

RVIB Nathaniel B Palmer  
EM122 Multibeam Echosounder  
Sea Acceptance Trials  
NBP1405  
June 14 – June 19, 2014

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*Cover image: The RVIB Nathaniel B Palmer in Puerto Montt, Chile.*

## Executive Summary

The Kongsberg Maritime (KM) EM120 multibeam echosounder (MBES) aboard the RVIB Nathaniel B. Palmer (NBP), installed in 2002, recently received two upgrades through the installation of a KM Seapath 330 position and attitude sensor (November, 2013) and replacement of the original EM120 transceiver with an EM122 transceiver (June, 2014). In conjunction with the EM122 Harbor Acceptance Trials (HAT) and Sea Acceptance Trials (SAT) performed by KM field engineers, the Multibeam Advisory Committee (MAC) participated in cruise NBP1405 to review the MBES system configuration, perform a calibration for angular offsets between the Seapath 330 and MBES, and assess swath coverage and bathymetric accuracy. The configuration review and calibration proceeded normally, yielding sensor offsets which should be maintained until sensors are moved or new surveys are performed. Conversely, results of the MBES performance assessment require immediate attention for the efficiency and effectiveness of upcoming scientific mapping programs aboard the NBP.

Of primary concern, MBES swath coverage and accuracy are degraded compared to manufacturer specifications, original SAT performance in 2002, and an EM122 recently installed aboard another UNOLS vessel. Symptoms include a 33% reduction in effective swath width in waters deeper than ~1500 m and a 50% increase in standard deviation of depths reported across the swath compared to data collected with fully functional systems. Unlike typical MAC evaluations, the limitations in swath width and artifacts in depths observed during NBP1405 required modification of survey lines for data collection and filtering of outliers for data analysis.

The symptoms documented in this report are consistent with weak transmission signal strength related primarily to failure of transmit (TX) array elements. According to KM analysis during NBP1405, about 11% of TX array elements exhibited impedance anomalies; this finding exceeds the manufacturer specifications for a fully functional TX array. Other factors compounding the weak transmission signal strength include damage to the TX array ice window and acoustic attenuation from bubbles swept beneath the arrays.

Of particular note, the EM122 transceiver is capable of frequency-modulated (FM) transmission modes which are expected to increase the effective swath width compared to the original EM120. FM transmission is used widely amongst other UNOLS vessels. It is possible to operate the NBP's EM120 TX array in FM mode, however, this would likely accelerate degradation of array elements and was not attempted during NBP1405 at the recommendation of KM field engineers.

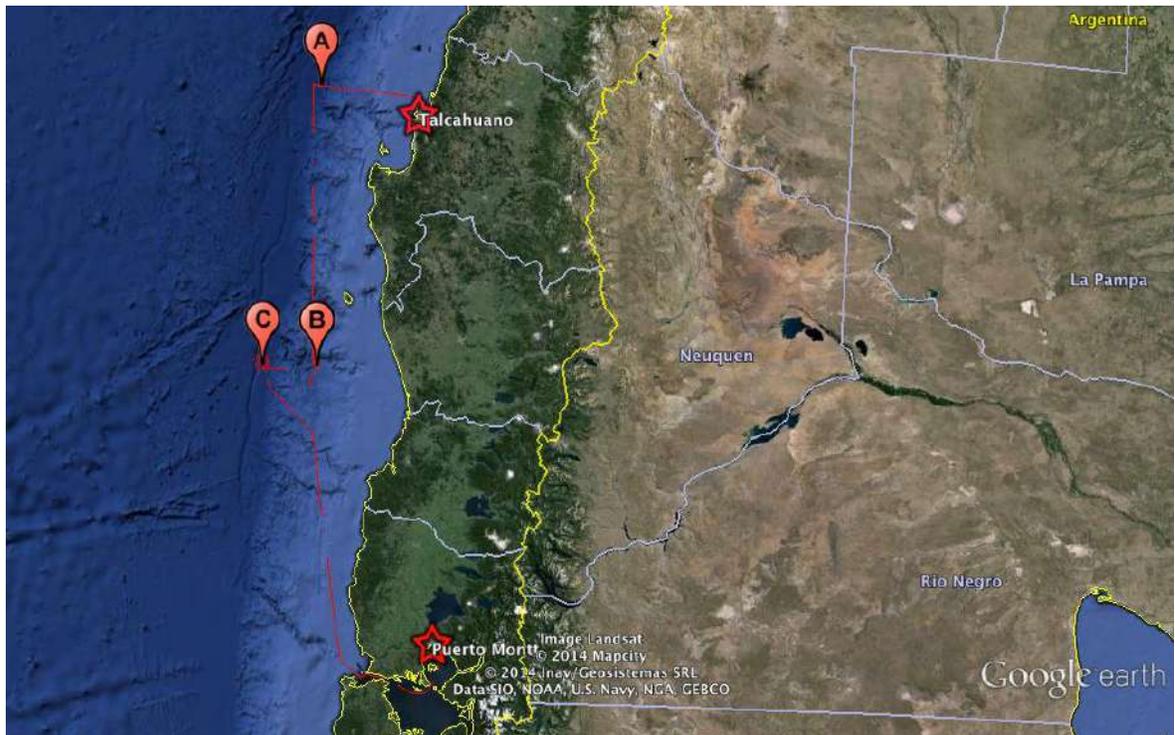
Based on the observed high rate of EM120 TX array element failure and likely prohibitive cost of individual module replacement, it is recommended that the EM120 TX array be replaced with an EM122 TX array at the next opportunity. Replacement would also address damage to the existing ice window and facilitate improvements in swath width using FM transmission. Additional consideration should be given to placement of both the TX and RX arrays to minimize exposure to bubble sweep. To ensure a comprehensive record of sensor offsets, a survey of MBES arrays, motion sensors, and antennae should be performed in dry dock and reported in a reference frame using KM conventions. Finally, a schedule should be implemented for routine Built-In Self-Tests (BISTs) to document element conditions over the effective lifecycle of the MBES arrays.

## Introduction

The research vessel icebreaker (RVIB) *Nathaniel B. Palmer* (NBP) undertook cruise NBP1405 in the vicinity of the continental shelf break between Talcahuano and Puerto Montt, Chile, from June 14-19, 2014 (Fig. 1) to perform a review of the vessel's multibeam echosounder (MBES). The MBES consists of Kongsberg Maritime (KM) EM120 transmit (TX) and receive (RX) arrays, both installed in 2002, and an EM122 transceiver unit installed in June 2014, immediately prior to NBP1405. The primary objectives of NBP1405 were to work with KM representatives during the Sea Acceptance Trials (SAT) of the EM122 transceiver, review the system geometry and configuration, and perform a calibration of the angular offsets between the echosounder and primary motion sensor. Paul Johnson and Kevin Jerram provided logistical and technical support for data collection and analysis.

This report:

1. Describes the data collected
2. Provides an overview of the processing methods used on the data
3. Presents the EM120/122 system performance for accuracy in deep water and swath coverage over the operational depth range during NBP1405
4. Documents changes made to the system configuration
5. Provides recommendations for future work



**Figure 1.** Red line shows the ship track for areas where multibeam data was collected during NBP1405. Stars indicate starting and ending ports. Marker A is calibration site 1, marker B is calibration site 2, and marker C is the reference surface and accuracy test site.

## Cruise Participants

Tim McGovern, NSF	Skip Owen, ASC
Mario Andino, Chilean Navy	Jeremy Lucke, ASC
Tony Dahlheim, Kongsberg	Joe Tarnow, ASC
Andrew Stradling, Kongsberg	Scott Walker, ASC
Paul Johnson, UNH-CCOM	Ross Hein, ASC
Kevin Jerram, UNH-CCOM	Andy Nunn, ASC
Tim Gates, Gates Acoustic Services	Kathleen Gavahan, ASC
Marisa Yearta, Gates Acoustic Services	Ethan Norris, ASC
	Adam Jenkins, ASC

## Survey System Components

The mapping system consists of the following primary components:

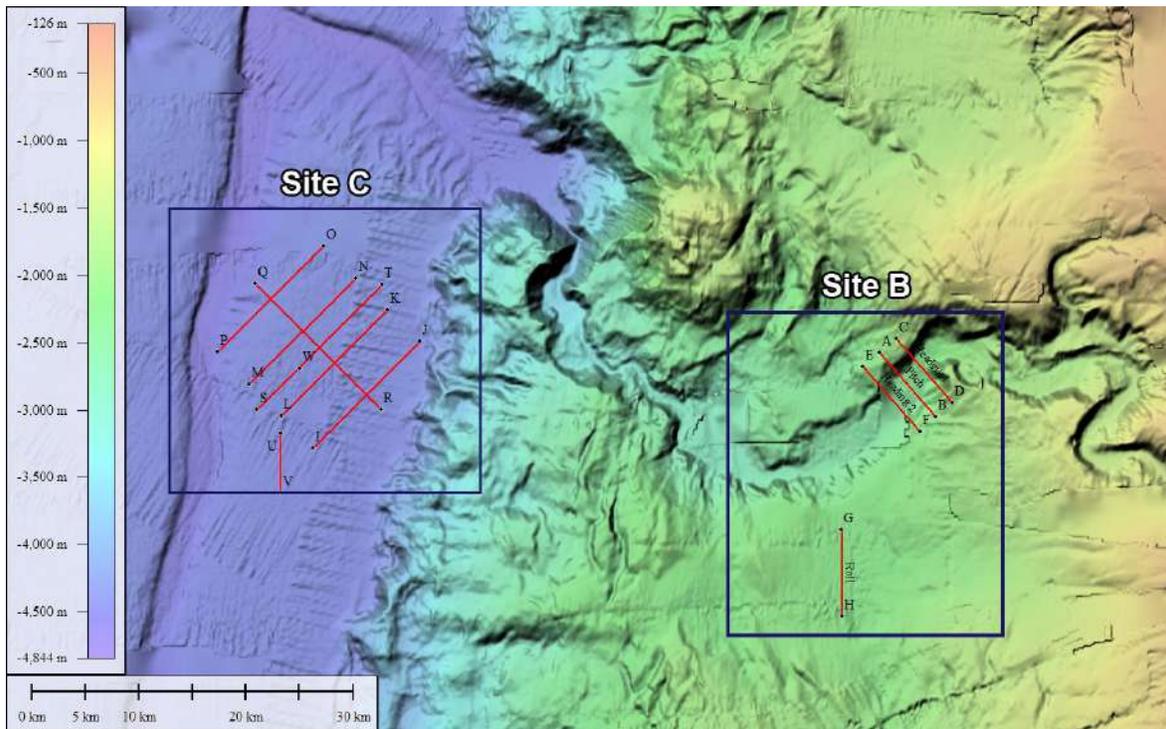
1. KM EM120 MBES arrays (12 kHz, 1° TX by 2° RX)
2. KM EM122 MBES transceiver
3. KM Seafloor Information System (SIS)
4. KM Seapath 330 vessel navigation system
  - o Seapath 330 GNSS antennae
  - o Seatex MRU-5, s/n 20934 ('Seapath 2' installed in 2013)
5. Surface sound speed sensor
6. Sippican expendable bathythermograph (XBT) profiling system

## Activities

Cruise activities by various participants included:

1. UNH CCOM
  - a. Review of documentation for linear and angular offsets of MBES components
  - b. Calibration for angular offsets ('patch test')
    - i. Figure 2, Site B
  - c. Creation of a reference surface
    - i. Figure 2, Site C
  - d. Accuracy evaluation with respect to the reference surface
  - e. Coverage/extinction testing on and off the continental shelf break
  - f. Installation and verification of Sound Velocity Profile Editor software
    - i. See <http://mac.unols.org/resources/tool-sound-velocity-profile-svp-editor-v105> for more information
  - g. Recommendations for data processing workflow
    - i. Discussed with MBES operators and not documented in this report

2. Kongsberg Maritime (See KM reports for more information)
  - a. EM122 Harbor Acceptance Trial (HAT)
  - b. EM122 BIST checks
3. Gates Acoustic Services (see GAS reports for more information)
  - a. Vessel and machinery acoustic noise testing



**Figure 2. Layout of operational areas for EM122 trials (using historic multibeam echosounder data downloaded from the National Geophysical Data Center). Site B was used for calibration and Site C was used for accuracy testing.**

## Overview of System Geometry

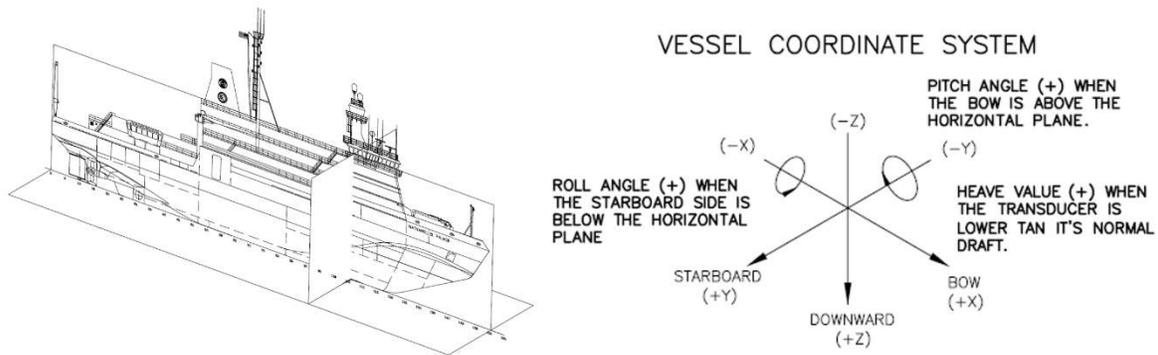
In this report, we use the term ‘system geometry’ to mean the reference frames of the vessel and the linear and angular offsets of the primary components of the multibeam mapping system, including the transmit array (TX), receive array (RX), and ship navigation sensor (‘Seapath 2’ MRU). These parameters are critical for data collection in an unbiased and repeatable manner.

NOTE: Due to time constraints, only the ‘Seapath 2’ MRU (installed in 2013) was calibrated for angular offsets; the parameters for the original ‘Seapath 1’ MRU (installed in 2002) remain undetermined. A separate patch test **must** be performed using the ‘Seapath 1’ MRU if this motion sensor is to be used for position and attitude feed to the MBES.

## Reference Frames

Two distinct reference frames have been employed for sensor configuration aboard the NBP since 2002. A primary reference frame was established during installation of the EM120 arrays by a ship survey performed (or contracted) by KM on July 10, 2002. This survey defines a right-handed

coordinate system with origin at the center of the RX array face using axis orientations and sign conventions in agreement with KM conventions (Figure 3). Though it may be more common aboard other ocean mapping vessels to define MBES reference frames with origin at either the TX array or MRU, the 2002 reference frame with origin at the RX array is used for all offsets in SIS aboard the NBP.



**Figure 3. NBP primary reference frame established during array installation in 2002. The origin is at the center of the RX array face. Image adapted from ship survey drawing 881-121282 (13 Sept 2002, '121282 Drawing1.pdf') provided by Kathleen Gavahan.**

A secondary reference frame was established during a survey performed (or contracted) by Kongsberg for installation of a second MRU ('Seapath 2') on November 17, 2013, in Talcahuano, Chile. This reference frame has an origin at survey point 'center of gravity' (CG) along the centerline and near the vertical and alongship centers of the vessel. It is unclear whether a physical marker exists at the point CG referenced in this survey. Offsets determined in this secondary reference frame were converted to the primary reference frame used in SIS.

The primary reference frame is documented in a single ship drawing and Excel spreadsheet. No additional survey documentation appears to be available for the primary reference frame. Likewise, the secondary reference frame is documented in a single Excel spreadsheet and referenced in the KM MRU installation report from 2013. Again, no additional survey documentation appears to be available. Without the opportunity to review survey reports from 2002 and 2013, the reference frames and offsets documented in the ship drawing and Excel spreadsheets must be used for this review.

All SIS configurations discussed herein are with respect to the primary reference frame with origin at the center of the RX array face, unless otherwise noted.

### TX and RX Arrays

Linear offsets of the TX and RX arrays in the primary reference frame were determined during the 2002 ship survey. A drawing and Excel spreadsheet with linear offsets are available, but no accompanying survey reports were known to exist at the start of NBP1405. The Excel spreadsheet includes zeroes for all array angular offsets except the TX array azimuth (Table 1).

The spreadsheet states that the TX and RX arrays were 'shimmed to level.' It is unclear whether the vessel and its reference frame were determined to be level during the survey or simply assumed to be level to yield zero roll and pitch array offsets after shimming. Though array offsets are not expected to have changed since the original survey or be a significant source of error in

data collected during NBP1405, a new survey of the arrays should be performed to confirm or negate the 2002 array offsets. A new survey will be mandatory if either or both of the arrays are replaced and should be reported using all conventions consistent with the KM reference system.

## MRU

The NBP is equipped with two Seatex MRU-5 motion sensors with Seapath 200 ('Seapath 1') and Seapath 330 ('Seapath 2') topside processing units. It is believed the Seapath 200 replaced a Seapath 2000 referenced in the 2002 survey, although this upgrade maintained the existing MRU installation. In November 2013, the Seapath 330 was installed with a secondary MRU located directly above the original MRU. Offsets to both MRUs were resurveyed in the secondary reference frame (with origin at CG), recalculated in the primary reference frame (with origin at the RX array), and documented in an Excel spreadsheet. No additional MRU survey documentation was available at the start of NBP1405.

Linear offsets for the original MRU in the primary reference frame documented in 2002 agree to within a few millimeters with those from the 2013 survey (Table N). No angular offsets for either MRU were determined in either survey, as these values are determined through patch testing.

Survey Result	X (m)	Y (m)	Z (m)	Roll (°)	Pitch (°)	Yaw (°)
<b>TX Array Center (2002)</b>	-10.28	+4.84	-0.06	0.00	0.00	359.98
<b>RX Array Center (2002)</b>	0.00	0.00	0.00	0.00	0.00	0.00
<b>Seapath 2000 MRU-5 (2002)</b>	+0.39	-0.10	-3.15	0.00	0.00	0.00
<b>Seapath 200 MRU-5 (2013)</b>	+0.383	-0.100	-3.147	-	-	-
<b>Seapath 330 MRU-5 (2013)</b>	+0.485	-0.098	-3.198	-	-	-

**Table 1. Survey results for linear and angular offsets in the primary reference frame.**

Prior to Seapath 330 installation, the SIS configuration included a roll offset of +0.05° for Seapath 200 attitude data. Pitch and yaw offsets were zero. At the start of NBP1405, SIS was configured to utilize Seapath 330 attitude and position data. All angular offsets for attitude data were set to zero in SIS to provide a 'clean slate' for patch testing. It is noted that any nonzero array angular offsets will be coupled into (and, in this process, inseparable from) the patch test results for MRU angular offsets.

## Seapath and SIS Configurations

A review of the Seapath 330 and SIS configurations revealed a possible mismatch between the shipboard locations at which the attitude and position data were referenced (or considered 'valid') in each system. The Seapath 330 was configured using the secondary reference frame (origin at CG) to provide attitude and position data valid at the Navigation Reference Point (NRP) coincident with CG. SIS linear offsets were configured to accept attitude and position data valid at the Seapath 330 MRU location. It is expected that this mismatch would have led to alongship, athwartship, and vertical offsets in bathymetric data equal to the differences between the NRP/CG location and the Seapath 330 MRU location. These offsets may have also impacted previous patch test results, particularly for pitch. To reconcile the Seapath and SIS configurations,

Seapath output was set to a 'Monitoring Point' (MP1) which had been created previously to calculate attitude and position at the 'Seapath 2' MRU location. SIS linear offsets for attitude and position data (valid at the 'Seapath 2' MRU location) were left unchanged.

## Calibration

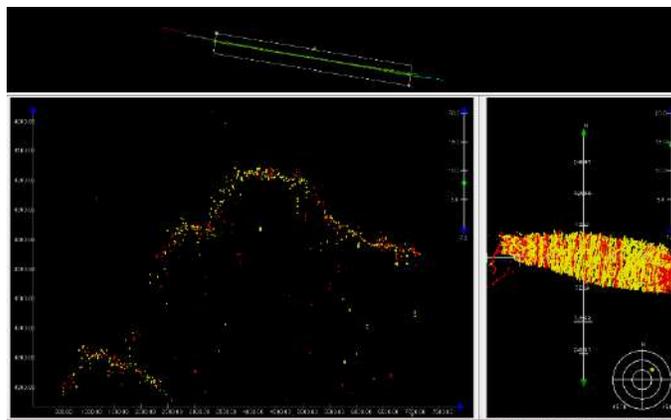
A patch test was first attempted near the continental shelf break west-northwest of Talcahuano (Fig. 1) as the first survey activity of NBP1405 to determine angular offsets of the Seapath 330 MRU. Descriptions of the rationale for calibration line planning are available in the *Cookbook for Caris HIPS 8.1 Patch Test with Kongsberg EM302* (though other details of this cookbook may not apply to NBP1405). A challenge in patch test line planning in this region had been the selection of areas in deep water (4,000+ m) with closely spaced seafloor features conducive to pitch, roll, and heading offset calibration. To increase the alongtrack sounding density on the calibration lines and attempt to reduce bubble sweep beneath the bow, vessel speed was reduced from typical survey speed of ten knots to six knots over ground. An XBT profile was acquired to 1830 m depth and applied in SIS prior to the pitch calibration lines.

Original planning for the patch test would have had the system configured to operate in DEEP mode with dual-swath and FM enabled (both capabilities added through the EM122 topside upgrade). However, during the Harbor Acceptance Testing conducted by KM it was noted that more than 10% of the TX elements did not pass the system's Built In Self Test (BIST) due to impedance anomalies. The original EM120 TX array was not designed to handle FM transmit modes, so FM capabilities were disabled to avoid potentially damaging further elements in the TX array. (Note: the TRU firmware was modified to prevent FM transmission regardless of the selection to enable or disable FM in SIS.) Because of this limitation the patch test was instead run in DEEP mode with dual-swath enabled and constrained swath width to increase alongtrack sounding density.

Heading into a swell, the EM122 had significant difficulty tracking the seafloor and providing swath coverage beyond 40° in DEEP mode (15 ms CW TX pulse). More consistent bottom tracking and broader swath coverage were obtained by switching the EM122 to VERY DEEP mode (22 ms CW TX pulse), though this mode does not support dual-swath transmission. Accordingly, the EM122 was configured as follows for the first calibration attempt:

Depth mode:	VERY DEEP
Transmit mode:	CW
Dual-swath mode:	not available
Yaw stabilization:	enabled (rel. mean heading)
Pitch stabilization:	enabled
Beam spacing:	High density equidistant
Swath width:	Pitch: 15°/15° port/stbd

Calibration data were collected using zeroes for all attitude angular offsets in SIS. However, the first patch test attempt at Site A in water depths of 4200-4600 m was abandoned due to difficulty tracking the seafloor bottom and associated failure to provide a sounding density near nadir which was sufficient for pitch calibration (Fig. 4).



**Figure 4. Sparse and noisy soundings near nadir from the first pitch calibration attempt in depths of 4200-4600 m.**

An alternative site (Site B in Figure 2) with suitable features at a shallower depth, approximately 2400 m, was selected with the idea that the shallower water depth would maximize signal return from the bottom and also allow for improved sounding density from a higher ping rate. As it turned out, data quality and density were sufficient for calibration at this site, when survey lines were collected on SE headings. The EM122 was configured as follows for the second calibration site attempt:

Depth mode:	DEEP
Transmit mode:	CW
Dual-swath mode:	enabled
Yaw stabilization:	enabled (rel. mean heading)
Pitch stabilization:	enabled
Beam spacing:	High density equidistant
Swath width:	Pitch: 15°/15° port/stbd (also used for latency)
	Yaw: 15°/55° port/stbd, 55°/15° port/stbd
	Roll: 60°/60° port/stbd

Survey lines for angular offset calibration were conducted at six knots in the order of pitch first, roll second, and yaw third. A latency calibration line was run at ten knots for comparison to the pitch line collected at six knots on the same heading. Independent estimates of the latency and angular offsets were made using the SIS (Johnson and Dahlheim) and Caris HIPS (Jerram) calibration tools. Final values were selected based on group discussion of the independent estimates, which typically agreed to within +/- 0.01°.

Each angular offset was updated in SIS after completion of its respective calibration procedure to minimize coupling of angular offsets in subsequent data collection. The only exception to this rule is that the latency line was collected with the same zero pitch angular offset used for the first pitch calibration line; application of the pitch offset before latency data collection at ten knots would have confounded the latency calibration. Pitch and heading lines were rerun with the calibration results entered in SIS for verification of these offsets. Roll verification was not done at calibration site B area and was instead performed using reciprocal lines during reference surface data collection (Site C in Figure 2), as it was hoped that the increase depth would magnify any residual roll bias present in the data.

## Calibration Results

Figures 5-8 depict single transects using the Caris HIPS Subset Editor calibration tool for the latency, pitch, yaw, and roll calibration data sets. Latency was determined to be negligible for this system and set equal to 0 s, though it is unclear as to whether latency of less than 1 s would be readily apparent in deep water and with relatively low-amplitude ship motion.

Each offset result in Table 2 is based on independent analyses of multiple transects in the Caris HIPS Subset Editor and SIS calibration tools. Pitch and yaw calibration results were verified and left unchanged, whereas the roll calibration result was modified from +0.33° to +0.29° after verification using reciprocal reference surface lines. All MRU angular offsets entered in SIS reflect the NBP1405 calibration results after verification.

Calibration Result	Roll (°)	Pitch (°)	Yaw (°)
Pre-NBP1405	+0.05	0.00	0.00
NBP1405 Calibration	+0.33	+0.05	+0.50
NBP1405 Verification	+0.29	+0.05	+0.50

Table 2. Summary of attitude sensor calibration results.

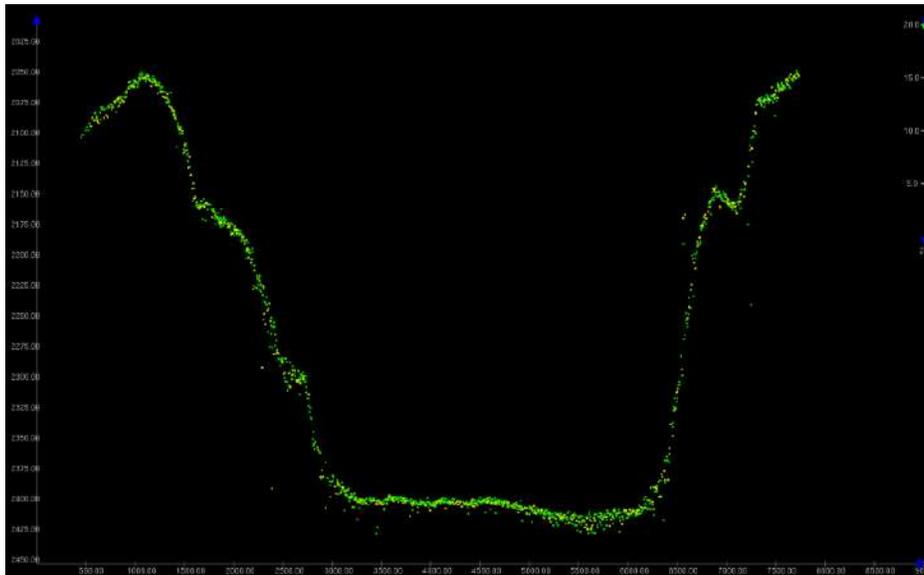


Figure 5. Latency calibration displayed in Caris yielding a latency of 0.00 s. Survey lines were collected at six and ten knots on a SE heading to reduce bubble sweep, thereby improving bottom tracking and sounding density for both lines. Due to the depth at the calibration site and resolution of the MBES, it is unclear whether a latency of less than 1 s would be visually apparent in this calibration procedure. Latency was not verified after this initial estimate.

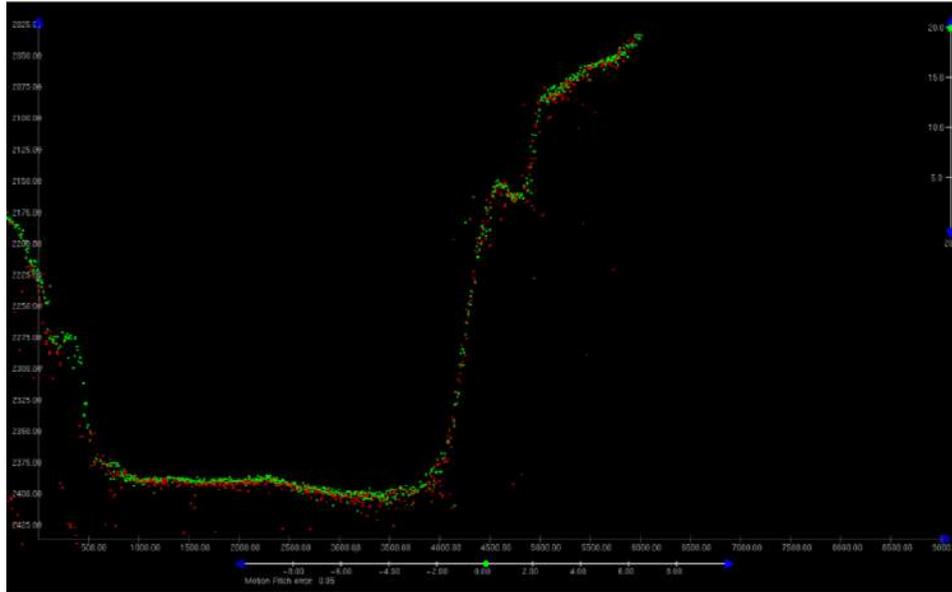


Figure 6. Pitch calibration displayed in Caris yielding a MRU pitch offset of  $+0.05^\circ$ . Survey lines were conducted on NW and SE headings, with significant bubble sweep causing frequent loss of bottom tracking on the NW heading (red points). The southern wall (center of figure) had sufficient ping density in both directions and a 'pointy' feature conducive to pitch calibration. The pitch offset was verified with repeat survey lines collected using this value.

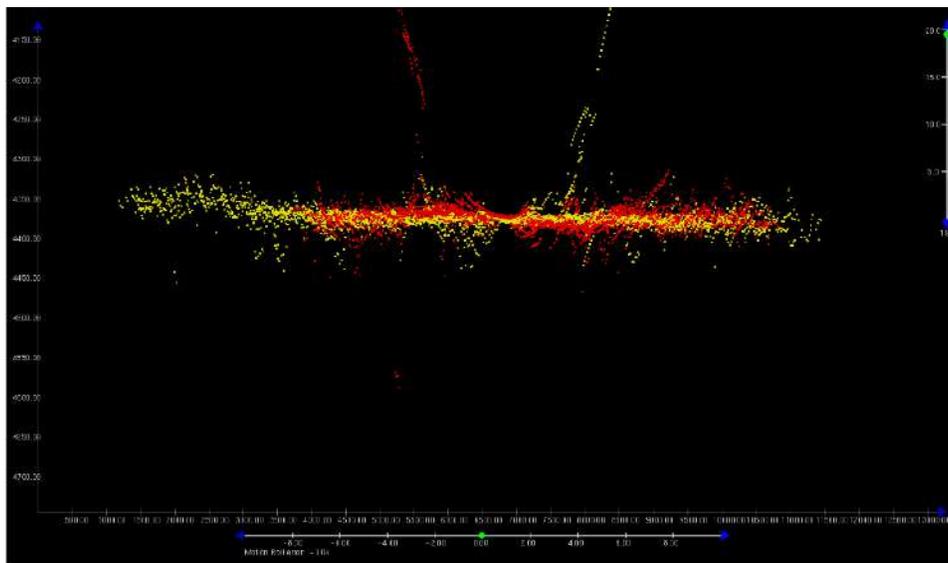
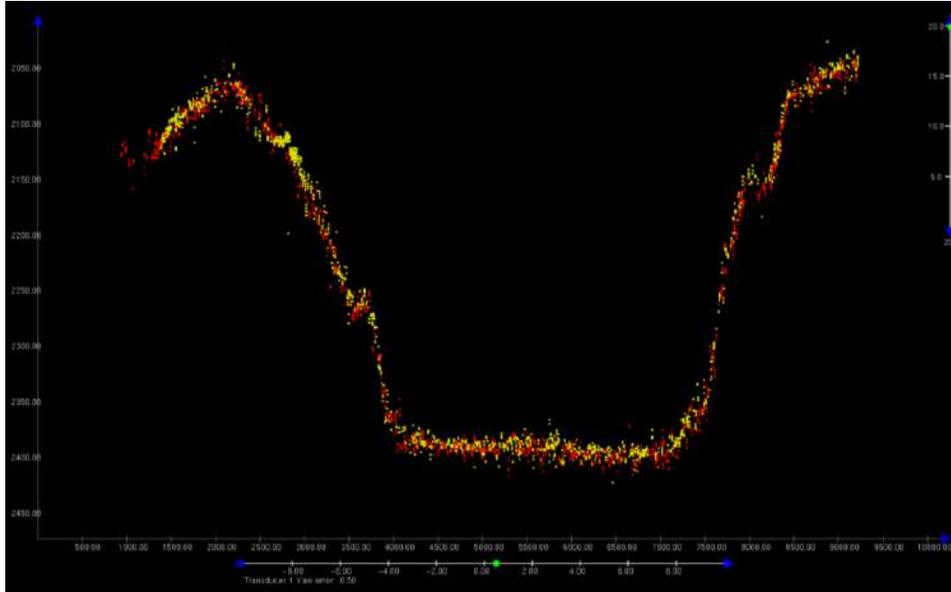


Figure 7. Roll calibration displayed in Caris yielding a MRU roll offset of  $+0.29^\circ$ . (Figure indicates  $-0.04^\circ$  correction applied during verification.) Initial survey lines were conducted on N and S headings with permissible sounding density in both directions. A slight refraction artifact was apparent in the outer beams, though this was not expected to significantly affect the initial roll calibration. The initial roll calibration offset of  $+0.33^\circ$  was refined to  $+0.29^\circ$  during verification using reciprocal lines on NE and SW headings at the reference surface site.



**Figure 8. Yaw calibration displayed in Caris yielding a MRU yaw offset of +0.50°. Survey lines were conducted on SE headings to reduce bubble sweep and produced acceptable sounding density on both walls. The yaw offset was verified with repeat survey lines collected using this value.**

The deep water roll verification was done using reciprocal cross lines from the reference surface area. Because of this all reference surface data was collected after final pitch and heading verification had been done, but prior to roll verification. From the cross line data a residual roll bias of  $-0.04^\circ$  was determined. This value was then added to the initial roll bias for a final verified value of  $+0.29^\circ$ . As the reference surface data were collected on lines separated by only one water depth (WD) with effective swath width of approximately  $45^\circ$  (providing 200% coverage between lines), the  $-0.04^\circ$  roll bias is expected to affect soundings by less than 0.1% WD across the swath. Survey lines were collected on the same heading, reducing the correlation among biased soundings in regions having 200% coverage between lines. Effects of this bias on the reference surface are further suppressed by CUBE processing and gridding the bathymetry at 200 m.

## **System Geometry and SIS Parameters (19 June 2014)**

Table 3 includes the SIS configuration for the linear and angular offsets of the TX and RX arrays and the MRU as of the end of NBP1405 on June 19, 2014. Aside from MRU angular offsets determined from the NBP1405 patch test, no modifications were expected or made to the SIS Installation Parameters. These offsets reflect best estimates of proper survey configuration based on available documentation and patch test results. All values are with respect to the KM (SIS) reference frame with origin at the center of the RX transducer face. These parameters are to be used until sensor locations or orientations are modified or it is determined that a new patch test should be undertaken.

	X (m)	Y (m)	Z (m)	Roll (°)	Pitch (°)	Yaw (°)
TX Transducer	-10.28	+4.84	-0.06	0.00	0.00	+359.98
RX Transducer	0.00	0.00	0.00	0.00	0.00	0.00
Pos, COM1	+0.4847	-0.0982	-3.1978	-	-	-
Attitude 1, COM2	+0.4847	-0.0982	-3.1978	+0.29	+0.05	+0.50

Table 3. SIS PU parameters for linear and angular offsets as of the end of NBP1405, using the center of the RX transducer face as the origin of the SIS reference frame.

## Accuracy Assessment

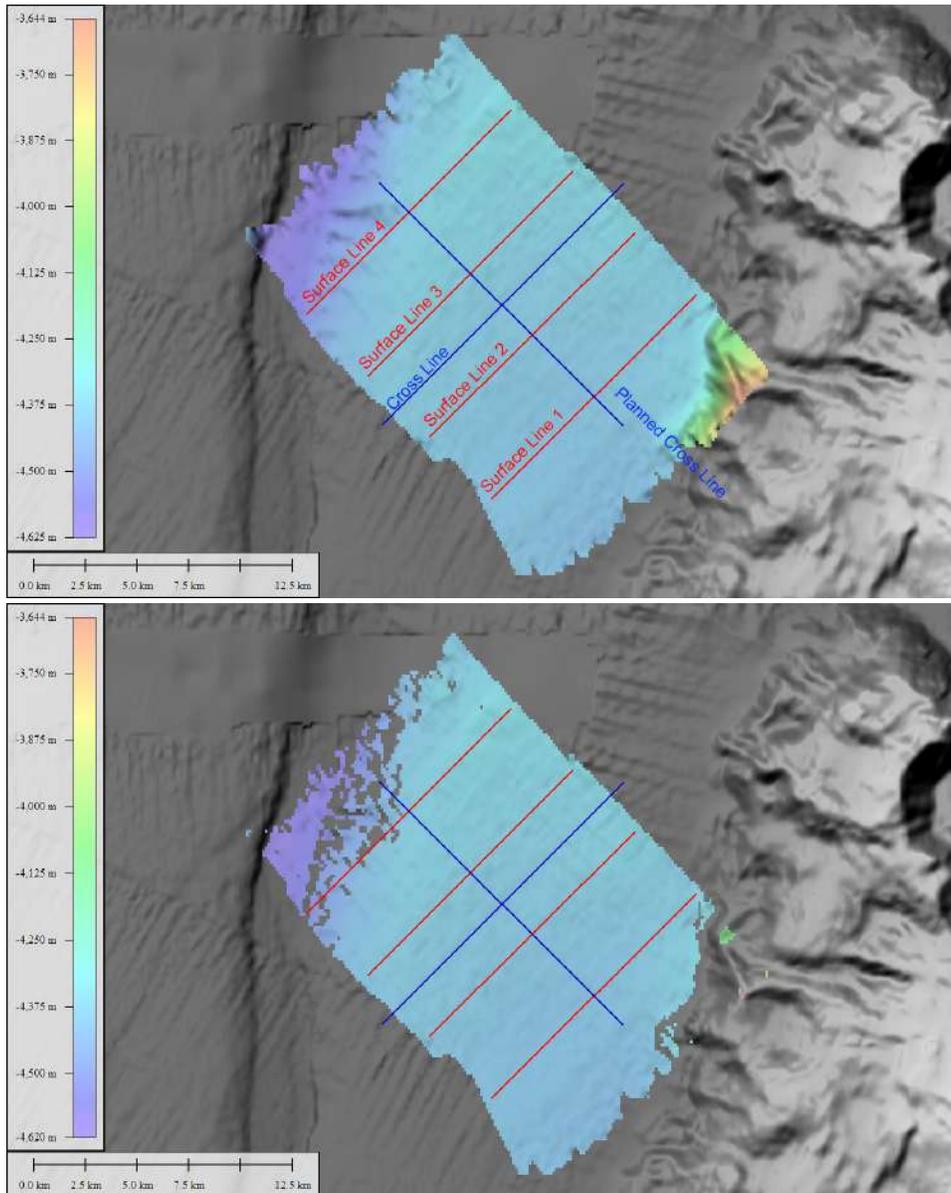


Figure 9. Overview of the reference surface area. Top figure shows the reference surface tracklines (red lines trending SW/NE), cross lines (blue lines trending SE/NW and SW/NE), and the 200 m resolution reference surface bathymetry grid (colored) overlaid on the historic bathymetry for the area (grey). Lower figure shows the results of masking the reference surface grid based on slope to remove regions with rugged topography.

A bathymetric reference surface gridded at 200 m was prepared from the main survey lines (red lines trending SW/NE) by utilizing only beams in the angular sector from +45° to -45° (see Fig. 9, top). An automated slope filter was then applied to the data to exclude areas having slopes greater than 5° from the cross line statistical analyses (see Fig. 9, bottom).

Cross lines were initially planned to be run in the orthogonal direction (SE/NW) from the surface collection lines with a vessel speed of 8 knots over ground (see blue line labeled Planned Cross Line in Fig. 9, top). However, due to increased noise and bubble sweep down from the prevailing current and wave direction it was necessary to change the orientation of the cross lines from the optimum orthogonal direction to parallel (see blue line labeled Cross Line in Fig. 9, top).

<b>SONAR RUN TIME PARAMETERS</b>	<b>Cross Line Settings 1</b>	<b>Cross Line Settings 2</b>	<b>Cross Line Settings 3</b>
<b>Sector Coverage</b>			
Max angle (port)	75	75	75
Max angle (stbd)	75	75	75
Max Coverage (port)	30000	30000	30000
Max Coverage (stbd)	30000	30000	30000
Angular Coverage Mode	AUTO	AUTO	AUTP
Beam Spacing	HIDENS EQDIST	HIDENS EQDIST	HIDENS EQDIST
<b>Depth Settings</b>			
Force Depth	n/a	n/a	n/a
Min depth (m)	3500	3500	3500
Max depth (m)	4700	4700	4700
Dual swath mode	DYNAMIC	OFF	OFF
Ping mode	DEEP	DEEP	VERY DEEP
FM disable	Unchecked	Unchecked	Unchecked
<b>Transmit Control</b>			
Pitch stabilization	ENABLED	ENABLED	ENABLED
Along direction	0	0	0
Auto Tilt	OFF	OFF	OFF
Yaw stab. Mode	REL. MEAN HDG	REL. MEAN HDG	REL. MEAN HDG
Heading	n/a	n/a	n/a
Heading filter	MEDIUM	MEDIUM	MEDIUM
Min Swath Dist	0	0	0
Enable Scanning	Off	Off	Off

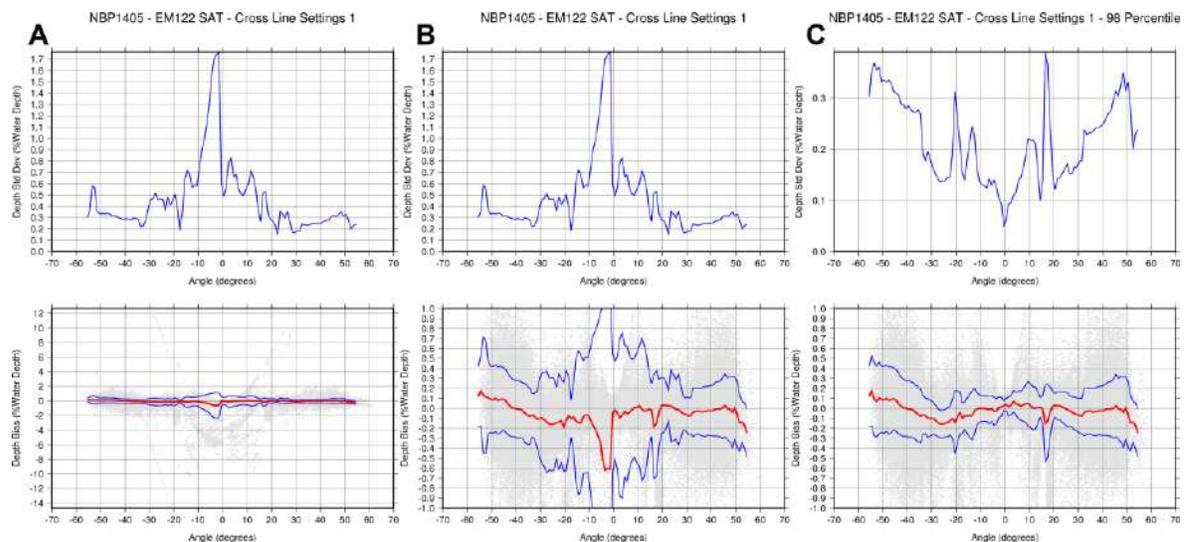
**Table 4. SIS Runtime Parameters settings for each cross line survey run over the reference surface.**

Table 4 shows the Runtime Parameters settings for each of the cross lines. Cross line settings 1 and 2 are the same except setting 1 had dual swath enabled and setting 2 has dual swath disabled. Cross line settings 3 had the depth mode set to VERY DEEP (dual swath is not available in this mode) in order to test the EM122 with a longer pulse length as a means of potentially improving bottom detection. This was only run as a test as the operating water depth at the reference surface site of ~4350 m was less than half the depth in which this mode would normally be used (~9000 m).

Soundings from each of the cross line tests were compared on a beam-by-beam basis against the reference surface and a difference between the two depths was calculated. This was done by sampling the reference surface grid depth at the coincident point reported by each beam. A table of beam depth, beam angle, reference surface depth, and depth difference was compiled for every sounding using this cross line sampling method.

In each figure the results are broken into three sections (A, B, and C). Section A of each plot shows the results for **all** beams which intersected the reference surface. Section B of each plot shows the same results but with the depth bias vertical scale limited to +/-1 (the more traditional way to plot the data). Section C shows a subset of the data where depth differences between the beam depth and the reference surface depth which fall out of the 98<sup>th</sup> percentile are excluded. This is done strictly as an automated means of removing “outliers” from the cross line analysis.

Results from the cross line analyses were then tallied into 1° bins with the mean depth bias as a percentage of water depth (%WD) and standard deviation about the mean were calculated for each bin. Figures 10-13 show the results of this analysis. The top panel for each section shows the depth standard deviation (%WD) versus the beam angle. The bottom panel shows the depth bias (%WD) versus beam angle. In the bottom panel there is a scatter plot (grey points) of the angle wise depth biases plotted against angle from nadir along with the mean (solid red line) and 1 standard deviation from the mean (solid blue line) for each 1° bin.

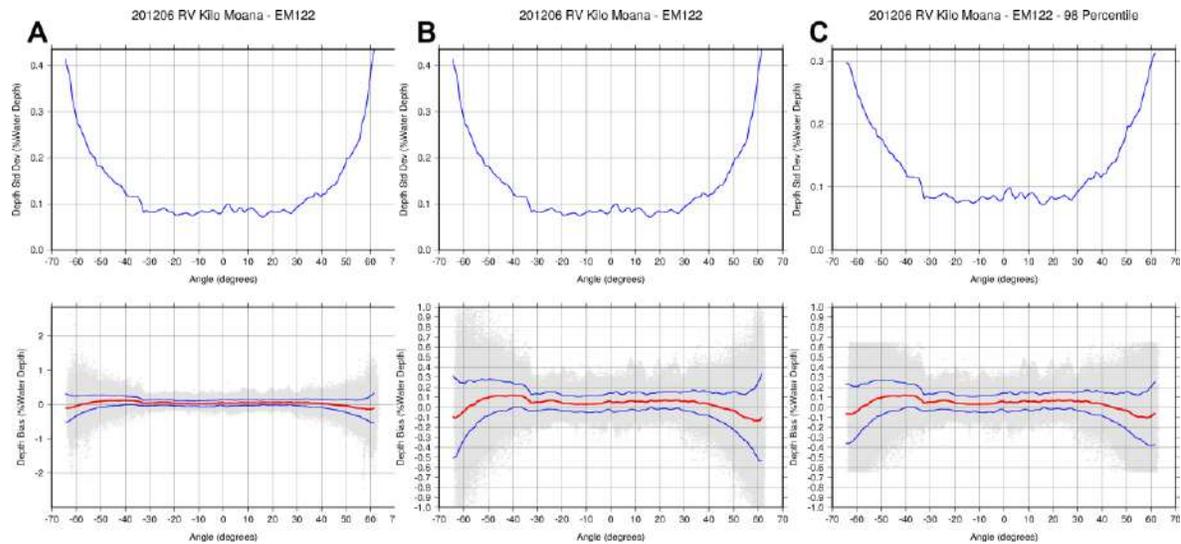


**Figure 10. Cross line analysis results for Line Settings 1. Red line is mean depth bias and blue line is 1 standard deviation from the mean depth bias.**

The results of the analysis indicate that there are some rather severe issues with both tracking the bottom and meeting the expected swath width of a typical EM122 system, even in the relatively moderate water depths, for an EM122 system, found at the calibration site. Typical accuracy testing for multibeam systems usually uses all soundings from the cross line files. However, as can be seen in bottom panels in Fig. 10 A & B the raw data included a significant number of outlier soundings (depths reported by the beam which were significantly different than the reference surface depths). Within +/- 30° of nadir the outliers appear to follow a trend which could possibly

be consistent with improper tracking of the transmit pulse in the dual swath mode. Also, the top panel of A & B show that the depth standard deviation (%WD) is above 0.3 over a majority of the swath when using all cross line points. This is much higher than would be expected from a typical EM122 system (see comparison to the R/V *Kilo Moana* data below) where values below 0.2 are typically expected over a majority of the swath width. Finally, the effective swath width, which was not limited by any acquisition setting, did not exceed  $\pm 55^\circ$  from nadir. This is narrower than what would be expected from a typical EM122 system (see swath coverage assessment section below).

In order to better evaluate the accuracy of the system, it was necessary to remove the outlier soundings from the cross file lines by eliminating all soundings whose depth differences between the sounding and the reference surface fell out of the 98<sup>th</sup> percentile. Section C of the panel of Figure 10 shows the results of the cross line accuracy analysis after the outlier removal. The depth standard deviation as a percentage of water depth has been reduced to between 0.04 and 0.39, a significant improvement from the unfiltered analysis. Even in the filtered analysis, the depth standard deviation reveals spikes at roughly  $\pm 20^\circ$  which manifests themselves as track parallel artifacts in the bathymetric data.



**Figure 11. Cross line analysis results from the R/V Kilo Moana SAT from 2012. Red line is mean depth bias and blue line is 1 standard deviation from the mean depth bias.**

Given that FM was not an option with the NBP’s EM122 installation due to possible TX array issues mentioned earlier, the operational settings of DEEP mode and dual swath used for Figure 10 represent the ideal configuration for the acquisition of bathymetric data in depths of water present at the accuracy verification site. Figure 11 (above) shows the results from R/V *Kilo Moana*’s (RVKM) EM122 SAT in 2012 which was conducted in very similar water depths (~4700 meters) and with similar acquisition settings, except that FM was enabled for the outer 2 sectors for both the port and starboard sides. As can be seen, the RVKM data required no filtering of its soundings based on differences between the reported beam depths and the reference surface depths (sections A and B compared to C in Fig. 11). The depth standard deviation (%WD) is 0.3 or

less for the entire swath in section C and below 0.2 for the region of the swath between 50° and 55°. The RVKM's system also collected reasonable data all the way out to +/-65°, as compared to +/-55° for the NBP's EM122. This is a **loss of 33%** of the overall expected swath width for the NBP data.

Figure 12 (DEEP Mode Single Swath) and Fig. 13 (VERY DEEP Mode) both show that the system did not work better than the DEEP Mode/Dual Ping operational modes shown in Figure 10. Figure 12 and 13 show that neither trends in depth standard deviation as a percentage of water depth nor are the swath widths improved in either of these alternative operational modes.

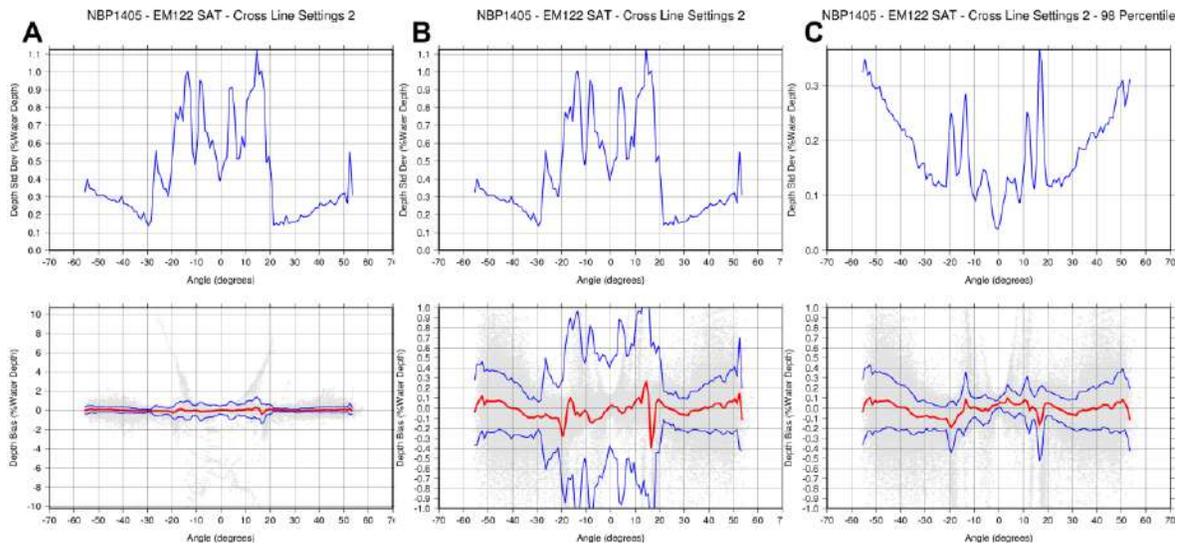


Figure 12. Cross line analysis results for Line Settings 2. Red line is mean depth bias and blue line is 1 standard deviation from the mean depth bias.

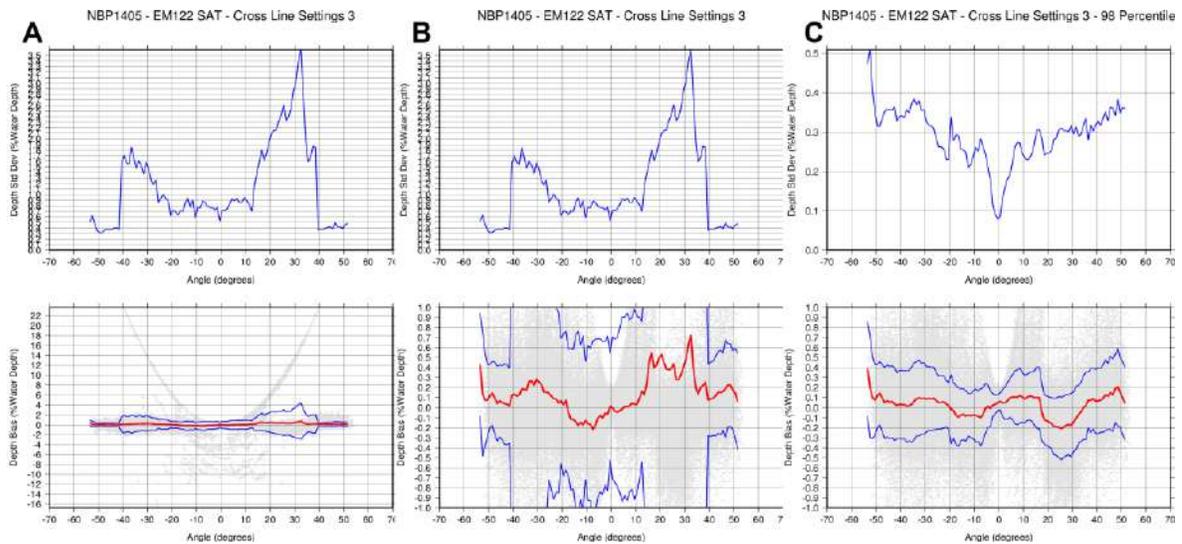
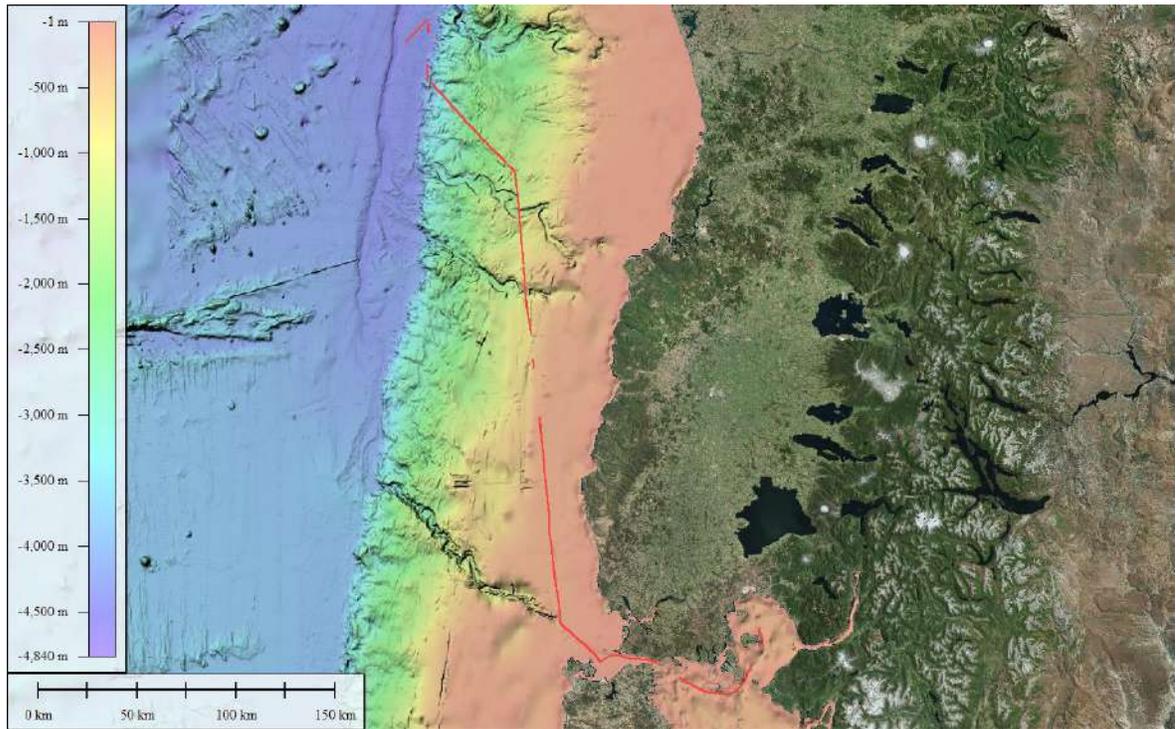


Figure 13. Cross line analysis results for Line Settings 3. Red line is mean depth bias and blue line is 1 standard deviation from the mean depth bias.

## Swath Coverage Assessment



**Figure 14.** Red line shows the trackline where bathymetric data included in the swath coverage assessment test was collected.

Data acquired during the transit from the reference surface site back to Puerto Montt (see Fig. 14) was used to prepare a swath coverage plot (Figs. 15) from the outermost port and starboard soundings. All data included in the swath coverage analysis were collected in automatic angular coverage mode and automatic depth mode in order to best optimize the system for maximum swath width to calculate the swath width as a function of depth. Unfortunately, due to other testing and system modification occurring during the transit, not all representative depths from the transit were collected. This includes a gap between 600 m and 300 m water depth.

The system tracked the seafloor out to 5 to 7 times water depth down to depths of ~1500 m. At depths between ~1500 m and 3250 m, the system tracked to about 4 times water depth. Unfortunately, between the depths of 3250 m and 4250 m, there was little to no data collected on the port side (likely related to bubble sweep further attenuating a weakened transmission signal) and the starboard side showed swath widths of only 2.5-3.5 times water depth. At the deepest depths collected during the transit, between ~4250 m and ~4500 m, the swath width was up to 3 times water depth.

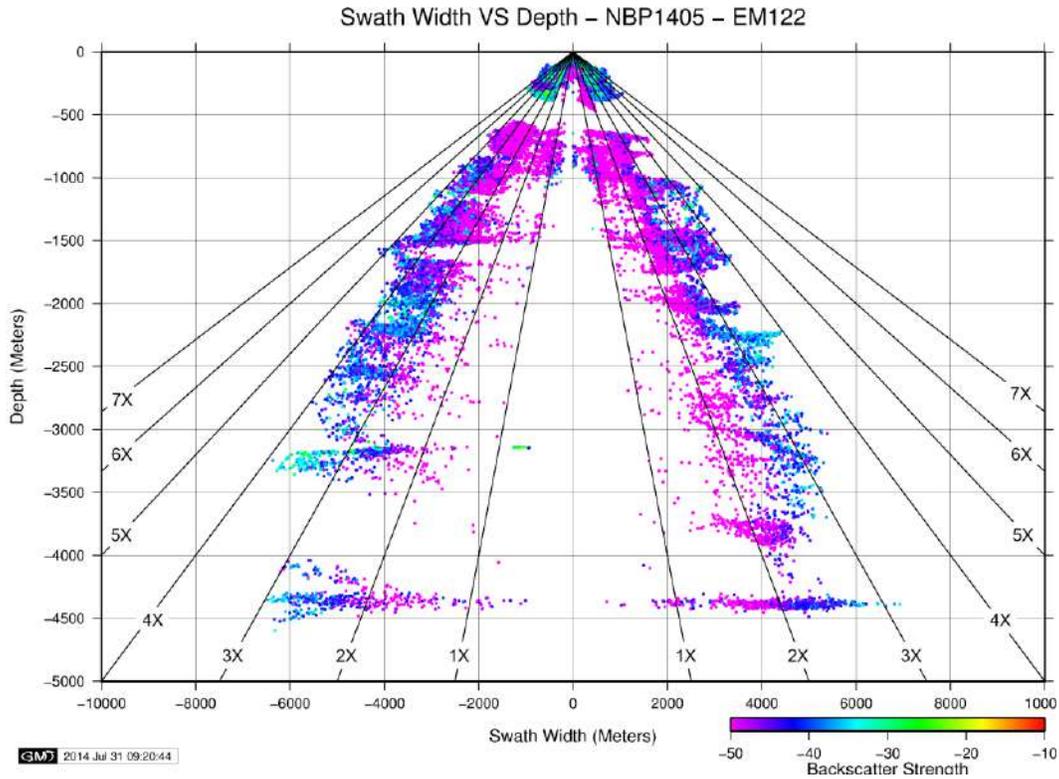


Figure 15. EM122 swath coverage achieved during the sea acceptance trials (NBP1405). Swath widths at ~4500 meters water depth are up to 3 times water depth. Coverage of 5 to 7 times water depth were achieved, but only in depths shallower than 1500 meters.

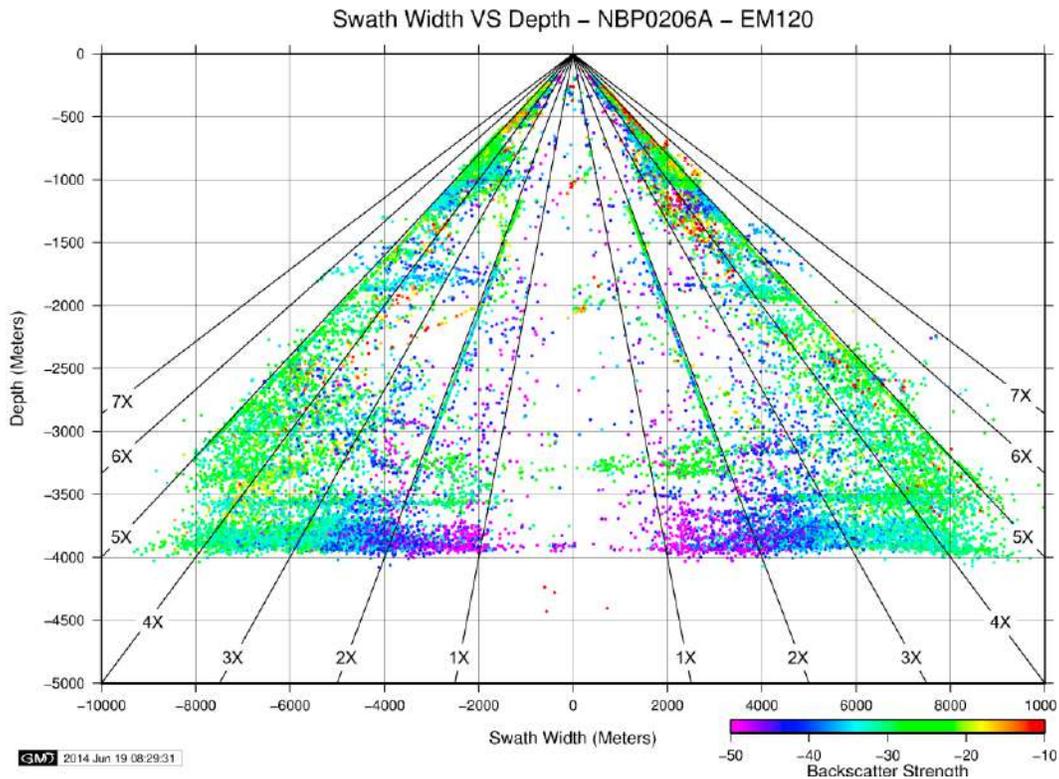


Figure 16. EM120 swath coverage achieved during the original sea acceptance trials (NBP0206A) in 2002. Swath widths as a function of depth are almost consistently higher than those achieved during the NBP1405 EM122 trials except in relatively shallow water.

In order to evaluate the collected swath width performance data against another dataset, Kathleen Gavahan provided data from the original NBP EM120 SAT conducted in 2002. This SAT utilized the same TX and RX arrays that the current EM122 is now using. Figure 16 is a compilation of all data from that SAT regardless of operational mode settings. As can be seen in the figure, the EM120 had swath widths 5 times water depth down to 3,500 m water depth. At 4,000 m (the deepest operational depths during the original SAT) the swath width was 4.5 times water depth. As a comparison between the two SATs, in moderate water depths of 3,000 m the current EM122's total swath width is about 3.5 times water depth whereas the original EM120's total swath width was 5 times water depth. This represents a **30% decrease** in effective swath width, which concurs with the results from the accuracy testing.

## Notes, Recommendations, and Observations

### System Geometry and Patch Test

- Both Kongsberg Maritime and the Multibeam Advisory Committee independently determined offset and angle values through a full review of the vessel layout documentation and patch test.
- Because the vessel documentation available for review was limited and portions of its lineage are unknown it is recommended that a full marine survey be done in the future, especially if any portions of the EM122's arrays or sensors are replaced or moved.
- If a new survey is conducted, it is recommended that the reference frame reported from the survey be agreement with the Kongsberg Maritime axis and sign conventions.
- Linear and angular offsets entered into the SIS Installation Parameters section should not be altered unless further historic documentation is discovered which modifies the results of the documentation review or if a new marine survey is performed.
- The static angular offsets (Pitch, Roll, and Heading) for the primary MRU (Seapath2) determined by the patch test conducted during NBP1405 are thought to be correct for the current installation. These values should be changed only if a new patch test is conducted or data suitable for offset determination is collected and reviewed.
- If the secondary MRU (Seapath1) is truly a spare, it should have static angular offset values determined for it by conducting a patch test when time is available as it is currently not useful as a spare without this information.

### Accuracy Assessment

- Even with the optimum system configuration (DEEP mode and Dual Swath) for the water depths present in the reference surface area, outliers were more prevalent in the raw accuracy data than had been observed when assessing other multibeam systems. This is likely related to both bubble sweep down over the arrays as well as weak transmit signal strength.

- Even with removal of the outliers, the NBP's EM122 did not perform as well as other EM122s that have been evaluated in waters operating in similar water depths (see the comparison to the R/V *Kilo Moana* data).
- The depth standard deviation (%WD) of the NBP's EM122 is above 0.2 for beams collected over 30° from nadir. This is higher than would be expected from a typical EM122 system (see comparison to the R/V *Kilo Moana* data) where values below 0.2 are typically expected over a majority of the swath width (between +/-55°).
- Even in portions of the swath where the depth standard deviation (%WD) is below 0.3, there are still spikes (at +/-20°) present in the data leading to along track artifacts.
- Data collected during the NBP's EM122 SAT over the reference area has swath widths of only +/-55°. As a comparison, the R/V *Kilo Moana's* swath width was 65° in similar water depths, providing 50% more across track coverage than the NBP's system.

### Coverage Assessment

- Some decrease in swath width when comparing the NBP's EM122 to the RVKM's EM122 (discussed above) can be attributed to the ice protected arrays on the NBP. However, comparing the NBP 2014 SAT swath coverage tests data to the NBP 2002 SAT data still reveals a serious problem. Both test utilized the same TX and RX arrays, while the 2014 has updated topside electronics. Looking at similar moderate water depths where coverage could be determined on both the port and starboard sides there has been a loss of 30% coverage (a change from 5 times water depth to 3.5 times water depth for swath width at 3,000 meters).
- The reduction of swath width from 2002 to 2014 along with the system's reduced ability to map in deeper water (while it can perform well in shallower waters), and observations in TX impedance anomalies documented during the HAT seem to indicate a problem with low transmit signal strength.
- It was also observed during the under-hull inspection in dry dock that the ice windows covering the TX array were cracked in several spots (see figure below). The effects from these cracks are unclear.



## Notes

- The Sound Velocity Profile Editor software was installed. It is recommended that this software be integrated into the routine data acquisition workflow.
- It is recommended that BISTs be collected more routinely, ideally at least once per cruise, in order to monitor transducer health over the lifetime of the arrays.

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