Oceans Melting Greenland

Bathymetric Survey

Northwest Greenland

2015 Operations Report

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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 along JPL provided trackline locations in both fjords and offshore locations from approximately Disko Bay to Melville Bay in Northwest Greenland. East Greenland operations, also included in this contract, are to be conducted in 2016.

The 2015 survey operations were broken down into two separate phases due to conflicting schedules for the survey vessel and expected ice conditions in Melville Bay. Phase 1 commenced on July 25th, 2015 and completed on August 19th, 2015. Phase 2 commenced on September 3rd, 2015 and was completed on September 23rd, 2015.

In total, 4832 linear nautical miles of data were acquired, averaging approximately 110 miles per day, over a total of 45 days.

Phase	Start Date	End Date	Comment
Mobilization	June 22	July 11	Cape Race mobilization in Belfast, Maine
Repositioning	July 11	July 23	Vessel repositioning from Maine to Aasiaat
Sea Trials	July 23		Final mobilization and calibrations
Survey	July 24	August 20	"Phase 1" survey operations
Planned Break	August 20	Sept 1	Break for conflicting vessel charter
Remobilization	Sept 1	Sept 2	
Survey (Phase 2)	Sept 3	Sept 21	"Phase 2" survey operations
Demobilization	Sept 22		Demobilization of survey equipment from Cape Race
Repositioning	Sept 22	Oct 4	Vessel repositioning from Aasiaat to Iceland

Table 1 – Project Timeline

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 working in high latitudes such as Greenland and Alaska, a site-specific safety plan was developed to ensure the safety of personnel and equipment. Senior TerraSond staff worked in conjunction with the owner and operators of the M/V Cape Race to develop an integrated plan for general safety at sea, operations in ice zones and procedures for operating in sparsely charted areas.

A pre-sail orientation was conducted by the Vessel Captain and crew upon the arrival of TerraSond personnel in Aasiaat, Greenland. During the orientation all personnel were shown the emergency equipment locations and emergency muster areas, as well as how to properly wear a Ship Abandonment Suit (Figure 1).

The Party Chief held a daily safety meeting to discuss the daily survey plan and review the previous days operations to improve the safety of operations over time. 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 or near-misses occurred during the operations.

Figure 1 – HSE Drill Wearing Ship Abandonment Suits

2.2 Mobilization

The Cape Race was put into dry dock for the mobilization of equipment prior to the commencement of the project at the Front Street Ship Yard in Belfast, Maine. The multibeam was installed as a hull-mounted system to better protect the multibeam from ice. A hull-mounted sonar increased the operational envelope in high-density ice areas and allowed for higher acquisition speeds than in previous years. The multibeam was housed within a hydrodynamic blister constructed by TerraSond and fitted at the ship yard (Figure 2 below). The blister was mounted slightly offset to the starboard of the keel and slightly aft of mid vessel.

Figure 2 – Hull-Mounted Blister

Other fabrication tasks in support of the survey were completed while in dry dock, such as the mounting of antennas, the Underway CTD mount and communications equipment. Concurrent to fabrication, survey sensors, cables and computers were installed and integrated on board. A vessel survey was conducted to determine the offsets between sensors. Upon completion of the mobilization and prior to the Cape Race's departure for Greenland, TerraSond personnel conducted a performance trial of survey sensors and communication equipment.

2.3 M/V Cape Race

The vessel Cape Race is a converted "North Sea" fishing trawler, see Figure 3. This hull design has been in use in Europe and North America for generations. They have proven to be excellent sea boats with large carrying capacity and the ability to handle very heavy weather safely. The vessel has ice strengthening in the forward .25L which consists of intermediate frames on 9" centers. The vessel is sub-divided into 5 separate, completely watertight compartments. A new CAT 3512 main engine was installed in 1996 and overhauled to factory specifications 8 years later.

Figure 3 – M/V Cape Race

2.4 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. Secondarily, the plan made sure the vessel complies with local requirements for position and status updates. Lastly, the plan provided means for the ship to provide scheduled updates on the survey progress.

The primary communications used for internet and telephone were the TracPhone V3IP / Iridium Pilot bundle. This combines a compact VSAT system (TracPhone V3IP) with an Iridium Pilot system to provide Internet, email and voice communications from pole-to-pole. The modem is configured to utilize the higher speed mini-VSAT system first and switch over to the Iridium system when VSAT service becomes unavailable.

The system performed as expected while on site; communications were reliable with the VSAT system in the southerly portion of the project area south of Upernavik. Communications north of Upernavik were done via the Iridium Pilot and remained reliable, though at a slower up and download speed. Communication blackouts did occur while the satellites were obstructed in the fjords, though they were typically short in duration.

Figure 4 – Communications Equipment

2.4.1 Aasiaat Radio

The ship made scheduled radio 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 VHF and MF marine radio. The reports were made at regularly scheduled 24-hour intervals. Both systems are operated by Aasiaat Radio and Tele-Post.

Aasiaat Radio's primary function is the monitoring of international emergency frequencies within Greenland waters, informing the Search and Rescue (SAR) authorities of requests for assistance and handling the communication between ships in distress and the SAR authorities. In addition, Aasiaat Radio broadcasts information regarding storms, gales and navigational warnings; information on ice conditions and maritime weather forecasts are available on request.

2.4.2 Real-time Tracking

Two Delorme inReach Explorers were onboard the Cape Race 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 (see figure below). 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 Cape Race. This system also doubled as a safety system that broadcasted the vessel position every two minutes in case of an emergency.

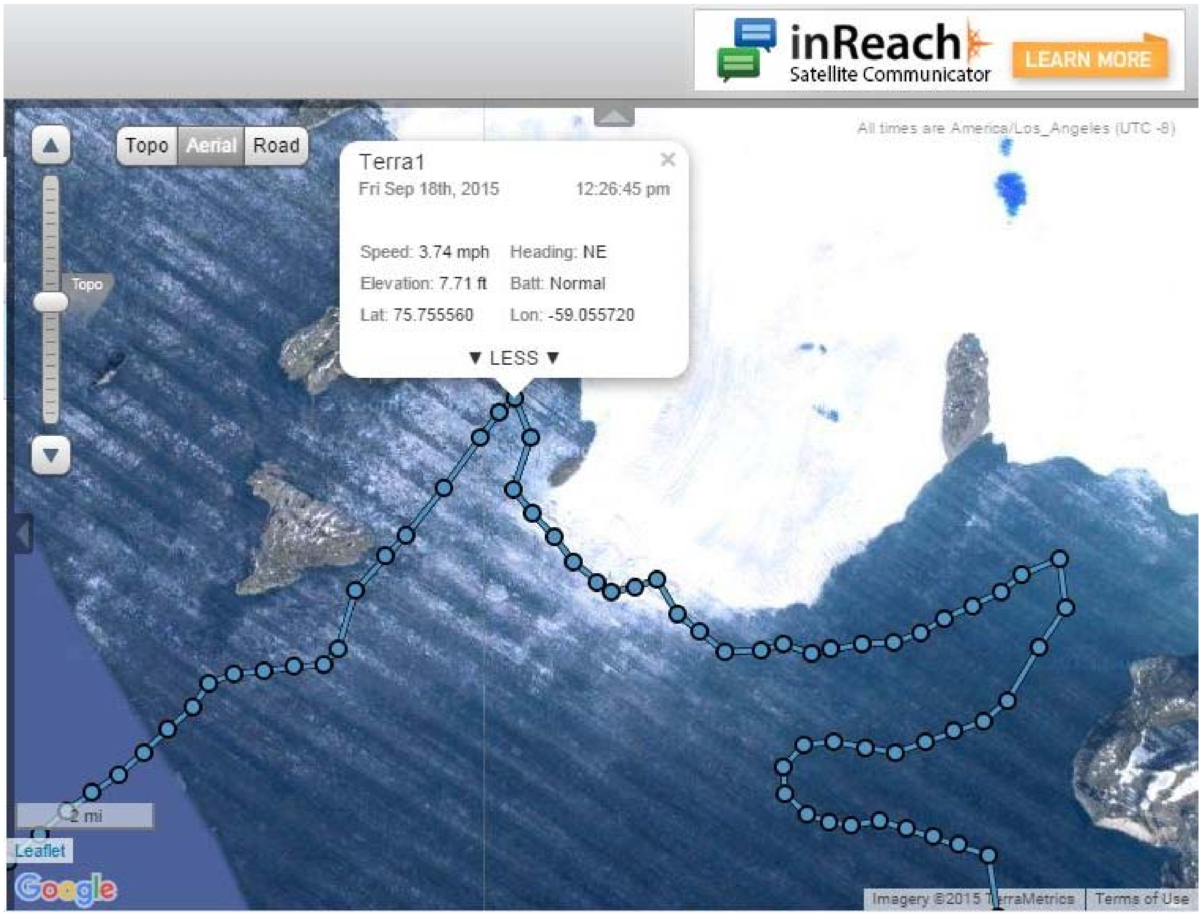


Figure 5 – Real-time position updates with the Delorme InReach Explorer.

2.5 Permits

A Permit was granted to survey within the Melville Bay Nature Reserve on September 9, 2015 from the Ministry of Nature, Environment and Justice. In order to obtain the permit TerraSond submitted a Notification of Proposed Research Cruise outlying the mission objective and the steps taken to mitigate any impact on wildlife.

The permit authorized operations within the Melville Bay Reserve September 12-19, 2015.

TerraSond acted in accordance with "The Manual for Seabird and Mammal Survey on Seismic vessels in Greenland", as per the required regulations.

A copy of the Permit to enter Melville Bay 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 21N Coordinate system. The final bathymetric points generated from the survey have been submitted in geodetic (latitude/longitude) horizontal coordinates.

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	21 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

Table 2 – Geodetic Parameters

Note: The survey encompassed two separate UTM projection Zones, 20N and 21N; Zone 21N 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 (discussed later in the report) 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.

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. Figure 6 shows the planned track lines compared to the actual surveyed tracklines.

Wind and seas were also a factor that resulted in deviations to the planned trackline locations. The July/August operations experienced remarkably calm and clear weather and presented no impact to the survey operations. Operations in September were significantly more challenging. 20-30 knot winds were typical and created marginal operating conditions, especially in offshore locations where 2-4 meter seas were typical.

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.

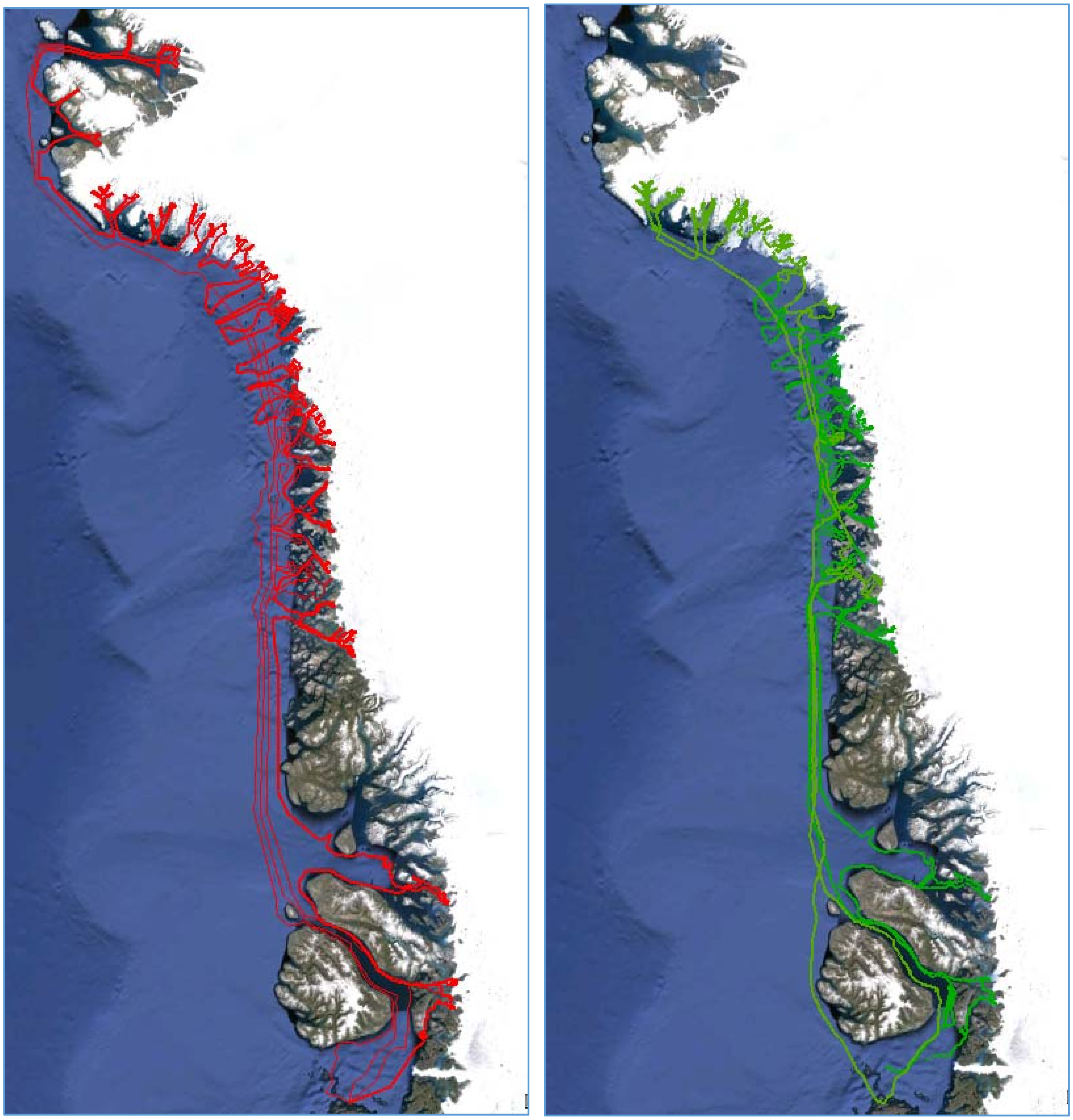


Figure 6 – Track lines Planned (red) and Run (green)

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 kilometers, 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 Ice Conditions

Ice conditions varied greatly throughout the survey. The density ranged from 100% coverage, precluding further access into fjords and severely impacting survey speeds to relatively ice-free waters offshore.

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. The top left image displays typical offshore open water. Ice bergs encountered while offshore were typically larger and very spread out, allowing for higher survey speeds. Shown in the top right image are 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. In 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.

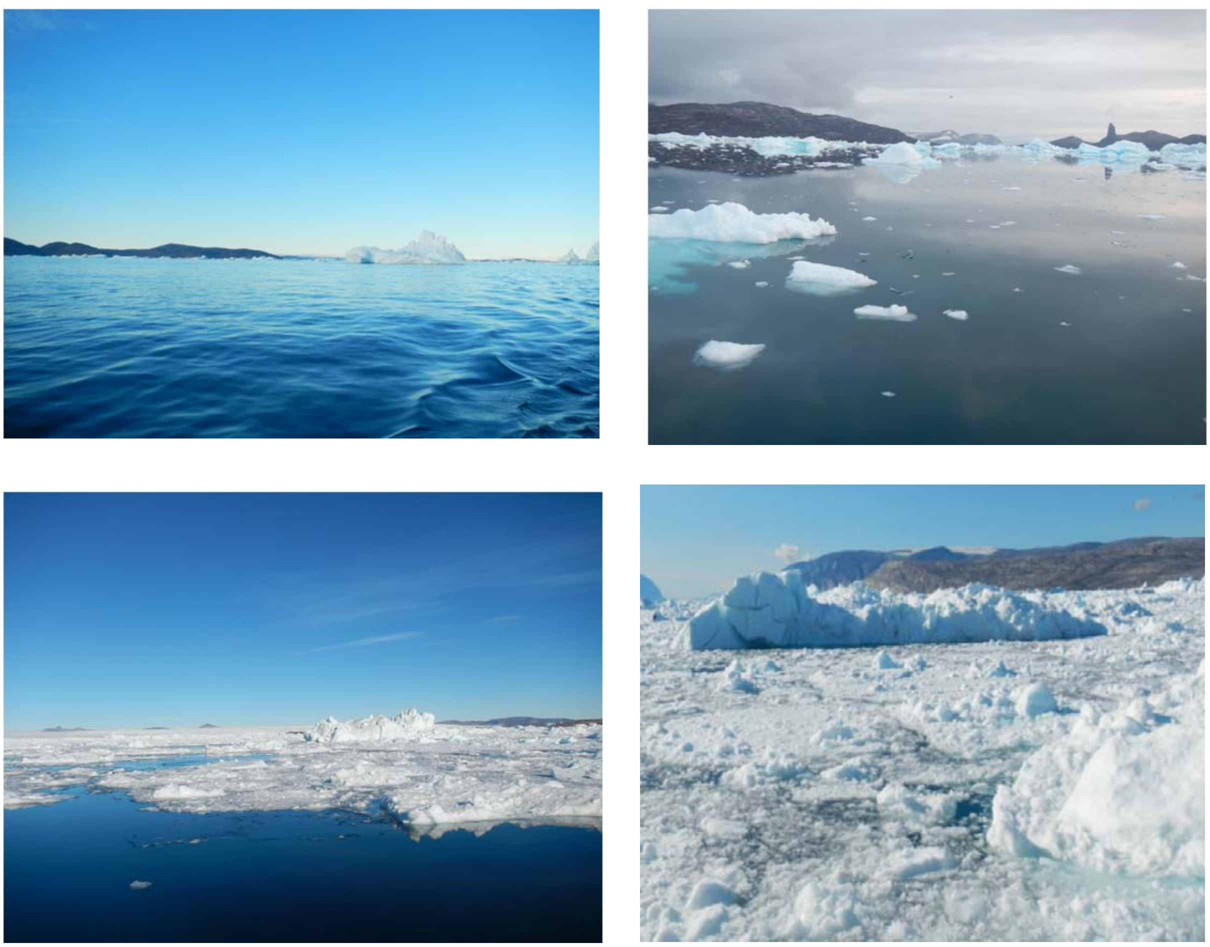


Figure 7 – Typical Ice Density

4.5 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 days operations and ascertain which fjords may or may not be accessible due to the ice conditions.

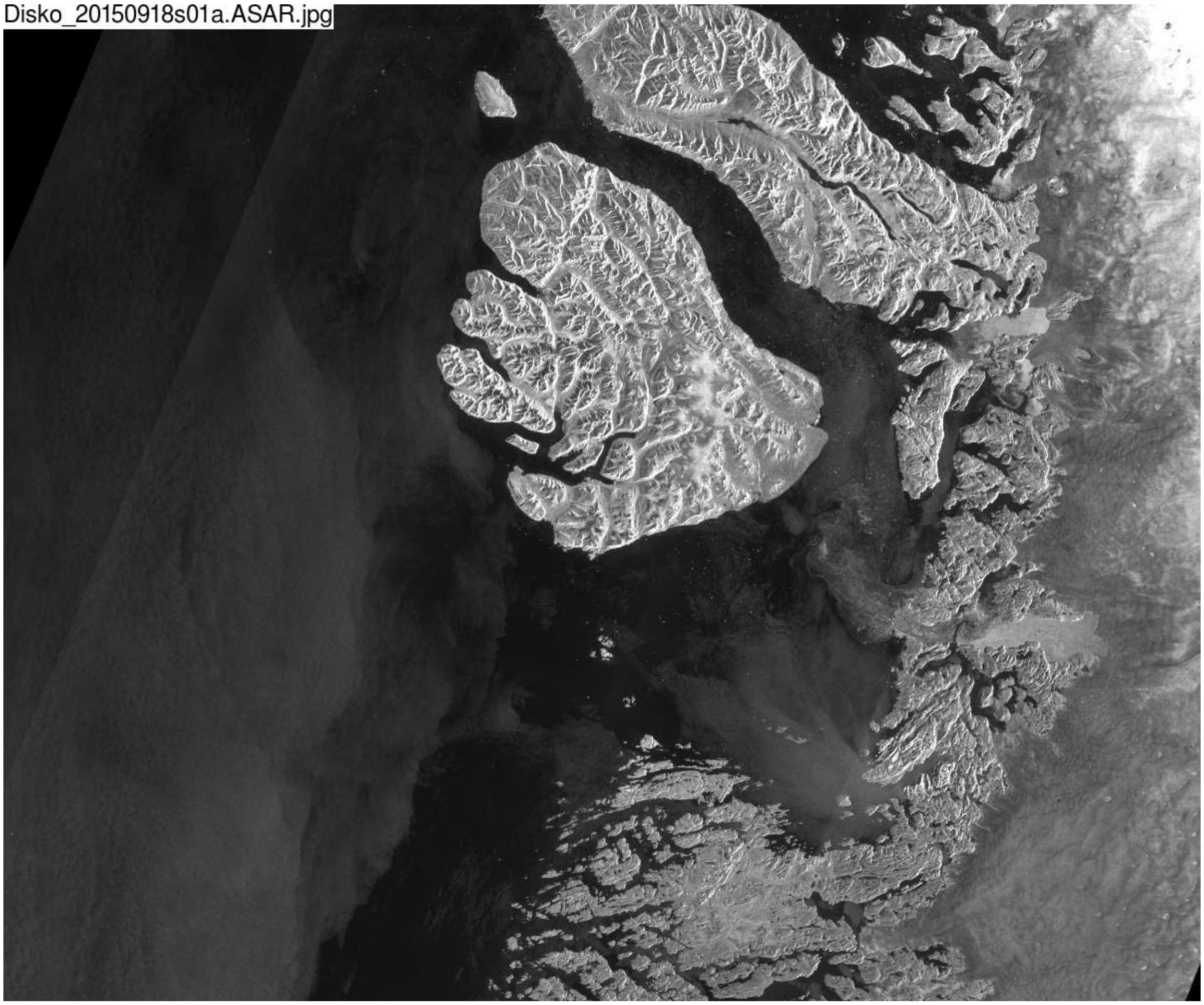


Figure 8 – Satellite Imagery

4.6 Melville Bay Operations

In order to show due diligence while in the Protected I and II areas of the Melville Bay Nature Reserve, operational restrictions were put in place to mitigate any effect the data acquisition may have on marine life. While in the Melville Bay Protected area speeds were reduced to no more than 5.4 knots in the Reserve and no more than 4 knots when operating in Protection Area II. Operations in Protected Area II were limited to periods between civil dawn and civil dusk, which is approximately 1.5 hours before and after sunrise and sunset. Additionally, due to the reduced visibility, Protection Area II was not entered if fog, rain, or snow reduced visibility to less than 500m.

No narwhals were sighted over the duration of this project. In the event a narwhal had been seen, corrective action would have been taken to maintain a 1000m buffer distance. If course change and speed were not sufficient to maintain the buffer, speed would be reduced to 2 knots. If any narwhal were to be within 500m, the vessel would be taken out of gear and the multibeam would be set to its lowest possible setting. Operations would be suspended until the narwhal had exited the 500m zone surrounding the Cape Race.

4.6.1 Soft starts

While operating in the Melville Bay protected area a technique known as soft starting of the multibeam was used in order to create minimum acoustic disturbance. Using this technique, the system was started up 60 minutes prior to entering the reserve and operated at the lowest possible power level. Power increases were done in 3-decibel increments every 20 minutes until a satisfactory bathymetry was obtained. While operating in this area the minimum power setting possible was used without having to sacrifice swath width or data quality.

4.6.2 Mammal Observation

While operating in the Melville Reserve, a log of observed marine mammals was kept in accordance with the permitting stipulations. In Protection Area II an observer was designated with the sole task of recording and keeping a lookout for narwhals. Recorded in the log were the following:

1. Time
2. Latitude and Longitude (Ship)
3. Location
4. Speed
5. Ice coverage
6. Species
7. Number
8. Range
9. Any additional comments

The predominant sighting was of seals; however, two polar bears were also observed.

A copy of the log is provided in Appendix I.

Figure 9: Polar Bear at Gade Glacier

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.

An AML Micro X Sound Velocity Sensor 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 15m 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 Coda F185+ 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 100 times per second. Pitch and roll values are measured to an accuracy better than 0.025° with heave being at 5% of heave amplitude of 5cm, heading accuracies using the Coda F185+ are 0.05°. Heading and attitude data were output from the Coda F180 and recorded in the acquisition software.

Due to the high latitudes, an Octans 30000 gyro compass was integrated as a backup if required. Unlike the Coda F185+ which uses dual GPS antennas for heading the Octans 3000 uses a fiber gyro for the computation of heading. The heading accuracy of the system is 0.1°secant latitude. The heading data were output via serial cable and recorded in the acquisition software.

For equipment Specification Sheets refer to Appendix H.

5.2 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

Table 3 – Acquisition Software

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 swath angle in addition to real time gates and filters.

QINSy -Acquisition Software
The Reson Topside computer operated QINSy and was used for navigation and real-time 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.

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 highest 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 at the maximum 150° 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, roughly 7 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, or the frequency at which the MBES sends out a ping, 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. Track lines and CTD locations received from JPL were imported into QPS.

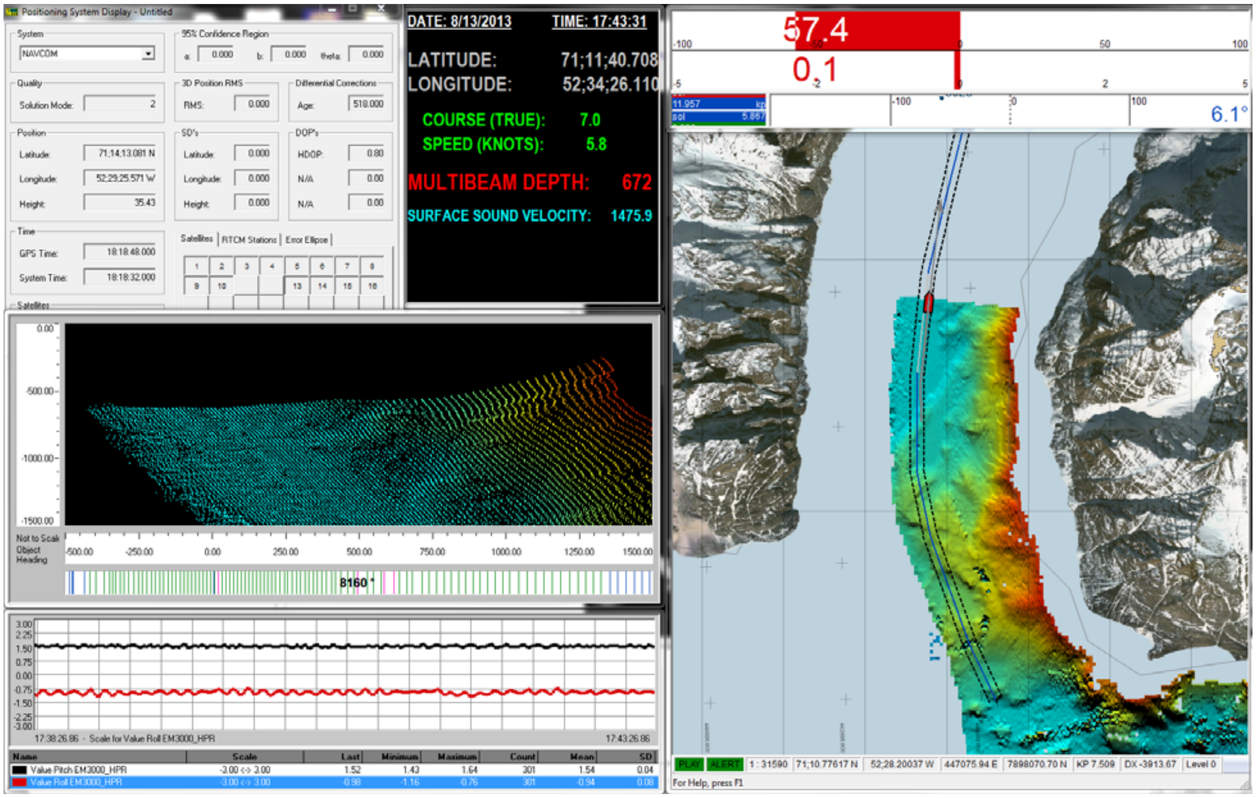


Figure 10 – QPS Acquisition Screen

6.0 CTD ACQUISITION

6.1 CTD Acquisition Equipment

Equipment	S/N#	Resolution		
		Conductivity	Temperature	Pressure
Teledyne OceanScience Underway CTD	702-0243 702-0051	0.005 S/m	0.002°C	0.5dbar
AML Oceanographic Minos X CTD	30436	0.001mS/cm	0.001°C	0.02%FS

Table 4 – CTD Equipment

For full specification refer to Appendix H

6.2 CTD Acquisition Procedures

CTD cast locations were along the planned track lines at locations provided by JPL; reference Figure 9 for project distribution. At times additional casts were made on an as-needed basis for sound velocity corrections to the multibeam data.

Casts took one of several forms; underway or stationary using an Ocean Science Underway CTD (UCTD) and stationary with an Applied Micro Systems Minos-X or UCTD system probe on a heavy line. The determination of what method to use was based on ice conditions at the time of cast. When using the AML Minos probe the maximum operational depth was 500m.

The preferred method was utilizing the UCTD underway, with its high-speed winch for retrieving the probe. 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 4 knots, this required 12 minutes and 1.4km of ice free conditions. Maximum cast depth achieved while underway was 500m.

If ice conditions were unsuitable for underway casts but still not packed tight around the vessel the UCTD winch would be used with the vessel stationary. Maximum cast depths were reached using this method, with a cast to 972m.

The UCTD used a probe that was allowed to freefall for a planned amount of time based on the current depth and vessel speed. Depths were determined on a drop-rate algorithm (Figure 13), when using the UCTD winch and a measured line when using the pot puller.

Once the vessel entered thick ice pack the small line attaching the UCTD to the winch was deemed insufficient to be safely used. At this point a heavier line was attached to the Minos-X or the UCTD probe only and deployed from the side of the vessel. An electric pot puller was used to retrieve the probe from the depths, reference Figure 10. Average time for these casts was 30 minutes and maximum depths of 600m.

Refer to Appendix C for CTD cast depths and locations.

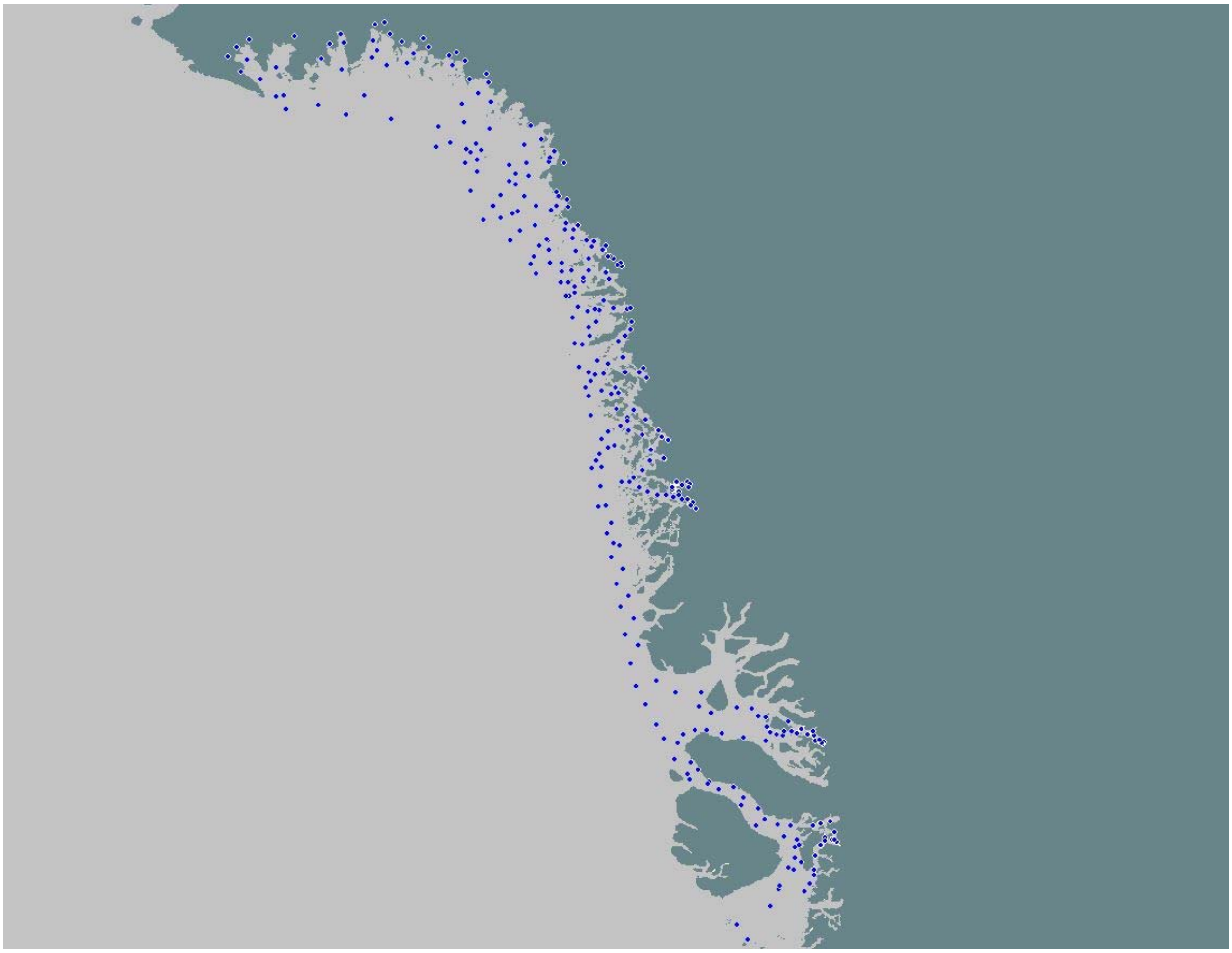


Figure 11 – CTD Cast Distribution

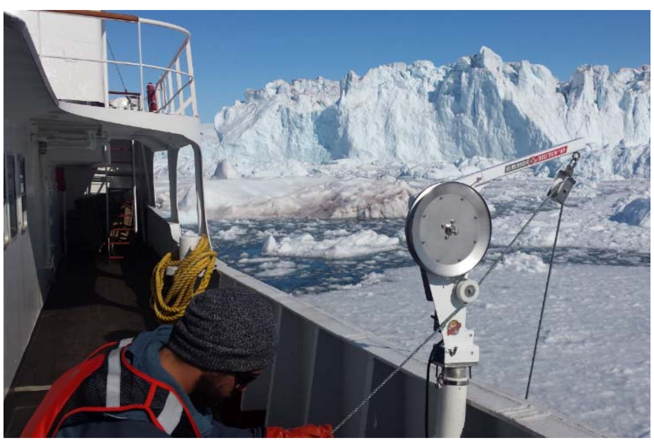


Figure 12 - CTD Cast in Heavy Ice and UCTD cast

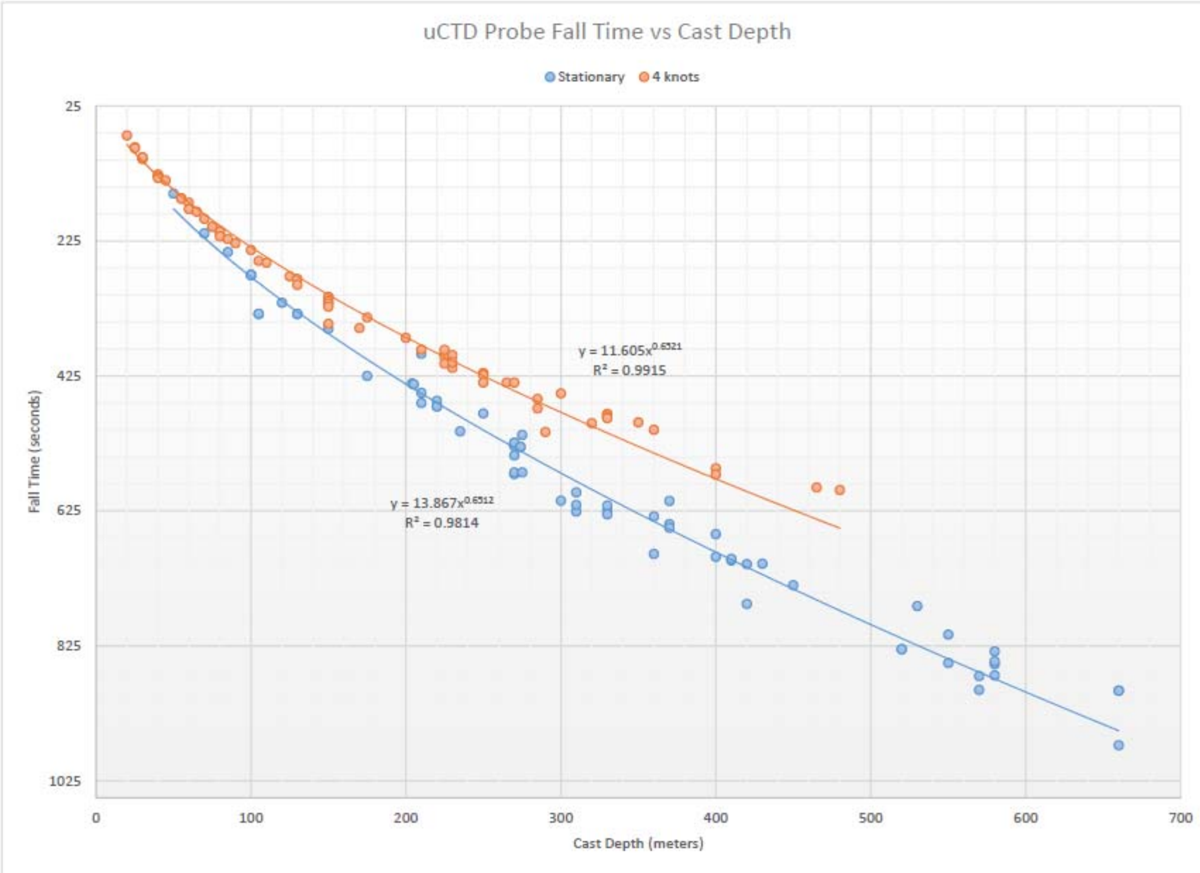


Figure 13 – UCTD freefall time versus depth.

6.3 CTD Acquisition Statistics

Project averages for CTD cast metrics were calculated and are shown in Table 4.

No. of Days	Total CTD Cast	Average Interval Between successive cast	Average Depth (m)
44	309	3 Hours 15 mins	450.6

Table 5 – Acquisition Statistics

As a check on the continuity of the computed sound velocity data, daily plots were generated for comparison, an example of which is shown in Figure 14.

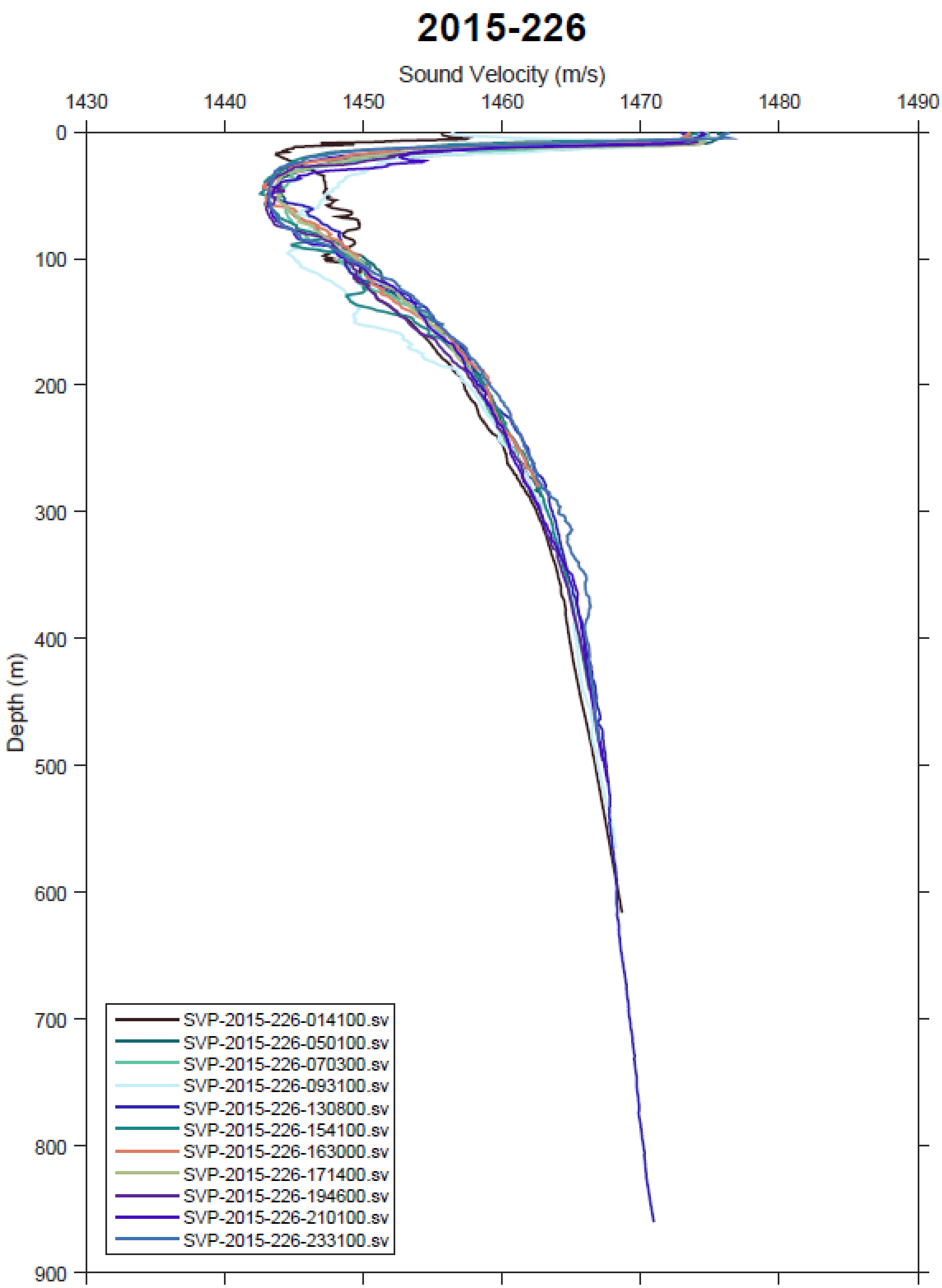


Figure 14 – Typical One Day Sound Velocity Variations

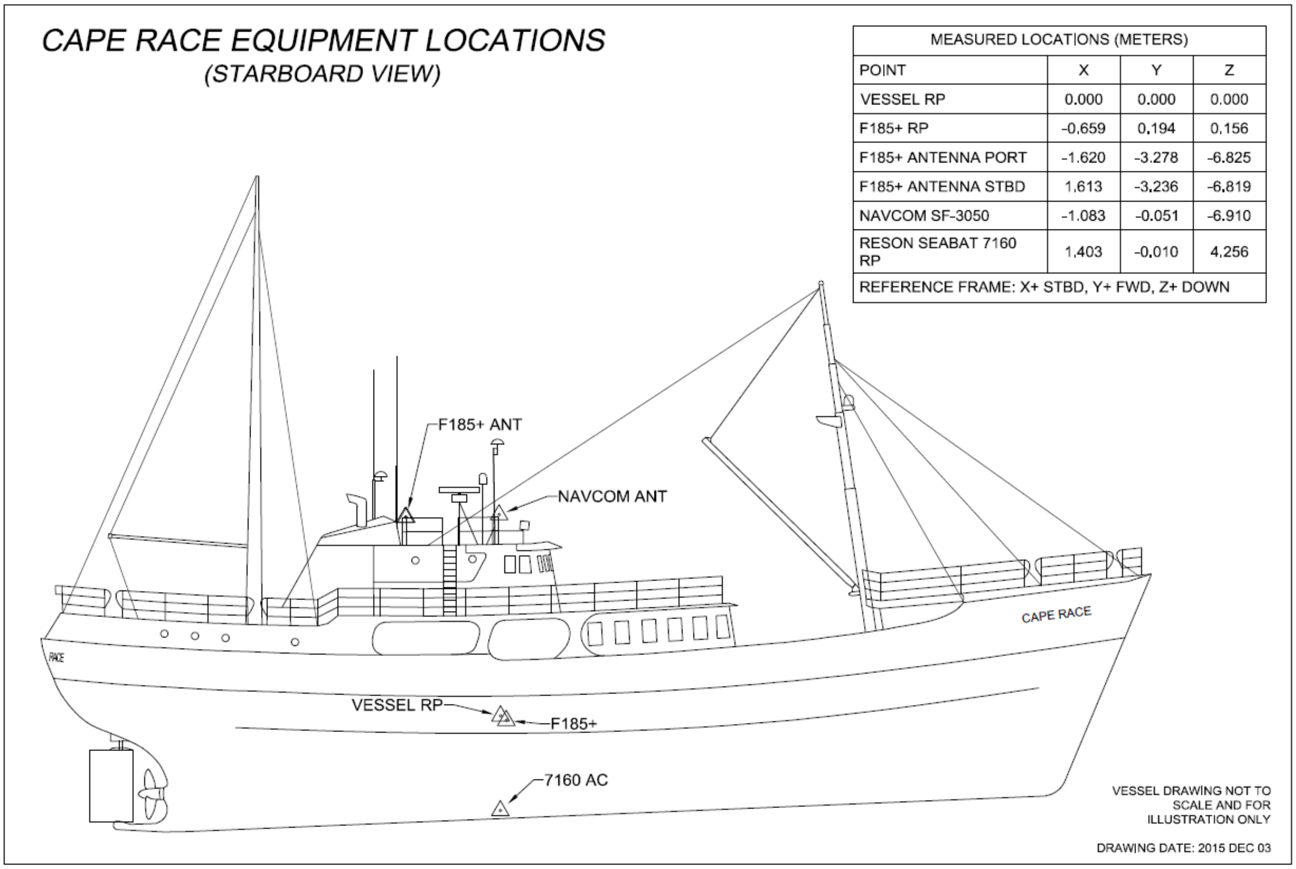
7.0 VESSEL CORRECTIONS

7.1.1 Vessel Survey

A vessel survey of the Cape Race was completed to establish a frame of reference for all navigation and bathymetric sensors. This survey was completed, between June 22nd and July 6th, 2015, while the vessel was dry docked in Belfast, Maine.

The survey was completed using conventional land survey equipment and techniques. From an arbitrary baseline established alongside of the vessel, a total station was used to determine horizontal coordinates of points on the vessel. Using a level, vertical values for each of these points was then determined.

AutoCAD was used to reduce these arbitrary coordinates to a vessel-based coordinate system. Rotations about the X-axis, for the pitch of the vessel, were used to bring water line marks at both ends of the hull to the same plane. Similar rotations about the Y- and Z-axes brought the port and starboard gunnels to the same plane and aligned the keel of the vessel with the Y-axis. A final shift was applied to locate the origin of the coordinate system at the Central Reference Point (CRP) of the vessel. The CRP is located in the engine room, along the center line of the vessel at approximately the waterline.



MEASURED LOCATIONS (METERS)			
POINT	X	Y	Z
VESSEL RP	0.000	0.000	0.000
F185+ RP	-0.659	0.194	0.156
F185+ ANTENNA PORT	-1.620	-3.278	-6.825
F185+ ANTENNA STBD	1.613	-3.236	-6.819
NAVCOM SF-3050	-1.083	-0.051	-6.910
RESON SEABAT 7160 RP	1.403	-0.010	4.256
REFERENCE FRAME: X+ STBD, Y+ FWD, Z+ DOWN			

Figure 15 – Vessel Offsets

7.2 Heading and Inertial Sensor Calibration

The heading offsets and attitude alignment of the Coda F185+ 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 heading errors common with a GNSS only heading system are due largely to GNSS receiver noise and multipath errors. By combining the Coda F185 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 July 25th 2014, at Latitude 69° 12’ 00” N and 51° 53’ 00” W Longitude. The patch values for pitch, azimuth (yaw), and roll were resolved using the processing software CARIS 9.0.20.

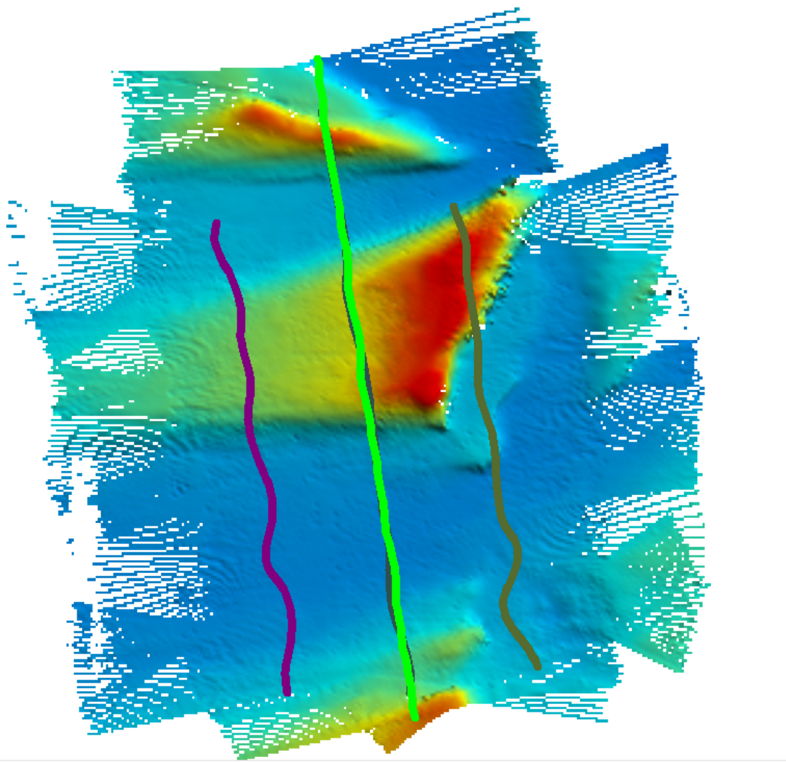


Figure 16 – Patch Test Feature

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 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.

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.

8.2 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.

MEASURED LOCATION (METERS)			
Point	**X**	**Y**	**Z**
Vessel RP	0.000	0.000	0.000
F180 RP	-0.659	0.194	0.156
F180 Antenna Port	-1.620	-3.278	-6.825
F180 Antenna Stbd	1.613	-3.236	-6.819
Navcom SF-3050	-1.083	-0.051	-6.910
Reson Seabat 7160 AC	1.403	-0.010	4.256

Table 6 – Sensor offsets onboard the M/V Cape Race

Date	Time	Sensor	Pitch (°)	Roll (°)	Yaw (°)
7/24/2015	00:00	Swath-SVP	-0.620	-1.480	1.450
9/6/2015	12:40	Swath-SVP	-0.620	-1.480	-2.830
9/6/2015	17:37	Swath-SVP	-0.620	-1.480	1.450
9/8/2015	04:09	Swath-SVP	-0.620	-1.480	-2.830
9/8/2015	05:09	Swath-SVP	-0.602	-1.480	1.450
9/13/2015	08:00	Swath-SVP	-0.602	-1.480	-2.830
9/13/2015	11:01	Swath-SVP	-0.602	-1.480	1.450
9/17/2015	12:30	Swath-SVP	-0.620	-1.480	-2.830
9/17/2015	14:03	Swath-SVP	-0.620	-1.480	1.450

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

Table 7 – Caris Patch Test Values

8.3 Tide

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

8.4 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.

8.5 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.

8.6 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.

8.7 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.

8.8 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.

8.9 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.

8.10 Subset Cleaning

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 erroneous were rejected manually throughout each region.

9.0 CTD TO SVP PROCESSING STEPS

Data collected at the client-supplied CTD sites were used for the calculation of the sound speed of water and used for the post-processing corrections of the multibeam data. To convert the CTD data to sound velocity, the program SBE Data Processing Win-32 was used for both the AML and UCTD data. The following steps were used for the calculation of Sound Velocity for the UCTD Probe. For the calculation of Sound Velocity using the AML step Number 2 was not conducted.

1. The raw *.asc file is imported into the SBE Data Processing Software; the columns and the scan rate are defined. The data are then exported to a known format *.cnv file.

2. The CTD data are then aligned using the *.cnv file created. The alignment is done due to the differing response time of the sensors, acquiring data at 16Hz can produce spiking in the salinity data when the temperature in the water column changes rapidly. In an effort to mitigate this artifact the alignment is done.

3. Salinity is calculated in Practical Salinity Units (PSU) via the Derive function in the Software using the PSS-78 algorithm.

4. Sound Speed and Depth are then computed using the Derive function in the Software using the Chen and Millero equation. A latitude of 71° was entered for all depth calculations.

5. The data were binned every 1m on the up cast.

6. The computed 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 Total Propagated Error 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). 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

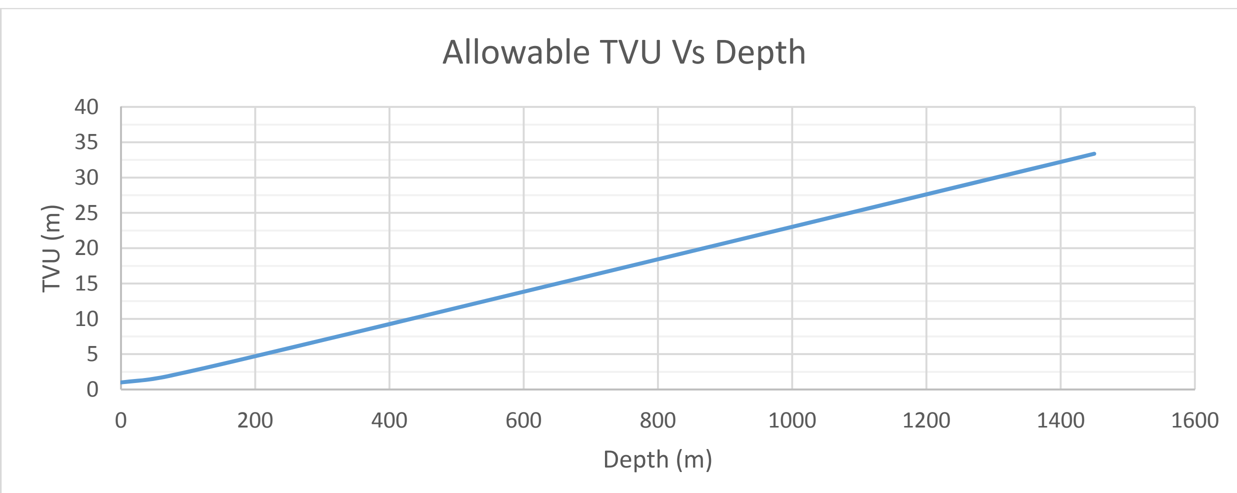


Figure 17 – Allowable Total Vertical Uncertainty, IHO Order 2.

10.2 Multibeam Crossline Analysis

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. Figure 18 shows the combined statistics from all five crossline analyses. Approximately 36000 soundings were analyzed.

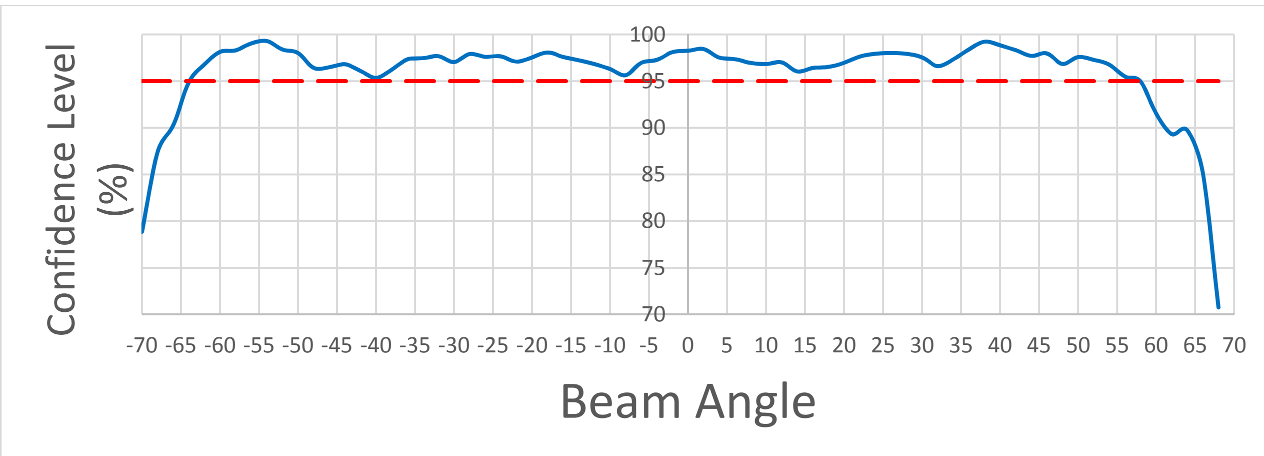


Figure 18 – Confidence Level Verses Swath Angle

The figure depicts that beams beyond approximately 60-65⁰ from nadir starts to deteriorate and falls below the 95% confidence level. A lower percentage of the soundings beyond 65⁰ met the IHO Order 2 accuracy specification. The lower accuracy of the outer beams is a function of refraction error, increased beam footprint size and susceptibility to pitch and roll error compared to the nadir beams.

Generally soundings beyond 70° were rejected from inclusion in the final gridded dataset; however, soundings from these beams were maintained as much possible to maximize the multibeam data coverage at the expense of lower accuracy in the outer edges of the swath. Particularly noisy data was filtered from the final dataset.

The Total Horizontal Uncertainty (THU) of the soundings were well within specification as the positioning system provided centimeter level of accuracy.

10.3 Data Quality

Generally, the data quality was very good. While only beams 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 are systematic, but not correctable due to the resolution of the sensor data or the spatial frequency of the sound velocity profiles.

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, see Figure 19.

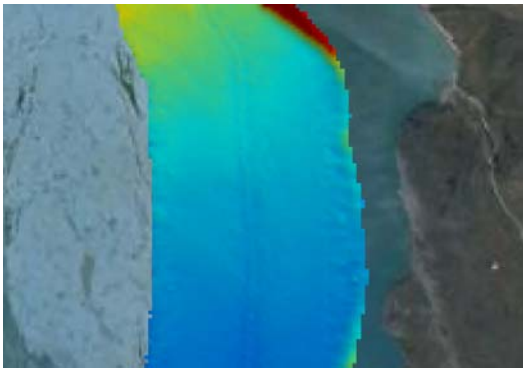


Figure 19 - Nadir Artifact induced by soft sediment

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, see Figure 20.

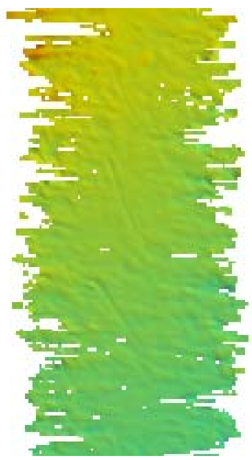


Figure 20 - Typical motion artifact

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, see Figure 21.

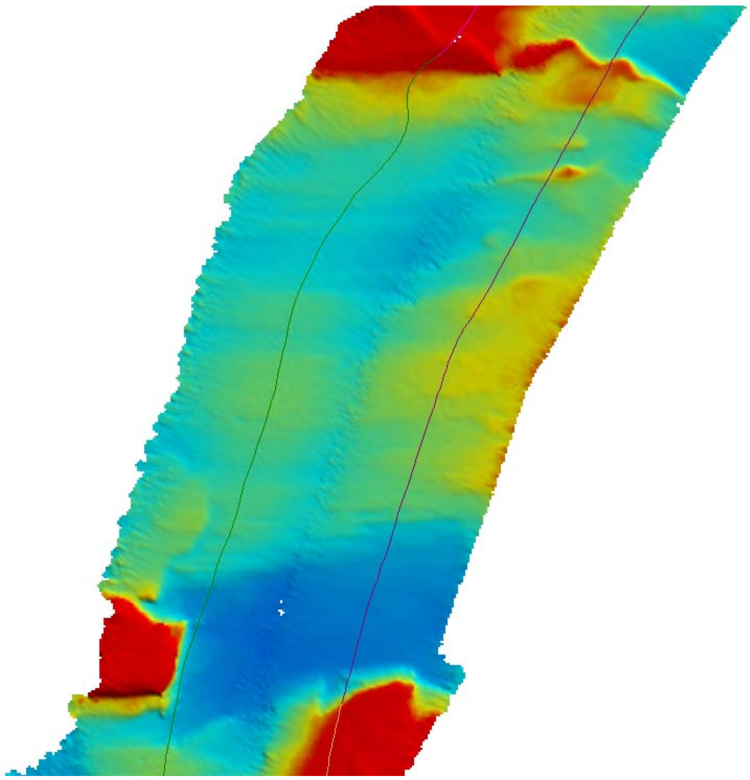


Figure 21 - Typical refraction artifact

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 *.kml files.

12.0 DELIVERABLES

12.1 Bathymetry Data

12.1.1 Gridded Points

Two 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 (21,517,190 points) and 50m (5,493,704 points) and are named as follows:

1. OMG-2015-25m_DecDeg_ASCII.TXT
2. OMG-2015-50m_DecDeg_ASCII.TXT

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 9^{th} decimal point. The exports are as follows:

1. OMG_2015_1min_Trackline
2. OMG_2015_10sec_Trackline

Google Earth KML 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_2015_Glacier_Photos
2. OMG_2015_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 21, meters. In order to keep the file size manageable, the images were broken into four regions. A small amount of overlap exists between adjacent regions. They are provided to give a graphical representation of the data provided in the ASCCI data files.

1. Disko Bay
2. Uummannaq
3. Upernavik
4. Melville Bay