Collaborative Nautical Charting and Scientific Seabed Mapping Missions: A Case Study in the Northwestern Hawaiian Islands

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***Abstract*- The Fall 2002 Mapping Expedition to the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve provided an opportunity for hydrographers from NOAA's Office of Coast Survey to assist scientists from other NOAA offices and the University of Hawai'i with acquisition of high quality bathymetric data. In twenty-six days at sea, the expedition completed the primary mission goal of defining the isobaths bounding the newly designated Reserve, as well as mapping approximately 11,000 square nautical miles of seabed in this environmentally sensitive region. This data set also provides the first new hydrography in over 70 years for nautical chart updates in the area. The expedition and partnership between the hydrographic and scientific teams are described, and preliminary hydrographic results of the survey are presented.**

I. INTRODUCTION

New positioning, depth sounding, and seabed imaging technology has revolutionized hydrography in the past 15 years. Unfortunately, many government hydrographic offices may be unable to apply this technology to their entire area of responsibility because the resources available are limited and must be devoted to the regions of highest vessel traffic volume. However, high resolution mapping equipment and techniques are now in widespread use throughout the academic research fleet, and many groups have gained the ability to acquire high quality bathymetric data. This presents an opportunity for hydrographic offices to assist these "non-traditional" users of seabed mapping technology by providing data acquisition, processing, and interpretation assistance while gathering modern data for updating nautical charts in areas where the offices may never be able to dedicate their own resources.

This paper describes a recent cooperative mapping project in the Northwestern Hawaiian Islands (NWHI) undertaken by the NOAA Fisheries Coral Reef Program, National Marine Sanctuaries Program and Office of Ocean Exploration, and the University of Hawai'i Undersea Research Laboratory. NOAA's Office of Coast Survey was asked to assist with this effort to ensure that the data acquired met the appropriate International Hydrographic Organization quality standards. The resulting high quality data will support generation of boundaries for the newly established Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve, ecosystem mapping, fisheries management, and the first new hydrographic data on nautical charts of this region in over 70 years. We plan to use this project as a model for future collaboration between academic and government ocean mapping organizations.

II. MOTIVATION FOR COLLABORATIVE MAPPING

A. Deficiencies of Historic Hydrographic Data

NOAA's Office of Coast Survey (OCS) is responsible for surveying and maintaining nautical charts of the 3.4 million square nautical mile Exclusive Economic Zone of the United States. Throughout this area, much of the data on current chart editions is old: of the hundreds of thousands of depths on NOAA charts, nearly half were measured before 1940, and there remain some areas of U.S. waters which have never been surveyed at all [1]. Although these historic surveys were conducted with the most accurate and reliable techniques available at the time, modern hydrographic survey technology produces a much more complete characterization of the seafloor.

Depth sounding before 1940 was typically accomplished by lead line [2]. While these direct measurements are highly accurate, the labor intensity of this technique often resulted in sparse data sets. Reliable vertical beam echo sounders introduced during World War II measure a continuous line of depths under the hull of the survey vessel. However, wide spacing between adjacent survey lines meant that the majority of the seabed was not examined and could be incorrectly charted.

Horizontal positioning of these measurements was an even larger potential source of error. Before the development and acceptance of satellite-based navigation systems, precise positions were determined in relation to known reference points ashore. Along the coast of the continental United States, where geodetic networks were well established, these positions could be quite accurate. However, horizontal control suffered when out of range of these land based systems or when surveying islands not referenced to the continental datum.

The introduction of swath bathymetric systems and the Global Positioning System (GPS) has largely eliminated these impediments to complete and accurate hydrographic surveys. Swath bathymetric systems, typically Multi-Beam Echo Sounders (MBES), allow hydrographers to ensonify and measure the entire seabed. This eliminates the gaps in survey data inherent to older techniques, producing "full bottom coverage" surveys. GPS allows modern hydrographers to accurately position depth measurements anywhere in the world.

B. Demand for Modern Surveys

As the accuracy of hydrographic surveying has increased, so has the need for modern, full bottom coverage, high resolution surveys. Both the number and size of vessels operating in U.S. waters have steadily grown, increasing the likelihood of collision or grounding with the attendant potential for environmental damage and economic disruption. These risks greatly reduce any margin for error in the accuracy of our nautical charts, and require that they depict the most complete, accurate, and current data available.

Nautical charts are obviously first and foremost a tool for safe and efficient navigation. However, with the advent of Geographic Information Systems (GIS) and digital data formats for charts and other bathymetric data, non-traditional use of these products is increasing. Nautical charts and hydrographic survey data are now often employed as a base layer for fisheries management, coastal zone management and planning, marine archaeology, disaster preparedness, and other scientific and civil functions. These users and the public they serve benefit significantly from accurate and complete hydrographic products. Unfortunately, the areas for which these users most desire new surveys and updated charts are not always compatible with Coast Survey's primary mandate to ensure safe navigation.

C. Limited Hydrographic Survey Resources

NOAA currently has the capacity to survey each year approximately 2000 square nautical miles of its area of responsibility with modern techniques, and to apply these changes to the affected nautical charts. In order to ensure that these resources are applied most efficiently, the agency has prioritized U.S. waters according to navigational significance, age of the most recent survey, cargo tonnage and content aboard vessels transiting in the area, and rate at which bathymetry is expected to change. The regions with the most pressing need for new surveys as identified by these factors have been designated "Critical Areas", while those with less immediate needs have been assigned Priorities 1 through 5 [3].

Three ships in the NOAA fleet are dedicated to hydrographic surveying, and the agency contracts with private industry for an equivalent additional capacity each year. In 2002, the Office of Coast Survey estimated that given these resources, it would take approximately 15 years to complete new surveys of just the areas identified as "Critical". Although NOAA's survey capacity is expected to increase over the next several years, it will clearly be some time before the agency is free to dedicate appreciable resources to anything other than areas of pressing navigational concern. As a result, the unfortunate reality is that many areas of U.S. waters which are too deep to be considered navigationally significant, or support minimal vessel traffic, may never be revisited by a dedicated survey vessel.

D. Resources of the Academic Fleet

While new single-purpose hydrographic survey vessels are comparatively rare, many of the modern multi-mission oceanographic research ships in the U.S. fleet have been designed with high accuracy mapping systems in their instrument payloads. In many cases, these multi-beam echo sounders, navigation systems, and attitude sensors are the same instruments as those deployed in NOAA's hydrographic fleet. Figure 1 illustrates the approximate distribution of these systems across the government and academic fleets of the United States. (The U.S. Army Corps of Engineers, which conducts surveys primarily in shallow federal dredging project areas, and private industry operators who may conduct some hydrographic surveys under government contracts, are not included in this plot.)

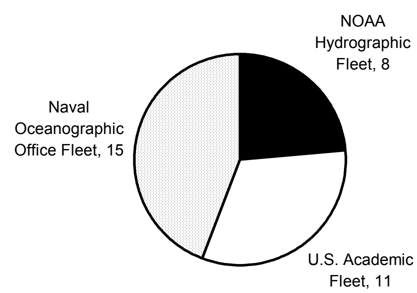

Fig. 1. Approximate distribution of multi-beam echo sounder equipped vessels operating in the U.S. public interest (excluding USACE), 2003.

Clearly the academic research fleet represents a significant portion of available ocean mapping resources. Unlike NOAA's units which are needed primarily to survey areas of the highest navigational importance, these research systems are dedicated to mapping areas of scientific interest, many of which are regions which would not be surveyed specifically for charting for many years, if ever. This presents Coast Survey with a significant opportunity to serve both its traditional and non-traditional constituencies at minimal cost by using bathymetry acquired as part of scientific research to update nautical charts.

However, it is important to note that high accuracy bathymetric mapping systems are not simply "turn-key" units. While the data quality requirements of many scientific seabed mapping missions can be met relatively easily with these systems, acquisition of soundings meeting the International Hydrographic Organization (IHO) specifications for nautical charting requires precise calibration and knowledgeable, experienced operators. Meeting these standards may also necessitate higher order vertical and horizontal control, such as application of tide correctors and differential GPS.

There is also substantial risk to NOAA in charting data which were not acquired under the agency's auspices and supervision. Once soundings are accepted for charting, NOAA assumes legal responsibility for their accuracy. Even though modern data of even marginal quality may be vastly superior to the historic data currently portrayed on charts in some areas, any new data must pass through an evaluation and validation process to determine the extent to which they can be applied to charts. This processing and the subsequent chart compilation require significant time and expertise. Like data acquisition platforms, these resources must be managed to efficiently update charts of navigationally significant areas. Incoming survey data from both NOAA and outside sources are prioritized to expedite the application of the most critical updates to charts.

E. Collaborative Surveying Model

In an attempt to capitalize on the opportunity presented by high quality hydrographic data acquired during scientific research cruises while meeting the requirements of NOAA's existing nautical charting process, the Office of Coast Survey has gradually developed a procedure for participating in these scientific expeditions and processing the resulting data.

Under this plan, the Office of Coast Survey, when requested, may provide a team of one or more hydrographers to scientific cruises which incorporate significant seabed mapping components in areas of interest to OCS. These hydrographers participate in the cruise as members of the science party, but are specifically responsible for working with vessel personnel to operate the seabed mapping systems, collecting relevant metadata on the vessel and instrumentation, and advising the Chief Scientist on data quality. The goal of the Hydrographic Team is to acquire bathymetry which meets the appropriate order of the IHO Special Publication 44 (S-44) standard, in a format compatible with the OCS data pipeline.

At the end of the cruise, the Hydrographic Team returns to the NOAA with a copy of the data set, which is further processed and documented for injection into the OCS Outside Source Data (OSD) pipeline. The OSD process is a new OCS system for evaluating, validating, and prioritizing hydrographic surveys from sources outside OCS control for application to nautical charts.

The key element of the collaborative charting plan is the benefit it provides to all involved. The scientific team gains the knowledge and experience of dedicated hydrographers, which translates into a higher quality bathymetric product at the end of the cruise. In addition, the nautical chart updates which eventually propagate through the OCS pipeline benefit all chart users, including scientists. NOAA benefits from the opportunity to update its charts in many under-surveyed areas for comparatively little cost. This model was first employed in the mapping mission to the Northwestern Hawaiian Islands described in this paper, and has since been tailored and implemented on several other research cruises.

III. THE 2002 NWHI MAPPING EXPEDITION

A. Significance of the Northwestern Hawaiian Islands

The Northwestern Hawaiian Islands are a chain of small islands and submerged banks stretching approximately 2200 kilometers west-northwest from the main Hawaiian Islands to Kure Atoll. With the exception of Midway Atoll (a U.S. federal territory), all are now part of the State of Hawaii. The islands were formed by the same volcanic processes which continue to shape the larger Hawaiian islands to the southeast, but as the seabed subsided after their formation, the islands sank back into the ocean. While only the peaks of the original islands remain above the water's surface, coral growth on submerged slopes of these mountains and seamounts has matched the rate of subsidence, creating reefs which account for nearly 70% of the total in the U.S.

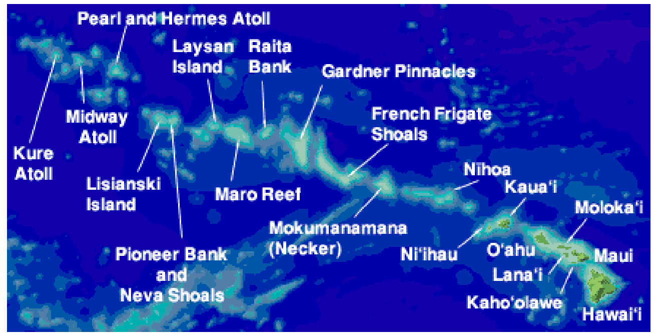

Fig. 2. The islands, atolls, and submerged banks of the Hawaiian Archipelago, including the NWHI (image courtesy of the NWHI Coral Reef Ecosystem Reserve).

The isolated islands and banks of the NWHI are unique ecosystems, supporting numerous species found nowhere else on Earth. Most of the land areas of the NWHI have been protected by the U.S. Fish and Wildlife Service as part of the Hawaiian Islands National Wildlife Refuge. In recognition of the unique aquatic environment of the waters and seabed in this region, the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve (NWHI CRER) was permanently established under the NOAA National Marine Sanctuary Program by executive order in 2001. The Reserve consists of a strip of the waters and seabed 100 nm wide along the island chain from Nihoa Island to Kure Atoll. Within this reserve are 15 Reserve Preservation Areas (RPAs) encompassing many of the islands and banks, in which "consumptive use" is prohibited or restricted. The offshore limits of the RPAs surrounding emergent land are based on specified depth contours, while those surrounding submerged banks are limited by radial distance from the geographic center.

B. Modern Survey Required

The NWHI are currently a poorly charted area. Although many of the atolls and reefs were used for military operations during World War II and after, the most recent complete surveys of the area date from the 1930s. Their accuracy and coverage are consistent with the technology available at that time.

Poor horizontal positioning is one of the most serious deficiencies of these historic surveys. Seventy years ago, isolated areas such as the NWHI could not be connected to existing continental geodetic networks. Surveys were conducted in local astronomical datums, based on the position of a horizontal control benchmark as determined by celestial navigation methods. While the positions of features and soundings acquired by these surveys were accurate relative to one another, the absolute accuracy was only as good as the position of the benchmark on which the local datum was based. The charts based on these surveys depicted islands, reefs, and banks as much as several miles from their true positions. Although recent IKONOS and LANDSAT imagery of the area has allowed Coast Survey to rectify the positions of several of these features on the 2002/2003 editions of the affected charts, many of the submerged banks too deep to be visible from space remain incorrectly charted.

The only new sounding data on the nautical charts of the NWHI acquired since the 1930s are anomalous soundings reported to NOAA (and its predecessor agencies) by commercial and military ships transiting the area. OCS policy is to chart these depths with the annotation "reported" until they can be confirmed or disproved by a survey. However, since no hydrographic unit has visited the area to conduct new surveys and investigate these reports, the charts are now cluttered with these depths and annotations. The uncertainty in the accuracy and position of these unverified soundings reduces the utility of the charts for both navigational and scientific users.

Finally, there are significant offshore areas in the Reserve for which there are no soundings at all. These regions are depicted simply as white space on the charts.

Although vessel traffic in the NWHI is low and those vessels which do work in the area tend to be comparatively small, there is obviously some risk of damage to the environment due to grounding or other maritime casualties resulting from inaccurate nautical charts. However, a more serious concern is the need for complete and accurate charts and survey data to support management of the Reserve and protection of its resources. Despite their deficiencies, NOAA nautical charts remain the only comprehensive and official seabed maps of the area available. NWHI Reserve planners, fisheries managers, and coral reef biologists all depend on the nautical charts as the seed data for their management tasks, decisions, and products.

Most importantly, when the NWHI CRER was established there were no data available to correctly define the isobaths which form the boundaries of the Reserve Protected Areas (RPAs). In addition, many of the submerged banks were incorrectly positioned on the charts, producing incorrect geographic centers. Without these data, the geographic positions of the boundaries could not be determined, publicized, or enforced. Since the location of these boundaries has the potential to impact both the livelihood of fishers and others affected by limitations on "consumptive use", and the survival of threatened species endemic to the RPAs, it is essential that complete and accurate data be used to define their limits.

Despite the deficiencies of the current survey data and the need for updated charts, nationally the NWHI remains a relatively low priority area for new hydrographic surveys. The majority of the navigable waters in the Reserve have been identified as "Priority 2" areas by the Office of Coast Survey. This designation applies to those regions which have not been surveyed since 1940, but have no measurable volume of commercial vessel traffic. If this area were scheduled for a new survey by OCS based strictly on its navigational significance, it would be addressed only after the areas identified as "Critical" or "Priority 1" (a total of approximately 100,000 square nautical miles) were completed.

C. Mapping Expedition Organized

To address these concerns, NOAA's National Marine Sanctuary Program, Office of Ocean Exploration, and National Marine Fisheries Service planned a benthic mapping expedition to the NWHI for Fall 2002. This cruise was Leg II of a larger initiative to map and characterize the coral reef habitats of the NWHI CRER in 2002. The primary goal of this second cruise was to locate and map the isobaths defining the boundaries of the NWHI CRER RPAs. Dr. John Smith of the Hawai'i Undersea Research Laboratory was designated Chief Scientist.

Funding was available for 26 days at sea aboard the University of Hawai'i operated research vessel *Kilo Moana*. This new ship, delivered to the university only months before the NWHI expedition, was designed and built to support seabed mapping as one of its primary missions. The Small Waterplane Area, Twin Hull (SWATH) configuration provided a stable platform, ideal for surveying in the unprotected and potentially stormy waters of the NWHI. Precision hydrographic survey systems, including Simrad EM1002 and EM120 mid- and deep-water multi-beam echo sounders, and TSS POS/MV position and attitude system, had been installed and calibrated by the shipyard and U.S. Navy prior to delivery. The only potential drawback of the ship was its draft (7.6 m / 25 ft), which, combined with the uncertain chart data, limited the mission's ability to approach the shoals and submerged banks of the area.

Figure 3. R/V *Kilo Moana* (University of Hawai'i photo)

The legal implications of RPA boundary generation required that the data acquired on the cruise be of the highest quality. The organizers of the mission also hoped that the resulting dataset could be used to support nautical chart updates for the region. As a result, the Office of Coast Survey was asked to support the mission by contributing personnel and expertise. As described in Section II above, OCS had significant incentive to comply with this request, as it would provide an opportunity to assist the scientific community and other NOAA activities while simultaneously acquiring new sounding data for an area which would not otherwise be surveyed. In addition, OCS's Marine Chart Division had recently compiled preliminary new editions of many of the nautical charts in the NWHI region. Although no new sounding data was available, the charts had been translated from the original local astronomical datums to the North American Datum of 1983 (NAD83) based on satellite imagery. By participating in the cruise, hydrographers would be able to verify the accuracy of the repositioned islands and reefs before the final chart editions were printed and released to the public. Finally, the mission would give OCS hydrographers first hand experience with the characteristics of the SWATH design, which had been proposed for the replacement of one of NOAA's existing hydrographic survey ships.

OCS agreed to support the expedition by providing shore side technical assistance and a hydrographer to join the science party. Under the collaborative charting model, this representative was to be responsible for assisting with data acquisition and processing, advising the chief scientist on hydrographic data quality, and guiding the dataset into the OCS charting pipeline. In addition, OCS began the process of formalizing its Outside Source Data ingestion process to streamline office processing and prioritization of this and other surveys offered by outside agencies to update nautical charts.

The lead author was assigned to join the expedition as OCS representative. Significant additional hydrographic and benthic mapping experience was provided by Dr. Smith, co-chief scientist Joyce Miller from the Coral Reef Ecosystem Division of the NMFS Pacific Islands Fisheries Science Center, and LTJG Jeremy Weirich of the NOAA Office of Ocean Exploration. While NOAA survey ships have in the past occasionally conducted scientific mapping in areas which were also of navigational significance, this was the first time that OCS hydrographers had deployed aboard an academic ship with the intent of acquiring data to update nautical charts.

D. Error Budget

Before the cruise, OCS personnel reviewed the mission plan to determine the appropriate allowable error budget and compared this with the likely sources of error in the survey. Under the current edition of the IHO's Special Publication 44 (the international document specifying accuracy requirements for hydrographic surveys), the regions surrounding the banks and atolls of the NWHI qualify as "Order 2" survey areas, as these waters are without harbors or vessel traffic lanes but are less than 200m deep [4]. The deep abyssal plains between the banks can be adequately described by less exacting "Order 3" surveys. IHO S-44 requires that the total propagated depth error in meters be less than

$$\pm\sqrt{a^2 + (bd)^2}, \qquad (1)$$

at 95% confidence, where d is the depth in meters. For both Order 2 and 3 surveys, a = 1 and b = 0.023. Horizontal positioning error at 95% confidence must be less than 20m + 5% of water depth for Order 2 surveys, and 150m + 5% of depth for Order 3.

The MBES systems, CTD instruments, and position and attitude sensors installed aboard *Kilo Moana* are all systems which have been deployed in the NOAA fleet as well. Therefore, the maximum measurement error attributable to each of these instruments was assumed to be no greater aboard Kilo Moana than it would be aboard a NOAA ship. Furthermore, since the vessel offsets and multi-beam sonar patch test calibration values had been determined during the navy's trials of the vessel only weeks beforehand, OCS assumed that these values would also have error no greater than a typical NOAA survey platform [5]. This left the following potential sources of error to estimate before beginning the survey:

Tide: Ordinarily, tides are the single largest source of error in hydrographic surveys, and adequately correcting for water levels often requires installation of local tide gauges in each survey area. Fortunately, tide range in the NWHI is minimal. Analysis of historical observed water levels indicated that even with no tidal corrector data, this error would not exceed +/- 0.5m.

Dynamic Draft: This error accounts for changes in the vessel's draft and vertical position of the sonar transducers due to changes in ballasting, fuel supply, and speed through the water during the survey. For higher order surveys conducted from NOAA platforms, this error is measured to populate corrector tables which are applied to the soundings, but values for *Kilo Moana* were not known. Although the unique dynamics of the SWATH configuration introduced some uncertainty into evaluation of this error, OCS estimated these effects to be no greater than +/-0.5m.

Horizontal Position: There is no U.S. Coast Guard differential GPS corrector service in the NWHI, and it was not feasible to install "fly-away" reference stations in the region. Fortunately, *Kilo Moana* was equipped with a military P-code GPS receiver, which reports position accurate to 7-10m without corrector service.

Combining these estimates with assumed instrument errors by root-sum-square, OCS determined that *Kilo Moana* could meet the requirements of the IHO Order 2 specification in the NWHI without installation of tide stations or differential GPS corrector service.

E. Survey Plan and Execution

R/V *Kilo Moana* sailed from Honolulu for the 2002 NWHI Mapping Expedition on October 22 and returned on November 16. To accomplish the primary mission goal of locating and defining the isobaths required for generation of the RPA boundaries (Table 1), "donut" surveys were planned around each of the critical islands, atolls, and banks from Nihoa to Lisianski Islands. This initial plan was deliberately conservative to allow for weather, daylight, and unforeseen delays, but the science team hoped to have time to acquire additional coverage of the region after meeting the primary cruise goals

Table 1. Minimum contour mapping requirements for RPA boundary generation.

Island/Atoll Area	Isobaths Required
Nihoa	25 fm, 100 fm
Necker	25 fm, 100 fm
French Frigate Shoals	100 fm
Gardner Pinnacles	25 fm, 100 fm
Maro Reef	25 fm, 100 fm
Laysan	50 fm, 100 fm
Lisianski	25 fm, 100 fm

Fortunately, due to careful survey line planning using pre-existing partial data sets from previous cruises, a skillful bridge crew, good weather, and good luck, the team was able to minimize "hunting" for the intended isobaths, and in most cases mapped the required areas in one pass. This put the mission considerably ahead of schedule when *Kilo Moana* reached Lisianski Island, allowing for additional coverage of the coral reefs, mapping of submerged banks not needed for the RPA limits, and opportunistic investigation of several new features on the way back to Honolulu.

F. Data Acquisition, Processing, and Quality Assurance

Kilo Moana's multi-beam echo sounders logged data continuously throughout the cruise. Where possible, both the mid- and deep-water systems were used for data acquisition, allowing the science team to select data from either system during processing. Backscatter imagery from both sonar systems was logged in addition to bathymetry for use in future bottom type classification and habitat assessment activities.

When operating in the vicinity of shoals and islands, the science team set an active acquisition watch to monitor data quality and log anomalies. In addition, when attempting to follow a specific contour, it was often necessary for the science watch standers to provide the bridge crew with guidance based on the MBES data. The wide swath of these systems provided a much more complete and accurate view of the seabed under and beside the ship than either the bridge single beam echo sounder or electronic chart system. This cooperation enhanced both data quality and vessel safety.

Sound velocity profiles were generated from a combination of CTD and expendable bathythermograph casts. During acquisition, watch standers monitored the bathymetry and surface sound velocity for signs of changing water properties. In general, full CTD casts were only required after transiting to a new working area.

In order to maintain control of the data and post-acquisition processing, separate copies of the raw data were maintained for scientific and charting purposes. The hydrographic team implemented the standard OCS data processing pipeline aboard *Kilo Moana.* Although this redundant processing was time consuming, it ensured that data destined for RPA boundary generation and nautical charting was cleaned according to established OCS standards.

G. Contributions of Hydrographic Team

The presence of the Hydrographic Team aboard *Kilo Moana* afforded significant benefit to the overall success of the NWHI mapping mission. In addition to the pre-cruise error budget analysis and the infusion of general hydrographic expertise and multi-beam sonar operation experience, the team made several specific contributions to the expedition.

While processing bathymetric data during the cruise, OCS hydrographers identified a systematic data artifact which had not been previously detected. The problem was discovered while working in the shallow (~50m) water surrounding Nihoa Island in sea states producing vessel heave on the order of +/-1m, and was reproduced later in the cruise while working in the vicinity of French Frigate Shoals. The hydrographers observed a consistent "ripple" pattern in the bathymetry data, with a height of 0.5 – 1m and period of approximately 10s (Figure 4). Since ripple was consistently perpendicular to the track of the ship regardless of heading, it seemed unlikely that this represented an actual seabed feature.

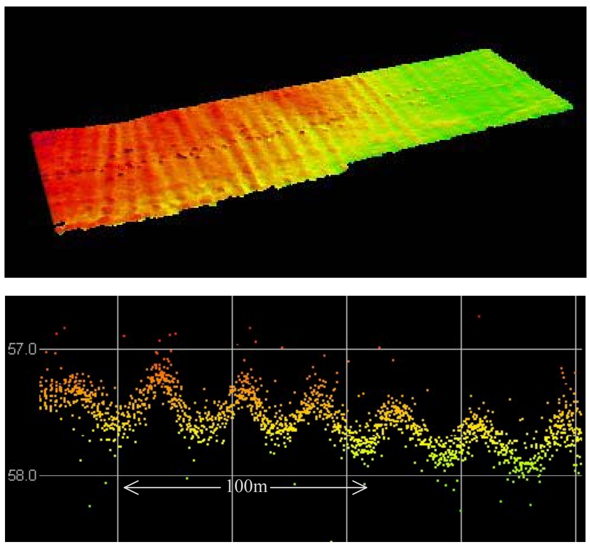

Fig. 4. Sun-illuminated surface and side view of "ripple" artifact. Vertical scale in side view in meters.

Although the error appeared to be the result of uncompensated vessel motion, analysis of the data, attitude sensor configuration, and instrument offset measurements and corrector tables did not locate the cause. Fortunately, while it was obvious in some portions of the data set, the total error was comparatively small and did not exceed the bounds imposed by the IHO S-44 Order 2 standard. In the course of investigating the problem, OCS hydrographers did find and correct an unrelated error in the vessel offset measurements in the positioning and attitude sensor.

Operationally, this was an unusual mission for a ship designed primarily for blue water oceanographic research, as substantial portions of the cruise were planned for comparatively shoal water. Many of the RPA boundary surveys required the ship to work in 25fm (~46m) of water or less, which in the extremely steep bathymetry of the NWHI, could be within a kilometer of exposed reefs and islets. During the planning stage of the expedition, the master of *Kilo Moana* expressed concern about the ability of the ship to safely operate in these waters, given the vessel's deep draft and the known inaccuracy of the nautical charts. To help address this, the OCS hydrographers worked with the Marine Chart Division to provide the expedition with preliminary versions of the new editions of the NWHI nautical charts. These new charts had the positions of islands and other emergent features corrected according to satellite imagery, but had not yet been printed or released to the public. The hydrographers brought these charts to the ship in a digital raster format compatible with the electronic chart system on the bridge.

In addition, the OCS hydrographers were able to continue to work with MCD while underway. The nautical charts of the NWHI were littered with shoal soundings reported by mariners who had passed through since the last hydrographic survey 70 years before. If correct, many of these depths would have posed a potential danger to *Kilo Moana*, and the master was understandably reluctant to take the ship into their vicinity. Having a link with MCD allowed the science team to request information on the origin of each of these reported depths. The history of these depths was useful in estimating the likelihood of their actual existence and planning an appropriately cautious approach. As discussed in the Results section below, most of these reported soundings were disproved by the new survey data.

The hydrographic team was also able to customize nautical charts for *Kilo Moana's* bridge crew with new, high density sounding data as they were acquired. This improved the crew's ability to safely navigate the vessel in the potentially hazardous waters of the NWHI. As the ship gradually worked into shoaler depths while surveying the RPA boundaries, the hydrographers compiled all available data from previous research cruises and earlier passes by *Kilo Moana* into a single dataset. Since two of the hydrographers were also qualified as underway Officers of the Deck on NOAA ships, they were able to produce large scale chartlets in a format familiar to the ship's bridge officers. These preliminary data products were completed and printed in near-real time as new data were acquired, using processing and presentation standards similar to standard nautical charts. They greatly increased the confidence of the master and bridge crews when navigating the ship in shoal, near shore areas, and contributed significantly to the success of the cruise in meeting the mission requirements.

IV. CRUISE RESULTS

The 2002 Northwestern Hawaiian Islands Mapping Expedition was very successful. The primary goal of the cruise was accomplished earlier than expected, leaving ample "free" time for opportunistic surveying of the coral reefs, geologic features, and unexplored waters of the NWHI. In total, over 11,000 square nautical miles of seabed were mapped [6]. This tremendous coverage was possible largely because of the generally deep, open water of the region. By comparison, in 2002 NOAA's combined internal and contractor hydrographic survey fleets surveyed less than half this amount in the labor intensive, near shore environment of the coastal U.S.

A. Reserve Protected Area Boundaries

The primary goal of the cruise was to map the isobaths required for generation of the NWHW CRER RPA boundaries. Although in general the cruise effectively mapped the specified contours, there were some minor gaps in the final data set. In particular, the 25 fm contour proved particularly illusive in some areas due to the narrow multi-beam sonar swath width, comparatively flat bathymetry, and limited vessel maneuverability at this depth. Fortunately, these gaps were not large enough to prevent the National Marine Sanctuaries Program from defining the RPA boundaries. Office of Coast Survey delivered final bathymetry to the NMSP for boundary generation in March of 2003, and these boundaries are expected to be added to new editions of the nautical charts as the printing cycle allows.

B. Scientific Results

In addition to supporting generation of RPA boundaries, the bathymetry and backscatter data acquired over the coral reefs of the NWHI will directly contribute to understanding of these critical ecosystems and planning and management for the Reserve. The data acquired aboard Kilo Moana has already been compiled with other source data (satellite remote sensing data and bathymetry from previous research cruises) into a comprehensive bathymetric atlas of the Northwestern Hawaiian Islands [7]. The first draft of this atlas was presented by Joyce Miller at the NWHI Coral Reef Ecosystem Reserve Science Planning Workshop in May 2003.

The additional sea days available after the completion of the primary cruise objectives provided time to survey some of the previously unmapped waters of the NWHI chain. This exploration produced hints of complex bathymetric features of volcanic, tectonic, and biologic origin throughout the region. It is beyond the scope of this paper to discuss these results in detail, but Fig. 5 provides an example of the new features which were located.

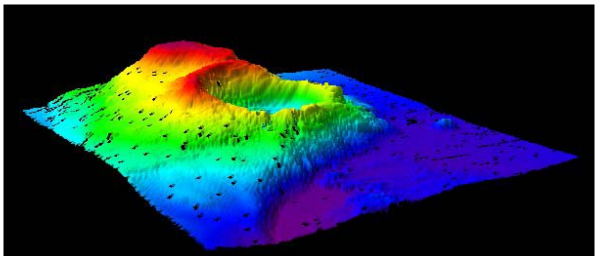

Fig. 5. Sun illuminated surface of a previously unknown submarine crater 50km SE of Maro Reef. The feature is approximately 6000m in diameter and rises 1200m above the surrounding seafloor.

Additional seabed mapping and submersible operations have been planned by the Hawai‘i Undersea Research Laboratory to further explore the region in the fall of 2003. Results and interpretation of this aspect of the 2002 *Kilo Moana* survey data will be presented by Dr. John Smith at the Fall 2003 American Geophysical Union meeting [8].

C. Hydrographic Results

The 2002 NWHI Mapping cruise produced the first new hydrographic data in 70 years for the region, affecting 8 nautical charts. Since the survey was successfully conducted to IHO Order 2 specifications, it is expected that the new bathymetry will fully supercede the previous data in the common area. In addition, copies of bathymetric datasets from several other recent research cruises in the area were obtained by the hydrographers. Although the quality of these data are less certain, they will be assessed for partial application to the charts. Several of the most navigationally significant results are described below:

Horizontal Datum Transformation: As discussed previously, the cruise provided the hydrographic team with an opportunity to verify the corrected NAD83 positions of features depicted on the preliminary charts provided by MCD. In most cases of emergent land visible from space, these transformations were confirmed as correct by visual observation and comparison of charted depths with survey soundings. However, in the case of Maro Reef, the datum shift was inadvertently misapplied, resulting in the reef being charted approximately 3.7km south of its true position (Figure 6). The hydrographers immediately forwarded their findings from the ship to MCD, where the error was corrected before the new edition was finalized and printed.

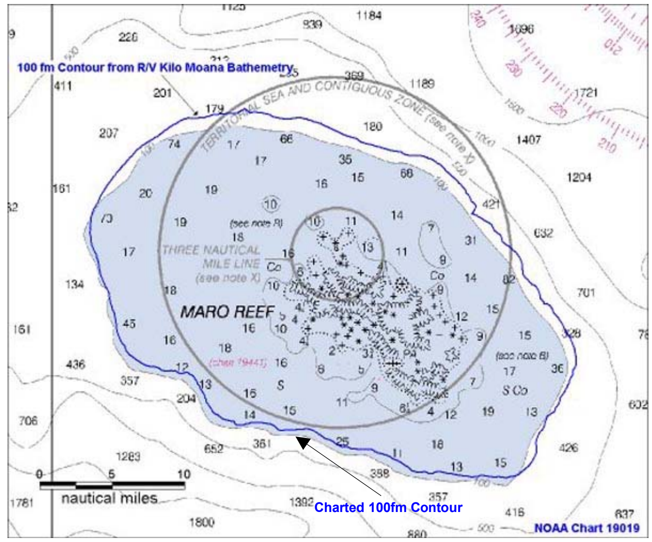

Fig. 6. Comparison of charted and surveyed 100fm curves around Maro Reef.

The data from *Kilo Moana* and previous scientific cruises will also be used to revise the charted positions of submerged banks which were not visible on the satellite. Several of these banks are referenced as RPA center points, so correcting their positions is of particular legal importance.

Several seamounts and banks with incomplete chart coverage were addressed by this survey as well. Fig. 7 shows the existing nautical chart of an unnamed NWHI seamount overlaid with soundings and depth contours from the present survey. Note that the new survey data completes coverage of the west side of the seamount, which will support charting the 500 and 1000fm contours around this feature.

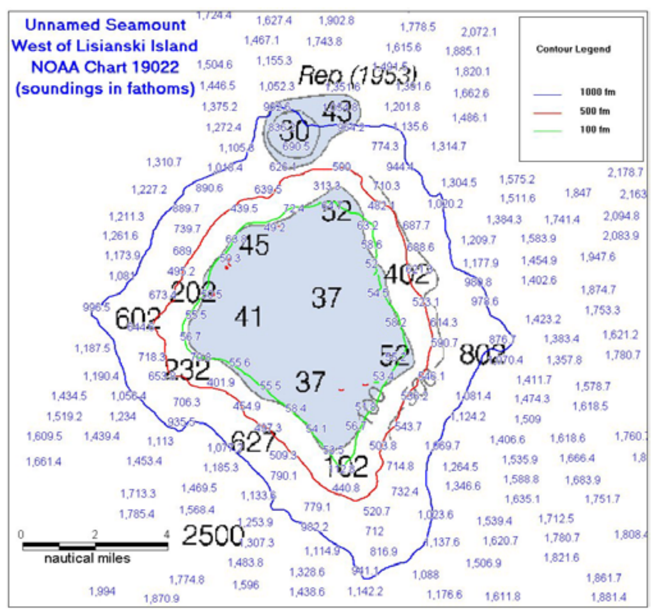

Fig. 7. Survey depths and contours on the existing nautical chart of an unnamed seamount approximately 55km west of Lisianski Island

Also note the disproved 30fm and 43fm “reported” depths on the north side of the bank in Fig 7. In total, the NWHI mapping cruise allowed hydrographers to investigate 8 of these reported soundings, none of which were located in their charted position. Many of these depths were charted adjacent to shoals which were located by the survey, leading hydrographers to suspect that poor horizontal positioning rather than depth sounder inaccuracy produced the incorrect reports. This survey will likely be considered sufficient to remove these distracting and erroneous depths from the chart. While survey soundings were generally found to be deeper than charted depths throughout the area, there were some cases where significantly shoaler depths were located. Fortunately, none of these were considered to pose a serious hazard to surface navigation.

These new hydrographic data sets have been fully processed, and are currently in Coast Survey's Outside Source Data pipeline for validation, verification, and compilation. The new soundings will be depicted on future editions of the affected nautical charts.

D. Improvement to the Collaborative Charting Model

While underway and during post-cruise processing, some opportunities for fine-tuning the collaborative charting model were identified. Chief among these was the need for improved documentation of the equipment and procedures in place aboard the survey ship. The legal implications of using data for nautical chart updates requires hydrographers to prove IHO specification compliance. This necessitates a higher level of survey system documentation than is typically needed by scientific seabed mappers. As a result, the hydrographers aboard *Kilo Moana* found that much of the information they had assumed would be readily available aboard had to be requested from other sources, generated from scratch, or done without. While data quality concerns for the NWHI cruise have been satisfied, this limited documentation has slowed the validation and verification process.

OCS is currently developing a "pre-survey check off list" for its field units to help ensure that all required testing and calibration has been completed and thoroughly documented before hydrographic surveys commence. Although the primary intent of this document is to help NOAA hydrographic units certify their equipment ready to survey, it is anticipated that it will be very useful to hydrographers deployed to unfamiliar platforms as well.

V. CONCLUSION

A. Mission Success

The 2002 NWHI Mapping cruise was a successful expedition which achieved its goals and produced a large volume of data which will be invaluable to scientists and hydrographers studying and charting this region in the future. Sufficient data was collected to support the generation of the RPA boundaries, numerous unmapped features were discovered, 8 nautical charts will benefit from updates, and a vast expanse of previously unexplored seabed was surveyed with state of the art equipment and techniques.

This achievement was in part due to the successful implementation of the Collaborative Charting model. The integration of OCS hydrographers in the scientific mapping team was shown to be of significant benefit to all parties, with very limited need for compromise. This achievement and the experience gained will make collaborative charting a useful resource to scientists and hydrographers in the future.

B. Collaborative Charting Now and in the Future

The success of the 2002 cruise to the NWHI and the value of including hydrographers in the science party has been noted by offices and programs throughout NOAA. In particular, the Office of Ocean Exploration (OE) has continued to foster this type of collaborative research cruise as it executes its mandate to support physical, geological, biological, chemical, and archaeological exploration of the world's oceans [9]. In 2003, OE included OCS hydrographers and NOAA Marine and Aviation Operations (NMAO) hydrographic survey technicians on multidisciplinary research cruises to locations as diverse as the Caribbean, seamounts in the North Atlantic, and the Arctic Ocean. These hydrographers again proved their value by handling processing and presentation of hydrographic data for the science party, increasing the efficiency and productivity of the expeditions. [10, 11]

As high resolution bathymetric systems continue to proliferate through the academic and NOAA fleets, the need for experienced, knowledgeable hydrographers to operate these systems and process and interpret the data will only continue to grow. At the same time, OCS remains actively interested in helping other bathymetric data users and NOAA programs meet their benthic mapping needs while collecting new, high resolution datasets for nautical chart updates. With a proven collaborative model to employ, cooperation to jointly support exploration, resource management and protection, and safety of navigation will continue.

ACKNOWLEGEMENTS

The 2002 Northwestern Hawaiian Islands Mapping Expedition was funded by the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve, the NOAA Office of Ocean Exploration, and the NOAA Coral Reef Program.

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