Using a Dynamic Ocean Surface to Perform a Geometric Calibration of a Bathymetric Lidar

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Abstract—A geometric calibration of an airborne lidar is an essential component to any bathymetric survey. A poorly-aligned system leads to erroneously reported depths, diminished system resolution and internally inconsistent point clouds. While most calibration procedures depend on the use of cultural features (like gabled roofs), one recently suggested methodology requires only a single broad, flat surface. Given the potential difficulty in identifying such a surface on land, this paper investigates the possibility of using the ocean surface instead. Simulations are performed to examine the anticipated influences of both surface waves and tidal variation. Finally, oceanic results are compared with the likely topographic alternative: using a narrow airport runway as the calibration surface.

I. INTRODUCTION

An airborne laser scanner, or lidar, uses a laser to collect elevation and depth data on the Earth’s surface from a remote platform, typically an aircraft. A lidar represents the fusion of several technologies: a laser, an inertial navigation system (INS) to determine the position and orientation of the vessel, and a scanning apparatus. The accuracy of the position of a laser spot on the ground or seafloor is directly related to the accuracy of the hardware components used (largely determined by the manufacturers) and the measured angular misalignments among these components (chiefly between the INS and the scanner – called the boresight angles). These boresight misalignments must be determined by the system operator using some calibration methodology. Unfortunately, there is no universal practice to determine these values.

Present lidar calibration routines can be a subjective, time-consuming and cumbersome affair. Due to the sparse nature of a lidar dataset, a point-to-point comparison cannot be conducted between separate swaths of data (as is done with multibeam echosounder calibrations or a photogrammetric strip adjustment). Instead, surveys are conducted over cultural features (like roads or buildings). From these datasets, the calibration values are either slowly incremented by hand (Fig. 1), or multiple planar and linear features are extracted from each survey line and then adjusted with neighboring strips (Fig. 2) \([1,2,3]\). However, not all survey areas are rife with gabled roofs. A more flexible calibration routine which can be conducted without transiting from the survey area and where the flight data can be processed by the field crew (rather than shipping the flight data back to the lidar manufacturer) requires development.

This paper focuses on one particular calibration routine which uses a weighted least squares adjustment to determine the system misalignments by fitting the point cloud to a single planar surface \([4]\). The routine was derived with the intent of finding a suitable planar surface on shore, but the surface of an ocean or lake also approximates a flat, planar surface. Through the use of a program designed to simulate a lidar point cloud under a variety of acquisition conditions, several trials are conducted to assess the consequences of using a dynamic sea surface instead of a more stable terrestrial one.

II. A PROPOSED LEAST SQUARES ADJUSTMENT

A weighted least squares adjustment (LSA) offers several advantages as a means of calibration. The procedure is automated and removes human subjectivity. In addition to determining the values of all the calibration parameters simultaneously, associated uncertainties are also reported. These uncertainties can then be applied to a general propagation of variances to determine the positional uncertainty of the final laser point positions. Lastly, examination of the residuals can identify outliers in the data.

An adjustment model that fits a collection of lidar points to a planar surface was suggested by \([5]\):

\[
  f(\vec{t}, \vec{x}) = \vec{n} \cdot (x_{\text{OBS}} - x_{\text{PLANE}})
\]

where \(\vec{n}\) = vector normal to planar surface
\(x_{\text{OBS}}\) = 3D coordinates of laser point from laser location equation
\(x_{\text{PLANE}}\) = 3D coordinates of fixed point on planar surface

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Rather than use buildings or other cultural features for the adjustment, [4] proposes to acquire a complete dataset over a single surface. With a dataset acquired over a flat surface, any misalignments within the system would yield a non-coplanar point cloud, see Fig. 3. The calibration values would then be adjusted, through (1), to restore the point cloud to its coplanar status. Provided the vessel experiences some dynamic motion during acquisition (a nominal amount of pitching/rolling and a shift in heading), then a flat surface provides all the geometry necessary to do a full boresight calibration, see Fig. 4. A complete explanation of the adjustment model is given in [6].

A. Sample Calibration

To demonstrate the performance of the above calibration algorithm (and provide a baseline for subsequent sections), a simulation of four flight lines was performed. The lines were flown in an orientation designed to decouple the boresight angles. Following the suggestion of [7], each line was flown with a different heading, in which half were at an altitude of 400m and half at 800m (Fig. 5). Each flight line traversed 1.5km (~20 seconds of survey time). In addition, the plane’s attitude was permitted to wander along each pass. That is, the vessel’s orientation could wander by as many as 5° about the pitch or roll axis and by 5° about the desired heading. For the calibration parameters, a 5° misalignment was rendered between the INS and the laser reference frame about the pitch, roll and yaw axes.

The results of the “successful” calibration are shown in Fig. 6. “Successful” because the three boresight misalignments were recovered, as is evidenced by fitting the incoherent point cloud to a single planar surface (Fig. 6, right). The true measure of the calibration is calculated standard deviations of the adjusted values. These offer realistic boundaries on how close the estimated calibration values will be to the truth when the random noise of the system components is experienced in the field (uncertainty of laser range, uncertainty of GPS position, etc.). With the full dataset available, the uncertainties (1σ) of the roll, pitch and yaw boresight misalignments (measured in degrees) were 1.7×10⁻³, 1.8×10⁻³ and 3.6×10⁻², respectively. The results of all the calibration trials are summarized within Table I of Section III.

B. Limitations Working Ashore

A potential hitch to the aforementioned calibration is the need for a flat piece of real estate of suitable size (at least 2km×2km). Short of surveying next to a dried lake bed, such a location can be difficult to locate. Ref. [4] suggests that one cultural feature likely available to all airborne platforms is an airport runway. The drawback is that the average runway is only 50m wide. The CZMIL system has a swath width of 300m, thus relying on so narrow a calibration surface will greatly reduce the number of points that can be used in the adjustment.

With the reduction in point density associated with a 50m-wide runway, one must ask how the confidence in the calibration values will be affected. In terms of the raw number of data points, the full dataset has 3,800 observations, while only 200 points lie on the runway (Fig. 7). Even with this diminished dataset, a successful calibration is still possible; however, the uncertainties get worse (larger) compared to the full dataset. The uncertainty in the roll boresight angle increased by a factor of 6, while both the pitch and heading angles degraded (got larger) by a factor of 4 (Table I). If possible, the sampling rate of the lidar could be increased to improve the data density (or additional flight lines could be flown); however, the degraded confidences are not due exclusively to the reduction in data points. For the two flight lines that traveled along the runway, only the forward and aft-most
beams are included in the calibration, the beams to port and starboard are neglected. Worse, the lines perpendicular to the runway only contributed a 50m cross-section to the calibration solution. Should a runway be selected for a calibration site, it may be worth the time to acquire a couple extra lines flying parallel to the runway, allowing some of the port and starboard beams to be included in the adjustment.

![Fig. 3](image1.jpg)
Fig. 3 (left) Two revolutions of the lidar with no boresight misalignments – notice both circular traces are coplanar. (right) With a 10° forward (i.e., towards the nose) pitch boresight bias, two revolutions are again depicted with the actual laser footprints shown in red and the miscalculated point cloud shown in black – notice the biased points are no longer coplanar.

![Fig. 4](image2.jpg)
Fig. 4 (left) Top view of a simulated point cloud from a vessel that exhibits a slow roll and change in heading. (right) Before calibration, the point cloud is incoherent (black), but after application of the LSA, the calibration values are determined and the point cloud is restored.

![Fig. 5](image3.jpg)
Fig. 5 Proposed flight plan designed to decouple the laser boresight angles. Image adapted from [7].
III. THE OCEAN SURFACE AS A PROXY FOR A PLANAR SURFACE

To overcome the dearth of suitable terrestrially-based calibration sites, we must consider the ocean surface itself. The nature of a bathymetric survey means ample access to an ocean, sea or lake. Further, most bathymetric lidars already have the technology and algorithms in place to log the position where the laser pulse strikes the water surface. However, when proposing to use the ocean’s surface as a proxy for a flat planar surface, we will consider the “flatness” of the ocean surface. For a given location, an instantaneous measurement of the ocean surface is subject to both wave and tidal influence. Meteorological considerations aside, even mean sea level (as a geopotential surface) will track with the undulations of the local geoid. Provided the calibration area is confined to a small region (less than 10km by 10km), the relief of the geoid can be assumed to be flat [8]; however the waves and tidal effects are not so easily controlled. The potential impacts of using the dynamic ocean surface as planar surface for the purposes of a geometric calibration require further investigation.

A. Contending with Waves and Swell

The casual observer will remark that the ocean is not flat. The sea surface is a dynamic landscape of waves and sea swell. Fortunately, a lidar’s laser footprint is intentionally expanded to a diameter of several meters at the water surface in order to satisfy eye safety requirements (while still maintaining a satisfactory pulse energy to provide reasonable signal-to-noise ratios) [9]. The relatively large laser footprint means any high frequency waves (Fig. 8, left) will be removed in the averaging that occurs across the system’s field-of-view. Conversely, long period swell (Fig. 8, right) will lead to an aliasing of the measured sea surface height. From shot-to-shot, adjacent footprints will report differing heights. This inconsistent vertical component to the
point cloud coordinates suggests the ocean surface may not be ideal for representing a single, constant planar surface. However, in much the same way that high frequency waves are averaged out within a single footprint, the vertical deviations exhibited by the laser points during long period swell may be averaged out with a sufficiently large temporal and spatial sampling. For the calibration algorithm to work, it is not necessary that every point be coplanar; instead, the points must just describe a planar surface. The claim as to whether the LSA still functions in the presence of waves and how it affects the confidence of the calibration parameters will now be further examined.

To simulate the effects of waves and swell, a two-dimensional wave equation was developed (Fig. 9) and added to the mean water level. In the simulation, the laser beam is modeled as an infinitely thin line, so the beams footprint has a theoretical diameter of zero. This implies the any wave, regardless of how small its wavelength is, will vertically shift the laser point. As an example of the effects of wave action, Fig. 10 shows the deflection that can occur on a point cloud between a calm and dynamic sea surface.

With the weighted least squares adjustment, a priori estimates of the uncertainties of all the measured quantities (laser range, scanner azimuth, etc.) must be provided. Accurate estimates will facilitate the algorithm’s rate of convergence and produce a more accurate estimate of the output uncertainties. The inclusion waves will adversely affect the previously used value for the estimated uncertainty of the measured laser range, thus far limited to just the manufacturer’s specifications of the hardware (0.01m). Since the adjustment model is fitting points to a planar surface, the uncertainties must report the confidence in the points describing that planar surface. That is, even with an error-free range measurement, the oscillating waves will prevent the laser points from ever laying on the theoretical mean sea surface (at least, it is unlikely).

![Fig. 8](left) When an ocean wave’s wavelength is much smaller than the lidar spot size, the dynamics of the wave height are averaged out, giving an approximation of the instantaneous sea level from any location. (right) In the presence of long period swell, a lidar’s entire spot may be focused on the wave’s crest or trough, resulting in different estimates of the sea surface height from shot-to-shot.

![Fig. 9](Simulated dynamic ocean surface that includes both long period swell and smaller waves.)

![Fig. 10](Two simulated point clouds acquired over calm (top) and dynamic (bottom) sea states. Mean water level indicated by blue rectangle.)
We must translate the vertical uncertainty associated with the waves, $\sigma_{WH}$, to a radial uncertainty for the laser range, $\sigma_\rho$. Suppose the lidar in question has a scan pattern directed 20° above nadir, then from Fig. 11 we have:

$$\sigma_\rho = \sigma_{WH} \sec 20^\circ. \quad (2)$$

For a sinusoidal wave with a peak-to-peak amplitude of $A$, the standard deviation of the height of said wave, $\sigma_A$ is given by:

$$\sigma_A = \frac{A}{2\sqrt{2}}. \quad (3)$$

Combining (2) and (3) then provides an estimate for the contribution to the laser range uncertainty due to wave action. Coupling this uncertainty with that of the instrument’s hardware capabilities ($\sigma_{INST}$) via a sum of squares, we have the total uncertainty in the laser range, $\rho$, as:

$$\sigma_\rho^2 = \sigma_{INST}^2 + \frac{\sigma_A^2}{8} \sec 20^\circ. \quad (4)$$

As anticipated, an increase in the wave height will produce an associated increase in the uncertainty of the laser range. Propagating through the weighted least squares adjustment, the increased uncertainty in the laser range should have a corresponding increase in the estimated standard deviation of the calibration values.

The flight plan shown in Fig. 5 was simulated four times over incrementally larger virtual sea states. A long period swell with wavelength of 50m was included with a height ranging from 1 to 4 meters. Results of the four calibrations are shown in Table I. As postulated above, increasing the wave height had a corresponding degradation in the confidence of the boresight angles. It is interesting to compare the results of the trials from the sea with that of the narrow runway. It is not until the wave heights grow larger than 3m that the confidence in the ocean-derived pitch and yaw solutions grows worse than that from the runway. This suggests that having a larger amount of data spread over a wider area (even if the points themselves have a higher uncertainty), makes for a better calibration than a confined (though with a higher confidence) dataset.

### B. Contending with Tides

In contrast to the relatively high frequency ocean waves whose deviations from the theoretical planar survey average out with sufficient spatial and temporal sampling, the problems introduced by tides increase with the duration of the sampling period. The longer the sampling session continues the greater the opportunity for tides to adversely affect the calibration. There are three approaches for contending with the changing tides. First, the tides may be disregarded. If the calibration flights involve a minimal amount of time, then the tidal effects may be negligible. Second, over an abbreviated window the change in tides can be viewed as nearly linear. A parameter representing the linear change in tides could then be included in the least squares adjustment. Third, if tidal data are available during the time of the calibration, then the vertical influence may just be subtracted from the laser spot’s coordinates. With the values reduced to a common datum, the adjustment may then proceed without further consideration to tides. Each method of coping with the tides will be further explored.

![Fig. 11 Deriving a relationship between the uncertainty of the wave height ($\sigma_{WH}$) and the uncertainty of the laser range ($\sigma_\rho$) in a wave with a peak-to-peak amplitude of $A_{WH}$.](image)

<table>
<thead>
<tr>
<th>Roll</th>
<th>Runway</th>
<th>1m waves</th>
<th>2m waves</th>
<th>3m waves</th>
<th>4m waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7×10^(-3)</td>
<td>1.1×10^(-2)</td>
<td>2.7×10^(-3)</td>
<td>4.4×10^(-3)</td>
<td>6.3×10^(-3)</td>
<td>8.2×10^(-3)</td>
</tr>
<tr>
<td>1.8×10^(-3)</td>
<td>7.0×10^(-3)</td>
<td>2.7×10^(-3)</td>
<td>4.4×10^(-3)</td>
<td>6.3×10^(-3)</td>
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</tr>
<tr>
<td>3.6×10^(-2)</td>
<td>1.5×10^(-1)</td>
<td>5.5×10^(-2)</td>
<td>9.0×10^(-2)</td>
<td>1.3×10^(-1)</td>
<td>1.7×10^(-1)</td>
</tr>
</tbody>
</table>

**TABLE I**

Uncertainties (1-sigma) in reported calibrated boresight angles resulting from several different acquisition scenarios: all data acquired on a flat surface, data limited to a 50m swath, and data acquired over a dynamic ocean surface (values reported in degrees).
Again, consider a lidar with boresight misalignments of $5^\circ$ along the roll, pitch and yaw axes, and no other system misalignments. Additional acquisition parameters include a flight altitude of 400m and vessel speed of 140 kts, with a laser firing rate of 50Hz, scanning at 1600rps. A simple tidal model is given by:

$$z(t) = \frac{R}{2} \sin\left(\frac{2\pi}{T} t + \phi\right), \quad (5)$$

where $z =$ instantaneous height of tide (m)

$R =$ tidal range (m)

$T =$ tidal period (hr)

$t =$ time (hr)

$\phi =$ tidal phase (radians).

In this simulation, we will consider a semidiurnal tide ($T = 12$hr) with a tidal range of 2m ($R = 2$m). To experience the tide at its maximum rate of change, we will assume a zero phase shift ($\phi = 0$).

The flight plan is divided into two components, see Fig. 12. First, a single dynamic flight line is conducted for a duration of 20 seconds. During this elapsed time, the theoretical tides defined in (5) will rise approximately 3mm. Using such a short flight line will test two things: whether even a minor change in tides will adversely affect the calibration and whether so minor a change in tides can be measured and removed by the least squares adjustment. Upon completion of the first acquisition line, the vessel will turn around and resurvey the same line. Six minutes is budgeted for the aircraft to complete the change of direction (based on average aircraft characteristics). By including this stagger in acquisition times, we will create a discontinuous set of tidal observations (increasing by 3cm during the off-time) and further test the calibration utilities tolerance to tidal artifacts in the data.

For the initial simulation of these two flight lines in the presence of tides, all random noise was removed from the observations (laser range, GPS position, etc.) to assess the theoretical limits of how well the algorithm could perform. Let us initially consider only the first survey line (Table II, left). To form a baseline of the best possible performance, the theoretical tide values were computed from (5) and subtracted from the point cloud. Once removed, a perfect set of boresight calibration parameters were found with the standard deviations indicated ($0.04^\circ$, $0.09^\circ$ and $0.11^\circ$ for roll, pitch and yaw, respectively). With these calibration parameters applied (and the tides removed), the adjusted cloud was perfectly flat with no points deviating above or below tide zero.

Next, the single flight line is left with the tidal signature intact, but then calibrated as if no tides were present. In this case, the calibration results were only nominally worse than the scenario in which the tides were removed in advance. When the calculated standard deviation is then considered, the difference is negligible. The calibrated dataset, depicted by the black line in Fig. 13, has been fit to the steadily increasing tidal plane. Rather than have a calibrated dataset comprised of a shifting series of horizontal scans (like a skewed stack of coins), the least squares adjustment, in its drive to fit the data to a single planar surface, tweaked the pitch bias so the “coins” would lie along the slope (similar to what is depicted in Fig. 3).

![Fig. 12 Simulated flight plan used to assess the influence of tides on the calibration routine.](image)

<table>
<thead>
<tr>
<th>Single Flight Line - Calibration Values</th>
<th>Reciprocal Flight Lines - Calibration Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tide removed</strong></td>
<td><strong>Tide ignored</strong></td>
</tr>
<tr>
<td>Roll</td>
<td>Pitch</td>
</tr>
<tr>
<td>5.00000°</td>
<td>5.00000°</td>
</tr>
<tr>
<td>5.00001°</td>
<td>5.00012°</td>
</tr>
<tr>
<td>5.00000°</td>
<td>0.000m</td>
</tr>
<tr>
<td><strong>Linear tide rate (m/hr):</strong></td>
<td>0.523 ±0.256</td>
</tr>
</tbody>
</table>

**TABLE II**

**BORESIGHT CALIBRATION RESULTS AND 1-SIGMA ESTIMATED CONFIDENCES IN THE PRESENCE OF TIDES. VALUES ARE GIVEN IN WHICH THE TIDES: WERE KNOWN A PRIORI AND REMOVED, WERE IGNORED, AND WERE MODELED BY A FIRST-ORDER LINEAR APPROXIMATION. VERTICAL DEFLECTION FROM A THEORETICAL PLANAR SURFACE (PLANAR ΔZ) AND ADJUSTED LINEARIZED CHANGE IN TIDES ALSO SHOWN.**
Having seen that the tide can conceivably be disregarded for this short flight line, we now investigate what effects can be achieved through approximating the tides with a linear model. Again, looking at Table II (left), we see a successful calibration is achieved by modeling the tides. Not only have the absolute accuracies of the boresight angles improved over their tidally-ignorant counterparts, but an estimation of the tidal rise is determined to be 0.523m/hr. This value is unsurprising when we consider (5) gives the height of the tide at any time, so its derivative would give the rate of change of the tide. That is,

\[
\frac{\partial z}{\partial t}(0) = \frac{R}{2} \cos \left( \frac{2\pi}{T} \cdot 0 + \phi \right) \frac{2\pi}{T} = \frac{2\pi}{2} \cdot \frac{2\pi}{12} \approx 0.523.
\]  

(6)

The superior results of the linearized tidal model (versus ignoring the tides entirely) can be seen in Fig. 13. The point cloud has again been fit to a planar surface (green curve), but the boresight values don’t have to be frivolously modified to account for a sloping datum.

A final note on the calculated uncertainties: the stated value for the confidence in the linearized change in tides (±430m/hr) is not a misprint. Because only 20 seconds of tidal data is acquired, it is difficult to extract the behavior of the tides in a statistically significant manner. To assess the affect on the calibration values, the flight line was simulated several times with random noise applied that is consistent with the component manufacturer’s literature. In every case, though the linearized change in tides varied wildly, the boresight values displayed a dispersion about the known value that agreed with the standard deviations stated in Table II. So many successful calibrations coupled with such poor estimates of the linearized change in tides further emphasize that (for short datasets) the tides can be all but ignored. Bear in mind, we are not attempting to design a mobile tide gauge; instead the additional parameter for the linearized change in tides included in the LSA should be thought of as a means of steering the boresight calibration in the correct direction by absorbing some of the vertical biases introduced by tides.

Having finished our analysis of a single flight line, we now examine the behavior of calibration routine over a longer time interval, resulting from a pair of flight lines. As expected, disregarding the tides for a dataset covering a larger time span will lead to larger uncertainties (Table II, right). The magnitude of the misclosures in the boresight angles are the largest detected in these tidal simulations (though still insignificant in comparison to the random error attributed to system noise). The tidal artifacts are plain to see (Fig. 14) when a calibration is performed and tides are neglected. Visible is both the slow tidal advance in the individual flight lines, as well as the 30cm gap between lines induced by the 6 minute delay in turning the aircraft. Similar to the case of the single flight line, a linearized rate of tide parameter included in the calibration succeeds in ‘flattening’ the point cloud to a tidal zero. More importantly, applying the linearization to both flight lines brings a coherence to the point cloud that is not achieved when the tides are merely neglected. Lastly, regarding the confidence in the LSA output of the linear change in tides, adding the second flight line improved the uncertainty (1σ) from 430m/hr to 0.25m/hr. Part of this improvement can be attributed to having twice as many observations (the reason for the improved calculated uncertainties in the boresight angles); but the larger reason for improvement is the collection of tide data over a broader time span (increasing from 20 seconds to 400 seconds). As a point of reference, the flight plan illustrated in Fig. 5 was also simulated in the presence of tides (again assuming 6 minutes elapsing between each flight line). The resulting reported confidence (1σ) in the estimated linear change in tides was reduced to 8cm/hr.
Fig. 14  Side view of the results of the calibration of reciprocal flight line in the presence of tides. The point cloud slope induced by tides is apparent in the two flight lines that did not account for tides in their calibration (black). By including a linearized change in tides of change in the adjustment, the two flight lines merge into one coherent dataset (green).

An observant reader might dismiss the above discussion with regard to tides because the temporal span of the simulation was so short – citing that only 7 minutes of simulated flight time was conducted; that not being enough time for the tides to significantly change. To that argument, the author would respond that those 7 minutes of flight time, including only 40 seconds of acquisition time contained enough point cloud information to determine the boresight angles to a precision of 0.004° for pitch and roll and 0.06° for yaw ($1\sigma$). Should a longer flight sortie be deemed necessary, then the local tide curves should be obtained and applied to the point data before a calibration is attempted. For shorter flights, a linearization of the tide curve is adequate.

IV. CONCLUSIONS AND FUTURE WORK

A method for performing a geometric calibration of an airborne lidar was tested under a number of different acquisition scenarios. While the algorithm performed well when presented with a large flat region to use as a calibration site, performance was reduced when confined to a narrow area, like an airport runway. The ocean surface was then shown to be a more than adequate stand-in for a narrow runway. Uncertainties introduced by ocean waves are averaged out given the broad sampling area, and tidal effects are minimal due to the short amount of time required to perform the calibration. If an ideal calibration site cannot be found ashore, then the lidar operator should give strong consideration to using a water surface return instead.

It should be emphasized that thus far the concepts presented in this paper have only been performed in a simulated environment. Once CZMIL is delivered, the algorithms can be tested in an operational setting. With the system in hand, trials can be conducted to assess first-hand what effects narrow runways, ocean waves and tides will have on the LSA’s ability to determine the system’s misalignments and the associated confidence in those values. If successful, future work will entail modifying the laser equations to accommodate other bathymetric (and perhaps topographic) laser scanners.

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