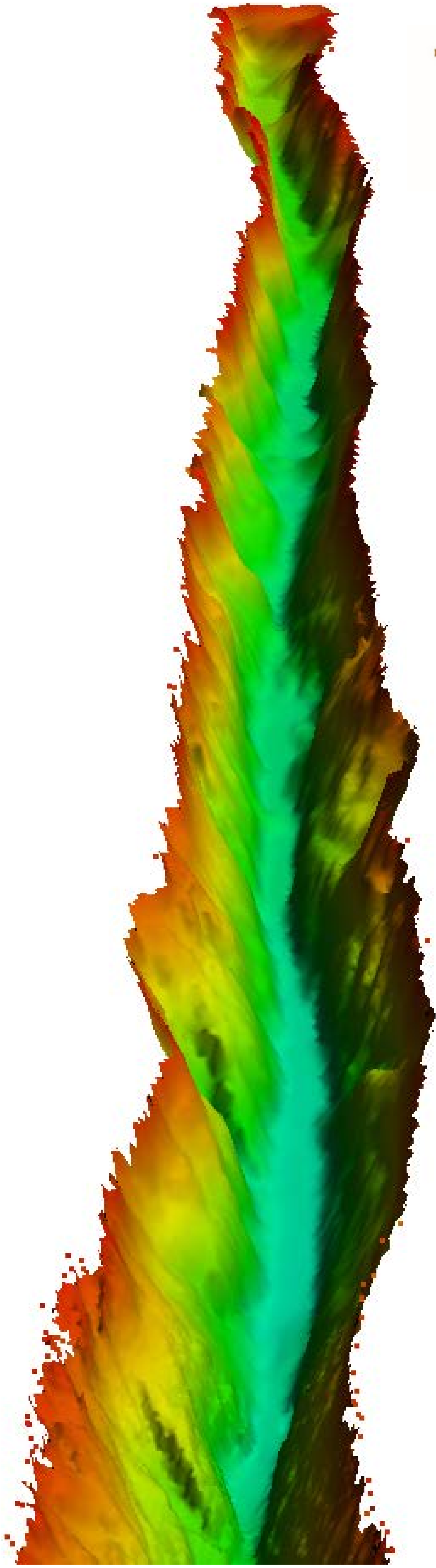

Oceans Melting Greenland

Bathymetric Survey

South East Greenland

2016 Operations Report

Submitted by:

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1.0 PROJECT OVERVIEW

TerraSond Limited (TerraSond) was contracted by NASA's Jet Propulsion Laboratory (JPL) to conduct a hydrographic Multibeam Echo Sounder (MBES) survey to support the Oceans Melting Greenland Project.

The scope of work was to collect multibeam bathymetry as well as Conductivity Temperature and Depth (CTD) data readings along JPL provided trackline locations. Data was acquired in Southeast Greenland in the fjords and offshore, from approximately Lindenow Fjord in the south to Kong Christian Fjord in the north.

Survey operations commenced on September 9th and were completed on October 7th. In total, 3,717 linear nautical miles of data were acquired, averaging approximately 145 miles per day, over a total of 27 days. Due to weather conditions on the transit to Greenland it was necessary to stage the vessel at Patreksfjorour and await a weather window for the transit. The vessel waited for weather conditions to improve for approximately 24 hours.

Table 1 Project Timeline

Phase	Start Date	End Date
Mobilization	3 Sept 2016	8 Sept 2016
Transit to Patreksfjorour	9 Sept 2016	10 Sept 2016
Transit to Greenland	11 Sept 2016	12 Sept 2016
Survey Operations	12 Sept 2016	5 Oct 2016
Transit to Iceland	5 Oct 2016	7 Oct 2016

2.0 PLANNING

2.1 HSE

This project has all the unique hazards found in high-latitude remote operations, including poorly charted waters and high concentrations of floating sea ice. Using experience gained from previous work in high latitudes such as Greenland and Alaska, a comprehensive safety plan was developed to ensure the safety of personnel and equipment. Included in the HSE package developed are the following documents, a copy of which can be found in Appendix J.

1. HSE Report
2. Field HSE Brief
3. Contact List
4. Emergency Notification Flowchart
5. Medical Emergency Response
6. Matrix of Permitted Operations
7. HAZID Matrix
8. Vessel Position Reporting and Response Procedure

Additionally while on site TerraSond Management and Field Staff coordinated with the Captain and Officers of the M/V Neptune to develop an integrated plan for general safety at sea, operations in ice zones and procedures for operating in sparsely charted areas. Included in the procedures developed on site were the Job Safety Analysis (JSA) documentation for specific tasks. The following JSAs were developed, a copy of which can be found in Appendix J.

1. Survey Operations in Vicinity of Glacier
2. Survey Drone Operations
3. Deploy and Recover AML Cast (Static Cast)
4. Deploy and Recover Underway CTD
5. MMO Operational Areas

A pre-sail orientation was conducted by the Vessel's Chief Mate upon the arrival of TerraSond personnel in Akureyri, Iceland. During the orientation all personnel were shown the emergency equipment locations and emergency muster areas.

The Party Chief held a daily safety meeting to discuss the daily HSE reminders/updates, survey plan, and review the previous days' operations. Personal Protective Equipment (PPE), such as safety boots, life vest and gloves, was used as required for safe operations on the deck of the vessel.

Zero injuries and no near-misses occurred during the operations.

2.2 Mobilization

Mobilization commenced in Akureyri Iceland, on the September 3rd to September 8th. The vessel leased was equipped with a hull mounted 8160 sonar and a POS M/V V4 (Figure 1). The 8160 was upgraded to a 7160 by installing and interfacing an upgraded Transceiver and Topside processor owned by TerraSond. The advantage of the upgrade is the number of beams 512, verses 126 with the 8160, and the increased swath angle. The NAVCOM SF-3050 was installed and integrated during this time, along with the integration of the POS M/V.

Figure 1 – Hull-Mounted Blister

Other fabrication tasks in support of the survey were completed while in Akureyri, such as mounts for the static and the Rapid Cast CTD. Concurrent to fabrication, survey sensors, cables and computers were installed and integrated on board. Survey and communication systems were tested upon the completion of mobilization while on transit to Patreksfjorour.

The vessel Neptune is a converted Icelandic fishing vessel built in 1976, which was overhauled in 2008 for survey operations (Figure 2). The vessel is powered by an ALPHS 6L 28-32 main propulsion engine producing 1800HP. To assist in vessel maneuverability a bow thruster rated at 330 kW and stern thruster rated at 257 kW were fitted.

Figure 2 – M/V Neptune

2.3 Communications

The primary goal of the communications plan was to ensure the ship has the absolute ability to contact either local authorities or a TerraSond office in the event of an emergency to enact a rapid response. Secondly, the plan made sure the vessel complies with local requirements for position and status updates. Lastly, the plan allotted for the ship to provide scheduled updates on the survey progress.

The primary communications used for internet was a V-Sat SeaTel 4006, the primary telephone used was an Iridium 9555 Satellite Phone with an external antenna. Secondary telephone communications were conducted using the V-Sat SeaTel 4006 system.

The communications systems, in general performed satisfactorily though internet capabilities were out for approximately 5 days as the vessel changed satellite coverage zones. When the subscription for the new zone was obtained the V-Sat performed as expected while on site. Additional communication blackouts did occur while the satellites were obstructed in the fjords, though they were typically short in duration.

2.3.1 Greenpos System

The ship made scheduled email contact in the form of position reports in accordance with the International Maritime Organization (IMO) circulation 221, May 29th, 2002. The means of reporting was via email. The reports were made at regularly scheduled 6 hour intervals. This email went out to the MRCC and to the Artic Command.

2.3.2 Real-time Tracking

Two Delorme inReach Explorers were onboard the Neptune for the entire duration of the survey; one as the primary tracker and the other as a spare or in case of emergency. Tracking was done through the Delorme website and could be viewed with a general map background or a Google Earth background (Figure 3). Interested parties could log into the Delorme account setup and check on the vessel progress at any given time and see updated tracklines. This was of great benefit as it allowed for greater flexibility in coordinating real time modifications to the survey plan between JPL and the Neptune. This system also doubled as a safety system that broadcasted the vessel position every two minutes in case of an emergency.

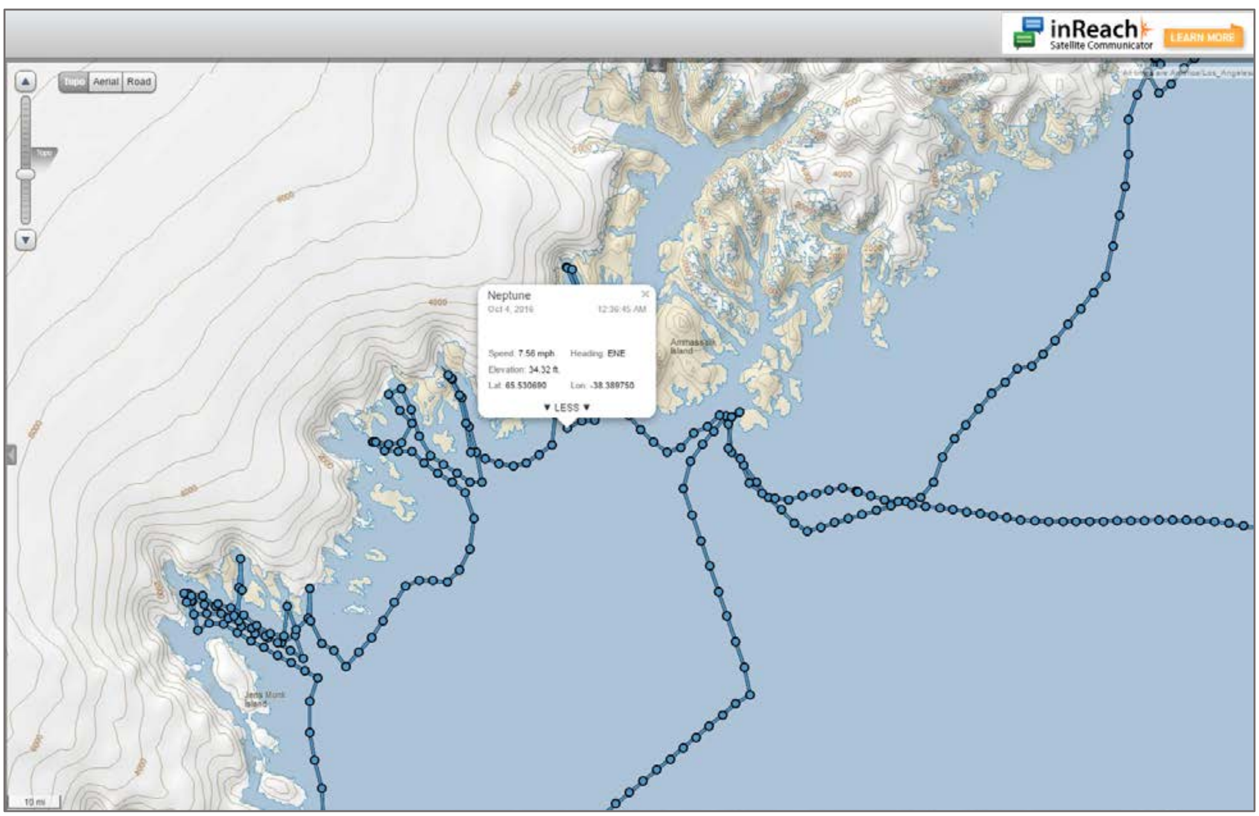


Figure 3 – Real-time position updates with the Delorme InReach Explorer.

2.4 Permits

An Application for Diplomatic Clearance of Government Ship was made to the Danish Ministry of Foreign Affairs for the conduct of this survey. In order to obtain the required permit TerraSond submitted a Notification of Proposed Research Cruise outlining the survey project objectives and methods.

A Permit authorizing survey operations was granted by the Danish Ministry of Foreign Affair, Joint Artic Command, on August the 5th 2016.

In accordance with the Permitting request a Marine Mammal observer was onboard, a copy of the repost was sent to the Danish authorities.

A copy of the Permit and the Notification of Proposed Research Cruise can be found in Appendix B.

3.0 PROJECT GEODETICS

3.1 Horizontal Datum

Horizontal datum for this survey was World Geodetic System of 1984 (WGS-84). The working projection used was Universal Transverse Mercator (UTM) Zone 24N Coordinate system. The final bathymetric points generated from the survey have been submitted in geodetic (latitude/longitude) horizontal coordinates.

Table 2 Geodetic Parameters

PROJECT GEODESY	
Horizontal Datum	World Geodetic System 1984
Ellipsoid	World Geodetic System 1984
Semi Major Axis (m)	6378137
Semi Minor Axis (m)	6356752.31420
Flattening (1/f)	298.25722
Eccentricity	0.081819190928906
Coordinate System	Universal Transverse Mercator
Zone	24 North
Central Latitude	0°00'00" N
Central Longitude	57°00'00" W
False Northing (m)	0
False Easting (m)	500,000
Scale Factor	0.9996

Note: The survey encompassed three separate UTM projection Zones 23N, 24N and Zone 25N. UTM Zone 24 was used exclusively throughout the project.

3.2 Vertical Datum

Vertical Datum for this survey was instantaneous water level during acquisition.

Tide data were not applied to the soundings due to the large spatial extent of the survey and the prohibitively large effort required to collect tide data with enough resolution to provide a meaningful increase in the data accuracy. The expected error in any sounding as a result of not applying tide is on the order of +/- 2 meters, well within the 6 -20 meter total allowable vertical error for this survey.

4.0 DATA ACQUISITION OVERVIEW

4.1 Preliminary Line Plans

Multibeam acquisition lines and CTD cast locations were conducted in accordance with the line files and targets supplied by JPL. The line files were updated and emailed to the acquisition crew at varying intervals, depending upon the objectives and new information obtained throughout the survey. Acquisition tracklines were subject to change based on information from other vessels, ice conditions observed by JPL or TerraSond personnel, weather and the current progress of the survey.

4.2 Field Adjustments

Over the duration of the survey, it was at times not possible, practical, or safe to exactly follow the client-supplied line files or CTD sites. In communication with JPL, acquisition personnel were told that if a trough in the seabed was observed, that mapping of the trough was a higher priority than following the client-provided line. Additionally, it was attempted during acquisition to map deeper water if possible; an example of this would be staying to the deeper side of a ledge if an underwater cliff was observed.

Due to the project taking place later in the year than previous surveys, the amount of daylight had an effect on the running of survey lines. Due to the additional hazards, including but not limited to, high ice density and calving of glaciers, data collection in proximity to glacial faces were only run during daylight hours. This safety measure did, at times, require running lines out of sequence, or transiting past fjords while working south, which would be surveyed while returning on the northerly return. In communication of the daylight limitations JPL supplied additional lines including troughs and smaller fjords that could be surveyed if necessary while awaiting daylight.

Heavy ice conditions were the main reason that deviations from the planned lines were made; however, charted and uncharted obstructions, such as rocks and shoals, were also reasons for deviations from the planned lines. In several instances, the route supplied was impassable and a best effort was made to collect the best data possible in the area given the conditions. Glaciers Deception CS, Kruuse and Laube were deemed inaccessible due to ice coverage and sea state, these were not surveyed. Figure 44 shows the planned track lines compared to the actual surveyed tracklines.

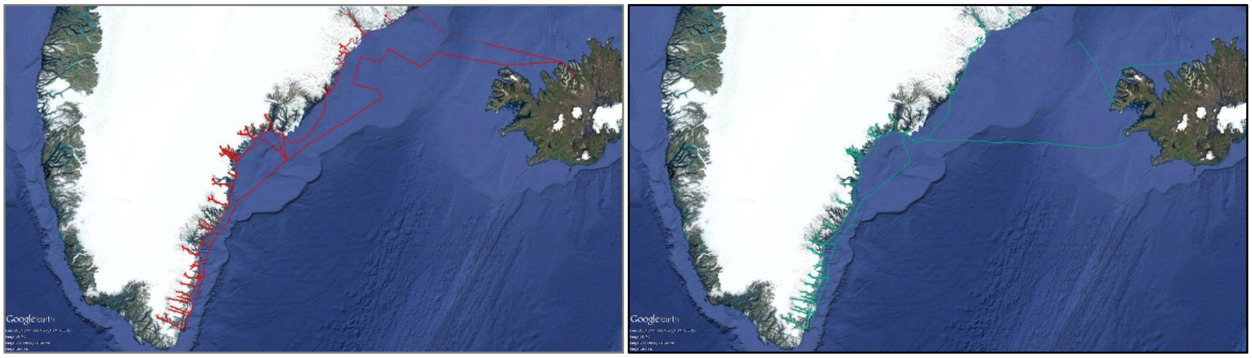


Figure 4 – Track lines Planned (red) and Run (green)

Wind and seas were also a factor that resulted in deviations to the acquisition plan. A majority of the project had exceptionally calm weather. The wind and sea state on the transit to Greenland were not conducive for CTD casts, the first cast was conducted 12th of September 2016. On the 5th of October on the transit to Iceland heavy weather was experienced. Due to the high wind speeds and sea state it was not possible to run any of the transit line back to Iceland.

If an area was not accessible, such as near the face of glaciers or near sills, a CTD cast was done in the nearest safe spot to the requested location. In areas where CTD casts were located in shoal water near a ledge, the cast was relocated to the deeper area.

4.3 Daily Field Reports

Progress Reports were generated daily and distributed to key personnel involved in the project. Included in the report were operational metrics such as total linear nautical miles, rate of progression, and the number of CTD casts taken for a given day. Preliminary multibeam imagery and CTD cast locations were included in the report as a visual display of the progress. A copy of the daily Field Reports can be found in Appendix A.

4.4 Glacier Observations

To maintain a record of the conditions, date, time and general observations a Glacial Observations Report was generated for each glacier. Included in the report are the latitude and longitude of where the vessel either paralleled the glacier within the safety perimeter, or the closest the vessel was able to get before turning around. Additionally images of the glacier, bathymetry, recent satellite imagery of the weather and a photo of the radar are included for reference. The Glacier Observation Reports can be found in Appendix K.

4.5 Ice Conditions

Ice conditions varied greatly throughout the survey. The density ranged from completely open water to 100% coverage. In 100% ice coverage the vessel could continue to collect data in modest brash and pan ice at a reduced vessel speed. Surface ice was becoming prevalent during the nights toward the end of the survey, this adversely affected data acquisition as it thickened the pan ice and froze the brash and pan ice together.

The vessel captain was at all times responsible for making decisions regarding the navigability through the ice. Primary reasons for aborting lines included thickening pan ice, large icebergs blocking any further route progress and changing conditions that may prevent the vessel from turning around to make it back to open water.

The images below display some of the differing ice conditions. In the top left image, is an example of ice bergs encountered while offshore that were typically larger and very spread out, allowing for higher survey speeds. Shown in the top right image is the typical low ice coverage areas seen while in the fjord systems. Survey speeds were reduced and the vessel was required to maneuver around for the larger berg bits. The bottom left image is typical, heavy ice conditions; data acquisition in these conditions was slow with heavy maneuvering to avoid larger ice bergs. The last image on the bottom right shows impassable ice coverage which forced the vessel to turn around.

Figure 5 - Open Water

Figure 6 - Light Ice Coverage

Figure 7 - 100% Ice Coverage Workable

Figure 8 - 100% Ice Coverage Non-Workable

4.6 Equipment Malfunctions

The POS M/V experienced a failure on the 9th of September 2016, during the transit from Iceland to Greenland. This failure resulted in the ceasing of data collection for 3 hours and 14 minutes during the transit, leaving a gap in the data. The failure was resolved by TerraSond field staff reseating the cards in the topside processor, no further technical issues were experienced with POS M/V.

In the early morning on the 20th of September 2016, a failure on the Rapid Cast levelwind was experienced resulting in the system being inoperable for approximately 18 hours until repairs were affected. Static CTD casts were completed during this time, though several CTD cast locations offshore were skipped over due to the weather and the time to do a static cast.

4.7 Satellite Imagery

Imagery data from the MODIS, Radarsat2 and Sentinel 1 satellite sensors were downloaded daily (if available) for the area of operation. The imagery was used to help guide the daily operations and ascertain which fjords may or may not be accessible due to the ice conditions.

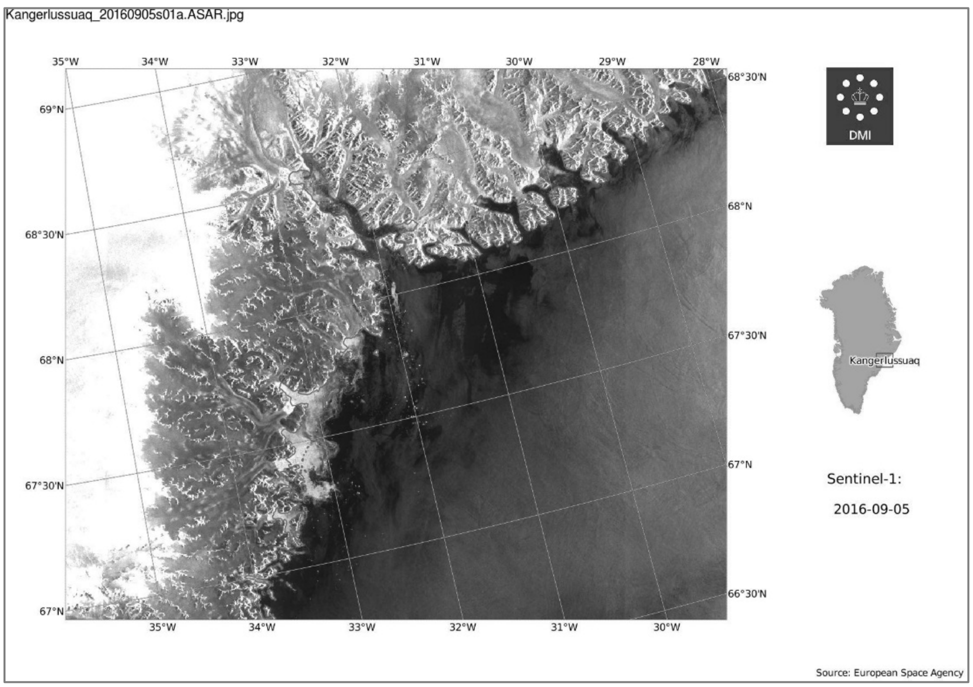


Figure 9 – Example Satellite Imagery

4.8 Marine Mammal Operations

Over the duration of the project a dedicated Marine Mammal Observer (MMO) was onboard in observation of the permit granted by the Danish government, a copy of the MMO Report can be found in Appendix I. The survey crew worked in conjunction with the vessel operators and the MMO to ensure every effort was made to mitigate the effect of data acquisition on marine life during survey operations. The predominant marine mammal sighting was of seals, followed by whale sightings.

On the 14th of September 2016, a pod of narwhals (Figure 10) was observed, as a precaution the vessel reduced speed and maintained a 500m buffer from the pod while the MMO observed the pod for signs of distress.

Figure 10 - Narwhal Pod

During a polar bear sighting in the 26th of September, the vessel was required to come to a stop under the direction of the MMO, due to Polar Bears swimming toward the vessel. The vessel did not resume making forward progress until the bears had begun swimming away from the vessel and further movements were deemed acceptable by the MMO.

Figure 11 - Polar Bears at Morgens Heinesen Fjord

In total 452 sighting of marine mammals were observed, reference Table 3 for a further breakdown of mammal sightings. The full compilation and observations by day can be viewed in Appendix I.

Table 3 Marine Mammal Observations

Animal	Species Name	Sightings	Individuals
Bear	Polar bear	9	14
Bear Total		9	14
Seal	Bearded seal	49	50
	Harp seal	75	166
	Hooded seal	3	3
	Ringed seal	11	11
	Unidentified seal	103	106
Seal Total		241	336
Whale	Baleen whale	14	26
	Fin whale	9	22
	Humpback whale	18	32
	Minke whale	2	2
	Narwhal whale	2	2
	Orca/ Killer whale	2	2
	Sei whale	1	5
	Sperm whale	5	5
	Unspecified whale	1	1
	White-beaked dolphin	1	5
Whale Total		55	102

5.0 MULTIBEAM ACQUISITION

5.1 Equipment

The Reson 7160 system employs a 1.5° along-track beam angle and a 2° across-track beam angle, with 512 beams when operated in equidistant mode. The nominal frequency of the sounder is 44 kHz, with an operational range of 3 to 3000m. Bathymetric datagrams were output from the Reson 7160 via an internal IP configuration to the acquisition software for recording and real-time data quality control. The system uses a combination of phase and amplitude bottom detection methods to provide soundings with the best possible accuracy.

A Valeport MiniSVP was fitted on the back of the hull mount and integrated with the Reson 7160 topside. The integrated probe provided real-time sound velocity to the system for aiding in the computation of beam forming.

Positioning was supplied via a NavCom SF-3050 GNSS System with Starfire Corrections. Positioning from the GNSS system has an accuracy of 10cm horizontally and 15cm vertically when the Starfire corrections are being received. Due to the operational extremes of the project area, Starfire corrections were intermittent; when corrections were not received the positioning accuracies are of autonomous quality. Positioning data were output from the SF 3050 and recorded in the acquisition software via a serial cable.

The POS M/V V4 provided attitude data, heave, pitch and roll along with real-time vessel heading. Heading was computed using dual GPS antennae separated at a known baseline distance to determine accurate values while the inertial measurement unit (IMU) measures accurate dynamic motion data as fast as 200 times per second. Pitch and roll values are measured to an accuracy better than 0.03°, heading accuracies are 0.03° with a 3m baseline. Heave accuracy is 5cm or 5% of heave amplitude whichever is greater. Heading and attitude data were output from the POS M/V topside and recorded in the acquisition software. For equipment Specification Sheets refer to Appendix H.

5.2 Software

Table 4 Acquisition software

System	Producer	Software	Parameters
Reson 7160	Reson	7k Controller	N/A
Vessel Navigation	QPS	QINSy	Software version 8.10 (Build 2014.01.01.01)
NAVCOM SF 3050	NAVCOM	StarUtil 3000	Version 1.2.33
POS M/V 320 V4	Applanix	PosVeiw	Version 3.4

Reson Seabat 7k Controller - Sonar Control Software
Reson Seabat 7k Controller is real-time control software designed to be the user interface of the Reson 7160, operating on the Windows 7 platforms. The 7k Controller controlled the user-defined settings including, power, gain, pulse width, swath angle, gates and filters.

QINSy -Acquisition Software
The Reson Topside computer operated QINSy which was used for navigation, real-time recording and quality control of bathymetric soundings. QINSy is an industry-leading navigation and data acquisition package produced by QPS. QINSy provided the helmsman with navigational displays for steering the vessel on the survey lines and planned waypoints.

StarUtil 3000 - GNSS software
This allowed for an interface to control the Starfire corrections and integration into the acquisition software. StarUtil 3000 gave real-time positioning accuracies and the number of satellites being tracked.

POSVIEW
Posview allowed for the integration and monitoring of the POS M/V data during acquisition.

5.3 Multibeam Acquisition Procedures

Every effort was made to conform to IHO Order 2 Hydrographic data specifications during the acquisition of data. Data was collected at the fastest possible safe speed, at the expense of along-track resolution to create the maximum amount of data in the allocated time. The swath angle of the system was set at the maximum of 150°, when practical, to collect as wide of a swath as possible. During the acquisition of data a qualified survey technician was monitoring and adjusting equipment parameters at all times. The acquisition station was on the bridge to facilitate easy communication with the vessel operators.

5.4 Typical Reson Settings

The nature of this project favored maximizing the amount of sea bottom ensonified over data quality and density. Whenever possible the full swath width, over 4 times water depth, was collected. To accomplish this range, pulse width and gain settings were regularly adjusted.

Increases in range setting while keeping a wide swath width also increased the across-track distance between each beam when they reached the seafloor, reducing data density. Additionally, as range and depth increase the maximum ping rate is reduced, resulting in a decrease of data density along the vessel track.

Pulse width settings affect the duration of the ping to help overcome signal attenuation. High pulse width settings increased the number of outer beams returned, especially in deep water.

High gain settings allow for lower strength signals from the outer beams to be interpreted. While this increases the swath width, these beams are often noisy resulting in a lower-accuracy interpretation of the bottom.

5.5 Typical QINSy Settings

Positioning, bathymetric and attitude data were interfaced into and recorded by QINSy. Data was populated in a QINSy grid, in real time for coverage display and quality control. In the display window attitude, positioning and timing were monitored for any anomalies. All data available was incorporated into the grid for navigation purposes. Tracklines and CTD locations received from JPL were imported into QPS.

5.6 MBES Naming Convention

To maintain consistency and a logical method of data tracking a line naming convention was assigned to all MBES data. The line naming is as follows “Sequential Line Number_Julian Date_Line Name_Sequential Number of Auto Breaks in Line”, example 0029_263_040_TINGMIARMIUT – 0001. The acquisition software QINSy was set to automatically create a new line at 200mb, hence “Number of Auto Breaks in Line”, this was done to ensure if a line was corrupted for any reason that only a small portion of the data collected that day was affected.

5.7 CTD Naming Convention

To maintain consistency and a logical method of data tracking a line naming convention was assigned to all CTD data. The line naming for CTD casts is as follows “Julian Date_Time UTC_Serial Number of Unit_Type of Probe_CTD”, example JD_262_2058_30436_AML_CTD.

6.0 CTD ACQUISITION

6.1 CTD Acquisition Equipment

Table 5 CTD Equipment

Equipment	S/N#	Resolution		
		Conductivity	Temperature	Pressure
Valeport Rapid CTD	52750/52756	0.001mS/cm	0.001°C	0.001% full scale
AML Oceanographic Minos X CTD	30436	0.001mS/cm	0.001°C	0.02% full scale

For full specification refer to Appendix H.

6.2 CTD Acquisition

CTD cast locations were along the planned track lines at locations provided by JPL (Figure 12). At times additional casts were made on an as-needed basis for sound velocity corrections to the multibeam data.

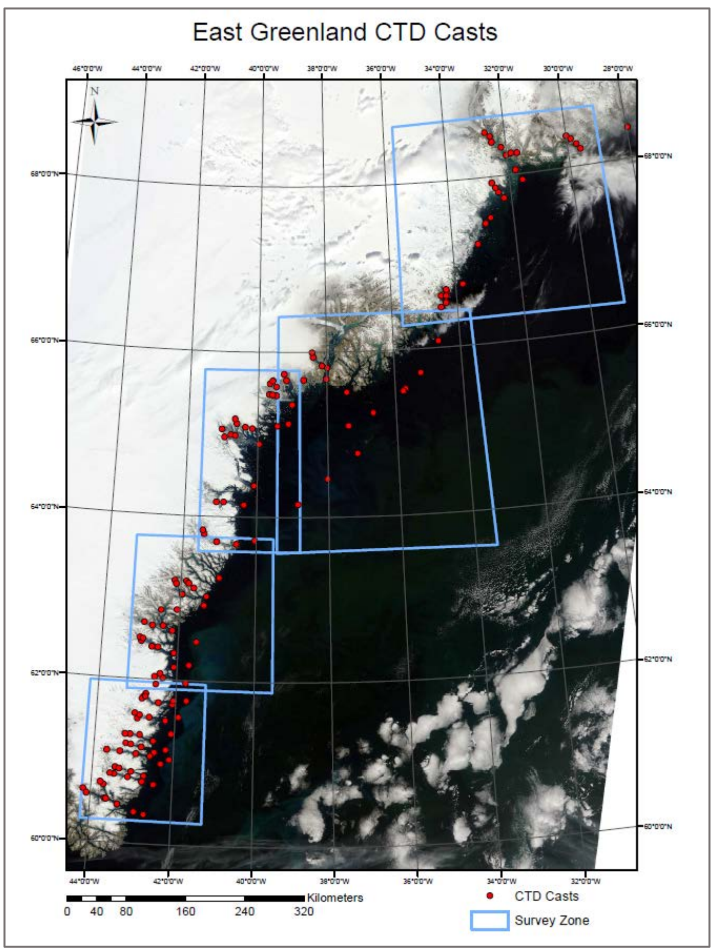


Figure 12 - CTD Distribution

Casts took one of two forms; underway using Valeport fast CTD Profiler with the Ocean Science Rapid Cast system or stationary with an Applied Micro Systems (AML) Minos-X system probe on a heavy line. The determination of what method to use was based on ice conditions at the time of cast.

The preferred method was utilizing the Rapid Cast while underway, with its higher-speed winch for retrieving the probe (Figure 13, left side). In order to conduct a cast underway it was required that no ice be encountered during the time the probe was in the water. For a 400m deep cast with the vessel traveling at 3 knots, this required 9.5 minutes and 0.88km of ice free conditions. Maximum cast depth achieved while underway was 702m.

Figure 13 – Static Cast Winch and Rapid Cast System

The Rapid Cast used a probe that was allowed to freefall for a planned amount of time based on a tension controlled pay-out. The system worked by maintaining 200 grams of tension on the line during payout, the motor speed was increased or decreased to maintain the tension. The tension controlled payout method lessened the effect of vessel speed and current on the drop time.

Once the vessel entered ice pack the small line attaching the Valeport fast CTD to the winch was deemed insufficient to be safely used. At this point a heavier line was attached to the Minos-X and deployed from the side of the vessel. An electric winch was used to retrieve the probe from the depths, a fall rate was calculated and the casts were timed to get to the required depth (Figure 13, right side).

An error on the setup of the Valeport fast CTD resulted in the top 10m of data not being recorded on casts 256_0912_52750_RC_CTD to 258_2106_52750_RC_CTD, all casts after which began recording at the surface.

Refer to Appendix C for CTD cast depths and locations.

6.3 CTD Acquisition Statistics

Project averages for CTD cast metrics were calculated and are shown in Table 6.

Table 6 Acquisition Statistics

No. of Days	Total CTD Cast	Average Interval Between successive cast	Average Depth (m)
23	151	3hr 36min	506

As a check on the continuity of the CTD Data, daily plots were generated for comparison, an example of which is shown in Figure 14 and 15.

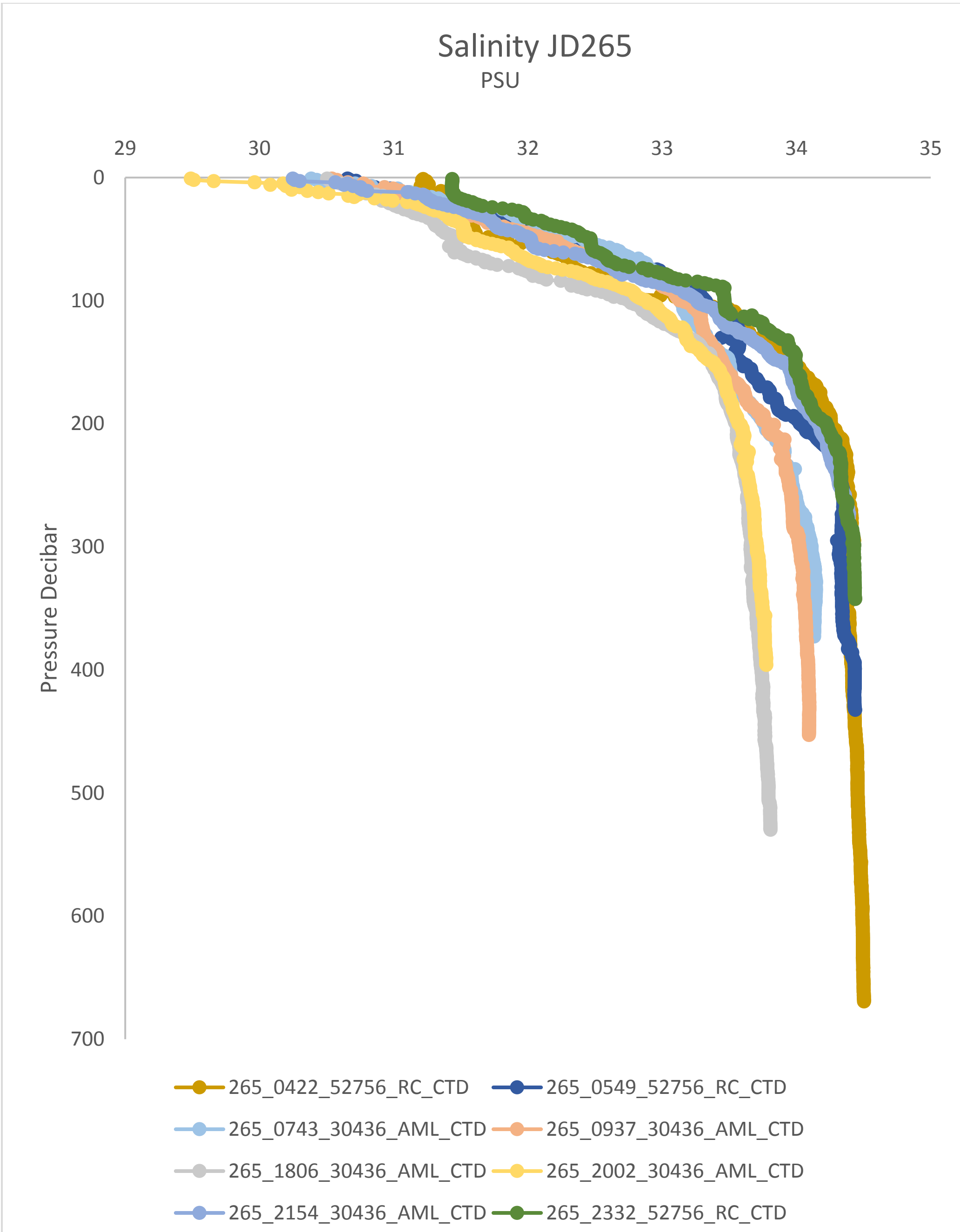


Figure 14 – Typical One Day Salinity Variations

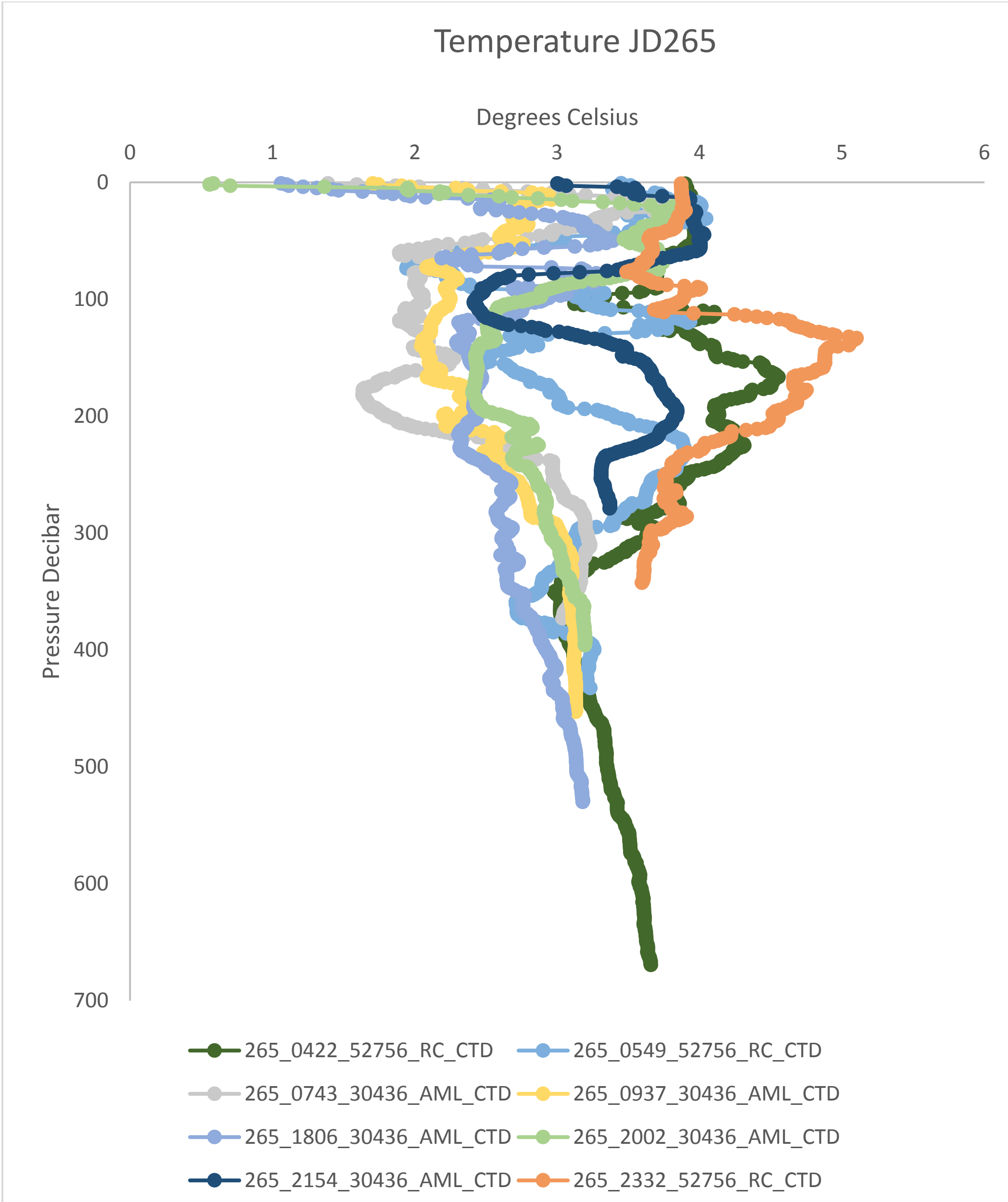


Figure 15 - Typical One Day Temperature Variations

7.0 VESSEL CORRECTIONS

7.1.1 Vessel Survey

A vessel survey of the M/V Neptune was conducted by NB Surveys in January 2013, while the vessel was in dry dock. The published values from the survey along with the Dimensional Control Report were supplied to TerraSond during the mobilization. The mobilization crew conducted checks on the offset values and found them to be correct. The measurements established a frame of reference for all navigation and bathymetric sensors. A copy of the Dimensional Control Survey can be found in Appendix

F. The TerraSond mobilization crew calculated all offsets to be referred to POS M/V as the Central Reference Point (CRP).

Relative to POSMV's MRU			
Point	X	Y	Z
POS M/V	0	0	0
NAVCOM SF-3050	-3.383	-2.655	-9.339
RESON SEABAT 7160 RP	3.362	1.813	5.494
POS M/V ANTENNA AFT	-3.482	-7.717	-8.731
POS M/V ANTENNA FWD	-3.493	-4.71	-8.713
REFERENCE FRAME: X+ STBD, Y+ FWD, Z+ DOWN			

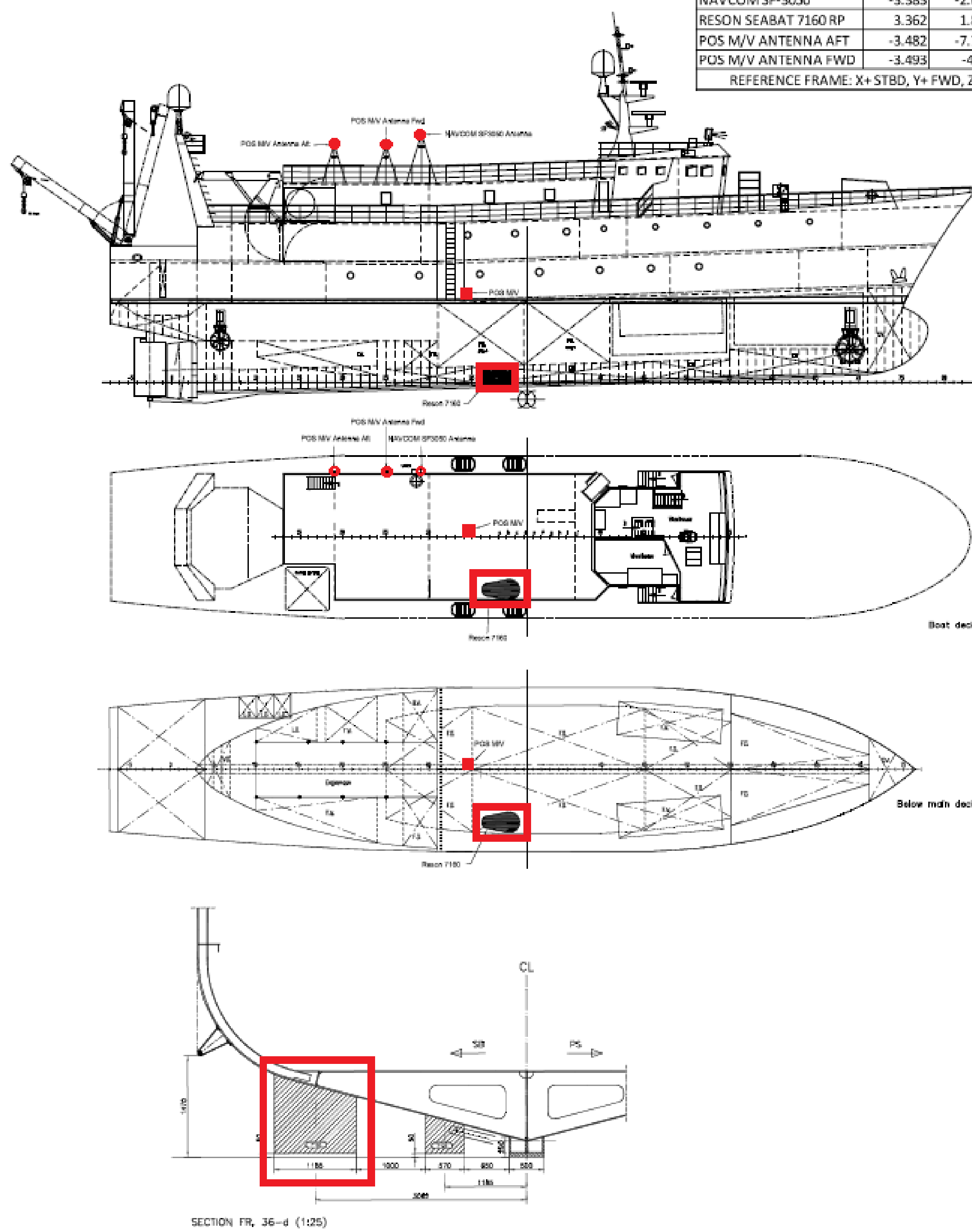


Figure 16 Vessel Offsets

7.2 Heading and Inertial Sensor Calibration

The heading offsets and attitude alignment of the POS M/V 320 V4 were computed during a calibration of the system to ensure it was operating at a high-degree of accuracy. The calibration subsystem uses the two GNSS receivers and antennas to determine a heading accurate to ±0.02° when coupled with the inertial navigation solution.

The system was aligned as the vessel performed a number of calibration maneuvers during the alignment processing, including, full turns, S-curves and figure-of-eight turns. The calibration is referred to as a GAMS calibration in the system interface, and during which the system must pass its own internal quality check to be considered online and ready.

The heading errors common with a GNSS only heading system are due largely to GNSS receiver noise and multipath errors. By combining the POS M/V GNSS information with the inertial navigation system in the Kalman Filter, the heading error can be largely mitigated with this system.

7.3 Multibeam Patch Test

A Patch test was performed to determine composite offset angles (roll, pitch and azimuth) between the transducer and IMU. The Patch test was conducted while transiting to the project site on Sept 12th 2016, at Latitude 67° 56' 30" N and 31° 35' 00" W Longitude. The patch values for pitch, azimuth (yaw), and roll were resolved using the processing software Caris 9.0.22. An image of the finalized Patch area can be seen in Figure 17.

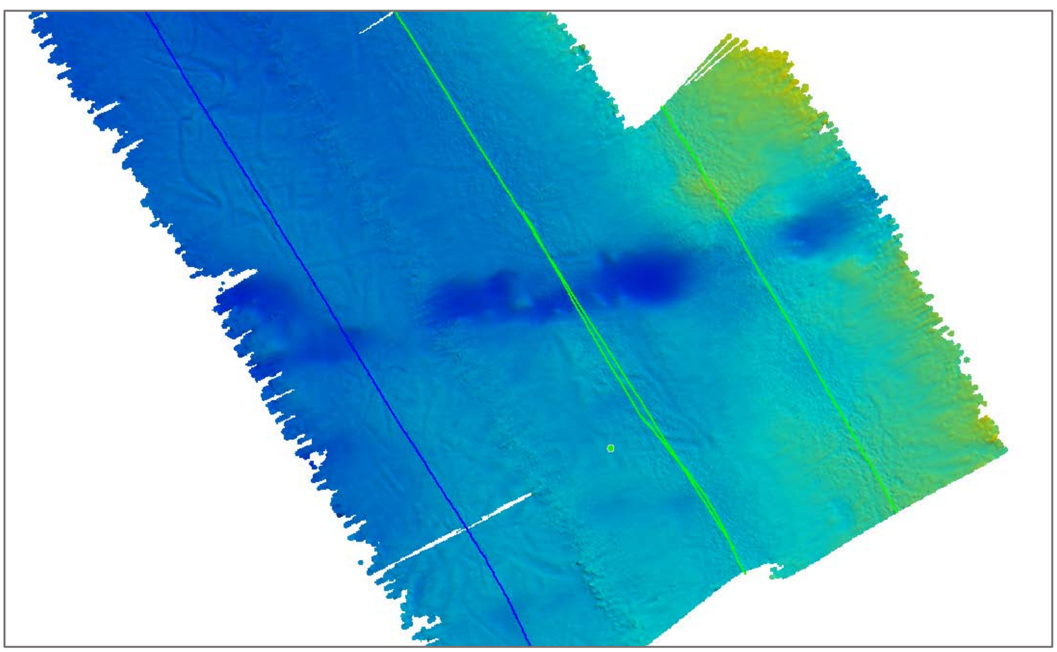


Figure 17 – Patch Test Area

Patch test lines were run as described below to determine the offsets values entered into the Caris Vessel Configuration File:

1. The Pitch offset was determined by running one pair of reciprocal lines at the same speed, perpendicular to a slope and feature.
2. The Azimuth offset was calculated by running one adjacent pair of reciprocal lines at the same speed perpendicular to a slope and feature.
3. The Roll was calculated by running one pair of reciprocal survey lines at the same speed over a regular and flat sea floor.

8.0 MULTIBEAM POST-PROCESSING

8.1 Survey Sheets

Due to the large spatial extent of the project it was broken down into 5 separate areas or zones in processing, subsequent point files were exported using the corresponding areas. Figure 18 displays the 6 different data zones generated.

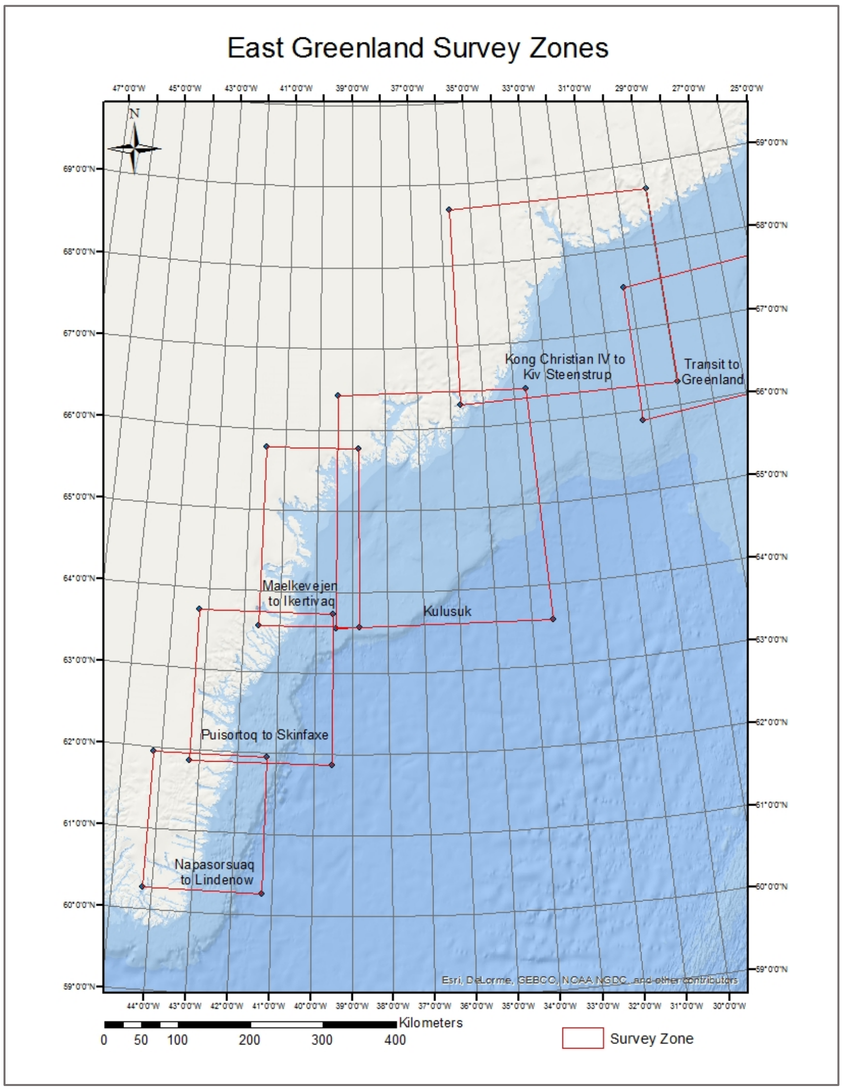


Figure 18 - Data Zones

8.2 Caris Conversion and Import

Caris HIPS software was used to create a folder structure organized by project, vessel and Julian day to store data. Raw multibeam data was imported into Caris HIPS using the Caris Conversion Wizard module. The wizard was used to import data into Caris by creating a directory for each line that separates the *.xtf file into various sub-files; these sub-files contain the individual sensor information. The multibeam data was also time-referenced using the time associated with the *.xtf file to relate the navigation, azimuth, and slant range depths from sensor files.

Caris HIPS does not allow raw data manipulation during the data processing. All raw data is maintained in the original, unmodified format to ensure data integrity. Defined procedures during the sounding reduction process and all actions are tracked by Caris to ensure that no steps are omitted or performed out of sequence.

8.3 Vessel Configuration File

Caris HIPS Vessel Configuration file (HVF) is used to define the offset configurations and associated error estimates for each sensor mounted on the survey vessel; these offsets and error estimates are required for creating final positions and depth records from the survey data. In the following tables, sensor offsets and patch test values are shown for the project.

Table 7 Sensor offsets onboard the M/V Neptune

MEASURED LOCATION (METERS)			
Point	**X**	**Y**	**Z**
Vessel RP	0.000	0.000	0.000
POS M/V RP	0.000	0.000	0.000
POS M/V Antenna Fwd	-3.482	-7.717	-8.731
POS M/V Antenna Aft	-3.493	-4.710	-8.713
Navcom SF-3050	-3.383	-2.655	-9.339
Reson Seabat 7160 AC	3.362	1.813	5.494

Caris Reference Frame: X (+) Starboard, Y (+) Forward, Z (+) Down

Table 8 Caris Patch Test Values

Date	**Time**	**Sensor**	**Pitch (°)**	**Roll (°)**	**Yaw (°)**
9/6/2016	00:00	Swath-SVP	1.240	0.850	0.670

8.4 Tide

For this survey, a zero tide was applied in post-processing to reduce all soundings to the instantaneous water level.

8.5 Sound Velocity

Sound velocity processing converts the soundings from raw beam angle and time-of-flight measurements to soundings based on the sound velocity profile of the water column and vessel attitude measurements. Vessel offset parameters computed from patch test results and vessel surveys are applied during this step.

8.6 Merge

Water level and other vertical corrections are applied to the soundings during the Merge process. The soundings are converted from time, beam, and ping format-referenced to the vessel location to a fully geo-registered sounding.

8.7 Navigation Editor

Data was examined in the HIPS Navigation Editor to check the integrity of the positioning. Parameters which can be examined, interpolated or rejected include the vessel speed, distance between position datagrams, and course made good.

8.8 Attitude Editor

Attitude data was examined for outliers in HIPS using the Attitude Editor; this editor displays sensor data related to the movement of the vessel such as heave, pitch, roll, gyro, and sound speed velocity for the Reson 7160 MBES. Data in this editor can be rejected, interpolated or smoothed if necessary.

8.9 Swath Editor

Soundings from individual lines are graphically-represented from the observed depth file and are cleaned in the Swath Editor; this editor allows the processor to examine and reject erroneous data and filter lines based on swath limits. The Swath Editor was used in the first cleaning of each line prior to any additional subset processing.

8.10 Base Surface

After the data has been swath cleaned, HIPS creates a gridded surface from the data called a base surface. The horizontal resolution of the surface is user-specified and depends on the resolution of the acquired data and accuracy requirements.

The surface type for this project was a Swath Angle surface, in which the weight attributed to each sounding is dependent upon the beam angle. In the surface creation algorithm, a higher weight is assigned to beams closer to nadir than to beams farther away. From these surfaces, geo-referenced images of a multi-attributed, weighted-mean surface for each survey area may be produced. Two base surfaces were made, one with a 25m resolution, the other with a 50m resolution.

In addition to providing geo-referenced images, base surfaces also provided visual aids for additional data cleaning and analysis of the merged lines, as well as depicting basic survey progress. The surface also facilitated the export of the XYZ text files of the area bathymetry for use in other digital terrain modeling software.

8.11 Subset Cleaning

The HIPS Subset Editor allows the processor to view data from multiple survey lines in a region in both a two-dimensional profile slice and three-dimensional point cloud visualization. The Subset Editor was used to inspect the BASE surface for outlying soundings (noise). Soundings found to be spurious were rejected manually throughout each region.

9.0 CTD TO SVP PROCESSING STEPS

Data collected at the client-supplied CTD sites was used for the calculation sound velocity, for the post-processing corrections of the multibeam data. To convert the CTD data to sound velocity, two different programs were used, for the AML Sea Cast Version 4.1.0 was used and for the Valeport Datalog X2 was used. Each software is native to the equipment and uses the same equations for the calculation of the sound velocity.

The calculation used to compute sound velocity was Chen Millero equation of 1977, with salinity being computed using the PSS-78 algorithm. This method was used in both sets of software, depth was computed using the latitude at the point of the cast. The resulting sound velocity data were then put in Caris format with their corresponding times and positions for the correction of MBES data.

10.0 QUALITY ASSURANCE

10.1 Crossline Analysis

The survey was conducted to International Hydrographic Organization (IHO) Order 2 specifications, which outlines a maximum allowable uncertainty of a sounding in three dimensions. Further this could be broken down into horizontal and vertical uncertainty components, or Total Horizontal Uncertainty (THU) and Total Vertical Uncertainty (TVU).

The THU and TVU vary by the order of specification of the survey and are a function of depth given in the equation below. For THU, IHO Order 2 allows constant 20m of uncertainty horizontally and an additional 10% depending on depth. As for TVU, it is based on a constant uncertainty (a) and a coefficient (b) that varies with depth (d). The constant a and the coefficient b were manually entered into CARIS. The depth for the general area was estimated and the a and b values calculated based on this. As an example for the 01_Kanger crossline analysis the average depth is around 870m, a =8.7 and b=0.2001. All the uncertainties are computed to 95% confidence level.

The IHO Order 2 maximum allowable THU and TVU are as follows:

Allowable THU = 20m + 10% of depth

Allowable TVU = $\pm\sqrt{a^2 + (b\ x\ d)^2}$

Whereby

a = 1.0 m

b = 0.023

d = Depth

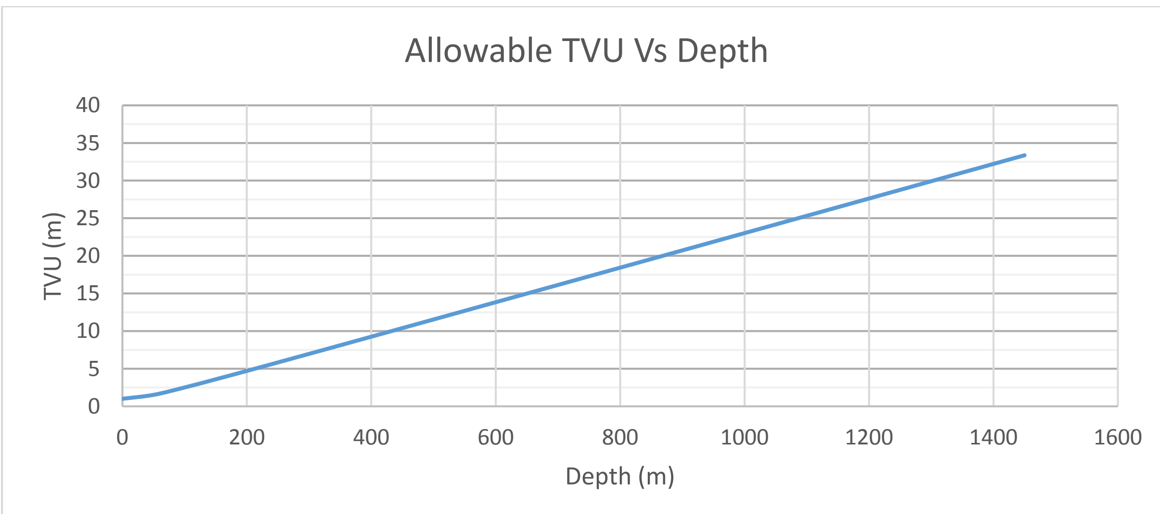


Figure 19 – Allowable Total Vertical Uncertainty, IHO Order 2.

To verify that Reson 7160 performed to the expected specification of survey, quality checks were carried out at locations distributed throughout the project.

Multibeam sounding accuracy is highly dependent on the beam angle. The vertical beams are generally more accurate, while the beams further out in the swath are much more susceptible to error as a result of vessel motion and refraction. A crossline examines the accuracy of the beams as a function of beam angle by comparing the soundings of one line to a reference surface generated from another line.

Caris HIPS & SIPS Quality Control tool was used to perform the check. This tool compares the individual beams (soundings) of one line to a reference surface generated from a second overlapping line. Each crossline analysis can be seen in Appendix E.

Table 9 Crossline analysis results

Crossline Analysis Name	Sum % > 95%	% of Beams Passing 95%
01_Kanger	21	100%
02_Kanger	21	100%
03_Polaric	20	100%
04_Polaric	21	100%
05_Laube	21	100%
06_Laube	21	100%
07_Laube	21	100%
01_Transit	12	100%
02_Ikertaviq	21	100%
01_Koge	21	100%
01_South_Danell	20	95%
01_Tingmiarmiut	21	100%
02_Mogens	21	100%

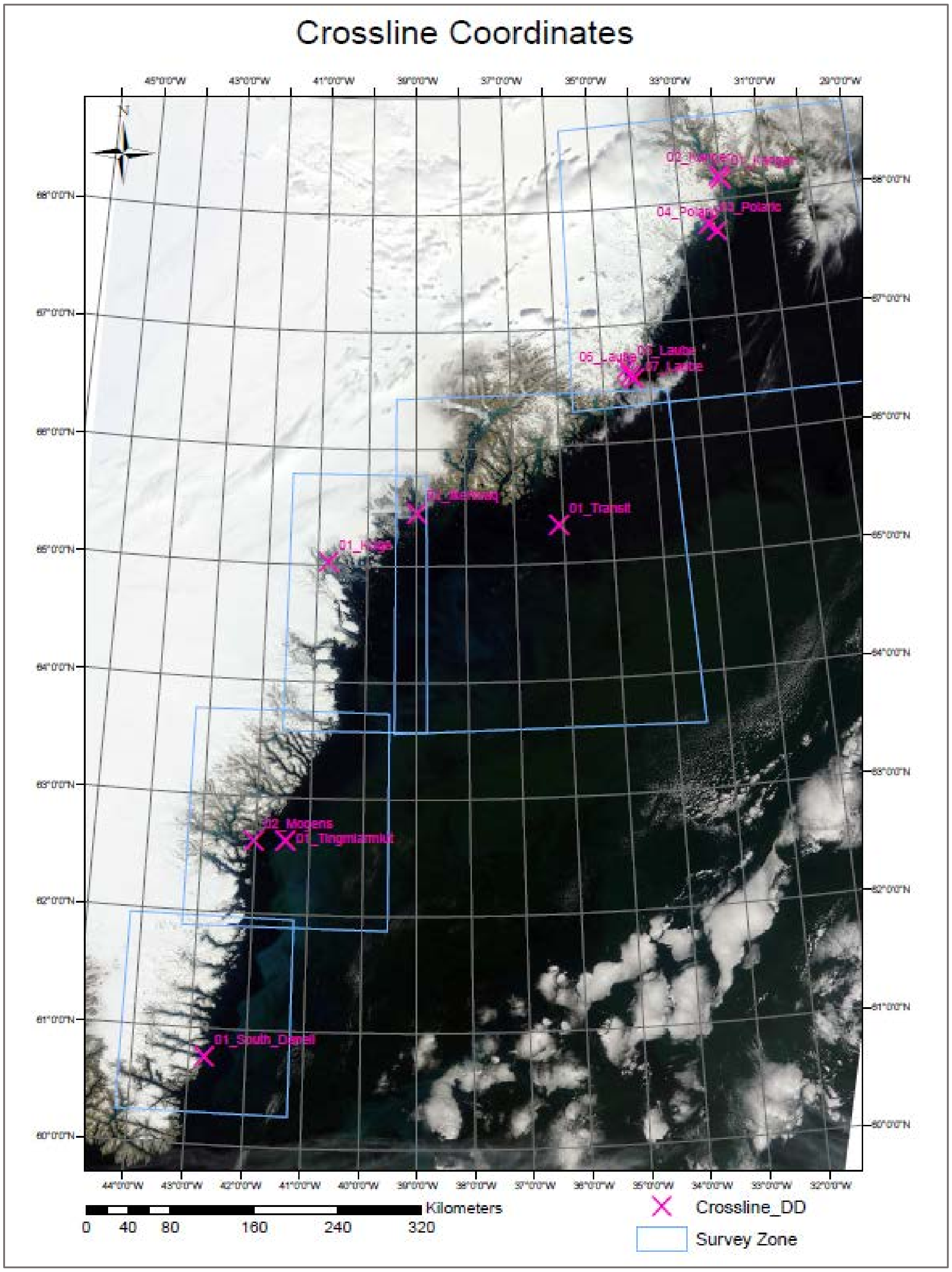


Figure 20 – Crossline Analysis positions.

10.2 Data Quality MBES

Generally, the data quality was very good. While only soundings that generally met or exceeded accuracy specifications were included in the final datasets, there may be locations that exhibit artifacts associated with the multibeam data and can be attributed to bottom types, excessive vessel motion and beam refraction. Artifacts are typically systematic, but not correctable due to the resolution of the sensor data or the spatial frequency of the sound velocity profiles.

As an offset check a leadline comparison was conducted on the 7th of Sept 2016. This check was done by measuring to the waterline from a known offset elevation perpendicular to the MBES then measuring to the seafloor on both the port and starboard side (Figure 21). Using the measurement from the offset point to the waterline the acoustic draft of the MBES is calculated (depth of MBES below waterline), the acoustic draft and the waterline measurement are subtracted from the total measurement to derive the depth beneath the transducer. This value is compared to the MBES depth. The delta between the leadline and MBES depth was 0.16m. The calculated delta between the leadline and the MBES was found to be within the allotted error budget.

In this particular leadline check only the portside leadline measurement was compared to the MBES depth. The MBES depth used was derived from the processing software Caris at half the breadth of the vessel off of the portside, not the depth directly beneath the transducer. This was done due to the irregular bottom where the check was done.

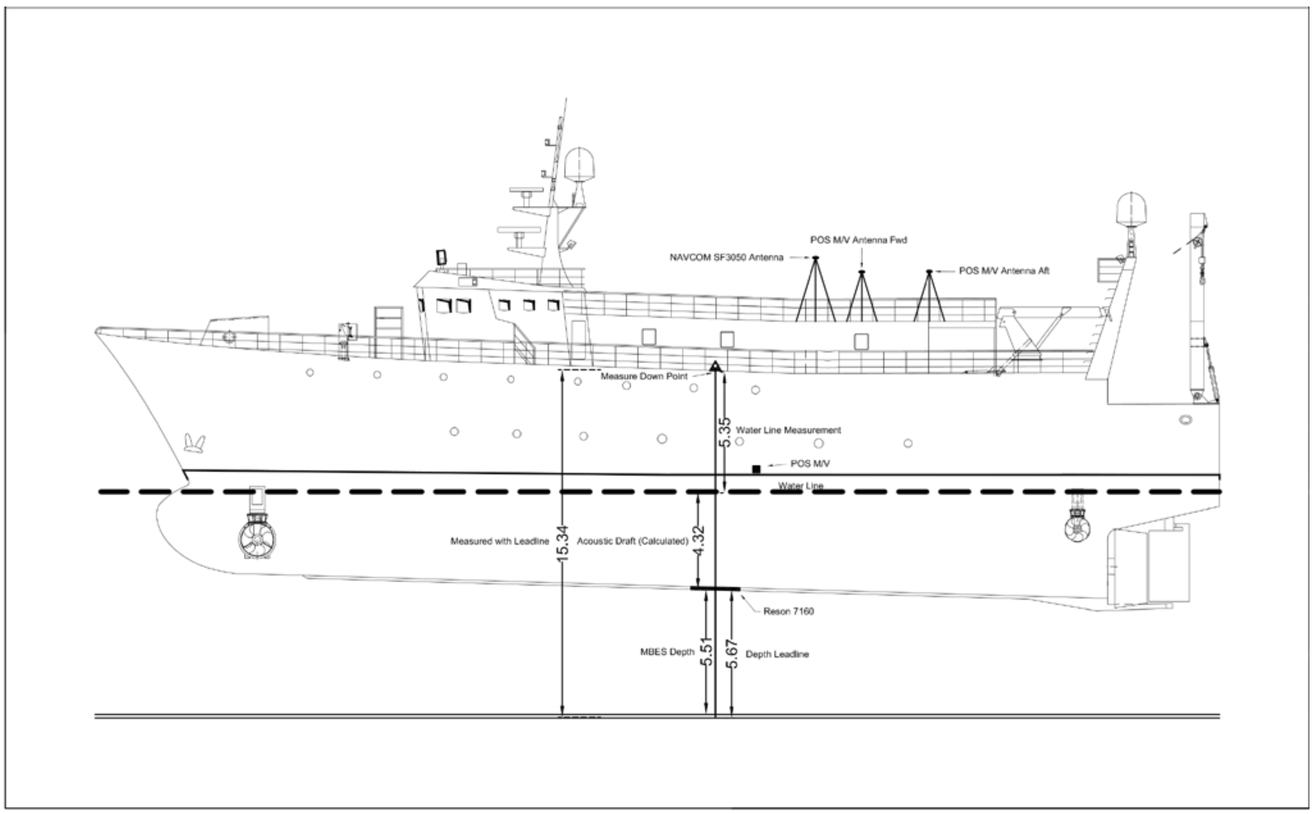


Figure 21 - Leadline

Data collected after the 5th of October 2016 09:13 UTC, line 0104_279_313_0003 onward are very poor in quality due to very poor weather conditions experienced during the transit to Iceland. The data collected during this time required corrections that were beyond the capabilities of the survey equipment in those conditions. It is recommended that discretion be used when using any part of this data.

Softer bottom types decrease the amplitude of the return wave from the multibeam and to compensate for this higher power and gain settings are used. However, with the system run in this configuration, an along-track artifact may be introduced into the data. This type of artifact will be at nadir (under the vessel) and will follow the track line (Figure 2222).

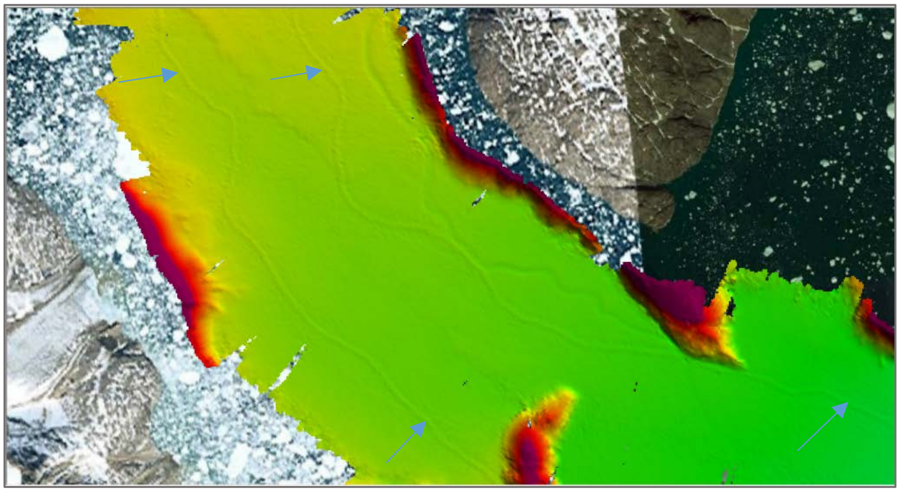


Figure 22 - Nadir Artifact induced by soft sediment denoted by arrows

Though the data is motion-corrected, excessive vessel motion due to high seas will degrade data quality. Typically outer beams lack a continuous swath coverage giving them a “ragged” look (Figure 23).

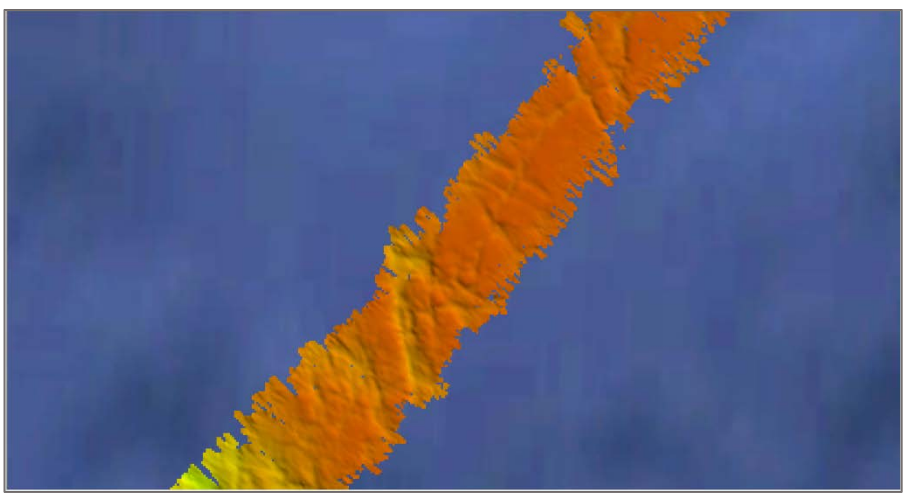


Figure 23 - Typical motion artifact

Refraction error is an artifact induced by the application of sound velocity to the data; as a result, the swath will have a concave or convex bias that will be more pronounced in the outer beams. Refraction artifact is difficult to detect in a single line but can be seen in over lapping lines, typically looking like a zipper in the portions of the swaths where the two lines overlap (Figure 244).

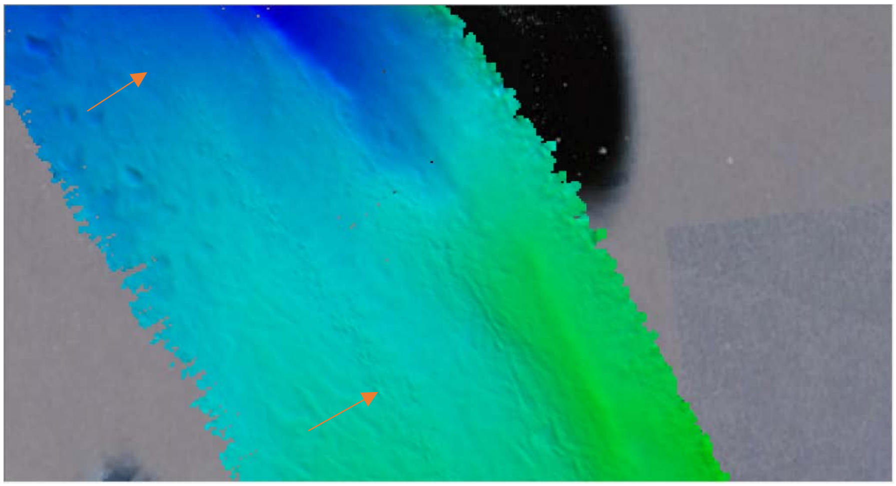


Figure 24 - Typical refraction artifact denoted by arrows

10.3 CTD QC

As a quality control measure simultaneous casts with both the Valeport fast CTD and Minos X CTD. This was done as a static cast on Julian dates 258 and 266 using the winch on the boat deck with both probes taped together. The resulting temperature and conductivity were graphed and inspected for deviations that would suggest errors in the data. The resulting comparison was deemed acceptable (Figures 25 & 26).

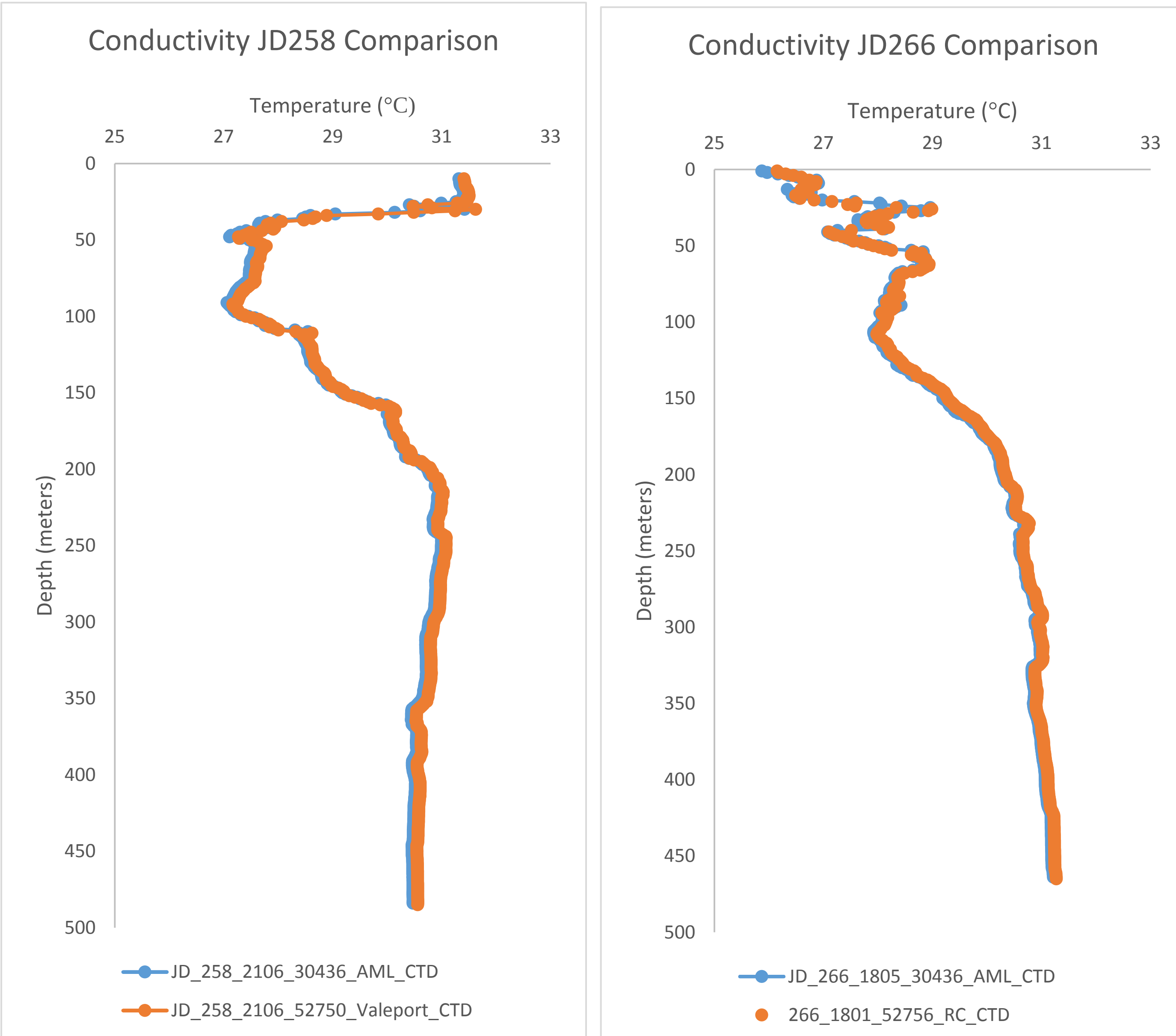
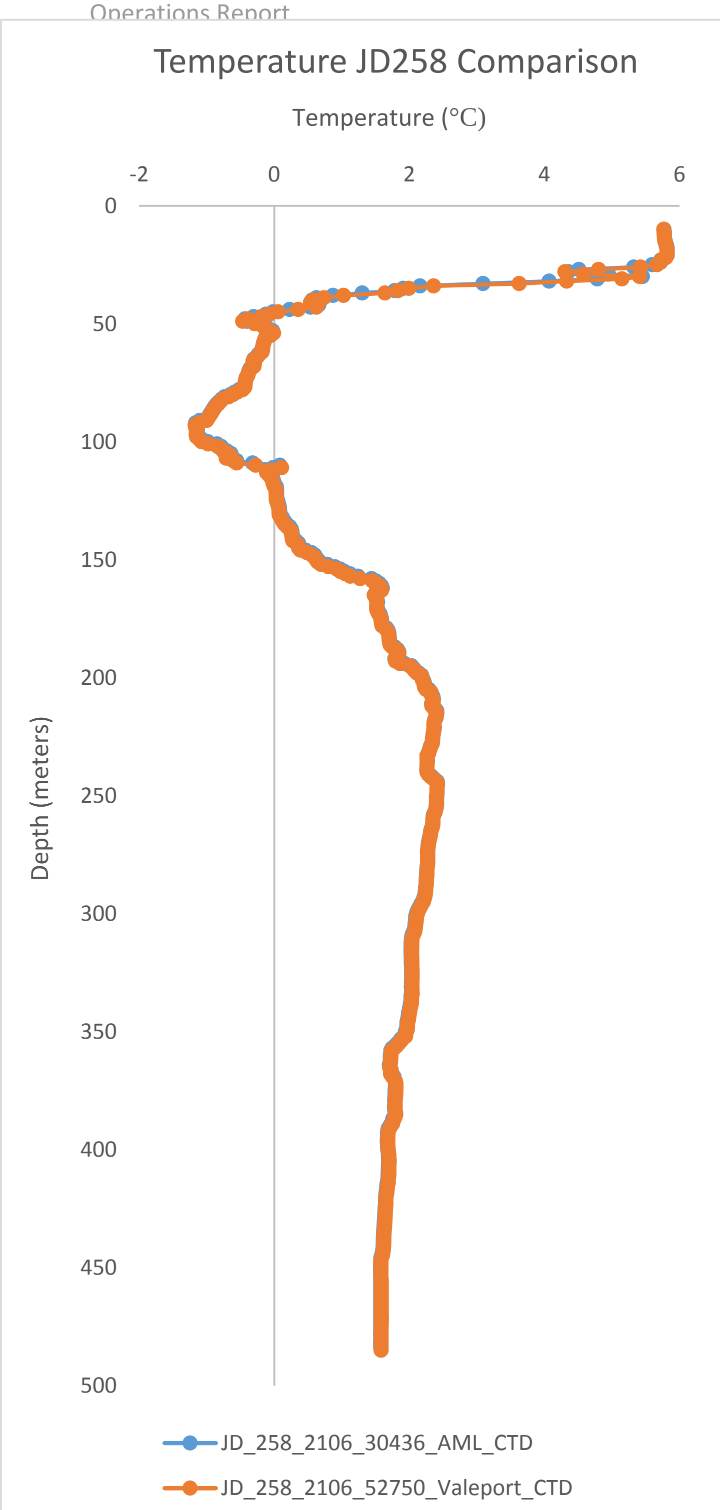


Figure 25 - Conductivity Comparison



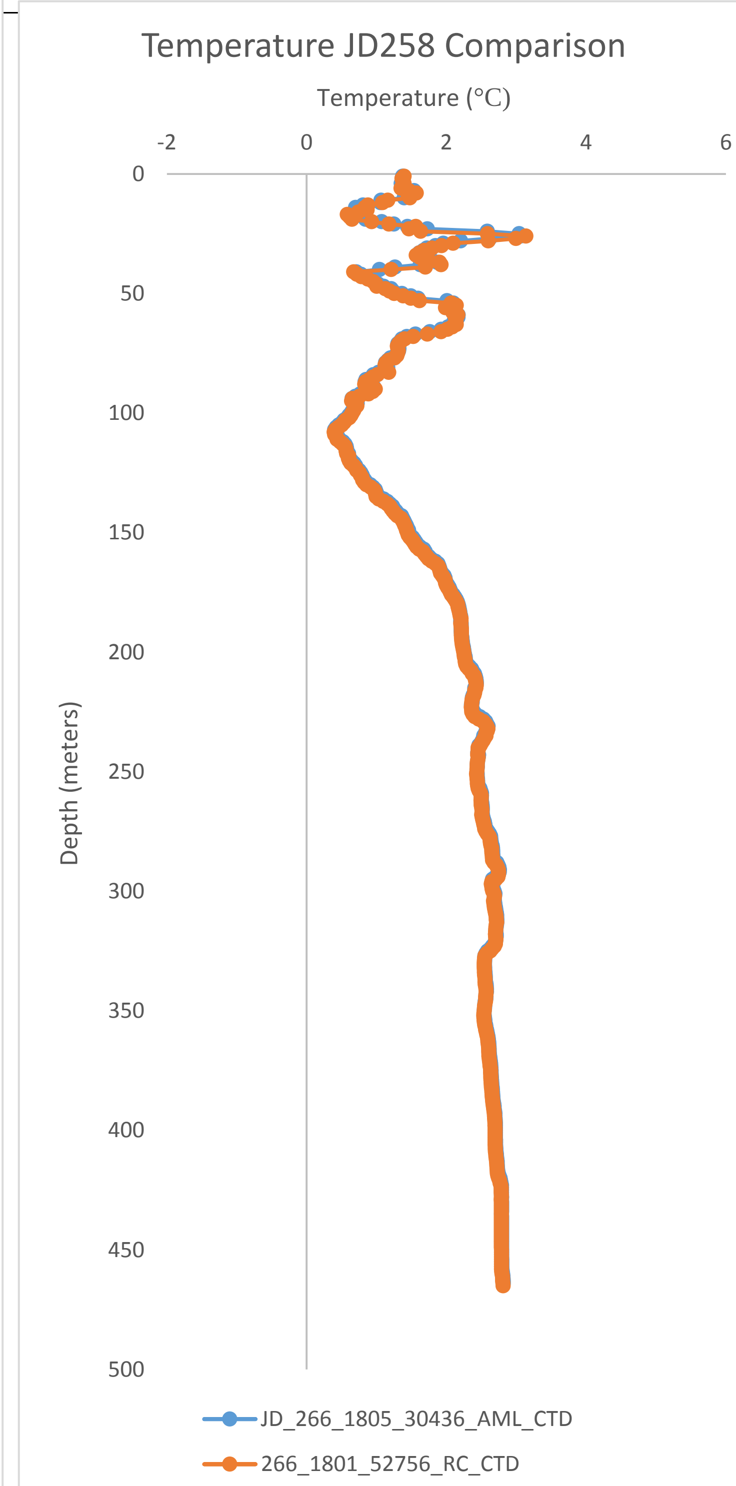


Figure 26 - Temperature Comparison

11.0 FIELD PHOTOS

Over the duration of the project, geo-referenced photos were taken at regular intervals while online and at glacier faces. These photos were to record the conditions at the time of the survey and were converted into *.kmz files.

12.0 DELIVERABLES

12.1 Bathymetry Data

12.1.1 Gridded Points

Sixteen gridded ASCII files were exported from Caris and included in this deliverable. The files are in latitude, longitude, (decimal degrees) and elevations reported to the decimeter. The exported resolutions are at 25m (11,855,349 points) and 50m (3,027,681points) and are named as follows:

1. OMG-2015-040_ALL_WGS84_UTM24_25m (11,855,349 points)
2. OMG-2015-040_ALL_WGS84_UTM24_50m (3,027,681 points)
3. 2015-040_OMG_ALL_LL84_DD_25m.txt (11,855,385 points)
4. 2015-040_OMG_ALL_LL84_DD_25m_with_glaciers.txt (11,857,587 points)
5. 2015-040_OMG_KONG_CHRISTIAN_IV_to_KIV_STEENSTRUP_LL84_DD_25m (1,978,599 points)
6. 2015-040_OMG_KONG_CHRISTIAN_IV_to_KIV_STEENSTRUP_LL84_DD_25m_with_glaciers (1979876 points)
7. 2015-040_OMG_KULUSUK_LL84_DD_25m (2,539,737 points)
8. 2015-040_OMG_KULUSUK_LL84_DD_25m_with_glaciers (2,571,640 points)
9. 2015-040_OMG_MAELKEVEJEN_TO_IKERTIVAQ_LL84_DD_25m (2,651,844 points)
10. 2015-040_OMG_MAELKEVEJEN_TO_IKERTIVAQ_LL84_DD_25m_with_glaciers (2,648,263 points)
11. 2015-040_OMG_NAPASORSUAQ_TO_LINDENOW_LL84_DD_25m (2,255,396 points)
12. 2015-040_OMG_NAPASORSUAQ_TO_LINDENOW_LL84_DD_25m_with_glaciers (2,257,289 points)
13. 2015-040_OMG_PUISORTOQ_TO_SKINFAXE_LL84_DD_25m (2,581,621 points)
14. 2015-040_OMG_PUISORTOQ_TO_SKINFAXE_LL84_DD_25m_with_glaciers (2,588,940 points)
15. 2015-040_OMG_T_Greenland_to_Iceland_LL84_DD_25m (1,373,799 points)
16. 2015-040_OMG_T_Iceland_to_Greenland_LL84_DD_25m (845,057 points)

12.1.2 Raw Data

Raw data is provided in Extended Triton Format (XTF) an industry standard and open format bathymetric data format. The XTF files contain time tagged bathymetry, GPS positioning data, heading, heave, pitch and roll. Data is organized by Julian Day.

12.1.3 Sound Velocity Profiles

Sound velocity profiles processed from the CTD data and used to correct bathymetry data are provided in the Caris Hips .SVP format. The file is ASCII format with each cast having a header record that includes cast time and location followed by the sound velocity profile binned at one meter depth intervals.

12.2 CTD Data

Raw CTD data is provided and organized by Julian Day. File names contain the date and UTC time of the cast. A revised cast location table in XLS format is provided.

12.3 Vessel Tracklines

Comma separated text file of vessel locations are provided at a 1 minute intervals and at 10 second intervals. Header format: Line filename, date, time (UTC), heading, latitude and longitude. Latitude and longitude are degrees decimal degrees to the 9th decimal point. The exports are as follows:

1. OMG_2016_1min_Trackline_Rev_1
2. OMG_2016_10sec_Trackline_Rev_1

Google Earth KMZ and Garmin GPX formats are also provided for convenience.

12.4 Photos

Geo Referenced photos taken while on line and at glacier faces were processed and exported to a *.kmz file. The exported *.kmz files are:

1. OMG_2016_Glacier_Photos
2. OMG_2016_Trackline_Photos

12.5 GeoTIFF Images

25 meter resolution imagery was created from the processed bathymetry. The projection used for all images was WGS84 UTM Zone 24, meters. In order to keep the file size manageable, the images were broken into five regions. A small amount of overlap exists between adjacent regions. They are provided to give a graphical representation of the data provided in the ASCII data files.