided by the bandwidth, or approximately 750/BW. Range resolution is transformed into cross-track resolution in the display, which may vary from approximately range resolution at maximum range (and small grazing angle) to more than 50 times worse beneath the vehicle, where the image is generally poorest, but depth resolution is best.

In practice, resolution is often less than the theoretical prediction due to limitations of display or data acquisition devices. A swath image will generally contain about 2000 elements ("pixels") or less per swath width, which is sufficient resolution for image processing, but only 1/10 the range resolution suggested above. When expressed in meters, pixel size varies with swath width. For GLORIA II, 2000 pixels in 60 km represents a cross-track resolution of 30 m. In some systems the transmit bandwidth is reduced to match the cross-track resolution to either the image processing or the along-track resolution, thereby reducing the in-band noise.

Along-track resolution is a function of bandwidth, altitude, vehicle speed and pulse repetition rate; and is generally much less than range resolution. Basically this is limited either by the footprint of the beam pattern on the seafloor or the forward progress of the vehicle between measurements, but cannot be less than the length of the transducer without special processing. This resolution is generally on the order of ten times worse than cross-track resolution unless cross-track resolution is further reduced in display processing as discussed above, or in the formation of cross-track beams for depth determination rather than image processing, as in the case of multibeam sonars which we will consider further below. For GLORIA II with an along-track beamwidth of 2.5°. the beampattern footprint results in along-track resolution of 218 m beneath the vehicle in 5000 m water depth.

Some background on each of the system mentioned above is provided in the following paragraphs and summarized in Table 1. Here a survey depth of 5 km is assumed, particularly for resolution and coverage numbers, except for the last row, where coverage for a 0.5 km survey depth is included for reference. In the last row, Hydro Chart (BSSS) coverage is substituted for Sea Beam, and the towed vehicle speed is the same as in the 5 km case (which may underestimate the coverage for vehicles which can be towed faster in shallow water). Throughout the table along-track resolution for towed vehicles is calculated for the range of tow altitudes indicated. In general cross-track resolution is determined by pulse length (or bandwidth) and along-track resolution by beamwidth. Bathymetric accuracy in 5 km depth is included for the two systems capable of swath bathymetry.

The systems are discussed below essentially in the order in which they were introduced to the community for deep seafloor mapping. While not intended to be a complete list of systems for deep sea surveying, the nine systems presented represent most of the presently active systems in the academic and commercial oceanographic communities. The characteristics of these systems are summarized for comparison in Table 1, where they are ordered by their operating frequency. Operating frequency generally determines range, as discussed above, which along with survey speed determines coverage rate.

Deep Tow

Of all the systems which have been utilized for seafloor mapping, the Deep Tow system of the Marine Physical Laboratory (MPL) at SIO has undoubtedly had the most impact on the oceanographic community. Development of this system began in the early 1960s as the result of interest in fine scale aspects of the sea floor which affect the direction of travel of bottom-reflected acoustic energy. Since that time its capabilities have been considerably expanded and its has been used extensively for deep seafloor investigations. Results of these investigations are too numerous to list here, including support for more than 20 doctoral theses and more than 200 scientific papers.

The first Deep Tow system consisted of simple up and down looking echo sounders towed near the seafloor by means of a long coaxial cable. In 1964 a magnetometer was added to aid in the study of lineated magnetic anomalies discovered a few years earlier by Mason and Raf at SIO[3], and a system of bottom-mounted acoustic transponders for navigation was developed to permit precise positioning of the vehicle (1m) and towing ship (10 m) while under way. In 1965 a side-looking sonar was added with support from ONR and the Navy's Deep Submergence program, following the loss of the U.S. Submarine *Thresher.* With a beam width of only ¾°, this side-looking sonar is still one of the highest resolution systems in use.

Since 1965 more than twenty different sensor and sampling subsystems have been added at various times to the Deep Tow instrument package, depending on the particular set of marine geophysical, acoustical, biological, and chemical probems being addressed (Figure 2). The present basic system consists of a narrow beam sounder, side-looking sonars, a 4/6 kHz subbottom profiler, an up-looking sonar, an obstacle avoidance sonar, a proton magnetometer, stereo still cameras, a snapshot TV, a transmissometer, a compass, a CTD system, a precision pressure gauge, and a transponder navigation system.[19] A transportable crane for launch, tow and recovery handling as well as a deep sea traction winch are also part of the system.

For deeply towed systems, survey speed is usually limited by the drag of the tow cable. The Deep Tow is generally towed at altitudes of 10 to 150 m by means of 9 km of armored coaxial cable, 1.7 cm (0.68 in) in diameter, which limits the towing speed to about 2 knots in 5 km depths, a limit common to essentially all near-bottom towed systems. The 110 kHz side-looking sonar systems of the Deep Two have a typical swath width of 1.5 km at a tow altitude of 150 m. This results in maximal areal coverage of about 133 square kilometers per day of bottom survey time. In actual fact this number may be

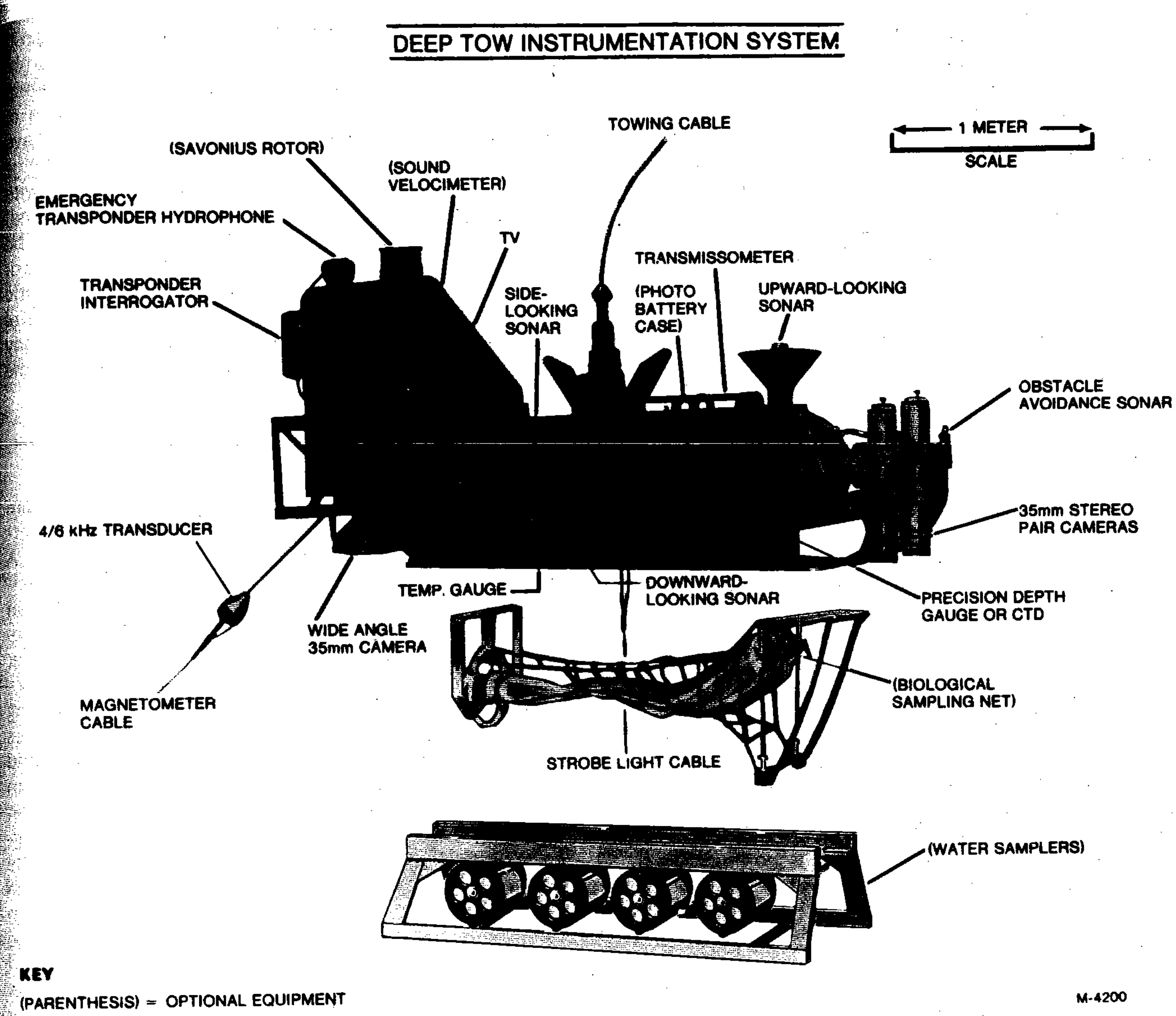


Figure 2. *Schematic diagram of the Deep Tow instrumentation system of the Marine Physical Laboratory, Scripps Institution of Oceanography, illustrating the possible complexity of near-bottom towed survey systems.*

reduced considerably due to track overlap, reduced coverage during turns and near bottom (10 m altitude) photographic work, as well as by operational limitations imposed by foul weather (such as being unable to tow downwind or make sharp turns). With additional time allowed for transponder planting and recovery as well as other geophysical sampling, deep tow cruises have generally involved detailed surveys of areas about 400 square km over 7-10 days.

GLORIA II

GLORIA II was introduced in 1977, primarily to solve the operational problems presented by the large (6 tonnes) GLORIA I vehicle. The GLORIA II vehicle weighs only 2 tonnes in a 7.75 m by 0.66 m vehicle. This new system produces scans to both sides of the vehicle out to 30 km with 10 kw acoustic power per side in beams 2.5° wide, and stores the returns digitally for data base achieving and postprocessing. A special purpose launch and recovery system was also developed to allow deployment of GLORIA II in rough seas.[21]

The U.S. Geological Survey (USGS) is presently using GLORIA II to provide reconaissance maps of the U.S. EEZ,[22] and recently acquired an updated GLORIA II system, called GLORIA III. The U.S. EEZ represents the region extending 200 nm seaward from U.S. territory. The USGS is using GLORIA II and III for this effort because of their large area coverage, which is in theory nearly 27,000 square km per day in deep water, with a swath width to 60 km and tow speed to 10 knots. In shallow water the swath width is reduced to roughly 10 times the depth, giving only 2,224 square km/day theoretical coverage in 0.5 km water depth. The USGS has already used GLORIA II extensively, including a complete survey of the EEZ off the west coast of the U.S., totaling more than 850,000 square km surveyed in 96 days, for an average of about 9000 square km per day. With the U.S. EEZ encompassing nearly 12 million square km (3.4 million square nm), the entire EEZ could be mapped in approximately 3½ years with a single GLORIA II system.

GLORIA II images are relatively low resolution, however (30 × 218 m in 5 km), and tend to show only large-scale geological features, without any quantitative measure of topography except directly beneath the tow ship. The principal advantage of the GLORIA maps is that they provide complete coverage of these large areas for the first time, already revealing several dozen previously unknown seamounts and other previously unmapped features. Utilizing USGS GLORIA maps to prioritize their efforts, NOAA is in the process of conducting detailed bathymetric surveys of the EEZ (with Sea Beam and Hydrochart multibeam bathymetric mapping systems). This prioritization is necessary since these bathymetric mapping systems will take 3 to 10 times as long to cover the areas mapped by GLORIA II.[22]

Sea Beam

In 1976 General Instrument Corporation introduced the Sea Beam multibeam bathymetric mapping system to the oceanographic community. Sea Beam is a sophisticated hull-mounted mapping system which developed out of previous work on narrow-beam echo sounders, and as such is oriented toward production of topography maps rather than the seafloor images common to traditional side-looking sonars. Sea Beam is side-looking in nature, however, and recent efforts to produce backscatter imagery with Sea Beam echoes have been reasonably successful.[23,24,25] Sea Beam bathymetry has depth resolution of 1 m, and accuracy between 10 and 50 m in deep water To accomplish this, the "center of mass" of the entire acoustic return within each beam is used to determine range rather than the first arrival sampled, and roll and pitch of the ship are removed very precisely, as errors of 1/10° are detectable in the data. For a water depth of 5 km the 2⅔° beam width gives along-track and across-track bathymetric resolution of 233 m beneath the ship to 264 m in the outer beams. Since Sea Beam uses a transmit pulse 7 msec long, the range resolution for Sea Beam imagery should be about 5 m, giving cross-track resolution of about 14 m for the outer beams in 5 km water depth. (Sea Beam outer beams only extend to 21° either side, compared with nearly 80° for most side-looking sonar images).

Aboard ship the bathymetric data is merged together with the best available navigation and plotted as a color-coded swath contour map within a few minutes of acquiring the data (Figure 3). This not only permits the scientists aboard the ship to alter their program based on what is being learned, but allows maneuvering of the ship to follow known features or explore newly discovered ones. Data from previous days' efforts can be processed aboard ship or returned to shore-based laboratories for postprocessing. At present the principal postprocessing problem remains correction of erroneous navigation information, which becomes apparent through registration of overlapping sonar swaths. When navigation errors have been removed the randomly oriented swath data can be merged into a regularly spaced (gridded) data base, with overlapping data removed and data gaps interpolated. From this data base various map presentations can be produced, such as traditional contour maps (Figure 4) or 3-D projections (Figure 5).[26] As detailed bathymetric data bases are accumulated for areas with data bases of seafloor backscatter imagery, presentations combining these complementary sets of information will become more and more common (Figures 6,7).

EDO 4075 Systems, SeaMARC I, and EG&G 990

The EDO Western model 4075 deep tow survey system was designed as a conventional side-looking sonar operating at 100 kHz, together with a subbottom profiler. A navigational responder was also included to allow navigation relative to the tow ship. Near-bottom operation was intended in depths to 5 km, with analog data frequency multiplexed over a single coaxial tow cable. Removal of geometric distortion in the final analog records was made possible by means of a data processing and graphic recorder system. The recorder determines vehicle altitude and ship speed from the input data and uses them to remove the water portion of the echo from the display as well as to correct the cross-track dimension for slant-range and angular distortion, and the along-track dimension for ship speed. This allows objects on the seafloor to be displayed in true form. Scans to 400 m to each side of the vehicle were intended, for a maximum swath width of 0.8 km. With a 0.1 msec transmit pulse and a 1° beam width, the cross-track resolution is limited to the recorder resolution of about 0.4 m, and the along-track resolution to the beam pattern footprint of 1.4 m (for an altitude of 80 m and a swath width of 0.8 km).

The EG&G model 990 tow fish was one of the first to utilize digital processing in a deep seafloor survey vehicle, making it more sophisticated than conventional side-looking sonars, and permitting routine digital storage of survey data. The 990 vehicle instrumentation includes side-looking sonar, subbottom profiler, heading, temperature and vehicle speed sensors. The data from these systems is digitally multiplexed over the coaxial tow cable. The 990 system was developed as part of the EG&G Seafloor Mapping System (SMS 960) developed earlier for shallow water, and is capable of deep-tow operations to depths of 6 km. In the vehicle the sonar echoes are corrected for amplitude variations, then digitally transmitted to the surface ship. Digital transmission is far less dependent on cable characteristics than analog transmission and it permits simple digital recording of the raw data for postprocessing by computer if desired. The shipboard SMS takes either the raw vehicle data or previously recorded data and applies traditional corrections to remove the water column, correct for slant

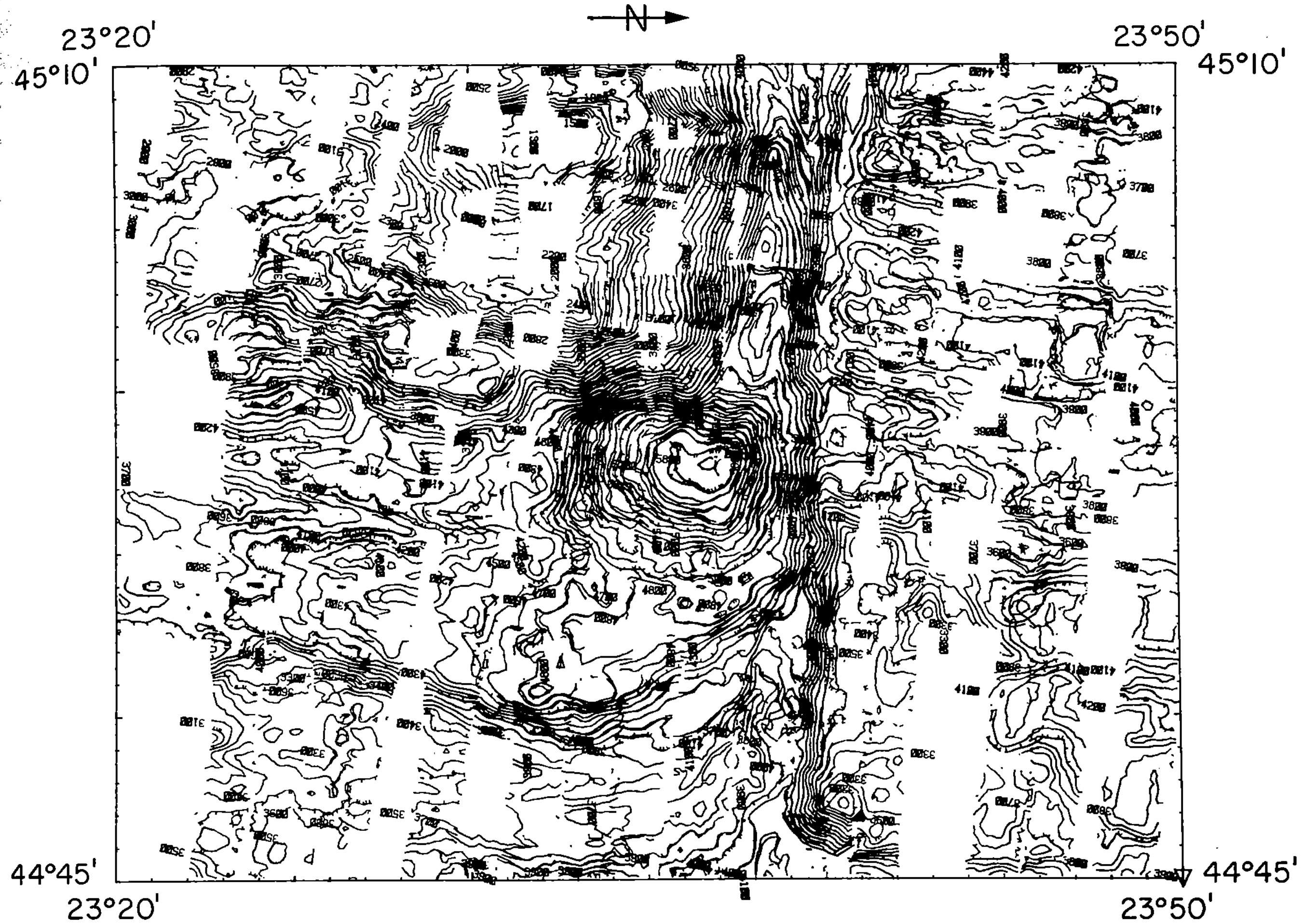


Figure 3. *Overlapping Sea Beam swath bathymetry such as might be displayed aboard ship with color coded depth contours. These data were collected from the Kane fracture zone, North Atlantic Ocean, in 3 to 4 days of survey time.*

range distortion, and normalize the final display across- and along-track. This results in corrected scan recorder paper records which can be overlayed to produce a mosaic aboard ship when desired. The system operates at a frequency of 59 kHz with a beamwidth of 1.2°. The sonar echoes are sampled 800 times across a swath, which is limited to 1 km by the SMS processor rather than the sonar. For a 100 m altitude and 1 km swath, cross-track resolution is 1.3 m and along-track resolution is 2 m.

The SeaMARC I system had its beginnings in instrument development for deep ocean mining undertaken for the mining consortium known as Ocean Management Inc., which included International Nickel. When interest in deep ocean mining diminished toward the end of the 1970's, the IST group was formed and began doing development for the oceanographic community. Working with the scientists at LDGO and with private funding, IST introduced its Sea Mapping and Remote Characterization (SeaMARC I) system in 1980 for use in the first near bottom search for the *Titanic*. While it failed to find the *Titanic's* location (primarily due to bad weather and lack of adequate ship time), it did demonstrate its value as a deep sea geological mapping system. Since that time it has been used extensively for detailed seafloor studies, primarily because the intermediate scale of its high quality images is a good match to the scale of seafloor geological processes (Figure 6).[14]

SeaMARC I operates at 27 kHz (port) and 30 kHz (starboard) with a beamwidth of 1.7°. In deep water the vehicle is typically towed several hundred meters above the seafloor in order to obtain swath widths to 5 km, with a maximum operating depth of 7 km. Digital processing is utilized in the vehicle to remove amplitude effects due to range, transducer beam pattern and altitude (as it relates to the angular dependence of seafloor backscatter). As in the EG&G system, the pulse length and cross-track digitization is variable to keep constant resolution across track, and is a function of swath width and altitude. The digitizer samples 2000 times across the swath, and the data is stored on digital magnetic tape aboard ship after all distortion corrections are applied. The SeaMARC I vehicle has subbottom profiler, transponder navigation, magnetometer, heading, depth, speed and vehicle attitude sensors in addition to the

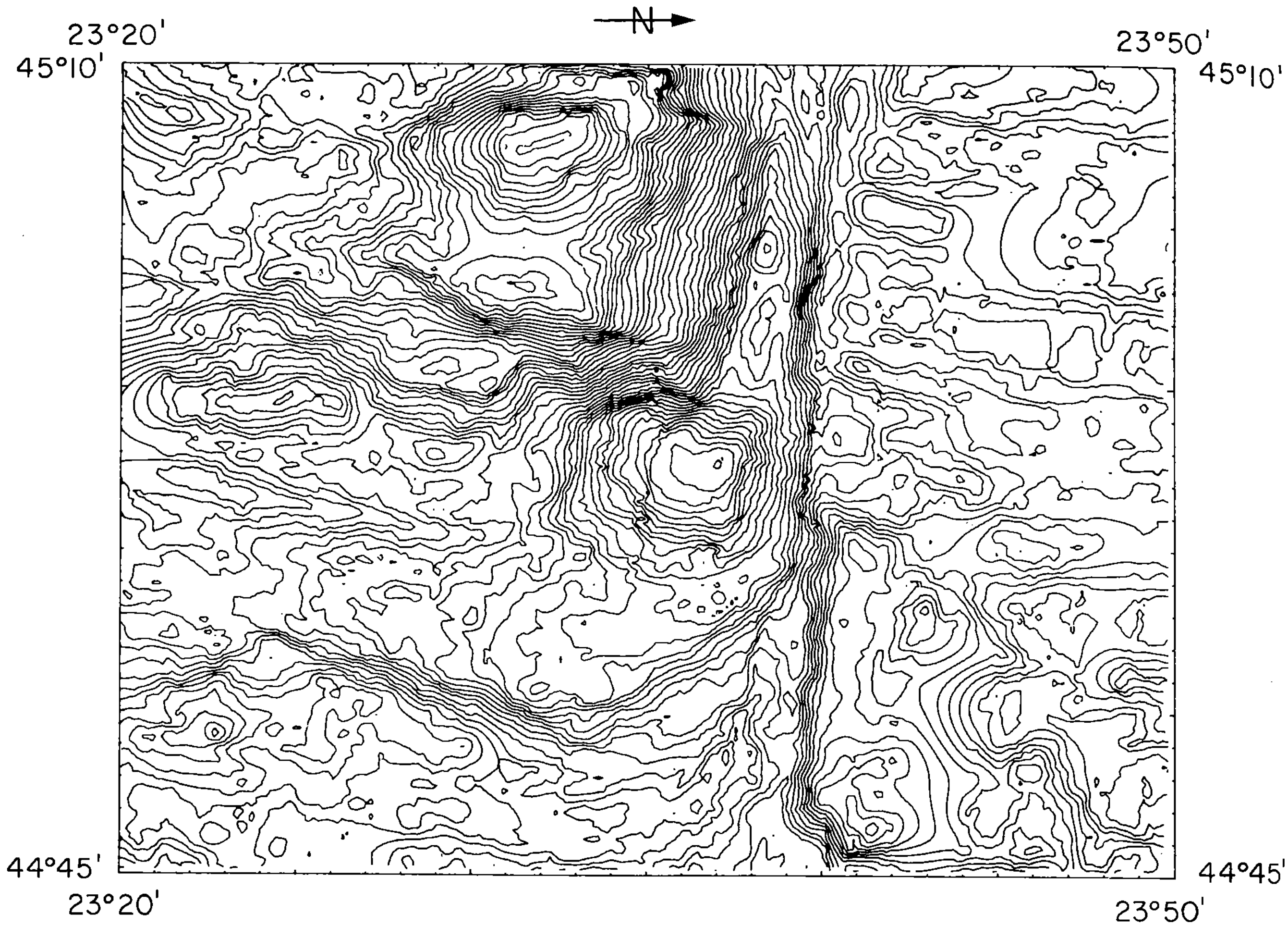


Figure 4. *Processed contour map produced from gridded version of Sea Beam data in Figure 3. Depth ranges from less than 1200 m at the shallowest to more than 6000 m at the deepest.*

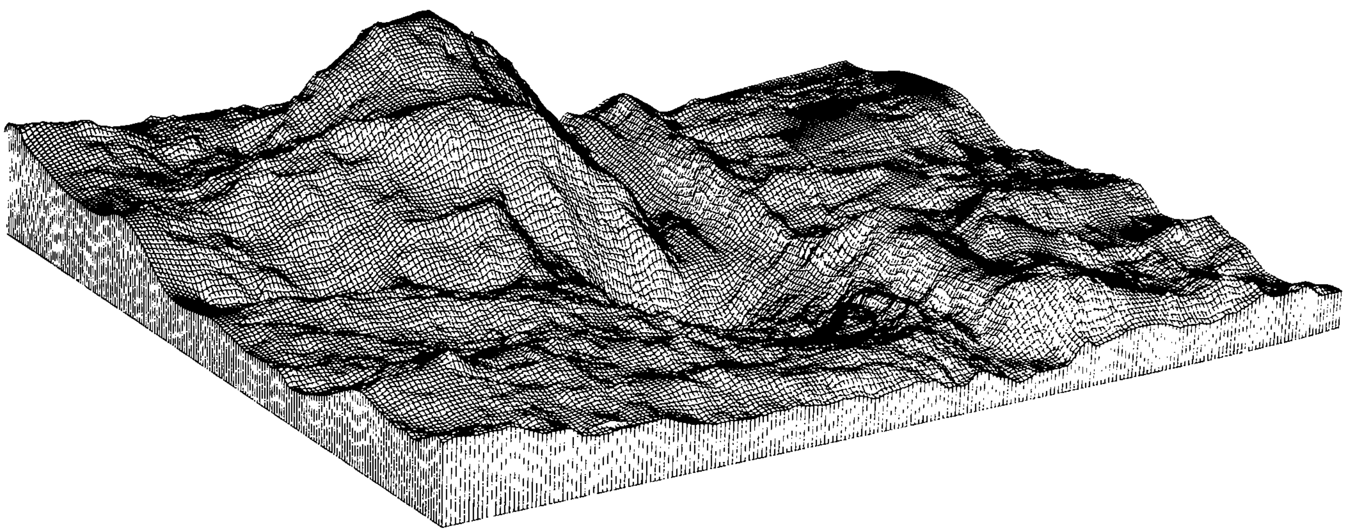


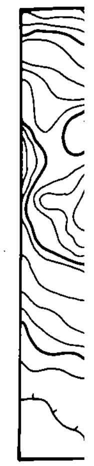
Figure 5. *3-Dimensional meshed surface display of the gridded data base used to generate Figure 4. Vertical exaggeration is approximately 3 times.*

side-loo
swath
resoluti
With p
track re
SeaMar
in 1984
with AF

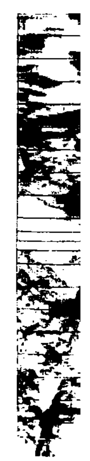
SeaMA

Reco
togethe
of Geo
MARC
of Nava
lower f

BA



SE



Figure

side-looking sonars. With a tow altitude of 500m and a swath width of 5 km, SeaMARC I has a cross-track resolution of 2.5 m and an along-track resolution of 15 m. With possible tow altitudes from 25 to 1250 m, along-track resolution varies from approximately 0.7 to 37 m. SeaMarc I was lost at sea during research work for LDGO in 1984. In 1985 SeaMARC IB was built for use by WHOI with ARGO.

SeaMARC II

Recognizing the need for long-range sonar imagery together with deep sea bathymetry, the Hawaii Institute of Geophysics and IST combined to develop the SeaMARC II vehicle, with later support from the U.S. Office of Naval Research. Introduced in 1982, SeaMARC II is a lower frequency (11 kHz port and 12 kHz starboard), shallow-towed, side-looking sonar system which also measures bathymetry.[16,17,18] Using the split beam approach, the phase of echoes received at two closely spaced transducers are compared to determine the arrival angle of the echo. This information together with the range to the bottom can be translated into depth information. To accomplish this, 20,000 amplitude and angle measurements must be digitized for each swath for postprocessing into bathymetry. During postprocessing the data is filtered to remove the interference caused by multiple echoes, and reduced to approximately 100 pairs of depth and cross-track distance measurements. Because only two closely spaced transducers are used in this split-beam approach, it is more prone to directional errors from multiple echo interference than the 40 transducer beamforming approach utilized by Sea Beam. At

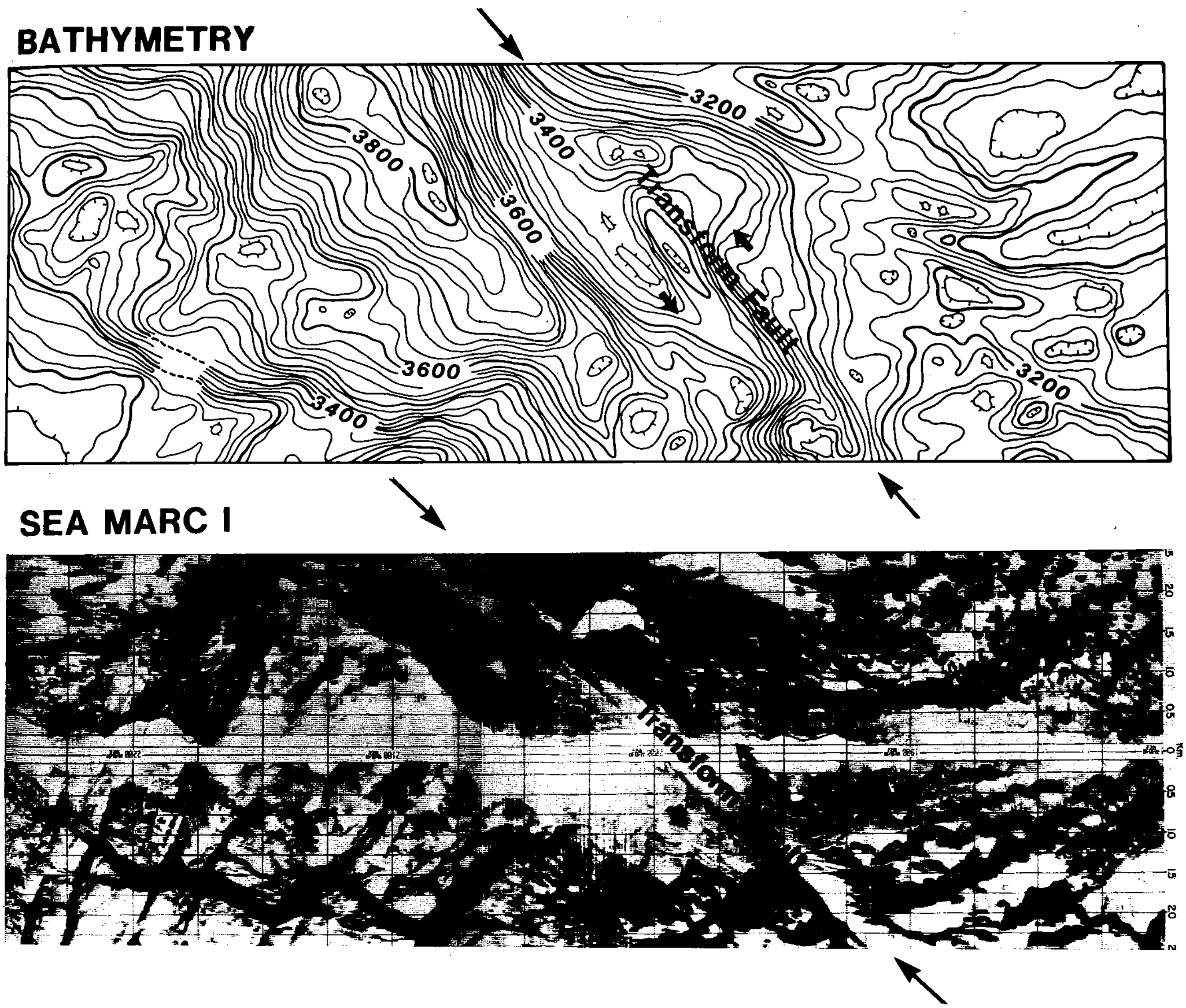


Figure 6. *Seafloor imagery from SeaMARC I and bathymetry from Sea Beam for the same area of the Clipperton Transform, Western Pacific Ocean. Figure courtesy of J. Fox (Univ. of Rhode Island) and W. Ryan (LDGO).*

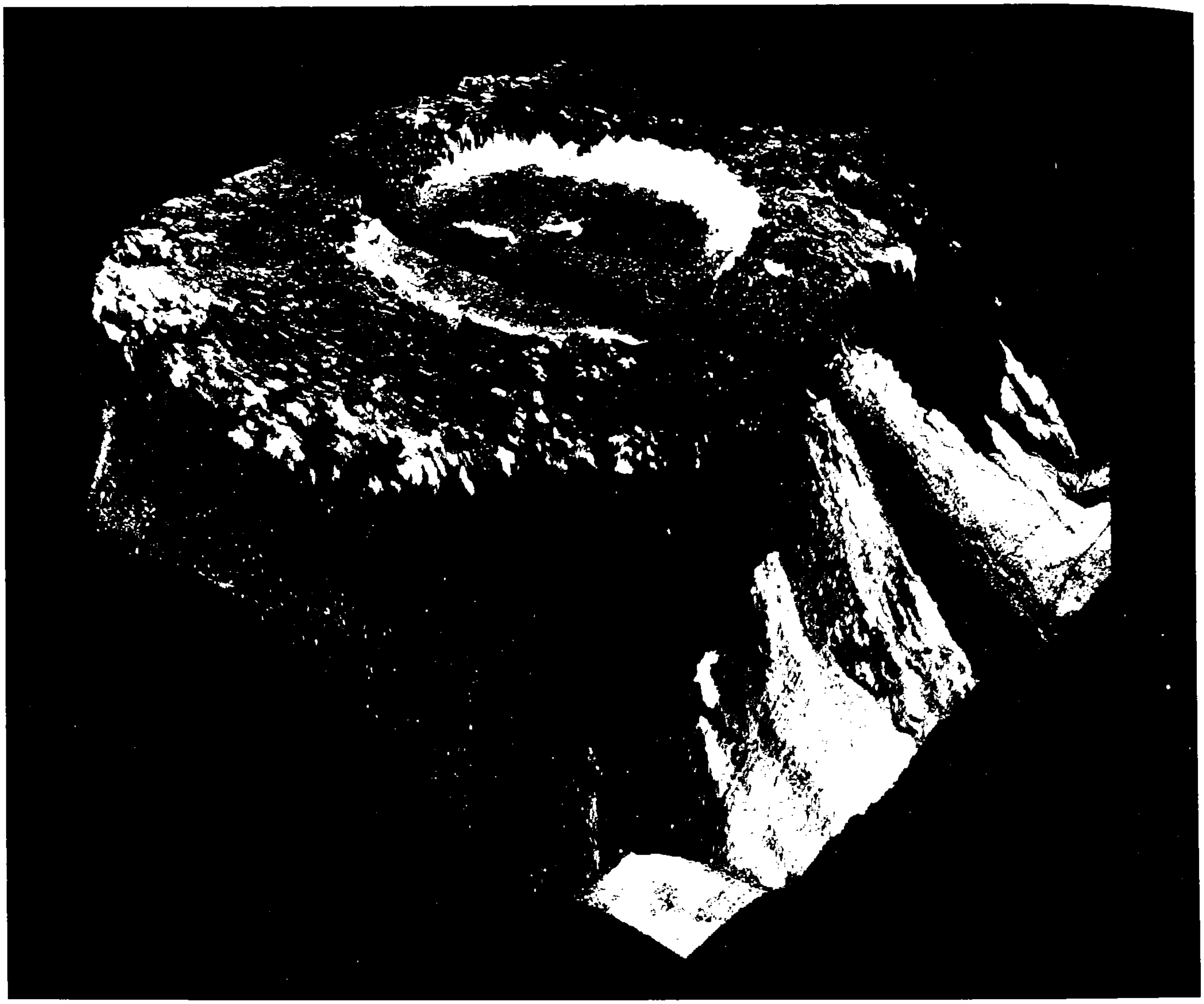


Figure 7. *3-Dimensional shaded relief presentation of combined SeaMARC I imagery and Sea Beam bathymetry.*[27] *Data shows a flat topped submarine volcano just off the axis of the East Pacific Rise near 13 degrees north. Figure represents a single swath of SeaMARC I imagery projected in 3-D by reference to corresponding Sea Beam Data. Seafloor depth in this image is about 2150 m, with the volcano rising 1000 m. Vertical exaggeration is 2 times. Figure courtesy of J. Farre (EPR), W. Ryan and D. Fornari (LDGO).*

present SeaMARC II postprocessing provides depth resolution on the order of 3% of water depth compared to 1% for Sea Beam. The SeaMARC II bathymetry swath is limited to about 3.4 times the water depth by interference from bottom echo multiples, compared to 0.8 times water depth for Sea Beam and 2.5 times water depth for Hydro Chart (limted by beam-former design).

In addition to the mapping system. SeaMARC II is equipped with heading, depth, and attitude sensors. With its lower operating frequency, this system can produce swaths up to 10 km for depths greater than 1 km. The beam width of SeaMARC II is 2° and the pulse width is adjusted to match a resolution of 2000 samples per swath. For 5 km depth and 10 km swath, the resolution is 5 m cross track and 175 m along track, with coverage to 3558 square km per day at 8 knots, its nominal tow speed.

ARGO/Klein and SAR

The most recently introduced deep sea survey systems are WHOI's ARGO system and the SAR system from IFREMER, the French agency for ocean research. Developed with U.S. Navy funding, the ARGO system is primarily a deeply towed sled equipped with several special video and still cameras for high altitude photo and video imagery. ARGO is equipped with sensors for heading, attitude, and transponder navigation. It is also equipped with a deep water side-looking sonar system manufactured commercially by Klein, and represents an extension to deep water of the extensive shallow water side-looking sonar capability of Klein Associates.[12] This is a conventional system with a 1° beam and a 100 kHz operating frequency. The sonar utilizes a swath width of 700 m at a tow speed of 1 knot (limited by ARGO), giving coverage of 31 square kilometers per day. ARGO is notable as the vehicle which, during some of its early tests, located the wreck of the *Titanic* in the summer of 1985. While the ARGO vehicle is unique, six other deep water systems from Klein Associates are presently in service.

Though tested in 1984, the French SAR system also saw some of its first application during the search for the *Titanic*, where it surveyed 80% of the planned area before ARGO finished the task.[15] This is a new sonar vehicle designed to provide detailed imagery of manganese nodule areas to a depth of 6 km. With operating frequencies of 170 kHz (port) and 190 kHz (starboard) it is one of the highest frequency side-looking sonars in use for deep seafloor mapping. With a beamwidth of 0.5° it is also one of the highest resolution systems. Despite its high frequency, FM transmission and associated signal processing permits the SAR to obtain swath widths of 1.5 km, which with a tow speed of 2 knots gives coverage of 133 square kilometers per day. The cross-track resolution of SAR is 0.3 meters and with an altitude of 150 m, its along-track resolution is 1.3 m. For altitudes from 10 to 200 m, the along-track resolution varies from approximately .1 to 1.7 m.

FUTURE DEVELOPMENT

The trend in seafloor mapping systems is toward combining sonar backscatter imagery and bathymetry. The value of surveys which combine quantitative backscatter measurements with accurate bathymetry will be tremendous. So far no system exists which does both well, though the technology exists and will be further developed. SeaMARC II is the first vehicle to combine both capabilities in a single vehicle, though Sea Beam images have begun to appear along with bathymetry. Figure 6 is an example of SeaMARC I and Sea Beam data for the same area, and illustrates the different but complementary information provided by each of these systems. Efforts at computer integration of high resolution SeaMARC I seafloor imagery and Sea Beam swath bathymetry for the same area have recently proven successful, resulting in three-dimensional (3-D) presentations of side-looking sonar images. An example of this work by John Farre at Exxon Production Research Company and William Ryan at LDGO is presented in Figure 7, where the Sea Beam topography has been used to project this single swath of SeaMARC I data into three dimensions. This is clearly a powerful technique which will not only see further application, but should motivate the development of future systems capable of producing such high resolution 3-D images directly.

At 9000 square kilometers per day, sonar imagery of the entire 12 million square kilometers of the EEZ can be surveyed in 3½ years by a single GLORIA II system. The world's oceans, totalling about 350 million square kilometers, could be imaged in about 50 years with two systems, a feat remarkable to contemplate. Our present bathymetric systems, however, would take more than 10 times as long for the deep water areas, and much longer in shallow water, because the coverage decreases proportionally with depth (just as it does for GLORIA II). If one-third of the EEZ is shallower than 1000 m and surveys take 5 times as long in such depths, then surveying these shallow water areas will take more than twice as long as the deep water areas. Thus there is a need for broader coverage bathymetric systems for shallow as well as for deep water.

The EEZ surveys proposed by NOAA and the USGS will provide data bases of sonar imagery and bathymetry more complete than ever before and will probably change the way we view and use our coastal seas. Provided that military concerns about public release of these high quality data can be overcome,[28] these data bases will most likely serve as the basis for more detailed surveys of areas of particular academic, commercial and military interest for many years to come. In the open oceans, the growing digital data bases from deep water surveys of seafloor acoustic imagery and swath bathymetry will provide increasing opportunities for the scientific community to understand the geological processes of the deep seafloor.

ACKNOWLEDGMENTS

As this technology review deals primarily with the products of others people's work, it was dependent on the assistance of quite a few people. I would like to thank Fred Spiess and Charles Bishop for their historical insight and continuing encouragement. I would like to thank Carma Ingram of EDO Western, Jim Kid of Klein Associates, Tom Dettweiler of the Deep Submergence Laboratory at WHOI, John Shaw of IST, Roger Searle of IOS, and Roger Karen of EG&G, for providing technical details on their systems. Bill Ryan and Dan Fornari of LDGO, Jeff Fox of URI and John Farre of EPR deserve special thanks for their willingness to share their hard-fought-for data. The Sea Beam data presented here comes from the NECOR/Sea Beam facility at URI, which is supported by grants from the National Science Foundation (Grant OCE-8418919) and the Office of Naval Research (Contract N00014-81-C00062) as well as by the individual research grants of numerous principal investigators.

REFERENCES

1. Reclus, E. 1886. A new physical geography, vol. 2, Air and Ocean, G.G. Virtue and Co., London, 500 pp.

2. Urick, R.J. 1979. Sound propagation in the sea, U.S. Government Printing Office, Washington, DC. No. 008-051-000071-2.
3. Spiess, F.N. 1980. Some origins and perspectives in deep-ocean instrumentation development. In Oceanography: The Past, Springer-Verlag, New York, M. Sears and D. Merriman Editors, pp. 226-239.
4. Tucker, M.J. and A.R. Stubbs. 1961. A narrow beam echo-ranger for fishery and geological investigations. British Journal of Applied Physics, V. 12, pp. 103-110.
5 Rusby, J.S.M. and M.L. Somers. 1977. The development of the 'Gloria' sonar system from 1970 to 1975. In: A Voyage of Discovery, Pergamon Press. New York, Martin Angel, Editor, pp. 611-625.
6. Laughton, A.S. 1981. The first decade of Gloria. J. Geol. Research, Vol 86, no. 812, pp 11511-115324.
7. Farr, H.K. 1980. Multi-beam bathymetric sonar: SEA BEAM and HYDRO CHART, Marine Geodesy, Vol. 4, pp. 77-93.
8. Renard, V. and J.P. Allenou. 1979. Seabeam, multi-beam echo-sounding in *Jean Charcot*: Description, evaluation and first results," Intern. Hydrogr. Rev. LVI(1), pp 35-67.
9. McCaffrey, E.K. 1981. A review of the Bathymetric Swath Survey System. Intern. Hydrographic Rev., LVIII (1), pp 19-27.
10. Popp, D. 1984. Improved multibeam sonar shallow water mapping system. Proc. Oceans '84, Vol. 1, pp. 195-199.
11. Spiess, F.N., and R.C. Tyce. 1973. Marine Physical Laboratory Deep Tow Instrumentation System. SIO Reference 73-4.
12. Clifford, P.J., F.R. Germain, and R.L. Caron. 1979. A totally new approach to seafloor mapping, OTC 3548, Proc. Offshore Technology Conf., pp 1681-1689.
13. Klein, M. 1979. New capabilities for side scan sonar system. Proc. Oceans '79, pp. 142-147.
14. Kosalos, J.G., and D.N. Chayes. 1983. A portable system for ocean bottom imaging and charting. Proc. Oceans '83, pp 649-656.
15. Harris, S.E., and R.D. Ballard. 1986. ARGO: Capabilities for deep ocean exploration, Proc. Oceans '86, Vol. 1, pp. 6-8.
16. Jarry, J. 1986. SAR, NAUTILE, SAGA, ELIT-Four new vehicles for underwater work and exploration: The IFREMER approach. Jour. of Oceanic Eng., Vol. OE-11, No. 3, July.
17. Hussong, D.M. and P. Fryer. 1983. Back-arc seamounts and the SeaMARC II seafloor mapping system. Trans. Am. Geophys. Union, Vol. 64, No. 45, pp. 627-632.
18. Blackinton, J.G., D.M. Hussong, and J.G. Kosalos. 1983. First results from a combination side-scan sonar and seafloor mapping system (SeaMarc II), OTC 4478, Proc. Offshore Tech. Conf., Vol. 1, pp 307-314.
19. Kosalos, J.G. 1984. Ocean bottom imaging, OTC 4717. Proc. Offshore Technology Conf., pp. 65-72.
20. Spiess, F.N., and P.F. Lonsdale. 1982. Deep Tow rise crest exploration techniques. Marine Tech. Soc. Journal, 16 (3) 67-75.
21. Somers, M.C., R.M. Carson, J.A. Review, R.H. Edge, R.J. Barrow and A.G. Andrews. 1978. Gloria II, an improved long range sidescan sonar. Oceanology International, Tech session J., London, BPS Exhibition Ltd., pp 16-24.
22. Hill, G.W. 1986. Mapping the seafloor at the rate of 2,500 miles per day, in Proceedings of the Pacific Congress on Marine Technology (PACON 86), Honolulu, Hawaii, March 24-28. pp. OST5/2-5.
23. deMoustier, C. 1986. Beyond bathymetry: Mapping acoustic backscattering from the deep seafloor with Sea Beam. Jour. of Acoust. Soc. Am., V. 79, No. 2, February.
24. deMoustier, C. 1986. Approaches to acoustic backscattering measurements from the deep seafloor. In Current Practices and New Technology in Ocean Engineering, T. McGuinnes and H.H. Shih Eds., A.S.M.E. OED Vol. 11, pp 137-143.
25. Kraeutner, P.H. 1986. Sidescan imaging with Sea Beam acoustic backscatter data: Theory, analysis and implementation. Univ. of Rhode Island thesis, M.S., Ocean Engineering, 84 pages.
26. Tyce, R., J. Miller, R. Edwards, and A. Silver. 1986. Deep ocean pathfinding—high resolution mapping and navigation, Proc. Oceans '86, Vol 1, pp. 163-168.
27. Farre, J.A., and W.B. Ryan. 1985. 3-D View of erosional scars on U.S. Mid-Atlantic Continental Margin, Am. Assoc. of Petrol. Geol. Bull. V. 69, No. 6 June, pp. 923-932.
28. Weisburd, S. 1986. Secrecy and the seafloor, Science News, Vol. 129, March 15, pp 170-173.