# Observations on Initial Use of Saildrone Surveyor for Deep-Sea Mapping

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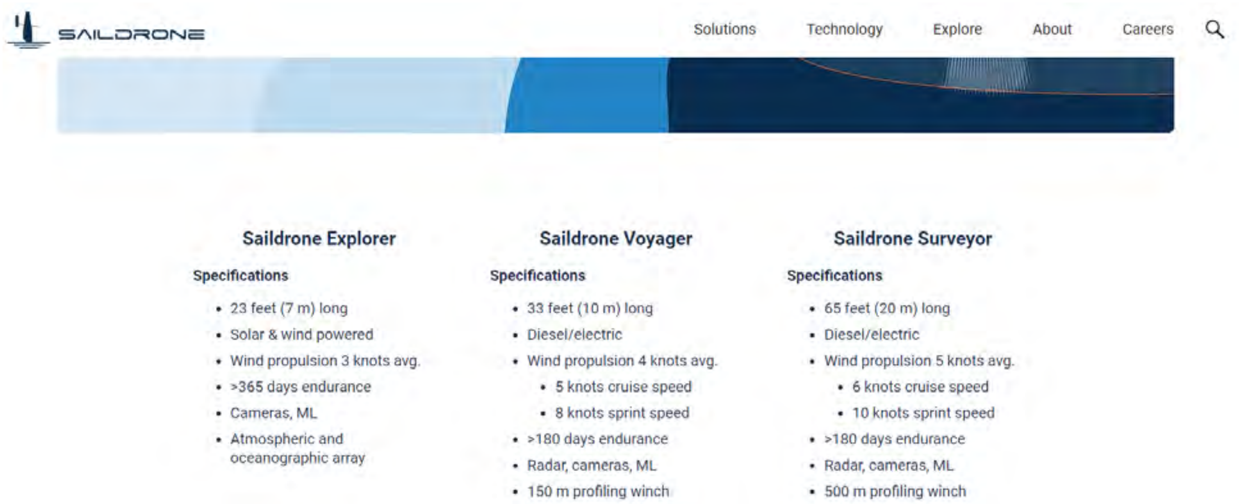
**Introduction:**

For the past few years NOAA and the University of New Hampshire have been looking at the viability of uncrewed mapping systems to support the nation's mandate to map, explore and characterize its EEZ, and more generally to support broader ocean mapping and ocean exploration activities. There is much hope that uncrewed systems will provide an environmentally friendly approach to the collection of ocean mapping and exploration data, offering the potential for great increases in efficiency and significant cost-savings. While these hopes are shared by many, there is still insufficient data to either prove or disprove the value of uncrewed system operations, or to better understand how these innovative new systems might be best utilized to ensure their most appropriate use (see Mayer 2023 for broader discussion). This report takes advantage of more than two years of operation of the prototype "Saildrone Surveyor," a 21 m sail and solar-powered (supplemented by a diesel engine) uncrewed vessel equipped with both shallow water (EM-2040) and deep water (EM-304) multibeam sonar systems, to evaluate special issues associated with the collection of seafloor mapping data from this uncrewed system and to attempt to better understand the efficiency of surveying from this platform.

**Background:**

Saildrone first introduced the concept of a wind-powered uncrewed surface vessel (USV) with the Saildrone Explorer, a 7m long, sail and solar-powered vessel designed for the collection of meteorological and oceanographic data, through a CRADA with NOAA's PMEL in 2014. Since that time more than 100 Saildrone Explorers have been produced and have proven to be extremely valuable and versatile platforms, demonstrating tremendous endurance (including a 370 day mission) and robustness (surviving hurricane winds in excess of 109 knots). To date the Saildrone fleet has sailed more than 1 million miles and spent more than 32,000 days at sea. While these vessels have been used for the collection of a wide range of oceanographic and atmospheric data including bathymetry from single-beam echo sounders, they do not have the power budget to support the collection of multibeam sonar-based bathymetry. In 2021, Saildrone developed the Saildrone Surveyor, a 21m long vessel equipped with a Kongsberg EM-304 and EM2040 multibeam sonar, capable of mapping in both shallow waters with the EM2040 and to water depths beyond 5000m with the EM304. This past year Saildrone introduced the 10m long Saildrone Voyager that is capable of carrying a shallow water multibeam sonar, but it does not support a deep-water multibeam sonar. Our analysis will focus on the Saildrone Surveyor and its deep-water mapping capability. Specifications for the three Saildrone vessels, as presented on the Saildrone website, are shown below:




From January through March, 2021, The University of New Hampshire, with NOPP funding through OER's Ocean Exploration Program, worked with Saildrone on the initial installation and sea-testing of the EM-304 and EM-2040 on the Saildrone Surveyor. After these sea trials, UNH, with funding from the Nippon Foundation-GEBCO Seabed 2030 program, contributed to the costs of the maiden voyage of the Saildrone Surveyor from San Francisco to Hawaii in July of 2021. This transit demonstrated the ability of the Surveyor to collect high-quality multibeam data in water depths beyond 5000m as well as the increased swath-width achieved when the vessel was under sail (Figure 1). However, the 3650 km long transit took 28 days, representing an average transit speed of approximately 3 knots. Additionally, the long transit was not representative of a typical ocean mapping survey where a prescribed area must be covered (constraining headings) and where swaths are overlapped to ensure 100 percent coverage.

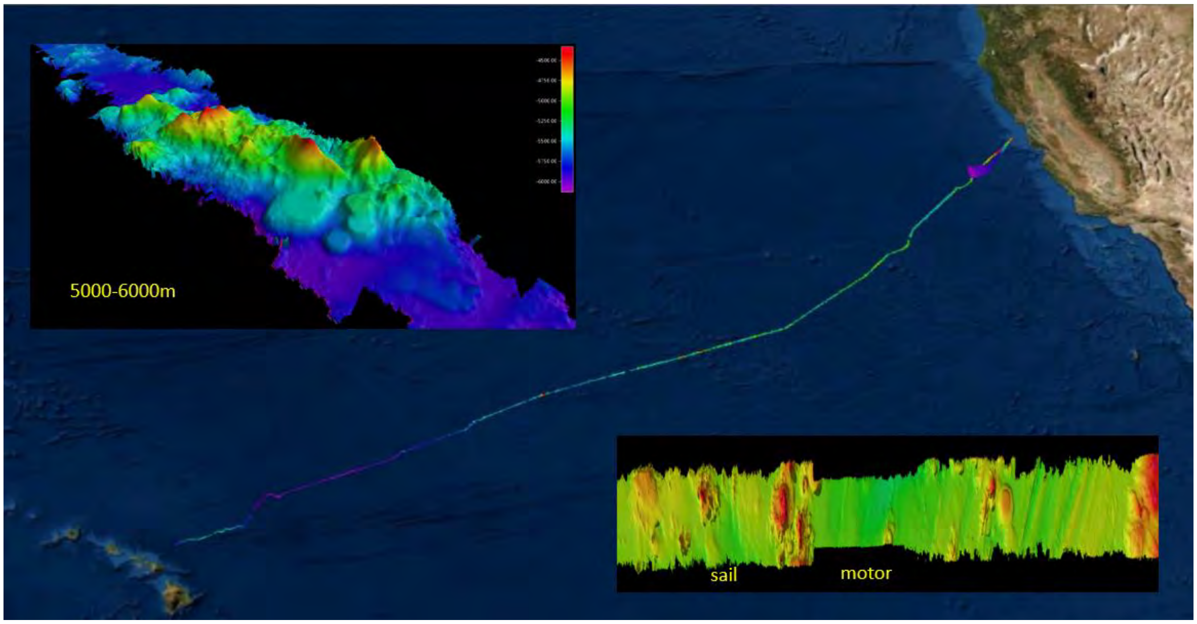



*Figure 1. Maiden mapping voyage of Saildrone Surveyor from San Francisco to Honolulu.*

To better understand the capability of the Saildrone Surveyor under more standard survey conditions, the University of New Hampshire contracted Saildrone, through the NOAA Ocean Exploration Cooperative Institute to collect seafloor mapping data in areas of importance for the U.S. National Ocean Mapping, Exploration and Characterization (NOMEC) strategy. Originally 96 days of effort were planned for a region along the Aleutian Islands, but weather terminated this survey after 51.5 days. An area off the coast of northern California was then identified where another 44.5 days of mapping were conducted (Figures 2 and 3). Collectively these surveys afforded the opportunity to evaluate the performance of the Saildrone Surveyor operating in a more traditional survey mode. In the case of the Aleutians, the surveys were divided into several smaller regions each requiring overlapping coverage with data collected under sometimes severe weather conditions and in regions of strong currents. The California survey represented a more traditional single large area where overlapping coverage was required and weather conditions were mostly moderate.

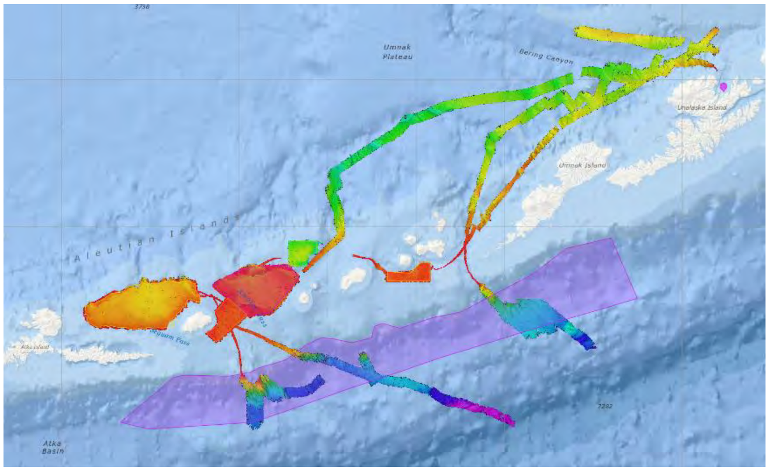


*Figure 2.  Areas surveyed by Saildrone Surveyor along Aleutian Islands*

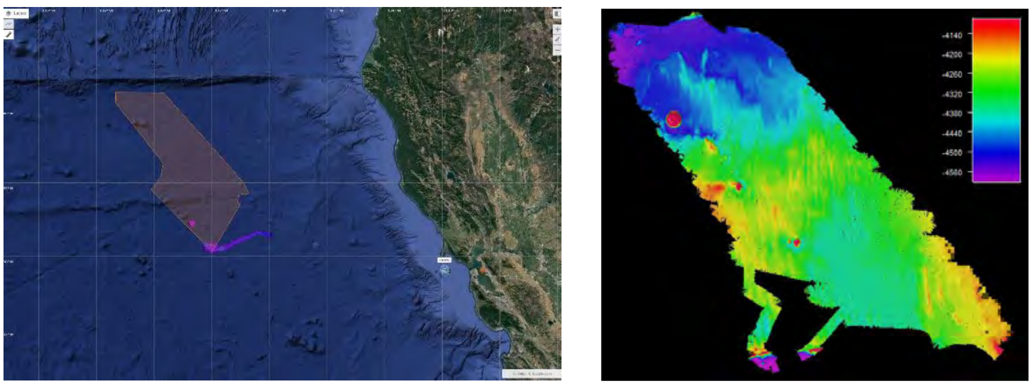


*Figure 3.  Area surveyed off Northern California by Saildrone Surveyor  (left).  Resulting bathymetric data (right).*

**The Surveys:**

The Aleutians surveys began with a 30-day transit of the Saildrone Surveyor from Alameda CA to Dutch Harbor AK, arriving in Dutch Harbor on 09 August 2022.  While the initial hope was that all the work would be conducted in on a single 96 day leg, engine maintenance required a return to Dutch Harbor after 29 days and then severe weather required termination of the second leg after 22 days (on 3 October) when the vessel began a transit back to Almeda CA. Between both legs 16,217 sq. km of seafloor was mapped at an average speed of 3.4 knots. A summary of the statistics for the Aleutians surveys as reported by Saildrone in their processing report, is presented in the table below.

| SD-1200-0012 | | |
|---|---|---|
| **Total Mapping Days** | 29.89 | (survey + transit) |
| **Average Mapping Speed** | 3.45 | (knots) |
| **Number of SVP casts** | 46 | *does not include pre-mission casts |
| **Line km Mapped** | 4301.44 | (km) |
| **Line nm Mapped** | 2322.59 | (nm) |
| **Square km Area Mapped** | 7409.89 | ($km^2$) |
| **Square nm Area Mapped** | 2160.38 | ($nm^2$) |
| **Number of eDNA Samples** | 56 | |
| **Data Quality Level** | Order 2 | IHO standard for depths >200m |
| **Data Volume** | 2 | (TB) |
| **SD-1200-0013** | | |
| **Total Mapping Days** | 21.64 | (survey + transit) |
| **Average Mapping Speed** | 3.36 | (knots) |
| **Number of SVP casts** | 23 | |
| **Line km Mapped** | 3128.9 | (km) |
| **Line nm Mapped** | 1689.47 | (nm) |
| **Square km Area Mapped** | 8807 | ($km^2$) |
| **Square nm Area Mapped** | 2578.6 | ($nm^2$) |
| **Number of eDNA Samples** | 42 | (sampling continues during transit, +15) |
| **Data Quality Level** | Order 2 | IHO standard for depths >200m |
| **Data Volume** | 1.23 | (TB) |

The California survey began on the 25th of November 2022 after a 2.5-day transit from Almeda CA. After 3 days of surveying south of the Mendicino FZ, the vessel made an emergency return to port due to a hatch leak. Surveyor returned to the survey area on 05 December but needed to again return to port due to loss of communication with the Seapath motion sensor. The combination of these two efforts represents the first 15.25 mapping days of the first segment of the California mapping program (SD1200-1400). The final, 29-day leg of the California mapping program began 22 January 2023 and ended on 20 February 2023 (SD1200-1500). Between SD1200-1400 and SD1200-1500 a total of 29,697 sq km was mapped at an average speed of 3.01 knots. A summary of the statistics for these surveys as reported by Saildrone in their processing report is presented below.

| SD-1200-0014 (OER CA) | | |
|---|---|---|
| Total Mapping Days | 15.25 | |
| Average Mapping Speed | 3.95 | (knots) |
| Number of SVP casts | 26 | *does not include pre-mission casts |
| Line km Mapped | 2411.8 | (km) |
| Line nm Mapped | 1302.3 | (nm) |
| Square km Area Mapped | 9814.6 | ($km^2$) |
| Square nm Area Mapped | 2861.48 | ($nm^2$) |
| Number of eDNA Samples | 48 | |
| Data Quality Level (IHO) | Order 2 | IHO standard for depths >200m |
| Data Volume | 387.78 | (GB) |
| **SD-1200-0015 (OER CA and Extensions)** | | |
| Total Mapping Days | 29.22 | |
| Average Mapping Speed | 2.07 | (knots) |
| Number of SVP casts | 30 | *does not include pre-mission casts |
| Line km Mapped | 5157.7 | (km) |
| Line nm Mapped | 2785 | (nm) |
| Square km Area Mapped | 19882.57 | ($km^2$) |
| Square nm Area Mapped | 5796.83 | ($nm^2$) |
| Number of eDNA Samples | 0 | Not Applicable to this Deployment |
| Data Quality Level (IHO) | Order 2 | IHO standard for depths >200m |
| Data Volume | 588 | (GB) |

Saildrone has provided detailed reports for these surveys including full descriptions of the systems and data acquisition parameters used, the handling of sound speed data, oceanographic, meteorological, and other environmental conditions, issues encountered during the surveys, and initial data processing and data quality assessment; these reports are available upon request.

**Post-Processing:**

While Saildrone did initial preliminary processing and data quality assessment of the data, UNH and NOAA also contracted for full processing of the data sets by independent contractors. The Aleutian data were processed by Erin Heffron and Lindsay Gee under contract from UNH and the California data were processed by Marcel Peliks under direct contract from NOAA-OER. The processing reports from each of these contractors are attached: SD1200-0012-13_MappingProcessingSummaryReport_v20230914.pdf and Saildrone vs. EX processing.pdf.

Along with the processing of the EM304 and EM2040 data collected during the Aleutian survey, the contract to Heffron and Gee called for an evaluation of data quality from a processor's perspective. In particular, the question asked to be addressed was whether there were issues with the data that might be different from those associated with standard crewed ship's surveys so that we might be better prepared to understand and evaluate the overall benefits of uncrewed surveys versus crewed surveys.

Analysis of Data Issues:

The detailed report by Heffron and Gee on issues encountered while processing the EM304 and EM2040 data collected with the prototype Saildrone Surveyor in the Aleutians is attached (SD-1200 System Performance & Data Processing Observations GEE HEFFRON v20230903). This detailed analysis highlighted a number of issues that were observed during data processing and that impacted the end products. Some of the issues identified were the result of the extreme environmental conditions encountered in the Aleutians regions and would have been an issue with any vessel operating in the area. Others, however, were unique to the uncrewed nature of the Saildrone, its relatively small size with respect to the sonar, and to operations under sail. We summarize the findings of Heffron and Gee below and then add our comments (*in italics*) about whether the issue is one that could affect any survey vessel, is an issue that can be resolved by upgrades to or improved practices in the operation of Saildrone or, is inherent to the design of Saildrone. A full read of the complete report by Heffron and Gee is highly recommended to better understand the discussion below.

Environmental Issues: The survey area had strong and highly variable currents, rapidly varying depths, severe and changeable weather, and strong temperature gradients. Issues with collecting sound speed profiles on Saildrone (limited number and limited depth) had a large impact on data quality. In the absence of sufficient sound speed profiles, Saildrone fell back upon the World Ocean Atlas to generate estimated sound speed profiles, however, the limited sampling in this remote region means that these estimates were often not very representative of the true sound speed structure in the area.

The limited number of actual sound speed profile observations (with even fewer in bad weather) combined with the limited depth of the profiles resulted in reduced data quality and coverage and was one of the factors that impacted the achievable grid resolution. There are likely remaining underlying sound speed issues in some of the data (swath vertical offsets, bending in swath) that may impact the final bathymetric surfaces, but other issues make it difficult to diagnose or ameliorate in post-processing. It was also unclear if absorption from CTD was used in backscatter data collection, if not, the backscatter mosaic could potentially be improved.

*Comments: The weather and changeable conditions of the Aleutians region would pose a challenge to data quality from any survey platform (manned or unmanned). Saildrone has excellent sea-keeping ability in bad weather (certainly weather beyond which a small, manned vessel could comfortably work) but it does not have the maneuverability of a powered vessel and inevitably severe weather takes its toll on data quality. The limited number of sound speed profiles and limited depth of the profiles is a problem of the current sound speed profiling system on*

*Saildrone. This is a problem that can be (and hopefully is being) addressed with modifications to winch design and other approaches to collection of sound speed data. The inclusion of absorption coefficients during backscatter data collection is a choice of the operator that can be implemented, however, if CTD data is not collected (as opposed to direct measurement of sound speed) absorption coefficients will have to be modelled or predicted. This again is not an inherent limitation of the Saildrone but is dependent on how data is collected about the water column.*

Firmware and Software Issues: Several software issues in Kongsberg firmware related to dropped pings and maximum roll were recognized and resolved by the Saildrone personnel during the initial transit to the survey areas before the actual surveys started. Extra detections were inadvertently turned on during the first transit but this too was caught quickly. Additionally Heffron and Gee, discovered several bugs in the QPS processing software (QPS Qimera = bathymetry, FMGT/Fledermaus Geocoder Toolbox = backscatter) and reported these to QPS. Those that were resolved by QPS necessitated complete reprocessing of affected files, increasing processing time. In other cases, fixes were not available, potentially reducing the quality of final products.

*Comments: Firmware and software bugs are sadly common in the industry as the creators of complex hardware and software are constantly trying to improve their product but sometimes these improvements have unforeseen downsides. This appears to be the case with respect to the problems encountered on the Aleutians cruise and are not at all unique to Saildrone. Given the detail at which Heffron and Gee processed the data, it is not unusual for them to also find software issues. Again, this is not at all a Saildrone issue.*

Limitations of Remote Access: Large lags caused by the limited bandwidth of the Inmarsat link created reduced interaction and situational awareness with systems on board the Saildrone including the mapping systems. As compared with a manned survey, this resulted in reduced monitoring of system settings and thus fewer system adjustments. This resulted in the occasional failure to quickly identify systems crashes, the collection of data with incorrect system settings (particularly overly-wide swath widths), gaps in coverage, noise, and quality of the data in some areas.

*Comments: Saildrone has a very sophisticated (and greatly appreciated) mission portal but given that these surveys were conducted remotely using Iridium Certus, these problems cannot be avoided. These problems are not unique to Saildrone but will occur with any uncrewed system with an over-the-horizon connection that depends on a low bandwidth satellite communication system. These issues will likely be resolved with the installation of Starlink or other another low-earth orbiting high-bandwidth satellite communication system. This problem would not occur on a manned survey vesse where the operators are on site with the acquisition system.*

Sail-related issues: Saildrone's ability to operate under sail offers many potential advantages with respect to mission endurance, quiet operation, and carbon footprint. However, collecting multibeam sonar data from a sailing platform also offers some challenges. Heffron and Gee explored these issues in detail. Summarizing their observations:

1- Sailing in a region of changing wind patterns and strong currents led to changing line orientation patterns and a limited ability to run crosscheck lines. This led to reduced quality control, impacts to overall coverage, and data gaps.
2- The significant variations in speed between opposing lines and often slow speeds typical of Saildrone and rapid and significant yaw (also a result of relatively small size of Saildrone with respect to the sonar) resulted in varying along track density, noisier data during severe weather, and gaps in coverage.
3- When under sail, under certain wind conditions, Saildrone will heel significantly. It was found that when there was a large (10 degrees or more) heel, the outer beams were distorted upward by about 10-15% of the depth on the downwind side of the swath. This required careful, line-by-line review to limit the rejection of 'good' data and to avoid causing gaps in the coverage; often 50 to 60 beams on the downwind side needed to be removed, substantially increasing processing time in areas where limited overlap did not allow more automated filtering or blanket application of beam clipping. The origin of this artifact is not yet understood but may be related to the limits of the roll stabilization implemented by Kongsberg.
4- The combination of these issues, and the SV issues, led to what is described by Heffron and Gee as reduced sounding density, vertical offsets in outer sectors, reduced overlap, generally lower resolution, increased data gaps, reduced backscatter quality and more noticeable artifacts than would be expected from a survey conducted on a manned survey vessel. The overall reduction in survey area based on what had to be edited and cleaned was 6.5%, reducing the area covered over the entire survey area from 16,217 sq. km to 15,133 sq. km.

*Comments: The issues raised under this heading are, for the most part, inherent to the nature of a multibeam sonar operating on a relatively small (with respect to the sonar size) vessel under sail and potentially represent challenges that may have to be considered when using a sail-based uncrewed vessel as opposed to a crewed vessel or non-sail-powered uncrewed vessel. When under sail, compromises must be made with respect to heading, and thus optimum line orientation (with respect to survey needs) may not be feasible. Saildrone also has a diesel engine, and this can be used to assist in running lines in any desired direction, but the continued use of the diesel compromises mission endurance, one of the prime advantages of a sail-powered platform. Future implementations of sail-powered vehicles for mapping missions should better account for prevailing wind conditions and this trade-off when considering mission endurance, required overlap, and needed check-lines in order to present a more realistic picture of expected* *coverage and survey time. This is also true of the variations in speed encountered. Again more realistic estimates of survey speed and approaches to mitigate changes in speed should implemented to maintain required data density and offer more realistic estimates of coverage and survey time. The problems associated with excessive heel need more investigation but may be resolvable by changes in Kongsberg software.*

*The wider swath achievable under sail is a real, inherent, advantage of a sail-powered vessel, however, as implemented, poor control of sound speed negated the value of this wider swath as refraction and other outer beam issues led to the editing of these extra outer beams. The choice of swath width also needs to be balanced with reducing swath width in unsuitable conditions. This problem is less severe in deep water where the system automatically reduces the swath width. In shallower water, this problem could be mitigated with more and deeper sound speed profiles (see above) though a robust solution to this problem from uncrewed systems has yet to be presented.*

*As noted by Heffron and Gee, the cumulative effect of the problems noted (some inherent to the sailing vessel and other resolvable by changes in firmware, software or procedures) was a 6.5% reduction of the area covered and reduced overall density when out of spec soundings and noisy data were removed.*

*In light of their experience processing the Saildrone data, Heffron and Gee also offered a series of recommendations for future operations with Saildrone (from the processors perspective):*

- Surveys should be planned with more overlap (never less than 50%), only reducing that overlap as the survey progresses if, weather conditions, sound speed environment, and regular review of the data warrant it. *(this will also depend on survey requirements which often are not rigorously produced for non-nautical charting surveys).*

- Be more pro-active manually limiting swath angles when weather conditions impact the data and the ability to collect sound speed observations.
- Monitor the vehicle position and orientation compared to the planned line and adjust subsequent lines to ensure the planned coverage is achieved. The extensive motion and yawing of the platform meant that the swath coverage was often reduced and varying along track data density.
- Take care to analyze different sound speed models in a region during planning and monitor during the survey, so as to be prepared if sound speed measurements become inadequate. Investigate other methods of collecting supporting sound speed observations (buoys, gliders?).

- Regularly collect survey crosslines, even if it means motoring.
- Plan for complete removal of any turn data in post-processing, especially mid-survey , unplanned turns or turns to accommodate line orientation change.

**Relative mapping efficiency of Saildrone survey vs. standard crewed survey vessel:**

Heffron and Gee have offered a detailed analysis of the issues found when processing data from the initial survey conducted by the prototype Saildrone Surveyor. Here we attempt to compare the relative mapping efficiency of surveying with the prototype Saildrone Surveyor as compared to a traditional data set collected by a crewed survey vessel. Given the extreme environmental conditions in the Aleutian region, we have chosen to focus our analysis on the survey conducted off the coast of California. This survey was processed by a consultant hired directly by NOAA/OER, (Marcel Peliks) but this consultant was asked only to process the data to normal NOAA/OER standards, and not do the detailed analysis that Heffron and Gee undertook. Nonetheless the report from Peliks did provide a few comments about problems encountered processing the Saildrone data. These observations area similar to some of those presented by Heffron and Gee:

- **Scarcity and depth limits of SVP's:** SVPs are only taken to a max depth of 200 m, and due to the mechanism can only be deployed during relatively calm conditions, leading to scarcity of profiles in some areas of the survey.
    - If there are sound speed artifacts in the data it is difficult to apply a different sound speed strategy during processing because there are too few profiles available. This was not a major issue for the CA surveys but could be in regions where sound velocity varies considerably.

- **Direction of ship survey line orientation:** At times the survey line orientation is adjusted for better sailing. This leads to overlapping lines and turns within the survey area. Processing in regions where survey line orientation is adjusted results in more data cleaning and adds uncertainty to the final surface. Although conventional vessels are subject to altering survey lines due to seas, the Saildrone appears more sensitive due to its size and primary propulsion method.

- **Wider swath width but outer beams may be suspect:** The quiet nature of Saildrone allows for a wider swath width than on a conventional research vessel. However, the outer beams are still subject to high uncertainty, especially if sound speed artifacts are present. If the survey line spacing is adjusted for wider coverage but outer beams end up being edited this could result in data gaps.

- **Surveying in rough weather is feasible but can also result in poor-quality data;** Since Saildrone is an uncrewed vessel, sailing in rough seas is more feasible than on conventional vessels. Nevertheless, data quality degradation and lack of SVPs during rough seas still impact the final product. Areas where Saildrone surveyed during poor weather have data quality degradation leading to more processing and more uncertainty.

Thus, similar processing issues were found in the California data set but given that the California survey represented a single large area in a region where crewed vessel surveying has been done, it presents a better opportunity to compare the mapping efficiency of the Saildrone to that of a conventional crewed survey vessel. Our approach to evaluating survey efficiency is based on the concept of area covered per unit time. We look first at the area covered per unit time for raw data collection and then adjust that to determine area covered per unit time for the final, post-processing data product, thus taking into account the quality of the data produced. The analysis does not take into account the time spent for processing, though this can be garnered from the reports of Heffron and Gee and Peliks.

**Analysis of Saildrone Survey Efficiency - Raw Data Collection**

We start our evaluation by looking at the raw data coverage of Saildrone expressed as sq km/hour. For these calculations, survey time is determined from the start and stop time of each data file. Thus this measurement of coverage is based ONLY ON ACTUAL DATA ACQUISITION TIME, it does not include any time that is spent not surveying (e.g., taking SVP profiles, transiting, weather down time, etc.). The California survey was divided into two missions (SD1200-0014 and SD1200-0015). The first mission (0014) covered 9838.83 sq. km in 367.76 hours (of just acquisition time) resulting in a coverage rate of 26.75 sq km/hr. The second mission covered 19882.6 sq km in 701.28 hours, resulting in a coverage rate of 28.35 sq km/hr. We will focus on the first (SD1200-0014) mission as we have a comparator survey done by Okeanos Explorer that is of similar size and in the same general region.

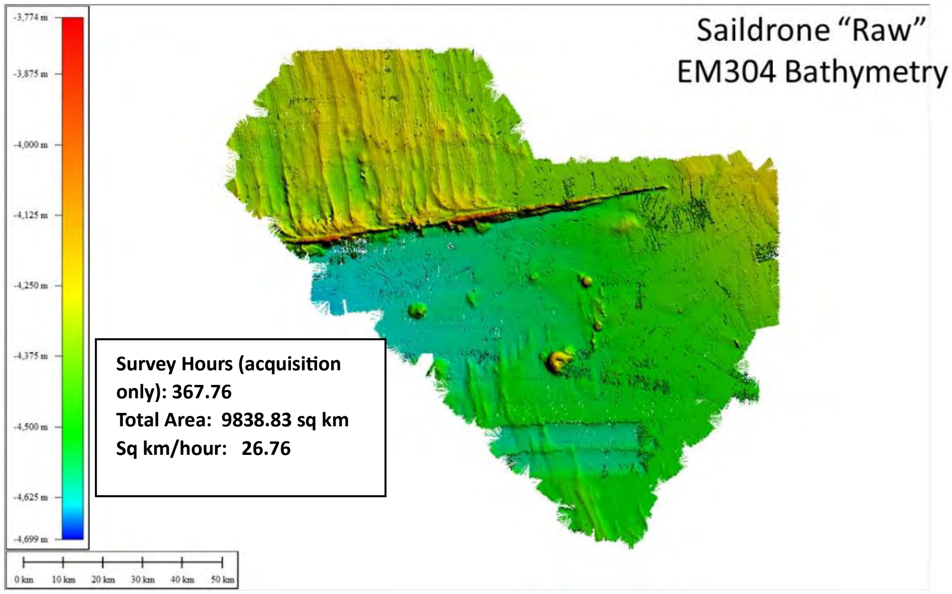



*Figure 4. Raw data from Saildrone collected in California Survey area*

As a qualitative measure of the overall quality of the survey data we also looked at how much "overlap" was achieved during the survey, making the simple, but reasonable assumption that more overlap will provide some redundancy and will generally improve the quality of the data. We define overlap as the presence in any given 100 m cell of soundings from two or more different swaths.

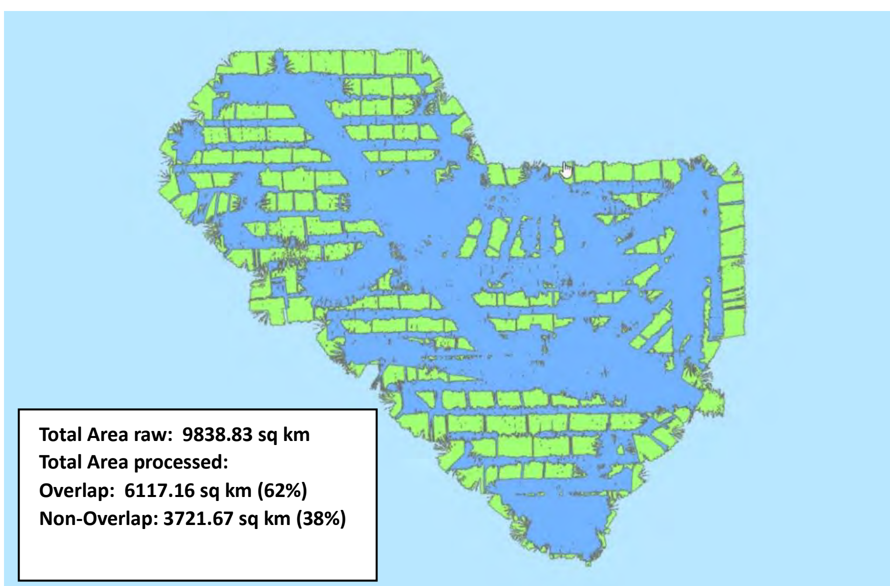



*Figure 5. Overlap in raw data – blue is overlapped and green non-overlap*

As shown in Figure 5, 62% of the raw data collected had soundings from more than one swath in a given gridding cell, though the non-overlapping swaths are distributed throughout the survey area..

If we then compare the raw data to the processed data, we see the impact of data quality as expressed in the amount of data edited by the processors. We will make the oversimplifying assumption that after processing the data are acceptable for NOAA OER purposes.

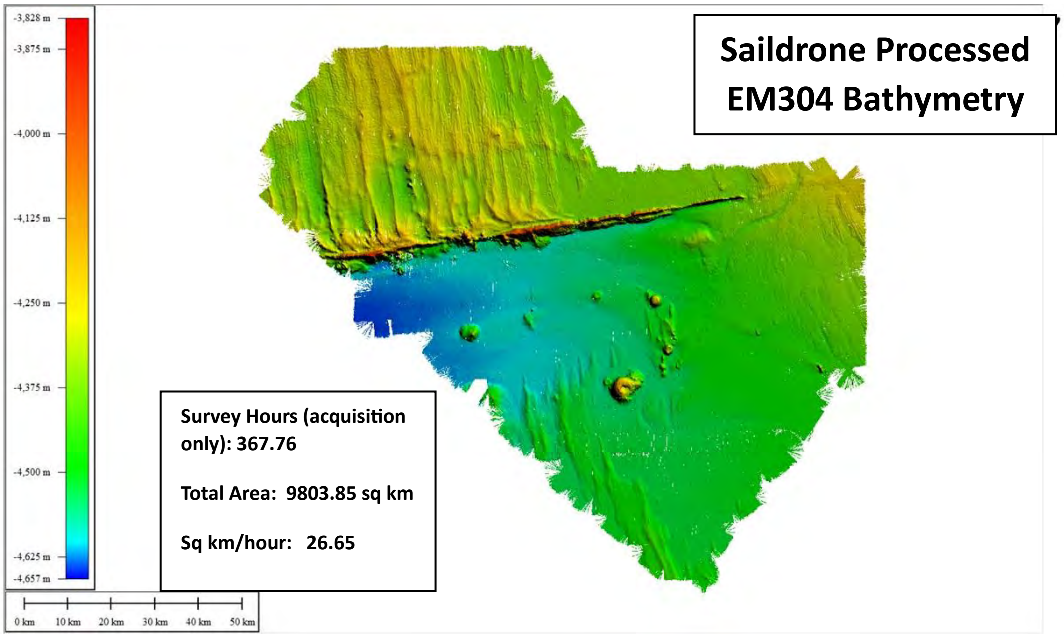



*Figure 6. Processed Saildrone Bathymetry from Mission DS1200-0014.*

After processing, the overlap the achieved overlap was also reduced slightly from 62% to 58% (Figure 7).

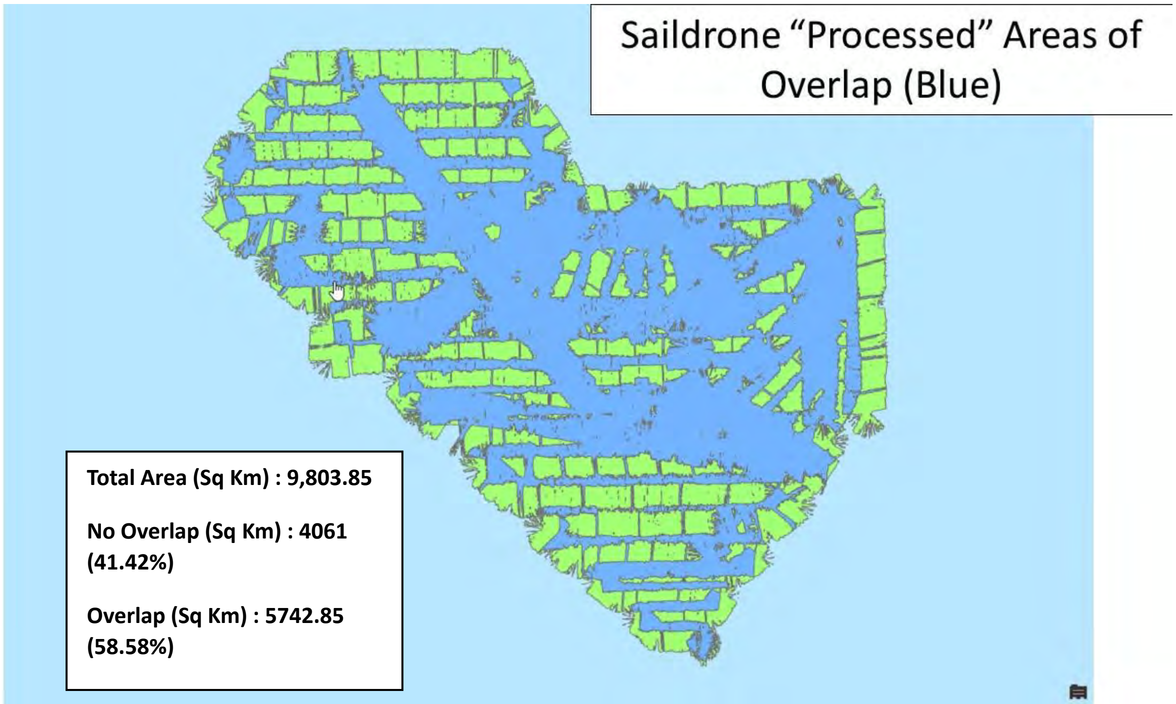



*Figure 7. Overlap in Saildrone processed data – blue is overlapped and green non-overlap*

Comparing the total area covered after processing the area covered in the raw data we see only a small reduction in coverage to 9,803.85 sq. km, representing a reduction in the area of only .2% after processing. This is in sharp contrast to the reduction of 6.5% determined by Heffron and Gee for the Aleutians survey. This contrast in the amount of data removed during processing may be the result of the significantly different environmental (weather and sound speed variations) conditions in the Aleutian region compared to the California survey area or due to different levels of aggressiveness in data cleaning; most likely it is a combination of both. Finally, we can look at the data density achieved during the Saildrone survey, post-processing (Figure 8).

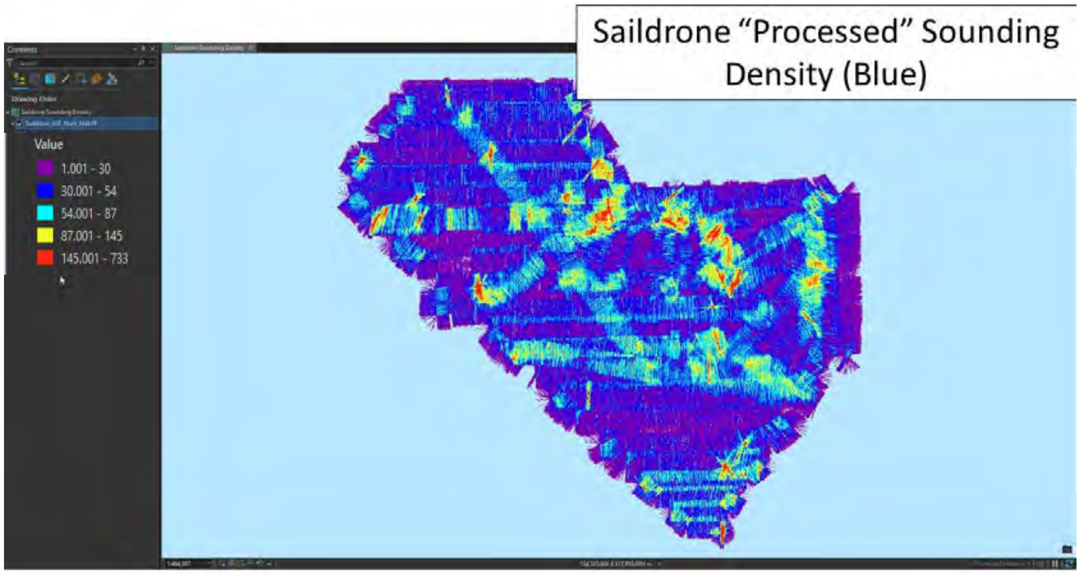



*Figure 8. Density of Saildrone sounding coverage after data processing – soundings/100 m grid cell.*

We now contrast the SD1200-0014 survey to an OKEANOS EXPLORER survey (EX2208) a 12,866 sq km survey conducted between October 16 - November 3, 2022 in area off the coasts of California and Oregon with similar water depth (Figure 8). The EX2208 used anEM304 MKII which has same frequency and power levels as EM304 MKI on Saildrone Surveyor; the Saildrone Surveyor EM304 is 1 x 2 deg while OKEANOS EXPLORER's EM304 is 0.5 x 1 deg, but this should not impact coverage or survey efficiency.

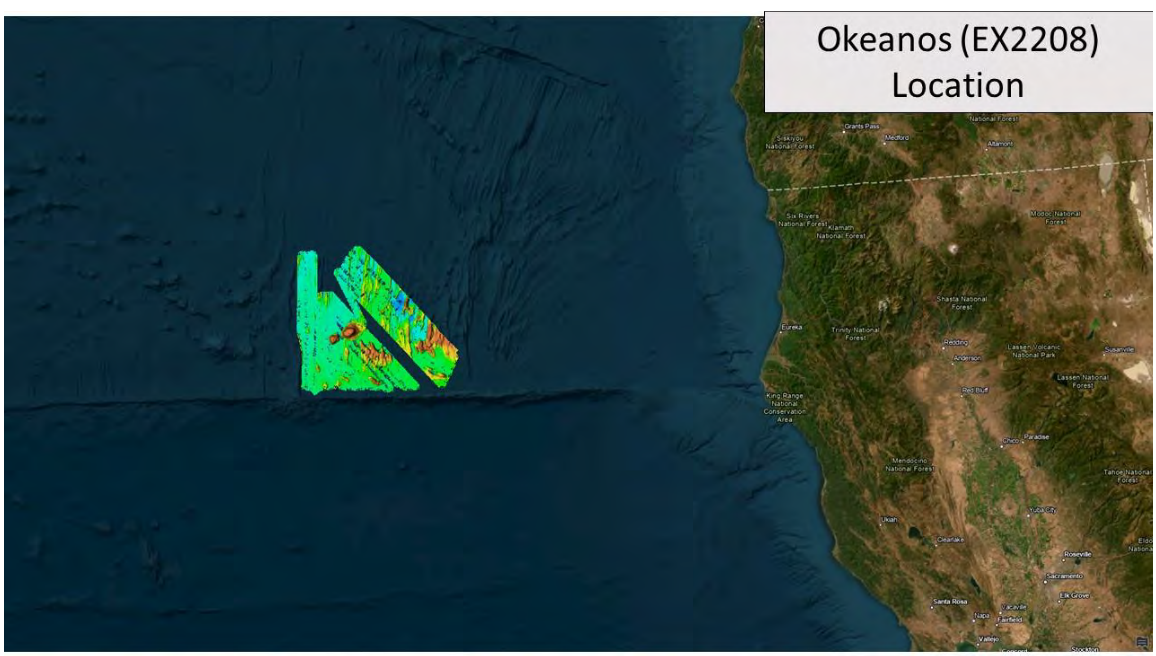



*Figure 8. OKEANOS EXPLORER CRUISE EX2208 – a 12,866 sq. km survey off coast of northern California and Oregon*

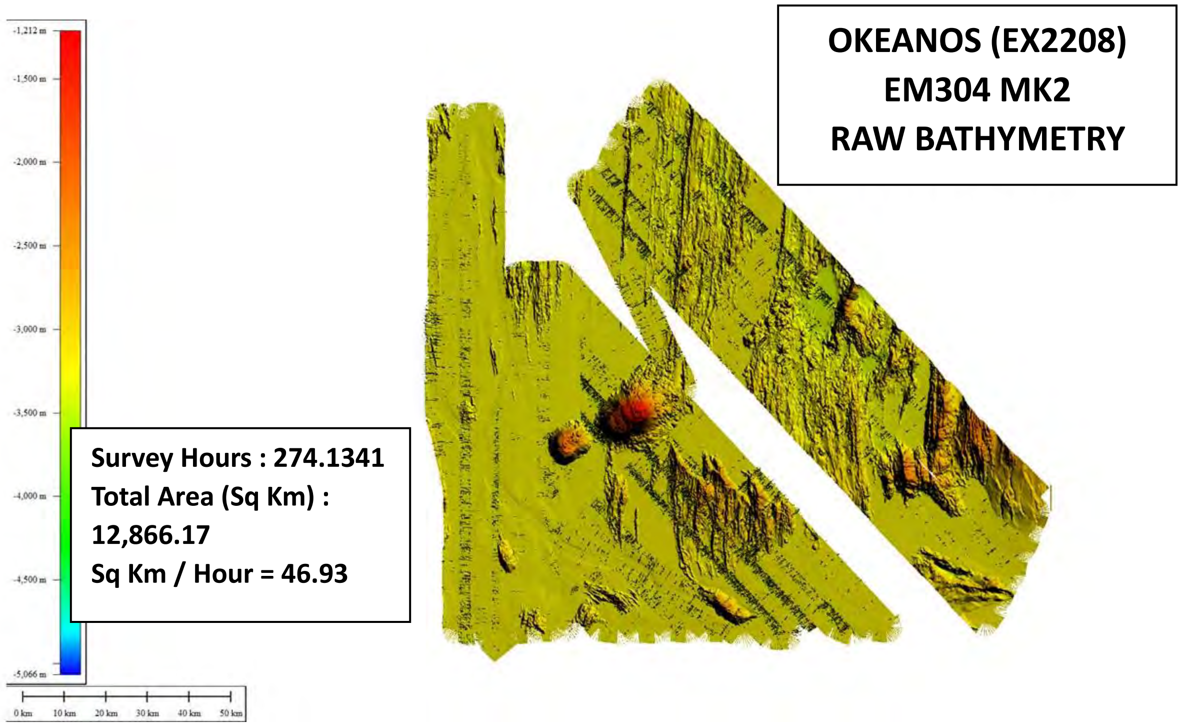



*Figure 9. Raw bathymetry from EX2208*

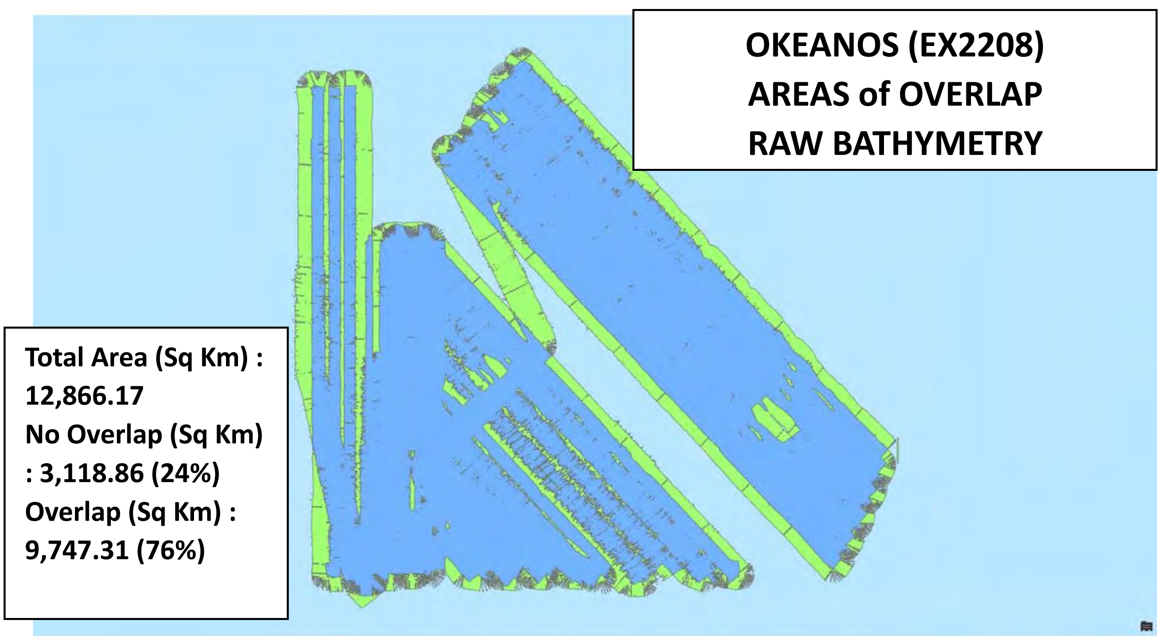
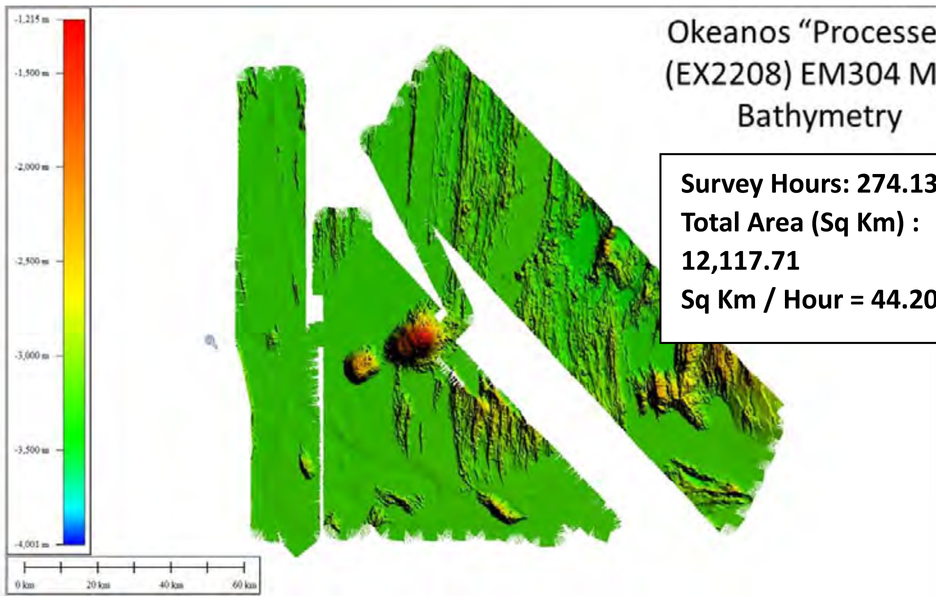



*Figure 10. Overlap in raw EX2208 data – blue is overlapped and green non-overlap.*

Looking now at the processed data for EX2208 (Figure 11), we see that the covered area is reduced from 12,866.17 sq. km to 12,117 sq km or a reduction of 5.8%. It is difficult to know whether this is due to environmental conditions or processing approach.

*Figure 11.*




*Bathymetry from EX2208 after processing.*

Despite the reduction in survey area resulting from processing (cleaning and editing), the percentage of area that had overlap remained at 76% indicating that most of the editing was of likely in areas of minimal or no overlap, e.g., outer-most swaths of the survey (Figure 12). It is important to note that most of the area that does not overlap is located on the outer edge of the survey area where overlap would not be expected. It also demonstrates the value of overlap for providing higher quality data that may not need to be edited as well as improving the quality of backscatter data.

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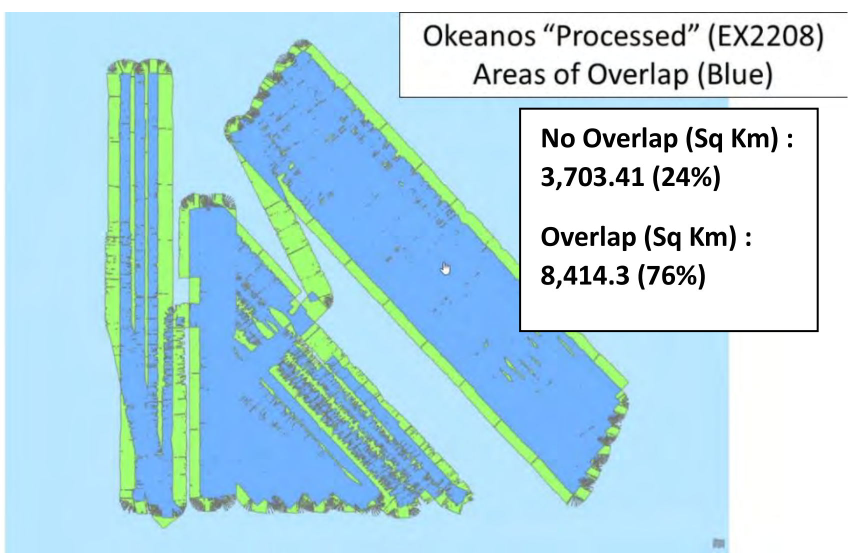


*Figure 12. Overlap in processed EX2208 data – blue is overlapped and green non-overlap.*

Finally, we look at data density for the OKEANOS EXPLORER survey.

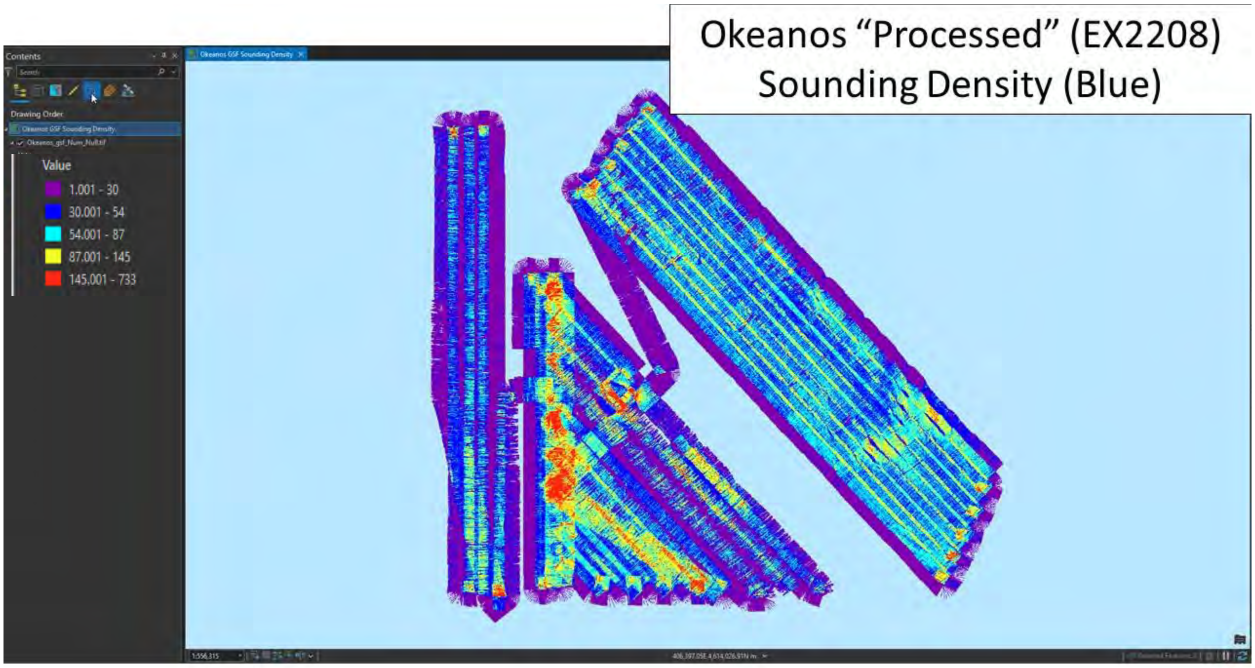


*Figure 13. Density of sounding coverage after data processing – soundings/100m grid cell.*

**Discussion:**

It is immediately clear from the comparisons above that in comparing coverage achieved through the comparison of the Saildrone data and the OKEANOS data indicates that the OKEANOS achieved significantly higher coverage as expressed in sq km/hour. This is true for the raw data (26.75 sq km/hr for Saildrone vs 46.93 sq km/hr for OKEX) where OKEX collected 1.75 times as much coverage per hour as Saildrone. When looking at the processed data, Saildrone collected 26.65 sq km/hr vs OKEX’s 44.20 sq km/hr or a factor of 1.66 times as much data per hour for OKEX (though we suspect that this difference reflects the differences in data cleaning approaches rather than survey efficiency). Another significant difference is found in the overlap achieved where 58.6% of the processed data Saildrone showed overlap while 76% of the OKEX overlapped. Areas with no overlap were mostly in the outer edges of the OKEANOS survey region while they were scattered throughout the Saildrone survey. Again, we associate more overlap with the higher quality data as increased redundancy will inevitably help increase signal to noise. This is supported by the data density plots that show, for the most part, that the OKEX achieved a much higher data density than the Saildrone.

Most significantly with respect to survey efficiency are the differences in coverage rate. This of course is mostly related to the difference in the speed of the survey (for SD1200-0014, Saildrone averaged 3.95 knots – the highest average speed of any Saildrone survey) while the OKEX surveyed at an average speed 7.95 knts. Superimposed on the differences in survey speed are achievable swath, efficiency of track line orientation, and amount of data edited, but inevitably it is the survey speed that is the major factor.  Given the difference in survey speed, it is surprising that the coverage rates are only different by a factor of 1.66.  This may be related to the wider swath achievable by Saildrone while sailing and the greater amount of overlap achieved by the OKEANOS EXPLORER . While the value of this wider swath was called into question by Heffron and Gee, it may be that even after editing there still is a wider swath achieved by the Saildrone while under sail.

Another approach to evaluating the relative efficiency of the Saildrone is to ask the question: “How long would it have taken a crewed vessel to do the same survey.    To explore this, we have used the “BathyGlobe GapFiller” program (Ware, Mayer and Johnson, in press), a software package designed to support planning for transit and area mapping, that adjusts line spacing to achieve desired swath coverage as a function of water depth and the known characteristics of the sonar being used, and then calculates detailed statistics representing planned survey coverage, overlap and time to complete the survey.

A polygon representing survey area SD1200-0014 was entered into GapFiller and the time to complete the survey using the OKEANOS EXPLORER was calculated.  The calculations were based on achieving 100% overlap (200 % coverage – i.e., the outer beams of the swath were aligned with nadir of the previous lines, thus every point was surveyed at least twice except for the outer-most swaths of the survey area).  The survey speed was set to 9 knots and the calculated swath width was constrained as a function of depth by the measured extinction curve of the EM304 on the OKEANOS EXPLORER (Figure 14). The results showed that the entire area could be surveyed by the OKEANOS EXPLORER at 9 knots with 100% overlap in 7.33 days.  As with the other estimates, this reflects only survey time, it does not include time for SVP profiles or other activities.

As a sanity check for the BathyGlope Gap Filler automated analysis, a manual estimate was done using the same parameters (speed, overlap, etc.) except instead of adjusting the swath for the known depths, an average depth of 4450m was used resulting in constant line offset of 3873 m.  This process resulted in an estimate of 7.58 days, similar enough, considering the difference in depth information used, to be fairly confident in these estimates.

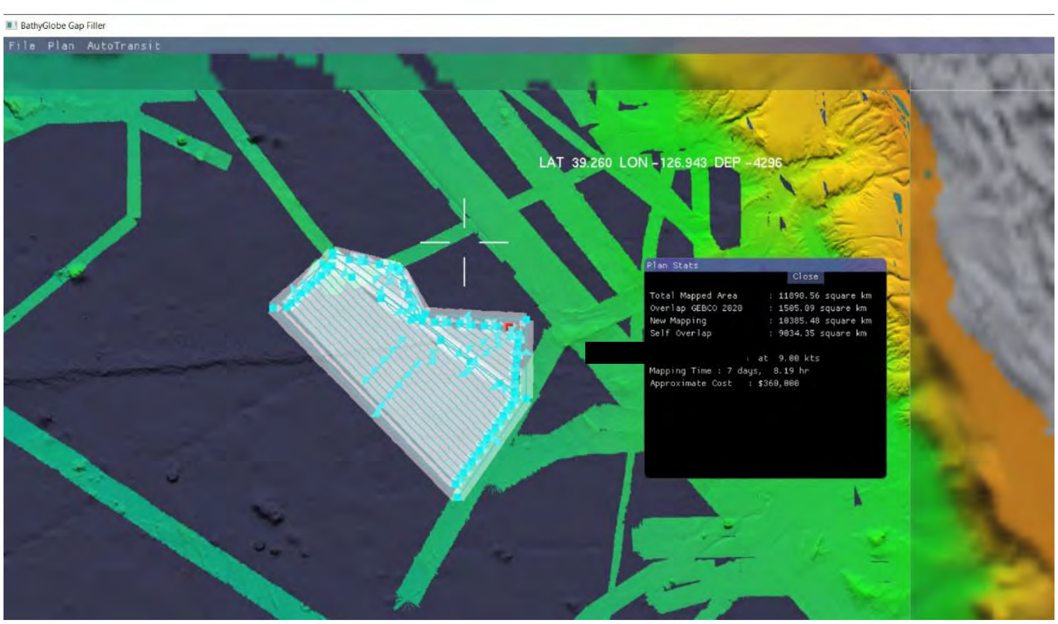

*Figure 14. BathyGlobe Gap Filler estimate of time required to cover survey area SD1200-0014 using the OKEANOS EXPLORER's EM304's measured extinction curve (coverage vs water depth) and swaths adjusted for actual seafloor depths derived from predicted bathymetry from satellite altimetry. A survey speed of 9 knots was assumed and 100% overlap.*

The estimates above were based on 100% overlap, an ambitious goal and one not often realized during exploration-based survey work (as opposed to surveying in support of chart-making). The actual OKEANOS EXPLORER survey used for comparison above, achieved approximately 76% overlap (after processing) and the Saildrone survey of SD1200-0014 achieved approximately 58.58% overlap after processing. Adjusting the BathyGlobe Gap Filler estimates to 58.58% overlap resulted in an estimated survey time of approximately 5.5 days; the manually calculated comparison (again using an average depth for the survey area of 4450 m rather than the actual changes in depth) resulted in a similar estimate.

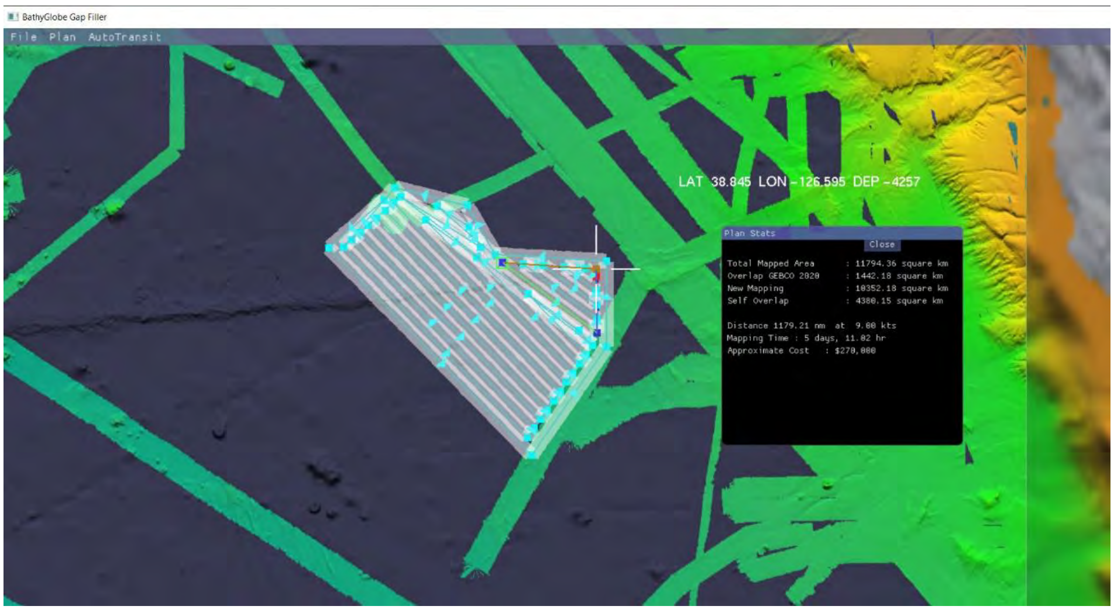


*Figure 14. BathyGlobe Gap Filler estimate of time required to cover survey area SD1200-0014 using the OKEANOS EXPLORER's EM304's measured extinction curve (coverage vs water depth) and swaths adjusted for actual seafloor depths derived from predicted bathymetry from satellite altimetry. A survey speed of 9 knots was assumed and 58% overlap.*

It should be noted that a value of 9 knots was used for the OKEANOS EXPLORER survey speed based on the NOAA OER Deepwater Exploration Mapping Manual which describes 8-9 knots as the optimal speed for OKEX deepwater mapping. Should lower speeds be used, it would increase the time estimates proportionally.

**Summary:**

Summarizing these observations, it took **Saildrone 15.25** mapping days to cover the area of SD1200-1400. Data **coverage rate** was about **26.65 sq km/hr** with an average speed of **3.95 knots** (which was significantly higher than any other Saildrone survey). In completing this survey, after data processing, approximately **58.58%** of the 100 m grid cells had soundings from more than one swath (overlap). Comments about data quality with respect to processing load can be found in the Heffron and Gee, and Peliks reports attached. Using a **comparator OKEANOS EXPLORER survey** in the same general area with similar water depths (EX2022), the OKEANOS EXPLORER had a **coverage rate** of approximately **44.20 sq km/hr** after processing with approximately **76%** of the grid cells have soundings from more than one swath (overlap).

Two efforts were also undertaken to estimate the time it would have taken to survey the SD1200-1400 area using the OKEANOS EXPLORER, a manual calculation using an average depth for the survey area and fixed line offset based on that average depth, and the newly developed survey planning software BathyGlobe Gap Filler which calculates achievable swath width based on predicted bathymetry from the GEBCO global grid compilation and a measured extinction curve for the EM304 on the OKEANOS EXPLORERER and then adjusts line spacing based on this. A survey speed of 9 knots was used for both approaches. The results of these two approaches were in reasonable agreement and showed that the OKEANOS EXPLORER could cover the same area that Saildrone surveyed in **15.25 days** in **7.33 days** of mapping while achieving **100% overlap.** To complete a survey of area SD1200-1400 with overlap of **58.58%**, equivalent to that achieved by the Saildrone Surveyor in **15.25 days**, it would take the OKEANOS EXPLORER approximately **5.5 days.** Had a 12 kHz (EM124) system been used for this survey area it could have been completed with **100% overlap** in **3.58 days** and at **58.58% overlap** in **3.16 days.**

**The comparisons presented herein reflect only the efficiency of survey time and relative quality of data. They do not address issues of crew safety, carbon footprint and relative costs. In comparing the overall cost-effectiveness of uncrewed vs crewed survey vessels, these factors must also be taken into account.**

**References:**

Hoy, S., Lobecker, E., Candio, S., Sowers, D., Froelich, G., Jerram, K., Medley, R., Malik, M., Copeland, A., Cantwell, K., Wilkins, C., and Maxon, A. (2020). NOAA OER Deepwater Exploration Mapping Procedures Manual. Office of Ocean Exploration and Research, Office of Oceanic and Atmospheric Research, NOAA, Silver Spring, MD 20910.

Ware, C., Mayer, L.A. and Johnson, P., in press, BathyGlobe GapFiller: A Planning Tool to Help Fill the Gaps in World Bathymentry, International Hydrographic Review

# Mapping Processing Summary Report

## SD1200-0012-13: Aleutians Uncrewed Ocean Exploration (Mapping)

Aleutian Islands Region, Alaska
Unalaska (Dutch Harbor), Alaska, to direct transit to Almeda, California
August 9, 2022 – October 3, 2022

Authors:
Erin Heffron[1], Lindsay Gee[1]

[1] Ocean Mapping Services LLC

August, 2023

Ocean Mapping Services LLC
978 South Street
Portsmouth, NH 03801

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# Introduction

The Aleutians Uncrewed Ocean Exploration expedition was facilitated and led by the NOAA Ocean Exploration Cooperative Institute (OECI)[1]. The goal of the expedition was to collect ocean mapping and environmental data in unexplored waters around the Aleutian Islands, identified as high priority for NOAA, BOEM, the U.S. Geological Survey, and the broader federal Interagency Working Group on Ocean Exploration and Characterization[1]. All work conducted contributed to the Seascape Alaska regional mapping campaign[1].

Data was collected by the Saildrone Surveyor SD-1200, an uncrewed surface vessel for ocean exploration. Along with Saildrone, the University of New Hampshire's Center for Coastal and Ocean Mapping and NOAA Ocean Exploration staff managed at-sea operations.

As described in the *Bathymetry Mission Plan: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012* (Saildrone et. al, 2022), the effort directly addressed one of the fundamental objectives of the OECI: the development of new approaches and technologies that will enhance the nation's ability to map, explore and characterize the oceans with particular emphasis on the potential of the use of uncrewed systems as a means to increase the efficiency and cost-effectiveness of these activities. The OECI's Ocean Exploration Technology theme includes the increase of identification and integration of new autonomous exploration vehicles for enhancing the collection of ocean exploration data. A fundamental constraint for the project of these systems is the limit of the bandwidth currently available for the transmission of control commands and data to and from autonomous vessels to shore-based facilities or a mother vessel. The project provided data on the limitations and constraints of working far "over-the-horizon." The lessons learned on the project can inform the efforts of all OECI partners (University of Rhode Island, Ocean Exploration Trust, University of Southern Mississippi, University of New Hampshire and Woods Hole Oceanographic Institute) as they work collectively to extend the footprint and efficiencies of exploration activities.

The project was initially planned to have one expedition leg, SD-1200-0012. The Surveyor briefly returned to Unalasksa (Dutch Harbor), AK for maintenance and data unload in September 2022. Acquisition before the return to Unalaska was thereafter called SD-1200-0012, while the leg after the September maintenance was called SD-1200-0013. Under advice from project partners and the national archive (NOAA's National Centers for Environmental Information or NCEI), the expeditions were combined for the purposes of reporting and archiving under the name SD1200-0012-13.

# Report Purpose

The purpose of this summary report is to briefly describe the acoustic seafloor processing methods used by Ocean Mapping Services LLC (OMS) for the Saildrone Surveyor SD-1200 Aleutians Uncrewed Ocean Exploration multibeam mapping legs SD-1200-0012 and SD-1200-0013, hereafter referred to as SD1200-0012-13, and to present a summary of mapping results.

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[1] https://oceanexplorer.noaa.gov/news/oer-updates/2022/uncrewed-saildrone-alaskan-waters.html

This report should be read in conjunction with the planning, calibration and acquisition documents created by Saildrone staff and project partners (also listed in References):

- *Saildrone Bathymetry Mission Plan: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August 09 – September 09, 2022* (Saildrone et al., 2022)
- *Saildrone Surveyor Bathymetry Data Structure Guide* (Saildrone, 2022d)
- *Saildrone Bathymetry Data Management Plan: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August – October, 2022* (Saildrone, 2022b)
- *SD-1200 Bathymetry Configuration. 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August 09 – September 09, 2022* (Saildrone, 2022a) – SAILDRONE PROPRIETARY
- *Saildrone Surveyor EM2040 & EM304 Multibeam Echosounder Sea Acceptance Testing Jan - Mar 2021* (Jerram, Johnson, and Mayer, 2021)
- *Saildrone Bathymetry Patch Report: 20220630 Offshore Testing SD-1200-0010, Saildrone Internal, Offshore San Francisco, Jun 30 – Jul 8, 2022* (Saildrone, 2022c) - SAILDRONE PROPRIETARY
- *Saildrone Bathymetry Acquisition Report: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August 09 – September 09, 2022* (Peters and Baechler, 2022a)
- *Saildrone Bathymetry Acquisition Report: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0013, Aleutian Islands Region, AK, September 11 – October 03, 2022* (Peters and Baechler, 2022b)

These supplementary documents are important references. Material in this report utilizing (or directly extracted from) these sources has been noted. In some sections, reference is made to the appropriate report in lieu of repeating information.

# Expedition Overview

The following expedition overview was extracted and updated where required from the following document: *Bathymetry Mission Plan: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012* (Saildrone et. al, 2022).

The Aleutian Island chain in western Alaska is one of the most remote and understudied regions of the U.S. EEZ. As an oceanic-arc subduction zone, the chain has consistently been identified as a priority area for NOAA programs such as the Office of Ocean Exploration and Research (OER), Pacific Marine Environmental Laboratory (PMEL), Deep-Sea Coral Research and Technology Program (DSCRTP), and the Office of Coast Survey (OCS), as well as the Bureau of Ocean Energy Management (BOEM) and the United States Geological Survey (USGS) with cross-disciplinary interests. Before any substantive exploration and characterization work can be completed, however, high resolution bathymetry coverage is needed across almost the entire region. At just 28% percent mapped, Alaska is the least mapped region of the U.S. EEZ by far.

The expedition used the Saildrone Surveyor SD-1200, a 22 m long, uncrewed surface vehicle that is equipped with both shallow and deep water multibeam mapping systems with a hull-mounted sound velocity probe and deployable sound velocity profiler to map remote areas of the Aleutians that were identified as priorities for multiple NOAA programs, interagency partners, and external stakeholders (**Figure 1**). Priority polygons covering approximately 52,571 sq km were identified at varying depth ranges (100 - 6,000 m).

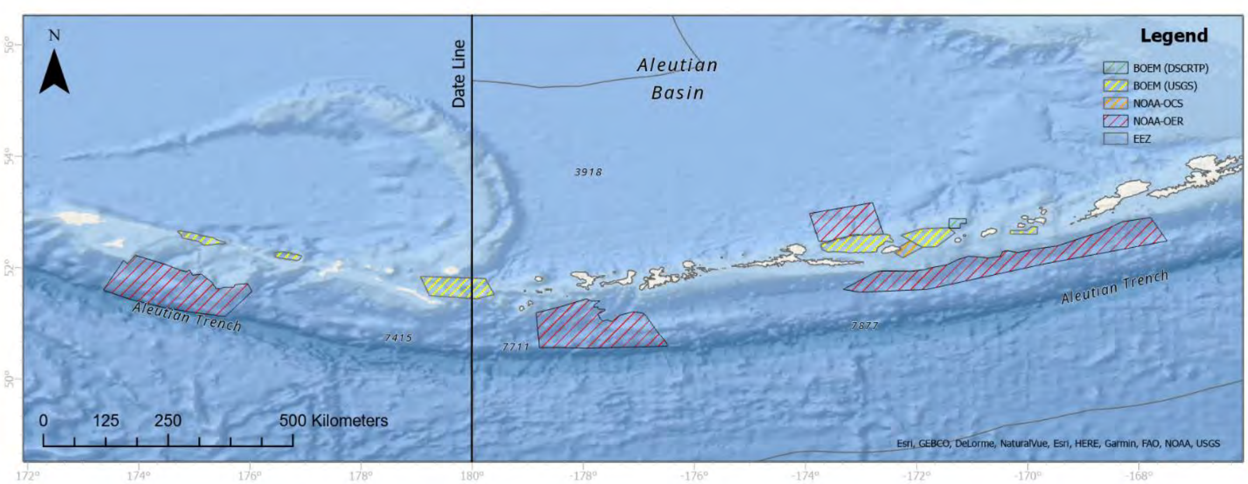



**Figure 1**. Overview of planned survey areas, from the mission plan (Saildrone et al., 2022).

# Processing Personnel

SD1200-0012-13 mapping data processing was undertaken remotely by personnel in Honolulu, HI and Portsmouth NH, February to August 2023 (**Table 1**). They had not been involved with planning of the surveys or data acquisition. Personnel involved in acquisition are listed in the *Saildrone Bathymetry Mission Plan: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012* (Saildrone et al., 2022).

**Table 1.** SD1200-0012-13 Mapping processing personnel.

| Name | Role | Affiliation |
|---|---|---|
| Erin Heffron | Mapping Processing Lead | Ocean Mapping Services LLC |
| Lindsay Gee | Mapping Processor | Ocean Mapping Services LLC |

# Summary of Mapping Processing Results

After post-processing, the area mapped by SD-1200 was 15,133 square kilometers (sq km) of seafloor from the 52 days of surveying for SD1200-0012-13. All the area was within the U.S. Exclusive Economic Zone and Territorial Sea. Polygons of multibeam bathymetry data coverage are shown in (**Figure 2**).

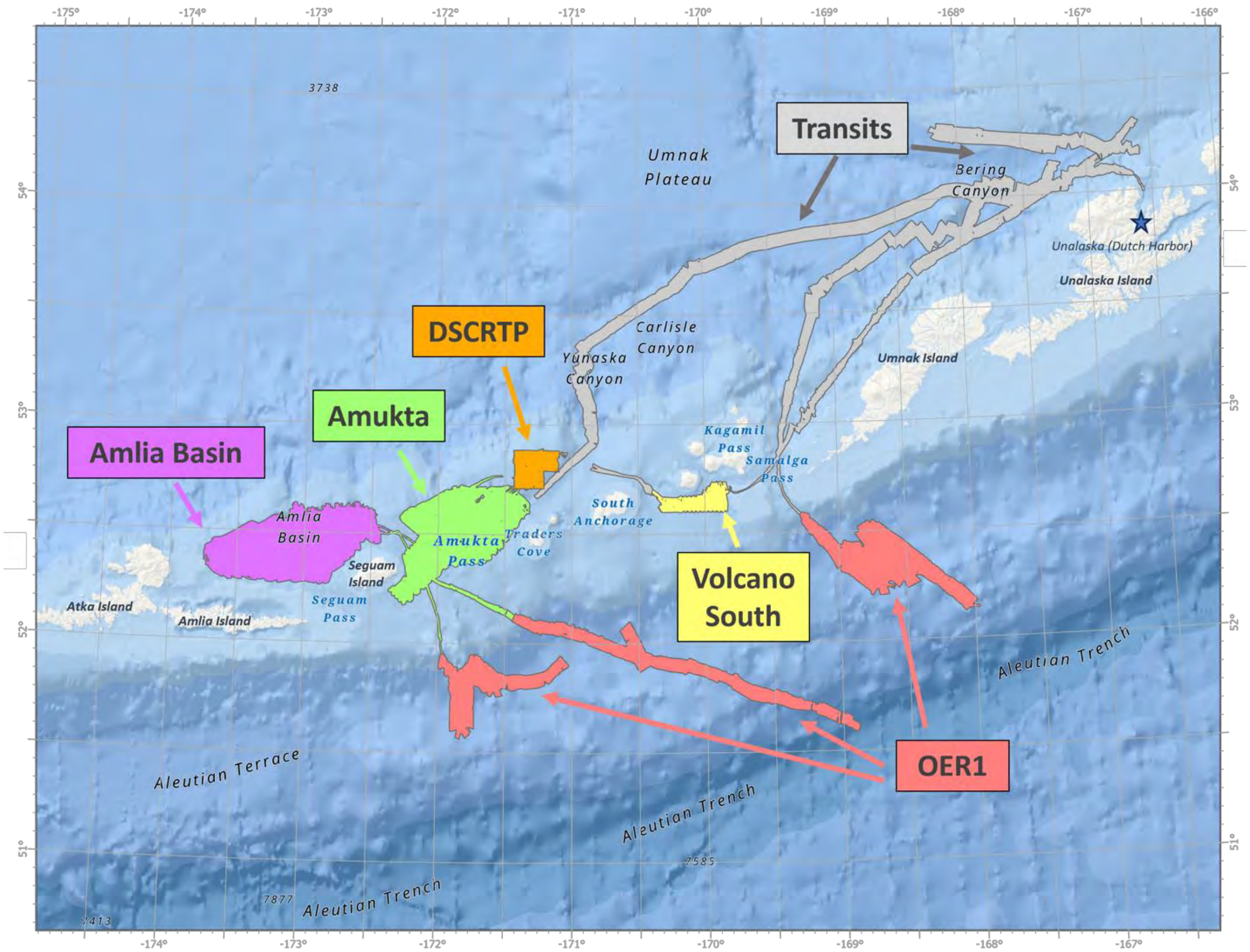



**Figure 2.** Overview of bathymetric mapping coverage completed during SD1200-0012-13.

# Mapping Statistics

**Table 2** provides summary statistics of ocean mapping results after processing for SD1200-0012-13 [August 10 to October 3, 2022] (UTC). Note that combining the area mapped for the EM 304 and EM 2040 as listed below results in a slightly higher total mapped area then listed in the Summary of Mapping Processing Results section above (15,138 sq km vs. 15,133 sq km). This is due to the existence of small areas where both EM 304 and EM 2040 data were collected. This repeated area was only counted once in the total area mapped.

**Table 2.** Summary statistics of ocean mapping after processing SD-1200 0012-13.

| Statistic | Value |
|---|---|
| SD-1200 Configuration – EM304 and EM2040 | See configuration and acquisition reports |
| Linear kilometers of survey with EM 304 | 6,311 |
| Linear kilometers of survey with EM 2040 | 1,016 |
| Square kilometers mapped with EM 304 (all within U.S. EEZ) | 14,759 |

| | |
|---|---|
| Square kilometers mapped with EM 2040 (all within U.S. EEZ) | 379 |
| Number/data volume of EM 304 and EM2040 processed multibeam files (.gsf) | 2,690 files/123 GB |
| Number and data volume of data products from EM304 and EM 2040 processed data | 2,952 files/41 GB |
| Number of SV, conductivity, temperature, depth profiler (CTD) casts | 69 |

# Mapping Sonar Setup & Data Acquisition Summary

Details of the Kongsberg EM304 and EM2040 multibeam sonars and the SD1200-0012-13 data acquisition can be found in the following documents, which were generated by the Saildrone team:

- *SD-1200 Bathymetry Configuration. 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August 09 – September 09, 2022* (Saildrone, 2022a) – SAILDRONE PROPRIETARY
- *Saildrone Bathymetry Acquisition Report: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August 09 – September 09, 2022* (Peters and Baechler, 2022a)
- *Saildrone Bathymetry Acquisition Report: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0013, Aleutian Islands Region, AK, September 11 – October 03, 2022* (Peters and Baechler, 2022b)

# Multibeam Sonar Bathymetric Data Processing and Quality Assessment

The bathymetry data were generated using a Kongsberg EM 304 MKI multibeam system and Kongsberg EM 2040 multibeam system and recorded using Kongsberg's Seafloor Information System (SIS) software as *.kmall files. Collocated to the bathymetric data, bottom backscatter data were collected and stored within the *.kmall files, both as beam averaged backscatter values, and as full time series values (snippets) within each beam. Water column backscatter data were recorded separately within *.kmwcd files. See the acquisition reports for more information (Peters and Baechler, 2022a, 2022b).

The full-resolution multibeam .kmall files (Level-00 data) were imported into QPS Qimera, and then processed and cleaned of noise and artifacts. Some files had issues preventing them from being loaded. In each case it was confirmed that the file was corrupt or contained no data, which in either case makes it unusable. Once that was confirmed, the file was removed from the project and the issues were noted in the line log for the appropriate system. Some of the loadable files were found to have major heading issues. These files were also removed from the project and noted in the log; further information is found in the Potential Seapath Issue section below. Files that only contained sharp turn data in areas where other data existed were also removed from the project, with a comment added to the line log. In all, 49 lines of the total 2739 raw files were removed from Qimera projects for various reasons and not processed.

Outlier soundings were removed using multiple methods including automatic surface filtering, line-based filtering of outer beams, and/or manual cleaning with the 2D Slice and 3D Editor tools. In some cases, extensive manual cleaning was done to minimize residual artifacts from sound speed biases, outer beam issues, and minimal overlap. There was also additional manual review and processing required to 'unreject' good soundings where they were rejected by surface based automatic filters. This was typically found on slopes, or where underlying data issues left a high density of poor data that biased the filter in a detrimental way. Notes about additional cleaning steps were compiled in a report, *SD-1200 System Performance & Data Processing Observation, SD-1200-0012 & SD-1200-0013* (Gee and Heffron, 2023), which is available by request[2].

In most cases, the sound speed profiles utilized in post-processing were those applied during acquisition (and therefore stored within the *.kmall files); in some cases, a different profile from the region was applied if it was more appropriate for the data in that region (closer in location or time, was an observed profiles from a similar region vs. a synthetic profile, etc.). The line report CSV exports for each survey area are included with the archived data and have a line-by-line list of which profile was applied, based on the naming within the Qimera project; Qimera processing projects were provided to project partners at the University of New Hampshire and may be available on request, but were not submitted to archive at NCEI. Final quality checks of the data were done using QPS Qimera and Fledermaus software.

There were no specific crosslines run during the surveys, and checks were only possible in some survey areas. For further details see Crossline Analysis section below and the reports in Appendix B for more details.

The backscatter processing in QPS FMGT utilized the *.gsf files exported from each survey area on completion of bathymetry processing to create survey area mosaics. There were two FMGT issues that affected the processing and the mosaics generated. The latest GSF library does not fully support the KMALL format and will produce a different processed result for mosaics generated with the GSF vs the raw KMALL. The preferred option would be to use the KMALL but there is currently no method of not including the data rejected during processing in Qimera. A second issue was reported on the next leg of the SD-1200 survey off the California coast and affects the way mosaics are generated. This bug revealed that the data is added to the mosaic sequentially in time, not geospatially in the location where the sonar footprints ensonified the seafloor. This is not evident in larger platforms with less motion than the SD-1200 and when pitch stabilization is used. Noting these issues, no attempt was made to adjust any offsets between lines or different sonar modes, and it is recommended that the backscatter be reprocessed once the issues have been resolved by QPS.

Each line of cleaned full resolution data was exported to a *.gsf file (Level-01 data) and .txt XYZ file (Level-02 data). The processed and cleaned .xyz files were used to create a static surface in QPS Fledermaus in the geographic WGS84 reference frame. This final surface was

[2] Contact: Ex.ExpeditionCoordinator@noaa.gov

saved as a .sd file for archiving. Using QPS Fledermaus, this *.sd bathymetric grid file was then exported into ASCII XYZ grid text file (*.xyz), sun-illuminated color image *.tif, floating point *.tif with bathymetric depth values, and Google Earth *.kmz file formats. The *.gsf files were used to create survey area mosaics using QPS FMGT. All products maintain horizontal referencing to WGS84 (G1762) and vertical referencing to the assumed mean waterline. There is a complete accounting of each individually archived multibeam data file and of each bathymetric surface product in the multibeam data processing logs (line logs) archived with the dataset (Ancillary data).

Final bathymetric grids of individual survey areas were imported into Esri ArcGIS Pro and the Raster Domain Geoprocessing tool was used to create survey footprint polygons of each survey (Ancillary data). The Calculate Geometry tool was then used to calculate the area in square kilometers of each polygon utilizing the Esri Cylindrical Equal Area (world) projection (Esri WKID 54034). This value was added to the attribute table for each polygon. All of the individual surveys were merged using the Merge Geoprocessing tool in order to calculate to total surveyed area for this expedition while also accounting for (and removing) areas of overlapping data between individual surveys (for example, areas where overlapping EM304 and EM2040 data was collected in the vicinity of the DSCRTP survey area); this value was used in all reporting of total surveyed area in this report. An additional overview raster domain was created after combining all of the processed GSF files into a single 100 m grid; note that calculated area for this file will be slightly exaggerated due that larger grid size. Surface statistics were also generated in QPS Fledermaus and provided (Ancillary data).

**Figure 3** summarizes the date processing and quality assessment flow.

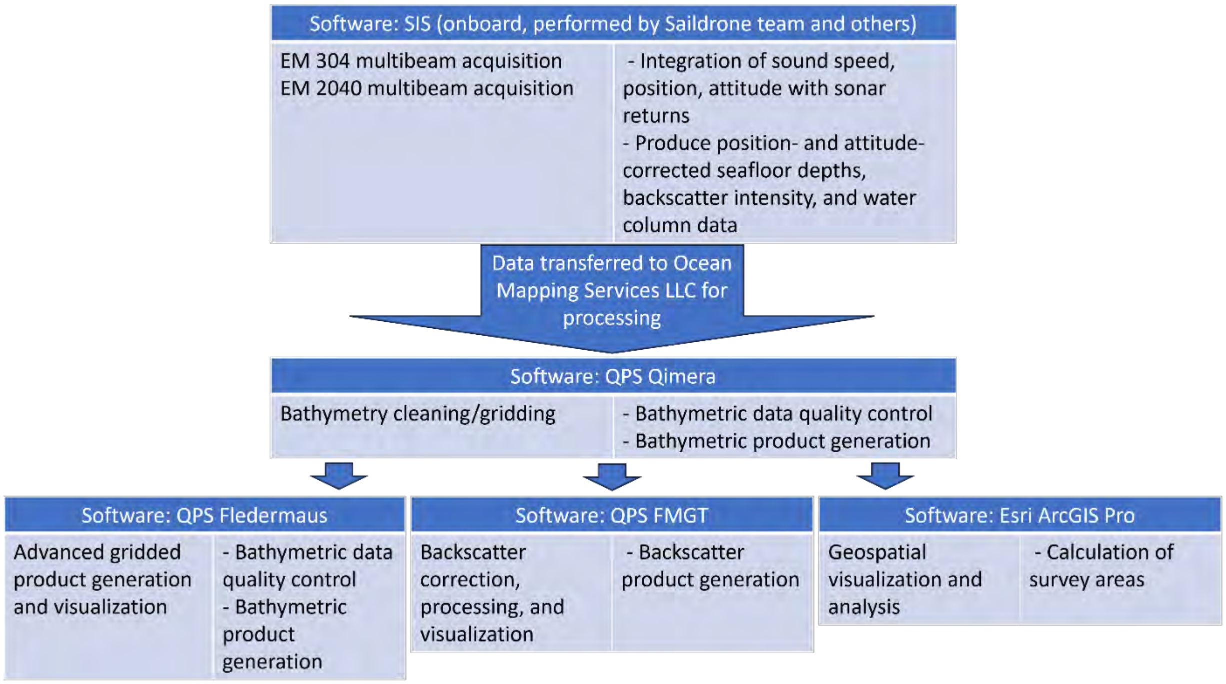



**Figure 3.** Multibeam data processing workflow.

# Crossline Analysis

There were no specific crosslines run during the surveys, and after processing a check was completed in some survey areas with the Qimera cross check tool by selecting lines that generally were orthogonal to the main survey lines. This was restricted because of the changing main line orientation to accommodate sailing in varying weather conditions.

The Qimera cross check tool provides an indication only of the internal consistency of the selected lines after processing compared to the final weighted gridded surface. The reported statistics do not include all contributions to the total uncertainty of the survey, or final assessment of the quality or order of each survey.

The check was completed in three survey areas: two in EM304 areas (Amlia and Amukta Basins) and the EM2040 area (DSCRTP). The results are included in Appendix B. The figures below (**Figure 4**, **Figure 5**, **Figure 6**) show the cross lines used in the analysis.

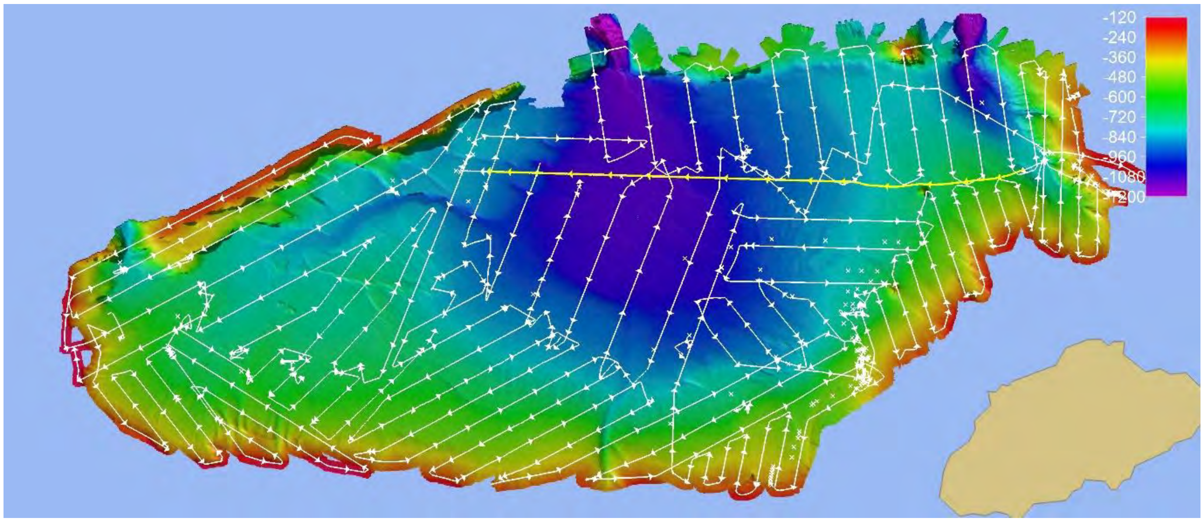



**Figure 4.** SD1200-0012-13 in the Amlia Basin EM304 survey area with selected crosslines (shown in yellow) against the bathymetric grid.

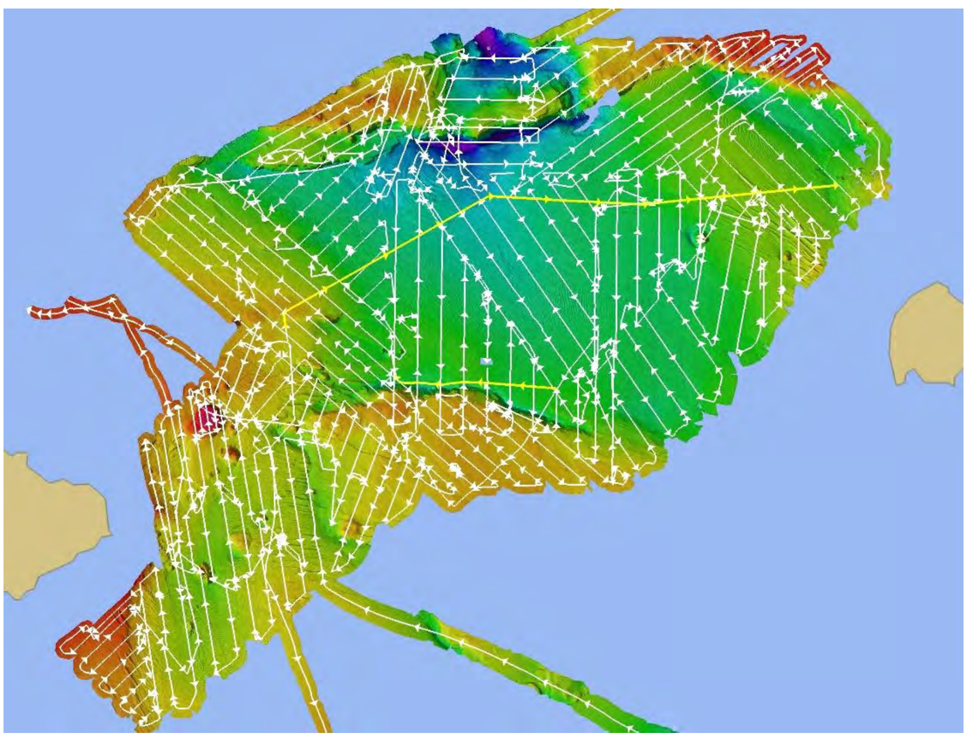


**Figure 5.** SD1200-0012-13 in the Amukta Basin EM304 survey area with selected crosslines (shown in yellow) against the bathymetric grid.

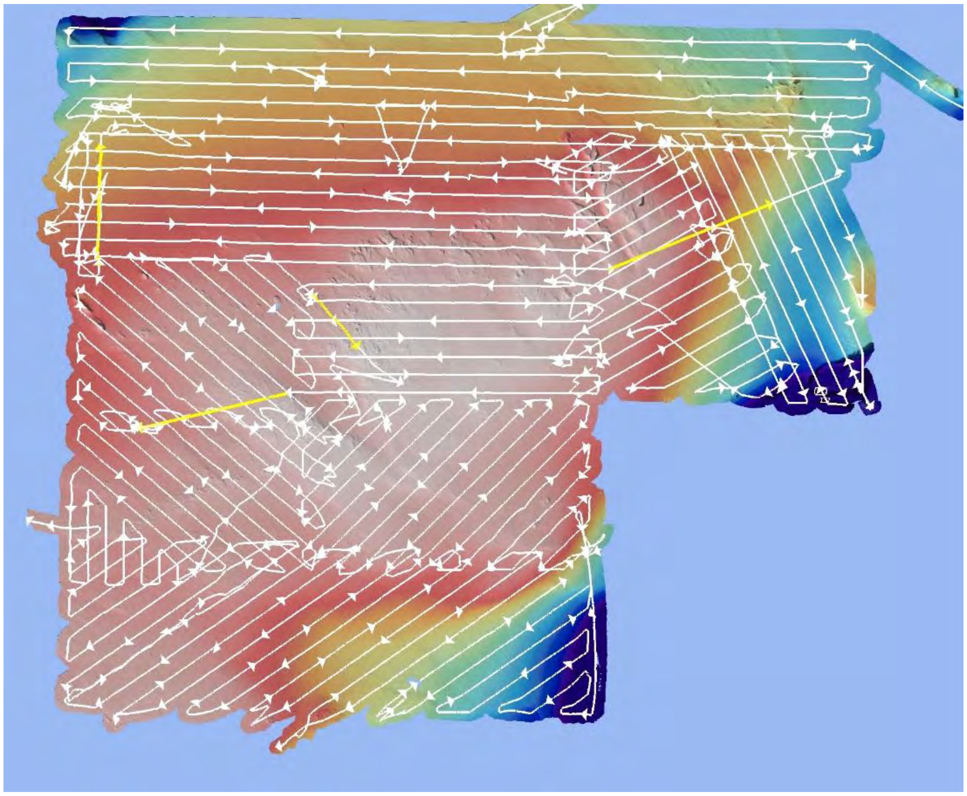


**Figure 6.** SD1200-0012-13 in the DSCRTP EM2040 survey area with selected crosslines (shown in yellow) against the bathymetric grid.

The following images (**Figure 7**, **Figure 8**) show the plot of the crosslines comparisons in two areas before post-processing editing (including online edits) and after post-processing, and illustrate the significant editing that occurred during the post-processing covered in this report.

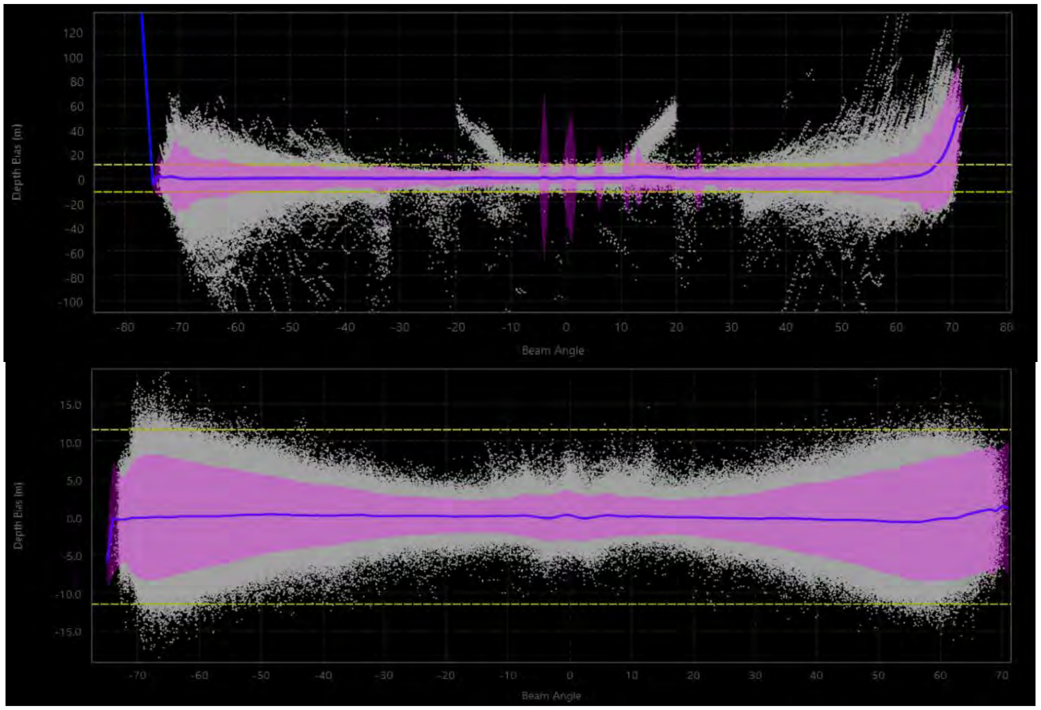



**Figure 7.** Amlia Basin EM304 crossline comparison plot before and after processing (yellow horizontal lines at same value in each image).

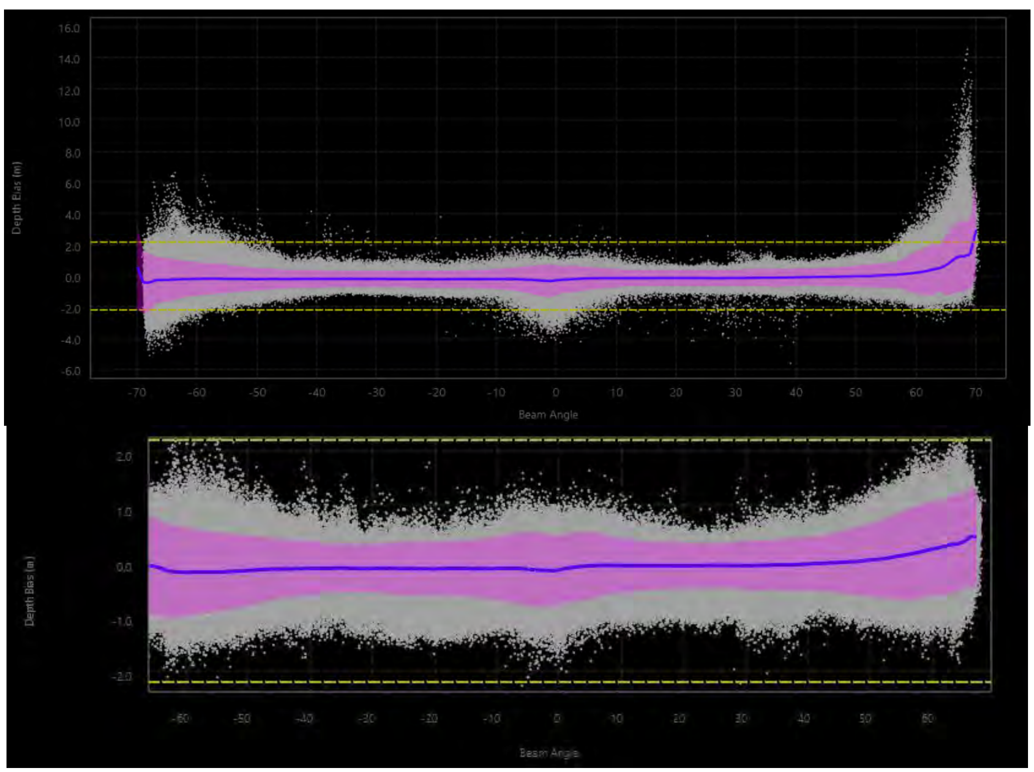



**Figure 8.** DSCRTP EM2040 crossline comparison plot before and after processing (yellow horizontal lines at same value in each image).

# Potential Seapath Issue

A large data offset/discrepancy was found in the Amukta Basin EM304 survey during processing. Several swaths of what should have been sequential or overlapping data along the edge of an escarpment were found to be offset from each other when reviewed in the Qimera 3D Editor and Slice Editor. This appears to be related to a short dropout or failure of the Seapath motion reference unit, with the heading being offset for a number of lines (**Figure 9**, **Figure 10**).

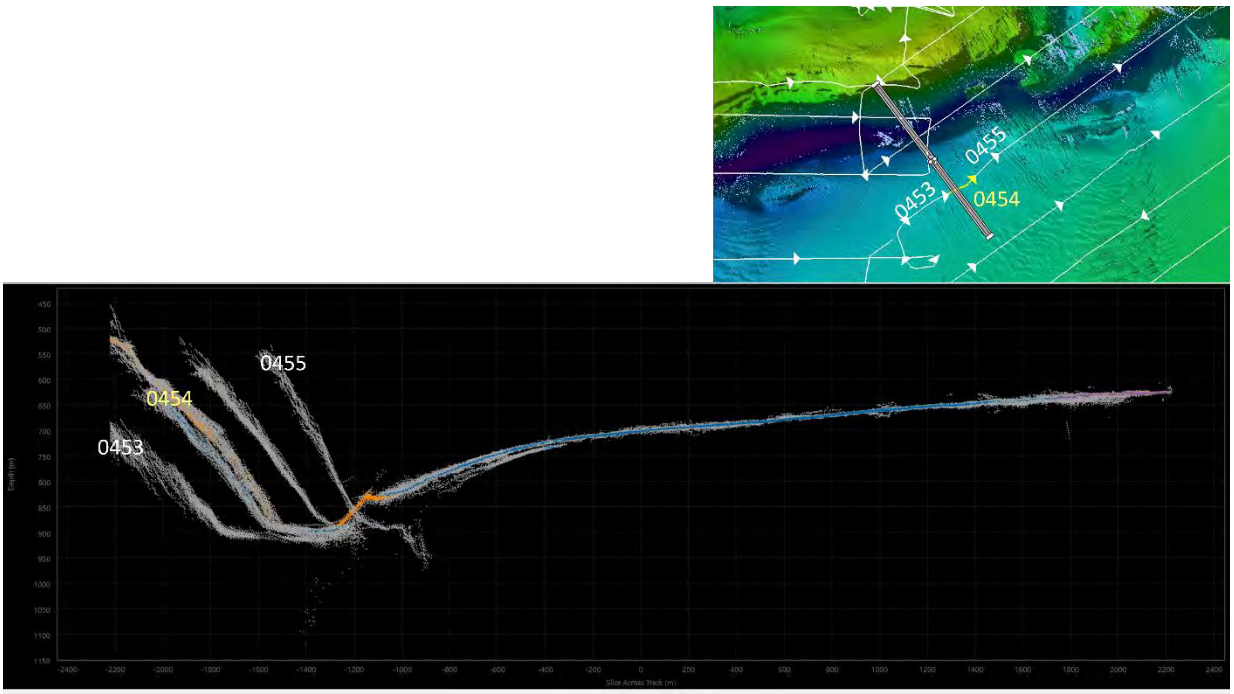



**Figure 9.** Top, location of lines and the corresponding line numbers for lines with offset issue. Bottom, the soundings from the lines in question shown in the 2D Slice Editor.

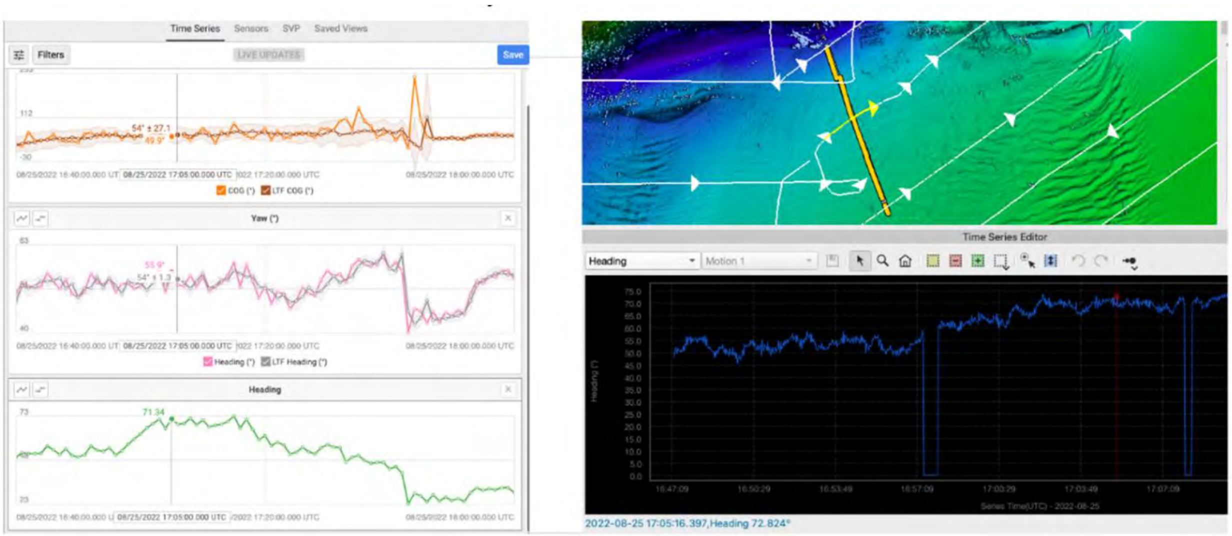



**Figure 10.** Left, attitude time series data from the Saildrone Mission Portal, specifically the navigation system's reported Course Over Ground (COG), Yaw, and Heading. Top right, the location of line 0453 in Qimera. Bottom right, the Qimera time series view for line 0453 heading, showing dropouts.

These files were removed from the project and all further processing, and were not included in any processed products. The affected files were:

0453_20220825_164713_SD-1200-0012-EM304.kmall
0454_20220825_171713_SD-1200-0012-EM304.kmall
0455_20220825_174713_SD-1200-0012-EM304.kmall
0456_20220825_175302_SD-1200-0012-EM304.kmall
0457_20220825_182302_SD-1200-0012-EM304.kmall

The raw files are still included in the data archive.

## Additional Processing Related Issues

The *SD-1200 System Performance & Data Processing Observation, SD-1200-0012 & SD-1200-0013* (Gee and Heffron, 2023) mentioned earlier in this report includes descriptions of issues encountered during processing, including several software bugs that resulted in issues or potential issues with some products. It is suggested that anyone utilizing this data extensively request that document[3].

# Processing Software

**Table 3** provides a list of the processing and analysis software versions that were used during SD1200-0012-13.

[3] Contact: Ex.ExpeditionCoordinator@noaa.gov

**Table 3.** Versions of processing and analysis software used during SD1200-0012-13.

| Software | Purpose | Version |
| --- | --- | --- |
| QPS Qimera | Bathymetry | 2.5.1, 2.5.2 and Beta 2.5.4 |
| QPS FMGT | Backscatter | 7.10.3 |
| KM Sonar Record Viewer | Data Analysis | 3.9.4 |
| QPS Fledermaus 7 and 8 | Data Visualization, Transformation and Export | 7.8.12 & 8.5.2 |
| Esri ArcGIS Pro | Data Analysis and Export | 3.1.1 Patch 2 |

# Data Archiving Procedures

All mapping data from the expedition will be archived using the National Centers for Environmental Information (NCEI) Cruise Pack application and publicly available via the National Centers for Environmental Information (NCEI) online archives. The Saildrone expedition data management plan (Saildrone, 2022b) describes the raw and processed data formats produced for this expedition. In lieu of survey areas with statistics in DXF format specified in that document, survey area shapefiles (and associated screengrabs) were produced. In addition to the files described in that document, ASCII XYZ format files for each processed multibeam file were generated. Raw data (Level 00), processed data (Level 01), derived products (Level 02), and ancillary files were generated and provided to NCEI, and may be available. **Table 4** and **Table 5** describe the data archived for each dataset. For further information about proprietary software and freeware that can handle the varying data types, refer to the NOAA OER Deepwater Exploration Mapping Procedures Manual (Hoy et. al, 2020).

**Table 4.** EM 304 and EM 2040 bathymetry and seabed backscatter dataset.

| Level | Description | File Type |
| --- | --- | --- |
| Level 00 | Raw multibeam files (in native sonar format) that include both raw bathymetry and backscatter (horizontal referencing = WGS84) | .kmall |
| Level 01 | Processed multibeam files in generic sensor format that include bathymetry and backscatter (horizontal referencing = WGS84) | .gsf |
| Level 02 | Gridded multibeam data and backscatter mosaics as well as ungridded per-line bathymetry in ASCII XYZ format for accepted soundings only (horizontal referencing = WGS84) | .txt, .xyz, .asc .tif, .tif (floating point GeoTIFF), .kmz, .sd |
| Ancillary files | Saildrone reports, Saildrone mission log, Sealog acquisition log, multibeam processing log, processed line report, | .xlsx, .csv, .txt, .shp, .png, .pdf |

| | | |
|---|---|---|
| | survey area polygons and screengrabs of statistics, surface statistics, processed swath extinction plots, cross line reports, built-in self test logs, processing unit parameters, telnet session records | |

**Table 5.** Sound speed profiles dataset.

| Level | Description | File Type |
|---|---|---|
| Level 00 | Raw profile data for the AML CTD, SV casts | .aml |
| Level 01 | Processed sound speed profiles created for multibeam data acquisition. This includes synthetic profiles from the World Ocean Atlas | .asvp |
| Level 02 | n/a | n/a |
| Ancillary Files | Saildrone reports, Saildrone mission log, Sealog acquisition log | .pdf, .csv |

In addition to the data listed in **Table 4** and **Table 5**, EM 304 and EM 2040 raw multibeam files that include water column backscatter (.kmwcd) were intended to be archived, with that process being handled by project partners.

All sonar data is permanently discoverable within the NCEI archives[4]. The locations for specific data types (at the time of writing this report) are detailed in **Table 6**. For any challenges accessing data, send an inquiry to NCEI[5].

**Table 6.** Locations of data collected during SD1200-0012-13 (at the time of writing this report).

| Data Type | Description | Location |
|---|---|---|
| EM 304 and EM 2040 bathymetry and backscatter data | EM 304 and EM 2040 bathymetric and backscatter data, supporting informational logs, and ancillary files are available through the NCEI Bathymetry Data Viewer | https://www.ncei.noaa.gov/maps/bathymetry/<br><br>If raw sonar data files (*.kmall's) are not directly downloadable, request them from ncei.info@noaa.gov with oer.info.mgmt@noaa.gov cc'd |
| Water column data | Once archived, water column data and any available supporting data are available through the NCEI Water Column Sonar Data Viewer | https://www.ncei.noaa.gov/maps/water-column-sonar/ |

4 https://www.ngdc.noaa.gov/
5 ncei.info@noaa.gov

| | | |
|---|---|---|
| Sound speed profiles | Ancillary sound speed profiles are available along with all mapping data per expedition in the NCEI data archives. | https://www.ncei.noaa.gov/maps/bathymetry/ |

# Expedition Schedule

The Saildrone bathymetry acquisition reports (Peters and Baechler, 2022a and 2022b) provide detailed expedition schedules for the individual legs. **Table 7** below provides a brief summary of major expedition milestones.

**Table 7.** SD1200-0012-13.

| Date (UTC) | Activity |
|---|---|
| 6/08 | Saildrone Surveyor SD-1200 deployed from Saildrone Headquarters in Alameda, CA. |
| 8/13 | Surveyor SD-1200 arrives Volcano South survey area. |
| 9/10 | Surveyor SD-1200 arrives in Unalaska (Dutch Harbor) for maintenance and data offload. |
| 9/11 | Surveyor SD-1200 departs Unalaska (Dutch Harbor). |
| 9/14 | Surveyor SD-1200 arrives OER1 survey area. |
| 10/03 | Surveyor SD-1200 departs region for return transit to Saildrone Headquarters in Alameda, CA. |

# References

Bureau of Ocean Energy Management (2022). BOEM-Sponsored Saildrone Surveyor Expedition Returning Home After Exploring Aleutian Islands. https://www.boem.gov/newsroom/ocean-science-news/boem-sponsored-saildrone-surveyor-expedition-returning-home-after (*last accessed 17 August 2023*).

Gee, L. and Heffron, E. (2023). SD-1200 System Performance & Data Processing Observations Report, SD-1200-0012 & SD-1200-0013. Available by request, contact Ex.ExpeditionCoordinator@noaa.gov.

Hoy, S., Lobecker, E., Candio, S., Sowers, D., Froelich, G., Jerram, K., Medley, R., Malik, M., Copeland, A., Cantwell, K., Wilkins, C., and Maxon, A. (2020). Deepwater Exploration Mapping Procedures Manual. Office of Ocean Exploration and Research, Office of Oceanic and Atmospheric Research, NOAA, Silver Spring, MD 20910. https://doi.org/10.25923/jw71-ga98

Jerram, K., Johnson, P., and Mayer, L. (2021). Saildrone Surveyor EM2040 & EM304 Multibeam Echosounder Sea Acceptance Testing Jan - Mar 2021.

NOAA Ocean Exploration (2022). Interagency Public-Private Partnerships Sends Uncrewed Saildrone to Explore Remote Alaskan Waters. https://oceanexplorer.noaa.gov/news/oer-updates/2022/uncrewed-saildrone-alaskan-waters.html (*last accessed 17 August 2023*).

NOAA Ocean Exploration (2023). Unexplored Waters of Alaska and California Mapped During Uncrewed Expedition. https://oceanexplorer.noaa.gov/news/oer-updates/2023/ak-ca-uncrewed-mapping.html (*last accessed 17 August 2023*).

Peters, C., and Baechler, N. (2022a). Saildrone Bathymetry Acquisition Report: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August 09 – September 09, 2022.

Peters, C., and Baechler, N. (2022b). Saildrone Bathymetry Acquisition Report: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0013, Aleutian Islands Region, AK, September 11 – October 03, 2022.

Saildrone, Ocean Exploration Cooperative Institute, NOAA Ocean Exploration, Bureau of Ocean Energy Management, University of New Hampshire, United States Geological Survey, Monterey Bay Aquarium Research Institute, NOAA Office of Coast Survey, and NOAA Deep Sea Coral Research & Technology Program (2022). Saildrone Bathymetry Mission Plan: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August 09 – September 09, 2022.

Saildrone (2022a). SD-1200 Bathymetry Configuration: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August 09 – September 09, 2022. SAILDRONE PROPRIETARY.

Saildrone (2022b). Saildrone Bathymetry Data Management Plan: 2022 – Aleutians Uncrewed Ocean Exploration, SD-1200-0012, Aleutian Islands Region, AK, August – October, 2022.

Saildrone (2022c). Saildrone Bathymetry Patch Report: 20220630 Offshore Testing SD-1200-0010, Saildrone Internal, Offshore San Francisco, Jun 30 – Jul 8, 2022 – SAILDRONE PROPRIETARY.

Saildrone (2022d). Saildrone Surveyor Bathymetry Data Structure Guide.

# Appendix A:

## Qimera Crossline Reports for Amlia Basin, Amukta Basin and DSCRTP Survey Areas

# Cross Check Report

**Project:** G:/QPS-Data/AMLIA_FNL_GSF_UTM2N

**Time of Report:** 2023-08-01 14:23:53

**Username:** lindsaygee

**Raw Files Used in Cross Check:**

0410_20220921_065859_SD-1200-0013-EM304_EM304.gsf

0411_20220921_072859_SD-1200-0013-EM304_EM304.gsf

0412_20220921_075859_SD-1200-0013-EM304_EM304.gsf

0413_20220921_082859_SD-1200-0013-EM304_EM304.gsf

0414_20220921_085859_SD-1200-0013-EM304_EM304.gsf

0415_20220921_092859_SD-1200-0013-EM304_EM304.gsf

0416_20220921_095337_SD-1200-0013-EM304_EM304.gsf

0417_20220921_102337_SD-1200-0013-EM304_EM304.gsf

0418_20220921_105337_SD-1200-0013-EM304_EM304.gsf

0419_20220921_112337_SD-1200-0013-EM304_EM304.gsf

0420_20220921_115337_SD-1200-0013-EM304_EM304.gsf

0421_20220921_122337_SD-1200-0013-EM304_EM304.gsf

0422_20220921_125337_SD-1200-0013-EM304_EM304.gsf

0423_20220921_132337_SD-1200-0013-EM304_EM304.gsf

0424_20220921_135337_SD-1200-0013-EM304_EM304.gsf

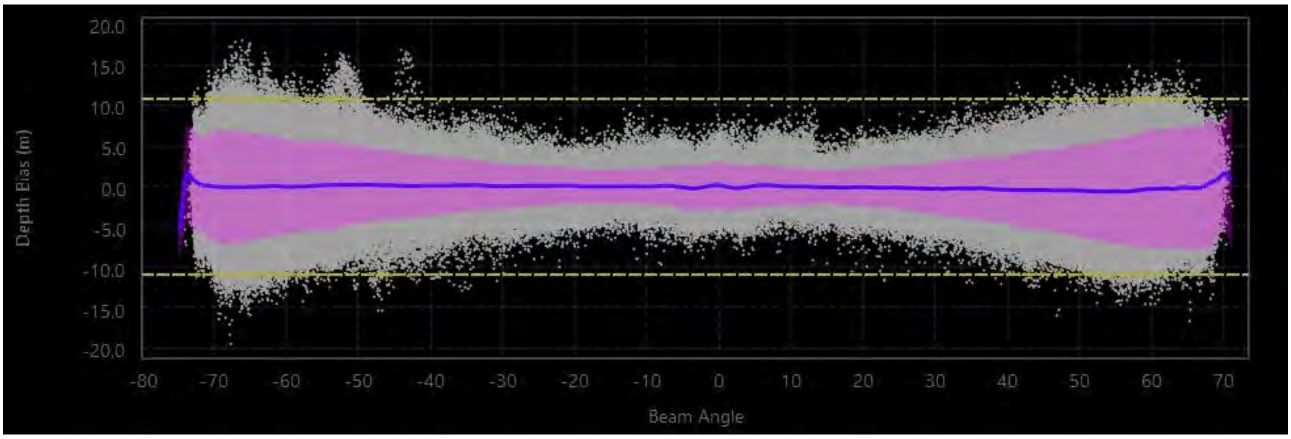
**Reference Surface Used in Cross Check**

SD1200-0012-13_MB_FNL_AmliaBasin_50m_UTM2N

# Summary

Survey Order: IHO S-44 Order 1

| Statistic | Value |
|---|---|
| Error Limit | 10.7843 |
| Number Rejected | 5189 |
| P-Statistic | 0.00150601 |
| Test | ACCEPTED |
| Number Of Points | 3445525 |
| Grid Cell Size | 50.000 |
| Difference Mean | -0.071 |
| Difference Median | -0.071 |
| Difference Std. Dev | 2.542 |
| Difference Range | [-19.440, 18.056] |
| Mean + 2*Stddev | 5.154 |
| Median + 2*Stddev | 5.154 |
| Data Mean | -828.744 |
| Reference Mean | -828.673 |
| Data Z-Range | [-1083.051, -446.606] |
| Reference Z-Range | [-1074.707, -454.954] |




Scatter Plot

# Cross Check Report

**Project:** D:/SD1200-AMUKTA-OCS_PROJECT-20230710/Amukta_OCS_UTM

**Time of Report:** 2023-07-25 17:00:09

**Username:** lindsaygee

**Raw Files Used in Cross Check:**

0962_20220903_231210_SD-1200-0012-EM304.kmall

0963_20220903_234210_SD-1200-0012-EM304.kmall

0964_20220904_001210_SD-1200-0012-EM304.kmall

0965_20220904_004210_SD-1200-0012-EM304.kmall

0966_20220904_011210_SD-1200-0012-EM304.kmall

0967_20220904_014210_SD-1200-0012-EM304.kmall

0968_20220904_021210_SD-1200-0012-EM304.kmall

0969_20220904_024210_SD-1200-0012-EM304.kmall

0970_20220904_031210_SD-1200-0012-EM304.kmall

0971_20220904_034210_SD-1200-0012-EM304.kmall

0972_20220904_041210_SD-1200-0012-EM304.kmall

0973_20220904_044210_SD-1200-0012-EM304.kmall

0607_20220828_094308_SD-1200-0012-EM304.kmall

0608_20220828_101308_SD-1200-0012-EM304.kmall

0609_20220828_104308_SD-1200-0012-EM304.kmall

0610_20220828_111308_SD-1200-0012-EM304.kmall

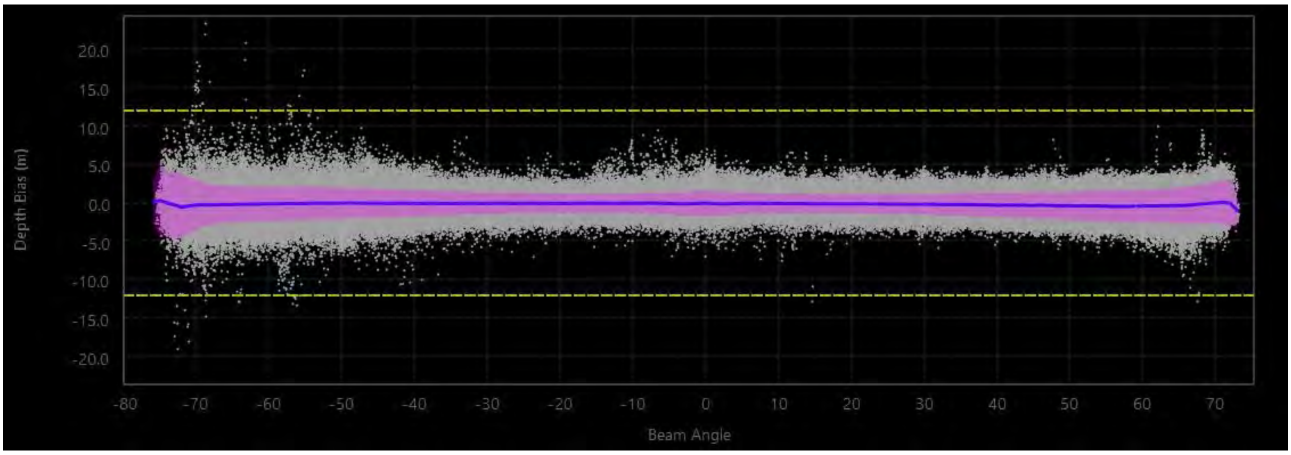
**Reference Surface Used in Cross Check**

SD1200-0012-13_MB_FNL_Amukta_20m_UTM2N

# Summary

Survey Order: IHO S-44 Order 2

| Statistic | Value |
|---|---|
| Error Limit | 11.9908 |
| Number Rejected | 113 |
| P-Statistic | 2.04029e-05 |
| Test | ACCEPTED |
| Number Of Points | 5538427 |
| Grid Cell Size | 20.000 |
| Difference Mean | -0.163 |
| Difference Median | -0.163 |
| Difference Std. Dev | 0.929 |
| Difference Range | [-19.001, 26.954] |
| Mean + 2*Stddev | 2.020 |
| Median + 2*Stddev | 2.020 |
| Data Mean | -519.686 |
| Reference Mean | -519.523 |
| Data Z-Range | [-766.871, -275.643] |
| Reference Z-Range | [-764.866, -277.512] |




Scatter Plot

# Cross Check Report

**Project:** G:/QPS-Data/SD1200-0012_EM2040-bathy

**Time of Report:** 2023-08-01 13:57:52

**Username:** lindsaygee

**Raw Files Used in Cross Check:**

0086_20220817_061919_SD-1200-0012-EM2040.kmall

0123_20220817_215107_SD-1200-0012-EM2040.kmall

0213_20220819_052620_SD-1200-0012-EM2040.kmall

0246_20220819_172512_SD-1200-0012-EM2040.kmall

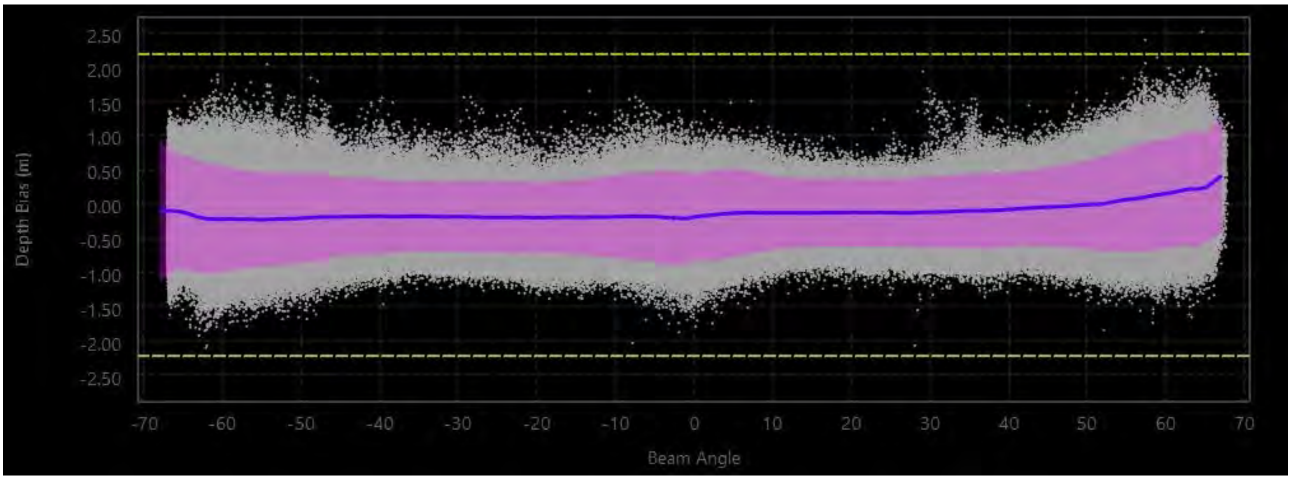
**Reference Surface Used in Cross Check**

SD1200-0012_MB_FNL_DSCRTP_8m_UTM2N

## Summary

Survey Order: IHO S-44 Order 1

| Statistic | Value |
|---|---|
| Error Limit | 2.2011 |
| Number Rejected | 13 |
| P-Statistic | 3.6524e-06 |
| Test | ACCEPTED |
| Number Of Points | 3559300 |
| Grid Cell Size | 8.000 |
| Difference Mean | -0.097 |
| Difference Median | -0.106 |
| Difference Std. Dev | 0.349 |
| Difference Range | [-2.089, 2.523] |
| Mean + 2*Stddev | 0.795 |
| Median + 2*Stddev | 0.803 |
| Data Mean | -164.987 |
| Reference Mean | -164.889 |
| Data Z-Range | [-241.506, -129.494] |
| Reference Z-Range | [-242.142, -130.530] |




Scatter Plot

# SD-1200 System Performance & Data Processing Observations Report, SD-1200-0012 & SD-1200-0013

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*Prepared for: Ocean Exploration Cooperative Institute (OECI) and project partners*
*Prepared by: Lindsay Gee & Erin Heffron, Ocean Mapping Services LLC*
*(info@oceanmappingservices.com)*

## Preface

These notes were prepared by Ocean Mapping Services, LLC in conjunction with processing of the multibeam sonar data from the inaugural Saildrone Surveyor SD-1200 missions SD-1200-0012 and SD-1200-0013 to the Aleutian Islands Region, Alaska from August to October 2022. These notes were not a primary deliverable, but the Ocean Exploration Cooperative Institute (OECI) partners who we communicated with for this project felt it would be useful to hear about some of the things we observed while processing the data. They are just our observations, have not been extensively investigated, and we are happy to discuss them further with any interested parties. Additional notes of overall observations and issues encountered during processing that are not necessarily tied to the SD-1200 system performance were also included when we felt their inclusion would be useful and potentially helpful for future mission planning.

These notes refer to the operating areas by the names used in the Bathymetry Acquisition Reports. All transits from Unalaska (Dutch Harbor) to the operating areas were grouped together as a single survey area called Transits. An overview map for the survey region utilizing the final coverage polygons is provided below (**Figure 1**).

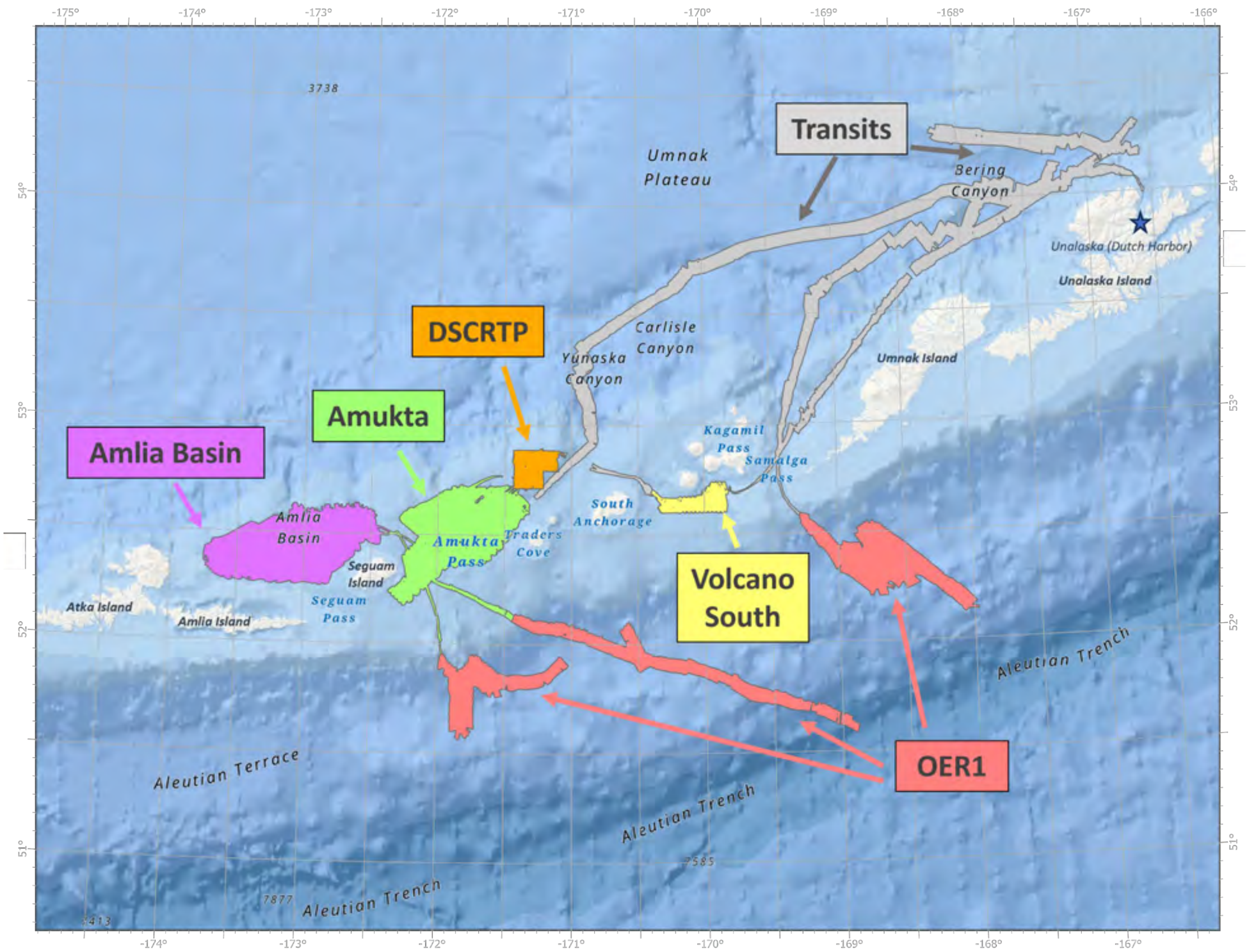



***Figure 1.*** *Overview map of survey areas. Projection WGS84 UTM zone 2N (note that transit data east of 168° W falls within UTM zone 3N; zone 2N was used for this map as a matter of convenience).*

# Introduction

*Note:*

1. *No standards were specified as a requirement for the survey or to assess quality, so comments relate mainly to general operational performance. OER should consider having consistent standards, requirements, or guidelines for all their mapping under grants and contracts.*
2. *Headings in the summary section and other blue text throughout the document links to bookmarks elsewhere in the document with further details and images.*
3. *Microsoft Word image correction tools (Sharpen/Brighten/Contrast) were used to make some of the screen capture images in this report easier to see. These corrections often degraded the appearance of bathymetric surfaces.*

The Saildrone platform has a number of differences that affect the acquisition of multibeam data, processing and overall data quality. Differences result primarily from the platform being uncrewed with only remote access, sail as the main propulsion, and the platform being smaller than generally used with a deep water multibeam system.

The Saildrone Bathymetry Acquisition Report for each leg (Saildrone Bathymetry Acquisition Report_SD-1200-0012.pdf, Saildrone Bathymetry Acquisition Report_SD-1200-0013.pdf) provided a good summary of the data acquisition, and also noted a number of platform specific considerations and issues encountered during the survey; we refer to them often in these notes. The notes found here outline some of the effects from considerations/issues noted in those reports and other issues based on observations made while processing the data and generating the resultant products. A standard processing report, *Mapping Processing Summary Report: SD1200-0012-13: Aleutians Uncrewed Ocean Exploration (Mapping)*, was also generated as part of the raw and processed data package Ocean Mapping Services LLC put together for submittal to NCEI (National Center for Environmental Information, https://www.ncei.noaa.gov/) for archive. This report will be available once the data makes it through to archive; it has also been provided to contacts at UNH and NOAA OE, and can be requested by emailing info@oceanmappingservices.com.

# Report Summary

## Processing Approach

The processing approach was to produce an optimum weighted average surface at the highest resolution that minimized data gaps, removed systematic artifacts (sound speed issues, outer beam, system dropouts), and removed areas of significant noise (outer beams). There remained some areas where there was still noise in the grid resulting from balancing the noisy outer beams with insufficient overlap between lines without leaving gaps. Additional standard processing information (software used, statistics, etc.) is found in the previously noted report, *Mapping Processing Summary Report: SD1200-0012-13: Aleutians Uncrewed Ocean Exploration (Mapping)*.

## Observations and Issues

The following is a summary of observations and issues noted during processing and, when applicable, observed effects in data and products. Further details are provided in the Detailed Observation Notes (linked to each summary item via bookmarks).

Saildrone Mission Portal

Saildrone provided access to their mission portal to support the processing. It was a very good interface to support processing, noting neither of the processors had been involved in the acquisition and only had limited knowledge of the platform and conditions during the surveys. The portal would be a useful application to have on both crewed and uncrewed surveys.

Challenging Region for Saildrone SD-1200 First Survey

The area has strong and varying currents, and varying depths, with changeable weather and temperature gradients. This region is also historically understudied and undersampled. For these reasons, the World Ocean Atlas (WOA), which was heavily utilized for synthetic sound speed profiles (also called sound velocity profiles or SVP), was not always a good representation of regional conditions. OER1 was a better operating area for this system and the conditions, being deeper and surveyed with a reduced swath (due to SIS operating in a deeper mode that limits coverage angles).

Overall Survey Area Reduced After Processing

A combination of a number of issues noted by the Saildrone team and encountered during processing resulted in a 6.5% decrease in area from the 16,254 sq km reported for unprocessed data in the acquisition reports to 15,133 sq km.

Firmware and Software Issues: Firmware update during transit and Qimera bug related to extra detections >> *reduced coverage, required reprocessing time and lowered surface resolution*

Limitations of Remote Access: Remote access allowed for less than normal interaction with online systems. There wasn't the normal level of online monitoring and routine changing of settings >> *missed some system failures, incorrect system settings not being noticed, gaps in surface, and not adjusting settings in turn affecting coverage, noise and quality of surface.*

Wide Swath, Noisier Outer Beams, and Heeling Artifact >> *more outer beam SV noise, need for outer swath clipping that reduced processed swath width, reduced overlap and created some gaps, and increased processing time.*

Significant Motion and Lower Speed Compared to Larger Vessels >> *allowed survey in bad weather, but resulted in noisier data, less overlap and gaps in coverage.*

Speed Variation: Significant variation in speed during all surveys >> *slow average speed, varying along track density/coverage and gaps in surface.*

Sound Speed Issues: Limited sound speed profile observations – and even fewer in bad weather – that were not deep enough >> *reduced data quality and coverage, and impacted the achievable grid resolution*. There are likely remaining underlying sound speed issues in some of the data (swath vertical offsets, bending in swath) that may impact the final bathymetric surfaces, but other issues make it difficult to diagnose or ameliorate in post-processing.

Poor Filtering Results: Underlying data issues such as variation in density and other artifacts caused filter-based rejection of good data >> *additional time to undelete and reprocess.*

Challenges of Sailing: The challenges of sailing in a region of changing wind patterns led to changing line orientation patterns and a limited ability to run crosscheck lines >> *reduced quality control, impacts to overall coverage, and data gaps.*

Resulting Bathymetric Surfaces: Combination of issues leading to reduced sounding density, vertical swath offset in outer sectors, and overlap >> *lower resolution surfaces, holidays, and noticeable remnant artifacts.*

Absorption: It is unclear if absorption from CTD was used in backscatter processing >> *mosaic could potentially be improved.*

# Software Bugs

Several bugs were discovered in the QPS processing software (QPS Qimera = bathymetry, FMGT/Fledermaus Geocoder Toolbox = backscatter), discussed throughout these notes and summarized under Qimera and FMGT Bugs and Versions. Some of these bugs required complete reprocessing of affected files, increasing processing time. In other cases fixes were not available, potentially reducing the quality of final products.

# Suggestions/Recommendations

A more complete pre-survey testing and calibration may have identified some of the platform specific issues that were identified both by the Saildrone survey team during acquisition and observed while processing the data. The Saildrone team did well to refine operations during the surveys, such as developing calculations for the feasibility of collecting sound speed profiles and revised line planning to accommodate the conditions. However, they could have optimized the operations with additional trials to have better understanding of sailing speeds, significant yaw and heeling under sail, sound speed observation limitations, etc. It is likely this would have included more overlap in the survey planning (as much as was within their power, as overlap specifications typically come from the client); this would have improved processing and reduced the areas with gaps in coverage. Filters likely would have worked better with increased overlap on the noisy data, and cutting out the outer swath wouldn't have led to such poor surface results on the edges between lines with limited overlap.

The Multibeam Advisory Committee (MAC) trials appear to mostly have been conducted under motor, and it is suggested that with a new and unique platform a more extensive 'first of class' set of trials would have provided the team with a better understanding of system performance and limitations in varying conditions.

In addition to the notes above testing and calibration, the following suggestions (which are repeated, in some cases with additional context, in the Detailed Observation Notes) may help improve future surveys for Saildrone and their clients:

- We suggest acquisition lines be planned for more overlap (optimum 100% and never less than 50%) and only reducing that overlap as the survey progresses if weather conditions, sound speed environment, and regular review of the data warrant it. Consider the newness of the platform and the vehicle limitations when making suggestions to clients.

- Be more pro-active manually limiting swath angles when weather conditions are impacting the data and the ability to collect sound speed observations.
- Plan for complete removal of any turn data in post-processing, especially mid-survey unplanned turns or turns to accommodate line orientation change.
- Monitor the vehicle position and orientation compared to the planned line and adjust subsequent lines to ensure the planned coverage is achieved. The extensive motion and yawing of the platform meant that the swath coverage was often reduced.
- Spend time analyzing different sound speed models in a region during planning and monitor during the survey, to plan for the best option if observations become too challenging. Investigate other methods of collecting supporting sound speed observations (buoys, gliders?).
- Collect survey crosslines, even if it means being on motor.
- Monitor data density. Ask clients to consider density needs and accommodate with changes in overlap, since speed varies greatly with direction under sail.

Suggestions for Kongsberg:

- Analysis of the observed ‘heeling error’ and automated solutions to flag that data.
- Recommendations or improvements to deal with the varying along-track data density with smaller vehicles that move a lot and operate at varying speed.
- Monitor the processing software suppliers and third party data formats (GSF) to ensure they fully support changes in KMALL format.
- Maintain traceability of file names of the SVP used in SIS to aid SVP analysis and downstream archiving with mixed values from observations and models.

# Detailed Observation Notes

## Saildrone Mission Portal

Saildrone provided access to their mission portal to support the processing. It was a very good interface to support processing, noting neither of the processors had been involved in the acquisition, and only had limited knowledge of the platform and conditions during the surveys. This also supported the notes from each leg's Bathymetry Acquisition Report.

The mission portal provides a map view on the left that has selectable observed data from onboard systems such as SVP observation, planned and acquired lines and survey area polygons. There are also multibeam layers that can be selected from web services for bathymetry, weather and marine forecasts, radar and navigation. The time series view on the right can be configured to display data such as wind direction and speed, wave period and height, roll, pitch, yaw, course and speed over ground, Surface SV, and other platform data.

It became an invaluable tool during processing in assessing issues related to bad weather conditions causing excessive roll, pitch and yaw that affected the data and also for locating a Seapath temporary drop out not noticed online (see Limitations of Remote Access section).

This tool would be valuable for supporting any post processing of data from either crewed or uncrewed systems.

The following images (**Figure 2** - **Figure 5**) show some of the portal views and interface options for the Mission Portal.

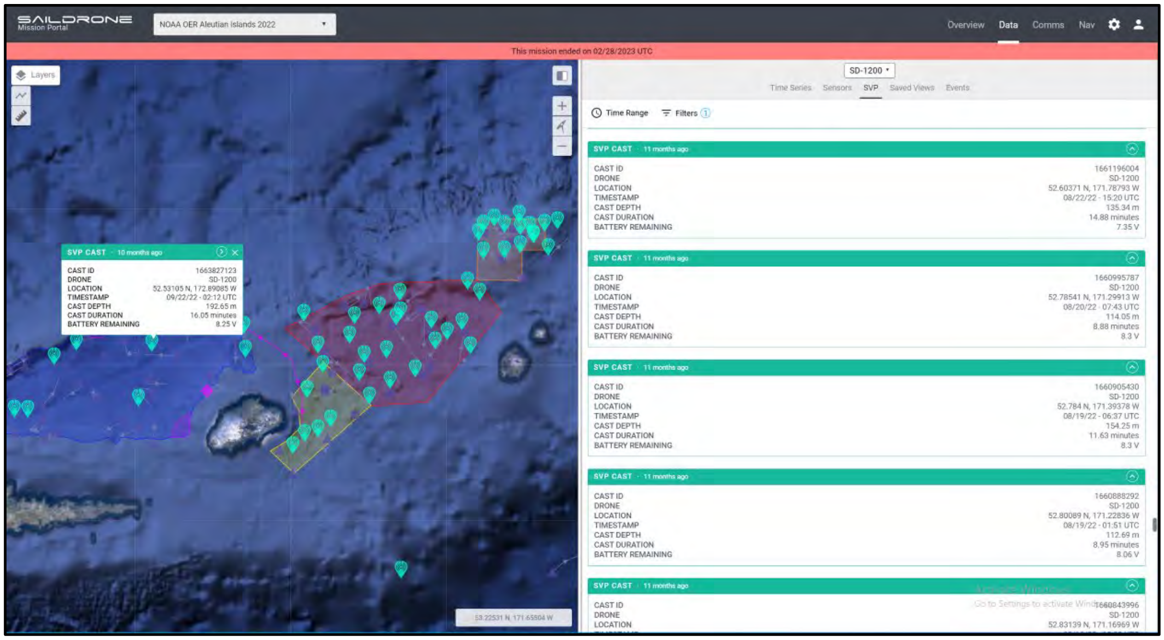



***Figure 2.*** *Overview of SV Profile observations in the SD Mission Portal - shows survey areas, green pins for sound speed profiles and link to further details.*

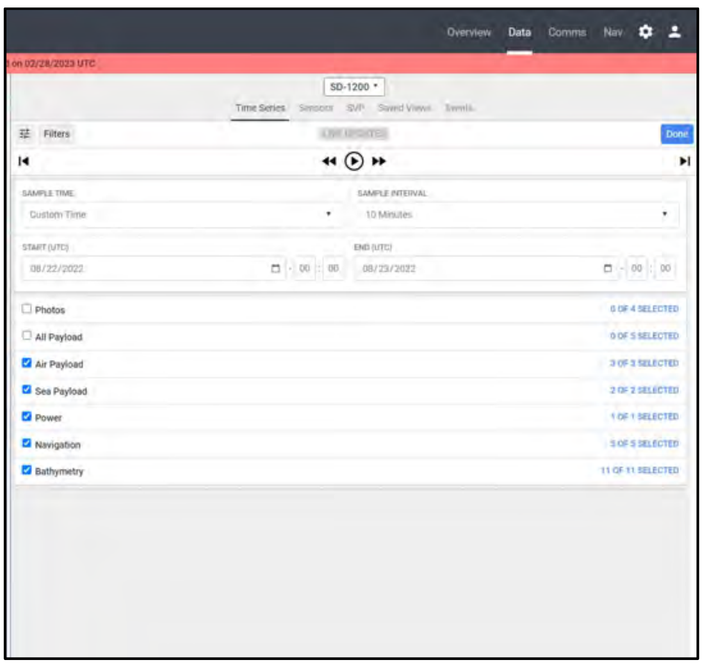



***Figure 3.*** *Mission Portal configuration options for processing.*

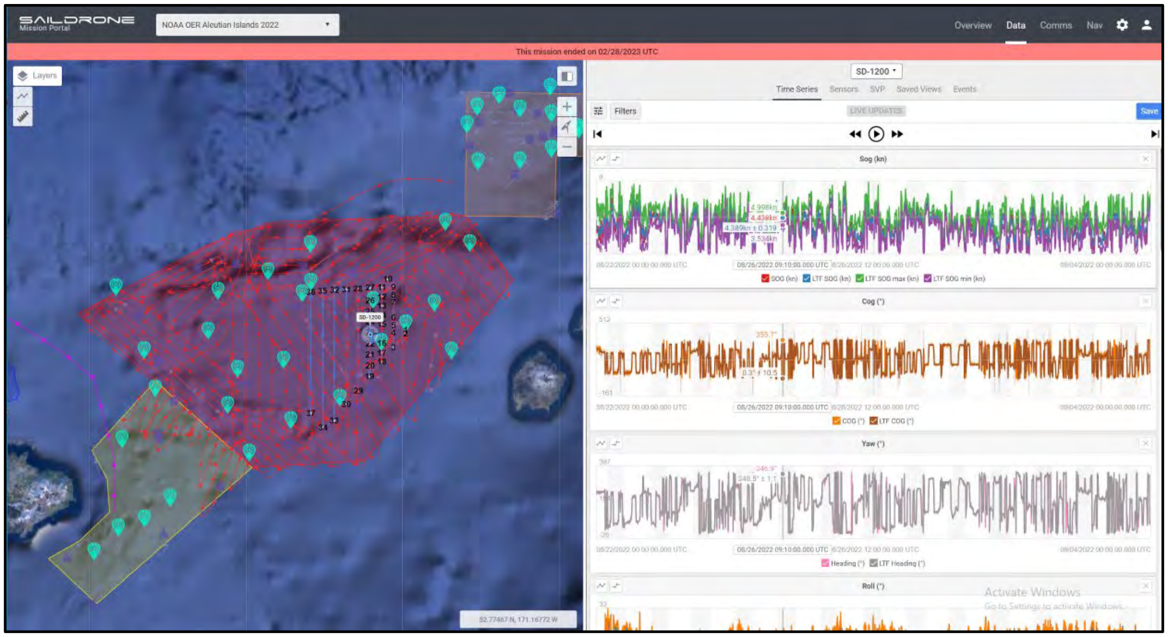



***Figure 4.*** *Overview of all lines for Amukta survey on leg 0012 - red lines show where data was acquired. Selectable time series in the right panel for selected navigation observations.*

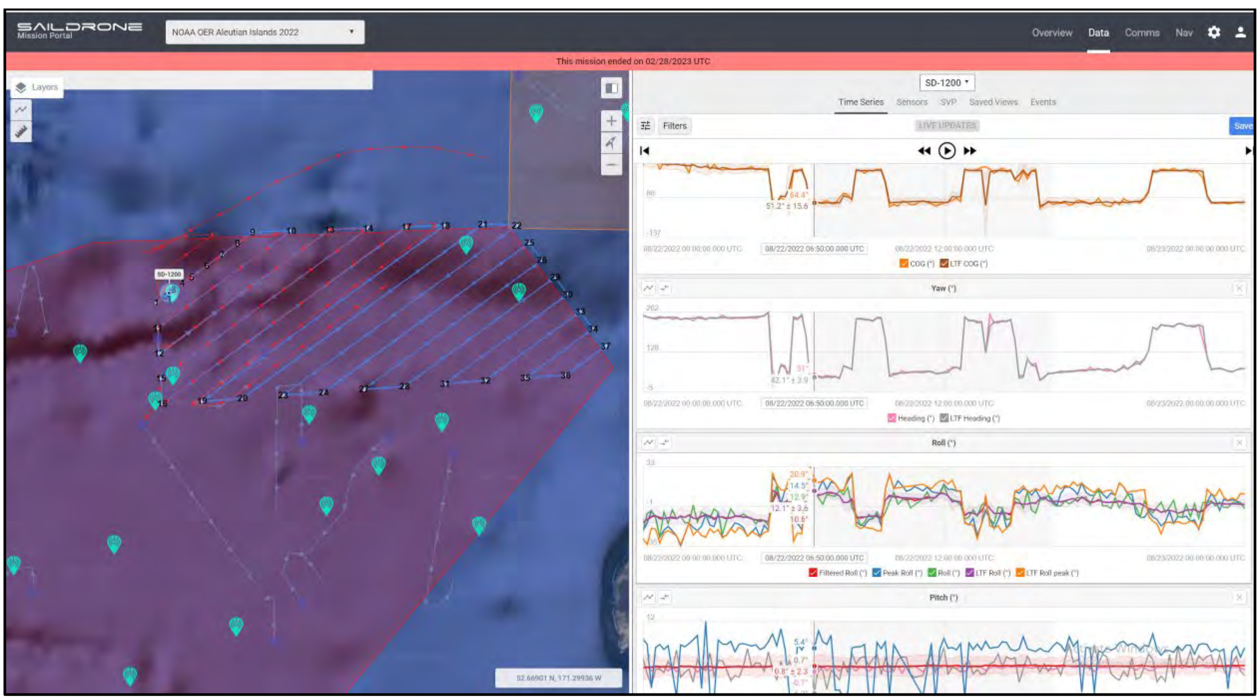



***Figure 5.*** *Overview of all lines for Amukta survey on leg 0012 - red lines show where data was acquired. Selectable time series in the right panel for selected navigation observations.*

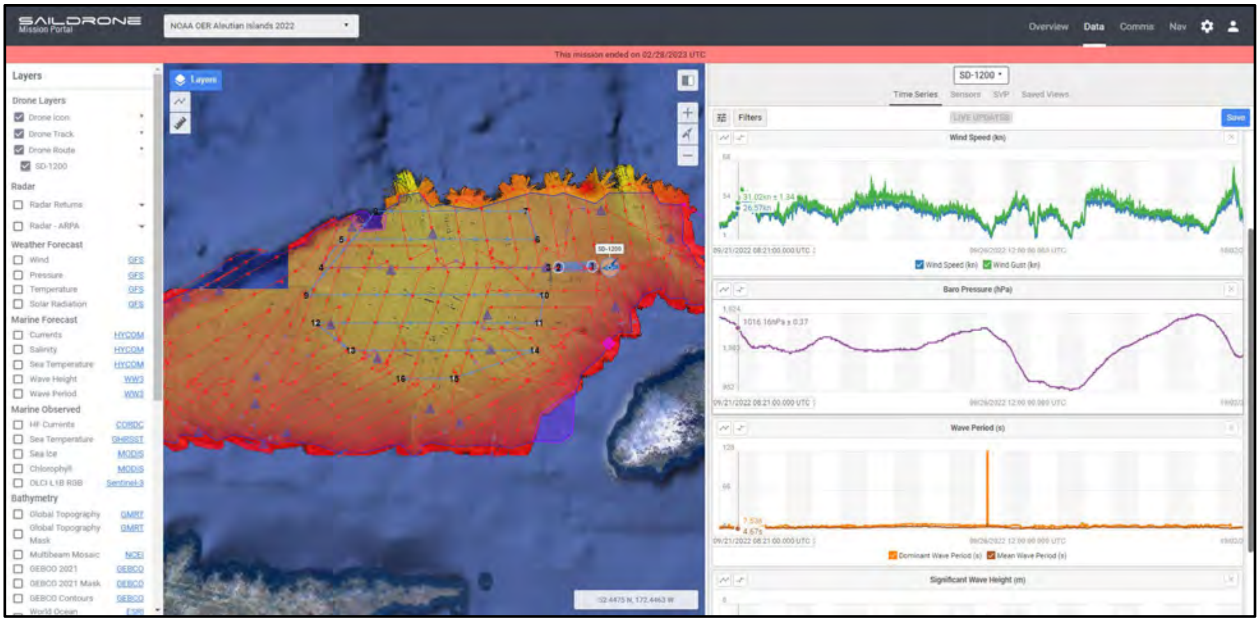



***Figure 6.*** *Image illustrates the change of the line plan because of a shift in wind direction. Blue lines are planned and red lines are actual lines where data was acquired. The frame on the left also shows the available layers.*

# Challenging Area

## *Extremely challenging region for the Saildrone SD-1200 first survey with strong currents, large depth variations, extreme and changeable weather and temperature gradients*

The Aleutians provided a very challenging survey area, pushing the limits of the system in collecting good multibeam and associated sensor data, and showed some of the system limitations.

The bathymetry around the islands and in the survey areas ranged from around 50 m to over 7,000 m, with 95% under about 3,800 m (**Figure 7**). Most areas north of the island chain were under 1,000 m.

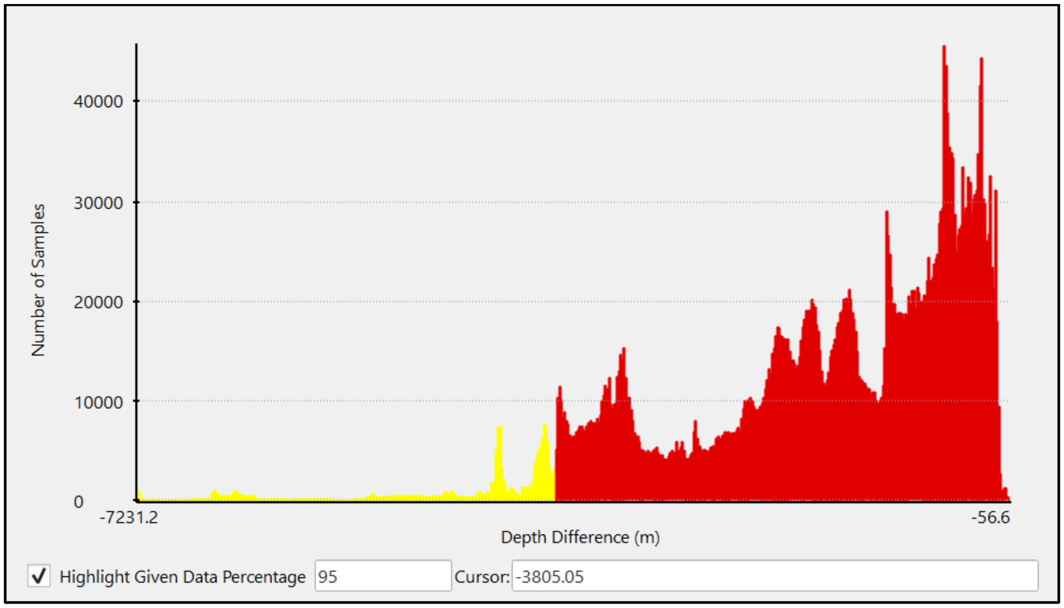



***Figure 7.*** *Histogram of depth for all survey areas.*

The acquisition report noted that “wind patterns around the Aleutian island chain are highly variable and swing unpredictably.” The wind and swell were at times excessive and would have likely reduced the survey output of a larger crewed vessel. The Aleutian Island chain creates a barrier to the oceanographic conditions with differences in swell, currents, surface sound speed and the sound speed profile models north and south of the island chain. There are also significant tidal currents around the islands, and this combined with the wind speeds resulted in varying Speed over Ground (SOG) and along track data density. The AML-6 CTD and sound velocity probe used for profiles of the water column to depth was limited above certain wind speed and wave height – the SD team determined the limits during this survey. When it could not be used, the World Ocean Atlas (WOA) was utilized, which wasn’t really appropriate for this region (see Sound Speed Issues).

One exception was the OER1 area south of the islands, which was in deeper water (depths to over 7,000 m). The swath width of the EM304 was automatically limited in the deeper depth modes. It did not have as many issues as the other survey areas, where depths were mostly under 1,000 m and the system was almost always surveying at maximum swath width.

Such a challenging area highlighted many of the issues noted below, and can assist in planning system upgrades, refining operations and in the planning of future surveys.

# Overall Survey Area Reduced After Processing

The issues noted below and by the Saildrone team in the acquisition report resulted in data being rejected during processing. Some of the outer beam issues reduced the swath width and the total calculation of area surveyed (**Figure 8**, **Figure 9**). The overall reduction was 6.9% or 1,121 sq km.

Some of the variation could also have resulted from the method of the area calculation. The final processed areas were calculated from ASCII Grids exported from Qimera which were imported into Esri ArcGIS Pro and used to generate raster domain polygons; the ArcGIS Pro Calculate Geometry tool was then used to calculate total area utilizing a Cylindrical Equal Area (world) projection (Esri WKID 54034).

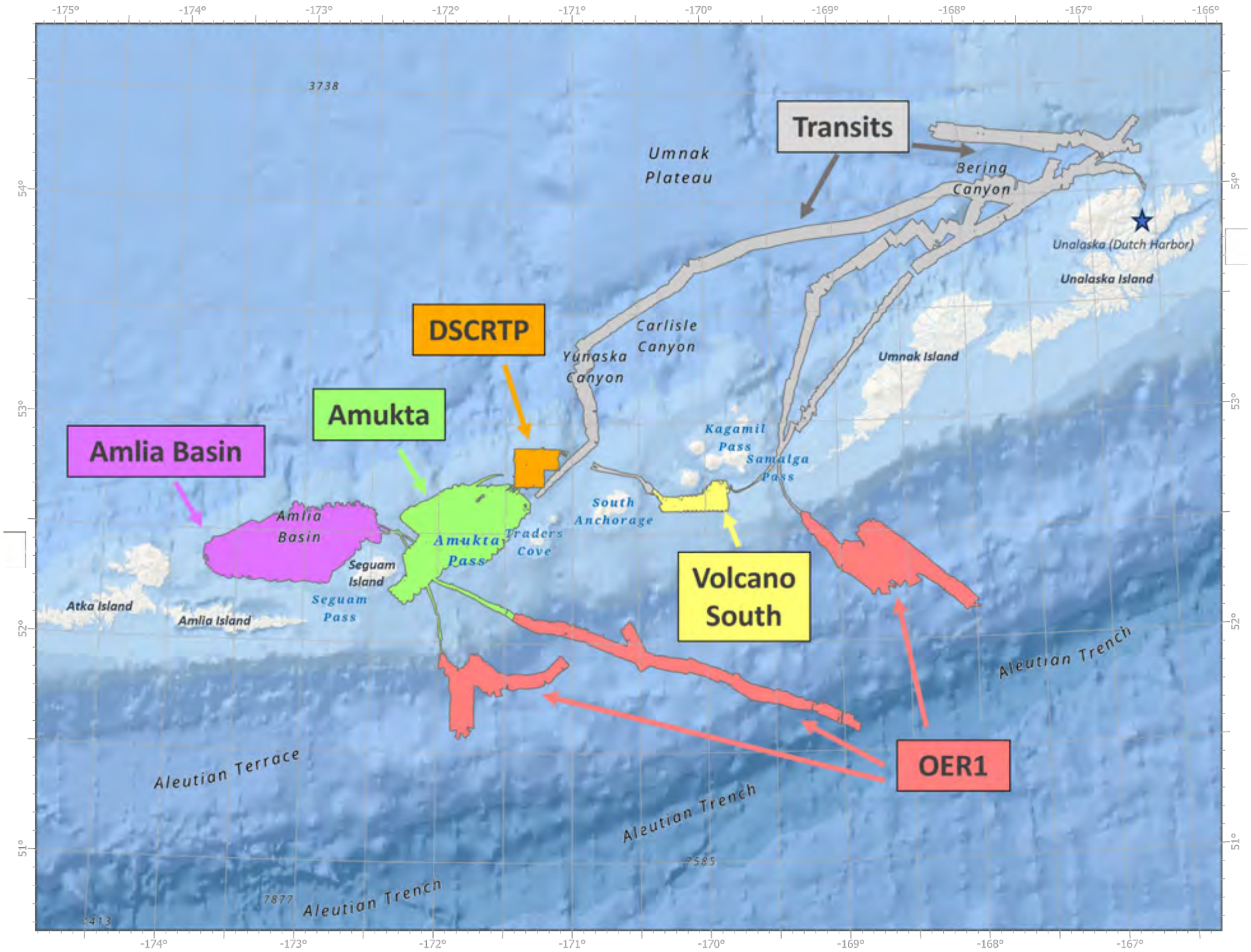



*Figure 8. Overview map of survey areas utilizing survey area raster domains generated after processing was complete. Projection WGS84 UTM2N.*

**Summary of areas surveyed:**

Acquisition reports

- Leg 0012 7910 sq km
- Leg 0013 8844 sq km
- ***Total 16254 sq km***

After processing

- Transits 5656 sq km
- Volcano South 363 sq km
- DSCRTP 379 sq km
- Amukta-OCS 2481 sq km

- OER1 3725 sq km
- Amlia Basin 2538 sq km
- ***Sum*** ***15142 sq km****

***Combined final GSF files at 100m grid 15193 sq km****
**Total survey area after processing is 15133 sq km***

*****_difference due to resolution of grids used to create the raster domains, minor overlap between EM304 and EM2040 surfaces_

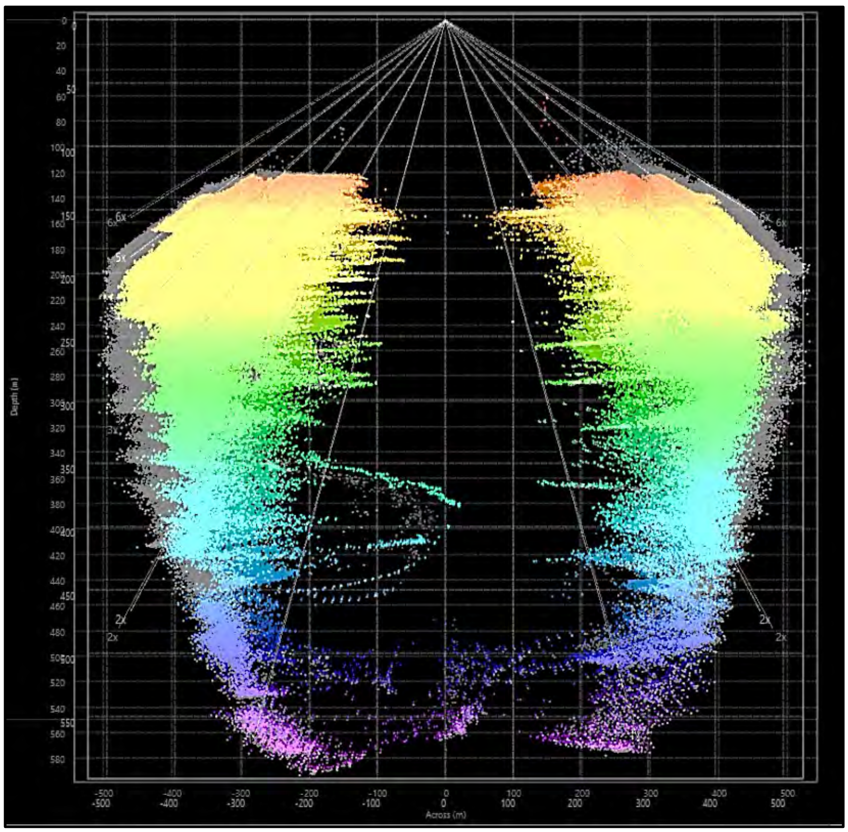


***Figure 9.*** *Example of DSCRTP EM2040 reduced swath extinction after processing (colored) and pre-processing (light gray). The post-processing extinction plot image was overlaid on the pre-processing extinction plot image and aligned as best as possible; the overlapping/offset labels are a result.*

# Firmware and Software Issues

## *Firmware update during transit and Qimera bug related to extra detections >> reduced coverage, required reprocessing time and lowered surface resolution*

## SIS Firmware Update

Extremely poor quality data early in the initial transit was found to be due to dropping of pings prior to the installation of a SIS/EM update. The update was applied in SIS partly through the transit and prior to the Volcano South survey. **Figure 10** and **Figure 11** below show the transit data that was losing pings prior to the update and resultant lower resolution surface (south and foreground), as well as the return transit surface after the update (north and background). Depth in the images below is approximately 1200 to 1800 m.

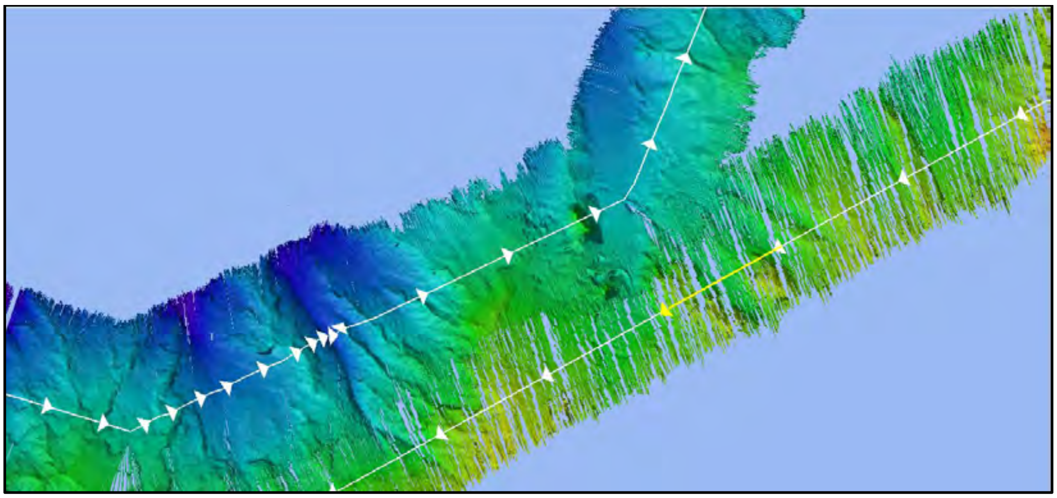


***Figure 10.*** *Example of data before and after SIS firmware update. Image is map view (top-down), north-oriented.*

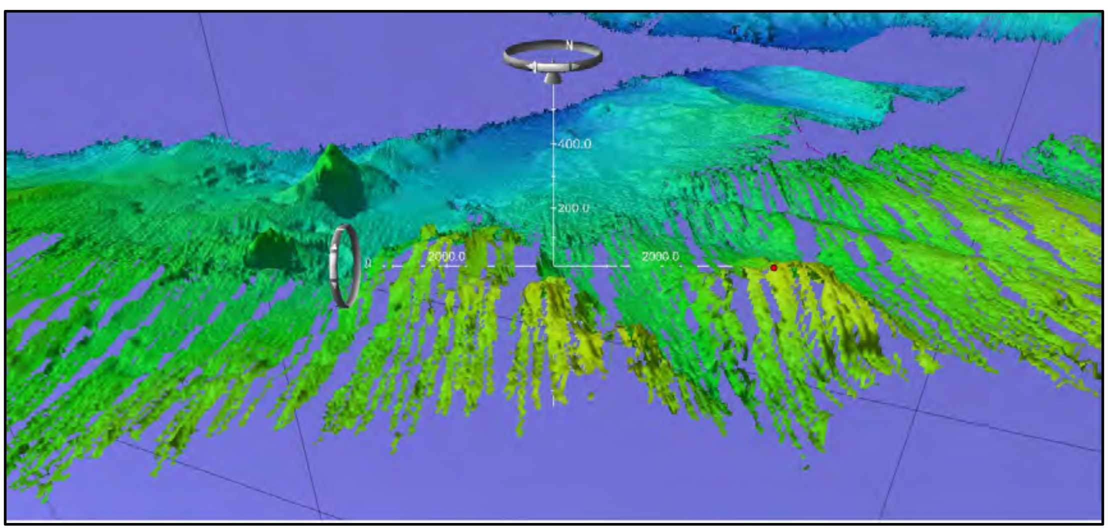



***Figure 11.*** *Example of data before and after SIS firmware update. Image is a 3D perspective view; note north is shown by the 'N' in the Qimera widget.*

We believe the firmware update was applied along the section of transit shown in **Figure 12**. The surface shown in **Figure 12** is a difference surface created by subtracting the deep processing surface generated by Qimera from the shallow processing surface – the shallow surface reflects the depth of the shallowest sounding in each grid cell, the deep surface the deepest depth in each grid cell. These surfaces are typically used to find outliers in the data during processing, and toward the end of processing, calculating a surface difference between them can help find areas that still need attention. In this case, the change in along track density before and post firmware update is visible (gaps between pings decrease from right to left). The image also shows the vertical depth spread in soundings of the outer swaths before the update. Red areas indicate differences of 12+ m between the shallow and deep surfaces.

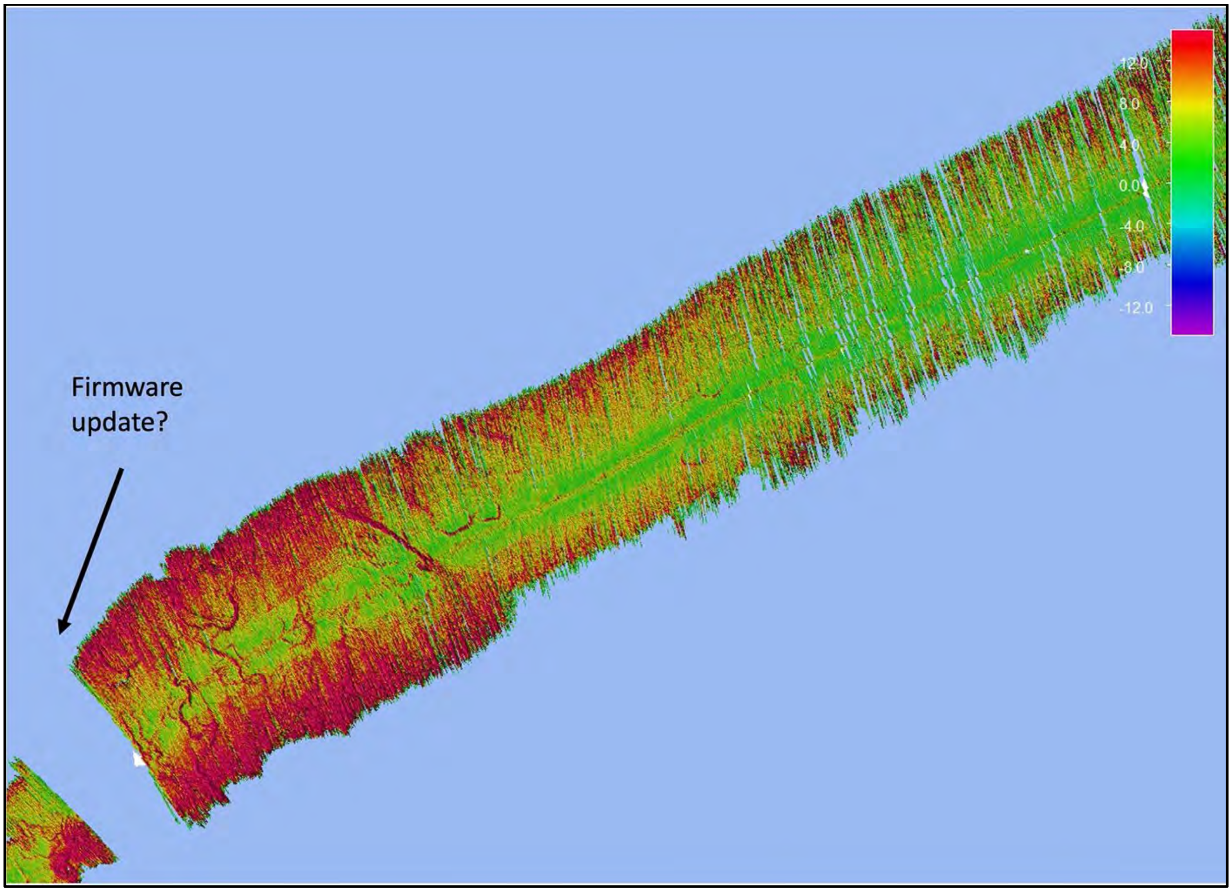



***Figure 12.*** *Map view (top-down ), north-oriented image of data collected around the period of the firmware update. The surface shown is a difference surface between the shallow and deep processing surfaces. Areas with zero to ~4 m difference are green; red areas indicate 12+ m of difference between the two surfaces.*

## Qimera Bug (CQM-6130): not supporting extra detections and corrupted GSF export

A bug related to incorrect Qimera support of extra detections in the KMALL was found during processing. The issue was first observed in the 3D editor while reviewing the initial transit data into the first few lines of Volcano South and was related to extra detections not being interpreted correctly. A check in the KM sonar record viewer found that the earlier lines had extra detections turned on; they were not turned off until after the start of the Volcano South survey. Late in the processing, it was discovered that these files would not unload/export to GSF correctly. GSF files are considered an important format for downstream processing – they are often used in backscatter processing because they reflect edits made to the bathymetry (artifacts/outliers are 'flagged' as rejected and turned off); NOAA OE's mapping procedures specify that GSFs should be used for final backscatter mosaics (https://oceanexplorer.noaa.gov/data/publications/mapping-procedures.html). They are also important for archiving and integration into some syntheses, again because they maintain processing flags.

The Saildrone online team did not realize that the extra detections had been turned on; the setting may have been turned off around the time of the SIS firmware upgrade. QPS fixed the bug and provided a beta version (28 April), but it required reloading the raw KMALL files in a new project for complete reprocessing in order to be able to unload the GSF files correctly, a time consuming but necessary process for the sake of downstream data products and archiving.

The initial transit and first few lines of the Volcano South survey (lines 0000_20220810_171041_SD-1200-0012-EM304.kmall through 0119_20220813_034616_SD-1200-0012-EM304.kmall) were affected. **Figure 13** shows how the bug manifested itself in QPS Qimera.

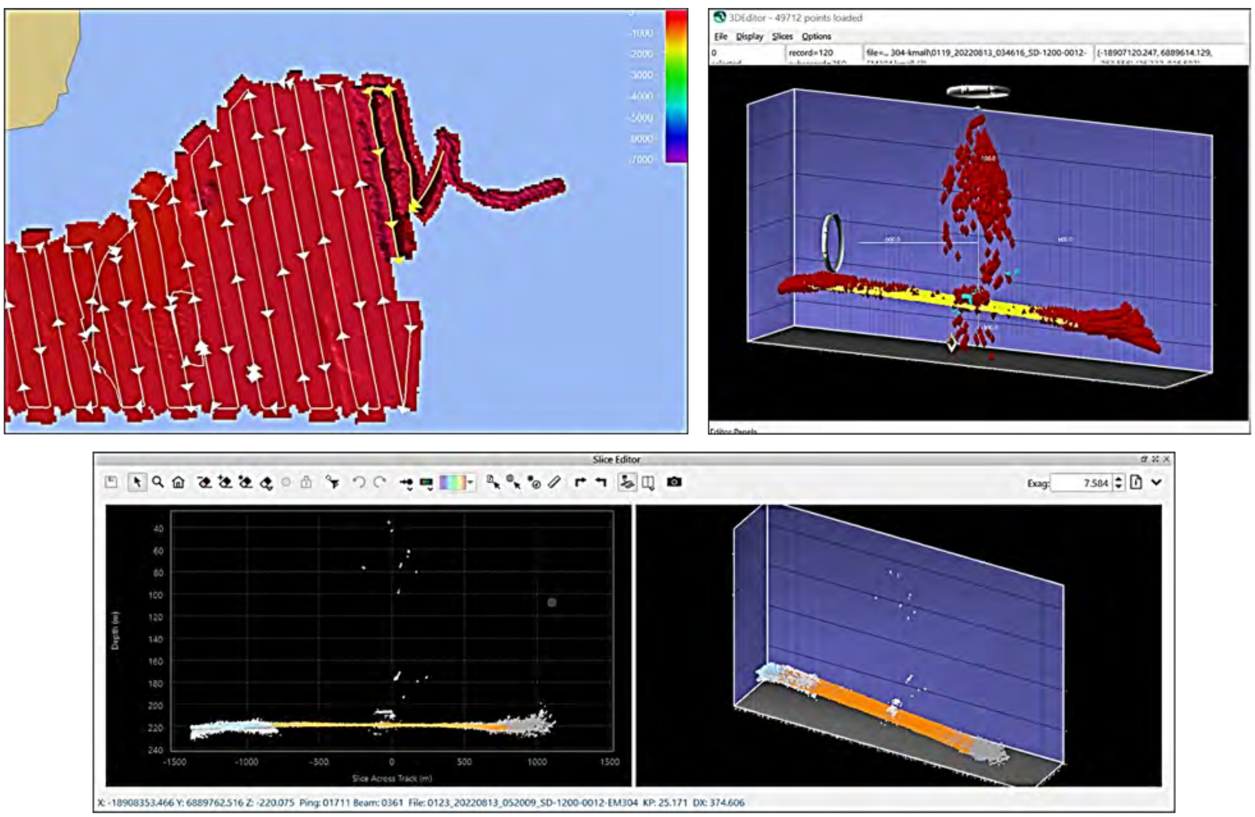



***Figure 13.*** *Images demonstrating the KMALL extra detections bug. Top left, highlighted yellow lines with issues. Top right and bottom, differences in the way the QPS editors were reading the data flags: top right, the QPS 3D editor shows the area as having rejected (red) soundings and additional (blue) soundings; bottom, the QPS Slice Editor shows the area having different rejected (light gray/white) soundings and no interpolated/additional soundings.*

# Limitations of Remote Access

## *Remote access allowed for less-than-normal interaction with online systems*

The remote access to the system reduced the normal interaction with SIS and ancillary sensors that one would find on a crewed, staffed system, and appeared to reduce some of the normal system mode changes and on-the-fly adjustments that come with direct monitoring and easy real-time access to systems and settings. This resulted in some missed system failures, incorrect system settings not being noticed, gaps in surfaces, and settings not being adjusted or not being adjusted quickly enough, affecting coverage, noise, and the quality of the bathymetric surface. Online surveyors were also not able to access the data mid-survey, removing the ability for near real-time QC that is typically standard for crewed vessels that are staffed with a mapping team. When crewed vessels are staffed with dedicated mappers, they are often evaluating and processing the data very soon after acquisition, allowing for operational adjustments that may not be deemed necessary based strictly on observing the data acquisition.

The limited interaction appeared to result in some tracking failures in the OER1 survey during a patch of rough weather (**Figure 14**, **Figure 15**), resulting in extended gaps in the surface once the areas of poor tracking were removed. There was also an extended Seapath failure during the Amukta survey that resulted in a number of lines being deleted during processing, leaving a gap in the final bathymetric surface.

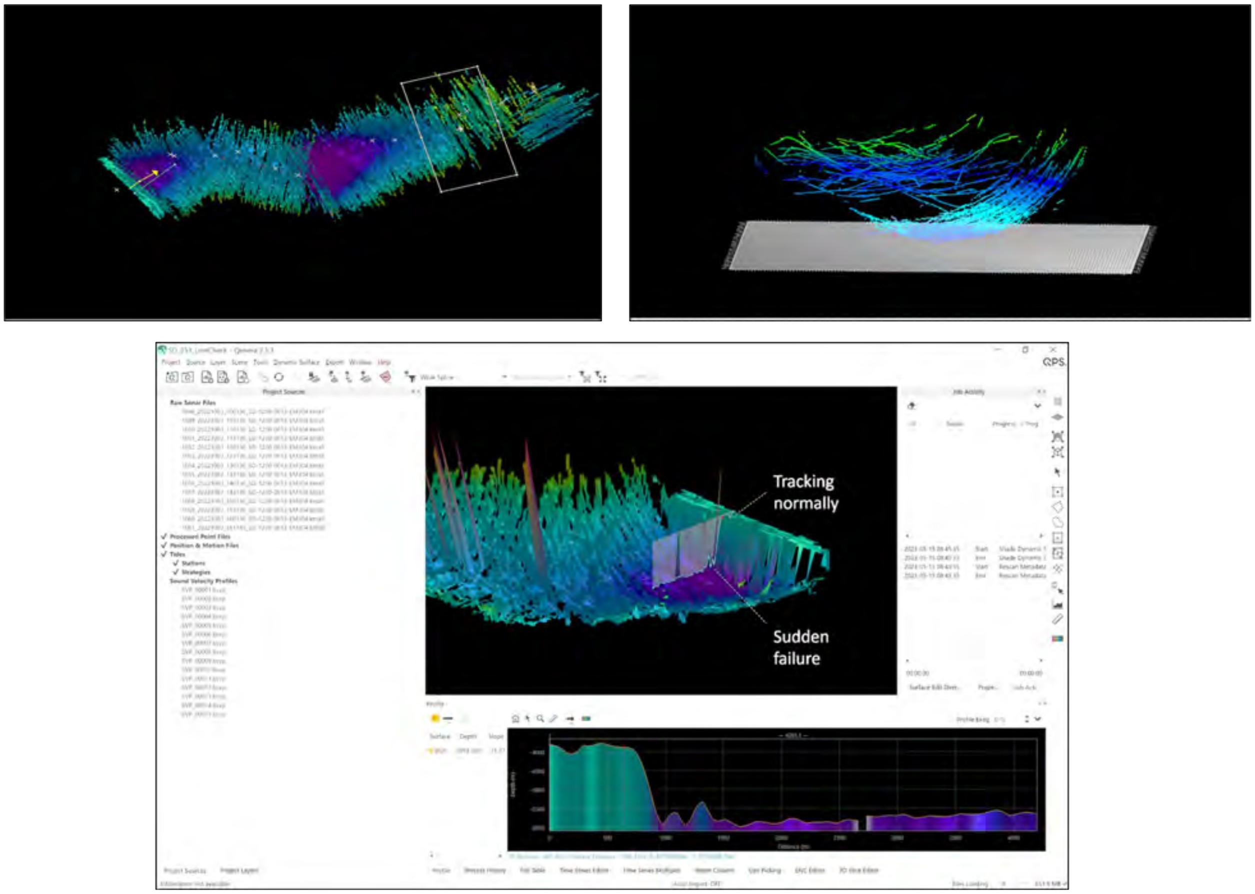



***Figure 14.*** *Images showing tracking failures in the OER1 survey area.*

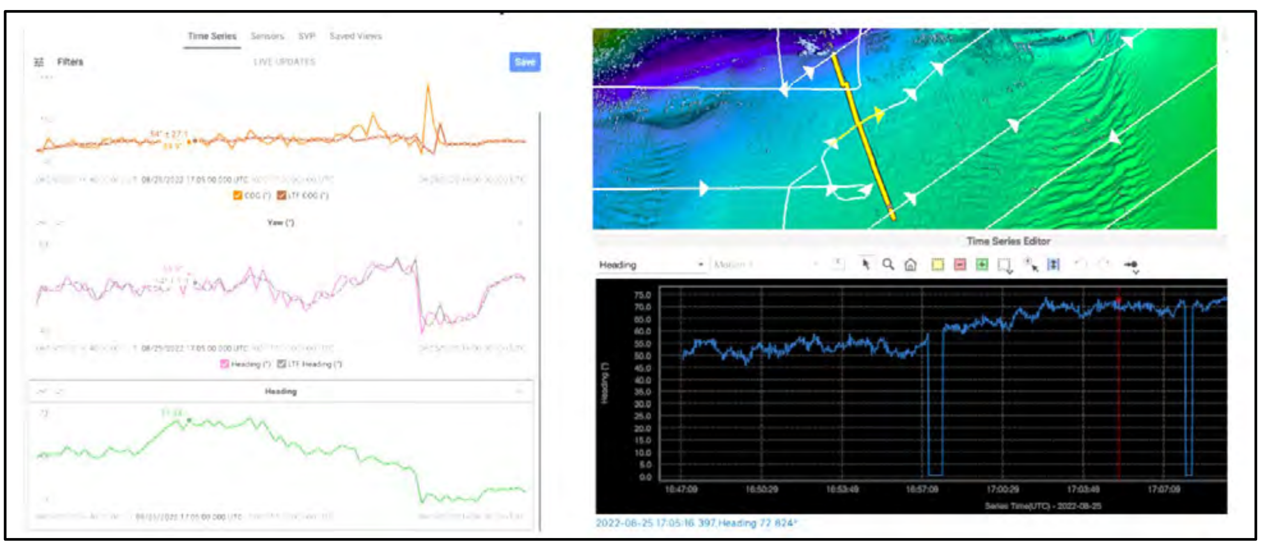



***Figure 15****. Seapath MRU failure in Amukta Area. The left side of the image shows the SD Mission Portal, specifically the navigation system's reported Course Over Ground (COG), Yaw, and Heading. The right side shows line 0453 in Qimera (bathymetry top right, heading time series bottom right). The images show the dropout of the Seapath at 1657; heading starts to drift up to about +20 degrees above Yaw, then drifts down to about -20. COG jumps at around 1743.*

The WOA model was not consistent with the regional surface sound speed (**Figure 16**), and as noted elsewhere in this document (see [Sound Speed Issues]) more sound speed profile observations should have been made, notwithstanding the periods of bad weather. With regard to limitations imposed by remote access, there was an issue during the Volcano South survey where the surface sound speed source in SIS was set to Profile rather than Probe; this setting determines what values are utilized for real-time beam forming, and should be set to the surface sound velocity sensor (the Teledyne Reson SVP-70) as long as that is operating correctly. This was very likely done inadvertently and might have been noticed earlier with direct system monitoring and easier access to system settings. As WOA model profiles were utilized often during the survey, it is likely that in some cases an inappropriate value from the WOA model was used for real-time beam forming. The issue was exacerbated by [Qimera bug CQM-6233], where the software is not allowing the user to change the surface sound speed to the sensor value (which is recorded in the KMALL, even if it isn't utilized real-time) for reprocessing. This resulted, we believe, in more outer beam noise, requiring additional filtering and processing and reducing the quality of the final bathymetric surface. It is recommended that post-processing utilization of the surface sound speed sensor values be checked once the bug has been resolved and an updated software version is released, to evaluate whether the final bathymetric surface can be improved (we are not sure what if any effect it may have).

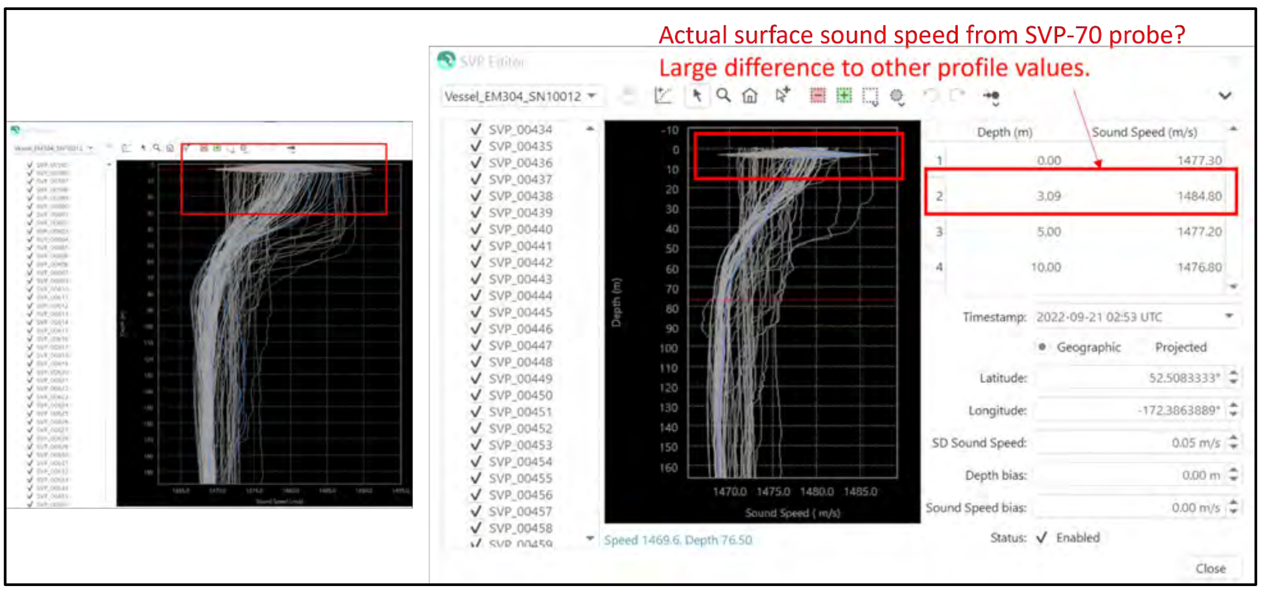



***Figure 16.*** *Surface sound speed variations compared to WOA - note significant difference for what we assume to be the surface/transducer depth sound speed from the SVP-70 sensor added to a WOA profile for OER1 and Amlia Basin. The horizontal spikes in the profiles around transducer depth seem to indicate this was the case for many of the profiles.*

## Wide Swath, Noisier Outer Beams, and Heeling Artifact

### Wider, noisier swath

The acquisition report noted that the swath width was wider than modeled by Kongsberg when sailing. The report notes that "the 'extra' outer beam data is unregulated by the normal flagging system implemented in real time during data acquisition, so it appears slightly fuzzier than data from other parts of the swath."

This was noticeable in all areas and complicated processing when the additional noise masked other issues, such as insufficient sound speed profiles causing bending of the swath. It also reduced the quality of the weighted average surface and CUBE surface and was mostly overcome by clipping about 50 beams from either side of the swath. However, residual along-track gridding artifacts remained along the outer sectors of swaths in some areas after initial processing, and the often-limited (or non-existing) overlap between swaths prevented the remaining outer beam 'fuzz' from being averaged out. This required extensive additional manual editing to optimize final product surfaces, and often left remnant artifacts. **Figure 17** and **Figure 18** below show examples of outer beam noise levels for both the EM2040 and  EM304.

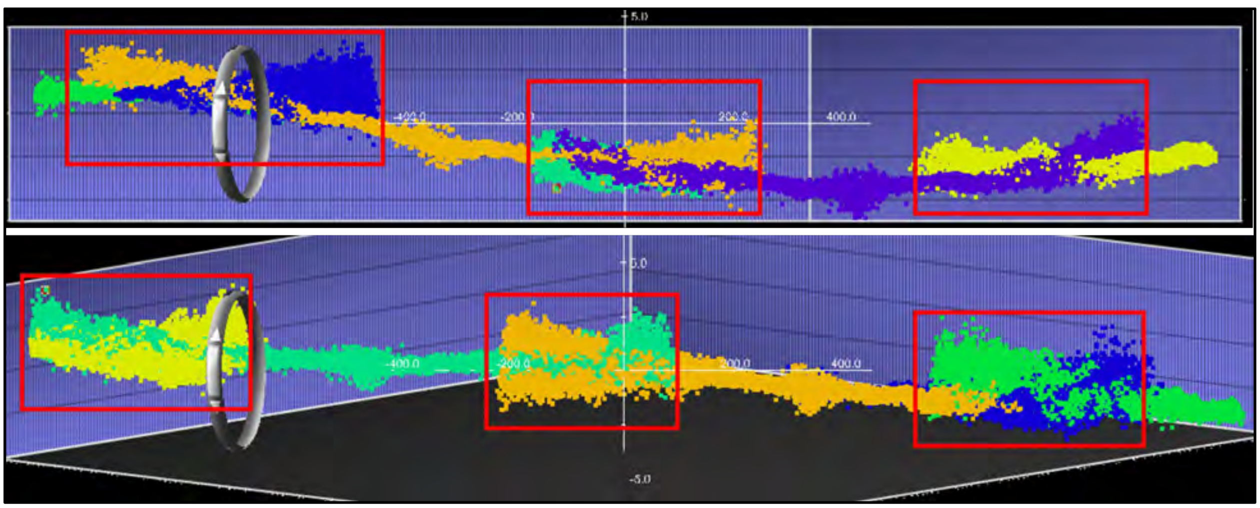



***Figure 17.*** *EM2040 data with noisy outer beams, likely masking additional sound speed issues.*

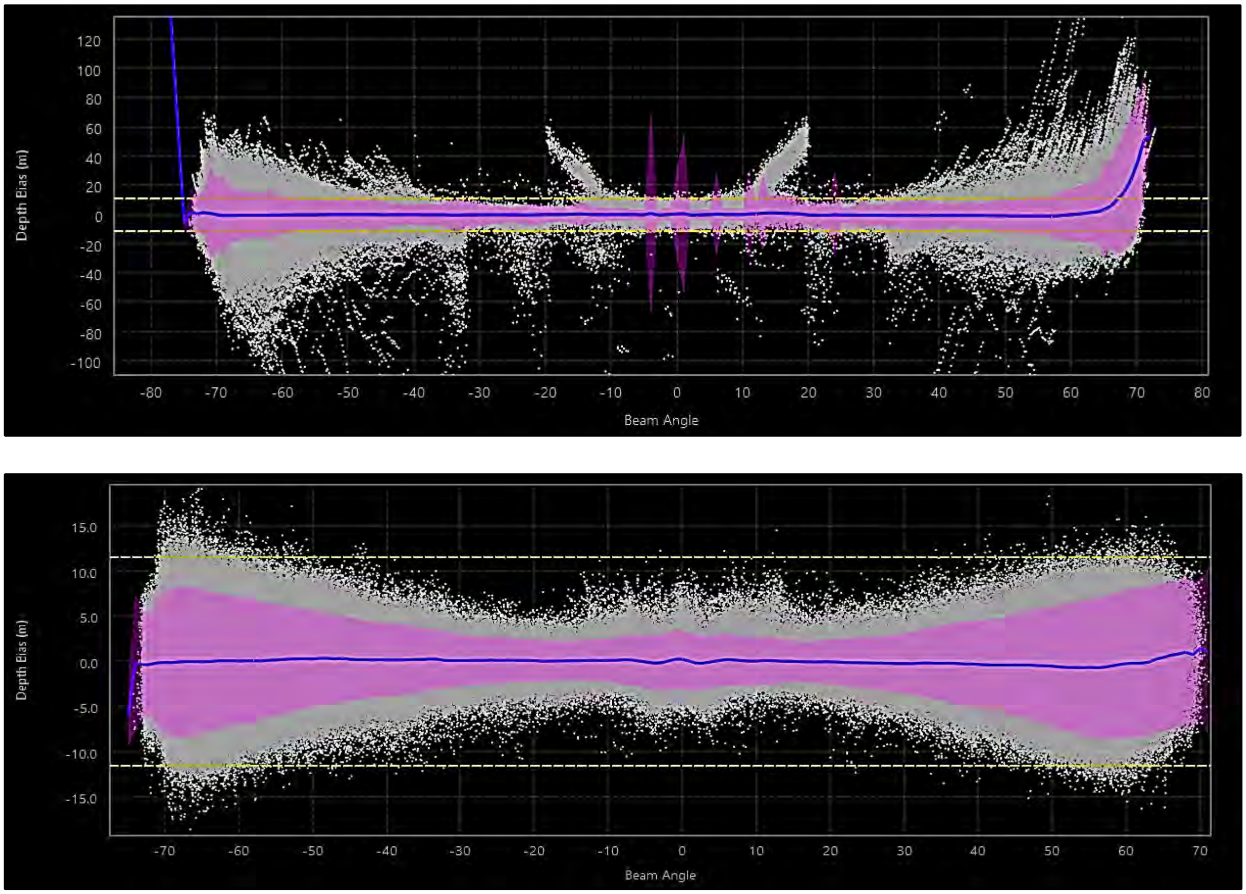



***Figure 18.*** *Cross-check analysis of EM304 data from Amlia Basin, before processing (top) and after processing (bottom), as an indication of the extensive outer beam noise prior to processing. The dashed yellow lines in both images show the same depth threshold (+/- around 12 m).*

We also feel that this wider real-time swath likely led to planning later lines based on those observed swath widths. Unfortunately post-processing revealed the outer beams to be unusable, further reducing the already-limited overlap that was planned for based on stated requirements.

## Heeling Artifact

The wide swath and vehicle heeling about 10 degrees when sailing often caused an artifact on the downwind side of the swath. The Bathymetry Acquisition Report showed an image with the issue (**Figure 19**) but it was initially thought to be just noise or a sound speed problem. The Saildrone Surveyor 2021 Sea Acceptance Test report also noted issues related to sound speed and heeling. During the surveys, this issue only appeared on the downwind side, and showed as an upward distorted outer beam of 10-15% of the depth. It is possible that this is beyond the roll stabilization and that the angle of the return signal could not be discriminated correctly, causing the artifact. **Figure 20** and **Figure 21** below show examples of the issue in Volcano South and Amlia Basin.

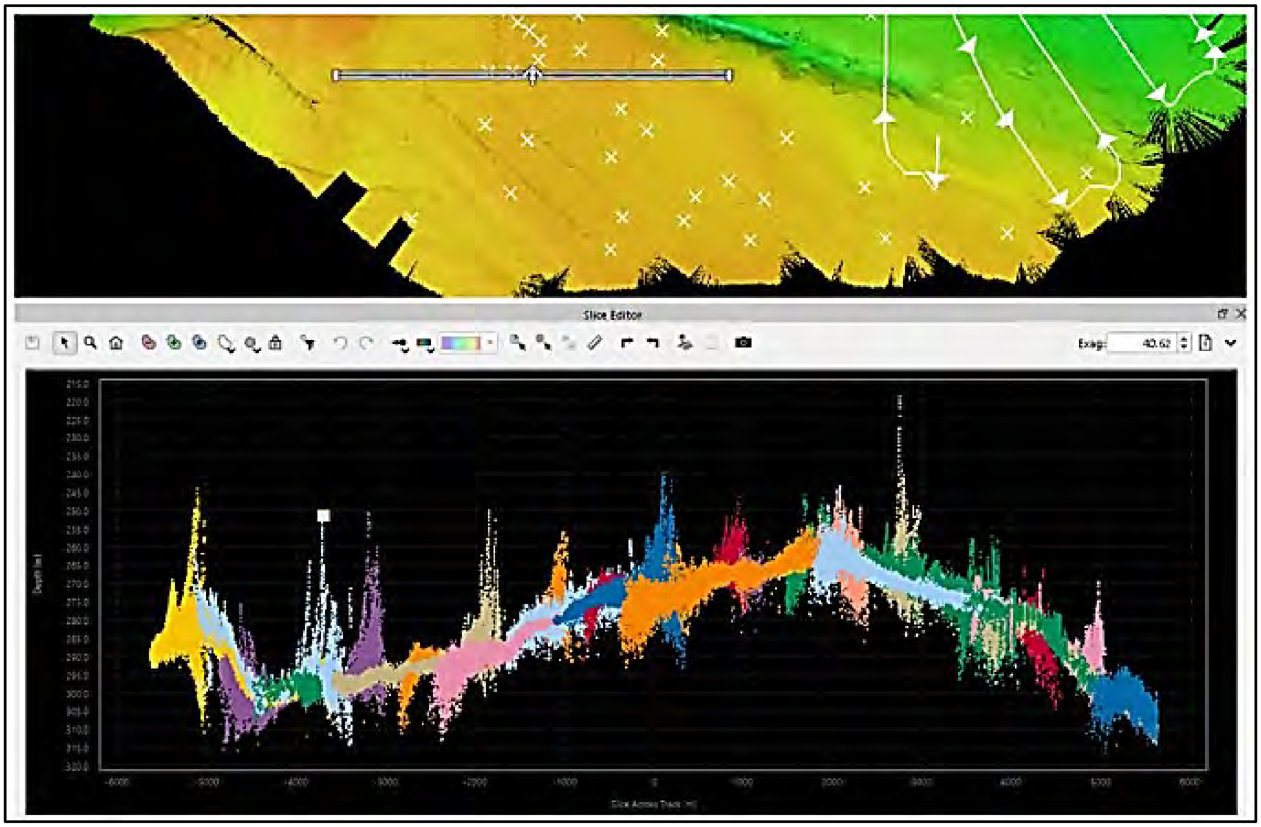



***Figure 19.*** *Image from the SD-1200-0012 Bathymetry Acquisition Report (Figure 14) showing the outer beam artifact we are referring to as the 'Heeling Artifact'.*

The solution to the issue was to clip 50 to 60 beams on the downwind side. This required careful line-by-line review to limit the rejection of 'good' data and to avoid causing gaps in the coverage. It substantially increased processing time of some survey areas, where limited overlap did not allow more automated filtering or blanket application of beam clipping.

Occurrences of this issue were reduced in deeper water when the EM304 automatically switched to deeper modes that utilize system/software-enforced reduced swath widths.

We would suggest that Kongsberg investigate this issue further and make improvements to better handle/flag this special-case (likely sailing-specific) artifact.

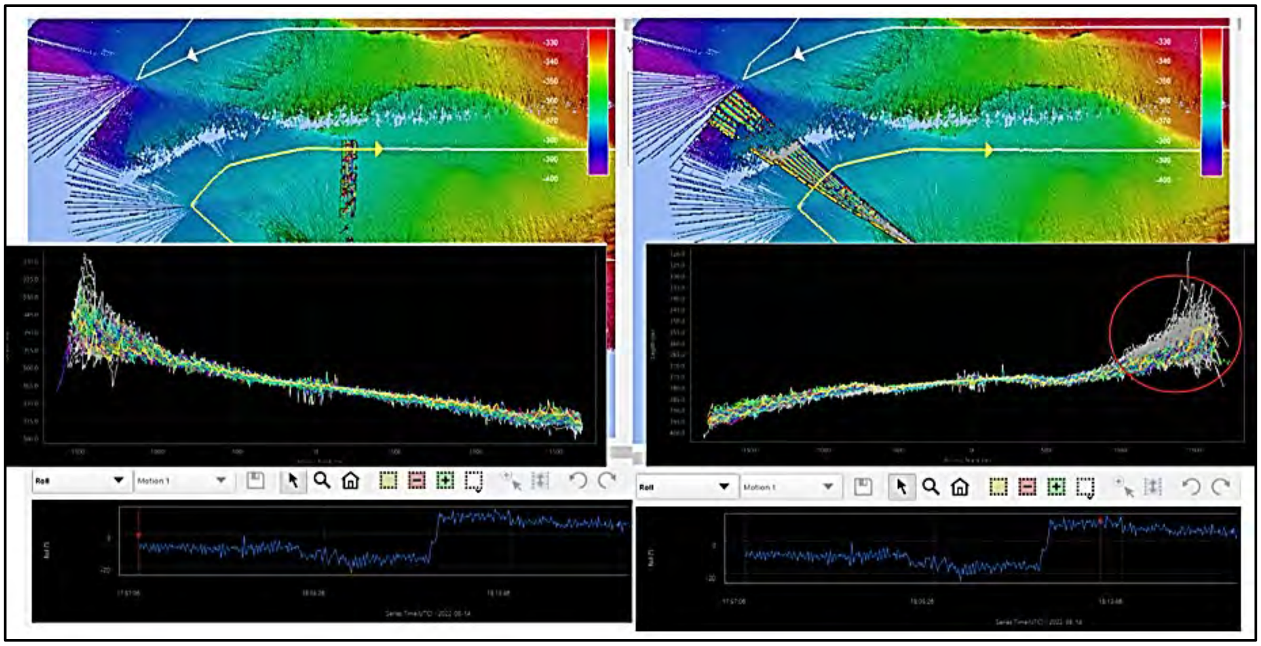



***Figure 20.*** *Volcano South Heeling Artifact. The bathymetry overview (top), swath view (middle) and profile (bottom) show a 25 to 30 m depth artifact in 370 m of water with a vehicle heel of about 10°. Wind from about 345°.*

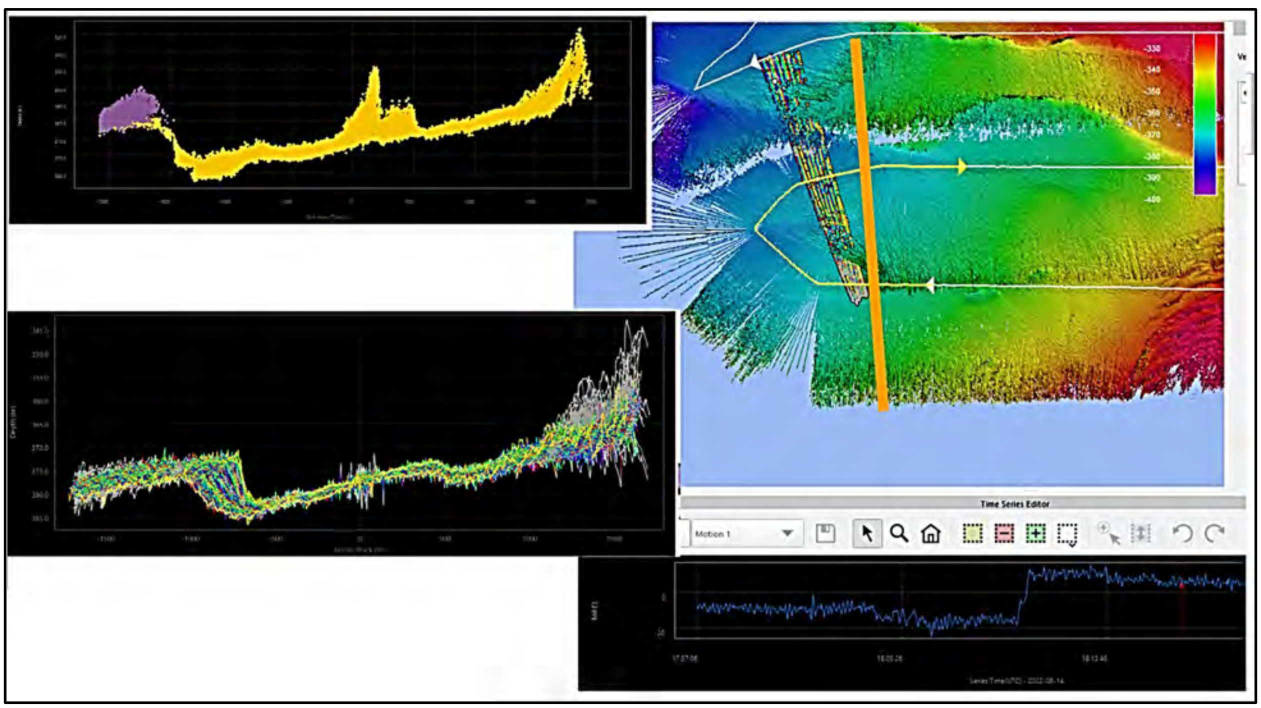



***Figure 21.*** *Additional images showing the large systematic fliers caused by the Heeling Artifact, Volcano South.*

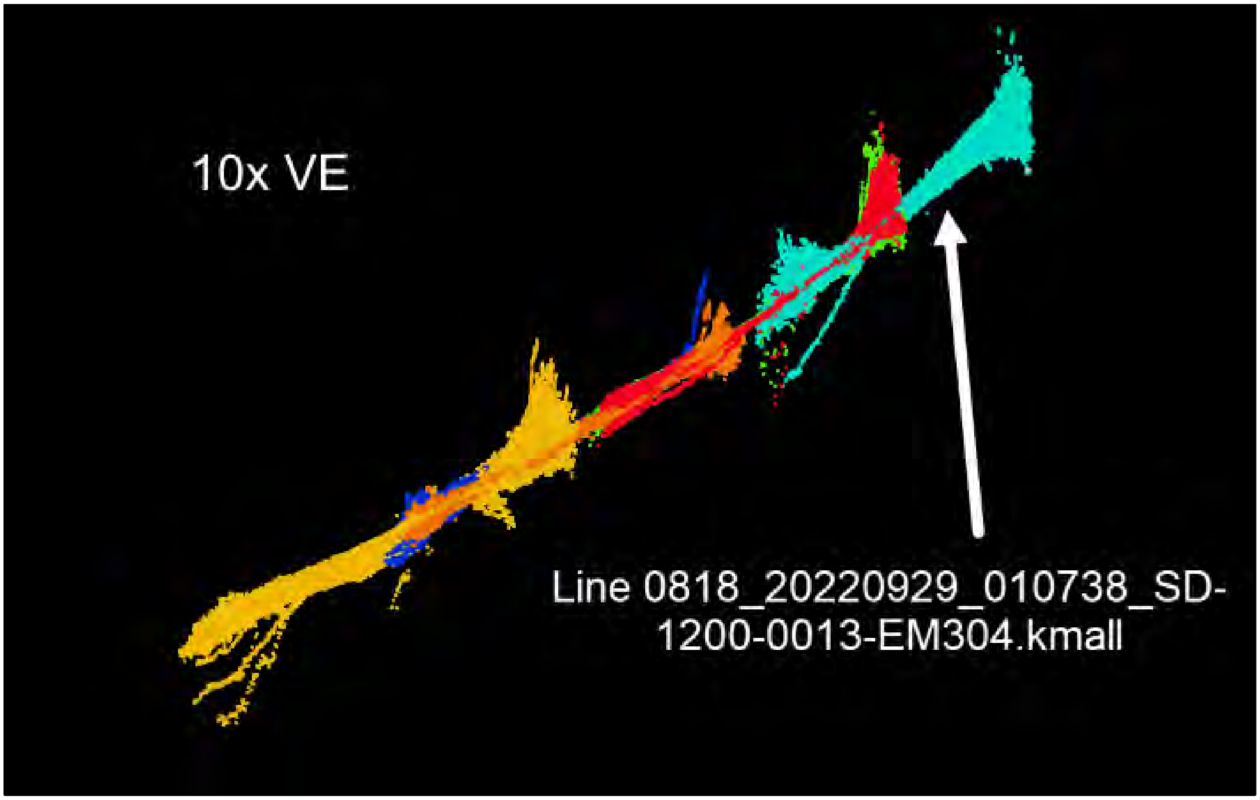



***Figure 22.*** *Heeling Artifact in the deepest part of Amlia Basin (~1,000 m water depth).*

# Motion and Speed Compared to Larger Vessels

## *Significant motion and lower speed compared to larger vessels >> allowed survey in bad weather, but resulted in noisier data, less overlap and gaps in coverage*

The SD-1200 is smaller than a traditional research vessel that would normally have an EM304 and is prone to more motion in all axes. It is more susceptible to wind and currents and is much slower than the traditional vessel, as noted below, and often sails with a significant yaw from the heading of the survey line (**Figure 23**). The latter results in less overlap than anticipated from planned lines, exacerbated by coverage being further reduced when noisy outer beam data was rejected in post-processing.

The SD team was able to continue operating in some bad weather with wind over 35 knots for periods, but this also increased motion and degraded the data with noisier outer beams, reduced along-track density, and gaps from resultant beam steering of the different sectors. During some of the bad weather in the DSCRTP area the EM2040 showed an intermittent failure in the outer sectors that was correctly rejected by SIS, but left gaps in the along-track coverage (**Figure 24**).

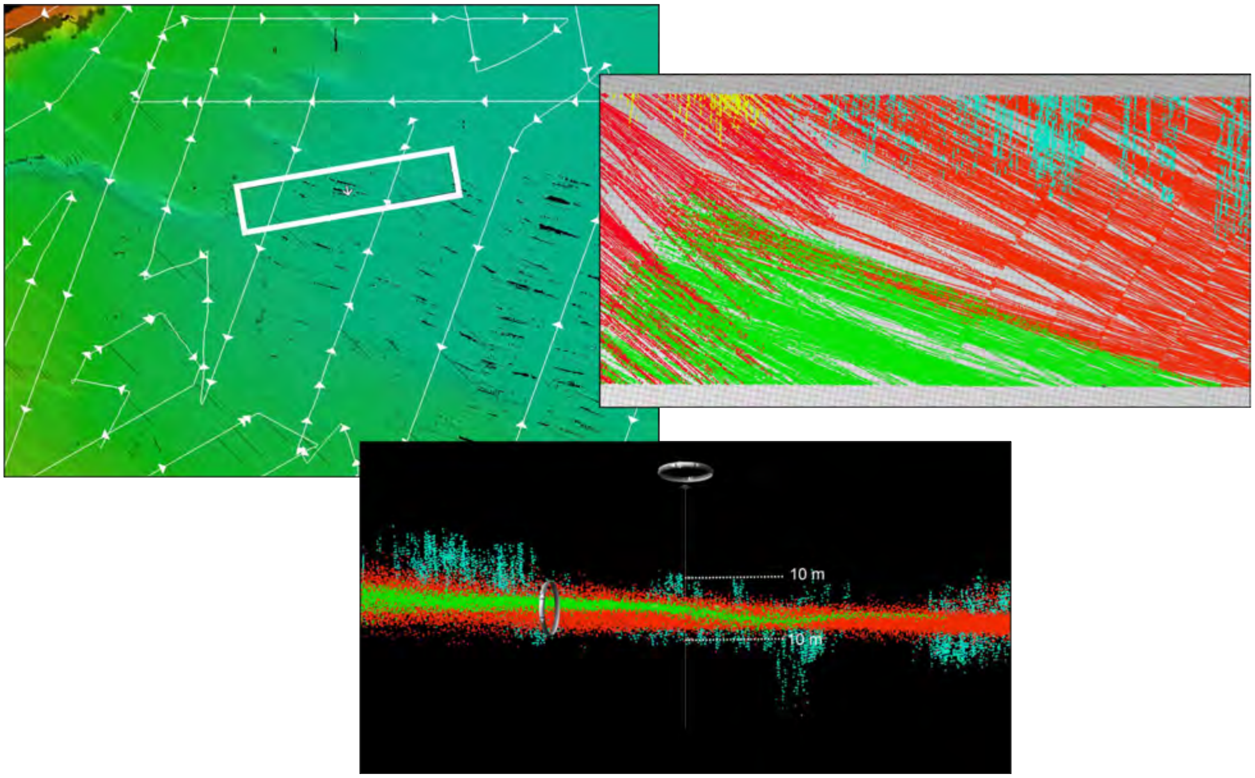



***Figure 23.*** *Coverage gaps caused by vehicle motion. This example of coverage gaps is from the deeper areas (1,000 m water depth) of Amlia Basin. The image on the left shows gaps in the 60 m resolution surface; the white box shows the portion of the surface shown on the right. The image on the right is the sounding coverage, with large gaps in coverage (note that the black grid squares underlying the red, green, yellow and aqua soundings are 60 m x 60 m). The bottom image is an oblique 3D view of the same area, showing the noisy outer beams of the east-west oriented line crossing just north of the area of focus.*

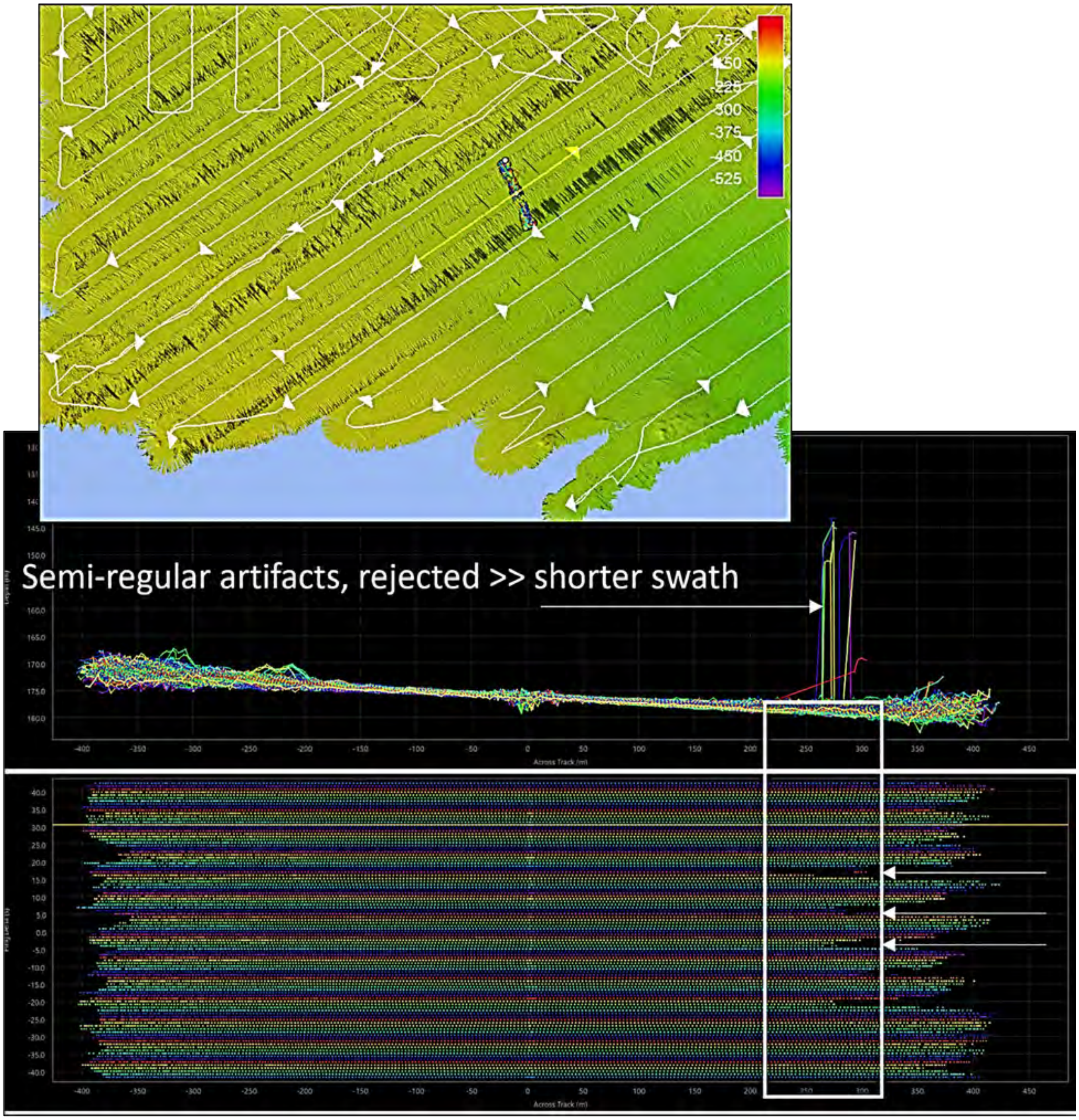



***Figure 24.*** *Example of artifacts in DSCRTP EM2040 area during bad weather including outer beam issues, sector fliers, and irregular swath. Sound velocity profiles could not be performed in bad weather, likely exacerbating outer beam issues.*

## Speed Variation

### *Significant variation in speed during all surveys >> slow average speed, varying along track density/coverage and gaps in surface*

As noted earlier, the Aleutian Islands' chain provided a challenging area to survey for the SD-1200 with changing wind patterns, periods of very strong winds and varying tidal currents. Based on the exported post-processing Qimera line reports, the SD-1200 averaged 3.4 knots for the 2,690 lines surveyed. The average speed for each survey is listed in **Table 1**. There was also a significant variation in speed, from about one to eight knots (**Figure 25**).

***Table 1.*** *Average speed per survey area*

| **Average Speed** | |
|---|---|
| Transits | 2.9 knots |
| Volcano South | 3.9 knots |
| Amukta-OCS | 3.5 knots |
| OER1 | 3.3 knots |
| Amlia Basin | 3.5 knots |
| DSCRTP | 3.7 knots |

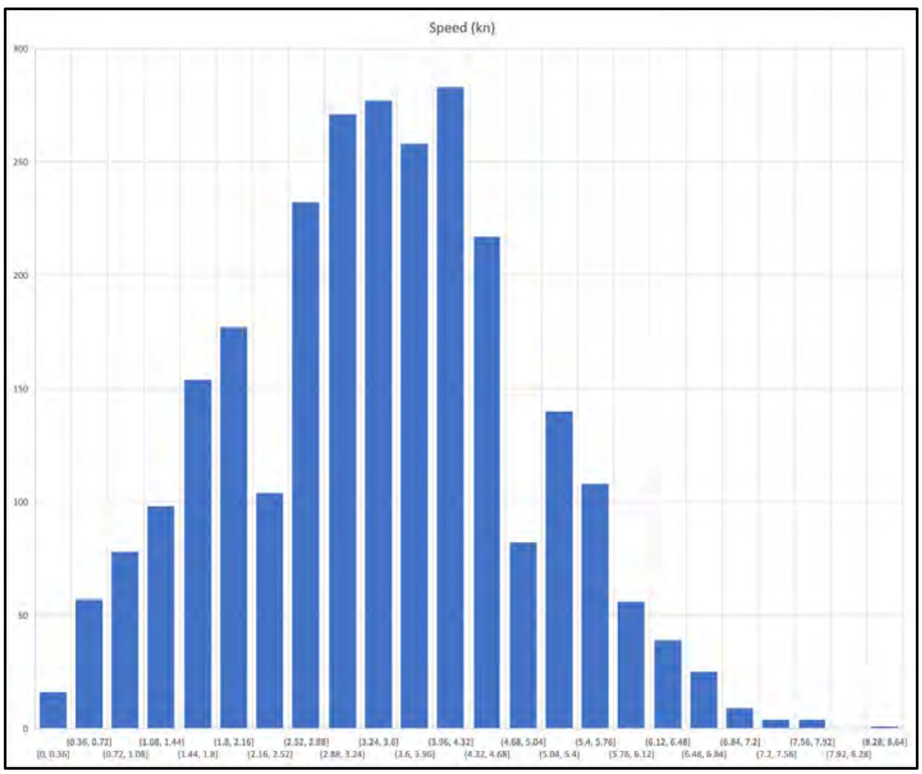



***Figure 25.*** *Histogram of speed for all lines accepted/exported to GSF files - average 3.4 knots, median 3.5 knots.*

The variation in speed, combined with some of the other issues (significant yaw and roll, see Motion and Speed… section) resulted in some areas where there was inconsistent density between lines (**Figure 26**) and the surface resolution was decreased to reduce gaps.

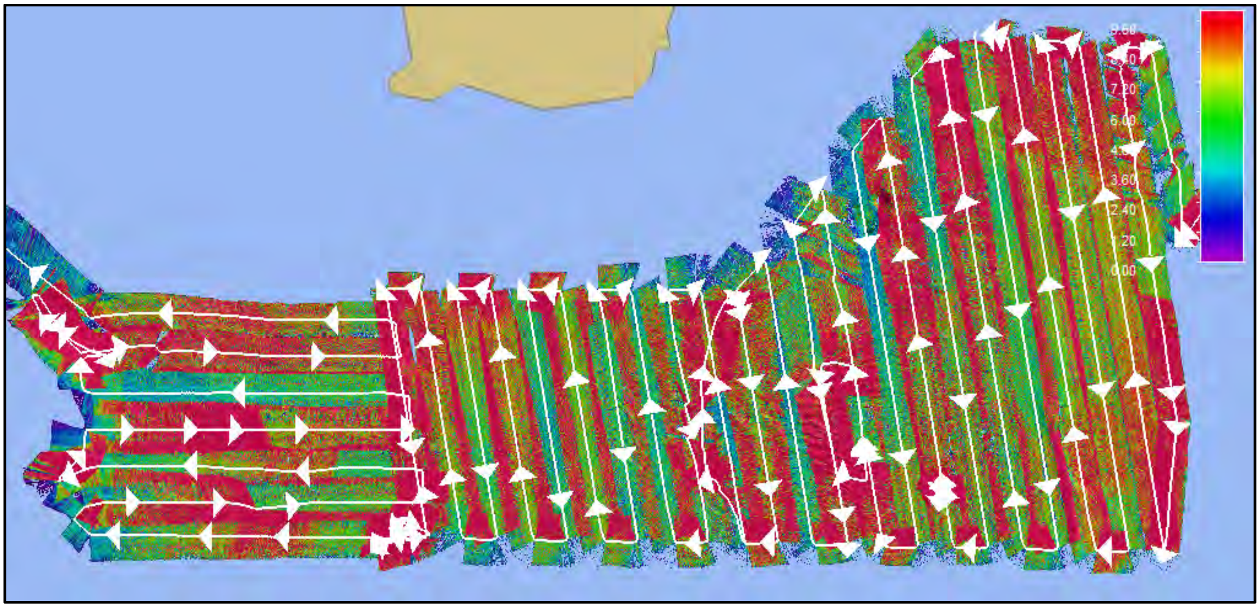


***Figure 26.*** *The Volcano South survey area, colored by sounding density. Large variations in speed resulted in variations in density along track. Main survey lines are typically broken automatically based on a specified time (30 minutes in this case, unless there was an issue or a planned turn), so longer lines generally indicate faster speed.*

## Sound Speed Issues

***Limited sound speed profile observations – and even fewer in bad weather – that were not deep enough reduced data quality and coverage and impacted the achievable grid resolution. There are likely remaining underlying sound speed issues in some of the data (swath vertical offsets, bending in swath) that may impact the final bathymetric surfaces, but other issues make it difficult to diagnose or ameliorate in post-processing.***

The acquisition reports note that sound speed profiles with the AML-6 were planned for every twelve hours in EM304 areas and every six hours in the EM2040 area. The Saildrone team developed a calculation to decide if conditions were suitable for a sound speed profile cast. The weather conditions limited the profiles that could be collected, and the World Ocean Atlas (WOA) 18 was used as a source of synthetic sound speed profiles in the region. There were 69 AML-6 sound speed profile observations versus 754 synthetic casts extracted from the WOA 18 model. Additionally, the sound speed profiles were limited to a maximum depth of 200 m in good weather conditions (based on the Saildrone Bathymetry Surveyor Configuration SD-1200-

0012.pdf, a limitation we believe is due to the winch), and in practice were often shallower due to currents.

The WOA was often significantly different from the continuously-measured SVP-70 sound speed observations near the surface. This is likely a result of the model not having a suitable resolution grid size across the island chain, due to limited observations and contributing data in this region.  It is recommended that further investigation of options be undertaken to improve sound speed modeling and the resulting bathymetry. This could include an analysis of spatial differences in the recorded surface sound speed in the various survey areas and extracting profiles from the HYCOM and other models to see if there is an  improvement to ray tracing solutions when compared to  the WOA 18 profiles that were utilized.

In future surveys it may be better to move beyond sound speed observations based on an arbitrary time schedule, utilizing the real-time variation of the surface sound speed observations from the vehicle and surface temperature forecasts (such as RTOFS, **Figure 27**) to drive the observation schedule. Improvements to the achievable profile depth would also be useful. When weather and system limitations prevent frequent observation and the models available for generation of synthetic profiles are inadequate, it would be advisable to manually reduce maximum coverage angle of the swath. This should be done in combination with reduced line spacing and preferably, more overlap.

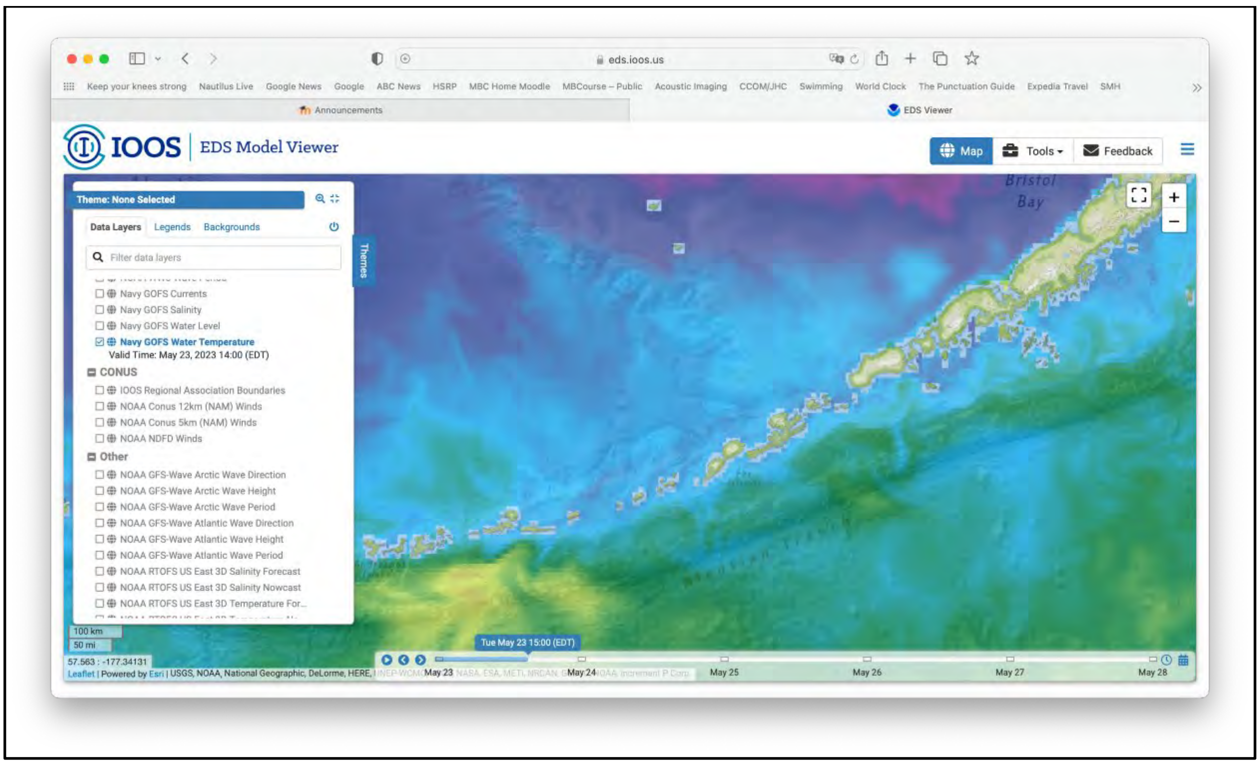



*__Figure 27.__ RTOFS Surface Temperature differences in the model across the Aleutian Islands chain.*

Note that there was also an issue during the early transit lines and the Volcano South survey with the sound speed at the transducer not being utilized in real-time – this is described in the Limitations of Remote Access section. Additionally, examples of effects of limited/poor sound speed control on the surface are found in the Resulting Bathymetric Surfaces section.

## Examples of Limited Sound Speed Profiles and Differences to WOA

### Volcano South Area

**Figure 28** shows five casts used in this survey, all from measured (AML-6) data; profile #12 was limited by the bathymetry (shallow water). Sound speed varied considerably within the survey with up to 4 m/s variation at surface, and up to 3.5 m/s at 150 m.

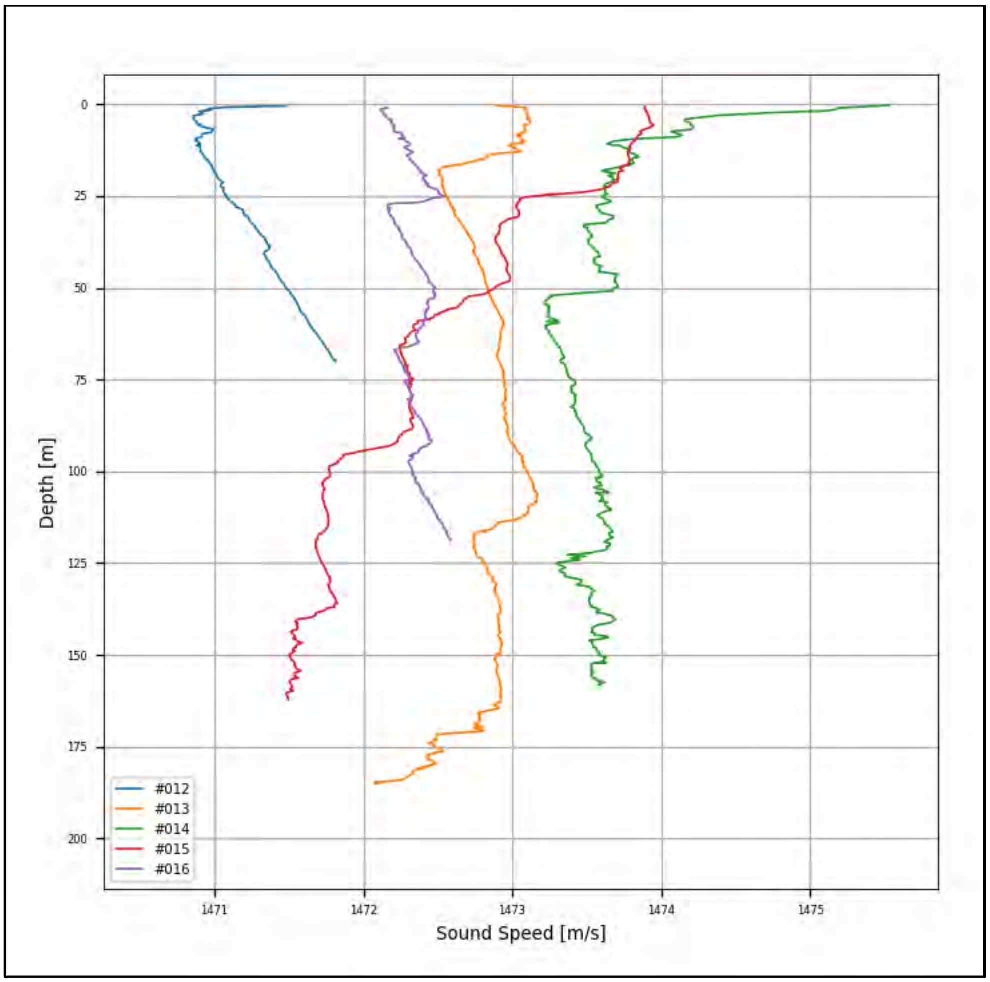



***Figure 28.*** *AML-6 sound speed profiles from Volcano South.*

The three figures below (**Figure 29**, **Figure 30**, and **Figure 31**) compare individual AML-6 casts (blue lines) to WOA reference profiles (yellow and red dashed and dotted lines). Observations were quite different from the WOA at the surface, problematic when the WOA was used (inadvertently) as the SIS surface sound speed source in other surveys. The 2-5 m/s difference between the casts and WOA at 150-200 m (max extent for the AML-6 on the Surveyor) could have been an issue for ray tracing.

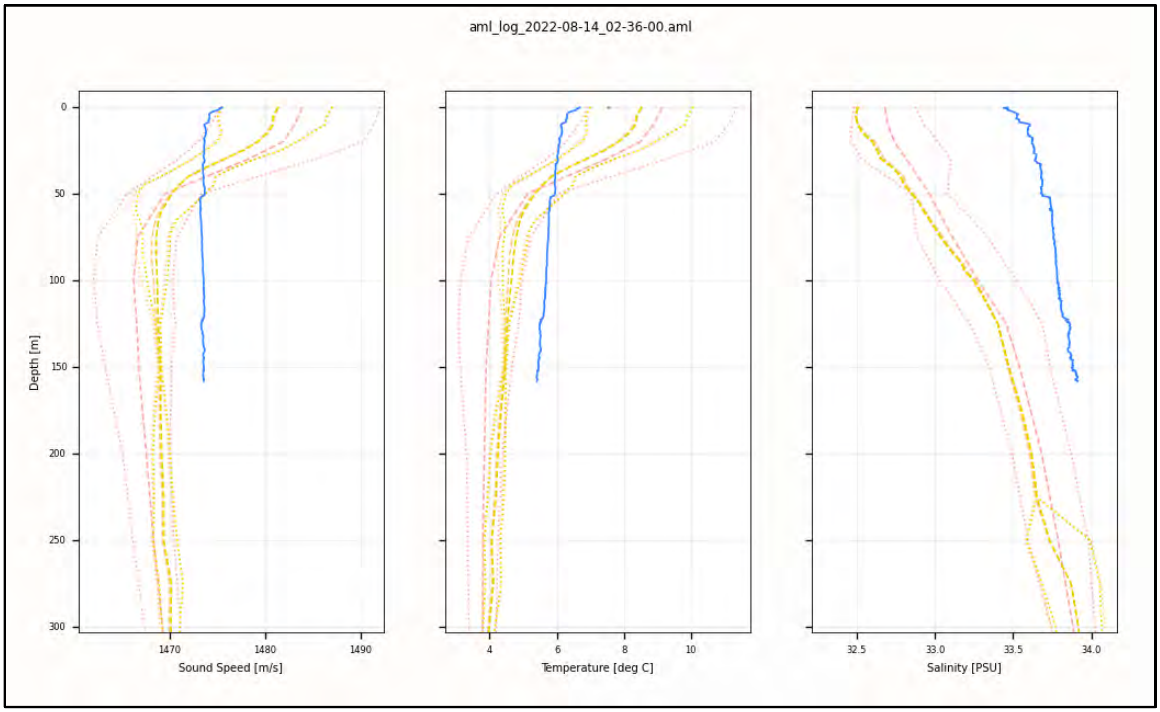



*Figure 29.* *AML-6 sound speed, temperature, and salinity profiles (blue lines) compared to WOA reference casts (yellow and red dashed and dotted lines).*

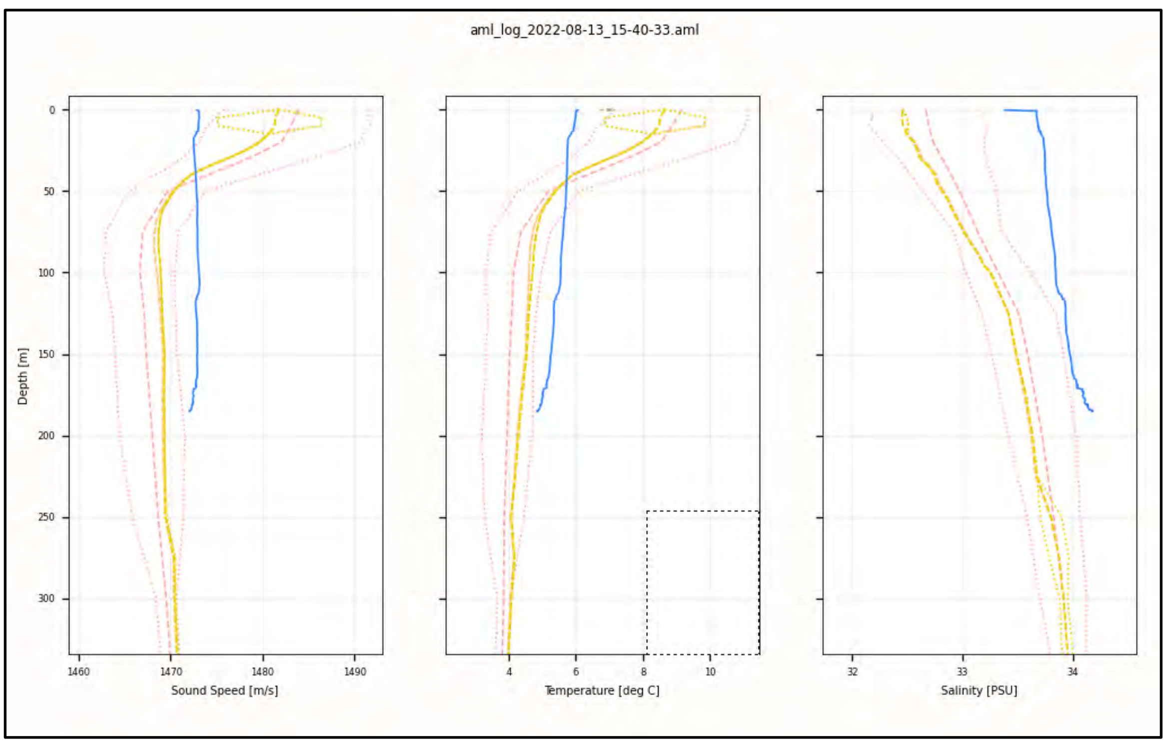



*Figure 30.* *AML-6 sound speed, temperature, and salinity profiles (blue lines) compared to WOA reference casts (yellow and red dashed and dotted lines).*

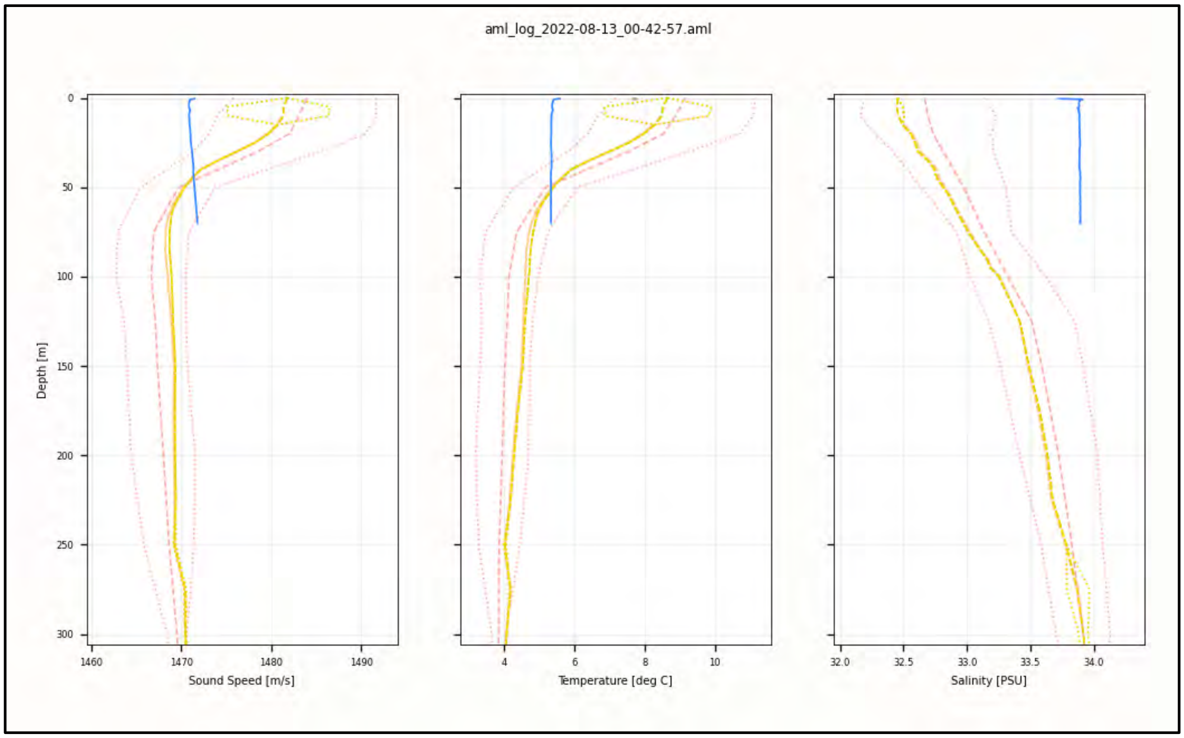



***Figure 31.*** *AML-6 sound speed, temperature, and salinity profiles (blue lines) compared to WOA reference casts (yellow and red dashed and dotted lines).*

## Southwest Amukta

In the Amukta bathymetry overview image below (**Figure 32**, left), the AML-6 sound speed observations are circled in red. In the Qimera SV Editor image below (**Figure 32**, right), the AML-6 casts are shown in blue. The remainder of the white X's on the left and white profiles on the right are from the WOA. WOA casts were used for the majority of this survey, and differ significantly from the AML-6 observations.

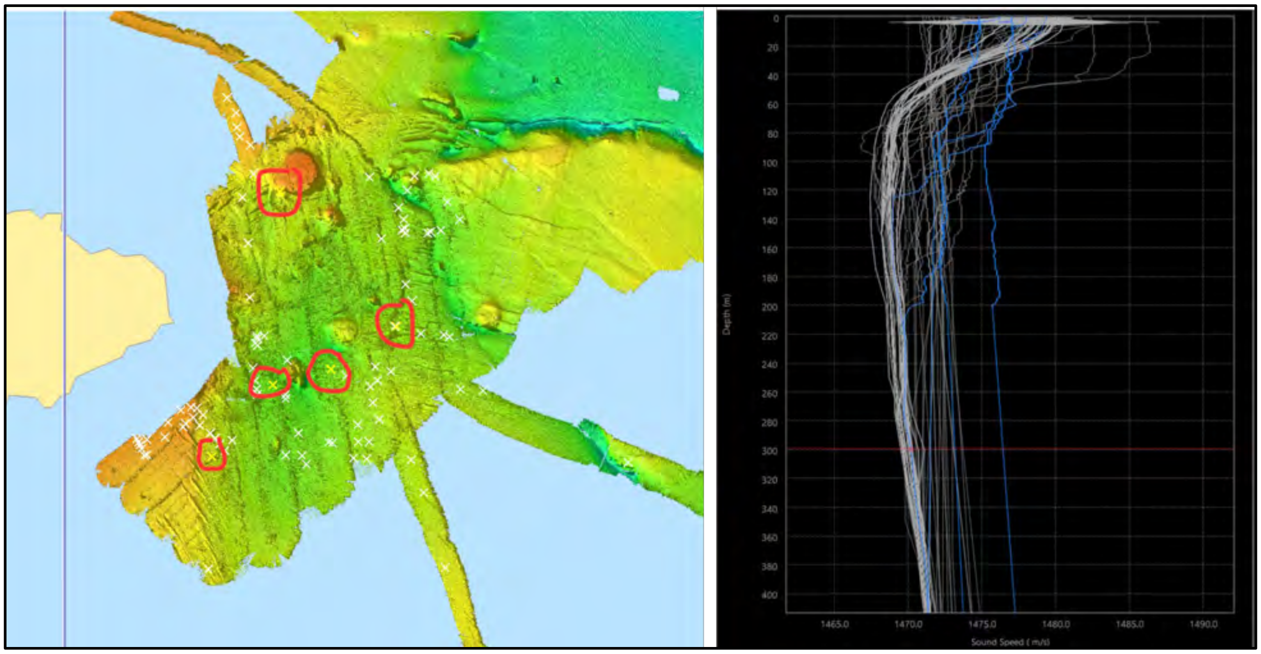



***Figure 32.*** *Comparison of AML-6 sound speed observations and WOA synthetic casts in the Amukta region. The image on the left shows the locations of casts (real and synthetic) applied to the data; those circled in red are from the AML-6. The image on the right shows all of the profiles (real and synthetic) in this survey; those from the AML-6 are shown in blue.*

## DSCRTP

Sound speed observations in the DSCRTP area were limited by bad weather (**Figure 33**), with wind speeds of 30+ knots. Observed bending of swath and some outer beam noise was likely due to lack of good sound speed control (**Figure 34**).

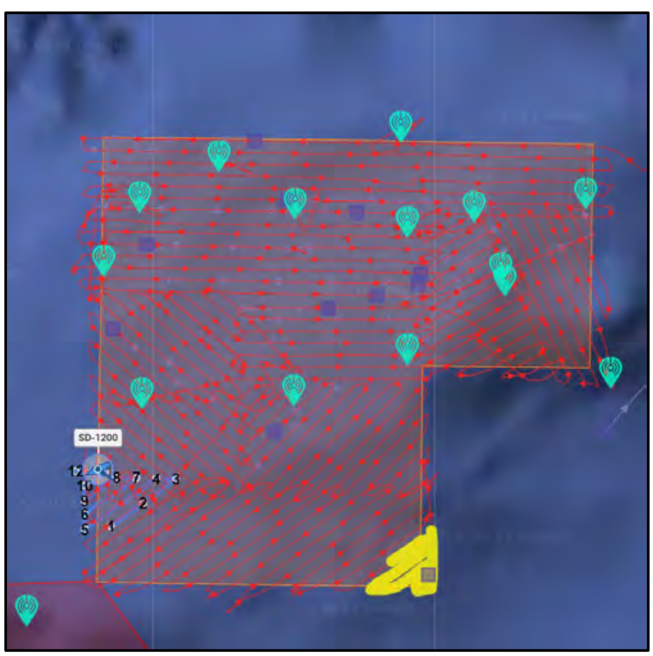



***Figure 33.*** *Locations of limited sound speed profiles in the DSCRTP survey area.*

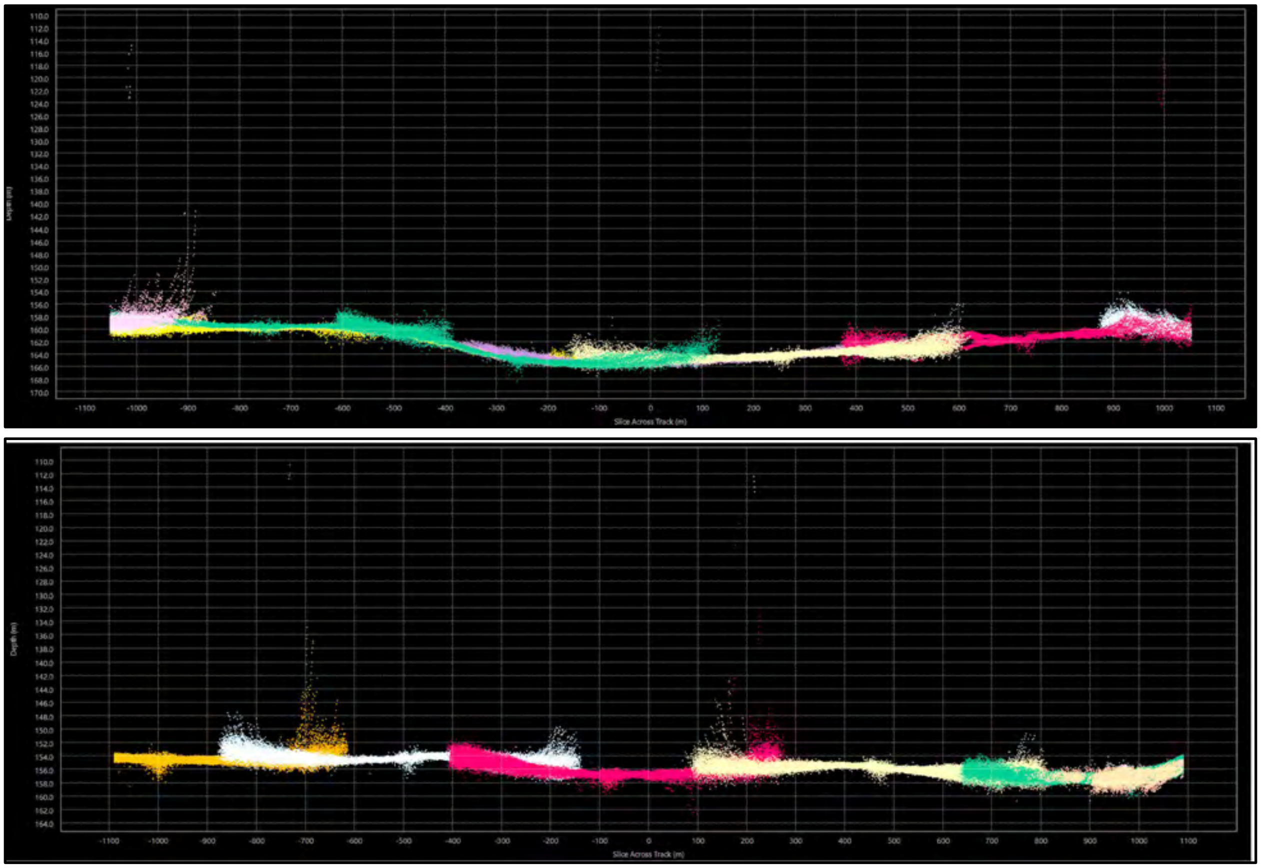


***Figure 34.*** *Examples from the Qimera Slice Editor of outer beam noise and sound speed issues (bending of the swath) of about +/- 2 m.*

# Poor Filtering Results

## *Underlying data issues such as variation in density and other artifacts caused filter-based rejection of good data >> additional time to undelete and reprocess*

Any automated surface generation and surface-based filtering, such as CUBE, CUBE filtering, and the Qimera spline filters, requires mostly good data for success. Underlying data issues noted throughout this report such as the outer beam heeling artifact, limited/shallow sound speed casts contributing to sound speed issues, noisy outer beam data obscuring sound speed issues, and changing along track density, resulted in sporadic failure of filters in certain areas that in turn caused poor results in the average surface that required remediation.

The decision to use filters (most often the Qimera spline filters) was based on early data evaluation; preliminary tests showed some slight over-filtering of good data, but this was considered minor compared to what we thought to be a more objective data processing approach that would save considerable time processing excessive outer beam noise. In practice, filtering saved time in some areas, but forced extensive manual processing to subjectively un-reject the ‘better’ data in areas where underlying data issues caused the filter to ‘make the wrong choice.’

The example below (**Figure 35**) was from early filtering tests in Amlia Basin. The filtering in this example was considered reasonable – there was some slight over-filtering of good data by the spline filter, but not enough to impact the bathymetric surface or have a noticeable effect on overall data density.

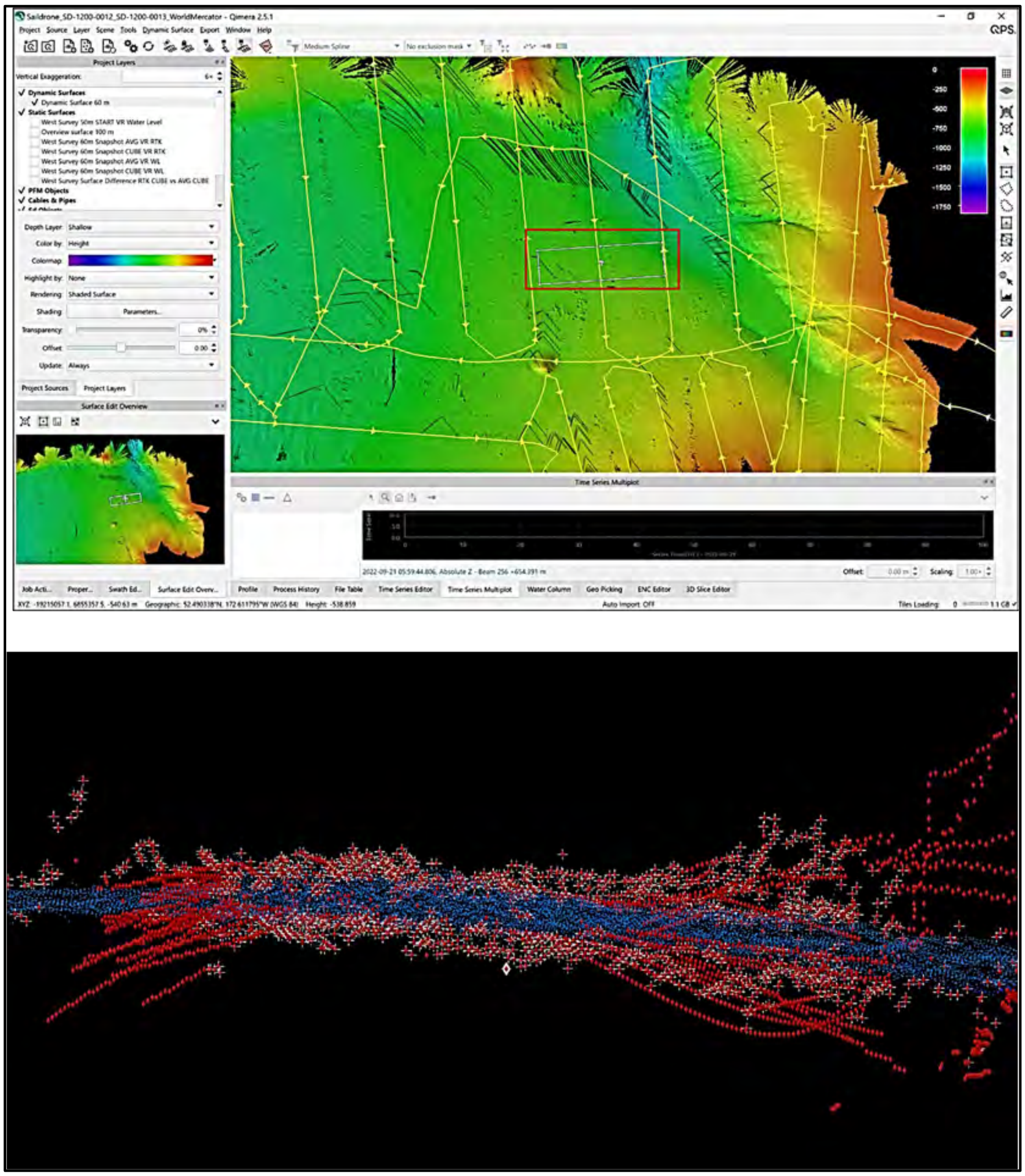


***Figure 35.*** *Example of ‘reasonable’ data filtering in Amlia Basin. The red box in the top image shows the area of interest. The bottom image shows the 3D Editor view, with rejected soundings shown as red diamonds. The soundings rejected by the spline filter have a white cross-hair; all other rejected soundings were rejected by SIS (no manual rejection was done at this point). Though there is some rejection of soundings close to the ‘good’ soundings that make up the surface, it wasn’t enough to impact the overall bathymetric surface.*

There were some cases of over-filtering on slopes (**Figure 36**), which was somewhat expected and amended where required by un-rejecting the filter rejected soundings. This type of over-filtering was found in predictable locations and was relatively easy to spot check and fix.

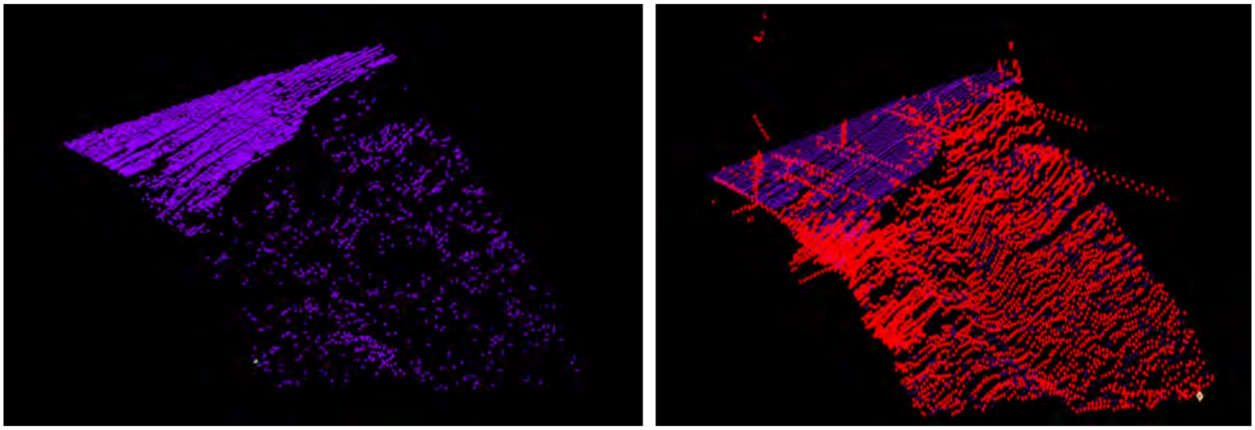


***Figure 36.*** *Example of over-filtering on slopes. Left, the accepted soundings post-filtering. Right, the same area with rejected soundings turned on (red diamonds). 'Good' soundings on the slope were un-rejected.*

The next examples show poor filtering due to underlying data issues. In the first example (**Figure 37**), the filter 'chose' the data from the aqua line as the 'good' data, rejecting the overlying soundings from the yellow line. This portion of the aqua line was from the outer beams of the system, where the soundings were well below the more central beam data found in the yellow line. This caused a depression in the average bathymetric surface that wasn't due to a real feature. This issue showing up in the average surface was a problem that needed to be resolved – Qimera generates shallow, average, and deep surfaces to aid in processing, but something that shows up in the average processing surface will very likely show up in the final products as the final gridding algorithm used is typically a weighted moving average.

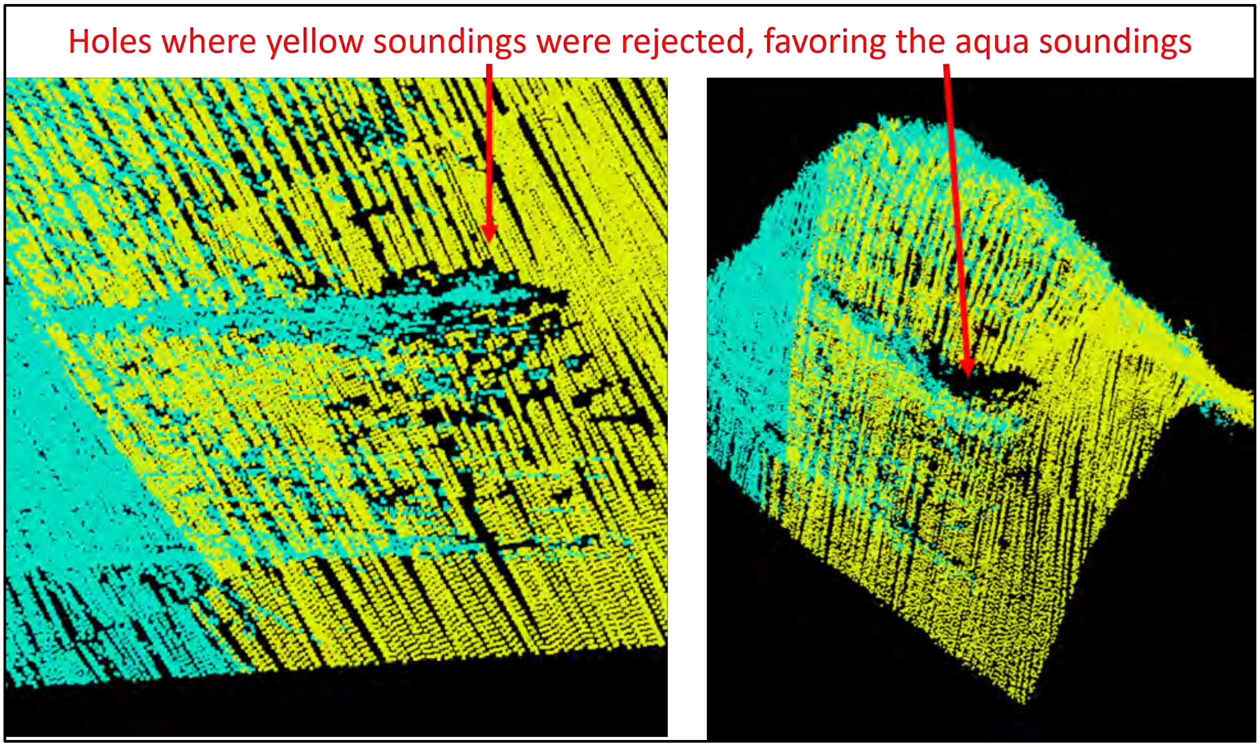



***Figure 37.*** *Example of over-filtering in Amlia Basin.*

The second example (**Figure 38**) shows the same issue, as well as the impact on the average bathymetric surface. The filter favored the dark blue and orange soundings, rejecting the 'better' overlying green and red soundings in the process. This resulted in deep depressions in the average bathymetric surface, as the soundings it kept were well below what one would consider the 'good' data making up the surface (see the yellow circle in the lower right image).

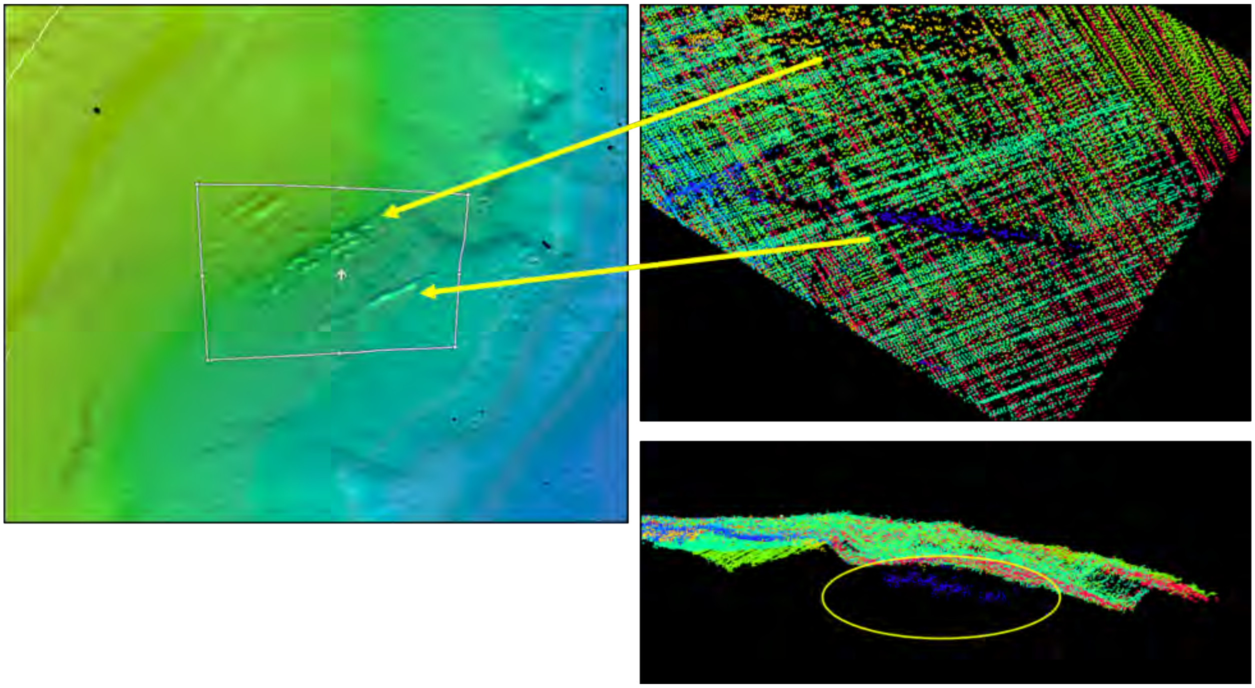


***Figure 38.*** *Example of poor filter results in Amukta Pass. The image on the left shows the average bathymetric surface. The image on the top right is a top-down view of the corresponding soundings, while the image on the bottom right is an oblique view – the filter-favored 'bad' soundings are well below the other data.*

# Challenges of Sailing

## *The challenges of sailing in a region of changing wind patterns led to changing line orientation patterns and a limited ability to run crosscheck lines >> reduced quality control, impacts to overall coverage, and data gaps*

It is noted in the data acquisition reports that line planning is difficult when also trying to use environment conditions to optimize the platform endurance. This resulted in changes in line plans during the survey with additional mid-survey turns and line orientation not optimized for the underlying bathymetry (**Figure 39**). Unplanned turns were not always broken out into their own lines and settings were left as-was for the turns, due to issues (we assume) with delays/reliability of remote access. The data around turns was often very noisy and required additional time for manual cleaning to remove outliers, or to extract and remove the turn altogether. In some cases, there wasn't enough overlap to accommodate the complete removal of the turn without leaving a gap. Changes in wind and currents also resulted in a number of gaps in data, particularly when completing infill with the orientation different to the original lines. The challenges of sailing were also noted as issues (in the acquisition reports) when trying to abut transit lines to and from Unalaska (Dutch Harbor).

The sailing-imposed limitations on line orientation also meant that there were limited orthogonal cross check lines in all areas, making it necessary to use lines that generally crossed the area for the internal consistency checks.

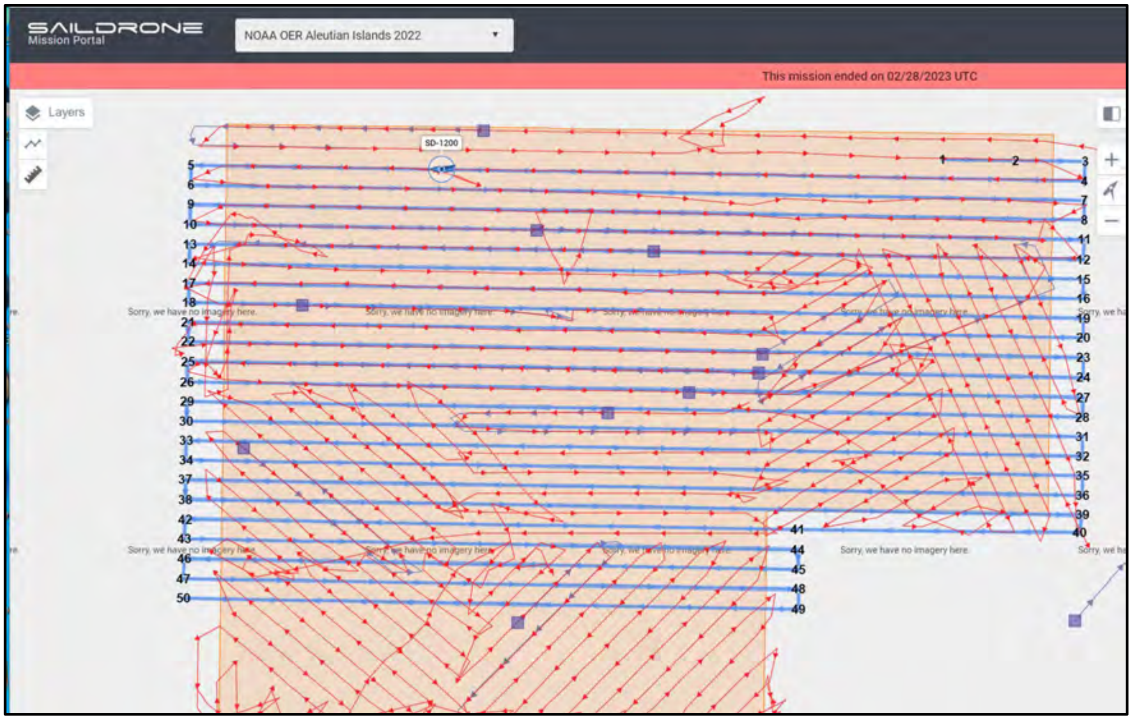



***Figure 39.*** *An example of line planning vs. reality in the DSCRTP area - initial planned lines are shown in blue, while the actual lines surveyed are shown in red.*

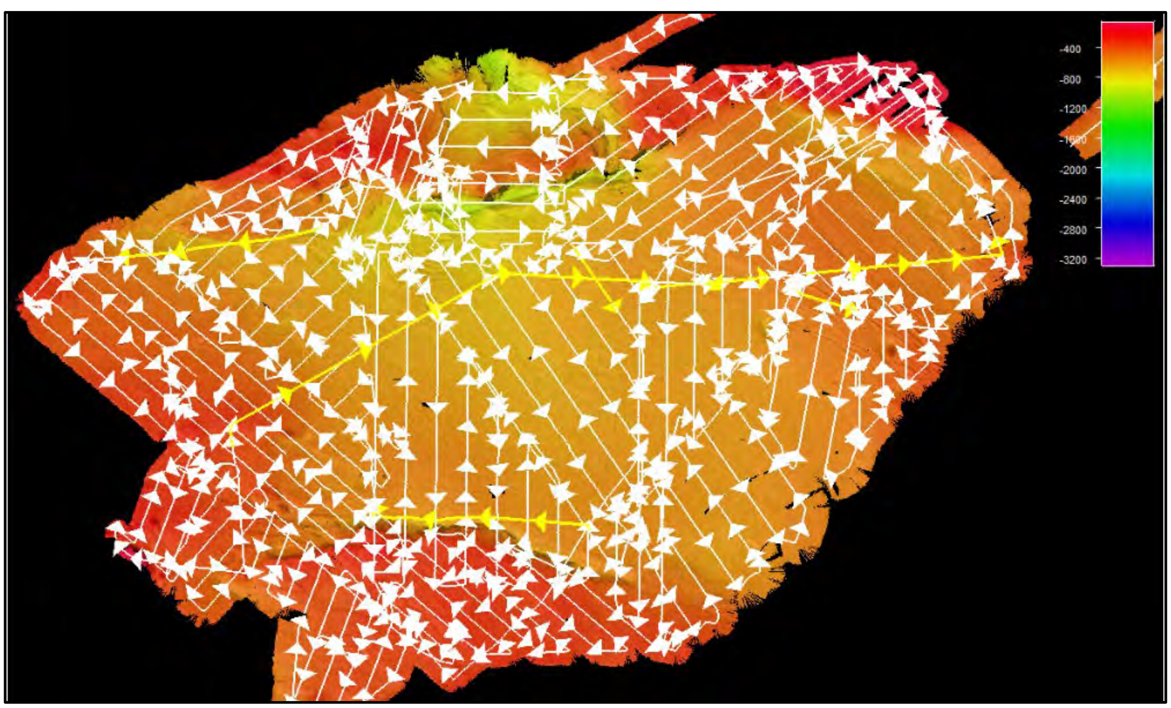



***Figure 40.*** *Example of survey lines utilized as cross lines (yellow lines) from the Leg 0013 Acquisition Report, Figure 37.*

# Resulting Bathymetric Surfaces

## *Combination of issues leading to reduced sounding density, vertical swath offset in outer sectors, and overlap >> lower resolution surfaces, holidays, and noticeable remnant artifacts*

The final resolution used for surfaces was often lower than might be expected for EM304 and EM2040 multibeam data. 1-5% of water depth is often used to estimate cell size for grids resulting from high resolution systems. The example below (**Figure 41**) shows the Amlia Basin survey, which had depths ranging from near 0 m to ~1200 m, gridded without interpolation at 20 m (~2% water depth) and 60 m (5% water depth). Use of a weighted moving average for final product creation often allowed for more continuous coverage at a smaller cell size/higher resolution.

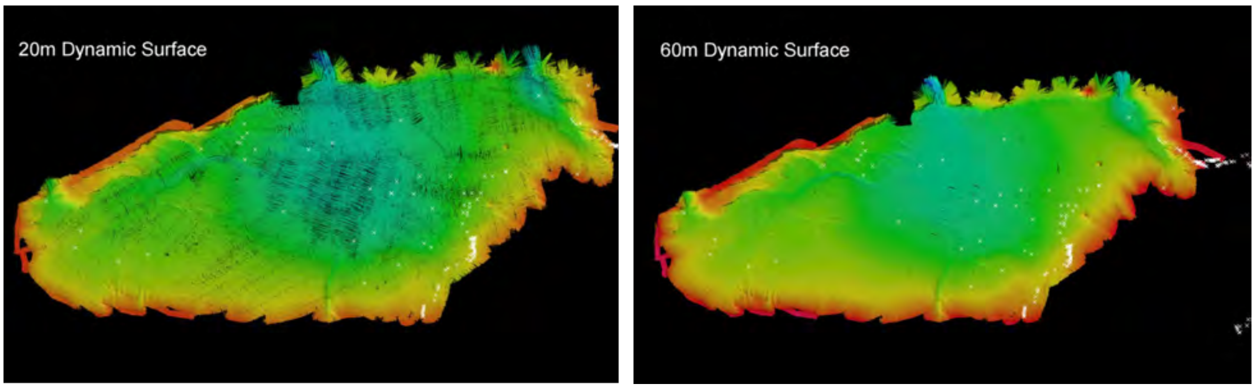



***Figure 41.*** *Example of decreased grid resolution (from 20 to 60m, no interpolation) to cover gaps in the data from various issues in deep areas (1,000m) of Amlia Basin.*

Poor overlap, outer beam issues and reduced sound speed control resulted in surface artifacts such as the along-track raised ridge shown below (**Figure 42**). Further editing of the data to reduce this issue would have resulted in a gap in the data.

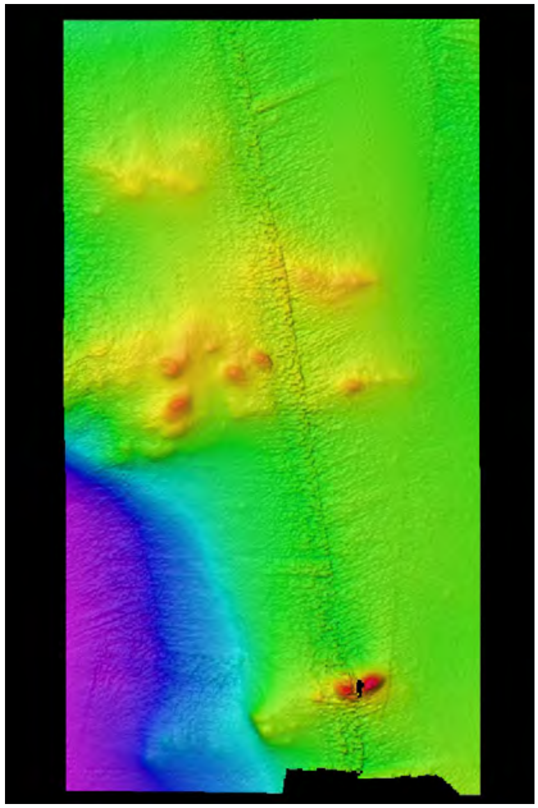


***Figure 42.*** *Resultant surface along-track ridge when limited overlap with noisy data and outer beam issue. Further filtering or manual editing would result in a gap.*

We strongly believe that increased overlap, beyond the planned for 25% (and well beyond the actual overlap remaining after processing and filtering), would have ameliorated many of the issues, resulting in improved final bathymetric surfaces. Forced limiting of the swath angles would also have improved the data and, if reduced swath widths were then used for line spacing planning, made more of the limited overlap usable.

# Absorption

## *It is unclear if absorption from CTD was used in backscatter processing >> mosaic could potentially be improved*

The SD-1200 has an AML-6 probe with sound velocity, conductivity, temperature, and depth/pressure sensors. It is unclear whether the values from the conductivity and temperature sensor were loaded in SSM and utilized for absorption value transferred to SIS, or only the sound velocity observations loaded to the SSM. The variations in oceanographic conditions in the area from north to south have likely resulted in some unknown issues in the backscatter processing and resultant mosaics generated. It is suggested that further investigation be undertaken to assess the potential in improving the mosaic products using the observed conductivity. Examples of two mosaics are below (**Figure 43**, **Figure 44**).

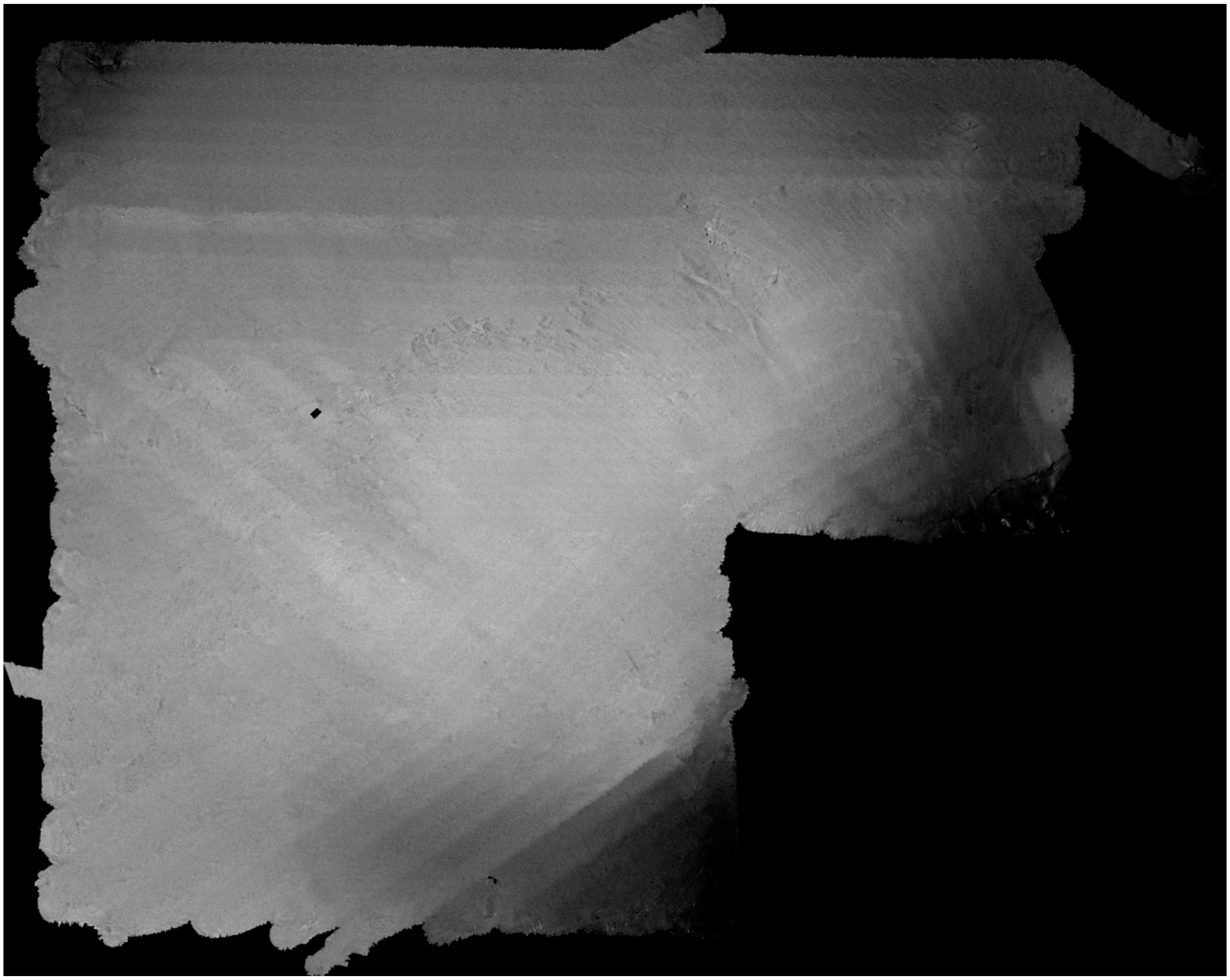


***Figure 43.*** *DSCRTP EM2040 preliminary mosaic from KMALL.*

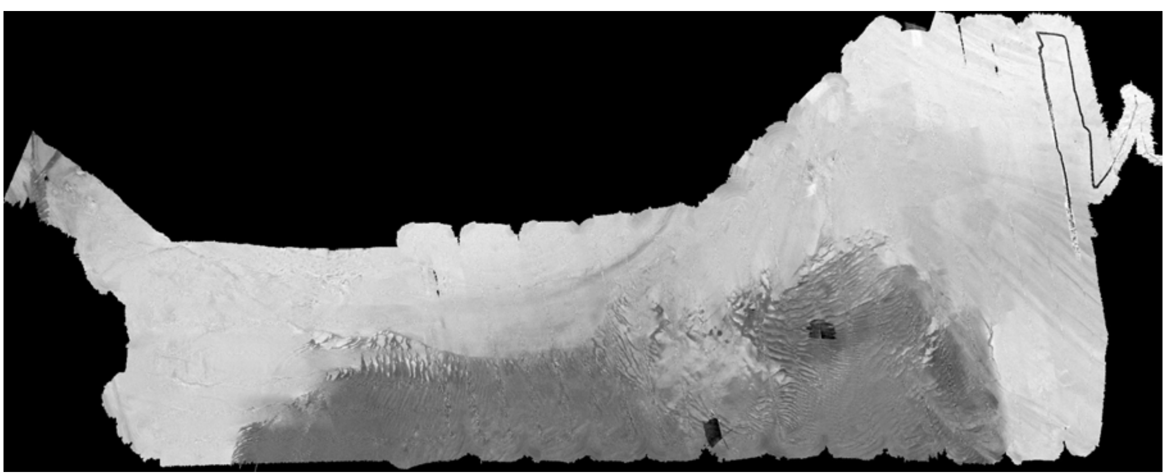


***Figure 44.*** *Volcano South EM304 mosaic from KMALL.*

# Qimera and FMGT Bugs and Versions

There were a number of software bugs that affected processing and resulted in reprocessing with fixed versions and additional overall processing time. Some have been mentioned previously in relation to performance observations and issues.

Several of the cases were related to the GSF format. GSF files are an export that preserves processing flags – all data is stored, with attribution or flags indicating whether a particular sounding has been rejected. GSF files also retain backscatter intensity information. These files are used for the final archive of processed data, are preferred for downstream integration of data in some global syntheses (GMRT), and are part of the pipeline for backscatter processing – NOAA OE utilizes GSF files for final backscatter mosaic productions (see *NOAA OER Deepwater Exploration Mapping Procedures Manual*, https://oceanexplorer.noaa.gov/data/publications/mapping-procedures.html). There have been ongoing issues with the various GSF implementations that affect these uses and processes. In this case further issues were related to the update from the Kongsberg ALL to KMALL format related to the use of extra detections, changes in data packets related to the backscatter, and accessing surface sound speed observations.

The backscatter processing in QPS FMGT of the GSF files was affected by a number of the FMGT issues listed below. The latest GSF library does not fully support the KMALL format and will produce a different processed result for mosaics generated with the GSF or KMALL. Because of this, the preferred option would be to use the KMALL, but there is currently no method of excluding the data rejected during processing in Qimera when using a KMALL. A second issue was reported related to the next leg of the SD-1200 survey off the California coast that affects the way mosaics are generated. The data is added to the mosaic sequentially in time and not geospatially the way sonar footprints ensonify the seafloor. This is not evident in larger platforms with less motion than the SD-1200, and when pitch stabilization is used. Noting these issues, no attempt was made to adjust any offsets between lines or different sonar modes, and it is recommended that the backscatter be reprocessed once the issues have been resolved by QPS.

Below is a summary of the issues logged with QPS during the course of this project:

- CQM-6047: Discrepancy between measurements, extinction plots in profile tool, measurement tool, extinction plots when project is in World Mercator
- CQM-6081: General - Geodetic - Support Geographic coordinates
- CQM-6130: GSF export bug and KMALL extra detections
- CFM-3465: FMGT GSF and KMALL dB offset
- CQM-6233: KMALL cannot change processing to Surface SV Sensor
- CQM-6325: GSF import with real-time scheduling for SVP fails
- CFM-3581: Backscatter mosaic issue

During the course of this project, a Qimera beta/release candidate was pushed out to resolve the issues with GSF export of files with extra detections; this fix was part of v. 2.5.4 (released July 18 2023).

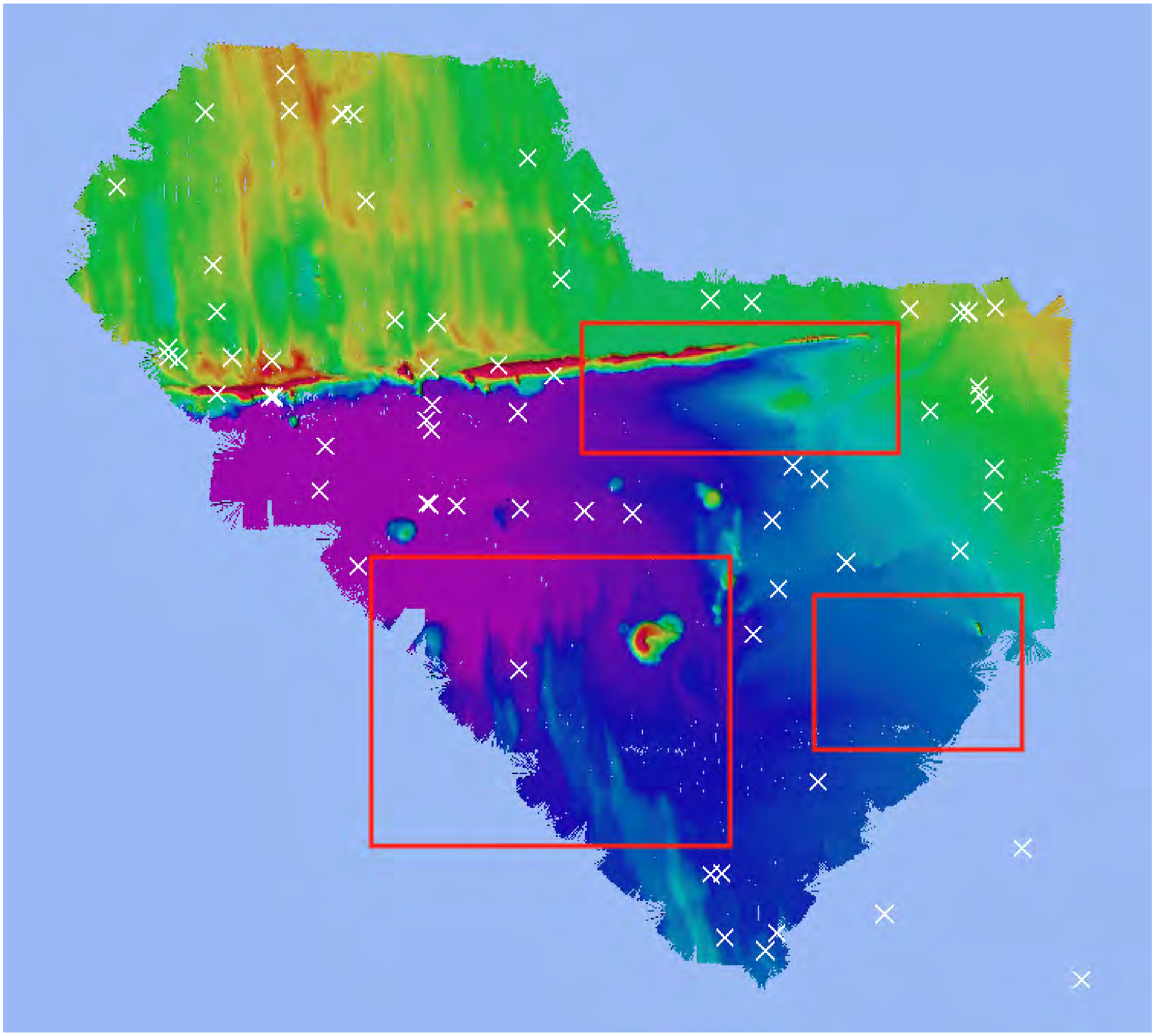
The FMGT v. 7.10.3 release (May 29 2023) improved the handling of KMALL, among other bug fixes, but was still awaiting update of the GSF library to fully incorporate the KMALL improvements.

**Notes on processing multibeam data acquired via saildrone vs. conventional vessel**
**From Marcel Peliks via Shannon Hoy 4 August 2023**

This document qualitatively assesses the data collected offshore of California via the Saildrone autonomous vessel on SD-0014 and SD-0015, compared to data typically collected via conventional vessels such as the NOAA Okeanos Explorer. The Saildrone data had already been imported into a Qimera project with select survey lines added, processing parameters set, and a weak spline filter applied. Cleaning the data was generally very similar to a conventional platform with a few minor differences noted in sections 1-4.

1. **Scarcity and depth limits of SVP's**

SVPs are only taken to a max depth of 200 m, and due to the mechanism can only be deployed during relatively calm conditions, leading to scarcity of profiles in some areas of the survey.



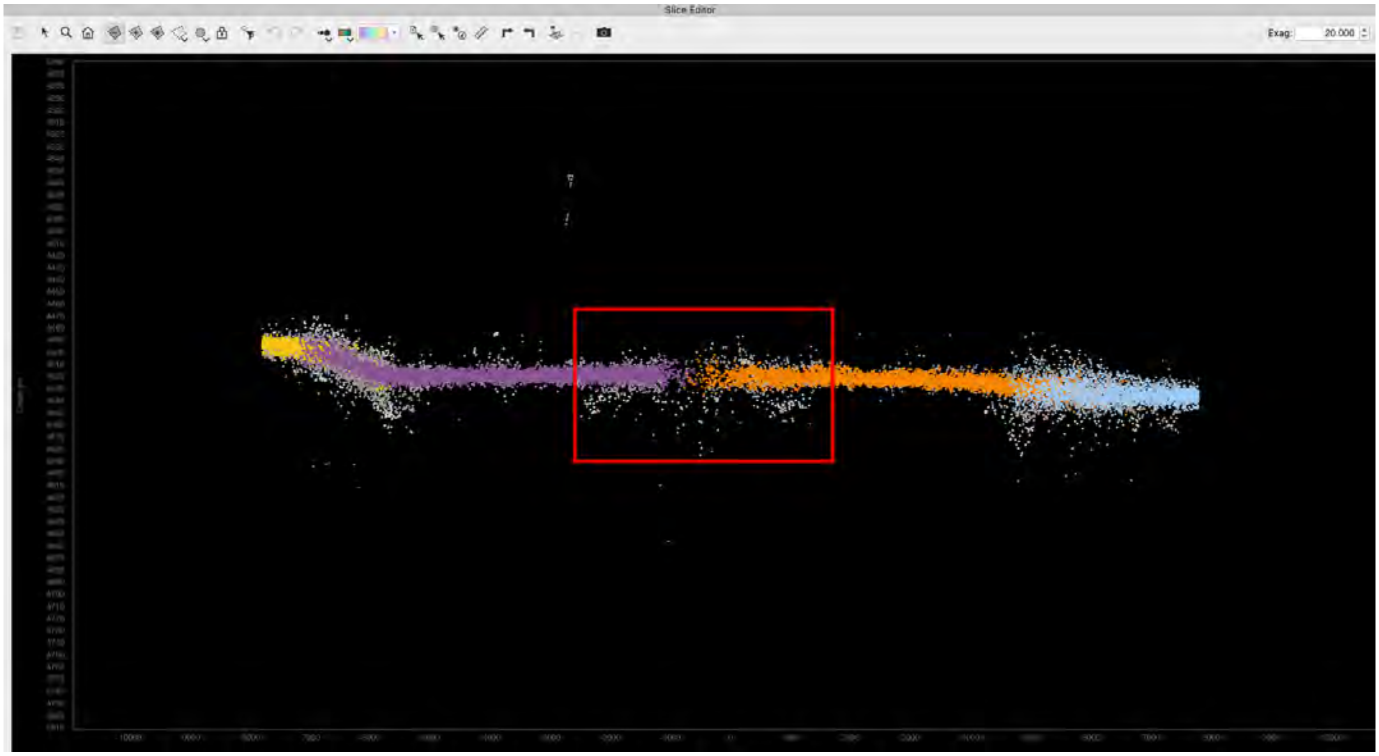
If there are sound velocity artifacts in the data it is difficult to apply a different sound speed strategy during processing because there are not many other profiles available. This was not a major issue for the CA surveys but could be in regions where sound velocity varies considerably.

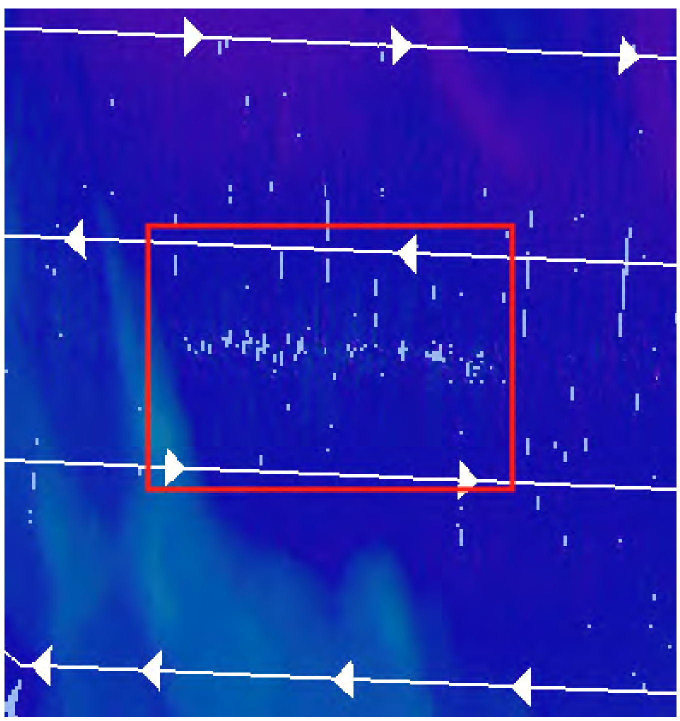
2. **Direction of ship survey line orientation**

At times the survey line orientation is adjusted for better sailing. This leads to overlapping lines and various turns within the survey area. Processing in regions where survey line orientation is adjusted results in more data cleaning and adds uncertainty to the final surface. Although conventional vessels are subject to altering survey lines due to seas, the saildrone platform appears more sensitive due to its size and primary propulsion method.

3. **Wider swath width but outer beams may be suspect**

The quiet nature of Saildrone allows for a wider swath width than on a conventional research vessel. However, the outer beams are still subject to high uncertainty, especially if sound velocity artifacts are present. If the survey line spacing is adjusted for wider coverage but outer beams end up being edited this could result in data gaps.



4. **Surveying in rough weather is feasible but could also result in poor-quality data**

Since saildrone is an autonomous vessel with no crew aboard, sailing in rough seas is more feasible than on conventional vessels. Nevertheless, data quality degradation and lack of SVPs during rough seas still impact the final product. Areas where Saildrone surveyed during foul weather have data quality degradation leading to more processing and more uncertainty.