

# High-Resolution Ocean Topography from GPS Reflections

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This note is based on the presentation on March 28, 2001 at the High-resolution Ocean Topography (HOT) Science Working Group (SWG) meeting. In this note we describe the salient features of the GPS reflection technique and discuss the altimetry application. Next, we summarize the history of GPS reflection development at JPL and the preliminary findings. We then illustrate what is required in terms of a GPS-reflections receiving system to make these measurements in a realistic space scenario. Last, we outline another application of the technique for coastal monitoring using fixed GPS receivers.

## 1. Motivation and Scientific Potential

The Global Positioning System (GPS), which was first conceived and built for the purpose of navigation, has been utilized in the last decade to study the Earth's interior, surface and environment in ways that far exceed anyone's original imagination. Scientific applications of the GPS include measuring seismic tectonic motions, Earth orientation and polar motion, gravimetry, neutral atmospheric temperature and water vapor profiling, and ionospheric electron density profiling and global monitoring. All of these applications have been well proven and provide new ways to enhance our knowledge about the Earth and its environment. The advantage of GPS is twofold: the transmitted signal is global and is there at all times and in all weather conditions and the receiver technology is rather inexpensive, compared to alternative remote sensing systems. More recent and less developed applications explore the possibility to utilize the GPS signals scattered off the ocean and sensed by an air- or spaceborne receiver in a bistatic radar geometry, as a means of doing altimetry and scatterometry (Garrison et al., 1998; Lin et al., 1999; Lowe et al., 2000; Zuffada and Elfouhaily, 2000; Zuffada et al., 2000; Treuhaft et al., 2001).

Currently, the constellation of 24 GPS transmitters broadcasts at two frequencies in the L-band (~ 1.2 and 1.5 GHz). Both carriers are modulated by one or two pseudo-random noise codes, which result in periodic sequences of positive and negative pulses, each unique to a given transmitter. The codes are referred to as Coarse Acquisition (C/A) and Precision (P). Upon impinging on the ocean surface, the signal is reflected (actually scattered off) primarily in the specular (forward) direction, in an amount dependent on surface roughness and angle of incidence. An airborne (or spaceborne) receiver, connected to a down-looking GPS antenna whose axis is ideally located in the specular direction, could collect such scattered signal. When considering the 24 transmitters and one such receiver a multistatic radar system is obtained, in principle capable of intercepting bounces from several areas of the ocean simultaneously, as illustrated in Fig.1. By analogy to traditional altimetry, the bistatic GPS reflected signal can be analyzed to derive the important descriptors of the ocean surface; i.e. ocean height and surface wind vector.

Traditional altimetry, such as on Topex/Poseidon, is limited to looking in the (nominal) nadir direction and obtaining one height observation at a time below the altimeter, following very nearly repeatable tracks passing over the same point every ten days. The track separation varies, being largest at the equator where it is about 300 km. By contrast, a GPS receiver in low-Earth orbit (LEO) with an antenna pointed toward the Earth's surface can, in principle, track about 10 GPS reflections simultaneously, therefore providing a coverage that is an order of magnitude denser than nadir-viewing altimeters. As seen in Fig. 2, the reflection ground tracks of a satellite at the altitude of 400 km would cover the Earth nearly uniformly in just 1 day, with across track separation at most about 75 km. Based on the GPS orbit repeatability, in any given cell of the Earth's surface of size 50 km<sup>2</sup>, there would be about 12 reflection measurements in 10 days, randomly occurring within the cell. The average of such measurements could produce the reading for the given cell size in the 10 days period. Such dense coverage can be translated into a higher temporal and spatial resolution than TOPEX/Poseidon, therefore

possibly indicating the ability to recover certain ocean topography features or processes that are precluded with traditional altimeters.

It is anticipated that the GPS altimetry will improve our current capability in two important ways:

- **High-resolution Ocean Topography**

These include the measurements of mesoscale eddies which play an important role in the transport of momentum, heat, salt, nutrients, and other chemical properties of the ocean. Mesoscale eddies are ocean features analogous to atmospheric storms, which result in sea-height changes above the mean (peaks and valleys) of about 10 cm on spatial scales between ~10-100 km with temporal evolution of ~ 1 week to 1 month.

- **Improved Temporal Resolution Through Rapid Coverage**

Another possible application of very rapid coverage of the ocean is the monitoring of fast moving barotropic waves that propagate across ocean basins too quickly to be seen by the TOPEX/Poseidon 10-day repeat cycle.

## **2. Direct and Reflected GPS Signals**

The process of acquiring the received signal consists of performing a cross-correlation between the incoming sequence and a replica of the transmitted signal, shifted in time and frequency to account for the proper propagation delay and Doppler. The output of the correlator is maximized in time when the incoming sequence and the appropriate replica are perfectly aligned. Additionally, for a direct signal the correlator is non zero when the alignment is within +/- 1 code chip away from perfect and has a symmetric shape around the maximum. (The chip is the rate of probable occurrence of code transition, and is 1.023 MHz and 10.23 MHz, for C/A and P codes, respectively. Hence, the chip duration over which the correlator output is non zero is the reciprocal of this rate.) By contrast the correlator output for the reflected signal is non zero over a period of several code chips and is not symmetric about its maximum. Therefore the reflected signal can be distinguished from the direct one based on its shape, as evidenced in Fig. 3; furthermore we will describe how the shape is affected by the state of the ocean surface in a manner that allows us to extract the ocean properties from it.

The areas of the ocean surface contributing to the reflected signal vary as a function of time according to the advancement of the wave front. For the sake of illustration let's define the plane of incidence as that containing transmitter, receiver and specular reflection point (chosen as the origin), i.e. the plane of Fig. 4. This plane is perpendicular to the mean ocean plane and is a plane of symmetry for the reflection. The shortest reflection path connects transmitter and receiver via the specular reflection point and hence its contribution is received at the earliest times. The contributions from the surrounding area in the ocean are received later on. Specifically, the points on the ocean plane contained in an elliptical annulus of progressively increasing axes (major axis in the plane of incidence) and center (also in the plane of incidence) moving towards the transmitter give rise to scattered fields which are received at the same time. The size of the annuli and their ellipticity is determined by the receiver altitude and reflection geometry; the higher the elevation angle, the more circular the annuli become. In general it can be observed that the ocean surface is sampled along preferential directions, according to the reflection geometry. Hence, the received signal senses different areas on the ocean as time goes by, thus affecting the resolution (see Zuffada and Elfouhaily, 2000).

## **3. Altimetry Measurement**

Assuming that a receiver is connected to both an upward looking and a down looking antenna, it will be able to acquire a direct signal followed in time by a reflected one (see Fig. 3). The delay between

the arrival of the peak of the direct signal and the contribution from the specular reflection point on the leading edge of the reflected waveform (usually not corresponding to the peak) is the quantity of interest for altimetry measurements. Such delay can be converted into path difference (reflected minus direct) by multiplication with the speed of light. From precise knowledge of the positions of transmitter and receiver and with an *a priori* estimate of the sea surface topography such path difference can be expressed in terms of the surface altitude below the receiver and the elevation angle. A retrieval scheme can be set up to solve for these parameters, accounting for various sources of error such as transmitter and receiver clocks, the ionosphere and the neutral atmosphere.

#### 4. Resolution

The cross correlation is equivalent to an integration over a time consistent with the coherence of the phenomena being observed. This in turn depends on the size of the target contributing to the scattering, i.e. the larger the area the shorter the coherence time. Since the GPS reflection measurement samples progressively increasing areas over the ocean, one must establish what area is sufficient to acquire the needed signal. For altimetry measurements it is important to collect the contribution from the point of specular reflection, which occurs one code chip following onset of non zero correlator output. This corresponds to an area over the ocean referred to as the first iso-range ellipse (see Fig. 4), implying that all the points contribute to the received signal with relative delay of no more than one code chip away from the minimum value. The size of this footprint depends on the receiver altitude (airborne or spaceborne) and on the reflection geometry ranging from a few square km to tens of square km.

The coherence time for the ocean at L-band ranges from a fraction of 1 msec to 10 msec, thus implying that one received waveform is generated at the corresponding rate. Because the signal level is very weak, many responses need to be combined to boost the signal and reduce the variance, thereby improving accuracy. To determine the measurement resolution one must examine the footprint behavior in the amount of time over which an incoherent average is performed. Such time is of order 1 to 10 seconds, depending on roughness conditions and needed accuracy. During this time the footprint will have moved by an amount determined by the receiver velocity along track, typically of order 1 to 10 km (see Zuffada et al., 2000).

#### 5. Accuracy

The altimetry measurement accuracy depends on how precisely the peak of the direct signal and the contribution from the specular reflection point on the reflected signal can be located in time. In essence, the limiting factors are the transmitted power levels, the scattering cross section coefficients at L-band, the receiver integration time, the receiving antenna gain and the number of incoherently averaged samples. The first four parameters contribute to the accuracy of the single sample waveform, while the fifth compensates for the sample-to-sample variability. The integration done in the receiver is equivalent to performing a spatial filtering with selectivity chosen by the designer, normally to be maximum at the specular reflection point, and tapering off away from it past the area of the first iso-range. The antenna gain can be chosen so that an additional spatial filtering is performed. These features also allow for a reduction of the effective footprint.

Once the average signal to noise ratio (snr) has been achieved through incoherent averaging, a prediction of the accuracy formal error can be obtained by performing a covariance analysis where the problem parameter is the relative delay error and the operator is the bistatic radar - forward scattering integral representing the cross correlation output. Hence, the initial choice of antenna gain will impact the final accuracy through the incoherent averaging process. The higher the gain the higher the snr at the expense of increased complexity and size and reduced beamwidth.

Based on the available GPS transmitted power and typical values of coherent integration times, we can determine the antenna gain necessary to achieve a desired target snr per single measurement. This target value is chosen so that we optimize the antenna requirements in terms of size/costs and we project

an accuracy sufficient for eddy resolution in 10 days with a given constellation of receivers. Naturally, to obtain the same height accuracy, one can increase the single measurement snr and decrease either the time or the number of satellites in the constellation. At the altitude of 400 km we found the target gain to be 30 dB, corresponding to an accuracy of 10 cm/4 sec of the averaged altimetry measurement. To increase the accuracy over this value many measurements need to be combined to define one average altimetry measurement in a given ocean cell size. A possible scenario is illustrated in the last section leading to resulting constellation sizes required for eddy resolution (see Zuffada et al., 2000).

## **6. Roadmap to GPS Altimetry**

### *6.1. Fixed Location GPS Receiver for Coastal Monitoring*

One of the severe limitations for the conventional radar altimetry is that it loses lock when approaching the coastline, thus leaving an area of 2~3 footprints (about 20 km) without reliable measurements. The GPS signal could be exploited for this application by installing fixed receivers along the coast at some altitude (for example 200 m) and spaced by about 20 km. This could be a simple experimental set-up: the receiver is not moving, the signal level is always adequate and the local coverage would be very dense over the period of time of a day or so. With this geometry the low elevation reflections over the ocean would be tracked. Because the ocean appears smoother at low elevations, it is likely that the reflections would have a coherent component, absent in the more general case instead, practically achieving the condition of reflection from a perfectly conducting plane, where coherent reflection rather than scattering is expected. In this case one can track the phase of the GPS signal, thus increasing the accuracy dramatically. This concept has been tested in an experiment at Crater Lake, which yielded very accurate height determination with rms errors of 2 cm in 1 sec (see Treuhaft et al., 2001), as illustrated in Fig. 5. This is very encouraging. A further demonstration of such a fixed location GPS receiver at the Harvest platform is undergoing.

### *6.2. Moving GPS Receivers for Ocean Altimetry*

In the last few years the Jet Propulsion Laboratory has been active in the development of the GPS-altimetry measurement technology within the funded GOALS Instrument Incubator Task. Initial development of data processing algorithm for ocean science applications has been funded through the NASA Research and Analysis program. Within the currently funded projects, JPL is pursuing investigations to (a) understand the impact of the fundamental ocean processes on the measured GPS-reflected waveform, (b) assess the measurement accuracy for general experimental conditions and system parameters and (c) feed this knowledge into the design of the next generation of JPL GPS receivers to process reflections.

At the beginning of this effort JPL obtained the first GPS reflected signal from space, by examining a calibration signal collected by the SIR-C flying on the Space Shuttle, whose antenna happens to have the right bandwidth for capturing the GPS L2 signal. Additional data was collected from a CESSNA airplane flying over the ocean west of Santa Barbara, CA in the first altimetry experiment carrying instrumentation to acquire and record raw GPS signals. The data was processed and a preliminary height accuracy of 9 cm in 5 minutes was demonstrated.

The work on GPS reflection technology development at JPL is founded on the considerable heritage of advanced GPS receivers developed at JPL. These began with the Rogue and TurboRogue geodetic ground receivers in the 1980s, and were followed by the TurboRogue Space Receiver (TRSR), which is now flying on GPS/MET as well as (in somewhat upgraded form) on the Danish Ørsted and South African Sunsat missions. The BlackJack represents a major redesign of the TurboRogue carried out over the past four years, intended primarily for flight applications. The first BlackJack recently flew on the space shuttle as part of the Shuttle Radar Topographic Mapper (SRTM), and several versions have been delivered for flight on a diversity of upcoming NASA and international missions. These include

Jason-1, ICESat, the Vegetation Canopy Lidar (VCL), the German CHAMP, the Argentine SAC-C, and the Australian FEDSAT missions.

## 7. Roadmap to an Eddy-Resolving Mapping Capability

The global coverage of the GPS signal makes it particularly appealing for possible sampling of mesoscale eddies, whose spatial features smaller than 50 km and temporal variability of the order of several days make them elusive to the currently existing altimetry systems. We have already pointed out that one single receiver at 400 Km altitude connected to a suitable receiving antenna system, would result in reflection ground tracks covering the Earth nearly uniformly in just one day, with across track separation at most about 75 km (see Fig. 2). Based on the GPS orbit repeatability, in any given cell of the Earth's surface of size 50 km<sup>2</sup>, there would be about 1.12 4-sec reflection measurements in one day, or 12 in 10 days, randomly occurring within the cell, thus reducing the effective cross track separation progressively as the cell is being populated. Due to the randomness of the errors and the independent measurements, an improvement in the accuracy according to the square root of the number of measurements is obtained. Based on this it is shown that already a constellation of two receiving satellites would achieve a height accuracy of 6 cm in 10 days in a 50 km<sup>2</sup> cell, while a constellation of eight satellites would accomplish the same thing in a 25 km<sup>2</sup> cell instead, showing the system scalability (see Zuffada et al., 2000). It is noted that another way of improving the accuracy consists of increasing the number of available reflections by increasing the number of transmitters. This is of practical interest since a European GPS constellation is planned to be deployed in the near future. The frequencies of operation and signal characteristics will be very similar to the existing US constellation so that the same acquisition and processing algorithms and hardware will be useful to process the wealth of available reflections.

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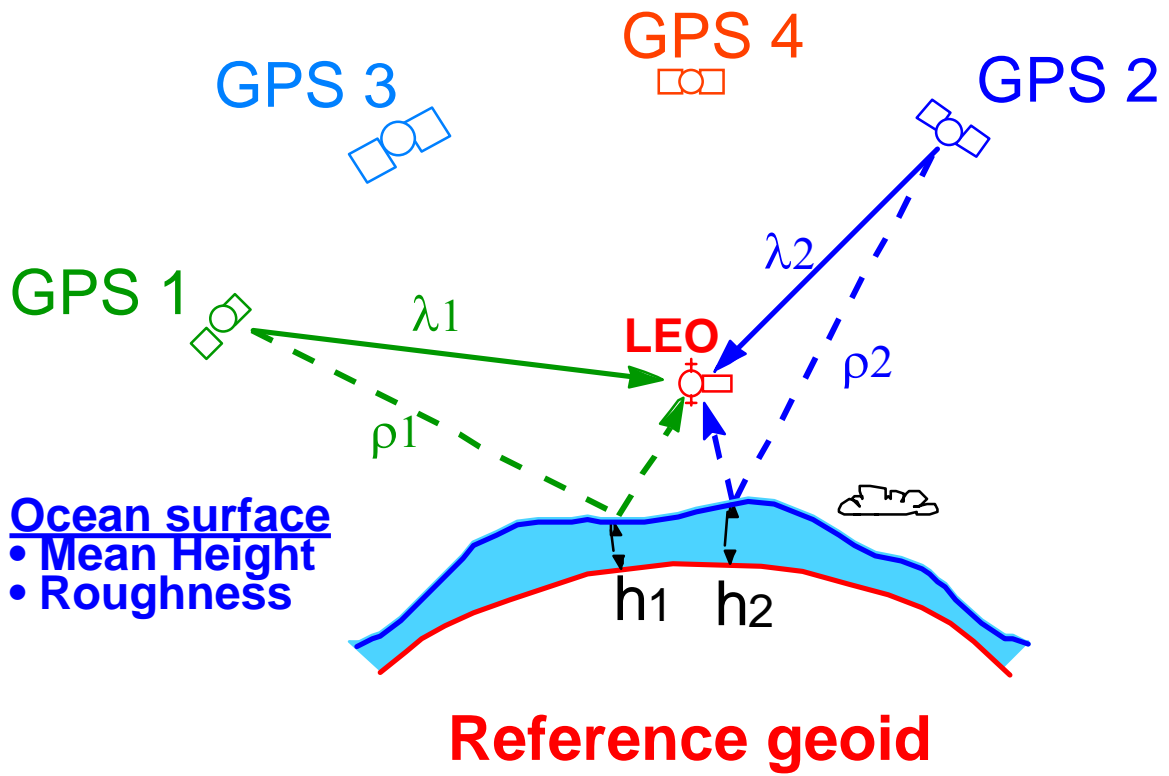
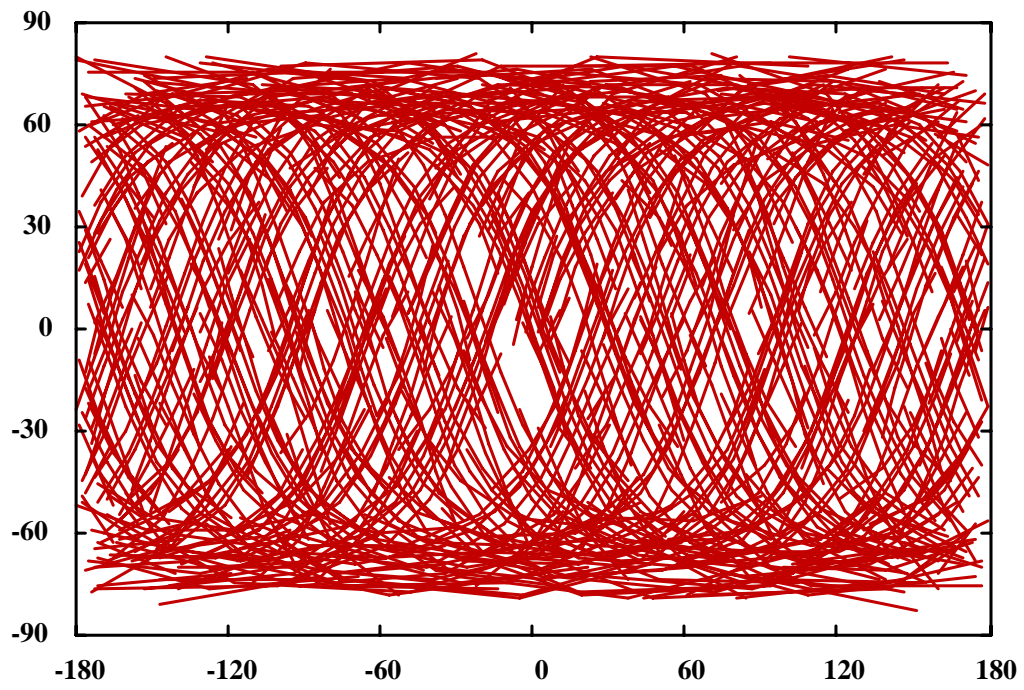
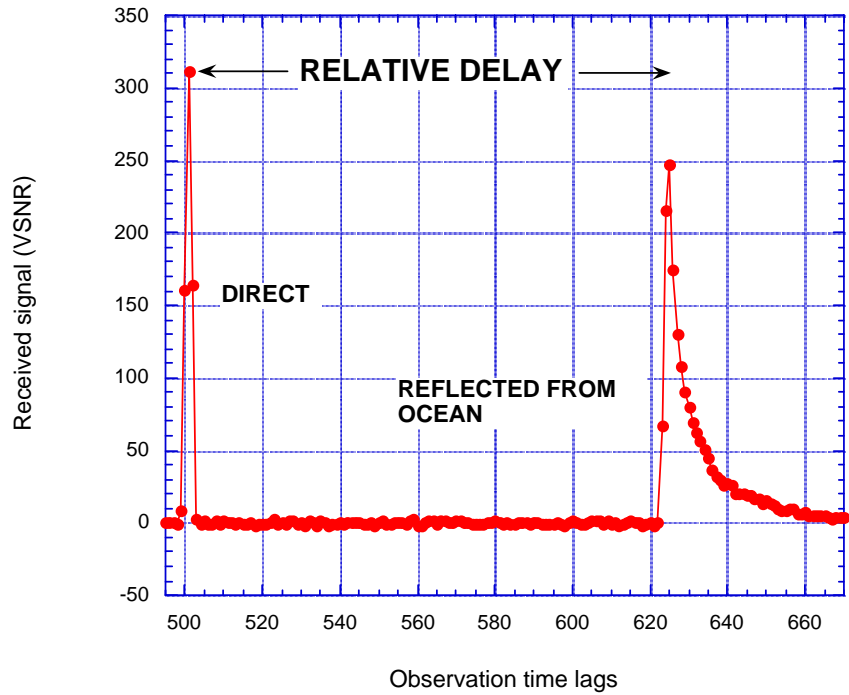


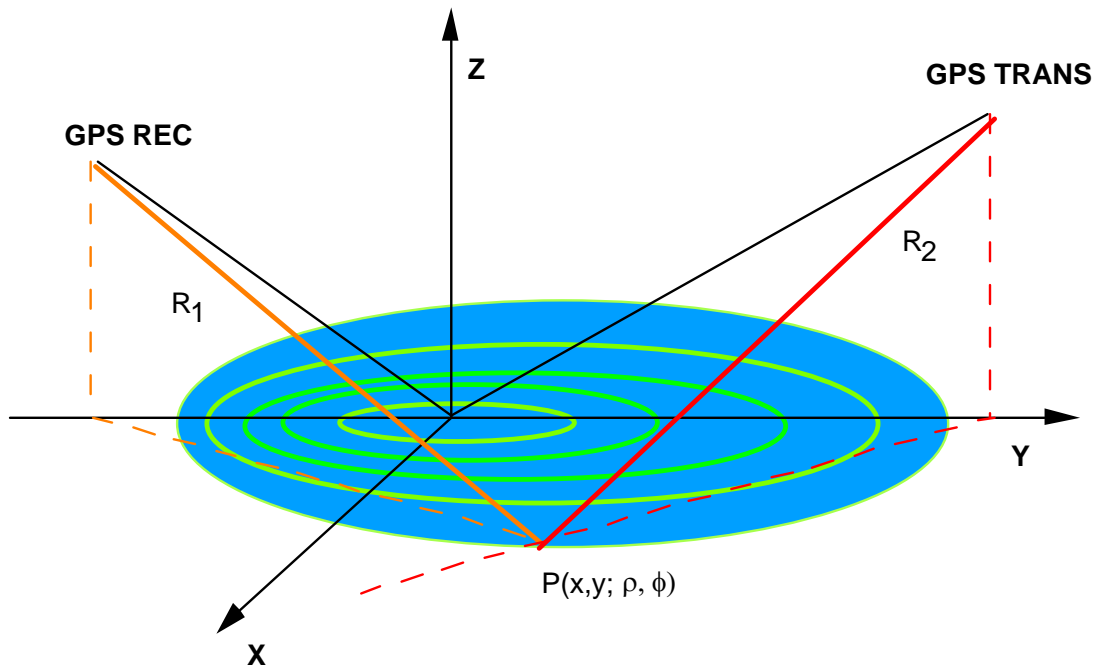
Figure 1. Bistatic GPS measurement concept.



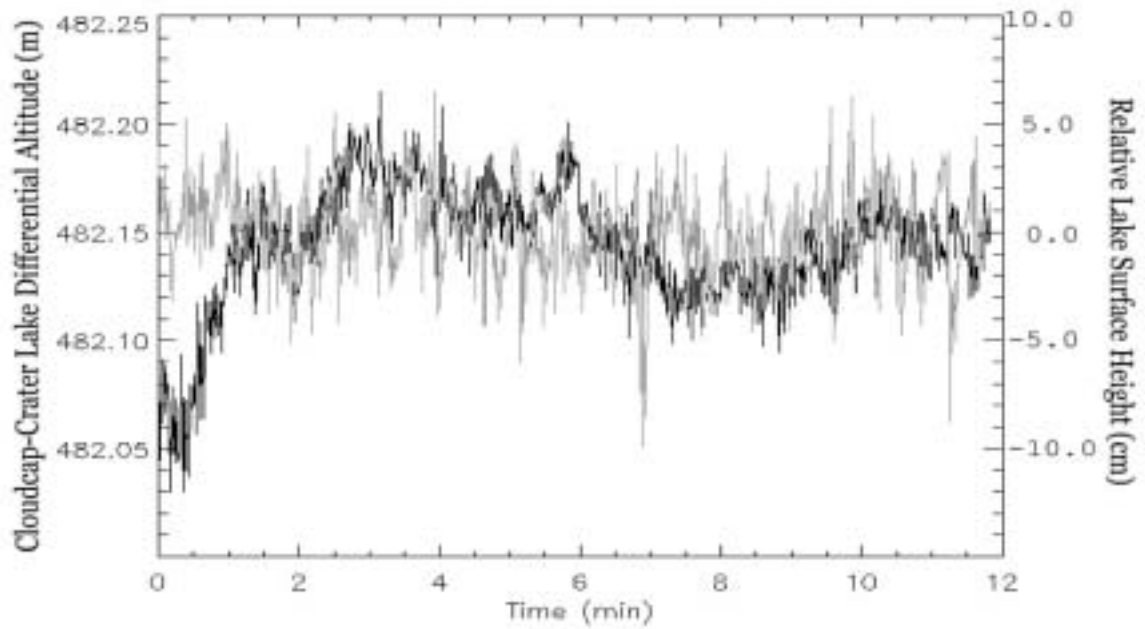
**Figure 2.** Reflection ground tracks corresponding to one day coverage from all transmitters and one single receiver at 400 km.



**Figure 3.** Direct and reflected GPS signal collected from receiver on board airplane.



**Figure 4.** Plane of incidence (YZ), iso-range ellipses and general scattering point.



**Figure 5.** Height of lake surface determined as height of GPS receiver at fixed site above body of water.