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Atmospheric water vapor and geoid measurements in the open ocean with GPS

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[1] We have conducted two experiments to determine precipitable water vapor (PWV) and sea surface heights from a cruising ship in the open ocean. During the first experiment (July 7–13, 02) GPS and radiosonde PWV agreed at the 2 mm rms level. During the second experiment (Aug 23–30, 03) GPS compared at 1.5 mm rms (1.1 mm GPS high bias) with eight ship-launched radiosondes and at 2.8 mm rms (1.2 mm GPS high bias) to a ship-based water vapor radiometer (WVR). We estimate that the vertical position of the GPS antenna in the open ocean was determined to better than 10 cm rms. After correcting for ocean tides GPS estimated sea surface heights from the second cruise compared to the CARIB97 geoid at the 32 cm level in the vertical. Because space based observations of PWV over the oceans generally require cloudless conditions and are accurate to about 5–10% we conclude that ship based GPS observations can provide additional useful meteorological information. Based on the 10-cm vertical position rms and the high horizontal resolution of ship-based positions we further conclude that useful geodetic information can be obtained from high accuracy GPS observations from ships in the open oceans. **Citation:** Rocken, C., J. Johnson, T. Van Hove, and T. Iwabuchi (2005), Atmospheric water vapor and geoid measurements in the open ocean with GPS, *Geophys. Res. Lett.*, *32*, L12813, doi:10.1029/2005GL022573.

1. Introduction

[2] Numerical weather prediction (NWP) requires high quality observations of the atmospheric state. Radiosondes and meteorological satellites often do not provide sufficient accuracy and temporal/spatial resolution to capture the distribution of atmospheric water vapor. GPS observations are now used routinely to compute atmospheric column water vapor or PWV with an accuracy of ~1 mm from fixed sites on land [*Bevis et al.*, 1992; *Rocken et al.*, 1993]. While land-based GPS sites provide PWV observations for NWP the technique is not yet widely used in the oceans because of the added complication of a moving platform that must be positioned simultaneously with the tropospheric delay estimation.

[3] Satellites provide the bulk of water vapor observations over the oceans. Radiosonde data from ships or islands are very sparse and irregular. PWV data from the Special Sensor Microwave/Imager (SSM/I) have shown 4–5 mm rms agreement with radiosonde observations under cloud-free conditions [*Jackson and Stephens*, 1995]. A recent study by *Gao and Kaufman* [2003] reports errors in the 5%–10% range for PWV measurement from the Moderate resolution Imaging Spectroradiometer (MODIS) aboard the NASA Terra and Aqua satellites. MODIS observations of column water vapor depend on the reflection of solar radiation from the surface and are thus limited to cloudless daytime conditions.

[4] Precise positioning of ocean platforms with GPS was demonstrated by *Kelecy et al.* [1994] and, more recently, by *Chadwell and Bock* [2001] who also estimated PWV from an ocean buoy. This paper evaluates the quality of GPS position and PWV estimation from a cruise ship in the open ocean.

2. Experiment Description

[5] We conducted two 1-week experiments July 7–13, 2002 and August 23–30, 2003 (Figure 1). During each cruise two GPS antennas were mounted near the front mast of the 138,000-ton ship ‘‘Explorer of the Seas’’. One antenna was mounted with bore sight towards zenith, the other was tilted with a bore sight about 25 degrees above the horizon. The zenith-looking antenna (a Trimble Geodetic antenna with ground plane) was used primarily for the estimation of the ship's position and the tropospheric delay. The tilted antenna (Dorne Margolin antenna with choke rings) measured the atmospheric slant delay as GPS satellites rose and set behind the ocean horizon for the purpose of atmospheric refractivity profiling [*Lowry et al.*, 2002]. This paper only considers zenith antenna observations. During the first cruise we used two Trimble 4700 dual frequency GPS receivers. For the second cruise the tilted antenna was connected to a Trimble 4700 receiver and the zenith antenna to a Trimble 5700 receiver. GPS carrier phase and pseudorange data were sampled at 1-sec during the entire cruise.

[6] During both cruises several radiosondes were launched from the ship, and pressure, temperature, and humidity data were collected on board. During the 2003 cruise a Radiometrics™ Model 1100 water vapor radiometer was operated next to the GPS antennas.

3. Data Processing

[7] The GPS data were processed in precise point positioning (PPP) mode [*Zumberge et al.*, 1997] with the Bernese GPS software 5.0. Precise GPS orbits (at 15 minute intervals) and satellite clocks (at 30-sec intervals) were obtained from the Center for Orbit Determination Europe (CODE) at the University of Bern, Switzerland, and interpolated to our 1-sec sampling rate.

[8] Data were processed in three iterative steps. Initially we processed only pseudorange observations to get meter-

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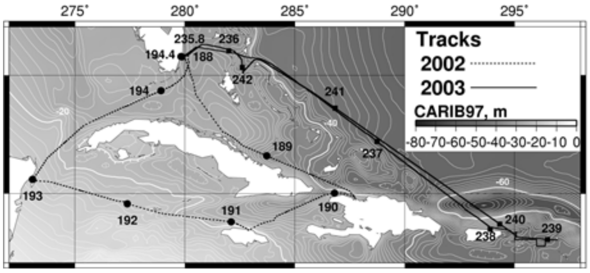

Figure 1. Ship tracks and days of the year for the 2002 (dashed) and 2003 (solid) cruises superimposed on the grey-shaded CARIB97 geoid. Dots mark departure times and ship positions at day changes. The ship's travel direction can be determined from the sequence of day numbers.

level a priori kinematic positions. Next GPS dual frequency phase and pseudorange data were processed with a 12° elevation cutoff to obtain improved kinematic positions. For this processing step we applied tropospheric delay based on default atmospheric values and did not estimate tropospheric delay in the GPS inversion. Finally, we processed the phase and pseudorange data with an elevation cut-off of 5° and simultaneous estimation of positions and tropospheric delay estimation. For this processing step we applied so-called direct mapping based on climatology [*Rocken et al.*, 2001] to map the dry zenith delay to the GPS satellite elevations and wet Niell mapping [*Niell*, 1996] to estimate the zenith tropospheric delay correction due to water vapor at 30-minute intervals. The 1-sec data were processed with a 1/cos(zenith angle) elevation dependent weighting.

4. Results

[9] Position validation in the open ocean is difficult. In order to obtain an estimate of the position quality that we should expect for the vertical component of the ship we processed data from a fixed land site in Miami FL in exactly the same way as the ship data during the week of the cruise. These results showed a 3 cm vertical bias and 8 cm rms scatter after solid Earth tides and ocean loading effects had been removed. This 8 cm vertical position rms is larger than typical geodetic vertical PPP errors of ~1 cm rms. However those cm-level errors are obtained for long 24-hour solutions where all higher frequency errors such as measurement noise and site multipath are averaged out, while we compute independent kinematic positions every second without any averaging. The 3 cm height bias is due to errors in the reference position, the PPP position, and the tidal models. Considering that multipath on the ship, with its metallic surfaces, is probably worse than at the Miami comparison site we have to expect that ship vertical positions will be somewhat worse than 8 cm. We therefore assume that the vertical positions of the GPS antenna on the ship can be determined with an rms error of approximately 10 cm.

[10] We compared the ship vertical positions to the CARIB97 geoid after removing the NAO tidal model [*Matsumoto et al.*, 2000] for the 2003 cruise (Figure 2). The CARIB97 geoid model has a resolution of $2' \times 2'$ and an rms agreement of ~62 cm compared to 32 GPS/tidal benchmarks [*Smith and Small*, 1999]. Clearly there is strong correlation between the ship's position and the geoid with a rms difference of 32 cm between the two traces. This difference is caused by a combination of several errors: (1) errors in the GPS positions (10 cm rms), errors in the geoid model (62 cm rms compared to tide gauges), and by changes in the height of the GPS antenna above the ocean surface. We could not calibrate these height changes because no measurements of the ship's draught were available. Based on information from ship engineers the ship's draught can change significantly during a cruise due to changes in the ship's weight (primarily its water tanks - the ship's draught increases by 1 cm with a 100-ton load) and speed. These height changes must be calibrated in future experiments to exploit open-ocean GPS positions for high-resolution geoid improvements and studies of ocean dynamics.

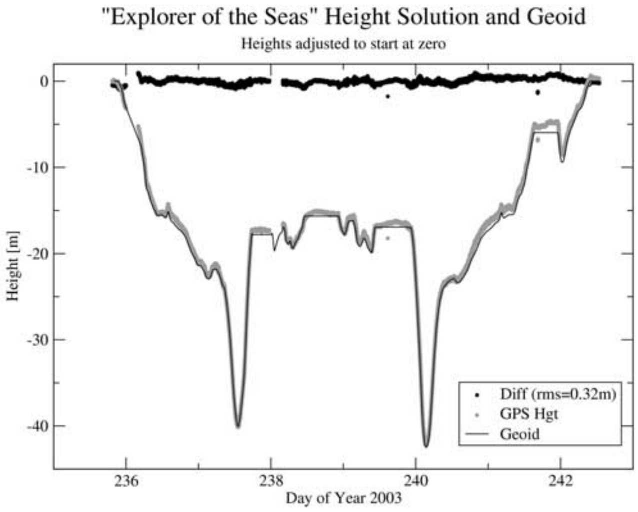

Figure 2. Height of the GPS antenna on the ship, corrected for ocean tides (grey) and the Carib97 geoid (thin black) for the second cruise. The two transections of the Puerto Rico trench are the dominant features. The rms of the difference (thick black) is 0.32 meters.

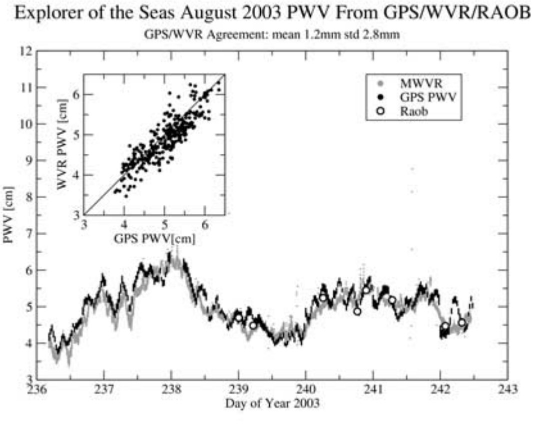

Figure 3. PWV time series from GPS (black), the WVR (grey) and the radiosonde launches (black circles) for the 1-week 2003 cruise. The inset shows a scatter plot of the GPS vs. WVR PWV. The slope of a line forced through the origin is 0.97.

[11] We compared GPS PWV to the ship-based WVR and ship-launched radiosondes. Comparisons for the 1-week 2nd cruise are shown in Figure 3. Radiosondes could not be launched during the outgoing leg of the cruise because of high winds on deck. GPS-determined PWV agrees to within 1.5 mm rms (and 1.1 mm GPS high bias) with the eight radiosondes that were released during the latter part of the cruise. Processing of the data from the first cruise (not shown) resulted in 2 mm rms agreement and 1 mm bias (GPS high) between radiosondes and GPS PWV. For WVR comparisons we excluded all observations when the liquid water exceeded 0.5 mm, because liquid water on the WVR window results in corrupted radiometer data. Comparison with the WVR shows 2.8 mm rms agreement and a bias of 1.2 mm, where GPS PWV is higher than WVR PWV. Both rms and bias are about three times larger than what is typically reported for fixed land based sites. This increase in noise is primarily due to the added error from the kinematic positioning.

5. Summary and Conclusion

[12] We have demonstrated that ship based estimation of the tropospheric delay and the column water vapor is feasible at the several mm rms level corresponding to a precision of about 5% for our sub-tropical data set. Such observations of open ocean water vapor can be useful for meteorology, climate studies and satellite calibration. Further we have shown that precise vertical GPS positioning of a ship in the open ocean can provide useful data for high resolution measurements of the sea surface for geodetic, and oceanographic studies when the height of the ship's GPS antenna above the sea surface remains calibrated.

[13] The results presented in this paper were obtained in post-processing mode. Application of ocean-based observations to weather forecasting requires near-real time processing. This can be achieved by using predicted GPS satellite orbit positions together with data from a real-time ground-based GPS receiver network to compute satellite clock corrections in real-time. The predicted orbits and computed clocks can then be used for precise point positioning and tropospheric delay estimation. While this approach is entirely feasible additional research is required to investigate the quality of near real time processing to obtain water vapor and sea-surface information from the open oceans.

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