Hydrographic Work Flow – From Planning to Products

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Abstract - The U.S. Naval Oceanographic Office's (NAVOCEANO's) six T-AGS 60 class and one T-AGS 51 class survey vessels provide multi-mission survey capabilities using the latest generation high-resolution multibeam and digital side-scan sonar systems, along with state-of-the-art positioning, orientation, oceanographic profiling, and ancillary sensors. Each of these platforms can accommodate two 34-foot hydrographic survey launches outfitted with shallow water multibeam and digital side-scan systems. These capabilities provide NAVOCEANO with an unprecedented ocean observing and mapping capability. However, these systems produce massive amounts of data that must be validated prior to inclusion in various bathymetry, hydrography, and imagery products. It is estimated that the amount of data to be processed will increase by an overwhelming 2000 times above present data quantities. The challenges associated with processing the massive data volume have been addressed by integrating NAVOCEANO developed area-based-editing (ABE) tools with commercial off-the-shelf (COTS) processing and visualization packages. The ABE has been integrated with Science Applications International Corporation's (SAIC's) Survey Analysis and area Based EditoR (SABER) software package and Interactive Visualization Systems' Inc. (IVS's) Fledermaus software package. These packages provide the tools required for data cleaning, validation, correction, and quality control. Three-dimensional visualization is an integral part of the overall workflow. Final validated data are exported to other COTS software packages for product production. This paper presents a high level overview of the flow of information through the various tools and systems covering the hydrographic and bathymetric survey stages from survey planning, to data acquisition, to processing and analysis to product generation. Key points raised include the efficiencies gained from integration and automation, the importance of appropriate Quality Control (QC), and how data are managed through the process.

Introduction

The inclusion of high-resolution multibeam and digital side scan sonar systems, along with state-of-the-art positioning and attitude sensors and other ancillary sensors on our ships and Hydrographic Survey Launches (HSLs) has provided the NAVOCEANO with the finest-equipped survey fleet in the world. Along with this tremendous increase in bottom-mapping capability comes a corresponding increase in the amount of data that must be validated prior to inclusion into the various shallow and deep- water hydrography, bathymetry, and imagery products that NAVOCEANO produces. With our ships operating 24 hours a day, 7 days a week, and 10 months a year or more, NAVOCEANO will soon continually collect more data than anyone else in the world. If maximum data rates are used, we could face a potential of a 22-fold increase in the amount of bathymetric data to be processed – a maximum of over 2.75 terabytes per year versus the present level of 125 gigabytes per year. This figure rises to an overwhelming 2400 times the present data quantity (roughly 300 terabytes per year) if multibeam imagery and digital side scan sonar are included. Figure 1 depicts the expected increase in future bathymetric/hydrographic data volumes and the amount that has been collected over the years that NAVOCEANO has been collecting multibeam data. Notice the prior 30 years of multibeam data barely registers on the graph! [1]

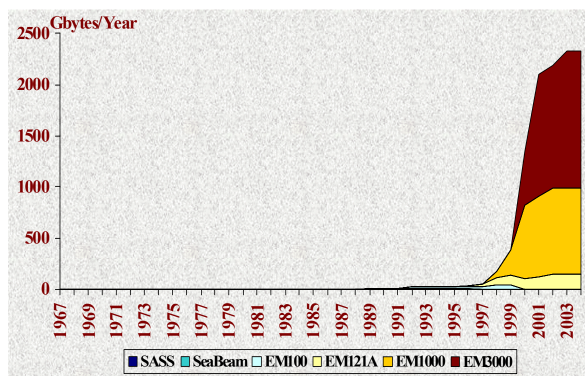

Figure 1. Expected bathymetry data volumes.

NAVOCEANO's modern multi-mission survey fleet is outfit with the latest generation of high-resolution navigation systems and bathymetric/hydrographic sensors enabled for world wide survey operations. Facets of the approach for most efficiently generating products and information from the data generated by these surveys include; (1) integration of onboard systems to centralize control and data management, (2) smart integration of processing and Quality Assurance (QA) into the real-time data acquisition environment, (3) smart automation of historically labor intensive processing with integrated quality assurance practices, and (4) smart data-basing of the information produced, while maintaining an effective approach for storing the full-resolution supporting datasets.

As defined by current NAVOCEANO procedures, the major blocks of the hydrographic work flow are: (1) definition of survey requirements, (2) creation of project plan, (3) definition of survey collectables, (4) collection of survey data, (5) ingest of survey data, (6) validation of data, (7) creation of products, and (8) delivery of products. The objective of this paper is to provide an overview of the work-flow currently utilized to produce hydrographic data products.

ISS-60 Overview

The Integrated Survey System (ISS-60) is a distributed network-based software system developed for NAVOCEANO's oceanographic and hydrographic vessels. It supports a variety of needs including high-resolution seafloor mapping, physical and chemical oceanography, and precision station keeping to accommodate over-the-side sensor deployments. Flexibility is the central design concept vital to the operator. The ISS-60 can be configured to meet the present needs of multiple NAVOCEANO user groups and provides a flexible foundation for expansion to support the potential requirements for future missions.

The concept of the ISS-60 is to establish a reliable, easily modified shipboard computer system for navigation, hydrography, bathymetry, and oceanography data acquisition and processing. It is an integrated system hosted on PC-compatible computers that provides a combination of mission planning functions, timing coordination, flexible real-time data acquisition, integrated error checking and diagnostics, sensor and ship controls, real-time data quality assurance, and sharable data control and display.

The modular ISS-60 software design allows for scalable configurations with the T-AGS 60 and T-AGS 51 class ship configurations distributed across four computer systems and with the HSL configuration fully functional on a single computer system. Although based on this scalable, distributed architecture concept, the four-computer ship configuration is operated from a single seat console, thereby minimizing the required number of operational personnel. The design of the ISS-60 allows one operator to control survey operations and monitor the quality and coverage of the navigation and environmental survey data.

In addition to supporting a wide range of real-time related data acquisition, and survey control requirements, ISS-60 includes a survey mission-planning module. The ISS-60 mission-planning module can be used in both the shipboard and the office environment.

Mission Planning

To effectively plan a survey operation, the hydrographer must have the capability of viewing available information about the survey area in a GIS-like environment. The ISS-60 Mission Planning module provides for viewing information from low-resolution sources such as the World Vector Shoreline and Digital Bathymetric Data Base (DBDB) contours of the ocean and from high-resolution sources such as raster digital charts, digitized shoreline and soundings, prior surveys, and gridded depth layers. Survey transects can be planned directly over these sources.

In some cases, large datasets are best viewed in GIS or drafting environments like Arc Info, ArcView, and AutoCAD. These packages allow rapid review of the existing data, for example side scan sonar mosaics, for planning additional survey lines to complete required coverage. Survey transects planned in these systems can be imported directly into the ISS-60 for completion of planning, scheduling, and surveying.

Initial planning for a Survey Operation (SURVOP) is normally carried out in the office with updates and revisions as necessary to fulfill requirements being done in the field as the survey progresses. Tidal characteristics of the area are analyzed, and tidal correction zones and parameters are defined for application of observed water levels to the various portions of the survey. Oceanographic analysis may also result in planning of sound speed profile zones.

The pre-survey analysis must include the expected temporal/spatial temperature and salinity variability and their potential impact on the sound velocity structure. This will include freshwater runoff, wind patterns, tidal influences, and diurnal warming and cooling.

Figure 2 illustrates the layout of the SURVOP area (blue), areas of special interest (blue), and tidal zones (red) overlain on a chart. These areas and zones can be imported from an external GIS software package or created interactively in Survey Planning by typing in coordinates or by selecting points on the screen. The World Vector Shoreline is shown in green.

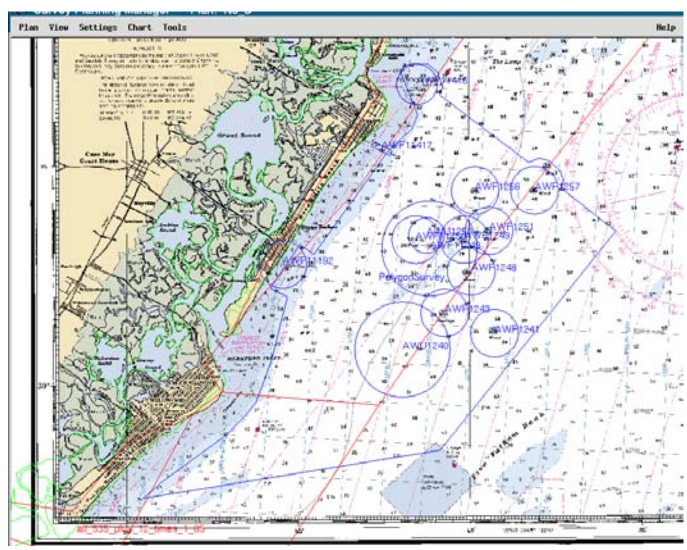

Figure 2. Areas (blue) and Tidal Zones (red) Over Chart.

The hydrographer must evaluate the requirements of the survey for coverage, object detection, and the accuracy of position and depth against the anticipated water depth and configuration of the survey area in order to plan the spacing and orientation of the survey lines to be run. The ability to plan while overlaying an existing chart or prior survey enhances the ability to plan efficient and safe vessel operations through selection of orientation, equipment, and speed. At the same time, the hydrographer can plan and visualize cross lines necessary for proper evaluation of the survey in progress and upon completion. Figure 3 illustrates planned survey lines.

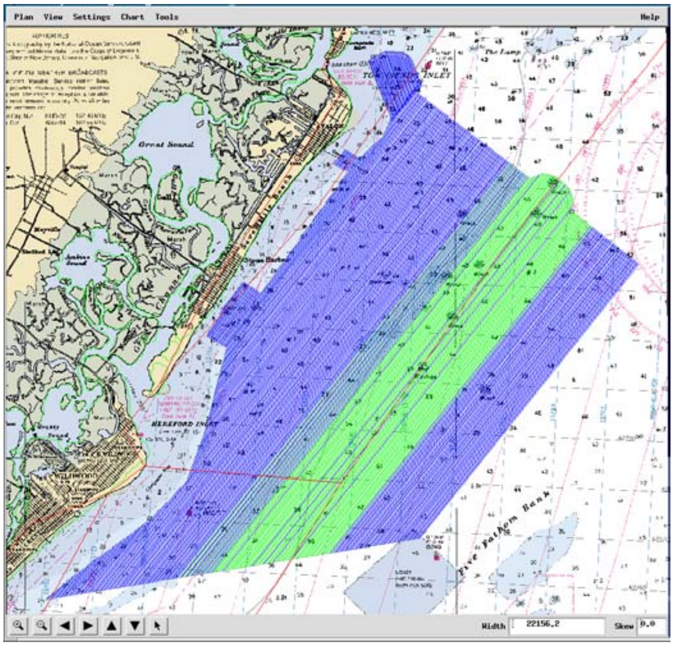

Figure 3. Survey Lines Planned Over Chart (Green indicates the line has been run).

Because it is seldom possible to have a water level gage in every portion of the survey, it is necessary to devise a scheme for correcting the observed values to representative values for each zone. Historic tide data and oceanographic analysis must be used to determine co-tidal and co-range lines from the planned water level stations. Zones must then be defined with associated correctors to keep the water level corrections for each zone within the allocated accuracy budget.

The planner must review historic survey and charting data, select items for special investigation, estimate the abundance of obstructions and features (manmade debris or natural), select tide station locations, and make trade-offs to optimize the equipment assigned and the survey effort required.

During the planning stage, a Hydrographic Project Specifications (HPS) is developed. The HPS document provides guidance for planning the survey in order to meet the data collection and processing standards required. The specifications include but are not limited to charts of the area, prior surveys, families of survey lines, line sequence plans, line spacing, survey classification, water level gage installation plan, tidal zone boundaries and associated correctors, reference bench mark and horizontal control mark descriptions and values, navigation and positioning plan, and the quality control quality assurance plan. The HPS document is assigned to the hydrographic party for execution. Day to day analysis and planning continue onboard until completion of the survey and delivery of all data to the office.

Figure 4 illustrates survey lines and a line sequencing plan which includes adequate spacing for turns, and provides the on-line and off-line distance required to complete the schedule. As the survey progresses the schedule will also show the on-line distance completed.

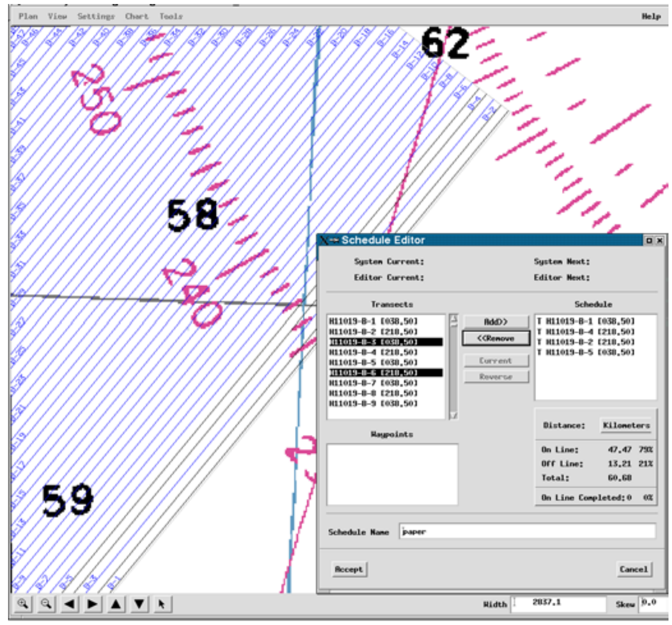

Figure 4. Survey Schedule and Distance Estimate.

ISS-60 System Configuration

The ISS-60, as installed on NAVOCEANO's T-AGS 60 and T-AGS 51 class ships and their HSLs, provides a centralized facility for survey planning, real-time data acquisition, real-time processing, coverage verification, visualization, and quality assurance of a wide variety of oceanographic data from navigation sensors, single-beam and multibeam sonar systems, and environmental sensors. The acquired data are saved into a common directory structure with a common file-naming convention using a common coordinate system and common units of measure. The ISS-60 X Windows/Motif Graphical User Interface (GUI) provides an intuitive, menu-driven structure for system configuration, data-logging control, survey evolution control, integrated diagnostics, and real-time data visualization. The operator interface is consistent across the T-AGS 60 class, T-AGS 51 class, and HSL system configurations. This high level of commonality across NAVOCEANO platforms facilitates the use of one set of operational procedures across the fleet and simplifies hydrographic personnel training requirements.

The T-AGS Mission Electronic Suite (MES) is the collection of shipboard oceanographic and hydrographic related computer systems, network systems, sensor systems, and peripherals. The ISS-60 system software and computer hardware provide the operational focal point for the personnel conducting survey operations. Figure 5 provides a high-level overview of the T-AGS 60 class ship MES. In this configuration, the ISS-60 resides on four computers refered to as the central suite. The central computer No. 1 (cc1) and central computer No. 2 (cc2) each drive two high-resolution flat panel monitors. All ISS-60 operator interaction, data monitoring, and quality control displays are realized on these four monitors. In addition to providing two high resolution monitors to the configuration, cc2 provides disk space and on-line redundancy for the primary cc1. Redundancy in real-time data recording is supported by simultaneously recording two copies of all acquired data, one to a file system on cc1, and a second to a file system on cc2. The ISS-60 data acquisition computer #1 (dac1) manages approximately 20 independent serial I/O channels to support the range of MES sensor interfaces. The data acquistion computer #2 (dac2) provides on-line redundancy for dac1 as well as system testing and operator training services.

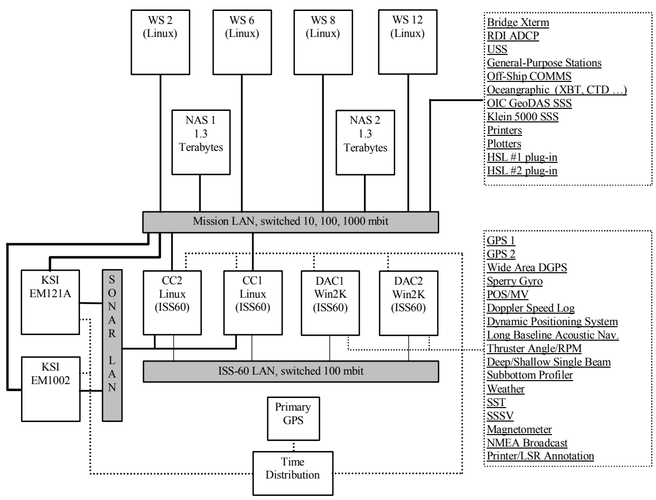

Figure 5. High-level ISS-60 and Mission Electronics Suite (MES) block diagram for T-AGS 60 class ship configuration.

ISS-60 interfaces with the majority of the permanently installed scientific sensors and provides generic data distribution and remote display services for roll-on/roll-off systems. The list of permanently installed sensors includes, the Kongsberg Simrad, Inc. (KSI) EM121A and EM1002 multibeam sonars, primary and secondary GPS receivers, wide-area differential GPS receiver, long baseline acoustic positioning system, gyro, doppler speed log, POS/MV, dynamic positioning system, thruster angle/RPM, single-beam systems, weather data, sea surface temperature, sea surface sound velocimeter, acoustic doppler current profiler underway survey system, and over-the-side profiling equipment.

Two network-attached storage (NAS) systems, each with 1.3 terabytes of disk capacity, provide the storage for all acquired data. The ISS-60 system can be configured to automatically archive logged data files from the primary logging disk to the NAS on a configurable periodic basis, or on operator request, such as at the end of each survey line.

Four dual-processor Linux workstations (WS2, WS6, WS8, and WS12) provide the seats used for shipboard data processing, validation and QC. All of these machines support 1 gigabit switched network connections to the NAS.

Each NAVOCEANO ship can accommodate two HSLs. These boats typically support daylight operations and are brought back onboard at the end of the day. Figure 6 provides a high-level overview of the HSL system configuration. On the HSL, the ISS-60 software runs on a single Linux computer system. The HSLs are equipped with the KSI EM3000 multibeam sonar system and the Datasonics System 1500 side scan sonar systems to support NAVOCEANO's high-resolution, shallow-water survey requirements. Plug-in network connections facilitate data transfer on and off the HSLs. The ISS-60 GUIs and operational procedures are the same between the ship and the HSL configurations, even though the mix of sensors is different. The processes and procedures for tasks such as modifying the survey plan, scheduling survey lines, acquiring and aborting survey lines, automated line following, managing the helm display, processing and applying sound velocity profiles, and monitoring the coverage and quality of the acquired data are basically identical between the ship and the HSL.

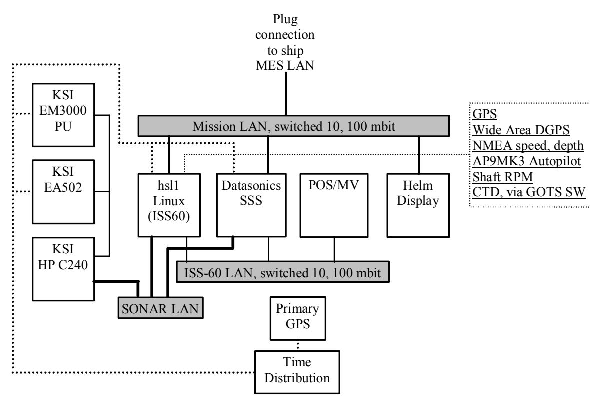

Figure 6. High-level ISS-60 and Mission Electronics Suite (MES) block diagram for HSL configuration.

Real-Time Survey Operations

The ISS-60 supports underway, station keeping, and line-following operations. Each type of operation may have a number of different activities; these include deep-water bathymetric, hydrographic, geophysical, acoustics, biological, and physical/chemical oceanographic activities. To support these operations, the ISS-60 can be configured in various ways to support the specific data collection rates, real-time processing, and data visualization required by the mission scenario.

The ISS-60 control program, shown in Figure 7, provides access to the system user configurable parameters. A separate configuration file is maintained for each survey platform to manage details such as which sensors are active, the sensor allocation to network and/or serial ports, frequency of data logging, frequency of file name change interval, and various tolerance monitoring parameters including GPS Dilution Of Precision, data timeouts, across-track error, etc. The lower portion of the screen shows the active sensors and active real-time processing programs. Each icon on the lower portion of the screen is color coded to indicate the current status. Green icons mean the task is fully operational with expected inputs and output. Red icons mean the task is running but has encountered some type of failure. The type of failure is reported to the ISS-60 central message display and recording facility. The error messages provided here can be referenced to assess and trouble shoot any faults that may be occurring. Yellow icons mean the task is fully operational with expected inputs and outputs, however the task has been configured to not record any data.

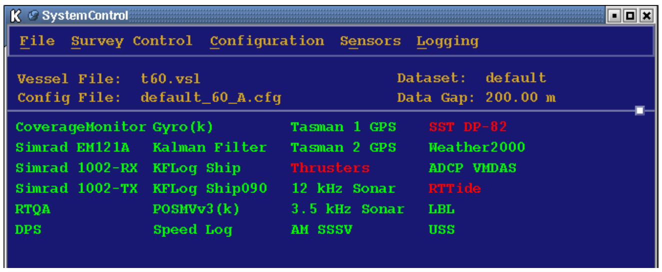

Figure 7. ISS-60's System Control program.

The bathymetry data acquired from the multibeam sonar systems are saved in a Generic Sensor Format (GSF). [2] All other logged data files are saved in space delimited ASCII format. All logged data file names are produced by the ISS-60 software, following a standard naming convention that includes a two-character platform designator, a two-digit year, a three-digit day, a three-character sensor identifier, and a two-digit sequence number. File names can be automatically changed based on elapsed time, current file size, and operator request. Two identical copies of the acquired data are logged in real-time. The primary dataset is recorded to the data disk on cc1. The secondary dataset is simultaneously recorded to the data disk on cc2. Separating these across two computer systems provides for a high level of fault tolerance.

The outputs of the ISS-60 survey planning effort described above load into the ISS-60 real-time navigation manager module. An example layout of the real-time navigation manager module is shown in Figure 8. Currently enabled display layers include survey line waypoints, survey lines, survey line labels, latitude/longitude graticule, ship icon, current line, next line, tide zones (red), and existing multibeam bathymetric coverage. A configurable status area at the bottom of the display depicts pertinent navigation information.

The line-sequencing plan (described in Figure 4) defines the intended ship routing as a series of waypoints and survey transects that specify the order in which the survey will be conducted. Once the plan has been loaded in the real-time environment, the line schedule can be adjusted as required by the events of the survey on a line-by-line basis if necessary. All the information developed in the planning phase can be layered on the real-time navigation screen.

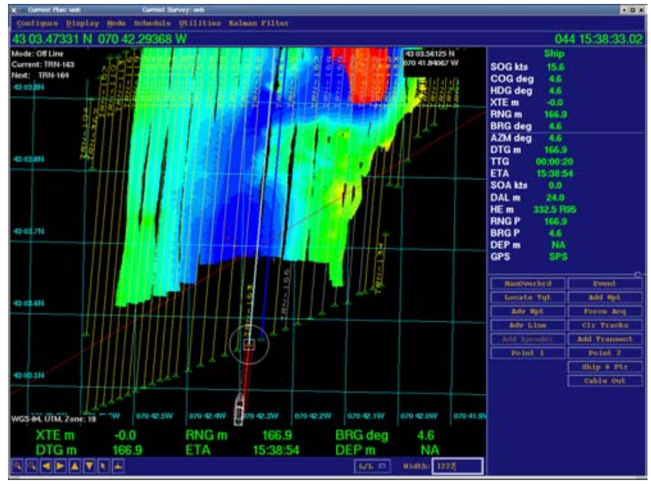

Figure 8. ISS-60 navigation manager display.

The ISS-60 helm display is shown in Figure 9. This display is hosted by a PC or an Xterm located near the helmsman on the bridge, but a synchronized copy of this display is also visible and fully conrollable by the ISS-60 operator. This feature is particularly useful in assisting with communication between the bridge and the survey operation.

Figure 9. ISS-60 helm display.

Begin-line and end-line events and their times are captured in the central message facility, and data files which may have been configured to flag (invalid) off-line data will no longer be flagged. ISS-60 supports an interface to the shipboard dynamic positioning system (DPS) and to the autopilot on the HSL configuration. When this interface is active, the ISS-60 will provide steering guidance to the autopilot to maintain platform adherence to the intended survey track. Survey system integration with the DPS/autopilot is a key feature for hydrographic survey operations, where line spacing is stretched to most efficiently cover the planned area while ensuring that the required seafloor coverage criteria are satisfied. With reliable wide-area DGPS and a suitably configured interface with the ship control systems, transect line following will typically be maintained to better than 5 meters of across-track error and in general is maintained to better than 3 meters of across track error.

The results of the tidal zoning and water level analysis completed in the planning phase are used during ISS-60 operations. The tide zone boundaries can be layered on the navigation manager and helm displays. During data acquisition, predicted water levels, applicable over the extents of each tide zone, can be applied to the bathymetric data.

Sound velocity zone definitions from the planning phase can be layered on the navigation manager and helm displays. Sound Velocity Profiles (SVP) are reduced from profiling CTDs, XBT, and XSSVs. These observations are processed using the NAVOCEANO "svpg" software with the outputs written into the ISS-60 dataset. The resulting profile is viewed within ISS-60 and can be applied to the appropriate sonar systems and long-baseline navigation solutions on operator request. Once an SVP has been applied, a record of the profile is maintained with the applicable data for traceability. On a continual basis, the current value from the sea surface sound velocity probe is compared with the current sound velocity profile at the appropriate depth. If the difference between the current surface velocity and the value from the last cast is greater than the set threshold, an operator alert is generated to suggest that a new profile should be taken. Commonality of the ISS-60 software allows the SVP reduction and application procedures to be consistent across the ship and HSL configurations.

The color-filled bathymetry data shown in Figure 8 are generated during data acquisition to assess seafloor coverage and overall quality of the bathymeric data. As data are received from the multibeam, the soundings are binned into a regularly-spaced X, Y grid file supporting several update modes. The cells can be updated based on first value, last value, average value, minimum value, or maximum value. In general, for real-time operations the last value option is most appropriate. Any gaps in coverage can be identified in the real-time environment and in the processing environment downstream of data cleaning. Fill-in lines can be added in either environment to complete coverage.

In addition to the geospatial coverage display, several swath oriented displays of the bathymetery data are supported during data aquisition. These include a scrolling color fill, scrolling waterfall of across-track depth profile, and scrolling 3D display of the total propagated error (TPE) estimates. Horizontal and vertical components of the TPE estimate are computed for each beam during data acquisition and saved with the bathymery data. These computations are based on the work of Reed et al. [3]

Depending of the type of SURVOP, the contents of the ISS-60 dataset are incrementally archived from the central suite to the NAS. This can be done manually, for example at the end of each survey line, or it can be done automatically based on file name changes. Data from the HSL are automatically archived after the HSL is brought onboard and connected to the ship network.

Side Scan Sonar Systems

NAVOCEANO employs a variety of Digital Side Scan Sonar (DSSS) systems for detailed sea floor object detection and bottom composition delineation. Klein 5000 systems are used primarily for mine warfare and can be used at higher speeds for high-resolution object detection. Datasonics systems are used with Oceanic Imagery Consultants' (OIC) GEODAS acquisition and preliminary processing systems primarily for hydrographic survey in water depths of 3 to 40 meters. Both systems can be towed from the T-AGS 51 and 60 class survey vessels and HSLs. The primary information for hydrographic operations required from the DSSS systems is object locations, bottom composition changes, and coverage assurance.

Targets are selected from the imagery data both in real-time and during post-time review. The target location and other information about the target such as dimensions, orientation, classification and operator comments are stored in a separate "target file". A small portion of full resolution imagery around the area of the identified target ("snippet") is also stored with the target information. Onboard, all DSSS data are converted to the Unified Sonar Image Processing System (UNISIPS) format for analysis. The imagery is archived, processed, and QC'd on the shipboard systems on a daily basis.

Processing Throughput - Objectives and Approach

After analyzing data volumes, processing requirements, and the personnel resources available for quality control and validation of the acquired data, an initial goal of 4:1 (collection time:processing time) was identified for the processing system just to be able to keep up with the amount of data being collected with the new sensors. This objective is straightforward for continental shelf and deeper water surveys but becomes considerably more challenging for high-resolution shallow water surveys, especially when both high-resolution multibeam and high-resolution side scan sonar are acquiring data. For such surveys, data rates can exceed 500 megabytes per hour per platform. The future goal for the collection:processing ratio is 10:1. Reaching this objective will require incorporating automated techniques (approaching artificial intelligence techniques) and additional upgrades to hardware and network components. However, COTS products have typically achieved a collection time to processing time ratio of at best 1:1.

Due to the tremendous increase in data we are facing, the key to making major improvements in processing throughput is to change the way we do business–***we can no longer look at every data point***! But we must have confidence that real hazards to navigation are properly characterized in shallow water, and we must have the capability to efficiently examine every data point in areas of specific interest. The software improvements for reaching these objectives include three major components: (1) an Area-Based-Editor (ABE), (2) an automated data cleaning filter, and (3) the incorporation of these two capabilities with COTS software packages to provide a complete integrated data processing solution. These components are designed to work in conjunction to achieve the 4:1 objective.

Two Cooperative Research and Development Agreements (CRADAs), with IVS of Fredericton, N.B. and with SAIC of Newport, RI have integrated NAVOCEANO's tools with each company's commercial product(s). This allows NAVOCEANO to migrate toward a COTS product that meets our specific requirements. Under the CRADAs, SAIC's SABER processing and analysis product and IVS's Fledermaus 3D visualization product have both been integrated with NAVOCEANO's ABE. These tools allow the analyst to view the bathymetry and imagery data geospatially, review and assess the data points invalidated by the automated data cleaning filter, cross compare different sources of bathymetry, and perform interactive editing. This approach provides the analyst with a seamless transition between the full-resolution swath-oriented data, geospatial-oriented presentations of the data, and interactive 3D visualization of the data. As shown in Figure 10**,** the link between the software packages is the Pure File Magic (PFM) file structure, which allows users to move easily and quickly between the visualization surfaces, the complete set of contributing data points, and if necessary, back to the supporting full-resolution swath oriented files. The PFM file structure includes a multi-surface binned file with fixed spatial extents, units, and cell size that supports direct access by position to the minimum depth, maximum depth, average depth, standard deviation, and number of observations for each cell in the bin file. In addition, the file structure supports direct access by position of all (filtered and unfiltered) measured data points that contribute to each cell. Pointers are maintained to allow direct indexing back to the source data files in order to access sensor specific or data type specific information.

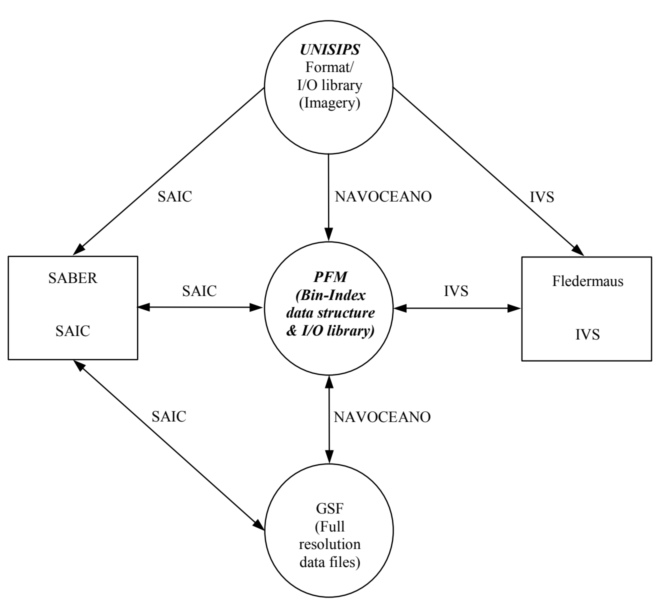

Figure 10. Data File Interfaces.

The huge volume of data that result from the new sensors has rendered traditional processing and validation techniques obsolete. This does not mean that the requirements for each phase of the workflow have been replaced but that the effort required and tools used to complete each phase of the work flow must change to reflect the data volume. The traditional approach consumed significant effort with manual time/line-based processing and was basically modeled after the processing and analysis work flow for a single beam survey. Data volumes have now demanded that the processing be more automated and less manually intensive, shifting the primary manual interaction to the validation and QC phases of the work flow. [1]

Shipboard Processing Analysis and Quality Control

Onboard data processing begins as soon as data files have been copied from the data acquisition systems to the NAS. As shown in Figure 5, four workstations are available for onboard post-processing and validation. These processing seats each access data stored on the NAS via a one-gigabit switched LAN. Through the PFM software libraries, the SABER and Fledermaus software products support the GSF bathymetry format output from ISS-60 and the UNISIPS side scan sonar target and mosaic formats. SABER directly integrates with the ISS-60 dataset directory structure, thereby eliminating any need for copy, import, or translations steps. Figure 11 illustrates the dataflow pipeline for data acquired on the T-AGS 51 and T-AGS 60 class platforms and their HSLs. SABER's hydrographic management system (HMS) reads the major survey milestones from the ISS-60 message file to assist with populating report templates and to summarize the progress of the survey and the processing.

Interfaces are also supported for data that originate from other acquisition and processing systems, allowing data from all assets involved in NAVOCEANO surveys to be processed with the same data structure and processing tools. Various multibeam sonar formats, including Reson, Simrad, SeaBeam, L3, and XTF, can be converted directly to GSF allowing for full reprocessing if required. In addition, SHOALS/CHARTS Lidar, CARIS HDCS, HTF, and ASCII x,y,z formats may be loaded directly into PFM to support data cleaning, sounding reduction, and product generation.

Initial processing tasks include line/file/event log generation and maintenance, graphic review of the navigation data for quality; review and/or update of correctors to the data; and record keeping. Navigation problems identified at this stage can be addressed by editing the offending position fixes directly in the GSF data files (thus having the potential to leave a gap) or by reconstructing the track line. Reconstruction is accomplished by going back to the raw positioning data, locating and invalidate fliers, and/or selecting an alternative raw position source, and feeding these inputs into a two-pass, forward/backward Kalman filter. The reconstructed trackline can then be replaced in the GSF file over the time frame of interest. Figure 12 shows the navigation from a family of survey lines displayed using SABER. This screen provides the interface for initial

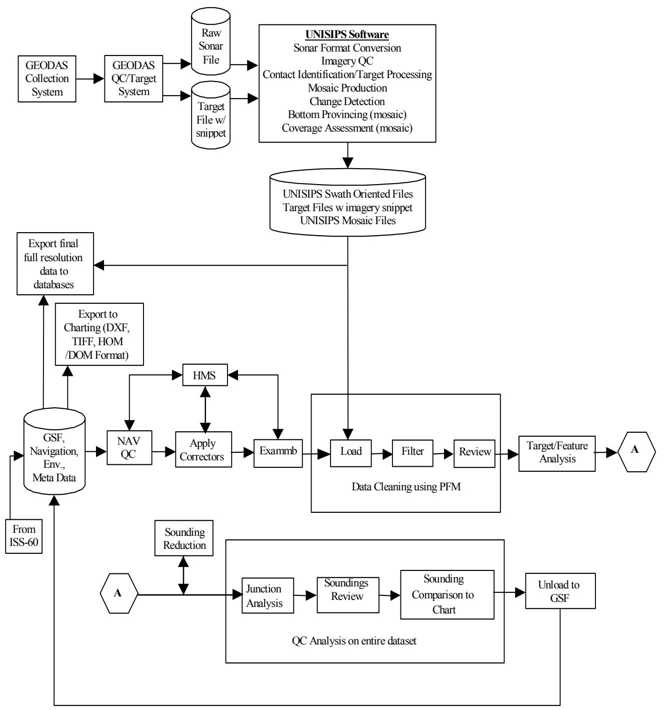

Figure 11. NAVOCEANO Shipboard Hydrographic / Processing Pipeline.

navigation QC. Interactive editing of navigation fliers, track-line reconstruction, and navigation merging steps are accessible from the SABER graphics area and menus as required.

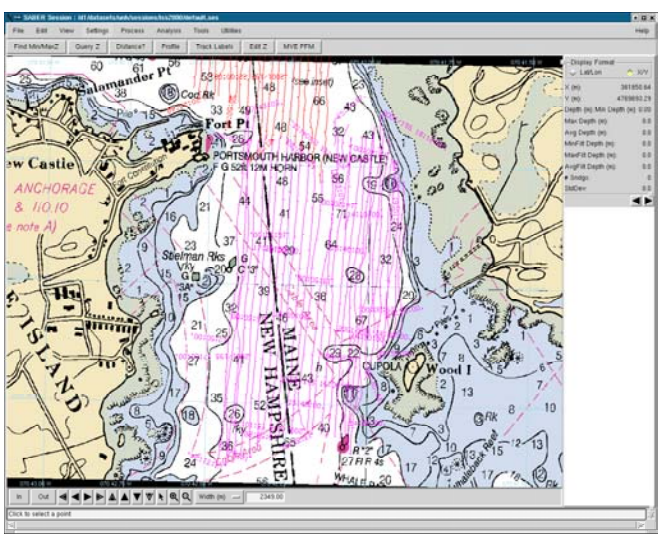

Figure 12. Initial Navigation QC.

Once the navigation has been verified and any issues resolved, then any known corrector updates can be applied. Since all corrections are applied during data acquisition, this step is typically limited to improvement of tide corrections with the application of preliminary observed water levels if these are available on a timely basis. If observed water levels are not available until some time later, then processing continues using the predicted value applied during acquisition. However, when necessary, the full range of systematic corrections including antenna and transducer offsets, alignment biases, SVP, draft and tides can be reapplied. Traceability is supported by maintaining all the offsets and correctors, including the applied SVP, with the raw data, allowing for reapplication of the corrections if necessary.

Following the flow presented in Figure 11, the next step is to "load" the bathymetry data from the swath-oriented full-resolution data files to the PFM data format. This consists of binning the depth values into a pre-defined grid that computes and saves the minimum, maximum, average, standard deviation, and the number of data points for each cell of the grid file. The bin cell size is determined by the resolution of the sonar so the full resolution data can be properly QC'd. For a hydrographic survey, the extents of the PFM file are typically defined by the sheet boundaries. All depth values that fall into each cell are maintained and can be directly accessed by position. During the load process, a statistical "area filter" can be used to identify erroneous soundings that need to be invalidated from further processing. Note that no data points are deleted; the outliers are simply flagged as invalid. The area filter provides a level of automation intended to replace the labor intensive "first-pass" of manual line-based interactive editing. For each data point, the area filter compares the difference between the observed depth and the mean value for the cell with a selectable tolerance (typically 3 sigma). If the tolerance is exceeded, the data point is identified as invalidated by the area filter. When available, targets identified from review of the side scan imagery can be used to establish a "no-filter" radius around the target location, so depths within the radius are not invalidated by the automatic filter. The no-filter radius is operator selectable and is based on the accuracy of the target location from the DSSS. Loading the targets into the PFM data structure can occur simultaneously with loading the bathymetry, or the bathymetry can be loaded first and targets loaded later. In the shipboard environment, this flexibility is necessary to allow bathymetry cleaning and review to occur parallel with the post-time review of the side-scan imagery for targets.

The full-resolution DSSS data are converted to UNISIPS format for further processing into a mosaic and eventual archive. The UNISIPS software suite creates mosaics, allows bottom province delineation, and provides access to the full-resolution scan-line data from the mosaic in the event full-resolution data must be viewed from the mosaic. The mosaic is used in conjunction with bottom samples to delineate bottom provinces. UNISIPS also provides more capabilities critical to mine warfare activities. Figure 11 outlines the functions and relationships of DSSS imagery collection and processing. All DSSS data are permanently archived in UNISIPS format. In general, the imagery data processing occurs parallel with the bathymetry data processing.

Figure 13 shows a 2D shaded relief visualization of the minimum filtered depth surface from a PFM file containing Reson 8125 data from Portsmouth, NH. This PFM file was created in UTM units with a cell size of 0.5 meters and a depth precision of 1 centimeter. The survey vessel track lines are superimposed on the bathymetry. Similar presentations are available for the maximum depth surface, average depth surface, standard deviation surface, number of observations surface, and for the unfiltered versions of the minimum, maximum, and average. The standard deviation surface visualized with the superimposed track lines can be particularly useful for locating potential problem areas as identified by patterns that are aligned parallel or perpendicular to the data collection azimuth. This surface can also help identify small-scale seafloor features that may not be readily apparent when viewing the minimum, maximum, or average surfaces.

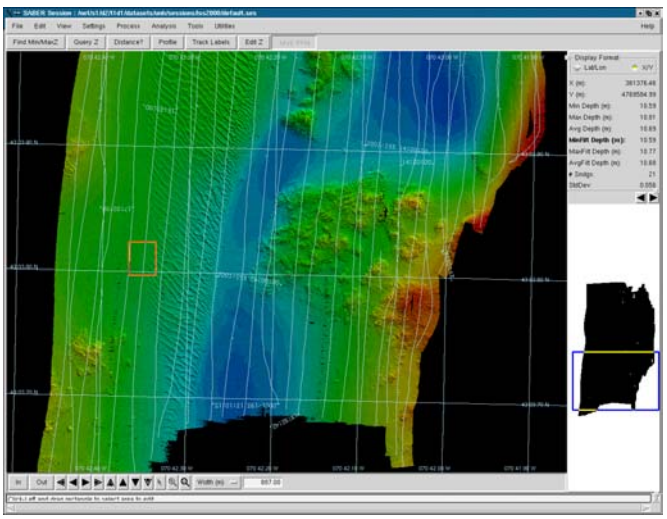

Figure 13. Reson 8125 data from Portsmouth, N.H. 0.5 meter PFM, minimum filtered depth surface colored by depth.

The human visual system has an enormous capacity for receiving and interpreting data quickly and efficiently and therefore must be an integral part of any effort to understand complex data. The key is to be able to present the data in as intuitive a fashion as possible. The more intuitive the presentation, the more rapidly data are interpreted and the more new information can be extracted. Integrating interactive 3D visualization into the overall processing system has allowed the analyst to take full advantage of data density and, simplifies analysis and interpretation by allowing interaction and exploration of complex multidimensional data. Bringing 3D visualization up to the front end of the processing pipeline provides a powerful capability to assess the quality of the data throughout the processing timeline. Even small-scale anomalies can be identified, and decisions regarding anomaly resolution can be made earlier in the process. This provides an essential capability for data interpretation and decision making during the processing workflow. The integration between SABER and Fledermaus allows the analyst to start one application from the other, visualizing the same extents of the data. The 3D scene presented in Figure 14 was generated simply by selecting the Fledermaus option from SABER to load the same section of the PFM. Fledermaus presents complex, multidimensional datasets in a natural and intuitive manner, allowing integration of multiple components from various sensors without compromise to the quantitative aspects of the data.[4] The concurrent SABER and Fledermaus displays enhance the analyst's perception of the area and rapidly focuses their attention to the significant features or anomalies resulting in overall improvement in data interpretation and processing decision making.

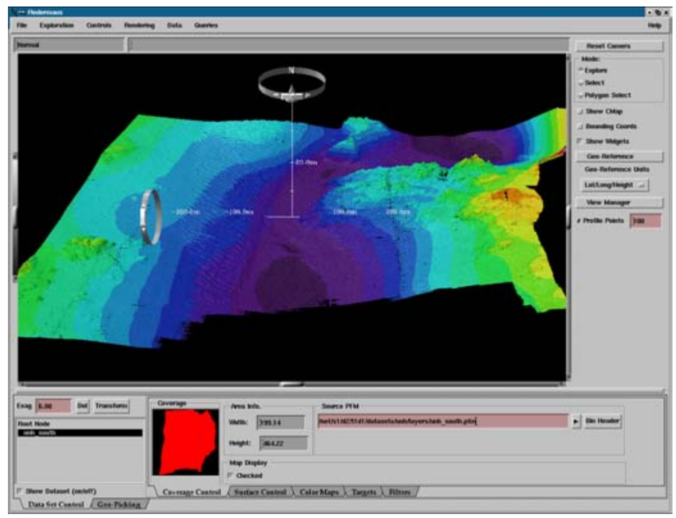

Figure 14. 3D visualization of same Reson 8125 data presented in Figure 13.

After the data have been loaded and the first pass cleaning completed by the area filter, each of the PFM bin surfaces are visualized over a "bin sub-area" of the extents of the PFM. Any outliers not invalidated by the area filter will be visible in either the minimum filtered or maximum filtered surfaces. The unfiltered minimum and the unfiltered maximum surfaces can also be visualized to review the data points invalidated by the area filter. When issues are noted, an "edit sub-area" of the displayed surface is selected for viewing all contributing data points. The small highlighted area west of the sand waves in Figure 13 was selected to launch SABER's Multi-View Editor (MVE). Figure 15 shows all data points that exist within the selected edit sub-area. The MVE allows the analyst to review all data points by individual and cumulative validity criteria, assess and modify invalidations made by the statistical area filter, manually validate or invalidate data points as appropriate, and review sounding selections. From the MVE, any sounding can be traced back to its location in the source data file. Targets derived from the side scan imagery are displayed in MVE and can be correlated with the appropriate least depths in the multibeam bathymetry. When appropriate, these least depth values are identified as "feature" selections for hydrographic data products. The edits are saved as changes to Boolean flags in the PFM data structure. When review of the edit sub-area completes, the sub-area is identified as “checked”. Checked sub-areas can be highlighted in SABER and Fledermaus to indicate which sub-areas have undergone detailed review. When all fliers have been resolved for the current view of the “bin sub-area”, this region can be marked as checked, and the analyst advances to the next bin sub-area. This approach allows the analysts to review relatively large sections of the PFM bin surfaces at a time, and focus their efforts on the areas that need additional cleaning, while requiring minimal (if any) efforts for areas were no additional cleaning is required.

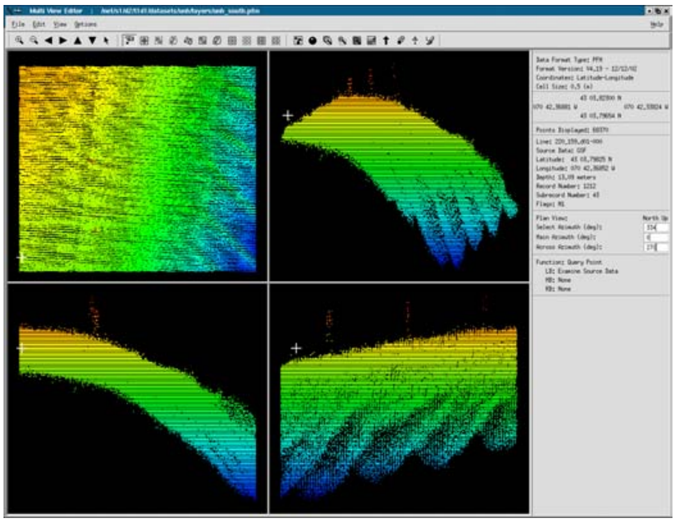

Figure 15. Multi-view interactive editor showing all contributing soundings selected from a subset of the PFM file.

The Fledermaus 3D editor, shown in Figure 16, has a similar interactive exploration interface as the main visualization window and allows the soundings to be colored by depth or attributes – file, line, ping, and beam. Deleted soundings can be shown or hidden in the display, as can the various binned surfaces. The editor also allows selection of soundings by various criteria and selection or deletion as significant features. Further details of the selected soundings can also be obtained by drilling down farther to the native files formats of the original data.

Side-scan targets are identified during acquisition, and the imagery files are reviewed post-acquisition to ensure that all significant contacts have been identified. Following this review the raw imagery, target files, and supporting data are archived to the NAS. The Datasonics’ files are then converted from OIC format to NAVOCEANO’s UNISIPS format, and mosaics are produced. The mosaics are used to help characterize the seafloor and assist in deciding where bottom sampling is to be performed.

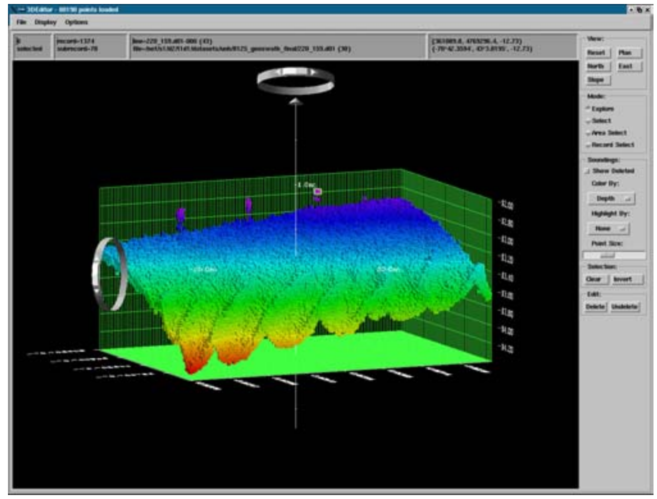

Figure 16. Fledermaus 3D editor showing same three features viewable in Figure 15.

The target files, containing the target position, a snapshot of the imagery for the target, and comments entered during the target identification, are loaded into the PFM file when review of the imagery is completed. All soundings within a user specified radius of the target location have their validity flag cleared if they were invalidated by the area filter. Any sounding flags modified by loading the targets will also have their “checked” flag cleared. The bathymetry and imagery data around each target can then be analyzed in SABER and/or Fledermaus for hydrographic decision-making.

Fledermaus displays the side-scan targets as point objects in the 3D scene and allows concurrent display of any side scan sonar image snippets, to aid in the verification and feature classification. An example of this is shown in Figure 17.

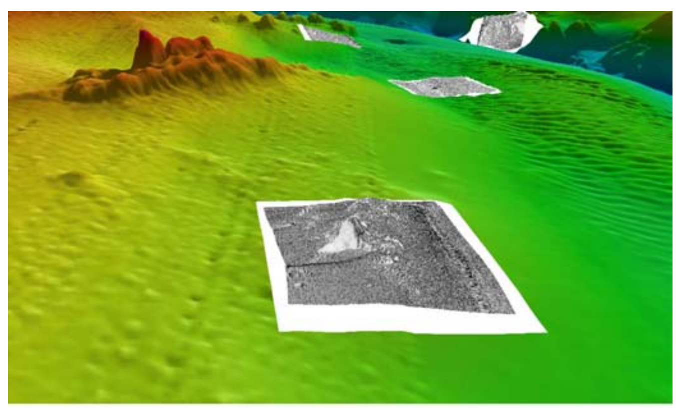

Figure 17. A scene of Portsmouth Harbor, New Hampshire. The main Digital Elevation Model is colored by depth from a multibeam sonar survey. Draped on the surface are a number of side scan sonar images.

In the shipboard-processing environment, new data are continually loaded into the current PFM as files become available from ISS-60 and the side-scan acquisition systems. As new data are loaded, the checked flag is cleared for each cell of the bin file that has been updated to clearly indicate the updated cells of the bin file. For large survey areas, multiple analysts can work on a common PFM simultaneously. The edits and review work of one analyst become visible to other analysts as the work progresses. At any time, the progress of the data cleaning effort, with respect to the area covered, is easily visualized by displaying one of the PFM surfaces showing the checked status.

While Figure 11 implies that the QC processes occur at the end of the workflow pipeline, in fact, QC processes are performed throughout the processing timeline. It is necessary to ensure that appropriate QC steps are performed when all of the survey data have been acquired and cleaned, and that sufficient processes are performed on a regular basis to ensure that any issues are identified in a timely manner. As an example, junction analysis at the intersection of main-scheme and cross-lines, and along adjoining sheet boundaries, is typically performed on a regular basis during the performance of a survey and then repeated at the completion of a survey. It should also be noted that performing the data cleaning review using an area-based approach presents the analyst with all data in the area of review. Any horizontal or vertical offsets between adjacent lines will be discernable, whereas, with the previous line-based approach, overlapping data from adjacent passes would not typically be displayed together.

For detailed sonar system performance metrics, a reference surface is established using only the near vertical beams from the multibeam sonar from data acquired with small line spacing. All soundings from all beams are compared with all points from the near vertical beams to produce a statistical assessment of system repeatability as a function of angle (or beam). In addition to providing an evaluation of each beam, these results also allow the hydrographer to evaluate the adequacy of all corrections applied to the data. This tool has proven useful for evaluating newly installed or upgraded systems prior to starting survey operations and for assessing the suitability of all corrections that have been applied to the data during survey operations. [1]

The sounding reduction algorithm uses an area-based approach to reduce the full dataset to a subset that preserves the significant seafloor features using a shoal-biased approach. Soundings that have been selected are highlighted in the displays allowing for detailed review and QC against all neighboring data points. Selected soundings may be displayed on the screen in text form superimposed on the current chart or highlighted in the 3D view for further review and QC.

On completion of sounding reduction and QC analysis, the edits which have so far been saved to the PFM data structure are "unloaded" back to the GSF data files. Primary product generation occurs from these updated GSF data files. This includes the exporting of selected soundings and soundings marked as features to COTS Electronic Navigational Chart (ENC) and Digital Nautical Chart (DNC®) production packages. For certain data products, the cleaned and validated full resolution native data files are input into various databases.

It should be noted that the while Figure 11 shows a stepwise processing approach, the combined SAIC and IVS tools do not require that the steps be completed in a specific sequence. This is an important point, as it may be useful to assess cross-check comparisons prior to completing data cleaning. Likewise, final water level corrections may not be available until 30-60 days following the survey, so final tides may be applied after data cleaning is completed. The ability to generate 3D visualizations of the bathymetry early in the process greatly assists with data interpretation and with identification of areas that need to be investigated.

In-House Processing and Quality Control

At the end of the survey, all survey planning files, raw hydrographic/bathymetric GSF files and ancillary ASCII data files, processed GSF hydrographic/bathymetric data files, full-resolution DSSS data files, target files from the DSSS, mosaics, and PFM data files are archived to 4mm DAT tapes. The DAT tapes, Report of Survey (ROS), and all field products are shipped back to NAVOCEANO. Upon arrival at NAVOCEANO, the data package is sent to Data Ingest. Data Ingest then catalogs all the data and copies it to the Data Warehouse. Once the data have been loaded into the Data Warehouse, the following QC processes are checked and/or verified (1) ensure that all data and support files are present and readable; (2) survey standards established in the planning phase were correctly followed, including verifying that horizontal and vertical control were properly established; (3) tides and sound velocity files are correct; and (4) bathymetry data have been completely processed, and observed tides have been applied. If predicted tides were applied during data collection, these files need to be replaced with observed tides when they become available. NAVOCEANO's Analysis and Validation Branch will then perform a rigorous in-depth data appraisal. It is important to note that this step is not a re-processing step. Each data type, such as bathymetry, SSS imagery, water levels, calibration data, etc. has its own QA/QC process. Check–off lists have been established to monitor the flow of data through the validation process. The final step will be to assign the final quality assessment of the data and then archive the data set.

With the improvements to our processing techniques (both software and hardware), NAVOCEANO's goal is to have all the survey completely processed in the field. Then, all that is required when the data arrives in-house is to have the data QA/QC. In addition, if observed tides were not available and predicted tides were used during data collection, the predicted tide files need to be replaced with observed tide files when they become available.

Product Generation

The output of the sounding selection module of the ABE goes directly into the CARIS chart production software. In addition to the final QA/QC selected soundings, additional digital data sources can be input to the CARIS production software.

These digital data sources include historical data from the NAVOCEANO Data Warehouse, satellite imagery for shoreline updates, and Notice to Mariners for navigational aides. Outputs from the CARIS production software suite include Digital Nautical Charts (DNCs), Electronic Navigation Charts (ENCs) and Tactical Electronic Chart Overlay Products (TECOs) such as Additional Military Layers (AMLs). TECOs are designed to enhance the user's understanding of his surroundings by depicting militarily significant information directly on the electronic navigational system. These products include area definition, dense sounding layer, high-resolution contour layer, mine warfare objects, and bottom sediment classification layers. Figure 18 illustrates a generalized production flow for NAVOCEANO

NAVOCEANO utilizes CARIS chart production software to generate both DNC® and ENCs. The CARIS software modules include the CARIS Object Manager for DNC® (CARIS DOM) and ENC (CARIS HOM), Digital Terrain Model (CARIS DTM), Geographic Information System (CARIS GIS), and CARIS Suppress Soundings. These tools are used mainly in compiling the soundings, creating and editing bathymetric contours, and rearranging the geometry of linear features to achieve proper topology. Other COTS software tools used for source evaluation, data extraction, and product displays are IVS's Fledermaus, ERDAS' Imagine, and ESRI's ArcView.

NAVOCEANO, in support of the fleet, is now a co-producer of electronic charts, in the form of DNC, under a memorandum of agreement with the National Imagery and Mapping Agency (NIMA). Under this agreement, NAVOCEANO is responsible for compiling DNC libraries directly affected by NAVOCEANO surveys, whether with navy survey platforms or with survey vessels cooperating under the International Surveys Program. Upon completion of the DNC library compilation using the CARIS software and after rigorous quality control using the NIMA VPF Validator software suite, the libraries are sent to NIMA for general dissemination as part of the NIMA chart maintenance and update program. The NAVOCEANO compilation may be used to produce an ENC in partnership with the International Surveys Program and foreign host nation hydrographic offices

Future Trends

NAVOCEANO's Survey Operations Center (SOC) System is being developed to provide real-time high-bandwidth communications to the T-AGS ships. The first C-Ku Band antenna will be installed and tested on the USNS PATHFINDER early this summer. All ships are scheduled to have antennas installed by 2005. The SOC, via ISS-60, will provide near-real-time quality control monitoring, acquisition, and data transfer back to NAVOCEANO. The SOC will also allow us to monitor the ship location along the scheduled survey track during the course of underway operations.

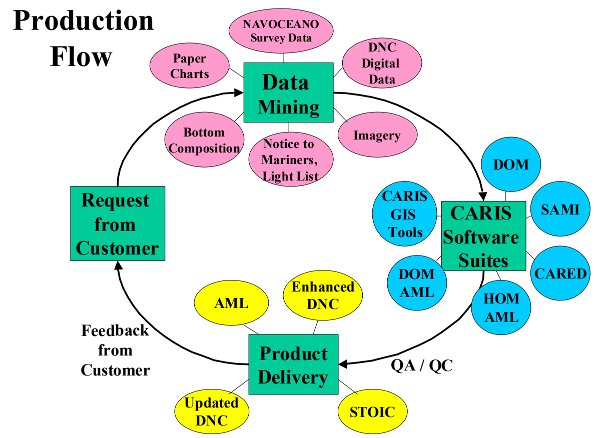

Figure 18. Data Product production flow.

The SOC will enable on-shore scientists, engineers, and analysts to evaluate the status and performance of shipboard systems. It will also allow personnel from the office to troubleshoot onboard data collection systems', monitor sensor calibration, data quality, survey progress, and coverage to assist with on-scene decisions; remotely manage software and hardware configuration control; and initiate shipboard software upgrades.

Future tactical chart production plans are to migrate to a GIS environment where full feature attribution can take place in accordance with DIGEST and S-57 transfer standards. An integral part of the required tactical charting process enhancement will involve developing/adopting a data model and data dictionary that accommodates the features and attributes needed to satisfy the requirements of all the standardized geospatial formats mentioned above. The objective is to maintain a schema during the process of building digital tactical charts that support developing a product database that can be translated into the suite of required geospatial formats. Figure 19 depicts a production path where a central database stores the attributed data in a general format not specific to product specifications.

The design and flexibility of the PFM structure allows the easy incorporation of developments such as the Combined Uncertainty and Bathymetry Estimator (CUBE) program[5], and work on the "Navigation Surface" both being developed at the Center for Coastal and Ocean Mapping/NOAA UNH Joint Hydrographic Center (CCOM/JHC) at the University of New Hampshire[6].

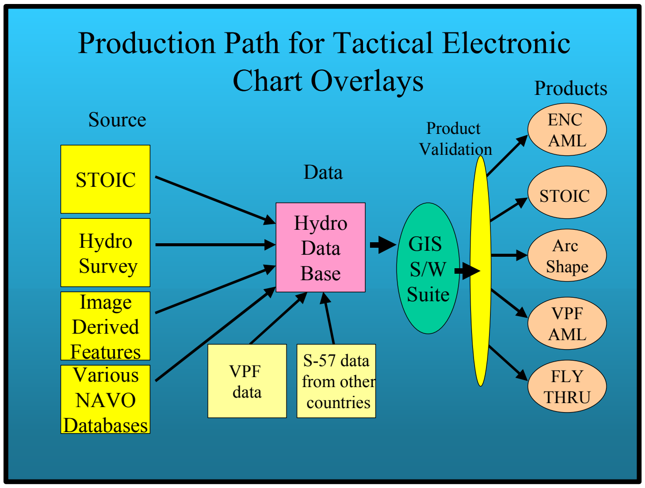

Figure 19. TECO Production Path.

Research at CCOM/JHC has shown that a significant improvement in the speed and objectivity of hydrographic data processing are possible and that the use of a Digital Terrain Model for charting has significant benefits. The CUBE approach is an attempt to deal with the majority of data processing requirements as automatically as possible. It incorporates robust statistical estimation techniques with an error model describing the MBES data being gathered and produces as output an estimate of depth and an estimate of the uncertainty in the depth estimates arranged in a grid over the area being surveyed. To make the estimation more robust, the model has been extended to allow multiple hypotheses about the true depth. Typically, this indicates a potential problem with the data being gathered and a count of the number of hypotheses is used as an indicator of where to concentrate manual validation and QC. The intention is to provide a surface that gives the 'best' estimate of the true depth in any area, along with a confidence of the estimate. The prototype integration of the CUBE modules with the PFM structure in Fledermaus has shown a significant improvement in automatic processing over the existing filters of the ABE and the feasibility of reaching the 10:1 collection:processing ratio goal [7].

The Navigation Surface eliminates the process of shoal-biased selected soundings in smooth sheet production and replaces it with a complete model of the seafloor including an uncertainty surface. The model is adjusted at critical places to exactly match the shoalest measured sounding. The result is a model on which automatic cartographic processes can be run to create a set of cartographic objects appropriate to any scale supported by the spatial resolution of the survey systems. Preliminary results indicate that significant time savings can be achieved, primarily through decreased manual cleaning and through automatic cartographic techniques. The Navigation Surface created on the ship is designed to be maintained and utilized through to chart production and in validation tests to date has been shown to provide a range of usable products [6]. In addition, the navigation surface allows for the survey archival data product to contain the full spatial resolution of the systems used to sample the seafloor. This offers a significant improvement in the resolution of the archival data product as compared with a traditional smooth sheet.

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