R/V Roger Revelle Multibeam Echo sounder System Review
RR1301
Multibeam Advisory Committee
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Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

*Cover image: Seafloor backscatter imagery draped over a 3D seafloor bathymetry model with mid water targets derived from thresholded water column imagery acquired by Revelle’s EM122 over hydrate ridge. Bathymetry processed in CARIS HIPS, backscatter imagery and water column processing in QPS FMGT and FM Midwater. Visualization prepared with QPS Fledermaus.*
Introduction

R/V Roger Revelle undertook a review of the vessel’s EM122 multibeam echosounder offshore of San Diego from January 21-23, 2013 (Fig. 1). Additional data were acquired during a transit from the test site to Anacortes, WA from January 23-28, 2013. Jonathan Beaudoin, Vicki Ferrini and Paul Johnson participated in the cruise (RR1301) as part of the NSF-funded Multibeam Advisory Committee (MAC) project, an effort to improve the data quality from multibeam echosounders in the U.S. academic fleet. It is the intent of this report to document the findings of the EM122 evaluations.

Cruise Participants

- Bruce Appelgate (SIO)
- Jon Meyer (SIO)
- Woody Sutherland (SIO)
- Aaron Sweeney (SIO)
- Jonathan Beaudoin (UNH, MAC co-PI)
- Paul Johnson (UNH, MAC co-PI)
- Vicki Ferrini (LDEO, MAC co-PI)
- Ashton Flinders (UNH student)
- Kevin Jerram (UNH student)
- Emily Mininberg (LDEO intern)

Survey System Components

The mapping system consists of the following components:

- Kongsberg Maritime EM122 multibeam echosounder (12 kHz), s/n 107
- Kongsberg Maritime Seafloor Information System (SIS), v 3.9.0, Build 183
- iXSea Hydrins MRU, model 6005212
- iXSea PHINS III MRU, model PAA00011, FrmWdSP4 INS v2 34, FrmWCINT ING 4 98 11
- Kongsberg Seatex Seapath 330+, v.1.02.01
- Trimble GPS, model GA530, v4.61 (2012-08-03)
- Surface sound speed source
  - Primary: Seabird SBE45 (s/n 0198), bow thruster compartment
  - Secondary: Seabird SBE45 (s/n 0318), aft lab
- Quoll Turo XBT system, TEST v4.03.3, User Interface v7.3.5
Activities

Cruise activities included calibration, accuracy and coverage testing of the EM122 system. MAC software tools were installed, configured and tested.

Figure 1. Area of operations for EM122 trials (map prepared from GMRT via GeoMapApp).

Deployment of MAC Software Tools, Utilities and Documentation

Cookbooks

The following MAC cookbooks were provided to ship technicians for their use:
- SIS Configuration Backup
- SIS Software Install
- SIS Software Uninstall
- SIS Startup
Additional cookbooks were prepared during the cruise and will be delivered after post-cruise review and finalization:

- BIST Basics
- SIS Patch Test
- SIS Survey Planning
- CARIS HIPS Start-up
- CARIS HIPS Patch Test
- CARIS HIPS Vessel Configuration

**SVP Editor**

**SVP Editor** is developed and maintained by the MAC and has the aim of streamlining and standardizing current practices regarding the acquisition, processing and application of SVPs to multibeam data (Beaudoin, 2012a).

The **SVP Editor** was installed on the XBT workstation and training was provided to Meyer regarding most of the basic functionality of the editor, along with the configuration of the Editor and of SIS to facilitate intercommunication. The **SVP Editor** was successfully tested with a Quoll Turo XBT profile that was acquired during the calibration exercises.

The following workflow was demonstrated during the cruise and is proposed as for use on Revelle:

**XBT**
1. Launch XBT probe.
2. Import the cast data in **SVP Editor**.
3. Process the cast: this involves loading salinity from the World Ocean Atlas, extending the profile from the World Ocean Atlas, and inserting the surface sound velocity measurement in the upper portion of the profile.
4. The cast is then delivered to SIS via UDP broadcast for immediate application and without further intervention on SIS.

There was not an opportunity to fully test a workflow for the CTD systems, however, the following workflow is suggested:

**CTD**
1. Perform the CTD cast.
2. Using the Seabird processing software, export a .cnv file that contains depth, sound speed, temperature and salinity. **SVP Editor** will not import pressure or conductivity values.
3. Import the cast data in **SVP Editor**.
4. Process the cast: this involves extending the profile from the World Ocean Atlas.
5. The cast is then delivered to SIS via UDP broadcast for immediate application and without further intervention on SIS.

As part of the software installation, a software manual was provided that documented the new workflow in more detail, including detail on the processing procedures within the MAC SVP Editor.

An additional feature of the SVP Editor is the ability to set it up in “server” mode. In this particular mode of operation, the software monitors position broadcasts from SIS and constructs synthetic sound velocity profiles based on the World Ocean Atlas and then delivers them to SIS for immediate application. This mode of operation was used during the transit from San Diego, CA to Anacortes, WA with no discernable refraction artifacts in the real-time graphical display in SIS. Future work will focus on providing guidance to operators as to when/where the server mode can be used in lieu of in situ measurements.

**BIST Plotter, Cross-line Analysis, Coverage Plotter**

A set of Python, MB System and GMT scripts were developed during the cruise to ease the process of analyzing BIST output for noise level monitoring, cross line analysis and coverage plotting. These require further refinement and will be delivered in time for the ship departure from Anacortes in March, 2013.

**System Geometry**

In this report, we use the term ‘system geometry’ to mean the linear and angular offsets of the primary components of the multibeam mapping system, including the transmit array, receive array, position sensor(s), and attitude sensor(s). These parameters are critical for data collection in an unbiased and repeatable manner.

R/V Roger Revelle was equipped with the following components subject to this review of system geometry:

- EM120* transmit array (TX)
- EM120* receive array (RX)
- Trimble GA530 position sensor (GPS)
- iXSea PHINS III attitude sensor (MRU)
- iXSea HYDRINS attitude sensor (MRU)
- Kongsberg Seapath 330+ attitude sensor (MRU)
*The EM120 arrays remain from the original EM120 installation and are used with upgraded topside EM122 electronics; collectively, the system is known as an EM122.

A general layout of the mapping system components is presented in Fig. 2.

![Diagram of sensor positions onboard R/V Roger Revelle]

Figure 2. General layout (not to scale) of sensor positions onboard R/V Roger Revelle.

The PHINS MRU is a new unit (replacing an older generation of PHINS MRU) installed shortly before the MAC visit. Under normal operation, the PHINS and HYDRINS are the primary and secondary MRUs, respectively. The Seapath MRU was installed (with Kongsberg support) for testing during the transit; this device has not been used historically onboard R/V Roger Revelle.

Of critical note, the vessel and sensors in this report use two distinct reference frames with different sign conventions for the linear and angular offsets under investigation. Throughout this geometry review and for all future work involving documentation of sensor position, careful consideration must be given to the reference frames and sign conventions used for sensors on individual bases.

The vessel reference frame was established by marine surveyors (see 2003 Blom survey, below) and is consistent with that used by Kongsberg Maritime:

- The origin is determined by the user (a point on the MRU mounting plate)
- The positive X axis points towards the bow
- The positive Y axis points to starboard
- The positive Z axis points downward
- A positive roll rotation bring the port side up and the starboard side down
- A positive pitch rotation brings the bow up and the stern down
• A positive heading or yaw rotation brings the bow to starboard, in agreement with the compass convention
• All linear and angular offsets are with respect to the origin

The reference frames used by PHINS and HYDRINS MRUs are sensor-centered coordinate systems:

• The origin is the center of the sensor
• The positive X axis points toward the bow
• The positive Y axis points to starboard
• The positive Z axis points upward
• A positive roll rotation brings the port side up and the starboard side down
• A positive pitch rotation brings the bow down and the stern up
• A positive heading or yaw rotation brings the bow to starboard, in agreement with the compass convention
• All linear and angular offsets are with respect to the origin

Though oriented differently in space, both reference frames are right-handed coordinate systems with sign conventions obeying the right-hand rule for rotation about the X and Y-axes and the compass convention for rotation about the Z-axis.

Two surveys and a text document of SIS PU Parameters were provided prior to the MAC visit with the aim of independently reviewing the sensor linear and angular offsets. The following data were relevant to this geometry review:

• **2003 Blom survey (San Diego)**
  o Baseline survey establishing:
    ▪ Vessel reference frame and origin
    ▪ Linear and angular offsets of EM120 TX array
    ▪ Linear and angular offsets of EM120 RX array

• **2011 Blom survey (Taiwan)**
  o Re-establishment of Blom 2003 (vessel) reference frame for:
    ▪ Linear offsets of primary GPS antenna mount

• **SIS Parameters (retrieved 10 Jan 2013)**
  o SIS configurations for:
    ▪ Linear and angular offsets of TX array
    ▪ Linear and angular offsets of RX array
    ▪ Linear offsets of primary GPS antenna

The following points of interest were raised during review of the above documentation.
2003 Blom survey (San Diego)

This survey unequivocally established the vessel reference frame origin as a point on the top surface of the MRU mounting plate directly beneath the MRU then in service. The positive X axis was chosen to run parallel to the centerline of the ship and offset 0.503 m to starboard from the central alongship vertical plane (plan view, Fig. 2). The X-Y plane was chosen as the top surface of the MRU mounting plate with positive Y axis to starboard and positive Z axis down, as described above.

Though the MRU surveyed is no longer in service, it is worthwhile to note two discrepancies existing in the Work Procedure section and one figure error:

1. The Work Procedure states (paraphrased):
   a. “The positive X axis is pointing forward along the ship centerline and 0.503 m to starboard of the center bottom of the MRU.”
   b. “The center bottom of MRU has the coordinate Y = 0.000 m.”
   c. Correction: the positive X axis was chosen to run along the top surface of the MRU mounting plate, beneath the MRU then in service, and offset 0.503 m to starboard of the central along-ship vertical plane. Statement (b) and the plan view in Fig. 2 are correct.

2. The Work Procedure states (paraphrased):
   a. “The positive Z axis is pointing down from center bottom of MRU.”
   b. “The center bottom of MRU has the coordinate Z = -0.048 m.”
   c. Correction: the positive Z-axis points down from the X-Y plane, which was chosen as the top surface of the MRU mounting plate. Statement (b) is correct.

3. The Key Plan and Ref. Points diagrams (not included in this report) are plan view and display a three-axis icon to indicate the positive X, Y, and Z axes. The positive Z-axis is erroneously pointing up from the X-Y plane.
   a. Correction: The Z axis is positive down from the X-Y plane.

The vessel reference frame established in this survey and all linear and angular offsets for the TX and RX arrays remain relevant for additional survey and SIS configuration.

2011 Blom survey (Taiwan)

This survey was conducted to augment the 2003 Blom survey with positions for external sensor mounts. The position of the primary GPS antenna mount (Survey Point N13) is the only survey datum of interest for this geometry review. Aside from including the Ref. Points diagram (showing the erroneous three-axis icon) used in the 2003 Blom survey, no obvious discrepancies exist in this survey.
**SIS Parameters (retrieved 10 Jan 2013)**

SIS parameters for sensor configuration were provided for review by the MAC before completion of MRU configuration. These parameters described the linear and angular offsets of sensors in the vessel and Kongsberg reference frames. Linear and angular offsets for the TX and RX were reviewed, as well as linear offsets for the GPS. Linear offsets for the MRUs were to be determined by measurement with a survey tape after installation; angular offsets for the MRUs were to be determined by patch testing during the MAC visit.

SIS parameters for the primary GPS antenna linear offsets were found to match the 2011 Blom survey values for Survey Point N13, plus 4” (in the negative Z direction) for the antenna base. SIS parameters for X, Roll, Pitch, and Yaw of the TX and RX arrays matched the 2003 Blom survey results, but the SIS parameters for Y and Z of the TX and RX arrays did not agree with these results. Table 1 presents a comparison of SIS parameters and 2003 Blom survey values for TX and RX linear offsets; all values are in the vessel reference frame, which is identical to the Kongsberg reference frame.

<table>
<thead>
<tr>
<th>Linear Offset</th>
<th>TX Array</th>
<th>RX Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y (SIS)</td>
<td>-0.030</td>
<td>-0.040</td>
</tr>
<tr>
<td>Y (Blom)</td>
<td>+0.535</td>
<td>-0.539</td>
</tr>
<tr>
<td>Z (SIS)</td>
<td>+5.630</td>
<td>+5.620</td>
</tr>
<tr>
<td>Z (Blom)</td>
<td>+5.580</td>
<td>+5.574</td>
</tr>
</tbody>
</table>

Though the reasons have not been determined for using SIS TX and RX parameters other than the 2003 Blom survey results, the following may explain the numerical values of the SIS parameters (within rounding or cut-off to 0.01 m by SIS):

- The Y parameter in SIS may include unnecessary and inconsistent compensation for the athwartship 0.503 m offset of the origin from the vessel centerline described in the 2003 Blom survey, plus inversion of the Y axis for the TX array:
  - -0.03 (SIS TX) = -[+0.535 (Blom TX) - 0.503 (offset)]
  - -0.04 (SIS RX) = -0.539 (Blom RX) + 0.503 (offset)

- The Z parameter in SIS may be referenced to the center bottom of the MRU in service during the 2003 Blom survey:
  - +5.63 (SIS TX) = +5.580 (Blom RX) - (-0.048) (Blom MRU)
  - +5.62 (SIS RX) = +5.574 (Blom RX) - (-0.048) (Blom MRU)
Geometry Modifications

Linear Offsets

In response to the discrepancies noted above, SIS parameters for Y and Z linear offsets for the TX and RX arrays were set equal to the 2003 Blom survey results. The magnitudes of changes to SIS linear offsets (Blom survey value – SIS value) are:

- \( \Delta Y (TX) : (+0.535 - (-0.03)) = +0.565 \text{ m} \)
- \( \Delta Y (RX) : (-0.539 - (-0.04)) = -0.499 \text{ m} \)
- \( \Delta Z (TX) : (+0.580 - (+5.63)) = -0.050 \text{ m} \)
- \( \Delta Z (RX) : (+5.574 - (+5.62)) = -0.046 \text{ m} \)

The SIS parameters for TX and RX linear offsets in the X direction were in agreement with the 2003 Blom survey; these values were left unchanged.

The PHINS, HYDRINS, and Seapath MRUs were configured to output attitude data corrected to the vessel reference frame origin; thus, the attitude output is that which would be sensed if the sensor center and vessel reference frame origin were coincident. To facilitate this, linear offsets from the origin were measured with a survey tape and applied during configuration of each MRU using the appropriate reference frames and sign conventions employed by iXSea and Kongsberg. Accordingly, all SIS parameters for MRU linear offsets are zero.

Fig. 3 depicts the SIS parameters for linear offsets reflecting the 2003 Blom survey data for the TX array, RX array, and primary GPS mount (Pos, COM1). The SIS parameters for the Hydrins MRU (Attitude 1, COM2/UDP5) and Seapath MRU (Attitude 2, COM3/UDP6) linear offsets reflect correction of attitude output to the vessel origin from these sensors. Configuration for the PHINS MRU is not shown.
Angular Offsets

The SIS parameters for TX and RX angular offsets matched the 2003 Blom survey results and were not modified during the MAC visit. All MRUs were configured in their respective software for zero installation angular offsets, with the aim of determining residual angular offsets for each motion sensor through individual patch tests. The only non-zero installation angular offset used for MRU configuration is the Seapath roll offset; this value was set to 180.00° (by a Kongsberg technician) to compensate for upside-down installation of the sensor.

Figures 4 through 6 depict the PHINS, HYDRINS, and Seapath configurations, respectively, for linear and angular offsets. It is critical to note that measurements for the PHINS and HYDRINS MRUs are with respect to the sensor, using the reference frame and sign conventions described earlier; the Seapath configuration reflects the sensor position in the vessel reference frame. Also, note that the Seapath Aft Perpendicular (AP) linear offsets were chosen arbitrarily for plotting the sensor position in the image; the AP is not used for any other linear offsets. The Navigation Reference Point (NRP) is the vessel origin from which all linear offsets for Seapath configuration are made and for which all Seapath attitude output are referenced.
Figure 4. PHINS MRU configuration showing linear offsets using iXSea sensor-oriented axis and sign conventions. The Primary and GPS lever arms are with respect to the sensor.

Figure 5. HYDRINS MRU configuration showing linear offsets using iXSea sensor-oriented axis and sign conventions. The Primary and GPS lever arms are with respect to the sensor.
Figure 6. Seapath MRU configuration showing linear offsets using Kongsberg vessel-oriented axis and sign conventions. The roll mounting angle reflects the upside-down sensor installation.

Figure 7. SIS parameters for angular offsets of sensors reflecting 2003 Blom survey results for the TX and RX arrays and patch test results for the Hydrins (Attitude 1) and Seapath (Attitude 2).
During the MAC visit, patch tests were conducted for the HYDRINS and Seapath MRUs to determine residual angular offsets of the motion sensors. The PHINS MRU exhibited erratic behavior (e.g., reporting very large (>10,000m) altitude errors and a positive drift in pitch) and was not subject to patch testing. As shown in Fig. 7, angular offsets determined during patch test evaluation in SIS were entered in the appropriate SIS parameters for the Seapath and Hydrins MRUs; TX and RX angular offsets matching the 2003 Blom survey values are also shown.

Note that the PHINS MRU was not patch tested because of a pitch drift error that was unresolved during the window for patch testing. If this sensor is removed for service and reinstalled after the MAC visit, measurement of linear offsets and patch testing for angular offsets will need to be performed.

**Summary of Current System Geometry**

A complete survey of all transducer arrays, motion sensors, and GPS antennae is expected to be completed during the maintenance period in Anacortes. Though all survey data presented herein may be superseded by this planned survey, it remains worthwhile to state completely the system geometry at the time of the MAC visit.

Table 2 lists a summary of the linear and angular offsets of the survey system components for R/V Roger Revelle. These offsets represent the survey configuration as of late January 2013 based on existing documentation (2003 and 2011 Blom surveys), MRU measurements made on board, and patch test results. Because no other MRU angular offset data exist, the patch test results are presented in the table. All values are with respect to the vessel (Kongsberg) reference frame.

**Table 2. R/V Roger Revelle linear and angular offsets as of early 2013.**

<table>
<thead>
<tr>
<th></th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Z (m)</th>
<th>Roll (°)</th>
<th>Pitch (°)</th>
<th>Yaw (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel Reference Origin</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Navigation Reference Point</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EM122 TX</td>
<td>+14.275</td>
<td>+0.535</td>
<td>+5.580</td>
<td>-0.029</td>
<td>-0.006</td>
<td>-0.064</td>
</tr>
<tr>
<td>EM122 RX</td>
<td>+9.663</td>
<td>-0.539</td>
<td>+5.574</td>
<td>-0.235</td>
<td>+0.103</td>
<td>+0.010</td>
</tr>
<tr>
<td>Trimble GPS</td>
<td>-20.407</td>
<td>-1.259</td>
<td>-11.591</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PHINS</td>
<td>-0.223</td>
<td>+0.026</td>
<td>-0.040</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>HYDRINS</td>
<td>-0.223</td>
<td>+0.261</td>
<td>-0.040</td>
<td>+0.48</td>
<td>-0.07</td>
<td>-0.15</td>
</tr>
<tr>
<td>Seapath</td>
<td>0.000*</td>
<td>0.000*</td>
<td>-0.032</td>
<td>+0.45</td>
<td>-0.15</td>
<td>+0.30</td>
</tr>
</tbody>
</table>
*It has been noted that the Seapath MRU configurations for X and Y linear offsets may not be correct. This table includes zeros for these offsets because the Seapath MRU is mounted approximately above the vessel reference frame origin. This MRU is to be removed in Anacortes and any permanent installation will be surveyed.

For reference, pictures of accessible sensors are presented in Figs. 8-9.

![Primary GPS Antenna (Blom 2011 Survey Point N13)](image)

*Figure 8. Primary GPS antenna (viewed looking astern).
Figure 9. MRU mounting plate (viewed looking astern).

**Calibration**

A patch test calibration routine was performed on the continental slope west of San Diego (Fig. 10). A “Deep Blue” XBT profile was acquired to 1,000 m depth prior to the calibration lines and was processed using SIO in-house sound speed processing scripts to extend the cast with the Levitus database using the mblevitus program (Caress and Chayes, 2005). The cast was uploaded to the EM122 for use in real-time ray tracing corrections.

Planning and execution of the calibration lines was undertaken by SIO and was as follows:

- **MRU pitch offset**: Reciprocal 9 kt runs of line A/B with a reduced swath width of 2,000 m. Along-track sounding density is increased due to the reduced total travel time associated with the constrained angular sector, this being the primary reason for constraining the angular sector. Across-track sounding density is increased as well.
- **MRU heading offset**: Single 9 kt run of line C/D with swath coverage steered toward corridor between A/B and C/D to increase sounding density in the calibration corridor. This pass is compared to the calibration line of the same heading from the pitch offset lines run on A/B.
- **MRU roll offset**: Hold station/heading with DP just west of station A for ~20 minutes; reverse ship’s heading by 180 and resume station keeping for ~20 minutes.
The procedure was followed first to solve the HYDRINS MRU alignment angles and repeated a second time for the Seapath MRU alignment angles. The PHINS sensor was not performing adequately at the time of the calibration and was not included in the calibration procedures.

The EM122 was configured as such for the HYDRINS calibration:
- Depth mode: DEEP with FM waveforms enabled
- Dual-swath: enabled
- Yaw stabilization: enabled
- Pitch stabilization: disabled
- Beam spacing: high-density equidistant

The second calibration for the Seapath used a similar configuration, however, with pitch stabilization enabled to improve along-track sounding density (Fig. 11).
Figure 11. Importance of pitch stabilization for maintenance of constant along-track sounding density. A roll offset was applied in the patch test tool to facilitate visualization of the differing along-track sounding densities.

Data were evaluated by SIO personnel using the SIS manual calibration module (independent assessments made by Applegate, Sutherland, Meyer, Sweeney and Ferrini). The offsets were independently determined in Caris HIPS by Flinders and in UNB/OMG SwathEd by Beaudoin. Results of the patch test are summarized in Table 3. Angular offsets were entered into SIS by adding to the initial MRU offsets for each sensor (initially zero), leaving the TX and RX sonar angular offset fields populated as they were prior to the calibration trials.

Table 3. EM122 Calibration Results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYDRINS Roll</td>
<td>0.48°</td>
</tr>
<tr>
<td>HYDRINS Pitch</td>
<td>-0.07°</td>
</tr>
<tr>
<td>HYDRINS Heading</td>
<td>-0.15°</td>
</tr>
<tr>
<td>Seapath Roll</td>
<td>0.45°</td>
</tr>
<tr>
<td>Seapath Pitch</td>
<td>-0.15°</td>
</tr>
<tr>
<td>Seapath Heading</td>
<td>0.30°</td>
</tr>
</tbody>
</table>
There was general agreement among all personnel that the patch test mapping geometry was sub-optimal at the first site, leading to a sense of uncertainty in the determination of the pitch and heading offsets due to the discrepancies between individual assessments of the patch test offsets (these were averaged to produce the results in Table 3). A second patch test calibration was planned using a seamount type feature west of the original calibration site (Fig. 1 and Fig. 12). The second calibration was planned and executed by Beaudoin as follows:

- **MRU pitch offset:** Reciprocal 6 kt runs of line C/D with a reduced angular sector of +/-45°. Along-track sounding density is increased due to the reduced total travel time associated with the constrained angular sector, this being the primary reason for constraining the angular sector. Across-track sounding density is increased as well.
- **MRU heading offset:** Single 6 kt run of line A/B with swath coverage steered toward corridor between A/B and C/D to increase sounding density in the calibration corridor. This pass is compared to the calibration line of the same heading from the pitch offset lines run on C/D.
- **MRU roll offset:** Verified during accuracy tests over the reference surface and during Hydrate Ridge water column test survey.

The EM122 was configured as such for the HYDRINS and Seapath calibration:

- Depth mode: DEEP with FM waveforms disabled
- Dual-swath: enabled
- Yaw stabilization: enabled
- Pitch stabilization: enabled
- Beam spacing: high-density equidistant
Data were evaluated in SIS by SIO personnel (Appelgate, Sweeney) and in UNB/OMG SwathEd by Beaudoin with the pitch and heading offsets determined in the first patch test being adequate for both sensors. Offsets were quickly confirmed with little discrepancy between personnel due largely to the distinct target shape as compared to the original patch test site.

**Noise Level Assessment**

**Speed Test**

A series of noise tests were conducted using the EM122’s Built-In Self Test (BIST). Ship speeds were varied from 0 to 12 knots in water depths exceeding 1,000 m in unusually calm seas. For each speed, ten *RX Noise Level* BIST tests were conducted, providing broadband noise levels for each module in the receive array (Fig. 13). The first BIST test of this run was a full suite of tests with all tests passing, subsequent tests in the run only used the noise level testing capability of the BIST suite of
diagnostics. The vessel was running with both main engines during the entire testing period even though a single engine would typically be used at lower speeds.

![Figure 13](image)

**Figure 13.** Broadband noise levels for each receive channel while dead in the water in calm seas. Data from 10 consecutive tests are plotted. The mean noise, calculated using linear units, across the array for all tests is drawn as the black line and is also indicated in the plot title.

Data from all tests are shown in Fig. 14; mean noise levels for each speed are plotted against ship speed in Fig. 15 (refer to Appendix A for plots from each speed test). The mean noise versus speed curve indicates that flow noise and machinery noise are below the system's noise floor at speeds below 6 kts. Noise levels grow at a rate of ~1.8 dB per knot of speed above 6 kts for a maximum of 47 dB at a speed of 12 kts. It must be stressed that these noise measurements likely represent the quietest that the platform will enjoy due to the unusually calm sea state during the trials. Increased noise levels can be expected in more typical sea conditions. It should also be pointed out that historic noise level measurements have given higher noise levels (Fig. 16).
Figure 14. Broadband noise levels for all receiver modules for speeds ranging from 0 kts to 12 kts.

Figure 15. Broadband noise level versus ship speed in very calm seas (Beaufort 1).
Figure 16. Broadband noise levels from 316 BIST tests dating back to 2009. The data in this plot were collected under a variety of conditions, some of which were specific to noise testing, and these should not be construed as representative of natural variations in Revelle’s noise level without examination of BIST test metadata. Red dots represent mean levels from RX Board 1, blue is from RX Board 2.

**Directional Effects**

A series of BIST noise level measurements were made while the ship maneuvered in an octagonal pattern in a 3-6 m swell (period of ~18 sec and wavelength of 370 m) and 7.8 m/s winds from 275°. Vessel speed was between 7.4-9.1 kts and each side of the octagonal pattern taking ~5 minutes to run with ten RX Noise Level BIST tests being acquired per side (Fig. 17).
Noise levels were higher when steaming into the seas with the highest levels being measured on the port quarter. The small number of BIST tests (10) collected over the time associated with each leg may lead to slightly misleading results since the noise transients associated with slamming of the vessel hull into the swell are episodic and may not be adequately characterized given the relatively low sampling rate of a series of BIST tests. Future testing should strive to acquire more BISTs per run to capture the true effects of transient noise events.

BIST tests for noise evaluations are of limited use for assessing the effects of bubble sweep as they only pick up increased flow noise levels but say nothing about the screening effect of bubbles washing across the transducer arrays. These effects are best assessed by acquiring multibeam data, including water column imagery, while performing the standard octagonal test described earlier. The imagery in Fig. 18 demonstrates the effect of bubble sweep on imagery depending on the orientation of the vessel with respect to the direction of the seas. Note the transient noise event in Line A, this is what would be picked up by a BIST test.

SIO personnel have mentioned that, in their experience, the multibeam performance, i.e. coverage, imagery quality, etc, can be improved with a forced
downward trim of the vessel when in higher sea states. If this is indeed the case, the octagonal noise trials should be done at a variety of vessel trims to determine ideal settings while recording water column imagery. MAC personnel can aid in the processing of these data if such tests are done.

Figure 18. Sample water column and seabed imagery of two survey lines in opposite directions over hydrate ridge. Line A, running with the seas, is of much higher quality than line B which ran against the seas and suffered from bubble wash down events in both water column and seabed imagery.

Accuracy
A deep-water accuracy test was conducted in 3,900 m depth over a flat and relatively featureless seafloor. Line spacing was set at 1x w.d., yielding a corridor with 300% coverage between the three survey lines (Fig. 19). The EM122 was configured to run in dual-swath, “Deep” mode with CW pulses for the innermost four sectors and FM pulses for the two outermost sectors on each side (for a total of four FM sectors). The angular sector was constrained to +/-60° and the vessel speed was 9 kts.

A reference surface was prepared from the main survey lines using a 2.0° beam width radius of influence and a linear beam-weighting scheme for the innermost 250 beams (the outermost 91 port and starboard beams were not included in the construction of the grid, effectively reducing the angular sector to +/-45°). A slope filter of 5° was used to mask areas of high topography for the purpose of the cross line statistical analysis.

Cross lines were run in the orthogonal direction with a vessel speed of 6 kts with the sounder in Deep mode, dual-swath with pitch/yaw stabilization enabled. The vessel speed was intentionally reduced to allow for more data due to the narrow corridor in which comparisons could be made. The cross lines were run twice for each MRU sensor with one line run in CW mode and the second line run with FM waveforms enabled, giving a set of four cross lines for analysis.

Soundings from each of the four cross line tests were compared on a beam-by-beam basis against the reference surface with statistics being compiled by sector and
swath number (Figs. 20-21, full sized figures for each of the four cases are available in Appendix B). Note that “swath number” refers to the swath number in the dual-swath geometry, i.e. swath 1 of 2 and swath 2 of 2.

Results from the cross-line analyses were tallied in 1° bins with the mean bias and standard deviation about the mean calculated for each bin. A scatter plot of the beam-wise biases are plotted against beam steering angle (nearly equivalent to incidence angle) along with the mean (solid lines) and standard deviation (dashed lines) from each 1° bin in Fig. 20. Both the mean and standard deviation lines are color-coded by sector number and by swath number. Fig. 21 shows only the standard deviation about the mean bias against beam angle, with similar results in all four cases as expected. High uncertainties were observed at nadir, these are associated with bottom mistracking on sub-bottom returns. The “penetration filter” was set to Medium during the cross-line acquisition and these results could perhaps have been improved with filter set to Strong.

![Figure 20. Sounding biases for Hydrins/Seapath MRUs and CW/FM waveforms.](image-url)
Examining Fig. 20, it can be seen that the system provides unbiased soundings over the majority of the swath. A small roll residual is apparent that is common to both MRU configurations as evidenced by the slight tilt to the mean bias curves in the region +/-30°. A small non-linear refraction-like bias is apparent in the outermost sectors for all four test cases as well, however, it is asymmetric about nadir, which is atypical of standard sound speed profile refraction-based biases (“smiles” and “frowns”). These types of asymmetric, non-linear “curl” biases are typically associated with errors in surface sound speed that create beam steering angle errors. Referring to Fig. 22, in a roll stabilized system, the beam steering error will vary with the amount of roll and will manifest itself as a roll-correlated, non-linear undulation of the seafloor with port and starboard undulations being out of phase (Hughes Clarke, 2003).
Bias images were prepared to allow for spatial examination of depth bias across the swath for all pings in each of the four cross lines (Fig. 23). The non-linear outer sector tilting can be seen on the port and starboard sides (reds on one side, greens on the other); the fact that these biases do not vary in time, despite vessel roll of +/− 3° during cross line acquisition, indicates that the curl artifact is not due to a surface sound speed error. Furthermore, there is no evidence of data integration errors, e.g. motion delay or incorrect linear offsets. This gives increased confidence in the system geometric configuration although it can be argued that the minimal sea state did not provide the dynamics required for full testing of motion related artifacts.

Figure 22. Depth biases due to biased surface sound speed during roll events (after Hughes Clarke, 2003; Fig. 10).

Figure 23. Sounding bias images in ping/beam geometry images for four cross lines (ping number is vertical axis, beam number is horizontal axis). Color-coding represents sounding depth bias relative to the reference surface, expressed as a percentage of water depth.
Other than the “curl” artifact across the swath, the observed mean biases and standard deviations are within the expected achievable abilities of the system as a whole. Behavior is consistent from swath to swath in the dual swath geometry and from sector to sector with little difference between FM and CW sector performance. Both the Hydrins and Seapath provided data of similar accuracy though it is admitted that the deep water testing in calm seas did not expose the sensors to the dynamics typically observed at sea and their abilities could diverge in higher sea states.

**Coverage**

**Achieved Coverage**

Coverage plots were prepared using the outermost valid port and starboard sounding from all data acquired during the transit between the calibration test site and the entrance to the Strait of Juan de Fuca (Fig. 24). The same data are plotted as a time-series along with the system depth mode to help interpret which data were acquired during system depth mode testing (Fig. 25). During the majority of the transit, the system was left to adjust its angular sector to as wide as it could maintain ("auto" angular coverage mode) with limits set at +/-75°.

Most notable in the coverage plot is an asymmetric coverage sector that, at first glance, could lead to the impression that the system is underperforming on the port side. The asymmetry in coverage is explained by the fact that the majority of the transit had the port sectors shooting down slope and subsequently suffering from signal extinction at shorter ranges than usual due to the increased incidence angle and weaker seafloor backscattering strength at grazing angles. This asymmetry in coverage is easily seen in the upper plot of Fig. 25 where the port and starboard outermost depths are plotted against time and diverge significantly, e.g. hours 8 to 18 and 30 to 35.

Discounting the port coverage reduction due to slope effects, the system tracks the seafloor routinely out to 5-6 times w.d. to depths of ~2,500 m and is comparable in performance to other EM122 systems (e.g. Beaudoin, 2012b). Further coverage testing should be done in deeper water to explore the system’s abilities at full ocean depths.
Figure 24. Coverage achieved during transit from calibration test site to Anacortes, WA. Asymmetric coverage is due to the significant across track seafloor slope associated with transiting northward along or near the continental shelf break.
Figure 25. Coverage achieved during transit from calibration test site to Anacortes, WA. The system was forced into shallower modes that it would normally choose in order to evaluate coverage performance in these modes, e.g., hours 33-45. Points are plotted for both port and starboard beams such that across track slope effects on coverage can be assessed, e.g., hours 8-18 and hours 30-35.

**Predicted Coverage**

A sonar performance model has been implemented by Xavier Lurton, of Ifremer, that attempts to fully account for the multi-sector nature of modern Kongsberg Maritime multibeam echosounders. In short, it provides a range performance estimate based on the classical sonar equation and accounts for the frequencies, pulse lengths, beam patterns and receiver bandwidths that all vary with transmit sector. This model has been used previously by Lurton to provide support to previous investigations by the MAC (Beaudoin, 2012b) and on other non-MAC cruises in which MAC personnel have participated (Beaudoin et al., 2012).

The Lurton model has been implemented in a real-time coverage-monitoring tool by Beaudoin and was tested during the time aboard *Revelle*. The MAC implementation of the Lurton model derives many of the required sonar equation parameters from a real-time data feed from SIS of the following datagrams:
• **Position:** latitude and longitude are used to query the World Ocean Atlas for temperature/salinity profiles for use in the calculation of the frequency dependent transmission loss (i.e. attenuation).

• **Runtime:** gives sonar mode, TX/RX beamwidths

• **Range/Angle:** gives number of sectors, sector RX bandwidth, sector frequencies and sector pulse widths.

• **Seabed Imagery:** seafloor backscatter at nadir and oblique incidence and TVG cross over angle (parameters describing the Kongsberg Maritime angular response model, (Kongsberg, 2000)).

• **Sound Velocity Profile:** used for ray tracing correction of range performance estimates and also calculation of true incidence angle at the seafloor for use in ensonified area calculations.

• **Depth:** outermost port and starboard soundings are extracted from the depth datagrams to compare to the predicted coverage performance.

Additional sonar equation parameters that are not available in the real-time data stream are derived from the following sources:

• **BSCorr.txt:** This seabed imagery beam pattern correction file profiles sector specific source levels for each depth mode for a nominal 4° transmitter. This file also provides transmit sector lobe widths and athwartship steering angles for use in transmitter beam pattern calculations. This file is retrieved from the TRU via FTP (refer to Beaudoin et al. (2012) for instructions).

• **Isotropic Noise Level:** this is manually configured based on BIST Receive Noise Level testing. Future implementations of the monitoring tool will ingest BIST data directly from SIS via UDP transmission.

The model and its implementation still require further testing and validation; however it is still informative to examine initial results. The model was tested for DEEP, MEDIUM and SHALLOW modes during the transit to Anacortes, WA (Figs. 26-28). Ship speeds were 10-12 kts with the noise level configured to 47 dB based on noise level testing done at the calibration site at the beginning of the cruise, however noise levels were likely slightly higher due to elevated sea state.

The coverage achieved by the system while underway suffers from the same asymmetry as explained in the previous section; this is immediately obvious when comparing the achieved coverage to the predicted coverage as the model does not incorporate seafloor slope into the ensonified area corrections associated with incidence angle. This is most obvious in the MEDIUM and SHALLOW mode tests. The starboard sector tracks near to what the model predicts for coverage, though there remains validation and fine-tuning work to be done that could yield predictions that more closely match what is achievable in practice.

The general good agreement in DEEP mode is helpful in that the model can be used to predict coverage at depths greater than were encountered during the transit, e.g. under the same oceanographic, seafloor and noise conditions, the system should
achieve 16-18 km swath width at 5,000 m depth, similar to what is achieved by R/V *Kilo Moana* (Beaudoin, 2012b).

Figure 26. Coverage achieved in DEEP mode with dual swath and FM enabled. Cyan lines indicate the +/- 75° angular sector limit; blue and red curves indicate the range performance of the system predicted by the Lurton model. For each swath received from SIS, the outermost valid port and starboard soundings are plotted as crosses and color-coded according to transmit sector.

Figure 27. Coverage achieved in MEDIUM mode with dual swath enabled and CW waveforms (note that MEDIUM mode does not use FM waveforms). The system was intentionally configured in MEDIUM mode to validate the coverage performance model.
Figure 28. Coverage achieved during in SHALLOW mode with dual swath enabled and CW waveforms (SHALLOW mode does not use FM waveforms). The system was intentionally configured in SHALLOW mode to validate the coverage performance model.

Data Quality

Bathymetry, seabed imagery and water column imagery were evaluated for DEEP, MEDIUM and SHALLOW modes. Overall quality was observed to be very good throughout the cruise with only the usual mistracking artifacts associated with higher noise levels and bubble sweeping in increased seas. Sample imagery for each of the modes is included in Appendix C.
Summary and Recommendations

The accuracy (repeatability, strictly speaking) analysis indicates that the system is performing within expected levels. The EM122 appears to be configured correctly and adequately calibrated. A full patch test calibration was conducted with the offsets being applied in SIS; follow up confirmation calibrations indicate that the offsets are correct. A residual bias exists in the system that is associated with the multibeam system itself and not the MRUs (as it was common to both the Hydrins and Seapath). The bias, though typical of a surface sound speed bias, cannot be explained by this and must have another cause. The bias should be raised with the manufacturer to better understand if this has been observed before.

Coverage performance of the EM122 is as expected and is consistent with Lurton’s model predictions in DEEP mode. Discrepancies in MEDIUM and SHALLOW mode indicate that further refinement of the model is required, however, the good agreement with the DEEP mode increases confidence in the predicted system coverage performance in deep water and indicate that it will be reasonable and on par with what is achievable with similar EM122 systems in the US academic fleet.

Data quality is satisfactory in terms of bathymetry, seabed imagery and water column imagery. No sector specific artifacts were observed in the bathymetry or seabed imagery. Slight signal level offsets were observed between sectors in the dual-swath geometry in water column imagery but they are typical of what is usually observed for Kongsberg Maritime dual-swath systems. Bubble sweep events were observed in typical sea states, however, SIO personnel indicate that their standard procedure is to ballast the vessel to trim the bow down slightly to mitigate these effects.

Small (<1 m) transmitter/receiver sensor offset errors were found during the review of the vessel geometry. These were corrected in SIS so the system is correctly configured to the best of our knowledge. Past data sets should be examined to determine at what point the system was incorrectly configured to aid in QA efforts undertaken by R2R and GMRT.

The following recommendations are made with respect to patch test calibration design and execution:

- Yaw/Pitch stabilization should be enabled for calibration routines to give nearly constant along-track sounding density.
- Dual swath should be enabled for calibration routines to give increased along-track sounding density.
- Vessel speeds should be slower than those typically used for mapping in order to increase the along-track sounding density, especially when attempting to resolve smaller topographic features.
• Smaller and more discrete topographic features should be chosen for pitch/heading calibration site.
• If stationary roll calibrations (holding station with dynamic positioning system and then reversing direction) are to be pursued, the MRU pitch and heading offsets must first be resolved and pitch stabilization should be enabled.
References


Caress, D. W., and Chayes, D. N. (2005). Mapping the seafloor: Software for the processing and display of swath sonar data. [5.0.6]. Columbia University. USA.


Appendix A – Noise Level Measurements
Appendix B – Accuracy Analysis Plots

DEEP CW DUAL Hydrins

[Graph showing depth deviation and depth bias as functions of beam angle.]

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DEEP FM DUAL Seapath

Depth Std. Dev (%w.d.)

Beam angle (deg)

Depth bias (%w.d.)

Beam angle (deg)
Appendix C – Data Quality

DEEP

Data File 0097_20130123_061945_revelle_bty.grd

Topography (m)
MEDIUM

Data File 0235_20130125_054042_revelle_bty.grd
SHALLOW

Data File 0418_20130127_040440_revelle_bty.grd