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Development of a Seabed Mapping System using SeaBeam2000 Multibeam Echo Sounder Data

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SeaBeam2000 다중빔 음향측심기를 이용한 해저면 맵핑시스템 개발

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Abstract

SeaBeam2000, a multibeam echo sounder, is a new generation seabed mapping system of which a single swath covers an angular range of -60° to 60° from the vertical direction with 121 beams. It provides high-density and high-quality bathymetric data along with sidescan acoustic data. The purpose of the research is to develop a system for processing multibeam underwater acoustic and bathymetric data using digital signal processing techniques. Recently obtained multibeam echo sounder data covering a survey area in the East Sea of Korea (37°00'N to 37°30'N and 129°40'E to 130°30'E) are preliminarily processed using the developed system and reproduced in the raster image format as well as three dimensionally visualized form.

요 약

다중빔 음향측심기인 SeaBeam2000은 차세대 해저면 맵핑시스템으로써, 단일 탐사폭이 121개의 빔으로 구성되어 탐사선의 수직방향을 중심으로 좌우 60°씩의 해저면을 탐사할 수 있다. 이 장비는 현재 한국해양연구소의 온누리호에 설치되어 운영되고 있으며, 다른 해저면 탐사장비에 비하여 짧은 기간 동

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안 넓은 해역에 대하여 고질의 해저 수심자료와 음압자료를 동시에 공급한다. 본 연구의 목적은 이러한 복합적인 다중빔 해저자료를 디지탈 신호처리 기술을 이용하여 처리하는 시스템을 개발하는 것이다. 본 논문에서는 다중빔 음향측심 자료를 이용한 해저면 맵핑시스템의 처리과정을 소개하고, 동해 일부 해역 (북위 37°00' - 37°30', 경도129°40' - 130°40')을 탐사하고 얻어진 다중빔 음향측심 자료를 개발된 시스템으로 처리한 결과를 2차원 및 3차원 영상으로 보여준다.

1. Introduction

1. Background

Ocean maps are essential to the management of ocean resources, which include passive use of the oceans for recreation, transportation, energy, and communications, and extracting food, oil, gas, and other minerals from oceans. The importance of ocean mapping for ocean resource management was highlighted by the establishment of Exclusive Economic Zones by most coastal nations over the past two decades, and the requirement in the 1982 *United Nations Convention on the Law of The Sea* that such nations deposit with the Secretary General of the United Nations seabed charts showing the jurisdictional limits it claims.

Seabed mapping includes both geometrical and physical mapping. The determination of where the seabed is (seabed topography) is called "bathymetry". Two generalized physical quantities characterize the type of seabed: seabed material type based on grain size and/or composition (sand, silt, clay, pebbles, silica, etc.) and the characteristic roughness, length, or textual classification based on grain size and geologic and hydrodynamic processes at work on the seabed.

Ocean mapping includes not only the seabed mapping but also mapping features in the water column such as biomass concentrations, features on the sea surface such as temperature and topography, and sub-seabed features such as stratigraphy, and it provides useful information for mariners, fishermen, ocean engineers, oceanographers, geologists, geophysicists, environmentalist, and biologists. For an instance, nautical charts, specialized ocean maps designed to aid safe navigation, contain information on navigational aids and hazards, coastal lines and coastal features, tides and currents, as well as bathymetry and seabed composition.

Experiments in using sound signals to determine bathymetry were begun in 1915, and by the late 1920s a practical echo sounding machine had been developed by the firm of Kelvin-Hughes (Fillmore and Sandilands, 1983). Many technical refinements have occurred since then, including improved transducers to generate the sound signal and listen for its echo, and more precise timing. For shallow water bathymetry, acoustic frequencies of 20 to 200kHz are used, while for the deep oceans lower frequencies of 2 to 20kHz are required to obtain a strong echo. Simple echo sounders are ineffective for obtaining detailed deep ocean bathymetry, because with a constant transducer size the lower the frequency the wider the acoustic beam angle. Narrow beam transducers are quite large - two degree beamwidth at 10 kHz requires a 3m transducer(or array of transducers), which is difficult to mechanically stabilize against roll and pitch. Two better strategies were proposed in 1960: electronically stabilized acoustic array and interferometry, which have more recently been adapted to multibeam and sidescan sonars, respectively(Davids, 1991).

2. Current Trends in Ocean Mapping

Because of limitations on ship's time, deep-ocean areas are rarely fully mapped. Instead, a series of straight line "swaths"(parallel tracks) are taken by a mapping mission. At a time of day when accurate navigation is available using global positioning system(GPS) data, a perpendicular swath is collected. Sonar has been the only practical sensor for turbid water imaging. Traditionally, underwater images have been produced using sidescan(side-looking) sonars. These sonars look in small azimuth angles and large elevation angles. The result is to "paint" a 2D acoustic reflectance map of the ocean , quite similar to a photograph, where the acoustic intensity value of each grid is influenced by the geometry, the angle of incidence, and the scattering properties of the material from which the acoustic energy is backscattered (Rosenblum 1993).

The sonar systems capable of mapping wide swaths in the deep ocean using two different kinds of measurements were developed over the past three decades to serve the needs of those whose primary interest is either bathymetry or geological seabed mapping: (Wells 1991)

- Bathymetric systems are designed to measure the travel time of the acoustic return from each of many narrow (in the crosstrack direction) beams, yielding an acrosstrack bathymetric profile for each sample. These travel times are converted to slant ranges and then to a crosstrack depth profile.
- Imaging systems are designed to measure the amplitude of the acoustic return from a broad (in the crosstrack direction) sidescan beam. Assigning ranges to this amplitude return as a function of time delay, acoustic backscatter information about a crosstrack profile of the seabed is obtained. Appropriate classification of this backscatter against ground truth provides information about the geology of the seabed, but does not provide depth.

Three-dimensional(3D) underwater imaging is another high-interest area growing in power and potential as volume visualization algorithms are integrated with data from sensors that just begin to provide sufficient resolution for 3D reconstruction.

3. Concurrent Survey System (Bathymetry and Sidescan Imagery)

A bathymetric system only provides information about the seafloor elevation. An acoustic image of the seafloor, however, reveals information about its texture, roughness, and composition. Standard sidescan sonar systems generate such images by transmitting two narrow beams of sound acrosstrack from a towed vehicle (tow-fish) and display the acoustic returns as a function of time or ground range (Somers and Stubbs, 1984). The absence of bathymetric information everywhere except at the nearest point below the tow-fish forces a flat bottom assumption for ground range correction in every scan. Traditionally, this required surveying the same area twice - once for bathymetry and once for sidescan imagery, which resulted in higher ship operating costs and problems of geographically registering the imagery and bathymetry that was obtained from two different surveys and often with two different navigation systems.

In order to obtain the bathymetry and imagery simultaneously, a number of processes have been tried over the years. One of the earliest was to use two arrays on each side of a tow-fish separated by a few wavelengths, and depth was determined from the fringe patterns generated by interference(Stubbs et al., 1974). The concept was refined to measuring the phase difference between the signals on two closely spaced receivers and relating the acoustic looking angle to the phase difference; hence, a number of systems using either high and/or low frequencies have been built, tested, and now are in operation(Denbigh, 1989). The major limitation of such systems is the receivers that are more than half a wave length apart, which translates into errors in depth measurement.

The first combined system to be routinely used was the SeaMARC II system. This system provided both a conventional sidescan image, and also a measure of off-track seabed topography. In contrast to the beam forming techniques used in multibeam sonars which utilize both longitudinal and transverse hydrophone array, the SeaMARC II system (with just longitudinal hydrophone arrays) uses interferometry to measure the angle of incoming energy. Sonar reflections off the seabed will be re-reflected off the sea surface and seabed in a series of multiple reflections. The principal advantages of a hybrid system are that more data are acquired for less ship time, and the registration between bathymetry and acoustic imagery is exact.

Since multibeam sonars -which will be described in detail in the next section - transmit a narrow fanlike beam similar to sidescan sonars but process the returns differently, attempts were made to preserve the acoustic backscattered returns and to produce sidescan like images(de Moustier,1986; de Moustier and Pavlicek, 1987). Since high-resolution bathymetry is available for every ping, it was shown that multibeam sidescan images that are corrected for actual bathymetry can be generated and processed into geographically correct mosaics(Talukdar and Tyce, 1990), although the images were of poorer resolution primarily because coverage was limited to angles near the vertical axis.

Multibeam bathymetry and backscatter imagery are complementary data types, both of which are necessary to provide complete ocean mapping. In particular, separating topography from composition is impossible without first draping the imagery over a digital terrain model.

Table1. Comparison of Deep Ocean Sonar Survey Systems (Revised from Robert C. Tyce,1986).

System	Gloria II	Sea MARC II	Sea Beam	Sea Beam 2000	EG&G 990	ARGO
Frequency(kHz)	6.2/6.8(FM)	11/12(CW)	12.158(CW)	12kHz	59(CW)	100(Pulse)
Introduction	1977	1982	1975	1990	1980	1985
Pulse length	2,4s	0.25-10ms	7ms	3 to 20ms	0.1-0.5ms	0.1ms
Pulse rep.(sec)	20-40	1-16	1-22		0.2-1	0.3
Bandwidth(kHz)	0.1	0.1-4	0.14	15	2-10	10
Bandwidth(deg)	2.5*30	2*40	2.7*2.7		1.2*40	1*40
Array length	5.33m	3.8m	2.8*2.8m	4.3	1.2m	0.8m
Vehicle Length	7.55m	5.5m	Hull mount	Hull mount	1.7m	4.3m
Stabilization	Heading	all axes	all axes	all axes		
Data Type	Digital	Digital	Digital	Digital	Digital	Analog
Tow Depth	30 - 60m	50-100m	Hull mount	Hull mount	to 6km	to 6km
Water depths	>10km	>10km	>10km	>11km	6km	6km
Crosstrack res.	30m	5m	14-233m	0.8deg	0.3-1.3m	0.1-0.4m
Alongtrack res.	218m	175m	233m	0.8deg	0.2-4.2m	0.2-0.9m
Bathy accuracy		150m(3%)	10-50m	1% depth		
Swath width	14-60km	1-10km	0.8depth	3.5depth	0.2-1km	0.1-0.7km
Survey speed	10kts	8kts	15kts	15kts	2kts	1kts
Coverage	imagery	imagery /bathy	bathy	imagery /bathy	imagery	imagery

One difficulty is very different swath widths involved - imaging sonar swath widths can be nearly ten times as wide as bathymetric sonar swath widths. Efforts have been made to combine data from multibeam and backscatter surveys over the same area, made from different ships at different times(Mitchell and Somers 1989). Surveys have been conducted with both systems installed on the same ship.

Over the years, the rapid development in the computer technology and digital signal processing have rendered the old analog beam forming obsolete. A new generation of multibeam bathymetric systems called *SeaBeam*2000 exploits the power of digital signal processing and does most of the signal processing and manipulation in software so that the system can be improved upon without costly hardware changes in future. The system has a full ocean depth capability and covers an expanded swath of approximately 3.5 times the water depth with 121 beams. A comparison of the coverage shows the increased capacity of the new system over earlier systems. More importantly, the system can generate real-time sidescan images corrected for the true seafloor profile, which is a significant breakthrough. And hull-mounted transducers and hydrophones alleviate the determination problems of tow-fish status (pitch, roll , heave, yaw) and location (latitude, longitude, height). Table 1 compares the characteristics of the deep-ocean sonar survey systems being mostly used these days.

II. SeaBeam2000 - Multibeam Echo Sounder

1. Hardware

The SeaBeam2000 can support projector arrays that have up to 64 units and hydrophone arrays that have up to 144 units. Such a system would provide resolution less than 0.8° * 0.8°. Both projector and hydrophone units are individually replaceable within their arrays. It is the size of these arrays and the number of their associated control and sensing modules, together with beam dimensions obtained from array sizes, which differentiate members of the SeaBeam2000 family.

Each projector unit contains several ceramic resonators with the radiating surfaces along a convex surface. This curvature creates a slight dip in the vertical response while projecting greater power in the athwartship direction. Although it has been optimized for operation in the 12kHz region, the low fall-off rate around the peak makes it possible to operate over a frequency range of 11 to 16kHz. All transmit beam patterns are computer controlled by the processor within the digital pitch compensator. Meanwhile, the hydrophone array consists of a number of wide band ceramic line elements configured into two identical sections and mounted athwartship. By configuring the array in two sections in the athwartship axis, it may be mounted in a "V" arrangement centered on the keel so that various hull angles can be accommodated with smooth hydrodynamic flow. The hydrophone amplifiers provide sampled digital amplitude and phase information to the software beam former. Their gain consists of both time-varying gain(TVG) and selectable steps of fixed gain. The filter bandwidth of the hydrophone amplifier is computer selected to match the transmit pulse width. Initial signal filtering is accomplished in

Table 2. General Specification of SeaBeam2000.

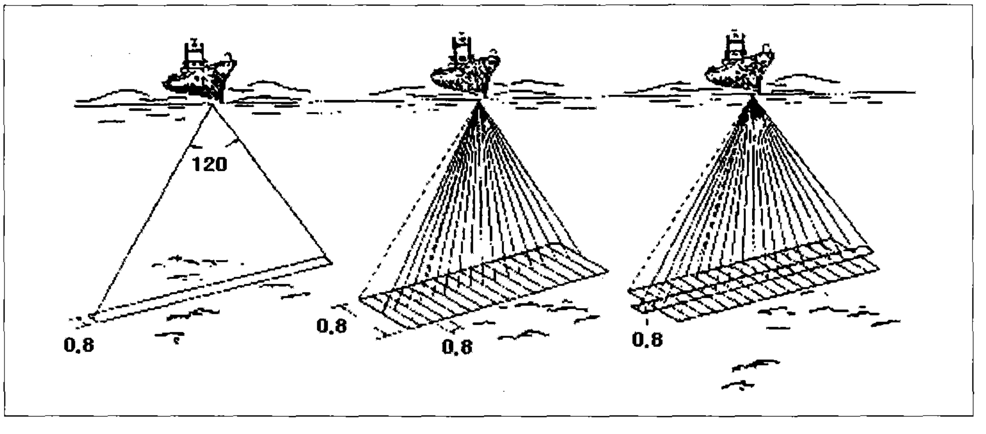
Depth range 10	to 11,000m
Swath width(to 4600m)	120°
Swath width(to 11,000m)	90°
Receive beam width(fore & aft)	15°
Pulse length	3 to 20*ms*
Pitch	± 7.5°
Roll	±10°

hardware, and final filtering is done digitally. Table 2 describes the general specification of SeaBeam2000.

2. Beam Forming Principle

Two groups of transducers are installed under the ship's hull, the projectors for acoustic signal emission , and the hydrophones for reception of echoes from the seafloor.

- Emission : The active part of the emission is made up of 28 projectors, each contained in a rectangular box. Each projector contains 4 magnetostrictive elements mounted in parallel. The 28 projectors are mounted in a 4.3*m* long berth placed along the keel of the ship under a protective dome. Each projector is excited separately. By control of the power and phase of the emission frequency, the emission diagram shown in Fig.1(a) is obtained. The area of seafloor insonified after emission corresponds to a rectangular area subtending angles of 120° by 0.8° . The plane of emission is transverse to the ship and is electronically stabilized for ship's pitch(within ±7.5°) so as to remain vertical.
- Reception : Each receptive hydrophone is made up of piezo-electric elements mounted with intercalating rings on a round bar covered by a rubber sleeve. The reception unit is composed of 40 such hydrophones mounted under a 5.3*m* long protective cover transverse to the ship's keel. The 121 beams are obtained by vector summation of the signals received by these 84 hydrophones. Fig.1(b) illustrates the 121 beams so created. They correspond to signals coming from 121 rectangular zones on the seafloor subtending angles of 15° by 0.8°



(a) (b) (c)

Figure 1. Beam forming schemes of the SeaBeam2000; (a) zones ensonified at emission; (b) zones covered at reception; (c) zones resulting from the combination of (a) and (b) sounded by the multiple beams(usable ensonified area) (Renard and Allenou, 1979).

with the long side parallel to the ship's axis. These zones are not stabilized for roll or pitch.

- Composite emission/reception : Fig.1(c) illustrates the creation of the 121 narrow beams as a result of the composition of the emission and reception diagrams of Fig.3(a) and 3(b). The received acoustic energy comes from 121 square zones, 0.8° by 0.8° , located in a vertical plane perpendicular to the axis of the ship, due to emission stabilization. Their transverse orientation varies continuously with ship's roll and is obtained by reference to a vertical gyroscope after reception of output signals.

3. Signal Processing

The SeaBeam2000 employs a number of algorithms in the array processors, which run parallel in order to determine an adaptive threshold, conduct software beam forming near the normal to the average slope of the seafloor, perform "snapshot" processing to determine ranges and angles for off-normal directions, and process the returned echo amplitudes to a scan of gray scales for generating the sidescan image and with a number of corrections to account for the ship's motion and sound velocity variation during the two-way travel time of the sound pulse.

Near the perpendicular to the average slope of the seafloor, SeaBeam2000 determines the range by an averaging algorithm. Consider two received beams, one near the vertical and one at the side as shown in Fig.1(c). As the sound pulse hits the seafloor and spreads out, it will be detected in the beams formed as the rising and falling amplitude modulated by the beam pattern. In order to estimate the arrival time T_1 and T_2 at the centers of the beams, the amplitudes from the beam former are first gated and then the samples that are above the predetermined threshold level are averaged by a "center of mass" type calculation. In the outer beam, however, the echo wave form extends over an interval that may be many times longer than the transmitted pulse length, making the center of mass calculation progressively less accurate. Since the coverage of

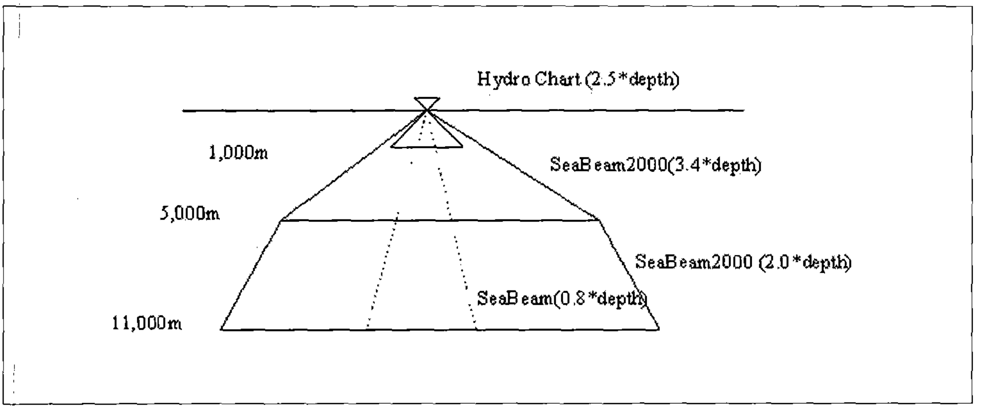


Figure 2. Swath coverage of Sea Beam, Hydrochart, and SeaBeam2000(Talukdar, 1992).

Table 3. Specification of Sea Beam 2000-2(Talukdar, 1992).

	Shallow	Intermediate	Deep
Depth(meters)	10 to 600	400 to 6000	4000 to 11,000
Transmit beam width (in deg.)	4	2	2
Receive beams(per ping)	61	121	91
Receive beam angular spacing(in deg.)	2	1	1
Receive beam width (in deg)	15	15	15
Pulse length(msec)	3	7	20

the SeaBeam2000 is significantly larger than the original SeaBeam, a new algorithm, called "snapshot" processing, is employed for the off-vertical directions. The snapshot processing will not be covered in this paper, and can be referred to (Satriano, et al., 1991) and (Talukdar, 1992). Fig. 2 compares the swath coverages of the original SeaBeam, Hydrochart, and SeaBeam2000.

To optimize the operation over the full 10 to 11,000*m* depth range, SeaBeam2000 operates in three depth modes as listed in Table 3. The shallow depth mode employes only 14 projectors and 42 hydrophone elements. This halves the array lengths, brings the far field closer by a factor of 4, and improves shallow water beam formation. The intermediate and the deep modes employ all the projectors and hydrophones - the difference being the shallow and the intermediate and between the intermediate and the deep modes. This overlap and the crossovers are selected by the operator to prevent frequent switching between these modes while working over bottoms with depths nearly equal to a switch-over value.

III. Post-processing and Survey results

1. Post-processing

SeaBeam data consists of header data(GPS date and location information), multibeam data(spacing from center, beam number, signal to noise ratio, pitch/rolling data), and other sensor data (speedometer data, XBT, gyroscope). The procedure of post-processing the SeaBeam2000 data can be divided into five steps as shown in Fig. 3. Each step works as following:

Step 1 : Archives raw multibeam files and navigation files from the R/V computer recording system.

Step 2 : Examines the validation of data either automatically or semi-automatically.

Step3 & 4 : process the navigation data and the multibeam data merged by time matching

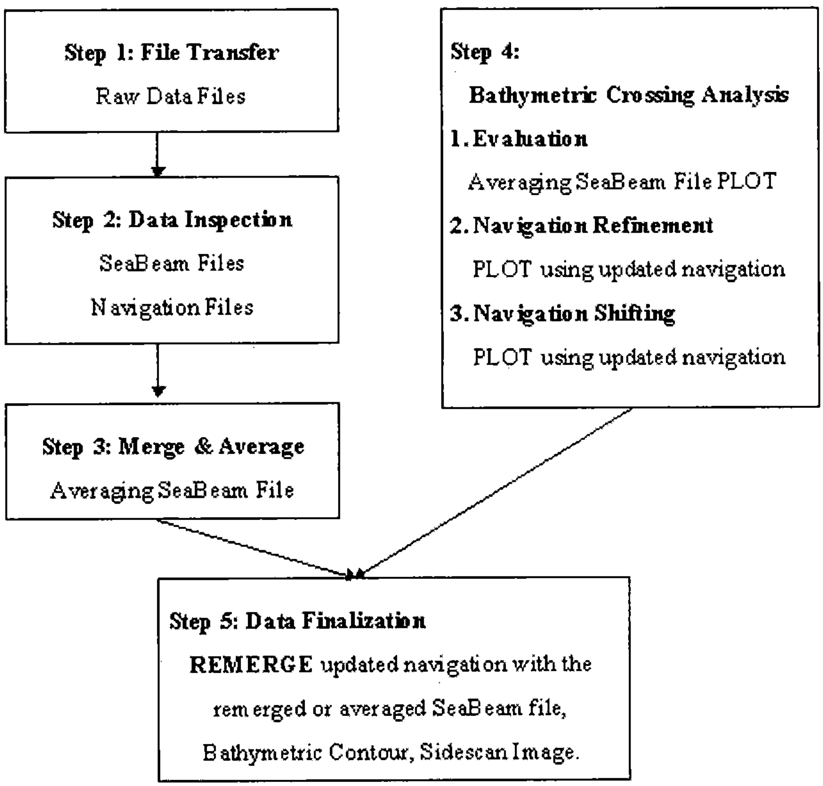


Figure 3. Procedures of post-processing SeaBeam2000 data.

techniques.

Step 5 : visualize the merged data either in 2D or in 3D.

We developed a PC-based post-processing system (Park, et al., 1994). The system provides a number of functions for data refinement and visualization (bathymetric and acoustic imagery). The system also has the interactive inspecting function as shown in Fig. 4 so that operators easily select a ping number and automatically examine a set of neighboring ping data using various filtering methods. Window operators are provided for interpolating unsampled data caused out of pitch & rolling limitation, and abrupt changes in the center beam are smoothed by considering adjacent beam data. The final data format after the post-processing is evenly spaced rectangular data set. Our system provides a gridding function to spatially convert the original data format to lattice data format.

Fig. 5 shows the waterfall display of bathymetric data. This function provides 2.5D online seafloor terrain view which makes it possible to roughly examine effects of seafloor terrain on the

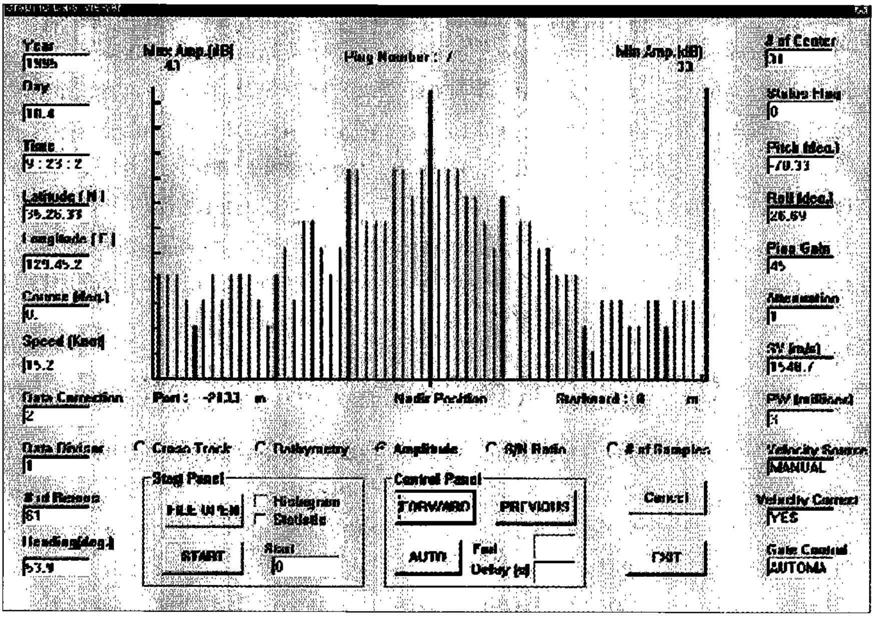


Figure 4. SeaBeam Data Viewer running on Window95.

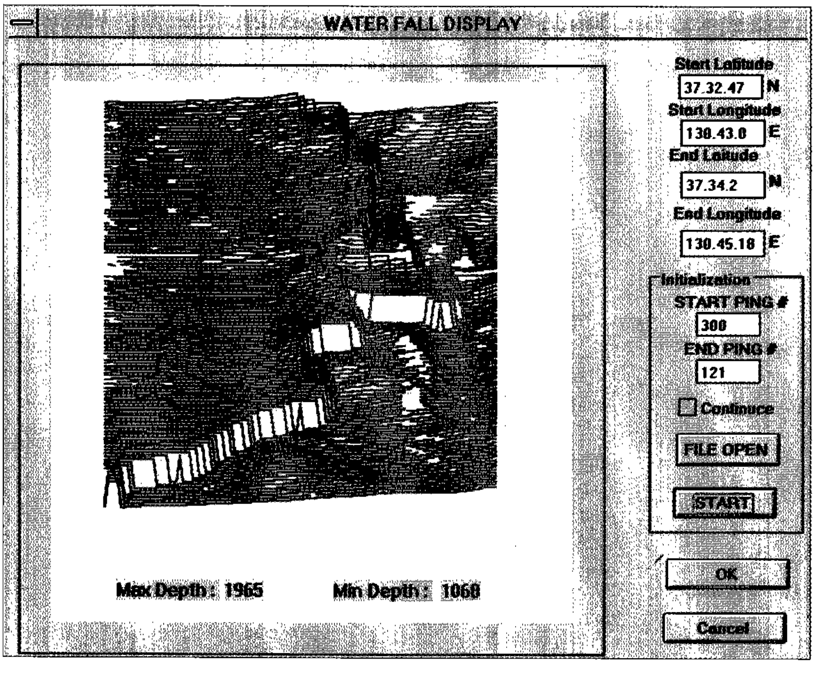


Figure 5 . Waterfall Display.

sidescan image.

Any gaps in the survey coverage are filled with a smooth, interpolated surface. Using the output gridded file, conventional continuous-line contour plots and colorfill contour plots can be created on pen or electrostatic plotters, and the lattice data set is transformed to DEM(Digital Elevation Model) or sidescan image format. Then, the raster image format data converted from bathymetric and acoustic amplitude data can be processed by digital image processing techniques for visual enhancement. Digital image produces final grids which closely correspond to the input multibeam swath data. Artifacts that appear in the final grid can usually be traced to poorly navigated swath data which should be removed to produce high quality swath maps.

2. Survey and Processing Results

During May 10 to 15, 1993, the swath mapping with SeaBeam2000 on the R/V ONNURI operated the East Sea of Korea which covers the area between 37° 00'N, 37° 30'N and 129° 40'E , 130° 40 E (74.490 km × 55.859km(UTM)) of depth ranging from 200m to 2000m. The size of resulted SeaBeam2000 ad navigation data is about 90 Mega Bytes.

Fig.6 shows the navigation track chart during the survey and Fig.7 is the bathymetric

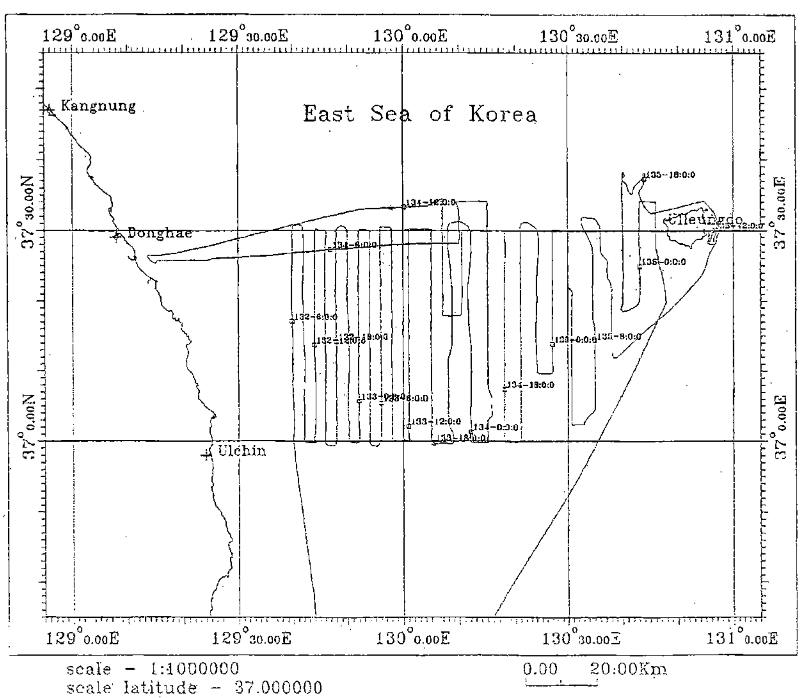


Figure 6. Navigation track chart. (1993, East Sea of Korea)

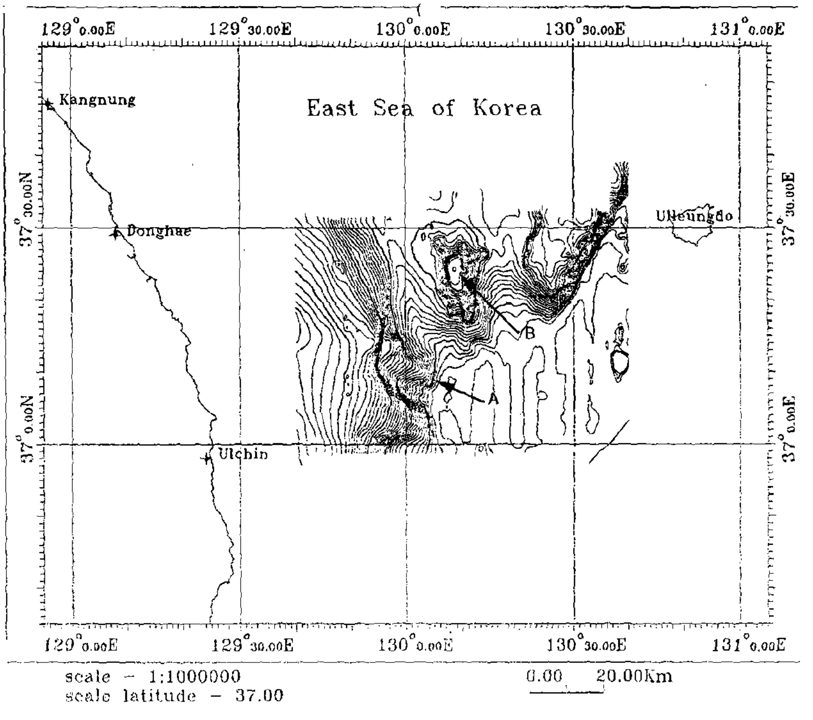


Figure 7. Bathymetric contour map.

contour map of survey area which is gridded by 500m * 500m square lattices. The thick contour line shows 500m intervals, and thin line is 50m contour interval. The 2000m contour line (A) describes the start of the Ulnung basin. The center of a seamount(B) locates at 37° 25'N , 130°09'E. The seamount has a steep-sided peak rising from 1,500m up to 900m in depth, and its peak spreads 10km in the direction of North-South, 5km in the direction of East-West. 10 small seamounts which have steep-sides are located in North-West and South-East to the seamount (KORDI, 1993).

Following the post-processing procedure describe above, the resulted sidescan image is displayed over the navigation track chart in Fig. 8, where white areas represent a strong backscattering amplitude which is caused by specular reflectance and high density composition of seafloor sediments. Finally, Fig. 9 shows three-dimensional visualization of the bathymetry. Figures 7 through 9 illustrate the use of SeaBeam2000 for a detailed seabed mapping utilizing a highly precise navigation accuracy. However, as one moves away from shore, navigation accuracy usually decreases. To counteract this, as water depth increases, the width of the SeaBeam2000 bands increases and so does the possibility of localizing large typical structures such as scarps and seamounts, which may be used as a tie point in a survey. SeaBeam2000 data

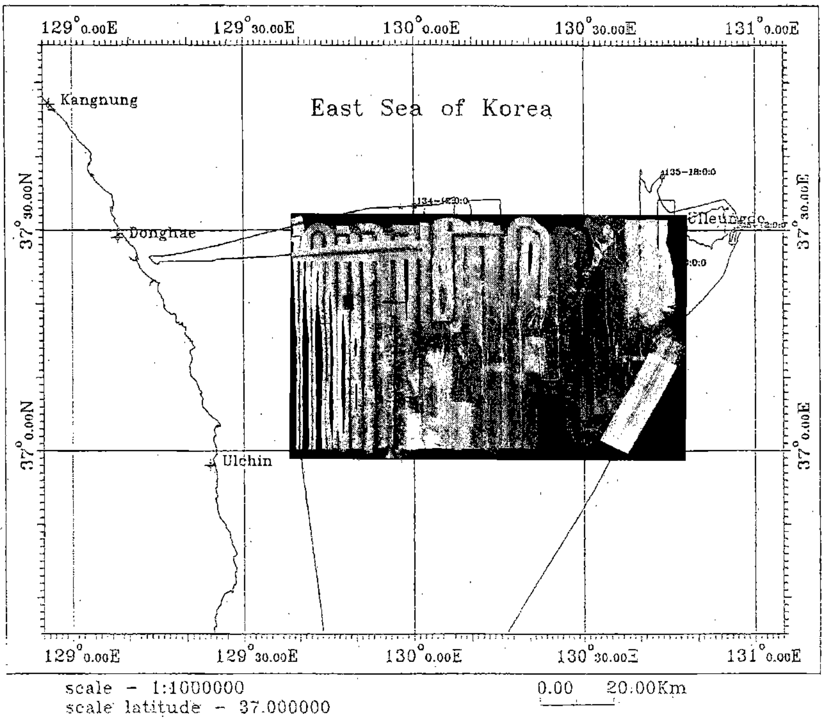


Figure 8. Sidescan image over navigation track chart.

collected along isolated lines have proved to be highly profitable. Systematic reading of seafloor structure orientation permits one to reveal the tectonic style of the area and to correlate it, for example, to an oceanic or a continental origin.

For station work, one usually wishes to keep the ship fixed relative to a seafloor structure. The SeaBeam 2000 can be used for that purpose by introduction of a fictitious speed in order to keep the plot running even though the ship is not moving. Motion of the ship relative to the bottom can be monitored, and corrections applied. For extensive station work, multibeam technology could be applied to measure depth both fore and aft as well as athwartship.

IV. Conclusions

The SeaBeam2000 opens up new horizons in the field of concurrent underwater remote sensing (Bathymetry and side scan image) for scientific and applied researches as well as in the realm of systematic marine cartography. The main advantages over mono-beam techniques are

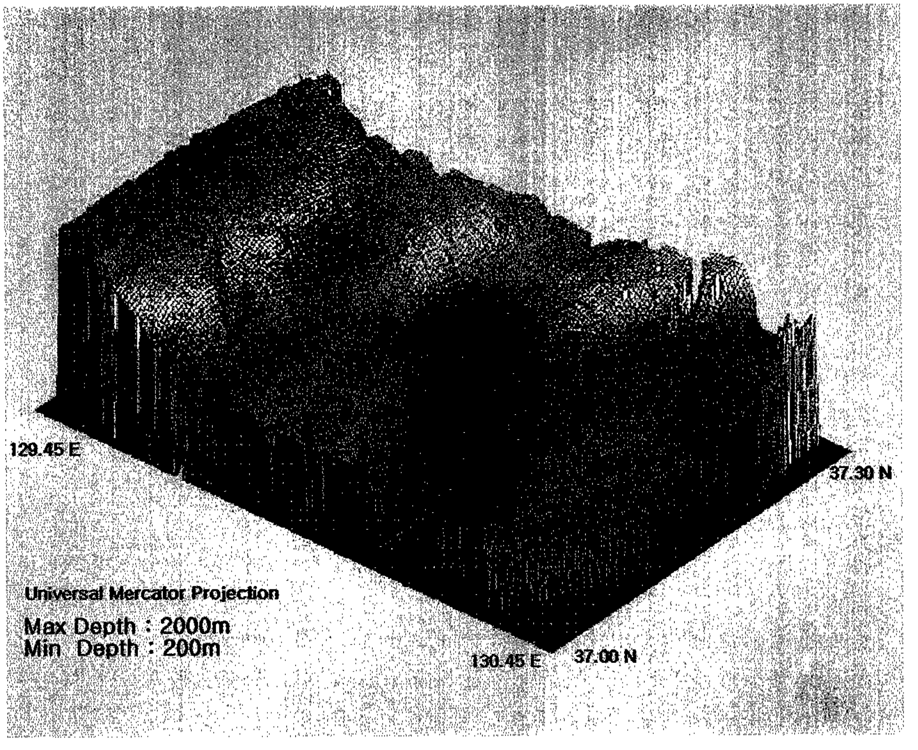


Figure 9. 3D reconstruction of Bathymetry.

that it provides 121 equivalent mono-beam tracks without the absolute need for precise ship positioning in order to get an equivalent set of data with a mono-beam system, and that both bathymetric and acoustic amplitude data are simultaneously acquired for less time.

In particular, digital bathymetric data for seafloor have been rapidly increasing in both volume and variety. They not only provide new perspectives on the morphology of the seafloor but also present a number of problems with regard to developing display methods that convey the large amount of information contained in them. Digital image processing and 3D computer graphics techniques have been employed to effectively display underwater bathymetry.

Further research works include the classification of seafloor based on the acoustic amplitude data and building an oceanographic database, and the system will be expanded to include other oceanographic data such as sea-surface temperatures, tidal information, etc.

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