BATHYMETRIC ATLAS AND WEBSITE FOR THE NORTHWESTERN HAWAIIAN ISLANDS

BY

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ABSTRACT

Until recently the only bathymetric data available in the Northwestern Hawaiian Islands (NWHI) came from single-beam charting surveys that were conducted before World War II. In many cases these data were poorly located, and individual banks could be mischarted by several kilometers. Because detailed bathymetric data are required for a variety of management and research purposes, including designation of boundaries for the NWHI Coral Reef Ecosystem Reserve, updating of nautical charts, and for ecosystem-based management (e.g., formulating benthic habitat maps and designating essential fish habitat), a consortium of National Oceanic and Atmospheric Administration (NOAA) and University of Hawaii scientists are collaborating to make data collected during mapping expeditions to the NWHI available to the public. Bathymetric data collected through August 2003 are combined to provide a baseline for planning future expeditions and for scientific and management use. Thirty maps span the NWHI from Kure Atoll to western Kauai. IKONOS satellite data provide sufficiently reliable estimated depths only to 16 m for the shallowest banks and islands. LIDAR data (0-30 m) are available at Kure, Midway, and Pearl and Hermes Reef.; mid-depth (15-100 m) multibeam coverage is 80% complete at Midway while all other areas have limited coverage at the 50-m boundary line.; deeper multibeam coverage (100-600+ m) is available from Nihoa to Lisianski Island, and limited multibeam coverage exists in depths greater than 600m. Methods used for registration and processing of the data are described, statistics are presented for the amount of area surveyed to date, and estimates are provided for level of effort to complete surveying in the NWHI.

INTRODUCTION

The Northwestern Hawaiian Islands (NWHI) is a chain of small islands and submerged banks stretching approximately 2,200 km west-northwest from the Main Hawaiian Islands (MHI) to Kure Atoll. In December 2000, the Northwest Hawaiian

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Islands Coral Reef Ecosystem Reserve (CRER), which is estimated to cover 351,195 km^2, was created by Executive Order 13178. Because this region was last surveyed in the 1930s, data on nautical charts were inaccurate (Evans et al., 2004), particularly with respect to horizontal positioning of the sounding data, and insufficient to define depth-dependent management boundaries (Table 1) that are needed for use in the NWHI CRER. In addition to improving charting and boundary designations, better mapping data are needed to fulfill requirements of a number of other federal statutes, and initiatives also require mapping data, including (e.g., the Endangered Species Act, the Magnuson-Stevens Fishery Conservation and Management Act, and the Coral Reef Conservation Program's (CRCP) plan to map all U.S. coral reefs by 2009).

Table 1. NWHI CRER boundary information required. Italics represent boundaries not mapped in 2002.

Boundary (fm)	**Boundary (m)**	**Island/Reef/Bank Where Boundary is Required (Minimum Set of Boundaries)**
25	46	*Nihoa*, Necker, Gardner, Maro, Lisianski,
50	92	Laysan
100	183	Nihoa, Necker, French Frigate Shoals, Gardner, Maro, Laysan, Lisianski, *Pearl and Hermes*, *Kure*

In 2002, NOAA and University of Hawaii scientists collaborated on a NWHI cruise to define these boundaries and to satisfy other urgent management requirements. Numerous NOAA agencies, including the National Marine Sanctuaries' (NMS) CRER, the CRCP, the Pacific Island Fisheries Science Center's (PIFSC) Coral Reef Ecosystem Division (CRED), the Western Pacific Regional Fishery Management Council (WPRFMC), and the Office of Coast Survey (OCS) provided funding and personnel for this collaborative cruise. The University of Hawaii's (UH) Hawaii Mapping Research Group (HMRG) and the Hawaii Undersea Research Laboratory (HURL) also provided personnel and support during cruise KM0206 aboard UH's R/V *Kilo Moana*. In order to most efficiently plan for mapping the required boundaries, NOAA and UH scientists combined existing bathymetric data from single-beam and multibeam echosounders, airborne LIDAR data, and "estimated depths" from IKONOS satellite imagery (Stumpf and Holderied, 2003). During the 26-day cruise in October/November 2002, all required boundaries except for those indicated in italics in Table 1 were mapped. The bathymetric data from the two *Kilo Moana* multibeam sonars were processed on board the vessel, and 27 maps were produced. The cruise data were processed independently by participants from NOAA's OCS and are being used to update nautical charts. Over 38,000 km^2 were mapped, primarily in water depths of 40-2,000 m.

NOAA and UH scientists cooperatively produced the *"Bathymetric Atlas of the Northwestern Hawaiian Islands: A Planning Document for Benthic Habitat Mapping,"* a draft of which was introduced at the May 2003 NWHI science workshop sponsored by NMS. Multibeam and single-beam bathymetry, LIDAR data, and IKONOS-estimated depths were combined to produce a series of 30 maps for the atlas. Additional data collected at Midway in August 2003 using CRED's 25-ft. survey launch R/V *AHI* (Acoustic Habitat Investigator) are being presented here. These data are not included in the printed atlas, but have been added to a Web version (http://crei.nmfs.hawaii.edu/BathyAtlas). Periodic updates to both printed and Web versions of the atlas are planned as new data become available from further mapping in the NWHI.

METHODS

Depth data described in this paper were produced from single-beam and multibeam sonars, an aerial LIDAR system, and IKONOS satellite imagery. Each of the data sources for the atlas and Website data are described with a discussion of characteristics and accuracy.

Sonar Data

A sonar (Sound Navigation And Ranging) uses one or more transducers to project sound down through the water column; the sound waves are reflected by the seafloor and received at the survey vessel by the sonar receiver(s). The time between the transmission of the sound, termed "ping,", and the resulting echo from the seafloor is measured accurately and combined with information about the speed of sound in water to calculate the water depth. (water depth = sound velocity/time). Single-beam sonars produce only a single sounding directly underneath the vessel with each ping, while multibeam sonars are designed to produce numerous depth measurements (multiple beams form a "swath") perpendicular to the survey vessel's track out to angles as wide as a total swath width of 150 degrees (~7.5 times water depth). In order to provide accurate positions and depths, multibeam sonars are coupled with GPS-based navigation sensors and motion sensors that measure vessel pitch, roll, heave, heading, and yaw. Single-beam sonars also require accurate navigation, but generally no high-resolution motion sensors. Depending upon transmitter and receiver configurations, the beam size, number of beams, and accuracy can vary widely.

Simrad EK50 single-beam sonar data were collected aboard the NOAA Ship *Townsend Cromwell* along the entire NWHI chain in 2001 and 2002. Ship position from shipboard GPS sensors was integrated with the depth data in real time. The data collection software that was used averages the incoming signal over five pings to reduce noise in the waveform data that also are collected. This averaging, as well as the large size of the beam, can reduce the accuracy of the output by as much as a factor of 10, and a single depth value can represent relatively large, averaged areas of the seafloor. Depth spikes were manually removed from the data. A ship's draft correction of 3.5 m also was also applied in post-processing. The sound velocity used for calculation of water depth was 1,500 m/sec.

Archival National Ocean Service (NOS) depth data, some of which dates back to the 1930s, also were used in limited areas; these were obtained from the National Geophysical Data Center. Multiple-source files were consolidated into single files for each bank and converted from the Old Hawaiian datum into NAD83. Metadata for each NOS data set used in the atlas have been developed to the extent possible, given the lack of documentation available for the original surveys. Based on GPS surveys of the emergent land areas in the NWHI conducted in 1999, sounding data for atolls with emergent land areas were relocated into positions that matched the GPS surveys. The assumption used for these position shifts was that the sounding data were internally consistent for each island group, even though they were not in the correct position. Only those areas with emergent lands (Laysan, Lisianski, Midway) to use as reference points were shifted successfully. Raita Bank and Brooks Banks bathymetry data were not moved, nor were data from Maro Reef, due to a lack of visible reference points. Of the sonar data used, these data must be considered to have the lowest accuracy.

Simrad EM120 multibeam bathymetry and imagery data were collected aboard the *Kilo Moana* between Kauai and Lisianski Islands on cruise KM0206 in depths of ~100 m and greater. The EM120 is a 12-kHz, 191-beam, bathymetric sonar system capable of hydrographic charting and seafloor acoustic backscatter imaging in water depths up to 11,000 m. Angular coverage is up to 150 degrees depending on depth, and beams are 1x2 degrees. Width of coverage is generally six times water depth up to 2,000 m, with a maximum swath width of 20 km. GPS data in the WGS-84 datum were obtained from an Applanix POS-MV model 320, which also measured pitch, roll, yaw, and heave. These position and motion data, as well as corrections for sound velocity, were integrated into the multibeam data in real time, but no tidal corrections were made. The bathymetry data were processed using a combination of Science Applications International Corporation's (SAIC) SABER software (Simmons et al., 2001), MB-System (Caress and Chayes, 1995), and Generic Mapping Tools (GMT) (Wessel and Smith, 1998). Bathymetric data were processed aboard ship using SABER to remove artifacts manually; preliminary grids also were also produced aboard ship using GMT and MB-System. No significant biases were observed in the EM120 bathymetric data.

Simrad EM1002 multibeam sonar bathymetry and imagery data were collected on KM0206 in depths of ~20-1,000 m. The EM1002 is a 95-kHz, 111-beam system with an angular coverage of up to 150 degrees. The width of the coverage is about 1,500 m in deeper waters (7.4 times water depth in shallower water), and beams are 2x2 degrees in size. EM1002 multibeam and backscatter data were collected and processed at sea identically to the EM120 data. A systematic sinusoidal bathymetry anomaly was observed in flat, shallow areas during periods of large swells, and analysis indicated the anomaly resulted from improper heave correction. The magnitude of this error (<0.4 m) is within system specifications. While the shallow data are certainly usable as bathymetry, caution must be used when interpreting the data so that the sinusoidal artifact is not assumed to be sand waves.

SeaBeam 210 multibeam sonar bathymetry data were collected aboard the UH R/V *Kaimikai-O-Kanaloa (KOK)* in 2000-2002. The SeaBeam 210 multibeam sonar system installed aboard the *KOK* is a 12-kHz, 16-beam, hull-mounted, roll- and- pitchcompensated, bathymetric deep seafloor mapping system capable of ensonifying a swath equal to 70-80% of the water depth. SeaBeam 210 does not have backscatter capability. The SeaBeam data were processed by HURL personnel using MB-System, and some artifacts remain in the data, particularly in shallow waters for which this low-frequency system is not designed.

Reson 8101ER multibeam sonar bathymetry and imagery data were collected using the NOAA survey launch R/V *AHI*, which was deployed only at Midway from the NOAA Ship *Oscar Elton Sette* in August 2004. The Reson 8101 is a 240-kHz, 101-beam system with an angular coverage of up to 150 degrees, has a maximum swath width of ~350 m, and a depth range of ~250+ m. Navigation and attitude data were obtained from an Applanix POS-MV and integrated using SAIC's ISS-2000 real-time survey system. Corrections for sound velocity, pitch, roll, heave, draft, and predicted tides were applied to the data in real time. The bathymetry data were processed using SAIC's SABER software to manually remove artifacts and to recorrect for verified Midway tides and sound velocity.

Aerial and Satellite Data

LIDAR bathymetric data were obtained using the airborne LADS MKII system at Kure Atoll, Midway Atoll, and Pearl and Hermes Atoll. These data were collected for comparison with the IKONOS-estimated depth data (Stumpf and Holderied, 2003). The aircraft ground speed is about 150 knots, resulting in a 4x4-m laser spot spacing across a swath of ~200 m. The maximum water penetration (where a return was reported) in the clearest water in this area exceeded 60 m. The survey met International Hydrographic Standards for accuracy of order 1. Vertical precision of measured relative water depth was 0.5 cm, as indicated by the cross-line comparisons. To determine height relative to mean lower low water, the standard datum for bathymetry, a tidal correction for Midway Island was applied (80 km from Kure and 130 km from Pearl and Hermes) because tide gauges were not present at either Kure or Pearl and Hermes.

IKONOS-estimated depth data are derived from 4-m multispectral imagery. The IKONOS satellite system provides multispectral data with three visible bands (blue, green, red) and one near-infrared (near-IR) band. IKONOS data were collected primarily to provide information for benthic habitat analysis in the NWHI (NOAA Publication 2003), but it was also possible to derive estimated depths from these data. Two algorithms were used to derive estimated depths. The standard bathymetry algorithm has a theoretical derivation (Lyzenga, 1978) but also incorporates empirical tuning as an inherent part of the depth-estimation process. A new depth-estimation model, developed by Stumpf and Holderied of NOAA's Biogeography Program, used the reflectance for each satellite imagery band, calculated with the sensor calibration files and corrected for atmospheric effects. Estimated depth data from both methods were compared with the LADS LIDAR data. Although Stumpf and Holderied's method allows calculation of estimated water depths in deeper waters, only estimated depth data down to 16 m were selected for inclusion in this atlas, due to uncertainty levels up to 30% in deeper water.

Data Synthesis

After processing the individual data types using appropriate methods, data were combined using MB-System and GMT. In these grids, data are prioritized by using the data with highest accuracy for each grid cell, so that *Kilo Moana* and *AHI* multibeam data are used whenever available, followed by LIDAR data, IKONOS-estimated depths, *KOK* multibeam data, and, last, single-beam values.

RESULTS

The first draft of the *Bathymetric Atlas of the NWHI* was presented at the May 2003 NWHI Symposium; these data were used as input to NOAA's *"Mapping Moderate Depth Habitats of the U.S. Pacific Islands with Emphasis on the Northwestern Hawaiian Islands: an Implementation Plan*," vol. 2, August 2003, and gridded data products were made publicly available at http://crei.nmfs.hawaii.edu/BathyAtlas in January 2004. NMS published the printed atlas (Miller et al., 2004), and copies were made available in November 2004 at the NWHI Third Symposium.

In the *Bathymetric Atlas of the NWHI*, 30 chart areas are used to display the NWHI area. A series of four figures is presented for each of 30 charts. Each four-page group of figures (Fig. 1) in the atlas includes maps "a", "b", "c", and "d.". Map "a" displays the location of each individual map (bold) in relation to all other maps. The bathymetry data shown in the "a" charts are predicted from satellite altimetry. The "b" plot represents only acoustic or satellite sources that provide both imagery and bathymetry data, and all data presented in the "b" plots were gridded at 60-m grid cell size. Map "c" displays the composite maps of all data sources, including IKONOS, EM-120, EM-1002, LIDAR, CRED, and NOS single-beam data. All data, except for the two single-beam data sources, were gridded at a 60-m grid cell size using MB-System. The single-beam data are not gridded, but plotted over the underlying grids as points. Map "d" shows the locations of each different data types as point plots; multibeam data points are decimated by a factor of 100. All of these figures are also available for download at the BathyAtlas web site.

Multibeam- and IKONOS-estimated depth data were combined for Midway Island as shown in Figure 2. These high-resolution bathymetric data show extensive spur and groove formations on the NW side of the Midway reef crest (Fig. 3) and provide evidence for possible previous stands of the sea at ~ 45- and 60-m depths.

DISCUSSION

Because of the need for accurate base maps, it is important to understand how much and what kind of mapping has been done, what mapping needs to be done, in what water depths, priorities for mapping specific areas or depth ranges, and how long it might take to complete this mapping using candidate technologies.

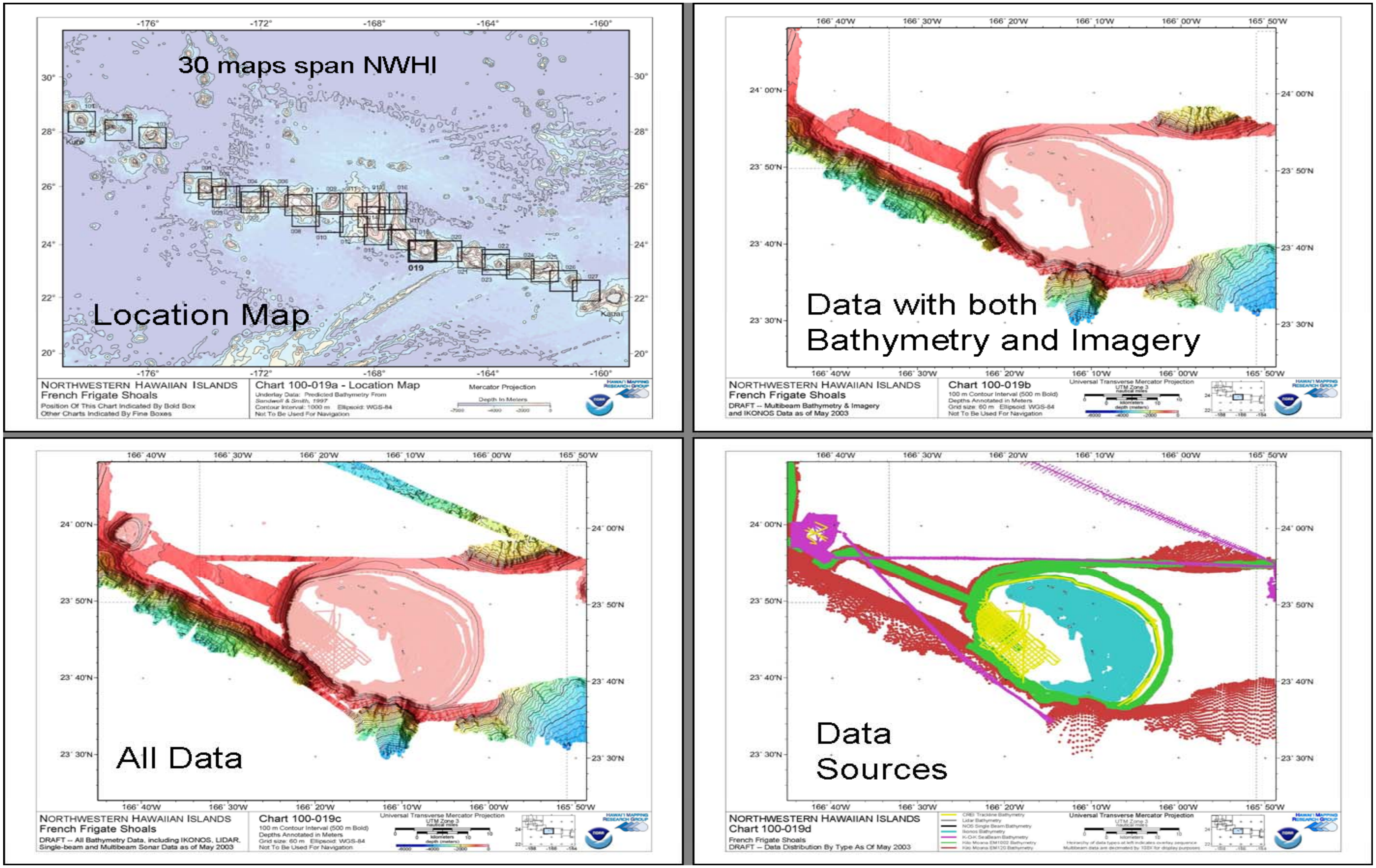

Figure 1. Example “a,” “b,” “c,” and “d” maps from Bathymetric Atlas of NWHI. See website at http://crei.nmfs.hawaii.edu/BathyAtlas/.

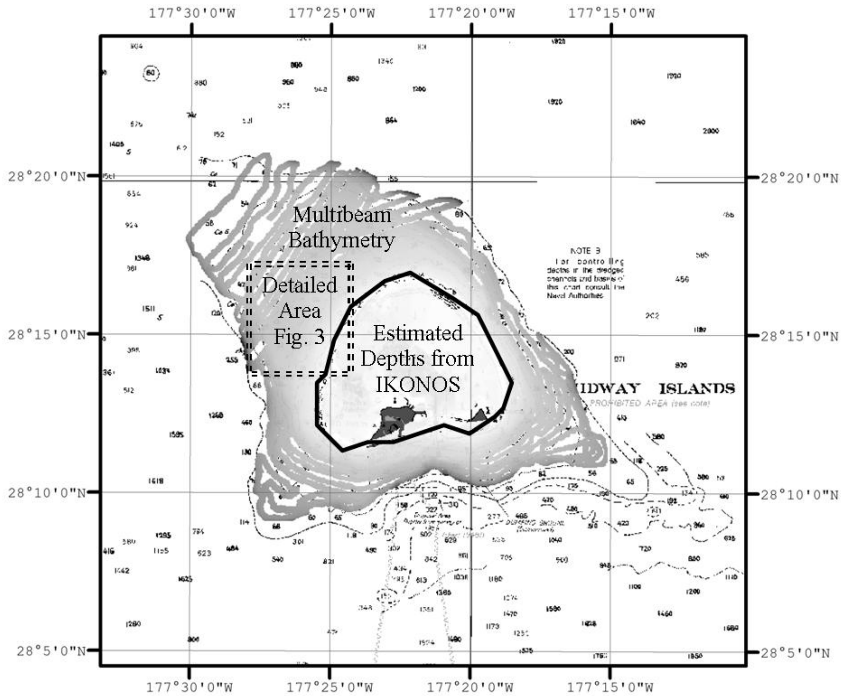

Figure 2. Hillshade of Midway multibeam and IKONOS-estimated depth data.

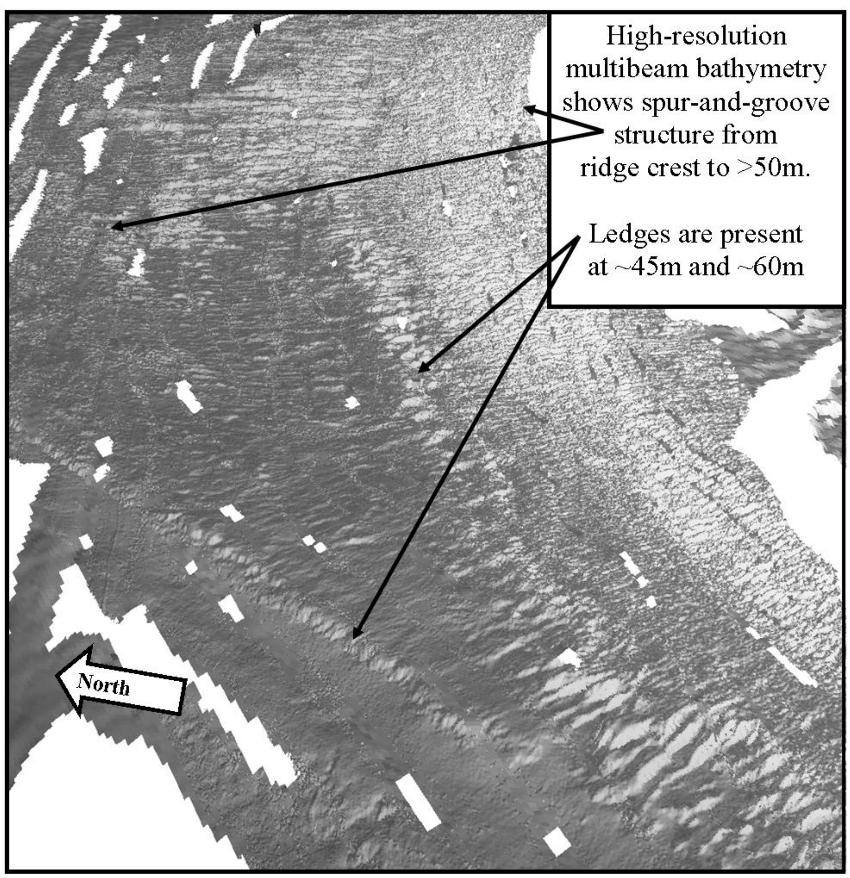

Figure 3. Detail of Midway multibeam hillshade on the NW side of the bank.

Mapping Estimates

In Table 2 we present an analysis of areas by water depth (in fathoms, because fathoms are used on existing nautical charts) included in the NWHI. These estimates were made as part of the document *Mapping Moderate Depth Habitats of the U.S. Pacific Islands with Emphasis on the Northwestern Hawaiian Islands: an Implementation Plan*. The CRER encompasses a total of 351,195 km^2 of which 13,708 km^2 are in the 0-100 fm range that is of primary interest for coral reef managers.

After presentation of the *Bathymetric Atlas of the NWHI* at the May 2003 NWHI Symposium, NMS identified the needs for statistics regarding how much mapping had been done. NMS incorporated these statistics (Table 3) into the atlas and published the final printed document. The areal extents of existing bathymetry data in the five depth ranges (0-10 fm; 10-100 fm; 100-200 fm; 200-500 fm; and greater than 500 fm) shown in Table 3 are subtracted from the total CRER areas shown in Table 2 to provide an estimate of the remaining areal extent that still needs to be mapped in the NWHI CRER. The results are presented in Table 4. Table 4 illustrates that the area within the 0-10 fm boundaries are 99% completed using derived depths from IKONOS imagery, but the critical 10-100 fm area that must be mapped using multibeam sonars is only 45% complete. Note that the total area in Table 2 in less than 10 fathoms (~18 m) of water is estimated at less than the actual area already mapped shown in Table 3. This is the result of inaccuracies in the older nautical charts as well as the methods used for estimation; however, the overall rough estimates are sufficient to determine approximately how much area is left to be mapped.

Mapping Capabilities and Operational Estimates

The primary systems and vessels for mapping in the NWHI in the immediate future are the NOAA Ship *Hi'ialakai*, which had two multibeams installed in early 2005 (mapping capability 10-3,000+ m); the NOAA survey launch R/V *AHI* (mapping capability 5-250+ m); and the NOAA Ship *Oscar Elton Settee,* which has no multibeams, but is used to collect a variety of other data.

To determine how long it might take to map specific areas, an understanding of operational factors is required. The four primary operational parameters affecting survey efficiency are: water depths and corresponding swath widths of individual sonars; vessel speed required to produce acceptable data; survey standards that must be met for data collection (e.g., density and overlap of data); and weather and sea conditions. A number of assumptions are necessary to produce realistic estimates:

- Average effective swath width of sonars on *AHI* and *Hi'ialakai* is assumed to be five times the water depth until limits of range are reached. On the *AHI,* the maximum swath width of ~350 m is reached in 70-m water depth and then remains constant to depths of up to 300 m.
- Almost all mapping (except for Midway) that has been done to date in the 120-1200-fm range was done as part of 2002 boundary surveys in the deeper part of this range (50 m and greater). Because surveying in shallower water is much more time consuming than surveying in deeper water, estimates in this depth range are being made for 30-40 m where the majority of the bank tops in the NWHI are located.

Table 2: Estimates of total NWHI areas based upon nautical chart information.

Area Description	Area (km^2)
NWHI CRER	351,195
Area Between 0-10 fm (0-18 m)	1,541
Area Between 10-100 fm (18-183 m)	12,167
Area Between 100-1,000 fm (183-1830 m)	46,435
Area in CRER > 1,000 fm (> 1830 m)	304,760

Table 3: Estimates of areas mapped in the NWHI as of November 2004.
(See Bathymetric Atlas of NWHI for estimates of areas for specific banks)

Mapped Areas (in square kilometers)						Bathymetry Data (in linear nautical miles)				
Less than 10 fm (18 m)	Between 10-100 fm (18-183 m)	Between 100-200 fm (183-366 m)	Between 200-500 fm (366-915 m)	Greater than 500 fm (915 m)	IKONOS	K-O-K SeaBeam	Kilo Moana EM1002 / EM120	CREI Single Beam	LIDAR	NOS Single Beam
1,759	5,478	2,454	6,550	53,778	1,848	7,946	57,509	5,157	181	26,952

Table 4. Estimates of area remaining to be mapped in NWHI as of Nov. 2004.

Area Description	Total Area (km^2)	Area Mapped (km^2)	Remaining to be Mapped (km^2)	% Mapped
NWHI CRER	351,195	70,018	281,177	19.9%
NWHI 0-10 fm* (0-18 m)	1,541	1,759	0*	99.9%
NWHI 10-100 fm (18 -183 m)	12,167	5,478	6,689	45.0%
NWHI 100-1000 fm** (183-1830 m)	46435	35,893	10,542	77.3%
CRER > 1000 fm***	304,760	26,887	277,874	8.8%

* Incorrect initial estimation of total area inside the 10 fm (18 m) boundary.

** Area mapped between 100-1000 fm (183-1830 m) was calculated using Table 3 100-200 fm plus 200-500 fm plus one-half of area greater than 500 fm.

*** Area mapped CRER greater than 1,000 fm (1830 m) was calculated using one-half of area greater than 500 fm.

- Minimal overlap will be needed in water depths less than 20 m. In general, multibeam mapping will not be attempted in 0-20 m depths.
- Ninety-five percent coverage of all areas is desirable.
- No mapping will be planned in depths greater than ~3,000 m due to sonar limitations.
- Mapping speeds required for acceptable data quality will be calculated at 5-7 knots in water depths less than 100 m and 10 knots on the ship in greater water depths.
- Multibeam data will be collected for 8 hrs/day using survey launch and 10 hrs/day on multimission cruises. On dedicated mapping cruises, this estimate of 10 hrs/day is also used, because it is critical also to collect photographic and video validation data in order to create benthic habitat maps.
- In general, it is wise to make conservative assumptions with respect to weather; sea conditions; operational needs such as conductivity, temperature, and depth (CTD); equipment failure; transits; and survey efficiency. A conservative estimate of 50% efficiency is commonly used.

Table 5 presents ship and launch survey efficiencies, given the assumptions above. From this table it can easily be seen that surveying in the shallow (10-50 fm) areas that make up a large portion of the NWHI is a very slow process. CRER banks cover only ~6.7 km^2 per day, compared to over 1,000 km^2 per day in the 1,000-1,500-fm depth range.

Table 5. Survey efficiencies.

Water Depth Ranges (fm)	Average Depth (m)	Vessel	Speed (kts)	Speed (km/hr)	Swath Width (km)	Coverage (km^2/hr)	Hrs/ Day	Coverage (km^2/day)	Effi- ciency	Adj. Coverage (km^2/day)
10-100	30	Either	6	11.1	0.15	1.7	8	13.3	0.5	6.7
10-100	75	Ship	8	14.8	0.375	5.56	10	55.6	0.5	27.8
100-1000	1000	Ship	10	18.5	5	92.6	10	926	0.5	463
1000-1500	2500	Ship	10	18.5	12.5	231.5	10	2315	0.5	1157.5

Applying these metrics to the overall NWHI areas allows a rough estimation of the time it could take to map in the NWHI (Table 6). The 120-1,200-fm banks have been divided into two separate areas. The first is based upon an estimation that 80% of the bank areas occur in approximately 10-25-fm of water and that either the *AHI* or the *Hi'ialakai* might be used to map in these areas at speeds of 5-7 knots. The second division is based upon the assumption that the *Hi'ialakai* would be used to map in the steep deeper areas that make up an estimated 20% of the 50-100-fm area. Approximately 803, 10-hr survey days are estimated for mapping the 10-25-fm areas, while only ~311 days are required to map in waters greater than 25 fm.

Table 6. Estimation of time needed to map NWHI CRER.

Area Description	Remaining to be Mapped (km^2)	Adj. Coverage (km^2/day)	10-hr Survey Days
NWHI CRER	281,177		**1114**
NWHI 0-10 fm (0 – 18 m)	0		
NWHI 10-100 fm (18-183 m) (80% - AHI or ship)	5351	6.7	**803**
NWHI 10-100 fm (18 – 183 m) (20% - Ship only)	1337	27.8	48
NWHI 100-1000 fm (183-1830 m)	10,542	463	23
CRER > 1000 fm (> 1830 m)	277,874	1157.5	240

Mapping Priorities

Given the extensive areas to be mapped and the number of days needed to map these areas, a unified mapping strategy must be adopted to map priority areas most efficiently. Furthermore, numerous groups have priorities for mapping in the NWHI, including NMS, CRER, CRCP, WPRFMC, the Pacific Islands Regional Office (PIRO), and USFWS. In preparation of the *Pacific Moderate Depth Mapping Implementation Plan*, a survey was done of NWHI stakeholders to determine what depths are of greatest interest for mapping. The consensus was that boundaries needed for management decisions are the first mapping priority; areas in waters between 20 and 400 m were the second priority, because these areas are critical to bottomfish fisheries in the area; completion of aerial or satellite mapping in waters less than 20 m is third priority, but these areas already are covered relatively well by IKONOS imagery; and that water depths greater than 400 m are of lowest priority.

In terms of which specific islands, atolls, and banks should be mapped and when, stakeholders have been queried several times over the past 2 years to determine changing priorities as mapping has progressed. The current consensus for prioritization of future multibeam mapping in the NWHI can be summarized as follows:

- Finish boundary mapping at Nihoa (25 fm), Kure (100 fm) and Pearl and Hermes (100 fm).
- Map in high-priority management areas where quantities of biological, oceanographic, and habitat data have been collected over the past 4 years in 0-400 m in order to facilitate efficient production of benthic habitat maps. These areas include French Frigate Shoals, Maro Reef, Necker Island, Laysan Island, and Lisianski Island.
- Continue mapping at submerged banks where submersible and bottomfishing data have been collected.

- Continue mapping deeper areas between islands, atolls, and banks on transits between islands.

Suggested strategies for optimizing survey efficiency include:

- Continuous updates of survey coverage are critical to efficient mapping. It is planned that the UH Pacific Islands Benthic Habitat Mapping Center will maintain an up-to-date database of survey coverage in the NWHI.
- Plan mapping expeditions to focus on one particular island, bank, or atoll, rather than mapping small, scattered portions of the chain in a single cruise (e.g., map as much of Kure, Pearl and Hermes, and/or Nihoa as possible when mapping the highest priority boundary areas).
- If it is not possible to cover all of an area at once, determine if perhaps coverage less than the targeted 95% may be an option.
- Begin mapping using widely spaced lines to determine the complexity and variability of habitats around an island, bank, or atoll. Then, if it is not possible to provide 95% or greater coverage, areas of particular interest can be chosen for complete coverage.
- Maximize mapping efficiency by providing guidelines for running transit lines for all *Hi'ialakai* cruises to the NWHI and all ships with multibeam sonars (e.g., *Kilo Moana*) that might be transiting through the area.
- On *Hi'ialakai* cruises, when mapping is not the primary focus of the scientific mission, ensure that personnel are available onboard to run the sonars in cases where no night operations are planned.

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