

Wave Glider–Enhanced Vertical Seafloor Geodesy

J. H. FOSTER

University of Hawai'i at Mānoa, Honolulu, Hawaii

T. L. ERICKSEN

USGS, Menlo Park, California

B. BINGHAM

Naval Postgraduate School, Monterey, California

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ABSTRACT

We have developed a low-cost approach for accurately measuring short-term vertical motions of the seafloor and maintaining a continuous long-term record of seafloor pressure without the requirement for costly ship time. We equipped the University of Hawai'i Liquid Robotics Wave Glider with an integrated acoustic telemetry package, a dual-frequency geodetic-grade global positioning system (GPS) receiver, meteorological pressure sensor, processing unit, and cellular communications. The Wave Glider interrogates high accuracy pressure sensors on the seafloor to retrieve their pressure and temperature data. We correct the seafloor pressure measurements using sea surface kinematic GPS location and atmospheric pressure data collected by the Wave Glider payload. By combining the concurrent seafloor and sea surface observations, we demonstrate the capability to provide timely, continuous, and high-accuracy estimation and monitoring of centimeter-scale vertical seafloor motions.

1. Introduction

Motion of the seafloor remains virtually unobserved despite the fact that many important signals, crucial to our understanding of a range of geologic processes and the hazards they present, are either mostly, or completely, expressed underwater and land-based observations are inadequate for characterizing them. The barrier to obtaining these observations is generally the extremely high cost of acquiring sufficiently accurate geodetic data underwater.

Most of the largest recorded earthquakes and most devastating tsunamis are generated at subduction zones underwater. Similarly, many volcanoes are partly (e.g., Santorini) or completely (e.g., Lō'ihi) submerged, and are not well observed and so are poorly understood.

Furthermore, landslide features ring many ocean basins, and huge debris deposits surround many volcanic oceanic islands. Subduction-zone megathrust faults, submarine landslides, and oceanic volcanoes generate earthquakes and slow-slip events, slump-and-collapse events, and magmatic storage and transport signals, all of which can create rapid vertical motions of the seafloor.

While there is a recognized need to vastly increase our underwater geodetic observing capacity, the high cost of acquiring geodetic data from the seafloor has limited the observations available to help us understand and model the behavior of these types of structures. Accurate recognition of these signals is essential for our understanding of the processes that generate them, while timely receipt of the data is important for making an informed response to events. Several techniques have been developed to image different aspects of seafloor deformation. Absolute horizontal motions have been measured using the GPS–acoustic ranging technique from ships (e.g., Gagnon et al. 2005) and horizontal network strain can be detected using seafloor acoustic sensor-to-sensor ranging (e.g., Brooks et al. 2009).

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Corresponding author: James H. Foster, jfoster@soest.hawaii.edu

Pressure measurements constitute some of the longest-running seafloor geodetic observations, and provide information on vertical motions. Two methods are used for seafloor pressure measurements: continuous observations and campaign measurements. Continuous observations are acquired from units deployed to the seafloor, left to record data, and then returned to the surface for data collection. This type of deployment provides valuable multiyear time series of pressure changes, and is particularly suited to measuring short-term vertical motions (Polster et al. 2009; Wallace et al. 2016). Alternatively, by using a remotely operated vehicle (ROV) or other methods to set a single mobile sensor down on a network of benchmarks, accurate relative depths to the benchmarks can be determined. Repeated occupation campaigns record the accumulated vertical deformation. If the gauges are shallow enough absolute pressure changes can be determined by tying the gauges to surface GPS measurements (e.g., Ballu et al. 2009). Using a combination of longer-term, multiyear, deployments and campaign-style measurements, seafloor pressure data from Axial Volcano have captured magma chamber inflation cycles (Chadwick et al. 2006; Fox 1990, 1993; Noonan and Chadwick 2009) and recorded both precursory motions and the subsidence signals of two recent eruptions (Chadwick et al. 2012; Fox 1999).

On Kilauea Volcano, most of the tectonically active south flank of the volcano is underwater, and the nature of fault slip, stress transfer, and strain accumulation is unclear. Phillips et al. (2008) used campaign-mode repeat pressure surveys to measure long-term vertical deformation rates of the seafloor at depths exceeding 2000 m offshore of the south flank. This pressure sensor survey method is both logistically and technically challenging and required much ship time; precisely placing a pressure sensor on a sequence of seafloor monuments while minimizing the sensor's vertical changes between benchmarks to limit measurement artifacts due to large sensor pressure changes. These surveys produced the first measurements of relative vertical motions of Kilauea's submarine south flank. They found uplift at most benchmarks, with a maximum rate of $\sim 9 \text{ cm yr}^{-1}$ at a site near the offshore bench. It is, however, unclear whether the uplift is the result of continuous, aseismic creep, or whether some, or all of the measured deformation is related to the discrete slow-slip events that are known to be occurring on the basal fault plane. This is an intrinsic limitation of campaign-mode surveys, and as getting better temporal resolution requires revisiting the area with a ship, it is best suited to reconnaissance investigations.

We demonstrate a new approach to this problem using one of the University of Hawai'i (UH) Liquid Robotics Inc. (LRI) Wave Gliders (WG) and a seafloor unit based

around a Sonardyne Sensor Logging Transponder (SLT) pressure sensor. Our system addresses several of the practical constraints on acquiring timely, continuous, high-accuracy measurements of vertical seafloor motion.

We reduce the cost by using the WG for retrieving the seafloor data. Both the WG and the seafloor unit have acoustic modems, which allow for regular data retrieval without interrupting the time series. Our seafloor monument is designed to allow for exact reoccupation with a new pressure gauge so that the time series can be extended beyond the battery life of the initially deployed sensor. We increase the accuracy of the vertical motion observations by using the geodetic GPS equipment onboard the WG. This provides data that can be processed to provide highly accurate estimates for the sea surface height: one of the key contributors to the measured seafloor pressure. In addition, a meteorological sensor measures sea surface pressure, further increasing our ability to accurately detect and resolve seafloor motions. Cellular communications onboard the WG provide a cost-effective means of transmitting all the data to shore. This allows for near-continuous monitoring, and the possibility of responding to evolving events rather than simply recording them for analysis after the fact.

2. Methods

Changes in pressure measured by a gauge on the seafloor reflect the sum of the pressure changes within the overlying ocean and atmosphere (Fig. 1):

$$\Delta P_{\text{sf}} = \Delta P_{\text{atm}} + \Delta P_{\text{sea}}, \quad (1)$$

where ΔP_{sf} is the pressure change measure by the seafloor gauge, ΔP_{atm} is the sea surface atmospheric pressure change, and ΔP_{sea} is the pressure change due to the weight of the ocean above the gauge. With seafloor and sea surface pressure gauges both ΔP_{sf} and ΔP_{atm} are directly observed. The change in ΔP_{sea} can further be expanded to show the various components affecting it:

$$\Delta P_{\text{sea}} = \Delta \text{SSH} \times g \rho_{\text{ss}} - \Delta z_g \times g \rho_{\text{sf}} + g \int_{z_g}^0 \Delta \rho_{\text{sea}} dz \quad (2)$$

where g is the local acceleration of gravity, ρ_{ss} is the mean water density at the sea surface, ρ_{sf} is the mean water density at the seafloor, and $\Delta \rho_{\text{sea}}$ is the change in water density with depth, relative to the mean density profile. We want to find Δz_g , the change in gauge elevation. The largest component in (2) is the change in sea surface height (ΔSSH). Outside of the higher frequencies of ocean waves, these changes are predominantly due to the ocean tides, though there may be significant contributions from transient ocean anomalies such as

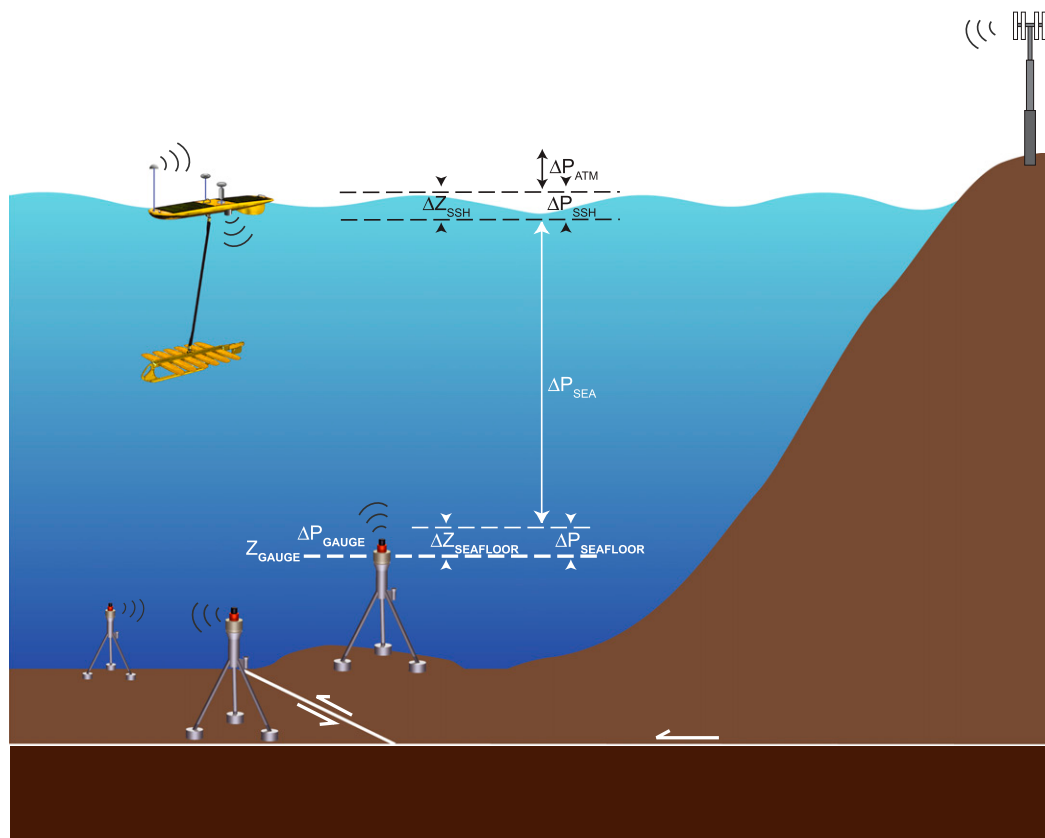


FIG. 1. Schematic illustrating elements contributing to seafloor pressure changes and our system for measuring them.

eddies or infragravity waves, or responses to changes in wind shear. In most geodetic studies using seafloor pressure, a mean mapping function is estimated that transforms model-predicted changes in SSH due to ocean tides into the observed changes in P_{sea} .

3. Hardware

a. Wave Glider payload

The WG has two payload sections (fore and aft) to accommodate user-designed instrumentation. For this project we developed a standalone geodesy payload system for the aft payload section. Our payload instrumentation system receives electrical power from the WG batteries, which are charged by the solar panels, but is otherwise independent of the WG electronics and communications. During our deployments the WG solar panels generated an average of $\sim 16 \text{ Wh}^{-1}$ (Oshiro 2016), sufficient to meet the combined draw of the WG itself and our payload. (Power curves for other locations and conditions are available in the Wave Glider user manual (Liquid Robotics 2010). Deck-mounted components (Fig. 2) were a cell modem antenna (Taoglas)

for high-bandwidth data communications when it is within cell coverage; a high-precision atmospheric barometer (Paroscientific Inc. MET1-2); and a dual-frequency GPS antenna (Antcom G5Ant52AT1). Within the aft payload box (Fig. 3) (Oshiro 2016), we installed a PC104 stack (Diamond Systems Corporation Helios PC/104 HLV800-256AV), cell modem (Sierra Wireless GX440), GPS/GNSS receiver (Novatel OEM628 board), acoustic modem (Sonardyne 6G Acoustic Comms Module), and voltage converters. The embedded PC104 stack (PC) acted as the central hub for all payload components. The acoustic modem, barometer, and GPS receiver communicate with the PC via serial connections. The cell modem is connected to the Ethernet port on the PC and allows remote access to the stack, providing access to all the payload devices and locally stored data. Cellular telemetry was chosen for communication between the WG and shore due to the relatively high communication bandwidth and low cost relative to satellite communication. For nearshore deployments, where cellular coverage can be available at regular intervals, this method of telemetry is convenient and cost-effective, but the general approach we present is not specific to the communication method.

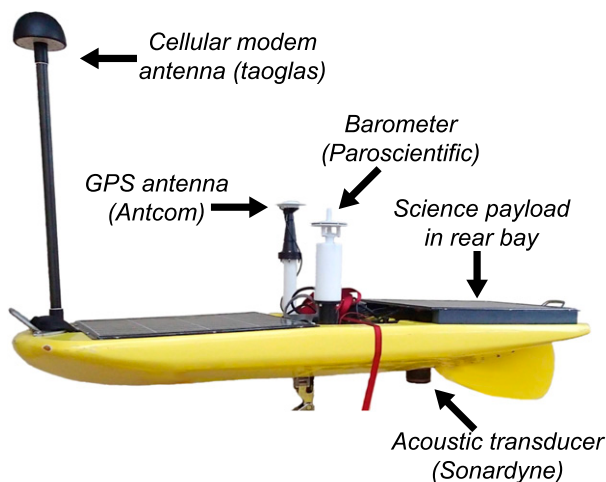


FIG. 2. View of our Wave Glider equipped for the seafloor geodetic mission.

The final element for the topside portion of our system is the acoustic transducer. This is electrically connected to the acoustic modem, mounted to the underside of the payload housing and protruding below the WG hull (Fig. 2). The transducer is a directional, multifrequency (19–34 kHz) unit with an operating range of >3000 m. The modem is capable of data transfer rates of up to 9 kbps.

b. Wave Glider payload software

Control and data archiving of the WG payload was accomplished using custom built software. This software was based on the Field Robotics Laboratory Vehicle Software (FVS) framework developed at UH, which makes use of the Lightweight Communications and Marshalling (LCM) toolkit for message passing and data logging (Bingham et al. 2011). Three custom software drivers were installed on the embedded computer for the acoustic modem, GPS receiver and barometric sensor.

Each of the drivers consists of a standalone process. Each process generates messages using the LCM libraries that are transported via User Datagram Protocol (UDP) datagrams to the LCM logger. The LCM logger writes each received message to disk, along with a time stamp of when the message was received. When the WG is within cellular range, they can be retrieved from shore for analysis and diagnosis.

The acoustic modem communications include health diagnostics for the surface and subsea components, information on the quality of the acoustic channel, time-of-flight estimate of the slant-range between the WG/SLT and the 500-byte data “pages” transferred from the SLT to the topside modem. All of this information is

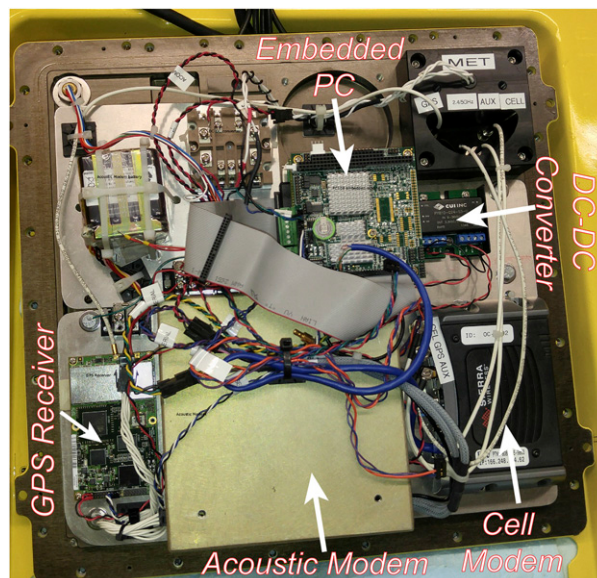


FIG. 3. Interior of the rear payload box showing the key components of our geodetic system.

recorded in a single log file with each LCM message, including time stamps for each message based on the PC system clock, which is synchronized with online time servers before and after each deployment.

c. Seafloor package

The bottom-side component of the system is composed of a Sonardyne SLT fitted with a floatation collar and mounted onto a monument tripod (Fig. 4) deployed on the seafloor. The SLT is a long-life multisensor instrument with integrated time-synchronized datalogger and acoustic modem. It is time synchronized to a common computer time and programmed to carryout predetermined measurements over several years. Internal clock drift can be estimated through another synchronization after recovery. The total deployment time is controlled by the interplay between the sensor sampling and recording strategy, and the battery power, and can support deployments on the order of 5 years or more. Logged data can be retrieved via acoustic telemetry.

The SLT configuration used herein had an extended-length aluminum housing holding two lithium batteries, and is fitted with a directional transponder and a mechanical release. It has the capability to periodically log sensor data and make acoustic baseline measurements. Our sensors include a 50-mm sound speed sensor, a temperature sensor, and a 3000-m-rated Paroscientific Digiquartz pressure sensor. These pressure sensors are commonly used for seafloor geodesy as they have excellent, ~1-mm equivalent depth change, sensitivity. Their primary weakness is long-term, largely linear,

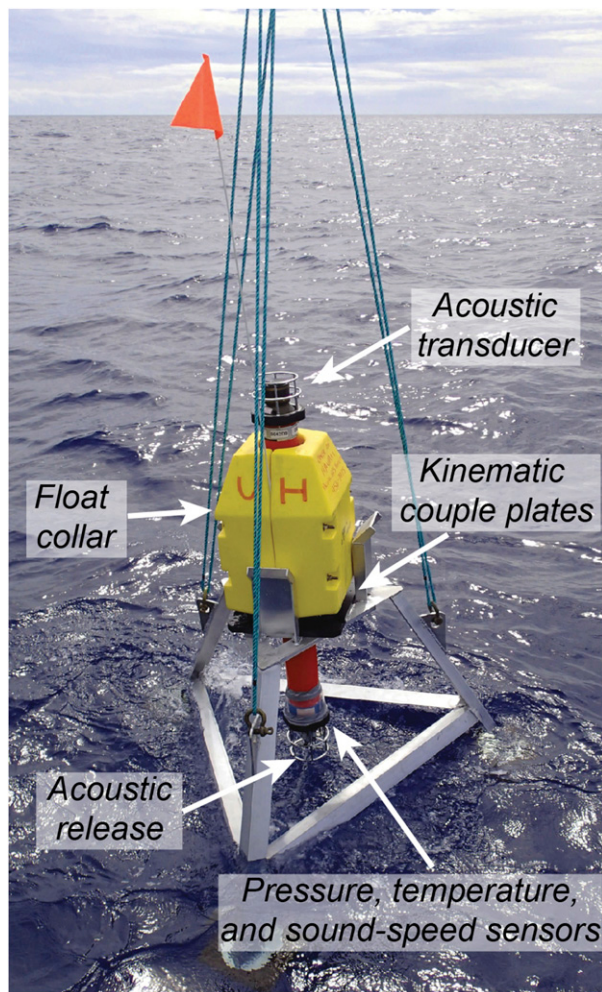


FIG. 4. Deployment of the seafloor monument with SLT mounted.

instrumental drift, which has been estimated as the equivalent of $\sim 8 \text{ cm yr}^{-1}$ depth change (Polster et al. 2009). Dual lithium batteries provide approximately 5 years of measurements in a single deployment, depending on the measurement strategy, and the number and duration of acoustic communications.

Buoyancy is provided by a 3000-m-rated syntactic foam collar that clamps around the pressure housing. Anchor weights suspended below the SLT, and connected to the acoustic release mechanism, maintain negative buoyancy.

Our custom designed monument is a tripod 1.02 m tall with equally spaced legs on a 1.83-m-diameter base. The tripod is constructed of aluminum alloy to resist corrosion in seawater. Guide arms welded to the upper surface of the tripod provide general centering of the SLT and float collar as it is positioned in the tripod. Precise indexing of the SLT in the monument is accomplished using a kinematic couple consisting of a grooved plate

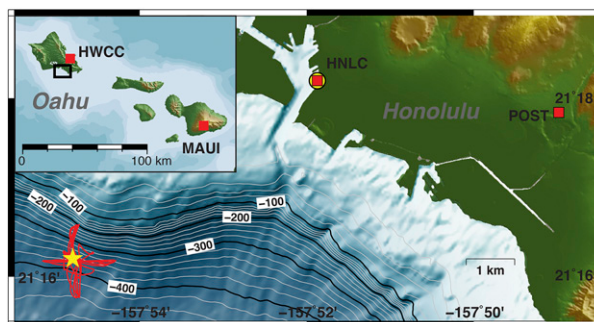


FIG. 5. Location of the demonstration experiment. SLT (yellow star) was deployed in ~ 380 -m water depth. The Wave Glider maintained station above it for ~ 3 days. GPS solutions used local cGPS sites (red squares). Tide gauge is marked by yellow circle collocated with HNLC.

bolted to the upper surface of the tripod and a ball plate clamped around the SLT pressure housing below the float collar.

For the initial deployment the SLT is fixed to the tripod using a chain bridle attached to lifting eyes on each foot and a ring or pear link attached to the acoustic release shackle. Subsequent reoccupations would require an anchor weight attached to the release shackle and ROV placement in to the tripod.

4. Deployment

The SLT was deployed 7 December 2014 in ~ 380 -m water depth, approximately 6 km southwest of Honolulu Harbor (Fig. 5). The WG was deployed multiple times to test and evaluate the technology and verify the ability to acoustically interrogate the SLT. The analysis and results presented here are associated with the 27–29 May 2015 deployment, which successfully recorded a complete suite of data, and demonstrated recovery and transmission of data from the SLT. The SLT was recovered at the completion of this WG deployment.

5. Data and processing

a. Sea surface height

The 1 Hz GNSS data from the OEM624 board were postprocessed using the TRACK (Herring 2006) package following the approach of Foster et al. (2009). This uses a double-difference processing strategy using a fixed reference site to determine the kinematic positions of the roving unit. To reduce the impact of multipath at the reference site, we processed against four Hawaii continuous GPS (cGPS) sites (Fig. 5) and formed the weighted mean from the four solutions as the best estimate of the WG position time series. We used 1-Hz data from

the cGPS sites HNLC, POST, HWCC, and MAUI operated by the Pacific GPS Facility, and precise orbits and satellite ephemerides from the International Global Navigation Satellite System (GNSS) Service. Standard Earth orientation and solid Earth tidal models were applied. Estimates of the GPS signal delay due to the neutral atmosphere were modeled as a constrained random walk process. The WG track position estimates were generated using an iterative approach: a 5-h window was used to select data for processing and the window was stepped forward in 4-h increments with the appropriate position solution from the previous window's solution used as an a priori location for the new solution. The standard deviations of the four height time series with respect to the best, weighted-mean, heights were 0.024, 0.026, 0.022, and 0.031 m for MAUI, POST, HNLC, and HWCC, respectively.

Validation of the resulting time series is performed by comparison with water-level measurements recorded by the Honolulu tide gauge (TG), located approximately 6 km to the northeast of the deployment site. At this range there should be little difference in the tidal perturbations, and only relatively small local effects such as wind shear and bathymetric interactions with the tides and wave field should lead to differences between the two sets of observations of water level. The WG elevation time series is adjusted to the nominal water line by applying a 0.38-m vertical offset to account for the antenna standoff height and the WG freeboard. The hourly Honolulu TG relative sea level measurements are interpolated to match the 1-Hz position observations and mapped to the ellipsoid using the measured offsets between the TG and the collocated GPS site HNLC. We applied a 6-min Gaussian smoothing function to the WG elevation time series to remove the high-frequency motion due to the wave field. This deployment was in modest sea conditions, with the significant wave height ranging between 0.8 and 1.0 m; however, we have found this smoothing approach successfully suppresses motions due to regular ocean waves in most sea states. We used the EGM2008 geoid to determine the geoidal height differences between the TG and WG. The resulting time series (not shown, but visually identical to Fig. 6) match with a mean bias of only 0.015 m and a standard deviation of 0.138 m. The bias is well within the expected range of uncertainty for the combined effects of the geoidal errors, water-line determination, and differential sea level anomalies due to local effects (Morales Maqueda et al. 2016; Penna et al. 2018). The standard deviation is in line with the expectations of 0.05–0.08-m vertical accuracies from kinematic GPS solutions (e.g., Foster et al. 2009; Liu et al. 2015), and the spectrum of likely oceanographic processes that

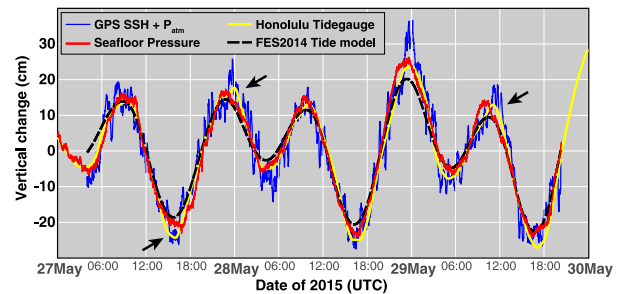


FIG. 6. Sea level changes from SLT pressure (red), WG GPS (blue), FES2014 tide model (dashed black), and Honolulu TG (yellow). Black arrows indicate periods of noticeable difference between the seafloor pressure and the surface measurements.

would introduce differential sea levels between the locations at periods above 5 min.

Notably, the comparison with the TG observations confirms that many of the differences between the WG time series and tide model predictions are real changes in sea level, not artifacts of the GPS processing. This confirms that, not only are the WG GNSS observations valuable for providing absolute measurements of the sea surface and its long-period variations (i.e., greater than daily) but they also capture significantly higher-frequency tidal and nontidal perturbations.

b. Atmospheric pressure

The MET1-2 unit was installed with its reference level 0.08 m above the nominal water line and observations were logged at 2-s intervals, with a time stamp from the embedded PC's onboard clock. As the embedded PC clock was not actively synchronized to UTC time, the measurement time stamps were transformed to UTC time using an empirical linear fit between UTC time and the embedded PC clock. A slight adjustment (~ 0.01 hPa) was made to the observed values to map from the observation reference level to sea level. The observations show the expected semidiurnal pressure cycle (e.g., Dai and Wang 1999), and indicate generally increasing pressure for the duration of the deployment.

c. Seafloor pressure

The SLT was configured to record 1-min samples based on a 1 min averaging window. Datasets logged include local sound speed and temperature. The integrated Digiquartz sensor provides pressure measurements, corrected via a calibration table using temperatures observed by its own integrated temperature sensor, whose measurements are also logged, leading to two different and independent temperature time series. Initial quality control on the pressure data identified and removed points with spurious values, as well as the initial

transient period while the unit fully equilibrated to the bottom water temperature, and during the return ascent to the surface.

The two temperature time series show the same higher-frequency signals, but with slightly different response times. The slower response of the Digiquartz sensor acts as a low-pass filter on the temperature anomalies. Strikingly, anomalously rapid excursions in the pressure data, on the order of 1 kPa (equivalent to 10-cm water column height change) over 5 min, correspond to times when the two temperature measurements differ the most. Although there is no definitive explanation for this, the Digiquartz temperature sensor is offset from its pressure sensor. As a result, during rapid ocean temperature changes they may experience slightly different internal temperatures. The in situ pressure transformation may then be performed with a temperature observation that differs from the correct value for the pressure observation location, introducing transient pressure artifacts. We found that a linear function of the difference between the Sonardyne and Digiquartz temperature measurements was highly correlated with the anomalous pressure perturbations (see supplemental material for more information). We conclude that the rapid pressure anomalies are an artifact of the thermal separation of the pressure and temperature sensors (although we note that these excursions fall within the manufacturer's specified measurement accuracy) and we use the linear correlation with the differential temperature to create a pressure correction. Applying this correction minimizes the anomalous pressure excursions. The use of this correction may introduce a small bias into the absolute pressure measurements but, as it is likely very small (<0.1 kPa; equivalent to <1 -cm water column height), and we are most interested in differential pressure changes, this was considered to be a reasonable compromise. This procedure leads to a slight improvement in the statistical comparisons between our datasets, but does not otherwise impact our interpretations or general conclusions. For future work this issue could be resolved either by using our empirical approach if observations from two temperature sensors are available, or by constructing a more complex calibration algorithm that includes temperature rate of change.

6. Results

We examine our processed and corrected time series in terms of equivalent sea level height perturbations. We first map our seafloor pressure perturbations into equivalent water column height changes using a scaling factor of $0.0997 \text{ m kPa}^{-1}$ based on the mean column density from a regional ocean model (Souza et al. 2015),

and the local value for the acceleration of gravity. We then sequentially model and remove sources of sea level perturbation from our data until we have a time series of residual apparent perturbations. As the island of Oahu is tectonically stable, and we have no reason to expect any local motion of the seafloor, we expect to find no detectable vertical motions in our time series data. We therefore treat our residual time series as characterizing the errors in our technique's ability to resolve vertical displacements of the seafloor.

A standard dispersion relationship describing wave-related particle motion is used to map the GPS estimated SSH perturbations into the predicted perturbations we would expect to measure at the seafloor:

$$A_z = A_0 e^{-2\pi z/\lambda},$$

where A_0 and A_z are the amplitudes at the surface and depth z , respectively, for a wave with wavelength λ . This acts as a low-pass filter, as high-frequency perturbations in sea surface height disperse with depth more rapidly than lower frequencies. Our seafloor pressure observations from the seafloor pressure gauge are 1-min samples from running 1-min averages. To directly compare our predicted 1-Hz seafloor perturbations against these observations we perform a 1-min running average and then downsample to the same 1-min interval as the pressure data. We execute the same procedure with the atmospheric pressure data. For observation periods longer than 3 days (Carrère and Lyard 2003) attention would be required to assess, and correct for, the impact of the "inverse barometer" effect, where local sea level responds to pressure changes (Wunsch and Stammer 1997). Over our 3-day campaign this effect is not significant and we ignore it here.

The transformed sea surface perturbations closely track the seafloor pressure perturbations (Fig. 6). The time series are dominated by the ocean barotropic tide signal, with both the Honolulu tide gauge measurements and the FES2014 tide model (Carrère et al. 2015) predictions duplicating the pressure and SSH data to first order. There are however significant second-order differences between the datasets at some points, indicated in Fig. 6, and these illustrate some of the issues that in situ observations from a WG can help resolve. Discrepancies are most obvious at some of the high and low tides, where significant lags between the seafloor pressure and both the SSH and TG measurements can be seen. The correspondence between the SSH and TG provides reassurance that these are real sea surface height changes, while the difference at the seafloor indicates these must be largely nonhydrostatic processes (Marshall et al. 1997).

Excursions from the simple tidal response are expected to reflect a range of oceanographic processes, including internal waves, internal tides, and larger-scale anomalies such as eddies. Eddies should be well captured by the local tide gauge record, and so their impact can be recognized and removed. Internal tides have high amplitudes around Oahu (Carter and Gregg 2006; Carter et al. 2008; Smith 2016). Although they are locked to the tidal cycle, the exact phase is very hard to predict, and so they are recognizable primarily as persistent perturbations from the expected tidal signal occurring at around the same point in the cycle. Internal waves are a widely observed source of higher-frequency perturbations. At the SLT location these are expected to be manifested as movement of the colder, deeper, water layers up the bathymetric slope (Smith 2016). This leads to a rapid drop in temperature followed by an increase as they recede. These are not modeled within current numerical ocean models, and they are not well observed by existing instrumentation on the south shore of Oahu, so they are recognizable mainly through their character: 10–30-min-period temperature spikes. The temperature perturbations are expected to be accompanied by pressure perturbations as the denser, cold water covers the SLT. However, as pressure changes are column integrals, they should be much less pronounced than the temperature excursions.

The formal standard deviations of the residuals after subtracting predicted/observed sea level perturbations from the observations are shown in Table 1. Over the 3-day time window, the nearby tide gauge provides the best fit. This is likely in part due to the heavily smoothed nature of tide gauge observations: little intrinsic higher-frequency signal is recorded. This means it captures the long-period nature of the seafloor observations, but without also capturing local, possibly nonhydrostatic processes that would increase the deviation. The next best fit is provided by the tidal model. For a scenario where there was no opportunity to perform surface measurements, this would be the obvious approach for predicting the first-order water column height perturbation. Tide models are unable to provide any information about higher-frequency processes such as internal tides, nor can they give absolute sea level anomalies due to other long-wavelength transients. That information would have to be inferred from satellite data, such as the AVISO sea level anomaly maps (<https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/msla-h.html>). As with the tide gauge data, the standard deviations are low partly due to the lack of any characterization of these processes. The residuals from the WG SSH measurements have a higher standard deviation, partly because these data have their own intrinsic noise, but also

TABLE 1. Standard deviations of the residual time series after subtracting the observed or predicted sea surface height perturbations. Over the 3-day Wave Glider deployment time window, the nearby tide gauge provides the best fit to the seafloor pressure data. The residuals from the Wave Glider measurements have a higher standard deviation, partly because these data have their own intrinsic noise, but also likely because they are capturing real, nonhydrostatic local surface perturbations.

SSH estimate	Std dev (cm)
FES2014 tide model	2.62
Honolulu tide gauge	2.47
Wave Glider GPS elevations	4.66
Wave Glider GPS + atmospheric pressure	4.44

likely because they are capturing real, nonhydrostatic, surface perturbations. It is notable that including the measured surface pressure perturbations significantly decreases the overall standard deviation of the residuals.

For this experiment the WG was deployed near fixed instrumentation (tide gauge) and in a location that has good model coverage, and accurate bathymetry, etc. While this was important for our proof-of-concept study, many of the locations of particular interest for geodetic studies are much farther from such infrastructure, and without existing nearby instrumentation. In these locations in situ data collection would be extremely valuable to enable the observation of the oceanographic signals and to deconvolve them from any transient seafloor motions. Wave Gliders have been deployed for several months at a time with little reduction in their function, so are well suited to long-term monitoring efforts. The modifications to our Wave Glider configuration needed for it to operate in a similar mode for these more distant types of locations are relatively straightforward. The communications solution in our payload is flexible: we used a cellular communications module. For more remote locations a satellite-based system such as Iridium would be swapped in. Although we have had success performing baseline-style GPS processing over 100-km-length baselines, in the deep ocean a more flexible positioning capability would be needed. One solution could be to subscribe the onboard GNSS receiver to a marine GNSS positioning service. This configuration would also be capable of true real-time operations as there would be no delay introduced by the need to transmit the raw GNSS data to shore for postprocessing that our rapid-response approach described here requires.

In Fig. 7 we show the residual water column height perturbations after subtracting the WG GPS SSH with atmospheric pressure measurements. Our particular interest in this study is in the ability of the WG observations to allow us to distinguish between transient seafloor motion events, and oceanographic signals. As we expect

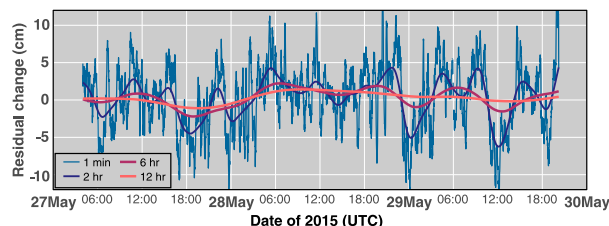


FIG. 7. Residual sea level changes after removing SLT pressure changes from WG GPS height solutions. Filters with 2-, 6-, and 12-h temporal width quickly reduce RMS to the centimeter level.

there to be no seafloor motions, we treat our residuals as characteristic of local oceanographic signals. The period of temporal overlap between these processes is likely on the order of tens of minutes to weeks (Muramoto et al. 2019). We apply Gaussian filters with widths of 2-, 6-, and 12-h range to the residuals and use the smoothed data as estimates of the noise levels at those periods (Table 2). The standard deviation falls quickly, and suggests that, for our experiment time and location, to be able to confidently detect a centimeter-scale offset would require at least 12-h averaging of the data.

To explore this further, we use the full 5-month time series of bottom-pressure observations. We adopt the processing approach used for the Axial Volcano pressure time series (Fox 1993), using a 40-h smoothing window to remove the tidal signal. We then compare the day-to-day differences of the mean equivalent daily seafloor depths to examine our ability to resolve step changes. As we do not have matching surface measurements for this period, we use the local tide gauge observations as the best-available correction for long-period oceanographic effects. We show the histograms of these differences in Fig. 8. Over this time period the tide gauge-corrected daily difference time series actually has slightly larger variance, 1.4 versus 1.0 cm for the uncorrected version. This is likely due to the influence of the coastal and shallow bathymetric effects creating stronger differences between the SLT location and the tide gauge during some wind and ocean current conditions than was the case during our deployment. Importantly, however, the mean value for the uncorrected differences corresponded to an apparent drift rate of 13.3 cm yr^{-1} . For the tide gauge-corrected differences the equivalent rate is 2.4 cm yr^{-1} . This indicates that applying the tide gauge correction, and by extension, surface monitoring with WG GPS, we can expect to reduce apparent drift in bottom pressure by correcting for long-period oceanographic changes.

A recent development in seafloor pressure technology is known as the “A-0-A” pressure sensor, which includes a self-calibration capability that can reduce the sensor drift

TABLE 2. Impact of smoothing on the day-to-day (24-h separation) differences of the residual time series. The expected difference here is zero: the data indicate that the ability to confidently detect a centimeter-scale offset would require at least 12-h averaging of the data.

Smoothing window (h)	Std dev (cm)
2	2.52
6	1.39
12	0.71

to near zero (Wilcock et al. 2017). These sensors are more expensive, but offer the possibility for better resolution of long-term vertical motions. They do not, however, remove the issue of deconvolving long-period oceanographic signals from tectonic motions that can be at least partly mitigated by the approach we present here.

7. Conclusions

We have demonstrated that by acquiring high-precision GPS and meteorological data with an autonomous surface vehicle, in this case a Wave Glider, concurrent with seafloor pressure and temperature data, we improve the accuracy of seafloor motion estimates. The standard deviation of our estimated equivalent vertical seafloor motions is 4.44 cm (for 1-min data samples). Detection of centimeter-scale vertical offsets is possible by forming 12-h averages of the observations. The surface data are also shown to greatly improve the apparent longer-term

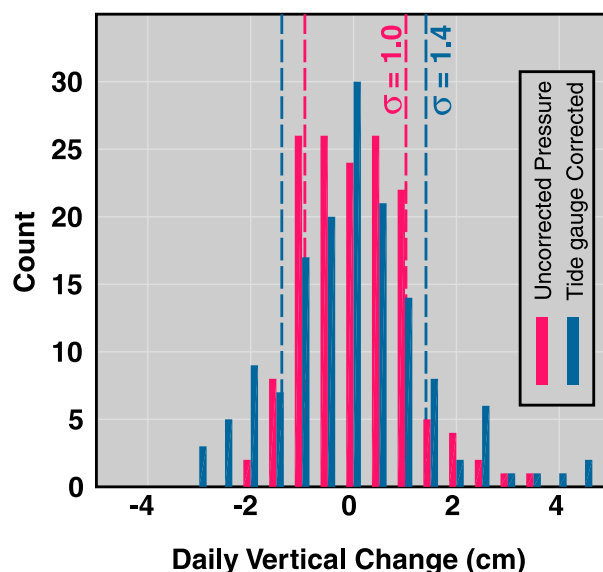


FIG. 8. Histograms of differences between consecutive 24-h averages of the sea level height residuals. Red represents the uncorrected 5-month pressure time series, and blue represents the pressure corrected using Honolulu TG measurements.

(several months) stability of the seafloor motion estimates. In addition, the Wave Glider is able to communicate with both the bottom sensor and the shore, allowing it to act as a relay, and permitting near-real-time monitoring of seafloor motions. This opens up the possibility of rapid response missions to, for example, acquire additional datasets, or initiate response protocols to evolving signals on the seafloor.

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