Validation of Geodetic Seafloor Benchmark Stability Using Structure-From-Motion and Seafloor Pressure Data

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Abstract One commonly used method to measure and detect centimeter-scale changes on land is structure-from-motion (SfM) photogrammetry, wherein sets of digital images are used to generate three-dimensional spatial models. Subcentimeter accuracy useful for geodetic studies is achievable when these surveys are conducted on land or from the air. This method has made its way into marine environments by way of scuba, remotely operated vehicle, and autonomous underwater vehicle-based surveys largely in the context of mapping. Repeated SfM photogrammetry surveys could be used to monitor changes in the stability of seafloor benchmarks and key sites as the interest in and need for marine geodetic measurements continues to grow. These studies require centimeter-level accuracy of better, and some rely on accurate placement, positioning, or relocation of geodetic monuments, benchmarks, and instruments. We assessed the accuracy of the photogrammetric method for this purpose by simultaneously conducting a remotely operated vehicle-based SfM photo survey to produce three-dimensional spatial data, and a precise pressure survey to accurately measure height information. We found that the SfM survey agreed with the pressure survey height within its uncertainty of ±6 cm while using a standard, off-the-shelf camera adapted for underwater use. This level of relative accuracy would allow us to detect changes in geodetic benchmarks or instrumented sites between repeated surveys where large changes or the accumulation of small changes is expected within the scene over several years. We believe that centimeter-level accuracy is obtainable with adjustments to the photogrammetry survey parameters, a higher-resolution camera, and inclusion of additional coded targets.

1. Introduction

Marine geodesy is a growing field for geophysical studies of systems that lie partially or completely underwater where land-based data are unavailable or coverage is limited, such as at subsea volcanoes and subduction zones (Burgmann & Chadwell, 2014). Offshore measurements are necessary to provide improved constraints in models and to bridge the gaps in understanding of these systems. However, marine geodetic measurements are inherently challenging. Many routine and effective methods used on land, such as GPS and InSAR, do not work underwater because they typically rely on the transmission of electromagnetic radiation, which is limited to a few hundred meters in water. Other instruments, such as tiltmeters, gravi-meters, and seismometers, deployed for use on the seafloor must function in a high-pressure and corrosive environment for long periods of time required to adequately resolve secular signals. Furthermore, without cabled infrastructure, long-term measurements are difficult due to the limited battery capacity of autonomously deployed instruments. In the last few decades, a number of instruments suited for marine deployments have been developed and used for continuous measurements of seafloor deformation including pressure gauges, tiltmeters, and acoustic transponders (Burgmann & Chadwell, 2014). In some cases, such as the GPS-Acoustic method and calibrated pressure sensors, it can be cost- and time-efficient to replace and relocate sensors or perform campaign-style surveys to capture long-term time series (Chadwell & Spiess, 2008; Fujita et al., 2006; Gagnon & Chadwell, 2007). These methods require benchmarks installed on the seafloor for accurate re-positioning. Another application is the installation of more permanent geodetic monuments that serve as fiducial markers and references for other studies.

One component of uncertainty in benchmark surveys depends on the stability of the benchmark. Additional offsets and errors would be introduced into the measurements if a benchmark is disturbed from its initial position (e.g., settling in sediment or being displaced from its original position on a sedimented seafloor or bedrock due to an external forcing). Other studies have observed little to no changes in benchmark...
placement and orientation of a centimeter or less over many years (Chadwick et al., 2006; Fujimoto et al., 2011; Nooner et al., 2007). Although changes in benchmark position on the order of several millimeter per year may not be significant in regions with considerable deformation rates of tens of centimeter per year such as volcanoes or resource reservoirs (Chadwick et al., 2012, 2006; Nooner et al., 2007), the same is not true in subduction zones or other regions where secular rates are on the order of a few centimeters per year or less (Burgette et al., 2009; Savage, 1995). Studies that span decades in regions with small secular rates will require careful assessments of benchmark stability since its contribution could be a considerable amount of the expected rate.

Photogrammetry is a technique that uses overlapping sequences of photographs to invert for a three-dimensional spatial model of the region within the photo survey area. This technique and its extension structure-from-motion (SfM), which simultaneously inverts for camera positions, are widely used for geologic studies on land and in the air, can achieve centimeter precision over areas up to tens of meters across, and be performed over relatively short periods of time, i.e., hours (Westoby et al., 2012). Surveys with similar levels of precision and durations would provide a great utility to and reduce the costs of marine geodetic surveys. However, their use in the marine environment is still relatively nascent and so far, has been limited to archaeological, biological, and relatively coarse mapping (Bennecke et al., 2016; Burns et al., 2015; Drap et al., 2015; Kwasnitschka et al., 2012; Westoby et al., 2012). In conjunction with other geodetic methods in the marine environment, SfM photogrammetry also has the potential to improve large-scale mapping, imaging, and navigation (Escartín et al., 2008; Kwasnitschka et al., 2016).

We designed an experiment to assess the viability and accuracy of SfM as a time- and cost-effective way to measure the stability of benchmarks within instrumented seafloor sites. We conducted a photogrammetric SfM survey with the remotely operated vehicle (ROV) Jason and compared the resulting model to pressure survey data to evaluate the accuracy of photogrammetric method. The results demonstrate that SfM photogrammetry in the water can be conducted without the need for specialized cameras, navigation, or ancillary equipment and could resolve several centimeter-level relative displacements on length scales of several meters. This could be useful for mapping geologic outcrops or monitoring instruments and benchmarks at seafloor sites. With additional considerations or resources, subcentimeter-level geodetic photogrammetry is certainly possible. Other studies have demonstrated photographic and imaging methods for collecting underwater measurements and maps when incorporating additional stereo cameras, lasers, or high-resolution multibeam bathymetry, in some cases with millimeter-level resolution (Dunlop et al., 2015; Dunlop et al., 2018).

2. Survey Design

The survey site included two geodetic monuments with known length scales installed on a sedimented seafloor a few meters apart along the continental margin offshore Oregon at a depth of 2,900 m (Figure 1). The primary monument was a circular concrete benchmark used for calibrated pressure surveys. It measures 76.2 cm in diameter, 15.2 cm thick, and weighs 319 lb. in air or 147 lb. in water. It includes two visual markers—an orange ring around the outside edge and three black radial lines at 120° spacing—to improve instrument placement and orientation consistency. The second monument consisted of 4 m of aluminum pipe inserted 3 m deep into the seafloor sediment so that 1 m extended above the seafloor. The pipe is coupled to the sediment at depth, which provides a stable, useful reference should be unaffected by any erosion, deposition, and perturbations at the seafloor surface, analogous to GPS monuments anchored at depth. The pipe was painted with alternating 15.0-cm-long black and yellow stripes to increase visibility and provide a vertical length scale that was easily resolvable in images at distances up to a few meters. A 15.3 × 40.3-cm metal plate with yellow-painted edges was fastened to the top of the pipe with a firehose coupling to hold a pressure recorder. Yellow was chosen as the primary color since it is bright and does not attenuate as strongly as red-hued colors; black was chosen since it offers high contrast to both yellow and the bare aluminum.

Agisoft Photoscan Pro software (v1.2.3.2331) was used to produce a three-dimensional model of the site that includes known control points, height scales, and length scales, which were compared to known
dimensions. As a further check, each monument was designed to accommodate a pressure sensor. The pressure difference between the two monuments provided a precise measure of the height difference to within ±1.1 cm, which served as a second, high-accuracy validation of the photogrammetry results.

### 2.1. Photogrammetry Survey

Many software suites that perform photogrammetry and SfM processing are freely or commercially available. We used Agisoft Photoscan Pro, which uses a pixel-matching inversion to generate three-dimensional spatial data and models. The software can establish a relative coordinate system without any ancillary information about the position and orientation of the camera. An absolute coordinate frame can be established with the addition of location and orientation data from GPS-enabled or inertial systems. Alternatively, user-defined ground control points (GCPs) defined by known parameters within the survey area are required to generate an absolute coordinate frame. The GCPs also provide crucial information for creating model scale. Model uncertainty is inferred from the RMS misfit of the model to the GCPs based on pixel error and pixel size.

The photo survey was performed with the ROV Jason. A series of 115 12-MP digital images were collected with a Sony HDR-CS560V camcorder and digital still camera, which was the standard camera on Jason, as the ROV circled the test site at different altitudes of 2 to 3 m and distances of 2 to 4 m. The camera had an intervalometer function set to capture one image every 5 s for the duration of the 10-min survey. The camera’s pan, tilt, and zoom were set such that most of the ROV body and manipulators were outside of the photograph frame. The pan and tilt were not changed during the photo survey, although this would be allowed since Agisoft Photoscan Pro does not necessarily require consistent orientation or orientation information. The zoom was fixed to prevent different amounts of geometric lens distortion, which would have required additional processing. The photos were processed with Adobe Photoshop CS6 for sharpness and contrast to improve image quality for the software processing. A generic Sony camera wide-angle lens correction was used to mitigate the geometric distortion and the frames were cropped to remove the ROV body from the image (Cook & DeSanto, 2019).

The ROV disturbed the sediment on the seafloor during the photogrammetry survey, which led to many suspended particles being captured in the photographs. We set the pixel-matching inversion to an intermediate setting that allowed misfit greater than the minimum possible to produce smoother meshes more representative of the seafloor and benchmarks rather than the suspended particles. We used the diameter of the concrete benchmark to establish a horizontal scale and the length of the painted stripes on the pipe to establish a vertical scale. The concrete benchmark tilt was measured with a mobile pressure recorder (MPR) and a second pressure recorder equipped with a tilt sensor. The pole tilt was measured with the MPR and a second, independent tilt sensor. The tilt measurements provided constraints for solving for the real coordinate system orientation.

![Figure 1](https://example.com/figure1.jpg)  
**Figure 1.** (left) A photo of the seafloor site and (right) a snapshot of the 3-D photogrammetry model. The monuments appear to be well resolved throughout, with some small exceptions along the length of the pipe, and the seafloor textures are apparent.
2.2. Pressure Survey

Pressure measurements can be used to measure vertical height changes or relative height differences because a 0.1-kPa pressure change is easily and reliably measured and corresponds to a 1-cm vertical height change. The measured pressure difference between the two platforms was used to determine the height difference between the two points. The pressure surveys were conducted over a couple hours, so the inherent pressure gauge drift was negligible. We used an MPR with two redundant Paroscientific pressure gauges and an internal tilt sensor to record the pressure and the extrinsic tilt of the two platforms (Cook & DeSanto, 2019).

The MPR was placed on the reference pole plate and the concrete seafloor benchmark in an alternating order. The two monuments were occupied 3 times each for 10-min intervals. The instrument’s lateral placement and orientation were kept constant to within a centimeter and 0.1°, respectively.

3. Results

The photogrammetry model space coordinate frame was generated using GCPs defined by the face of the benchmark and without any camera position and orientation information, which was not collected by the ROV. The GCPs were defined such that the benchmark face was assumed to be a horizontal plane and the z axis was aligned with the vector normal to the benchmark face. However, the benchmark was slightly tilted in the seafloor, so the modeled space differed from the true, physical space in the amount of the benchmark tilt. The tilt of the modeled reference frame biased the height difference by a small amount and required a rotation to correctly determine the height difference. We used the in situ tilt measurements to rotate the model to a true vertical system that was aligned with the gravity vector to correct the height difference.

Figure 2 is a schematic drawing of the seafloor site, with the relevant geometry and values to calculate the height difference between the benchmark and plate. Coordinates and angular measurements in the true, physical space coordinate frame are denoted by a nonprime system by $Z, L, \theta$, and $\phi$. Values in the modeled, benchmark-normal space coordinate frame are denoted by a prime system by $Z', L', \alpha'$, and $\theta'$. Since we only need to rotate along the line of sight (LOS) between the benchmark and the pole and not the entire system (Figure 2), we can use a simplified geometric correction described by a series of equations to calculate the height difference in the true vertical reference frame, $Z$.

$$B = L\tan \delta_{LOS}$$
$$A = \z' - B$$
$$Z = A \cos \delta_{LOS}$$
$$Z = (\z' - L\tan \delta_{LOS}) \cos \delta_{LOS}$$

The correction only required the tilt, or dip angle, of the benchmark in the LOS direction between the two monuments, $\delta_{LOS}$. The tilt of the pole, $\phi$, is not needed because the height of the point at the top of the pole is independent of its angle. The azimuths of the benchmark tilt, $\alpha_{bench}$, and pole tilt, $\alpha_{pole}$, were not measured in situ, so we solved for them using a system of equations.

$$\sin(\theta) \cos(\alpha_{bench}) - \sin(\phi) \cos(\alpha_{pole}) = \sin(\theta')$$
$$\alpha_{bench}' + \alpha_{pole}' = \Delta \alpha'$$

The first equation imposed the condition that the difference between the LOS projection of the measured tilts matched the modeled difference. The second equation required that the difference of the true tilt azimuths matched the modeled value. Table 1 lists the calculated angles, including the LOS tilt between the benchmark and pole, which was determined to be $2.2 \pm 0.8^\circ$.

| Parameter                  | Model space | Physical space |
|----------------------------|-------------|----------------|
| Benchmark tilt             | $\theta = 3.0^\circ$ | $\theta = 4.0^\circ$ |
| Pole tilt                  | $\phi' = 6.0^\circ$  | $\phi = 6.0^\circ$ |
| Difference in azimuth of tilt/dip | $\Delta \alpha' = -41.2^\circ$ | $\Delta \alpha$ |

Figure 2. A schematic drawing of the projection of the model coordinate frame onto a true, gravity-normal coordinate frame.
The software calculated a distance between the benchmark and pole, $L'$, of 243.0 ± 2.3 cm and a height difference, $Z'$, of 111.7 ± 2.3 cm. These uncertainties represent the 95% confidence interval of the misfit. After applying the geometric correction to $Z'$, the true height difference between the benchmark and pole, $Z$, was determined to be 102.2 ± 6.0 cm.

The pressure data were first corrected for ocean tides using a computed tide model generated by Some Programs for Ocean Tidal Loading (SPOTL) software, and then with linear least squares to minimize the difference between the measured pressures on the plate and benchmark (Agniew, 2012). The best fit pressure difference was 9.97 ± 0.11 kPa, which is equivalent to a height difference of 99.7 ± 1.1 cm. The uncertainty represents a 95% confidence interval.

4. Conclusions

The results show that commercially available photogrammetry software can produce a good three-dimensional model of a seafloor site based on a relatively limited photo survey with a consumer-grade camera. The pressure survey height difference of 99.7 ± 1.1 cm falls within the range of the photogrammetry modeled height difference of 102.2 ± 6.0 cm, so the photogrammetry survey is accurate within its uncertainty range.

We completed one photogrammetry survey to establish an initial model of the site. Multiple photogrammetry surveys would allow us to measure relative changes within the site over time. Changes to the benchmarks, camera, and survey designs could improve accuracy and model results. In our survey, some areas of the model were incomplete and overmodeled due to the inherent challenge of resolving thin, long, and complex structures as opposed to large, broad structures. Additional limitations included color inaccuracy and limited visibility range, an insufficient number of low, high, far, and near viewpoints, and few visual targets for the software to register. These could be improved by using different high-contrast paints (e.g., orange instead of yellow) and employing more known references, markers, or coded targets, which can be generated by the software. Given consistent camera resolution, density of control points, and camera distance from the scene, we would expect comparable uncertainties over larger survey areas of tens of meters at the cost of additional ROV time and computing resources.

Several survey-based geodetic methods require stable benchmarks to reliably measure secular crustal motion and deformation. Pressure surveys can be useful for assessing vertical benchmark motion and settling but they can be time consuming. We believe that photogrammetric SfM surveys could be used as a cost-effective method to monitor benchmark stability over areas of several meters with suitable visual reference information. Separating the signals attributed to benchmark movements and perturbations from tectonic signals would improve the fidelity of repeat pressure or GPS-Acoustic surveys and could allow measurements made at a disturbed benchmark to be corrected and tied to measurements made at the originally undisturbed benchmark. At the current level of accuracy, this method is limited to regions of significant expected ground motion or disturbance, such as areas that may be trawled, or to regions where the rate of motion may be small but could accumulate over periods of several years. On their own, repeated photogrammetry surveys can detect relative changes within a photo survey scene. However, they can also provide more complete spatial coverage than individual instrumental measurements and are complementary to other mapping methods being used and developed to capture changes in geodetic monuments and benchmarks, geologic outcrops, slope failures, hydrothermal vents, seafloor instruments and cables, and so on. The absolute pressure or GPS-Acoustic measurements could also be used to tie a photogrammetry survey to an absolute reference frame or multiple photogrammetry surveys together. Our results confirm the viability of the method without the use of special cameras or other equipment for studies of marine geologic, biological, and archaeological processes. Including the use of orientation or inertial navigation sensors, higher-resolution cameras, and coded targets could improve results, making them sufficient for monitoring geodetic instrumented sites over periods of a few years.

While photogrammetry can routinely be done with high levels of accuracy on land, it is significantly more challenging in water. We find that incorporating standard consumer-grade cameras and simple survey designs can achieve centimeter-level results that have applications and utility in the context of geophysical and geodetic research. However, we also recognize that the development and investment of specialized or dedicated equipment, such as lidar, can be done to achieve better results at subcentimeter levels.
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