5-cm-Precision aircraft ocean altimetry using GPS reflections

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[1] We present the first two aircraft Global Positioning System (GPS)-reflection altimetry measurements, the most precise GPS ocean-altimetry measurement, and demonstrate the altimetric precision and spatial resolution necessary to map mesoscale eddies. Our first experiment demonstrated a 14-cm precision single-satellite ocean altimetry measurement while our more recent experiment demonstrates 5 cm altimetric precision with 5-km spatial resolution. The new results show significant improvement over our previous effort, due to improved modeling, greater aircraft altitudes and velocities, improved receiver positioning, and better experimental control. Plans to further reduce speckle and refine models to obtain 5-cm altimetric accuracy are presented. INDEX TERMS: 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4520 Oceanography: Physical: Eddies and mesoscale processes; 4594 Oceanography: Physical: Instruments and techniques

1. Introduction

[2] Current-generation orbiting altimeters such as Topex/Poseidon (T/P), ERS-1 and 2, and Jason-1, with their intrinsic global coverage, have greatly improved our understanding of ocean circulation and its role in the Earth’s climate [Fu and Cazenave, 2001]. The most prominent limitation of current radar altimeters is their inability to measure mesoscale processes. These processes, which currently dominate global climate modeling errors, require finer altimetric spatial and temporal resolutions than that offered by traditional altimeters. The possibility of using reflected GPS signals for remote sensing was proposed [Martín-Neira, 1993], and fixed-platform experiments demonstrating GPS-reflection altimetry have been performed ~20 m over the ocean [Anderson, 1996] [Martín-Neira et al., 2001], 450 m above Crater Lake [Treuhaft et al., 2001], and 10 m over a pond [Martín-Neira et al., 2002]. Global GPS altimetry would involve an orbiting receiver that obtains position and timing information from the GPS constellation as usual, but measures ocean height using the arrival time of GPS signals reflected from the surface. The advantage over mono-static radar altimeters is that the receiver could produce about ten simultaneous measurements (or ~20 when the Galileo [Galileo] system is operational), distributed over an area thousands of km across-track, and the instrument is a passive device making it relatively inexpensive. The challenge is to demonstrate that GPS-reflection measurements can be made at accuracies necessary to map mesoscale eddies.

[3] There have been limited studies of GPS-reflections from space, and only two such GPS-reflection experiments have been performed to date. The first space-based GPS reflection measurement [Lowe et al., 2002a] used SIR-C data collected on the Space Shuttle to create a preliminary link budget, and a number of Earth-grazing detections have been observed in Champ occultation data [Beyerle and Hoche, 2001] [Beyerle et al., 2002]. The experiments described here are designed to verify the physics of bistatic reflection models and develop an error budget using receivers on aircraft, where greater experimental control, larger data sets, and higher signal levels are available than will be obtainable from orbit. These data can be used to test the accuracy of our models, leading to a credible prediction of spacecraft GPS altimetry performance and the design of future orbital Instruments.

2. Experimental Setup

[4] The experimental hardware, including the GPS receivers, recorders, antennas, and in-flight data-storage devices, and the first level software processing by a software GPS receiver, developed specifically for GPS-reflection remote sensing, is described in detail for both altimetry experiments elsewhere [Lowe et al., 2002b]; only a brief summary is presented next.

[5] The first experiment, performed in Oct. 1998, was not designed for altimetry, but rather to collect GPS reflections from a wide variety of terrain types. In spite of that, that portion of the data recorded over the Pacific Ocean, off the coast of Santa Barbara, California, was used to perform an altimetric retrieval. A single-channel system recorded the combined direct and reflected GPS signals from an up-looking antenna, mounted on top of a single-engine Cessna, and from a down-looking, hand-held 12 dBi LCP helibowl antenna. A modified TurboRogue GPS receiver [Thomas, 1995] tracked the direct signal to give aircraft positioning while open-loop data samples were recorded at ~20 Msam/sec. These samples were post-processed with a software receiver to extract the direct and reflected-signal waveforms. The plane’s altitude and velocity during this experiment were ~1.5 km and ~50 m/sec.

[6] The more recent experiment, performed in Jan. 2001, recorded data over Platform Harvest off the coast of California, near Point Conception. The Harvest site was chosen because it is a T/P calibration site [Christensen et al., 1994] and high-accuracy altimetric ground truth is available. An 8-channel recording system was used to separately record the GPS L1 and L2 signals [Spilker, 1980] from both an up-looking antenna, mounted on top of a Cessna 310 twin, and a nadir-looking 3 dBi LCP patch antenna. The front-end electronics from two modified TurboRogue receivers down-converted and sampled the signals, which were recorded at ~20 Msam/sec. These data were processed with the software receiver to extract the direct and reflected-signal waveforms. Dual-frequency data from an Ashtech Z12 GPS receiver was used to kinematically estimate the aircraft position with an RMS accuracy estimated at <10 cm. The flight during this experiment consisted of 5 back-and-forth straight paths, laterally spaced about 1.2 km, where the third pass corresponded to the nominal ascending T/P flight path over Harvest. The plane’s altitude was approximately 3.0 km and its velocity relative to the ground was about 50 m/sec for the Northwest passes and 80 m/sec for the Southeast passes due to strong winds.

[7] For both experiments, the recorded samples were processed with a software receiver that detects the GPS signals, initiates delay and phase tracking loops and cross-correlates complex phase...
3. Ocean Height Determination

The $\Delta T$ measurements are obtained by tracking the peak of the direct signal with the software receiver’s delay-locked loop, and fitting the reflected signal to a model waveform. The model used to generate the reflected signal waveform is a slightly modified version of the model described by [Zavorotny and Voronovich, 2000]. The scattering cross section is modeled as a function of upwind and crosswind surface-slope variances, which are expressed as functions of a model wind vector as described in [Elfouhaily et al., 1997].

The model waveforms are computed for each 2-sec data sum and fit to the data using an amplitude parameter and a measured reception-time difference parameter, $\Delta_{\text{obs}}^t$. This fit requires special care; in attempting to measure $\Delta T$ to a small fraction of a sample, our initial fitting algorithms showed large biases depending on where the discrete samples lay relative to the signal peak. These effects have been largely eliminated using a finite impulse response (FIR) filter to effectively increase the sampling rate by a factor of 100.

The ocean height determination requires a geometric model to calculate the expected reception-time differences, $\Delta_{\text{mod}}^t$. Using satellite positions obtained from the JPL FLINN products [Jefferson et al., 1999], the receiver positions from the onboard receivers, the WGS 84 Earth model [DMA, 1984], and survey information on the antenna locations within the aircraft and the average aircraft orientation during flight, a geometric model is created to compute the model delay differences. The delay-differences, $\Delta_{\text{obs}} - \Delta_{\text{mod}}$, are fit using an ocean-height parameter relative to the WGS 84 surface and a constant clock parameter. The clock parameter primarily accounts for hardware-timing differences in the up and down-looking signal channels, but can also absorb other constant clock-like systematic errors.

Figure 2 shows the ocean height residuals for the Oct. 1998 Y-code data, color-coded by GPS satellite. Meter-level systematic errors are visible, especially as the aircraft made a slow turn in the first 5 minutes. These errors are presumably caused by modeling inadequacies because the data from different satellites appear to cluster somewhat. The RMS scatter of the 289 2-sec points is 1.95 m. The 76 2-sec points after 1900-sec, where the plane was flying relatively flat and straight, have an RMS scatter of 1.19 m, indicating an average sea-height precision of about 14 cm over 2.5 min. The retrieved ocean height was $-35.7$ m relative to the WGS 84 model, differing from a ground-truth altimetry database by $\sim 10$ cm. Although the Y code used here is classified, receivers using codeless techniques and high-SNR direct-signal observations can produce results equivalent to a Y-code receiver [Dunn and Young, 1996]. Preliminary work using the public C/A-code data [Lowe et al., 2000] gave an RMS scatter equivalent of 2.2 m for 2-sec points. The lower C/A-code precision is due to a factor of 10 lower chipping rate compared to the Y code, and perhaps due to C/A-code autocorrelation sidelobes [Lowe et al., 2002b]. Because the antenna was hand held, only meter-level receiver positions were obtained, and these data were not collected for the purposes of altimetry, no further efforts to reduce systematic errors are planned.

Figure 3 shows the 2-sec height residuals for the Jan. 2001 Y-code data, color-coded by GPS satellite. Note that modeling inaccuracies are still present as the data cluster somewhat by GPS satellite, and correlations with the back-and-forth flight path is evident. Overall the measurement is greatly improved compared to our Oct. 1998 experiment. This is due to improved receiver positioning, a more stable platform with a pilot experienced in remote sensing experiments, a fixed and surveyed antenna mount, greater signal SNR, and higher-elevation observations. We note an additional reduction in scatter, presumably due to more complete averaging of signals from numerous ocean surface facets, termed speckle here, from the larger glistening zone associated with the increased aircraft altitude.

The height residuals in Figure 3 from the highest two GPS satellites, at about 55° and 60° elevation, are shown in red and blue, respectively. For clarity, Figure 4 shows the height residuals for these two satellites. These measurements are expected to be more sensitive to ocean height and less sensitive to modeling errors.
than the lower-elevation satellite data. The average 2-sec RMS scatter for these 14 passes (7 flight passes times 2 satellites) is 56 cm. This is much greater than the white system noise errors, expected to be about 1–4 cm, and is presumably due to speckle. Also note the scatter is lower for the higher-velocity SW passes (46 cm) than the NE passes (64 cm), also consistent with better averaging of speckle. Computing the structure function of the residual’s time series indicates the scatter is consistent with a white noise process from 1 to 100-s time scales, again consistent with speckle, and does not show the correlated noise typical of tropospheric fluctuations. Given the residuals are consistent with a white-noise process and can be averaged down as \( \sqrt{n} \), the precision of all 14 passes in Figure 4 are calculated to be between 4.7 cm and 7.6 cm, with a 5.5 cm average. Each pass required 3–4.5 minutes, corresponding to about 14 km tracks along the ocean. Combining the data from both satellites demonstrates 5-cm precision with 7-km spatial resolution. Using all satellite observations in Figure 3, and accounting for the lower altimetric sensitivity from lower-elevation observations, we estimate an equivalent ~5-km spatial resolution. Before 5-cm accuracies can be obtained, a better understanding of the systematic effects seen in Figures 3 and 4 must be gained and a comparison to ground-truth measurements must be made. The RMS scatter of all 1761 points in Figure 3 is 79 cm, indicating systematic errors and actual altimetric features contribute at about the 50–70 cm level. No work on this experiment’s C/A-code data has been performed.

4. Summary and Roadmap to Achieve 5-cm GPS Altimetry Accuracy

[14] We have presented the first two GPS aircraft altimetry measurements, and have demonstrated 5-cm-precision ocean altimetry with 5-km spatial resolution, proving the feasibility of mesoscale mapping with GPS reflections at aircraft altitudes. The largest systematic errors appear to be speckle and geometric modeling deficiencies. The scattering cross-section calculation, which assumes the surface scattering is described by geometric optics and depends on upwind and crosswind surface-slope variance parameters, is a likely suspect, as is our antenna beam-pattern model. Upcoming work will focus on methods to characterize and reduce these errors. For example, we plan to perform additional experiments at higher altitudes to both reduce and better characterize speckle, and by flying a more complicated flight path we can more fully populate the geometric parameter space with observations which should reveal the cause of the systematic errors seen in Figures 3 and 4. Attempting more detailed wind-vector retrieval as a function of time or using external wind-vector measurements may improve the model. Using 6 simultaneous GPS signals, we see systematic errors not reported in other GPS scatterometry experiments using only 1 or 2 satellite signals [Komjathy et al., 2001, and references therein]. For example, we see a persistent correlation between wind speed and direction, which requires further analysis. Solving these problems will likely produce state-of-the-art scatterometric GPS wind-vector retrievals as a by-product. Work to understand the statistical properties of the scattered GPS signals, to reduce speckle, has begun [Zuffada and Zavorotny, 2001].

[15] The insight gained in developing ~5-cm altimetry at aircraft altitudes, combined with the our quantitative spacebased measurement and those expected in the near future from SAC-C and Champ, will allow us to credibly estimate the expected error budget and science return from a spaceborne GPS altimeter.

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Galileo, ESA GPS-like navigation system planned to be operational in 2008. More information can be found at http://www.esa.int/navigation/pages/indexGNS.htm.


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