Multibeam Surveying with an Uncrewed Wind-Driven Platform:

Results from Saildrone's Mission to Alaska

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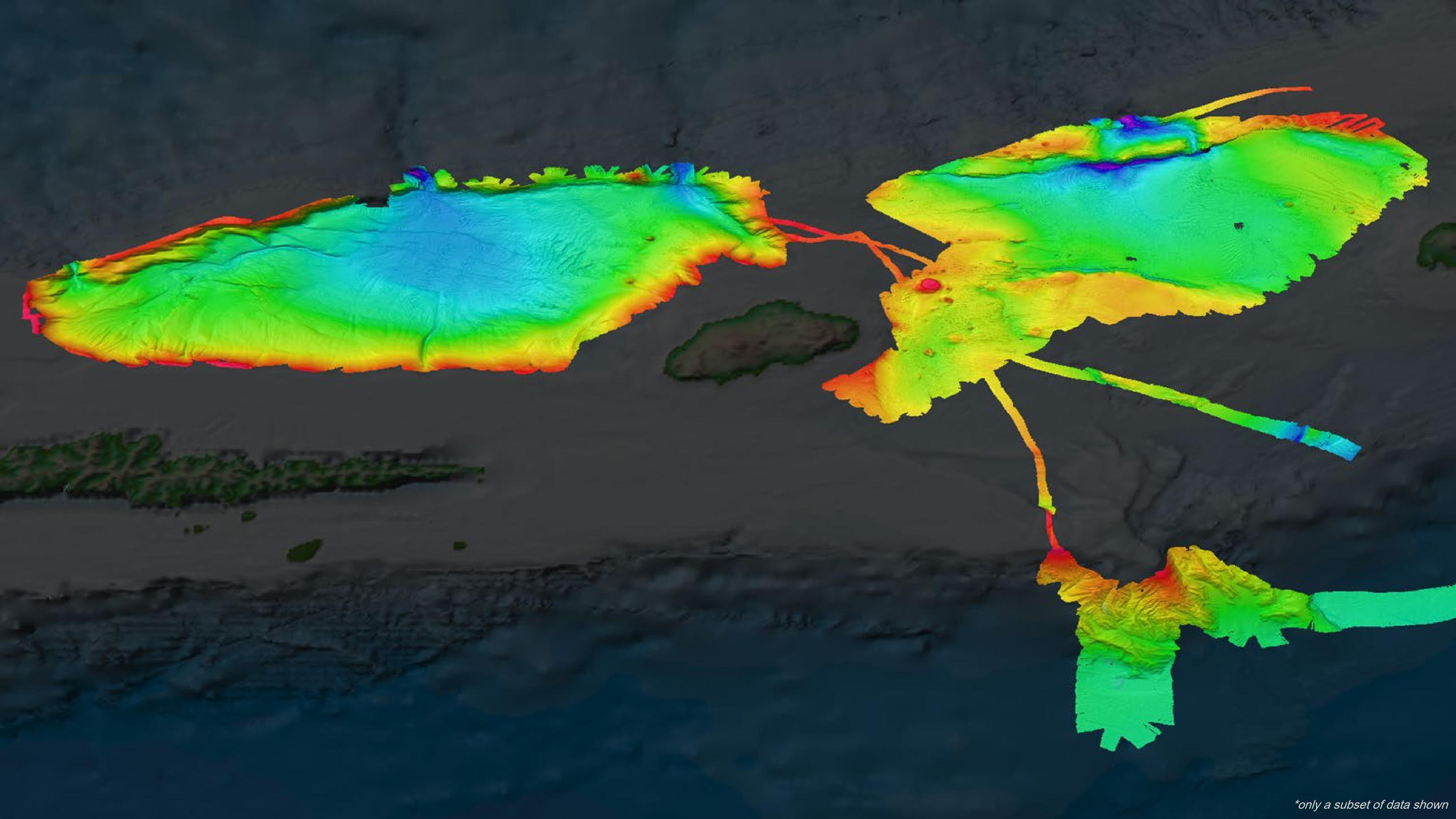
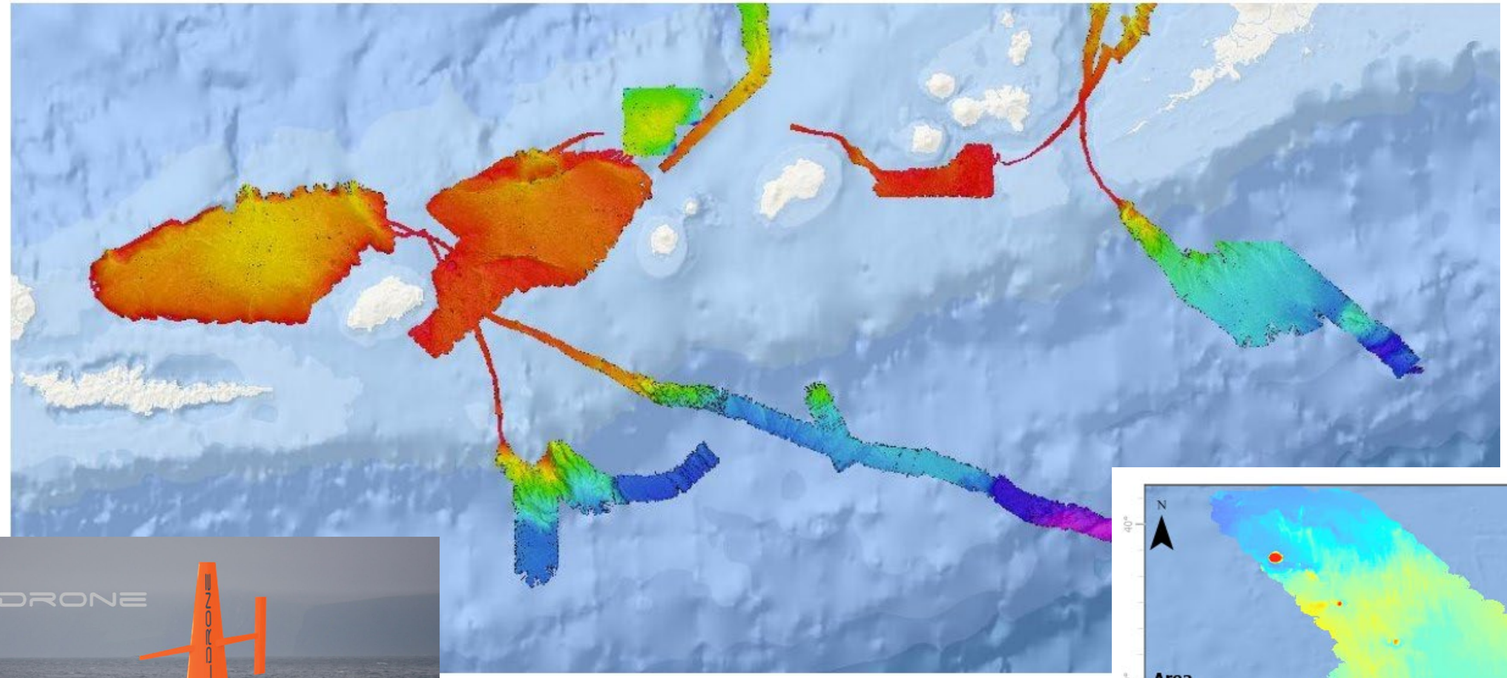
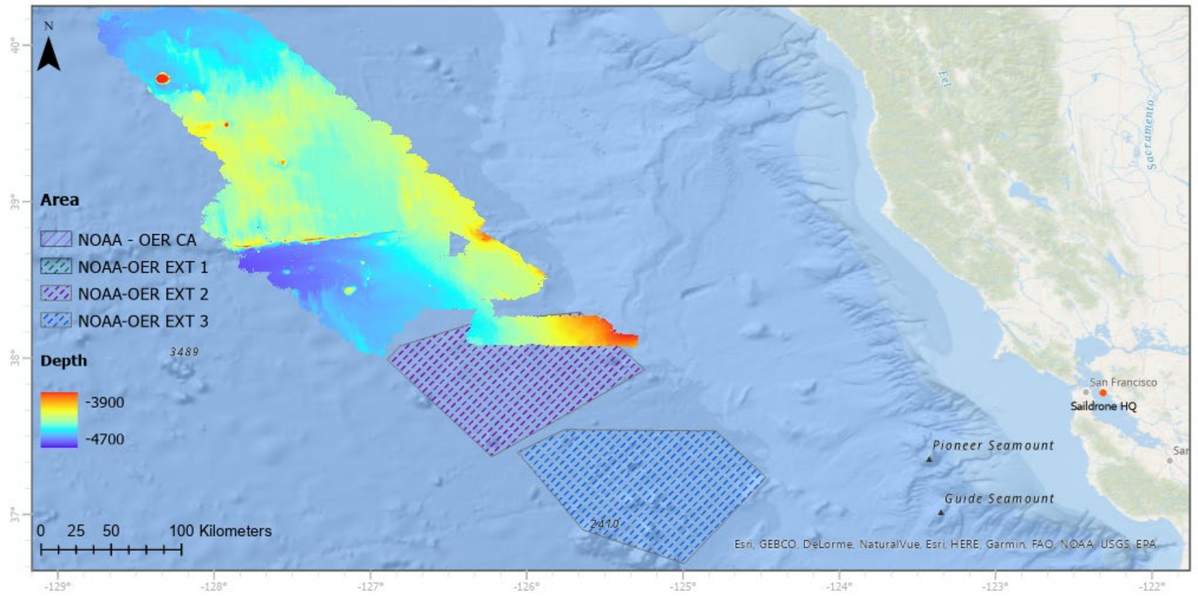
OCEAN EXPLORATION COOPERATIVE INSTITUTE
oeci
NOAA OCEAN EXPLORATION
BOEM
Bureau of Ocean Energy Management
University of New Hampshire
USGS
science for a changing world
MBARI
Monterey Bay Aquarium Research Institute
Office of Coast Survey
The Nation's Chartmaker
NOAA
DEEP SEA CORAL
Research & Technology Program



*only a subset of data shown

Saildrone Surveyor Public-Private Partnership





- Mapped 15,133 km^2 in the Aleutians
- Mapped additional 29,720 km^2 off California

Data Acquisition and Mission Operations

Aleutians Uncrewed Ocean Exploration 2022

A Multi-Partner Collaboration

Collaborative effort through NOAA Ocean Exploration Cooperative Institute with:

- NOAA Ocean Exploration
- NOAA Pacific Marine Environmental Laboratory
- NOAA Deep Sea Coral Research Technology Program
- NOAA Office of Coast Survey
- The Bureau of Ocean Energy Management
- The United States Geological Survey
- Monterey Bay Aquarium Research Institute

“This effort directly addresses one of the fundamental objectives of the NOAA Ocean Exploration Cooperative Institute (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.”

Pg. 5 Aleutians Mission Plan

Aleutians Goals
High Level Objectives

Identify limitations and constraints of the Surveyor platform - R&D

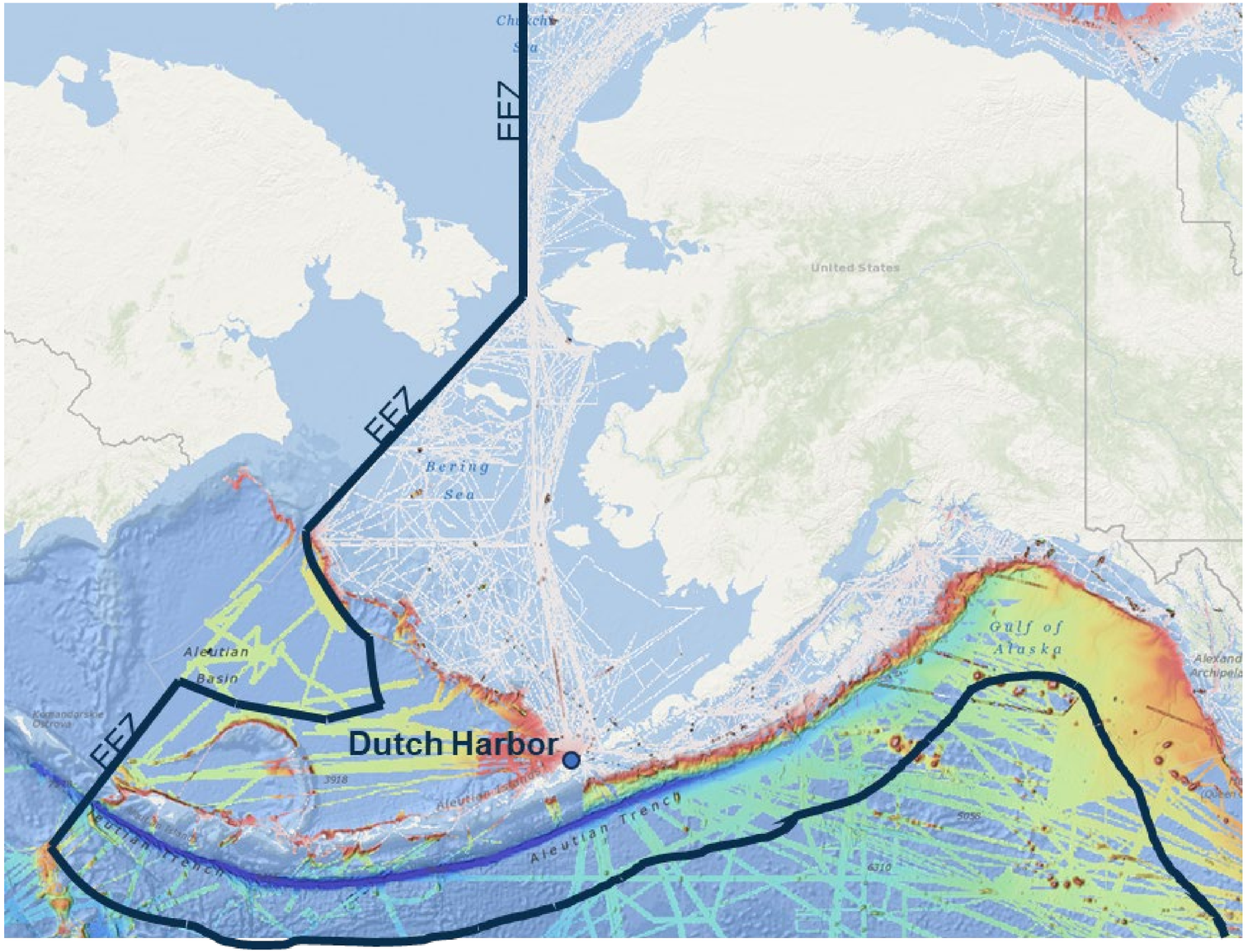
- Working far “over the horizon”
- Data quality
- Endurance and weather performance

Expand Alaska EEZ mapping

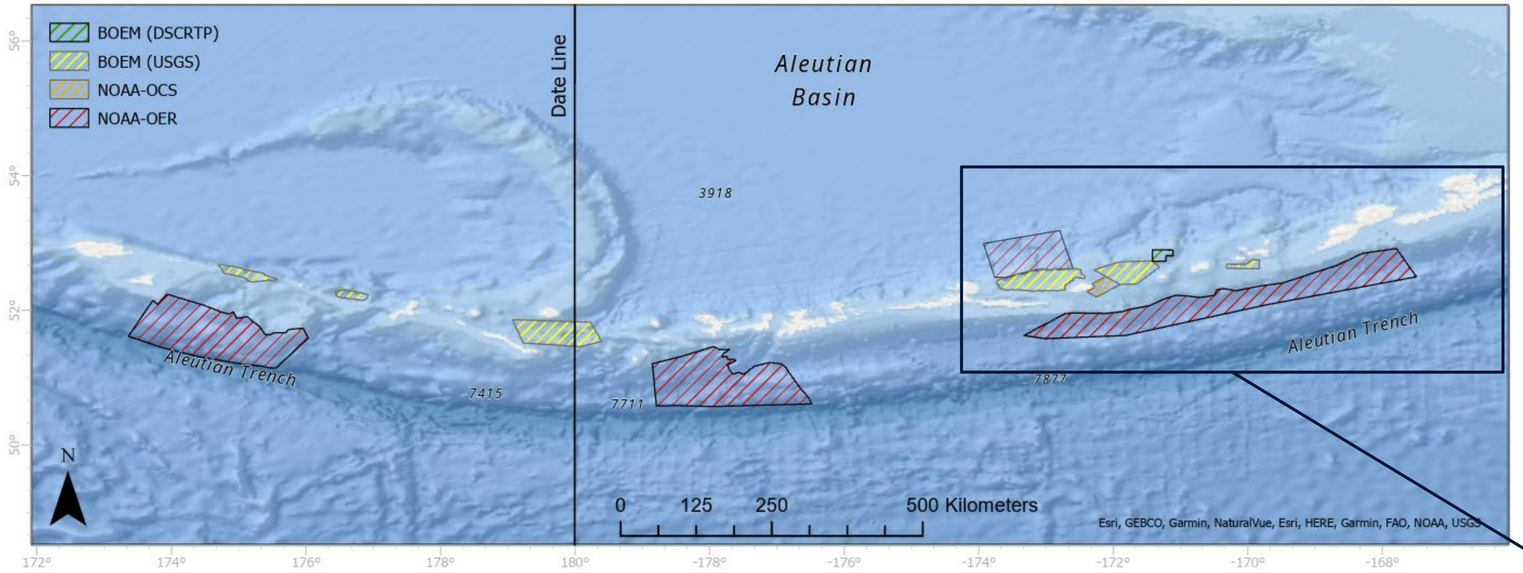
- Pre-mission it was at 28%
- Alaska has 1.5 million miles of EEZ
- Accounting for ~1/2 the US coastline
- Most surveys done prior to 1990

Support further exploration and characterization

- Supporting concentrated efforts by individual organizations
  - Remotely Operated Vehicle (ROV) ops
  - Marine mineral exploration/characterization
- Characterize biodiversity
  - Deep sea coral habitat
  - eDNA Sampling



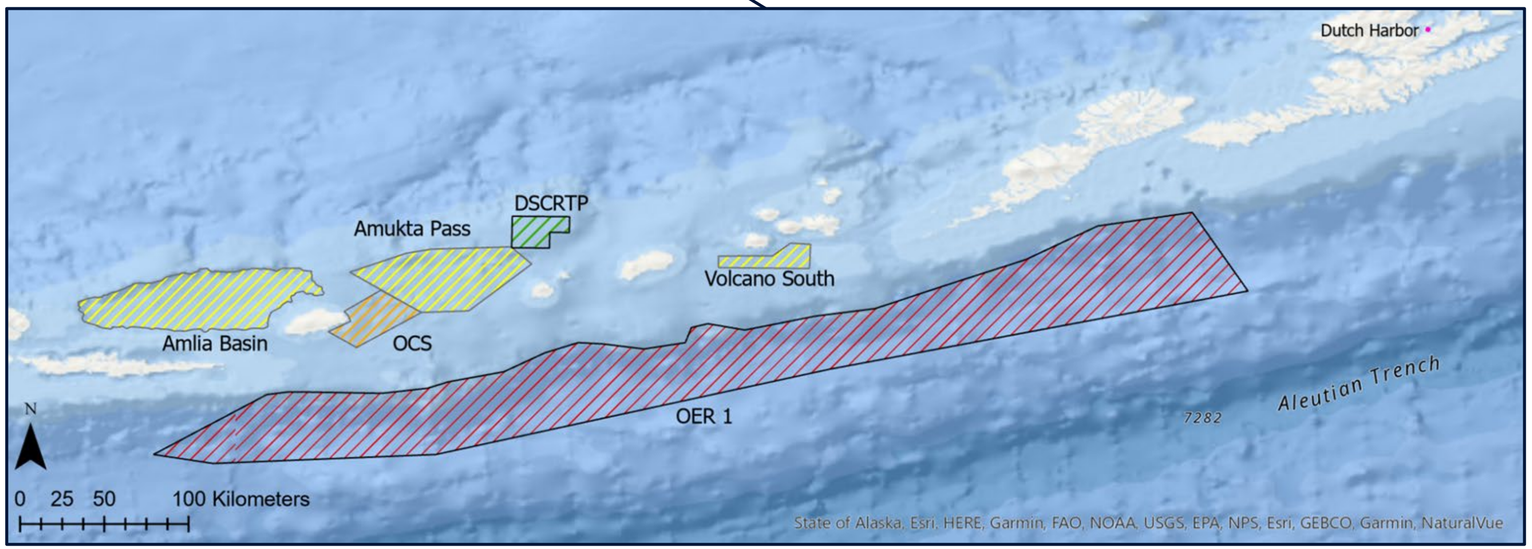
Aleutians Goals
Planned Survey Areas



Polygon Name	Area km²
BOEM Ingenstrem Depression	709
BOEM Buldir Basin	368
BOEM Sunday Basin	3140
BOEM Amlia Basin	2283
BOEM Amukta Pass	1631
BOEM Volcano South	313
BOEM DSCRTP	320
OER 1	15246
OER 2	11221
OER 4	4711
OER 5	12082
OCS	547
Total	**52571**

Delays lead to a re-prioritization of survey areas based on proximity to Dutch Harbor:

- Volcano South
- DSCRTP
- Amukta Pass
- OCS
- OER 1
- Amlia Basin



What Is a Saildrone?

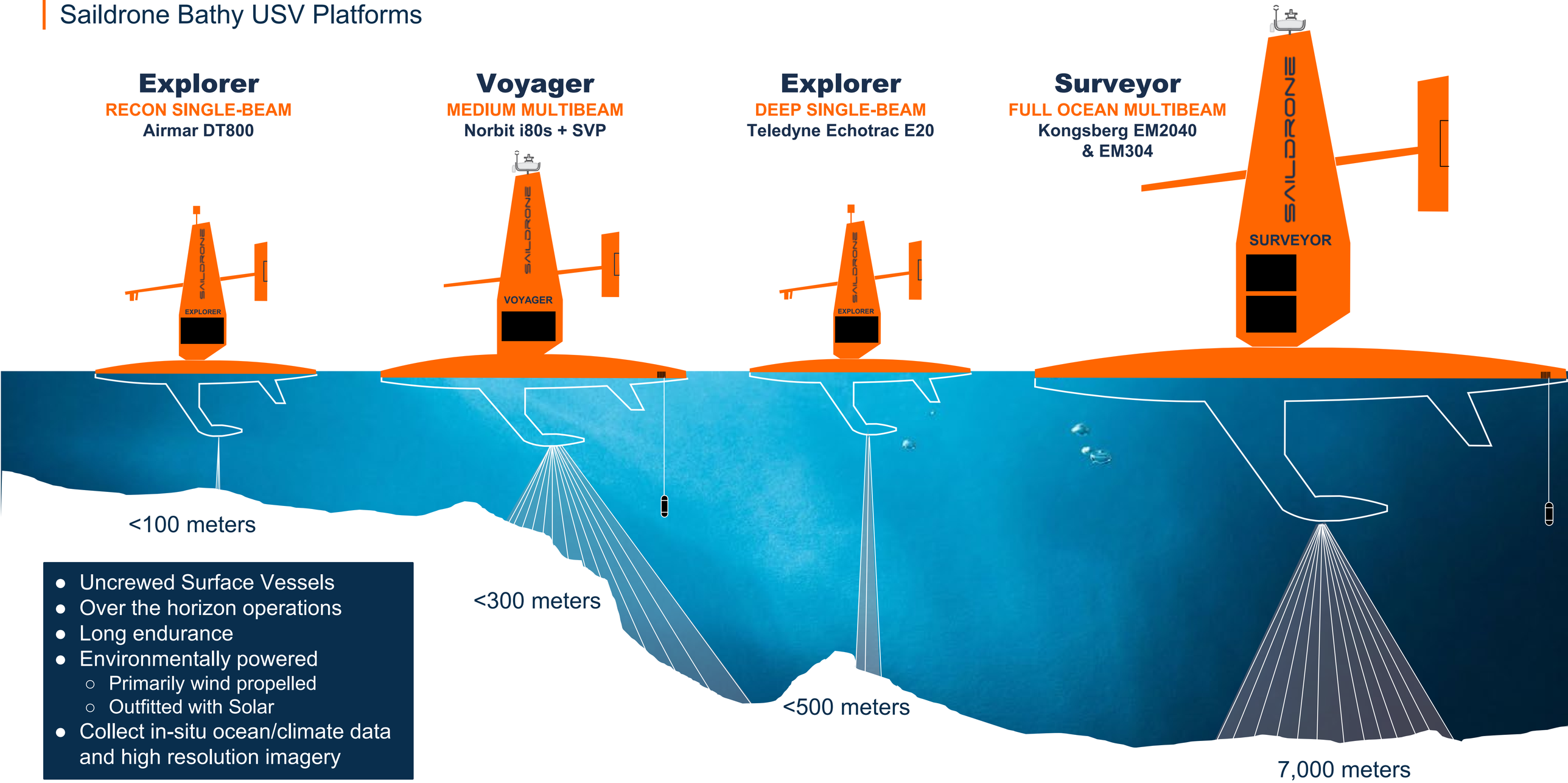
Saildrone Bathy USV Platforms

Explorer
RECON SINGLE-BEAM
Airmar DT800

Voyager
MEDIUM MULTIBEAM
Norbit i80s + SVP

Explorer
DEEP SINGLE-BEAM
Teledyne Echotrac E20

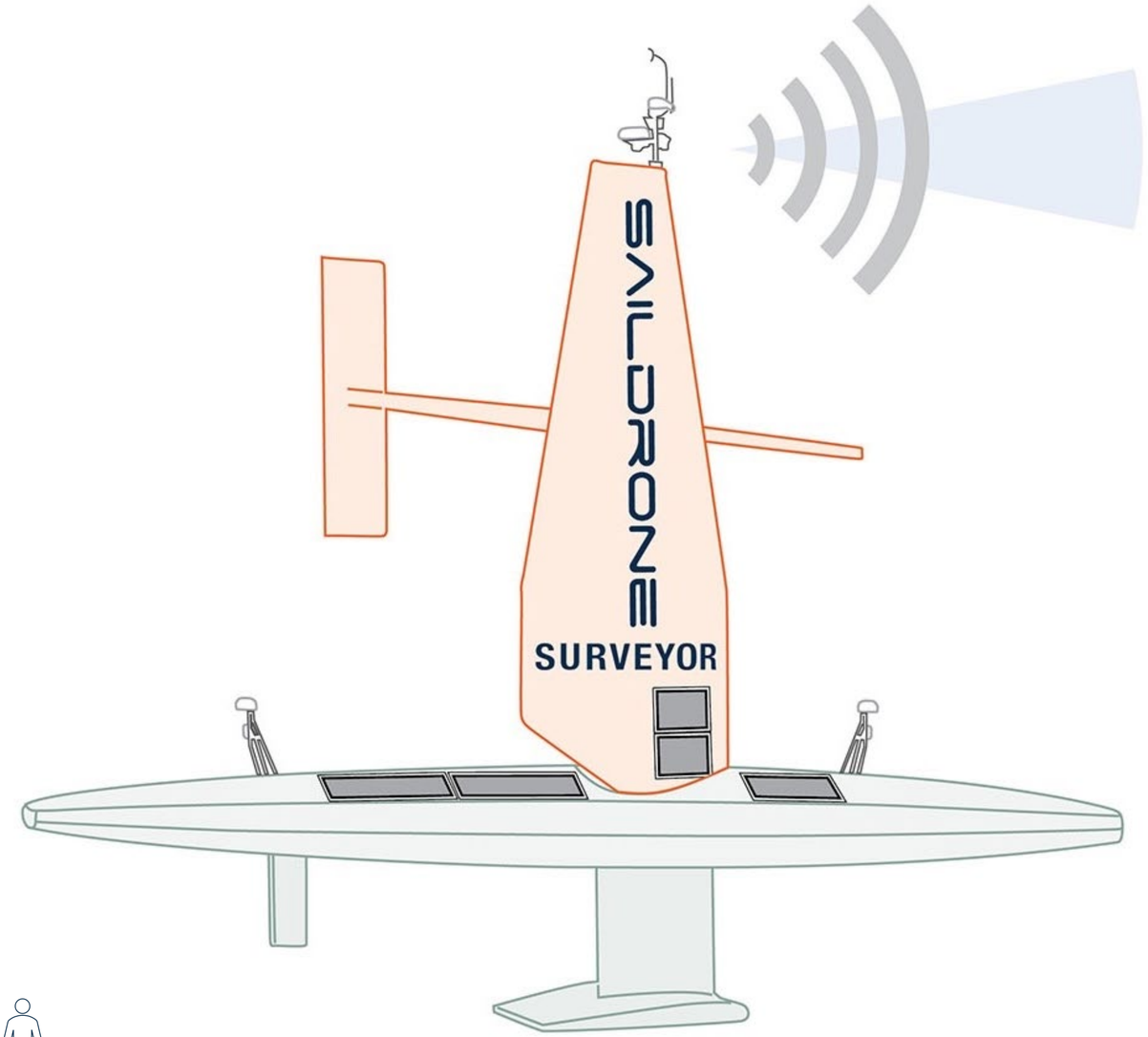
Surveyor
FULL OCEAN MULTIBEAM
Kongsberg EM2040 & EM304



- Uncrewed Surface Vessels
- Over the horizon operations
- Long endurance
- Environmentally powered
  - Primarily wind propelled
  - Outfitted with Solar
- Collect in-situ ocean/climate data and high resolution imagery

Saildrone Surveyor

Meet *SD-1200*

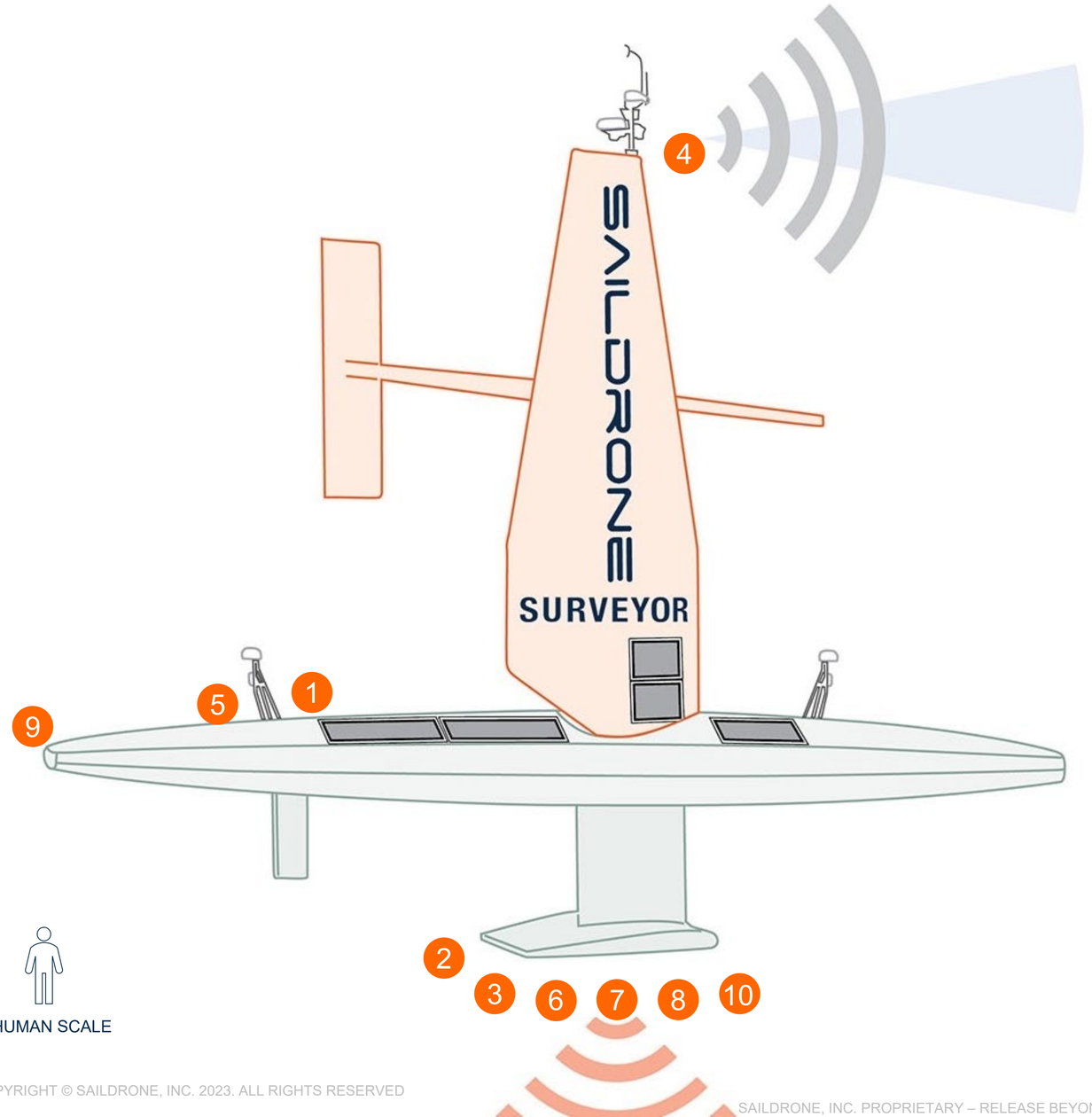


HUMAN SCALE

Vehicle Specs	
Hull Length:	72 ft. / 22m
Wing Height:	44 ft. / 13m
Draft:	11ft. / 3m
Primary Propulsion:	Wind (Saildrone Wing)
Auxiliary Propulsion:	75 hp high efficiency diesel
Mapping Speed:	4 Knots
Vehicle Endurance:	2,500 nm at 6 knots under power
Payload Power Draw:	2,000 W steady state 3,000 W peak)

Saildrone Surveyor - *SD-1200*

Meet *SD-1200*



Bathy Specs		
No.	Variable	Sensor
1	Positioning	Seapath 380+ GNSS/INS system (Fugro corrections)
2	Deep-water bathymetry	Kongsberg EM 304 multibeam sonar
3	Shallow-water bathymetry	Kongsberg EM 2040 multibeam sonar
4	Wind speed & direction	B&G WS730S
5	Barometric pressure	Yacht Devices YDBC-05N
6	Ocean currents	Simrad EC150 ADCP
7	Ocean currents	Teledyne Pinnacle 45 ACDP
8	Fish biomass	Simrad EK80 echo sounder
9	Sound velocity profiler	AML - 6 sound velocity probe (cast depth 200m)
10	Surface sound	Teledyne SVP 70 (fixed on bottom of gondola)

Platform Specific Considerations

Known Prototype Constraints

Hardware Troubleshooting:

- Vehicle is Uncrewed - Physical troubleshooting is not an option while underway
  - No cable jiggling / reseating boards etc.
  - Limited to in GUI troubleshooting, GUI restart and power cycling capabilities
  - Supplementing with shoreside checks / maintenance

Prototype Winch:

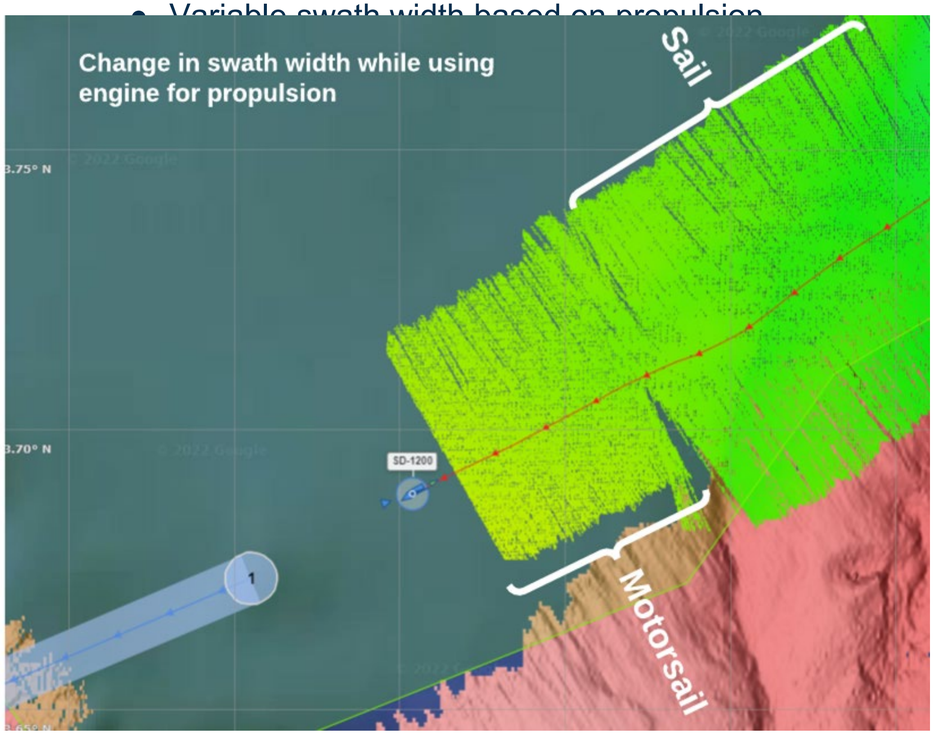
- 200m limit on casts
- Daily cast limits:
  - 2x day for EM304 operations
  - 4x for 2040 operations
- Relying on Synthetic casts from the WOA18 database for additional SVP

Data Monitoring

- Extremely limited connectivity bandwidth (Iridium Certus)
  - Limited access to SIS / Qinsy / Qimera

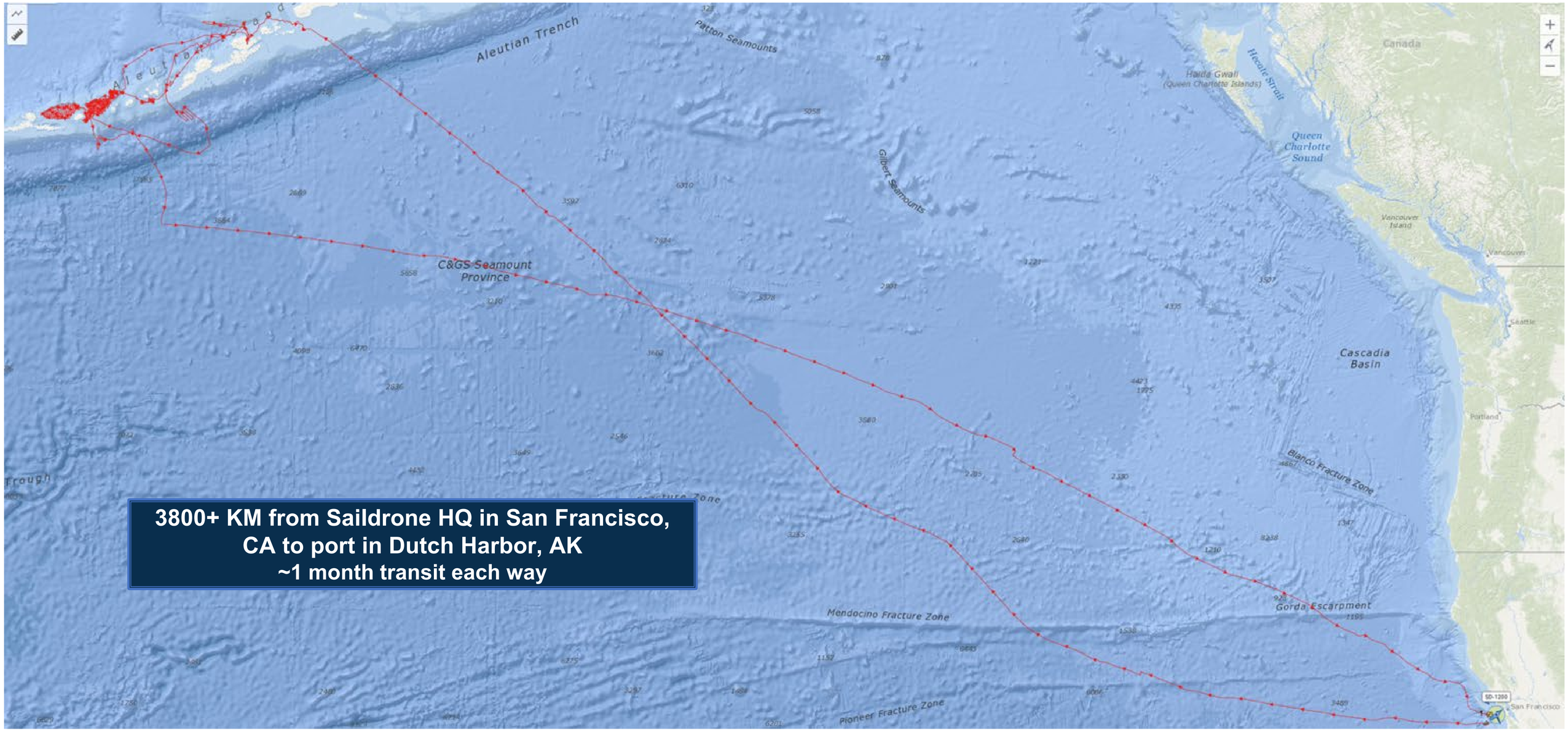
Vehicle Motion:

- Wind driven line planning
  - Heeling
  - Asymmetrical swath
  - Tacking upwind (Beating)
- Increased roll
- Variable swath width based on propulsion

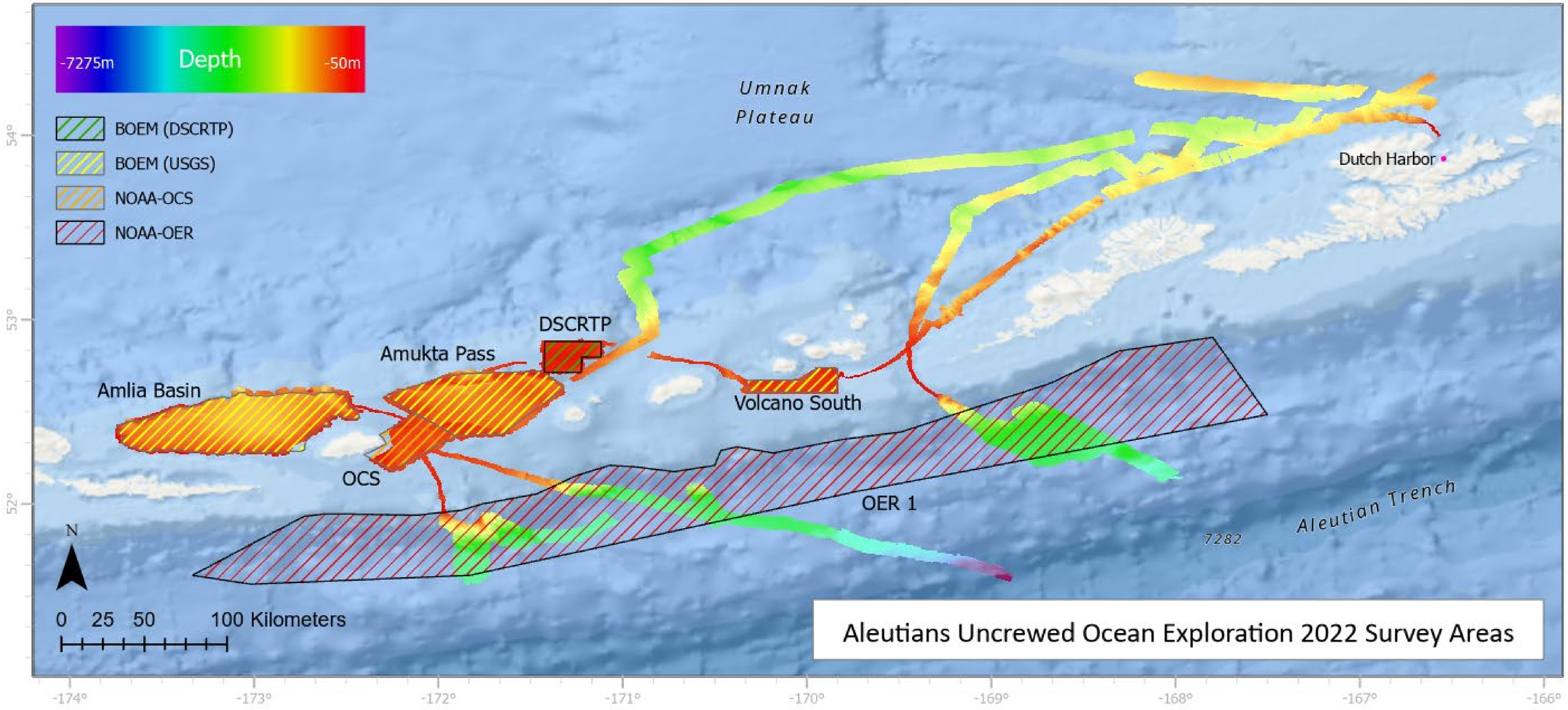


Mission Timeline

Transit and Aleutians Operations



Results
Survey Areas



Results
Survey Statistics

Aleutian Mission Survey Statistics		
Contracted Days	96	(survey areas, transit between survey areas + 1 planned port call)
Days Vehicle Engaged in Mission*	112.65	(Includes transit to and from AK)
Days Underway in AK	52.82	(DH to start of survey not billable)
Port Days (not billable)	2.21	(Unplanned pre-survey stop)
Port Days (billable)	1.62	(Planned vehicle, data, eDNA service)
Survey Mapping Days	36.81	(Days mapping in survey areas)
Transit Mapping Days	13.10	(Mapping while in transit)
Leg 1 Totals		
Total Mapping Days	29.89	(survey + transit)
Average Mapping Speed	3.45	(knots)
Number of SVP casts	46	
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 Volume	2	(TB)
Leg 2 Totals		
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	8844.36	(km^2)
Square nm Area Mapped	2578.6	(nm^2)
Number of eDNA Samples	42	(sampling continues during transit, +15)
Data Volume	1.23	(TB)
Grand Totals		
Mission Days	**51.53**	**(Billable days)**
Total SVPs	**69**	
Total Line km Mapped	**7430.34**	**(km)**
Total Area Mapped	**16254.25**	**(km^2)**
Remaining Mission Days	**44.47**	**(US West Coast)**

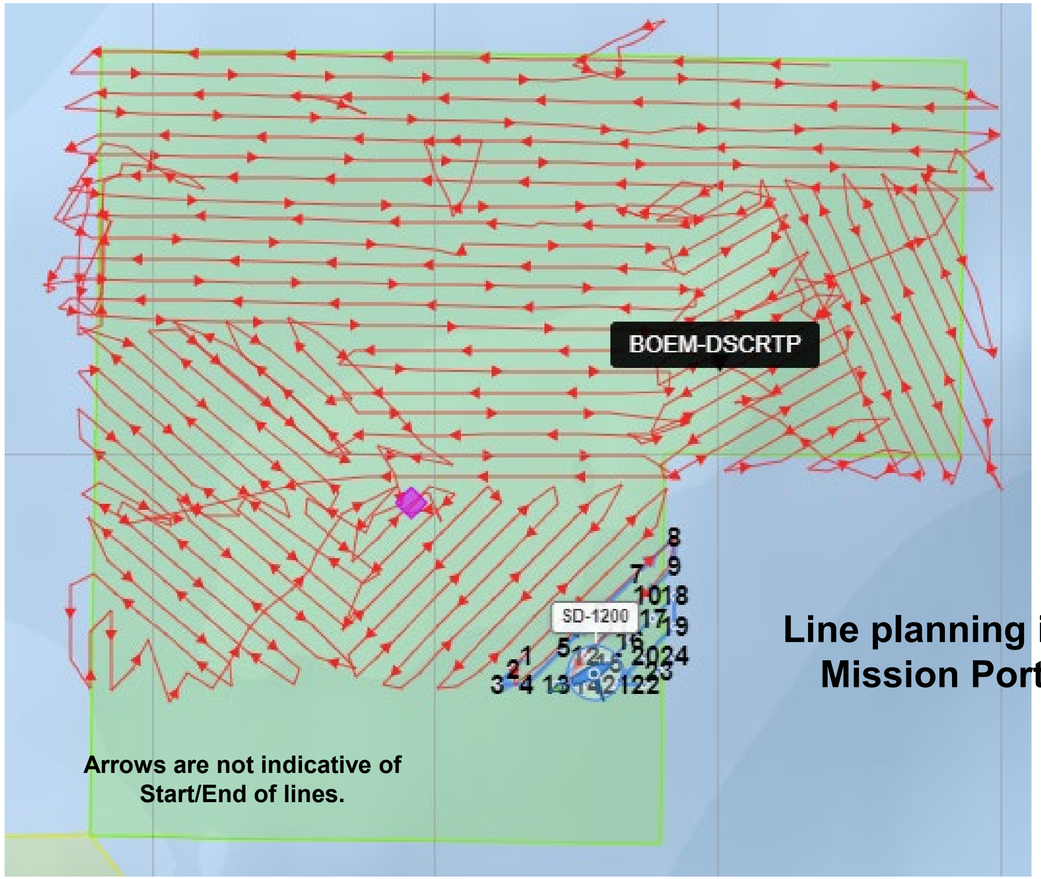
Fuel Economy Stats:

- 35.5 L of fuel used per operational day on average
- 1846 L of fuel used total

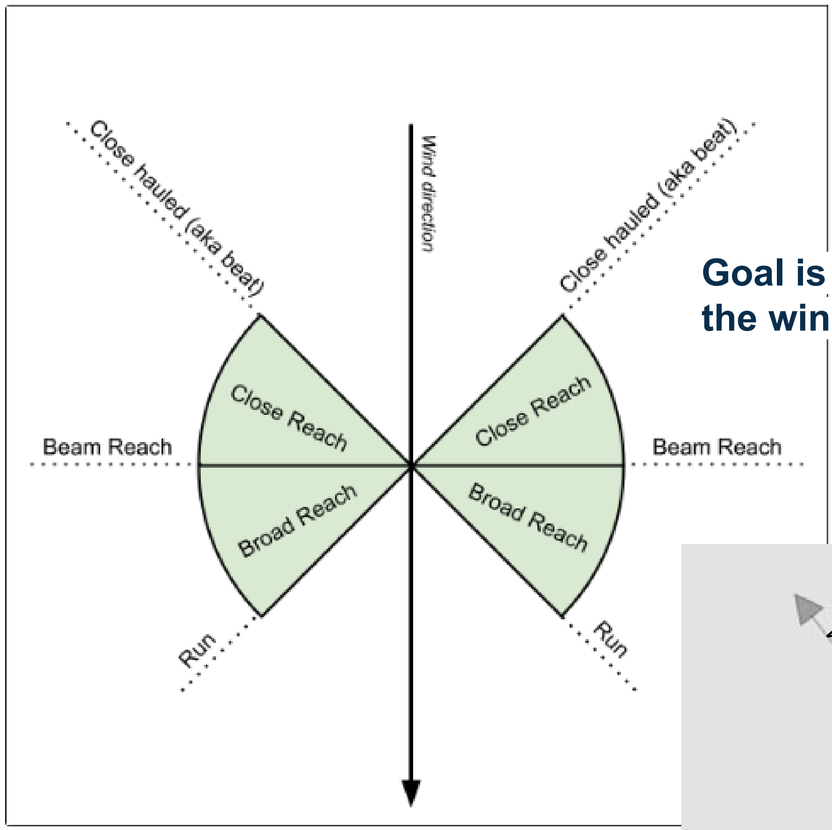
Acquisition

Mapping with a Sail

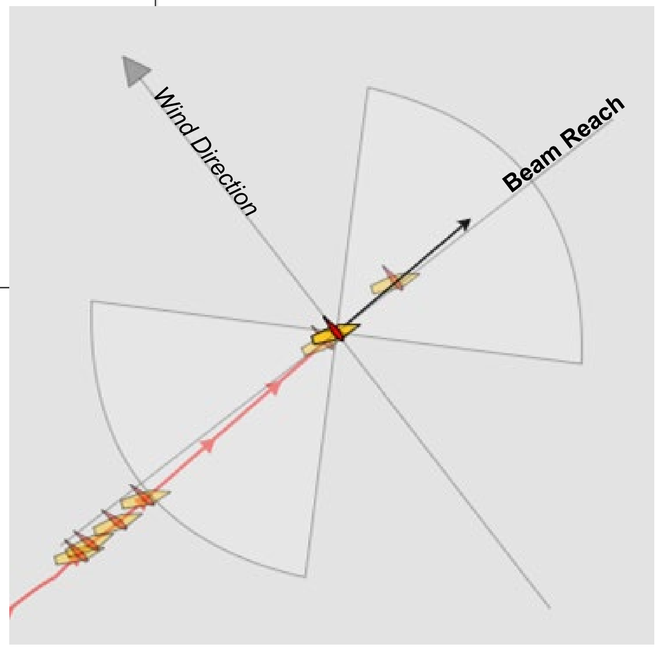
- Rigid wing is always utilizing wind propulsion
  - Wind assist while motoring AND Sailing
- Planning lines based on the wind forecast
  - 12-24 hour survey blocks
  - Transit minimized between blocks
  - Respond in real time to unexpected wind shifts



Line planning in proprietary Mission Portal software

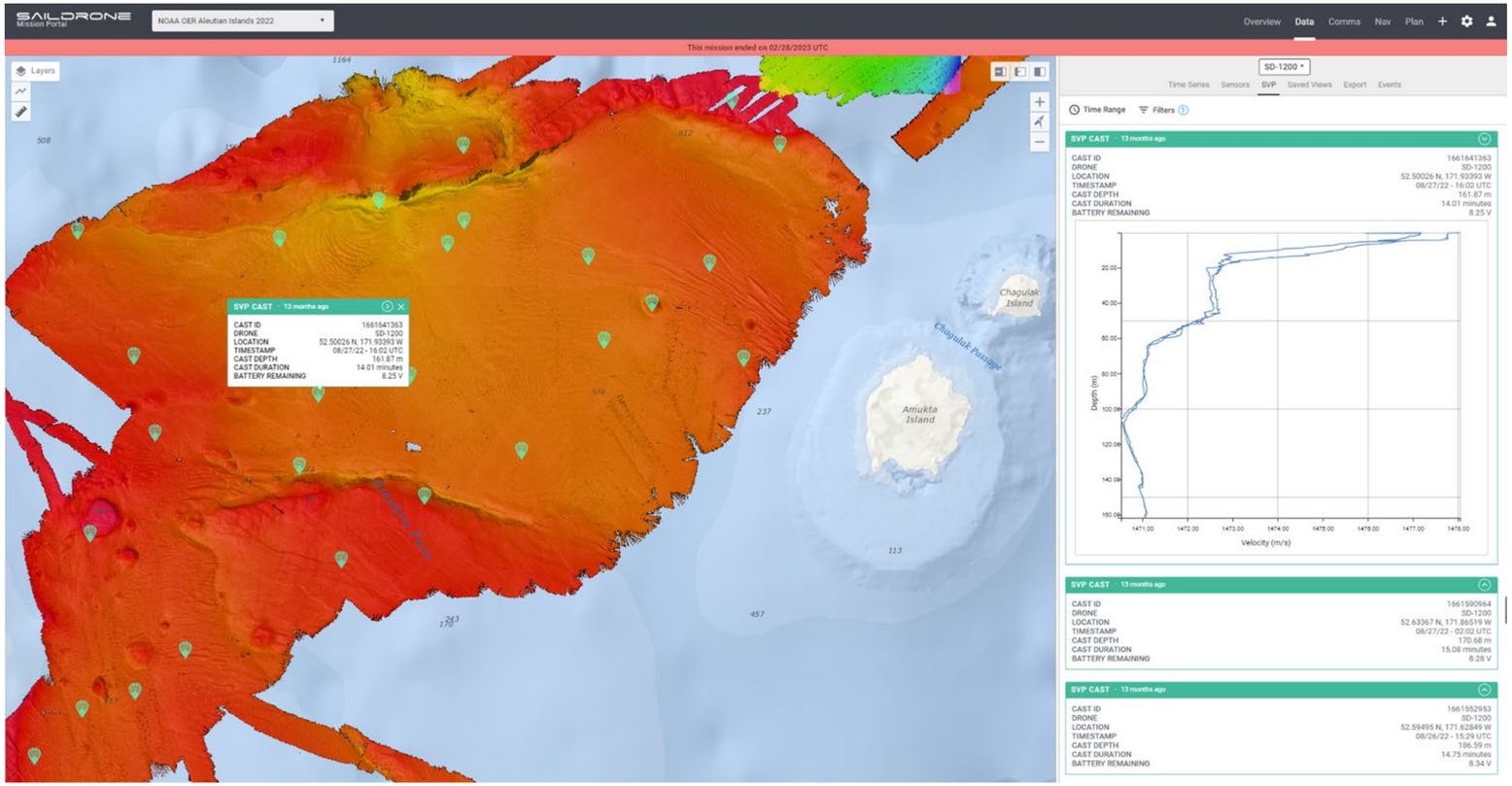


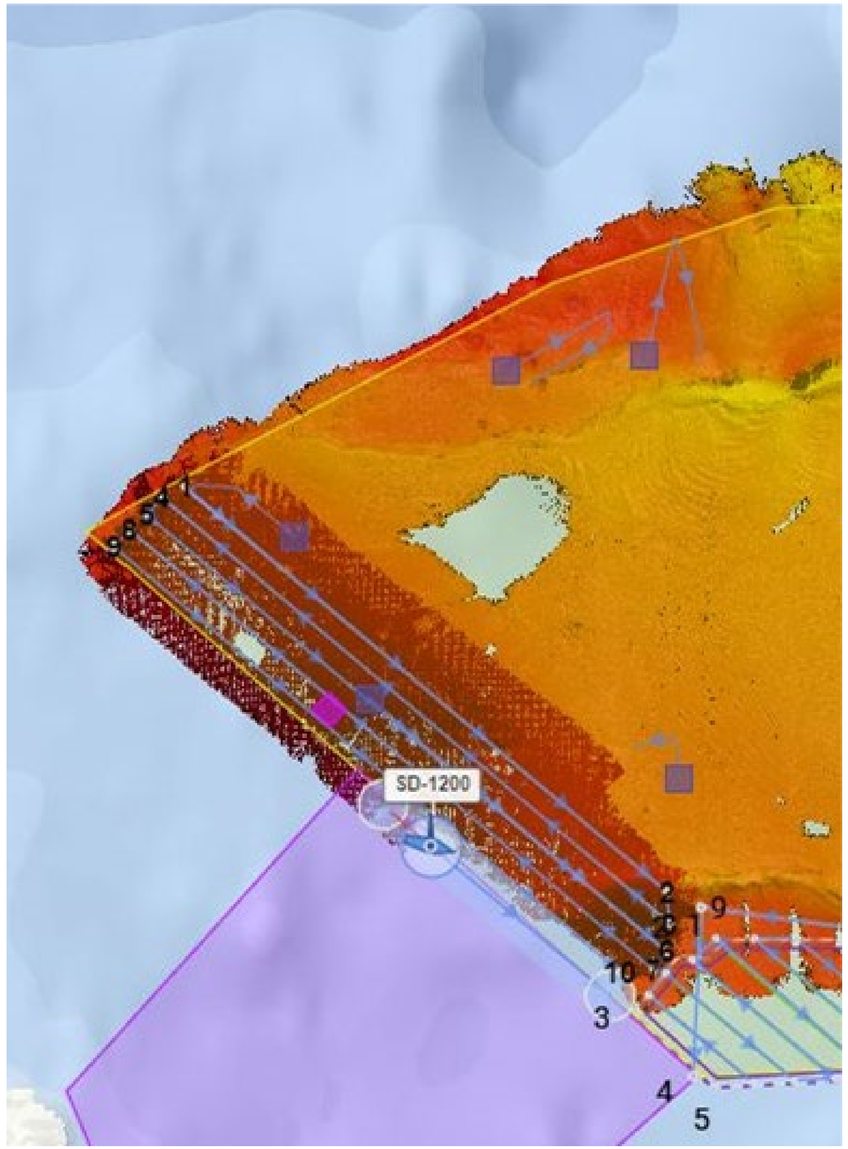
Goal is to sail perpendicular to the wind direction (Beam Reach)



Acquisition

Data Monitoring in Mission Portal



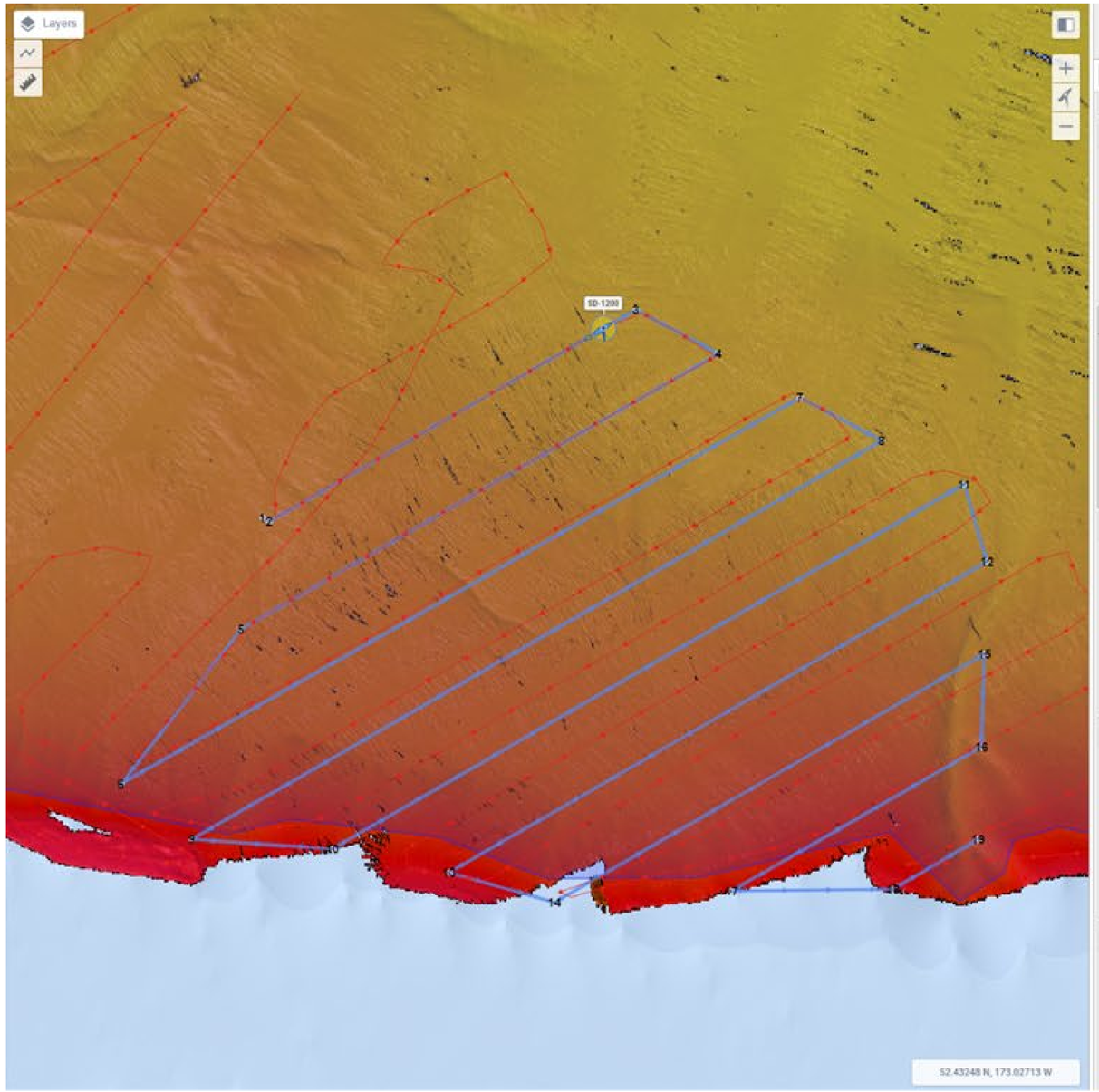


Data Monitoring in Mission Portal

- Daily Products on a 0 - 5000m color scale
- NRT Grid Capabilities - real time data updates every 15 minutes
- SVP profile locations plotted geographically
    - Raw profile viewable
- Time Series data displays navigation, environmental, sonar health over a custom timeframe, with live updates

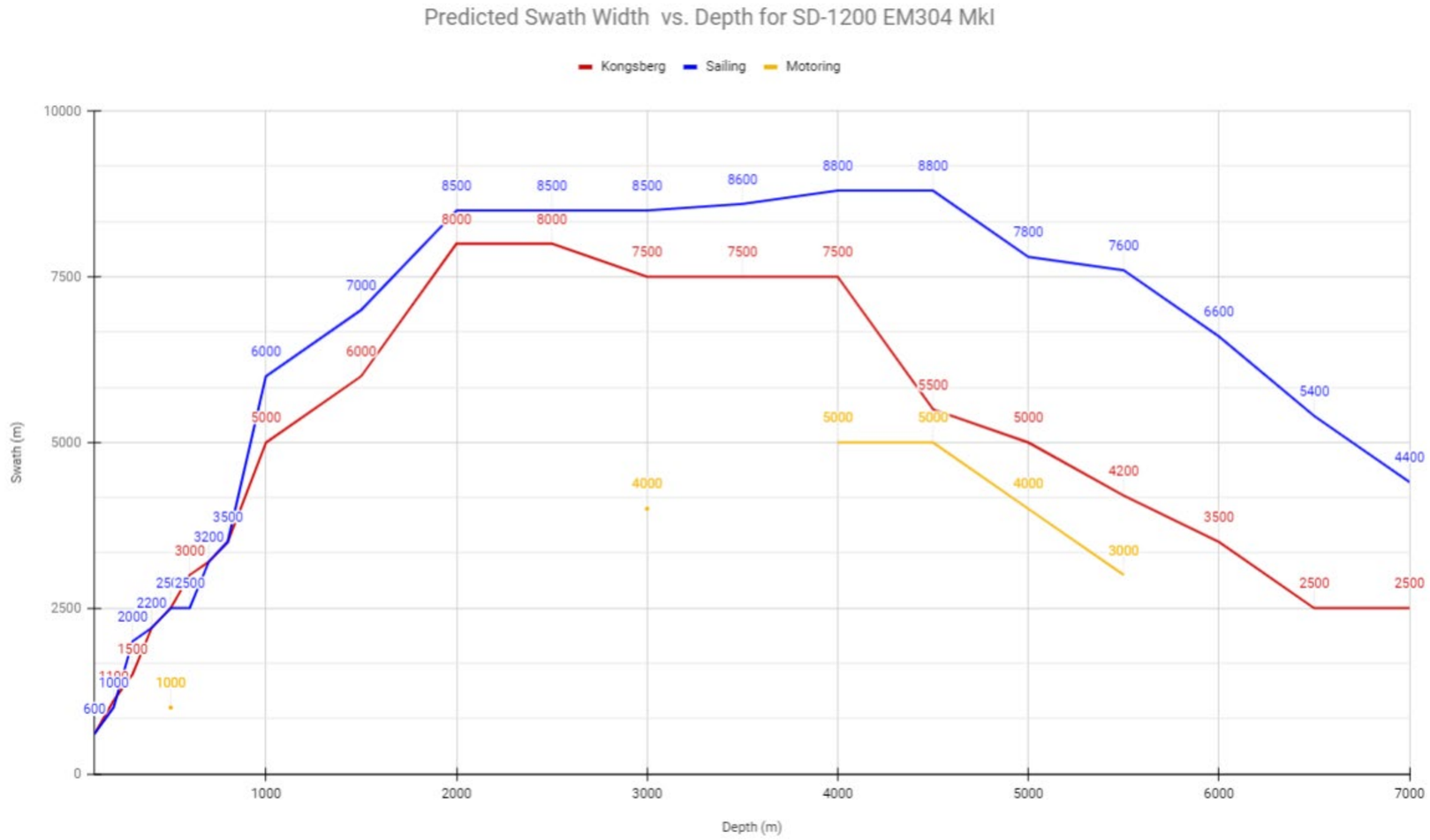
Acquisition

Time Series Data in Mission Portal



Lessons Learned

Unprecedented Raw Swath Width



Raw swath is wider than SIS is actively flagging - We're working with Kongsberg to improve flagging in the outer beams to make the additional swath usable data.

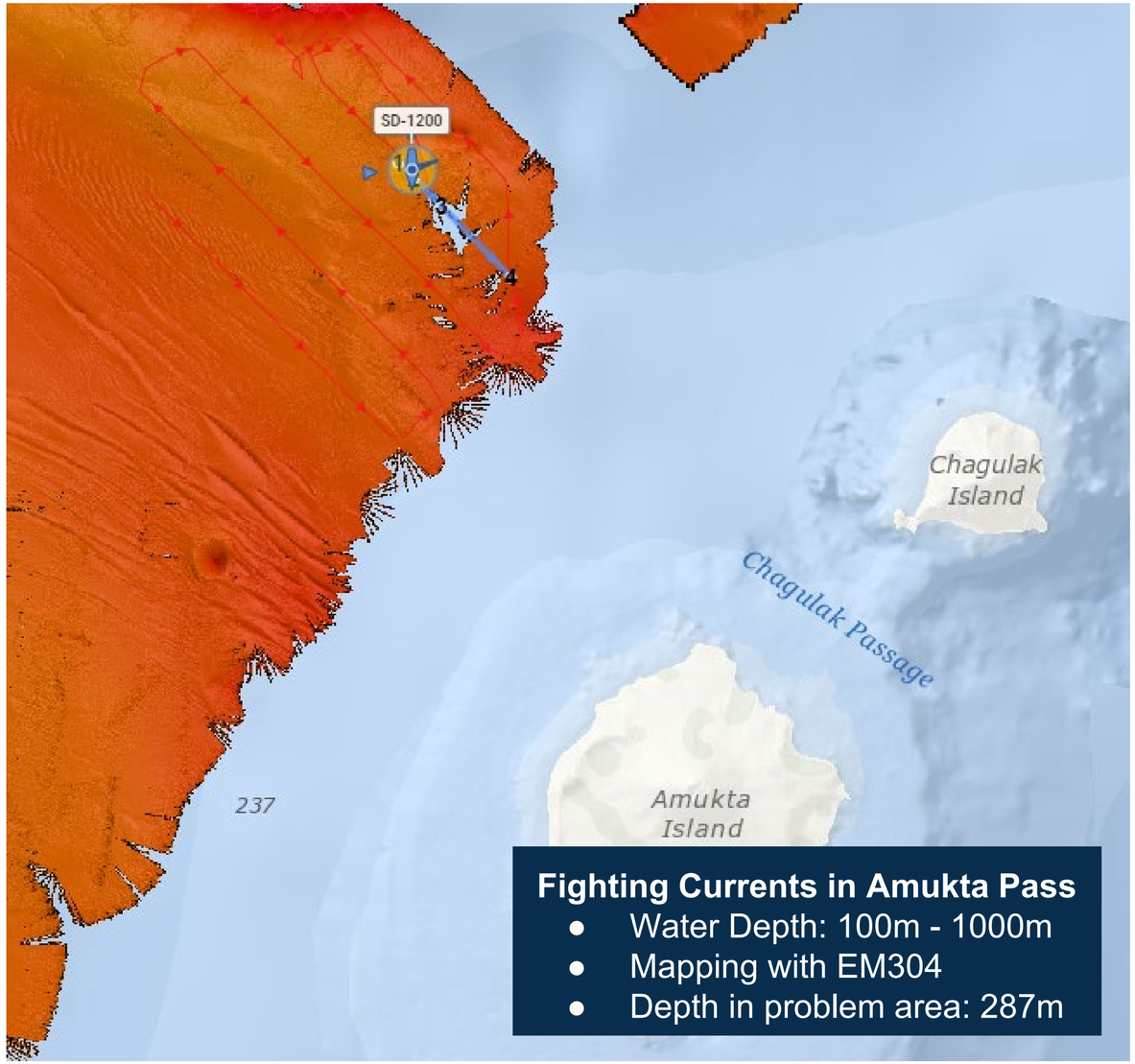
Swath angles were left wide open throughout the survey to identify system capabilities

Raw Surveyor Swath Width Compared to Kongsberg estimates:

- Blue: Surveyor under sail power
- Red: Kongsberg system specs
- Yellow: Surveyor under engine propulsion (Not enough data quite yet to be conclusive)

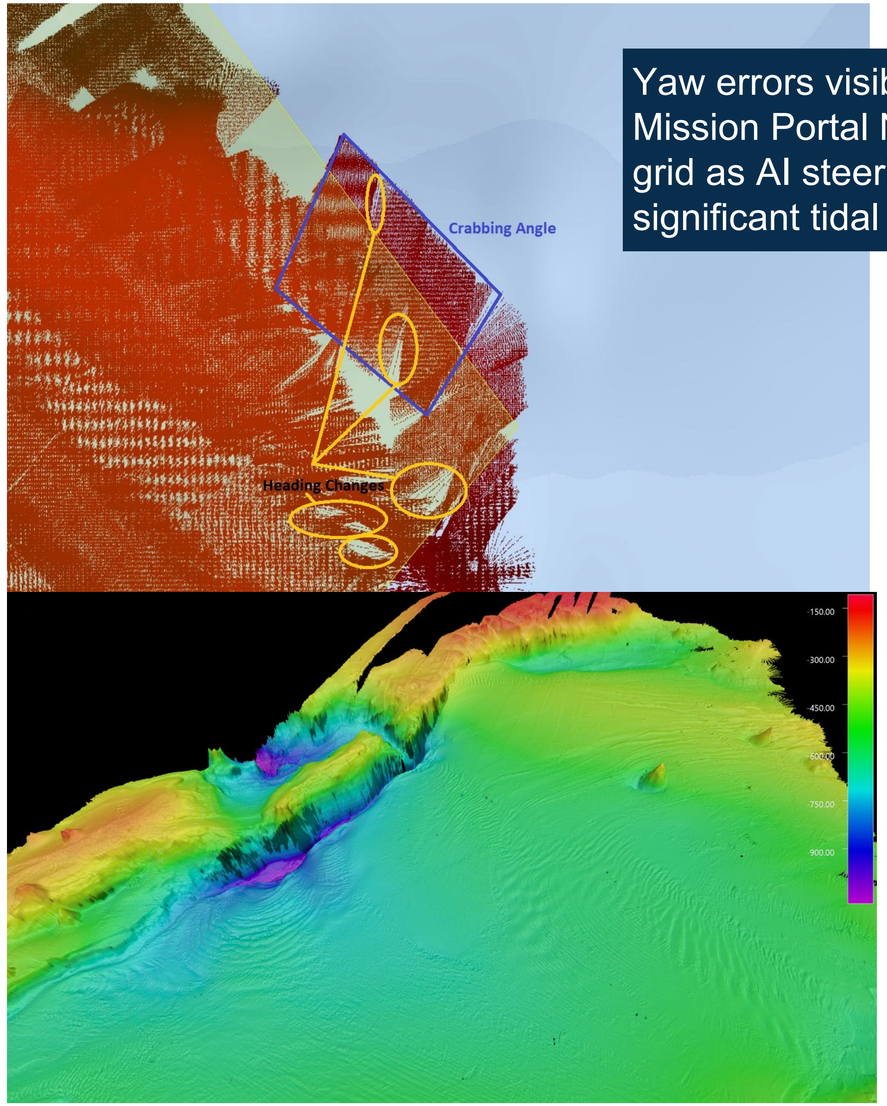
Lessons Learned

Aleutians Tides and Currents



Fighting Currents in Amukta Pass

- Water Depth: 100m - 1000m
- Mapping with EM304
- Depth in problem area: 287m

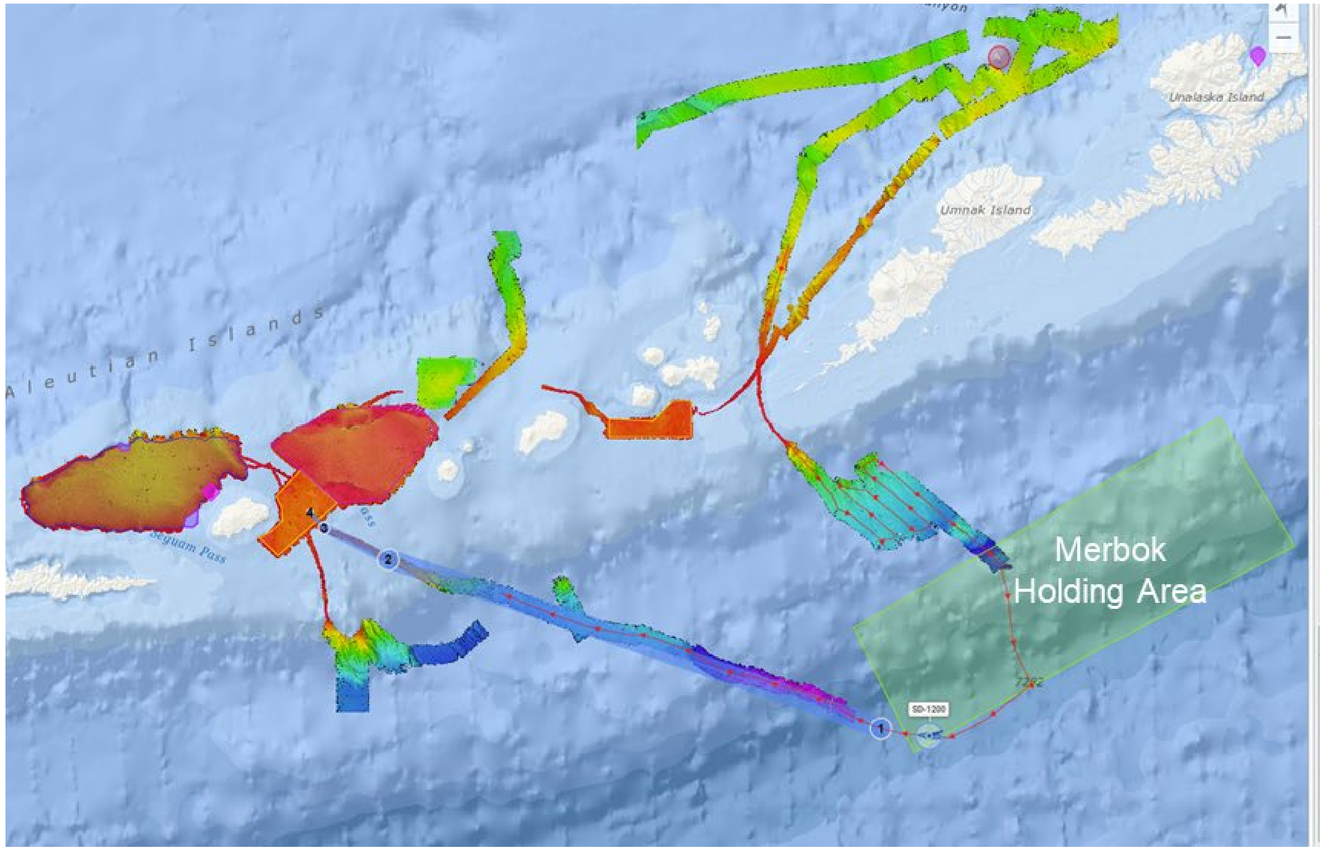


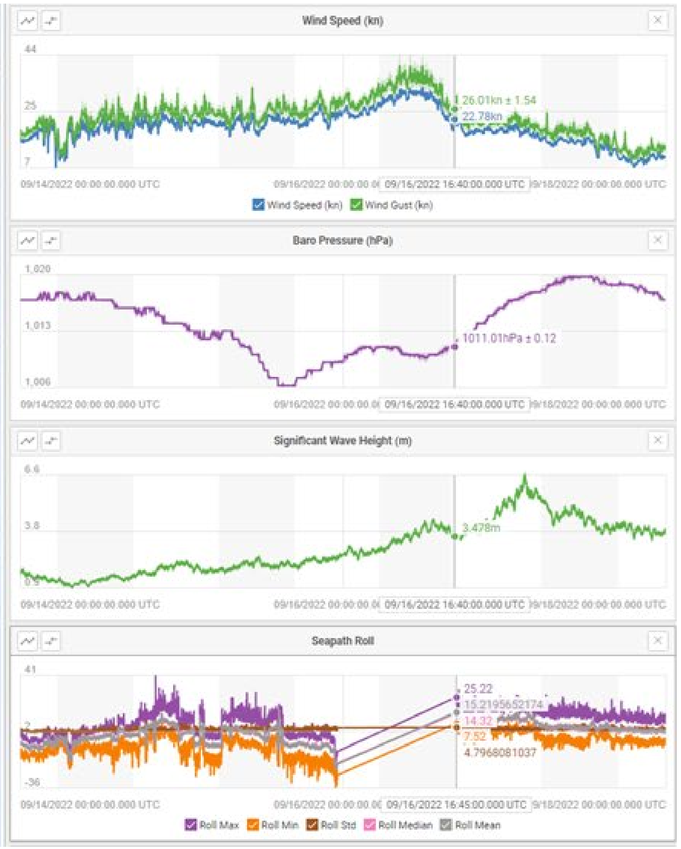
Yaw errors visible in the Mission Portal Near Real Time grid as AI steering fights significant tidal current force.

Lessons Learned

Aleutians Weather Response

One major weather interruption for the entirety of the survey: 23-hour break for Typhoon Merbok





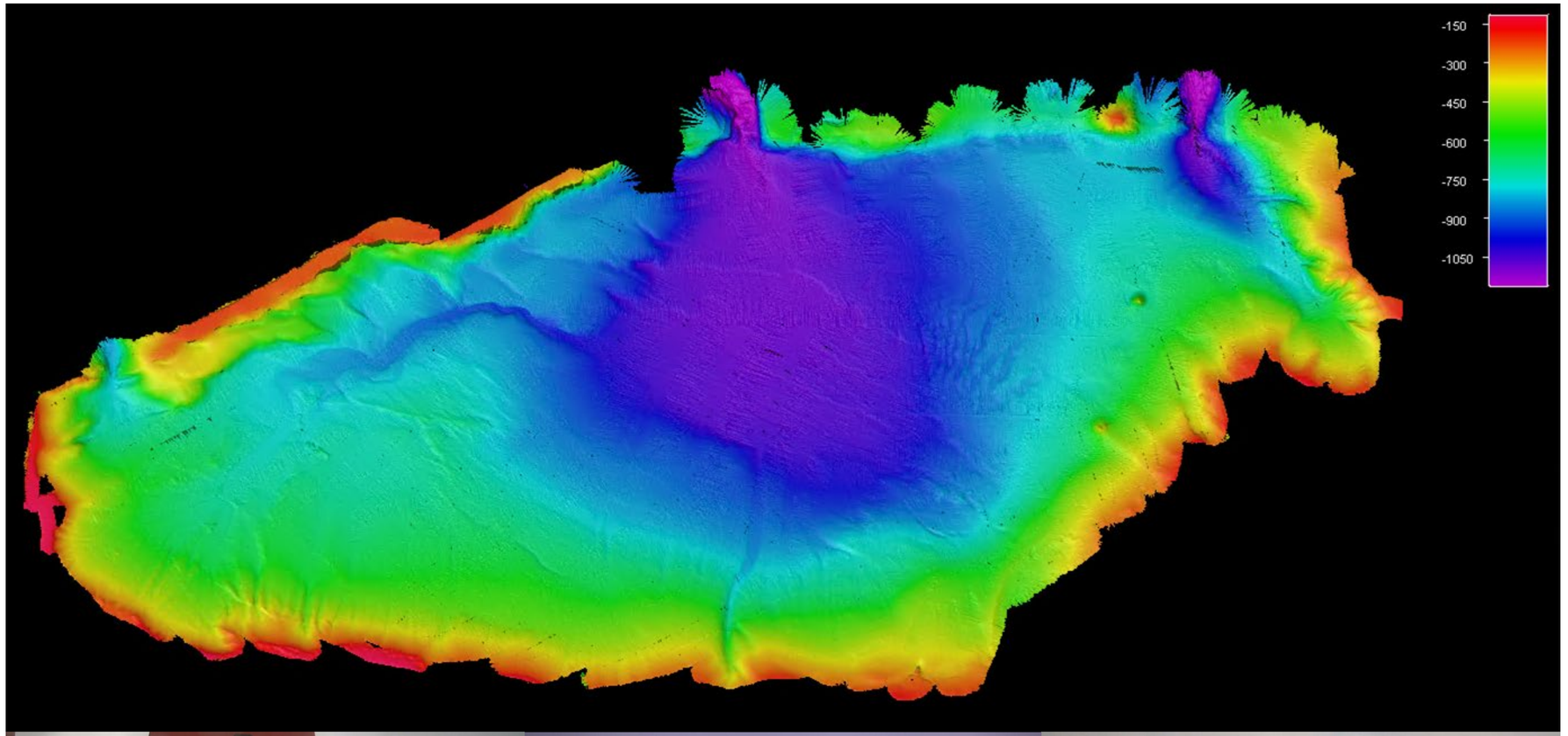
Survey operations were paused for SD-1200 to charge or move into a True Wind Angle hold at other times, but data collection continued during these periods.

- SD 1200 deviated from Bering sea to avoid shallow, tidal, and current heavy waters
- Weathered the storm over the Aleutians trench and mapped OER Polygon once it was safe to do so

- SD 1200 recorded waves at 6.6 m and winds at 44 knots
- Alaska's west coast saw winds at 90 mph and a 12-foot storm surge, which led to Governor Mike Dunleavy declaring a state of emergency

Lessons Learned

Aleutians Weather



Raw data in Amlia Basin

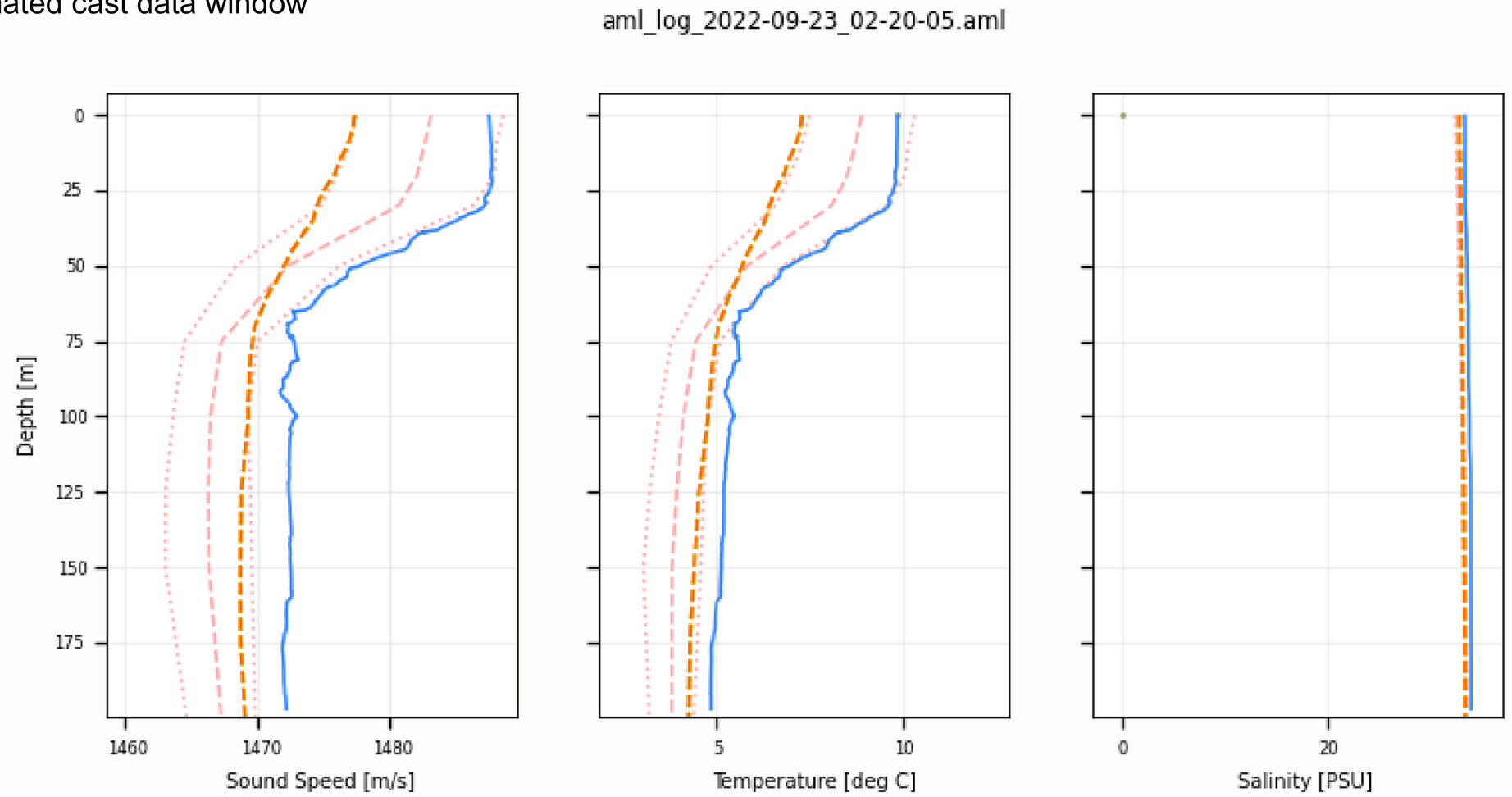
- Maximum sea state: 7.2m
- Sustained Winds up to 58 knots
- Max roll recorded at 60 degrees

Lessons Learned

Sound Velocity

The World Ocean Atlas 18 had very little oceanographic data in the Aleutians Islands leading to SVP issues with synthetic casts.

Yellow: WOA18 Synthetic Cast
Blue: AML-6 CTD Casts Collected by SD-1200
Pink: WOA18 Estimated cast data window



Lessons Learned

Remote Access and Connectivity

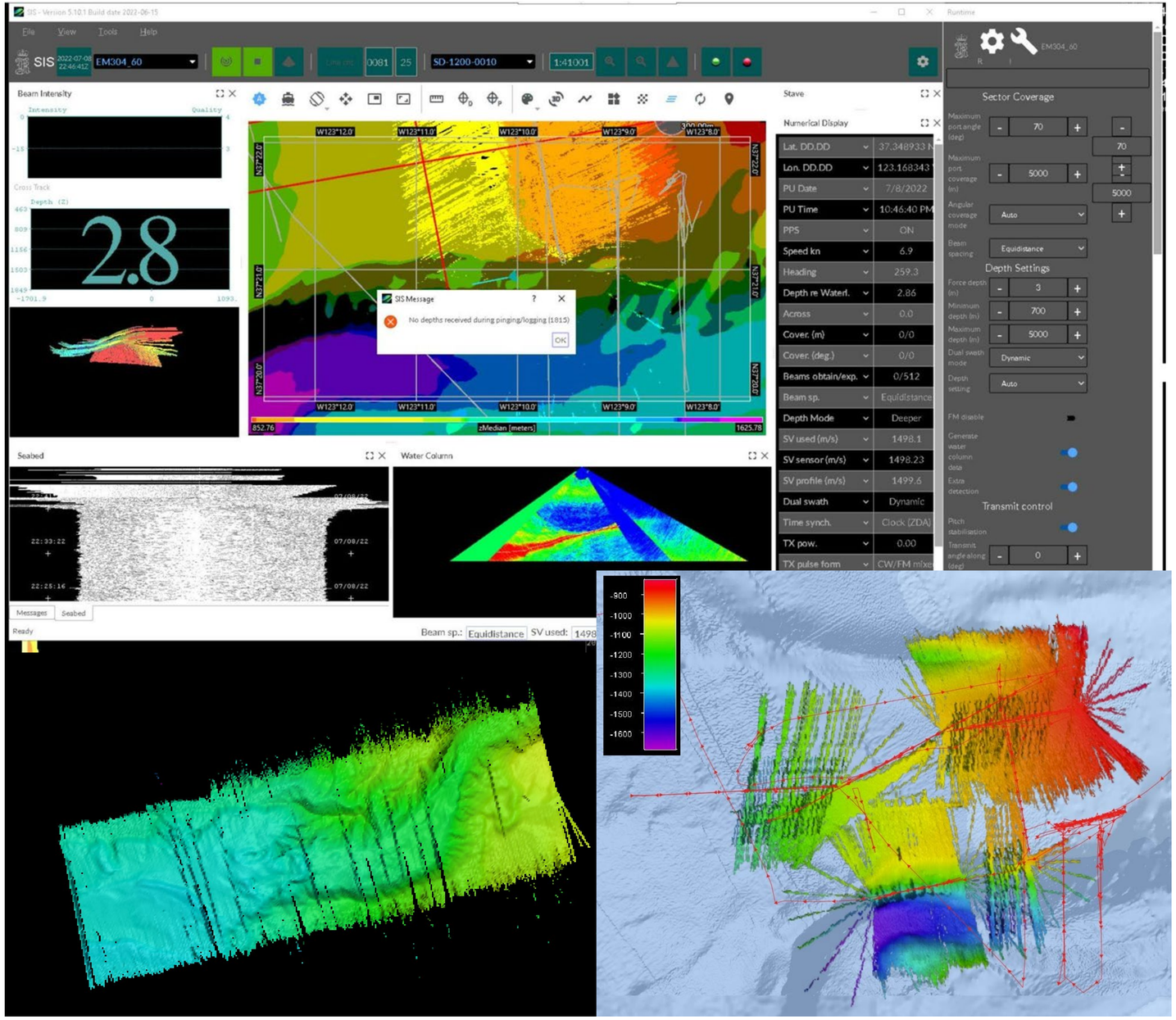
Inability to maintain a stable connection to vehicle Virtual Machines amplified other system issues:

1. Limited ability to check systems
2. Unable to move large amounts of data on/off the drone while underway
3. Limited ability to visualize and QC data
4. Click Delay/ Latency
    a. Changing settings was very difficult - Can’t respond dynamically to data/weather issues
5. Limited troubleshooting capability
    i. Hard to visualize issues
    ii. Can’t tell what was clicked

Lessons Learned

SIS Software/Firmware

- **Max Roll Value:**
  - SIS had a max roll value of 20 degrees
  - Drones frequently heel/roll more than that
  - Software update with a resolved max roll value was issued for Saildrone just prior to the mission
- **Dropping Pings**
  - SIS was sporadically dropping pings
  - PU update fixed the issue while on transit out of Dutch Harbor
- **Extreme Outliers**
  - Still under consideration
- **Outer-swath flagging**
  - Still under consideration
  - Increased swath width is an asset if we're able to effectively flag and use it



Processing Observations & Results

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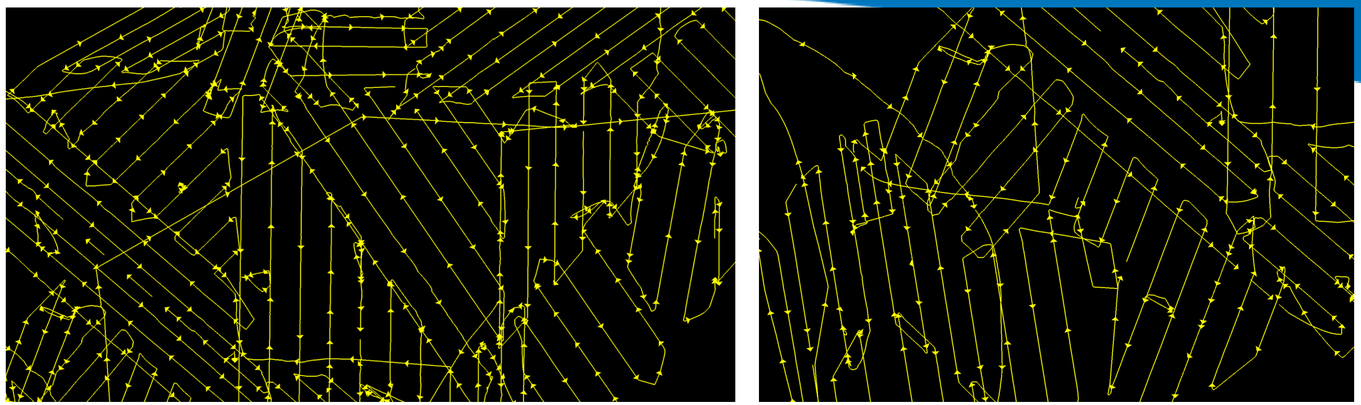
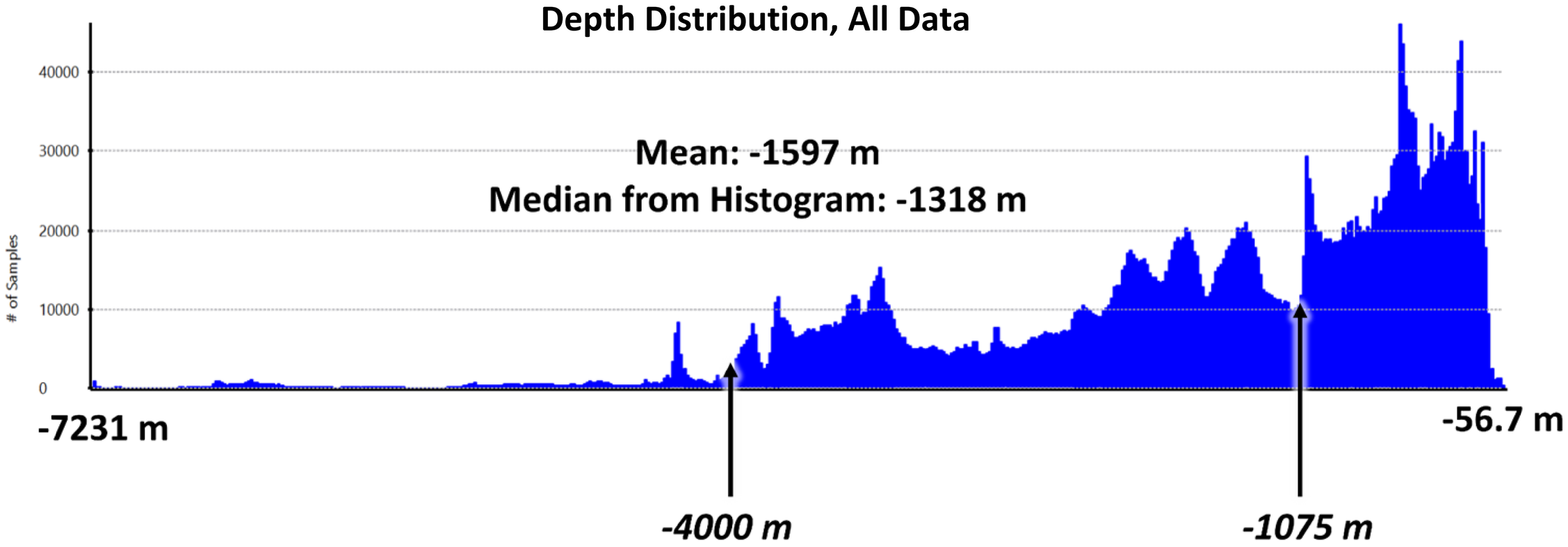
Initial Data

- ~51 days of 24-hr ops survey data
- 16,254 sq km preliminary area covered
- ~2700 lines, 85% EM304, 15% EM2040
- Tasked with bathymetry and backscatter
- All processing in QPS Qimera, FMGT

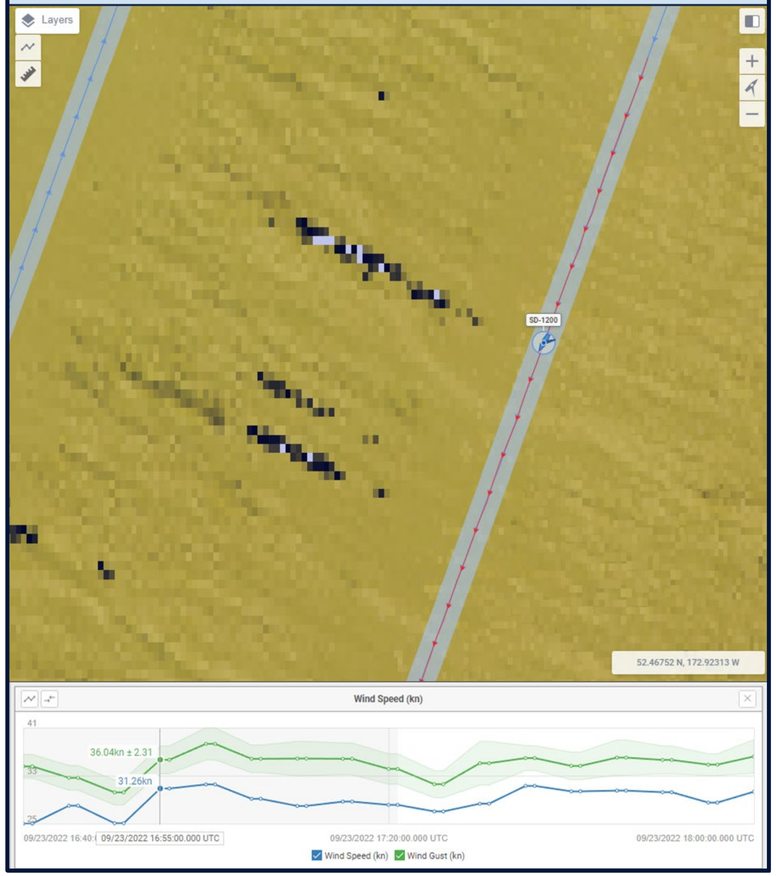




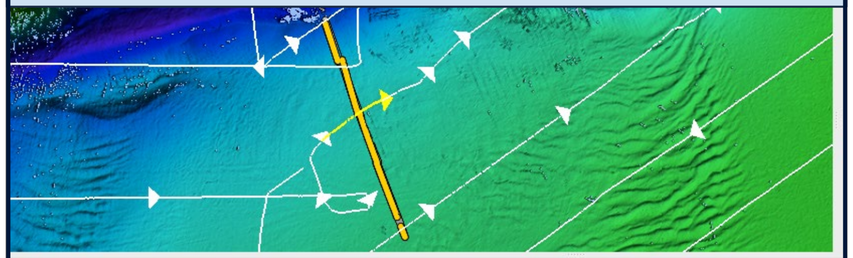
Mission Portal

INCREDIBLY helpful for interrogating/investigating during post-processing

Interrogation of Conditions

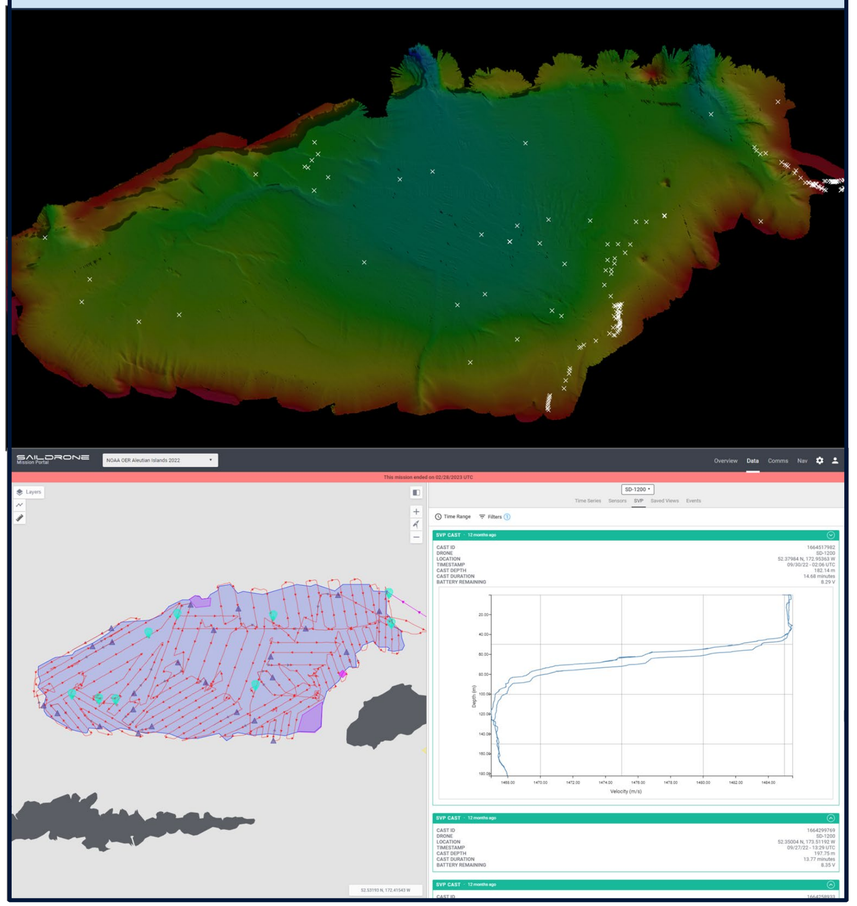


Investigation of System Issues

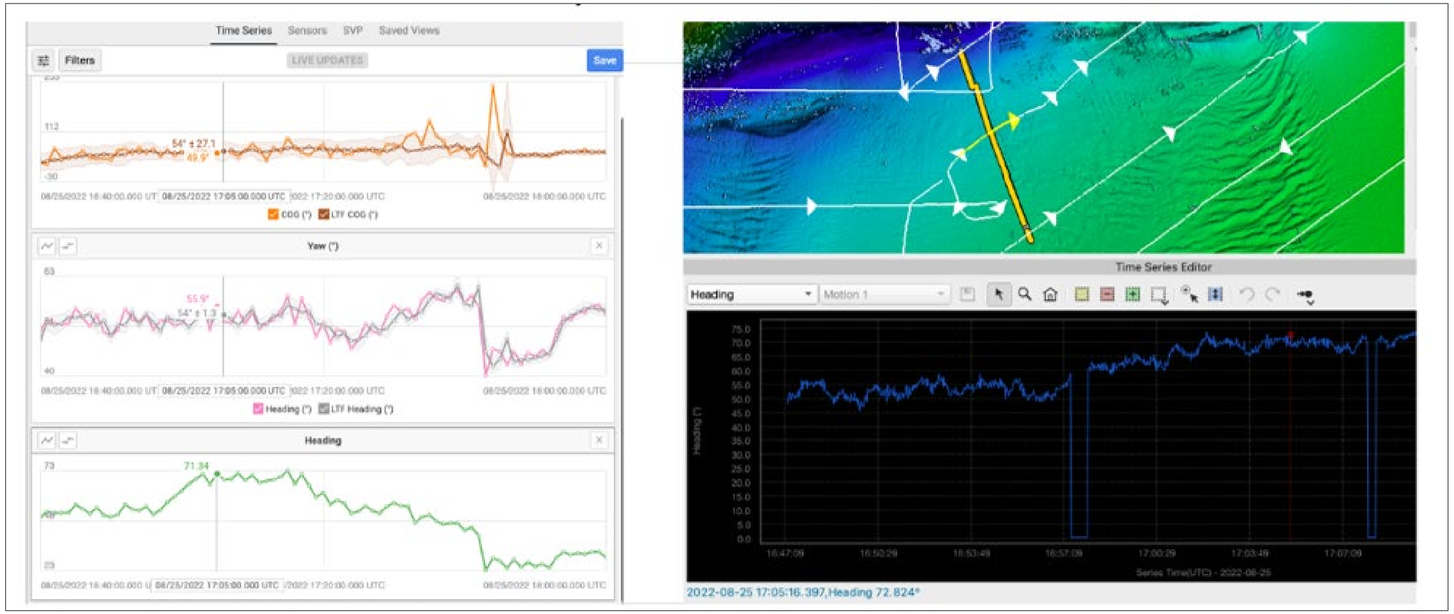


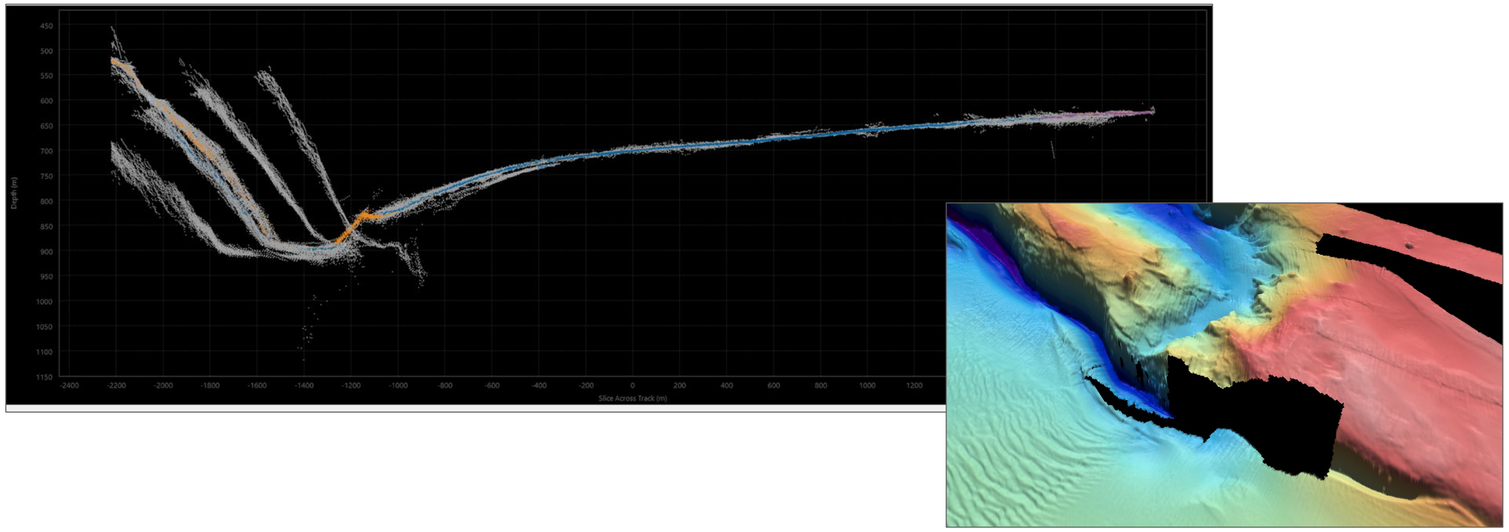
A geospatial, visual mission log!!

Review of Sound Speed Obs



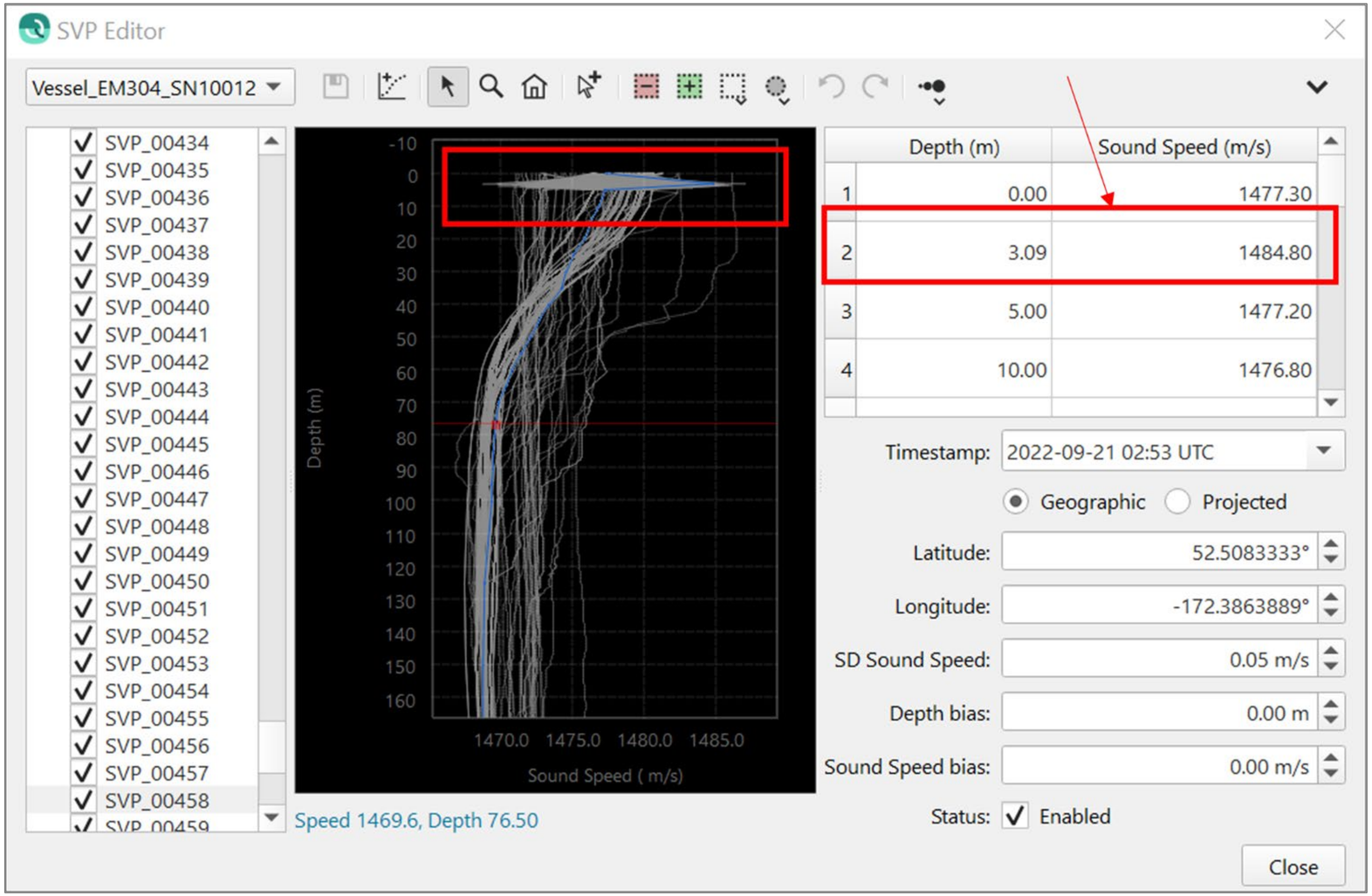
Limitations of Remote Access



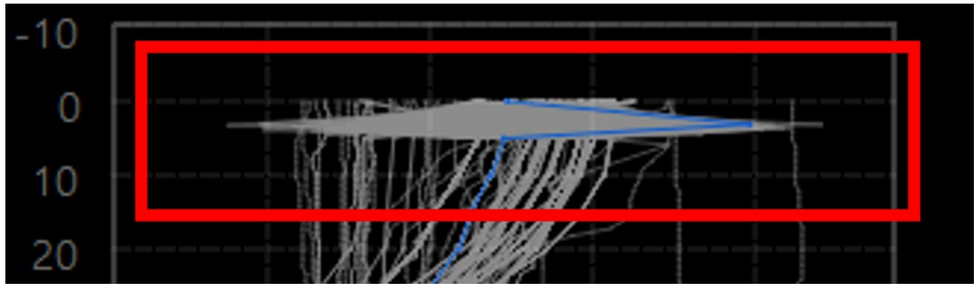


- Incorrect system settings for extended periods – *extra detections, SV at transducer set to profile*
- Missed system failures – *Seapath dropout, prolonged mistracking*
- Limited ability for online mitigation to improve results
  - *Dealing with turns - sharp, difficult to remove from data*
  - *Forcing modes for better results*
  - *Reducing coverage angles for better results*

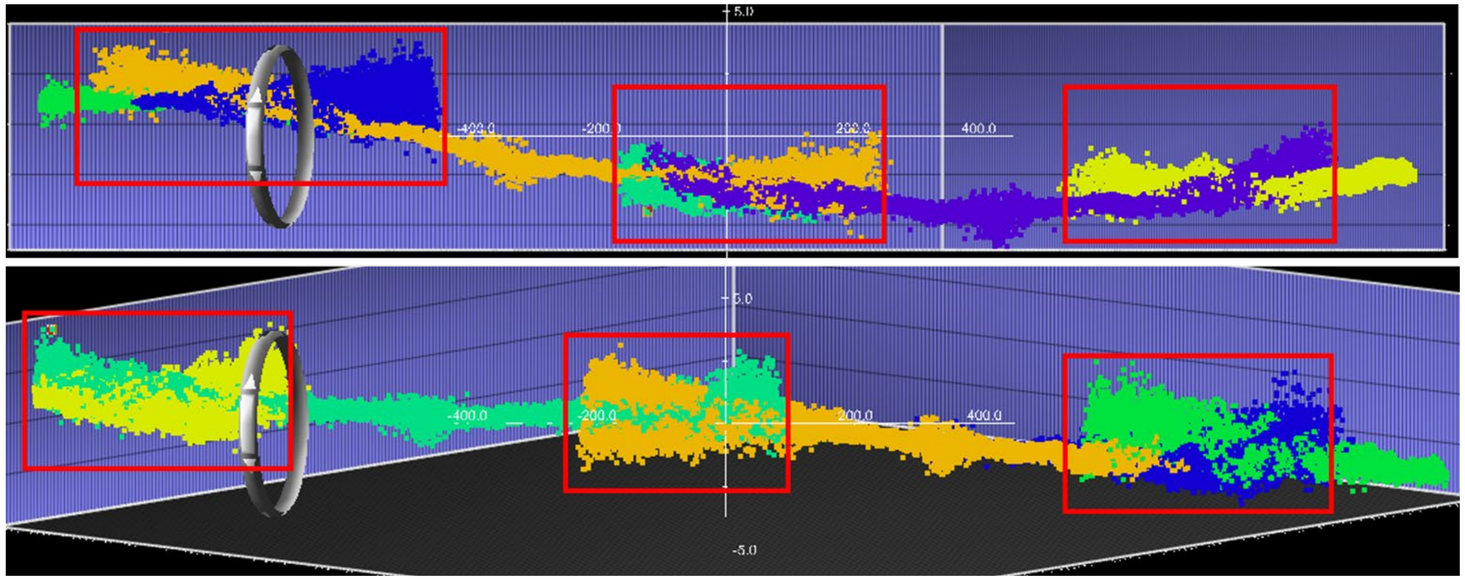
Limited Sound Speed Control



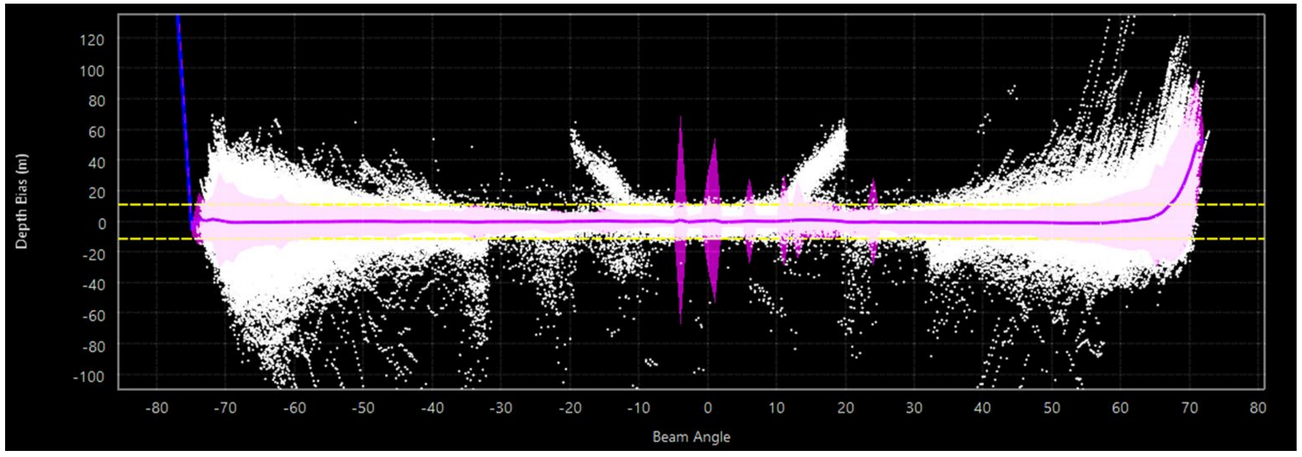
- Depth limitations of winch (200 m)
- Planned for 2x/day EM304 ops, 4x/day EM2040 ops based on hardware limitations
  - Not enough for this region
  - Observations further limited by conditions
- Heavy reliance on WOA
  - 69 actual observations
  - 754 synthetic casts applied

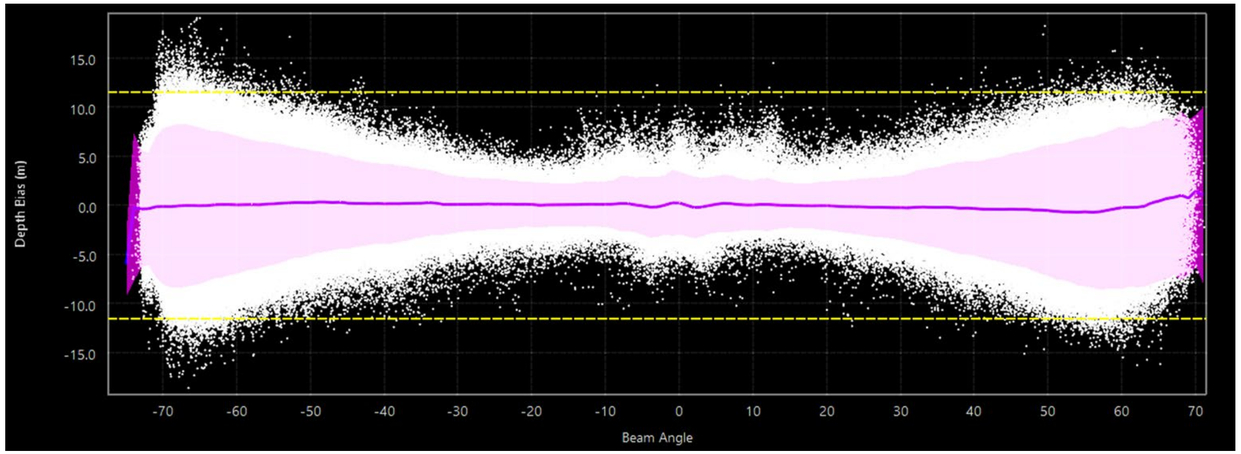


Unprecedented swath width, or *overly* wide swath??

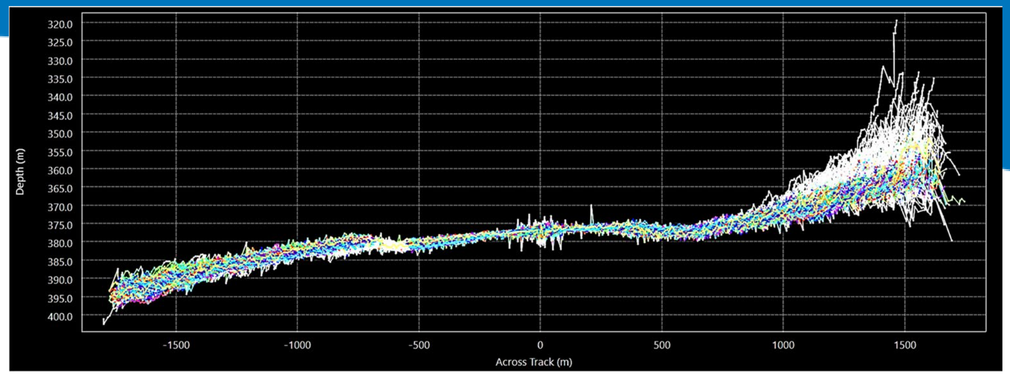


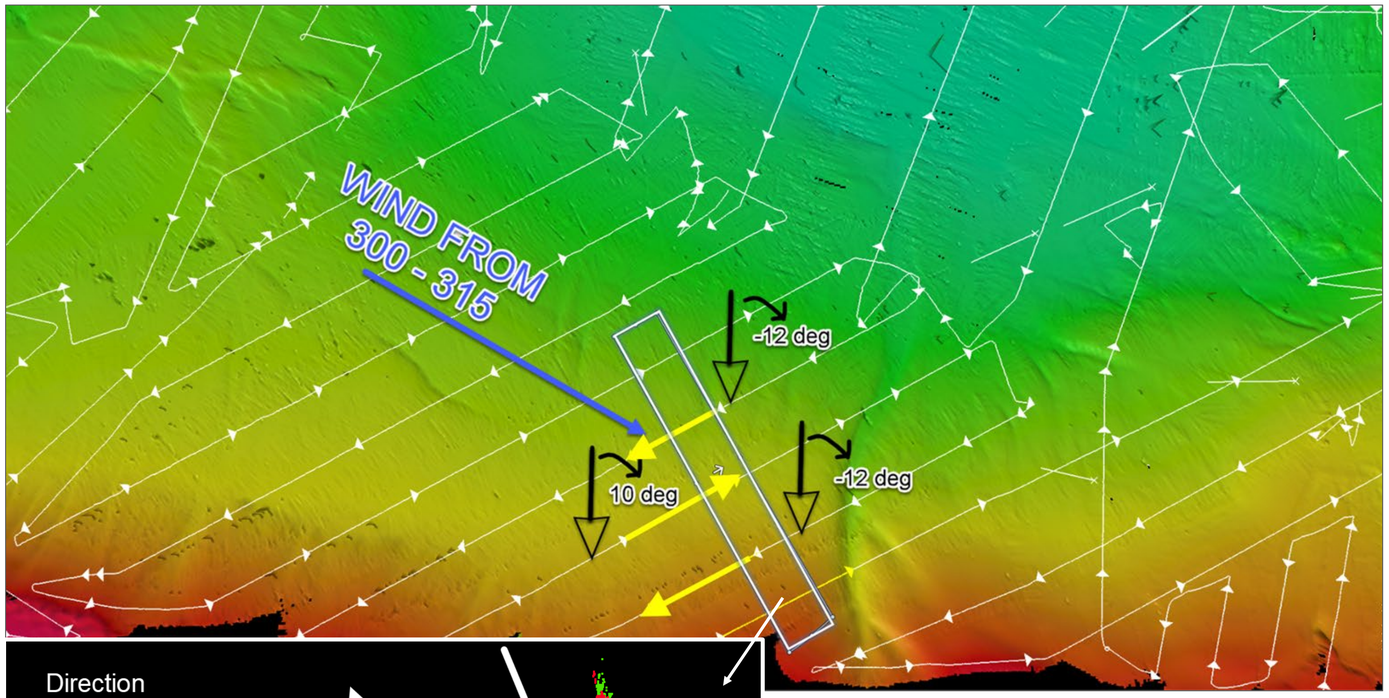
- Noisy outer beams – often ended up cutting out 60-80 outer beams (total), evaluated on almost a per-line basis
- Exacerbated by limited sound speed profiles
- Possibly exacerbated by incorrect sound speed at head?

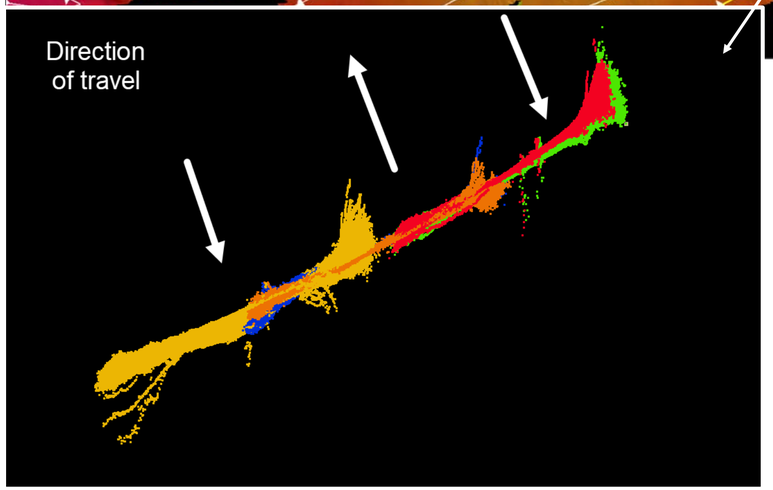




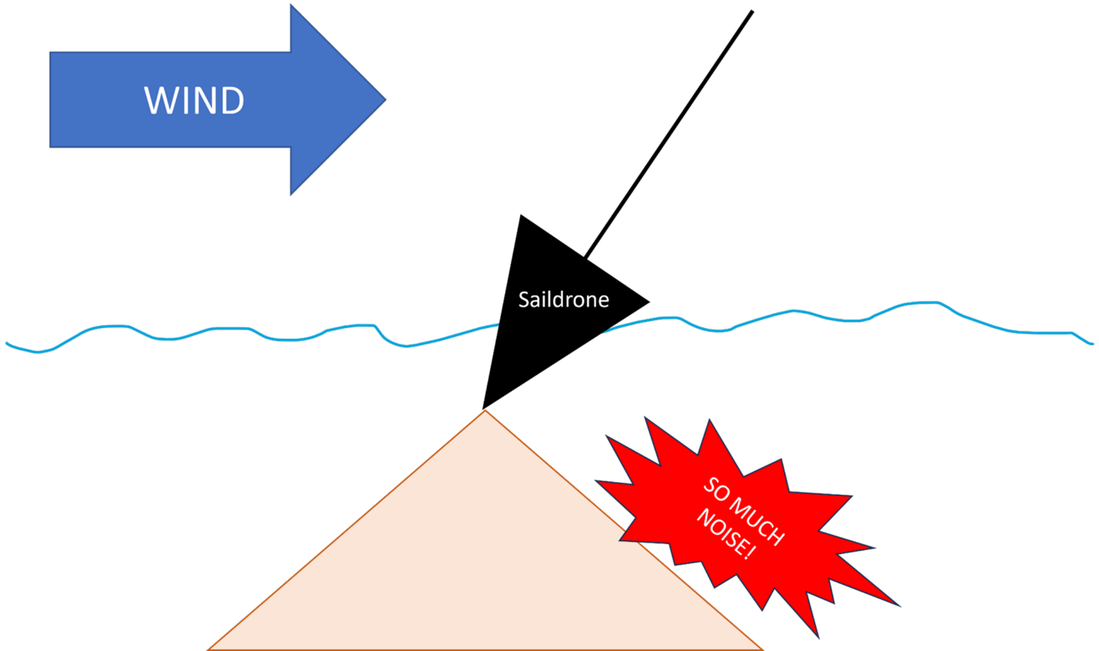
Unprecedented swath width, or *overly* wide swath??



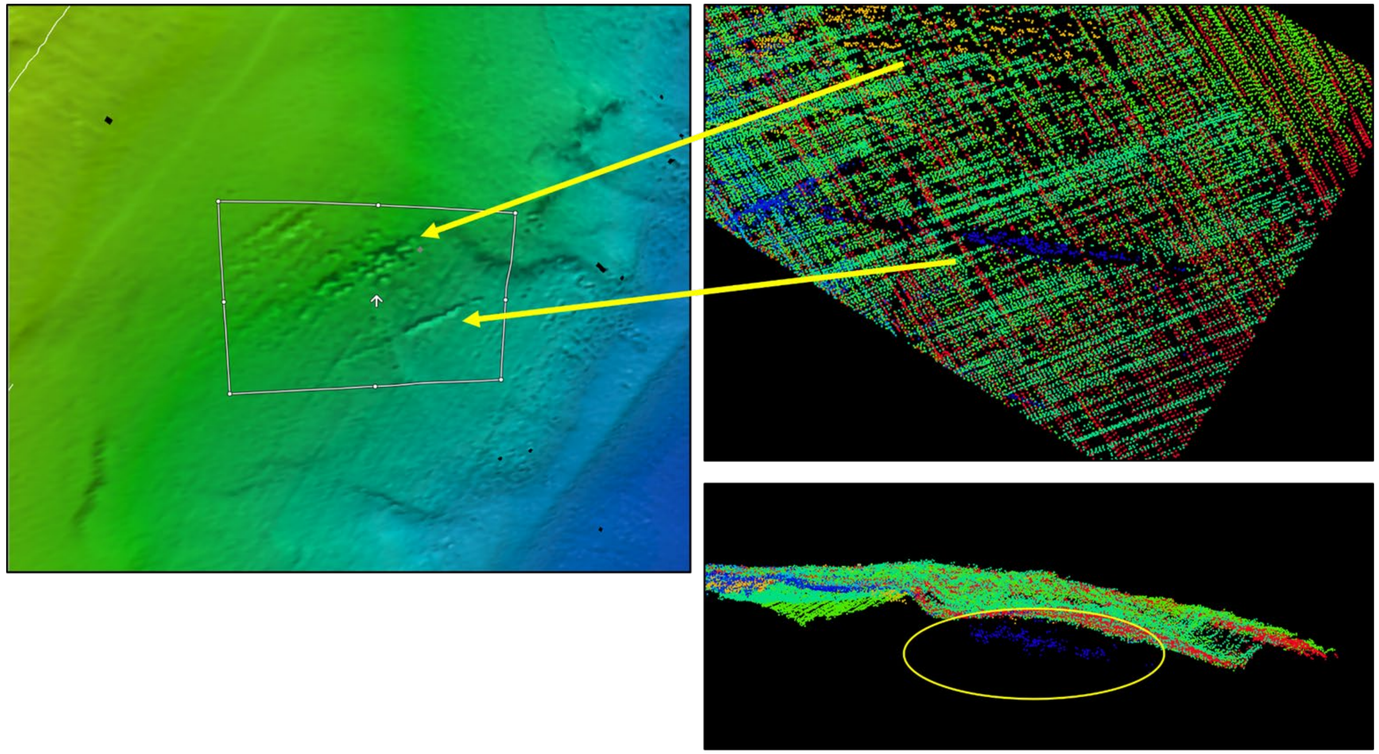




- 'Heeling Artifact'
- Exacerbated by limited profile observations and hard to separate 'normal' sound speed issues from this additional artifact
- Exacerbated by incorrect sound speed at head?



Limited Sound Speed Control + Overly Wide Swath =



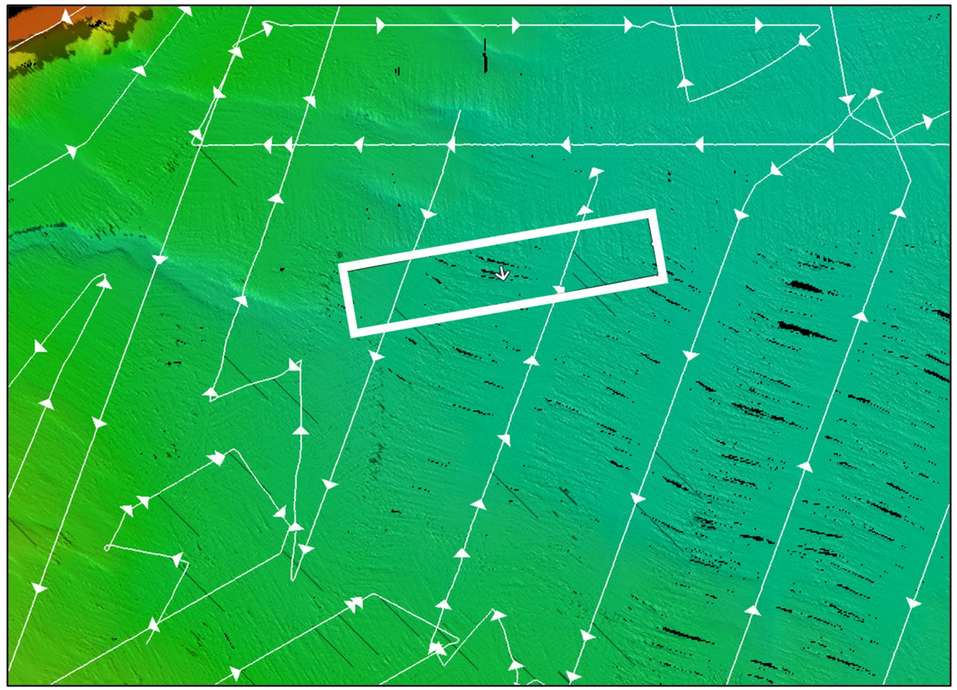
= Extensive clipping of outer swath

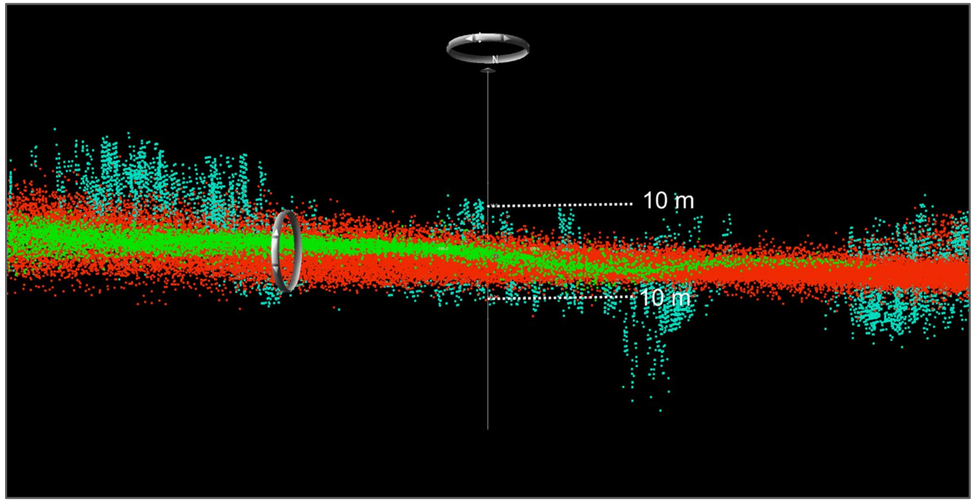
= Reduced overall coverage, reduced overlap leaving little to no overlap in some locations

= Remaining sound speed issues, difficult to address

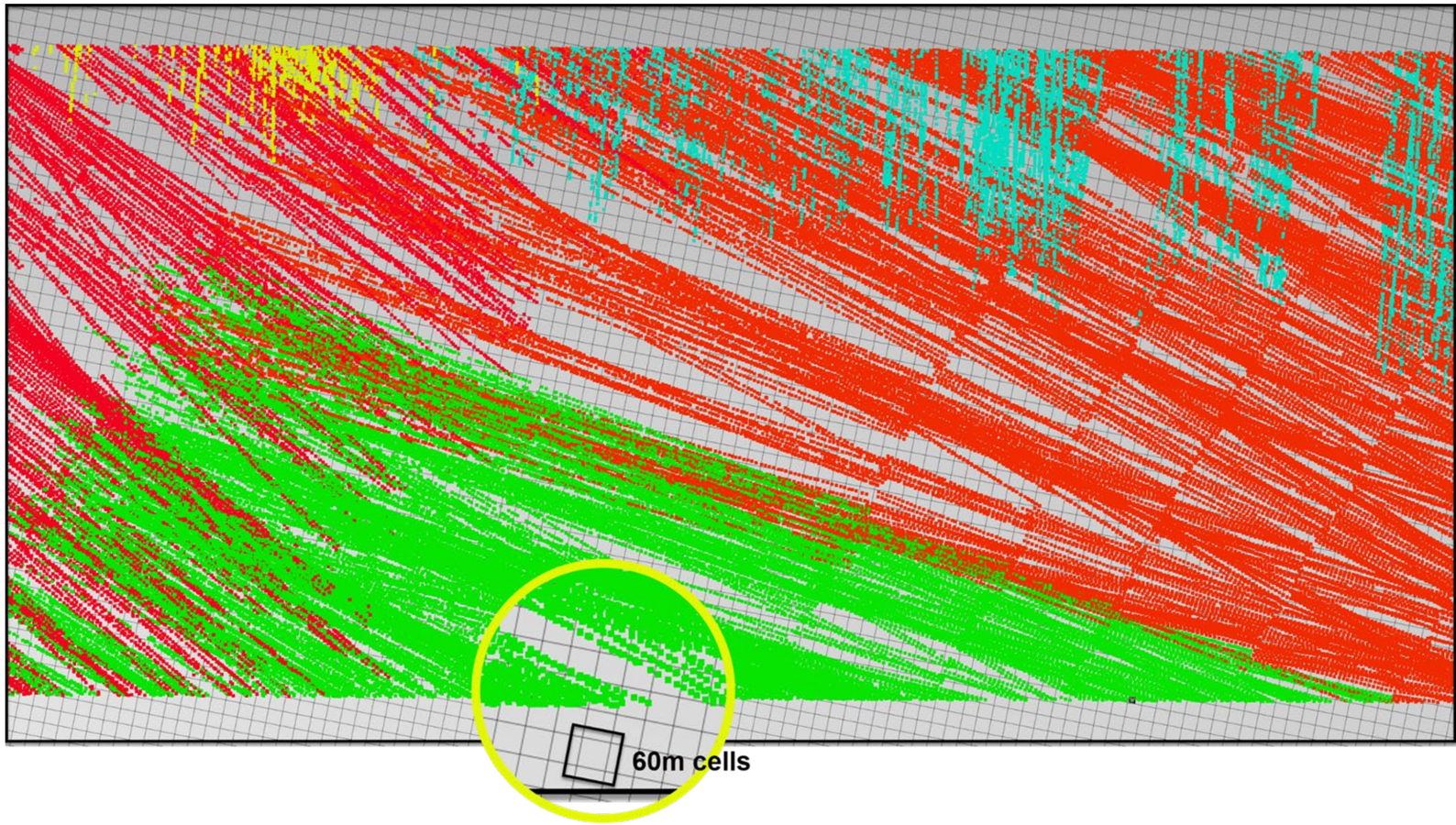
= Failure of processing filters/extensive manual processing due to underlying data issues that couldn’t readily be addressed

Significant Motion

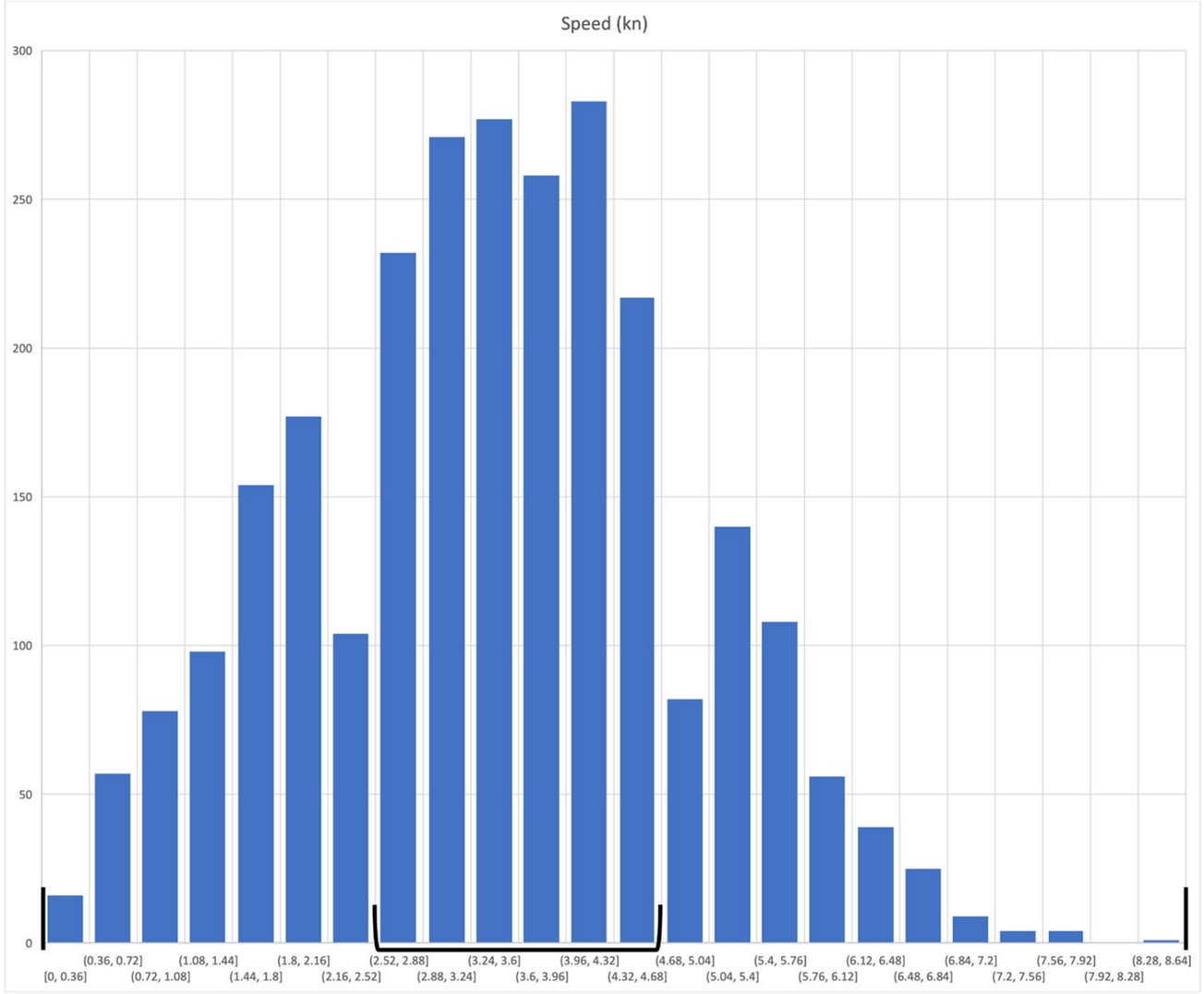




- Lots of yaw (especially in bad weather) but prone to more motion in all axes
- Susceptible to wind and currents



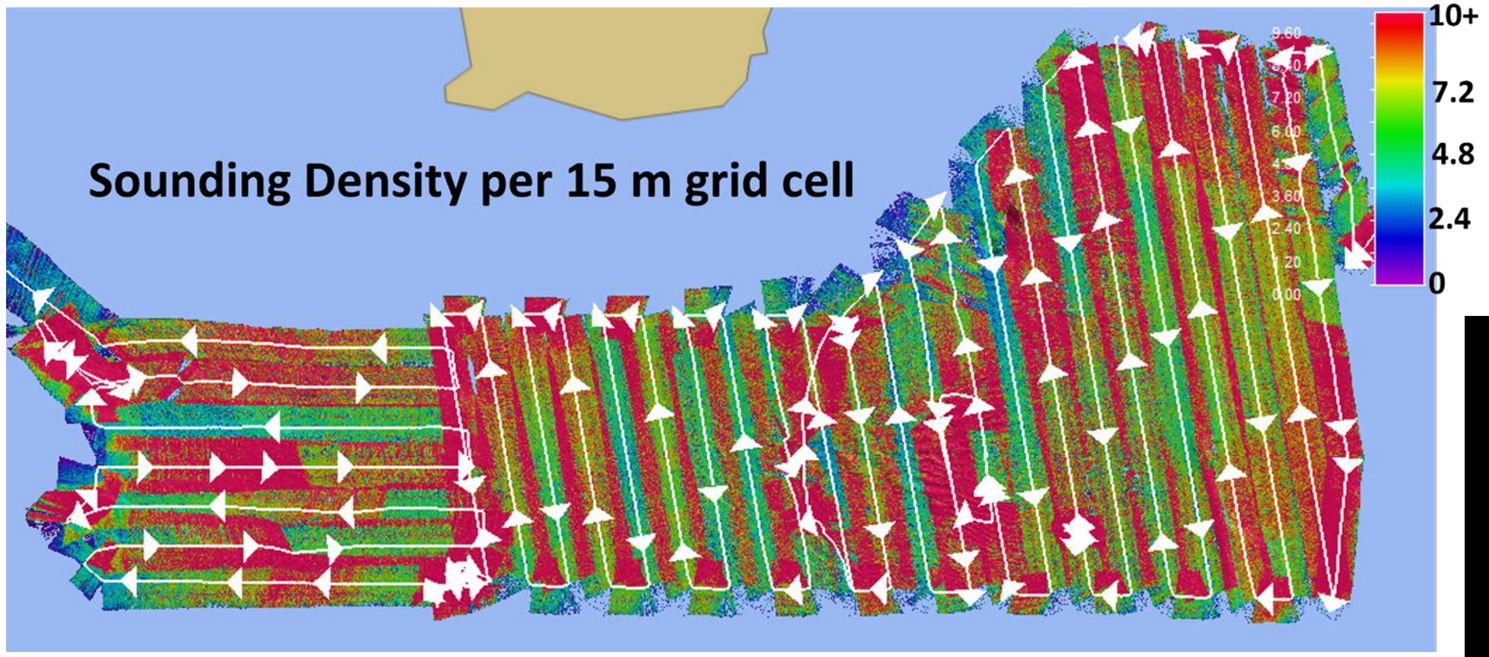
Speed Variations



0 kn **2.52 -------- 4.68 kn** **8.64 kn**

- Average speed for whole survey 3.4 knots
- Varied considerably, <1 to 8+ knots

Significant Motion + Speed Variations =

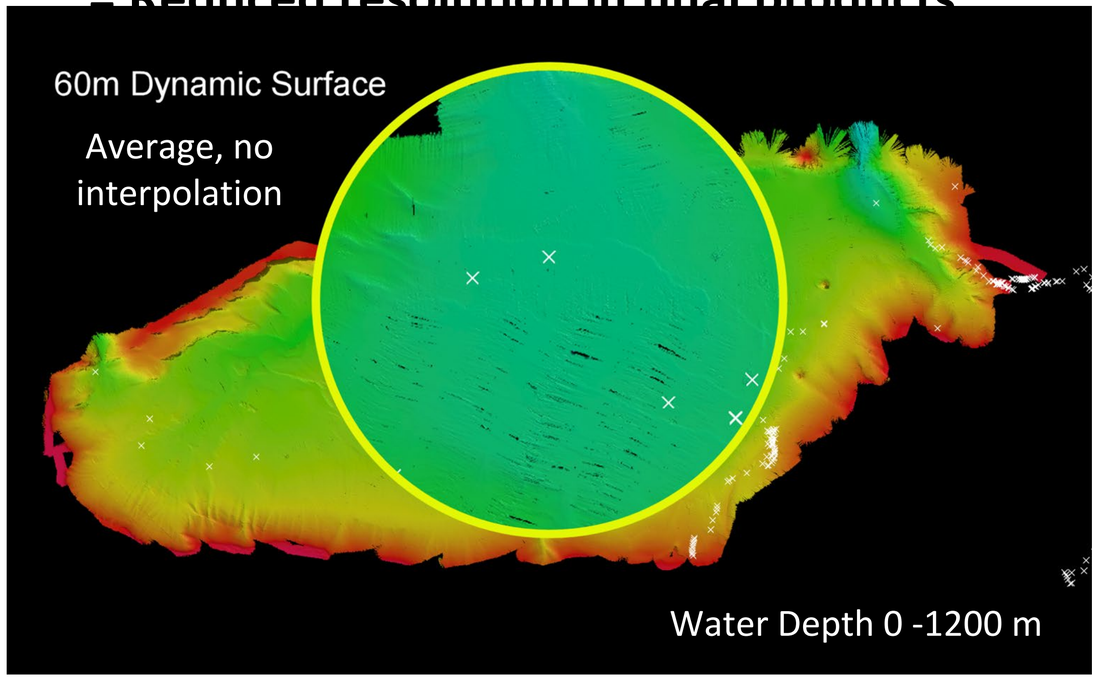


= Reduced and irregular along-track density

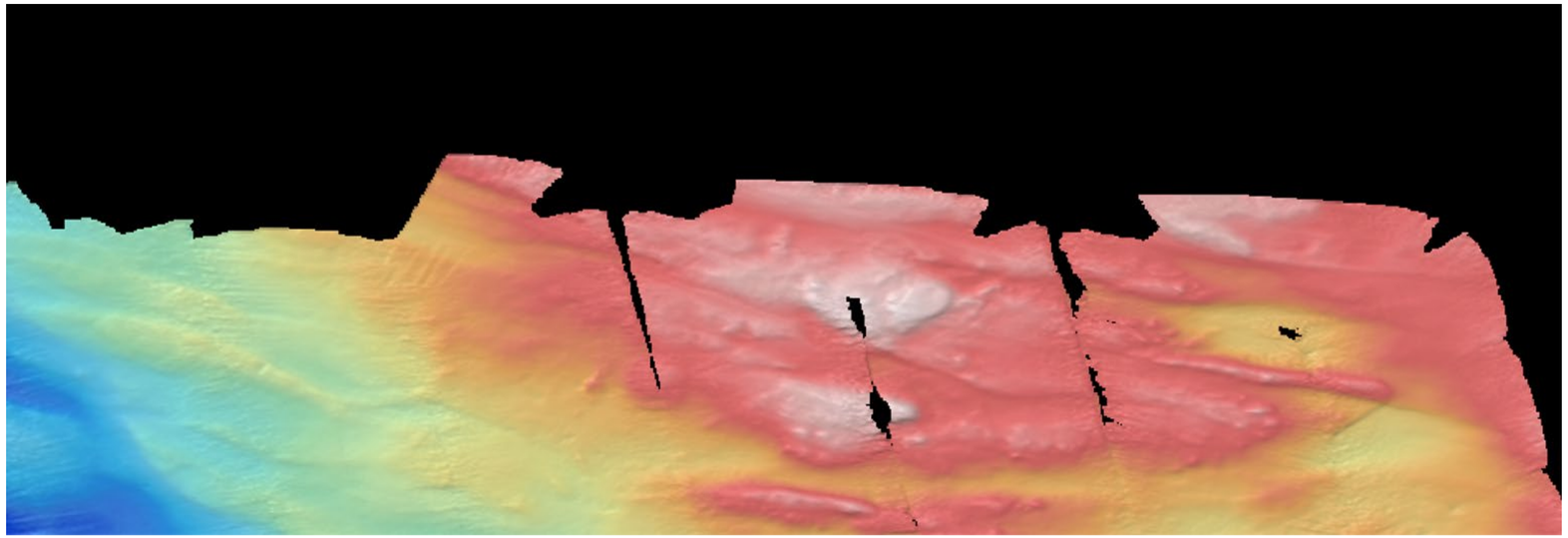
= Gaps in coverage, without enough overlap to compensate

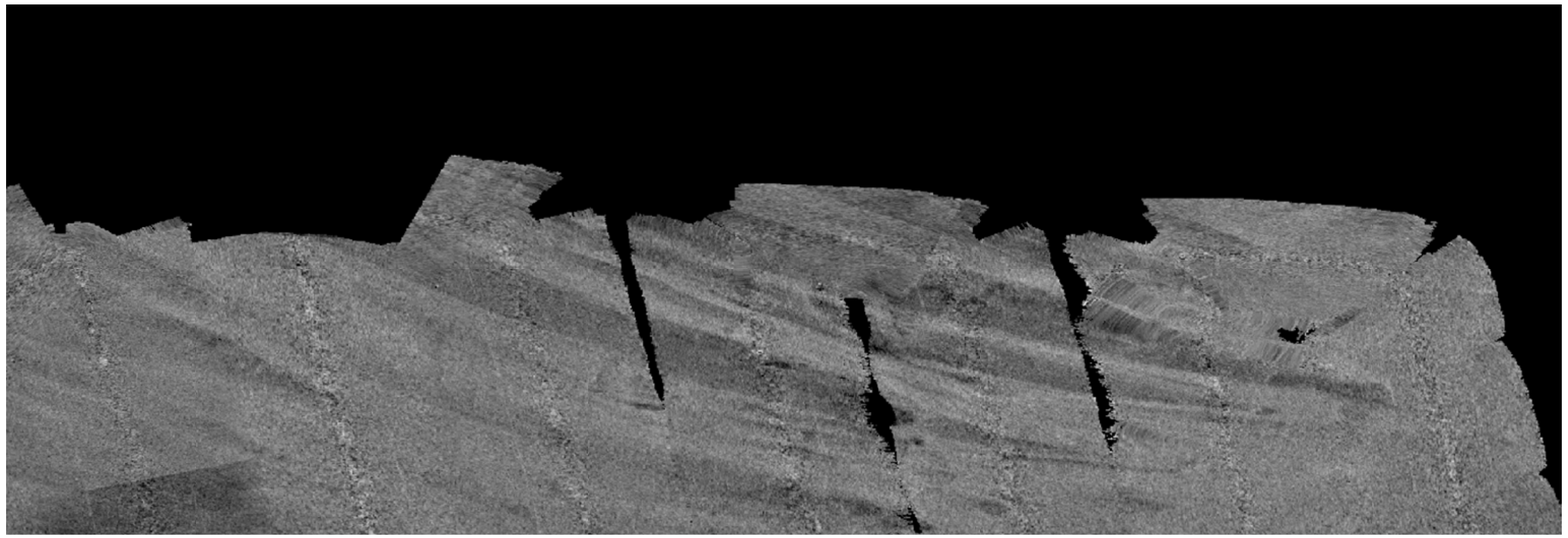
When combined with other issues…

= Reduced resolution in final products



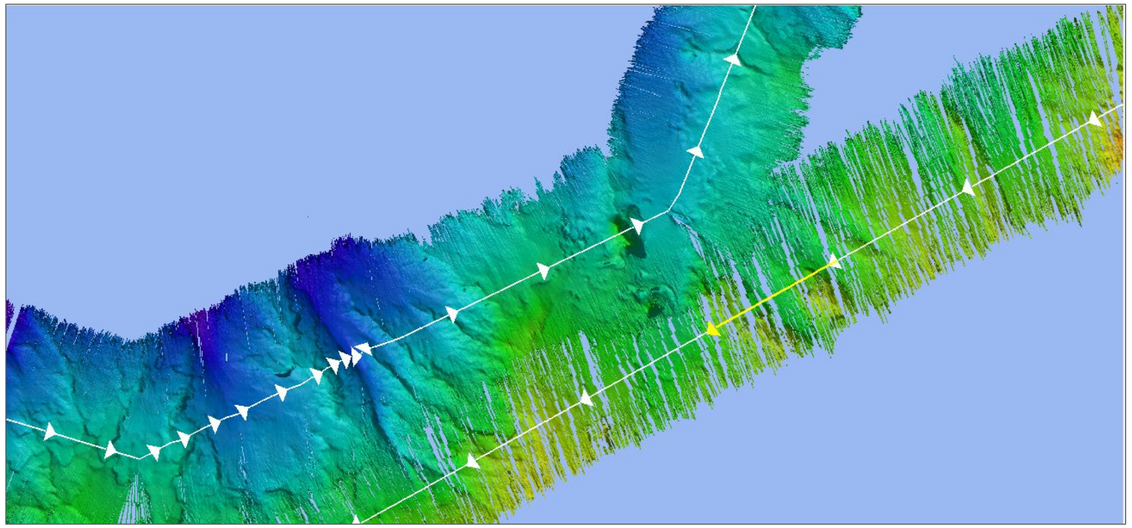
Challenges of Sailing



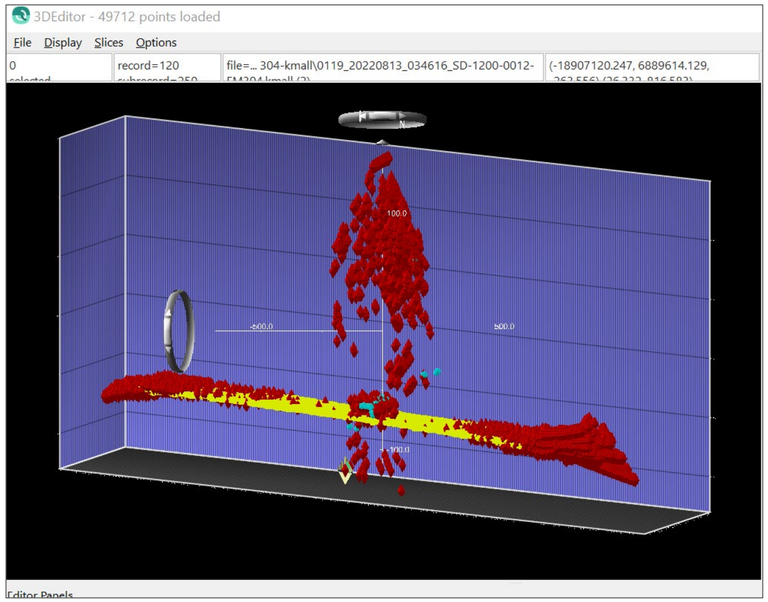


- Regular changes to line orientation are part of working under sail
- Can’t easily dictate line orientation, even under motor
  - Challenging to do cross-lines
  - Directional gap filling not really possible (*important for backscatter*). ANY gap filling can’t really be guaranteed.
  - Difficult to abut pre-existing lines

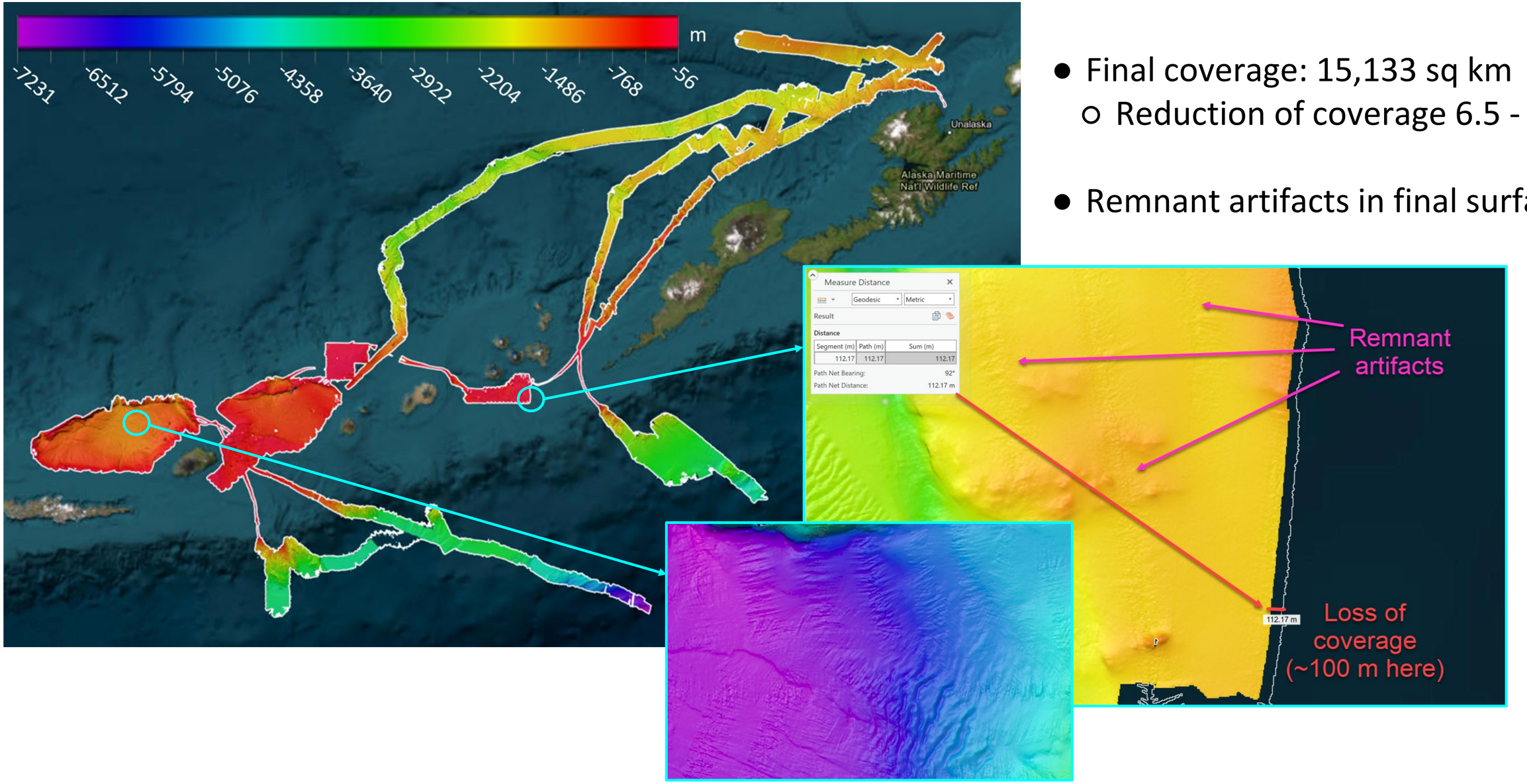
Firmware/Software Issues



- KM Firmware update part way through transit to first survey area
- Qimera issue with Extra Detections **= extensive reprocessing**

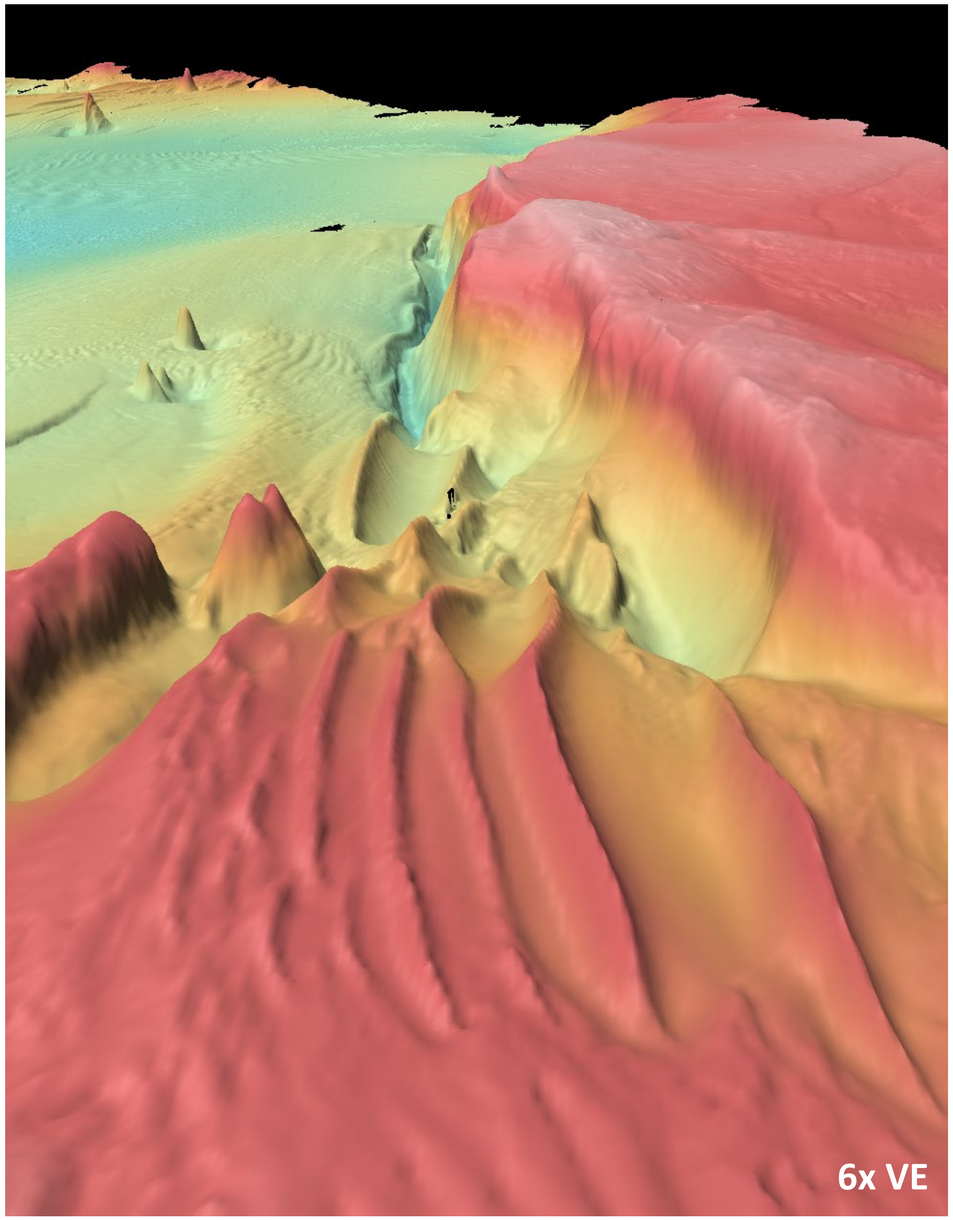


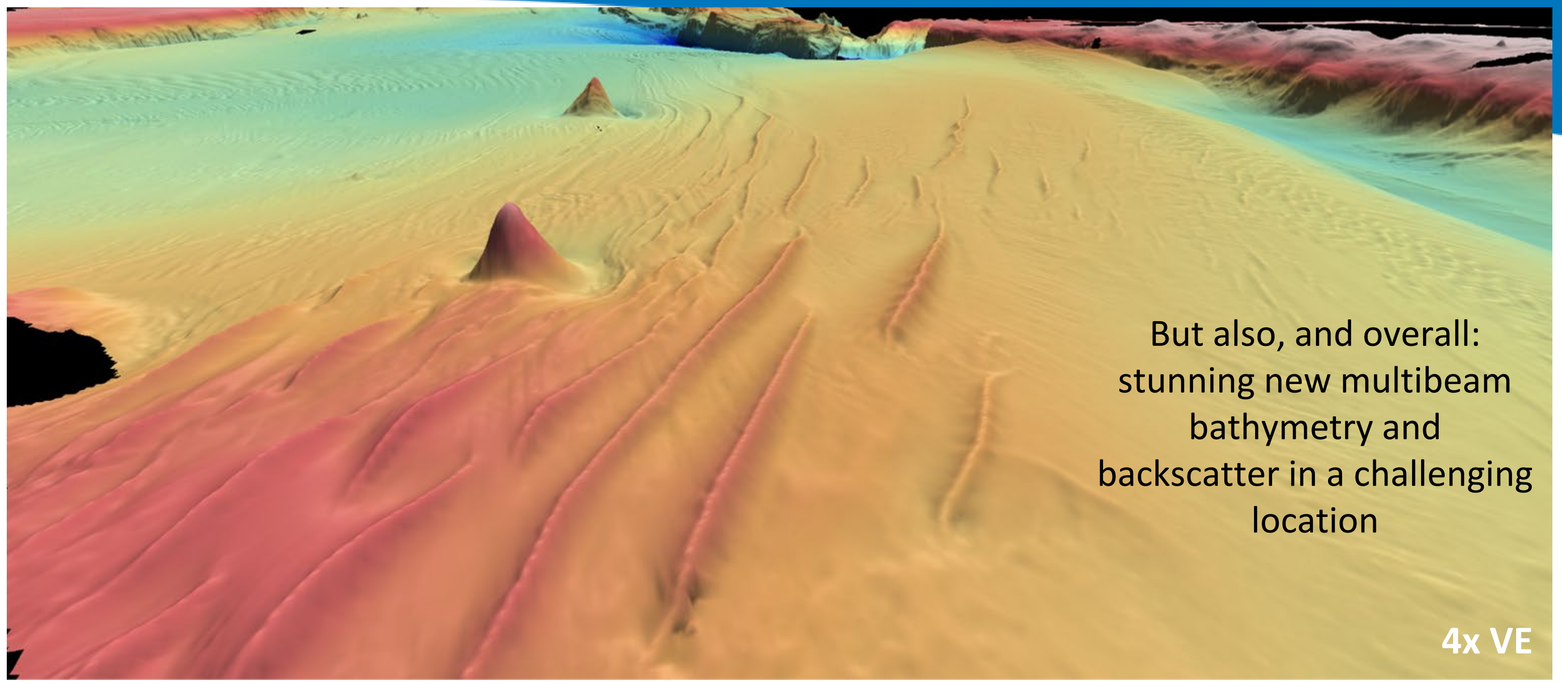
Processing Results

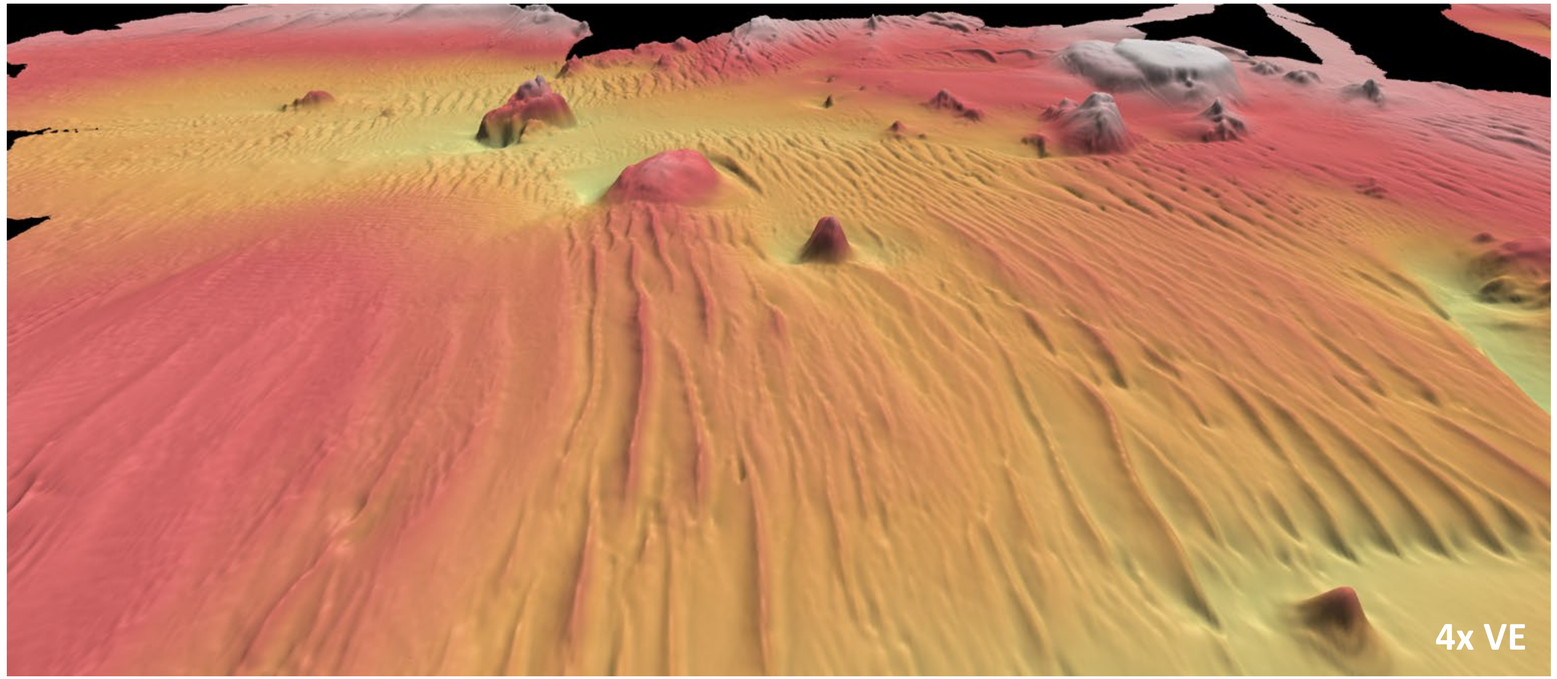


- Final coverage: 15,133 sq km
  - Reduction of coverage 6.5 - 7%
- Remnant artifacts in final surfaces

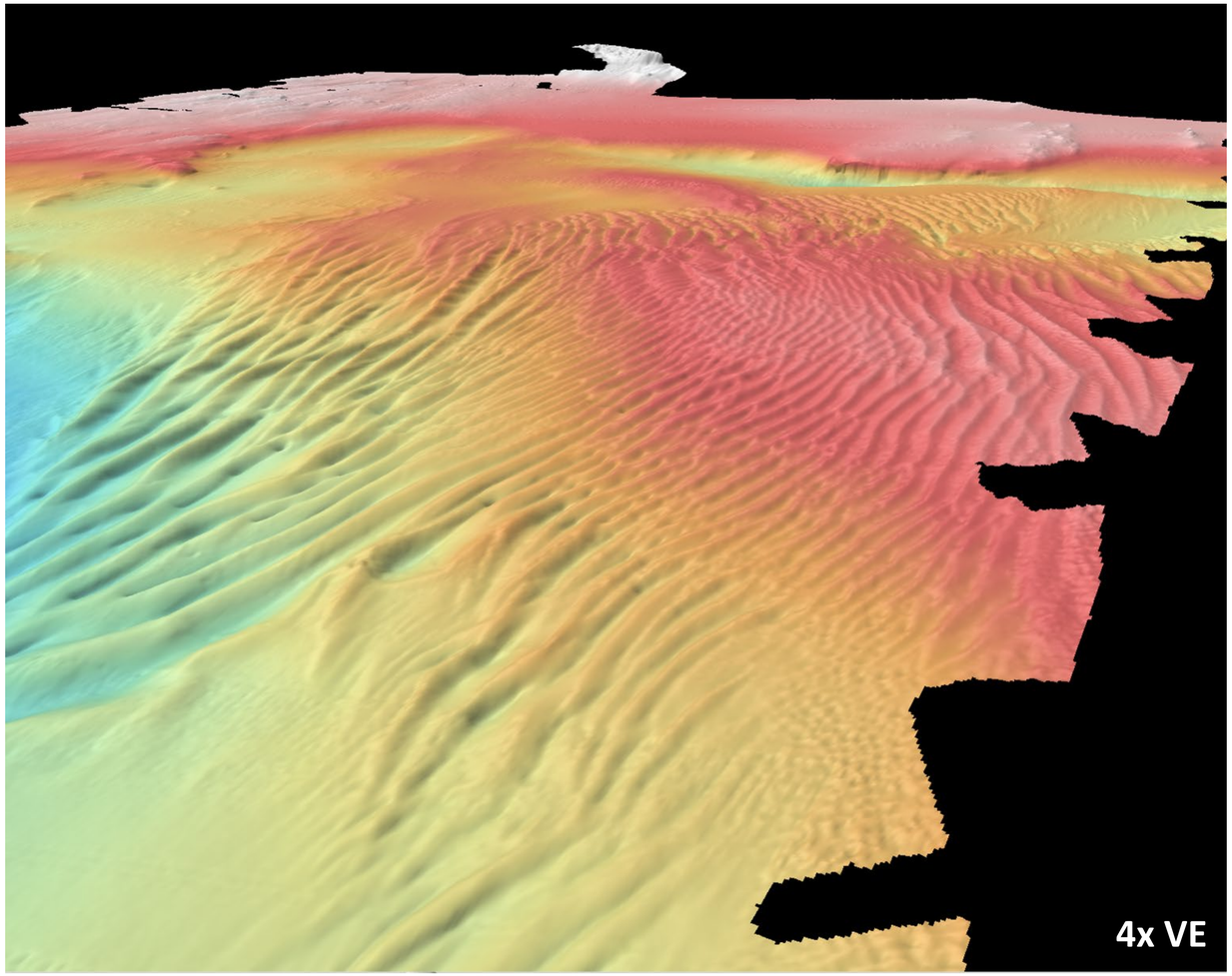
Processing Results

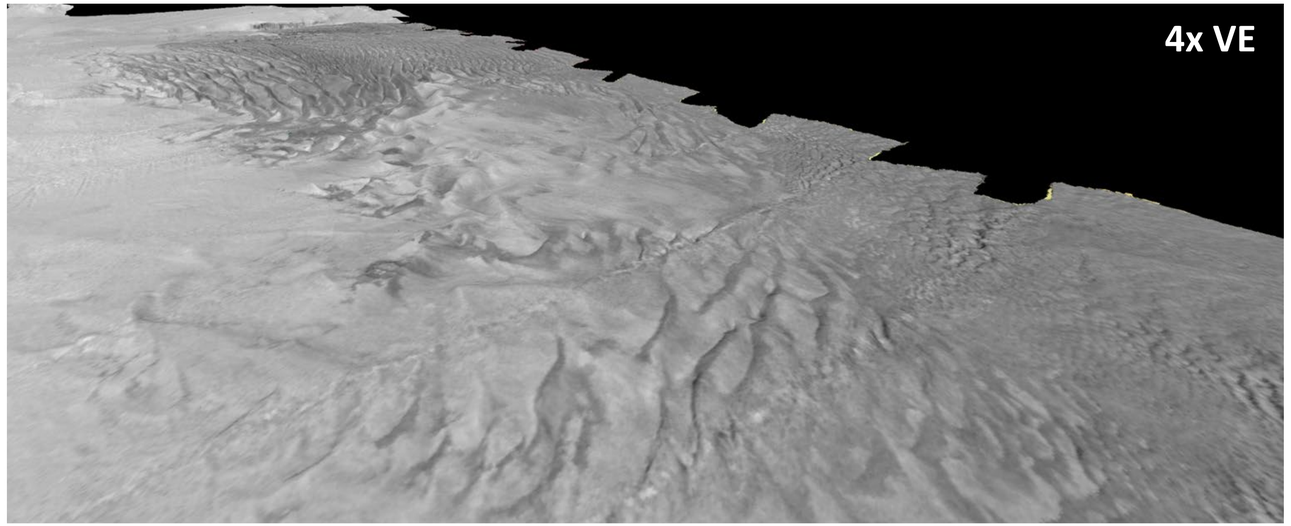


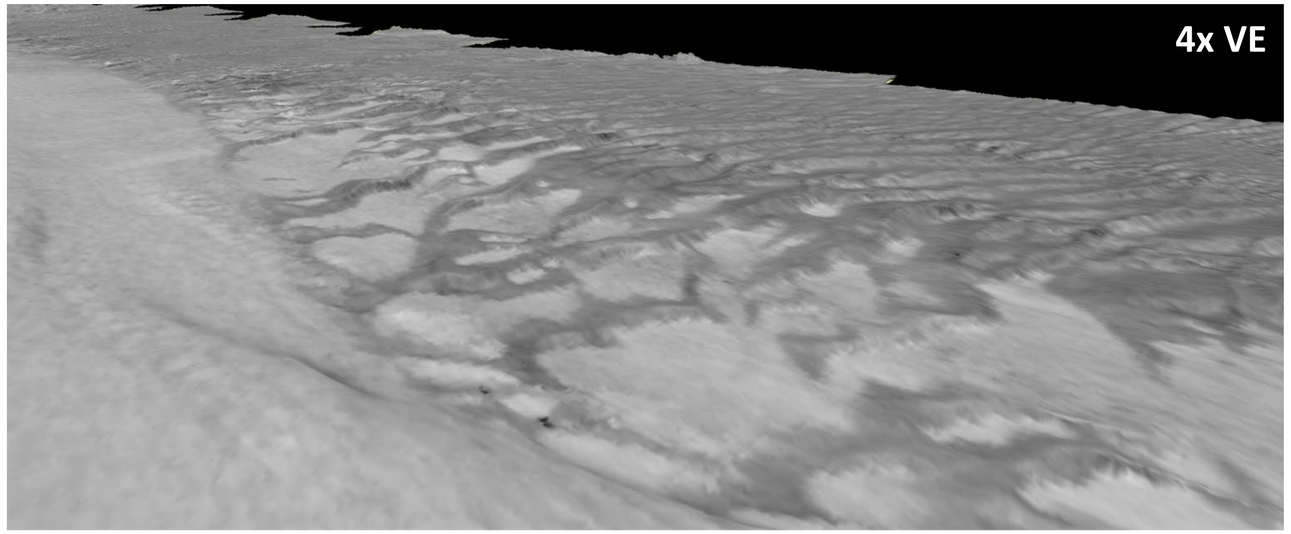




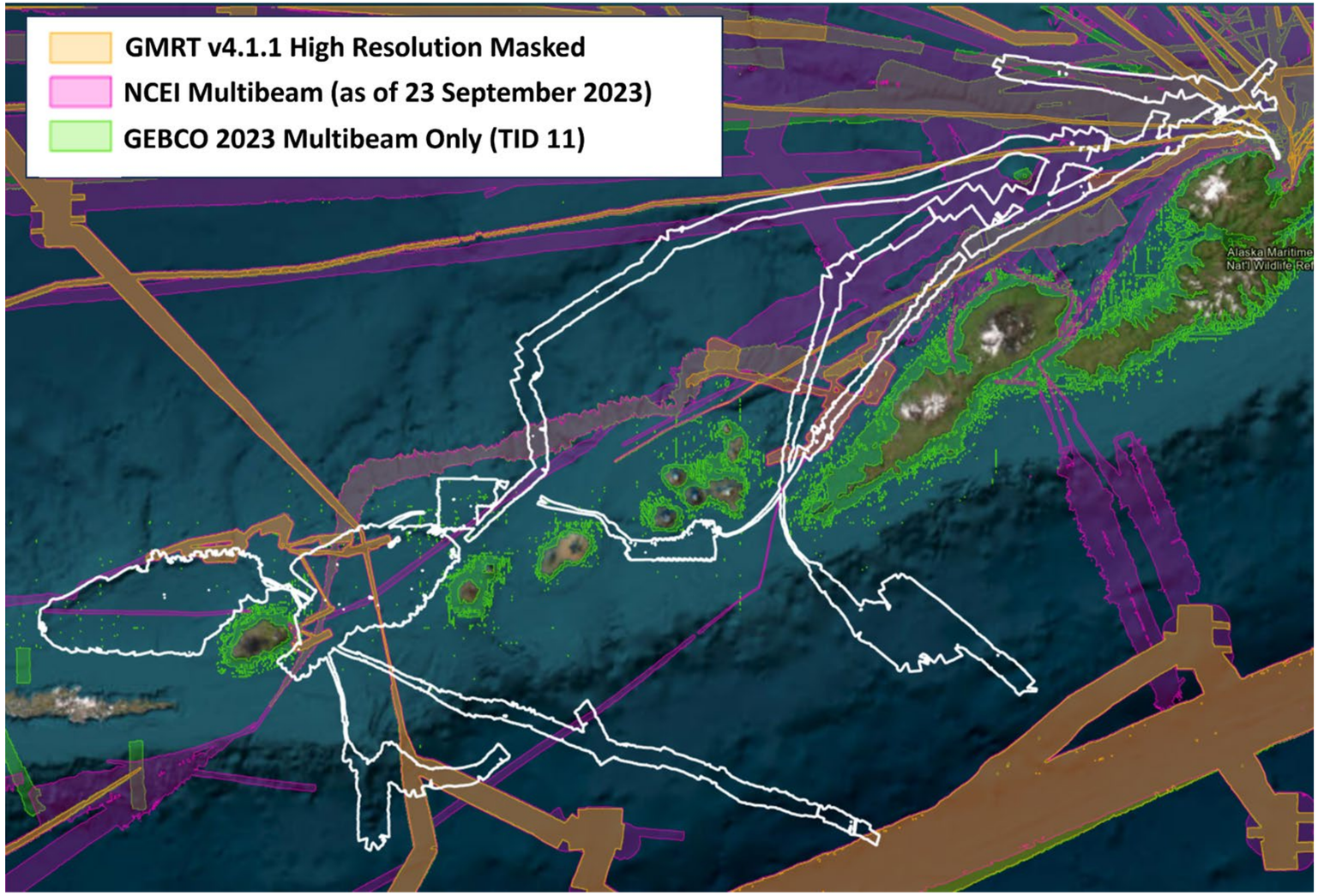
Processing Results







Processing Results



- Roughly **10,000 sq km** of ***NEW*** multibeam coverage
- INCREDIBLY challenging region

when compared to NCEI Multibeam Mosaic as of 23 September 2023 (~90 m resolution), GMRT v 4.1.1 Multibeam Only (~100 m resolution), and GEBCO 2023 Multibeam Only (~400 m resolution)

Recommendations

For Saildrone & their clients:

- More extensive trials as new Saildrone systems with different sensor configurations come online.
- Improved sound speed solutions – *improved winch great, but also **more investigation of best models** for a region prior to survey, investigation of ways to use **other methods** (gliders, buoys, etc.)*
- **More overlap**. *Default as close to 100% as you can stomach, adjust **only** if **weather - data quality - sound speed control allows**. Base planning on a Kongsberg model for anticipated swath or specific angles (i.e. don't depend on that extra swath to be useable). More data doesn't mean more good data.*
- Proactive limiting of swath angles and forcing depth modes during survey to improve results.
- Actively monitor density and vehicle position compared to planned line – adjust overlap accordingly.

Recommendations

For Kongsberg:

- Analysis of observed ‘heeling error’ issues, automated solutions to flag that data.
- Proactive limiting of swath angles and forcing depth modes – is *better Kongsberg automation possible here?*
- Recommendations or improvements to deal with the varying along-track data density with smaller vehicles that move a lot and operate at varying speed - *is better Kongsberg automation possible here?*

For Kongsberg + Processing Software Supplies, 3rd Party Formats:

- 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. **SERIOUSLY THIS IS SO ANNOYING!**

Allow for some Saildrone follow-up at end? Improved connectivity during the mission via…(I forget). Expected improvements with move to Starlink. Other things being considered/addressed….

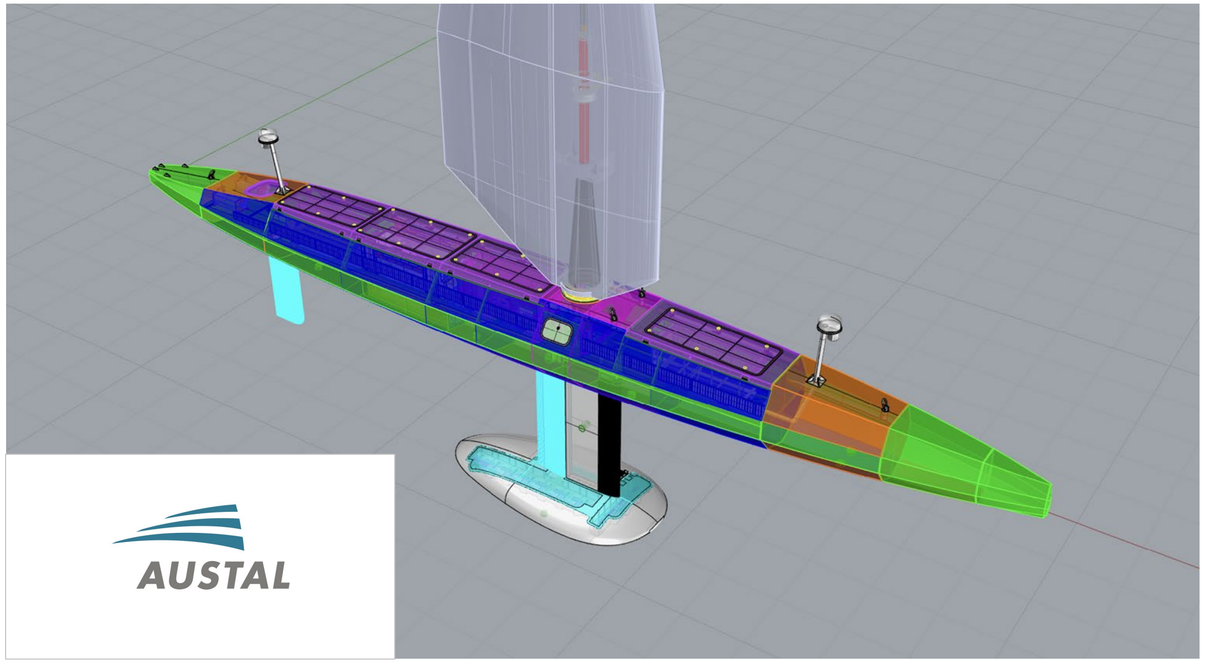
Lessons Learned - Solutions!

What's Next:

- **Sound Velocity**
  - Backup Oceanographic models accessible for remote areas
  - SVP Redundancy
- **Connectivity Issues:**
  - Starlink
    - Able to move data on and off vehicles while underway for shoreside data processing
    - Significantly increased bandwidth for data monitoring
  - Mission Portal
    - More data monitoring in Mission Portal
      - Integrating quality alarms
      - Integrated Event Log
      - Increased NRT and Daily Product capabilities
- **Unprecedented Raw Swath Width:**
  - Working with KM to improve flagging and eliminate outer beam fliers

Surveyor V2

- 65' length
- 25%+ faster - Streamlined hull
- Aluminum hull
- EM304 MkII and EM2040
- Dual Winch with AML SVP
- Teledyne Pinnacle ADCP



Contributions to the USV Community

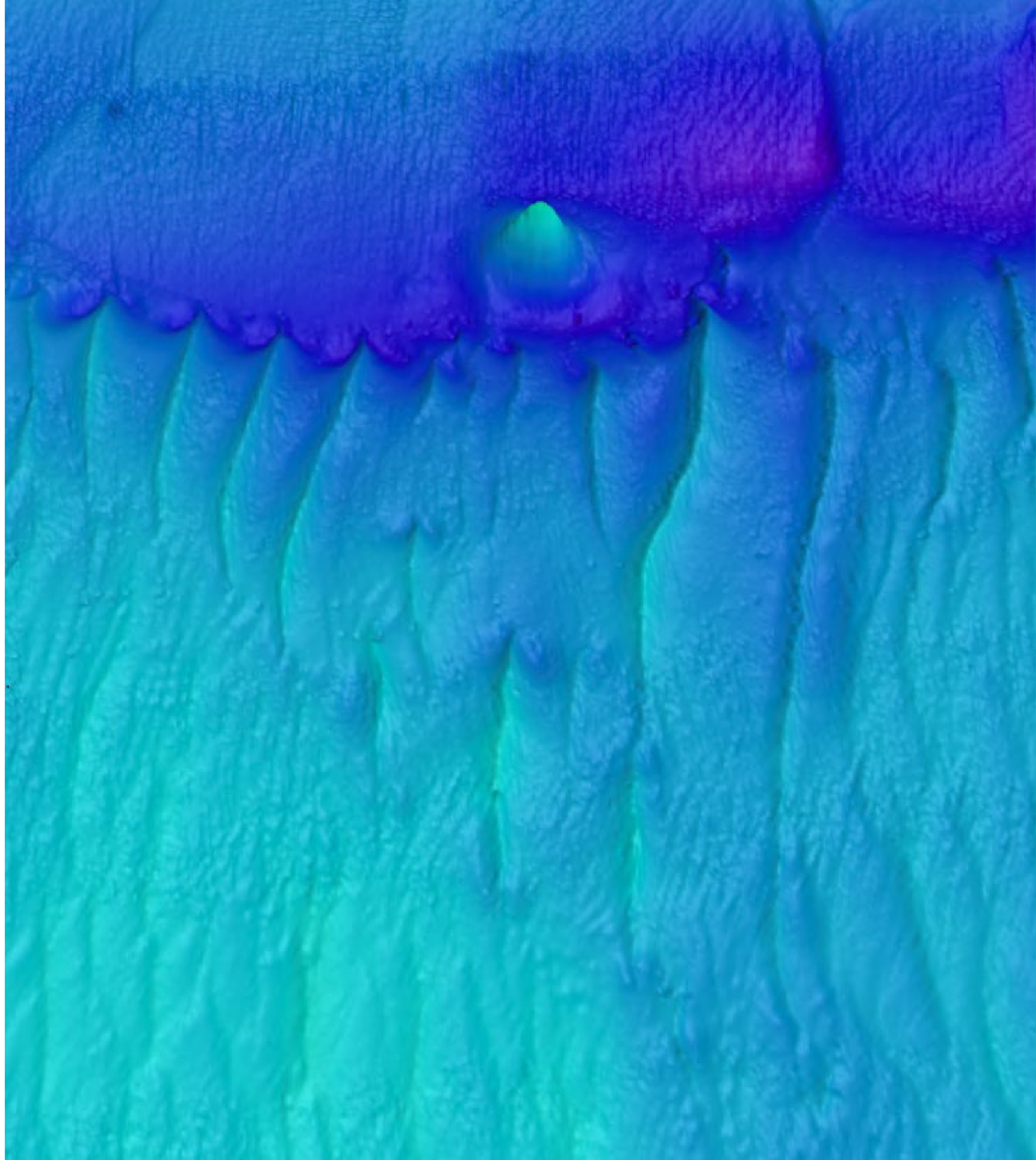
Kongsberg Discovery

Colleen Peters, Product Manager

FEMME
EDINBURGH | 2023

Kongsberg Discovery

Software



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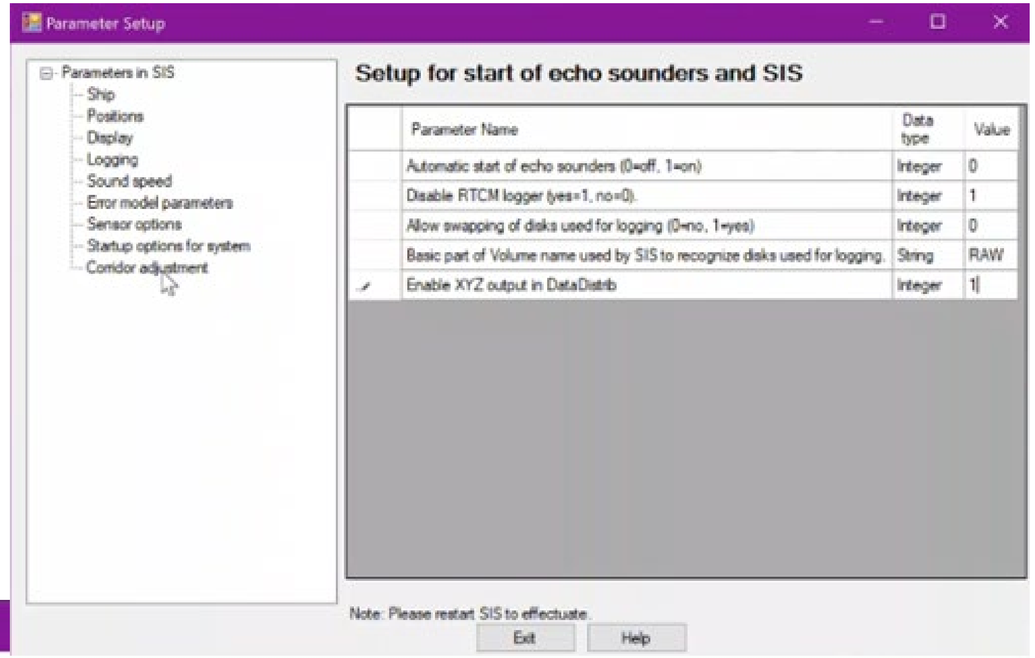
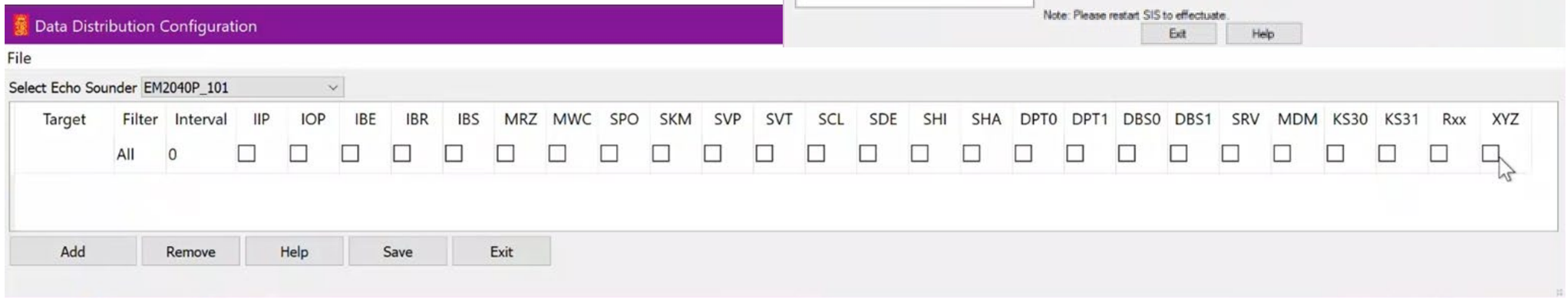
Seafloor Information System

XYZ Output

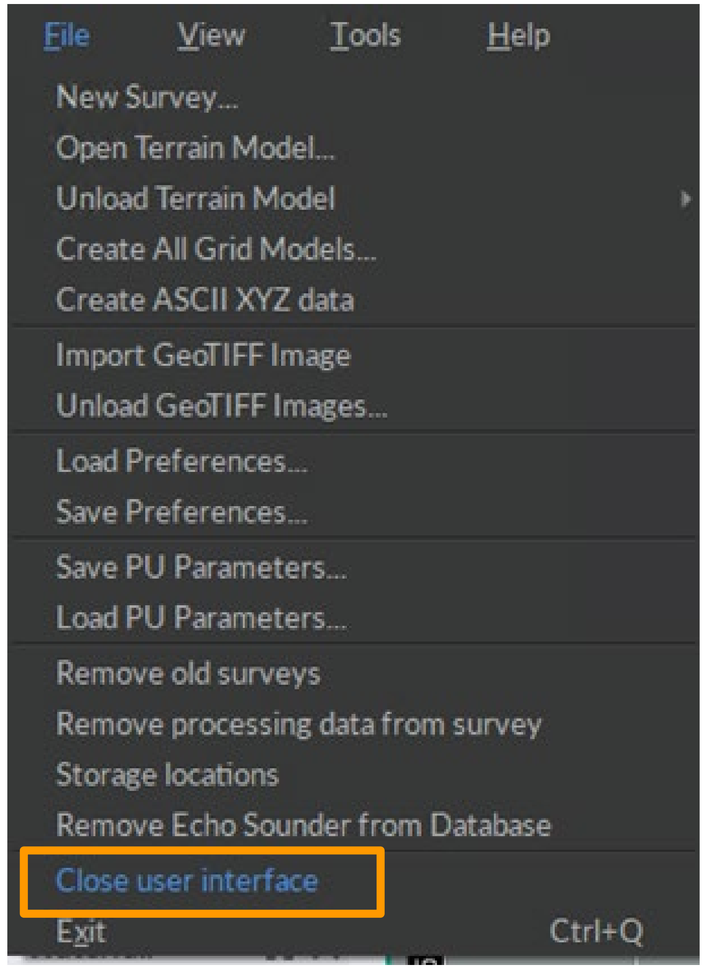
- Designate destination IP and port
- Designate data rate (interval)
- Log in another system
- Stream into another system (e.g., vehicle control software) to visualize point cloud
  - otherwise wait until kmall file is closed, then process





Reduced Resources

- Visual application closes
- Reduced CPU and GPU usage
- Processes (pinging, logging, etc.) run in the background
- Use “Restart SIS GUI” shortcut to open again



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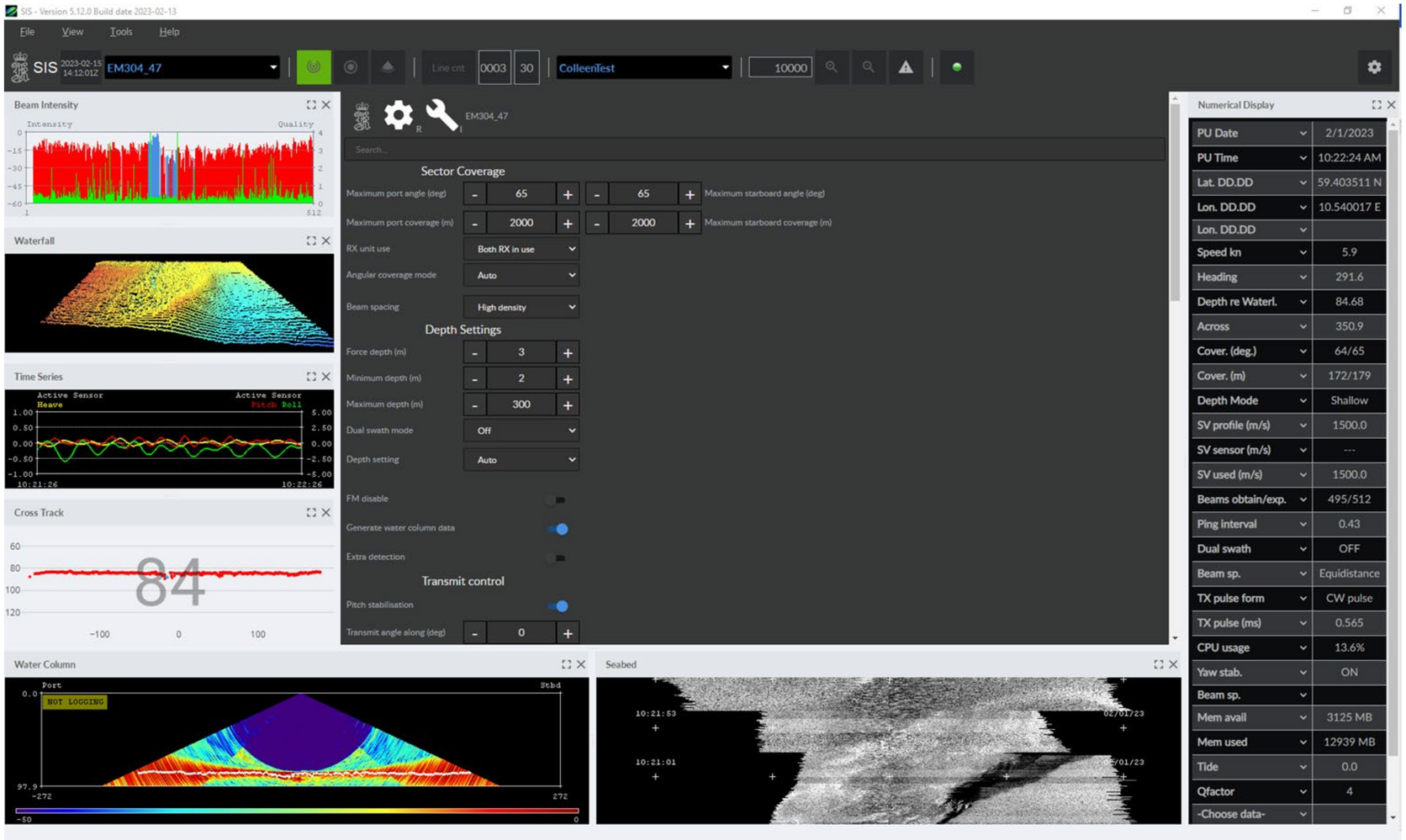
Seafloor Information System

SIS Basic

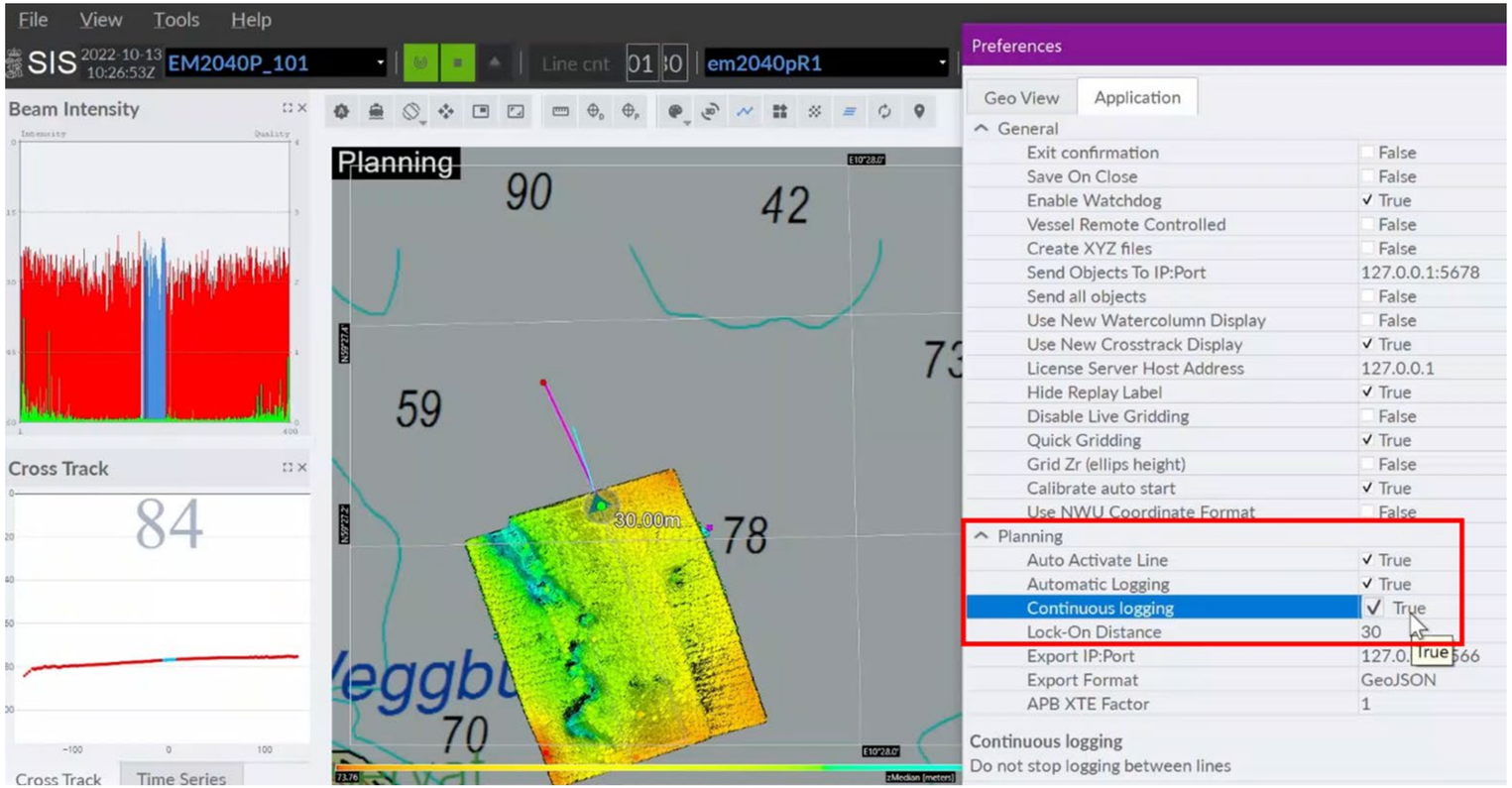
- Run all of the features of SIS minus the geographic display and gridding
  - lower GPU requirements
  - logging benefits of SIS/kmall format
  - same ping displays
  - integrate with 3rd party applications using less resources



Seafloor Information System

Line Logging Options

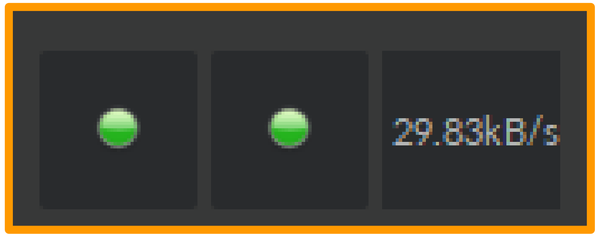
- Create a line plan
- Auto activate line
- Break the line files at the start and end of the line (continuous logging)
- Set the distance for the endpoints
- Don’t stop and start logging but eliminate turn lines in processing

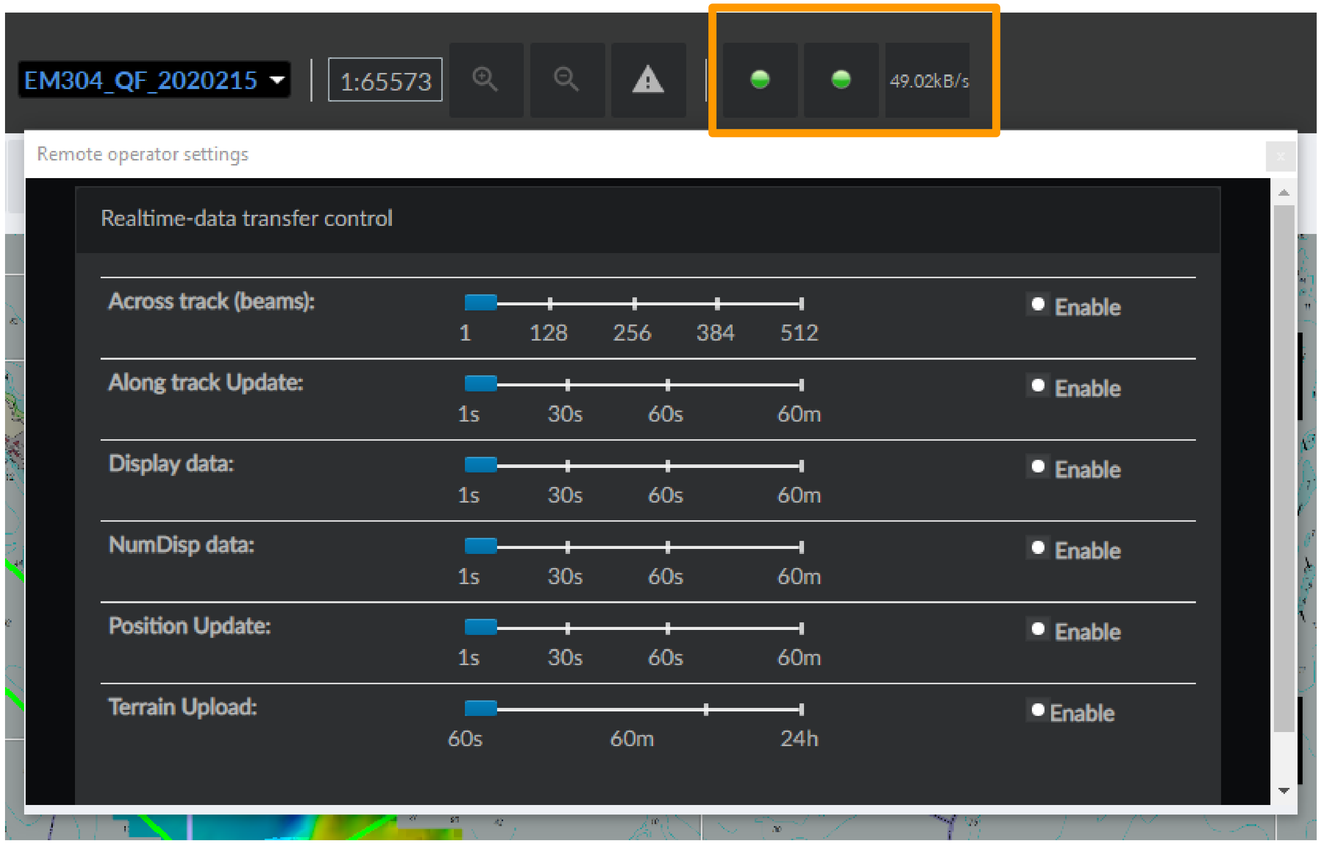


Seafloor Information System - Remote

Operator Bandwidth Control

- See the data rate in SIS Remote to ensure good data control
- Enable/disable feeds
- Change the intervals
  - less when on transit
  - more when on survey

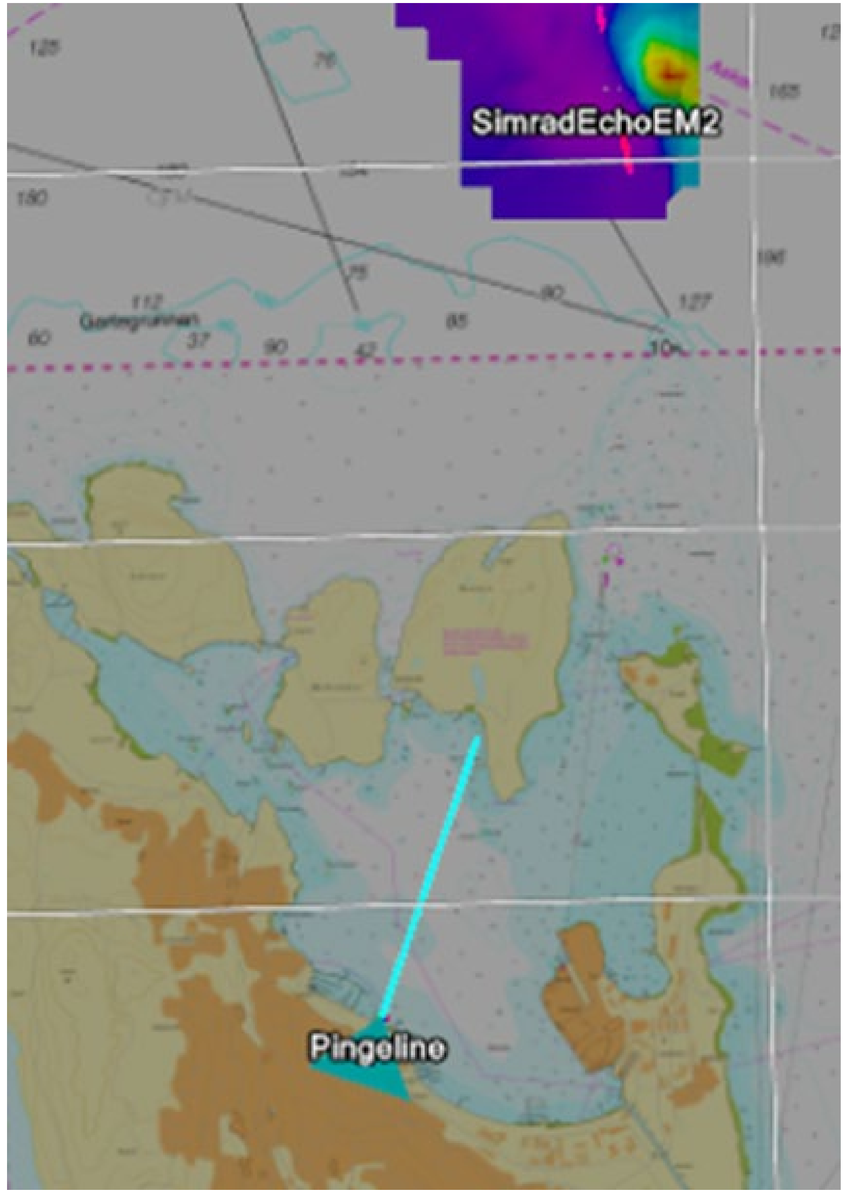




Seafloor Information System - Remote

Multi-Vehicle Monitoring

- Monitor multiple vehicles in one view
- Indicated with a label
- Switch between vehicles and or systems in one interface



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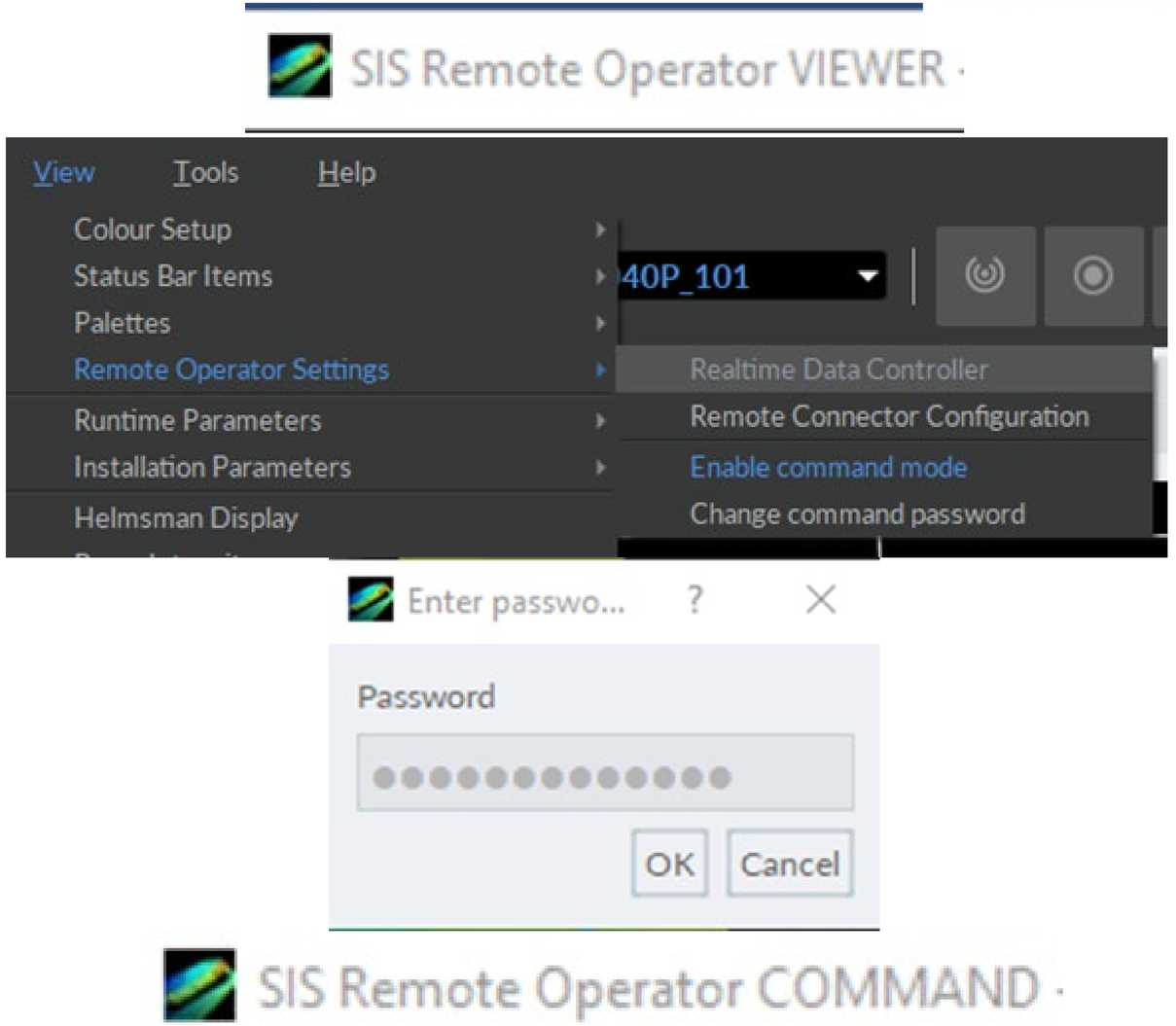
Seafloor Information System - Remote

Command and View Modes

- As of SIS 5.12.1 SIS Remote opens in VIEWER mode
- Enter a password to switch to command mode
- Change the password as often as you like
- Command mode enables full control over settings



Kongsberg Discovery

Hardware

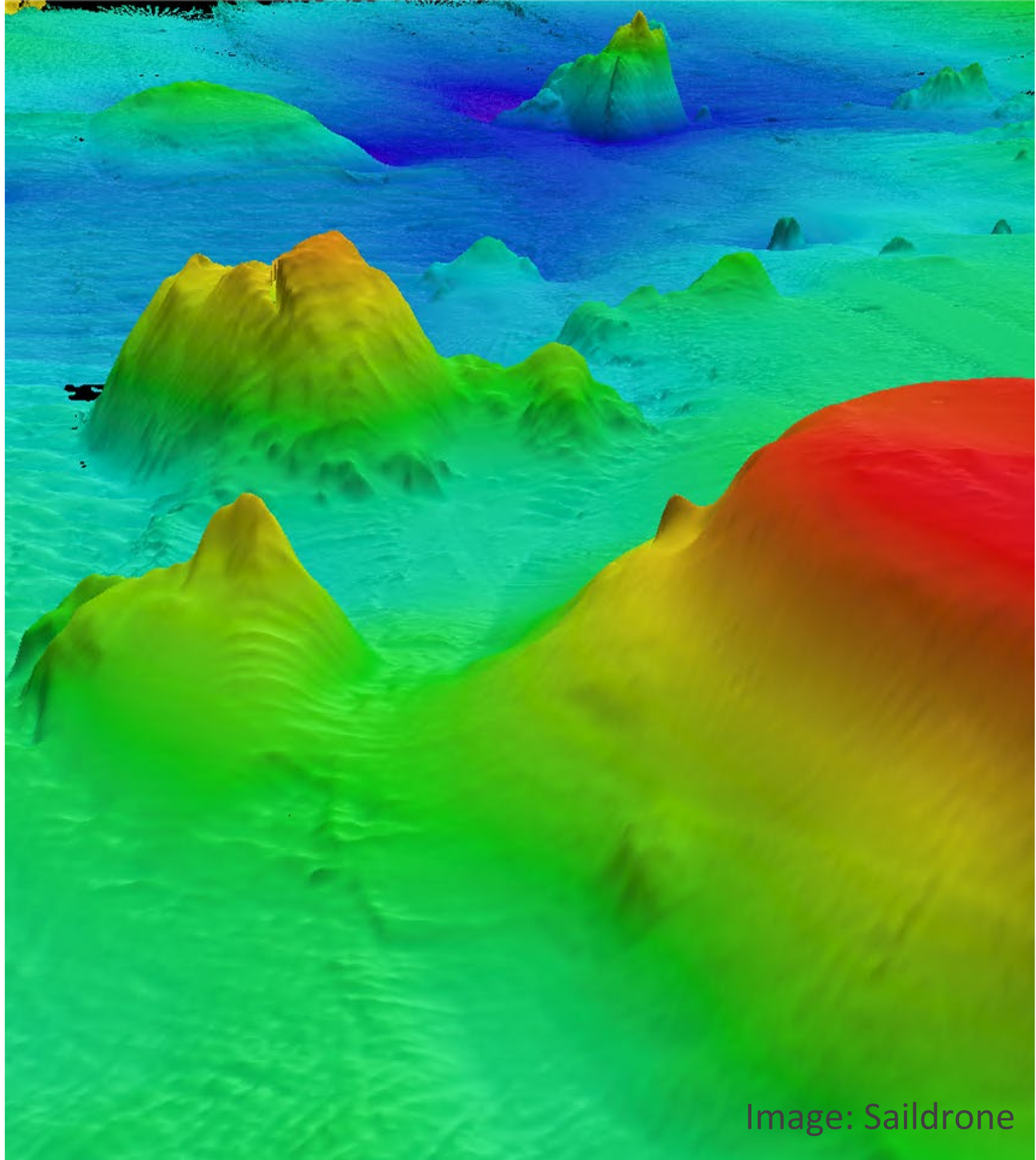


Image: Saildrone

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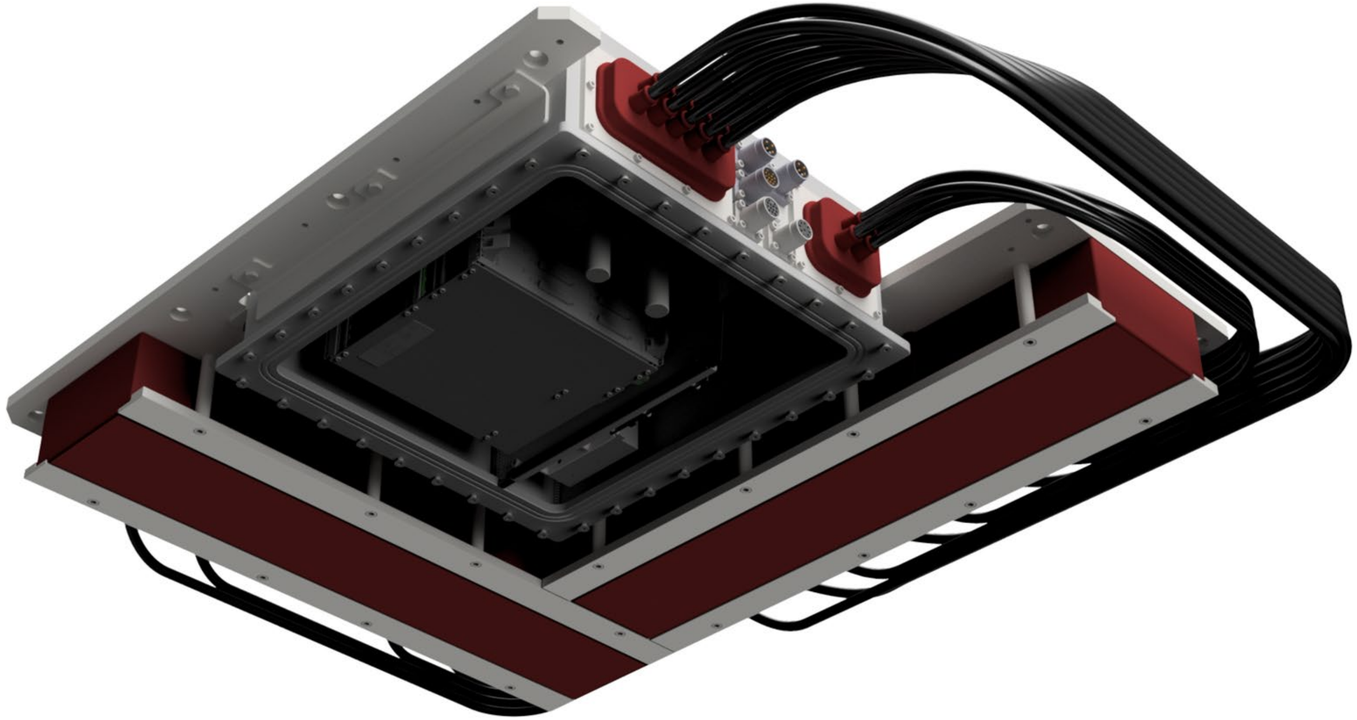
Exail & UNH CCOM - Drix

EM 712 USV

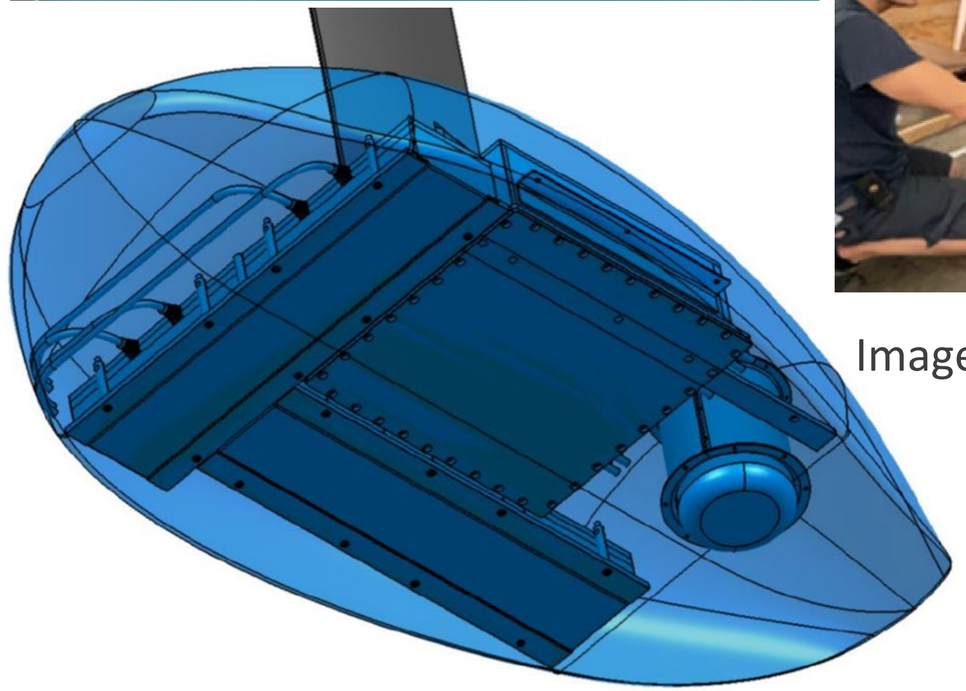
- Reduced size
- Subsea compartment for electronics
  - Tx unit
  - Rx unit
- Fewer cables (5 to topside)
  - custom lengths available
- Same performance as standard 1x1 system
- Access panel on underside of gondola



Exail & UNH CCOM - Drix

EM 712 USV

- Interchangeable gondola
- Serviceable onboard the vessel
- Temperature and leak sensors included in the underwater cabinet



Images: UNH/CCOM

KONGSBERG

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Kongsberg - Saildrone

EM 304 Mk I - Initial Feedback

- Number of units to install
  - weight
  - location
  - power
  - cabling
- AC Power source
  - units
  - cabling
  - conversion

Image: Saildrone

Kongsberg - Saildrone

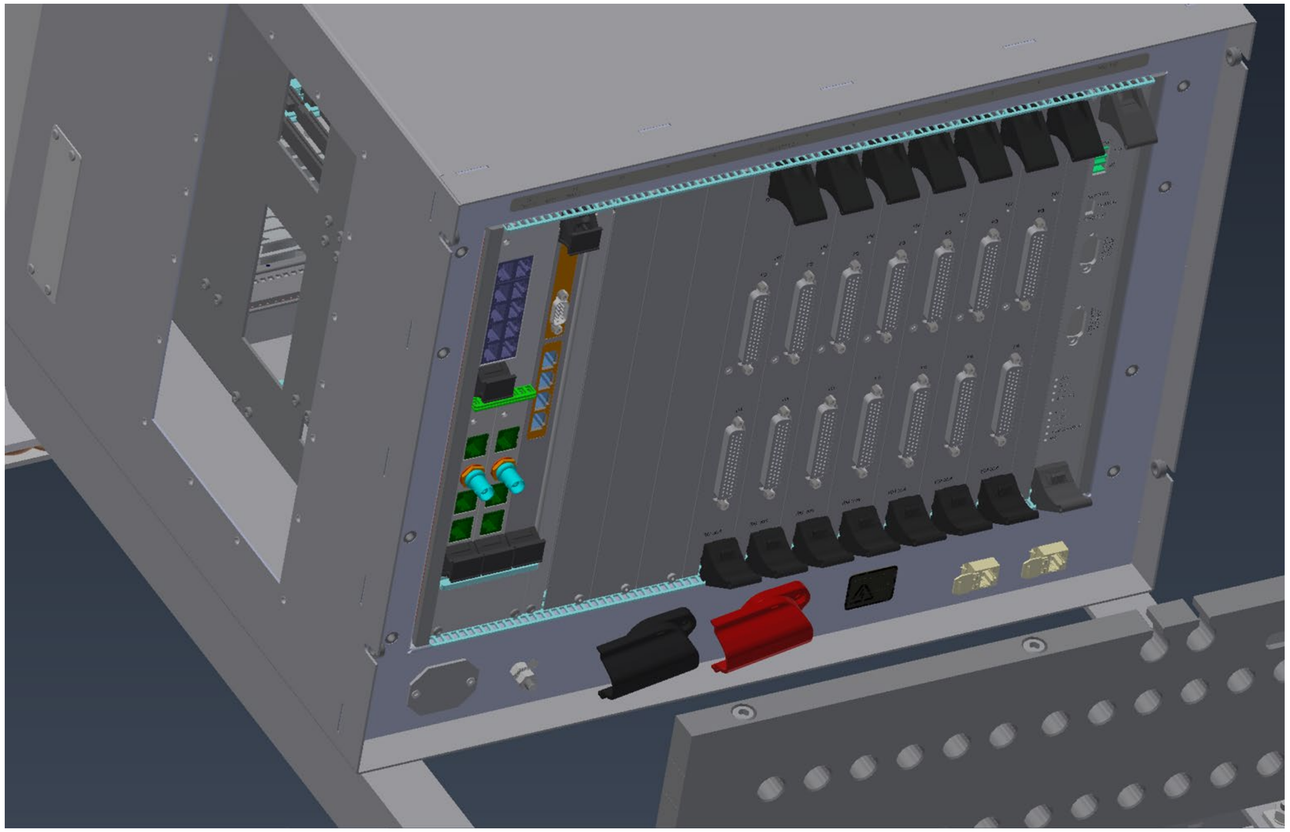
EM 304 48 VDC - System Overview

- Same Transducer arrays
- Combined TXU and PU
  - smaller form factor and
  - shorter cabling
- Direct DC power - range of 40-58 VDC
  - no inverter
  - less unit
  - less weight
- Same expected performance as the AC system

Kongsberg - Saildrone

EM 304 DC - Integrated PU

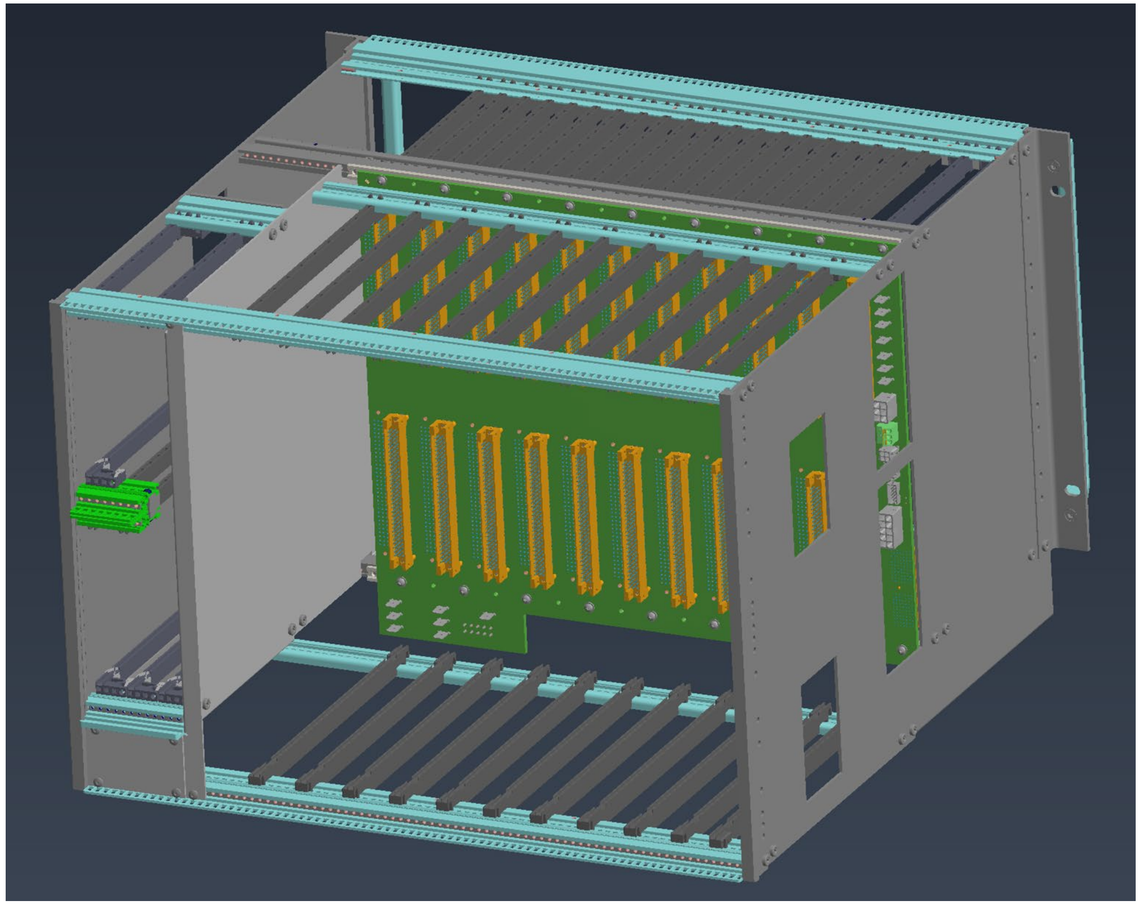
- PU mounted in the TXU
  - use existing PU boards in new housing
  - increased power efficiency
    - 12V power supply shared between the PU and TXU
    - new power supply for the PU



Kongsberg - Saildrone

EM 304 DC - Field Exchangeable

- TXU Conversion is field exchangeable with existing cabinet
  - new internal rack
  - reuse existing cards
  - install DC terminals
  - change power supply for low voltage heat sink
  - replace high voltage heat sink and power supply
  - TXU supports 10 modules (up to 0.8 degree)
- Replace RXU power supply

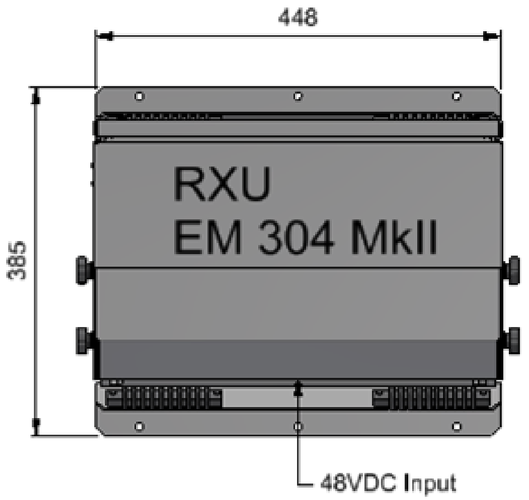


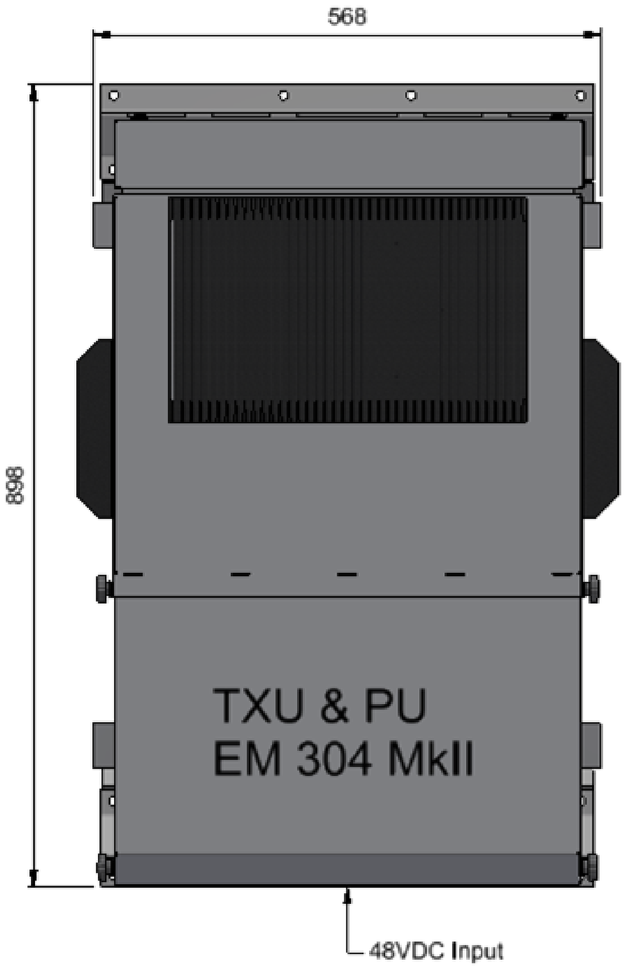
Kongsberg - Saildrone

EM 304 DC - Summary

- The system will be available in Spring 2024 (official launch will be announced)
- Can be purchased new
- Can convert an existing system

SPRING 2024!!





Questions?

Thank you!

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