NOAA Technical Memorandum NOS CS 50

A PLAN TO FINISH MAPPING THE PACIFIC US EEZ

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noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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July 2020

noaa **National Oceanic and Atmospheric Administration**

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Introduction

We present here a detailed plan to complete the mapping of the U.S. Pacific Islands (Figure 1). Most of the remaining effort is in very shallow-water (less than 40 m) and very deep water (more than 3,000 m). We strongly recommend addressing the shallow work to 40 m with airborne lidar, and estimate this would take approximately 143 days of lidar acquisition (light detection and ranging). We understand that 40 m depth coverage with lidar is optimistic, but this is achievable in optimal conditions in the Pacific where water clarity is usually remarkable. In contrast, it would take 1,319 ± 40 days of boat-based work to map these shallow areas, four times the effort of acquiring lidar. The deep-water work (679 ± 20 days) will require dedicated mapping missions on ships equipped with systems like the 12 kHz Kongsberg EM122 on the NOAA Ship *Ronald H. Brown*. Geographically, a large portion of the work (89%) is in the Northwestern Hawaiian Islands (NWHI, 58%) and Pacific Remote Islands (PRI, 31%), while a fraction — but still significant portion — of the work remains around Guam and the Commonwealth of the Northern Marianas Islands (CNMI, 7%), as well as the main Hawaiian Islands (4%).

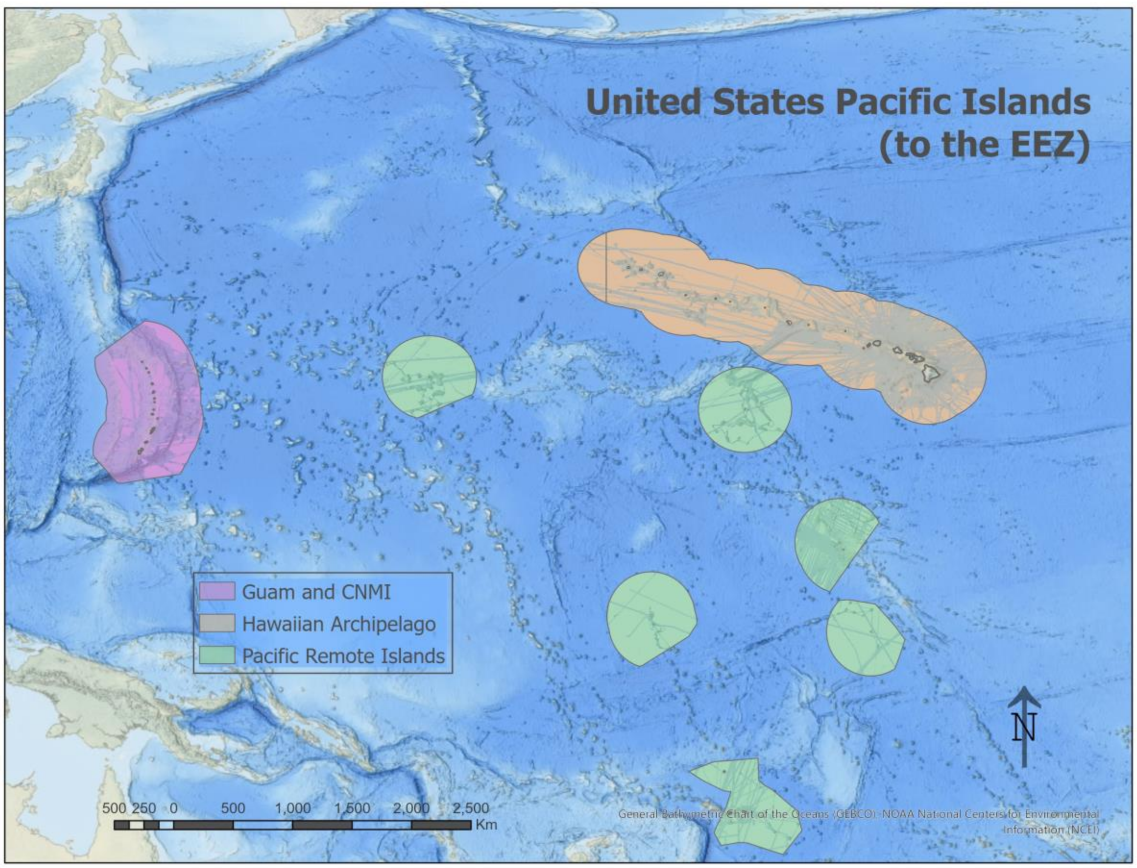

Figure 1. Overview of US EEZ in the Pacific Ocean.

Purpose

Program offices throughout NOAA are interested in mapping US waters across the Pacific Ocean; we present here a detailed estimate of the time required to map this area. With a limited number of properly outfitted mapping vessels, and an increasing number of collaborative projects, level of effort estimates is crucial to sea day allocation and big picture decision making. Using a model-based approach created by NOAA's Office of Coast Survey (Coast Survey) (Greenaway et al., 2019)— based on the proportion of survey coverage to water depth, and survey efficiency — we computed the estimated level of effort required to finish mapping the unmapped areas in the Pacific U.S. Exclusive Economic Zone (EEZ) (Figure 1), and include them in this report. For these estimates, we follow Greenaway et al. (2019) and consider areas mapped with modern multibeam echo sounder (MBES) systems to be 'mapped'. We expect that some areas considered surveyed in this analysis may need to be remapped to meet specific applications or to account for temporal variability of the seafloor, so our estimates here should be considered as a baseline from which additional requirements may be developed by partners and stakeholders. We also provide a detailed and realistic plan to complete this work based on water depth, which is broken down into three different parts: the shallow-water areas, deep water areas, and everything in between. Our plan is to utilize lidar in the shallowest depths, and multibeam everywhere else. We then present a regional breakdown for mapping specific areas (Appendix 1), recommendations for systems able to achieve the specified survey coverage, and a list of potential vessels that are already outfitted for the job (Appendix 2).

Background and Approach

NOAA's Office of Coast Survey has been working with government, academic, and industry partners through its Integrated Ocean and Coastal Mapping Program to strategically map the bathymetric data gaps in U.S. waters by 2030 (Westington et al., 2019). Our approach here is to define the areas that need to be mapped and model the effort required to map them.

The first step — defining areas that need to be mapped — seems trivial, but this seemingly trivial binary determination (mapped or not), instead depends closely on the anticipated use. For example, a deep ocean area with very sparse soundings may be sufficiently mapped for surface navigation while being considered completely unmapped from the perspective of habitat characterization or mineral prospecting. This diversity of use for mapping data is explored at length by Mayer (Mayer et al., 2018) and Westington (Westington et al., 2019). Here we mirror the approach of Greenaway (Greenaway et al., 2019) and consider areas to be mapped if fully covered with modern multibeam or side-scan sonar systems. For the Pacific, this definition includes surveys conducted by Coast Survey specifically for charting, as well as surveys conducted under the extended continental shelf program, exploration surveys conducted by the Office of Ocean Exploration and Research (OER), and transit surveys conducted by academic partners. We understand that in some cases, areas we have considered mapped in this analysis may need to be resurveyed to meet a specific use case or specification. An example of this would be habitat mapping purposes, where previous coverage may have been acquired without backscatter quality in mind. Nevertheless, we hope that this approach provides a framework for these application-based analyses and expect that this plan will evolve with additional inputs.

To evaluate the effort required to survey the areas we consider 'unmapped', we first use a modification of the methods outlined by Greenaway (Greenaway et al., 2019) to calculate the linear nautical miles (LNM) of survey required. This method recognizes that survey efficiency (in terms of area covered per unit time) is inversely related to depth (as shown in Figure 2) and developed an empirically tuned model to estimate effort for full multibeam coverage of any given area. We add to this approach a more accessible day/ year metric and an alternative calculation to estimate the effort required to map the shallowest areas with airborne lidar. Lidar is generally limited to shallow, clear water, but can be dramatically more efficient than boat-based multibeam in these areas.

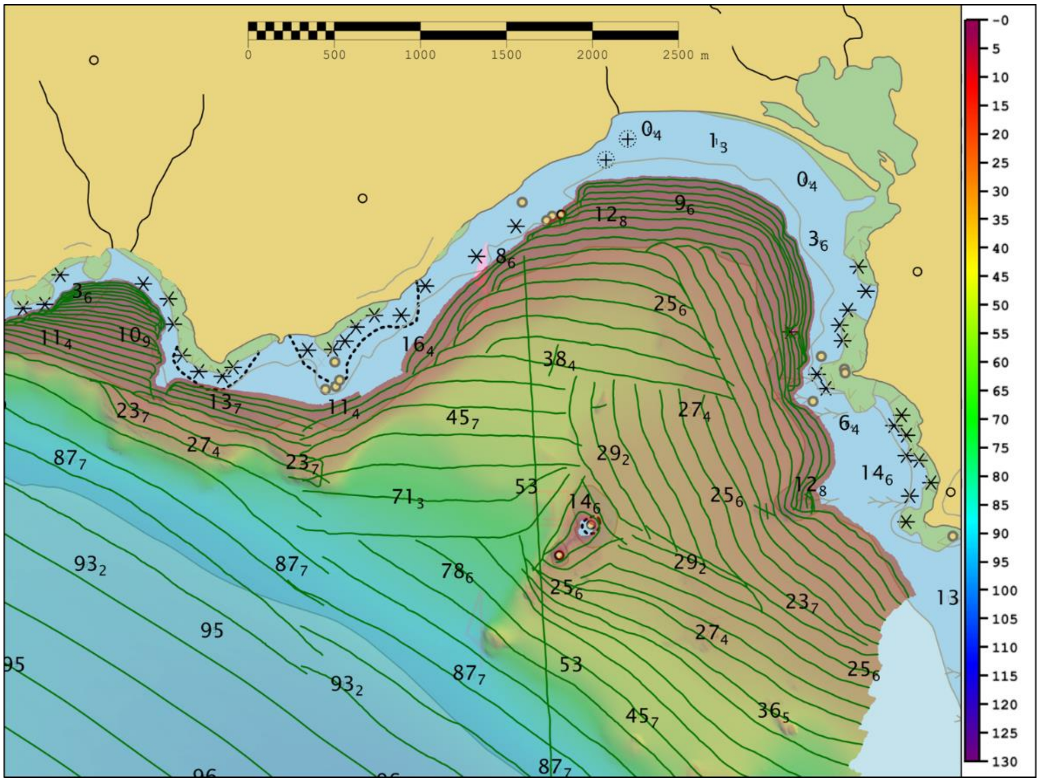

Figure 2. Example of vessel track line spacing and multibeam swath width decreasing as water depth decreases, from a RAINIER survey of Ugak Bay, AK. Here, the survey coverage shown is in units of meters, overlaid on Electronic Chart US4AK50M.

We divide our analysis of level of effort into geographic areas, and recognize that the optimal equipment used to map the seafloor in waters to a depth of 5,000 m is very different from the instruments and platforms used to map in 50 m. Attenuation of acoustic energy in seawater is strongly frequency dependent; higher frequency signals are rapidly attenuated while lower frequency signals are not (see system comparison in Figure 3) [5, 6, 13]. However, lower frequency systems require significantly larger array sizes to achieve the same resolution as higher frequency systems. Generally, lower frequency echo sounders (12-100 kHz) are designed for deeper depths, and high frequency systems (200-400 kHz) are designed for higher resolution at shallower depths. For example, the 300 kHz systems currently mounted on NOAA Ship *Rainier's* survey launches have an array length of 0.4 m and are optimally suited for depth between 4 and 200 m, while the 12 kHz system on the *Ronald H. Brown* has an array length of 7.8 m and is best suited for depths over 3,000 m. Accordingly, we break up the analysis into depth bands appropriate for specific instrumentation currently available in the mapping-capable fleet.

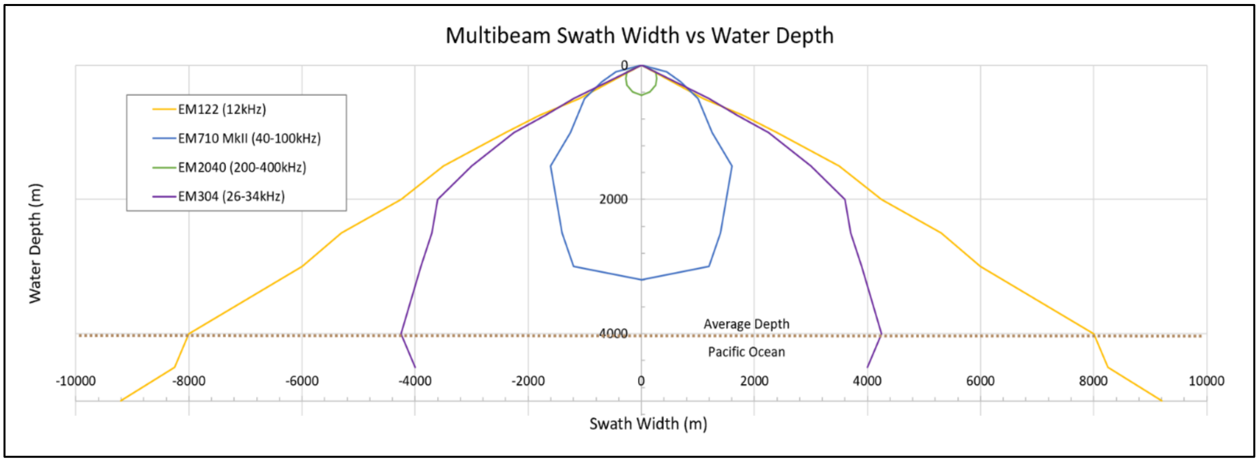

Figure 3. Comparison of multibeam swath width versus depth for four common Kongsberg multibeam systems [5, 6, 13].

We also depart from the method outlined by Greenaway (Greenaway et al., 2019) to arrive at estimates of time required, i.e., how many days or years will be required to complete the work. Greenaway et al, mirroring Mayer (Mayer et al., 2018), used a notion of a ship-year to convert from linear nautical miles to a notion of time. Their definition of a ship-year, a ship acquiring data continuously at 7.5 knots for one year, while simple to understand, is clearly unrealistic in operational practice. Here, we use a more realistic model of survey productivity (LNM per day in different depth bands) to arrive at an estimate of required days-at-sea. These days are in turn put together into reasonable projects to arrive at our final estimates in terms of years.

For our lidar estimates, we used the Track'Air Track32 software for line planning and a rough figure of four and a half hours of flight for a lidar project day. Actual time on project is going to vary greatly (as much as three times our estimates) depending on several factors, such as project specifications, geographic area, and environmental conditions. We used 40 m for our maximum achievable depth using lidar. Here we do not intend to overpromise or overestimate lidar capabilities, but in clear tropical water measured depths of approximately 40 m are realistic. We recognize that in areas such as harbors, channels, and river or stream discharges water clarity could be more highly variable than in other places along the coasts. We exclude the main Hawaiian Islands, Guam, and CNMI from our lidar estimates, since we consider these effectively mapped from a lidar mobilization cost perspective. Throughout Guam and CNMI, the following islands have modern lidar coverage as of 2019, with mapping continuing into 2020: Guam, Rota, Tinian, Saipan, Pagan, Anatahan, Sarigan, Guguan, Alamagan, Agrihan, and Asuncion.

Methods

We calculated the LNM for the unmapped areas using the "LNM Estimator" toolbox, created by Amber Batts (NOAA NCCOS) for ArcGIS based on mapping data explored by Mayer (Mayer et al., 2018) and Westington (Westington et al., 2019) and by the methods outlined in Greenaway (Greenaway et al., 2019). Unmapped areas were provided and analyzed using depth bands as derived from GEBCO (GEBCO, 2020) world bathymetric data. Again, we emphasize that these estimates do not take into account areas which may need to be remapped to produce higher quality bathymetry or products in addition to depth information, such as acoustic backscatter. Additionally, much unmapped data is interspersed with mapped data, and sparsely mapped regions may result in resurveying already mapped areas, thus increasing the work requirements per area. Take a simple scenario like painting a wall: at a certain point it is more productive to cover the entire wall with fresh paint rather than fill in individual pieces. For both these reasons this estimate should be considered a low-end estimate.

To move from LNM to days-at-sea, we modeled the productivity (Table 1) of currently available NOAA assets. Based on our experience with actual survey work, we estimated a rate of acquisition of 35 LNM per day from a hydrographic survey launch (5 hours of on-line acquisition at 7 knots during acquisition, after transit, turns, and supporting effort including CTD casts, etc.). While ships like *Rainier* and *Fairweather* can carry up to four survey launches, we assume that the operational configuration for the near-shore work in the Pacific would include only two launches, so other dive-based scientific missions could be accomplished simultaneously. This is the anticipated configuration for the *Rainier* based Pacific mapping work that was planned for 2020-2021. For dedicated ship-based work, we modeled 200 LNM per day (approximately 20 hours of acquisition a day, at 10 knots, performing underway sound speed casts). Actual amount of time it will take to survey an area will vary depending on mission requirements. For instance, if a ship could only acquire 120 LNM per day, the estimated time to survey the same area would increase by about 70%.

Efficiency Assumptions	
No. of Launches	2
Speed (kts)	7
Hours/Day	5
LNM/Day (total)	70
No. of Ships	1
Speed (kts)	10
Hours/Day	20
LNM/Day	200
No. of Aircraft	1
Hours/Day	**4.5**

Table 1. Parameters used in estimating time from LNM.

We model using hydrographic survey launches in depths between 4 m and 200 m (utilizing a 200 - 400 kHz system such as the Kongsberg EM2040). We see the work between 200 m to 1,500 m would be done with a ship using a 40 to 100 kHz system (e.g., Kongsberg EM710). Waters deeper than 1,500 m could be mapped with either a 30 kHz (e.g., EM302) system or a 12 kHz system (e.g., EM124), while waters deeper than 3,000 m are best mapped with a 12 kHz system. At this stage, we have considered each depth band independently. We later discuss the possibility of combining efforts (e.g., mapping the nearshore by day with launches and doing the deeper offshore areas at night).

Unlike multibeam sonar, the coverage rate of airborne lidar is not strongly dependent on depth, but depth performance is dependent on water clarity. The water and atmospheric conditions around the Pacific Islands are those particularly amenable to survey by lidar. An aircraft on a lidar survey typically flies set line spacing over the area, so is primarily driven by area, line spacing, and survey speed. We estimate the lidar coverage based on a project day of four and a half hours; however, this is highly dependent on location and prevailing environmental conditions. We anticipate a system similar to the Leica HawkEye 4X lidar system to yield reliable results to depths of 40 m in Pacific Islands.

Results

To complete the mapping work of the US Pacific EEZ would require 305 days of lidar acquisition and 905 days of ship-based work based on our estimates in Table 4 (see Appendix 1 for a further breakdown by region). However, this estimate would more realistically look like 284 days of lidar and 960 days of ship-based work, due to remoteness of survey areas and physical limitations of aircraft. These ship-based estimates are again based Greenaway et al. (2019)'s work for time on project, and do not include transit times and other factors. Although areas may be good candidates for lidar, in some cases, they may be too remote to be worthwhile. That being said, lidar is tremendously advantageous in this region. Without lidar, mapping the shallow areas using full bottom coverage multibeam sonar would more than double the required ship-based time to 2,200+ days of work. We found that virtually all the lidar work is in the North West Hawaiian Islands (NWHI), with some in the Pacific Remote Islands (PRI), particularly around Johnson Atoll (Table 27 and Table 28; see Appendix 1). If we do use lidar for waters less than 40 m, 86% of the remaining effort is in water deeper than 3,000 m, with the remaining 14% of the work in depths 40-3000 m.

In these waters deeper than 3000 m, we found that essentially all of this remaining work is likewise in the NWHI (34%) and PRI (45%). With modern multibeam systems, coverage is proportional to depth and frequency, and it is much, much slower to map in shallow-water than it is to map in deep-water. As explained by Greenaway (Greenaway et al., 2019), surveys in deep-water make rapid progress on adding area to the mapped tally; even so, we estimate that it will take about 680 ship days to completely map areas deeper than 3000 m. A 30 kHz system is certainly capable of mapping at this depth, but a 12 kHz system will have a swath width that is nearly twice as wide.

Of the remaining 14% of ship-based effort — if lidar is utilized, nearly 80% is in the NWHI in depths between 40 and 200 m. Here field units would likely utilize shallow-water systems (200-400 kHz) mounted on survey launches. The majority of the rest of the work is located in waters between 200 and 3000 m in Guam and CNMI, and the PRI. Using the findings shown in Table 4 we created an operational plan with these system performance considerations in mind. See Appendix 1 for additional detail.

To calculate flight hours for the areas of interest for topobathy lidar acquisition, we utilized the Remote Sensing Division's (RSD) standard flight planning software "Tracker32". Our estimates are based on acquiring at an altitude of 1,300 feet, flying at 100 knots with a five-minute turn time from line to line, and 50% sidelap (overlap between adjacent flight lines). Using an aircraft with a higher airspeed and minimizing sidelap would significantly increase survey efficiency, and decrease these time estimates. After configuring our flight plans, the software calculates the number of hours and minutes to acquire the data. These estimates are for time on station, and do not account for transit time from base of operations to project site. The uncertainty in these time estimates grow as the survey area is located further away from the base of operations, since surface weather and cloud cover can be different from what is predicted by meteorologists at weather stations hundreds of miles away.

REGION: US Pacific Islands	LNM						TOTAL
	4m-25m	25m-40m	40m-200m	200m-1500m	1500m-3000m	3000m-11000m	
Guam and CNMI	1,976	197	356	1,083	2,888	10,618	*17,118*
Northwestern Hawaiian Is	59,561	25,268	10,998	2,074	927	45,668	*144,495*
Main Hawaiian Islands	1,421	253	917	285	10	7,938	*10,824*
Pacific Remote Islands	3,395	219	98	369	2,165	71,536	*77,783*
TOTAL (LNM)	66,353	25,937	12,369	3,811	5,990	135,760	250,220

Table 2. Total level of effort estimates in linear nautical miles for the unmapped Pacific Islands.

REGION: US Pacific Islands	Days with MBES Systems Only (no Lidar)							TOTAL
	200 to 400 kHz				30 to 100 kHz	12 to 30 kHz	12kHz	
	4m-25m	25m-40m	40m-200m	0m-200m	200m-1500m	1500m-3000m	3000m+	
Guam and CNMI	28	3	5	36	5	14	53	*109*
Northwestern Hawaiian Is	851	361	157	1,369	10	5	228	*1,612*
Main Hawaiian Islands	20	4	13	37	1	0	40	*78*
Pacific Remote Islands	48	3	1	53	2	11	358	*423*
TOTAL (Days)	948	371	177	**1,495**	**19**	**30**	**679**	**2,223**

Table 3. Total level of effort estimates in days, utilizing only multibeam systems, for the unmapped Pacific Islands.

REGION: US Pacific Islands	Days Per Acquisition System					
	Lidar TOTAL	200 to 400 kHz	30 to 100 kHz	12 to 30 kHz	12kHz	Vessel TOTAL
	0m-40m	*40m-200m*	*200m-1500m*	*1500m-3000m*	*3000m+*	*40m-3000m+*
Guam and CNMI	-	5	5	14	53	*78*
Northwestern Hawaiian Is	249	157	10	5	228	*400*
Main Hawaiian Islands	-	13	1	0	40	*54*
Pacific Remote Islands	22	1	2	11	358	*372*
TOTAL (Days)	271	177	19	30	679	905

Table 4. Total level of effort estimates in days, utilizing lidar and multibeam, for the unmapped Pacific Islands.

REGION: US Pacific Islands	Days Per Acquisition System Summary						
	Lidar TOTAL	200 to 400 kHz	200 to 400 kHz	30 to 100 kHz	12 to 30 kHz	12kHz	Vessel TOTAL
	0m-40m	*0m-40m*	*40m-200m*	*200m-1500m*	*1500m-3000m*	*3000m+*	*40m-3000m+*
Guam and CNMI	-	-	5	5	14	53	*78*
*Northwestern Hawaiian Is**	121	29	157	10	5	228	*429*
Main Hawaiian Islands	-	-	13	1	0	40	*54*
Pacific Remote Islands	22	-	1	2	11	358	*372*
TOTAL (Days)	**143**	**29**	**177**	**19**	**30**	**679**	**934**

*Lidar estimates include Nihoa, Necker, French Frigate Shoals, and Gardner; MBES estimates include Midway and Kure for depths 0-40 m

Table 5. Summary of estimated number of survey days, only considering areas where lidar acquisition is feasible, as discussed in our shallow-water operational plan.

Uncertainty

Using the modeled uncertainty for multibeam survey as discussed by Greenaway (Greenaway et al., 2019), we determined the total uncertainty in our estimates to be about five percent. Our total estimated effort for the Pacific U.S. EEZ is 250,200 LNM ± 6,200 LNM (1-sigma). This is about 31 ship days on project, which is roughly half of a typical NOAA ship field season. Because the uncertainty is based on a campaign of independent surveys where region and field unit — as counterintuitive as it may seem — do not matter, the modeled uncertainty is only dependent on the number of LNM. To highlight this point made in Greenaway (Greenaway et al., 2019), we illustrate the estimated uncertainty as a function of total LNM in Figure 4.

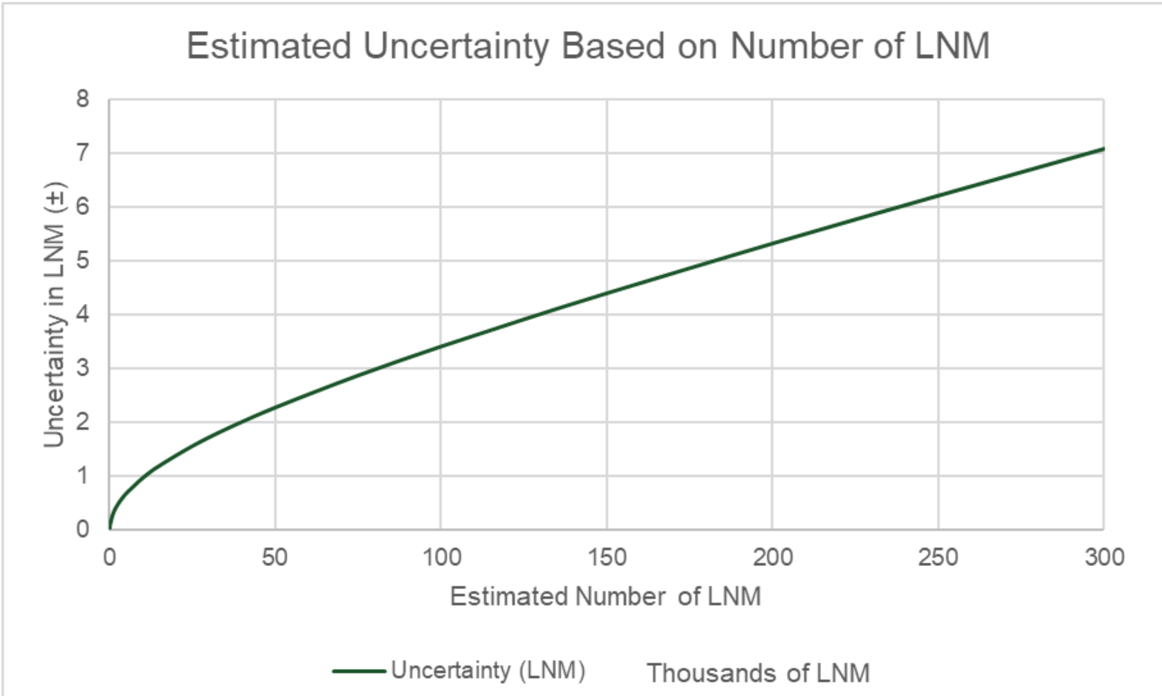

Figure 4. Plot of the estimated number of LNM for a multibeam survey area versus the estimated uncertainty in LNM, in thousands of LNM and at 1-sigma.

Operational Plan

Our operational plan to completely map the US EEZ in the Pacific (Figure 1) is broken into three sections: the shallowest areas, the deepest areas, and everywhere in between. The shallow and deep-water depths can be independently surveyed at any time; however, the remaining survey areas are best to survey following adequate coverage in the shallowest depths. As we previously discussed, system performance and efficiency are proportional to water depth, and it would be more productive, cost effective, and safer to survey these areas with traditional multibeam after knowing more about the area — by way of lidar or other technology. Before any survey, it is necessary to gather any existing data from available sources in order to effectively plan survey operations, overlap with existing coverage (junction), effectively develop features, and to avoid duplicating effort. We planned our lidar surveys to cover land areas as well as nearshore bathymetry, which will provide additional datasets for use in studies above the waterline, and greater efficiency in flight planning.

We designed our plans based around a single vessel, working alone at a typical operational tempo. In many cases, such as the Pacific Remote Islands, our objective was to maximize time on project and minimize transit time between survey and port locations, all while maintaining the standard pace of operations. Overall project lengths were kept within timeframes similar to those found in a typical NOAA ship field season. A single vessel designed for maximum endurance in remote locations would likely be the most effective mapping solution for areas around the Pacific Remote Islands. In contrast, areas like the NWHI, where survey areas are close together though spread out over a large area, dividing work up among several platforms and utilizing transit routes to acquire new data would be more efficient than dependence on a single vessel. (We stress that acquiring data during transits must still be done with an appropriate acoustic system.) The work in the deeper portions of the EEZ will be routine "mowing the lawn" type projects, where a single vessel uses set line spacing based on a known sonar swath width to acquire multibeam data. In this case, a multi-mission vessel with a full complement of smaller launches would be underutilized. We discuss in the next section how technology could play a role in completing this effort.

Details regarding the estimated level of effort for the various sub-regions with the Pacific Islands are found in Appendix 1.

<u>Shallow water (less than 40 m)</u>

Our strategy for mapping the nearshore areas in the Pacific is to utilize technologies that are not depth dependent, and therefore more efficient in shallow-water than multibeam systems. We plan to use active sensors, such as lidar from aircraft, wherever possible. The two primary aircraft used by NOAA's Remote Sensing Division are the DHC-6 Twin Otter and Beechcraft King Air 350CER, which are based out of Lakeland, Florida (see Appendix 2 for summary information on these platforms). We recognize bringing either platform to remote areas of the Pacific and operating would present numerous cost and logistical challenges, and that the King Air would be a better operational fit. Our plan's level of detail here mainly focuses on the where and what aspects of the operational plan, without diving deep on aircraft logistics.

Where we have increased operational and logistical complexity by using lidar, we make up for with increased navigational safety for vessel-based survey personnel and significant reduction in scope of work in these shallow-water areas, as well as confidence in ensuring a seamless final product. Lidar can also be augmented with other technologies, such as autonomous aircraft and satellite based active and passive sensors, as discussed further in the next section, Challenges and Opportunities. In some areas, utilizing contractors and interagency partners may be a realistic approach, and yield more creative solutions. Based on NOAA's King Air performance capabilities, the uncertainty in our estimates grows with the distance an aircraft is required to transit (see Figure 5 example for NWHI).

Northwest Hawaiian Islands: With NOAA awarding a contract for another King Air (Shannon, 2019), NOAA could gain more flexibility for in-house lidar surveys in some of the NHWI. Using lidar for Nihoe Island, Necker Island, French Frigate Shoals, and Gardner bank would save about 540 multibeam survey days. However, due to the remoteness of the NWHI, many of these survey operations west of Gardner Pinnacles would be beyond the King Air's capabilities (Figure 5), and require contract or cooperative surveys with specialized aircraft or other technologies.

The closest and most western airport relative to the NWHI is Lihue airport on Kauai. The airport facilities on Midway, one of the last islands in the Hawaiian Archipelago, is operated by the U.S. Fish and Wildlife Service and has been shut down since 2012. It is currently only used for emergency landings for trans-Pacific flights, making aircraft operations logistically challenging and increasing the uncertainty of our time on project as we look at islands west of Lihue.

Because most of the waters around Nihoa are at the edge of the physical depth limits of lidar systems, flying lidar first for reconnaissance would increase vessel safety and may also reduce the amount of survey work in depths from the 40-200 m. From a cost benefit point of view, there would need to be some comparison between lidar and ship operations, and risks associated with both. Another option would be to fly lidar only in the shallowest areas, and use ships' multibeam sonar equiptment for the remaining work.

For areas like Midway and Kure, which only require about 30 days of multibeam acquisition in the 4-40 m depth range, we include these in as part of our vessel operational plan in Table 17. If neither NOAA nor contract aircraft were able to support lidar mapping around islands such as Midway, Kure, or other remote islands, we see opportunities here to augment our multibeam surveys with other technologies (discussed in the next section, Challenges and Opportunities).

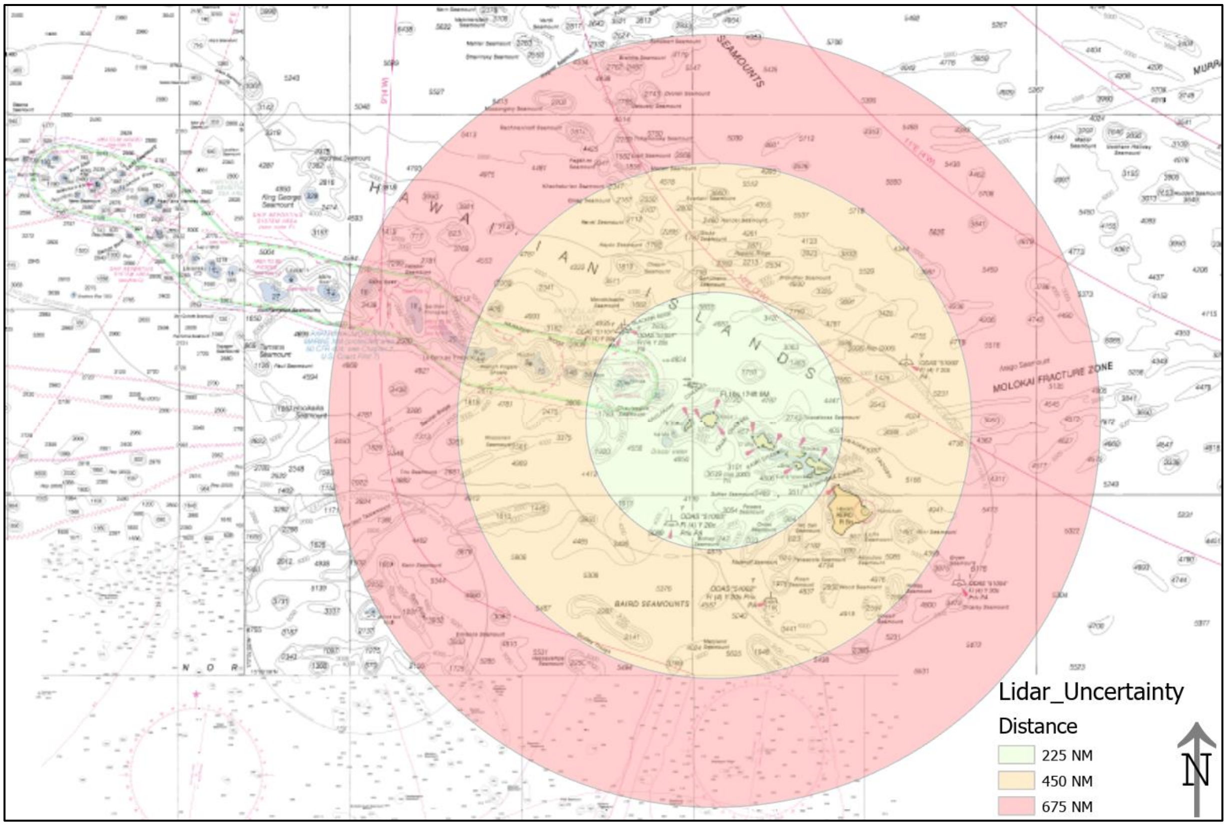

Figure 5. Uncertainty in the estimated number of lidar days based on distance from Lihue Airport. Our theoretical operational range is based on a King Air cruising at a speed of 240 kts. Here green corresponds with low uncertainty, yellow medium uncertainty, and red high uncertainty. Anything beyond the red extents would not be possible with the King Air.

Northwest Hawaiin Islands	Area (NM^2)	Time on Project in Hours (130 knots)	Days on Project*	Number of Flight Lines	Transit Distance (NM)**	Round Trip Transit Time @240 knots (HR)**	Required Time on Project Uncertainty
Nihoa	303	89	20	685	169	1.5	Low
Necker	457	127	28	949	310	2.8	Medium
French Frigate Shoals	514	151	34	1,149	419	3.7	Medium-High
Gardner	718	176	39	1,220	510	4.5	High
Laysan	277	79	18	619	727	6.5	not feasible
Lisianski	520	136	30	985	833	7.4	not feasible
Pearl and Hermes Reef	252	68	15	509	966	8.6	not feasible
Midway	186	62	14	507	1,202	10.7	not feasible
Kure	102	31	7	243	1,268	11.3	not feasible
Maro Reef	746	187	42	1,320	740	6.6	not feasible
Other (to EEZ)	48	18	17	18	1,130	10.0	not feasible
* One project day is defined as 4.5 hours							
** Distance calculated by using the centroid of each area of operations to corresponding airport							

Table 6. Operational breakdown of lidar survey flights for the NWHI.

The Pacific Remote Islands (Table 7) would likely be even more difficult to cover with lidar simply due to their remoteness and a lack of facilities, with the closest services inside the US EEZ being in Hawaii, Guam, and American Samoa. Outside of US territories, the closest airports to survey areas in the PRI are Cassidy International Airport (210 NM from Jarvis Island; 400 NM from Kingman Reef), Kanton Island Airport (365 NM from Howland Island), and Lihue Airport (750 NM from Johnston Atoll), again, with Lihue being the only airport in a US territory. The priority in PRI would be Johnston Atoll, since it would end up taking about 42 days to map with multibeam, using two vessels per day (Table 27; see Appendix 1).

Pacific Remote Islands	Area (NM^2)	Time on Project in Hours (130 knots)	Days on Project*	Number of Flight Lines	Transit Distance (NM)**	Round Trip Transit Time @240 knots (HR)**	Required Time on Project Uncertainty*
Johnston Atoll	60.0	20.3	5	168	-	-	-
Wake Island	7.8	4.1	1	40	-	-	-
Kingman Reef and Palmyra Atol	42.1	11.7	3	126	-	-	-
Jarvis Island	2.3	1.7	0.4	18	-	-	-
Howland Island and Baker Islar	3.5	3.1	1	34	-	-	-
Total	**115.6**	**40.9**	**9**	**386**	-	-	-
* One project day is defined as 4.5 hours							
** Will be determined by airport logistics							

Table 7. Operational breakdown of lidar survey flights for the PRI.

Operating out of Pago Pago airport would be an effective location to survey all of the shallow depths of American Samoa (Table 8). The main bases of aircraft operations in American Samoa will be Pago Pago International Airport, which is a Department of Defense (DoD) contract fuel location. It is unlikely that a NOAA aircraft would feasibly reach American Samoa; this would likely be a contract survey.

American Samoa	Area (NM^2)	Time on Project in Hours (130 knots)	Days on Project*	Number of Flight Lines	Transit Distance (NM)**	Round Trip Transit Time @240 knots (Minutes)**	Required Time on Project Uncertainty
Ofu and Olosega Islands	10.2	4.3	1	40	63	15	Low
Rose Atoll	2.6	2.2	0.5	24	153	40	Low
Swains Island	1.9	1.8	0.5	21	190	50	Low
Tau Island	17.7	7.3	2	67	73	20	Low
Tutuila Island	150.7	38.8	9	275	-	-	Low
Total	**183.0**	**54.4**	**12**	**427**	-	-	-
* One project day is defined as 4.5 hours							
** Distance calculated by using the centroid of each area of operations to corresponding airport							

Table 8. Operational breakdown of lidar survey flights for American Samoa.

<u>Deep-water (greater than 3000 m)</u>

At these depths the type of multibeam system used will have a big impact on survey efficiency, as shown in Figure 3. A 30 kHz system (e.g. as installed on *Okeanos Explorer*) system can certainly reach the seafloor, but a 12 kHz system will have a swath width that is nearly twice as wide. That is why our deep-water mapping plan is based on a minimum of one vessel utilizing a 12 kHz system capable of mapping full ocean depths greater than 3000 m. These projects would be focused solely on mapping and would not be in support of other missions, though opportunistic sensor deployments and recoveries could still take place if planned accordingly. As discussed earlier, most of the remaining ship-based mapping work is in the deepest areas of the Pacific. Factoring in transit time, the majority of the effort is in the Pacific Remote Islands, followed by the NWHI.

Pacific Remote Islands: With almost a year's worth of work in the deepest regions of the Pacific Remote Islands, it will take dedicated mapping missions with vessels utilizing systems capable of full ocean depth mapping (Table 9). Most mapping of the Pacific Remote Islands, including Howard and Baker Islands, appears feasible by way of operations out of the port of Tutila, near Pago Pago on American Samoa.

Additionally, a stop at Jarvis Island en route from Hawaii to American Samoa, adds only about 100 NM to the great circle route between the two sites. We therefore planned all mapping at Jarvis to coincide with transits between Hawaii and American Samoa. Our plan breaks the existing work into two separate missions, which could be accomplished by the same vessel, or two separate vessels without any duplication of effort. Considerations of the two projects should require the need for a second period of 'cleanup' of areas missed during the first stage.

Leg	Area	Depart	Transit Time (Days; 11-12kts)	Remaining Mapping Days	Days on Project	Arrive	Leg Total (DAS)	Season Total (DAS)
Jarvis - Howland/Baker - American Samoa (Depths > 3000m)								
1	Jarvis	Pearl Harbor	8.75	59	16	Tutulia (Pago Pago)	24.8	
2	Howland/Baker	Tutuila (Pago Pago)	7.5	86	17	Tutulia (Pago Pago)	24.5	
3	Howland/Baker	Tutuila (Pago Pago)	7.5	69	17	Tutulia (Pago Pago)	24.5	
4	Howland/Baker	Tutuila (Pago Pago)	7.5	52	17	Tutulia (Pago Pago)	24.5	
5	Howland/Baker	Tutuila (Pago Pago)	7.5	35	11	Tutulia (Pago Pago)	18.5	
6	Howland/Baker	Tutuila (Pago Pago)	7.5	24	11	Tutulia (Pago Pago)	18.5	
7	Howland/Baker	Tutuila (Pago Pago)	7.5	13	13	Tutulia (Pago Pago)	20.5	
8	American Samoa	Tutuila (Pago Pago)	1	60	18	Tutulia (Pago Pago)	19.0	
9	American Samoa	Tutuila (Pago Pago)	1	42	24	Tutulia (Pago Pago)	25.0	
10	Jarvis	Tutuila (Pago Pago)	8.75	43	16	Pearl Harbor	24.8	224.5
Jarvis - American Samoa - Johnston Atoll - Kingman Reef/Palmyra Atoll - Main Hawaiian Islands (Depths > 3000m)								
1	Jarvis	Pearl Harbor	8.75	27	10	Tutulia (Pago Pago)	18.75	
2	American Samoa	Tutuila (Pago Pago)	1	18	18	Tutulia (Pago Pago)	19	
3	Jarvis	Tutuila (Pago Pago)	8.75	17	17	Pearl Harbor	25.75	
4	Johnston Atoll	Pearl Harbor	5.5	67	14	Pearl Harbor	19.5	
5	Johnston Atoll	Pearl Harbor	5.5	53	19	Pearl Harbor	24.5	
6	Johnston Atoll	Pearl Harbor	5.5	34	19	Pearl Harbor	24.5	
7	Johnston Atoll	Pearl Harbor	5.5	15	15	Pearl Harbor	20.5	
8	Kingman Reef/Palmyra Atoll	Pearl Harbor	7.25	20	20	Pearl Harbor	27.25	
9	Main Hawaiian Is.	Pearl Harbor	1	40	17	Pearl Harbor	18	
10	Main Hawaiian Is.	Pearl Harbor	1	23	23	Pearl Harbor	24	221.75

Table 9. Operational breakdown of multibeam survey legs for PRI, allowing for extra time on project.

Guam, CNMI, and Wake Island: Guam and CNMI are the farthest US territories from the continental US. The work around Guam and CNMI covers a large area, roughly 740 NM long and 340 NM wide, and has been sporadically mapped over the years. Some of the work here will require longer transits between surveys, while others will be large swaths of the ocean floor where continuous new coverage is achievable. Operationally, the field unit could plan to strategically map certain areas while transiting to and from port locations (Table 10).

We were surprised by how logistically difficult it would be to completely map around Wake Island, which is remote and still has a considerable amount of work remaining. Our strategy for completing acquisition in this area is to map everything in a single project over the course of several legs, based out of Pearl Harbor and Apra Harbor (Table 10). The vessel utilized in our planning would have a maximum endurance of about 30 days, although a higher endurance platform would greatly reduce the number of legs, and overall season length. Additional technological solutions could also be utilized to decrease the amount of time human operated vessels are required to spend on project.

Leg	Area	Depart	Transit Time (Days; 11-12kts)	Remaining Mapping Days	Days on Project	Arrive	Leg Total (DAS)	Season Total (DAS)
Wake Island - Guam/CNMI - Wake Island (Depths > 3000m)								
1	Wake Island	Pearl Harbor	13.5	66	10	Guam (Apra)	23.5	
2	Guam/CNMI	Guam (Apra)	10	53	8	Saipan Harbor	18	
3	Guam/CNMI	Saipan Harbor	10	45	15	Saipan Harbor	25	
4	Guam/CNMI	Saipan Harbor	8	30	10	Guam (Apra)	18	
5	Guam/CNMI	Guam (Apra)	6	20	12	Guam (Apra)	18	
6	Guam/CNMI	Guam (Apra)	6	8	8	Guam (Apra)	14	
7	Wake Island	Guam (Apra)	10.5	56	14	Guam (Apra)	24.5	
8	Wake Island	Guam (Apra)	10.5	45	14	Guam (Apra)	24.5	
9	Wake Island	Guam (Apra)	10.5	30	8	Guam (Apra)	18.5	
10	Wake Island	Guam (Apra)	10.5	20	14	Guam (Apra)	24.5	
11	Wake Island	Guam (Apra)	13.5	8	8	Pearl Harbor	21.5	230

Table 10. Operational breakdown of multibeam survey legs for Wake Island and Guam/CNMI.

Northwest Hawaiian Islands EEZ: The Northwestern Hawaiian Islands have 45,668 linear nautical miles remaining to be surveyed in depths greater than 3,000 m and within the EEZ. The NWHI EEZ spans from Niihau to areas west of Kure Island. With Pearl Harbor as the only available port for this project, transit times vary from two to five days (one way). Our plan for acquiring data within the EEZ, and accomplishing all 228 days of remaining survey assume the ability to collect data while strategically transiting within the EEZ. The operational plan we've created (Table 11) requires more than the average number of days at sea for a single ship field season, and may require breaking up further. One benefit of operating around the NWHI is that the areas requiring longer transits and more days at sea can be separated by those closer to Pearl Harbor requiring shorter transit times.

Leg	Area	Depart	Transit Time (Days; 11-12kts)	Remaining Mapping Days	Days on Project	Arrive	Leg Total (DAS)	Season Total (DAS)
EEZ NWHI (Depths >3000m)								
1	West of Kure Island	Pearl Harbor	10	228	15	Pearl Harbor	25	
2	Nihoa	Pearl Harbor	2	208	10	Pearl Harbor	12	
3	West of Kure Island	Pearl Harbor	10	198	15	Pearl Harbor	25	
4	Nihoa	Pearl Harbor	2	178	10	Pearl Harbor	12	
5	/idway Island/Pearl and Hermes	Pearl Harbor	9	168	16	Pearl Harbor	25	
6	Nihoa	Pearl Harbor	2	148	10	Pearl Harbor	12	
7	Lisianski	Pearl Harbor	7.25	138	12	Pearl Harbor	19.25	
8	Lisianski	Pearl Harbor	7.25	123	12	Pearl Harbor	19.25	
9	Nihoa	Pearl Harbor	2	108	10	Pearl Harbor	12	
10	Laysan	Pearl Harbor	6.5	98	10	Pearl Harbor	16.5	
11	Laysan	Pearl Harbor	6.5	85	9	Pearl Harbor	15.5	
12	Necker	Pearl Harbor	3.25	73	10	Pearl Harbor	13.25	
13	Maro Reef	Pearl Harbor	6	62	13	Pearl Harbor	19	
14	Maro Reef	Pearl Harbor	6	46	13	Pearl Harbor	19	
15	Necker	Pearl Harbor	3.25	30	10	Pearl Harbor	13.25	
16	Maro Reef/Gardner	Pearl Harbor	6	20	10	Pearl Harbor	16	
17	FFS	Pearl Harbor	3.75	10	10	Pearl Harbor	13.75	287.75

Table 11. Operational breakdown of multibeam survey legs for the NWHI.

Filling the Gaps (Depths 40-3000 m)

After the all shallow and deep areas are sufficiently mapped and data has been assessed, filling in the remainder is the next step. This allows us to more safely junction with surveys in shallow-water, and clean up any gaps found in shallow-water as well as the shallower deep-water (approaching the limits of system capabilities). These surveys would be done with a vessel capable of carrying survey launches, and would be prime candidates for multi-purpose missions, including coral reef assessments and other projects that involve diving. This plan is based on a minimum of one vessel utilizing a 30-100 kHz system, and two survey launches with 200-400 kHz systems. Because only a small percentage of the remaining work is located in the 40-3000 m range (Table 5), most of the work is able to be accomplished with only a few days on project, if transits are used productively.

Pacific Remote Islands: All of the Pacific Remote Islands could be surveyed in less than two months if all water depths between 0-40 m were surveyed ahead of time using lidar (Table 28). We have added additional days on project for each area to provide opportunity for additional science missions, as well as attempt to account for unforeseen weather and technical issues (Table 12). Even with this additional time, each leg would be quite short, and could potentially be lengthened or further divided to accommodate other objectives. This is assuming lidar is flown prior to the multibeam survey. Without lidar, it would require an additional 48 days on project, with most of the time being spent at Johnston Atoll.

Leg	Area	Depart	Transit Time (Days; 11-12kts)	Remaining Mapping Days	Days on Project	Arrive	Leg Total (DAS)	Season Total (DAS)
Johnston Atoll - Howland/Baker - American Samoa - Kingman Reef/Palmyra Atoll - Jarvis (Depths 40-3000m)								
1	*Transit*	Pearl Harbor	-	-	-	-	-	
	Johnston Atoll	-	2.5	4.9	6	-	-	
	Howland	-	3.6	0.25	1	-	-	
	Baker	-	0.1	0.25	1	-	-	
	American Samoa	-	3.2	1.1	2	Tutulia (Pago Pago)	19.4	
2	*Transit*	Tutuila (Pago Pago)	-	-	-	-	-	
	Kingman Reef	-	5	3.5	5	-	-	
	Palmyra Atoll	-	0.2	3.5	5	-	-	
	Jarvis	-	1.5	0.1	1	-	-	
	Transit	-	4.7	-	-	Pearl Harbor	22.4	42

Table 12. Operational breakdown of multibeam survey legs for PRI, assuming prior lidar coverage.

Guam, CNMI, and Wake Island: Since Wake Island is such a remote area, we reserved additional time while on project to make sure it was complete (Table 13). After reaching the Mariana islands, a ship could spend several days mapping around Guam before their first in port. From Guam (Apra Harbor), the team would be able to spend two weeks mapping around Guam before moving on to Rota while on their way to Saipan. Since Saipan is the most northern port location in the CNMI, island hoping on the way north why filling in the gaps would be our recommended strategy for the remaining islands.

Leg	Area	Depart	Transit Time (Days; 11-12kts)	Remaining Mapping Days	Days on Project	Arrive	Leg Total (DAS)	Season Total (DAS)
Wake Island - Guam/CNMI (Depths 40-3000m)								
1	Wake Island	Pearl Harbor	8.25	0.7	2	-	-	
	Guam/CNMI	-	5.25	36.5	3	Guam (Apra)	18.5	
2	Guam	Guam (Apra)	-	14	14.5	-	-	
	Rota	-	0.25	3	3.5	Saipan Harbor	18.25	
3	Tinian	Saipan Harbor	-	3.5	4	-	-	
	Saipan	-	0.1	3.5	4	-	-	
	Sarigan, Anahatan, Zelandia, Farellon de Medinilla	-	0.2	6	8	-	-	
	Guguan	-	0.15	1	1.5	Saipan Harbor	17.95	
4	Alamagan	Saipan Harbor	0.6	0.5	1	-	-	
	Pagan	-	0.1	0.5	1	-	-	
	Agrihan	-	0.1	1.5	2	-	-	
	Asuncion	-	0.2	1	1.5	-	-	
	Maug	-	0.1	0.5	1	-	-	
	Farellon de Pajaros	-	0.1	0.5	1	-	-	
	Transit	-	1.25	-	-	Guam (Apra)	9.95	64.65

Table 13. Operational breakdown of multibeam survey legs for Wake Island and Guam/CNMI.

Due to the impacts of COVID-19 (SARS-CoV-2), NOAA Ship *Rainier's* original 2020 field season in Guam and CNMI is postponed until 2021. In preparation for the field season, we completed extensive planning in cooperation with NOAA's Pacific Island Fisheries Science Center (PIFSC). In this multidisciplinary project, *Rainier* will serve as both a dive mission and a survey platform, as part of the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP). A significant amount of lidar data has already been acquired by NOS contract surveyors on Guam, Rota, Saipan, Tinian, and Pagan, and assets will potentially be directed to several other islands as well. This project will demonstrate the power of combining resources and using the best available asset to meet mission goals. In 2021, we intend to execute our operational plan found in Table 14 and Table 15.

The disparity between the estimated number of remaining mapping days in Guam/CNMI and the total number of estimated days on project (Table 3 and Table 4) is because a significant outcome of this project will be the creation of habitat maps. Most of the existing nearshore multibeam survey data do not meet backscatter quality requirements for use in making habitat maps, so these areas must be resurveyed to support these products. The actual achieved lidar coverage will also impact if areas need to be resurveyed. This operational plan is an example of how the level of effort for a survey area can change as a result of project requirements.

Leg	Area	Depart	Transit Time (Days; 11-12kts)	Remaining Mapping Days	Days on Project	Arrive	Leg Total (DAS)	Season Total (DAS)
			Wake Island - Guam/CNMI (Depths 40-3000m)					
1	Wake Island	Pearl Harbor	8.25	0.7	2	-	-	
	Guam/CNMI	-	5.25	25	3	Guam	18.5	
			Based on planned NOAA Ship RAINIER 2021 Project					
2	Guam	Guam (Apra)	-	-	4	-	-	
	Rota	-	0.25	-	5	-	-	
	Tinian	-	0.25	-	1	-	-	
	Saipan	-	0.1	-	0.5	Saipan Harbor	11.1	
3	Saipan	Saipan Harbor	-	-	10	-	-	
	Aguijan	-	0.1	-	3	-	-	
	Tinian	-	0.1	-	3	-	-	
	Saipan	-	0.1	-	0.5	Saipan Harbor	16.8	
4	Saipan	Saipan Harbor	-	-	1	-	-	
	Tinian	-	0.3	-	2	-	-	
	Aguijan	-	0.1	-	1	-	-	
	Rota	-	0.2	-	2	-	-	
	Guam	-	0.25	-	5	-	-	
	Saipan	-	0.5	-	1	-	-	
	Pagan	-	0.6	-	2	-	-	
	Maug	-	0.45	-	4	-	-	
	Pagan	-	0.5	-	2	-	-	
	Saipan	-	0.6	-	3	-	-	
	Guam	-	0.5	-	0.5	Guam (Apra)	27.5	

Table 14. Operational breakdown of planned multibeam survey legs for NOAA Ship RAINIER's 2021 field season.

Leg	Area	Depart	Transit Time (Days; 11-12kts)	Remaining Mapping Days	Days on Project	Arrive	Leg Total (DAS)	Season Total (DAS)
			Wake Island - Guam/CNMI (Depths 40-3000m)					
5	Guam	Guam (Apra)	-	-	1	-	-	
	Sarigan	-	0.75	-	1	-	-	
	Zelandia	-	-	-	1	-	-	
	Pagan	-	0.05	-	2	-	-	
	Asuncion	-	0.3	-	2	-	-	
	Agrihan	-	0.2	-	4	-	-	
	Pagan	-	0.1	-	5	-	-	
	Alamagan	-	0.6	-	1	-	-	
	Guguan	-	-	-	1	-	-	
	Tinian	-	-	-	1	-	-	
	Guam	-	0.45	-	1	-	-	
	Saipan	-	0.45	-	0.5	Saipan Harbor	23.4	
6	Saipan	Saipan Harbor	-	-	1	-		
	Pagan	-	1	-	1	-		
	Maug	-	0.45	-	1	-		
	Farellon de Pajaros	-	0.2	-	2	-		
	Maug	-	0.2	-	8	-		
	Asuncion	-	0.05	-	2	-		
	Pagan	-	0.3	-	1	-		
	Guam	-	1	-	0.5	Guam (Apra)	19.7	117
					87.5			

Table 15. Operational breakdown of planned multibeam survey legs for NOAA Ship RAINIER's 2021 field season (continued).

Main Hawaiian Islands: Similar to the deep-water mapping work around the main Hawaiian Islands, most of the work offshore is already complete. The remaining areas that need to be surveyed to modern standards are sporadically located throughout the islands, with the largest concentration of work found in the waters around Maui (Table 22). Again, we have worked additional time into the schedule to account for down time due to weather. It should take less than one month to finish the mapping work in this depth range (Table 16).

Leg	Area	Depart	Transit Time (Days; 11-12kts)	Remaining Mapping Days	Days on Project	Arrive	Leg Total (DAS)	Season Total (DAS)
Main Hawaiian Islands (Depths 40-3000m)								
1	*Transit*	Pearl Harbor	-	-	-	-	-	
	Ka'ula	-	0.5	1.3	3	-	-	
	Kauai	-	0.2	0.5	2	-	-	
	Offshore (to EEZ)	-	0.1	0.05	1	-	-	
	Oahu	-	0.4	1.6	3	-	-	
	Molokai	-	0.2	1.9	4	-	-	
	Transit	-	0.2	-	-	Pearl Harbor	14.7	
2	*Transit*	Pearl Harbor	0.4	-	-	-	-	
	Maui / Kaho'olawe	-	0.1	7.3	10	-	-	
	Lanai	-	0.3	0.9	2	-	-	
	Big Island	-	0.6	1.1	3	Pearl Harbor	16.3	31.0

Table 16. Operational breakdown of multibeam survey legs for main Hawaiian Islands.

Northwest Hawaiian Islands/EEZ: The majority of mapping remaining in the NWHI within the 40-3000 meter depth range is in depths less than 200 m. A platform with both launch (high frequency systems) and ship surveying capabilities, and the ability to secure vessel discharges for extended periods, would be ideal for this project. Transit times within the EEZ were estimated using an average of transit times from Pearl Harbor to various locations in the NWHI. A more efficient approach to surveying remaining areas within the EEZ may require further breakdown of the distribution of unmapped areas. It is possible that much of this work can be completed while transiting or while on site at other working locations. To increase efficiency, we grouped project areas that were close together and could be completed during the same mission. This includes: Kure and Midway, Laysan and Maro Reef, as well as Necker and Nihoa. It is important to remember that, since most of the effort is in shallow-water, survey launches would be the primary survey assets. As aforementioned in the shallow-water mapping operational plan, Midway and Kure require about 30 days of multibeam acquisition in the 4-40 m depth range. We include these as part of our operational plan here in Table 17. A challenge unique to the NWHI, which we discuss in the next section, is their locations within the Papahānaumokuākea Marine National Monument, which has strict vessel discharge requirements.

Northwest Hawaiian Islands/EEZ (Depths 40-3000m)									
1	EEZ	Pearl Harbor	5	34.9	15	Pearl Harbor	20.0	
2	EEZ	Pearl Harbor	5	19.9	10	Pearl Harbor	15.0	
3	EEZ	Pearl Harbor	5	9.9	10	Pearl Harbor	15.0	
4	Kure/Midway	Pearl Harbor	9	39.7	15	Pearl Harbor	24.0	
4	Kure/Midway	Pearl Harbor	9	24.7	15	Pearl Harbor	24.0	
4	Kure/Midway	Pearl Harbor	9	9.7	9	Pearl Harbor	18.0	
5	Pearl and Hermes	Pearl Harbor	8.25	9.2	10	Pearl Harbor	18.3	
6	Lisianski	Pearl Harbor	7.25	32	11	Pearl Harbor	18.3	
7	Lisianski	Pearl Harbor	7.25	21	11	Pearl Harbor	18.3	
8	Lisianski	Pearl Harbor	7.25	10	10	Pearl Harbor	17.3	
9	Laysan/Maro Reef	Pearl Harbor	6.5	12.6	14	Pearl Harbor	20.5	
10	Gardner	Pearl Harbor	4.75	41.1	13	Pearl Harbor	17.8	
11	Gardner	Pearl Harbor	4.75	28.1	13	Pearl Harbor	17.8	
12	Gardner	Pearl Harbor	4.75	15.1	16	Pearl Harbor	20.8	
13	FFS	Pearl Harbor	3.75	10.4	11	Pearl Harbor	14.8	
14	Necker	Pearl Harbor	1.75	6.9	8	-	-	
	Nihoa	-	1.75	16.6	6	Pearl Harbor	17.5	
15	Nihoa	Pearl Harbor	2	10.6	10.3	Pearl Harbor	12.3	309

Table 17. Operational breakdown of multibeam survey legs for NWHI.

Challenges and Opportunities

In addition to level of effort, there are a number of challenges to consider if we are going to complete our goal to map the U.S. EEZ. As alluded to by their name, the Pacific Remote Islands (remote islands) are geographically far from the developed world and associated maritime industry support. Outside of the main Hawaiian Islands, most of the remaining unmapped areas are remote and have little work that can be accomplished by a vessel like *Rainier* and its survey launches. As with any mapping operation, poor weather conditions and mechanical breakdowns are a matter of when and will affect the actual number of days on project. In the end, mobilization costs for any mapping effort will be a deciding factor, particularly in remote areas like the Pacific.

<u>Remoteness</u>

Remoteness in terms of logistics is not the only challenge. The majority of the remaining effort in waters deeper than 200 m is in very deep water, exceeding 3000 m. This will require dedicated mapping missions using a 12 kHz system. This deep-water mapping work could likely not be done in conjunction with daytime dive-based mapping in the shallow areas simply because most of the work is considerable (up to 200 NM) away from the reefs. These cruises would likely have different personnel requirements than how NOAA vessels typically operate, since the ship would be driving back and forth — "mowing the lawn" — and not demand large numbers of people to operate multiple supported platforms (survey launches).

<u>Capabilities and Asset Mix</u>

The current NOAA fleet is primarily equipped with shallow-water mapping capabilities (0-200 m), for the intended purpose of nautical charting and safety of navigation. Only one "full ocean depth" system exists in the fleet; a handful of additional systems are appropriate to mid-ocean depths. Through our analysis we have determined a need for more deep-water mapping capabilities, and for vessels with longer endurances, in order to make the most out of long transit distances. A surprising finding is that a 12 kHz system is twice as effective as a 30 kHz system at mapping depths in the Pacific, since it is able to maintain a much broader swath width in deeper waters. All of our time estimates presented here would essentially need to be doubled if utilizing a 30 kHz system in depths greater than 3000 m.

<u>Environmental Discharge Restrictions and Permitting</u>

Most of the Northwestern Hawaiian Islands are contained within the Papahānaumokuākea Marine National Monument (PMNM), which covers an area of more than 1.5 million square kilometers. The Monument is co-managed by four trustee agencies, representing both the federal government and the State of Hawaii. As such, it has extensive permitting, monitoring, and reporting requirements. The trustees require permit requests to be completed between four and six months prior to anticipated entry date. Discharge regulations within the Monument require the ship to travel outside of the 12 nautical mile PMNM boundary to discharge blackwater that is unable to be processed on board the vessel. Additionally, certain Special Management Areas (Midway Atoll) and Special Protection Areas around many of the atolls allow no discharge (including graywater) at all. In these regions, vessels must have sufficient storage capacity for all discharges occurring during the period of operation in the SMA or SPA.

Lidar Mobilization Flight Time

Because there is an unequal level of effort required to map the bathymetric data gaps in shallow waters relative to deeper waters (Greenaway et al., 2019), vessel mounted multibeam systems are often not the best tool for the job. In contrast, airborne bathymetric lidar is an extremely efficient way to acquire large swaths of data in shallow waters, dramatically reducing effort, and eliminating vessel and personnel exposure to hazardous nearshore areas. However, for many of the remote islands, it would not be possible, or it would be costly to get an asset out to many of these locations.

Autonomous Platforms

NOAA established an unmanned systems (UxS) strategy, in order to increase the application and use of UxS in every NOAA mission area, and to accelerate and enhance capabilities through commercial and organizational partnerships (NOAA UxS Strategy, 2020). More specific to ocean mapping, NOAA's Office of Coast Survey has been investigating the use of autonomous survey systems to support hydrographic survey operations since 2004, in order to provide more efficient and effective acquisition of environmental data to support NOAA's navigation products and services (Office of Coast Survey, 2018).

We see deep waters where there is a need to acquire data over large swaths of seafloor as an opportunity to force multiply using UxS. The aforementioned survey areas are generally in remote locations and relatively simple from a ship driving perspective. One consideration and opportunity will be that the UxS would need to be one developed with specialized capabilities for deep-water mapping, while keeping in mind the required size of the array — and resulting size of the UxS. There will certainly be technical problems, and operators and technicians will need to be standing by to render support and troubleshooting when problems arise. This large-scale effort appears to be the ideal application for UxS, and their successful implementation would give way to completing this mapping effort in a fraction of our estimated time.

NOAA has also been increasingly operating both small autonomous aircraft from both land and vessels. Applications have ranged from seafloor and habitat mapping, to emergency response, to ocean exploration, marine mammal and fishery stock assessments, and at-sea observations that improve forecasting of extreme events, such as harmful algal blooms and hypoxia (Hall, 2020). NOAA is also partnering with the Navy in order to evaluate new UxS technologies for ocean science applications through the Advanced Naval Technology Exercise (ANTX) program. This program enables scientists and engineers to participate in the testing and assessment of experimental technologies that can support missions of both agencies (Hall, 2020). With how rapidly these technologies are advancing, it's hard to know what even the near future holds. We expect these autonomous systems are going to play a key role in mapping remote nearshore environments.

Space-based Technologies

Researchers have developed numerous algorithms for deriving bathymetry from satellite imagery since the 1970s (Polcyn et al., 1975), with the deployment of multispectral satellite platforms such as Landsat. In recent years, NOAA has adopted satellite derived bathymetry (SDB) for a number of different applications, from habitat mapping (Pacific Islands Fisheries Science Center, 2020) to reconnaissance for hydrography. SDB is based on passive, multispectral satellite imagery, and is more susceptible to false readings when compared to active sensors. The Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) was launched in September 2018, and carries an active sensor, the Advanced Topographic Laser Altimeter System (ATLAS) (Parrish et al., 2019). Parrish (Parrish et al., 2019) preliminary analyses for a number of coastal sites showed several salient examples of seafloor detection in water depths of up to ~40 m, with agreement to within 0.43—0.60 m root mean square error (RMSE) over 1 m grid resolution. Parrish (Parrish et al., 2019) go on to suggest the synergistic fusion of active (specifically, ICESat-2) and passive (multispectral satellite imagery) data may ultimately provide the optimal solution for shallow nearshore bathymetric mapping by leveraging the strengths of each, and recommend that a new bathymetric data product from ICESat-2 be considered.

Conclusion

We completed our estimates and recommendations based on equipment and assets that are already available (Appendix 2), although we acknowledge other technologies could decrease our effort in the future. Most of the remaining mapping work is located in the shallow areas (0-40 m) of the Northwestern Hawaiian Islands and in areas with water depths in excess of 3000 m. There is some work in the shallow areas around the main Hawaiian Islands, Guam, and CNMI but most of this work would be best accomplished using traditional multibeam, since NOAA program offices already have planned surveys in these areas. For remote areas such as the NWHI and PRI, using other technologies, such as bathymetric lidar, UxS, or ICESat-2 data and SDB will significantly reduce the number of ship days required to map nearshore areas.

The majority of the remaining mapping work will require a 30 kHz or lower frequency system, such as those mounted on NOAA Ships *Ronald H. Brown* and *Okeanos Explorer* (see Appendix 2). With current available NOAA assets, it would take 934 ± 28 ship days to map the Pacific region of the EEZ. Since most of the remaining effort is in remote areas that generally are not navigationally significant, program offices will have to balance mobilization costs and days at sea with the benefits of mapping these areas, and the opportunity to work on collaborative projects. Using available survey estimation tools, and vessel information listed in Appendix 2, it is possible to do this type of analysis for the remainder of the U.S. EEZ, or other parts of the world.

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Appendix 1. Level of Effort Breakdown by Region

<u>Guam and the Commonwealth of the Northern Mariana Islands</u>

A large portion of the remaining survey work in Guam and CNMI (Figure 6) can be accomplished using either 200/400 kHz or 12 kHz systems. Using two survey launches with 200/400 kHz systems in depths of 200 m or less, and a ship with a 30-100 kHz system, we estimate it would take approximately 10 days to finish mapping in the 40-1500 m range (Table 4). Because most of Guam and CNMI have already been mapped or are currently being mapped with lidar, and NOAA Ship *Rainier* is scheduled to finish mapping all other areas in 2021, the majority of the remaining work is in deep-water. In these areas with water depth greater than 3000 m, 53 days of survey efforts remain, requiring a 12 kHz system (Table 4). A smaller proportion of survey work could utilize a 12-30 kHz system (1500-3000 m, 14 days).

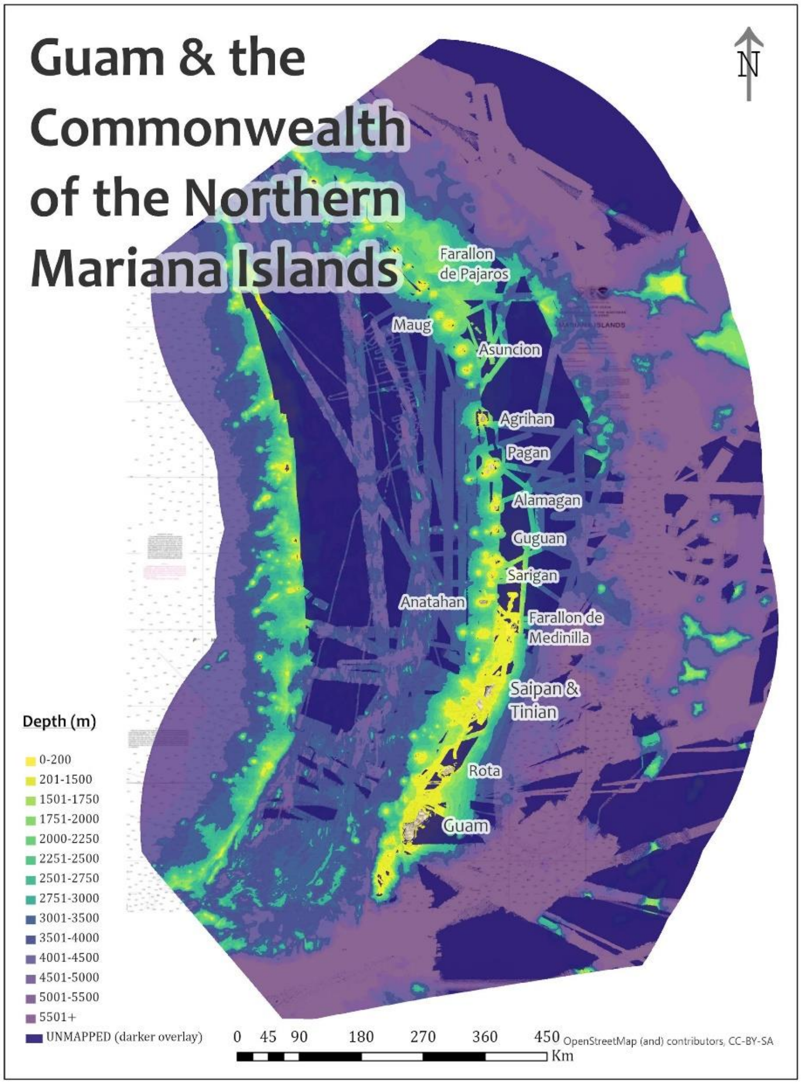

Figure 6. Overview of unmapped areas in Guam and the Commonwealth of the Northern Mariana Islands.

Hawaiian Archipelago

Cumulatively, the Hawaiian Islands require approximately 1,400 days to survey water depths of 200 m or less, and 285 days for depths 200-3,000+ m. It's estimated that two survey launches with 200/400 kHz systems would require 871 days to complete survey work in depths of 4-25 m, and 365 days to complete work in 25-40 m. Additionally, this launch work would be in dynamic water depths in unprotected areas, increasing risk of an environmental incident. This time is reduced to approximately 280 days flying an aricraft with a lidar system, though we recognize this will not be possible in all areas. The remaining launch work (40-200 m) is estimated to require 170 days. The majority of survey areas around Hawaii are depths greater than 3000 m, requiring a 12 kHz system and 268 days.

SUB-REGION: Hawaiian Islands	LNM						TOTAL
	4m-25m	25m-40m	40m-200m	200m-1500m	1500m-3000m	3000m-11000m	
Northwestern Hawaiian Is	59,561	25,268	10,998	2,074	927	45,668	*144,495*
Main Hawaiian Islands	1,421	253	917	285	10	7,938	*10,824*
TOTAL (LNM)	60,982	25,521	11,915	2,359	936	53,607	155,319

Table 18. Total level of effort estimates in linear nautical miles for the unmapped Hawaiian Islands.

SUB-REGION: Hawaiian Islands	Days with MBES Systems Only (no Lidar)							TOTAL
	200 to 400 kHz				30 to 100 kHz	12 to 30 kHz	12kHz	
	4m-25m	25m-40m	40m-200m	0m-200m	200m-1500m	1500m-3000m	3000m+	
Northwestern Hawaiian Is	851	361	157	1,369	10	5	228	*1,612*
Main Hawaiian Islands	20	4	13	37	1	0	40	*78*
	871	365	170					
TOTAL (Days)				**1,406**	**12**	**5**	**268**	**1,690**

Table 19. Total level of effort estimates in days, utilizing multibeam, for the unmapped Hawaiian Islands.

SUB-REGION: Hawaiian Islands	Days Per Acquisition System					
	Lidar TOTAL	200 to 400 kHz	30 to 100 kHz	12 to 30 kHz	12kHz	Vessel TOTAL
	0m-40m	*40m-200m*	*200m-1500m*	*1500m-3000m*	*3000m+*	*40m-3000m+*
Northwestern Hawaiian Is	249	157	10	5	228	*400*
Main Hawaiian Islands	-	13	1	0	40	*54*
TOTAL (Days)	**249**	**170**	**12**	**5**	**268**	**455**

Table 20. Total level of effort estimates in days, utilizing lidar and multibeam, for the unmapped Hawaiian Islands.

Main Hawaiian Islands

Most of the areas around the main Hawaiian Islands (Figure 7) have been mapped to modern standards. There are 37 days of survey work that would require a 200/400 kHz system; all other depths would require a 12 kHz system mapping for 40 days (Table 22). NOAA Coast Survey has planned nearshore multibeam surveys scheduled for around the main Hawaiian Islands, so we do not consider lidar here in our estimates for the 4-40 m depth range.

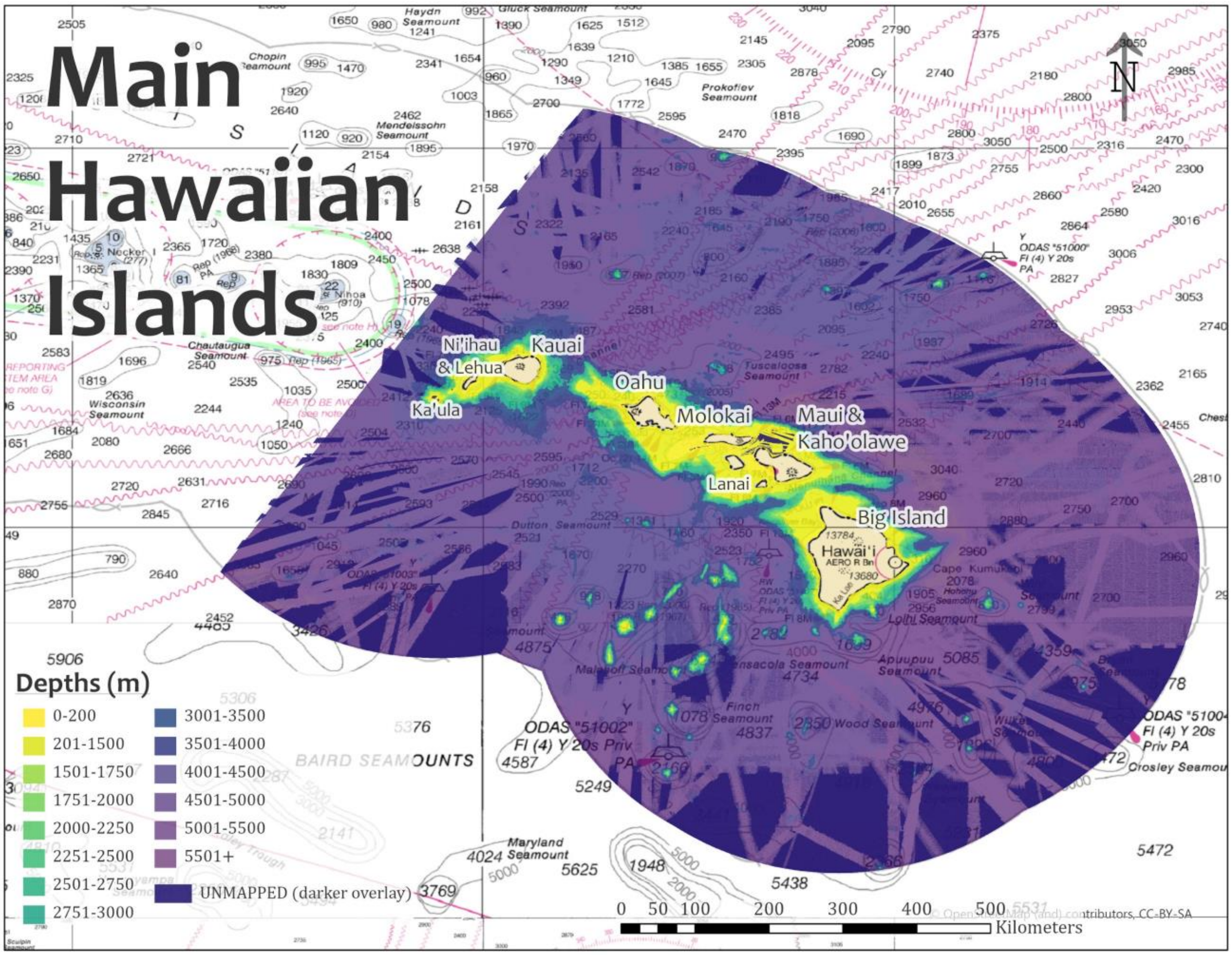

Figure 7. Overview of unmapped areas around the main Hawaiian Islands.

Ka'ula: It would take less than two days to complete surveying around this island from depths of 4-200 m. However, for 40-200 m depths, it would take a little more than one day to survey using a 200/400 kHz system.

Ni'ihau/ Lehua: The furthest most west island of the main eight Hawaiian Islands, it would take approximately six days to survey these two areas using vessels with 200/400 kHz systems.

Kauai: The second most west of the main eight Hawaiian Islands, Kauai has approximately six days of survey work to complete. This effort is decreased to half a day's work using a 200/400 kHz system for depths 40-200 m, if lidar data is acquired to 40 m.

Oahu: The most populated Hawaiian island, Oahu has approximately six days of survey work with a 200/400 kHz system to finish mapping to modern standards.

Molokai: Located in the middle of the archipelago, Molokai has approximately four days of survey work to complete. It would take about three days to survey areas from 40-200 m using a 200/400 kHz multibeam sonar system, and less than one day to map areas from 200-1500 m with a 30-100 kHz system.

Lanai: South of Molokai and Maui, Lanai has about two days of survey work to complete. The depths of 40-200 m require a 200/400 kHz system, and the small remaining portion will require a 30-100 kHz system.

Maui/ Kaho'olawe: The most survey work needed in the main eight Hawaiian Islands is located off the coast of Maui, requiring approximately 12 days of surveying. A 200/400 kHz system would be used for 11 days in depths of 40-200 m, and a 30-100 kHz system could finish the remaining work.

Big Island: Most of the area surrounding the Big Island of Hawaii is already mapped to modern standards. The majority of the work remains in the very nearshore areas, in water depths of less than 200 m. Given the small amount of effort remaining, about three days of hydrographic survey launch work with a 200/400 kHz system would fill in the gaps around the island.

Offshore to EEZ: All offshore work would take approximately 40 days to complete. These survey areas require a 12 kHz system and are 3,000+ m deep.

SUB-REGION: Main Hawaiian Is	LNM 4m-25m	25m-40m	40m-200m	200m-1500m	1500m-3000m	3000m-11000m	TOTAL
Ka'ula	4	9	90	0	0	-	*103*
Ni'ihau / Lehua	423	11	-	1	0	-	*436*
Kauai	327	64	33	-	-	-	*425*
Oahu	230	80	114	1	-	-	*425*
Molokai	74	5	117	44	-	-	*240*
Maui / Kaho'olawe	239	64	434	222	0	-	*960*
Lanai	73	10	54	13	-	-	*149*
Big Island	51	9	75	2	0	-	*138*
Offshore (to EEZ)	-	-	-	0	9	7,928	*7,937*
TOTAL (LNM)	1,421	253	917	284	10	7,928	10,812

Table 21. Total level of effort estimates in linear nautical miles for the unmapped main Hawaiian Islands.

SUB-REGION: Main Hawaiian Is	Days with MBES Systems Only (no Lidar) 200 to 400 kHz 4m-25m	25m-40m	40m-200m	0m-200m	30 to 100 kHz 200m-1500m	12 to 30 kHz 1500m-3000m	12kHz 3000m+	TOTAL
Ka'ula	0	0	1	1	0	-	-	***1***
Ni'ihau / Lehua	6	0	-	6	0	-	-	***6***
Kauai	5	1	0	6	-	-	-	***6***
Oahu	3	1	2	6	0	-	-	***6***
Molokai	1	0	2	3	0	-	-	***3***
Maui / Kaho'olawe	3	1	6	11	1	-	-	***12***
Lanai	1	0	1	2	0	-	-	***2***
Big Island	1	0	1	2	0	-	-	***2***
Offshore (to EEZ)	-	-	-	-	0	0	40	***40***
	20	4	13					
TOTAL (Days)				**37**	**1**	**0**	**40**	**78**

Table 22. Total level of effort estimates in days, utilizing multibeam, for the unmapped main Hawaiian Islands. Areas deeper than 1500 m around islands are considered "offshore" for accounting purposes.

Northwestern Hawaiian Islands

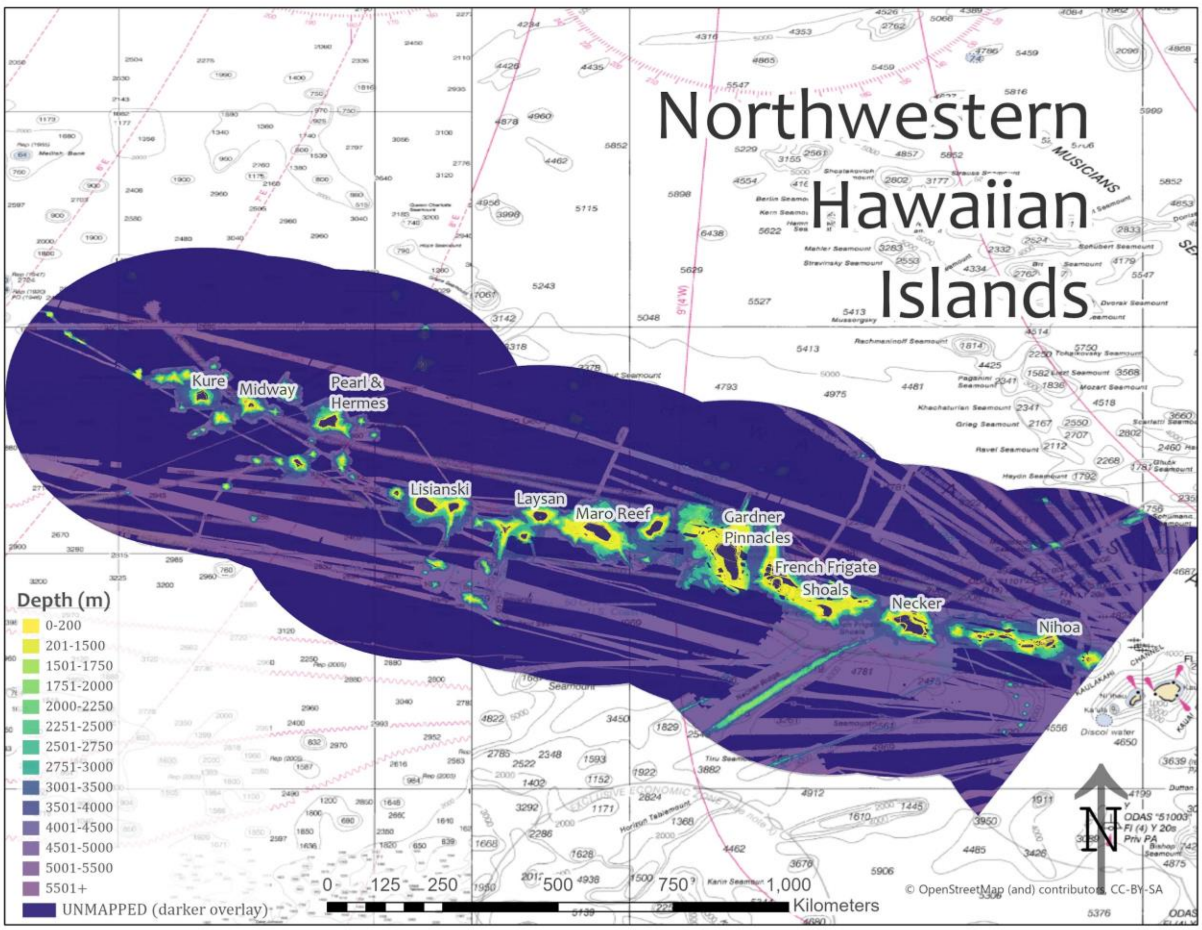

Figure 8. Overview of the Northwestern Hawaiian Islands.

Nihoa: Most of the shallow areas surrounding Nihoa have already been mapped. With two survey launches operating 200 to 400 kHz systems this is estimated to require 14 days to map to 40m. This same area, using a lidar system, can be surveyed in 20 days, but again our lidar estimates cover a larger area to provide reconnaissance. The remaining work in 40 to 200 m can be accomplished in approximately 16 days with two survey launches utilizing 200 to 400 kHz systems. Less than a day's worth of surveying lies beyond depths of 200 m. Because most of the waters around Nihoa are at the edge of the physical limits of lidar, flying lidar first for reconnaissance would increase vessel safety and may also reduce the amount of survey work in depths from the 40 to 200 m.

Necker: A total of 166 days of surveying remains in the water surrounding Necker. The majority of this work is in depths less than 40 m (159 days, and two survey launches). Utilizing airborne lidar would cut the work in depths less than 40 m down to about 20 days. Approximately six days of work lies within the 40-200 m depth range and can also be accomplished with two survey launches operating 200/400 kHz systems. An additional day of survey time is necessary in depths 200-1500 m and requires a 30-100 kHz system.

French Frigate Shoals: Similar to Necker, French Frigate Shoals has survey work remaining largely in shallow-waters less than 25 m deep (157 days). An additional 19 days of surveying can be spent in 25-40 m depths; this can be accomplished using two survey launches with 200/400 kHz systems or a lidar system instead. Outside of these depth ranges, only approximately 10 days of estimated survey time remains. Seven of these days are in depths of 40-200 m (200/400 kHz system), and three of these days are in depths 200-1500 m (30-100 kHz system).

Gardner: Survey efforts remaining in Gardner are largely within the 0-200 meter depth range (227 days) and can be accomplished using two survey launches with 200/400 kHz systems. Approximately 187 days are required in depths of less than 40 m, and can be reduced to approximately 27 days with the use of a lidar system. An additional 40 days remain in the 40-200 m depth range. Just under two days of estimated survey efforts lie outside of the 200m depth.

Maro Reef: The reef requires 227 days of multibeam surveying to complete the area. All of this work is within the 200 m depth range, and assume the use of two survey launches operating 200/400 kHz systems. However, 97% of this work (0-40 m) can be completed in about 42 days using a lidar system.

Laysan: The sixth atoll in the Northwest Hawaiian Island chain, Laysan needs approximately 53 days of surveying. Almost all of this work is at depths less than 200 m: 23 days for 4-25 m, 23 days for 25-40 m, and 6 days for 40-200 m. The total days of MBES surveying can be reduced to 12.5 days, with the use of lidar to 40 m. This survey effort can be completed with a 200/400 kHz sonar system.

Lisianski: The seventh atoll in the Northwestern Hawaiian Islands chain, Lisianski needs approximately 200 days of surveying. All survey work is less than 200 m deep and can be completed using a 200/400 kHz sonar system. With lidar data to 40 m, the MBES survey work can be reduced to around 45 days of surveying.

Pearl and Hermes: The eighth atoll in the Northwestern Hawaiian Islands chain, Pearl and Hermes needs approximately 160 days of surveying. Almost all of this work is at depths less than 200 m: 147 days for 4-25 m, four days for 25-40 m, and nine days for 40-200 m. With lidar data to 40 m, the MBES surveying can be reduced around 18 days and be completed using a 200/400 kHz sonar system.

Midway: The ninth atoll in the Northwestern Hawaiian Islands chain, Midway needs approximately 15 days of survey work. All of this work is in depths less than 40 m. Using lidar data to depths of 40 m requires a similar amount of time to complete. This survey area can be conducted using a 200/400 sonar system.

Kure: The last, most western atoll in the Northwestern Hawaiian Islands chain, Kure needs approximately 24 days of surveying. Most of this work is at depths less than 200 m: 14 days for 4-25 m, three days for 25-40 m, and seven days for 40-200 m. With lidar data to 40 m, the MBES surveying can be reduced around nine days and be completed using a 200/400 kHz sonar system.

Remaining to EEZ: The most survey work needed to be completed is located from the extent of the Northwestern Hawaiian Islands to the EEZ. There is a total of 322 days of survey work to complete. With the use of lidar data to 40 m, the MBES survey work can be reduced to 267 days. A 200/400 kHz sonar system is needed for 27 days, a 30-100 kHz sonar system is needed for four days, a 12-30 kHz sonar system is needed for three and a half days, and a 12 kHz sonar system is needed for 228 days to complete this survey area.

SUB-REGION: NW Hawaiian Is	LNM						TOTAL
	4m-25m	25m-40m	40m-200m	200m-1500m	1500m-3000m	3000m-11000m	
Nihoa	133	840	1,150	48	18	1	***2,190***
Necker	5,497	5,614	399	241	16	1	***11,768***
French Frigate Shoals	11,009	1,334	495	665	65	60	***13,627***
Gardner	4,334	8,793	2,757	332	121	11	***16,349***
Maro Reef	12,698	2,871	437	17	3	0	***16,025***
Laysan	1,628	1,601	444	4	3	0	***3,680***
Lisianski	8,735	2,856	2,240	9	1	0	***13,842***
Pearl and Hermes	10,261	279	642	3	1	-	***11,187***
Midway	1,027	3	48	3	0	-	***1,080***
Kure	1,004	174	516	25	3	-	***1,722***
remaining to EEZ	3,234	902	1,871	727	697	45,524	***52,955***
TOTAL (LNM)	59,561	25,268	10,998	2,074	928	45,597	**144,425**

Table 23. Total level of effort estimates in linear nautical miles, utilizing multibeam, for the unmapped NWHI.

SUB-REGION: NW Hawaiian Is	Days with MBES Systems Only (no Lidar)							TOTAL
	200 to 400 kHz				30 to 100 kHz	12 to 30 kHz	12kHz	
	4m-25m	25m-40m	40m-200m	0m-200m	200m-1500m	1500m-3000m	3000m+	
Nihoa	2	12	16	30	0	-	-	***31***
Necker	79	80	6	164	1	-	-	***166***
French Frigate Shoals	157	19	7	183	3	-	-	***187***
Gardner	62	126	39	227	2	-	-	***229***
Maro Reef	181	41	6	229	0	-	-	***229***
Laysan	23	23	6	52	0	-	-	***53***
Lisianski	125	41	32	198	0	-	-	***198***
Pearl and Hermes	147	4	9	160	0	-	-	***160***
Midway	15	0	1	15	0	-	-	***15***
Kure	14	2	7	24	0	-	-	***24***
remaining to EEZ	46	13	27	86	4	5	228	***322***
	851	361	157					
TOTAL (Days)				**1,369**	**10**	**5**	**228**	**1,612**

Table 24. Total level of effort estimates in days, utilizing multibeam, for the unmapped NWHI.

SUB-REGION: NW Hawaiian Is	Days Per Acquisition System					
	Lidar TOTAL *0m-40m*	200 to 400 kHz *40m-200m*	30 to 100 kHz *200m-1500m*	12 to 30 kHz *1500m-3000m*	12kHz *3000m+*	Vessel TOTAL *40m-3000m+*
Nihoa	20	16	0	-	-	***17***
Necker	28	6	1	-	-	***7***
French Frigate Shoals	34	7	3	-	-	***10***
Gardner	39	39	2	-	-	***41***
Maro Reef	42	6	0	-	-	***6***
Laysan	18	6	0	-	-	***6***
Lisianski	30	32	0	-	-	***32***
Pearl and Hermes	15	9	0	-	-	***9***
Midway	14	1	0	-	-	***1***
Kure	7	7	0	-	-	***7***
Other (to EEZ)	3	27	4	5	228	***263***
TOTAL (Days)	**250**	**157**	**10**	**5**	**228**	**400**

Table 25. Total level of effort estimates in days, utilizing lidar and multibeam, for the unmapped NWHI.

Pacific Remote Islands

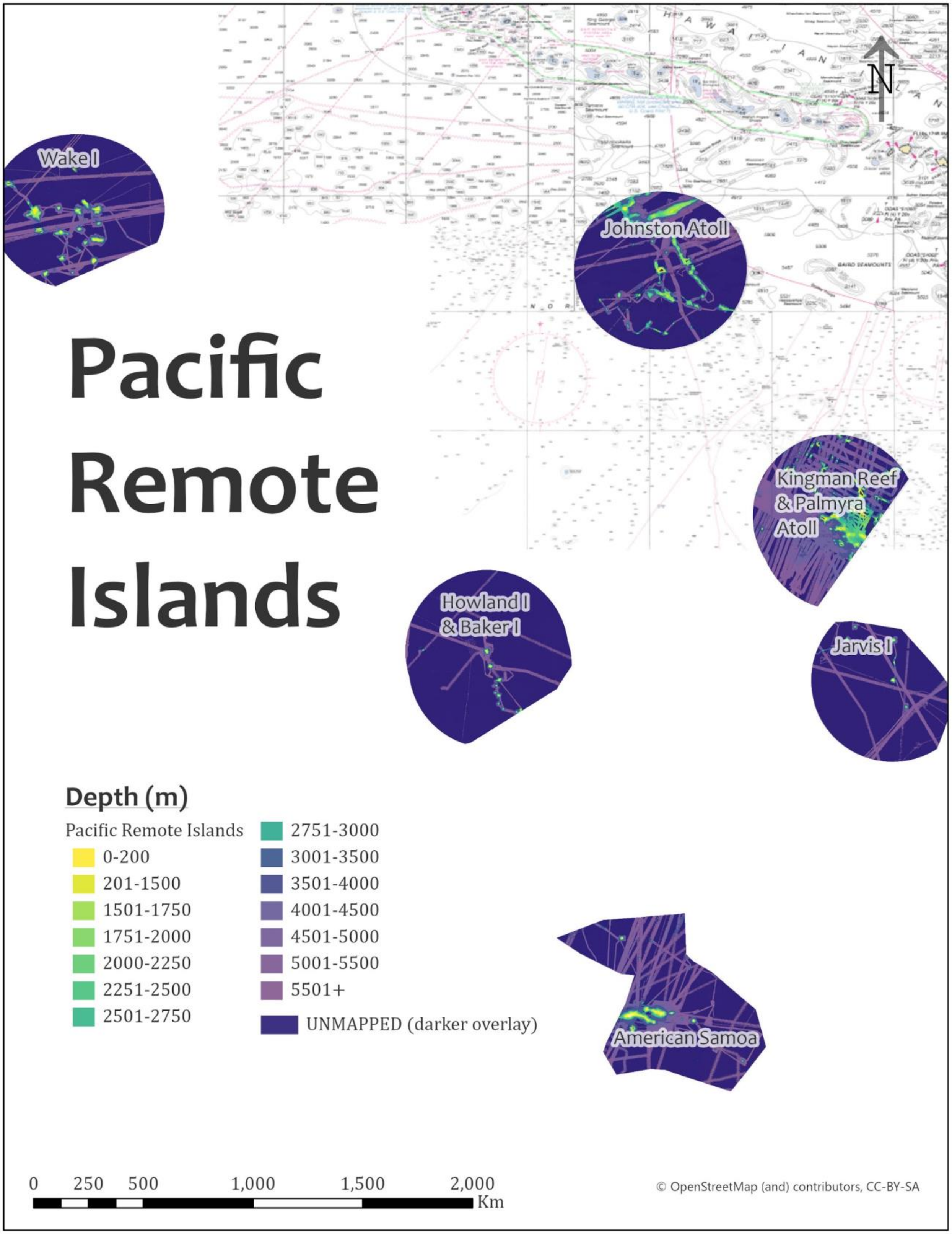

Figure 9. Overview of unmapped areas around the Pacific Remote Islands.

American Samoa: Much of the area in coastal waters (less than 200 m) surrounding American Samoa has been surveyed. Estimated time for completion of survey to 40 m is between four days (survey launch using a 200 to 400 kHz system) and 12 days (using lidar; here the lidar would also cover land areas). However, it is estimated that approximately 60 days' worth of ship survey (utilizing a 12 kHz system) remains in depths greater than 3,000 m. It would only take about one day to fill in the gaps for depths between 40 and 3,000 m.

Howland & Baker Islands: Almost the entirety of survey work surrounding Howland/Baker is in water depths greater than 3,000 m and can be accomplished with a 12 kHz system in 86 days. The total of remaining work from 4 to 3,000 m is estimated to require less than one day.

Jarvis Island: Located approximately 1500 nautical miles southwest of Honolulu, this area requires 59 days of survey work in depths greater than 3,000 m, requiring a 12 kHz system.

Johnston Atoll: The atoll is located about 720 nautical miles southwest of Honolulu. The majority of the effort remaining at Johnston Atoll is in both the shallow nearshore areas and the deep areas. Using two survey launches with 200/400 kHz systems, it would take about 40 days to finish mapping depths less than 25 m, while it would take only one day to fill gaps in the 25-200 m range. Using bathymetric lidar, it would be possible to map all depths less than 25 m in about five and a half days. The remaining work is in depths greater than 3000 m and would require a 12 kHz system, although a 30 kHz system could be used for depths up to about 6000 m.

Kingman Reef & Palmyra Atoll: The remainder of survey work around the atoll is estimated to require 32 days. The majority is in depths greater than 3000 m (20 days) with a 12 kHz system. About six days are required for depths 200-3000 m, and six additional days for depths less than 200 m (two launches with 200/400 kHz systems).

Wake Island: The atoll requires approximately 66 days of ship survey work in depths greater than 3000 m with a 12 kHz system. Less than a day is estimated to be spent in other areas (200-3000 m) using either a 30-100 kHz or a 12-30 kHz system.

SUB-REGION:	LNM						TOTAL
Pacific Remote Is	4m-25m	25m-40m	40m-200m	200m-1500m	1500m-3000m	3000m-11000m	
American Samoa	174	105	47	14	56	11,902	***12,298***
Howland & Baker Islands	18	-	1	10	60	17,123	***17,212***
Jarvis Island	15	1	-	5	27	11,852	***11,900***
Johnston Atoll	2,895	39	23	41	871	13,522	***17,391***
Kingman Reef/Palmyra Atoll	293	73	27	251	1,055	4,042	***5,741***
Wake Island	-	1	1	48	96	13,095	***13,241***
TOTAL (LNM)	3,395	219	98	369	2,165	71,536	***77,783***

Table 26. Total level of effort estimates in linear nautical miles, utilizing multibeam, for the unmapped PRI.

SUB-REGION: Pacific Remote Is	Days with MBES Systems Only (no Lidar)							TOTAL
	200 to 400 kHz				30 to 100 kHz	12 to 30 kHz	12kHz	
	4m-25m	25m-40m	40m-200m	0m-200m	200m-1500m	1500m-3000m	3000m+	
American Samoa	2	2	1	5	0	0	60	*65*
Howland & Baker Islands	0	-	0	0	0	0	86	*86*
Jarvis Island	0	0	-	0	0	0	59	*60*
Johnston Atoll	41	1	0	42	0	4	68	*114*
Kingman Reef/Palmyra Atoll	4	1	0	6	1	5	20	*32*
Wake Island	-	0	0	0	0	0	65	*66*
	46	2	1					
TOTAL (Days)				**53**	**2**	**11**	**358**	**423**

Table 27. Total level of effort estimates in linear days, utilizing multibeam, for the unmapped PRI.

SUB-REGION: Pacific Remote Is	Days Per Acquisition System					
	Lidar TOTAL	200 to 400 kHz	30 to 100 kHz	12 to 30 kHz	12kHz	Vessel TOTAL
	0m-40m	*40m-200m*	*200m-1500m*	*1500m-3000m*	*3000m+*	*40m-3000m+*
American Samoa	12	1	0	0	60	*61*
Howland & Baker Islands	1	0	0	0	86	*86*
Jarvis Island	0	-	0	0	59	*59*
Johnston Atoll	5	0	0	4	68	*73*
Kingman Reef/Palmyra Atoll	3	0	1	5	20	*27*
Wake Island	1	0	0	0	65	*66*
TOTAL (Days)	**22**	**1**	**2**	**11**	**358**	**372**

Table 28. Total level of effort estimates in linear days, utilizing lidar and multibeam, for the unmapped PRI.

Appendix 2. Platform Capabilities

Aircraft: NOAA uses the DHC-6 Twin Otter for almost all coastal bathymetric lidar operations, and the Beechcraft King Air 350CER for most photogrammetry mapping. There have been instances where Twin Otters have been used for photogrammetry, and the King Air has been used for lidar, but the King Air requires special outfitting of the lidar sensor because it is a pressurized aircraft. The King Air's speed and endurance give them an advantage in collecting data over a large area, but this shouldn't detract from the Twin Otter's utility and performance in rough weather conditions. NOAA policy often becomes the limiting factor for King Air operations, but about seven hours of flight time is pushing maximum endurance, regardless of pilot duty time limitations. Twin Otters are very capable in remote operations in adverse weather conditions, but they are limited by range.

Aircraft	Endurance (HR)	Cruise Speed (kts)	Survey Speed (kts)	Range (NM)
Twin Otter	6	145	100	850
King Air	7	240	170	2200

Table 29. General aircraft capabilities for the Twin Otter and King Air.

Bringing a Twin Otter to Hawaii would require extensive planning, permissions, and special configurations, including dual auxiliary fuel tanks, operating over gross weight, and using a ferry pilot. The transit would be highly dependent on weather conditions. The King Air would be able to make the transit to Hawaii without any configuration changes, but it would require special permissions.

The basic aircraft maintenance requirement is a 4-5 day maintenance period every 100 flight hours. This equalized maintenance maximum availability (EMMA), and must be conducted in a hangar that meets certain FAA requirements, with NOAA personnel performing the maintenance. Typical operating procedure while on project will have the plane operate out of various airports in a project area, and return to a EMMA compatible airport for maintenance. In Hawaii and American Samoa, Lihue and Pago Pago would likely be the airport for both a base of operations and maintenance. If the EMMA could not be completed in Lihue, Oahu has other capable airports.

Vessels: NOAA operates four dedicated hydrographic vessels (FA, FH, RA, TJ; Table 30), and three multi-mission vessels with up-to-date hydrographic capabilities (NF, EX, RB; Table 30). Of the hydrographic ships, two are based on the west coast (FA, RA) and two are focused on work on the east coast and in the Gulf of Mexico (FH, TJ). Two of the multi-mission vessels are global platforms (EX, RB), while the third (NF) is primarily in the Gulf of Mexico and the east coast. Platform details and survey capabilities are summarized below:

NOAA Ship	Survey Depth Capabilities		
	4-200m	200-3,000m	3,000-11,000m
Fairweather (FA)	x	x	
Ferdinand Hassler (FH)	x		
Nancy Foster (NF)	x	x	
Okeanos Explorer (EX)		x	x
Rainier (RA)	x	x	
Ronald Brown (RB)		x	x
Thomas Jefferson (TJ)	x	x	

Table 30. NOAA Ship survey depth capabilities.

NOAA SHIP FAIRWEATHER:

NOAA SHIP FAIRWEATHER is a hydrographic survey vessel whose primary mission is to map coastal waters to update nautical charts. She is a 231 f~~oo~~t vessel equipped with four Kongsberg EM 2040 multibeam echo sounders, one Velodyne VLP-16 sensor, one CEEPulse single beam, two Klein high speed, high resolution side scan sonars, and one Kongsberg EM710 multibeam sonar system. The Kongsberg EM 2040s are located on the four Hydrographic Survey Launches (HSL) and have a low frequency (200 kHz), intermediate frequency (300 kHz), and high frequency (400 kHz) transmit array with swath coverage of 140°. The typical operational depth range for the EM 2040 is rated from 0.5-600 m; however, field application has shown the maximum operable depth is closer to 200 m. The Velodyne VLP-16 sensor is for lidar and creates 360° 3D images by using 16 laser/detector pairs with a range of 100m. The CEEPulse single beam is a self--contained single beam system designed for mobile applications. This system operates at a 200 kHz frequency, with a ping rate of up to 10 Hz, and has an operational depth range of 0.25-100 m. The Klein High Speed, High Resolution Side Scan (SSS) Sonar system is a beamforming acoustic imagery device, integrated system including a KLEIN 5500 towfish, a Transceiver/Processing Unit (TPU), interfaces to a computer for control and monitoring. The towfish operates at frequency of 455 kHz and a vertical beam angle of 40°, and can resolve up to 5 discreet received beams per transducer stave. It has a long-range reconnaissance mode up to 250 m and 500 m~~eter~~ depth rating (200 m with bathymetry option). The Konsberg EM-710 Multibeam Sonar System is for ship hydrography. It operates at sonar frequencies in the 70 to 100 kHz range with the across-track swath width up to 5.5 times water depth. The EM-710 operates in water depths of 200-3000 m, with a published maximum depth of more than 2000 m. The FAIRWEATHER has a fully equipped survey department and a high level of expertise on board.

NOAA SHIP FERDINAND HASSLER:

NOAA SHIP FERDINAND HASSLER is one of the newest ships in the NOAA fleet and the only twin hull catamaran. Her primary mission is to conduct hydrographic surveys, and is a valuable national asset in hurricane response operations. She is a 124ft vessel with increased stability from her twin hull. Primarily, FERDINAND HASSLER operates two Kongsberg EM-2040s, one installed on both port and starboard sides. This system is Kongsbergs only dual transducer system in the world where the two transducers work like one swath, which is advantageous because there is only one reference point for both transducers. As a result, only one SBET and line file is processed for both. Considered a hydrographic shallow-water system, the FERDINAND HASSLER is particularly suited for routine work around the coast of Florida in survey depths of 25-30 m. In the past, this system has also been able to accommodate surveys of about 200 m, however with a swath width of diminishing returns. The swath is typically described as 3x the water depth, which holds true until about 100-130m after which the observed swath width becomes a little less than 3x the water depth. At 300 kHz this system is ideal for surveys from 15-250m and collects decent object detection and water column data. Operating at 400 kHz produces a product with decent resolution that's not sidescan. Due to the 14 m~~eter~~ hull separation, survey work in depths less than 10 m produces a gap between swaths of the EM 2040s. FERDINAND HASSLER does have a towed Klein 5500 V2 sidescan, however it's not functional due to the coupling of windows 10 and OMAO domain software permissions, along with an older TPU. A TPU update, would return the side scan capability, and likely result in a new side scan all together.

NOAA SHIP NANCY FOSTER:

NOAA SHIP NANCY FOSTER is a multi-mission oceanographic platform that supports fish habitat and populations studies, seafloor mapping surveys, in addition to physical and chemical oceanography studies. The NANCY FOSTER is a 187 f~~oo~~t vessel equipped with a Kongsberg EM710 MKII and Kongsberg EM 2040 multibeam echo sounders. The MKII EM 710 has an extended frequency range (40-100 kHz) that increases the effective depth range of the system. Acceptance testing confirmed proper operation of the EM 710 in depths of 40 to 2500 m. The maximum swath is described as 5.5x the water depth with a maximum swath width of 2300 m. The EM 2040 has a low frequency (200 kHz), intermediate frequency (300 kHz), and high frequency (400 kHz) transmit array with swath coverage of 140°, which typically operates in a depth range of 0.5 to 600 m. The NANCY FOSTER is equipped with a survey department and regularly surveys as a part of their mission.

NOAA SHIP OKEANOS EXPLORER:

NOAA SHIP OKEANOS EXPLORER operates under NOAA's Office of Ocean Exploration and Research. It is a multi-mission platform dedicated to discovery. As such, this 224 ft. vessel is equipped with a variety of sonar to provide scientists with high-resolution maps of the seafloor for feature identification and further exploration. OKEANOS EXPLORER operates a Kongsberg EM-304 multibeam echo sounder, a Simrad EK60 split beam echo sounder, and a Knudson SBP 3260 (Sub-bottom profiler). Depending on water temperature, noise level, and bottom type, the Kongsberg EM-304 can satisfy depths from 10-7000+ m. It's operating frequency is between 26 and 34 kHz, with a swath width typically 5.5x water depth (or more than 9km). The nominal frequency of the EM 304 is 30 kHz with two swaths per ping with eight frequency coded transmit sectors per swath. This system delivers bathymetric data, seabed imagery data, water column data, and extra depth detections. The last patch test for the EM 204 was in October 2019. The Simrad EK60 Splitbeam ES operates at 18 kHz, 38 kHz, 70 kHz, 120 kHz, 200 kHz, or 333 kHz. The OKEANOS EXPLORER does not currently utilizse the 333 kHz band. Last calibration May 2019. The Knudson SBP 3260 is a full ocean depth system (10,000+ m) that is used for ocean survey and research. It is configured for a frequency range of 3.5-210 kHz with a max output power of 10kW on the 3.5 kHz channel and 2kW on the 2 kHz channel. This system offers wideband chirp and correlation processing, sub-bottom sediment profiling data, and deep-water target detection.

NOAA SHIP RAINIER:

Sister to FAIRWEATHER, NOAA SHIP RAINIER is a 231 ft. hydrographic survey vessel dedicated to mapping coastal waters and updating nautical charts. She operates a Kongsberg MKII EM-710 multibeam echo sounder and supports five survey launches. Four of the launches operate Kongsberg EM-2040 multibeam echo sounders, while one operates an Echotrac CV200 paired with a Simrad 50/200 Combi D transducer. The Kongsberg EM-710 multibeam echo sounder is the ship's sonar system. The EM-710 utilizes frequencies of 40-100 kHz, with a minimum acquisition depth of 3m below its transducers up to approximately 2000m. Typical operations are in depths of at least 200m. Across track coverage is described as 5.5x the water depth in areas of 2000 m or more. The four Kongsberg EM-2040 Multibeam echo sounders are used for coastal surveying. A wide band high resolution shallow-water multibeam echo sounder, this system operates between 200 and 400 kHz; ideal for survey depths of 15-200 m. Lastly, RAINIER uses an Echotrac CV200 by Teledyne Odom Hydrographic paired with a Simrad 50/200 Combi D transducer. The Simrad transducer combines two transducers (50 kHz and 200 kHz) and one temperature sensor in a single housing. It is designed with a streamlined shape for hull mounting on small vessels, making it best suited for coastal and shallow-water data acquisition. The 50 kHz transducer has a longitudinal beam width of 10° and a transverse beam width of 16°. The 200 kHz transducer has a longitudinal and transverse beam width of 7°. RAINIER has a full hydrographic survey team onboard, and a number of experienced small boat coxswains for the completion of its operations.

NOAA SHIP RONALD BROWN:

NOAA SHIP RONALD BROWN is a global-class oceanographic and atmospheric research platform, whose primary mission is to travel worldwide supporting scientific studies to increase our understanding of climate and the ocean. She is a 274 foot vessel equipped with a Kongsberg EM 122 multibeam echo sounder. The EM 122 has a nominal sonar frequency of 12 kHz with an angular coverage sector of up to 150 degrees and 864 soundings per ping. Achievable swath width on a flat bottom is normally up to six times (143º) the water depth. This frequency is standard for deep ocean echo sounding, gives a good balance between reasonably small dimensions/narrow beams, and good range capability. It operates in water depths of 1000-5000+ m. A swath width of about 30000 m is generally achievable for deep-waters, depending upon bottom conditions and chosen system beamwidth. With a low noise vessel, a swath width of more than 40 km has been achieved. The RONALD BROWN does not conduct survey operations as a regular mission and does not have personnel aboard with formal hydrographic training.

NOAA SHIP THOMAS JEFFERSON:

NOAA SHIP THOMAS JEFFERSON is a hydrographic survey vessel whose primary mission is to map coastal waters to update nautical charts. She is a 208 foot vessel equipped with one Kongsberg EM710 MKI multibeam echo sounder, three Kongsberg EM 2040 multibeam echo sounders, two EdgeTech 4200 side scan sonars, one Odom Echotrac CV-200 single beam echo sounder, and one Klein 5000 MKII-B High Speed, High Resolution Multibeam Side Scan Sonar. The Kongsberg EM710 MKII multibeam echo sounder operates at sonar frequencies in the 65 to 100 kHz range in shallow-waters, and can use frequencies down to 40 kHz to extend coverage in deep-waters. It has across track coverage is up to 5.5 times water depth, to a maximum of more than 3000 m. It is recommended that the ship limit the survey swath to 45 degrees on either side by running in Single Sector mode. Although the problem still persists at times even within the reduced swath the minimum acquisition depth is from less than 3 m below its transducers, the maximum acquisition depth is approximately 2800 m, depending upon array size. The three Kongsberg EM 2040s have a low frequency (200 kHz), intermediate frequency (300 kHz), and high frequency (400 kHz) transmit array with swath coverage of 140°, which typically operates in a depth range of 0.5 to 600 m. Two are mounted on HSLs and one is mounted on DriX, a customizable autonomous vessel. The two EdgeTech 4200 side scan sonars consisted of a topside system and a stainless steel towfish. The towfish is a dual frequency 300/600 kHz capable of simultaneous acquisition in both frequencies. The towfish is fitted to the HSLs in a hull-mounted configuration. The 4200 is restricted to the depth of the draft of the HSL. The EdgeTech 4200 uses Multi-Pulse (MP) technology to enable survey speeds up to 10 knots while maintaining 100% bottom coverage. When operated in simultaneous dual frequency acquisition mode, speed must be reduced since the frequencies alternate between 300 and 600 kHz with a maximum depth of 6,500 feet. The Odom Echotrac CV-200 is a single beam echo sounder that has a low band frequency of 3.5-50 kHz and a high band frequency of 100 kHz-1MHz allowing for surveying to depths of up to 4000 m. The Klein 5000 MKII-B High Speed, High Resolution Multibeam Side Scan Sonar (SSS) system is a beam-forming acoustic imagery device. The integrated system includes a Klein 5000 towfish, a Transceiver/Processing Unit (TPU), and a computer for user interface. The towfish operates at a frequency of 455 kHz and a vertical beam angle of 40°, and can resolve up to 5 discrete received beams per transducer stave. The system is capable of ranges up to 250 m, however THOMAS JEFFERSON does not use the 150m or the 250m reconnaissance mode. The THOMAS JEFFERSON has a fully equipped survey department and a high level of expertise on board.