Oceanography with GPS

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Abstract. This paper discusses a new technique for ocean remote sensing based on detecting GNSS signals, i.e. those transmitted from the Global Positioning System (GPS) or GALILEO (in the future), after they are reflected off the ocean surface, to measure sea surface topography and roughness (from which wind speeds are retrieved) at high spatial resolution and rapid temporal coverage. The topography measurement is suitable for the global monitoring of ocean eddies, which is currently precluded by the existing altimeters, due to their track separation and repeat cycle. The basic description of the technique is provided and the connection between the engineering measurement and the ocean descriptors (altimetry and winds) is outlined. A discussion of measurement accuracy and resolution is provided, and the concept of combining many independent measurements to provide an "average" over a given cell size and time interval, as opposed to repeat measurements, is outlined. To address the issue of systems needs for global coverage, an estimate of the scaling of accuracy with the number of available receivers of a hypothetical remote sensing system is given, showing that a constellation of 6 receivers with reflection antenna gain of 30 dB would be adequate for eddy resolution and monitoring. Furthermore, the latest experimental results demonstrating a measurement precision of 5 cm in a few minutes from airplane flying over rough ocean and 2 cm/sec from fixed-site over a lake are summarized, together with the basic features of a data acquisition/processing system developed for investigating the measurement phenomenology. Lastly, the requirements on the GPS receiver technology necessary to track and process reflections on board, and those of the antenna system necessary to capture all available reflections, are discussed.

Keywords. High-resolution sea surface topography, eddy monitoring, GPS-based altimetry and scatterometry, bistatic scattering from rough surfaces.

1 Introduction

The Oceans, and their interactions with the atmosphere and the lithosphere, play a significant role in Earth's climate. Understanding climate variability is very important to insure the well being of our planet; this implies quantifying all the significant processes that contribute to climate and its changes. One such process, mesoscale ocean eddies, analogous to atmospheric storms, is thought to play a very significant role which is presently difficult to quantify. In fact, eddies play an important role in the transport of momentum, heat, salt, nutrients, and other chemical properties of the ocean. Ocean eddies have a typical spatial scale on the order of 10 to 100 km and a temporal scale from days to weeks. The sea level signal associated with mesoscale eddies is usually 10 cm or more.

At present, quantifying the role of mesoscale eddies in the ocean circulation and therefore climate variability cannot be done simply because their spatio-temporal structures are not resolved by the conventional remote-sensing techniques. Observations of sea surface temperature, (e.g., those from Advanced Very High Resolution Radiometers) are frequently contaminated by clouds in the atmosphere. The conventional satellite radar altimeter measures the sea surface height at high spatial resolutions along its ground track (e.g., 7-km for TOPEX/Jason). However, the cross-track distance is usually quite large. For a 10-day repeat orbit with TOPEX/Jason, the cross-track distance is more than 300-km at the equator, which is too coarse to resolve the evolution of ocean eddies.

Another limiting factor is the long repeat cycle of a given satellite, e.g., 10 days for TOPEX/Jason, 17 days for the Geosat-Follow-On (GFO), and 35 days for ERS. Because of the long repeat cycle, some fast propagating ocean waves cannot be properly resolved by satellite altimetric observations. Additionally, some barotropic (i.e., vertically uniform) waves with a periodicity of 20 days or less can be aliased into the 10-day sea level map produced by the TOPEX/Jason data. Hence, there is a need for high spatial and temporal resolution altimetry.

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High-resolution ocean altimetric measurements will allow oceanographers to compute high-order quantities like vorticity and eddy fluxes, which will be used to study the interactions between the eddy fields and the time-mean flow. Several important science questions can be addressed by such a high-resolution data. For example, what is the role of mesoscale (ocean) eddies in the large-scale ocean circulation and climate variability? What is the impact of mesoscale eddies on the biological production and therefore the global carbon cycle? If mesoscale eddies are important in modulating the large-scale ocean circulation and climate, there is a need to resolve (or parameterize) ocean eddies in the Earth System Model (coupled atmosphere-ocean-land) for climate prediction purposes.

2 Novel Technique: Altimetry and Wind Measurement with GPS

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 expectation. 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 (see for example, *Beutler et al., eds*., 1996). 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 always globally present and the receiver technology is inexpensive, compared to alternative remote sensing systems.

Recent research efforts have begun using GPS signals scattered off the ocean and sensed by an air- or space-borne receiver in a bistatic radar geometry, as a means of doing altimetry and scatterometry. A concept for GPS-based altimetry was first proposed by *Martin-Neira*, (1993) and contains a high-level overall system description. Since then, several additional theoretical work modeling the expected signal waveform and accuracy have appeared (*Picardi et al*., 1998; *Zavorotny and Voronovich*, 2000; *Fung et al*., 2001). An air-borne delay-mapping GPS receiver was developed (*Garrison and Katzberg*, 1998; *Garrison and Katzberg*, 2000) and used in several experiments that demonstrated the capability of retrieving wind speed (*Komjathy et al*., 2000; *Garrison et al.,* 2002). Further experimental campaigns to characterize GPS altimetry from a fixed location over a lake (*Treuhaft et al*., 2001) and an airplane (*Lowe et al*., 2002a) have recently been conducted. The first GPS reflection from space was detected fortuitously from analyzing the data collected from SIR-C on board the space shuttle (*Lowe et al*., 2002b). More evidence of GPS reflections were also found in the CHAMP occultation data (*Beyerle and Hocke*, 2001).

Upon impinging on the ocean surface, the GPS signal is reflected primarily in the specular (forward) direction, in an amount dependent on surface roughness and angle of incidence. An airborne or space-borne receiver, connected to a down-looking antenna, could collect such scattered signals. One such receiver, and the 24 transmitters, form a multistatic radar system, capable of intercepting reflections from several areas of the ocean simultaneously (see 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. Because of the multi-static nature of the GPS observations, they will improve our current capability of global sea surface measurements in two important ways: improved spatio - temporal resolution and coverage.

Traditional altimetry 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. The concept of wide-swath ocean altimetry improves the coverage and spatial resolution of traditional altimetry by filling the gaps between satellite tracks. However, the wide-swath ocean altimetry uses the same ground tracks of TOPEX/Jason repeating every 10 days. 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. For example, the reflection ground tracks of one single satellite at the altitude of400 km would cover the Earth nearly uniformly in just 1 day, with at most about 75 km across-track separation, as shown in Fig. 2. Such dense coverage can be translated into a higher temporal and spatial resolution than that of TOPEX/Jason or the proposed wide swath coverage, thereby providing the ability to recover certain ocean topography features or processes that are precluded with traditional altimeters. A feasibility study (*Zuffada et al.*, 2000) shows that already a single GPS receiver in LEO can achieve 8 cm ocean altimetry measurements in 10 days, with 50 km^2 spatial resolution. Because this system primarily consists of a GPS receiver and an antenna, a system of several satellites could be deployed within reasonable cost constraints. With many receivers, and the availability of the European GPS system (GALILEO) in the near future, the measurement density could improve by an additional order-of-magnitude.

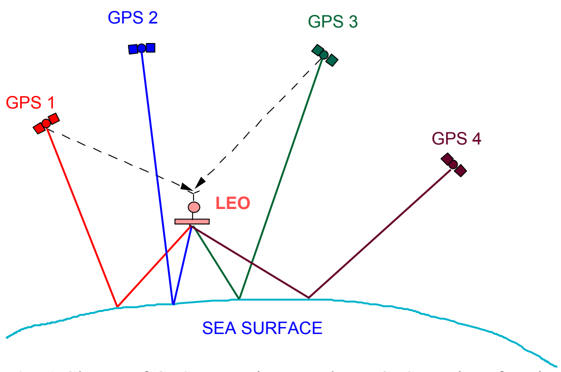


Fig. 1 Cluster of GPS transmitters and one GPS receiver forming a multistatic radar, collecting reflections off the ocean surface. The basic measurement is the difference between the time of arrival of the direct signal (direct path is shown in black) and that of the reflected signal.

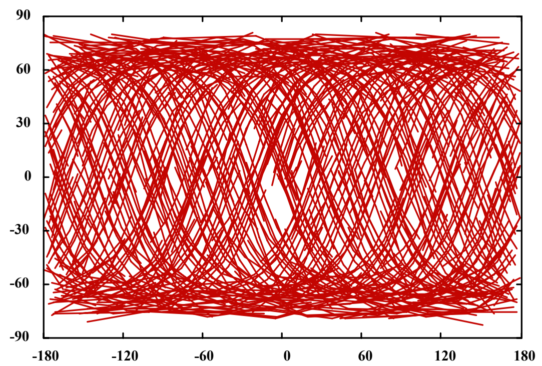


Fig. 2 Reflection point loci for one receiver at 400 km altitude, assuming its antenna beam can capture all available reflections, per day. Horizontal axis is longitude, vertical axis is latitude.

These preliminary conclusions need further corroboration, obtained with data sampled at different altitudes, angles, and sea state conditions. Even if the GPS altimetry measurement accuracy proves to be lower than that of TOPEX/Jason along track, the promise of higher spatial and temporal resolution can still be achieved. The availability of such a wealth of measurements will provide a powerful augmentation to the traditional remote sensing instruments for oceanography, by 'filling the gaps' between existing tracks with rapid turnaround time. Oceanographers will be able to combine this dense data type with the more accurate sparse TOPEX/Jason data to infer higher resolution ocean topography features.

Analysis of the GPS reflection waveform also provides an estimate of the wind speed and direction. While scatterometers such as QuikScat or SeaWinds provide near global coverage in one day, the observations are not necessarily collocated in time and space with the GPS altimetry observations. Instead, GPS reflections provide a unique set of collocated sea surface height and wind observations with near-global daily coverage and with resolution suitable for studying mesoscale features. Accurate sea surface height retrieval requires simultaneous measurements of ocean vector winds. The accuracy of GPS wind measurements is about 2 m/sec for wind speeds ranging from 3 to 15 m/sec (*Komjathy et al.,* 2002), comparable to the traditional radar scatterometer. Thus, the GPS-measured ocean winds will complement the existing radar scatterometer wind observations and, in the context of sea surface height measurement, will provide the needed data set to retrieve the sea surface height with high accuracy.

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

- High-spatial-resolution ocean topography.
- 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.

3 Direct and Reflected GPS Signals

The present constellation of 24 GPS transmitters broadcasts at two L-band frequencies, termed L1 and L2, at 1227.6 and 1575.42 MHz, respectively. Both carriers are modulated by one or two pseudo-random noise codes, referred to as Coarse Acquisition (C/A) and Precision (P), unique to a given transmitter. 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.

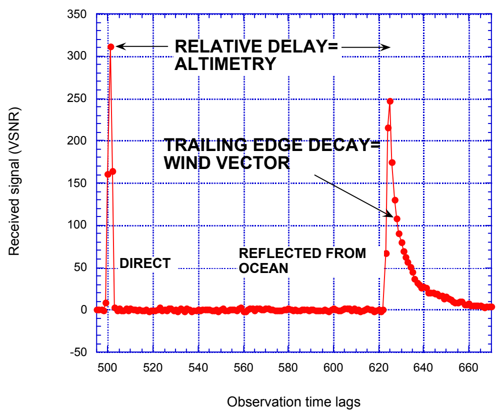


Fig. 3 Time sequence of the correlator output (Volts) showing the reception of a direct GPS signal followed by a signal reflected off the ocean surface. The horizontal scale is in lag, i.e. half of a code chip, the natural time separation used in GPS receivers. 1 chip = 1/1.023 sec for C/A code.

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 we 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 propagation path connects transmitter and receiver via the specular reflection point and hence its contribution is received at the earliest time. The contributions from the surrounding area in the ocean are received later.

Within each area the generic scattering point is shown, to illustrate that while initially the scattering is mainly specular, as time progresses scattering from many directions make up each contribution. 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 defining the resolution (*Zuffada* et al., 2003).

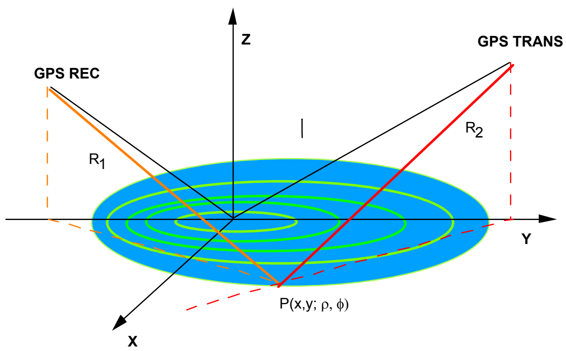


Fig. 4 Reflection geometry showing the areas on the ocean (elliptical annuli) whose contribution to the measurement is received at the same time.

4 Altimetry Measurement

Assuming that a receiver is connected to both an upward looking and a down looking antenna, the cross correlation will output a direct signal followed in time by a reflected one (see Fig. 3). The general expression of the received reflected power waveform is

$$P(\tau) = A \int \{ \frac{\Lambda_m^2 (\tau - (R_1(\xi) + R_2(\xi))/c)}{R_1^2(\xi) R_2^2(\xi)} \sigma_0(U_{10}, \xi)$$

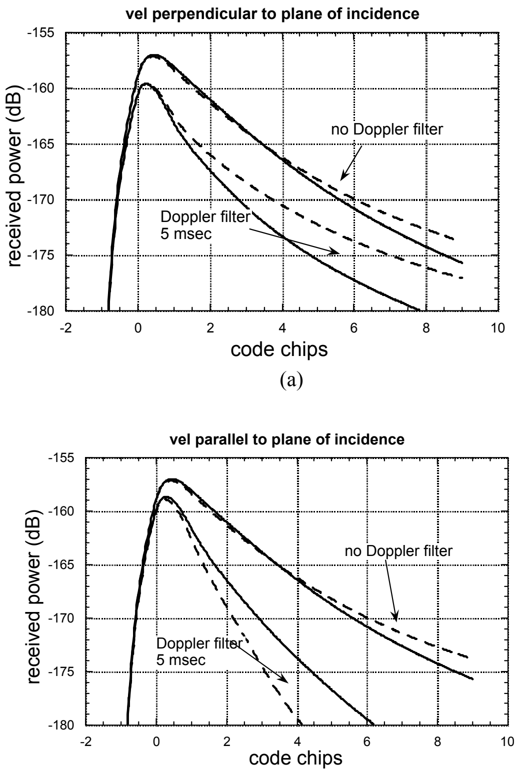
$$F(\Delta f(\xi)) \quad G(\xi) \} d^2 \xi \qquad (1)$$

where τ is the observation time, Λ_m is the modified correlator function accounting for the statistical distribution of heights (*Zuffada* et al., 1999; *Hajj and Zuffada*, 2002), $R_1(R_2)$ is the distance between transmitter (receiver), and the correlator is maximum at a time representing the light travel of the contribution from the specular reflection point on the ocean. Furthermore, is the scattering cross section coefficient and depends on the probability density of surface slopes (and hence wind speed at a height of 10 m, U_{10}) in a manner described in (*Zavorotny* et al., 2000), $F(\ f)=[\sin(2\ \ fT_i)/(2\ \ fT_i)]^2$ is the spatial filtering function associated with the receiver integration time (the reciprocal of the bandwidth, f), G is the receiving antenna gain and the integral is performed over the ocean surface, whose generic point is represented by the vector with origin at the specular reflection point. The constant *A* is a scaling factor that represents the incident GPS power. It has already been pointed out that the area contributing to the power received at a given time is a thin elliptical annulus, moving outwardly as time increases. 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 (= 0, usually not corresponding to the peak) is the quantity of interest for altimetry measurements, and can be converted into path difference (reflected minus direct) by multiplication with the speed of light. From the knowledge of the system parameters of Eq. 1, and an estimate of the roughness, models are generated for use in a fitting process. From precise knowledge of the positions of transmitter and receiver and with an *apriori* estimate of the sea surface topography, a 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 two parameters, accounting for various sources of error such as transmitter and receiver clocks, and the extra delay introduced by the ionosphere and the neutral atmosphere (*Lowe* et al, 2002a).

5 Wind Measurement

The peak value and the behavior of the trailing edge of the reflection waveform contain information about the wind speed, or more appropriately sea roughness, as represented by the scattering cross section coefficient in Eq. 1, illustrated in Fig. 5 for a typical case.

Specifically, the dependence is through in Eq. 1. In the geometric optics limit of the Kirchhoff' approximation, this depends on the probability density of surface slopes (*Zavorotny and Voronovich*, 2000), in the form of the mean square slope (*mss*) of the rough surface in the along-wind and across-wind directions. This descriptor is a measure of roughness. For a wind driven ocean, roughness is described by a spectrum of elevations, dependent on wind speed U_{10}, so that one can connect the *mss* to wind speed. In principle, given *mss* one can retrieve wind speed, and this has been used in wind retrieval algorithms. For the relationship between *mss* and U_{10}, see *Elfouhaily et al.,* 1997.



(b)

Fig. 5 Predicted waveforms (received power in dB) versus C/A chips with coherent integration time 5 msec, airplane altitude of 10 km, satellite at 45° elevation and wind speed 8 m/sec. Continuous line indicate wind along the ellipses minor axis, broken lines indicate wind along the ellipses major axis. (a): airplane velocity perpendicular to plane of incidence. (b): airplane velocity parallel to plane of incidence

It is noted that the sensitivity to wind direction is exhibited by the separation of the trailing edge of waveforms corresponding to the same wind modulus, i.e. the width of the waveform can be made to correspond to a specific wind direction. The peak increases with the decrease of wind speed, a situation analogous to the traditional altimetry waveform. Solving for wind requires data from a variety of satellites at different elevation as well as a multitude of azimuths, to sample the waveforms widths and peaks necessary to constrain the retrieval scheme to obtain a unique solution. More details can be found in (*Zavorotny* et al., 2000; *Garrison* et al., 2002; *Zuffada* et at., 2003).

The considerations presented in this section are applicable at airplane altitudes, because the characteristics of the waveforms are due to the relative size of the isorange annuli in combination with the distribution of the scattered field as a function of local scattering geometry. This geometry is highly dependent on the location of the receiving platform. Additionally, while at airplane locations the antenna pattern is broad and G in Eq. 1 can be taken to be constant, in space the need to use high gain antennas, and hence narrow beam widths, results in waveforms whose trailing edge behavior is dictated predominantly by the antenna pattern. Additionally, the Doppler filtering effect f also contributes to further drop in the trailing edge, independent of wind speed. In space the main detector of wind speed is the peak amplitude of the waveform, as illustrated in Fig. 6, for the case of the L-band antenna on board the Space Shuttle carrying the SIR-C experiment. The relevance of this experiment to demonstration of GPS altimetry will be summarized later in this paper.

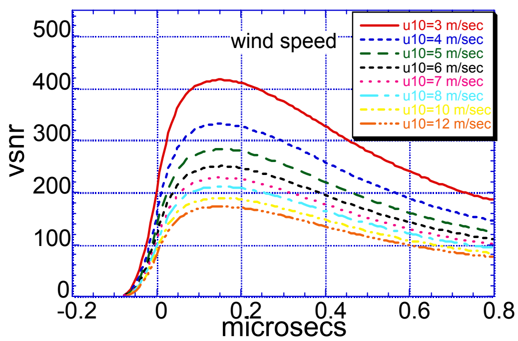


Fig. 6 Models of early part of reflection waveform for receiver altitude of 207 km, satellite at 30° elevation and antenna gain of 35 dB, as in SIR-C. The velocity of the Shuttle is perpendicular to the plane of incidence

It is noted that the resolution decreases rapidly with wind speed increase, raising concerns about the feasibility of this measurement at high altitude, since it might be difficult to calibrate the GPS transmitter to this high accuracy. Additionally, the wind direction detection remains elusive, since it is related to being able to sample the areas where the scattered fields are decreasing most rapidly. From space this area is not sampled because it is outside the antenna footprint.

6 Resolution

The received power of Eq. 1 is the result of an integration over a time chosen to be 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 that 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.

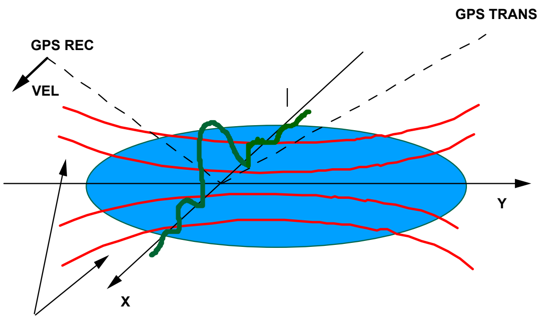
The coherence time for the ocean at L-band ranges from a fraction of 1 msec to 10 msec (*Elfouhaily* et al, 2002; *Zuffada* et al, 2003), and each received waveform is generated with an integration time consistent with the coherence time. Because the signal level is very weak and speckle is a significant source of variation, 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 50 km (see *Lowe* et al, 2002, (a)).

The receiver integration is performed over a range of values for the delay and the Doppler to maximize the output. At the end, a time series, analogous to the waveforms presented in Fig. 3, is produced corresponding to the optimal value of Doppler and delay. The Doppler value is sometimes referred to as the receiver compensation Doppler. Since the Doppler of the points on the ocean varies (iso-Doppler lines are hyperbolae), the compensation process will match the value very well at some points, namely along the correct iso-Doppler, and less well away from them, resulting in a reduction in the available signal to noise ratio.

Fixing the integration time T is equivalent to setting a bandwidth in the receiver, meaning that oscillations (Doppler shifts) higher than the threshold set by the reciprocal of the integration time, are not resolved. This is equivalent to a spatial filter, which limits the extent of the footprint in preferential directions, according to the platform motion. An example of this effect is presented in Fig. 7, where the shape of the Doppler filter is outlined. For further considerations see, for example, (*Elfouhaily* et al, 2002; *Zuffada* et al, 2003).

7 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 (roughness), the receiver integration time, the receiving antenna gain and the number of incoherently averaged samples.



ISODOPPLER CURVES

Fig. 7 Iso-Doppler curves and filter function associated with the receiver integration, for the case of a platform moving perpendicularly to the plane of incidence. The contributions from different points on the ocean are weighted according to the curve in green, thus creating a strip along the ellipse's major axis corresponding to the highest contribution. For platform moving parallel to the plane of incidence, the strip lies along the minor axis.

The first four parameters contribute to the accuracy of the single sample waveform, while the fifth compensates for the sample-to-sample variability. The antenna gain can be chosen so that an additional spatial filtering is performed, determined by the beamwidth. This feature also allows for a reduction of the effective footprint. Here we describe the steps involved in estimating the measurement accuracy, and point out the assumptions made to arrive at our estimates. From Eq. 1, the power signal to noise ratio (PSNR) for one coherently integrated sample is given by

$$P_{SNR} = \langle A \rangle / \langle N \rangle = P / kTB \qquad (2)$$

where P is the left hand side of Eq. 1, k is Boltzman's constant, T is the system's noise temperature and B is the receiver bandwidth, and we have introduced explicitly two random processes, the signal and the noise, whose mean are represented by <A> and <N>, respectively. The incoherent average over n_A samples for the signal and n_N samples for the noise yields a voltage SNR (*Zavorotny,* personal communication, 2000)

$$VSNR = \sqrt{\frac{\pi}{4-\pi}} \frac{\sqrt{\langle A \rangle + \langle N \rangle} - \sqrt{\langle N \rangle}}{\sqrt{\langle A \rangle / n_a + \langle N \rangle / n_n}} \qquad (3)$$

From this a basic estimate of the altimetry accuracy, by analogy with the estimate used for a direct GPS signal, is obtained

$$\sigma_h \propto 0.1 \frac{\Lambda_{chip}}{VSNR} \qquad (4)$$

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. Also, fewer samples are needed for incoherent averaging and hence the resolution is higher.

Based on the available GPS transmitted power (-157 dBm) and typical values of coherent integration times (a few msec) and roughness, 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 obtain 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 27 cm/4 sec of each averaged altimetry measurement, from Eq. 4. To increase the accuracy over this value many independent measurements need to be combined to define one average altimetry measurement in a given ocean cell size. For such orbit, there are 1.2 measurements per day for any given cell of size 50 km by 50 km. Simple averaging, assuming random error, will increase the accuracy to 18 cm/4sec in 2 days or 8 cm/4sec in 10 days, as summarized below.

Note that these measurements do not repeat at the same points but are distributed at random within a cell, so the measurement accuracy must be intended as pertaining to a cell centroid. If one considers two receivers instead, the accuracy for 2 days is 13 cm/4sec and for 10 days it is 6 cm/4sec. If one considers eight receivers, the same accuracy as above can be obtained in an area one quarter of the size, and so on. 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 for deployment 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.

Table 1. Accuracy versus number of receiving satellites and averaging time, showing that a constellation of 8 satellites would be adequate for an eddy resolving mission.

	1 SAT		2 SAT		8 SAT	
CELL KM	2 day/10 day cm		2 day/10 day cm		2 day/10 day cm	
50 x 50	18	8	13	6	-	-
25 x 25	-	-	-	-	13	6

The orbits of the LEO satellites are assumed errorless; however, orbit errors will affect the products from bistatic altimetry, particularly at the centimeter level of accuracy. Precise orbit determination error is discussed e.g. in Wagner and Klokocnik, 2003.

8 Validating GPS Altimetry: Results from Experiments

In the last few years the Jet Propulsion Laboratory has been active in the development of the GPS-altimetry measurement technology. The specific objectives are 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 (c) feed this knowledge into the design of the next generation of JPL GPS receivers to process reflections and (d) identify key system components and make design recommendations on an end-to-end space-based system capable of acquiring and processing reflections to deliver data useful to the science community.

To collect reflections an experimental hardware system was developed for wide-band recording (20 MHz) of bit sequences representing direct and reflected signals. To extract the waveforms, and have maximum flexibility on data manipulation, a software receiver system with a 50 nsec time resolution, unlimited number of delay points, and up to 8 kHz output bandwidth was developed; this can coherently integrate by any multiple of 125 sec for maximum data processing flexibility. This system serves the purpose of a new receiver technology simulator, to provide feedback on receiver design for ocean reflection processing. The software can perform the internal cross-correlations with different frequency offsets, mapping the reflected signal's Doppler contributions to produce Doppler maps (*Lowe et al*., 2002c).

The first GPS reflected signal from space was detected fortuitously, by examining a calibration signal collected by the SIR-C flying on the Space Shuttle in 1994, which happens to have the right bandwidth for capturing the GPS L2 signal and a high gain antenna (*Lowe et al*., 2002, (b)). It is illustrated in Figure 8, together with a model of the measurement, based on the knowledge of the measurement geometry, the antenna radiation pattern and adjusting the unknown parameters of transmitted and scattered power to obtain a peak value match.

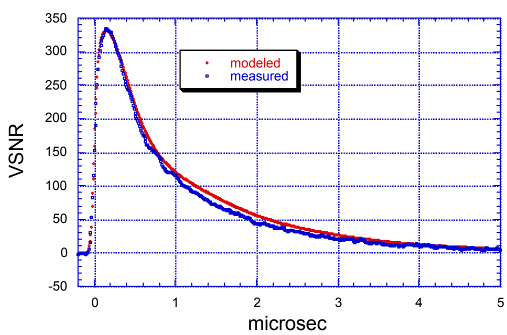


Fig. 8 Measured GPS reflection Voltage Signal to Noise Ratio (VSNR) averaged over 4 seconds. Some possible reasons for the discrepancy between measurement and calculations are (a) incomplete knowledge of the antenna pattern and (b) insufficient accuracy of the scattering model.

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. From experimental efforts over the past few years, a precision of 5 cm in a few minutes has been demonstrated to date (*Lowe* et al., 2002a), and is illustrated in Figure 9.

Additionally, an experiment was conducted at Crater Lake, OR, using a fixed observing system looking into the lake at grazing angles. In this case one can track the phase of the GPS signal, thus increasing the accuracy substantially. This experiment yielded a lake surface height determination with rms precision error of 2 cm in 1 sec (see *Treuhaft* et al., 2001), as illustrated in Figure 10.

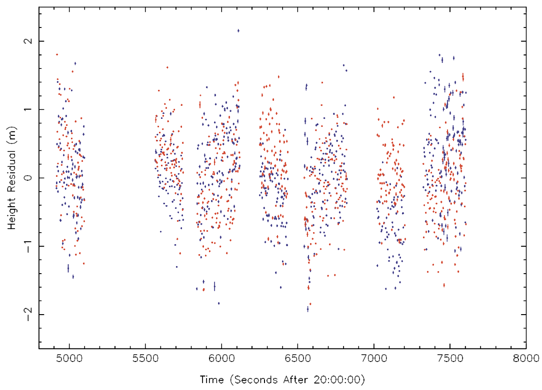


Fig. 9 Dots are RMS of sea surface heights determined with two GPS satellites, identified by colors, whose reflections were detected by an acquisition system in a CESSNA flight over the Pacific off the coast of Santa Barbara, CA. Each point is the results of incoherent summations over 1 sec. At the times corresponding to no data the aircraft was changing course.

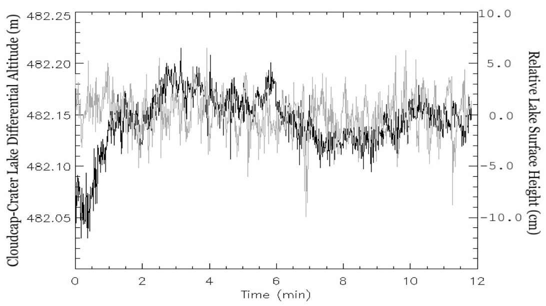


Fig. 10 RMS height of Cloucap Lookout Point, Crater Lake National Park, OR, recovered from GPS low elevation reflections from two satellites, showing measurement combined precision of 2 cm in 1 sec, obtained from reflected phase estimation.

The results from this experiment are very encouraging because they demonstrate that an altimetry measurement can be made at low elevation geometry. Currently we are analyzing data from a similar experiment over the ocean to investigate whether this technique is still applicable when the roughness is much greater than over a small lake. If this proves to be the case, this approach can be used for monitoring of coastal oceans from fixed sites elevated above sea level, such as towers or natural coastal features.

9 Next Steps

In order to deploy a space-based system for high resolution sea-surface topography using GPS reflections, two key technology components must be developed and integrated. Specifically, (a) a receiver capable of tracking and processing many simultaneous reflections and generating on board correlation products and (b) a receiving antenna system with ample field of view and high gain, necessary to capture the multiple reflection points moving over the ocean.

The antenna requirements can be met by a steerable multi-beam system, with a large enough aperture (about 2 m^2) to achieve gain of 30 dB or about. Existing switched-beam or phase-array technology could be suitable for this application, although their cost is high.

The work on GPS reflection technology development is founded on the considerable heritage of advanced GPS receivers developed at JPL. Blackjack is NASA's high-precision science GPS flight receiver that has successfully flown on 6 satellites in low-Earth orbit, and 11 more receivers have been either delivered and awaiting launch or committed for delivery.

Currently the BlackJack does not have reflection processing capabilities to track and process reflections on board. Aided open-loop acquisition software for SAC-C and CHAMP BlackJack receivers has been developed experimentally. However, much work remains to be done to implement multi lag synchronization in order to output reflection waveforms possibly spanning 30-50 lags. Additionally, JPL has demonstrated the possibility of steering GPS antenna beams by means of the phase shifters in a GPS receiver, leading to an alternative approach at designing a phased-array. The approach uses nominal models for reflection, direct signal for clock error correction and outputs correlation products at high rate. Because of the low cost of GPS receiver phase shifters, this strategy might prove to be more cost effective than existing alternatives. The next steps involve the development of a highly parallel multi front-end GPS receiver, capable of on-board processing of reflections, and of steering a multi-beam high gain array for acquisition and processing of simultaneous reflections. Then we need to integrate the receiver, with a high gain antenna array, and fly it on airplanes at a variety of altitudes to collect abundant measurements, and thus establish the intrinsic GPS-reflections measurement accuracy for a spaced-based deployment.

New data acquisition and analysis approaches will lead to a more thorough understanding and reduction of altimetric error from airborne and coastal-based platforms. The roles of speckle and the tropospheric delay will be investigated at the cm level.

10 Conclusions

The paper illustrates a new technique for ocean remote sensing based on using the signal transmitted GPS and reflected off the ocean surface, to measure sea surface topography and roughness at high spatial resolution and rapid temporal coverage. The importance of this measurement for the global monitoring of ocean eddies, which is currently precluded by the existing altimeters, is discussed The basic description of the technique is provided, summarizing the basic theoretical approach based on the physical processes taking place on the ocean. The key issues relevant to the measurement accuracy and resolution are outlined, and the concept of combining many independent measurements to provide an "average" over a given cell size and time interval, as opposed to repeat measurements, is introduced. An estimate of the scaling of accuracy with the number of available receivers of a hypothetical space-based remote sensing system is given, showing that a constellation of 6 receivers with reflection antenna gain of 30 dB would be adequate for eddy resolution and monitoring, provided the antenna field of view were large enough to capture all available reflections. To validate the GPS altimetry measurement, the latest experimental results demonstrating a measurement precision of 5 cm in a few minutes from airplane flying over rough ocean and 2 cm in 1 sec from fixed-site over a lake are summarized, showing that such measurement is feasible. The basic features of the flexible experimental data acquisition/processing system developed for investigating the measurement phenomenology, are described. To actually fly a GPS remote sensing mission, a highly parallel multi front-end GPS receiver, capable of on-board processing of reflections, and of steering a multi-beam high gain array for acquisition and processing of simultaneous reflections must be developed.

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