The Potential Use of GPS Signals as Ocean Altimetry Observable

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BIOGRAPHIES

Sien-Chong Wu is currently a Technical Group Leader in the Tracking Systems and Applications Section at JPL. He has been involved with the development of various tracking systems for deep-space as well as near-Earth space vehicles, and their applications to precision geodesy. His current interest is in the area of real-time wide-area differential GPS and special applications of GPS technologies. Sien received his Ph.D. degree from the University of Waterloo, Ontario, Canada.

Thomas Meehan is currently the task manager for NASA's GPS-on-a-Chip hardware development. This project will produce a credit-card sized, science quality GPS instrument for future NASA missions. He is a co-developer of the TurboRogue GPS instrument for both ground and space applications and continues as a co-investigator for the GPS/MET occultation receiver. He has helped to develop many of the advanced tracking techniques demonstrated on GPS/MET as well as those proposed for future space-basal GPS instrumentation. Tom received his BSEE from California Polytechnic State University at San Luis Obispo.

Larry Young supervises the GPS Systems Group at JPL. This group has developed the TurboRogue GPS receiver for NASA's scientific applications, and has adapted it for use on satellites. The group is currently developing a GPS receiver specifically for satellite applications, and is investigating novel applications for a highly capable flight receiver. Larry received his Ph.D. degree from SUNY, Stony brook.

ABSTRACT

This paper investigates a potential application of GPS signals for ocean altimetry. The altimetry information is derived from dual-frequency GPS signals reflected from the ocean surface and received at a low-altitude satellite. Such altimetry would be superior to conventional radar altimetry in three respects: (1) Thanks to the global GPS constellation, sea surface heights at up to 12 points can be determined instead of a single nadir point at any one time; (2) The user satellite only need be equipped with a GPS receiver which also serves as the receiver acquiring direct GPS signals for orbit determination; and (3) The delay spread of the reflected signal is a function of the sea-surface roughness, so that this technique may allow scatterometry-like measurements of surface weather conditions.

The paper addresses several criteria for the GPS altimetry to be viable. These include the signal strength, delay characteristics and polarization of the reflected GPS signals, the receiver capability of discriminating and tracking these signals from the direct signats, the determination of the reflection points on the sea surface, and the information content of these signals.

INTRODUCTION

Satellite onboard radar altimeter has been used exclusively for precise measurement of ocean surface height in modem years [1–3]. The radar signal is transmitted vertically downward by the satellite, usually at low altitudes. The signal, upon reflection back from the ocean surface, is received by the same satellite. The ocean surface height can then be derived from the radar signal delay and the precise height of the independently determined satellite orbit. Since only a single shot of measurement directly below the satellite is made at any one time, the satellite orbit has to be properly designed and measurements over a prolonged period of time are required for a global coverage of the ocean.

GPS measurements have demonstrated to be capable of precise positioning of users on earth as well as on low altitude satellites. Positioning to cm-level accuracy has been reported [4-6]. Can a highly-modified GPS receiver be used to derive ocean topography by tracking the GPS signals as they reflect from the ocean surface, leading to low-cost altimetry missions?

During a July 1991 JPL measurement tracking a setting GPS satellite from the top of the Mauna Kea volcano, a beat frequency was noticed in the measured phase and "amplitude which was consistent with a signal reflected from the ocean, about 3 to 13 dB down in amplitude, adding to the direct signal. The investigators noticed that the height of the receiver above the ocean could be crudely determined as a function of the beat frequency between the direct signal and the one reflected from the ocean surface.

Glazman [7,8] has demonstrated a form of bistatic radar to measure sea height using a tower-mounted transmitter and receiver. He used the amplitude modulation caused by the addition of direct and reflected signals, as a function of transmit frequency, to deduce the sea height. His work demonstrated a technique for the separation of sea height from surface roughness, leading to sea-height accuracy of about 3 cm.

A group of investigators at NASA Langley and at the University of Colorado is investigating the use of reflected GPS signals for ionospheric calibration of a single-frequency altimeter. They have successfully tracked the reflected GPS signals from an air-borne platform[†].

NASA's Office of the Mission to Planet Earth has funded an investigation at the JPL that will plan how GPS Altimetry could be used to supplement more traditional ocean altimetry missions.

ADVANTAGES

GPS altimetry would be superior than conventional, vertical only, radar altimetry in three respects: (1) Sea surface heights at up to 12 points can be determined instead of a single nadir point at any one time; (2) The user satellite only need be equipped with a GPS receiver which can also serve as the receiver acquiring direct GPS signals for orbit determination; and (3) The delay spread of the reflected signal is a function of the sea-surface roughness, so that this technique may allow scatterometry-like measurements of surface weather conditions.

To provide a feel of the potential geographic coverage of the altimetry measurements, Fig. 1 shows the geographic coverage of the reflection points where sea surface height is to be determined. Here, a 24-satellite GPS constellation is assumed; Topex satellite (1,336-km altitude) is used as the user satellite. Altimetry measurements are made for all GPS ' satellites above Topex's local horizon (-22° elevation at the reflection point on sea surface) over 1 day at 2-minute intervals. For comparison, Fig. 2 shows the Topex ground track which represents the geographic

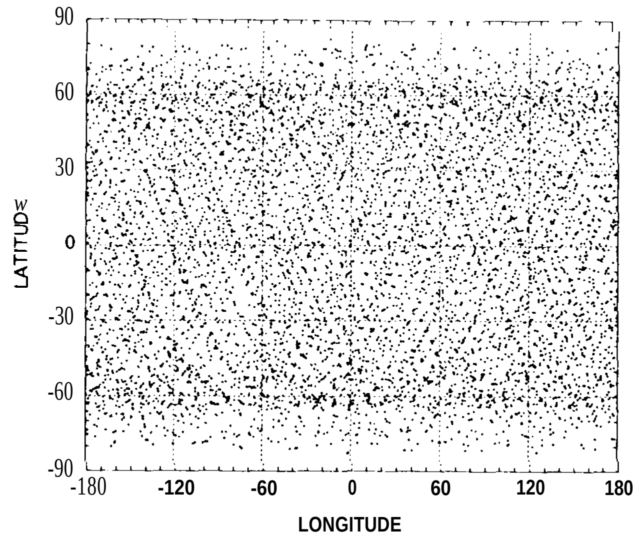

Fig. 1. Geographic coverage of GPS- Topex altimetry measurements over 1 day at 2-minute intervals

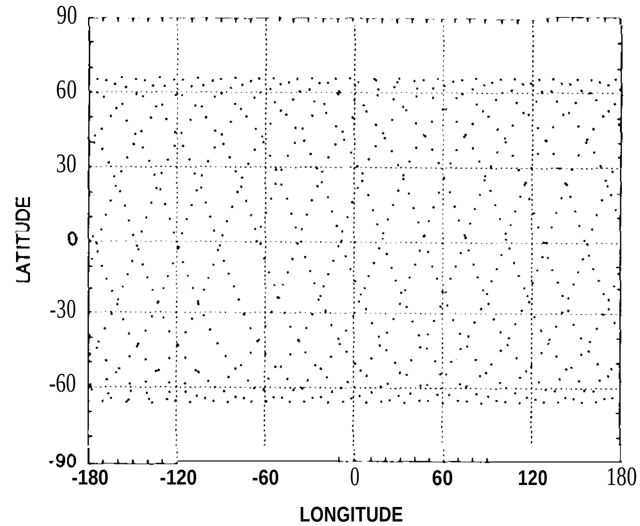

Fig. 2. Geographic coverage of conventional Topex altimetry measurements over 1 day at 2-minute intervals

coverage of ***conventional*** altimetry. The coverage in Fig. 1 is better by a factor of 8.5, which will be even greater if a lower elevation cutoff is used.

CHARACTERISTICS OF REFLECTED GPS SIGNALS

The viability of GPS altimetry depends on the amplitude and coherence of the reflected signals. One demonstration of the strength of the GPS signal reflected from the ocean was described by Jean-Claude Auber *et al.* [9]. Their intent was to investigate the likelihood of ocean multipath interfering with GPS navigation of aircraft. In their paper,

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[†] **Jim Garrison, Quarterly** NASA GPS Users Council Videoconference, January 8, 1997

they show relative levels of GPS signals received directly and reflected from the ocean. The reflected signals had total amplitudes within 4 to 6 dB of the direct signal, with a doppler spread depending on the angle of incidence, and a delay spread depending on the aircraft altitude and sea state,

The polarization of the reflected signals is primarily left-circular polarized, which helps distinguish them from the right-circular polarized direct signals.

Given the expected signal strengths, group delay measurements are expected to give several-decimeter errors, while carrier phase tracking would give cm-level errors. Phase coherence of the reflected signal will be crucial to making cm-level phase delay measurements. Coherence is difficult to determine analytically, as the radio wavelength is of the same order of magnitude as ocean waves, so neither specular nor diffuse reflection approximations are valid. Experiments will be conducted to measure the reflected signal's coherence.

The calculated footprint of the first Fresnel zone seen by a satellite at 800 km varies from -300 m to several km, depending on the angle of incidence.

Synoptic measurements can be made to multiple satellites, with the reflecting points spreading over a few thousands of kilometers.

RECEIVER

The receiver is required to track direct GPS signals as well as the delayed signals which have been reflected from the ocean surface. The strawman design is a receiver with input from an up-looking omni-directional antenna as well as from one or more left-circularly-polarized antennas directed toward the ocean. The down-looking antennas may consist of receiver-steered phased arrays, so that significant gain may be directed toward reflections.

In order to acquire the reflected signal from a given satellite, the receiver will form a model delay and doppler using data from the direct track of that satellite, along with knowledge of the locations and velocities of the receiver and GPS satellites, and approximate knowledge of the ocean surface and deflections of the local vertical.

After acquisition, this same information will be used to allow a narrow tracking loop to track the residual delay and doppler, and the delay-width of the reflected signal. The output delay and doppler, along with the post-processed orbits of the GPS and user satellites will be used to map the 3-d location of reflecting pixels. In addition, the delay width of the reflected signals, along with their dopplers, will be used to estimate the ocean wave height and direction.

The TurboRogue receiver has been previously used in a similar mode, as instrumentation for an antenna range. For that use, the receiver tracked a reference GPS signal which was split off before being transmitted to the antenna under test. The signal received through the antenna under test was tracked by the same receiver. The reference and received signals from the antenna range application have direct analogies to the direct and reflected signals for GPS altimetry.

DETERMINATION OF REFLECTION POINTS

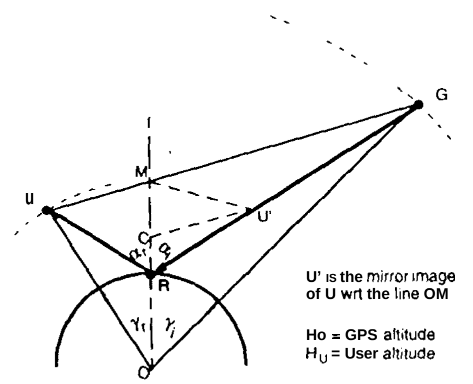
Although the earth's shape can be thought of as an ellipsoid, the equipotential surface of its gravity field (the geoid) has an undulation from such a reference ellipsoid. The earth's mean sea surface again deviates from the geoid due to ocean dynamic current. Earth's tides and other effects deviate the sea surface even further. Therefore, the determination of the reflection points on the sea surface becomes one of the key issues that has to be addressed for the GPS altimetry. A two-step algorithm has been devised and is outlined in this section. In the first step an approximate nominal sea surface is assumed and in the second step the reflection point is refined with a more precise surface.

Step 1: Ellipsoidal sea surface

Assume that the sea surface is on an ellipsoid but that the surface normal vector coincide with the radial vector

Referring to Fig. 3, let the geocenter be at O, the GPS be at G and the user be at U. The positions of G and U, and their height H_G and H_u above the ellipsoid arc known. So is the angle $\gamma_i + \gamma_r$.

An initial guess of the geocentric position vector of M is,



$UM/MG = MU'/MG = CU'/MG . RU'/RG = RU/RG = H_U/H_G$

↓

$UM/UG - H_U/(H_U+H_G)$

$UM - H_U/(H_U+H_G)UG$

↓

$M - U + \{H_U/(H_U+H_G)\} (G - U)$

Fig. 3. Geometry of GPS (G), User (U) and reflection point (R)

according to Fig.3,

$$\mathbf{M} \approx \mathbf{U} + \{H_U/(H_U+H_G)\}\ (G\ -U)$$

The geocentric position vector of R, and the two angles γ_i and γ_r can then be determined. The incidence angle α_i and reflection angle α_r can then be calculated from the triangles ORG and ORU, respectively.

The two angles α_i and α_r, computed above are, in general, unequal to each other. A better approximation is to take their weighted sum

$$\alpha'_i = \alpha'_r = (H_G \alpha_i + H_u \alpha_r) / (H_G + H_U)$$

Re-calculate γ_i from the triangle ORG, say γ'_i; and γ_r from the triangle ORU, say γ'_r. The average value of γ_i is given by

$$[\gamma'_i + (\gamma_i + \gamma_r) - \gamma'_r] / 2$$

Re-calculate M and then **R** from the average value of γ_i. Then re-calculate the α_i and α_r and iterate until $\alpha_i = \alpha_r$. A simulation in the following section shows that only 5 or 6 iterations are needed for α_i and α_r to agree to each other to better than 0.0001 radian.

Step 2: Corrected sea surface

The actual sea surface deviates from being on an ellipsoid. The reflection point estimated in Step 1 above would be in error if proper correction to the sca surface is not made. Detailed mean sea surface maps [10] and ocean tide model [11] arc readily available for such corrections. The deviation between the sea surface normal vector and the geocentric radial vector (used in Step 1 above) can be calculated from these models, from which the correction to the reflection point can be determined.

The reflection point correction is decomposed into the "in-plane" and the "out-of-plane" components. The former is in the plane containing U, R and G. The latter is in the plane rotated by 90° with respect to the local vertical. The two planes are as shown in Figs. 4 and 5, respectively.

The components of the adjustment to the reflection point are independentl y determined in the two planes. In each plane, the condition that the incidence and the reflection angles be equal is imposed while the reflection point is updated.

In-Plane Component:

Let the in-plane component of the deviation between the sea surface normal vector and the geocentric radial vector be A. Referring to Fig. 4, the corrections Δ_r and Δ_i to the incidence and reflection angles can be determined by the following two equations:

$$\Delta_r + \Delta_i = 2\Delta$$

$$\underline{RU}\sin\Delta_r = \underline{RG}\sin\Delta_i$$

where $\underline{RU}$ and $\underline{RG}$ are the distances, respectively,

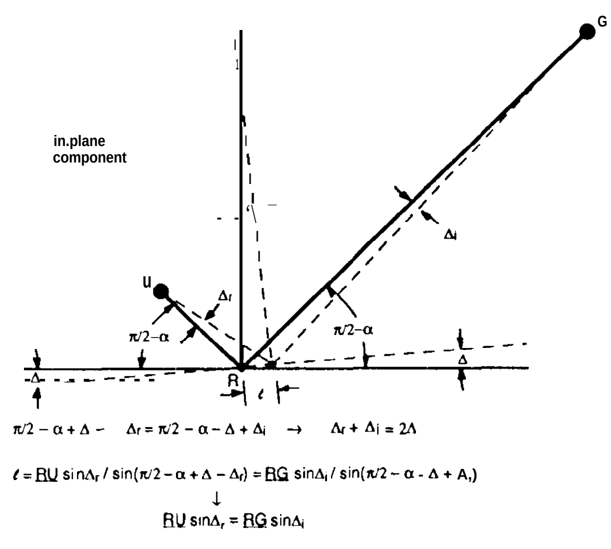


Fig. 4. Adjustment of reflection point on sea surface due to the deviation of normal vector from geocentric radial vector: ORG plane component

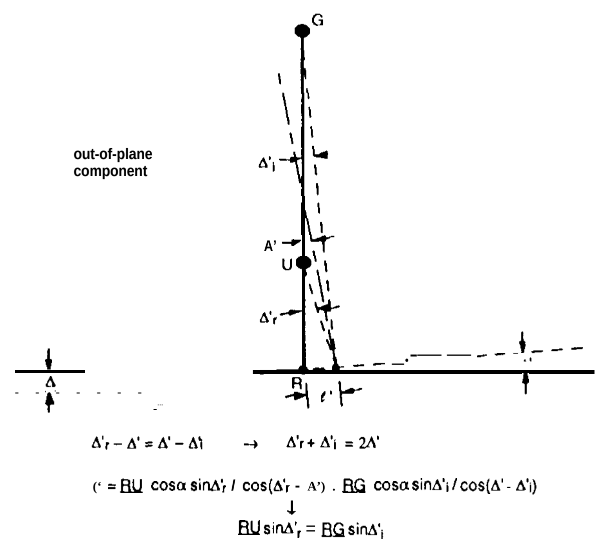


Fig. 5. Adjustment of reflection point on sea surface due to the deviation of normal vector from geocentric radial vector: component in a plane orthogonal to ORG plane

between R and U, and between R and G. Note that for the first of the above two equation to be valid, the incidence and reflection angles relative to the geocentric radial vector have to be equal to each other before the correction. This is why these angles need be made equal to high precision in Step 1 above.

Eliminating Δ_i and noting that A is of the order of 0.10 hence the small-argument approximation, $\cos\Delta_i \approx 1$, we have

$$\sin\Delta_i = \underline{RU} \sin 2A / (\underline{RG} + RU \cos 2A)$$

from which A, can be deter-mined and the adjustment to the reflection point is given by

$$\ell = \underline{RG} \sin\Delta_i / \cos(\alpha + A - A,)$$

Out-of-Plane Component:

Let the out-of-plane component of the deviation between the sea surface normal vector and the geocentric radial vector be A'. Refernng to Fig. 5, the angles Δ'_r and A', can be determined by the following two equations:

$$\Delta'_r + A, = 2A'$$

$$\underline{RU} \sin\Delta'_r = \underline{RG} \sin A',$$

Eliminating Δ'_r and using small-argument approximation, $\cos\Delta'_i \approx 1$, again yields

$$\sin\Delta'_i = \underline{RU} \sin 2\Delta' / (\underline{RG} + \underline{RU} \cos 2\Delta')$$

from which A', can be deter-mind and the adjustment to the reflection point is given by

$$\ell' = \underline{RG}\ \mathit{cosa}\ \sin\Delta'_i / \cos(\Delta' - A,)$$

After both in-plane and out-of-plane corrections are made, A and A are incrementally adjusted to account for the shift of the reflection point ℓ and ℓ '. The process is repeated until the last adjustments in ℓ and ℓ ' are small. Only one or two iterations may be needed for this process.

INFORMATION CONTENT OF REFLECTED GPS SIGNALS

The information content is defined in terms of the sensitivity of the sea surface height to the measurement error. A lower error sensitivity implies a higher information content,

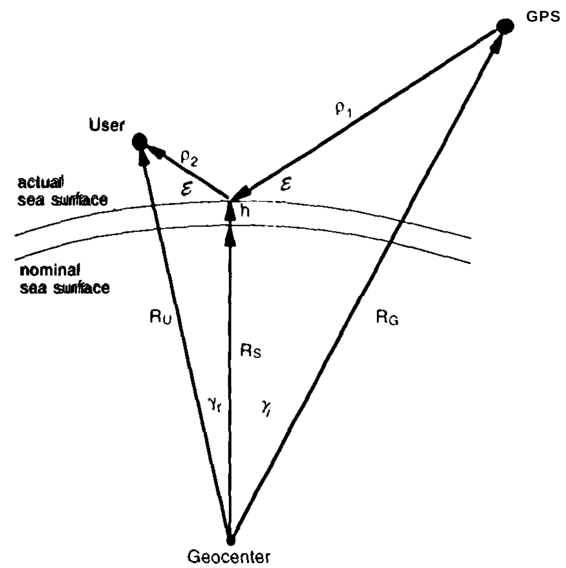


Fig. 6. Determination of altimetry height h from reflected GPS to User range measurements

As shown in Fig. 6, the reflected range measurement from GPS to the user satellite is

$$\rho = \rho_1 + \rho_2$$

where

$$\rho_1 = [R_G^2 + (R_S+h)^2 - 2\ R_G (R_S+h) \cos\gamma_i]^{1/2}$$

$$\rho_2 = [R_U^2 + (R_S+h)^2 - 2\ R_U (R_S+h) \cos\gamma_r]^{1/2}$$

R_G, R_U and R_S are, respectively, the geocentric distances to GPS, User satellite and the nominal reflection point.

The measurement partial derivative with respect to the sea surface height, h, is

$$\left.\frac{\partial\rho}{\partial h}\right|_{h=0} = (R_S - R_G \cos\gamma_i)/\rho_1 + (R_S - R_U \cos\gamma_r)/\rho_2$$

$$= -\cos(\pi/2-\varepsilon) - \cos(\pi/2-\varepsilon)$$

$$= -2 \sin\varepsilon$$

where ε is the elevation angle at the reflection point,

The sensitivity of h solution to error in p is

$$\sigma_h/\sigma_\rho = -0.5 / \sin\varepsilon$$

The sensitivity has a magnitude of 0.5 for $\varepsilon = 90°$ (overhead GPS), 1.5 for $\varepsilon = 20°$ and 2.9 for $\varepsilon = 10°$.

RESULTS OF SIMULATION

A simulation analysis is performed to demonstrate the convergence of the iteration algorithm for the determination of the reflection point. The same assumptions used in Figs. 1 and 2 are used.

Fig. 7 is a histogram showing the number of iterations needed for the convergence of reflection point determination. The criterion for convergence is for the incidence and the reflection angles to be within 100 microradians (-20 arcsec) of each other. This simulation shows that 6 or fewer iterations are needed at all times.

Fig. 8 is a histogram showing the elevation angle ε of the GPS signals at the reflection points. Note that ε is 20° or higher at all times, implying that the error sensitivity to the range measurement is < 1.5 at all times. As a matter of fact, over 75% of the sensitivity has a value lower than 1, as shown in Fig. 9.

DETERMINATION OF DOPPLER SHIFT OF REFLECTED GPS SIGNALS

For the onboard receiver's tracking loop to acquire the reflected GPS signal, the doppler shift of this signal needs to be predetermined. Note that only a crude estimate is sufficient for this purpose. This can be furnished with the following onboard non-iterative algorithm.

Referring to Fig. 6, the reflected GPS to user range measurement is

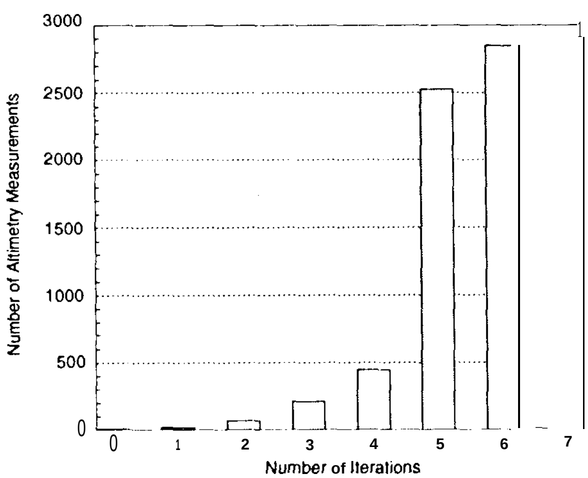


Fig. 7. Number of iterations for reflection point determination

$$\rho = \rho_1 + \rho_2$$

The doppler shift is the time derivative of p, which is given by

$$\frac{\partial\rho}{\partial t} = \frac{\partial\rho_2}{\partial t} + \frac{\partial\rho_1}{\partial t}$$

$$= \mathbf{V}_U \cdot \hat{\rho}_2 - \mathbf{V}_G \cdot \hat{\rho}_1$$

where $\mathbf{V}_G$ and $\mathbf{V}_U$ are the velocity vectors of the GPS and the user, respectively; $\hat{\rho}_1$ and $\hat{\rho}_2$ are unit vectors. The fact that p is minimum and hence invariant with respect to the reflection point has been used in arriving the second line

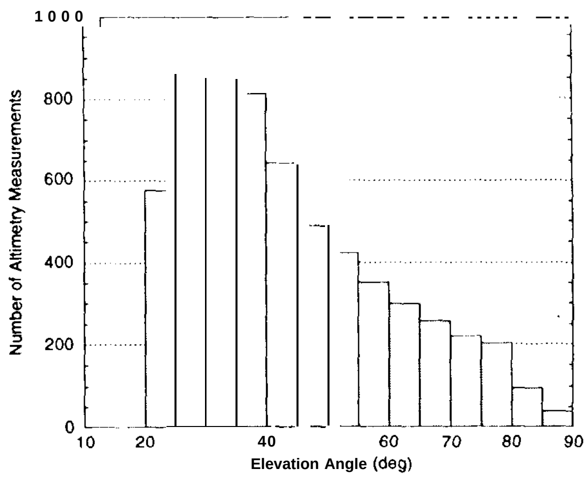


Fig.** 8. **Elevation angles at the sea surface reflection points

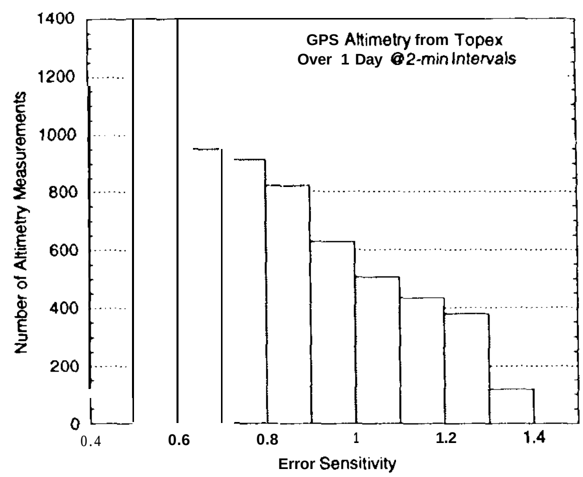


Fig. 9. Sensitivity of sea surface height determination to reflected GPS range measurement error

of the above equation,

Since $\mathbf{V}_G$ and $\mathbf{V}_U$ can be predicted ahead of time to sufficient accuracy, the determination of the doppler shifts becomes that of $\hat{\rho}_1$ and $\hat{\rho}_2$.

Assuming a spherical earth and for nominal GPS and user altitudes, the angles y, and γ_r can be expressed, respectively, as quadratic and cubic functions of the GPS elevation at the user, with an accuracy better than O.1°.

The reflection point **Rs is** given by the set of three linear equations:

$$\hat{\mathbf{R}}_G \cdot \mathbf{R}_S = R_e \cos \gamma_i$$
$$\hat{\mathbf{R}}_U \cdot \mathbf{R}_S = R_e \cos \gamma_r$$
$$\hat{\mathbf{R}}_G \times \hat{\mathbf{R}}_U \cdot \mathbf{R}_S = 0$$

where $\hat{\mathbf{R}}_G$ and $\hat{\mathbf{R}}_U$ are the unit vectors of $\mathbf{R}_G$ and $\mathbf{R}_u$, respectively, and R_e is the earth's radius.

From these actuations the coordinates of $\mathbf{R}_S$ and, in turn, $\hat{\rho}_1$ and $\hat{\rho}_2$, and the doppler shift, can be determined.

The doppler shift for the reflected GPS signals as observed by Topex covers a range of ±56 kHz at L1 frequency, as shown in Fig. 10. This range is about 37910 wider than that for direct GPS signals, which is ±41kHz.

SUMMARY

The potential use of GPS signals as ocean altimetry measurements has been investigated. This preliminary investigation indicates that GPS signals reflected from ocean surface contain strong altimetric information and the technology is viable and promising.

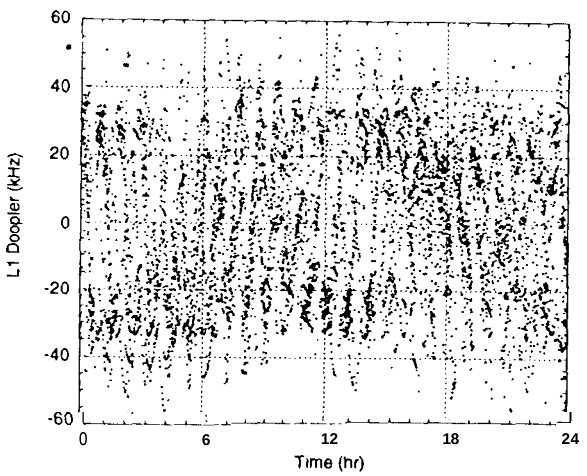


Fig. 10. Doppler shift of reflected GPS signals observed by Topex over 1 day at 2-minute intervals

A two-step, iterative algorithm has been devised for the determination of reflection point on sea surface, which is vital for altimetry with GPS signals. Results of a simulation analysis show that not more than six iterations are required for the convergence of GPS signal ray path angles to within 10-4 radian in Step 1, which assumes an ellipsoidal sea surface with geocentric radial vector as the normal vector. Step 2, which corrects for the approximated sea surface shape and normal vector in Step 1, is expected to require about one or two iterations.

The next version GPS receiver being developed at JPL will be capable of simultaneously tracking the direct GPS transmission from an upward-looking antenna, and the reflected signal through an antenna pointing toward the ocean. In order to exploit this capability, receiver software must be developed.

The analysis reported in this paper is only preliminary. Other related issues to be addressed include the assessment of reflected GPS signal quality, the optimal usc of GPS pseudorange and carrier phase data types, the recovery of sea state, and the determination of sea surface height from simulated data.

ACKNOWLEDGMENT

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