NEW BATHYMETRIC SURVEYING AND PROCESSING SYSTEM BASED ON SEA BEAM 2000†

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Abstract

The Hydrographic Department, Japan Maritime Safety Agency has installed the most advanced bathymetric surveying system of 90 degrees swath width, called SEA BEAM 2000, which is a new system developed by the SeaBeam Instruments Incorporation, on the newly built survey vessel Meiyo in October 1990. The practical survey using this newest system has been carried out.

The present SEA BEAM 2000 has a good capability of 120 degrees swath width and side scan image output by combining interferometric technologies since February 1992. By adopting the interferometric technique, the resolving performance of bottom reflection wave and the multi beam depth measurement are improved remarkably.

Also, we developed a new integrated navigation system and a new data processing system for the SEA BEAM 2000. For example, the computer program which rejects erroneous data of 1 or more percent abnormalities by automatic analysis of abnormalities based on the continuity of the topographic feature is very useful. Since SEA BEAM 2000 records additionally intensity data of 121 beams, we made grazing angle and position corrections of the beam intensity data and prepared the intensity map by using a digital color photograph printer. Furthermore, we tried to make a 3-dimmentional intensity map by using depth data. This map indicates very detailed topography of the sea floor, such as faults, complex rock walls and channels.

Introduction

The Hydrographic Department, Japan Maritime Safety Agency, installed the most advanced bathymetric surveying system of 90 degrees swath width, called SEA BEAM 2000 on the newly built survey vessel Meiyo in October 1990, with the close cooperation of the SeaBeam Instruments Incorporation (SBI).

As the SEA BEAM 2000 was a new system developed by the SeaBeam Instruments Inc., it took a few months to finalize the adjustment step of the instrumentation in the field at sea, before actual survey operations were inifiated with the system. The first practical survey using this newest system was carried out in the sea areas off Boso-peninsula in March 1991, followed by the survey conducted off the coastline of Miyagi- and Fukushima-prefecture in April 1991 and around the seamount Mikura in August

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1991.

The present functions of the system incorporated in the SEA BEAM 2000 were confirmed through these survey operations. Also, the integrated navigation system and a new data processing system were contributed at the designing and developing stage proceeded together with the project to build the new Meiyo as replacement of the old Meiyo.

Since Februaly 1992, the Sea Beam 2000 on the Meiyo has been upgraded with addition of capabilities of 120 dagrees swath width as well as side scan image output by combining interferometric processing techniques by Sea Beam Instruments Inc. The sea test was conducted in and around the Bonin Trench having varying depths of 100 to 9000 meters, and a good result was obtained (Asada, 1992).

In March 1992, following the test, the bathymetric survey using the Sea Beam 2000 with 120° swath width was conducted around south area of Izu peninsula.

We have processed this data and prepared a detail bathymetric contour chart and an impressive beam intensity map. At the same time, we also tried a simple analysis of the data quality.

In August 1992, we conducted the survey through 20 days around Nankai Trough at the highest ship's speed over 15 knots, becasue we required the widely covered bathymetric data of a map area 1/500,000. As the result, we aquired the Sea Beam 2000 data covering most of the important area with some error of flow noise. These erroneous data have been rejected satisfactorily by the automatic rejection program of erroneous data.

In Octover 1992, the signal-to-noise ratio function of the reciver in the Sea Beam 2000 system was improved by the engineer of SBI. After this improvement, the erroneous data of the Sea Beam 2000 under the rough sea condition like the sea state of over 5 or at high ship's speed have been decreased remarkably. The sea test of the system evaluation at the 100 to 2000 meters deep area brought us a noiseless and good result under the conditions of wind speed over 15 meters/second, wave hight over 3 meters and ship's speed about 10 knots.

As the Meiyo of 621 tons is a middle size vessel, the rough sea condition or high ship's speed had brought sometime critical damage to the bathymetric data. However, it is now confirmed that the Sea Beam 2000 on the middle size vessel Meiyo enables us to carry out surveys even under such a considerably bad condition. The Sea Beam 2000 have operated well around Bonin Trench in spite of the winter's strict sea condition, such as wind speed of 30 meter/seconds.

1. SEA BEAM 2000 surveying system

To efficiently carry out survey operations with the SEA BEAM 2000 and others, efforts were placed on production of a blue-print for an intergrated navigation system based on a designing concept consistent with that of the SEA BEAM 2000. The resulting system was installed on board the new vessel Meiyo.

The integrated navigation system has a reference clock, to which all the surveying devices are synchronized. In the past, a time deviation between the positioning and the sounding data always brought us troublesome headaches. The SEA BEAM 2000 receives the data of clocks, posistions, sea-surface temperatures, gyro and log outputs, etc. from the navigation system. The navigation system also records measurements which are transferred from the SEA BEAM 2000. An exellent capability of CPU HP835CHX built in the navigation system, which has been provided by advanced techologies in the field of computer science, allows us to process measurements acquired onboard, such as to prepare contour charts traced along the tracks of the SEA BEAM 2000, etc.

1—1. Improvement of surveying equipment

(1) Special functions of the integrated navigation system

There are 3 models of GPS equipment, a 2-channel type MX4400GPS, a 12-channel type MX4810GPS and a 6-channel type MX4200GPS placed onboard the vessel as the GPS positioning device. In the field at sea, MX4810GPS independently determines position-fixes and also acquires pseudo-range data, and in a reference point on land, another 12-channel type MX4818GPS for differencial positioning, which is a reference station systematized with an IBM PS-2 computer, calculates and stores corrections for the pseudo-range data. The reference station has a 600Mb (300Mb on one side) magneto optical disk to record a great number of differential data. Both MX4810 and MX4818 can primarily store about 30 Mb of differential data in a day. A cesium frequency standard supports the reference clock, Loran-C range measurements and GPS fixes. MX4400GPS can determine position-fixes with only 2 GPS satellites. The reference clock for the whole surveying devices onboard is syncronized at a higher accuracy by the time reference function of MX4200.

For Loran-C navigation, 2 sets of specially designed, highly accurate receiving equipments are incorporated. These equipments have a fixing resolution of $0.01\mu s$ and a capability to determine position-fixes in a hyperbolic and a range-range mode. The Loran-C equipment can fix 4 hyperbolic line-of positions (LOPs) and range lines from 5 transmitters. And the system can select any LOPs to fix position and automatically compute all offset of LOPs by compairing with each LOP with one of GPS fixes determined during a 6-hour period. The operator also can insert corrections either manually or automatically. The corrections are added to the value of each LOP so that no position deviation can result from the change of the LOPs used in due course.

The system also incorporates an ability to operate in a mode of Trisponder; i.e., a microwave position fix system.

The integrated navigation system normally performs a multi-mode measuring function with 5 or more positioning assemblies and continuously outputs the best position-fixes. The 5 assemblies include MX4400GPS, MX4810GPS, 2 sets of Loran-C receiving equipement and SNX(GPS). SNX, we call, calculates a 2-dimentional positon from all the pseudo ranges, using GPS data supplied by MX4810GPS. Each range is weighted by HDOP, S/N, etc. Most of the earlier GPS receivers on the market at the time of the development stage of this positioning system generally adopted a method to randomly select and combine 4 GPS satellites for position calculation, not taking account of the optimum combination of DOP, and then produced satellite-fixes in poor quality. In addition, it was frequently experienced that position determinations in 2-dimension with 3 satellites provided more accurate fixes than those in 3-dimension with 4 satellites. Recent GPS receivers have been incorporated with a position calculation technique derived from the similar concept of ours.

In these positioning assemblies, the operator choses 3 assemblies as the primary measurement tool of the system. The system assesses processing conditions of each assembly and identifies the order of priority for preference; when a higher priority assembly was somehow degraded, the one positioned at the next priority will automatically take the higher place, and when the degraded resumed its normal condition, it automatically goes back to the previous location. We usually select MX4400GPS, MX4810

GPS and R-R Loran-C as the 3 primary assemblies.

A graphic CRT indicates 3 curves of tracks individually produced by the 3 positioning assemblies, together with planned measurement lines and shorelines.

At the same time, navigational information to assist in taking the courses along the measurement lines is also displayed on the CRT, together with current flows, wind directions and wind speeds.

The integrated navination system is connected to all the surveying devices onboard, and provides necessary information, as well as records all the data from the SEA BEAM 2000, a gravity meter, a geomagneto meter and an acoustic doppler current meter.

Under and after the surveying operation at sea, the system can produce the best position-fixe among the data provided by 4 routs of positioning elements; above 3 asseblies plus DGPS, through a graphic data processing in a conversation mode. This system also enables us to prepare a depth contour chart along the tracks, a track chart and a sounding chart, utilizing the data the SEA BEAM 2000 provides. For the CPU of the system, 835CHX of the HP9000 series is employed. In future, we well improve the processing capability of the system on board, incorporating a processing software being developed for the machines for land use.

1—2. Re-establishment of processing software

We rearranged the existing software (A. Asada, 1988) and relocated them on the HP-400 UNIX computer. Additionally, we developed some new programs to improve the processing capability. We will present these programs in the following paragraphs. Details of the new programs will be presented mainly.

(1) Positioning

a) GPS differential post-precessing

b) Position-fix correction program

With this program, we can call various data acquired by each of the positioning sensors on the graphic display, set process time to get optimum position data on the CRT screen by using a mouse to select the data and put the data to be processed with an optimum filtering, a calculation to shift determined fixes to absolute positions and a smoothing of data connections, through a graphic conversation technique. The program enables us, easily and at a high speed as well as a good accuracy, to remove spike errors in the position-fixes, to smooth meanderings caused by instability of the position-fixes and to process difference in levels resulted from combination change of the GPS satellites. An example of the display on the processing is shown in Figure 1.

Simultaneously treated position data:

to choose max. 4 pairs from

GPS Positioning Assemblies (Navigation fix, Differential fix),

Loran-C Positioning Assemblies (Hyperbolic Navigation, Range-Range Navigation), and

Micro-wave Positioning Assemblies.

Function of processing

Variable scale indication: to indicate navigation data of 4 paired LOPs at random scales.

Patch-work processing: to connect optimum position data by a patch-work, absolute position shifts and parallel position shifts through a mouse.

Off-setting: to compensate irregular at the data connections created by the patch-work process-

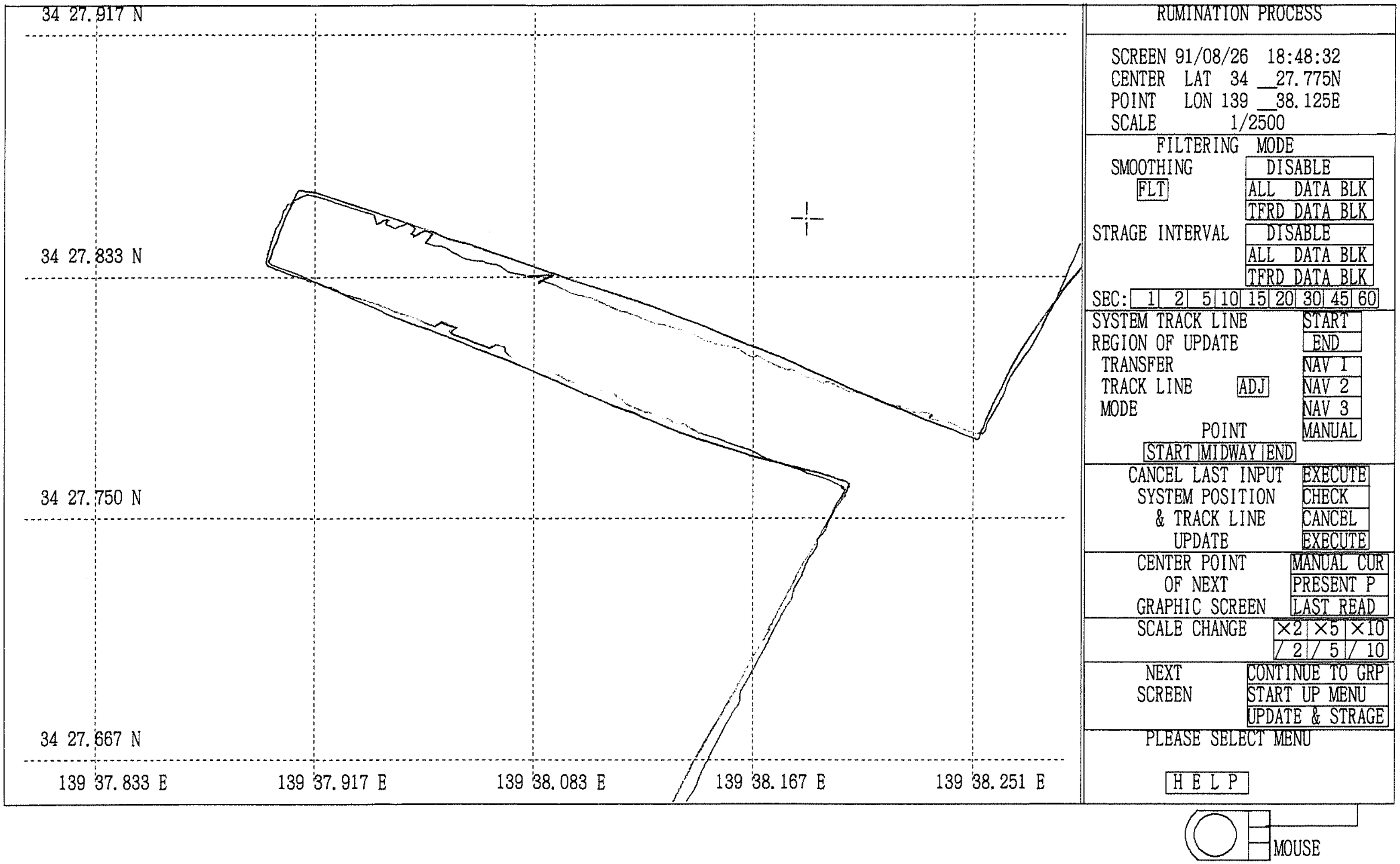

Figure 1. An example of the position-fix correction on the display.

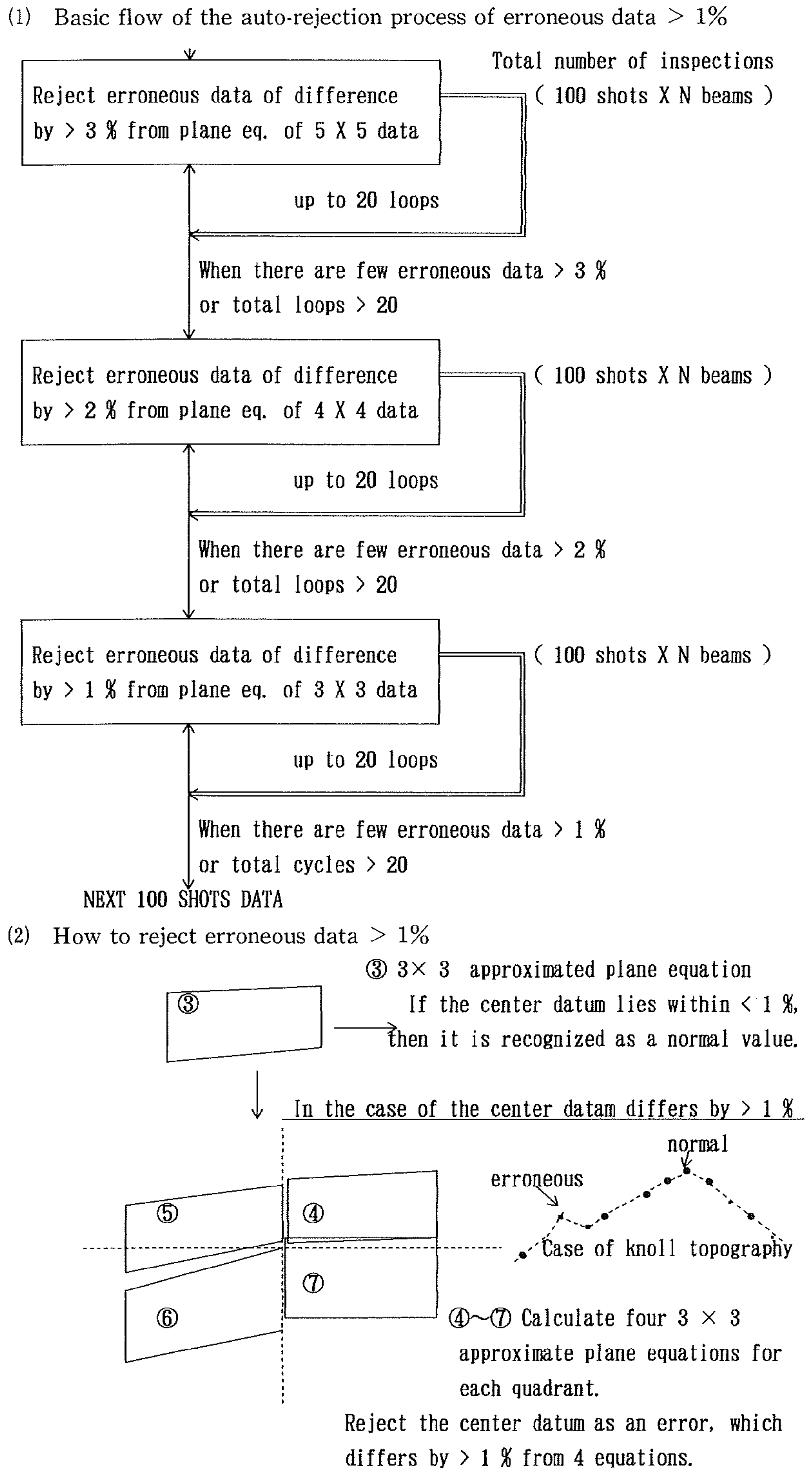

Figure 2. The auto-rejection process of erroneous data

ing.

Filtering: to reproduce actual tracks by filtering wavy track data resulted from variation of the data values.

c) Track chart processing

(2) SEA BEAM 2000

a) Transfer to JMSA unified format

This program changes format of the data provided by all the multi-beam sounding devices to that of the unified in order to process the output data with the programs below. The unified format can treat the data having 1 up to 200 of the beam number. We have so far programmed the software for the SEA BEAM 2000, the SEA BEAM, the Hydrochart II, the HS-10, the HS-200 and the Hydrosweep.

b) Automatic rejection of erroneous data

We have devised a computer program which eliminates 1 or more percent abnormal data by automatic analysis of abnormalities based on the continuity of the topographic feature. We assess raw data and must not modify. A basic flow of the program is shown in Figure 2. The program is somehow adjusted to be consistent with the characterizations of actual data. The foundation to define error data depends on the fact that there is no topographic feature which has only one spike datum. Furthermore, we identify that the data which have no correlation to the surroundings must be erroneous. However, erroneous data sometimes have like a continuous topographic feature. And this phenomenon is often caused when most of data in same shot are bad, and due to flow noise under the transducer. Thus, we designed the program not to identify as erroneous data in the areas with complex topograpy where there are faults, sea-knolls, etc. This scheme has provided a nearly perfect rejection of erroneous data by an automatic method. The execution of this program was impossible for traditional computers to accomplish it due to the time limitation, because the process requires quite a lot of calculation jobs. The advanced technology on work-stations in the computer system these days, enables us to clear the problems in carrying out a great number of calculations. The several improvemens of the program have been made through actual processings. The latest fundamental processing flow of the program is as folows:

1) To read data at the size of 100 shots.

2) To remove much erroneous data, by checking every data for 3 or more percent of abnormality. This is a kind of technique which first eliminates larger errors and then reject smaller errors. Each point datum is judged from the 5 x 5 data which are extracted in the fore and after shots, the left and right beams of itself.

* To extract 7 x 7 data from the fore and after shots, the left and right beams of the checked point.
* To calculate the approximated plane of 5 x 5 around the center.
* The data are regarded as normal, when they lie within 3 % of the approximated plane.

If the data are regarded as doubtful;

* To calculate the approximated planes of each 5 x 5 corresponding to the four quadrants which place the data point at the origin.
* To remove the data which makes 3 or more percent differnt from the approximated planes of the four quadrants, identifying the data are approximated planes of the four quadrants, identifying the data are erroneous.

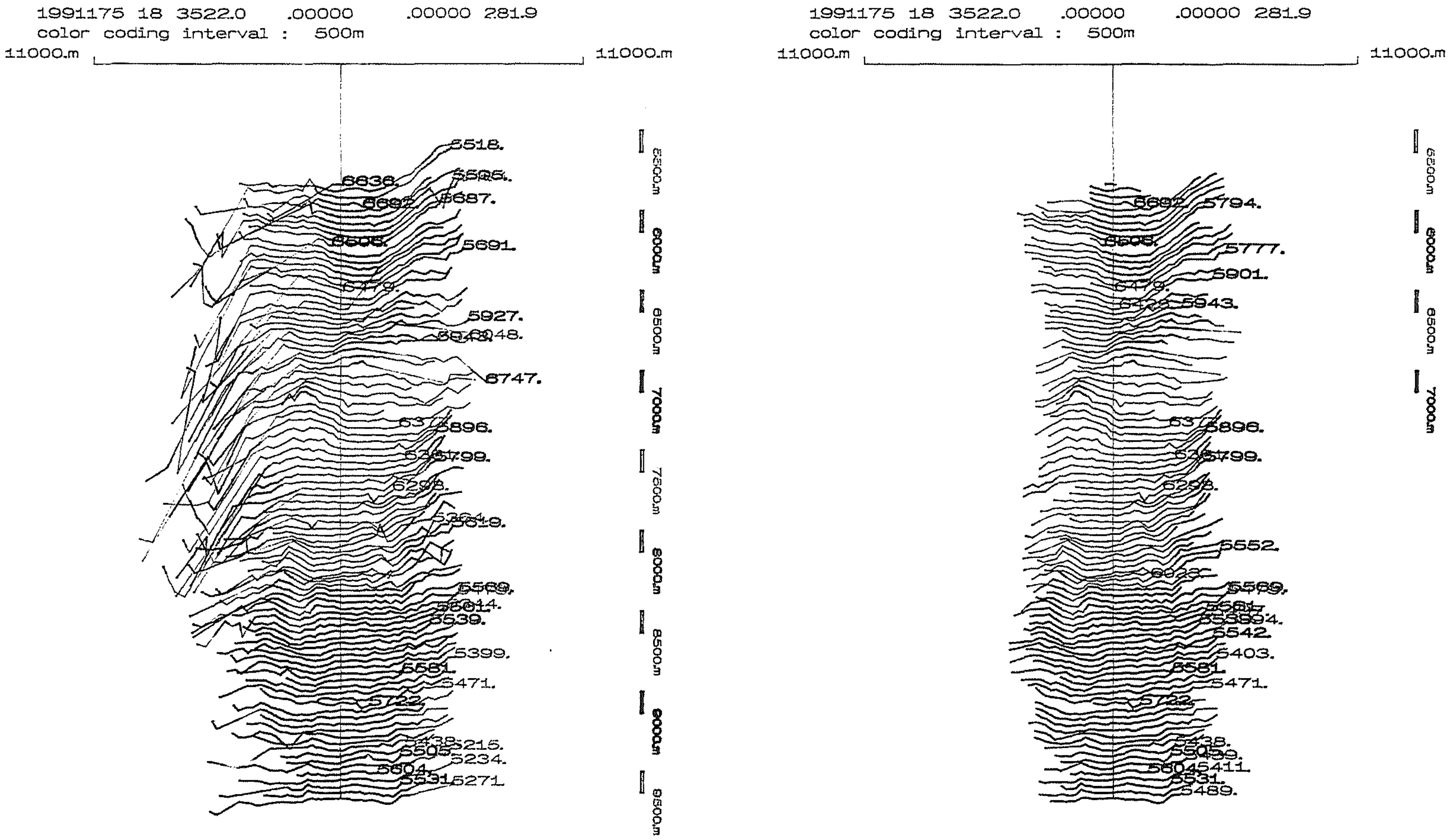

Figure 3. Water-fall display by the Auto-rejection Process of SEA BEAM 2000 data of poor quality. Original data are shown on the left, and processing data is shown on the right.

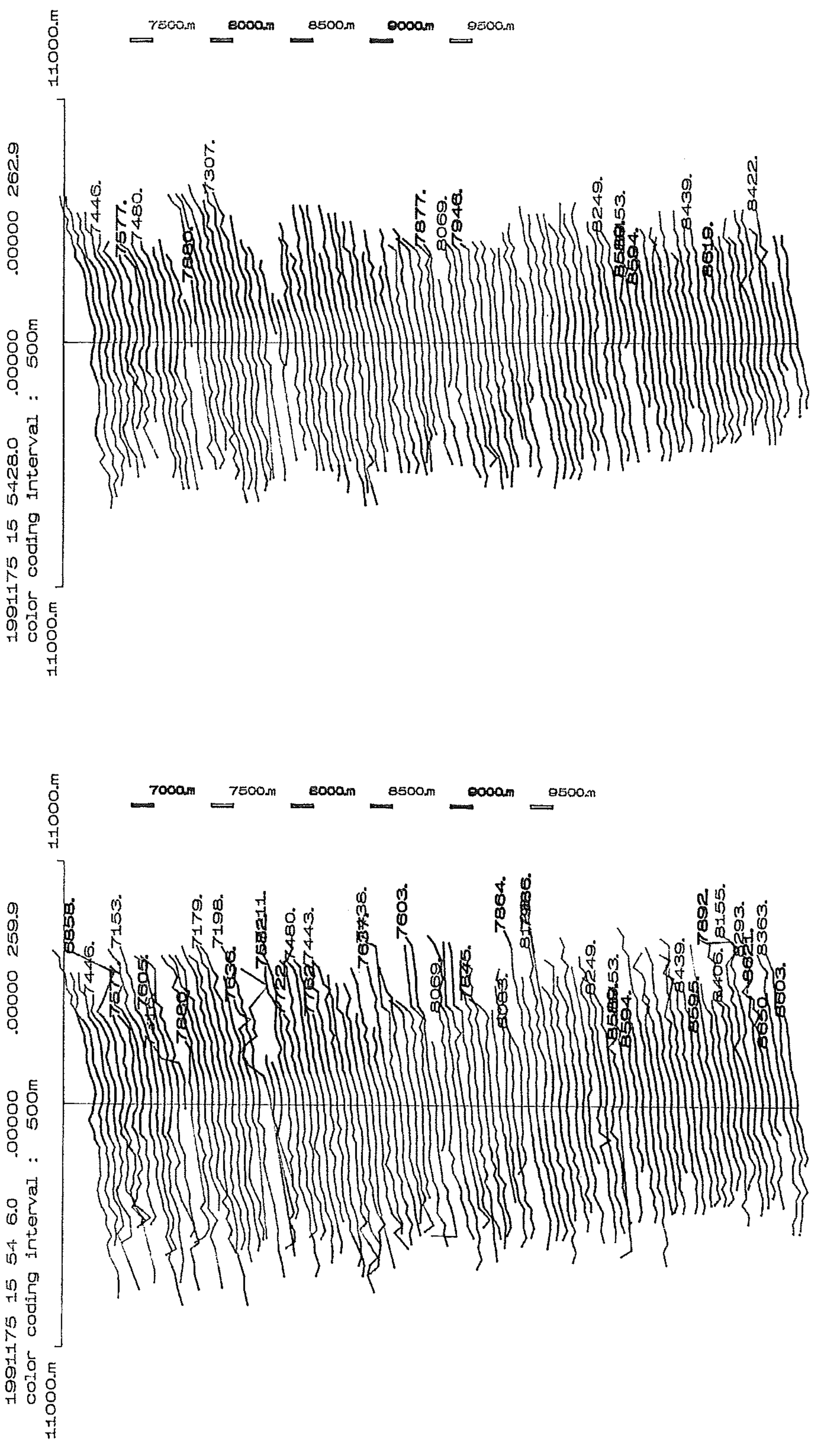

Figure 4. Water-fall display by the Auto-rejection Process of SEA BEAM 2000 data of poor quality. Original data are shown on the left, and processing data is shown on the right.

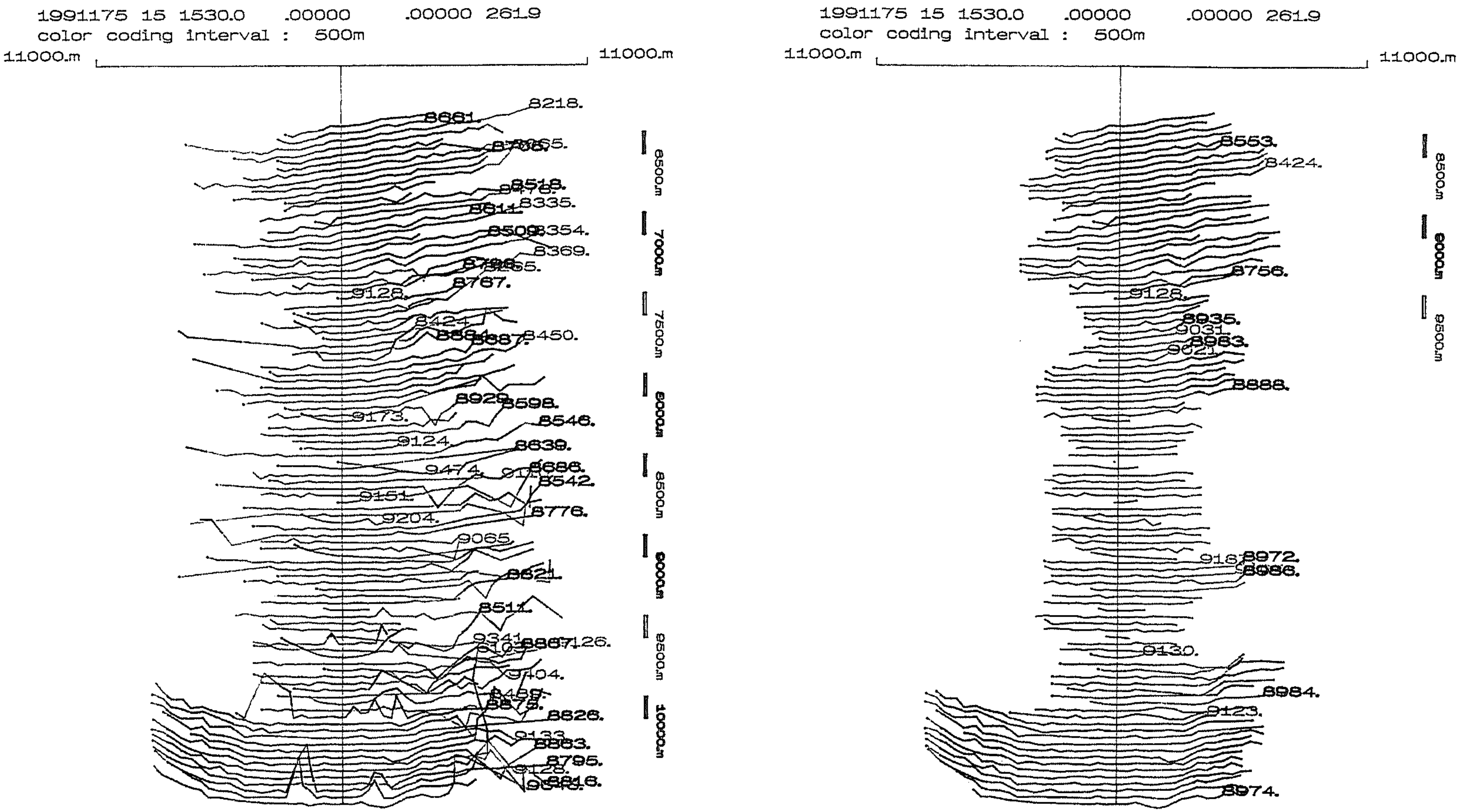

Figure 5. Water-fall display by the Auto-rejection Process of SEA BEAM 2000 data of poor quality. Original data are shown on the left, and processing data is shown on the right.

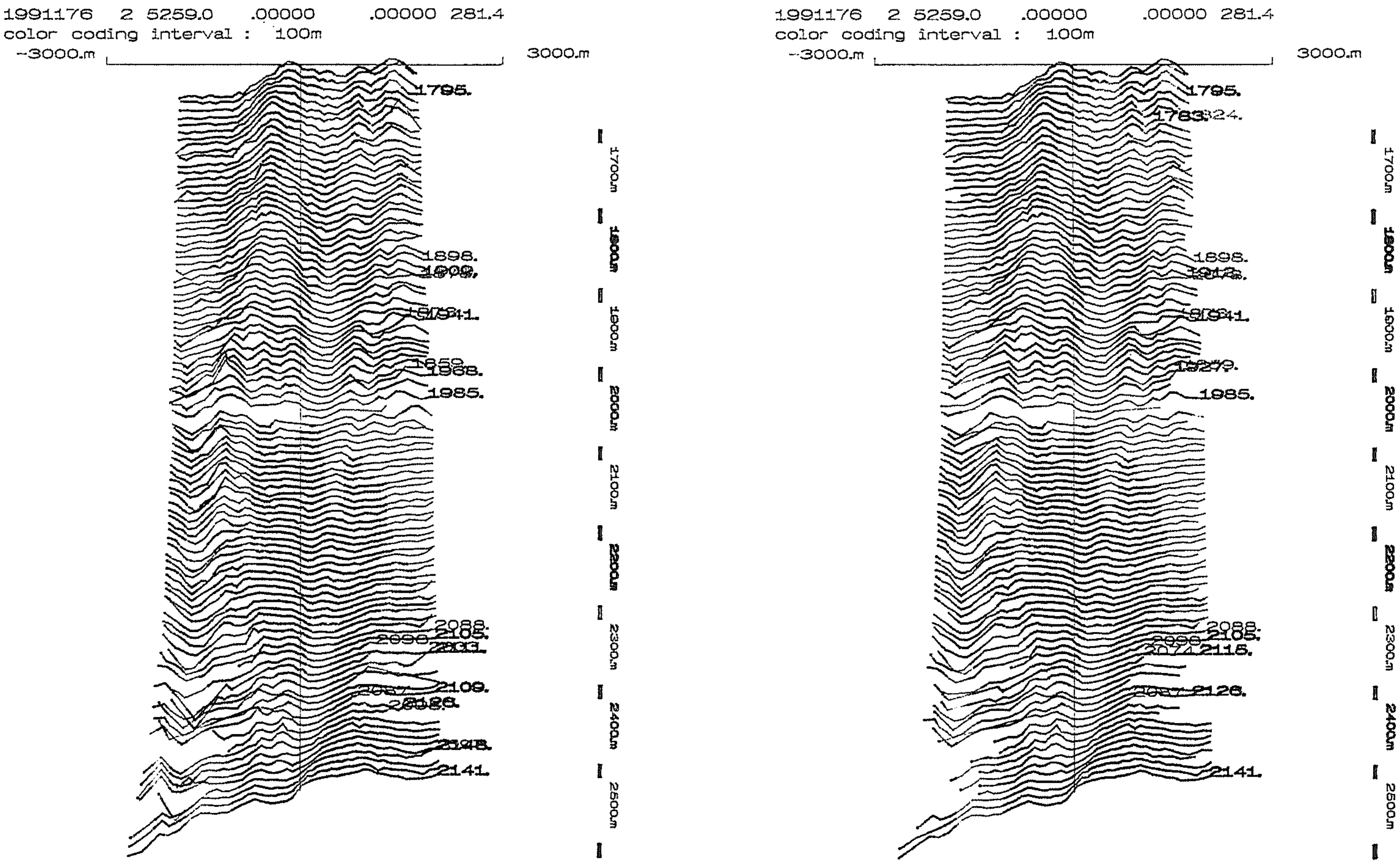

Figure 6. Water-fall display by the Auto-rejection Process of erroneous data. Original data are shown on the left, and processing data on the right. Complex topography data were not rejected.

* To check and remove erroneous data for each beam of 100 shots, repeating the steps above up to 20 cycles or when the erroneous data are few.

3) To check every data of one point for 2 or more percent of abnormality.

This procedure is almost the same as 2). The different points are as follows:

The size of the approximated plane is 4 x 4.

The percent of the judgement is 2%.

4) To check every data of one point for 1 or more percent of abnormality.

This procedure is almost the same as 2) also. The different points are as follows:

The size of the approximated plane is 3 x 3.

The percent of the judgement is 1%.

5) To store the results of the 5th to the 96th shot.

6) To add the 96 shots to remaining the final 4 shots and repeat the steps 1) to 5) above.

Examples of the execution with this program are shown in Figures 3~6. The left side indicats raw data and the right side the processed results. The same information is displayed on the CRT as the same figure. These data explain that the sea area surveyed was in bad condition, the survey operation with the SEA BEAM 2000 was not well accomplished or the sea-bottom had a complex topographic feature. These bad data are suitable to show the performance of the program. As we can see in the figures, only bad data are automatically rejected from the original data; data of sea-knoll and fault, etc. are not rejected. Outputs of the SEA BEAM 2000 for 100 shots require about 18 to 60 seconds to be fully processed by HP400. Data acquired during one segment of a survey operation, which corresponds to about 150 - 500Mb, needs a day for automatic processing.

c) Replacing of the position-fix data to the post-processed data in the unified format

d) Contour processing time-sequentially

This program is to produce a depth contour chart with the swath width along the tracks.

e) Contour processing (A. Asada and A. Nakanishi, 1986)

* Calculate beam position (from center lat., lon., heading, crosstrack distance → to beam lat., lon.)

This is to calculate the latitude and longitude of each beam.

* X,Y Coordinate Transfer (TM, UTM, LAMBELT, MERCATOR & Others)

This program translates the geographic positions of the beam to X-Y coordinatetes on a chart. These two processes always allow us to make highly accurate mapping. The heading of a vessel usually differs from the direction on a X-Y chart. The difference becomes greater as the latitude ascends higher. The crosstrack distance of beam is also always different from a distance on a X-Y chart. By these reason, this procedure is very important.

* Meshing (with Z, X, Y dimensions)

Each mesh also has a position information to provide accurate mapping.

* High accurate contouring with Z, X, Y dimensions (not gridding)

This program draws accurate contours based on the Z, X and Y of the meshes so that the contour chart and the sounding chart are in a perfect accordance.

f) Sounding chart processing

g) Application software

Table 1. Comparison between SEA BEAM and SEA BEAM 2000 by the Sea Beam Instruments Inc.

	SEA BEAM	SEA BEAM 2000
DEPTH RANGE (M)	43-11,000	10-11,000
FREQUENCY	12.158 kHz	12 kHz ± 50 Hz
ACCURACY	0.25 % of depth	0.1 % of depth
DOPPLER COMPENSATION	NO	YES
TRANSMIT ARRAY SIZE (M)	2.8 X 0.16	4.6 X 0.45
PROJECTOR BEAM (DEG)	54 X 2.67	100 X 2, 4
PULSE LENGTH (MSEC)	7	3 - 20
RECEIVER ARRAY SIZE (M)	2.9 X 0.4	5.25 X 0.5
MOUNTING	(V TO 15 DEG)	(V TO 10 DEG)
RECEIVER BEAM (DEG)		
VERTICAL BEAM	2.67 X 20	2/4 X 15/30
15-DEG BEAM	2.67 X 20	2/4 X 15/30
45-DEG BEAM	N / A	2/4 X 15/30
SIDE LOBE LEBEL (DB)	-25	-25
PULSE REP (SECONDS)	1 - 15	1 - 22
NUMBER OF BEAMS	16	61 / 121
BEAM FORMING	HARDWARE	SOFTWARE DIRECTED
COMPUTERS:		
DATA PROCESSOR	DG ECLIPS	DEC VAX 4000
REALTIME-CONTROL	HARDWARE	INTEL 80386
SIGNAL PROCESSING	HARDWARE	TI TMS320C30
ARCHITECTURE	DATA GENERAL	PASSIVE AT BACKPLANE
EQUIPMENT SIZE	2 RACKS	3 RACKS
DISPLAYS:		
CROSS-TRACK PROFILE	YES	YES
BEAM INTENSITY	YES	YES
REAL-TIME CONTOUR	YES	YES
SCROLLING 3-D WATERFALL	NO	YES
NAV-CORRECTED CONTOUR	NO	YES
SIDE-SCAN IMAGE	NO	YES

* 3-dimensional image processing with color coding by using mesh data (Asada, 1986)
* Magnitude mapping of sea bottom inclination with color coding by using mesh data
* Direction mapping of sea bottom inclination with color coding by using mesh data (A. Asada, S. Kato and S. Kasuga, 1989)
* Intensity or sidescan image processing by using raw data
* 3-dimensional intensity or sidescan image processing with Color Cording by using raw data

These softwares are available to use a digital color photograph printer, Pictrography 2000, instead of the traditonal color plotter, such as ink jets, thermal or electrostatic plotters. The pictography 2000 has the capacity of 2048 x 2560 pixels and each pixel contains a 8-bit increments of 0 to 255 for each red, green and blue lights. This equipment prints out relatively small size of A4 but claims to have a most excellent capability in this kind of products in the world.

h) Others

* RMS error calculation software
* Roll-bias assessment sofware
* Tidal correction software
* SVP re-calculation software
* Sounding accuracy assessment software

2. Characteristic of ray correction in SEA BEAM 2000

The details of the SEA BEAM 2000 are described in the paper by W. J. Capell and K. C. Kiesel (1989). Here, we will discuss some advantages of this equipment in correcting and compensating by sounding velocities. Table 1 shows a comparative list of the SEA BEAM and the SEA BEAM 2000.

2—1. Ray curve correction

(1)Refraction correction by mean sound volocity

The SEA BEAM does not provide corrections to the ray curve in terms of a strict sense, because of the narrow swath width. The sound velocity varies according to the depth in the sea water. Thus, sound rays are refracted in water and reach the sea botom. The SEA BEAM calculates a mean beam refraction angle, determining a mean sound velocity in water for each beam. In other words, the SEA BEAM considers the sound velocity profile in water as one layer with a mean sound velocity.

Some of the other multi-beam sounding equipment apply one value of a mean sound velocity to all the beams and frequently cause a sounding error over 1% at a high beam angle, such as 60°. The results in this case incur much serious problem when the equipment is used for surveys of the sea bottom in complicated features such as in the vicinity of the Japanese archipelago. Each beam will hit separate points at various level of depth and is subject to have different mean sound velocities.

Application of one mean velocity to all beams produces following errors. This method is not used in SEA BEAM, but is used in many systems in the world. Now, a beam at 60° supposedly hits a point at the depth of 1000 m with mean sound velocity 1498.9 under the condition of Table 2 that the depth of vertical beam is measured as 200 m and the mean sound velocity is calculated as 1532.8m/s, which is a quite common assumption in the areas around Japan.

Then, calculated beam angle is

$$\sin\theta / 1532.8 = \sin(60) / 1498.9$$

Table 2. Calculation errors of depths and cross-track distances by mean velocity method, using real CTD profile data.

CALCULATION ERRORS of DEPTHS BY MEAN VELOCITY METHOD

depth (m)	vel. (m/s)	mean V (m/s)	surface ray angle (deg.) & depth (m) 0	10	20	30	40	50	60	
.0	1540.3	1540.3	.0	.0	.0	.0	.0	.0	.0	
50.0	1541.1	1540.7	50.0	50.0	50.0	50.0	50.0	50.0	50.0	
100.0	1541.9	1541.1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
200.0	1506.9	1532.8	200.0	200.0	200.0	200.0	200.0	200.0	200.1	
300.0	1494.2	1522.0	300.0	300.0	300.0	300.0	300.0	300.1	300.4	
500.0	1490.0	1510.1	500.1	500.1	500.1	500.1	500.1	500.2	500.8	
700.0	1487.7	1504.0	700.1	700.1	700.1	700.1	700.1	700.3	701.1	
1000.0	1486.2	1498.9	1000.1	1000.1	1000.1	1000.1	1000.2	1000.4	1001.3	
1500.0	1486.1	1494.6	1500.2	1500.2	1500.2	1500.2	1500.2	1500.5	1501.5	
2000.0	1491.5	1493.2	2000.2	2000.2	2000.2	2000.2	2000.2	2000.5	2001.6	
2500.0	1498.2	1493.5	2500.2	2500.2	2500.2	2500.2	2500.2	2500.5	2501.6	
3000.0	1505.8	1494.9	3000.2	3000.2	3000.2	3000.2	3000.2	3000.5	3001.7	
4000.0	1523.0	1499.8	4000.3	4000.3	4000.3	4000.3	4000.4	4000.9	4002.9	0.1%
5000.0	1540.7	1506.2	5000.7	5000.7	5000.6	5000.7	5000.9	5001.9	5006.4	
6000.0	1559.4	1513.5	6001.4	6001.3	6001.3	6001.3	6001.8	6004.0	6014.1	
7000.0	1578.4	1521.4	7002.5	7002.4	7002.4	7002.5	7003.3	7007.6	7028.1	0.3%
8000.0	1597.6	1529.7	8004.1	8004.0	8003.9	8004.1	8005.6	8013.2	8051.2	
9000.0	1617.0	1538.4	9006.3	9006.2	9006.0	9006.3	9008.8	9021.3	9087.3	1%
10000.0	1635.9	1547.2	10009.1	10009.0	10008.8	10009.2	10013.0	10032.4	10141.6	
11000.0	1658.7	1556.3	11012.7	11012.6	11012.2	11012.8	11018.5	11047.9	11225.2	2%

CALCULATION ERRORS of CROSS-TRACK DISTANCES BY MEAN V METHOD
(uppers are true, lowers V MEAN method)

depth (m)	vel. (m/s)	mean V (m/s)	surface ray angle (deg.) & cross-track dist.(m) 0	10	20	30	40	50	60	
			.0	.0	.0	.0	.0	.0	.0	
.0	1540.3	1540.3	.0	.0	.0	.0	.0	.0	.0	
			.0	8.8	18.2	28.9	42.0	59.6	86.7	
50.0	1541.1	1540.7	.0	8.8	18.2	28.9	42.0	59.6	86.7	
			.0	17.6	36.4	57.8	84.0	119.3	173.5	
100.0	1541.9	1541.1	.0	17.6	36.4	57.8	84.0	119.3	173.6	
			.0	35.2	72.6	115.1	167.2	237.1	343.4	
200.0	1506.9	1532.8	.0	35.1	72.4	114.7	166.4	235.6	339.9	
			.0	52.6	108.5	172.0	249.4	352.9	508.8	
300.0	1494.2	1522.0	.0	52.3	107.7	170.5	246.7	347.6	496.8	20m
			.0	87.2	179.7	284.4	411.7	580.4	830.1	
500.0	1490.0	1510.1	.0	86.4	178.0	281.2	405.9	569.0	804.8	
			.0	121.6	250.6	396.3	573.0	805.8	1147.0	
700.0	1487.7	1504.0	.0	120.5	248.0	391.7	564.5	789.2	1110.6	50m
			.0	173.0	356.4	563.4	813.5	1141.3	1616.6	
1000.0	1486.2	1498.9	.0	171.5	353.0	557.0	801.8	1118.8	1567.6	
			.0	258.5	532.4	840.8	1212.5	1696.9	2391.8	
1500.0	1486.1	1494.6	.0	256.4	527.8	832.4	1197.1	1667.4	2327.9	
			.0	343.9	708.1	1117.9	1610.8	2251.3	3164.4	
2000.0	1491.5	1493.2	.0	341.6	702.9	1108.4	1593.6	2218.2	3092.9	
			.0	429.3	883.8	1395.0	2009.3	2806.0	3937.6	
2500.0	1498.2	1493.5	.0	427.1	878.9	1385.9	1992.7	2774.0	3868.4	
			.0	514.7	1059.8	1672.5	2408.4	3361.9	4713.3	
3000.0	1505.8	1494.9	.0	513.0	1055.8	1665.1	2394.9	3335.8	4656.8	
			.0	686.3	1413.0	2229.9	3210.9	4481.7	6282.0	
4000.0	1523.0	1499.8	.0	686.3	1412.9	2229.6	3210.3	4480.5	6279.6	100m
			.0	858.6	1767.9	2790.4	4019.1	5612.5	7874.4	
5000.0	1540.7	1506.2	.0	861.6	1774.7	2802.8	4041.5	5655.9	7972.1	
			.0	1031.8	2124.7	3354.5	4833.8	6755.8	9494.6	
6000.0	1559.4	1513.5	.0	1039.2	2141.4	3385.2	4889.5	6864.8	9744.0	
			.0	1205.9	2483.6	3922.5	5655.6	7913.1	11146.2	
7000.0	1578.4	1521.4	.0	1219.1	2513.4	3977.2	5755.4	8109.9	11607.2	
			.0	1381.0	2844.8	4494.6	6485.0	9085.4	12832.1	
8000.0	1597.6	1529.7	.0	1401.4	2890.6	4579.1	6639.7	9393.7	13574.2	
			.0	1557.1	3208.2	5070.9	7322.3	10273.6	14555.5	
9000.0	1617.0	1538.4	.0	1586.0	3273.3	5191.1	7543.1	10718.5	15661.0	
			.0	1734.2	3574.0	5651.7	8167.8	11478.3	16319.1	
10000.0	1635.9	1547.2	.0	1773.0	3661.3	5813.2	8466.1	12086.5	17885.7	
			.0	1912.4	3942.3	6237.1	9021.9	12700.7	18126.6	
11000.0	1658.7	1556.3	.0	1962.6	4055.3	6446.6	9410.8	13504.4	20289.1	

Table 3. Calculation errors of depths and cross-track distances by mean velocity method, using assumption profile data by (V = 1470+ D * 0.017).

CALCULATION ERRORS of DEPTHS BY MEAN VELOCITY METHOD

depth (m)	vel. (m/s)	mean V (m/s)	surface ray angle (deg.) & depth (m) 0	10	20	30	40	50	60	
.0	1470.0	1470.0	.0	.0	.0	.0	.0	.0	.0	
1000.0	1487.0	1478.5	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	
2000.0	1504.0	1487.0	2000.1	2000.1	2000.1	2000.1	2000.1	2000.2	2001.0	
3000.0	1521.0	1495.5	3000.3	3000.3	3000.2	3000.3	3000.4	3001.0	3004.5	0.1 %
4000.0	1538.0	1504.0	4000.6	4000.6	4000.6	4000.6	4001.0	4002.6	4012.4	
5000.0	1555.0	1512.5	5001.3	5001.2	5001.2	5001.3	5001.9	5005.3	5027.6	0.5 %
6000.0	1572.0	1521.0	6002.2	6002.2	6002.1	6002.2	6003.4	6009.8	6054.0	
7000.0	1589.0	1529.5	7003.5	7003.4	7003.3	7003.5	7005.5	7016.3	7097.9	1 %
8000.0	1606.0	1538.0	8005.1	8005.1	8004.9	8005.3	8008.3	8025.7	8168.6	
9000.0	1623.0	1546.5	9007.3	9007.1	9007.0	9007.5	9012.0	9038.5	9281.2	
10000.0	1640.0	1555.0	10009.9	10009.7	10009.5	10010.2	10016.6	10055.8	10462.3	
11000.0	1657.0	1563.5	11013.0	11012.8	11012.5	11013.5	11022.4	11078.5	11763.3	

CALCULATION ERRORS of CROSS-TRACK DISTANCES BY MEAN V METHOD
(uppers are true, lowers V MEAN method)

depth (m)	vel. (m/s)	mean V (m/s)	surface ray angle (deg.) & cross-track dist. (m) 0	10	20	30	40	50	60	
			.0	.0	.0	.0	.0	.0	.0	
.0	1470.0	1470.0	.0	.0	.0	.0	.0	.0	.0	
			.0	177.4	366.4	581.8	847.4	1208.6	1773.2	
1000.0	1487.0	1478.5	.0	177.4	366.4	581.8	847.4	1208.6	1773.2	20m
			.0	355.8	735.1	1168.1	1703.3	2434.6	3589.8	50m
2000.0	1504.0	1487.0	.0	356.9	737.5	1172.6	1711.8	2452.2	3635.1	
			.0	535.3	1106.2	1758.9	2567.6	3678.3	5452.4	100m
3000.0	1521.0	1495.5	.0	538.5	1113.5	1772.6	2593.4	3732.4	5596.1	
			.0	715.8	1479.8	2354.3	3440.6	4940.3	7363.7	
4000.0	1538.0	1504.0	.0	722.3	1494.4	2381.8	3492.9	5051.1	7669.1	
			.0	897.4	1855.8	2954.2	4322.4	6221.0	9326.9	
5000.0	1555.0	1512.5	.0	908.2	1880.2	3000.5	4410.5	6410.4	9870.2	
			.0	1080.1	2234.1	3558.8	5213.0	7521.0	11345.5	
6000.0	1572.0	1521.0	.0	1096.3	2271.0	3628.6	5346.8	7812.6	12220.6	
			.0	1263.8	2614.9	4167.9	6112.6	8840.8	13423.4	
7000.0	1589.0	1529.5	.0	1286.5	2666.8	4266.3	6302.2	9260.2	14748.6	
			.0	1448.5	2998.1	4781.8	7021.4	10181.0	15565.0	
8000.0	1606.0	1538.0	.0	1479.0	3067.6	4913.8	7277.3	10756.2	17493.7	
			.0	1634.3	3383.8	5400.3	7939.3	11542.3	17775.3	
9000.0	1623.0	1546.5	.0	1673.6	3473.5	5571.2	8272.5	12303.7	20514.6	
			.0	1821.2	3771.9	6023.5	8866.6	12925.2	20060.1	
10000.0	1640.0	1555.0	.0	1870.5	3884.5	6238.5	9288.6	13906.3	23904.8	
			.0	2009.1	4162.4	6651.4	9803.4	14330.5	22426.2	
11000.0	1657.0	1563.5	.0	2069.6	4300.7	6916.1	10325.9	15568.5	27832.5	

where, $\theta = 62.3^\circ$

Therefore, an error of calculated depth is

$$\text{Err.} = 1000/\cos(60)/1498.9 \times 1532.8 \times \cos(\theta) - 1000 = -50.1\text{m}(5.0\%)$$

This error may become much greater in wider beam angle. When the vertical depth is 500m and the depth at 60° beam is 1000m, the sounding error goes 1.5%. When the vertical depth is 700m, the sounding error goes 0.7%.

(2)SVP Correction

The SEA BEAM 2000 provides true ray curve calculation by sound velocity profile correction. For a wide swath sounding equipment, we must precisely know the beam angle, since a slight off-set of the angle may cause a large sounding error.

Tables 2 and 3 show the results of a simulation to compute the errors in refraction corrections derived by mean sound velocity method. The sound velocity profile of Table 2 is derived from samples of actual CTD measurements.

The profile of Table 3 is from a modeled profile which assumes that the sound velocity varies consistently corresponding to the depth. As the actual sea has various sound velocity profiles depending on the seasons and locations, it is impossible to explain all the cases by applying only this example. The interesting point is the mean sound velocity procedure creating an error of around 0.1% even with a direct beam perpendicular to the sea-bottom. It is clear that the error of the mean sound velocity procedure increases as the depth and the beam angle become greater. A beam sounding with this procedure with a beam angle of 60° produces the higher errors at the depth over 6000m, which are not acceptable levels.

The mean sound velocity procedure is a simplified processing method, devised in the days the computer systems were at a lower ability of processing, which had been employed in traditional SEA BEAMs and many of multi-beam sounding systems. The error of crosstrack distance is also important. For the deep sea, 100m of crosstrack error may be a problem.

2—2. Surface-layer Refraction Correction

The traditional multi beam system introduces errors in ship's roll correction of the beam formed angle. This error becomes greater as the beam angle increases. SEA BEAM 2000, therefore, establishes a real-time beam forming based on the sound velocity at the surface of sea water, continuously observing the velocity. In this way, it always builds up highly accurate beam forming.

Let's consider a case where there is a difference in the sound velocity between a designed one at the stage of beam-forming and an actually observed one at the sea surface. Assuming the beam angle of 45°, the surface sound velocity of 1530m/s, the designed beam-forming sound velocity of 1500m/s and the rolling angle of 5°, we will get:

(1)the beam angle at the surface sound velocity of 1500m/s;

$$45^\circ + 5^\circ$$

(2)the true beam angle at the velocity of 1530m/s;

$$\sin^{-1}(\sin(50) \times 1530/1500) = 51.39^\circ$$

(3)the calculated beam angle by the traditional corrections;

$$\sin^{-1}(\sin(45) \times 1530/1500) + 5 = 51.16^\circ$$

Thus, a roll angle of 5° produces a beam error of 0.23°. A roll angle of 10° will result in a 0.52° error of the beam angle. The error in the beam angle causes an error in the sounded depth. For example, when a beam angle of 45° will have this angle error at depth 4000m, the errors of depth will be as follows:

for the roll angle of 5° at depth 4000m;

Err. =4000 x cos(45.23)/cos(45) − 4000= −16.1(0.40%)

for the roll angle of 10° at depth 4000m;

Err. =4000 x cos(45.52)/cos(45) − 4000= −36.5(0.91%)

If there is no rolling, this type of the error never occurs. No correction of beam forming by rolling will cause the error of 1.39° in the beam angle at the roll angle of 5°. Then, in this example:

for the roll angle of 5°;

Err. =4000 x cos(46.39)/cos(45) − 4000= −98.2(2.46%).

3. Survey Results of SEA BEAM 2000

The Hydrographic Department, Japan Maritime Safety Agency installed a SEA BEAM 2000 on the newly built survey vessel Meiyo in October 1990. The practical survey using the SEA BEAM 2000 system was carried out in the sea areas off Boso-peninsula in March 1991 as the beginning, off the coastline of Miyagi- and Fukushima-pref. in April 1991 and around the seamount Mikura in August 1991.

At the survey off Boso-peninsula, the SEA BEAM 2000 could get well the data for the depth over 200 m, but could not get the data for the depth of 200m or less. As the sea-bottom at the depth less than 200m forms rather flat topography, data to be processed is replaced by outputs of a 200KHz echo sounder.

In the areas off the coastline of Miyagi- and Fukushima-pref., the SVP corrections were not perfectly made in the field at sea, since the variation of the sound velocity was so great. This allowed us to acquire survey data in shallow areas but the imperfection in the SVP corrections made the detected value by side beams less deep. But, XBT observations were taken with a very thickened manner, we are now making the SVP correction in a post-correction mode with these data. We would say that the SVP re-calculation of depth data is more difficult than the re-calculation by the mean velocity method.

The survey conducted around the seamount Mikura provided very useful data.

Figure 7 shows a contour chart which is drawn up through post-processing. As the processing system was closely established, this chart was made up only in 2 days. For this survey operation, almost no sounding error were detected by the procssing of rejecting erroneous data.

Figure 8 shows an 3−dimentional image view map illustrated by using the Pictrography which is a color picture developing device in a digital form having a capacity of 2048 x 2560 pixels. The equipement was developed in Japan. Each pixel functions as an excellent color printer, covering 256 increments of each green, red and blue lights. The high resolution of the characteristics has made meshed and irregularity in colors, which have been obscured in a traditional access, appear clearly on the printed. Therefore, we imporved the software to divide the meshes in a smaller size. This figure clearly indicates the details of the sea-bottom.

In February 1992, the SEA BEAM 2000 was improved by using interferometric technique, and an evaluation test survey was conducted. By the result, the present SEA BEAM 2000 has a capability of

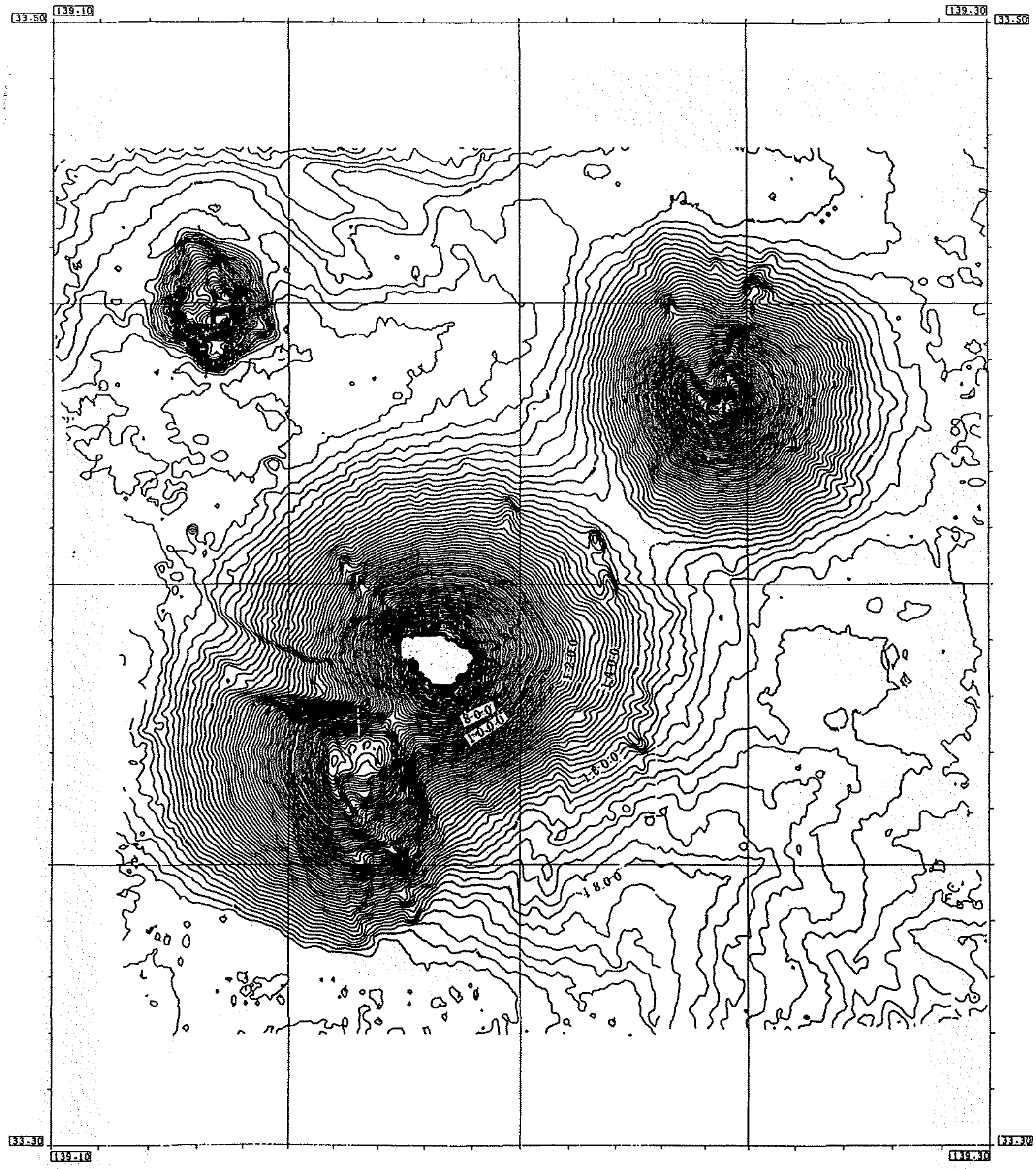

Figure 7 Contour chart of Mikura sea-mount and it's vicinity by SEA-BEAM 2000 survey in August 1991. Contour interval is 20m.

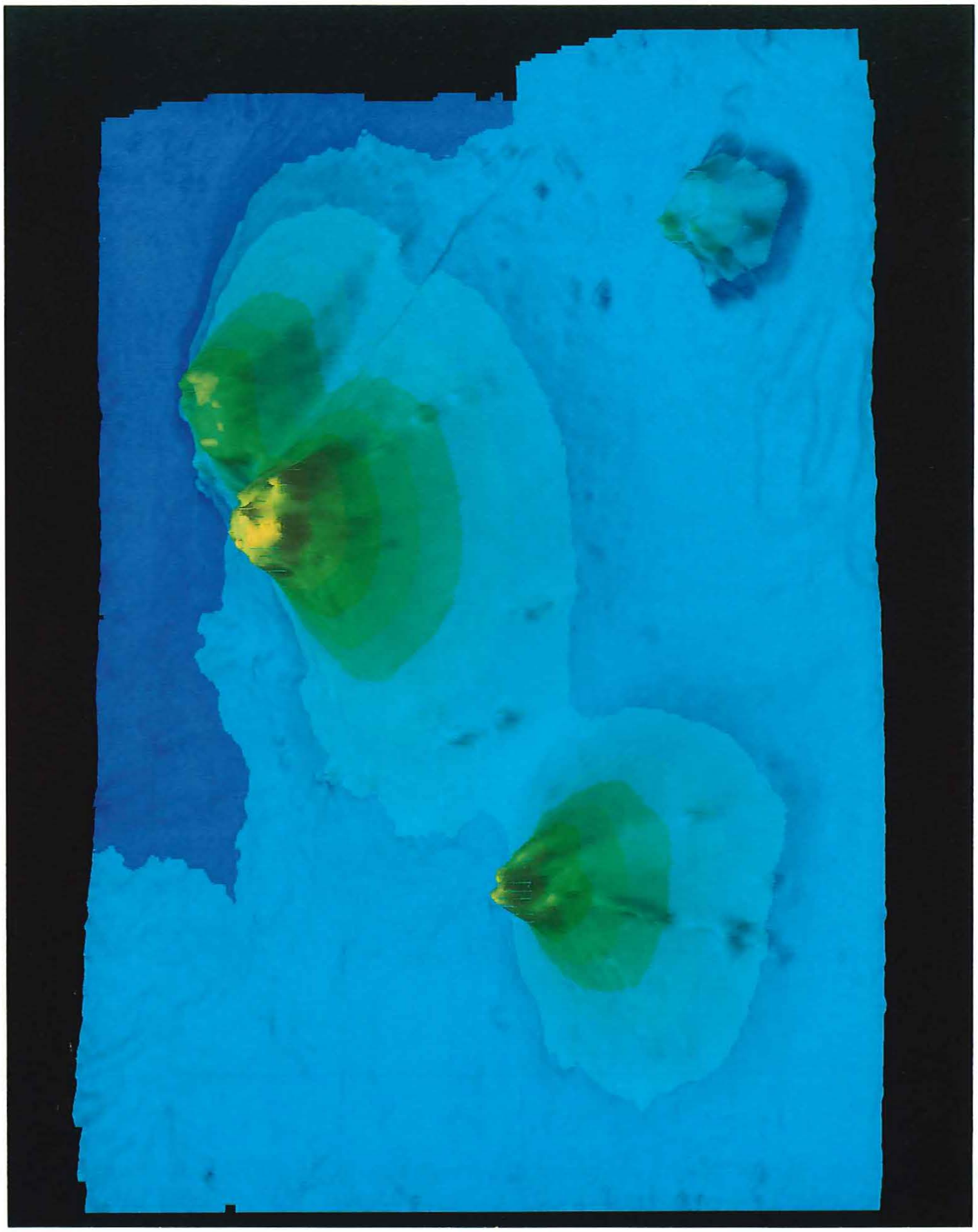

Figure 8 3-dimentional image view from north of Mikura sea-mount and it's vicinity.

of the 120 degrees swath improvement in Februaly 1992.

This chart with 100% coverage survey of 120 degrees swath width indicates that the contours of neighboring sounding lines are in good accordance. In the area up to 5000m deep, SEA BEAM 2000 has good capability of 120 degrees swath survey. In 9000m deep area, about 80% of 90 degrees swath mode proved successful. By adapting the interferometric tecunique, the resolving performance of bottom reflection wave and the multi beam depth measurement are improved remarkably. Especially as for flat bottom, the phenomenon such as Tunnel Effect (C. de Moustier and M. C. Kleinrock, 1986) will not occur. The white areas of contour lines in the swath were placed the steep slope bottoms, and a few beams in these areas had same reception time from sea bottoms, or the distance in a beam width of 2 degrees was very large. These white areas show a good performance on the multi beam bathymetric survey. The real time contour chart is highly valuable as it indicates the areas of poorly sounded and of requiring additional surveying to the survey program planners. It should also be a great help in dredging as it precisely provides actual features of the sea-bottom. For the vessel Meiyo, the integrated navigation system also can produce the same chart through post-processing.

Figure 10 shows real-time side-scan records with 16 grey levles 1024 pixels per swath in the same area. By a comparison with another side-scan record. this record shows detail topography. Figure 11 shows a post processing intensity map in the same area. SEA BEAM 2000 records additionally intensity data of 121 beams. We made grazing angle and position correctons of the beam intensity data and prepared this map by a Pictrography with 256 gray levels. This intensity map is as good as the real-time side-scan record, because the beam intensity has 100 dB dynamic range and position and ship's heading informa-

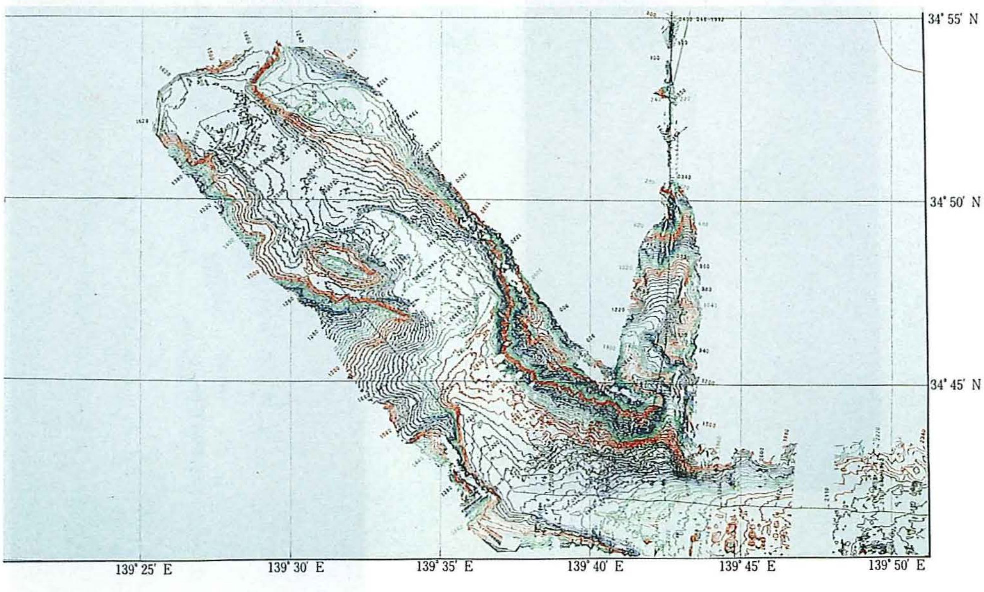

Figure 9 Real-time contour chart of eastern area off Osima Island by SEA BEAM 2000 sea test in Februaly 1992. Contour interval is 20m.

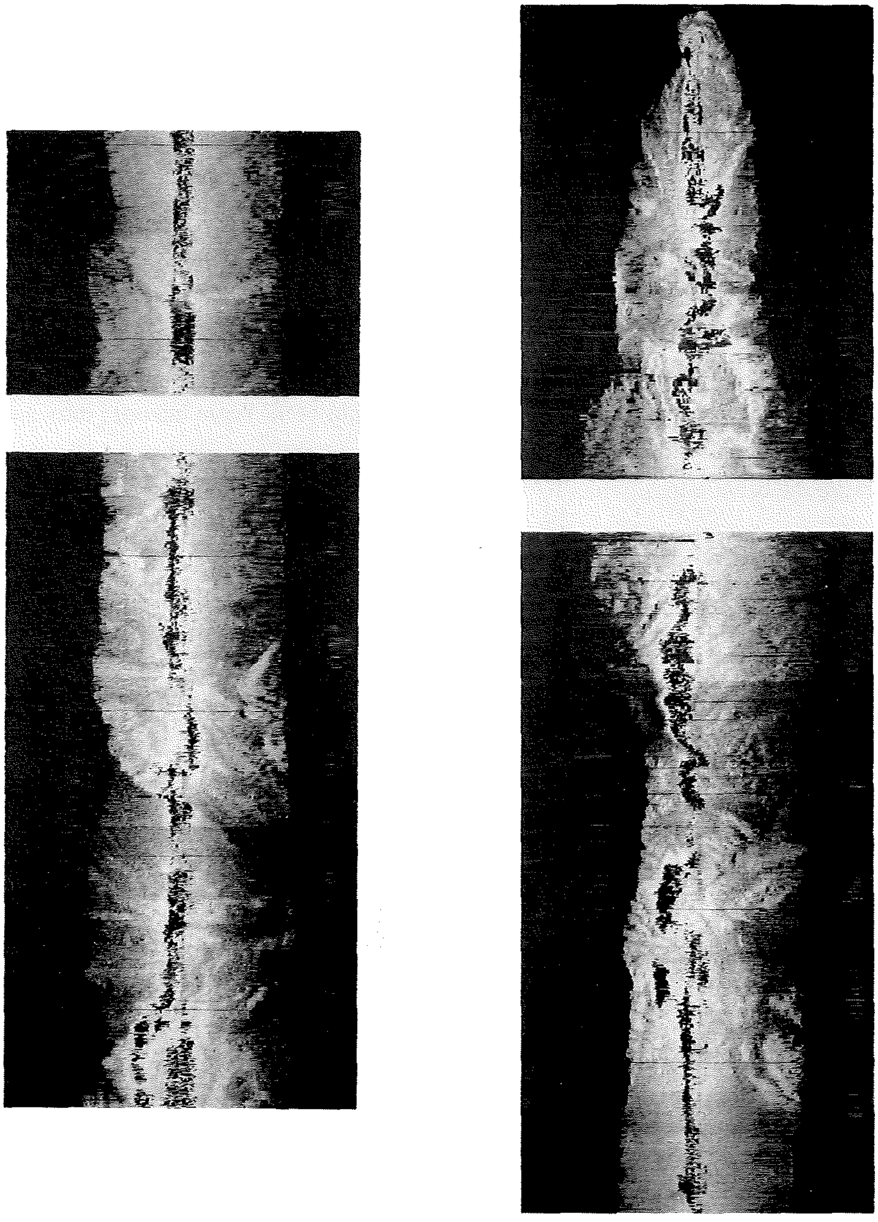

Figure 10 Real-time side-scan records of eastern area off Osima Island by SEA BEAM 2000 sea test in Februaly 1992.

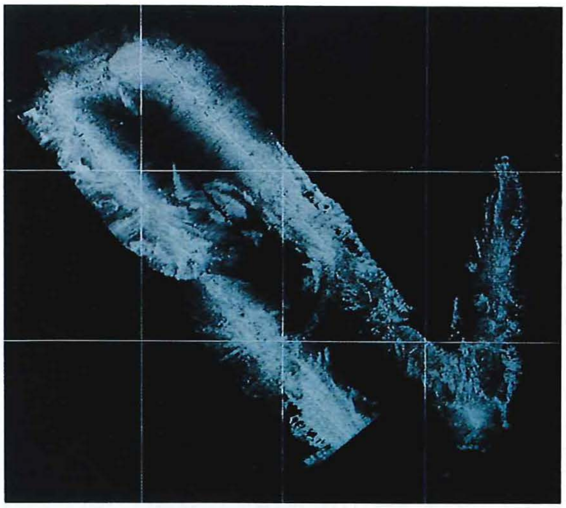

Figure 11 Beam intensity map of eastern area off Osima Island.

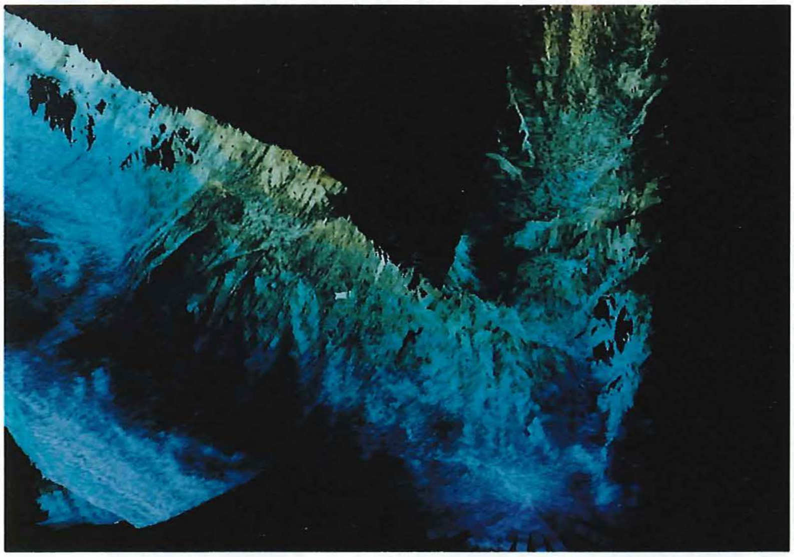

Figure 12 3-dimensional beam intensity map of eastern area off Osima Island.
View direction is from shouth. Color coding interval 200m.

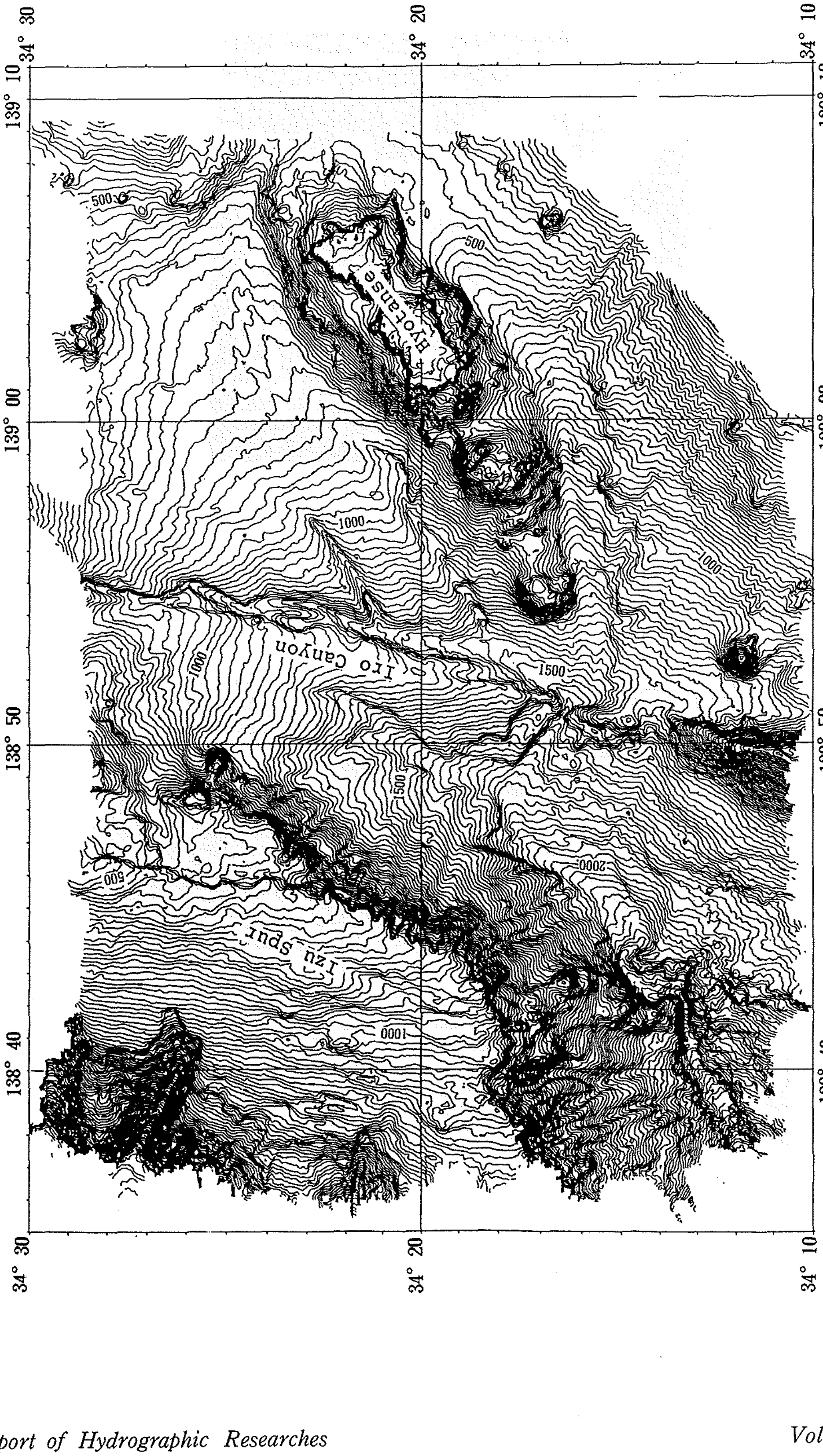

Figure 13 Contour chart of southern area off Izu Peninsula by SEA BEAM 2000 survey in March 1992
Contour interval 20m.

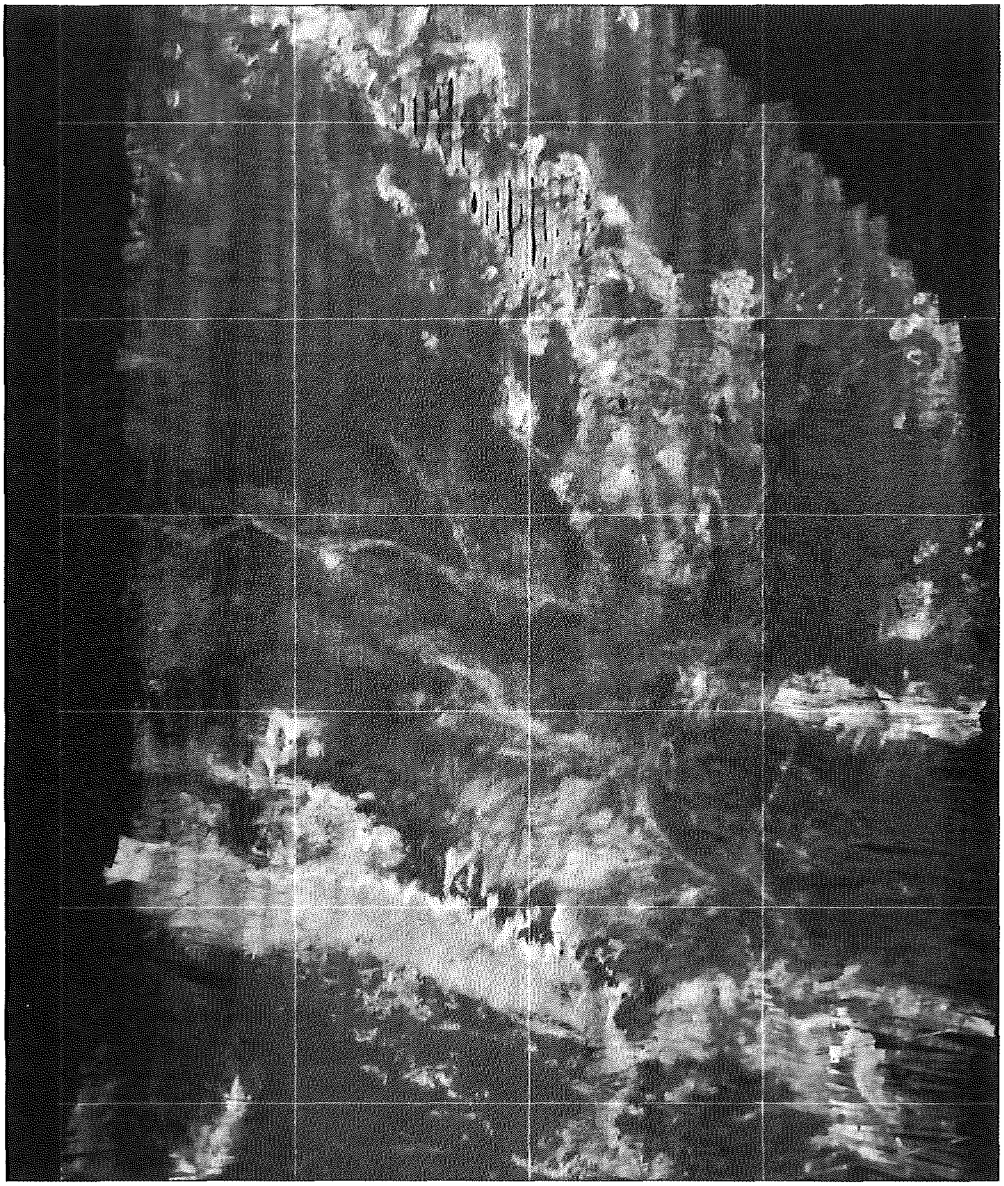

Figure 14 Beam intensity map of southern area off Izu Peninsula.

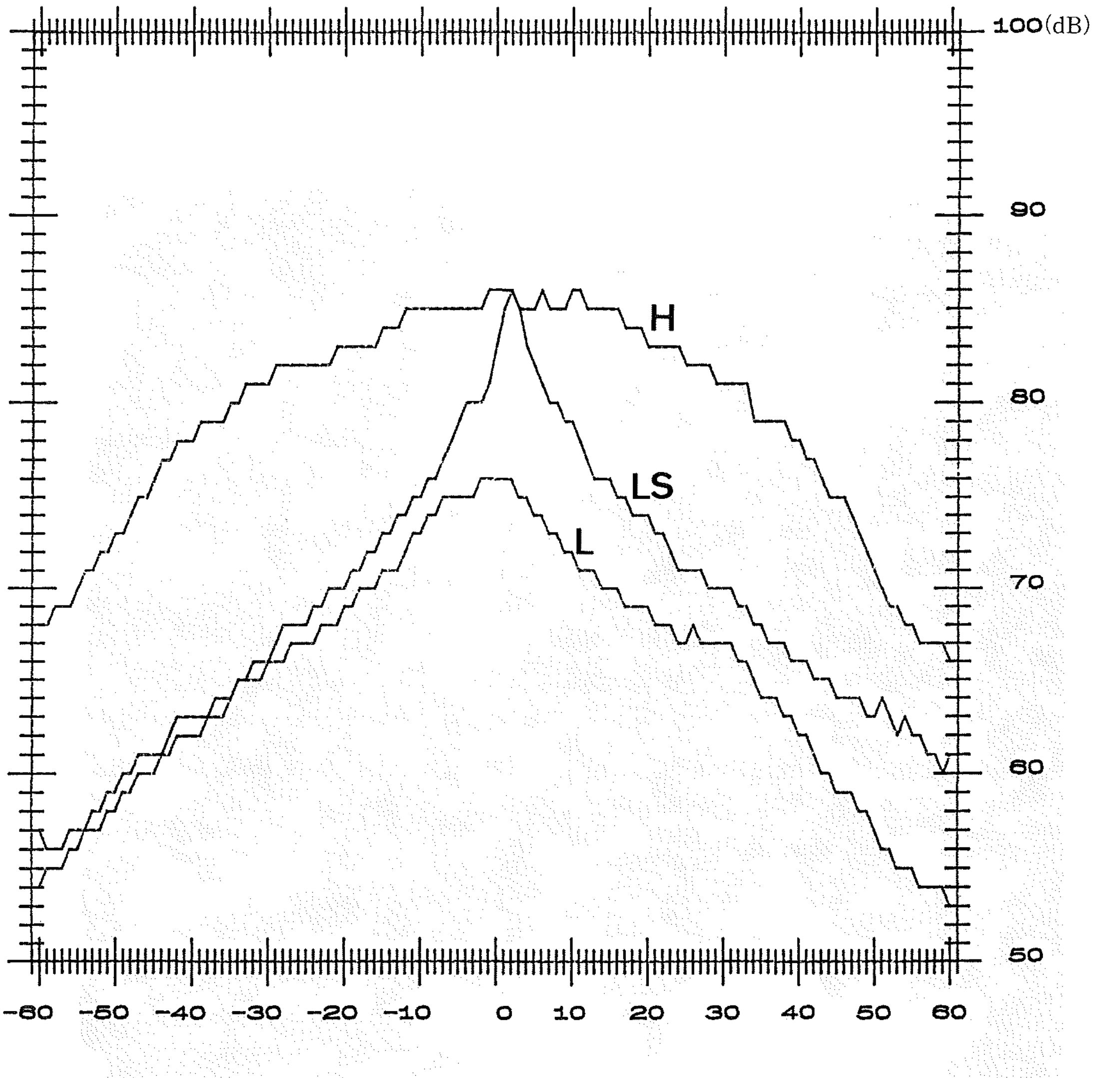

Figure 15 Three paterns of beam intensity measured by survey of southern area off Izu Peninsula. Figure 14 was made by correction using these paterns. H : supposed high intensity botom, L : supposed low intensity bottom, LS : supposed low intensity and smoosed bottom.

this map by a Pictrography with 256 gray levels. This intensity map is as good as the real-time side-scan record, because the beam intensity has 100 dB dynamic range and position and ship's heading information. Furthermore, we tried to make a 3-dimensional intensity map by using depth data as shown on Figure 12. This map indicates very detailed topography of the sea floor, such as complex rock wall and channels. The results of upgrading the SEA BEAM 2000 on the Meiyo seems successful.

A practical survey using the new 120 degrees swath system of the SEA BEAM 2000 was conducted in March 1992. The survey area is located in the south off Izu Peninsula. Figure 13 shows the processed bathymetric chart. Figure 14 shows a post processing intensity map of the same area. Bright area which is the strong reflection area is supposed to be the rock outcrop or rough sea floor. Dark color area which is the weak reflection area is supposed to be the mud and fine sediment covering sea floor. The intensity corrections of grazing angle, sea floor slope and beam directivity were made by using three paterns of real intensity data in Figure 15. This intensity map presents the evident lineament, fault, with 3 to 5 meter desplacement at depth 500 meters deep which is not able to be extracted from the bathymetric chart. It is possible that the fault is an earthquake fault which appeared at the Izuhanto-oki Earthquake.

We tried a simple estimation of data quality by analizing the SEA BEAM 2000 data of the survey off Izu Peninsula. The data was processed by the automatic rejection program of erroneous data. The map area was divided into 7 sections, and the data quality was estimated for each section, because the total number of data was too much about 500Mb.

a) At first, the data was distributed into the mesh system of 150 x 150 meters dimension.

b) Becasue the ocean bottom topography is very complex, only data of flat bottom meshes were processed.

So there are many kinds of data between 100 and 200 data, such as of different beam angles and 100 to 3000 meters depth in a mesh, because the 200% coverage survey of reciprocate and cross tracks was conducted.

c) An approximate plane equation of each mesh was calculated by using all data in the mesh, and the difference from the equation was estimated as an error. The error was expressed by the percentage of each data against the equation.

d) The standard deviation of the differnce error at each beam angle was calculated by using all data of each section.

e) Seven figures of the standard deviations were made (Figure 16).

The data quality of first section seems to be somewhat worse like as 0.4 to 0.8% erroneous, but it is due to including erroneous data under rough sea condition. Other results show that the standard deviations of error are 0.2 to 0.5%. The results include the scattering error, the effects of different beam angles and positioning by reciprocate and cross track survey. The automatic rejection program of erroneous data is very useful in order to extract a practical performance of multi beam data. And the practical accuracy of SEA BEAM 2000 is good.

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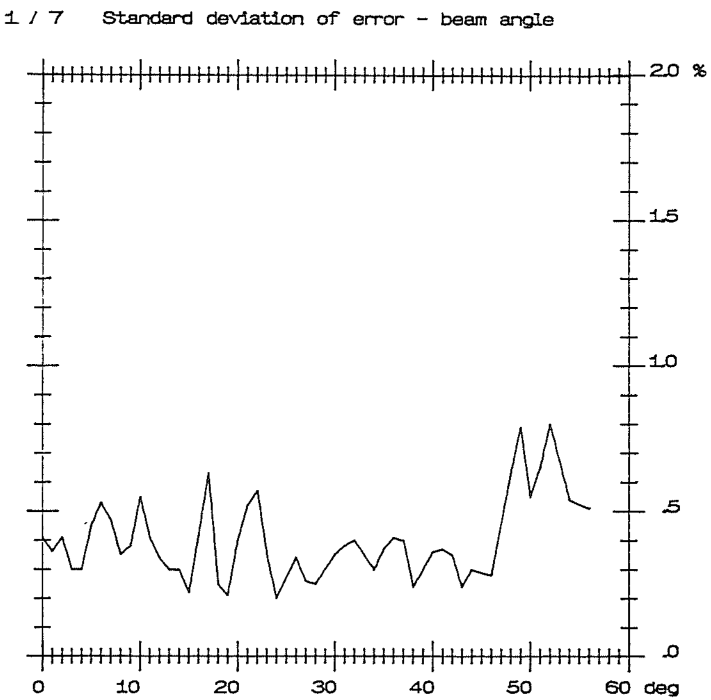
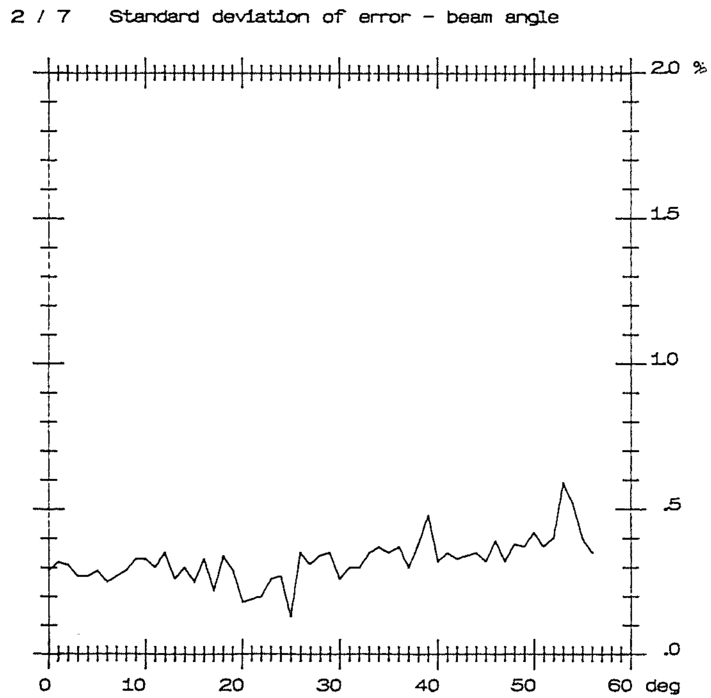
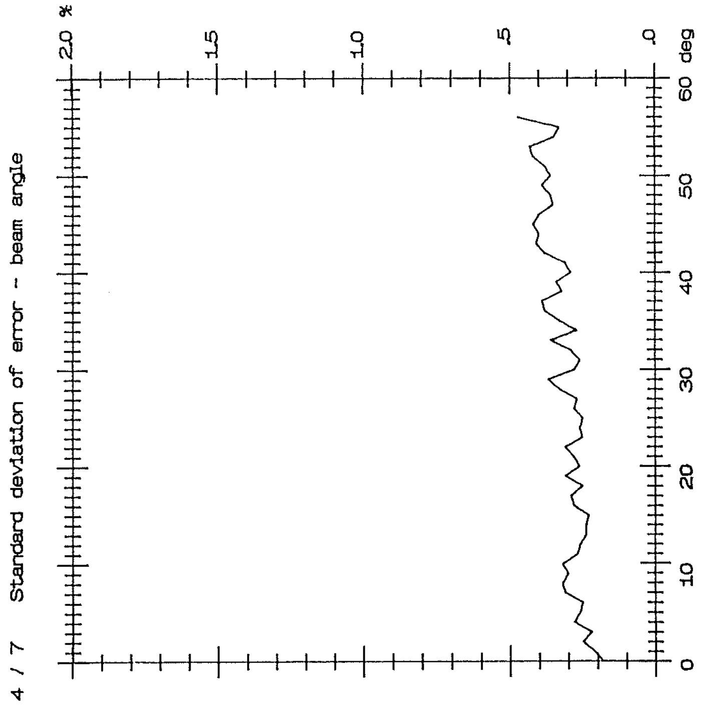


(1) Section of longitude 138°35'—138°40' in figure 13.

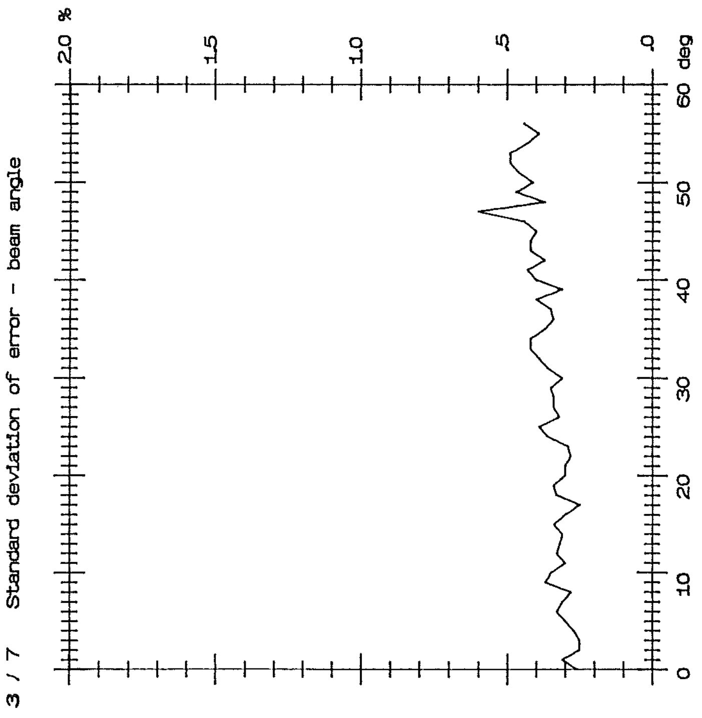


(2) Section of longitude 138°40'—138°45' in figure 13.

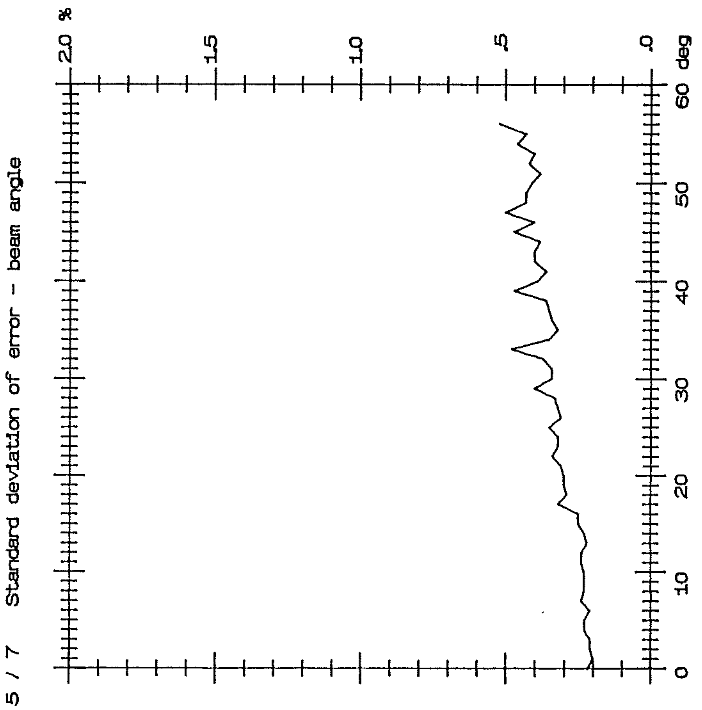
Figure 16 Quality of SEA BEAM 2000 bathymetric data. Standard deviation at each beam angle was calculated from differnces between each datum and an approximate plane equation of mesh.



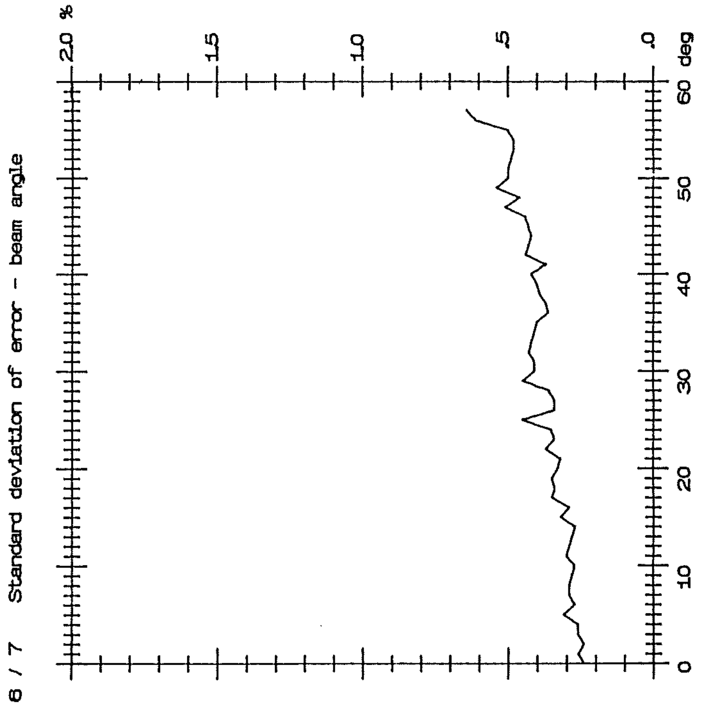
(4) Section of longitude 138°50'—138°55' in figure 13.



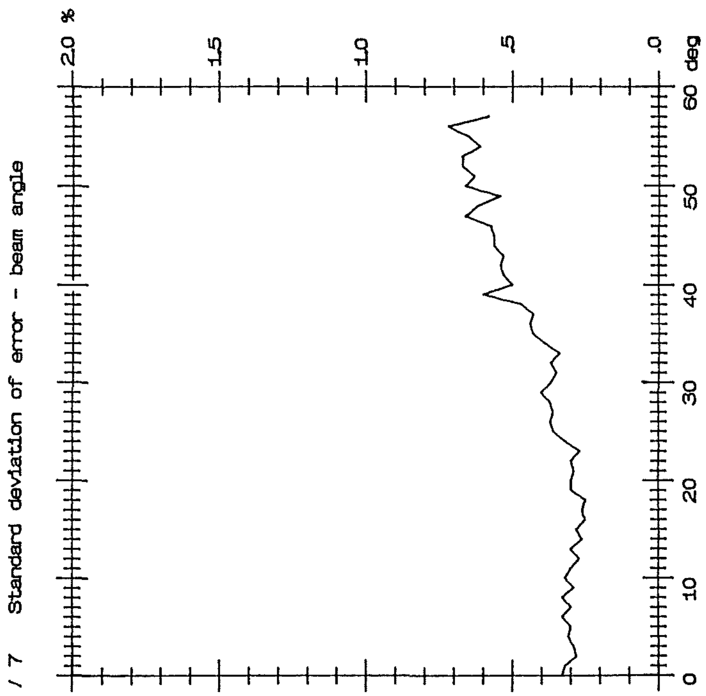
(3) Section of longitude 138°45'—138°50' in figure 13.



(5) Section of longitude 138°55'—139°00' in figure 13.



(6) Section of longitude 139°00'—139°05' in figure 13.



(7) Section of longitude 139°05'—139°10' in figure 13.

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