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NEW TECHNOLOGY FOR SHALLOW WATER HYDROGRAPHIC SURVEYS

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with additional excerpts from a paper by
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The United States Office of Coast Survey is developing technology for shallow water hydrographic surveys in order to increase the efficiency with which hydrographic data are acquired and to improve the likelihood that all potential dangers to navigation are detected in the course of a hydrographic survey. Three areas of technology hold the greatest promise for meeting those goals: Airborne Lidar Hydrography (ALH), Shallow Water Multibeam Sonars (SWMB), and digital side scan sonar, especially the Coast Survey's new High Speed, High Resolution Side Scan Sonar (HSHRSSS). The Coast Survey expects that all its ALH surveys will be outsourced to private sector contractors, and that its SWMB and side scan sonar surveys will be accomplished by both NOAA survey vessels and by private sector contractors. This diversity of sources for survey data influences the strategy for managing these new technologies.

AIRBORNE LIDAR HYDROGRAPHY

The Office of Coast Survey has been involved in the development of ALH technology since the 1970s. Coast Survey was involved in the development of the U.S. Army Corps of Engineer's Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system and continues to be actively engaged in data quality assurance, system upgrades, and advanced algorithm development.

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In 1995, the Coast Survey reported on a comparison of results of a SHOALS test survey with those of a traditional NOAA echo sounder and side scan sonar survey in the approaches to Tampa, Florida (RILEY, 1995). Since then, the Coast Survey has sponsored SHOALS projects in the approaches to Gaviota and Ellwood, California in 1996 and the approaches to Miami and Port Everglades, Florida in 1997. These surveys have demonstrated that SHOALS general depth data meet NOAA and International Hydrographic Organization Order 1 standards for depth and position accuracy. Indeed, the SHOALS bathymetry from the California surveys is currently being compiled for application to a NOAA chart. At the same time, however, experience has shown that the operational detection of navigationally significant small features using SHOALS, and by extension any ALH, must be carefully scrutinized.

Coast Survey has performed a mathematical analysis based on the SHOALS system to model the probability of detection of obstructions on the sea bottom with ALH (GUENTHER, et al, 1996). Detection probability was modeled for variations in sounding density, depth, water clarity, and target size. Two categories of detection were defined. "Type-1" detection occurs when the return from both the target and the sea bottom can be separately discerned and measured in automated waveform processing. "Type-2" detection occurs when, although the target is not separately discerned from the bottom, the depth determined from automated waveform processing accurately (no more than 10 cm deeper) represents the least depth of the target. No detection occurs when a target is not illuminated, or when the waveform returned from an illuminated or partially illuminated target does not meet either of the above criteria.

The following key results and conclusions are excerpted directly (but selectively and somewhat condensed) from the paper by GUENTHER, et al:

> The target detection probability is based on the determination of a "detection area" within the square sampling cell representing the mean laser shot spacing. Since all points within the square are equally likely positions for the center of the target disc, the target detection probability is the detection area divided by the area of the cell. Within a representative cell, a 4m x 4m square, the target detection area is defined as that region within the square where a successful type-1 or type-2 detection occurs, including a test on the target extinction coefficient, when the center of the target disc is within that region. The target detection areas for the different cases are determined manually by moving the target center to various points within the sampling cell and examining the resulting waveforms for type-1 and type-2 detections not exceeding the extinction criterion. Because target detection areas overlap into adjacent cells, the total detection area in a cell is the union of detection areas from that cell and surrounding cells.
>
> The targets studied in most detail are flat-topped circular cylinders of 1 m and 2 m heights with surface areas of 1 m² and 4 m² (diameters of 1.13 m and 2.26 m). Detection probabilities for these four objects, for a 4m x 4m sounding grid and a twenty-degree scanner nadir angle in air, are presented as a function of bottom depth in Figs. 1 and 2. Four values of water clarity ranging from very

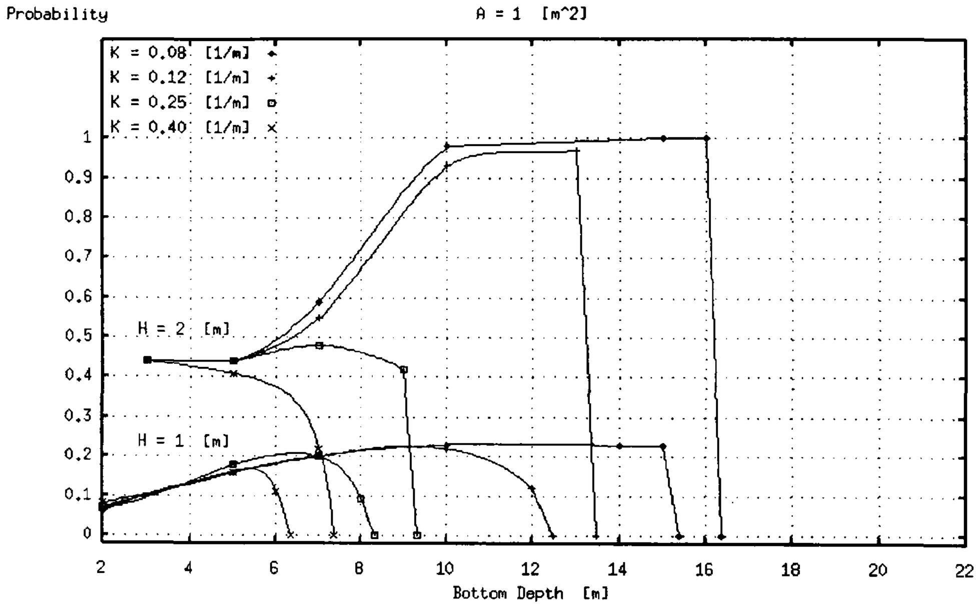

FIG. 1.- Detection probabilities for 1-m^2 circular cylinders in various water clarities, for 1-m and 2-m target heights, using a 20° scanner nadir angle on a 4m x 4m sounding grid.

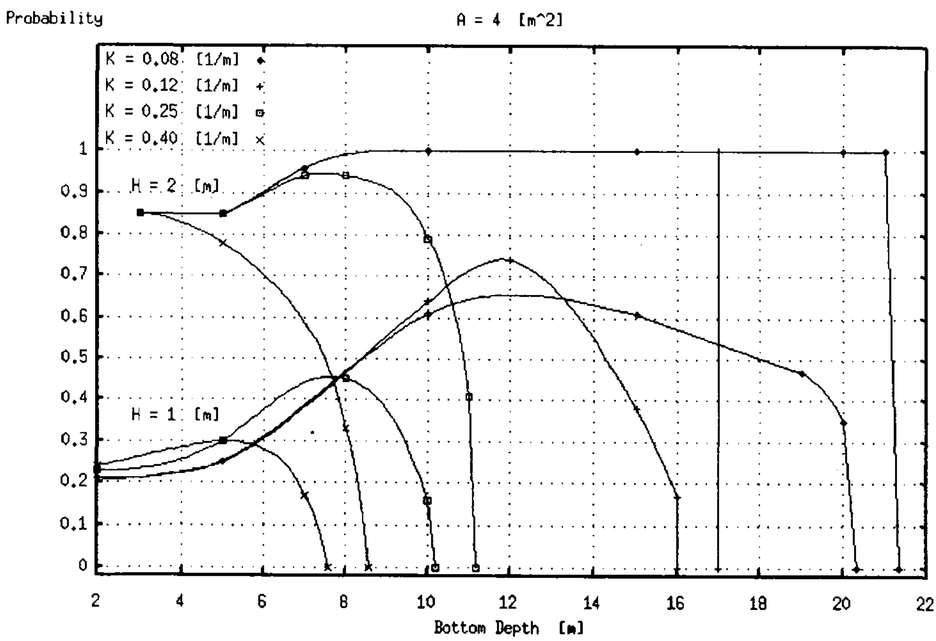

FIG. 2. Detection probabilities for 4-m^2 circular cylinders in various water clarities, for 1-m and 2-m target heights, using a 20° scanner nadir angle on a 4m x 4m sounding grid.

clean (0.08 m^{-1}) to very dirty (0.40 m^{-1}) are represented. Not surprisingly, performance is better for larger target heights, larger target areas, and for cleaner waters. For depths at or under 5 m, the probabilities are seen to be mostly independent of water clarity, strongly dependent on target height, and somewhat less so on target area. In this depth range, probabilities for the case of H=1 m and A=4 m^2 are strongly affected by type-2 results. Probabilities rise at middle depths as the beam expands, and water clarity becomes a significant factor. Probabilities for the 2-m height are at or near unity in the 10 - 20 meter depth range for the two cleaner water cases. Results for the 1 m height are rarely above 0.6 for the A=4 m^2 case and do not exceed 0.25 for A=1 m^2. The maximum detection depth depends strongly on water clarity, as might be expected. Extinctions can occur precipitously with increasing depth as the full target area becomes too small to yield a strong enough return according to the extinction equation. For typical coastal water clarities (the two middle cases), the target extinction depths range from 8-13 meters for the 1 m^2 target area and from 10-17 meters for the 4 m^2 area. The largest detection depth is just over 21 m for K=0.08 m-1.

The effects of survey density can be inferred by considering the ratios of other cell areas to the 16 m^2 used to obtain the above results. These ratios are 1.78 for 3m x 3m, 0.64 for 5m x 5m, and 0.16 for 10m x 10m. The detection probabilities for the other sounding densities can be estimated by multiplying the 4m x 4m results presented here by these ratios. This only applies, of course, when the result is less than unity. One can ask, for example, whether it would be worthwhile to decrease the spacing to 3m x 3m. The largest effective benefit of the factor of 1.78 occurs for 4m x 4m probabilities around 0.5, because these will be increased to near unity. This is true for both the H=1 m, A=4 m^2 case and the H=2 m, A=1 m^2 case. For the H=1 m, A=1 m^2 case, probabilities remain below 0.5. For all but the smallest targets, it would, therefore, be worthwhile to reduce sounding spacing to 3 m. This can be achieved by flying with a narrower swath. Systems with 10m x 10m spacing will have detection probabilities only one-sixth as large as those with 4m x 4m spacing. In that case, the probabilities rarely exceed 0.2.

Small objects on the bottom can frequently be detected by an ALH system, but detection cannot generally be guaranteed unless the density of soundings is higher than is currently considered normal. Because target returns are frequently much weaker than the adjacent bottom return, they could easily go unrecognized unless the waveform processing software is specifically designed, first, to detect small objects on the bottom, and, second, to retain information on the detections.

The reported detection probabilities depend on the validity of the model, on the input parameters, and on the detection algorithms. Values for different algorithms could vary considerably; it is believed that the algorithms used here are nearly optimal. It is felt that these results, although clearly approximations, fairly reflect trends in nature and should be representative for SHOALS. The uncertainty of the results is greater in shallow water, because it takes a fairly large change in the target location within the illuminating beam to have a significant effect on the total target response function which, in that domain, is dominated by the laser source pulse. Because parameterization and pulse detection procedures vary from system to system, detailed results for similar systems will vary. It is expected, however, that the general trends will hold because they depend primarily on natural phenomena. Finally, systems not specifically designed to find these target returns generally will not.

Based on conclusions stated above and the results of NOAA-funded operational SHOALS surveys, Coast Survey has established a policy for application of SHOALS data to NOAA nautical charts. SHOALS depths, when acquired and processed as part of a NOAA-funded survey, are acceptable for superseding prior NOAA hydrographic and shoreline surveys except for point features, which are dealt with on a case-by-case basis. Hydrographic survey project instructions must specify water-clarity (or signal-quality), feature size limits, and sounding density standards for SHOALS disproval of rocks, coral heads, wrecks, or obstructions originating with prior surveys.

Experience to date has also shown that, like sonar, lidar returns are often received from reflectors above the bottom. These returns may represent valid obstructions on the bottom, or they may represent fish, off-beam-center reflections from steep slopes, vegetation, or drifting debris in the water column. Evaluation of these returns is based on the characteristics of the lidar waveform and the presence or absence of supporting soundings. As with sonar surveys, if these returns cannot confidently be attributed to side reflections or harmless targets in the water column, they should be considered and reported as dangers to navigation and scheduled for follow-up investigation by sonar, additional lidar observations, and/or diver.

SOFTWARE FOR ACQUISITION AND PROCESSING OF SHALLOW WATER MULTIBEAM SONAR AND DIGITAL SIDE SCAN SONAR DATA

Coast Survey continues to develop operational techniques for meeting our requirements to conduct full-bottom-coverage surveys of critical navigation areas and to determine least-depths and geographic positions of discrete obstructions or shoal areas. Coast Survey's Multibeam Working Group has been developing procedures for the acquisition and processing of multibeam bathymetry, with its imagery, and towed side scan sonar (SSS) imagery, since 1994. These techniques are based on a generic "minimum system" such as a launch-based multibeam system and are easily scaled to larger platforms and additional sensors. Generally, the acquisition hardware and software used by Coast Survey are commercial products capable of taking input from a variety of sensors and writing the data in processing software-supported formats. The diversity of multibeam systems to be accommodated by Coast Survey requires that the acquisition phase operate independently of the processing phase. Coast Survey also must have the capability to process data from other government agencies and from private contractors as well (Fig. 3).

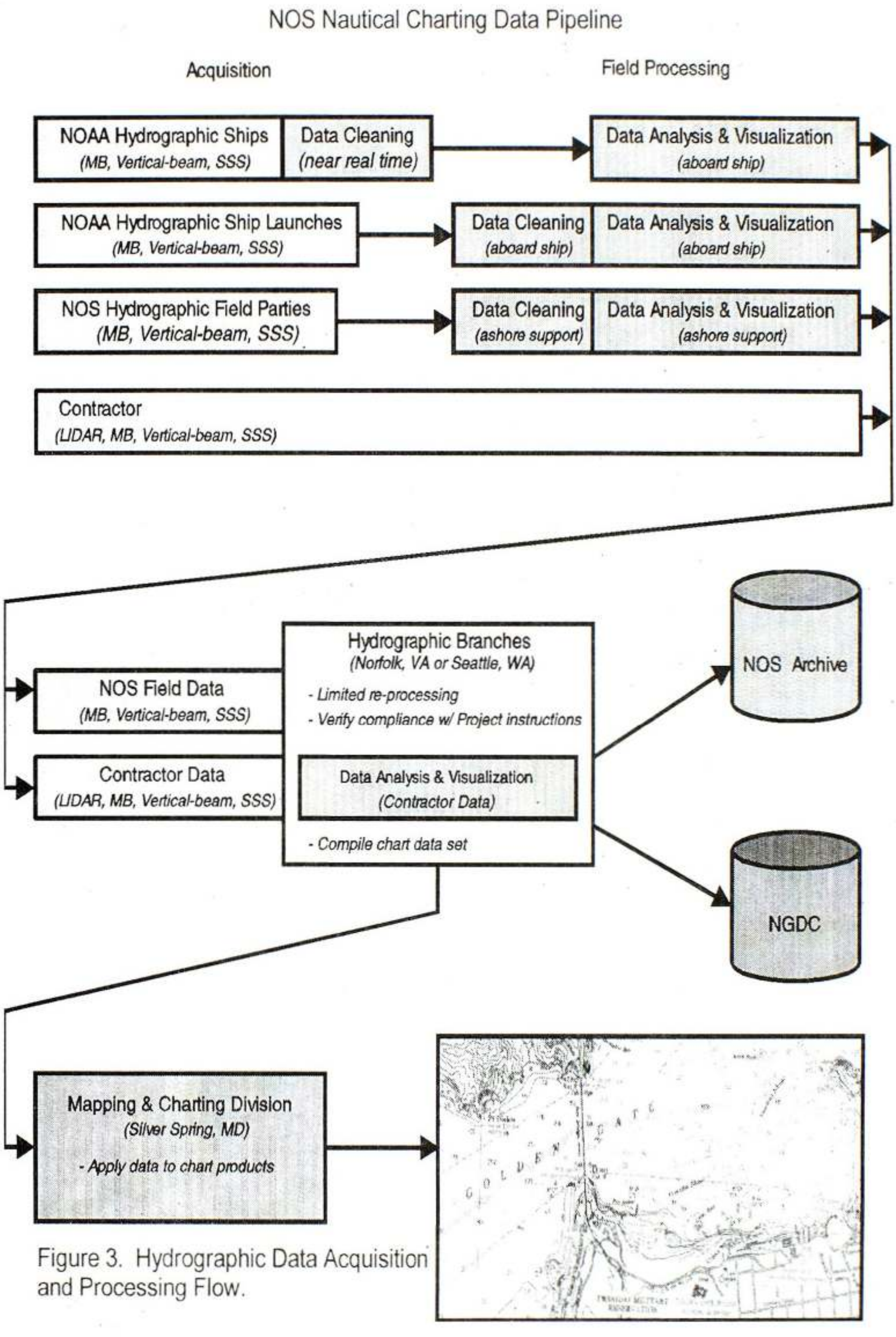

Figure 3. Hydrographic Data Acquisition and Processing Flow.

Acquisition

The typical NOAA acquisition system will record data from a suite of sensors which include: differential global positioning system (DGPS) receivers, vessel attitude sensor, vessel heading sensor, multibeam sonar, side scan sonar, and vertical-beam echo sounder. The main objectives for the acquisition systems are to:

- time-tag all sensor inputs to a common reference and store in a raw, uncorrected data format to a network server,
- provide near real-time quality control capability to detect and correct acquisition blunders and monitor data accuracy and compliance with NOAA and International Hydrographic Organization (IHO) standards,
- provide near real-time visualization of the along and cross-track swath profile, swath width, and cumulative area coverage,
- provide near real-time visualization of multibeam bathymetry and its imagery,
- provide near real-time visualization of towed side scan sonar imagery.

Coast Survey has determined the following online tools, operating in near real-time, are desirable for the field hydrographer to efficiently produce quality survey data:

- 2D waterfall display and along- and cross-track swath profiles for the multibeam bathymetry
- high resolution multibeam-based side scan imagery (if available) and full side scan sonar imagery (when operating with towed SSS)
- geo-referenced, corrected swath plot of the multibeam bathymetry (in color-coded contour or sun-illuminated depths)
- georeferenced, corrected mosaic for towed SSS imagery
- determination, by beam angle, whether or not beams meet IHO & Coast Survey requirements.

No single commercial acquisition package presently provides all of these tools. Coast Survey has focused on the Triton-Elics International Isis data acquisition system (Fig. 4). NOAA operates Isis with towed side scan sonars and Seabat 9001, 9003, and 8101 shallow water multibeam sonar systems. The Seabat 9003 system is presently operational aboard *NOAA Ship RUDE* and was used in the approaches to Portsmouth, New Hampshire in 1997 to complete NOAA's first 100% bottom coverage multibeam survey. *NOAA Ship RAINIER* operates Isis with the Seabat 8101 on several launch-based platforms in Alaska.

Processing

To maintain accountability for all soundings on NOAA nautical charts, Coast Survey processing objectives include the requirements to (1) maintain a complete audit trail for each sounding throughout the processing pipeline, and (2) retain the ability to apply and reapply correctors. These objectives are complicated by the requirement to accept data from a variety of sensors and sources. Coast Survey requires that the full raw data set be maintained during processing. Data is flagged solely for identifying the edited subset and for exclusion from the display rather than being deleted from the data set. Other processing issues for Coast Survey are managing data, improving tide corrector application, reducing data cleaning time, providing efficient sonar contact correlation methods, and using specialized hardware for processing.

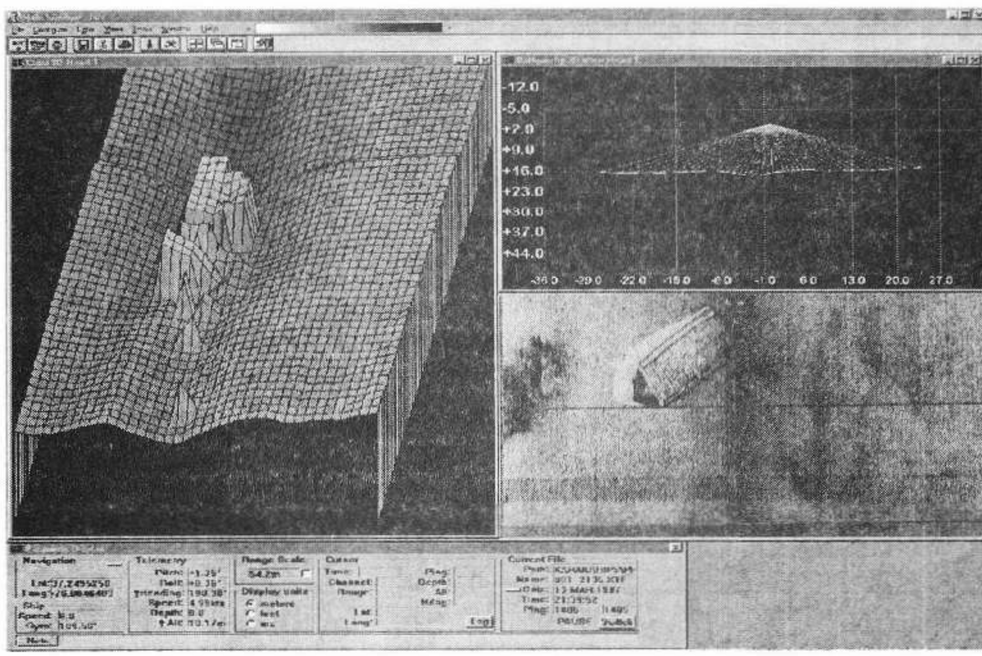

FIG. 4.- Triton-Elics Isis Data Acquisition screen view, with Seabat multibeam sonar and EG&G side scan sonar data.

An essential requirement of any raw format is that it must contain all information necessary to apply the following correctors:

- refraction for specific sound velocity profile
- tides
- vessel dynamic draft
- vessel attitude
- sensor offsets effects

Some acquisition systems apply correctors during the acquisition phase, which requires that the raw format have the requisite information to allow those correctors to be "backed out" of the data by the processing system and subsequently be reapplied.

In the case of privately contracted data, Coast Survey receives the full raw data set and an edited subset (reduced) data set. The raw data are delivered in a supported format as described. The edited data must include x, y, z, time, and tide such that, as a minimum, final tide correctors may be reapplied. This is particularly important for those contract efforts where final tide correctors are to be provided by Coast Survey. Reapplication of other correctors would require reprocessing the raw data - a step that is generally not anticipated.

The application of tide correctors presents new concerns for multibeam hydrographic surveys. Conventional NOAA vertical-beam hydrography is acquired using predicted tides. This approach has been adopted in Coast Survey in recognition that many of our survey projects take place in areas where localized tidal datums are not yet established and tide gauges are operated concurrently with survey data acquisition. Real (final) tidal datums and tidal sounding reducers are computed from the tide gauge observations and applied in post-processing to the completed survey. In contrast to those conventional methods, processing efficiency for multibeam hydrography requires real tide data early in the processing pipeline. Coast Survey is working on several initiatives designed to produce real tides within two days of logging the tide data. In addition to the problem of timeliness, the current method of zoning a survey area for tides allows substantial (> 0.1m) steps due to changes in amplitude and phase correctors between adjacent zones. Because of the resolution of shallow-water multibeam sonar systems, the steps are clearly visible in the data. Decreasing the size of the tide zones within a survey area, such that tidal corrector differences across zone boundaries are no more than 0.05 m, will minimize these discontinuities.

Coast Survey's Multibeam Working Group has collaborated with Universal Systems Ltd. to insert several new processing capabilities in their CARIS/HIPS software. Specifically, these enhancements are designed to enable the processing of Reson Seabat 9001, 9003, and 8101 multibeam data. Enhancements to date include:

Sound Velocity (SV) Editor - An SV editor was added to CARIS/HIPS to enable importing and editing of SV files. The SV profiles can be viewed in a graphic presentation and the depth or speed-of-sound values edited according to time stamp. The merge function in HIPS was modified to enable a complete refraction correction of the multibeam data (Fig. 5).

Vessel Configuration File (VCF) Editor - The VCF editor was enhanced to allow for offset computations for the multibeam sensor if it is different from the vessel's reference point. A dynamic draft table section was added, and the merge function was enhanced to enable application of heave correctors. These changes to the VCF also enable the correct refraction solution for the multibeam data. Also, a towed side scan sonar layback and offsets section was added to enable the recomputation of towed imagery navigation information. Cable-length and fish-height editors are in beta-test at headquarters and aboard the NOAA survey launch, *Bay Hydrographer*.

Navigation Editor - The navigation editor was enhanced to allow the operator to search for speed and timing changes that might indicate poor position data. Rather than manually stepping through a track line of data, the operator can simply specify a delta speed change and the editor will search for the next speed jump.

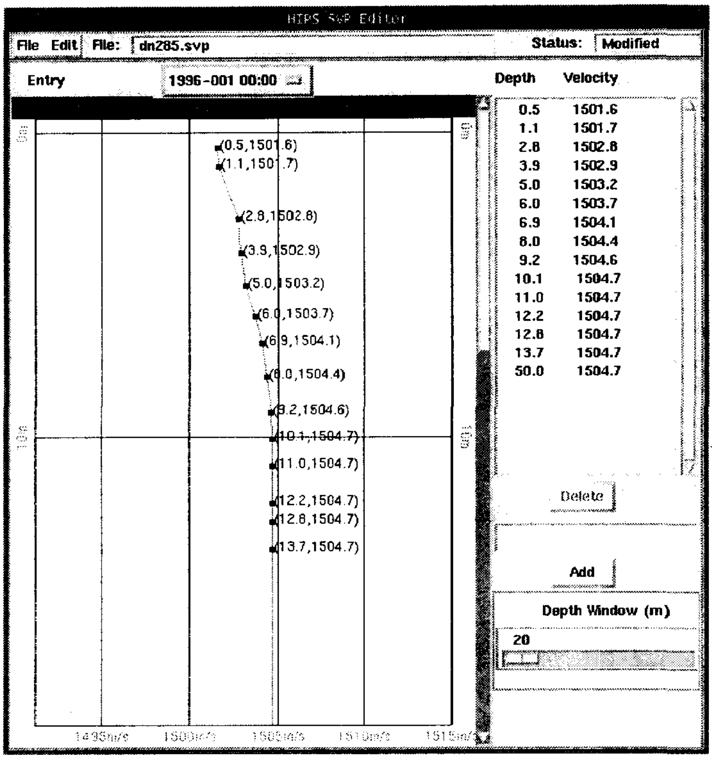

FIG. 5.- CARIS HIPS sound velocity editor screen view.

Single Beam Editor – Universal Systems Ltd. has enhanced the HIPS software to read Coastal Oceanographics, Inc. HYPACK single beam data using recommendations from the Hong Kong Hydrographic Service, the Canadian Hydrographic Service, and NOAA. In its present form, HIPS can read HYPACK data specific to Hong Kong. Single beam data is treated essentially as a special case of multibeam data, and the SV, VCF, and Navigation Editor enhancements will support NOAA's processing of this data once the HYPACK data conversion routine is complete.

Multibeam Soundings Editor (Swath Editor) - CARIS now fully supports conversion of the Triton-Elics ISIS data format. An ISIS data file can contain both the full Seabat bathymetric data package (including the RIθ data), as well as the digital side scan package from an Edgetech 260 towed side scan or from the Seabat side scan imagery (Fig. 6). During swath editing in HIPS, the operator can choose to display the beam point imagery (derived from the RIθ data), or the imagery from either of the digital side scan sources recorded in the datafile. The concurrent availability of imagery data while editing multibeam data is necessary for resolving small discrete features, where the operator may have difficulty discriminating between bad multibeam depths and a true submerged hazard.

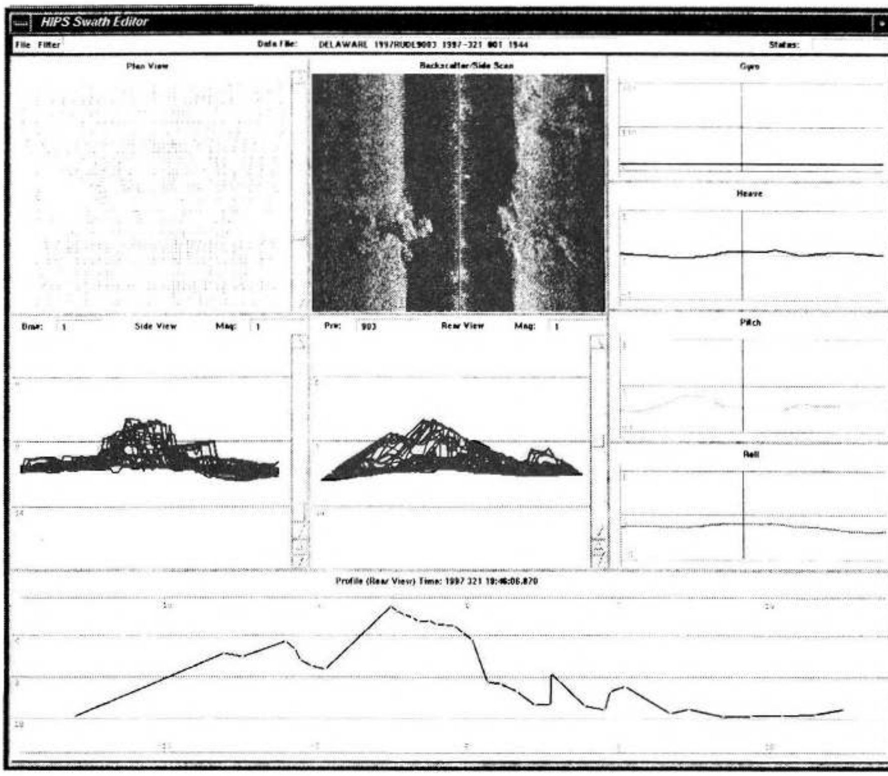

FIG. 6.- CARIS HIPS swath editor with multibeam sounding data and side scan sonar imagery.

HIGH SPEED HIGH RESOLUTION SIDE SCAN SONAR

NOAA has recently begun operating a new high speed high resolution side scan sonar system, which was designed and built to specifically address the needs of the Office of Coast Survey to conduct near shore and in-shore hydrographic surveys for the detection and documentation of wrecks and obstructions.

Conventional side-looking sonars, previously used by NOAA for this type of survey work, suffer from several drawbacks: namely the relationships between along-track resolution, tow speed, and cross track ranges combined to restrict productivity. The new system provides sonar imagery with higher along track resolution and can be towed much faster, thereby providing increased productivity. The family of high speed high resolution sonars, built by Klein Associates Inc. have been designated the KLEIN SYSTEM 5000 series of side scan sonars. The MODEL 5500 delivered to NOAA has 20-cm along track resolution and can be towed up to 5 m/sec while operating on a 150 m range scale, without the usual gaps in bottom coverage. This improvement in productivity is a direct consequence of the system design, which simultaneously forms five dynamically focused beams per side on each ping.

The MODEL 5500 is of modular design, consisting of the following components: Klein Digital Towfish, Klein Sonar Transceiver Processor Unit, Triton-Elics Data Acquisition Module, and EPC thermal plotter. The EPC plotter is intended only for printout of excerpts from the data, which is recorded and displayed digitally. In the latest configuration, the Klein Transceiver Processor Unit provides output data on a 100 Base T Ethernet Local Area Network for optimum distribution of data, permitting simultaneous multiple processing functions for hydrographic applications.

The salient features of the KLEIN MODEL 5500 are as follows:

- Dynamically focused, multibeam side scan sonar operating at a frequency of 455 kHz;
- Five digitally formed beams per side with 20 cm along track width;
- 100 percent primary coverage out to 150 m range at 5 m/sec with additional (secondary) coverage when operating at less than 150-m range and/or less than 5 m/sec.
- Display of sonar data on a high resolution 17-inch flat color monitor with subset ZOOM capability to full sonar resolution;
- Mensuration (sizing) and position marking of targets in the normal waterfall display.

The Sonar Towfish, shown in Figure 7, is negatively buoyant. It is somewhat larger, but similar in configuration to current single beam unfocused side scan sonar towfish shown in the foreground of Fig. 7. The exception to the similarity is that the multibeam focused sonar transducers are much longer, extending essentially the full length of the towfish. A detachable passive hydrodynamic depressor, mounted on a bracket on top of the towfish and well clear of the transducers, is used for depression force. The KLEIN MODEL 5500 is primarily a towed sonar system however it also has the capability to be operated in fixed mode under a hydrographic launch.

The Sonar Transceiver Processor Unit is a stand-alone module that develops five formed beams per side and provides 227,500 samples per second of 12 bit resolution data. In the Coast Survey implementation of this system the data from the Klein sonar processor unit is passed to a PC or workstation, logging its data via a parallel-port interface digital-signal-processor (DSP) card. (In the latest Klein configuration, a 100 Base T Ethernet local area network has replaced this interface.) Control of the sonar system is accomplished from a PC or workstation through use of a Graphical User Interface (GUI).

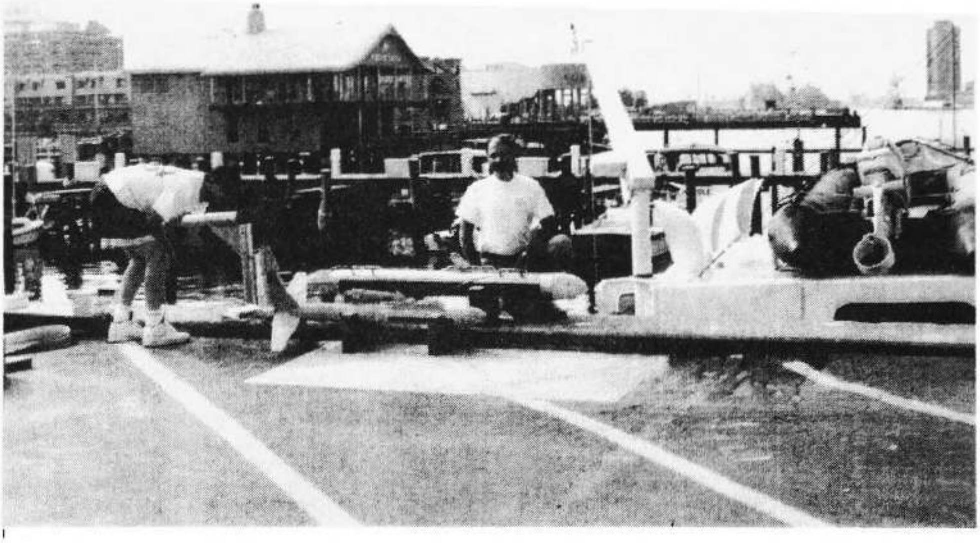

FIG. 7- High Speed, High Resolution Side Scan Sonar Towfish.
A standard side scan sonar towfish is shown in the foreground for comparison.

Target marking and measurement can be accomplished on-line in the Triton-Elics International Isis system through operator control of the cursor, using a trackball. However, normal Coast Survey procedure is to review and evaluate the sonar data off-line in post-processing using CARIS SIPS. The hydrographer identifies sonar contacts in a waterfall display where they are measured, annotated, and stored in a database for correlation with other data. All parameters associated with a contact are stored along with the contact image.

The Triton-Elics Isis Data Acquisition Module controls two internally mounted Exabyte Model EXB-8505XL 8-mm tape drives for storage of all raw data. Coast Survey logs this data across a LAN connection to a RAID array on a Windows NT or Unix server. Raw data stored by Triton-Elics Data Acquisition Module include the following:

1) Date and time, referenced to GPS, of each transmitted ping;

2) Speed over ground, in a $GPVTG message format;

3) Roll, Pitch, and Heading of the underwater instrumentation housing (towfish);

4) Ping number, starting at 1 on each new data file;

5) All side scan sonar amplitude data, with designation of primary imagery or secondary imagery;

6) Settings of all Sonar parameters under Operator control.

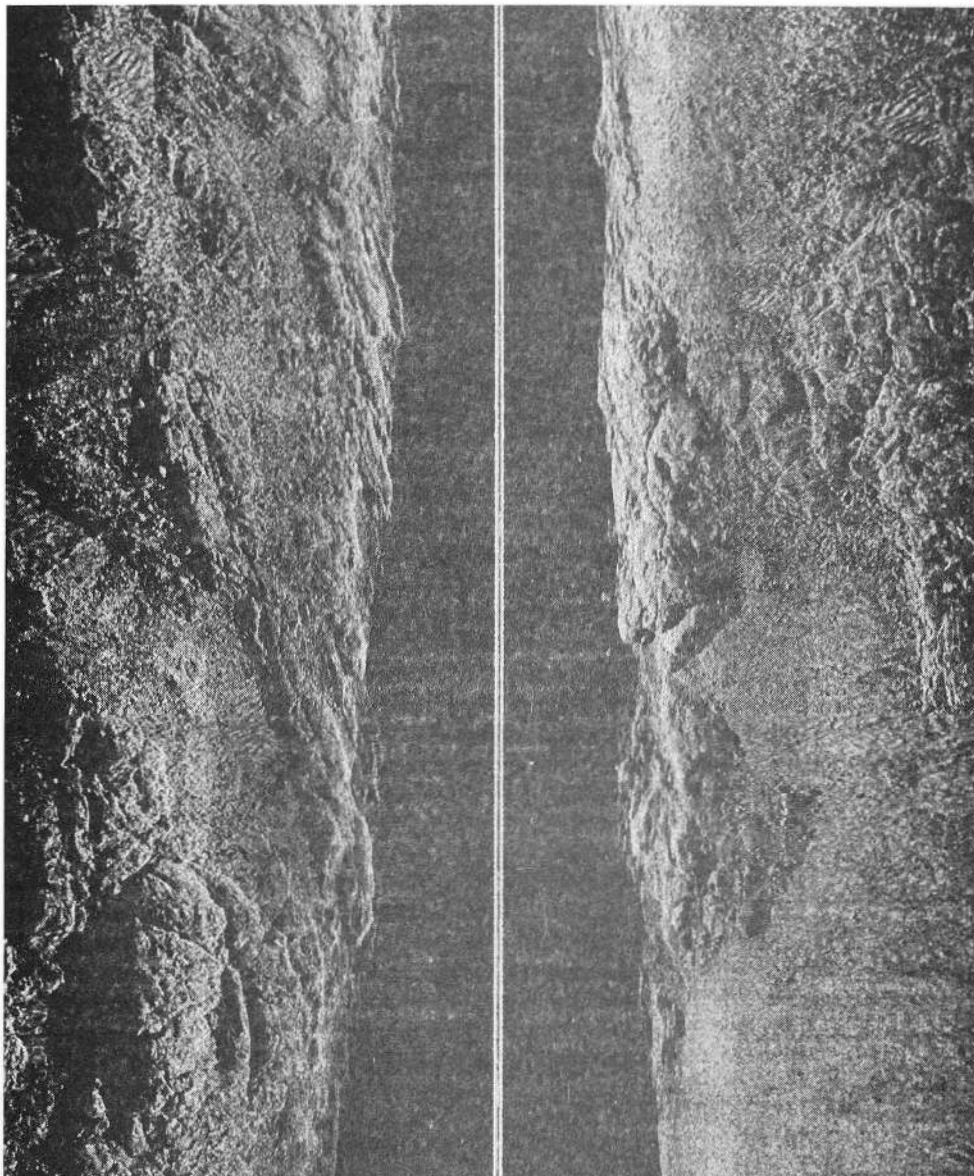

FIG. 8.- Klein Model 5500 high speed high resolution side scan sonar image of the seabed acquired at 10.4 knots on the 100-m range scale.

Simulations using the sonar design have indicated that the system has the capability to detect natural bottom features or man-made objects as small as 1m x 1m x 1m, when operated between 3 and 15 meters above the bottom on range scales from 50 to 150 m. Actual sonar performance will be dependent upon environmental conditions in the operating area.

The KLEIN MODEL 5500 has been designed with weight, power, and handling considerations as major design parameters. The resulting sonar system is sufficiently lightweight and modular to permit operations from either survey launches or hydrographic ships. The nominal mass of the Model 5500 topside equipment is 99 kg. The mass of the underwater instrumentation housing (towfish) is 100 kg.

Data from each of the focused beams is designated as primary or secondary, depending on the speed over the ground and operating range scale. Given an operating range of 150 m, the sonar will ping approximately five times per second. At slow speeds, for example 1 m/sec, only one of the beams with 20 cm along track width is required (1/5 = 1 x 0.2) to provide 100 percent bottom coverage. Since data from all five beams are always recorded, one beam would be designated as primary and the other four beams would be designated as secondary. If the speed were to increase to 4 m/sec the number of beams designated primary and secondary would be four and one, respectively, (4/5 = 4 x 0.2). When the imagery is processed, it will basically be accomplished using only the primary beam data. However in certain post processing circumstances, for example during the construction of a mosaic, it might be desirable to employ more sophisticated image processing algorithms which could potentially improve image quality by including the secondary beam data.

Figure 8 is an image of the seabed acquired off the coast of New England on the 100-m range scale at a towing speed of 10.4 knots. The sea bottom consists of exposed granite ledges with silty sand sediments in the low-lying regions. The detail of the granite ledge is very finely displayed and shows no indication of having been spatially undersampled. There are also well-defined patches of sand waves, some of which appear at the outer limits of the image.

This KLEIN MODEL 5500 has been operated on the NOAA Ship WHITING and the NOAA survey launch BAY HYDROGRAPHER for over one year, acquiring data at speeds up 10 knots (5 m/sec).

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