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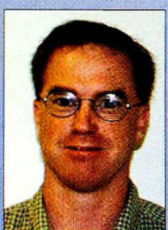

Hydrographic Workflow – From Planning to Products

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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 accommodates two 34-foot Hydrographic Survey Launches (HSLs) outfitted with shallow water multibeam and digital side-scan systems. These capabilities provide us with an unprecedented ocean observing and mapping capability that produces massive amounts of data that must be validated for use in bathymetry, hydrography and imagery products. The amount of data to be processed will continue to increase to more than 2000 times today's data quantities.

To meet these challenges, the NAVOCEANO developed area-based-editing (ABE) tools have been integrated with Science Applications International Corporation's (SAIC's) Survey Analysis and area Based EditoR (SABER) software package and the Interactive Visualization Systems Inc. (IVS) Fledermaus software package. These integrated packages have fielded the tools for data cleaning, validation, correction and quality control. Three-

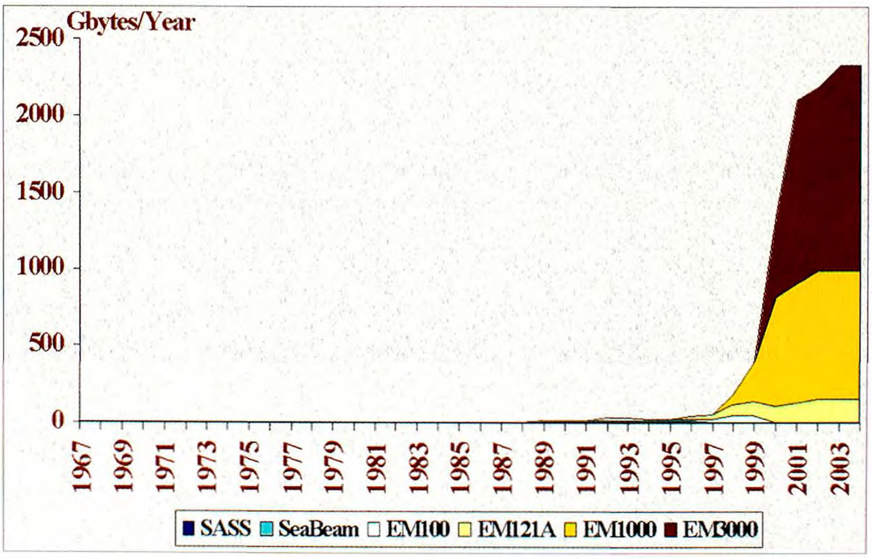

Figure 1: Bathymetry data volumes

dimensional visualisation is an integral part of the overall workflow. Final validated data are exported to other COTS software packages for product production. Key points include the efficiencies gained from integration and automation, the importance of Quality Control (QC) and how data are managed through the process.

Introduction

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 HSLs, have provided the NAVOCEANO with one of the best equipped survey fleets in the world. With this tremendous increase in bottom-mapping capability comes a corresponding increase in the data that must be validated for inclusion into the shallow and deep water hydrography, bathymetry and imagery products that we produce. 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 will. We 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 recent level of 125 gigabytes per year. This figure rises to roughly 300 terabytes per year when multibeam imagery and digital side scan sonar are included. Figure 1 depicts the increase in bathymetric/hydrographic data volumes. The 30 years of multibeam data prior to 1997 barely registers on the graph! [1]

NAVOCEANO's survey fleet conducts world-wide survey operations. Our approach for most efficiently generating products and information from this survey data includes; (1) the integration of onboard systems to centralise operation, data management and QC, (2) the integration of processing and Quality Assurance (QA) into the real-time data acquisition environment, (3) the automation of historically labour intensive processing with integrated quality assurance practices and (4) the smart data-basing of the information produced, while maintaining an effective approach for storing the full-resolution supporting datasets.

Under current NAVOCEANO procedures, the major blocks of the hydrographic workflow are: (1) definition of survey requirements, (2) creation of project plan, (3) definition of survey collectables, (4) collection of survey data, (5) ingestion 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 workflow to produce hydrographic data products using NAVOCEANO's currently deployed capabilities.

ISS-60 Overview

The Integrated Survey System (ISS-60) is a distributed network-based software system installed in all 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 accommodating over-the-side sensor deployments. The ISS-60 is easily configured to meet the needs of various user groups, provides a flexible foundation for present operations and allows easy expansion to support potential requirements for future missions.

ISS-60 is an established, 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 providing a combination of mission planning functions, timing coordination, 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. Each of these configurations is operated by a single operator who controls survey operations and monitors the quality and coverage of the navigation and environmental survey data.

The operator interface is consistent across the T-AGS 60 class, T-AGS 51 class and HSL system configurations. This commonality across NAVOCEANO platforms allows the use of one set of operational procedures across the fleet and simplifies hydrographic personnel training.

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 opera-

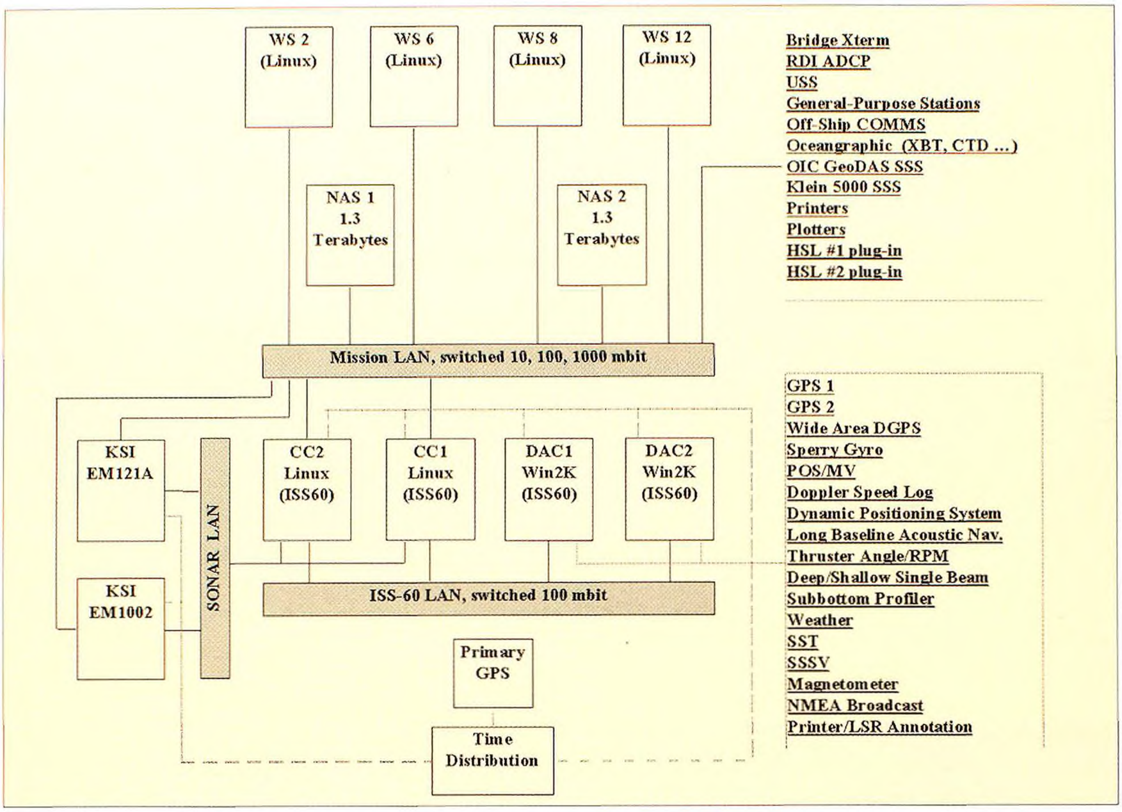

Figure 2: ISS-60 and Mission Electronics Suite (MES) block diagram for T-AGS 60 class ship configuration

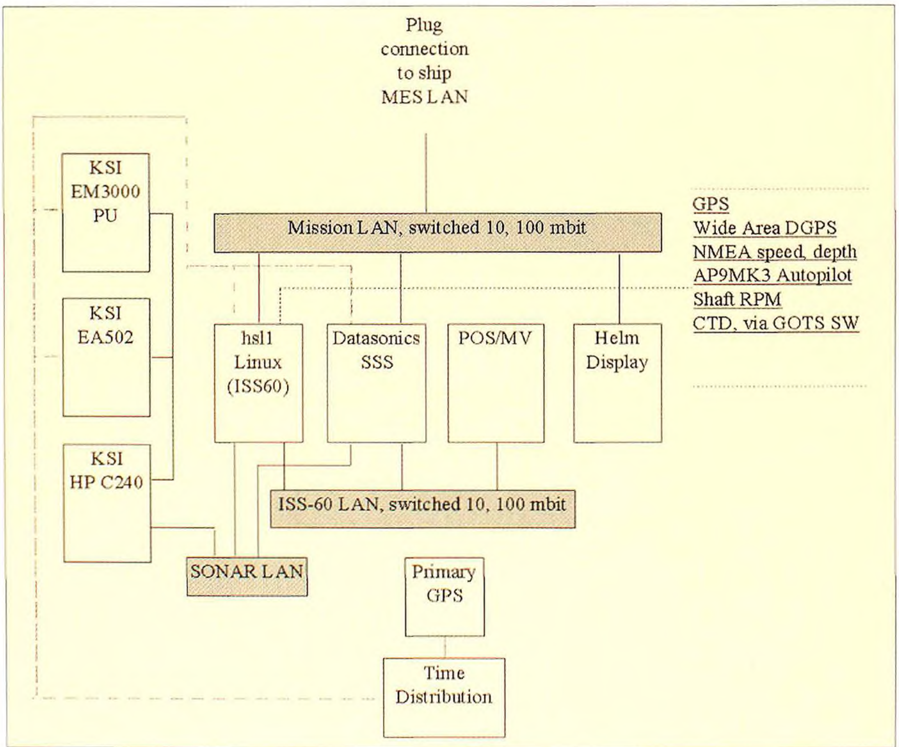

Figure 3: High-level ISS-60 and Mission Electronics Suite (MES) block diagram for HSL configuration

tional focal point for the personnel conducting survey operations. Figure 2 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. 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.

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. 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.

Each NAVOCEANO ship accommodates two HSLs. These boats typically support daylight operations and are brought back onboard at the end of the day. Figure 3 provides a high-level overview of the HSL system configuration. Plug-in network connections facilitate data transfer on and off the HSLs. The ISS-60 Graphical User Interfaces (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 are basically identical between the ship and the HSL.

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 that can be used in both the shipboard and the office environment.

Mission Planning

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

In some cases, large datasets are viewed best in

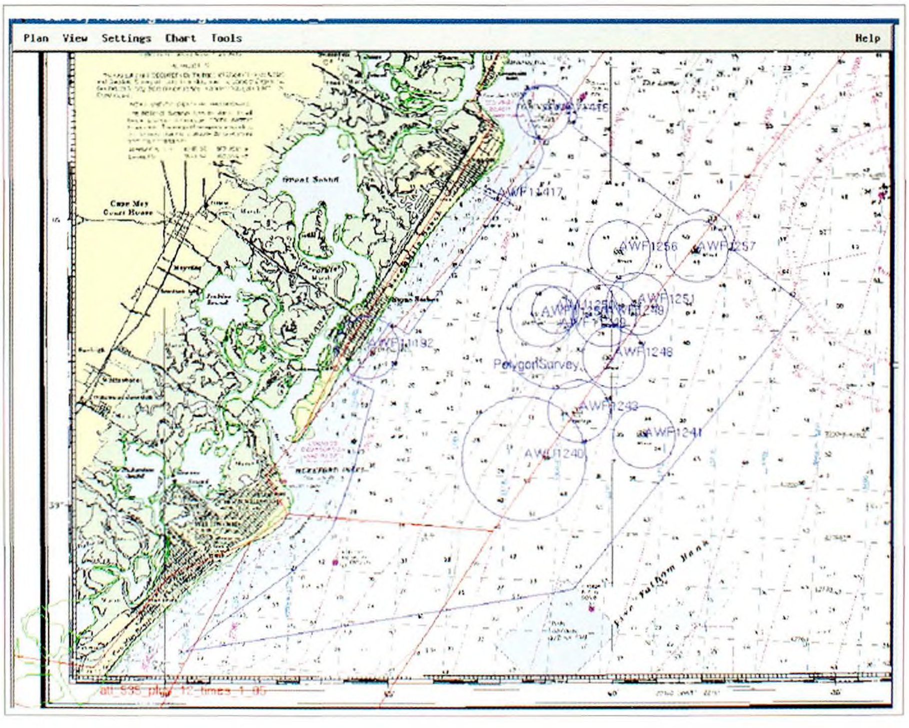

Figure 4: Areas (blue) and tidal zones (red) over chart

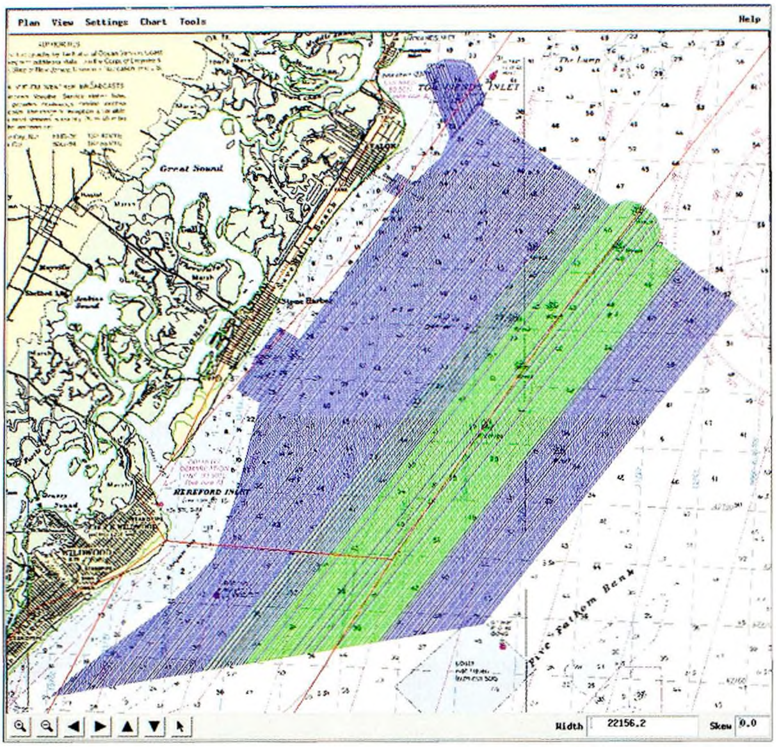

Figure 5: Survey lines planned over chart (Green indicates the line has been run)

GIS or drafting environments (Arc Info, ArcView, AutoCAD etc.). These packages allow rapid review of the existing data, such as 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 is normally carried out in the office with updates and revisions being done in the field as necessary to fulfil requirements as the survey progresses. An area's tidal characteristics are analysed and tidal correction zones and parameters are defined for application to observed water levels for various portions of the survey. Oceanographic analysis may also result in planning of sound speed profile zones.

The pre-survey analysis includes 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 4 illustrates the layout of the survey operation area (blue), special interest areas (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 ISS-60 Survey Planning by typing in coordinates or by selecting points on the screen. The World Vector Shoreline is shown in green.

The hydrographer evaluates 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 when planning the spacing and orientation of the survey lines to be run. The ability to plan while overlaying an existing chart or prior survey enhances efficient and safe vessel operations through selection of orientation, equipment and speed. At the same time, the hydrographer can plan and visualise cross lines necessary to properly evaluate survey adequacy. Figure 5 illustrates planned survey lines.

It is seldom possible to have a water level gauge in every portion of the survey, so a scheme must be devised for correcting the observed values to representative values for each zone. Historic tide data and oceanographic analysis are used to determine co-tidal and co-range lines from the planned water level stations. Zones are defined with parameters to keep the water level corrections for each zone

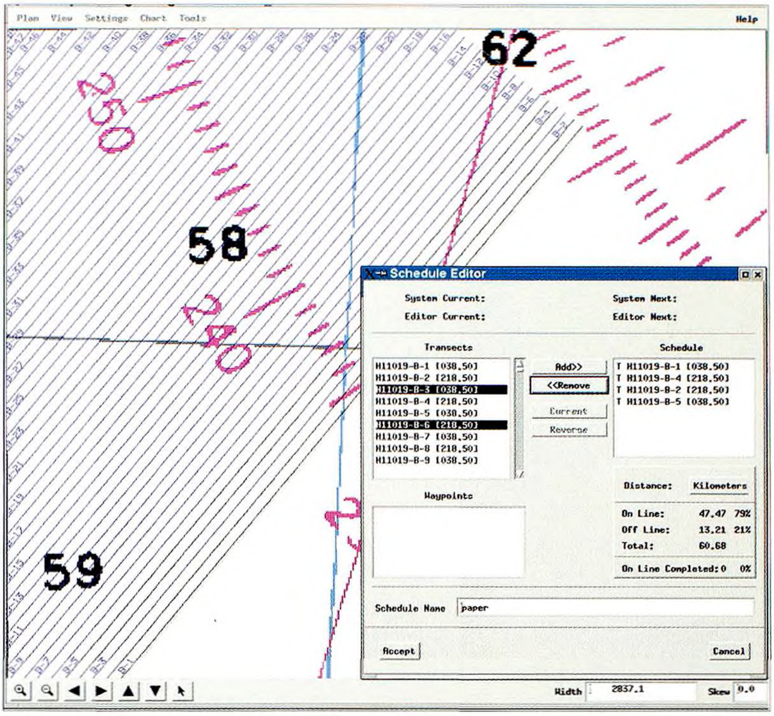

Figure 6: Survey schedule and distance estimate

within the allocated accuracy budget.

The planner reviews historic survey and charting data, selects items for special investigation, estimates the abundance of obstructions and features (manmade debris or natural), selects tide station locations and makes trade-offs to optimise the equipment assigned and the survey effort required.

During the planning stage, Hydrographic Project Specifications are developed. This document provides guidance for planning the survey to meet the data 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 gauge 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 Specifications are assigned to the hydrographic party for execution.

Figure 6 illustrates survey lines and a line-sequencing plan with adequate spacing for turns and provides the on-line and off-line distance required to complete the schedule. As the survey progresses the schedule also shows the on-line distance completed.

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 for specific data collection rates, real-time processing and data visualisation required by the mission scenario.

The ISS-60 system 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 active sensors and active real-time processing programs. Each icon on the lower portion of the screen is colour-coded to indicate the current status. Green icons mean the task is 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 can be referenced to assess and trouble shoot any faults that may be occurring. Yellow icons mean the task is operational with expected inputs and outputs, however the task has been configured to not record any data.

The bathymetry data acquired from the multibeam sonar systems are saved in a Generic Sensor Format (GSF). [2] All other logged data files are

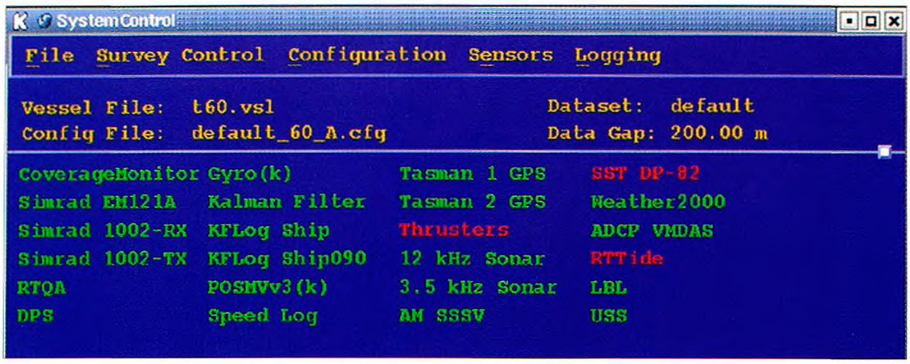

Figure 7: ISS-60's System Control program

saved in space delimited ASCII format. All logged data file names are produced by the ISS-60 software and follow 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. The separation 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 (Figure 6) 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. All the

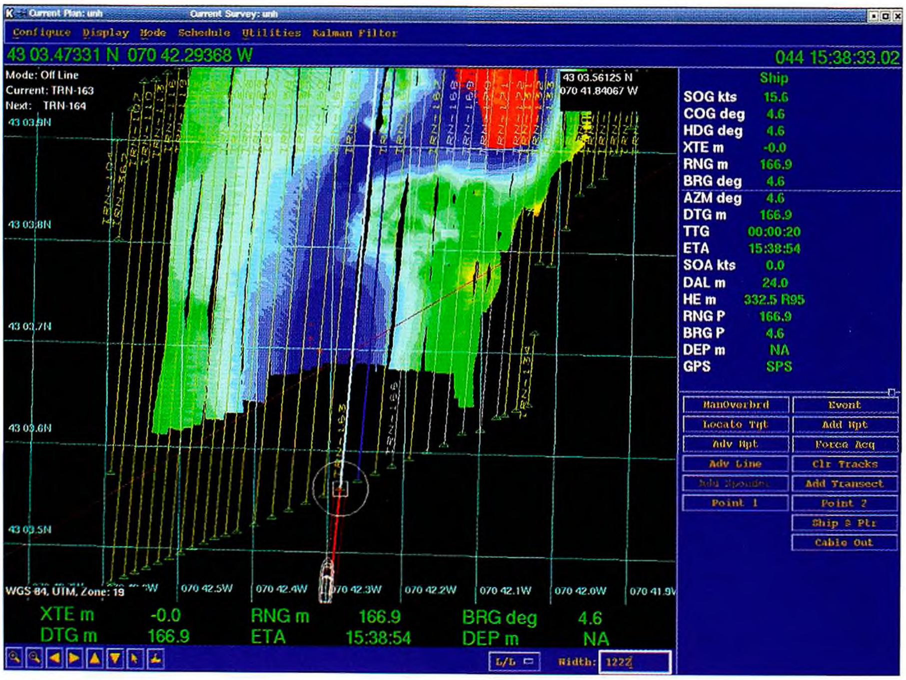

Figure 8: ISS-60 Navigation Manager Display

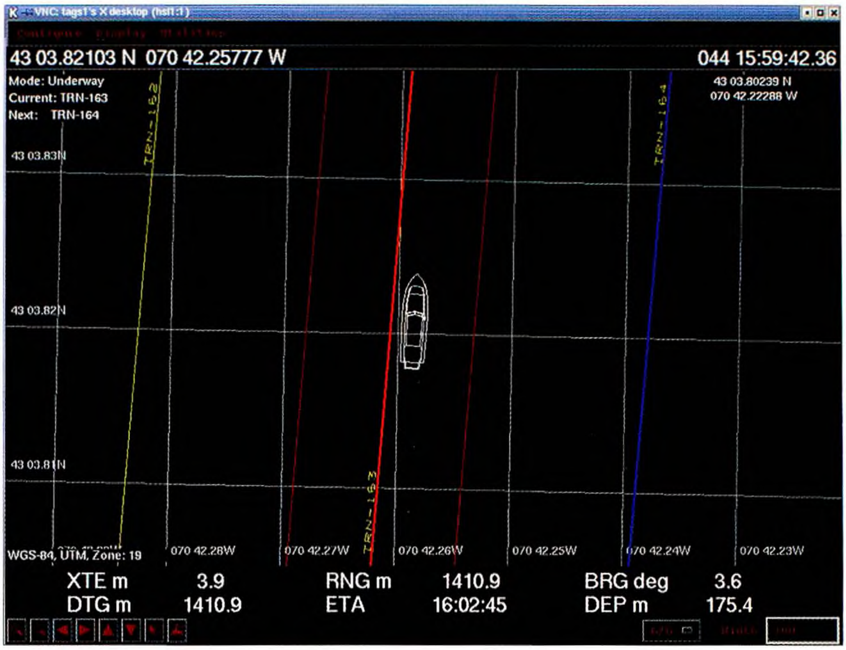

Figure 9: ISS-60 helm display

information developed in the planning phase can be layered on the real-time navigation screen.

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

ISS-60 interface to the shipboard dynamic positioning system and to the autopilot on the HSL provides steering guidance to maintain platform adherence to the intended survey track. This 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 metres of across-track error and in general is maintained to better than 3 metres of across track error.

The tide zone boundaries can be layered on the navigation manager and helm displays. During data acquisition predicted water levels can be applied to the bathymetric data with applicable parameters for each tide zone. These predictions can be replaced with observed water levels during processing in SABER.

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 with the results 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. The current value from the sea surface sound velocity probe is compared continually 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.

The colour-filled bathymetry data (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 bathymetry data are supported during data acquisition. These include a scrolling colour 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 [3] are computed for each beam during data acquisition and saved with the bathymetry data.

The contents of the ISS-60 dataset are incrementally archived from the central suite to the Network Attached Storage unit. 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.

Sonar Systems

NAVOCEANO employs a variety of multibeam echo sounders for bathymetry and hydrography and Digital Side Scan Sonar (DSSS) systems for detailed sea floor object detection and bottom composition delineation.

The list of permanently installed ship 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. The HSLs are equipped with the KSI EM3000 multibeam sonar system and the Datasonics System 1500 side scan sonar systems.

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' GEO-DAS acquisition and preliminary processing systems primarily for hydrographic survey in water depths of 3 to 40 metres. 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 side scan sonar 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 analysing 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 data are acquired. 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. COTS products typically achieve a collection time to processing time ratio of, at best, 1:1.

The tremendous increase in present and future data collection dictates making major improvements in processing throughput by changing the way business is done. To keep up, the hydrographer can no longer look at every data point! Nevertheless, real dangers to navigation must be properly characterised in shallow water and the hydrographer must efficiently be able to examine every data point in areas of interest. Data volumes have demanded that the processing be more auto-

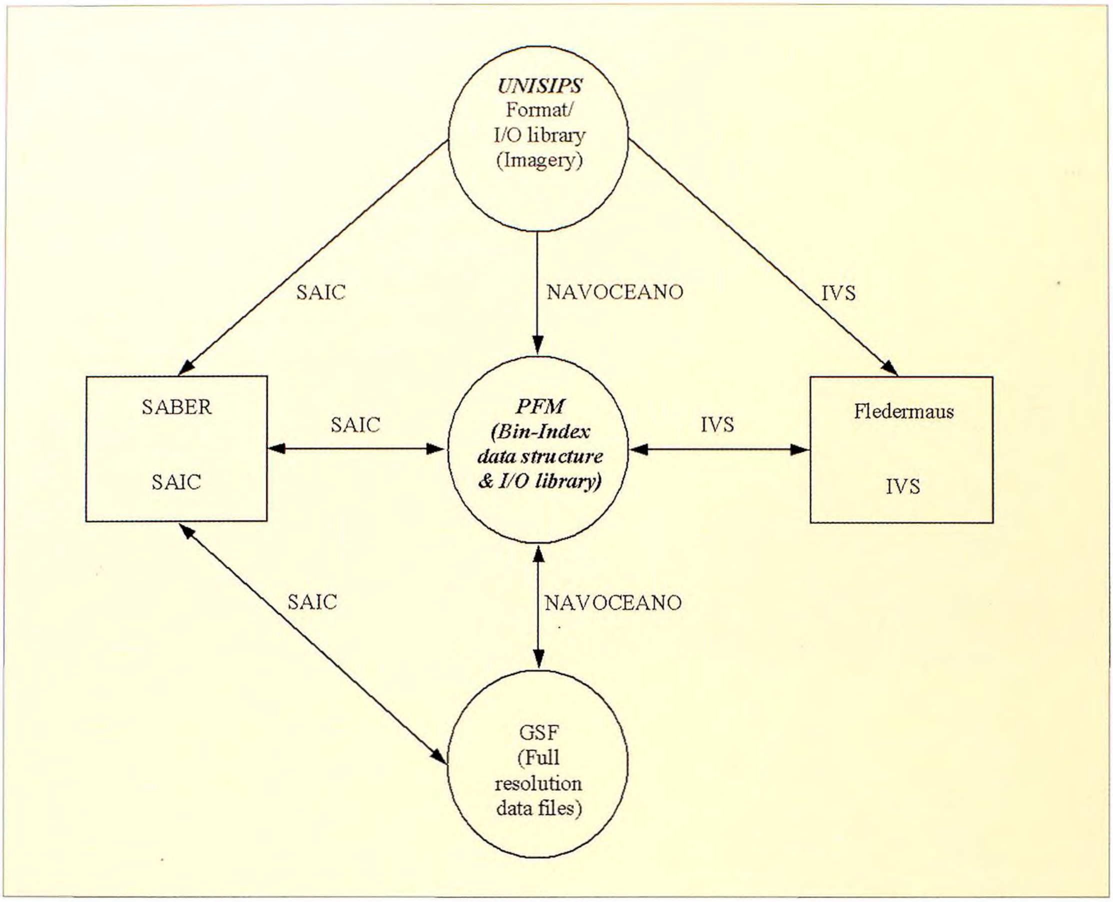

Figure 10: Data File Interfaces

mated and less manually intensive, shifting the primary manual interaction to the validation and QC phases of the workflow.[1] 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 together to achieve the 4:1 objective.

Two Co-operative Research and Development Agreements (CRADAs), with IVS of Fredericton, N.B. and with SAIC of Newport, RI resulted in the integration of NAVOCEANO's tools with each company's commercial product(s). Under the CRADAs, SAIC's SABER processing and analysis product and IVS's Fledermaus 3D visualisation product have both been integrated with NAVOCEANO's Area Based Editor. 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 visualisation 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 visualisation 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.

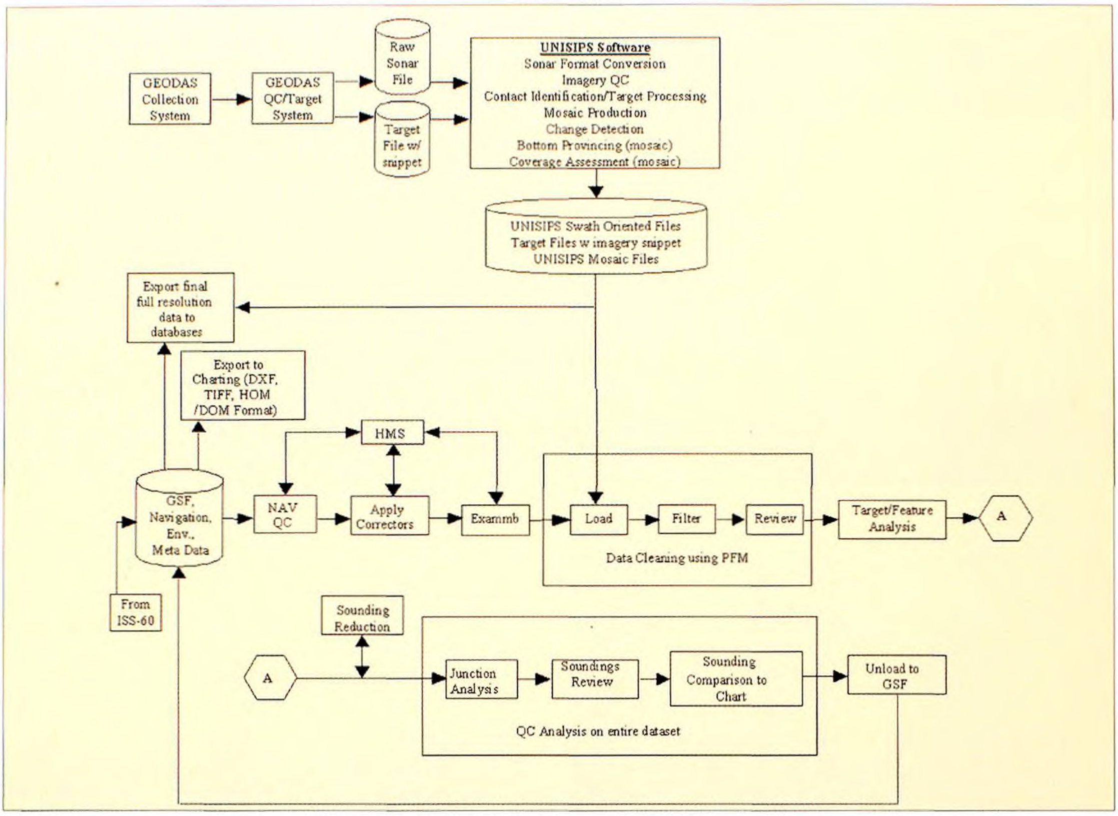

Figure 11: NAVOCEANO Shipboard Hydrographic / Processing Pipeline

Pointers are maintained to allow direct indexing back to the source data files in order to access sensor specific or data type specific information.

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 Network Attached Storage unit. Four workstations are available for onboard post-processing and validation (Figure 2).

These processing seats each access data stored on the Network Attached Storage unit via a one-gigabit switched Local Area Network. 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, 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 reads the major survey milestones from the ISS-60 message file to assist with populating report templates and to summarise 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 fixes from the

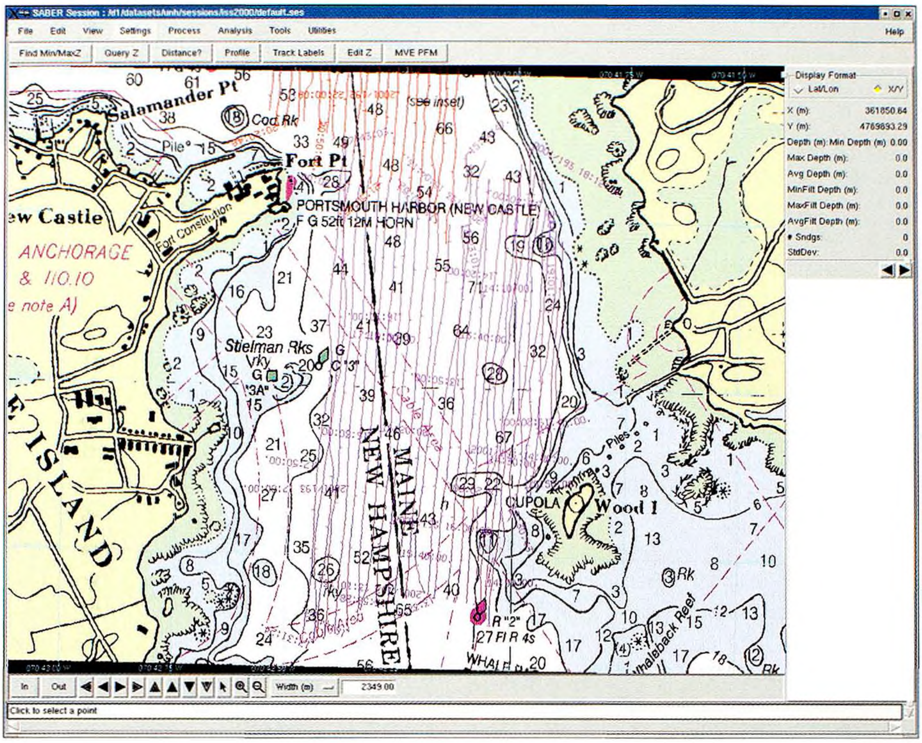

Figure 12: Initial Navigation QC

raw position data and reconstructing the track line using a two-pass forward/backward Kalman filter, or by selecting an alternative positioning source. 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 navigation QC.

Once the navigation has been verified and any issues resolved, 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 available. If observed water levels are not available until some time later, then processing continues using the predicted value applied during acquisition. 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 as needed.

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 labour 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.

Side-scan targets are identified during acquisition and the imagery files are reviewed post-acquisition to ensure that all significant contacts have been identified. 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 following completion of imagery review. The bathymetry and imagery data around each target can then be analysed in SABER and/or Fledermaus for hydrographic decision-making.

The full-resolution side scan sonar data are converted to UNISIPS format for further processing and archiving. The UNISIPS software suite creates mosaics, allows bottom province delineation and provides access to the full-resolution scan-line data from the mosaic. The mosaic is used in conjunction with bottom samples to assist in bottom province delineation. UNISIPS also provides more capabilities critical to mine warfare activities. Figure 11 outlines the functions and relationships of DSSS imagery collection and processing.

Figure 13 shows a 2D shaded relief visualisation 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 centimetre. 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 visualised 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.

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

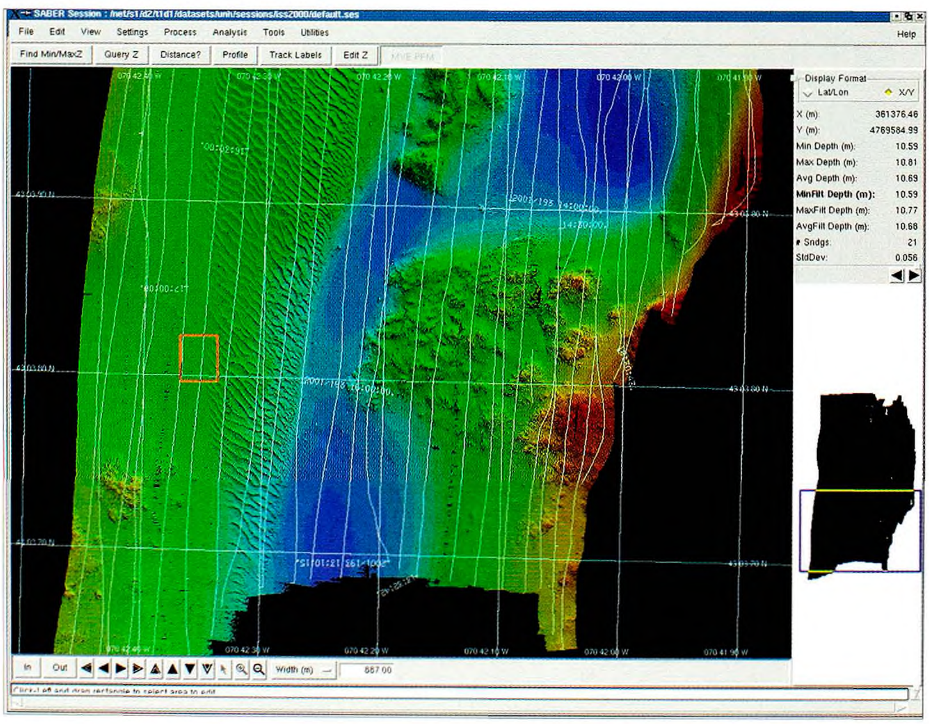

Figure 13: Reson 8125 data from Portsmouth, N.H. 0.5 metre PFM, minimum filtered depth surface coloured by depth

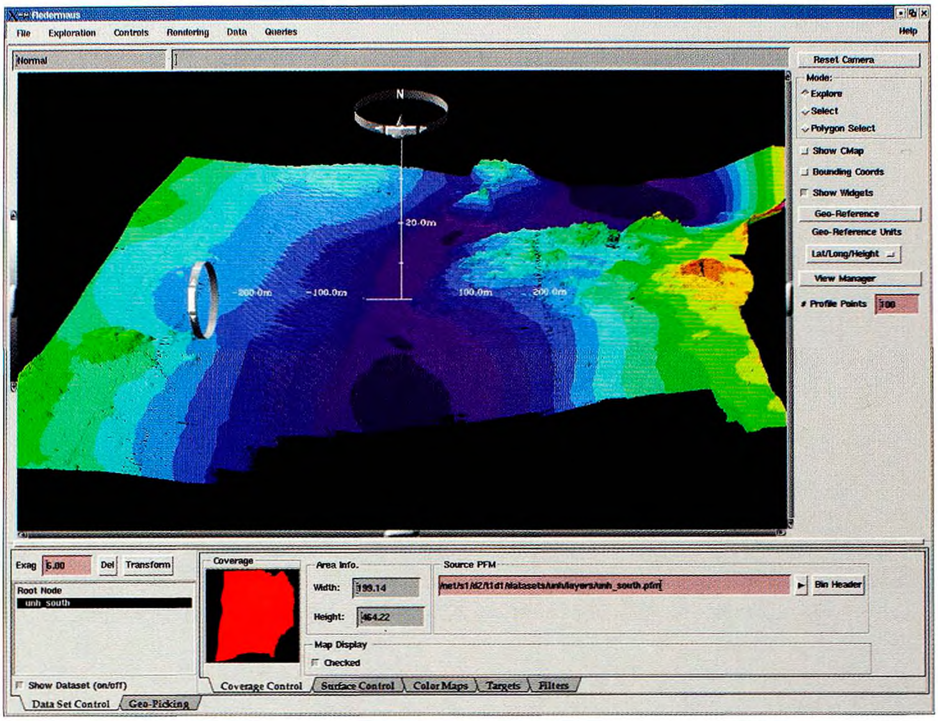

Figure 14: 3D visualisation of same Reson 8125 data presented in Figure 13

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 visualisation 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 visualisation 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, visualising 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. This results in overall improvement in data interpretation and processing decision making.

After the data have been loaded and the first pass cleaning completed by the area filter, each of the PFM bin surfaces are visualised 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 the maximum filtered surfaces. The unfiltered minimum and the unfiltered maximum surfaces can also be visualised 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 invalidation's made by the statistical area filter, manually validate or invalidate data points as appropriate and review sounding selections. From the MVE, any

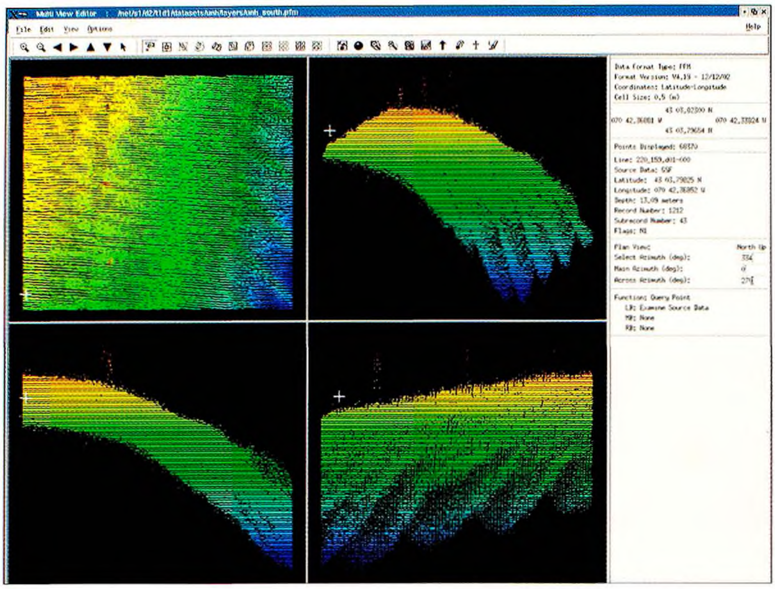

Figure 15: Multi-view interactive editor showing all contributing soundings selected from a subset of the PFM file

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

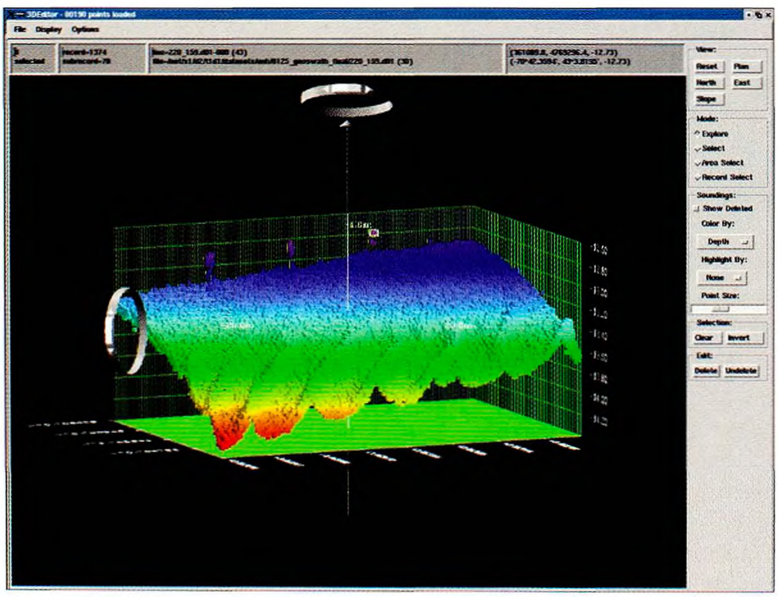

Figure 16: Fledermaus 3D editor showing same three features viewable in Figure 15

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.

The Fledermaus 3D editor (Figure 16) has a similar interactive exploration interface as the main visualisation window and allows the soundings to be coloured 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. 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 (Figure 17).

In the shipboard-processing environment, new data are continually loaded into the current PFM as files become

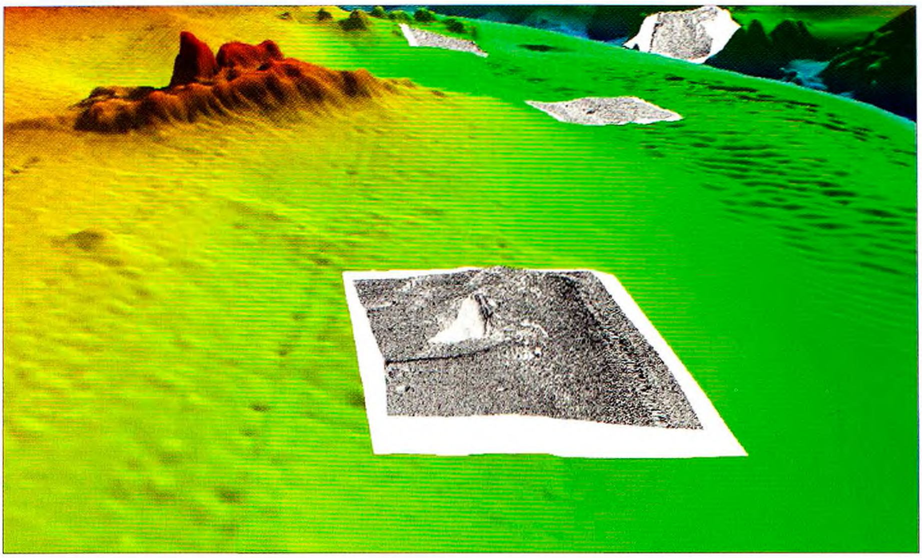

Figure 17: A scene of Portsmouth Harbour, New Hampshire. The main Digital Elevation Model is coloured by depth from a multibeam sonar survey. Draped on the surface are a number of side scan sonar images

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 visualised easily 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, QC processes are performed throughout the acquisition and processing timeline to ensure that any problems 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 process makes any horizontal or vertical offsets between adjacent lines discernable, whereas, with the previous line-based approach these problems would not be easily seen.

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 approach 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 shoal-biased down-sampling. Soundings that have been selected are highlighted in the displays allowing for detailed review and QC against all neighbouring 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 that 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 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 visualisations 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 and all field products are shipped to NAVOCEANO. Upon arrival at NAVOCEANO, the data package is sent to Data Ingest for cataloguing and copying to the Data Warehouse. Once the data have been loaded into the Data Warehouse, the following QC processes are checked and/or verified (1) 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 then performs 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 data flow through the validation process. The final step is to assign the final quality assessment of the data and then archive the data set.

With the improvements to 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 exercise Quality Assurance procedures.

Product Generation

The output of the sounding selection module of the Area Based Editor goes directly into the CARIS chart production software. In addition to the final selected soundings, additional digital data sources can be input to the CARIS production software. These 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 generalised production flow for NAVOCEANO.

NAVOCEANO utilises 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. Other COTS software tools used for source evaluation, data extraction and product displays are IVS's Fledermaus, ERDAS' Imagine and ESRI's ArcView.

In support of the fleet NAVOCEANO is now a co-producer of electronic DNC charts 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. Upon completion of the DNC library compilation using the CARIS software and after quality assurance 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.

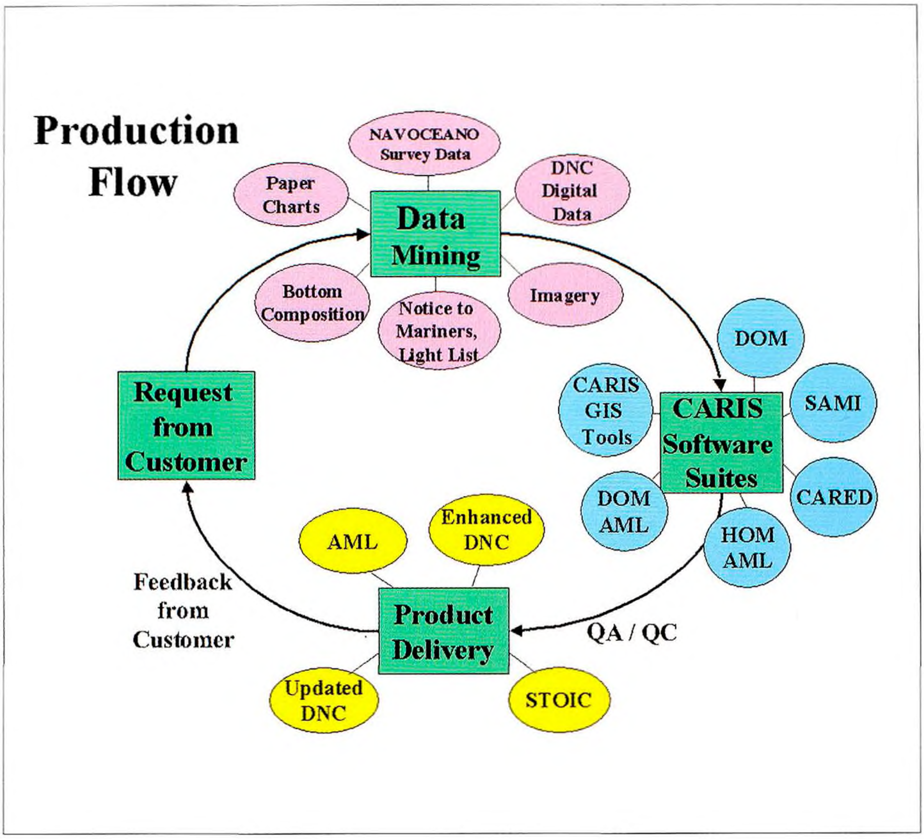

Figure 18: Data product production flow

Future Trends

NAVOCEANO's Survey Operations Centre (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 monitoring of the ship location along the scheduled survey track during underway operations.

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 standardised geospatial formats mentioned above. The objective is to maintain a schema during the process of building digital tactical charts that supports 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 Centre for Coastal and Ocean Mapping/NOAA UNH Joint Hydrographic Centre (CCOM/JHC) at the University of New Hampshire [6].

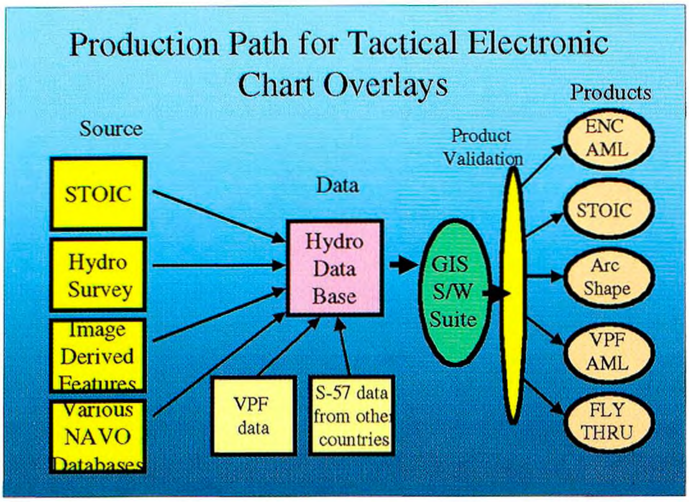

Figure 19: TECO production path

Research at CCOM/JHC has shown that a significant improvement in the speed and objectivity of hydrographic data processing is possible and that the use of a Digital Terrain Model for charting has significant benefits. The CUBE approach is an attempt to deal with most data processing requirements as automatically as possible. It incorporates robust statistical estimation techniques with an error model describing the Multibeam Echo-sounder (MBES) data being gathered and produces 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 Area Based Editor 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, resulting in 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 utilised through to chart production. In validation tests to date, it has been shown to provide a range of usable products [6]. In addition, the Navigation Surface allows 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.

Acknowledgements

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Biographies

Dough Cronin graduated from Oregon State University in 1981 with a BS in Marine Science and from Colorado State University in 1983 with a BS in Geology. Mr. Cronin then started his professional career in 1986 as an oceanographer with the Special Projects Department of the Naval Oceanographic Office (NAVOCEANO). This assignment included working with the integration of sensors involved with deep-towed oceanographic vehicles. In addition, he was responsible for processing deep-water bathymetry and side scan sonar data. In 2000, Mr. Cronin returned to school to obtain an MS in Hydrography from the University of Southern Mississippi. In 2001, he was responsible for managing NAVOCEANO's Autonomous Underwater Vehicle program. In 2002, he was selected as the Technical Lead of the Hydrography Department at NAVOCEANO.

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Barbara Reed is the Hydrography Department Director at the Naval Oceanographic Office at Stennis Space Center in Mississippi, USA. The Hydrography Department has 150 people involved in the global collection of hydrographic data and production of specialised products in support of surface and subsurface navigation, ocean and acoustic modelling, and environmental characterisation for the US Navy. She has also been a scientist collecting, processing, and validating geophysical, hydrographic and oceanographic data for the Naval Oceanographic Office at Stennis Space Center in Mississippi for over 20 years. She has a Bachelor of Science degree from Florida Institute of Technology and a graduate degree in Geophysical Engineering from the Colorado School of Mines.

John Shannon Byrne received the B.S. degree in Mechanical Engineering from the University of Rhode Island in 1987, and the M.S. degree in Ocean Engineering from the University of Rhode Island in 1990. Mr. Byrne is the lead engineer for SAIC's real-time and post-processing software systems to acquire, visualise, quality control, and analyse data from shipboard navigation and environmental sensors. Mr. Byrne's specific interests are in the development of systems, tools, and techniques to characterise the shallow water seafloor.

Walter S. Simmons is a Senior Engineer, Chief Hydrographer, with Science Applications International Corporation, Newport, Rhode Island, USA. He is a graduate of Texas Tech University, and George Washington University. Mr. Simmons has more than 24 years experience with NOAA, and over 9 years developing systems and conducting multibeam and side scan surveys with SAIC.

Lindsay Gee is the General Manager of Interactive Visualisation Systems, has over 20 years experience with hydrographic and ocean mapping surveys. In recent years after realising the earth is not flat, his work has been concentrated on the application of interactive 3D visualisation to the field of ocean mapping and hydrographic surveying. He is a member of the Institution of Surveyors, Australia and The Hydrographic Society and holds a bachelor of surveying science from the University of New South Wales.

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