Precise Estimation of Tropospheric Path Delays With GPS Techniques

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Tropospheric path delays are a major source of error in deep space tracking. However, the tropospheric-induced delay at tracking sites can be calibrated using measurements of Global Positioning System (GPS) satellites. A series of experiments has demonstrated the high sensitivity of GPS to tropospheric delays. A variety of tests and comparisons indicates that current accuracy of the GPS zenith tropospheric delay estimates is better than 1-cm root-mean-square over many hours, sampled continuously at intervals of six minutes. These results are consistent with expectations from covariance analyses. The covariance analyses also indicate that by the mid-1990s, when the GPS constellation is complete and the Deep Space Network is equipped with advanced GPS receivers, zenith tropospheric delay accuracy with GPS will improve further to 0.5 cm or better.

I. Introduction

Signal delays originating in the troposphere can seriously affect the major radiometric data types used for deep space navigation. The wet troposphere in particular is one of the major error sources for Very Long Baseline Interferometry (VLBI) [1,2,3]. Uncalibrated tropospheric delays, typically 5 cm at zenith, can also limit the accuracy for Doppler and ranging systems. For example, the fluctuating troposphere component is the limiting error for Magellan navigation [2], and the systematic component, if calibrated to only 5 cm accuracy at zenith, also becomes a limiting Magellan navigation error source at low elevations.

The Deep Space Network (DSN) has obtained and is presently installing advanced Global Positioning System (GPS) dual-band receivers for ionospheric calibrations [4]. GPS data are also used elsewhere for a wide variety of precise positioning applications, including satellite orbit determination and ground-based geodetic studies. There are presently seven developmental and four operational GPS satellites in high-Earth orbit (20,000-km altitude) and by the mid-1990s, the 21-satellite operational constellation will be complete. In some GPS applications, uncalibrated tropospheric delays can be a serious error source and must be estimated from the GPS data along with other adjusted parameters [5]. Substantial improvement in GPS orbit and ground-station coordinate accuracy has resulted from the use of a sequential square-root filter estimation approach for tropospheric calibration [5,6,7]. It follows that stochastic GPS estimates of the tropospheric path delay at DSN sites could also be provided by the same DSN GPS receivers that are used for the ionospheric calibrations. In this article, we report on recent results based on GPS experimental data acquired between 1985 and 1988. These data have been used previously to determine high-accuracy GPS orbits and ground-station coordinates as part of a demonstration of GPS positioning techniques [6,7]. In the present study, however, attention is focused on the accuracy of the time-varying GPS tropospheric delay estimates determined along with the precise GPS orbits. Potential benefits for calibration of deep-space radiometric data are discussed.

II. Experimental Data

The data used for the GPS troposphere study were obtained in GPS experiments in November 1985 and January 1988. Most of the results are based on the 1988 experiment. In the November 1985 experiment, data from nine GPS receivers deployed in North America were used, spanning two weeks. The nine sites included the locations of six VLBI observatories [Hatcreek, CA; Mojave, CA; Owens Valley Radio Observatory (OVRO), CA; Fort Davis, TX; Richmond, FL; and Haystack, MA] and three sites in Mexico. For a more detailed description of the 1985 experiment, see [8]. In the 1988 experiment, data from several dozen locations in the South Pacific; North, Central, and South America; and Europe were collected over a three-week period [9]. The 1988 troposphere results shown in this article are based on data in a one-week interval from North America, South America, and Europe. The 1988 North American sites included five of the six VLBI sites occupied in the earlier 1985 experiment.

In the November 1985 experiment, most stations collected data for about 8 hrs each day. Since a portion of this period had unfavorable geometry, typically 5–8 hrs of high-quality tropospheric delay estimates were determined. In the January 1988 experiment, due to better geometry, one additional satellite, and the larger tracking network, the longer view periods enabled tropospheric delay determination over periods of up to 12 hrs. In these experiments, water vapor radiometers (WVRs) were operated at some of the Mexican and South American sites, and at Haystack and Mojave on selected days. These WVR data were used for comparison purposes to assess the GPS tropospheric delay measurements.

III. Approach and Results

The GPS techniques used to determine tropospheric delays at ground tracking sites are described in [5,6,7]. A key element in the estimation of parameters such as tropospheric path delays and station coordinates using GPS is the accuracy of the GPS orbits. To minimize orbit error, three reference sites were held fixed at their VLBI coordinates and all other ground site positions were estimated simultaneously along with other parameters. Multiday arcs were used to further improve orbit modeling. The zenith tropospheric delay was estimated at each ground site. For the November 1985 data, dry tropospheric delay calibrations (from surface pressure measurements, as described in [4]) were applied to the data, and, when available, WVR calibrations were also applied to correct for the wet path delay [5]. GPS corrections to these calibrations were estimated with a stochastic model that treats the zenith tropospheric delay as a random walk. If the GPS and WVR wet troposphere measurements were in agreement, the GPS corrections determined in this fashion should be zero.[1] With the January 1988 data, the procedure was varied slightly in order to further test the sensitivity of GPS observations to the troposphere: Here, *no troposphere calibrations* were applied, so the GPS data were used to estimate the *entire* (wet and dry) zenith path delay. These delays were then compared to the sum of the WVR measured delay and the dry delay (from surface measurements). The time-varying tropospheric zenith delays from GPS were estimated in a square-root filter simultaneously with other parameters such as station coordinates, GPS orbital epoch states, station and satellite clocks, and GPS carrier phase biases.

The WVR measures the brightness temperature of the atmosphere. WVRs utilize at least two radio frequencies. One frequency is near water resonance spectral features. The WVR antenna is moved through a variety of elevations (tipping curves) so that the elevation dependence of the water vapor content can be determined, and from that the water vapor content can be determined based on a homogeneous model of the atmosphere. A description of the method for determining wet path delays from WVRs can be found in [5], which also contains numerous other references both for the instruments themselves and for the water vapor content retrieval algorithms. The accuracy of modern three-frequency WVRs is believed under good conditions to be better than 1 cm. However, the accuracy of wet tropospheric delays determined from WVR measurements can be compromised by various hardware effects (electronic drifts, erroneous antenna temperatures); uncertainties arising in the retrieval algorithm (see [5] and references therein); and in some cases can be affected by

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[1] Another approach involved applying only dry calibrations and then comparing the GPS estimate of the wet delay to the WVR estimate of the wet delay. This produces essentially the same result as the method described above (applying wet and dry calibrations, then estimating a correction with GPS), as long as the a priori covariance on the GPS-determined tropospheric delay parameters is unconstrained (large).

the amount of liquid water present in the form of rain, fog, or clouds. The retrieval algorithm [10] used in this study incorporates surface meteorological data to constrain the temperature profile of the atmosphere. The WVR tipping data were combined to produce an equivalent zenith wet path delay. This wet delay and the dry zenith delay (the latter determined from surface barometric pressure data), when used to calibrate GPS data, were mapped to the appropriate GPS line-of-sight elevations with an analytic formula [11]:

$$\rho = \rho_{z_d} R_d(\theta) + \rho_{z_w} R_w(\theta) \qquad (1)$$

where ρ_z is the zenith tropospheric path delay, R is the analytic mapping function, θ is the elevation angle, and w or d refers to the wet or dry components. To first order, both functions R_d and R_w behave as $1/\sin(\theta)$.

GPS data are also sensitive to tropospheric path delays since all the GPS signals pass through the troposphere prior to ground reception. The GPS receivers have the benefit of tracking multiple GPS satellites simultaneously through a variety of different elevations. The GPS carrier-phase data type has several-millimeter precision and when continuously tracked, which is the normal procedure, is sensitive to subcentimeter atmospheric fluctuations. By fitting tropospheric delay parameters to the induced signatures in the pre-fit residuals, GPS data can determine an effective zenith delay. Experiments with GPS data [5,6,7] as well as covariance analysis [12] have demonstrated that estimates of GPS orbits and of GPS-determined ground station coordinates are very sensitive to uncalibrated tropospheric delays. For example, wet tropospheric delays would be the dominant error for GPS orbits [13] and for ground baselines [12] if the data were uncalibrated and no troposphere parameters were estimated.

Figure 1 shows the difference between the GPS and WVR wet zenith troposphere delay estimates at two Mexican sites. The Mazatlan WVR was an R04 model, which uses two frequencies (20.7 and 31.4 GHz), while the Cabo San Lucas model was a J01 model, which is a newer instrument with three frequencies (20.7, 22.3, and 31.4 GHz), has lower noise, and is believed to be more reliable than the R04. The Mazatlan GPS estimates are in good agreement with the WVR, with better than 1-cm root-mean-square (rms) difference, although there appears to be a slight bias offset between the WVR and GPS estimates. Note that an error in the dry calibration would be absorbed into the GPS wet troposphere estimate, thereby leading to a potential bias between the GPS and WVR wet delays. Since the accuracy of the dry calibration is believed to be several millimeter [5], such biases would presumably be small. The comparison at Cabo San Lucas shows excellent agreement between GPS and WVR with just a few millimeter difference. Figure 2 compares the GPS-determined *total* tropospheric zenith delay with the sum of WVR wet+dry calibrations for Mojave, CA, and for Limon, Costa Rica. In both these cases, the WVR and GPS zenith delays agree to one centimeter or better (rms). Again, there is a small (several-millimeter) bias offset between the GPS and WVR+dry estimates of the tropospheric delay. The WVRs used at Mojave and at Limon were both two-frequency models (type R07, which is an older model, and type D1, which is a newer model). Figure 3 shows comparisons of total tropospheric delay with GPS and the WVR+dry zenith delay for Haystack, MA, where a modern three-frequency J01 WVR was used. In addition to showing subcentimeter agreement, it is notable that Fig. 3 shows that *both* the GPS and WVR techniques seem to track the *same* rapid variations in zenith delay on both days. These variations of several centimeters over several hours are unusually large and were rarely seen even in much more humid sites in South and Central America where the total wet path delays were often larger than 30 cm. Nearly all the variation seen in Fig. 3 is due to changes in the wet troposphere.

Figure 4 compares daily baseline repeatability in the Gulf of California using GPS troposphere calibrations and using WVR troposphere calibrations. In a majority of the baselines, the GPS calibrations improved the rms baseline scatter over the rms scatter with WVR calibrations, particularly in the vertical component. These results suggest that calibrations based on GPS estimates of tropospheric delays, in some cases, may be more accurate than those obtained from WVRs and separate dry tropospheric calibrations. One advantage of the GPS tropospheric delay estimates is that they can absorb and correct for any dry calibration errors, while the WVR measures only the wet component and the final calibration will still include any dry calibration error. Another factor that may be relevant to Fig. 4 is that the GPS troposphere estimates are averages along the same lines of sight from which GPS observations were used to determine the baselines, while the WVR and dry calibrations are essentially averages over the whole sky. Due to spatial inhomogeneities, it might be expected that the GPS calibrations would be more correct to use with the GPS data if their intrinsic accuracy were comparable to the accuracy of the WVR calibrations. One additional possibility, which cannot be evaluated presently, is that the GPS tropospheric delay parameters are absorbing some other, unknown systematic error in the GPS measurement system. In light of the close agreement between WVR and GPS troposphere calibrations, however, the author believes that this latter possibility is unlikely.

IV. Discussion

A. Elevation Dependence

In the data analyzed here, GPS scans were made as low as 7 deg from the horizon. The WVR elevation cutoff, however, was about 25 deg. The relatively high WVR cutoff is necessary to avoid ground spillover contamination of the signal (the WVR beamwidths were about 8 deg). For DSN applications, this elevation cutoff may be a concern since intercontinental VLBI observations often require low elevation measurements (below 10 deg) for at least one site. It is desirable to make tropospheric delay calibrations in these cases using data at low elevations. The ultimate low elevation limit for GPS observations is probably determined by ground multipath. Approximately 2 percent of the GPS experimental data analyzed here were below 15 deg. Ground-station coordinates estimated with and without the low elevation data agreed to about 1.5 cm or better. When the GPS data were reprocessed and the low elevation data were *excluded*, daily baseline repeatability *worsened* slightly (by ~ 1 cm) in the vertical for four out of six baselines involving the relatively wet Mexican sites in the Gulf of California. The GPS–VLBI 2000-km baseline (between Hatcreek, CA and Fort Davis, TX) comparison was also slightly *worse* when the GPS low elevation data were *excluded*. The best results were obtained using *all* the GPS data, including low elevation data. Other baselines, such as the Mojave–Owens Valley 245-km baseline in California also showed better GPS–VLBI agreement when *all* the GPS data were used. These results seem to indicate that such low elevation data can actually enhance GPS system accuracy, probably through improved troposphere calibrations. The capability to include low elevation data is a definite advantage for using GPS measurements to calibrate tropospheric delays.

B. Flexibility

The GPS technique is flexible and can be combined with other tropospheric delay calibration methods if they are available. For instance, GPS data can be used to estimate the *entire* tropospheric delay, wet+dry.[2] Or, if dry calibrations are available, GPS estimates of just the wet contribution can be made. With WVRs, not only are separate and simultaneous dry calibrations required, but any error in the dry calibration will bias the final answer. However, the GPS wet tropospheric delay can be estimated as a correction on top of the dry calibration, so it will absorb any dry calibration errors easily and correct for them also by lumping them into the effective wet path delay.

GPS observations measure the mean tropospheric path delay for the lines of sight to satellites viewed simultaneously at a given time. The measurement intervals can be relatively dense (every second) or sparse (every five minutes), depending on how often the troposphere calibrations are needed. In the GPS field experiments, data rates were typically between two and five measurements per minute, and the data were later compressed to six-minute intervals. With the currently used ground tracking networks, which tend to be rather sparse, and the relatively small number of transmitting GPS satellites, formal errors computed in the Kalman filter for the GPS tropospheric delays were between 0.5 and 2 cm with multiday arcs, with 1.25 cm a typical value. This would apply to possible *biases* in the measured troposphere delays. An upper limit on the formal uncertainty for *point-to-point variations* (GPS points are six minutes apart) in the troposphere parameters is set by the process noise model used, about 0.3 cm in this instance. This is consistent with the centimeter-level and subcentimeter agreement shown in Figs. 1 through 3, which indicate, in fact, that these formal errors, at least for the bias portion, may be conservative.

A covariance analysis was performed to determine what expected performance would be in the 1990s with a full GPS constellation (21 satellites plus three spares) and a worldwide tracking network consisting of advanced GPS receivers at the three DSN sites and seven other sites worldwide. A similar worldwide network with at least six ground sites will be operating in support of the TOPEX/POSEIDON mission [14], scheduled for launch in 1992. Furthermore, a similar geodetic worldwide GPS ground network is presently operating [15] and this network is expected to expand in the near future. The data from this network are and will continue to be distributed to interested users. The covariance analysis predicts that with a 12-hr GPS tracking arc, tropospheric zenith delays from GPS will have an accuracy of 0.2–0.5 cm over the entire data arc. Figure 5 shows an error budget for the tropospheric delay accuracy at a representative time in the middle of a 12-hr GPS pass based on a consider error analysis in which the DSN station locations, the geocenter, and gravitational constant (GM) are considered as systematic (unadjusted) error sources. The expected root-sum-square

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[2] When the *entire* delay was estimated in this study with a single parameter, the dry mapping function was used. In principle, this is not entirely correct, since the dry mapping function would apply to ~ 90–95 percent of the total delay and the wet mapping function should be used for the remaining ~ 5–10 percent portion due to water vapor. A more exact approach would be to estimate a wet delay parameter and a dry delay parameter with approximate nominal values of 200 cm and 15 cm, respectively. A calculation (D. Tralli, 1989, personal communication), however, shows that the error resulting from using the dry mapping function for the entire delay was a few millimeters or less for the geometries in the GPS experiments in this study, and in fact was too small to be detected.

(RSS) error is about 0.3 cm for the zenith tropospheric path delay estimate returned every 10 min. This assumes that the GPS-determined DSN baselines are accurate to 3 cm per component and that GPS can determine the geocenter to 5 cm per component (see Table 1). Present-day accuracy for GPS baselines of several thousand kilometers is about 2 cm [8], and it is expected that several-centimeter accuracy will be achieved over intercontinental baselines in the near future with GPS. GPS measurements presently show little sensitivity to the geocenter because of the sparseness of the current constellation, but by the mid-1990s, it is expected that the geocenter will be determined to better than 5 cm from GPS observations [16].

There are other possibilities for using GPS tropospheric delay estimates in conjunction with other techniques. As suggested in [17], it may be promising to combine GPS calibrations with WVR data for determination of fluctuating dry and wet path delays. Another approach utilizes GPS data to calibrate out possible biases that can affect WVR measurements. Or, as Figs. 1 through 3 suggest, in the absence of WVRs, GPS technology alone can provide centimeter-level tropospheric delay calibrations even with only a partial GPS constellation and ground network. This represents about a factor of five improvement over available calibrations at the DSN from surface data [2]. The ultimate, yet-to-be determined limitation on the GPS calibrations for deep-space tracking will probably be due to the fact that the GPS lines of sight do not, in general, coincide with the lines of sight to the spacecraft of interest [17].

C. Operational Considerations

Two major considerations for operational tropospheric calibration at the DSN are the amounts of temporal and spatial information on the troposphere provided by various different calibration techniques.

The GPS troposphere estimates provide a thorough time history of zenith tropospheric delays since the tropospheric parameters are adjusted stochastically in a square-root Kalman filter using continuous GPS data. When a worldwide tracking network is used, however, there can be some delay expected in bringing all the data together for processing. For applications where near-real-time turnaround is needed (such as a planetary mission encounter), there are several possibilities for using GPS. Technology is presently being developed by the National Aeronautics and Space Administration (NASA) for continuously operating GPS networks [18], which return GPS orbits and related parameter estimates in less than a day. The new technology involves new hardware and software inside the GPS receivers that can handle in real time much of the processing that is currently done after data from different sites are brought together. Although these continuously operating networks are being designed for monitoring crustal motion and advanced earthquake detection, the same technology could be used for near-real-time monitoring of tropospheric delays and satellite navigation. Since GPS orbit prediction with better than 1-m accuracy has been demonstrated [8], such predictions might make simultaneous orbit/troposphere estimation unnecessary, considerably reducing the amount of calculation needed to determine tropospheric delays from GPS observations at the DSN. Considerations such as these will be studied in future analyses.

In principle, a WVR can be operated in a co-pointing mode to better calibrate line-of-sight tropospheric path delays in the direction of the spacecraft being tracked. The accuracy of line-of-sight WVR calibrations, however, has yet to be demonstrated. In practice, however, line-of-sight WVR calibrations will not be effective below the minimum elevation angle for the WVR, which is presently about 25 deg due to the large radiometer beamwidth. This reduces considerably the scope for using co-pointing WVRs since most intercontinental VLBI observations and many one- or two-way DSN tracking observations are made at lower elevations. It is expected that low-elevation WVR performance will improve in the future with the development of WVRs with narrower beamwidths. One relevant future study would compare the accuracy of GPS tropospheric delay calibrations and WVR calibrations for VLBI and/or conventional DSN observations made at low elevation. There may be some advantage to using the GPS data due to the inclusion of low elevation data. A co-pointing WVR would have the advantage of being directed towards the general area of the sky of the target spacecraft, but would have the disadvantage of having to use data from higher elevations only. In each case, a compromise is made, and a detailed study of the trade-offs would be desirable. Perhaps the ultimate troposphere calibration system would utilize some combination of GPS and pointed WVR measurements, appropriately weighted. There are also methods for minimizing the error in the GPS calibration by mapping troposphere delays from the GPS closest to the target spacecraft [17].

V. Summary and Conclusions

A demonstration of a centimeter-accurate estimation of time-varying tropospheric path delays using GPS observations and a square-root Kalman filter has been completed. The accuracy of the GPS zenith delays is comparable to that of delays determined from WVRs. The WVR- and GPS-determined zenith tropospheric delays agree at the centimeter-level or better, a five-fold improvement over present-day calibrations routinely available at the DSN. The GPS results are consistent with the formal errors from covariance analysis, and as the GPS constellation is filled out in the early 1990s with worldwide ground tracking, the GPS zenith tropospheric delay estimates should further improve to better than 0.5 cm.

The use of GPS as a tropospheric calibration system for the DSN is attractive for a number of reasons. These include: the use of GPS hardware already procured and used at the DSN for ionospheric calibrations; high-precision and complete sky coverage of GPS; flexibility of GPS-based calibrations, with a capacity for both wet and dry tropospheric calibrations; continuous tracking of GPS, and therefore continuous return of fluctuating tropospheric delay estimates as a function of time; high sensitivity of GPS data to the troposphere and the capability to measure path delays in the presence of clouds, fog, and even rain; and the possibility for eventual near-real-time turnaround with advanced receivers currently being developed elsewhere by NASA. Although the GPS calibrations require the presence of a ground tracking network, such networks are presently operating and will be considerably expanded and improved by the time the GPS constellation is complete. The data from these networks are presently distributed to users worldwide, and in the future could be used to complement the primary GPS data collected at the DSN. The primary disadvantage of GPS troposphere calibrations is expected to be that GPS lines of sight and the line of sight to the spacecraft being tracked will not, in general, coincide.

Since GPS data are easily obtained and GPS-based tropospheric calibration appears to be so promising, it should be pursued as a potentially important technique at the DSN that can substantially reduce the effect of tropospheric delay errors on deep-space observations.

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Table 1. Assumptions for covariance analysis

Estimated parameters	A priori uncertainty
GPS orbital states	2 m per component (position) 0.2 mm/s per component (velocity)
GPS solar pressure parameters	0.25 scale for x, z coefficients 10^{-12} km/s Y-bias parameter
Non-DSN station coordinates	10 cm per component
Clocks and carrier phase biases	1 km (clocks estimated as white noise)
Wet zenith tropospheric path delay	10 cm (bias portion) 1.2 cm/$\sqrt{\text{hr}}$ random walk stochastic model
Consider (unadjusted) parameters	Consider sigma
DSN station coordinates	3 cm per component
Knowledge of geocenter	5 cm per component
GM	1 part in 10^8
Data Noise: 5-cm pseudorange 0.5-cm carrier phase 1 meas/10 min	

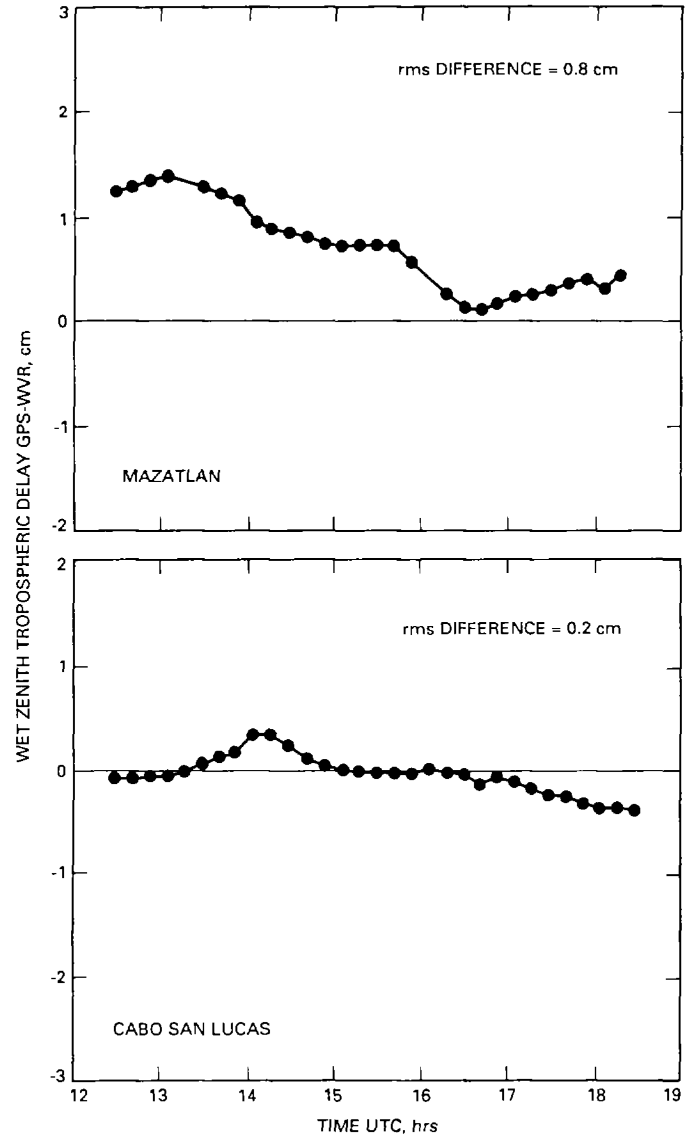

Fig. 1. Difference between GPS and WVR estimates for the zenith wet tropospheric delay estimated on November 22, 1985 at Mazatlan and on November 18, 1985 at Cabo San Lucas. Both sites are in relatively humid locations in Mexico, and during the experiment, total wet path delays of 30–40 cm were not uncommon.

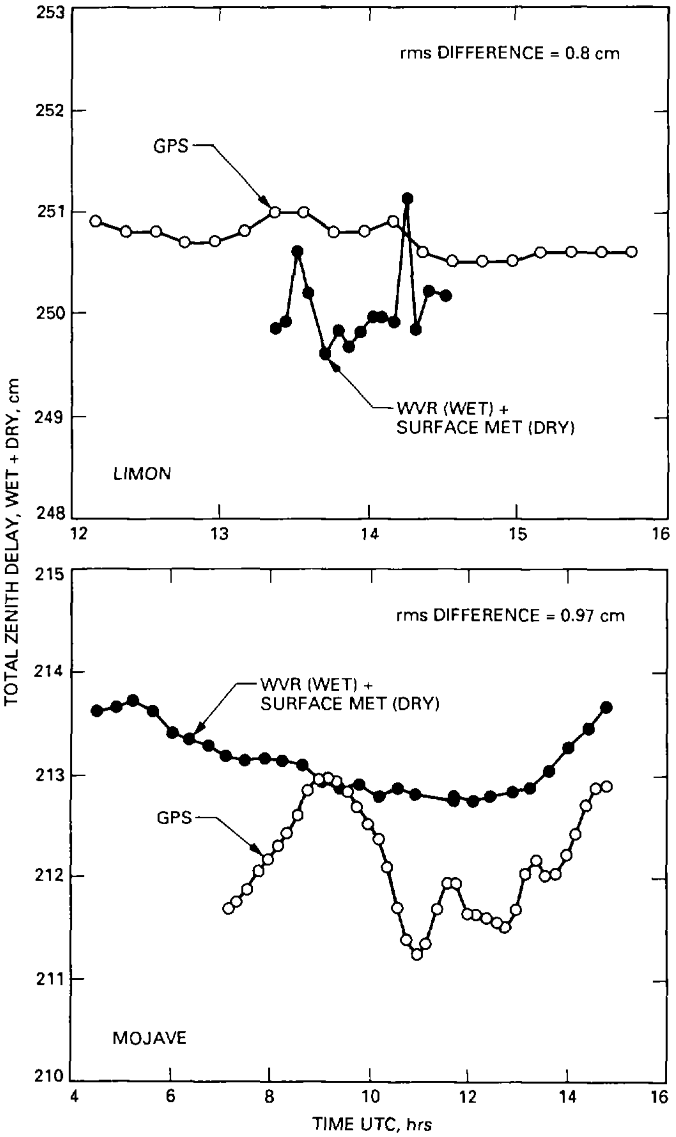

Fig. 2. Comparison of estimates of *total* tropospheric path delays determined using GPS and using the sum of WVR-measured wet delays plus dry delays from surface data. The comparison is shown for Limon, Costa Rica (a relatively humid site) and for Mojave, California (a relatively dry site) both on January 21, 1988.

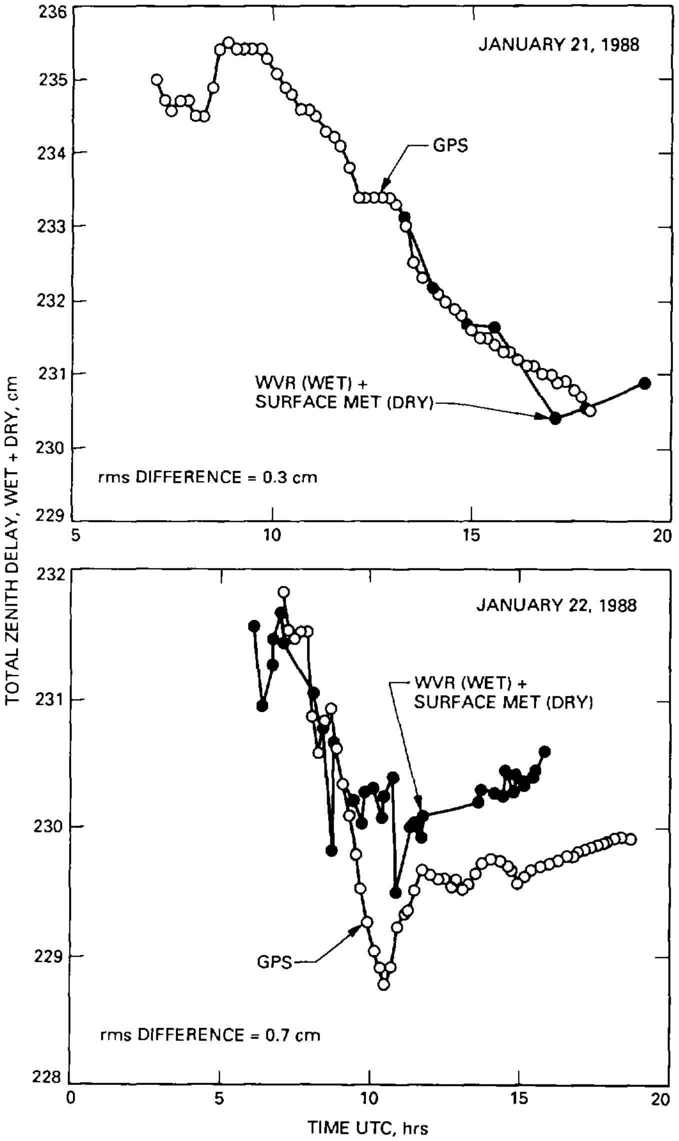

Fig. 3. Comparison of *total* tropospheric path delays from GPS and WVR+dry measurements, similar to Fig. 2, shown for the site near Haystack Observatory in Massachusetts on January 21 and 22, 1988. The subcentimeter agreement between different tropospheric delay measurement methods is sustained through periods of rapid fluctuations in the wet path delay.

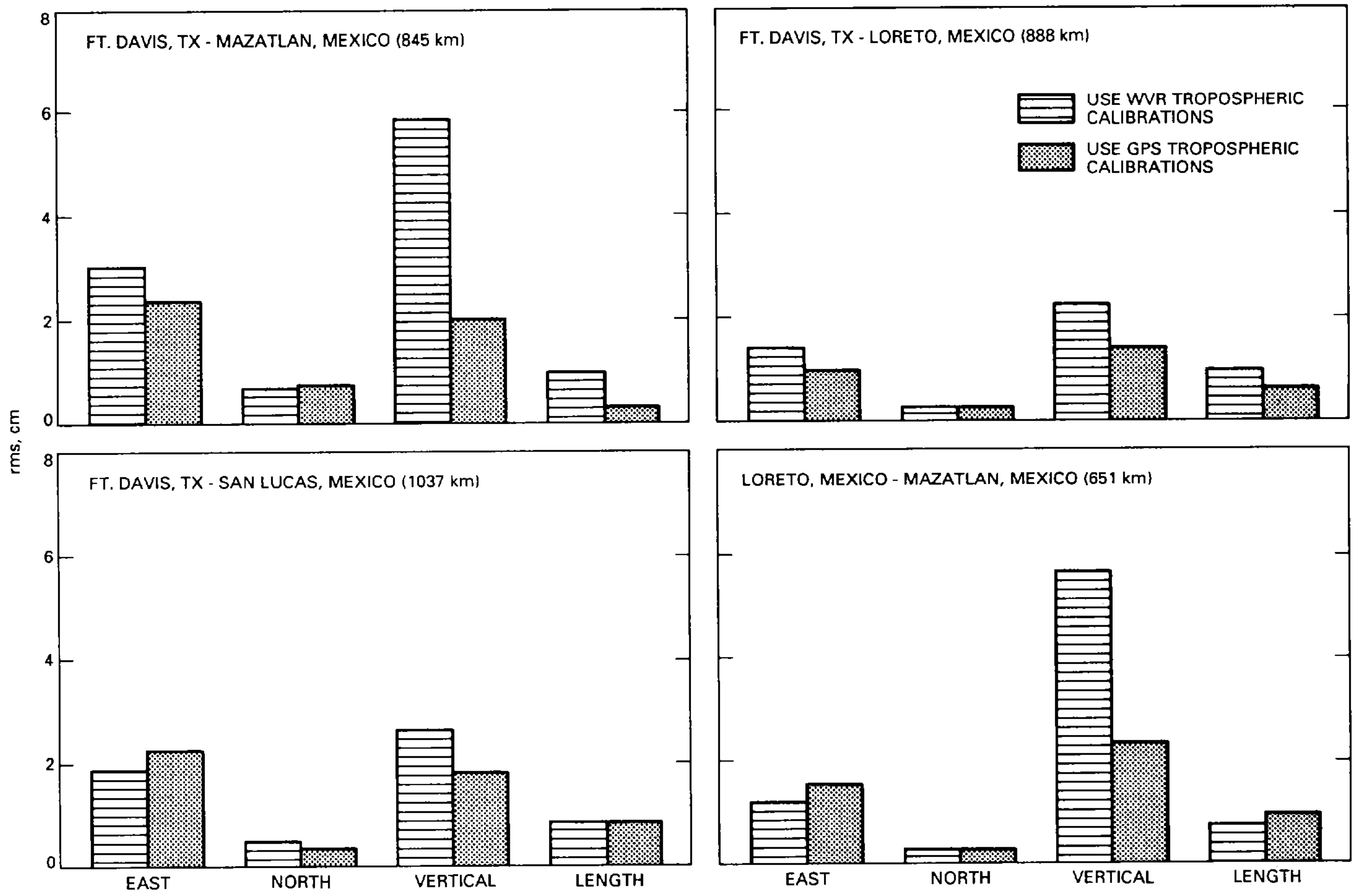

Fig. 4. Ground baseline daily repeatability from two-week GPS orbit solution arcs comparing two methods of tropospheric delay calibration: (1) using GPS, and (2) using WVRs. In most instances, the GPS calibrations resulted in lower rms scatter in the baseline estimates.

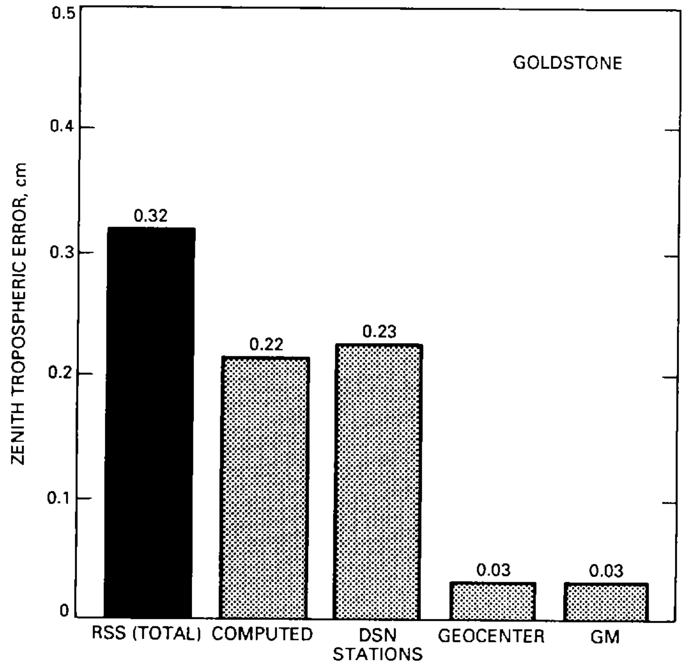

Fig. 5. Predicted error budget for zenith troposphere determination at a DSN site (Goldstone) based on the assumptions in Table 1. The "computed" error is from the square-root Kalman filter and implicitly includes effects from GPS orbits, data noise, geometry, and other estimated parameters. The other error sources are from the consider analysis and reflect quantities which are not expected to be estimated simultaneously with the tropospheric parameters: DSN station coordinates, relative location of the geocenter, and the value of GM (Earth's mass).