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A FEW PARTS IN 10^8 GEODETIC BASELINE REPEATABILITY IN THE GULF OF CALIFORNIA USING THE GLOBAL POSITIONING SYSTEM

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Abstract. Global Positioning System (GPS) geodetic measurements of 350-650 km baselines across the Pacific-North America plate boundary in the Gulf of California are presented. The analysis employs a four-station U.S. fiducial network and combined carrier phase and pseudorange data. Water vapor radiometer (WVR) data at the Gulf sites are used to calibrate the GPS signal for wet tropospheric path delays. Residual tropospheric delays are modeled as first-order exponentially correlated stochastic processes. The measurement precision for horizontal components is a few parts in 10^8 or better. Comparison of the Gulf data with other geodetic techniques is not yet possible, however the system accuracy appears to be about 1 part in 10^7 based on simultaneous GPS solutions of a baseline in California collocated with VLBI. The results are encouraging because a high level of precision with GPS is demonstrated even with stations located outside a fiducial network and when wet tropospheric path delays are significant, typically exceeding 20 cm at zenith.

Introduction

Geodetic measurements using radio signals from the Global Positioning System (GPS) were acquired across the southern Gulf of California (Mexico) in November 1985. This region spans the Pacific-North America plate boundary, thought to be spreading at about 4.8 cm/yr [Demets et al., 1987]. GPS has already been demonstrated to be a precision geodetic tool over regional (several hundred km) distances. Accuracies of about 1 part in 10^7 to a few parts in 10^8 have been obtained in Alaska [Beutler et al., 1987] and the southwestern United States [Bock et al., 1986b; Lichten and Border, 1987]. At these locations wet tropospheric corrections are relatively small and well-located control (fiducial) stations are available. The GPS network in the Gulf, however, is outside the U.S. fiducial network employed in previous experiments. Moreover, it is in a humid region where wet tropospheric path delays exceed 20 cm at zenith and are a potentially major error source for both vertical and horizontal baseline components unless properly calibrated [Tralli et al., 1988]. This paper summarizes an analytical approach yielding geodetic baseline repeatabilities of a few parts in 10^8 from the first epoch GPS occupation of the Gulf of California.

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GPS Data Analysis

GPS system characteristics are given by Spilker [1978] and Milliken and Zoller [1978]. Techniques for precise geodetic positioning using GPS are described by Bossler et al. [1980], Remondi [1985], and Lichten and Border [1987]. Briefly, a network of ground receivers records dual-band group and phase delay signals transmitted from several GPS satellites. The two L-band carrier frequencies (L1, 1575.42 MHz and L2, 1227.6 MHz) are modulated with a pseudo-random P-code for precision range determination. For a group delay measurement, the signal is cross-correlated with a receiver's internal code replica to yield "pseudorange", so termed because of range errors associated with satellite and receiver clock biases. For a more precise phase delay measurement (also termed integrated Doppler) the total change in phase is measured over several hours and converted to a corresponding range change. The phase data are ambiguous by an integer number of wavelengths for a given satellite-receiver pair. This ambiguity can be estimated simultaneously with the geodetic parameters (satellite and receiver locations), but this may result in relatively large east baseline component uncertainties given the dominantly north-south ground tracks of the current satellite constellation. This ambiguity is better constrained when pseudorange data are available and can be combined with carrier phase data [Lichten and Border, 1987] or when bias fixing techniques are applied [Bock et al., 1986a; Blewitt, 1988]. Path delays associated with radio wave propagation through the troposphere require calibration based on surface meteorological (SM) measurements combined with empirical atmospheric models, and/or water vapor radiometer (WVR) measurements. Both calibration approaches are used in this study, depending on the availability of WVR data at a given station. Residual delays remaining after calibration are then estimated along with the geodetic parameters of interest.

The data used in this study comprise an eight-station network which includes "mobile" sites at Loreto and Cabo San Lucas in Baja California and Mazatlan on the Mexican mainland (whose positions are solved for), as well as five sites in the United States whose positions are well known a priori ("fiducial" sites) and are fixed in the analysis. The fiducial network which defines the reference coordinate system consists of International Radio Interferometric Surveying (IRIS) sites (Haystack, MA, Richmond, FL, Ft. Davis, TX) and the Owens Valley Radio Observatory (OVRO), CA. Very long baseline interferometry (VLBI) geodetic data are available at all these sites and at Mojave, CA. The site at Mojave (treated as mobile in this study) provides a VLBI reference baseline to OVRO for comparison to GPS. Six consecutive days of carrier phase and pseudorange data of generally high quality are available at Cabo San Lucas and Mazatlan, from November 18 to 23. Typically a "day" of data consists of 4 to 8 hours of observations of 6 or 7 GPS satellites. Only four days of high-quality data are available at Loreto in this period, determined from analysis of post-fit residuals indicating about a factor of 2 larger root-mean-square (rms) scatter than at other sites, suggesting calibration problems in the receiver and increased data noise. All sites were occupied with TI-4100 receivers, except OVRO and Mojave where Series-X receivers were used. A three-channel WVR (J0-1) was available at Cabo San Lucas; Loreto, Mazatlan, OVRO, and Mojave had older two-channel WVRs, while the remaining sites had no WVRs. SM measurements were obtained at all sites. A more detailed description of the experiment is given by Dixon et al. [1988]. Wet zenith path delays were high at the Gulf sites during the entire experiment, increasing 30 to 50% over the six days analyzed here and often exceeding 20 cm at zenith, but the atmosphere was very stable during any given satellite observation period [Tralli et al., 1988].

All data processing was carried out using the GIPSY (GPS Inferred Positioning System) software developed at the Jet Propulsion Laboratory, which employs a least-

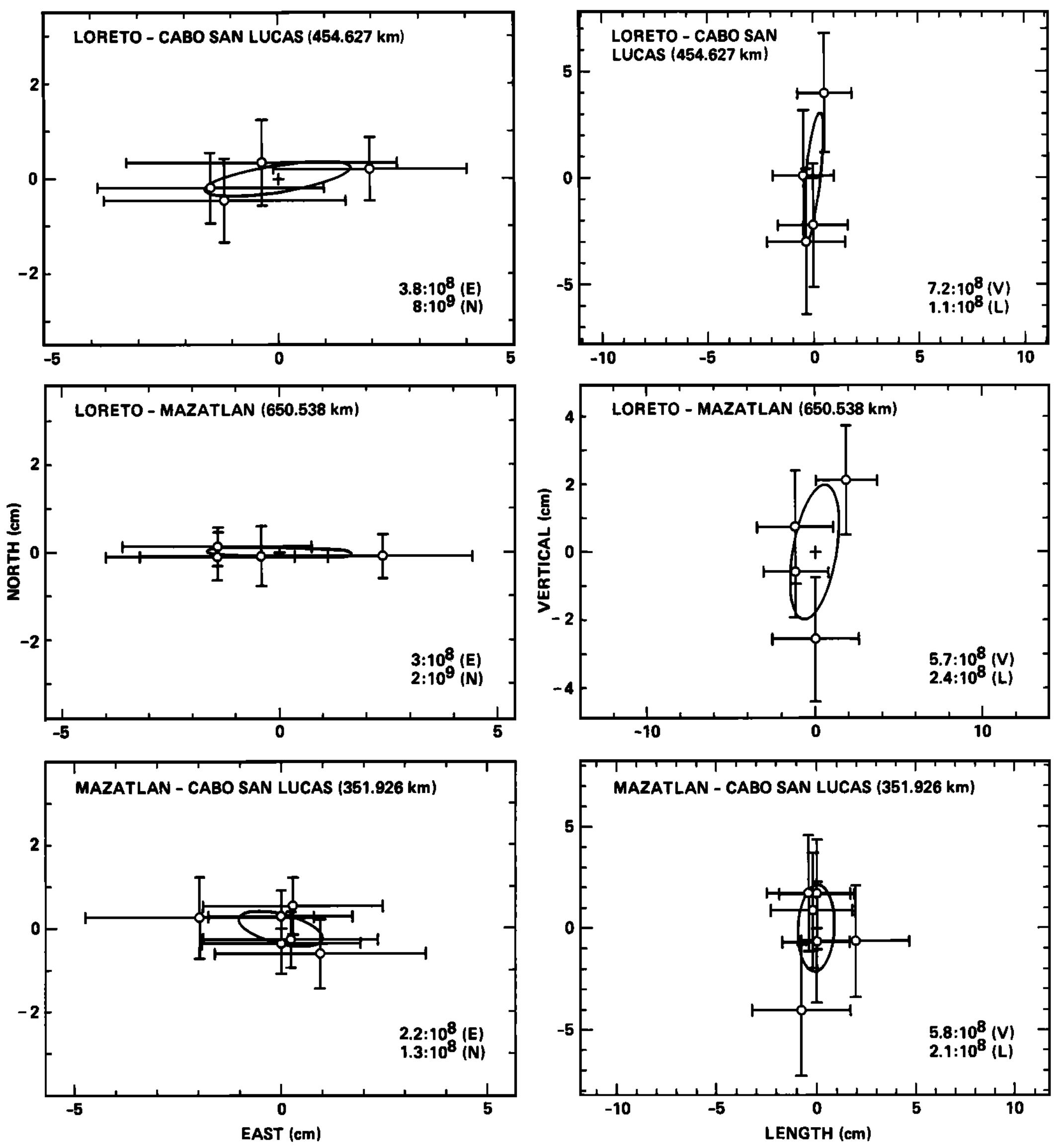

Figure 1. Baseline component (E, N, V) and length (L) solutions for each of the three Gulf baselines using combined carrier phase and pseudorange data. Solutions for each day are plotted about the weighted mean of all solutions. The errors are described in the text. Only four days of high-quality data are available for Loreto. The one standard deviation repeatabilities are in parts per 10^8 (or 10^9). Note that for the east-west Cabo San Lucas to Mazatlan baseline, the east component and length are essentially identical.

squares estimation algorithm based on a batch sequential upper-diagonal (U-D) factorization filter [Bierman, 1977; Thornton and Bierman, 1980]. Satellite and receiver clocks are modeled as white noise processes [Wu et al., 1986], with a hydrogen maser at OVRO used as the system reference clock; this is equivalent to double differencing to eliminate clock errors [e.g. Bock et al., 1986a]. No bias fixing is undertaken; rather, the range ambiguity is estimated jointly with the geodetic parameters. The satellite elevation angle cutoff is 15 degrees, with most of the data collected between 30 and 60 degrees elevation.

WVR data are used to estimate the zenith wet tropospheric path delay at each Gulf site and at OVRO and Mojave. The availability of WVR data at the latter (drier) sites is not critical [Tralli et al., 1988]. For sites without a WVR, calibration is based on SM measurements and the Chao [1974] atmospheric model. After calibration for the wet troposphere, a residual zenith delay is also estimated simultaneously with the geodetic parameters. This residual wet path delay is modeled as a first-order Gauss-Markov stochastic process [e.g. Bierman, 1977] with correlation times of 8 or 16 hr and corresponding steady-state deviations of 2 or 10 cm depending on whether the calibration is based on WVR or SM measurements [Tralli et al., 1988]. A constant bias is also estimated for each site-day, with either a 2 cm or unconstrained a priori uncertainty if calibration is based on WVR or SM data, respectively. Calibration of dry tropospheric path delays is based on surface measurements of pressure without estimation of a residual dry delay [Tralli et al., 1988].

Discussion of Results

Figure 1 shows the results obtained for the three Gulf of California baselines for each day of observation with the combined use of carrier phase and pseudorange data. Each day is treated independently in the analysis. The baseline component solutions for each day of observation are plotted about their mean, weighted according to the reciprocal square of the error (determined from the least-squares parameter estimation), shown by the error bars. These errors, or data noise, do not include contributions from potential systematic errors, such as fiducial station mislocations. The error ellipses about the weighted means are at one standard deviation and correspond to the day-to-day baseline repeatability, a measure of the precision of the geodetic measurements. Although the data population is small, the repeatability is comparable to the data noise, suggesting that this is an adequate measure of precision.

The satellite ground tracks are dominantly north-south and yield a better constraint on solutions of north baseline components relative to east components when only carrier phase data are used. Pseudorange data, when combined with carrier phase data, improve resolution of the east component by constraining system clocks and range ambiguities [Lichten and Border, 1987]. Figure 2 compares baseline component repeatabilities with and without the use of pseudorange data. The largest improvements are in the east component, by a factor of about 2 for baselines involving Loreto and up to a factor of 5 for the Mazatlan to Cabo San Lucas baseline. The north component repeatabilities are also improved, typi-

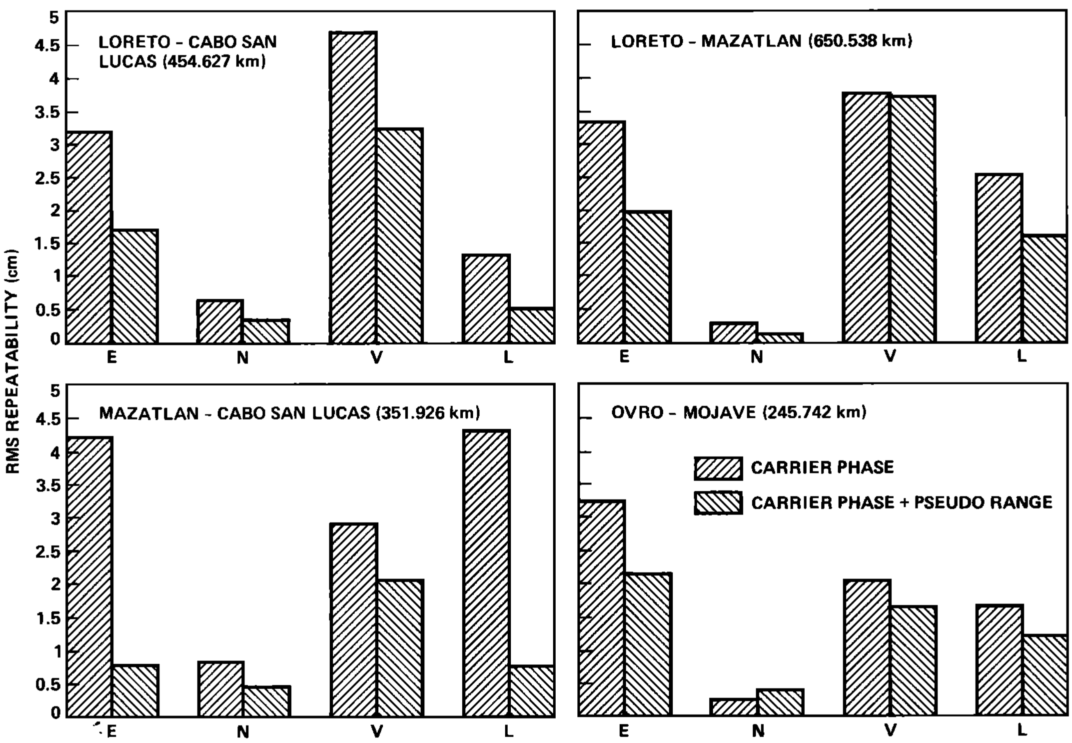

Figure 2. Histogram of baseline component (E, N, V) and length (L) repeatabilities using carrier phase data with and without pseudorange data.

cally by factors of about 2. Improvements in the vertical repeatabilities with the addition of pseudorange are less than a factor of about 1.5.

The baseline length repeatabilities are 1.1, 2.1, and 2.4 parts in 10^8 for the Loreto to Cabo San Lucas (~ 450 km), Mazatlan to Cabo San Lucas (~ 350 km), and Loreto to Mazatlan (~ 650 km) baselines, respectively, using combined carrier phase and pseudorange data. A good understanding of system accuracy will not be possible until data from several GPS occupations of the same baselines are available and comparisons can be made with satellite laser ranging results for Mazatlan to Cabo San Lucas. Pseudorange data are not available for the SERIES-X receivers at OVRO and Mojave in California, limiting the precision and accuracy attainable on the OVRO-Mojave baseline (~ 245 km). However, comparison with VLBI provides some information on GPS system accuracy. The OVRO-Mojave baseline agrees to within about 0.7 cm in the east component and slightly over 3 cm in the north component. System accuracy on this baseline is thus about 1 part in 10^7. The precision of the OVRO-Mojave baseline is 4.9 to 6.8 parts in 10^8, with or without the use of pseudorange data at all other sites. Since the precision of the Gulf baselines is slightly better, we suggest that the accuracy of the Gulf baselines is no worse than $1{:}10^7$.

The relatively high level of precision reported in this study, a few parts in 10^8 or better for the horizontal baseline components, is attributable to optimum estimates of the wet tropospheric delays and combined use of carrier phase and pseudorange data. The baseline solutions are determined using single-day orbital arcs, whereby satellite and receiver positions are estimated jointly for each day of data. A multi-day arc strategy can result in improved precision, [Lichten and Border, 1987], as can bias optimization [Blewitt, 1988]. We intend to apply these techniques to the Gulf of California data. The feasibility and desirability of continued GPS geodetic measurements in the Gulf are clear. Plate motion rates of about 4.8 cm/yr [Demets et al., 1987] should be detectable with GPS experiments spanning just a few years, and kinematic models of plate motion which differ by less than 1 cm/yr should be distinguishable within a decade.

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