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Janice Eisenberg
Earth Resources Technology, Inc.

Michael Davidson
NOAA

Jonathan Beaudoin
University of New Hampshire, Durham

Steve Brodet
NOAA

Recommended Citation

Eisenberg, Janice; Davidson, Michael; Beaudoin, Jonathan; and Brodet, Steve, "Rethinking the Patch Test for Phase Measuring Bathymetric Sonars" (2011). *US Hydrographic Conference*. 809.
https://scholars.unh.edu/ccom/809

Proceedings: US Hydrographic Conference, Tampa, FL, 25-28 April 2011

Rethinking the Patch Test for Phase Measuring Bathymetric Sonars

Janice Eisenberg
Earth Resources Technology, Inc., 6100 Frost Place, Suite A, Laurel, MD, 20707, Janice.Eisenberg@noaa.gov

Michael Davidson
NOAA Ship *Thomas Jefferson*, Marine Operations Center Atlantic, 439 York Street, Norfolk, VA 23510

Jonathan Beaudoin
UNH Center for Coastal and Ocean Mapping-Joint Hydrographic Center, 24 Colovos Road, Durham, NH 03824

Steve Brodet
NOAA Office of Coast Survey, 1305 East-West Highway, Silver Spring, MD 20910

Abstract

While conducting hydrographic survey operations in the Florida Keys, NOAA Ship *Thomas Jefferson* served as a test platform for the initial operational implementation of an L-3 Klein HydroChart 5000 Swath Bathymetry Sonar System[1], a hull-mounted phase measuring bathymetric sonar (PMBS). During the project it became apparent that the traditional patch test typically utilized for multibeam echosounder (MBES) systems was poorly suited to the HydroChart – and perhaps other PMBS systems as well. These systems have several inherent characteristics that make it difficult to isolate and subsequently solve for biases under the traditional patch test paradigm: presence of a nadir gap, wide swaths (typically greater than 6 times water depth), and relatively poor object-detection capability in the outer swath. After "rethinking" the patch test to account for these characteristics, the authors propose a new patch test paradigm that is better suited to the HydroChart and other PMBS systems.

1.0 Introduction

A large portion of NOAA's nautical charting hydrographic survey effort is focused on acquiring bathymetric data in waters shoaler than 20 meters. Data acquisition by single-head MBES systems, which presently constitute much of NOAA's hydrographic systems inventory, is relatively inefficient and sometimes hazardous under these conditions, particularly when surveying near the shoreline or within close range of dangers to navigation. Single-head MBES swath widths are typically constrained to 3 or 4 times water depth in order to achieve stringent nautical charting hydrographic data requirements, making it relatively difficult to (1) efficiently obtain full bottom coverage and (2) maintain a safe distance from both visible and submerged hazards to navigation. Acquisition of airborne lidar bathymetry in many of these areas is often precluded by water clarity and data resolution requirements.

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[1] *Mention of a commercial company or product does not constitute an endorsement by NOAA, National Ocean Service, or Office of Coast Survey. Use of information from this publication concerning proprietary products or the testing of such products for publicity or advertising purposes is prohibited.*

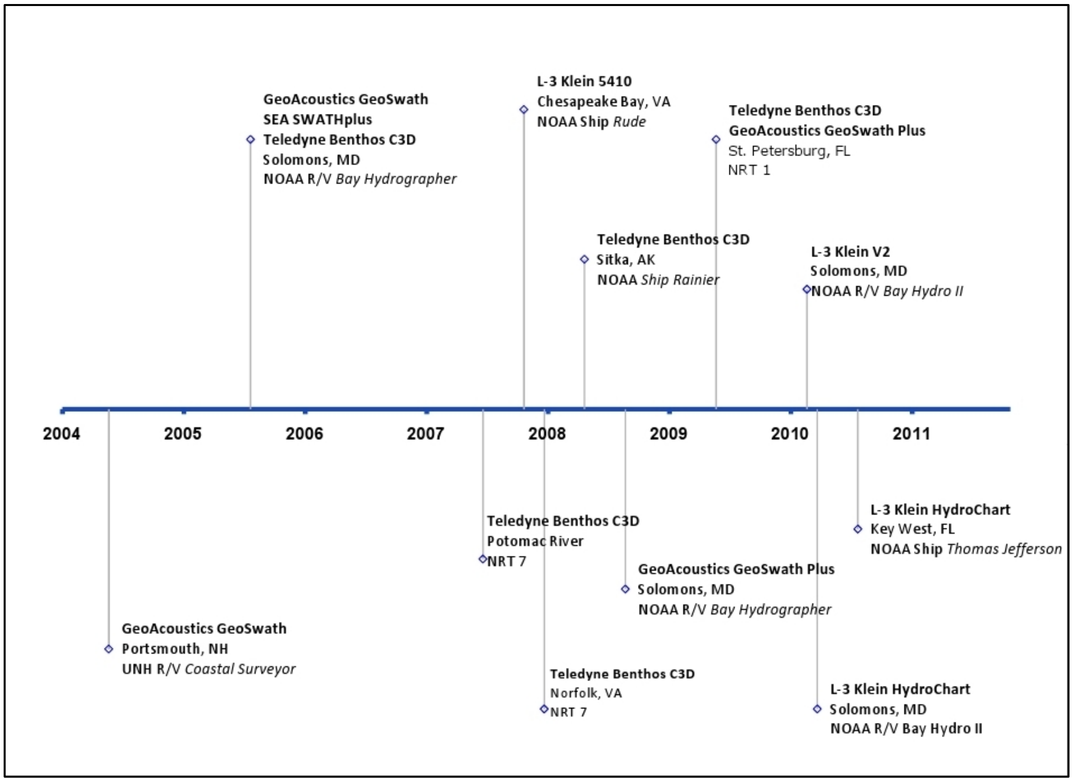


Figure 1. Timeline of NOAA's test and evaluation of phase measuring bathymetric sonars.

Since 2004, NOAA's Office of Coast Survey has undertaken an effort to test and evaluate PMBS technology as a tool to improve the efficiency and safety of hydrographic survey operations in shallow water environments while meeting NOAA's nautical charting hydrographic data requirements (Figure 1). Recent studies undertaken as part of this effort (Gostnell and Yoos, 2007; Brodet et al., 2010) have demonstrated that PMBS technology holds promise as a cost-effective method to acquire high-resolution, wide-swath (up to approximately 10 times water depth for hull-mounted systems) bathymetry with co-located imagery, effectively doubling the areal coverage per time of that achievable with single-head MBES systems in waters shoaler than 10 to 15 meters while simultaneously improving the overall safety of operations.

As part of ongoing test and evaluation efforts, the Office of Coast Survey recently procured an L-3 Klein HydroChart 5000 Swath Bathymetry Sonar System (Brodet et al., 2010) with intent to conduct an operational test and evaluation on NOAA Ship *Thomas Jefferson* Survey Launch 3102 during an Integrated Ocean and Coastal Mapping (IOCM) project in the Florida Keys National Marine Sanctuary (Figure 2). During data acquisition in the Florida Keys it became apparent that the traditional patch test typically utilized for MBES systems was poorly suited to the HydroChart – and perhaps to other PMBS systems by extension. PMBS systems have several inherent characteristics that impede the direct application of traditional MBES patch test methodology, including: presence of a nadir gap, wide swaths, and limited object-detection capability (particularly in the relatively noisy outer swath). The impact of these characteristics upon application of the traditional patch test methodology is discussed further in the next section.

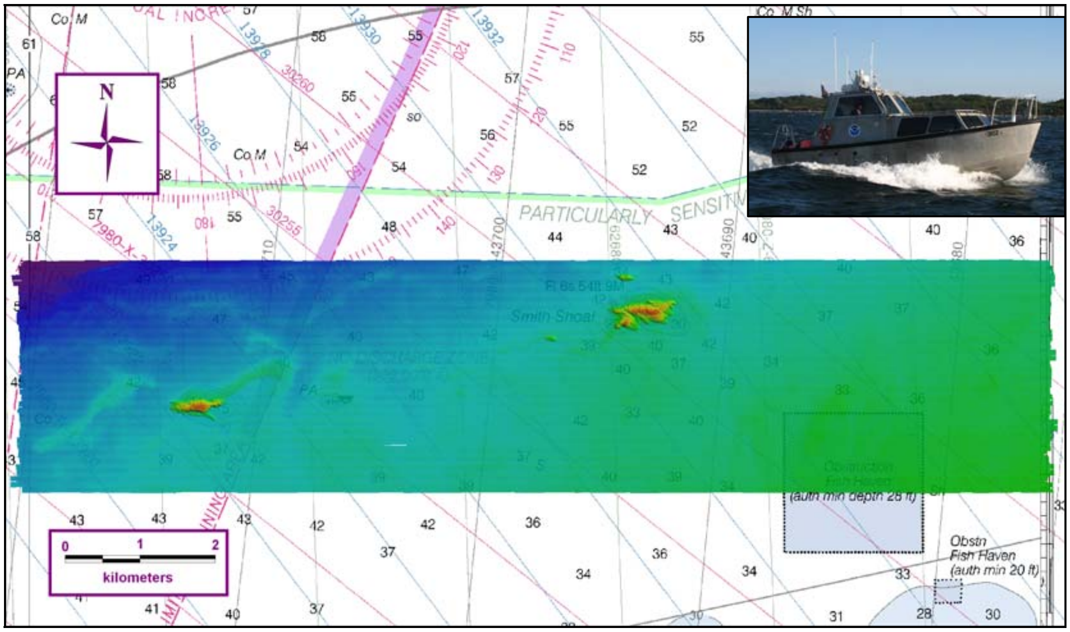


Figure 2. L-3 Klein HydroChart 5000 bathymetry from Integrated Ocean and Coastal Mapping (IOCM) project in Key West, FL, August 2010. HydroChart bathymetry was acquired for operational test and evaluation purposes only. Inset: NOAA Ship Thomas Jefferson Launch 3102.

This concept paper describes the limitations of applying the existing patch test methodology to PMBS systems and presents the authors' best effort to define a new set of patch test procedures that is better-suited to PMBS systems. The new patch test paradigm calls for re-organizing the order in which the biases are solved for, as well as rethinking the methodology utilized to solve for individual biases; in particular, the use of imagery is recommended to solve for navigation timing and yaw biases. A sample patch test dataset, utilizing the new methodology, was acquired with a Teledyne Benthos C3D installation on NOAA R/V *Lookdown* in Annapolis, MD in March of 2011. This paper describes the survey plan utilized to acquire the sample patch test dataset as well as some preliminary results. The preliminary results indicate that the use of imagery to derive patch test correctors for PMBS systems is promising; however, the derivation of highly precise correctors is difficult using the tools currently available. The authors subsequently propose the development of a new tool for deriving patch test correctors from PMBS imagery.

2.0 Limitations of the Existing Methodology

The original methodology for determining the angular misalignment of the sonar and vessel reference frames for MBES systems was developed by NOAA's National Ocean Service as part of an effort to map the US Exclusive Economic Zone (EEZ) in the late 1980s (Wheaton, 1988; Herlihy et al., 1989). This approach was subsequently adapted for high-resolution, shallow-water multibeam systems (Godin, 1998), yielding the traditional MBES patch test that is well-established today. Godin's approach further utilizes a post-processing system that allows for the visualization of swaths in plan view and cross-section, as well as for the digital manipulation of sounding data, allowing for the easier determination of patch test correctors.

The approach previously taken by the Office of Coast Survey to derive patch test correctors for PMBS systems has been to utilize the traditional patch test methodology virtually "as-is". This approach (Figure 3) utilizes the same order of solving for biases (timing-pitch-yaw-roll), but allows for off-nadir data to solve for navigation timing and pitch. There are several limitations to utilizing this approach:

- *Cross-Talk*: Use of off-nadir data to solve for pitch introduces "cross-talk" with roll and yaw, particularly when solving on a bounded slope (Wheaton, 1988). It is therefore impossible to solve for pitch before roll and yaw are resolved, forcing an iterative solution between the three biases to close in on the "correct" values. The effect of cross-talk was particularly pronounced in the HydroChart installation on NOAA Ship *Thomas Jefferson* Launch 3102, for which the nadir gap was increased to 20° from vertical on each side to mitigate the effect of acoustic return from the keel (Figure 4).

- *Poor object detection capability*: The traditional patch test methodology utilizes a "submerged and conspicuous bathymetric feature" (Godin, 1998) to solve for a navigation timing latency as well as pitch and yaw biases. Traditionally, PMBS systems have proven useful for acquiring generalized bathymetry, but have performed poorly relative to MBES systems with regard to object-detection capability using bathymetry (Gostnell and Yoos, 2007; Brodet et al., 2010), thus limiting the usefulness of solving for timing, pitch and yaw biases utilizing PMBS sounding data acquired over a discrete object (Figure 5).

- *Yaw Sensitivity:* For PMBS systems, which are capable of achieving swaths of nearly 10 times water depth as opposed to the 3 to 5 times water depth achievable by most single-head MBES systems, yaw is closing the gap with roll as the most "sensitive" bias in the patch test (Figure 4). At the same time, deriving a precise yaw bias value for PMBS systems is made more difficult for both reasons noted above (cross-talk and limited object-detection capability).

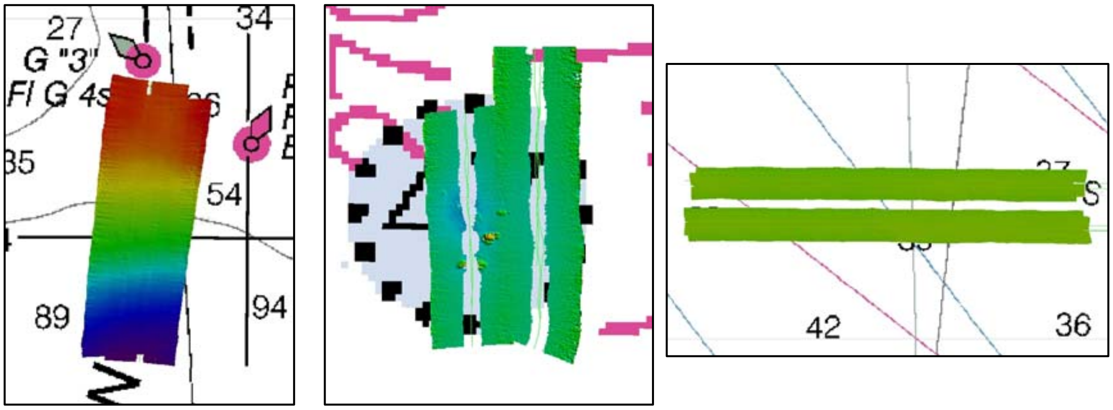


Figure 3. HydroChart patch test from Key West, FL. From left: timing and pitch tests (bounded slope); yaw test (discrete object); roll test (flat seafloor). These calibration lines comprise a dual-transducer patch test modified from the MBES methodology.

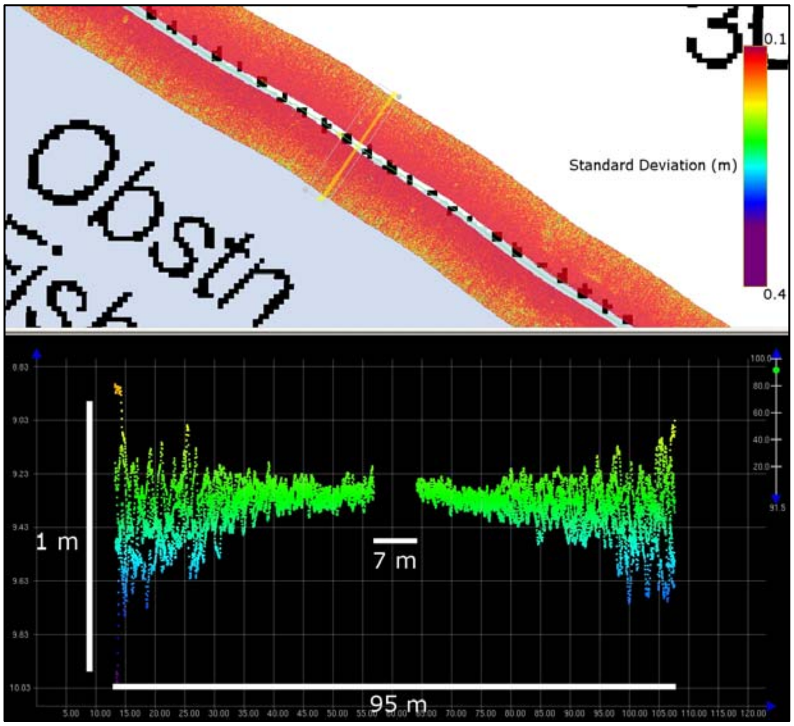


Figure 4. 2D view of HydroChart swath from Solomons, MD survey in April 2010. Water depth is approximately 9.5 m. Note wide swath (approximately 10 times water depth) and pronounced nadir gap, as well as increasing standard deviation of soundings in outer swath. Total magnitude of outer swath "fluff" is 1.2 m in this image. The HydroChart nadir gap is typically 15° from vertical on each side, but was increased to 20° for the installation on Launch 3102 to mitigate the effect of acoustic return from the keel.

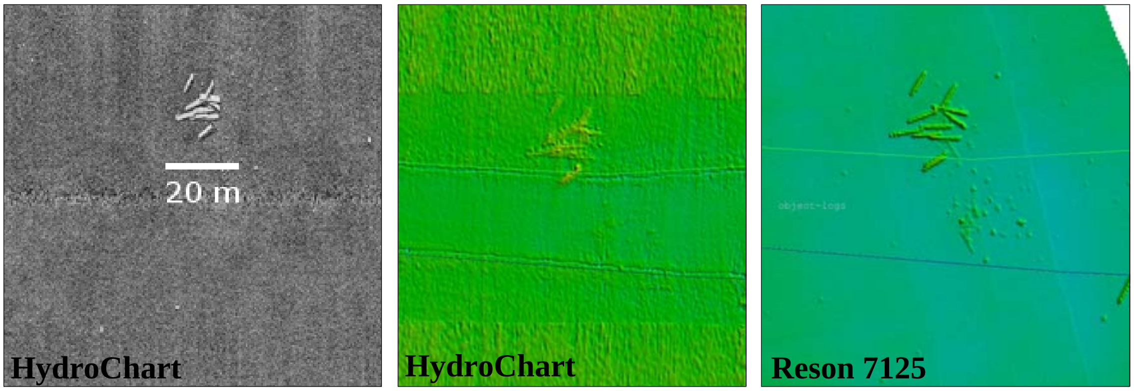


Figure 5. View of debris pile from Key West, FL survey in August 2010 in HydroChart imagery (left image), HydroChart bathymetry (center image) and Reson 7125 bathymetry (right image); grid resolution of HydroChart and Reson 7125 bathymetry is 0.5 m. Debris rise approximately 50 to 60 cm above the seabed. These features are poorly resolved in the HydroChart bathymetry, but appear sharp in the imagery.

3.0 A New Patch Test for PMBS Systems

In view of the above limitations of applying the existing patch test methodology, the authors have endeavored to determine a new set of patch test procedures that is better-suited to PMBS systems. This new paradigm calls for reorganizing the order in which the biases are solved, as well as rethinking how some individual biases are solved.

3.1 Order of Solving Biases

To mitigate the problem of cross-talk, the recommended order of solving for biases is as follows:

1) Navigation timing latency
2) Roll offset
3) Yaw offset
4) Pitch offset

After resolution of the navigation time latency, the roll offset should be resolved next as it does not require the previous determination of yaw and pitch offsets. The yaw offset should be resolved next, followed by the pitch offset. Though pitch can contribute to cross-talk in the derivation of the yaw offset, this effect can be mitigated by using the PMBS imagery, rather than bathymetry, to solve for yaw, as described below.

3.2 Methodology for Solving Biases

This patch test methodology assumes a dual-transducer configuration, which is the case for PMBS systems that have separate port and starboard transducers for which pitch, yaw and roll errors need to be resolved separately.

3.2.1 Navigation Timing Latency

To assess a navigation timing latency, coincident lines are run at different speeds (slow and fast) perpendicular to a discrete linear feature, such as a pipeline, on a flat shallow bottom (Figure 6). If no linear feature is present in the survey vicinity, one can create a linear feature by dragging a mushroom anchor behind the vessel on a soft bottom, or by dropping acoustic targets at regular intervals for a “connect the dots” linear feature on a hard bottom (the acoustic targets should have surface floats to facilitate retrieval). If it is not possible to find or create a linear feature, an alternative is to run lines over a discrete object in the inner swath. Particularly for the alternative scenario, care must be taken to ensure that the vessel follows, as nearly as possible, the same trackline on each pass in order to mitigate the influence of cross-talk with roll and yaw. Due to the potential for additional motion-induced cross-talk (if a navigation timing latency exists, it is often coupled to an attitude timing latency), navigation timing latency calibration lines should be acquired during flat calm conditions.

The navigation timing delay can be assessed in post-processing using sounding data in a semi-automated patch test calibration (e.g., Caris HIPS calibration tool), though this approach is subject to the limitations discussed in the previous section. An alternative approach which may mitigate these effects is to solve for the navigation timing delay using a manual imagery calibration. A manual imagery calibration can be performed by either: 1) re-generating mosaics upon effecting a change to patch test corrector values to visually assess the alignment of the target seafloor geometry, or 2) assigning contacts to the target seafloor geometry in each line of a calibration line pair, then re-computing contact position upon effecting a change to the patch test corrector values to visually assess the alignment of the contacts.

The use of imagery to assess a navigation timing delay mitigates the problem of cross-talk with roll, which may cause an apparent vertical displacement of sounding data in the bathymetry patch test. Imagery also tends to be much “sharper” than the bathymetry for PMBS systems, allowing for better definition of the edges of discrete objects used to assess the navigation timing delay (Figure 5). However, a major limitation of using imagery is the difficulty of deriving correctors unless the timing latency is large enough to induce a noticeable shift in the mosaics; mosaics cannot be used to correct relatively small timing latencies where the grid resolution is coarser than the position displacement induced by the latency. The use of the second method – that of aligning contacts digitized from the high-resolution imagery display (e.g., Caris Side Scan Editor display) – may allow for the determination of a more precise timing latency.

The benefit of using a discrete linear feature to solve a navigation time delay, coupled with use of an imagery patch test, is that it allows the human eye to visually “connect” the linear feature to give an intersection point at nadir. This nadir point cannot be imaged by PMBS systems, but is required to minimize cross-talk with pitch and yaw. A more robust solution to obtain this intersection point would be to develop a tool that fits a regression line to the image target, yielding the exact trackline intersection point at nadir. This intersection point is computed for both runs of the line. The navigation latency can then be modified until the nadir intersection points are exactly the same for both runs. Because this tool would yield a mathematical solution rather than a purely visual one, it could also be capable of producing a more “precise” timing latency.

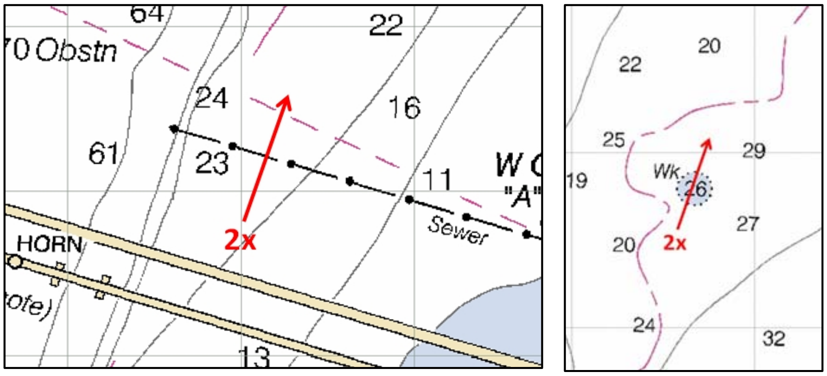


Figure 6. Proposed calibration line geometry for PMBS navigation timing test. Coincident lines are run at slow and fast speeds. Left: Test over a discrete linear feature (submerged sewer pipeline). This is the recommended geometry for solving a navigation timing latency for PMBS systems. Right: Test over a discrete object (wreck). Images are from a line plan for an example patch test survey on NOAA R/V Lookdown in Annapolis, MD.

3.2.2 Roll Bias

The procedure for solving a roll bias for a PMBS system is approximately the same as that for a dual-head MBES system. To solve for a roll bias, a set of reciprocal offset lines are run in both directions, at the same speed, over a flat seafloor (Figure 7). Line spacing should be equal to one-half of the total swath width, yielding 100% overlap. The four runs of the two lines provide the ability to independently solve for port and starboard side biases. Though roll lines are typically run in relatively deep water (Godin, 1998), one should be careful not to exceed the maximum depth rating of the PMBS system.

The roll bias is subsequently assessed in post-processing using the PMBS sounding data in a semi-automated patch test calibration, such as the HIPS Calibration Tool.

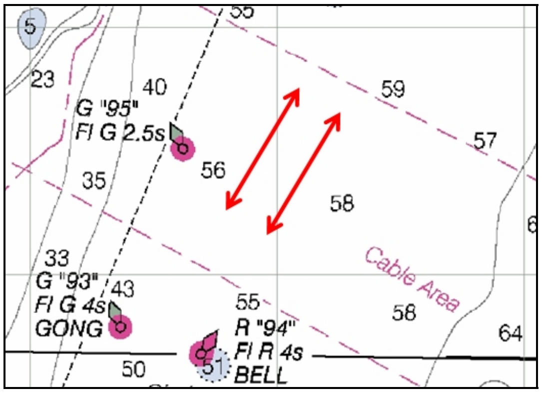


Figure 7. Proposed calibration line geometry for PMBS roll test. Reciprocal lines are offset by approximately one-half the total swath width, yielding 100% overlap (line spacing is exaggerated in this image). The water depth should not exceed the maximum depth rating of the PMBS system; here a depth of 17m is used. Image is from a line plan for an example patch test survey on NOAA R/V Lookdown in Annapolis, MD.

3.2.3 Yaw Bias

To solve for a yaw bias, a set of reciprocal offset lines are run, at the same speed, perpendicular to a discrete linear feature, such as a pipeline, on a flat shallow bottom (Figure 8). If one cannot find or create a discrete linear feature in the survey vicinity, an alternative is to run lines over a discrete object in the outer swath. Line spacing should be such that the adjacent lines overlap slightly (~15%) while covering the feature; where possible, the feature should be wide enough to ensure adequate sampling (Godin, 1998). As with the roll offset, the lines are run in both directions to allow for separate estimation of the port and starboard transducer yaw offsets.

The yaw bias can be assessed in post-processing using sounding data in a semi-automated patch test routine, or using a manual imagery calibration as described in Section 3.2.1. The use of imagery to assess a yaw bias will mitigate the influence of an unresolved pitch bias, which may cause an apparent vertical displacement of soundings from consecutive lines. The imagery is also considerably sharper than the bathymetry for PMBS systems, particularly so in the outer swath, allowing for better definition of discrete objects for assessment of the yaw bias. However, as with the assessment of navigation timing delay, a major limitation of the imagery patch test is the difficulty of deriving correctors unless the yaw bias is large enough to induce a noticeable shift in the mosaics.

The ideal seafloor geometry (that of a discrete linear feature in shallow water) makes the best use of the imagery patch test, as an unresolved yaw bias alters the azimuth of the linear feature, leading to a discontinuity in the overlap region between calibration lines. To solve for the yaw bias, one simply brings the calibration line pair back into alignment. While an unresolved pitch offset would also contribute to along-track displacement of the linear feature, this displacement should be minimal compared with the displacement due to a yaw bias. This is because pitch is typically the least sensitive of the biases in shallow water; for example, a pitch bias of 1° will yield a horizontal displacement of 25 cm at nadir for a nominal water depth of 20 m.

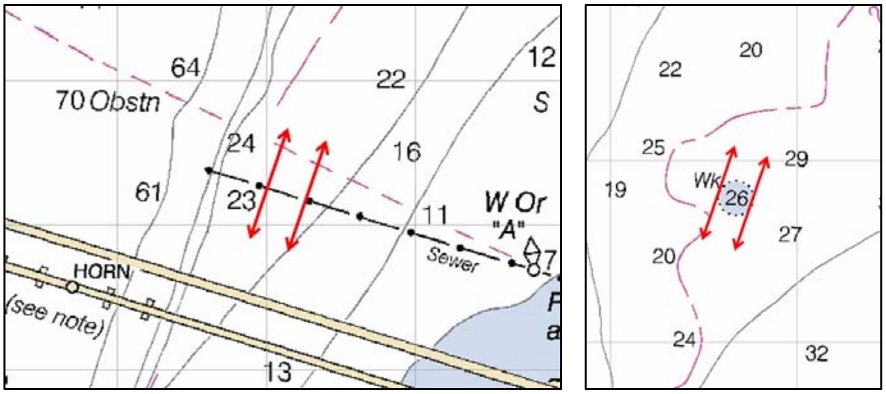


Figure 8. Proposed calibration line geometry for PMBS yaw test. Reciprocal lines are offset to allow for 15% overlap between adjacent swaths (line spacing is exaggerated in these images). Images are from a line plan for an example patch test survey on NOAA R/V Lookdown in Annapolis, MD.

3.2.4 Pitch Bias

The procedure for solving a pitch bias for a PMBS system is approximately the same as that for a dual-head MBES system. To solve for a pitch bias, a set of reciprocal offset lines are run, at the same speed, perpendicular to a bounded slope (Figure 9). Line spacing should be equal to one-half of the total swath width, yielding 100% overlap.

The pitch bias is subsequently assessed in post-processing using the PMBS sounding data in a semi-automated patch test calibration, such as the HIPS Calibration Tool. Because the pitch bias is determined by examining off-nadir sounding data, which is susceptible to cross-talk with yaw, it is important to determine a precise yaw bias before attempting to solve for pitch. Failure to do so will require an iterative sequence of solving for yaw and pitch to close in on the "correct" values.

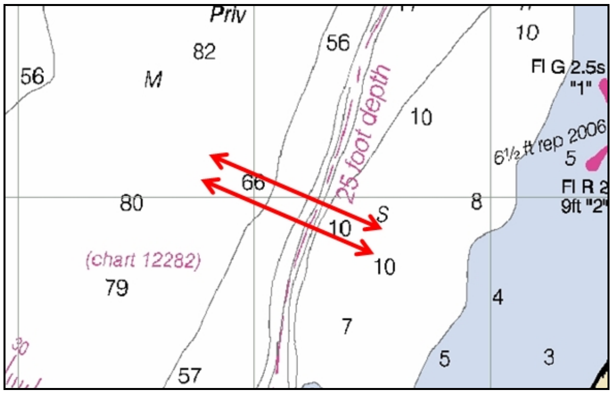


Figure 9. Proposed calibration line geometry for PMBS pitch test. Reciprocal lines are offset by approximately one-half the total swath width, yielding 100% overlap (line spacing is exaggerated in this image). Image is from a line plan for an example patch test survey on NOAA R/V Lookdown in Annapolis, MD.

4.0 An Example PMBS Patch Test

An example PMBS patch test utilizing the proposed methodology was conducted with a Teledyne Benthos C3D installation on NOAA R/V *Lookdown* in Annapolis, MD on March 8th, 2011 (Figure 10). During survey operations sound speed casts were acquired approximately every 2 hours using a Sea-Bird SBE 19*Plus* CTD. Vessel motion correctors and position were provided by an Applanix POS MV WaveMaster; attitude and kinematic data were logged for the duration of the survey in the POS MV controller software.

C3D bathymetry and imagery were fully processed using the Caris HIPS and SIPS software package. All sound speed correctors, water level correctors, and positioning and kinematic correctors were applied to the C3D data in post-processing. Sounding data were reduced to the ellipsoid using the HIPS Compute GPS Tide function, eliminating the need for zoned tides. The ellipsoid heights applied in post-processing are referenced to the GRS 80 ellipsoid (meters) and were computed using a POSPac SingleBase high-accuracy differential GNSS routine with inertially-aided kinematic ambiguity resolution (Applanix, 2010).

In post-processing, patch test correctors for the C3D installation on R/V *Lookdown* were determined for the starboard transducer only due to a pronounced artifact of unknown origin in the port transducer data.

4.1 Preliminary Results

Patch test correctors for the C3D installation on NOAA R/V Lookdown were derived using the new PMBS patch test methodology outlined in Section 3.0. This section describes the preliminary results of utilizing the new methodology.

Figure 10. Teledyne Benthos C3D installation on NOAA R/V Lookdown.

4.1.1 Navigation Timing

Calibration lines to assess navigation timing latency were acquired over a submerged sewer pipeline located at a water depth of approximately 7 meters MLLW (Figure 6). Navigation timing latency was derived using two different methods of manual imagery calibration. The first method comprised generating a mosaic of the calibration line pair, which was subsequently re-generated upon effecting a change to the navigation latency value in the Caris HVF file. The second method comprised digitizing contacts from the leading edge of the pipeline in the imagery of each line from the calibration pair, then re-computing contact position upon effecting a change to the navigation latency value in the Caris HVF file. Whereas mosaics for the navigation timing test were generated at a resolution of 50 cm, the contacts were digitized from the imagery in the Caris Side Scan Editor display, which was of a higher resolution.

The first method, which directly utilizes the mosaic to visually assess alignment of the pipeline, was not useful for solving the navigation time latency. While inducing a navigation timing latency in the Caris HVF file clearly induced an offset in the pipeline position between the individual line mosaics (GeoBars), it was not possible to visualize this offset in the combined mosaic, in which the imagery from one line always overlapped the other (Figure 11). It was impossible to determine the navigation timing latency without being able to simultaneously view the pipeline position from each line of the calibration pair.

The second method, which utilizes digitized contact positions to visually assess alignment of the pipeline, proved to be a much more precise method for solving the navigation timing latency. Contacts were digitized from the leading edge of the pipeline for each line of the calibration pair, and the navigation latency in the Caris HVF was subsequently tweaked until the two contacts came into alignment. An induced navigation timing latency of 1 second induced a noticeable discrepancy in the recomputed contact positions (Figure 12), indicating that this methodology is capable of resolving sub-second navigation timing latencies. The navigation latency for the C3D installation on R/V *Lookdown* was found to be approximately zero.

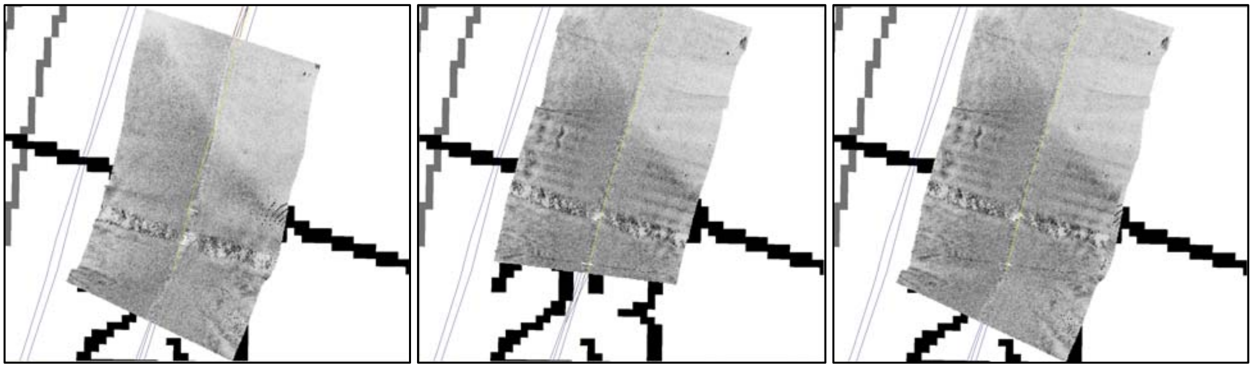


Figure 11. A manual calibration method for assessing navigation timing latency from PMBS imagery. Left: Line mosaic (GeoBar) of calibration line 'A' with induced timing latency of 10 seconds. Middle: Line mosaic of calibration line 'B' with induced timing latency of 10 seconds. Note that the pipeline position has shifted relative to calibration line 'A'. Right: Combined mosaic of calibration lines 'A' and 'B' shows pipeline location from calibration line 'B' only. Because both pipeline positions cannot be visualized simultaneously, it is impossible to assess navigation timing latency using this method. Imagery resolution in each image is 50 cm.

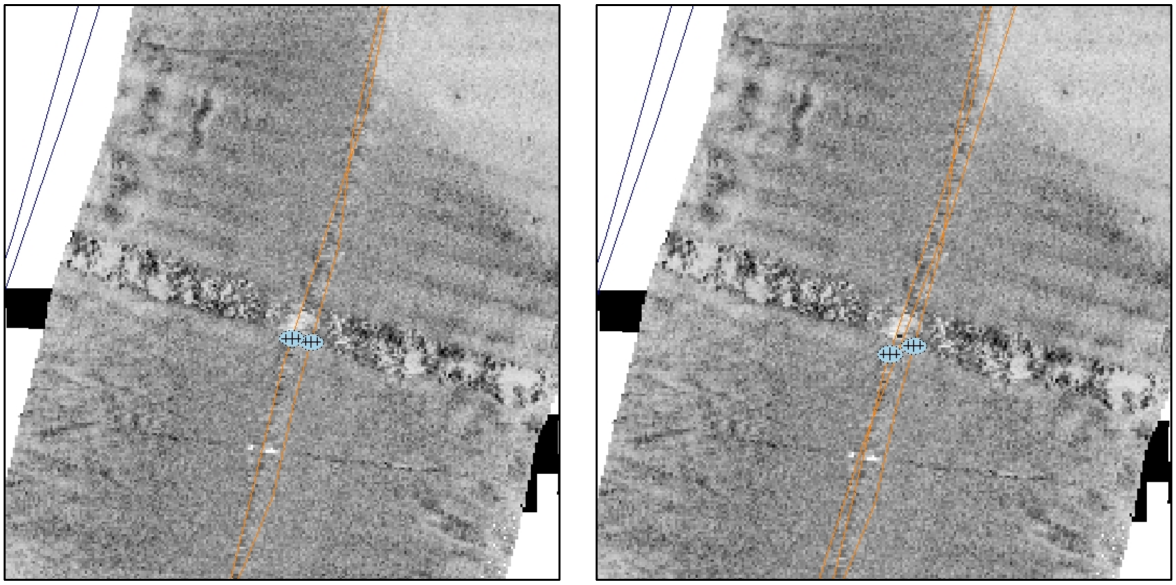
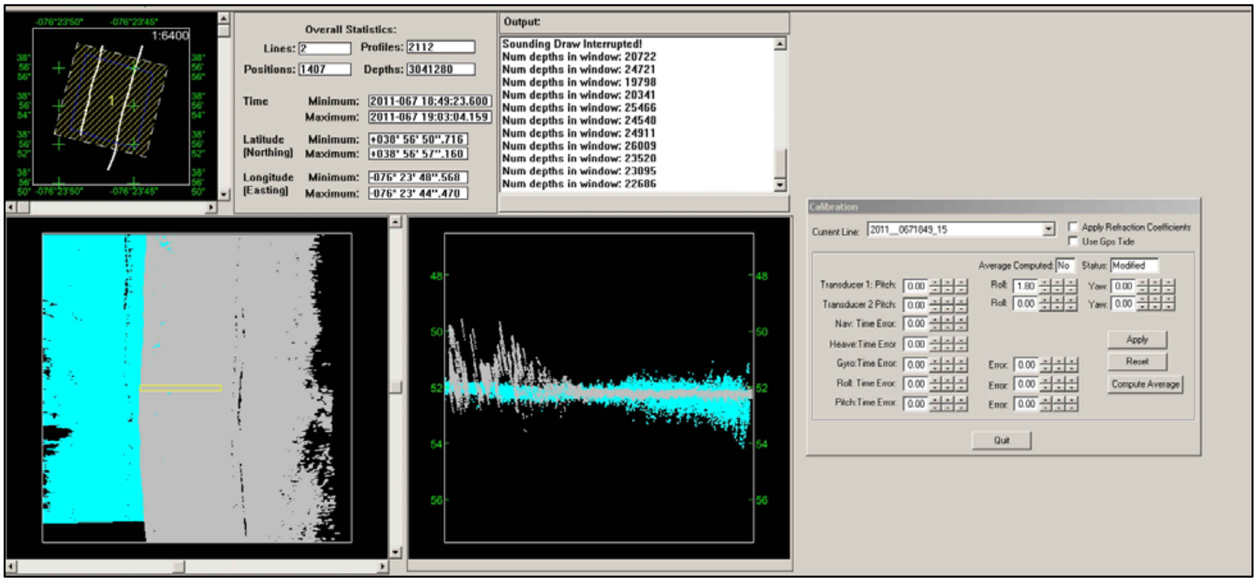


Figure 12. A manual calibration method for assessing navigation timing latency from contacts digitized from PMBS imagery. Left: Contacts digitized from calibration lines 'A' and 'B' with navigation time latency of zero; the contacts are in alignment, indicating the latency is approximately nil. Right: Contacts digitized from calibration lines 'A' and 'B' with an induced navigation time latency of 1 second. Imagery resolution in each image is 50 cm.

4.1.2 Roll Bias

Calibration test lines to assess port and starboard roll biases were acquired over a flat seafloor area at a water depth of approximately 15 meters MLLW. The starboard roll bias was assessed in post-processing by examining C3D sounding data with the Caris HIPS Calibration Tool, exactly as it would be for a dual-transducer MBES system. As anticipated, this process was relatively straightforward. The starboard roll bias for the C3D installation on R/V *Lookdown* was found to be approximately 1.80 degrees.

Roll calibration of PMBS systems is made somewhat more difficult by the necessity of aligning the "fluffy" outer swath of one line with the much neater inner swath of its counterpart in the calibration line pair (Figure 13). The process can be made even more difficult by the presence of a refraction artifact, which is often more pronounced in wide-swath PMBS data, in one or both lines in the calibration line pair. The C3D patch test data appeared to have a slight refraction artifact, which may or may not have appreciably impacted the determination of a starboard roll bias.



Overall Statistics:

Lines: 2
Profiles: 2112
Positions: 1407
Depths: 3041280
Time Minimum: 2011-067 18:49:23.600
Time Maximum: 2011-067 19:03:04.159
Latitude (Northing) Minimum: +038° 56' 50".716
Latitude (Northing) Maximum: +038° 56' 57".160
Longitude (Easting) Minimum: -076° 23' 48".568
Longitude (Easting) Maximum: -076° 23' 44".470

Output:

```
Sounding Draw Interrupted!
Num depths in window: 20722
Num depths in window: 24721
Num depths in window: 19798
Num depths in window: 20341
Num depths in window: 25466
Num depths in window: 24540
Num depths in window: 24911
Num depths in window: 26009
Num depths in window: 23520
Num depths in window: 23095
Num depths in window: 22686
```

Calibration

Current Line: 2011__0671849_15
☐ Apply Refraction Coefficients
☐ Use Gps Tide
Average Computed: No
Status: Modified
Transducer 1: Pitch: 0.00
Roll: 1.80
Yaw: 0.00
Transducer 2 Pitch: 0.00
Roll: 0.00
Yaw: 0.00
Nav: Time Error: 0.00
Heave:Time Error: 0.00
Gyro:Time Error: 0.00
Error: 0.00
Roll: Time Error: 0.00
Error: 0.00
Pitch:Time Error: 0.00
Error: 0.00

Figure 13. Assessment of roll bias using the Caris HIPS Calibration Tool. Note the difficulty of aligning the "fluffy" outer swath of one line with the much neater inner swath of its counterpart in the calibration line pair (center window). Note the presence of a slight refraction artifact, most visible in the outer swath "fluff".

4.1.3 Yaw Bias

Calibration test lines to assess the port and starboard yaw biases were acquired over a submerged sewer pipeline located at a water depth of approximately 7 meters MLLW (Figure 6). This was the same feature utilized to assess the navigation timing latency.

The starboard yaw bias was assessed in post-processing using the two different methods of manual imagery calibration utilized for the navigation timing latency test. The first method, which directly utilizes the mosaic to visually assess alignment of the pipeline, was somewhat useful for solving the yaw bias. A large yaw bias entered in the Caris HVF clearly induced an offset in the pipeline position between the individual line mosaics; this offset was still visible in the combined mosaic, as the imagery from one line only partially overlapped the other (Figure 14). However, it was relatively difficult to use this method to determine a precise yaw bias, as the sensitivity of this test obviously depends on the resolution of the imagery. The resolution of imagery used for the C3D yaw bias test was 1 m, which is the same magnitude of the along-track discrepancy induced by a yaw bias of approximately 1.1° at a range scale of 50 m (this was the range scale utilized during the C3D patch test). Using this first method the yaw bias for the C3D installation on R/V *Lookdown* was found to be approximately zero, give or take ~1° due to the limitations of the imagery resolution.

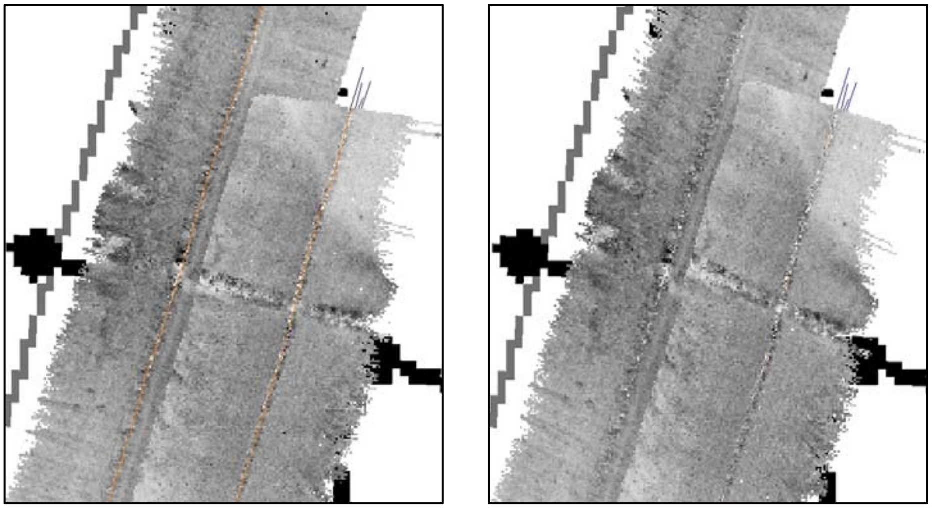


Figure 14. A manual calibration method for assessing yaw bias from PMBS imagery. Left: Combined mosaic of calibration lines 'A' and 'B' with yaw bias of zero. Right: Combined mosaic of calibration lines 'A' and 'B' with an induced yaw bias of 10 degrees; note displacement of pipeline. Imagery resolution in each image is 1 m. Note: Data quality of imagery from the port swath (i.e., non-overlapped region) is poor due to an artifact, of unknown origin, inherent to the C3D installation used for the survey.

The second method, which utilizes digitized contact positions to visually assess alignment of the pipeline, was not used, as it was very quickly demonstrated that contacts cannot be utilized to assess yaw bias. Though the navigation timing latency is "applied" to the contact position through the process of re-computing towfish navigation and re-computing contact positions, the other patch test correctors in the Caris HVF file (i.e., roll, pitch and heading biases) are not likewise applied to determine the contact position (Figure 15). Lacking the ability to effect a change in positioning of digitized contacts by altering patch test values in the Caris HVF, one cannot use contacts to solve for the yaw bias.

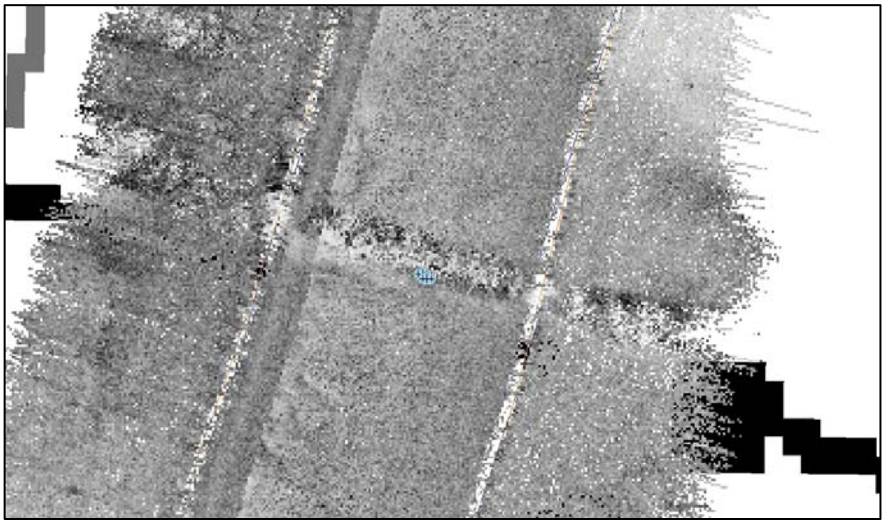


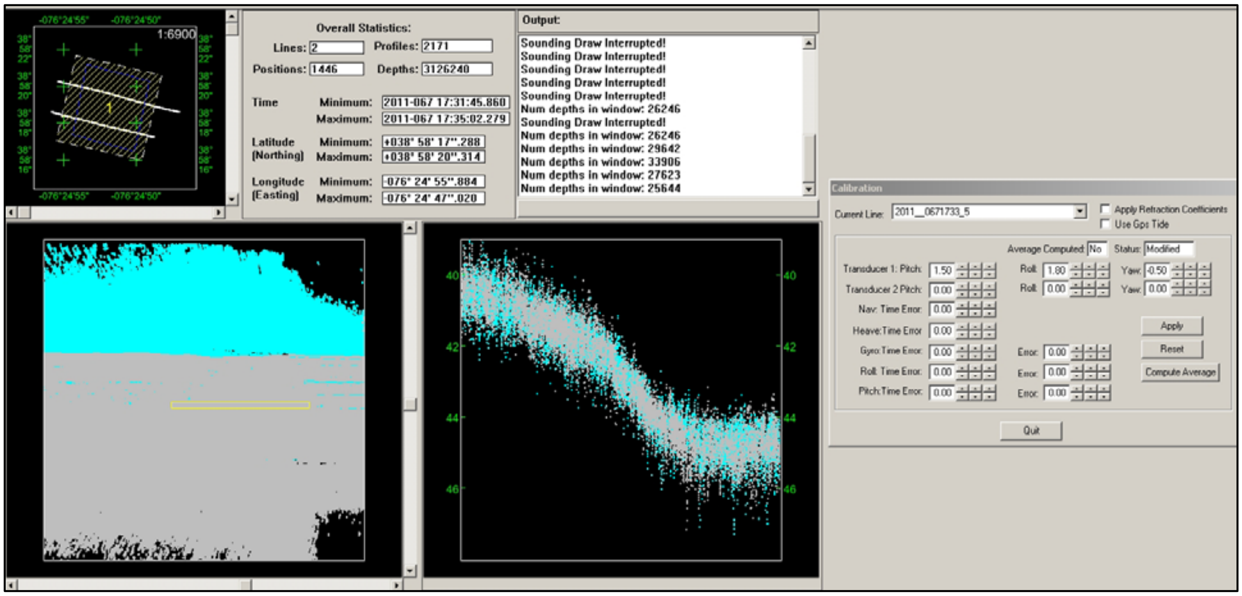
Figure 15. A manual calibration method for assessing yaw bias from PMBS imagery. Contacts digitized from yaw calibration lines 'A' and 'B'. Changing the yaw bias value in the Caris HVF file does not effect a change in re-computed contact positions; hence this method cannot be used to solve for yaw bias.

4.1.4 Pitch Bias

Calibration test lines to assess port and starboard pitch biases were acquired over a bounded slope with a nominal water depth of approximately 5 meters MLLW. The starboard pitch bias was assessed in post-processing by examining C3D sounding data with the Caris HIPS Calibration Tool, exactly as it would be for a dual-transducer MBES system (Figure 16). As anticipated, this process was relatively straightforward. The starboard pitch bias for the C3D installation on R/V *Lookdown* was found to be approximately 1.50 degrees.

5.0 Discussion and Conclusions

Preliminary results from the recent C3D survey on R/V *Lookdown* indicate that the new methodology for deriving patch test correctors for PMBS systems, comprised of a new order of solving for biases as well as new tools and seafloor geometries to solve for the navigation timing latency and yaw bias, is capable of overcoming many of the limitations inherent to the traditional patch test methodology, including the potential for cross-talk between pitch, roll and yaw biases. In particular, the use of imagery to solve for the navigation timing latency and yaw bias is a significant improvement upon the existing methodology when used in concert with calibration lines acquired over a discrete linear feature. For solving a navigation timing latency, this procedure allows the human eye to visually "connect" the feature across the nadir gap to derive an intersection point for assessing navigation timing latency without cross-talk from roll and yaw. For solving a yaw bias, this procedure allows one to "connect" the feature between adjacent lines for solving the yaw bias without cross-talk from pitch.



Overall Statistics:
Lines: 2
Profiles: 2171
Positions: 1446
Depths: 3126240
Time Minimum: 2011-067 17:31:45.860
Time Maximum: 2011-067 17:35:02.279
Latitude (Northing) Minimum: +038° 58' 17".288
Latitude (Northing) Maximum: +038° 58' 20".314
Longitude (Easting) Minimum: -076° 24' 55".884
Longitude (Easting) Maximum: -076° 24' 47".020

Output:

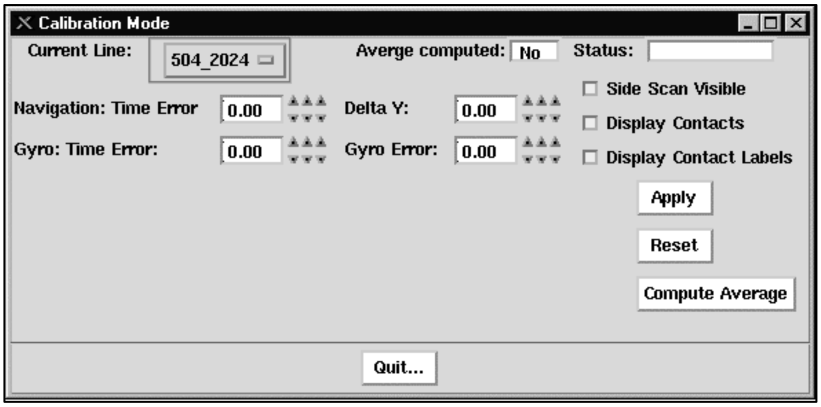
```
Sounding Draw Interrupted!
Sounding Draw Interrupted!
Sounding Draw Interrupted!
Sounding Draw Interrupted!
Sounding Draw Interrupted!
Num depths in window: 26246
Sounding Draw Interrupted!
Num depths in window: 26246
Num depths in window: 29642
Num depths in window: 33906
Num depths in window: 27623
Num depths in window: 25644
```

Current Line: 2011__0671733_5
☐ Apply Refraction Coefficients
☐ Use Gps Tide
Average Computed: No
Status: Modified
Transducer 1: Pitch: 1.50
Roll: 1.80
Yaw: -0.50
Transducer 2 Pitch: 0.00
Roll: 0.00
Yaw: 0.00
Nav: Time Error: 0.00
Heave:Time Error: 0.00
Gyro:Time Error: 0.00
Error: 0.00
Roll: Time Error: 0.00
Error: 0.00
Pitch:Time Error: 0.00
Error: 0.00

Figure 16. Assessment of pitch bias using the Caris HIPS Calibration Tool.

Whereas implementation of the new methodology demonstrates the utility of using high-resolution PMBS imagery to solve for the navigation timing and yaw biases, the "tools" explored in this paper – those of a manual imagery calibration using either mosaics or vector data such as digitized contacts – cannot derive correctors with the precision inherent to the traditional patch test methodology. The first method, which utilizes mosaics to visually assess alignment of a discrete object in response to manual "tweaking" of applied patch test values, is not altogether useful as the precision of the derived bias is limited by the mosaic resolution. Whereas the second method, which examines discrepancies in contact positions in response to tweaking of applied patch test values, is capable of deriving a more precise bias (i.e., to sub-second resolution for the navigation latency), this method can only be used to assess a navigation timing latency since pitch, roll and yaw biases are not "applied" to digitized contacts.

Since the determination of highly precise patch test correctors is inhibited by the tools currently available for conducting an imagery-based calibration, the authors propose development of a new tool for the dynamic calibration of imagery and vector data based on parameters including (but perhaps not limited to) navigation timing latency and roll, pitch and yaw biases. Such a tool would allow for the simultaneous display of imagery and vector data, and both would be dynamically updated in response to tweaking the corrector parameters, similar to the dynamic update of sounding data in the Caris HIPS Calibration Tool. A tool similar to the one proposed was formerly implemented in Caris SIPS Unix (Universal Systems Ltd., 1998), and allowed for dynamic calibration of imagery based on parameters including navigation time latency, gyro time latency, gyro error, and fore/aft offset of the navigation antenna with respect to the vessel's reference point (Figure 17).



Current Line: 504_2024
Averge computed: No
Status:
Navigation: Time Error 0.00
Delta Y: 0.00
Gyro: Time Error: 0.00
Gyro Error: 0.00
☐ Side Scan Visible
☐ Display Contacts
☐ Display Contact Labels

Figure 17. Caris SIPS Unix Calibration Tool.

A potential solution for deriving even more precise navigation timing latency and yaw bias correctors for PMBS systems would be to develop a tool that examines the raw intensity time-series for each line in the calibration line pair. Such a tool would derive an along-track time-series of intensity values of the first bottom return for each line of the calibration pair; these time-series could then be shifted along the time axis until the intensity peak (corresponding to the object at nadir) comes into alignment. The precision of a navigation timing latency derived using this method would presumably be limited only by the sampling rate. This would be a vast improvement upon the current methodology, in which the precision of the navigation timing latency is limited by the mosaic resolution and/or resolution of the side scan display, which is used to digitize contacts.

6.0 Future Work

As stated in the conclusions, there is a strong need to develop a new tool that allows for the dynamic calibration of imagery and vector data based on parameters including the navigation timing latency and roll, pitch and yaw biases. The tools currently available for an imagery patch test only allow for manual calibration using mosaics and digitized contacts, and are inadequate for determining precise navigation timing latency and yaw bias correctors. The determination of precise yaw bias correctors is particularly important for PMBS systems, which are capable of achieving swaths of nearly 10 times water depth, approximately twice the swath width achievable by most single-head MBES systems.

Future work will be necessary to determine the validity and effectiveness of the new patch test methodology for PMBS systems. A potential method of determining the effectiveness of the new methodology is comparison of the standard deviation of surfaces computed using correctors derived using the original (adaptation of the traditional patch test procedure) and new methodologies. Another consideration in assessing the effectiveness of the new patch test is usability; potential usability metrics include overall time required to derive patch test correctors, as well as variability in derived corrector values (navigation timing latency and roll, pitch, and yaw bias) produced by redundant patch test processors.

7.0 Acknowledgments

The authors wish to thank Jay Lazar and LTJG Colin Kliewer for their support in acquiring the survey data used to test the methodology presented in this paper. The authors also thank CDR Shep Smith for his contribution in identifying a potential solution scope during the early days of this effort. Thanks to Vitad Pradith and Mike Annis for reviewing the results presented in this paper, and to ST Doug Wood of the NOAA Ship *Thomas Jefferson* for preparing several key images of PMBS data.

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