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Ship-based measurements of sea surface topography

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[1] By equipping the research vessel Kilo Moana with a geodetic GPS receiver and a radar water level gauge, and using a kinematic GPS processing package, accurate 1 Hz estimates of the sea surface height were obtained. Geodetic positioning of ocean-platforms using only the GPS system cannot account for changes in the draft of the platform. This is especially problematic for ships, where changes in the load, speed and/or ocean density can change the ship's draft by 10s of centimeters. By installing a radar gauge this noise source can be removed from the estimates of the sea surface height. We envision that this technology could routinely provide high resolution information on the geoid, or the variation of the sea surface height, including sea-state, from an existing reference geoid. **Citation:** Foster, J. H., G. S. Carter, and M. A. Merrifield (2009), Ship-based measurements of sea surface topography, *Geophys. Res. Lett.*, *36*, L11605, doi:10.1029/2009GL038324.

1. Introduction

[2] The topography of the sea surface is controlled by many static, periodic and transient processes, and accurate measurements of sea surface height (SSH) can be used to infer information about, and constrain models for these processes. The most common sources of SSH measurements are from tide gauges, bottom-mounted pressure sensors and satellite altimeters. Tide gauges and pressure sensors provide high temporal resolution but are point measurements. Altimeters provide global spatial coverage at coarse temporal sampling (~10–30 days), and currently ~100 km spacing between swaths. Regional studies of a range of important oceanographic processes (e.g., transient coastal flows, eddies, tides, long surface gravity waves) would benefit from a complementary observing capability that could provide high space-time resolution SSH mapping.

[3] GPS-based approaches to measuring SSH have been demonstrated using various platforms, including buoys [e.g., *Chadwell and Bock*, 2001] and small boats [e.g., *Bonnefond et al.*, 2003] close to shore. A more ambitious project demonstrated that high accuracy geoid measurements were possible using a cruise ship [*Rocken et al.*, 2005]. This experiment however was unable to assess and account for changes in the draft of the ship which introduces decimeter scale uncertainties in any SSH estimates. Here we demonstrate a technique to retrieve high accuracy (better than 10 cm) estimates of the SSH using ships, for distances up to 200 km from land.

2. Equipment and Data Acquisition

[4] The University of Hawaii operates the Kilo Moana (KM) research vessel. The KM performs regular cruises to the Hawaii Ocean Time-series (HOT) location Station ALOHA, ~120 km north of the island of Oahu (Figure 1). For HOT cruise 188 a geodetic grade GPS receiver and a radar gauge were installed on the KM to assess whether it could serve as a floating tide-gauge.

[5] The KM is equipped with a POS MV navigation system, which includes twin single-frequency GPS receivers. The system's antennas are dual-frequency capable, so 1 Hz dual frequency pseudorange and carrier phase GPS data were easily acquired by attaching a Trimble NetRS GPS receiver to one of the existing antenna cables. The twin hull design of the KM makes it very simple to install a radar sensor looking vertically down on the sea surface, unbroken by the ship's own bow wave. An OhmartVega VEGAPULS62 radar gauge was installed on the catwalk directly below the GPS antennas (Figure 2). The gauge was configured to switch off the normal internal data integration and processing in order to acquire high-frequency, independent range estimates. The gauge was polled by a VegaMet625 unit, and its data file was downloaded twice daily to a laptop PC.

3. Data Processing

[6] GPS data were processed using the TRACK kinematic GPS processing module from the GAMIT geodetic GPS software package [*Herring et al.*, 2006]. The processing strategy used a local 1 Hz reference station operated by the Pacific GPS Facility with precise orbits and satellite ephemerides from the Scripps Orbit and Permanent Array Center. 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. Due to memory issues, the ship track position estimates were generated using an iterative approach: a 4-hour window was used to select data for processing and the window was stepped forward in 2 hour increments with the appropriate position solution from the previous window's solution used as an a priori location for the new solution.

[7] The kinematic GPS solutions provide a time series for the 3D location of the GPS antenna. The vertical component of the solution is reported with respect to the ITRF2000 ellipsoid (Figure 3b). In order to obtain estimates of the SSH itself, the ellipsoidal heights need to be further reduced, as shown in Figure 2, by including the vertical offset between the radar tide gauge reference point and the GPS antenna, and the ranges from the tide-gauge to the sea surface (Figure 3c). Applying these corrections generates a time series of the SSH with respect to the ellipsoid. The short period component of the time series is due to the wave field. In order to focus on the longer period portion that is due to the geoid, tidal effects, and mesoscale phenomena, we run a 5 minute running-mean filter to generate a

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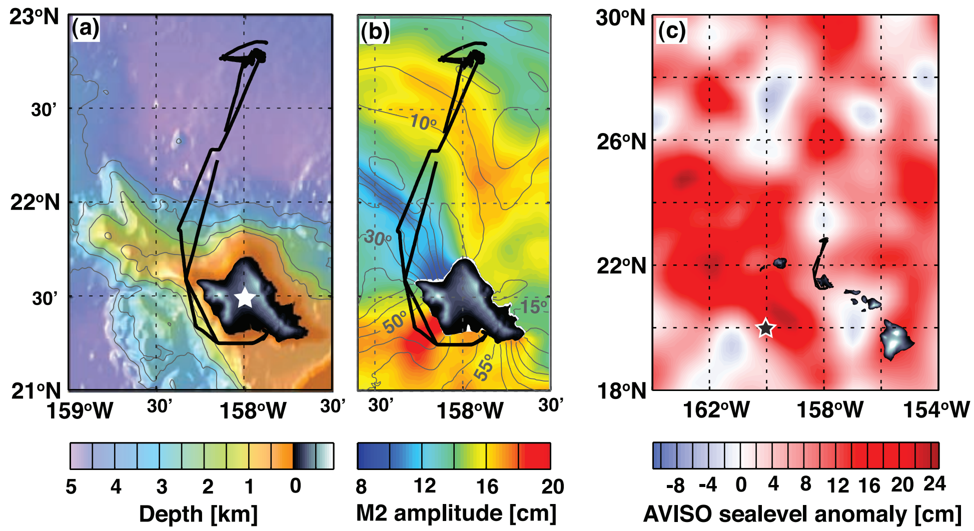

Figure 1. Kilo Moana cruise track for HOT leg 188 superimposed on (a) bathymetry, (b) predicted M2 tidal amplitudes, and (c) AVISO mesoscale sea level anomaly. Reference GPS site HWWJ marked with white star in Figure 1a, and NOAA wave buoy 51003 by black star in Figure 1c.

smoothed time series. One of the possible applications of this technique would be to generate a high-resolution map of the geoid [e.g., *Rocken et al.*, 2005] (or at least the mean SSH which is a near-approximation) by processing many tracks over a region. As we have data for a limited time only, we chose instead to look at spatio-temporal variations from a model of the geoid. GEIOD03 is currently the most accurate model for the Hawaiian Islands and surrounding oceans. By sampling this model along the track of the ship, the geoid height is predicted (Figure 3d) and can be removed from the SSH time-series to produce a time-series of SSH with respect to the geoid (Figure 4). An offset of 9.0 cm was evident in the original processing. Comparison of mean sea level at the tide gauge at Honolulu with the ellipsoidal height of the collocated GPS site HNLC revealed a 9.3 cm discrepancy between the GEOID03 prediction and the observed mean sea level value. This offset has been applied as an additional constant correction to the time series.

4. Results and Discussion

[8] The KM left port late on Dec 08 (GMT) and returned late on Dec 12 (Figure 3a). As sea level in the harbor is relatively undisturbed by waves and other high frequency transient changes we used solutions from the first half of Dec 08, while KM was at its dock ~25 km from the reference GPS site and ~2.5 km from the Honolulu tide gauge, to assess error magnitudes. Errors/noise in kinematic GPS solutions are mostly due to atmospheric heterogeneities, multipath due to the GPS signals being reflected towards the antenna by nearby surfaces, and errors in satellite orbits and/or earth orientation parameters. The rms of the 1 Hz SSH height estimates with respect to the observed tidal signal is 9.3 cm and applying a simple 5-minute running mean filter reduces the rms to 8.3 cm. It is difficult to determine the relative contributions to the rms of errors in the GPS estimates and real, non-tidal perturbations in the SSH; a short-baseline GPS-buoy study [*Chadwell and Bock*, 2001] found 2.4 cm rms after smoothing, while a long-baseline, ship-based experiment [*Rocken et al.*, 2005] estimated 10 cm vertical errors. While docked the ship is in a particularly high multipath environment so these rms values probably reflect a larger contribution from multipath than would be expected on the open ocean and, as there is probably also some small but real SSH variation, 8 cm therefore represents a conservative estimate of the accuracy. During the cruise the rms of the unsmoothed and uncorrected 1 Hz estimates, with respect to a model SSH, increases to 56 cm. Applying the gauge corrections increases it still further to 69 cm. This makes sense, as the rms includes real signal and applying the radar range corrections effectively adds in the portion of the high-frequency wave field that the ship (and hence the GPS) does not fully respond to. Encouragingly, the running mean filter reduces the rms values to 16.1 cm and 13.3 cm respectively, indicating that the radar corrected values better represent perturbations

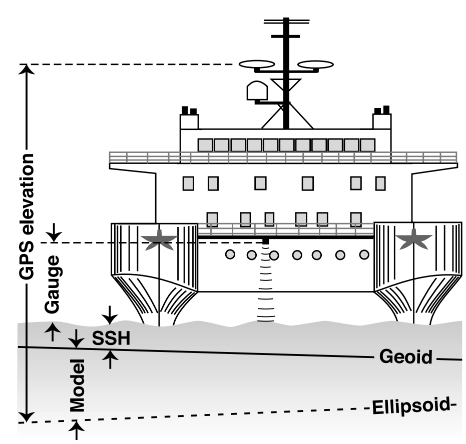

Figure 2. Schematic showing relationship between vertical measurement reference levels and corrections.

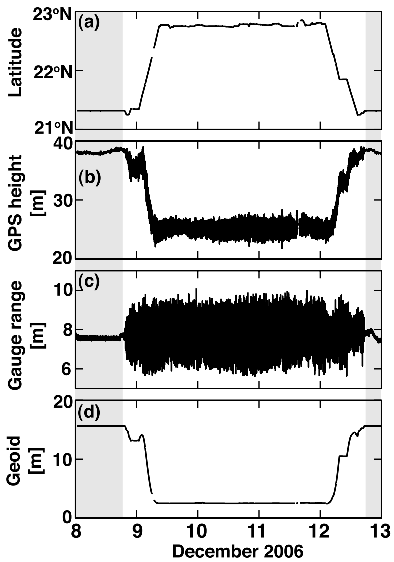

Figure 3. Time series from cruise showing (a) ship latitude, (b) estimated height of GPS antenna above ellipsoid, (c) range to sea-surface from radar gauge, and (d) GEOID03 model geoid height above ellipsoid.

about the mean level, and that we are observing SSH variations from our model values.

4.1. Tides

[9] The sea-surface time series shows a strong semi-diurnal component, indicative of an ocean tide signal (Figure 4). Around Hawaii the barotropic tide is complicated by the interaction between the submarine bathymetry and the M2 semi-diurnal component which generates a strong internal tide [*Carter et al.*, 2008]. As this cruise track is to the side of the main beam of internal tide energy, the predicted maximum amplitude of the internal tide component is too small (<2 cm) for this data set to resolve with any statistical significance, however the broader comparison between the predicted tidal height (Figures 1b and 4) and the ship-estimated values shows very high correlation for the longer period portions of the time series, confirming that this technique could identify and estimate the parameters of internal tides with slightly higher amplitudes.

4.2. Mesoscale Anomalies

[10] The complex currents and bathymetry around the Hawaiian Islands give rise to many mesoscale anomalies that propagate along the island chain and can have major impacts on coastal inundation as well as marine bioproductivity. For the time and track of the HOT 188 cruise, the AVISO satellite mapped mesoscale sea-surface anomaly field has only low amplitudes (Figure 1c). Comparison with the ship-estimated height anomalies (Figure 4) confirms the low amplitude of the signal. Interestingly, the sea-surface estimates are better matched by the AVISO adjusted tide model for the first portion of the time series, but show a discrepancy during the return leg of the cruise. This could be a limitation of the GEOID03 model as the cruise crossed over the extreme bathymetry to the north east of Oahu.

4.3. Geoid

[11] The low residual signal visible in Figure 4 implies that the geoid along the cruise track is generally well described by GEOID03. Some of the excursions from the predicted tidal signal for this cruise, however, and more strikingly for a subsequent cruise (not shown) that headed WNW towards Kauai, show strong correlations with shallow bathymetry, suggesting that some higher frequency components of the geoid are not well captured by GEOID03, especially perhaps perpendicular to the satellite altimeter tracks which pass roughly north–south at this latitude and so are nearly parallel to this HOT cruise track.

4.4. Sea-State

[12] Although our primary focus in this paper is on the longer spatial and temporal wavelength signals, there is also the opportunity to retrieve information about the sea-state from this technique. The high frequency portion of the GPS time-series reflects the ship's vertical displacement due to the wave field, while the corresponding portion of the radar gauge time-series records the sea-surface with respect to the ship. Simple subtraction of the gauge ranges from the GPS elevations eliminates the ship's response to the waves and produces a time series of the vertical component of the wave field. Figure 5 shows a spectrogram of the wave field for the cruise and, for comparison, the spectral power density from a NOAA wave buoy (51003) located southwest of Oahu. As the instruments on the KM were only temporarily installed, they did not share a common time base; we had to estimate a linear correction, based on the time-series' correlations, that mapped the radar gauge clock to the GPS clock. This reduces the confidence that can be placed on any fine details visible in the results. The beginning and end of the spectrogram, when the KM was in port, show the expected

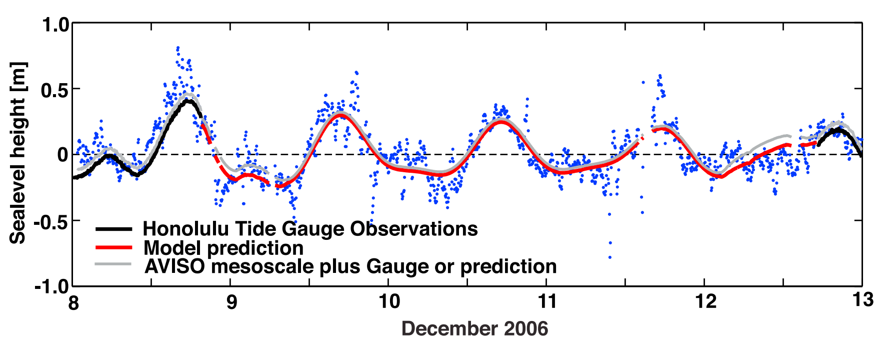

Figure 4. Time series of sea-surface elevation with respect to GEOID03 model, after correcting for ship draft (blue dots). Solid lines indicate the observed (black) and predicted (red) tide heights and tides + mesoscale anomalies (gray).

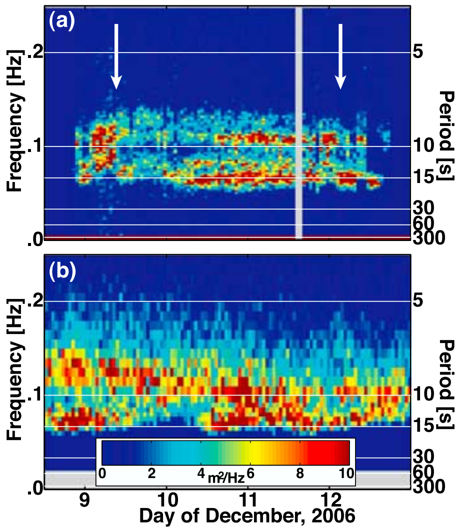

Figure 5. (a) Spectrogram of high-frequency (4 to 300 s period) component of the sea-surface elevations. White arrows indicate when Kilo Moana arrived at and departed the HOT study area, and (b) wave power density from NOAA wave buoy 51003 for the same period.

extremely low wave power density. In the open ocean the power is mostly in two bands at ~9 and 15 seconds. When the ship was nearly stationary at the HOT study area (white arrows, Figure 5) both these frequencies are evident, with a decrease in power between 9 and 10 Dec visible in both data sets. The coarser frequency resolution of the wave buoy data, and the large spatial distance between the two sets of observations makes detailed comparison difficult, but it is notable that the KM spectrum does not see quite the same wavelength changes for the ~9 s band. Unlike a wave-buoy, the frequency of the KM time-series is modified by the ship's velocity, and an accurate spectrum for the wave field cannot be uniquely determined when the ship is underway without additional information on the angle between the ship's heading and the wave fronts. Nevertheless some useful information is available, and, by incorporating accelerometer data, for example, more information might be extracted.

4.5. Improving Processing

[13] As the distance between ship and reference site increases it becomes increasingly difficult for the processing software to identify and set the integer phase ambiguities. The processing approach detailed here was able to resolve all, or most, of the ambiguities over the entire cruise, which was mostly at 100–150 km from the reference station. A subsequent cruise was successfully processed out to 200 km from the reference site, which perhaps represents the limit for phase ambiguity resolution with this approach. Although this means that this particular approach cannot be employed for ships in the open ocean far from land, it does allow for high accuracy results for those large areas of the ocean that are within 200 km of land. As satellite altimetry systems suffer land contamination problems within several km of the coastline this technique could effectively fill in these shadow zones. Alternative processing approaches [e.g., *Rocken et al.*, 2005; O. L. Colombo et al., Long-baseline (>1000 km), sub-decimeter kinematic positioning of buoys at sea, with potential application to deep-sea studies, paper presented at the 13th ION GPS 2001, Institute of Navigation, Salt Lake City, Utah, 2000] have demonstrated high accuracies over >1000 km baselines, and these approaches could be employed to retrieve sea surface topography for more remote cruises. In addition, multipath mitigation techniques might improve the accuracy of the GPS solutions.

[14] Although geoid mapping is perhaps the only one of the applications described here likely to provide the primary motivation for a scientific cruise, the range of sea-surface information that can be retrieved by our technique, and its low set up and ongoing costs, suggests a role as an ancillary system collecting valuable additional data (including meteorological parameters [e.g., *Bevis et al.*, 1992]) on any cruise.

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