ALTIMETRY WITH REFLECTED GPS SIGNALS: RESULTS FROM A LAKESIDE EXPERIMENT

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ABSTRACT

In the fall of 1999 an experiment was performed at Crater Lake, Oregon, to demonstrate the feasibility of surface altimetry with GPS. A GPS antenna was directed at the lake - its axis pointing slightly downward – from a steeply dropping rock. This arrangement allowed to collect both the direct GPS signal as well as that reflected off the lake surface. The relative delay between direct and reflected signals, related to the height of the receiver above the body of water and the reflection geometry, is used to infer the height of the lake surface. The site was chosen for its elevation, resulting in clear separation of direct from reflected signal waveforms. The paper discusses the experimental set-up, the data processing main steps and the findings of the investigation to determine feasibility and accuracy of this new type of altimetric measurement. Based on preliminary findings, height precision of 1 cm in 10 minutes can be inferred based on the analysis of carrier phase of 'Coarse Acquisition' (C/A) signals alone. These measurements are the first step in understanding measurements of reflections from airborne and spaceborne receivers, since they provide the means for uncovering the systematic instrumentation and processing errors, unmasked by the effects of platform motion and strong surface variation.

INTRODUCTION

The possibility of utilizing the GPS signals scattered off the ocean and sensed by an air- or space-borne receiver in a bistatic radar geometry, has been explored recently as a means of doing ocean altimetry and scatterometry (*Garrison et al.*, 1999; *Hajj et al.*, 1999). When considering the constellation of 24 GPS transmitters and one such receiver a multistatic system is obtained, capable of intercepting bounces from several areas of the ocean simultaneously. By extension of the traditional altimetry approach, the bistatic path delay can be analyzed to derive the important descriptors of the ocean surface such as height, surface wind and significant wave height.

To assess the feasibility of this new type of potentially very valuable measurement, we need to understand its accuracy as a function of both the sea state, the many relevant system's parameters and the observational geometry. To accomplish this, it is advantageous to first perform a simple experiment, limiting the complications to a minimum, where the receiver is not air-borne but rather at a fixed location over a lake. The problem is that of finding the height of the lake surface below the receiver, and its temporal variation due to the lake surface roughness. The choice of a small lake possibly reduces the surface roughness compared to the ocean, therefore providing an experimental condition as close as possible to the reflection from a plane wave from a (locally) planar interface, particularly at high incidence angles. This set up allows us to understand the basic systematic measurement errors inherent to this technique.

EXPERIMENTAL SETUP

Crater Lake (located in Oregon) is a body of water approximately round in shape, of about 10 km in diameter, surrounded by steep rocky sides, at nominal elevation of 6178'. For our experiment a large distance between the receiver and the water is desirable in order to separate the direct GPS signal from the reflected one, at least part of the time. It is noted that we are primarily interested in observing the GPS signal scattered in the forward direction, where the return is the strongest. Furthermore, it is desirable to minimize the effect of the rocky sides on the signal multipath and to prevent the collection of reflections coming from regions too close to the rock and therefore not representing solely the reflection from water.

The experimental equipment was placed on a rock, directly overhanging the water at nominal elevation of

7780'. Therefore, the rough relative height of the receiver above the water was 1602', or about 489 m. A Dorne-Margolin (chokering) RHC polarized GPS antenna was oriented with its axis almost horizontal, looking across the lake. The L1 GPS signal from this antenna, containing both the direct and reflected portions, was fed into a receiver front-end, modified to receive raw signals, and then recorded onto an AIT tape by means of a Sony SIR-1000 1-channel digital data recorder at the rate of 20.456 MHz. A second similar antenna, with its axis kept vertical, was used to track the GPS satellites and was connected to a Turbo-Rogue GPS receiver for direct positioning measurements.

REFLECTION GEOMETRY

Assuming a fixed receiver, as the GPS satellites rise and set in the sky, the points of specular reflection on the lake move along approximately straight lines at a non uniform rate, depending on the elevation angle ε. At very shallow elevation angles the Rayleigh's criterion is presumed to be satisfied and a strong coherent signal is expected. Our experimental set-up favors this situation since the direct and reflected signals would arrive almost along the main antenna axis (with maximum gain) and at very low angles the Fresnel reflection coefficients for RHC polarization ($F^{rhc}=F^{par}+F^{per}$) is maximum. The drawback however, is that the separation between the direct and reflected signal, $R_{sep}=2H\sin\varepsilon$, becomes negligible thus making the data analysis considerably more difficult.

At high elevation angles the scattering is expected to become more diffusive, decrease in strength and change in polarization. The additional penalty of a reduced antenna gain at high elevation angles will make the received signal even weaker. Furthermore, as the scattering becomes diffuse the footprint of the collection area on the lake will increase from the Fresnel ellipse (order 10 m) to the iso-range ellipse (order 1 km) with the possibility of signal contamination from surfaces other than the lake. From examination of the USGS map of the lake, we inferred that the slope of the rocky side was approximately 45° with respect to the horizontal direction, at the chosen location. Clearly, as the elevation angle approaches this value and the surface is rough, the possibility of the rock affecting the received signal increases. In fact, contamination from rock is expected to arise even before onset of diffuse scattering due to multipath propagation. The above considerations guided us in establishing priorities for data analysis; specifically, we selected reflection tracks as close as possible to the antenna pointing axis and time intervals corresponding to elevation angles between about 5° and 25°.

DATA ANALYSIS PROCEDURES AND RESULTS

A description of the GPS raw data processing steps is outlined in (*Lowe et a*l., 2000); here we report a brief summary of the major points. The first processing step consists of performing cross-correlations between the data and a model (replica) of the expected GPS signal, parameterized in delay and Doppler, over an integration time of 20 msec. During this time a search is performed over a range of possible values and is complete when the output of the cross-correlation is maximized. The search simulates the operations of a GPS receiver, specifically the phase-locked loop which determines first the value of delay, and then of Doppler, necessary to lock onto the peak of the direct signal and keep its phase at 0°. Hence, amplitude and phase of a time series (one data point every $(20.456\ \text{MHz})^{-1}$ sec), encompassing both direct and reflected signal are available every 20 msec.

RECOVERING HEIGHT FROM PHASE DATA

From the complex time series one can locate the maximum of the reflected signal by observing the occurrence of the strongest change of real and imaginary parts as a function of time, i.e. at each 20 msec intervals. By contrast, the direct signal presents the weakest variation at the peak. In fact the phase-locked loop maintains the imaginary part of the peak at zero. An example phase data stream is illustrated in Fig.1, compared with a model of the same phase, for reflection geometries with elevation angle of ~ 7°.

The phase is very well behaved over long time periods, and this provides the strongest evidence that we observed coherent reflection. To understand the phase behavior we constructed a model, based on the assumption that the reflected signal is simply a 'copy' of the direct one, delayed, reduced in amplitude and shifted, such that

$$\mathrm{Re}\,c = A_d e^{i\omega t_d}\Lambda(t-t_d) + A_r e^{i\omega t_r}\Lambda(t-t_r)$$

where the complex received signal Rec is composed of the direct signal, indicated by the suffix d, and the lake reflected signal, indicated by the suffix r. The symbol Λ represents the GPS correlation function which peaks at $t=t_d$ for the direct signal. By referencing the phase to the direct signal, we can write the phase as

$$\Phi = ATAN\left(\frac{\dfrac{A_r\Lambda(t_{r'}-t_r)}{A_d\Lambda(t_{r'}-t_d)}\sin\{\omega(t_{r'}-t_d)\}}{1+\dfrac{A_r\Lambda(t_{r'}-t_r)}{A_d\Lambda(t_{r'}-t_d)}\cos\{\omega(t_{r'}-t_d)\}}\right)$$

were we allow the phase to be evaluated at the time $t_{r'}$, to account for an error in the determination of t_r, i.e. the true peak of the reflected signal. The ratio of amplitudes multiplying the sin and cos terms is time dependent and will decrease with increasing separation between peaks. Such ratio is not known a priori, and the precise value of this parameter is obtained in the solution process.

The phase model is constructed by converting the modeled range difference to phase by multiplication with $2\pi/\lambda$, where λ is the wavelength of the L1 GPS signal. This forms the model for the argument in the sin and cos terms. In this process a reference time is selected for the phase model, resulting in a phase offset with the data; the value of this offset becomes a parameter to be determined in the solution process. By taking the Fourier transform of the phase we obtain a spectrum of Doppler frequencies, whose peak locations depend on the reflection geometry and can be used as a detector of the surface height.

The first basic issue in this analysis is the determination of the sensitivity of the measurement to height variation. This implies determining the thermal noise present on the data and mapping it to the uncertainty in the Doppler and eventually into a vector of uncertainty in the location of the specular reflection point. To this end we have analyzed the behavior of the Doppler variation versus height from our model. Typical values of σ_ϕ of 0.1 rad were obtained per 20 msec intervals, resulting in $\sigma_\Delta = 0.796$ Hz. To improve on the accuracy a number of measurements, N, must be processed; the corresponding improvement on σ_Δ scales like $N^{-3/2}$. In our case the indetermination is reduced to 10 cm in ~ 8 sec and to 1 cm in ~ 37 sec.

To corroborate the statement, an estimation of the increased accuracy was obtained by simulating the measurement covariance based on the phase model of Eq. 2, with phase parameters obtained by examination of 6 minutes of data. Based on the noise present on the data, the predicted results are illustrated in Figure 10.

By denoting with N the number of independent phase measurements, note that the accuracy improves with $\sim N^{-5/2}$ and $\sim N^{-3/2}$, respectively, with and without estimating the total zenith tropospheric delay.

With the assumed 0.1-radian data noise on the phase, the surface height can be determined to 10 cm with a data span of 200 sec if the tropospheric delay is perfectly removed. On the other hand, if the delay is simultaneously estimated with the same data set, it would take longer than 1000 sec to get the surface height to better than 10 cm.