A Novel GPS-Based Sensor for Ocean Altimetry[1]

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A technique for a novel application of GPS signals to ocean altimetry is described. The entire Earth surface is divided into a triangular grid of points nearly-uniformly spaced. The sea surface heights at the grid points are determined using the GPS signals reflected from the surrounding area. Practical grid size and data sampling rate are determined. An efficient estimation scheme is devised to solve for the thousands of parameters. A simulation analysis shows that global ocean altimetric information can be recovered to better than 10 cm with only 1 day of reflected GPS signals.

INTRODUCTION

GPS measurements have demonstrated to be capable of precise positioning of users on earth as well as on low-altitude satellites [1–3]. A novel potential application of GPS signals is for ocean altimetry. The GPS signals reflected from the ocean surface and received at a low-altitude Earth satellite contain sea surface height information and thus can serve as altimetry measurements. Such altimetry would be superior to conventional radar altimetry in three respects: (1) A snapshot of reflected GPS observations contains information on surface heights at up to 12 points over a few thousand km, instead of a single nadir point with conventional radar altimetry. Hence, quick synoptic altimetric information can be obtained. Furthermore, global sea surface height information can be recovered with observations over a relatively short period of time (one day); (2) The low Earth satellite only need be equipped with a GPS receiver which can either be dedicated to acquiring the ocean reflected GPS signals for altimetry, or double 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 SAC-C satellite of Argentina, scheduled to be launched in May 1999, will carry a highly capalbe GPS receiver with multiple antennas. It will be the first of a series of flight experiments to develop bistatic GPS reflection technology.

In [4], a few key characteristics of reflected GPS signals have been described and an efficient algorithm for the determination of reflection points on the ocean surface has been devised. In brief, it is a two-step algorithm. The first step involves an iteration process assuming an approximate nominal sea surface (e.g., an ellipsoid); the second step refines the reflection points in terms of the deviations from a precise surface defined by the mean sea surface [5] and tidal corrections [6].

This paper presents a filtering scheme for the estimation of sea surface heights with reflected GPS signals. The entire Earth surface is divided into a triangular grid of points nearly-uniformly spaced. The sea surface heights and tropospheric delays at the grid points are determined using the GPS signals reflected from the surrounding area. An efficient estimation scheme is devised to solve for the thousands of parameters. A simulation analysis is carried out assessing the potential accuracy with which oean altimetry can be recovered with reflected GPS sigmals.

GRID POINT PARAMETER ESTIMATION

The quantity of interest is the sea surface height as a function of geodetic latitude and longitude. Because the tropospheric delays cannot effectively be removed, they have to be simultaneously estimated with the same reflected GPS signals. Fortunatedly, these two parameters can be well separated since, to the first degree, the former is proportinal to $\sin\gamma$ (γ being the elevation angle) while the latter is proportinal to $1/\sin\gamma$. These parameters can easily be modeled in terms of spherical harmonic coefficients; but they would be globally correlated, requiring simultaneous estimation with a huge filter. Instead, we chose a grid-point-value model here. The localized property of such modeling allows parallel estimation with multiple filters of manageable size.

The grid points are recursively generated, starting from a spherical icosahedron (12 grid points, 30 grid lines); new grid points are generated at the mid-points of existing grid lines; then new grid lines are added in by connecting neighboring new grid points, as shown in Fig. 1. The total number of grid points increases with the number of recursion N as $10\times4^N+2$. After 4 recursions (5 generations in all), there are a total of 2,562 grid points. The grid size is ~454 km, or ~4° over the ocean surface. For the satellite velocity of 7.5 km/sec, a proper non-redundant data sampling rate is ~1 per minute. With an average of 9 GPS satellites observed simultaneously, there are ~5 measurements per grid point over a period of 1 day, appropriate for estimating both the sea surface height and zenith tropospheric delay. A further recursion would increase the number of grid points by a factor of 4 while

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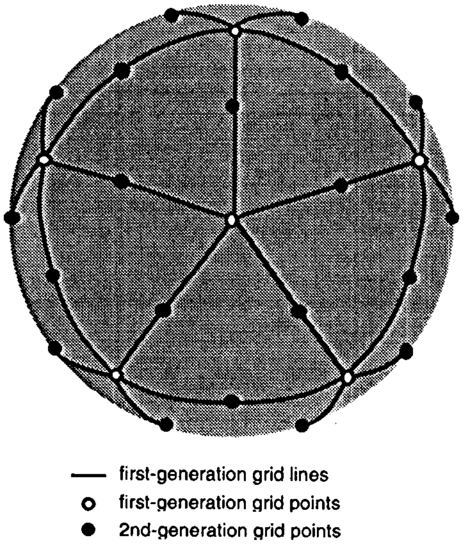

Fig. 1. Generation of grid points from a spherical icosahedron

increase the number of grid points by a factor of 4 while increasing the number of non-redundant measurements only by a factor of 2 and would be under-sampled.

Simultaneously estimating the 2×2562 parameters would require a huge filter. To reduce the filter size, the entire global surface is divided into 12 subregions, centered at the first-generation grid points, as shown in Fig. 2. There are now 226 grid points in each subregion (25 of which on the boundary). The grid-point values within each subregion are estimated independently of those in other subregions. Therefore, only 452 parameters are to be estimated in each filter. The values away form the grid points are modeled as piecewise planar within the triangle defined by the surrounding grid points.

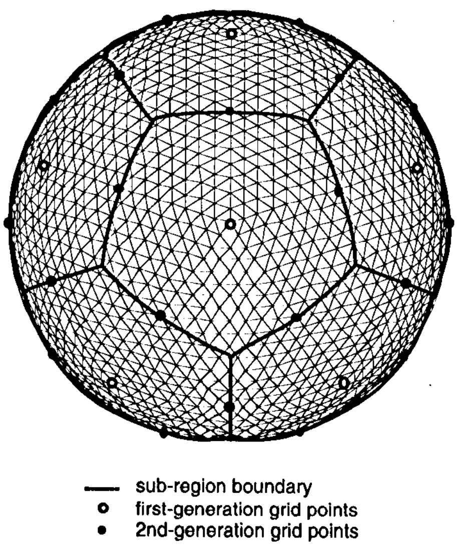

Fig. 2. Division of the global surface into 12 subregions

Physically valid temporal and spatial constraints are applied to strengthen the grid-point solutions. The zenith tropospheric delays ρ_z are treated as a random-walk model over time (3 cm each hour) while the sea surface heights h are treated as constant over the entire estimation period, typically 1 day. Also, correlation constraints (25 cm for h and 30 cm for ρ_z) are applied between neighboring grid points. After grid-point values over all subregions are estimated, the grid-point values on a boundary between two subregions take the weighted means of the two subregion solutions, thus assuring soltuion continuity across subregion boundaries.

SIMULATION

To assess the potential accuracy of recovering the sea surface heights from reflected GPS signals, a simulation analysis is performed. The SAC-C of Argentina, with a polar 600-km orbit, is assumed as the user satellite. The parameter "truth" models are

$$h = 50 \cos 3\lambda \cos 3\phi \quad \text{(cm)}$$

$$\rho_z = 20 \cos 3\lambda \cos 3\phi \quad \text{(cm)}$$

where λ is geodetic longitude and ϕ geodetic latitude. Fig. 3 is a contour plot for h; the plot for ρ_z looks identical except with a different scale.

Surface reflected GPS pseudorange measurements from all visible GPS satellites above local horizon of SAC-C are simulated at the rate of once per minutes over a period of 1 day, which cover 15 revolutions of SAC-C orbit. Different levels of data noise are assumed to reflect different receiver capabilities: 1 cm (pseudorange smoothed by carrier phase); 10 cm (premium pseudorange); and 75 cm (conservative).

With a 10-cm data noise, the recovered sea surface heights and their formal errors are as shown in Figs. 4 and 5,

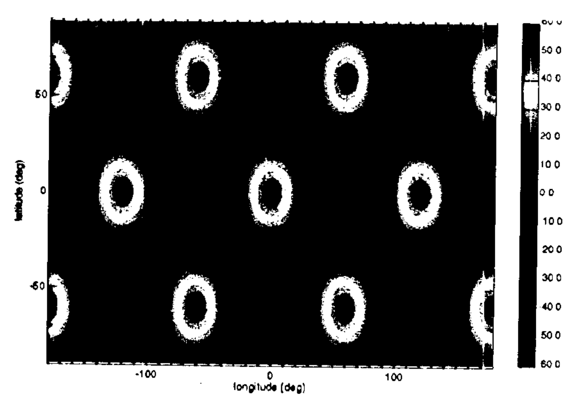

Fig. 3 Sea surface height "truth" model

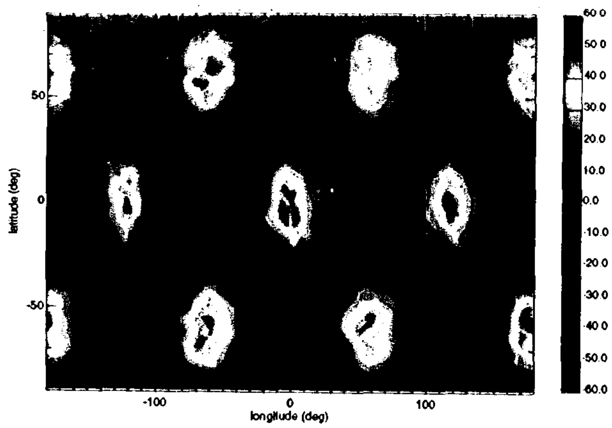

Fig. 4. Recovered sea surface height solution (cm)

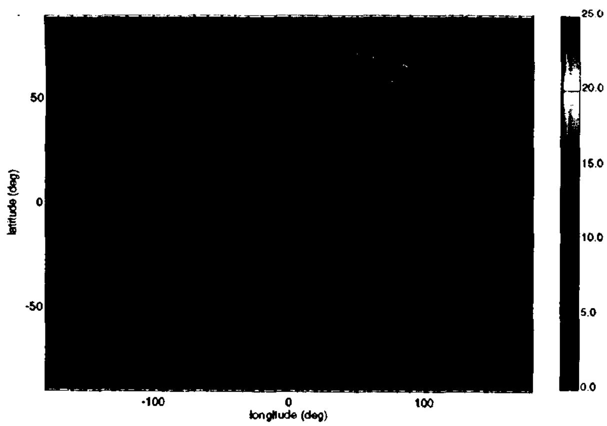

Fig. 5. Recovered sea surface height formal error (cm)

respectively. The sinusoidal pattern is closely recovered (Fig. 4). The solution formal errors are typically 8–15 cm around the Equator and mid-latitudes; and below 5 cm near polar regions. The deviation of the recovered solution from the truth has an RMS value of 4 cm and the overall formal error has an RMS value of 8 cm.

When different levels of data noise are assumed, the solution deviation and formal error scale accordingly, but less than directly. Fig. 6 summarizes the RMS solution deviation and the formal error as a function of pseudorange data noise. With 1-cm carrrier smoothed pseudorange data, the sea surface height can be determined to 4 cm; and to 15 cm even with pseudorange data at the conservative 75-cm quality.

SUMMARY

A simulation analysis has been carried out assessing the potential accuracy with which sea surface height can be recovered with reflected GPS pseudorange measurements. Such measurements are capable of quick (~1-day) global ocean altimetry recovery. Global altimetry at the 15-cm level can be expected with pseudorange data of conservative 75-cm quality. GPS altimetry better than 10-cm accuracy is possible when

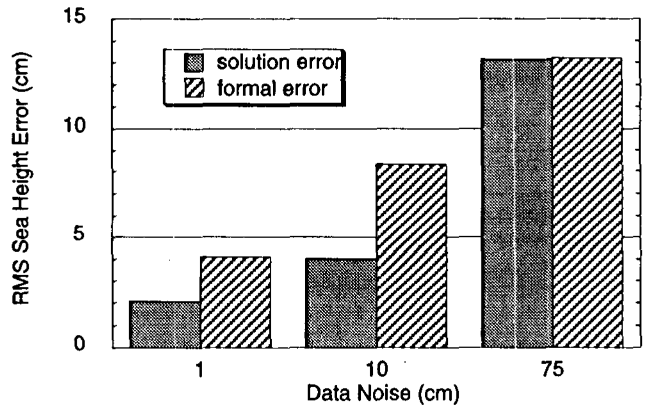

Fig. 6. Solution and formal errors as a function of pseudorange data noise

premium pseudorange of 10-cm quality is available. Such data quality will depend on the signal strength received. Ultimately, GPS altimetry better than 5-cm accuracy is not out of reach if carrier phase can be acquired for smoothing of the pseudorange data. The key factor here is phase coherency of the reflected GPS signals.

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.

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