Multibeam Backscatter and Bathymetry Synthesis for the Main Hawaiian Islands

Final Technical Report

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Background

Benthic habitat substrate is key for determining the spatial distribution of demersal living marine resources. In collaboration with JIMAR, PIFSC is developing multi-gear fishery-independent surveys for the commercially important bottomfish stock in the Main Hawaiian Islands (MHI). Surveys and quantitative gear comparisons have been completed in the Maui Nui island region, where comprehensive bathymetry (depth) and backscatter maps exist that provide benthic topography and substrate composition. Expansion of this study into an operational survey has been slowed due to the lack of synthesized information on substrate hardness in the rest of the MHI (Fig. 1).

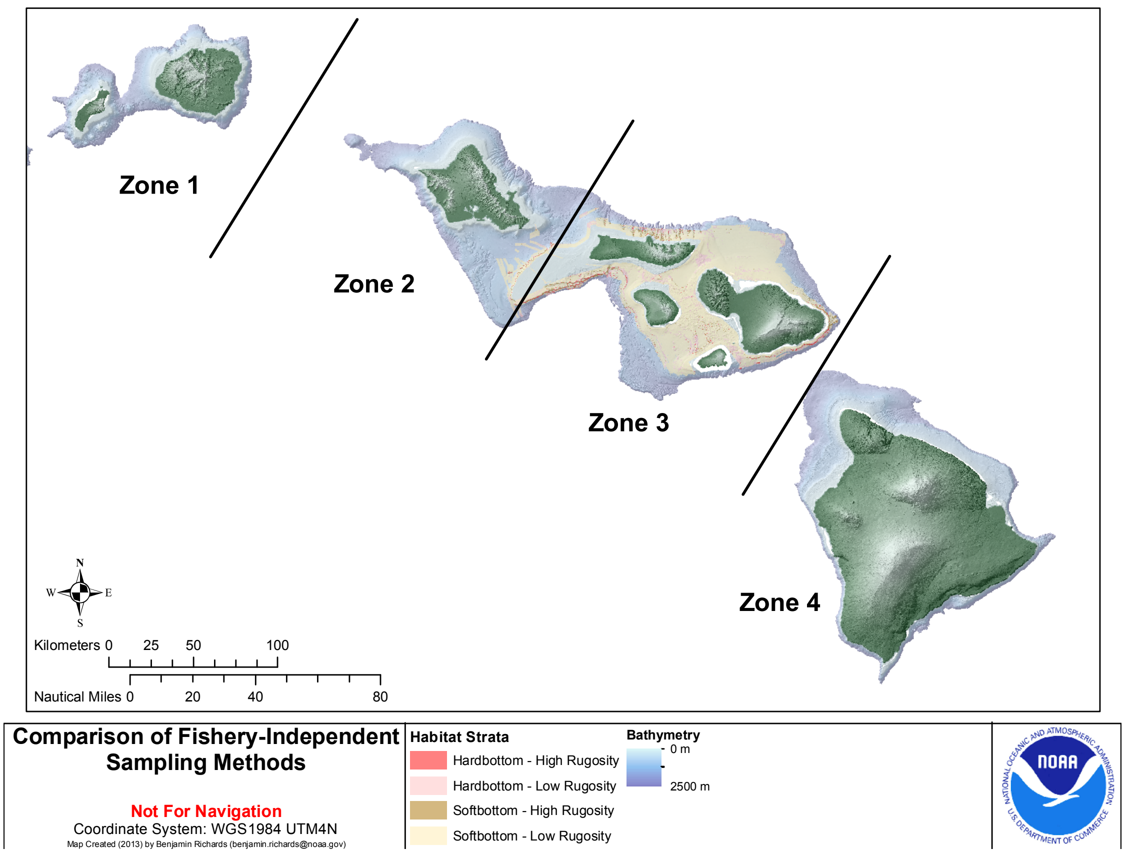

Figure 1. Map of the Main Hawaiian Islands (MHI) dividing into four research zones. Bathymetric data (blue shading) exists for all zones. Prior to the current project, benthic composition data (pink and tan shading) existed only for zone 3. Benthic composition data for zones 1, 2, and 4 had been collected, but had not been synthesized into a comprehensive map layer. Creation of a synthesized benthic composition map layer for all research zones is necessary for the development of a properly stratified experimental design across all research zones.

In order to conduct a comprehensive, robust multi-gear fishery-independent survey for the MHI bottomfish stock, it is important to have maps of water depth, benthic topography, and substrate composition which are known to structure the population densities and community composition of ecological communities (Richards *et al*., 2012). The study referenced above developed and validated a six-point stratification based depth (75-200m, 200-400m), benthic slope (0°-20°, 20°-90°) and substrate composition (hard bottom, soft bottom), and synthesis data for the first two factors already exist for the MHI sampling domain.

The multibeam backscatter data necessary to resolve substrate composition for the MHI domain have been collected, but with a variety of sensors operating at a range of different frequencies, such that similar numeric values from disparate areas do not signify similar levels of substrate hardness. The lack of readily available backscatter synthesis products across the MHI survey domain is an impediment to the development of a properly stratified operational fishery-independent survey for MHI bottomfish.

Objectives

In collaboration with partners at the University of Hawaiʻi Undersea Research Laboratory (HURL), JIMAR conducted a one-year habitat assessment to address the lack of an integrated benthic habitat mapping of the MHI. The project objectives were to:

1. Create a synthesized benthic habitat substrate characterization (hard or soft bottom) with 20 m resolution from existing backscatter data in the Main Hawaiian Islands extending from the shoreline to a depth of 400 m;
2. Develop a synoptic survey stratification and sampling allocation for the MHI survey domain using the newly created MHI benthic substrate composition synthesis in combination with existing bathymetric and topographic products as well as a stratified variance structure for MHI bottomfish resources for implementation of a fishery-independent survey of demersal fishery resources.

Only objective #1 is discussed within this report.

Approach

Backscatter data have been collected and archived for virtually all of the Main Hawaiian Islands at depths from 100 to 400 m and to a lesser extent from the shoreline down to 100 m. Separate data sets have been collected from a number of ships at different times and spatial scales, using a variety of multibeam systems. Recently, a protocol using GIS tools has been resolved and applied. Basically, backscatter values from these data sets were reprocessed and standardized to a uniform scale of intensity. This protocol was used to create a 60 m resolution backscatter synthesis of the entire Main Hawaiian Islands seafloor to abyssal depths (Kelley and Smith, 2014). For this project, the method was applied to create a higher resolution 5 m backscatter synthesis for the 75 to 400 m depth range that provides the benthic habitat substrate characterization needed for bottomfish studies. A corresponding 5 m multibeam bathymetry synthesis was also developed and used to correct the backscatter data for topographic slope. The depth range for both products extends from as shallow as data were available to at least 500 m and much deeper in some portions of the project area.

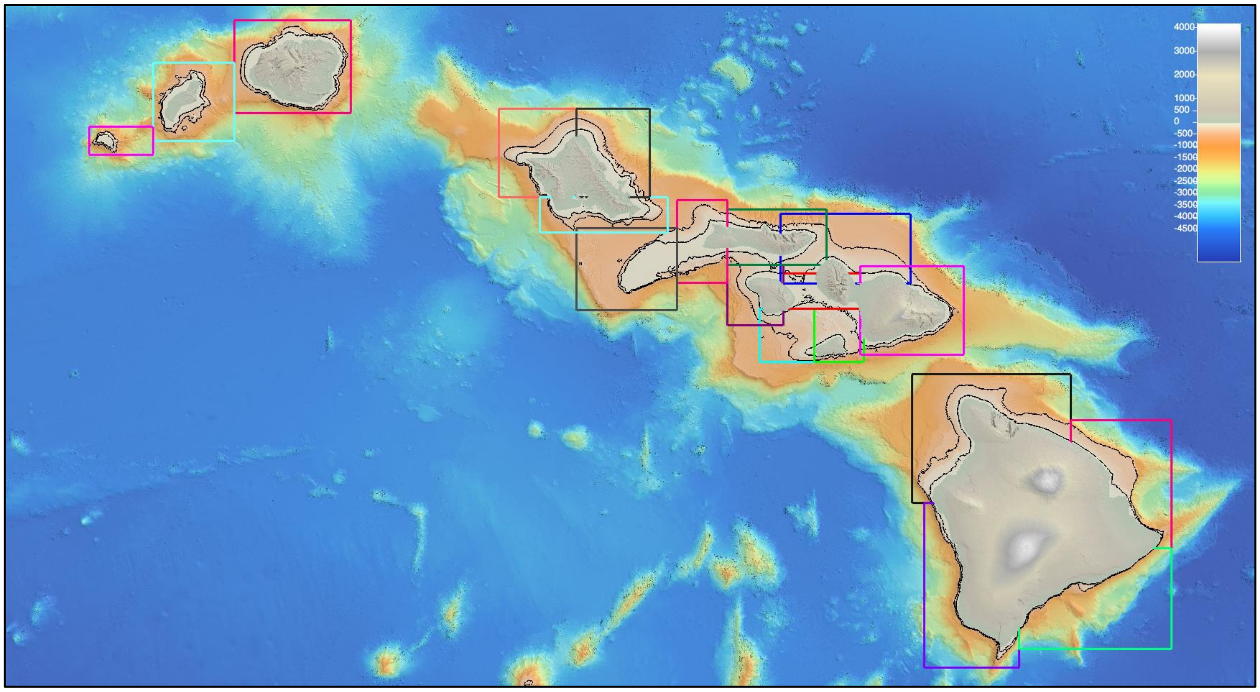

Figure 2. Bathymetry and topography of the Main Hawaiian Islands with variously colored lines delineating the individual grid boxes used for this study as discussed in the text.

Data sets incorporated into the syntheses

In order to generate grids of the backscatter and bathymetry syntheses at 5 m cell size, each research zone depicted in Fig. 1 was further broken up into smaller grid boxes (Fig. 2). This was done to speed up gridding, remain within computer memory limits, and simplify data management for the numerous multibeam input files. This resulted in three boxes for Kaua‘i County, three for Honolulu County (O‘ahu), nine for Maui County and Penguin Bank (Maui Nui), and four for Hawai‘i County (Big Island) for a total of 19. The individual grids were then merged into one grid for each county, and eventually into one grid for the entire chain.

Modern multibeam systems collect coincident bathymetry and backscatter data that are incorporated into the same file or file system. By simply manipulating options in the post-processing software, either component can be further processed, edited, gridded, plotted, and/or merged with other like data. Older multibeam systems only collect bathymetry data. To further complicate the issue, not all backscatter data are of equal quality and scaling, and thus cannot be meaningfully and directly merged with such data from other ships, systems, and/or frequencies. While the quality and resolution of multibeam bathymetry data also vary between different installations, these data can be meaningfully and directly combined, although one usually employs weighting factors to produce the best result.

A total of 34,618 individual multibeam bathymetry files from hundreds of cruises traversing the Main Hawaiian Islands were interrogated to see if they would contribute bathymetric coverage to each of the 19 grid boxes discussed above. The contributing files were then incorporated into a much smaller list with appropriate weighting and gridding was accomplished. The number of files used in each grid varied considerably depending on number of surveys or opportunistic transits crossing the grid box, systems used and extent of water depth ranges, the latter two factors affecting track line spacing. Using all data available (unless it contained obvious artifacts) allowed the creation of complete grids with limited data gaps where there were no multibeam data available. Regarding the backscatter synthesis, files were selectively chosen manually and only dedicated surveys, as opposed to opportunistic transits, were included unless a gap in coverage needed filling. This allowed for the highest quality product and was necessary to reduce the manual workload.

Sensors and research teams that produced the original data sets

Backscatter data acquired with the following systems and vessels were used in the project:

Kongsberg EM 120 [12 kHz], R/V *Kilo Moana*
Kongsberg EM 122 [12 kHz], R/V *Kilo Moana*
Kongsberg EM 300 [30 kHz], M/V *Ocean Alert*, NOAA Ship *Hi'ialakai*
Kongsberg EM 302 [30 kHz], NOAA Ship *Okeanos Explorer*, R/V *Falkor*
Kongsberg EM 710 [40 – 100 kHz], R/V *Kilo Moana*, R/V *Falkor*
Kongsberg EM 1002 [95 kHz], R/V *Kilo Moana*
Kongsberg EM 3002d [300 kHz band], NOAA Ship *Hi'ialakai*
Reson 8101-ER [240 kHz], R/V *AHI* (30 ft shallow draft boat for near shore work)

Bathymetry data acquired with these and other multibeam systems and ships were used, including SeaBeam classic, SeaBeam 2000, SeaBeam 2112, Hydrosweep, and LIDAR.

The organizations who carried out and/or funded these surveys included, but were not limited to:

University of Hawaiʻi Undersea Research Laboratory and the Hawaiʻi Mapping Research Group
U.S. Geological Survey (USGS), Western Coastal and Marine Geology Program
NOAA/PIFSC Coral Reef Ecosystem Division, Pacific Islands Benthic Habitat Mapping Center
NOAA Undersea Research Program and the Office of Ocean Exploration and Research (OER)
NOAA Pacific Islands Regional Office (PIRO)
Monterey Bay Aquarium Research Institute (MBARI)
Schmidt Ocean Institute (SOI)

Methods used to produce the syntheses

Bathymetry

When available, edited versions of the original multibeam "swath files" (collected by the sonar systems) were used in the bathymetry gridding schemes. These data were edited by the survey teams while aboard ship and/or sometime afterwards ashore using a variety of open source and commercial software including, but not limited to, MB-System, SABER, Caris, and Fledermaus. When edited data were not available, the files were typically assigned a low weighting so that better quality data would take precedence in the grid. The same idea applied for dedicated versus opportunistic transit survey data. Further editing of bathymetry data was beyond the scope of this project, although time was spent investigating obvious artifacts, determining the offending files, removing them from the data lists, and then rerunning the gridding process.

Gridding of the bathymetry component was exclusively carried out using the MB-System (Caress and Chayes, 1995, 1996) and Generic Mapping Tools (GMT) (Wessel and W. Smith, 1991) open source software packages. These are community standards and are run from the command line or in job scripts in a Unix/Linux shell. Examples of the gridding and filtering commands, respectively, are provided below.

```
mbgrid -E5.0/5.0m! -F1 -A2 -C10 -I$datalist1 -N -O$outgrid -R$range1
-V -JU -S7

grdfilter $outgrid -G$filtgrid -D0 -Fm50
```

Once all 19 final bathymetry grids were run, they were fused into grids for each county, and then further merged into one grid for the entire Main Hawaiian Island chain (Fig. 3).

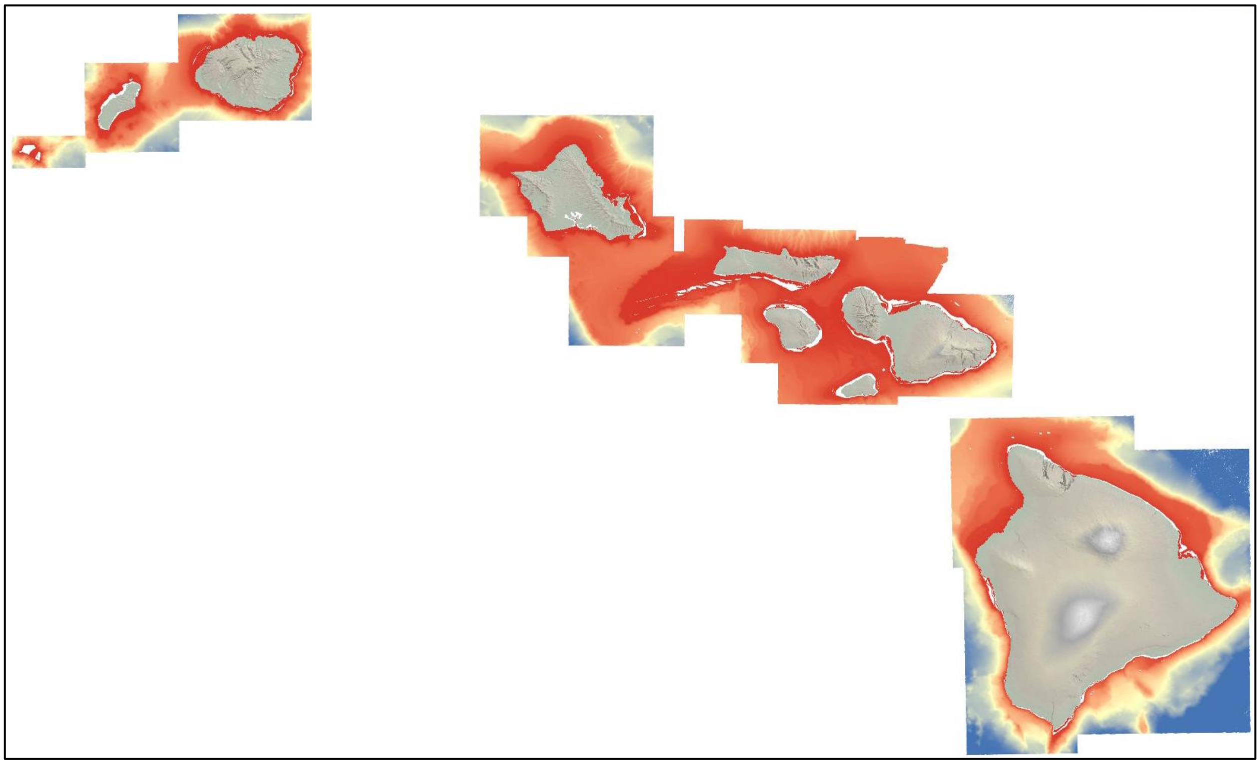

Figure 3. Five-meter resolution multibeam bathymetric synthesis for the Main Hawaiian Islands with island topography in gray shades. Cooler colors (*i.e.*, blue) indicate shallow depths, while hotter colors (*i.e.*, red) indicate shallow depths.

Backscatter

Backscatter processing was generally carried using the raw swath files in most instances. The reasons for this were to create a more consistent product across surveys, systems, and ships, and to employ the open source Geocoder software module (embedded in in the commercial QPS's Fledermaus/FMGT software package). This is a relatively new technique and had not been applied to any of the existing data to the best of our knowledge. However, for multibeam data, FMGT will only accept *raw.all* or certain Generic Sensor Format (GSF) files and not the edited bathymetry files. Thus, to compensate for bathymetric data artifacts, filtered bathymetry "reference" grids were read into the FMGT project to correct the backscatter data. FMGT is also far more sensitive to corrupted or missing data or metadata in the files, along with being more memory limited than MB-System programs. As a result, FMGT will crash repeatedly when it encounters a significant error, or refuse to begin processing until memory issues are addressed.

After the metadata are extracted, FMGT computes the coverage and extracts the navigation of each line. In all but one case, the default settings for FMGT were used in processing the backscatter data. The software reads the swath files' metadata and automatically adjusts the processing scheme to produce the best result. The metadata contains information such as geographic extents, datagram packet numbers, sonar modalities, and sonar type. The one excursion from the default values occurred when processing EM 1002 data from R/V *Kilo Moana*. Here, the Backscatter Source was changed from the default Beam Time Series to Beam Average (calibrated) in order to produce a more consistent result, or look, for the entire survey.

The following statements regarding the processing steps carried out in FMGT are paraphrased from the online Fledermaus Reference Manual (2016). FMGT first adjusts the backscatter data by extracting the backscatter then executing radiometric corrections based on sonar type and bottom topography. Next, it performs filter processing that includes angle varying gain (AVG) adjustments along with anti-aliasing of the backscatter data. As this stage advances, it transmits the results of the backscatter adjustment to the project hierarchy. Finally, FMGT builds the desired mosaic using the pre-calculated or manually assigned resolution. This value is pre-computed by FMGT during coverage processing and is estimated based on the sonar beam configuration and along track coverage. For this project, all data set resolution estimates were overridden and manually assigned the value of 5 m. At this point, interactive manipulation of toggling off files because of turns, data artifacts, or overlapping swaths occurred. The mosaics were then re-rendered and output to ArcGIS grids for incorporation into the next phase of the process (Fig. 4). Data from identical multibeam systems and ships (and multiple cruises of same ship) were processed and combined into the same mosaic and resultant grid.

The surveys (files) that could not be read into FMGT were processed using the mbgrid module of MB-System. This method allows the manual setting of various options and does not read the file metadata to automatically optimize the processing options and flow. The result is a "rougher" look, including more noticeable nadir artifacts that do cause more false "hard bottom" classification. However, the program is extremely robust – able to read, process, and grid nearly every available sonar system format. Jobs can be batched and run autonomously once the options are chosen, leading to a high degree of computational efficiency. Example command lines using MB-System for backscatter gridding and conversion to ArcGIS format, respectively, are given below. Again, single system, single ship, multiple cruises, and then the resultant grids from this package were ready for import into ArcGIS to accomplish the next processing steps (Fig. 4).

```
mbgrid -E5.0/5.0m! -F1 -A4 -JU -C5 -U5 -N —I$datalist2 —O$outgrid -V
—R$range2

mbm_grd2arc -V —I$outgrid —O$arcgrid
```

ESRI ArcGIS is where the magic happened. An outline of the major processing steps is given below, using Niʻihau as an example, followed by a more detailed description of the critical reclassification procedure.

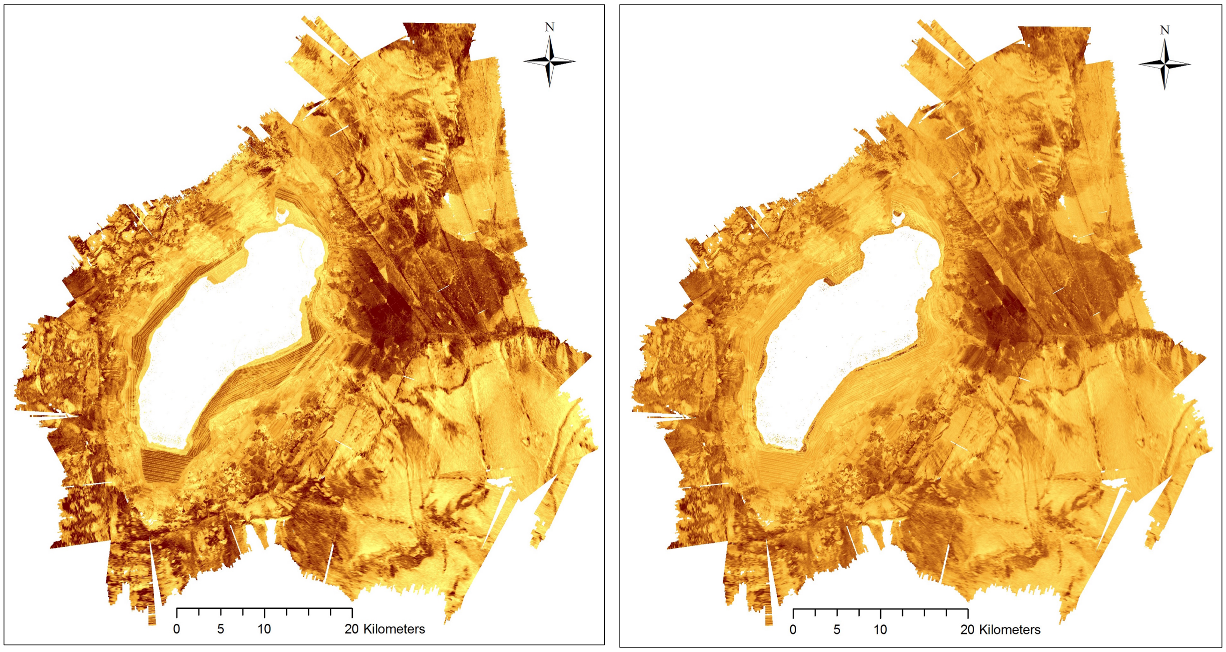

Figure 4. Backscatter data around Niʻihau. Brown color indicates harder seafloor, while yellow/gold denotes softer seafloor. Left side image is a stack of five ʻrawʼ data sets. Right side are same data sets after going through reclassification and synthesizing process described in text and depicted in following figures.

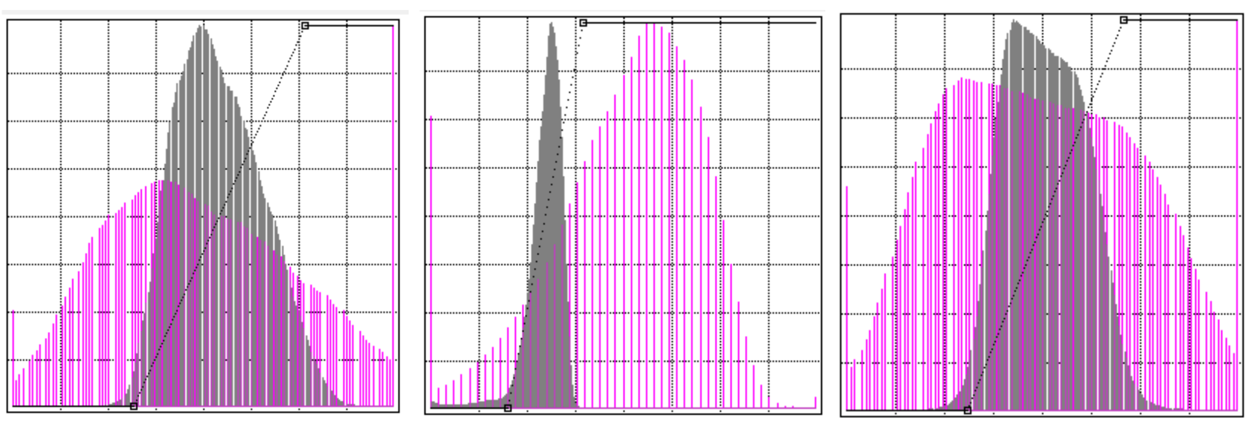

Figure 5. Three examples from Niʻihau the data sets showing how the histograms from the raw grids (gray) are adjusted (magenta) in ArcGIS by using the sliders on top and bottom of graph. X-axis is backscatter value, Y-axis is pixel count. See Fig. 6 for more examples and explanation.

We converted the ASCII grids to rasters (floating point), defined the projection (UTM zone 4N), generated a histogram and manually trim the upper and lower tails (Fig. 5), then compared the result to other grid layers already imported and reclassified. Iterated as necessary. *This is one of two mostly subjective steps in the process*. When satisfied with the look of the backscatter match between grid layers in the display, the reclassify tool was then used to apply the reclassification

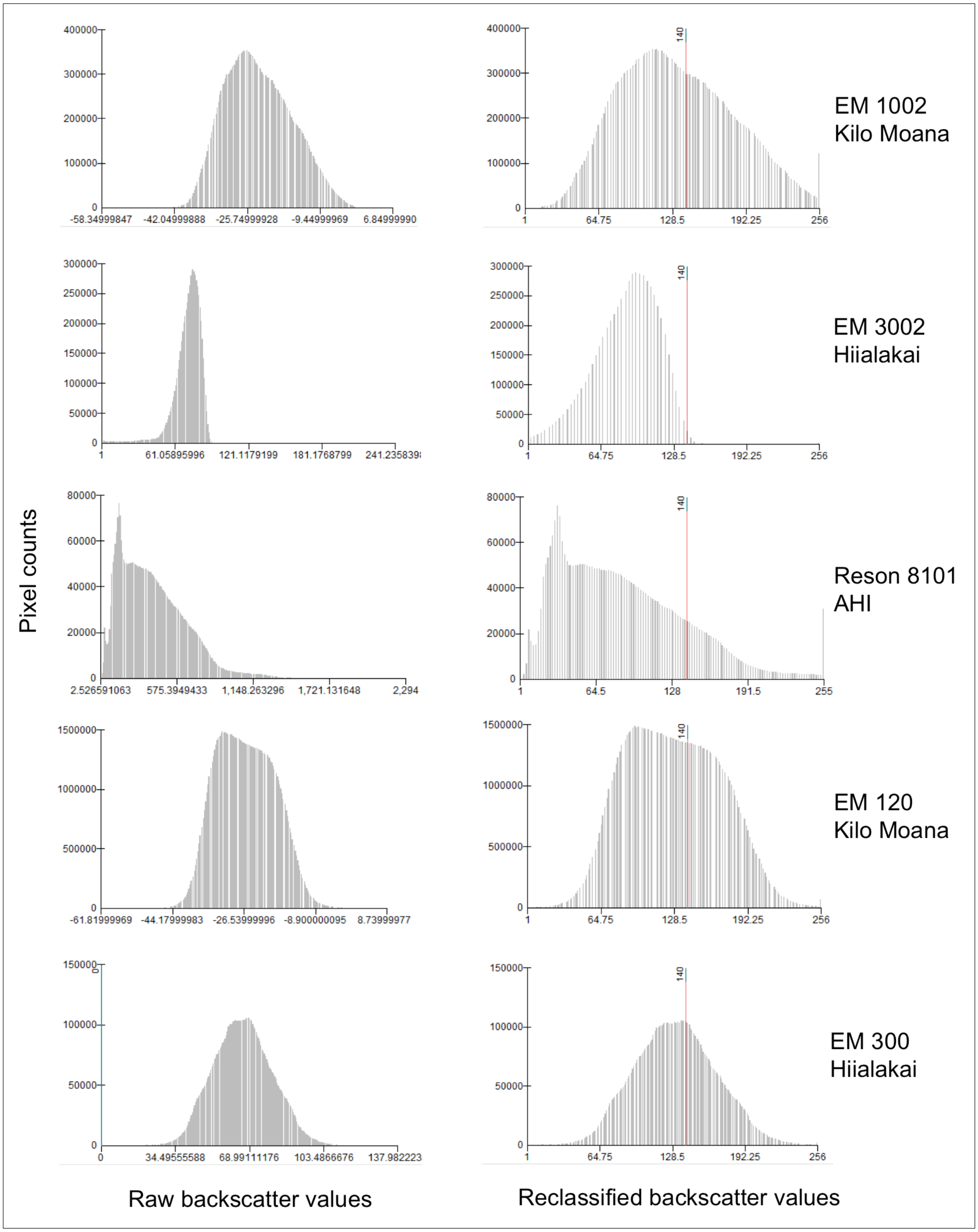

Figure 6. Histograms extracted from all five data sets making up the Ni‘ihau mosaic, as shown in Fig. 4. Left column shows raw grids prior to reclassification, and afterwards (right column). The multibeam systems and vessels are indicated on right side, and were mosaicked in this order, from top to bottom. The red lines labeled 140 shows the position of the chosen threshold hard-soft value on each reclassified histogram. Note the wide range of backscatter values on the X-axis within the left column and how they become standardized in right column.

values to the grid itself, rather than just to the display (Fig. 6). One caveat must be noted here. The reclassification back to grid feature was disabled by ESRI after ArcGIS version 10.0. In newer versions, it only operates on the display, thus we have maintained one software installation of ArcGIS 10.0 simply to allow use of this feature for backscatter synthesizing. After properly ordering the stack of grid layers (generally best data on top, worst on bottom), the final step in the process was to generate a combined mosaic for the grid box by using the Mosaic to New Raster tool (Fig. 7). The same tool was later used to produce mosaics for entire counties (island groups) and the whole main island chain (Fig. 8).

The reclassification step, also referred to as outlier adjustment, is the critical and also the subjective stage of this method. It allows the user to visually adjust usually overlapping backscatter grid layers produced with data from different multibeam systems so that they have a similar, if not identical look. This is regardless of the actual numerical range of the original grid values, which get rescaled to an imagery standard of 1 to 256. This actually happens twice, first when brought into ArcGIS, but remains only in the display. Adjusting the histograms reassigns the 1 to 256 range to the new, trimmed histogram, also still in the display only until one enters the Reclassify tool and applies the changes to the actual grid values.

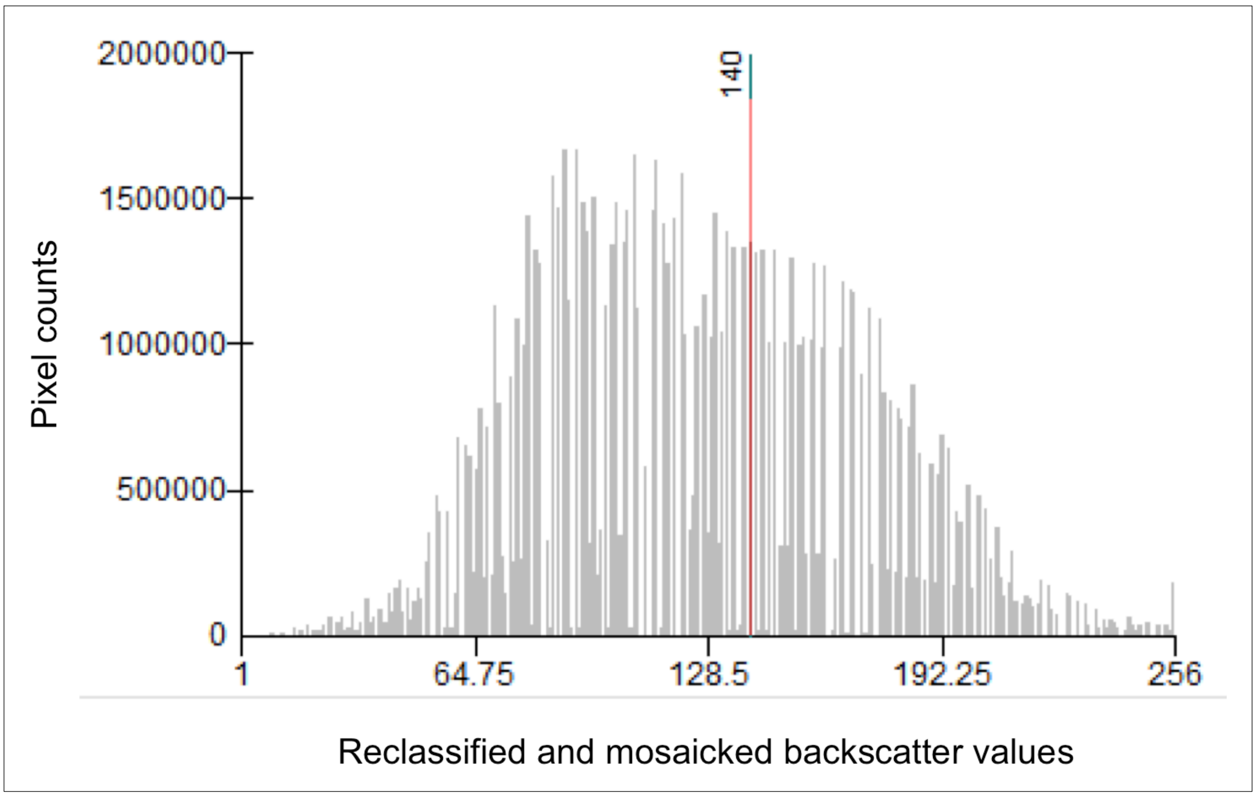

Figure 7. Final histogram of the five reclassified and synthesized Niʻihau data sets with the 140 threshold indicated by red line and label. Note the appearance of overlapping histograms within the same range of values and a more Gaussian shape overall. In this case, there is somewhat of a notch in the histogram at the breakpoint of 140.

Interpretation of the data

The next stage in the process (also the second mostly subjective step) was developing the threshold-based hard/soft categorization, or breakpoint value. From this, an interpretative substrate map delineating hard and soft bottom values could be generated. This interpretative phase was based on the initial work done by Dr. Christopher Kelley of UH/HURL on the assemblage of disparate backscatter data sets. He worked primarily with the USGS and MBARI survey data using the EM 300 data from M/V *Ocean Alert* to determine hard/soft transitions based on ground-truthing in the form of video observations from the HURL *Pisces* submersibles. Here, he chose a threshold value of 187 and greater (out of 1 to 256) which was independently derived by Dartnell and others (2006) based on work using the same system from the same vessel offshore California.

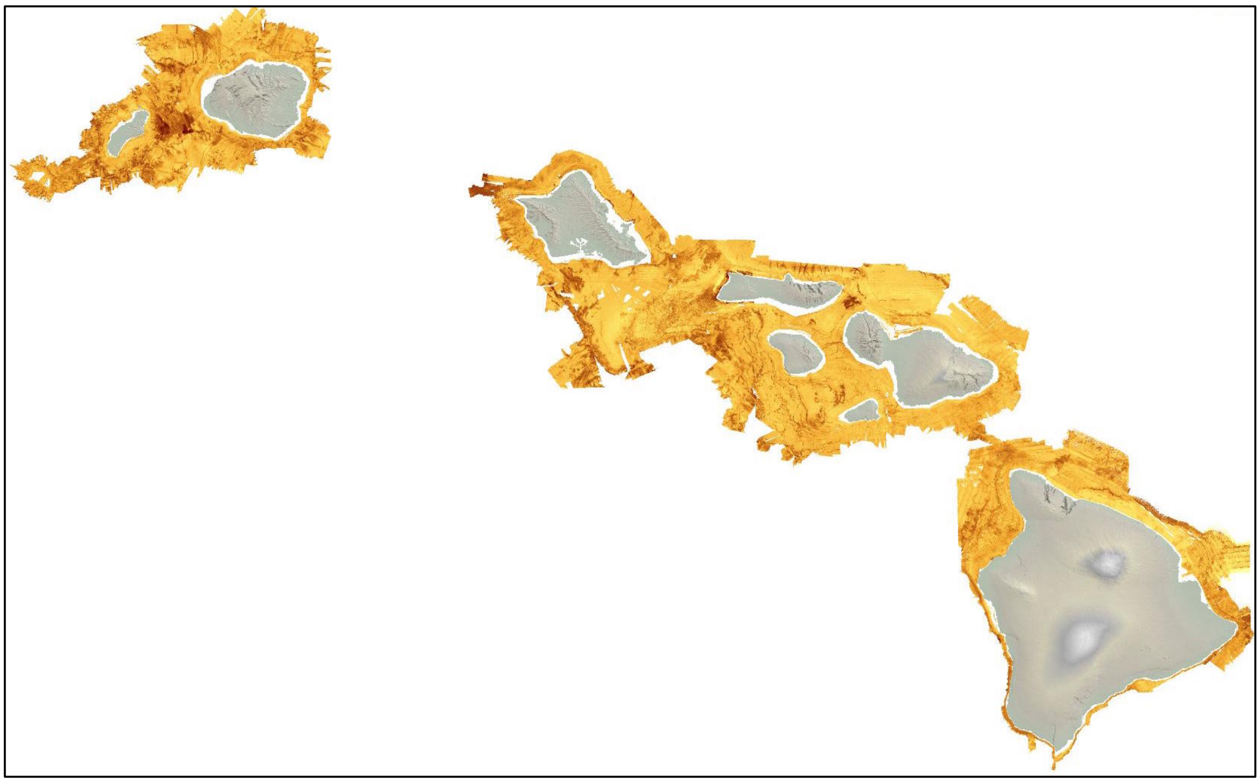

Figure 8. Final five-meter resolution multibeam backscatter synthesis for the Main Hawaiian Islands with island topography in gray shades. Brown color indicates harder seafloor, while yellow/gold denotes softer seafloor.

While the 187 value provided a starting point for this study, it was realized that the hard/soft value would not be the same for the synthesized data sets because of the reclassification required to merge them into one coherent grid. This lead to the analysis of histograms for the reclassified EM 300 data for Maui Nui, where we found an obvious breakpoint in one histogram with a value of 146. The next step involved building layers displaying only values of 146 to 256 for the reclassified and synthesized data sets for the other counties. Additional layers were generated with values of 130, 135, 140, 141 (all to 256) and repeatedly compared with the "original" 187 to 256 data sets to determine which threshold value from the new syntheses most closely matched the original value and/or best represented the delineation of hard versus soft bottom. We also considered how known data artifacts may skew the threshold value. Potential variability of the reclassified syntheses between counties was also examined. In the end, a single best-fit threshold value of **140** was chosen for all counties, and at this point the four different backscatter mosaics were fused into one final grid representing the entire Main Hawaiian Island chain (Fig. 9).

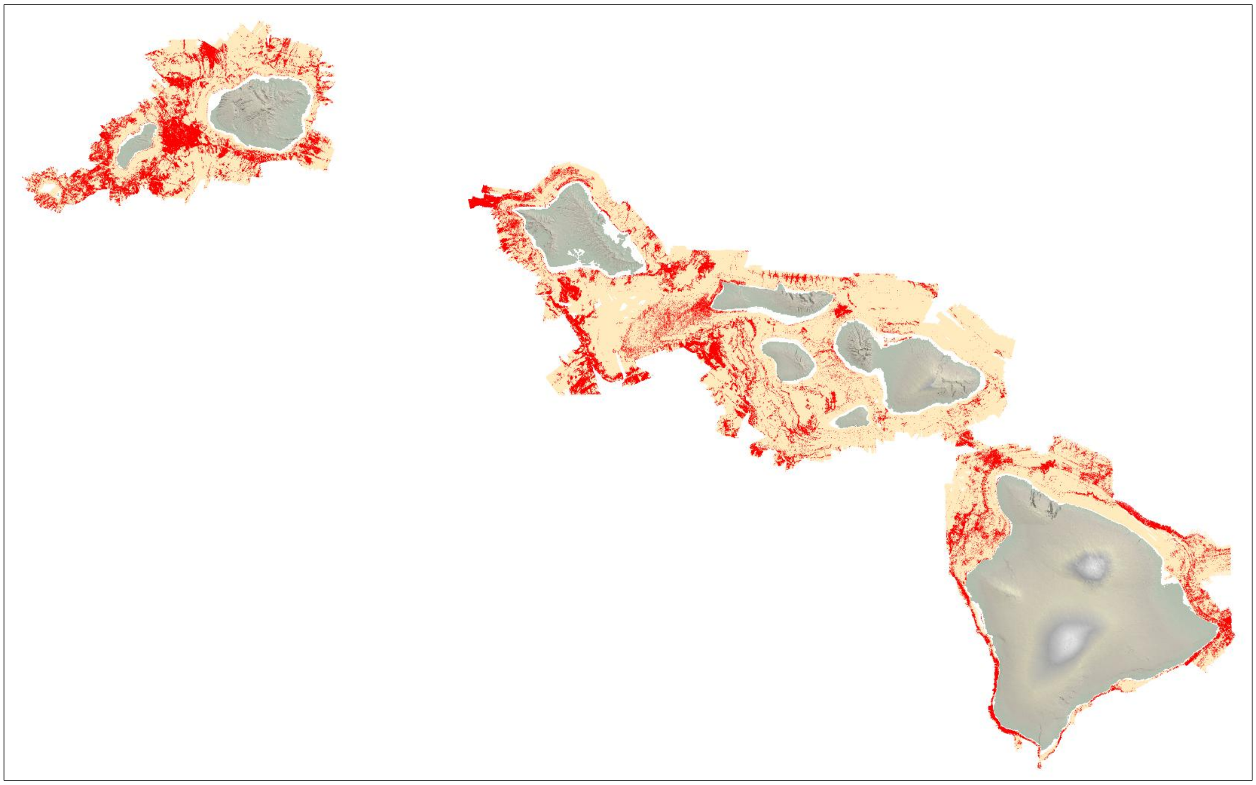

Figure 9. Final five-meter resolution hard-soft grid for the MHI derived from the backscatter synthesis exhibited in Fig. 8. All values from 140-256 are red (hard bottom), those 0-139 are tan (soft bottom).

Verification of accuracy

Regarding the bathymetry synthesis, much care was taken during its build to examine, identify, and ferret out individual files with bad data that created noticeable artifacts when compiled. Fortunately, there were usually enough overlapping surveys and data swaths in the archive that we had the luxury of toggling off obviously bad sources and/or low-weighting inferior data, and still had sufficient coverage to produce contiguous bathymetry grids. For the backscatter synthesis, survey geometry and quality were considered when choosing the surveys/files to include. We also carefully evaluated in what order the data sets for each area should be stacked, based on system capability, installation quality, available coverage, processing algorithm used (FMGT vs. MB-System), and consistency of the reclassification results with other data sets. As a result, the backscatter layer stack order changed slightly or greatly for each mosaicked area to produce the best and most uniform product.

Ideally, one would compare the new hard-soft bottom grid directly with ground-truth data from submersibles, ROVs, towed/drop cameras, substrate samplers, etc. taken from a wide variety of locations, geomorphologies, and water depths throughout the Main Hawaiian Islands. However, this task was beyond the scope of the project. Therefore, in addition to the exercise comparing our results with the previous 187 categorization described in the preceding section, we also did spot checking of our '140 layer' with the full-value-range backscatter synthesis and bathymetry synthesis produced as part of this study. In general, the hard (high) values correspond with expected geologic and morphologic features such as reef terraces, steep scarps, debris channels with coarse sediment, exposed lava flows and cones, current swept surfaces, headlands, submarine canyon walls, and carbonate platforms. Soft values (low) values demarcate features including sediment basins and other catchments, low-slope abyssal seafloor, and nearshore areas in close proximity to high terrestrial runoff.

Known issues

Some known issues, also referred to as data artifacts in this report, warrant identification and further explanation for potential users of these products. Attempts were indeed made during processing to diminish their manifestation. Additionally, some comments are presented regarding how the effect of the artifacts on these products can be minimized during use.

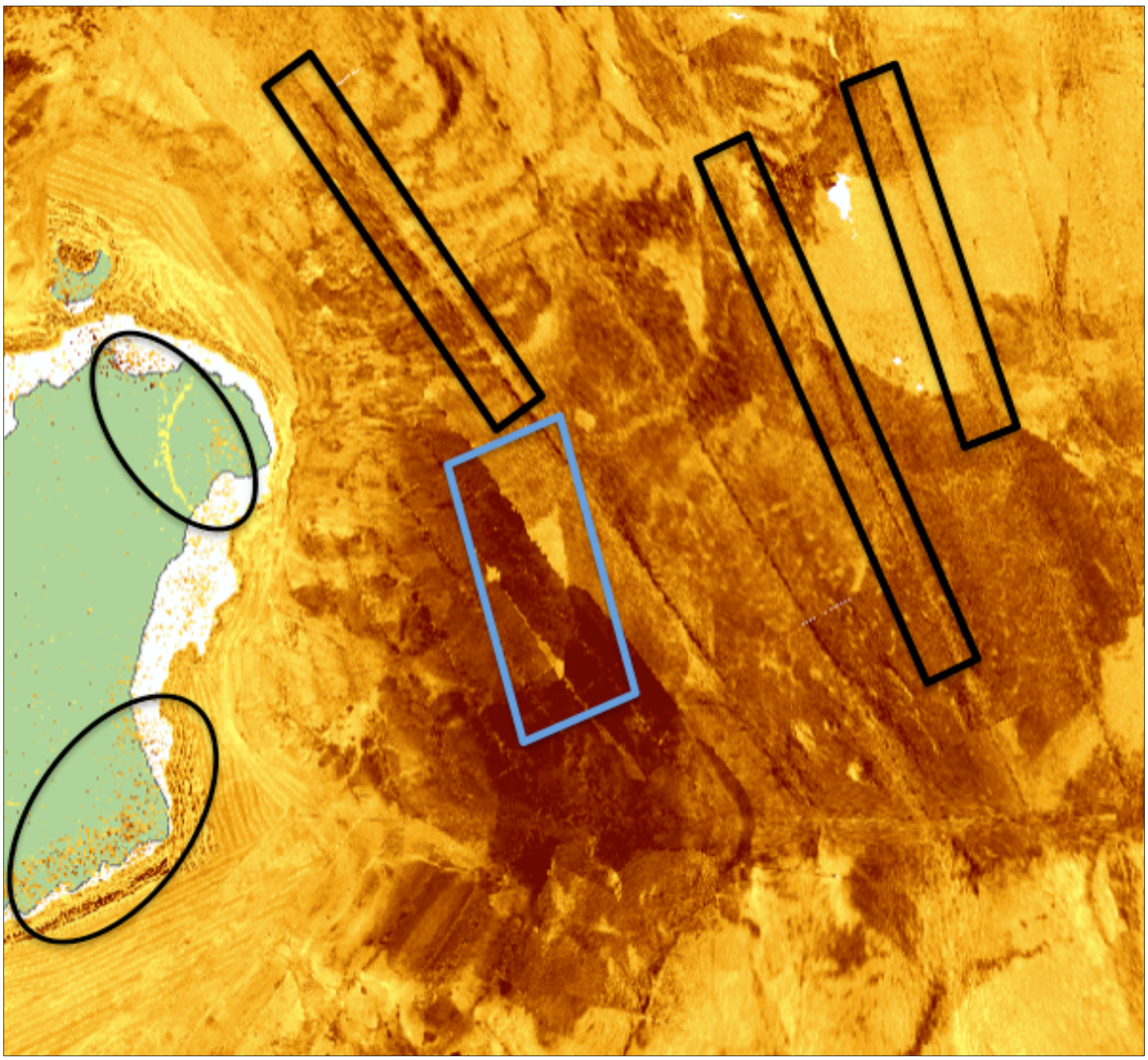

Figure 10. Close-up view of backscatter data off the northeastern end of Niʻihau showing three different artifacts: nadir lines (indicated by black rectangles), variable power/gain (blue polygon), on-land chatter (ellipses). See text for explanation and Fig. 4 for location.

Several different artifacts are highlighted in Figs. 10 and 11. The black boxes show nadir artifacts. Nadir lines in backscatter basically represent the ship track and is the portion directly under the vessel where no useable backscatter are acquired since this data type relies on slant range sonar returns. As a result, the nadirs appear darker than the data from the rest of the swath to either side of the ship. More sophisticated processing and filtering algorithms can remove or at least subdue, many of the nadir artifacts. When possible, FMGT/Geocoder was used in this project to process the backscatter data, which did a good job of blending the nadirs. Geocoder failed on several of the data types, including *Hi'ialakai* (EM 300, EM 3002), USGS 1998 data from *Ocean Alert* (EM 300), and *AHI* (Reson 8101). In these cases, MB-System (mbgrid) was utilized which is more robust but has less complexity in its processing and options.

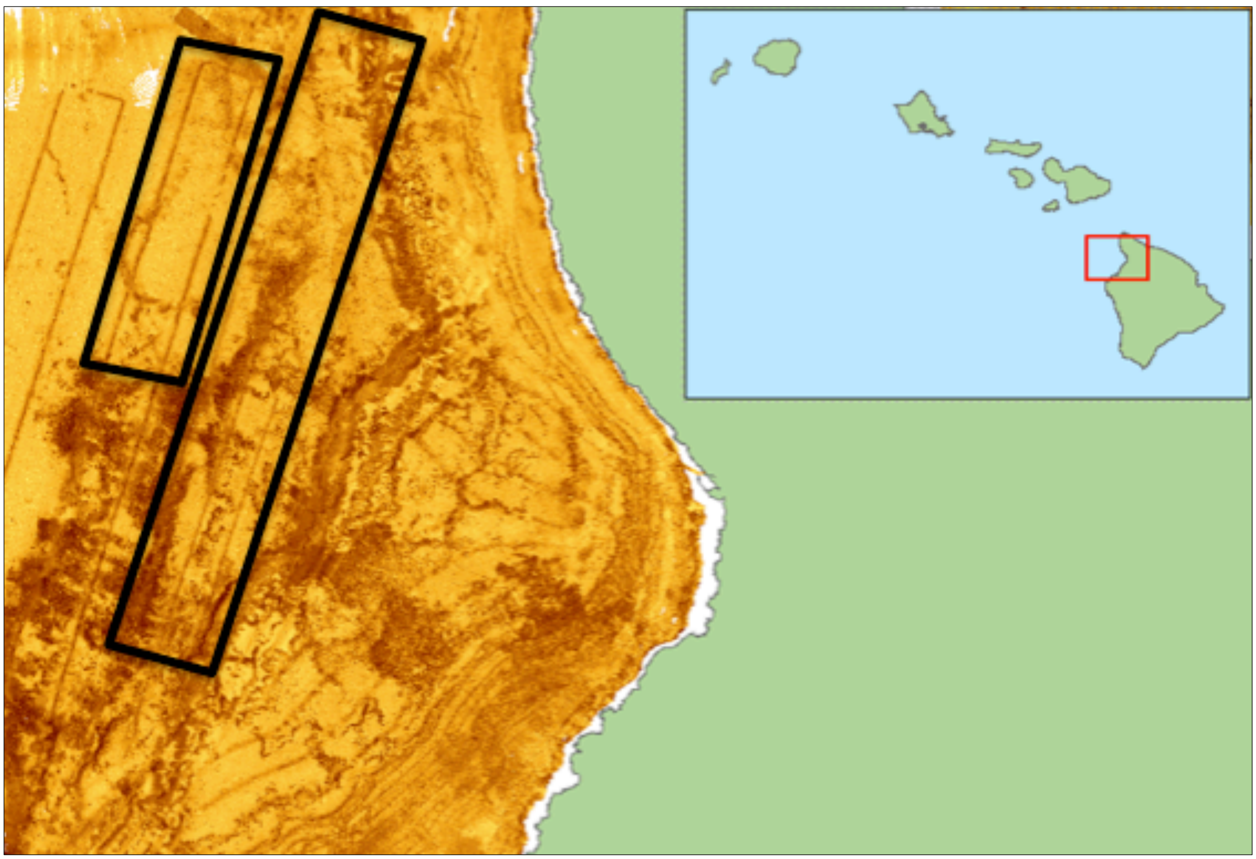

Figure 11. Close-up view of backscatter data off the northwestern side of the Big Island of Hawai'i showing nadir artifacts (indicated by black rectangles). See text for further explanation and inset map for location.

The blue box in Fig. 10 shows a probable automatic power and/or gain increase in one of the shallow/intermediate multibeam systems operating near its depth limit (*e.g., Kilo Moana's* EM 1002). Some of these show up in waters deeper than 500 m, well below the bottomfish range of interest and thus beyond the boundaries of the synoptic survey stratification grid cells. The circled artifacts in Fig. 11 that overlap the terrestrial domain resulted from processing the AHI backscatter data in MB-System's mbgrid. In some cases with *AHI* Reson 8101 data, Geocoder could be used and such artifacts did not appear, although with the larger data sets, such as at Ni'ihau, it crashed repeatedly. Again, the depth range in which these artifacts occur is beyond (above) the depth range of interest for which this project was developed. Creating a mask using the bathymetry and/or topography to exclude the artifacts is another method that could be implemented to lessen their effects.

Finally, while high slopes generally will produce strong returns in backscatter suggesting a hard bottom, in reality, this is not always the case. It really depends on the survey geometry. In some cases, one has to drive the ship into the same steep area from numerous angles just to get some coverage because of the high slope. If the slope is facing 'away' from the swath, little to no acoustic return will be received. Likewise, even if the ship is navigating along an ideal heading to map the morphology, extremely steep slopes can cause shadowing of the fan-shaped swath downslope, leaving gaps in both the bathymetric and backscatter data. Repeated passes from adjacent lines are the only way to achieve more complete coverage, at the expense of more ship time! For more extensive discussion of multibeam backscatter acquisition, processing and interpretation, the interested reader is referred to Lurton and Lamarche (2015).

Education and outreach activities

Education and outreach activities were not incorporated into the proposed project. However, a number of entities requested use of the data products during the course of the effort. These included a doctoral student at the UH/HIMB using it for modeling mesophotic hard coral distribution across the Main Hawaiian Islands, the State of Hawai‘i DLNR/DAR to assemble a geodatabase for bottomfish management use, a film production group from the UK doing a documentary for National Geographic, and the NOAA Office of Exploration and Research for use as base maps for ROV dives from *Okeanos Explorer*.

Acknowledgements

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