Ins rumental Biases in Ionospheric Measurement s
Derived from GPS Data

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Biographies

Brian Wilson, a member of the GPS Network Operations Group at the Jet Propulsion Laboratory in Pasadena, CA, has been studying the ionosphere using Faraday rotation and GPS data for five years. He is the Cognizant Design Engineer of the current operational ionosphere calibration software for the Deep Space Network, which is based on single-site GPS data and is used to correct navigation radiometric data for media effects. He continues to pursue efforts to improve the calibration system and validate its accuracy by comparisons with independent ionosphere measurements such as Very Long Baseline Interferometry, integrated dual-frequency Doppler, and the TOPEX dual-frequency altimeter. He is currently investigating the potential for using GPS data from 30–40 sites to produce hourly global ionospheric maps.

Anthony J. Mannucci is a member of the technical staff in the GPS Network Operations Group at the Jet Propulsion Laboratory in Pasadena, CA. He has spent the last four years developing and characterizing ionospheric calibration systems for deep space tracking and Earth-based satellite applications. He has over ten years of experience developing high accuracy measurement techniques in a variety of technical areas, and is currently focusing on the production of global ionospheric maps using GPS data from a worldwide network.

Abstract

Line-of-sight ionosphere measurements derived from differencing dual-frequency Global Positioning System (GPS) range data are corrupted by instrumental biases in both the receiver and GPS satellite transmitters due to hardware delays in the L1 and L2 signal paths. The line-of-sight differential delay can be modeled as the sum of a receiver bias, a satellite transmitter bias, and the line-of-sight ionospheric delay or TEC (total electron content). While the receiver bias can be calibrated directly for some types of receivers, the satellite biases must be estimated from the GPS data itself by using a model of the ionosphere. Ignoring the satellite (receiver) biases when computing TEC measurements from GPS will result in an error of ±9 (±30) TECU (1 TEC unit = 10^{16} electrons/mctcr2).

Using a global ionospheric shell model to fit GPS- based ionospheric delay data from a world-wide network of 30-40 receivers, we can estimate, with a single fit, satellite biases for the entire GPS constellation and receiver biases for all the uncalibrated receivers. Current studies indicate that the estimated receiver biases agree with the hardware calibrations at the level of 1 nanosecond (ns) and the day-to-day scatter of the estimated satellite biases ranges from 0.3 to 0.5 ns. Preliminary results show our estimated satellite biases agree with other reported values only at the level of 0.7 ns (RMS difference over all satellites). Further investigation will be required to reconcile these differences. If the true accuracy is 0.5 ns, as derived from day-to-day scatter, then the total uncertainty in line-of-sight TEC measurements derived from GPS is 0.6 ns or 1.8 TECU (1 ns corresponds to 2.85 TECU).

Introduction

Line-of-sight ionosphere measurements derived from differencing dual-frequency GPS delays are corrupted by instrumental biases in both the receiver and GPS satellite transmitters. The instrumental bias is the difference of the two dispersive delays introduced by the analog hardware in the L1 and L2 signal paths. The line-of-sight differential delay can be modeled as the sum of a receiver bias, a satellite transmitter bias, and a constant times the line-of-sight ionospheric total electron content (TEC). The receiver bias can be obtained directly from hardware calibration for some but not all receivers. For example, the Rogue receiver can be calibrated, and bias values usually lie in the range of ±10 nanoseconds (ns) of differential delay with an uncertainty of 0.2 ns. Estimates of the satellite transmitter biases indicate they lie in the range of ±3 ns or ±9 TECU (1 ns of differential delay at L band = 2.85 TECU). Therefore, obtaining absolute measurements of TEC from GPS data requires the simultaneous estimation of the satellite biases (or the sum of the biases for uncalibrated receivers).

Numerous studies have reported satellite bias values derived from various estimation strategies [B. D. Wilson, *et al*, 1992; G. E. Lanyi and T. Roth, 1988; D. S. Coco, et *al*, 1991; E. M. Gaposchkin and A. J. Coster, 1993; Esther Sardón and Lambert Wanninger, 1993; S. B. Gardner, 1993; and others]. Currently, the reported values

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do not agree at the expected level of approximately 0.5 ns of differential delay or 1.5 TEC units. The disagreement has led to some discussion of the possibility that the biases arc varying in time. Initial results from our current estimation method indicate that the satellite biases arc constant in time at the level of 0.5 ns. We believe that the large (±2 ns) temporal variations observed by some groups (including ourselves using previous techniques) may bc due to inadequacies in the ionosphere model which result in systematic errors in the bias estimates, If the biases are in fact constant, a reproducible, best set of satellite biases would be a useful contribution to the ionosphere community using GPS. The purpose of this paper is to report some of our recent bias results and discuss some of the difficulties wc have encountered in estimating the biases.

Almost all of the bias estimates reported previously by other groups have been based on data from one GPS receiver. Single-site techniques have been used for several years as part of an operational ionosphere calibration system for the Deep Space Network [Lanyi and Roth, 1988]. In 1992, we moved to what we believe is a more effective strategy of fitting data from many (30-40) receiver sites simultaneously using a global TEC model. Of course, our primary motivation in pursuing multi-site fits was the potential for producing global-scale ionospheric maps [see Mannucci, et al, 1993a, at this con ference; Wilson, *et al,* 1993; Mannucci, *et al,* 1993b; and Wilson, *et al, 1992]*. But since the ionospheric delay and the biases must be estimated simultaneously, we have found that the tasks of estimating the biases and modeling the ionosphere are intertwined and complementary. Recent improvements in our ionospheric fitting and mapping techniques have led to improved bias estimates as evidenced by reduced day-to-day scatter in the bias values. A multi-site technique allows us to bring much more data to bear on the bias estimation problem and solve for the receiver and satellite biases separately. By comparing estimates of the receiver biases to hardware calibration values for those receivers that are calibrated, we can assess the accuracy of the bias estimates. Wc have also used a strategy of performing special bias determination fits in which only nighttime data are used, since at night the ionosphere is quiet and the small horizontal gradients are easier to model, thereby minimizing systematic errors in the bias estimates due to limitations in the ionospheric modeling. With an improved TEC model, we have been able to relax the nighttime only restriction and use all the data to estimate the biases and the daytime ionosphere simultaneously.

We will present bias estimates derived from two multi-site fitting techniques which use quite different models of the vertical TEC. The first technique (denoted HARM for harmonics) uses surface harmonics as a global basis to fit 12-24 hours of GPS data. The second technique (denoted TRIN for triangular interpolation) uses local basis functions and allows for stochastic estimation to track ionospheric changes every 30-60 minutes. For the TRIN fits, the global ionospheric shell is tiled with 1280 triangles (approx. 5 degrees on a side) and the TEC at each of 642 vertices is estimated by local interpolation of the GPS data within the triangles. These models are described in detail in Wilson, *et al, 1993* and Mannucci, et *al,* 1993a. A summary of the various parameters characterizing the HARM and TRIN models is given in Figure 1. Early results indicate that bias estimates derived from TRIN fits exhibit a smaller day-to-day scatter than the HARM bias estimates and appear to support the claim that the biases are constant in time. We will also compare our satellite bias estimates to values obtained by other researchers. Finally, we will present a suggested error budget characterizing the accuracy of line-of-sight TEC measurements derived from GPS data.

Ionosphere Model and Intimation Technique

Both the HARM and TRIN models assume a thin spherical shell model similar to that described in Lanyi and Roth, 1988. The shell model assumes that the

	HARM	TRIN
TEC model	2-D shell model approximation	2-D shell model approximation
Vertical TEC fit to	8th order surface harmonics	Triangular grid, 642 vertices
Support of the basis set	Global	Local, interpolation within triangles
Spatial resolution	Continuous	5 degrees in latitude& longitude
Temporal resolution	4-24 hours; maps are time averages	Every 30 minutes; can track short-term changes
Parameter estimation	No stochastic	TEC at each vertex is treated as a random walk
Defects	Not 3-D; averaging over temporal changes leads to systematic mismodeling, corrupting the bias estimates	Not 3-D; current basis set is too local—derivative is not continuous across triangle boundaries; computationally intensive
Day-to-day scatter of our estimates of the satellite biases	0.7 -1.5 ns	0.2 -0.5 ns

Figure 1 — HARM versus TRIN: a summary of the parameters characterizing the two models.

vertical TEC can be approximated by a thin spherical shell at a fixed height of 350 km. The TEC is also assumed to be approximately independent of time over several hours in a "solar-magnetic" reference frame in which the latitude is geomagnetic latitude and the zero of longitude is nearly fixed with respect to the Earth-Sun axis. This is a reasonable assumption as the two principal drivers of the ionosphere are solar radiation and the Earth's magnetic field, The longitude axis actually "wobbles" back and forth ±11 degrees with respect to the Earth-Sun axis every 24 hours. (It is not possible, of course, to define an orthogonal coordinate system that is simultaneously fixed with respect to the Sun and the geomagnetic equator.) The intersection of the line-of-sight from the receiver to the GPS satellite with the spherical shell defines a "shell" latitude and longitude. The line-of-sight TEC is then assumed to be related to the vertical TEC by an elevation mapping function M(E), which is the simple geometric slant ratio at the shell height h:

$$M(E) = \{1 - [\cos E/(1 + h/R)]^2\}^{-1/2}$$

where E is the elevation angle and R is the radius of the earth. The line-of-sight differential delays for the ith receiver looking at the jth GPS satellite can be modeled by the following expression:

$$\tau^{LOS}_{ij} = \tau^r_i + \tau^s_j + K\, M(E_{ij})\ TEC(\theta_{ij}, \phi_{ij})$$

where τ^{LOS}_{ij} is the line-of-sight differential delay, τ^r_i is the bias for the ith receiver, τ^s_j is the bias for the jth satellite transmitter, K (= 2.85) is a constant relating differential delay at L band in nanoseconds to ionospheric TEC in TECU, $M(E_{ij})$ is the elevation mapping function, and $TEC(\theta_{ij}, \phi_{ij})$ is the vertical TEC at shell latitude θ_{ij} and shell longitude ϕ_{ij}. The vertical TEC over the entire globe can then be fit to a surface harmonic expansion in θ and ϕ (HARM) or estimated by local triangular interpolation (TRIN), while simultaneously estimating the receiver biases for all uncalibrated receivers and all satellite biases (or their sum).

In producing large-scale TEC maps from multi-site GPS data, there is a tradeoff between shell coverage and temporal resolution. To achieve adequate shell coverage given a limited number of ground sites and the speed of the GPS satellites, a certain period of time must pass so that the line-of-sight from the ground site to the satellites can traverse a region of the ionospheric shell. However, the ionosphere is changing '(even in solar-magnetic coordinates) over hours, hence the time span of the fit should be minimized in order to optimize the accuracy and temporal resolution of the maps. The same tradeoff also applies to bias estimation. Since it is the elevation dependence of the ionosphere that allows one to separate the line-of-sight TEC from the constant biases, a certain period of time must pass so that the satellites cover a range of elevation. But the ionosphere at a fixed shell location is changing during the time span of the fit, so the ionosphere may be rnismodcled, leading to an improper separation of the TEC and the biases. Taking too long a data span results in averaging over unmodeled temporal changes in the ionosphere, which produces systematic errors in the bias estimates. The TRIN model treats the TEC at each vertex as a random walk and stochastically updates the values every 30-60 minutes so it is less susceptible to time-averaging errors than HARM. TRIN can track short-term ionospheric changes and therefore should yield more accurate biases than HARM.

The two-dimensional shell mode] is obviously a simplification. The notion of "mapping to vertical" only makes sense when horizontal TEC gradients are not too large. The assumption that the ionospheric shell height is constant everywhere is also an approximation. If the actual equivalent shell height is larger than 350 km, then mapping errors at low elevation will cause the ionosphere to be underestimated and *vice versa.* These systematic errors in the elevation mapping function at low elevations will corrupt both the ionosphere and bias estimates. To mitigate this problem, we use only data with elevation angles above 20 degrees. This kind of elevation-dependent ionospheric mismodeling can be minimized only by moving to a three-dimensional ionosphere model in which the TEC observable is properly modeled by integrating ionospheric densities along the line of sight.

For all the reasons described above, the bias values obtained from any one fit may be corrupted by incorrect fits to the ionospheric TEC. However, assuming the biases arc constant on a time scale of weeks to months, improved bias estimates may be obtained by averaging the values from many fits over 10-15 days. To further reduce the effects of ionospheric rnismodeling, the estimation procedure can be applied using only nighttime data when the ionosphere has smaller spatial gradients and is relatively constant in time and therefore less susceptible to modeling errors. Nighttime data are defined to be those observations with ecliptic shell longitudes in the nighttime quadrant opposite the sun.

The multi-site dataset allows one to solve for the receiver and satellite biases separately since lines of sight from neighboring receiver sites will overlap on the ionospheric shell. Since the observable is sensitive only to the sum of the receiver and satellite biases, one or more of the receiver biases are constrained tightly to *a priori* values based on periodic hardware calibrations, while the rest of the receiver biases and all of the satellite biases are essentially unconstrained. This strategy allows one to estimate absolute levels for the satellite and receiver biases. Constraining several receiver biases simultaneously may reduce sensitivity to a single erroneous receiver calibration.

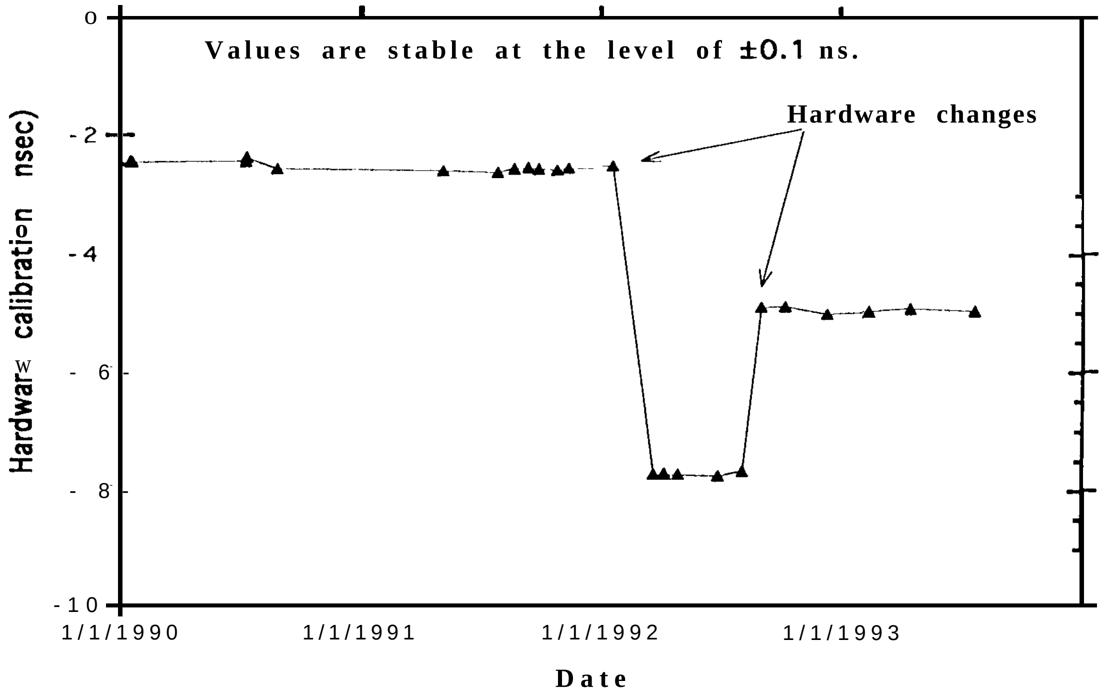

Figure 2 — Three-year history of hardware calibrations for the Goldstone Rogue receiver.

Results

I. Receiver biases—measured versus estimated

The Rogue receiver developed at JPL has a hardware calibration mode in which one connects a jumper cable so that the same radio frequency signal is sent through both frequency (1.1 & L2) paths in the analog portion of the receiver. By averaging the difference of the two delays over 20 minutes or longer, one can directly measure the instrumental bias introduced by the particular state of the receiver analog hardware. Rogue receivers have been operated by JPL at several sites since 1990 (e.g., Goldstone, CA; Madrid, Spain; and Canberra, Australia). The receiver biases have been calibrated every few months for several years, The calibration history indicates that the receiver bias is constant at the level of ±0. 1 ns, except when a part in the analog portion of the receiver is swapped out for repair or upgrade. The new analog electrical components will in general have a different signal path delay and therefore a different calibration value,

The bias calibration history for the Goldstone receiver for the period of 1/1 6/90 to 7/21/93 is shown in Figure 2. As can bc seen from the figure, there were two hardware changes during the period, hence the hardware calibration has had three reproducible values: -2.5, -7.7, and -4,9 ns. The other two sites have shown similar behavior. At one point, the calibration at Madrid drifted by 0.5 ns necessitating a hardware swap after which the bias remained constant. Except for such anomalies, the behavior of the Rogue receiver has been so consistent that we have been able to infer when an unexpected hardware swap occurred by noting the change in the calibration value.

The receivers at all three sites have also been left in hardware calibration mode for several days to look for a diurnal (temperature-dependent) signature in the receiver bias. The time-series of calibration values was flat for all three sites with a standard deviation over 48 hours of ±0. 1-0.2 ns. Note that the receivers at these three sites are in temperature-controlled environments, Unfortunately, wc do not have continuous calibration values for other receiver sites in the global network. A receiver in a less controlled environment may exhibit diurnal or other variations in the calibration value.

This consistent behavior of the Rogue receiver over several years is encouraging. Since we have so much experience with data from Rogue and TurboRogue receivers and little with other receivers, we use only GPS global network sites that have Rogue-type receivers in our global map fits. Our experience with hardware failures indicates that one should periodically calibrate any receiver to check for anomalies. GPS receivers that do not have a calibration mode (e.g., TurboRogue) can be calibrated by collocating them with a calibrated receiver and running the same antenna feed into both receivers, Differencing the two datasets and averaging yields the difference of the two receiver biases.

Receiver Site	Hardware Calibration	Estimated Receiver Bias	Difference
ALGO	1.1	2.1	1.0
DRAO	-7.8	-8.4	-0.6
FAIR	-8.7	-8,7	0.0
GOLD	-4.9	-5.7	-0.8
HART	0.7	3,0	2.3
HOBA	-0.9	-1.4	-0.5
JPLM	-4.1	-5,0	-0.9
KOKB	5.9	4.3	-1.6
KOSG	-3.4	-3.6	-0,2
MATE	-6.7	-7.2	-0.5
MCMU	-2.3	-1.8	0.5
NYAL	-0.8	-1.5	-0,7
ONSA	0.7	2.3	1.6
RCM2	1.0	1.6	0.6
SANT	-3.1	2.8	5.9
TAIW	-8,1	-9.2	-1.1
TIDB	-3.1	-3.2	-0.1
TROM	-8.8	-8.8	0.0
YAR 1	-2.8	-3.6	-0.8

Figure 3 — A comparison of measured and estimated (TRIN) receiver biases for the period of March 12-23, 1993.

One can also estimate the receiver biases by fitting multi-site data from a global network of GPS receivers. Only one calibrated receiver is required to set the absolute level of the biases. Unconstrained estimates of calibrated receivers can be used to verify the accuracy of the filter estimates by comparing them to the measured calibration values.

Figure 3 shows such a comparison for the period of March 12-23, 1993. The receiver biases were estimated for each of the 12 days using a global TRIN fit to GPS data from 38 sites, The 12-day average of the receiver biases is shown for those sites for which we have a hardware calibration. Except for the anomalous site Santiago, Chile (SANT), the agreement is quite good. The large difference for SANT leads us to suspect that the hardware calibration is not up to date, but we have not been able to verify this yet. Excluding SANT, the mean of the differences is -0.1 ns and the standard deviation is 1.0 ns.

Although we have done these comparisons only for limited periods, it appears that wc have a rough capability to calibrate a receiver simply by including its data in a global fit. We can certainly track the large changes in receiver bias which occur when the receiver hardware is changed. Figure 4 shows a plot of the day-to-day scatter in the receiver biases for daily global HARM fits of 19 sites during the period Jan. 22- Feb. 13, 1991. Note that the biases are flat for three of the sites, while the PGC 1

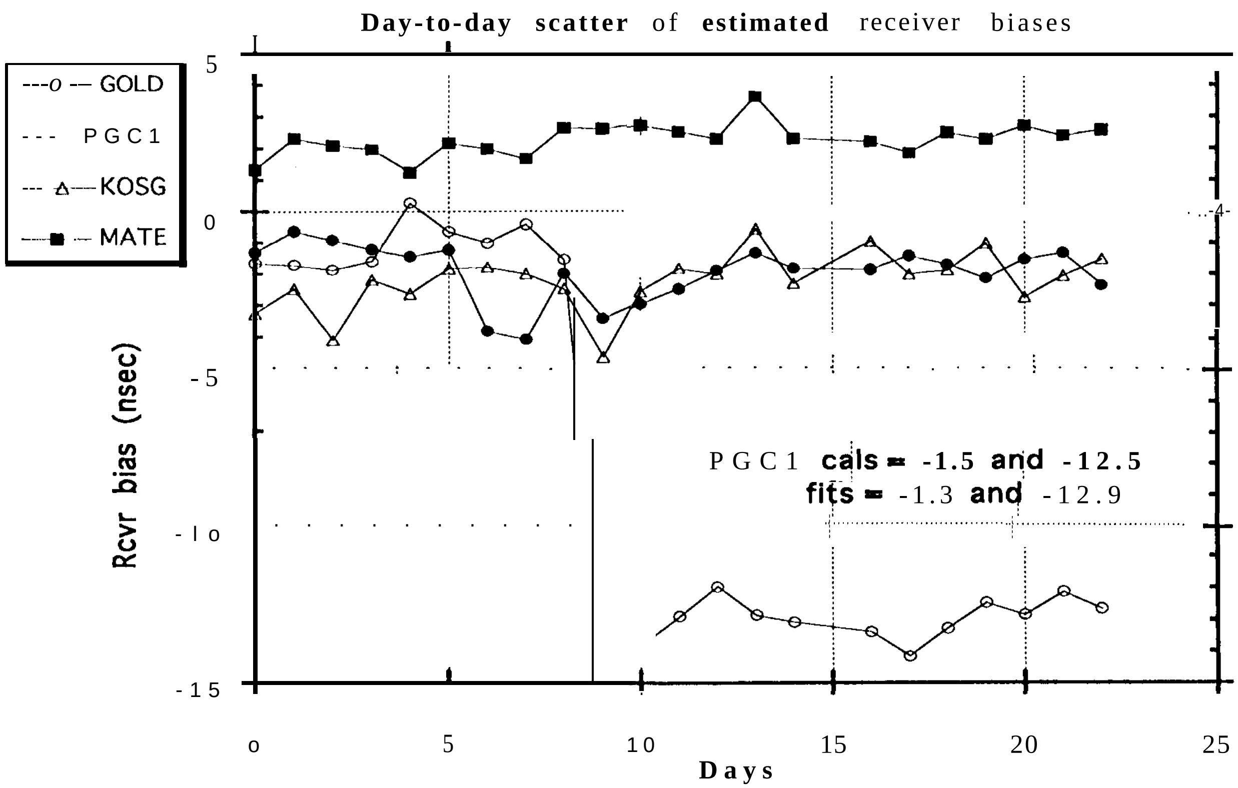

Figure 4 — Receiver bias day-to-day scatter from 4 of the 19 sites in global HARM fits for the period Jan. 22 - Feb. 13, 1991. The fits were able to track the change in the receiver bias at PGC1 caused by a hardware change.

site exhibits two distinct levels. We discovered after the fact that the hardware calibration at PGC 1 changed from -1.5 ns to -12.5 ns on Jan. 31 due to a hardware change. The average of the daily receiver bias estimates is -1,3 ns before Jan. 31 and -12.9 ns afterward, which agrees well with the calibrations.

11. Estimated satellite biases

In order to improve the accuracy of our ionospheric global maps, we have improved the ionosphere modeling by moving from a surface harmonics (HARM) model to a triangular interpolation (TRIN) model which treats the TEC at each vertex as a random walk, We have found that using TRIN also reduces the day-to-day scatter of the estimated satellite biases, presumably because TRIN does not average over short time-scale changes in the ionosphere as HARM does. As a test case, we used GPS data from 38 sites for the 12 days of March 12-23, 1993 and performed both HARM and TRIN fits. The absolute level of the biases was set by constraining the Madrid receiver bias to its calibration value of 8.3 ns. Figure 5 shows a table of estimated satellite biases and day-to-day scatters derived from daily HARM fits of nighttime data only. The quoted biases and scatters are the averages and standard deviations of the 12 daily values. Note that the scatters range from 0.7 to 1,8 ns. Figure 5 also shows the same biases derived from TRIN fits of all the data, both day and night. The TRIN scatters range from 0.2 to 0.5 ns. Even though TRIN has to track the larger gradients of the daytime ionosphere, the TRIN satellite biases still exhibit a day-to-day scatter which is substantially smaller than tbc HARM biases, indicating that there is much less systematic mismodeling of the ionosphere.

Figure 6 illustrates the typical day-to-day scatter for two satellite biases (PRN#'s 13 and 15) derived from three different fits: the March HARM and TRIN fits described above and another 12-day TRIN fit in August 1993. The levels of the biases have been adjusted arbitrarily in order to separate the lines for visibility. The top two lines are the March HARM biases; the middle two are March TRIN; and the bottom two are August TRIN. Notice that the TRIN scatter is much lower than that of HARM for March, and the August TRIN scatter is even smaller since the ionosphere was so quiet during the period August 6-17. The other feature of interest for the HARM bias estimates (the top two lines) is that they tend to move up and down in unison. The TRIN fits also exhibit this behavior at a reduced level of variation. It is presumably systematic ionospheric mismodeling that causes all the bias estimates to move up or down in unison.

The reduced level of scatter seen in the TRIN fits strongly suggests that the biases are in fact constant in time. We believe that the apparent variations (as large as 2 ns) which have been observed are the result of ionospheric mismodeling. For HARM fits, the day-to-day scatter is about three times larger than the formal errors produced by the least-squares fits, which might lead one to believe the variations are real (assuming the data noise has been set properly). However, the variations are quite random; no reproducible trends arc evident. For TRIN fits, the day-to-day scatters are comparable to the formal errors (with the same data noise). Figure 7 shows the satellite biases with error bars derived from day-to-day scatter for January, March, and August of 1993. Although there arc inconsistencies for several satellites, the data are consistent with the claim of constant biases at the level of 0.7 ns (RMS of differences).

111. Comparisons to other studies

We have compared our values for the satellite, biases with those obtained by other groups with mixed results. Figure 8 shows a comparison to three other groups: E. M. Gaposchkin and A. J. Coster at Lincoln Laboratory (1.1.), Esther Sardón at the Instituto de Astronomic y Geodcsia (IAG), and Lambert Wanninger at the Institut fur Erdmessung (IfE). Each group has quoted bias values which are averages of data from several time periods. Unfortunately, the time periods are different for each group so this comparison presupposes that the biases are constant. The amount of data used in the averaging varies from an entire year for LL to 2 days for IfE. Also, we have not obtained formal errors for the IAG and IfE biases so we cannot rigorously decide if we are consistent with their values. Nevertheless, this is the best comparison we have assembled to date. Our values are closest to the IAG values. The differences have a mean of -0.1 ns and an RMS of 0.7 ns (2 TECU). LL's values are not consistent with our values; the RMS of the differences is 1.4 ns (4 TECU). Further investigation will be required to reconcile the differences.

IV. Preliminary TEC error budget

Line-of-sight TEC measurements derived from differential carrier-aided pseudorange measurements are corrupted by system noise, the cycle ambiguity in the carrier phase, multipath, and instrumental biases in the receiver and satellite transmitter, A tentative error budget is shown in Figure 9. Both the differential pseudorange and carrier phase provide a measure of the ionosphere, but using the carrier phase is preferable since the system noise is much lower and the carrier phase is less susceptible to multipath. However, the carrier phase has a cycle ambiguity so the pseudorange must bc used to set the absolute delay, which reintroduces some of the pseudorange multipath noise. Deciding on the proper value for the uncertainty in the satellite biases is somewhat problematic. Although our day-to-day scatter indicates a value of 0.5 ns, comparison of our values to JAG gave agreement at the level of 0,7 ns. We have quoted the uncertainty as 0.5 ns.

The total RSS error is 0,55 to 0.62 ns or 1.6 to 1.8 TECU. It is dominated by the uncertainty in the satellite biases, which is why it is so crucial to reduce the bias error to 0.5 ns or less. In order to get line-of-sight TEC measurements with an accuracy of, say, 1 TECU, the

Satellite PRN #	HARM satellite bias and scatter (ns)	TRIN satellite bias and scatter (ns)
1	-1.4 ± 0.8	-0.5 ± 0.3
2	-1.0 ± 1.0	-0.5 ± 0.3
3	0.7 ± 1.2	1.2 * 0.4
11	1.1 ± 0.8	1.5 ± ().3
12	2.0 ± 1.3	2.3 ± 0.3
13	1.0 ± 0.8	1.3 ± 0.3
14	-0.7 ± 0.8	-(),6 ± 0.4
15	-1.5 ± 0.7	-0.5 ± 0.2
16	-0.3 ± 0.8	0.0 ± ().4
17	-1.4 ± 07	-0.8 ± 0,2
18	-].5 ± 1.0	-1,7 * 0.5
19	-1.6 ± 0.9	-0.6 ± 0.3
20	-1.5 ± 1.8	-0.5 ± 0.2
21	-1.2 ± ().7	-0.3 ± 0.3
22	-2.4 ± 0.6	-1.9 ± 0.4
23	-1.9 ± 0.8	-1.1 ± 0.3
24	-1.0 ± 0.8	-03 * 0,3
25	-3.7 ± 1.0	-3,0 * 0.3
26	-3.2 ± 0.9	-2.7 ± 0.3
27	-3,2 ± 1.2	-2.0 * 0.3
28	-3.2 ± 0,9	-2.5 * 0.2
29	-3.3 ± 0.8	-3.1 ± 0.3

Figure 5 — Estimates of satellite biases derived from HARM and TRIN fits of 38 GPS sites covering the 12-day period of March 12-23, 1993. The HARM day-to-day scatter ranges from 0.7 to 1,8 ns, while the TRIN scatter ranges from 0.2 to 0.5 ns.

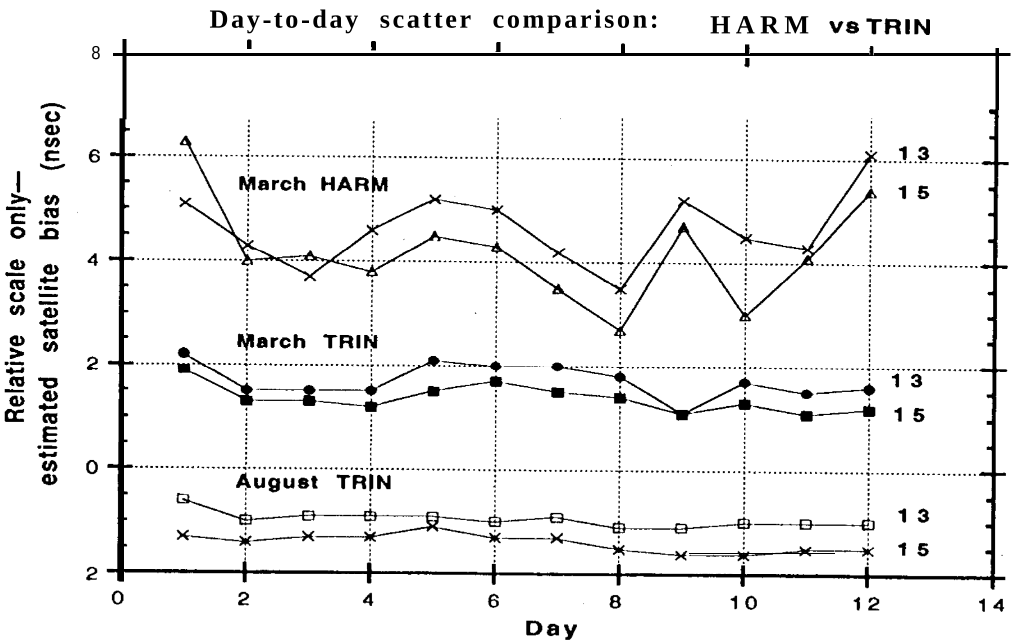

Figure 6 — A comparison of the day-to-day scatter of estimated satellite biases for three 12-day fits: (top) HARM fit in March, (middle) TRIN fit in March, and (bottom) TRIN fit in August, 1993. Two satellites (PRN#'s 13 and 15) are shown for each fit. The absolute level is correct only for the August biases; the March values have been shifted upward arbitrarily for visibility. Note the decrease in the size of the scatter from top to bottom.

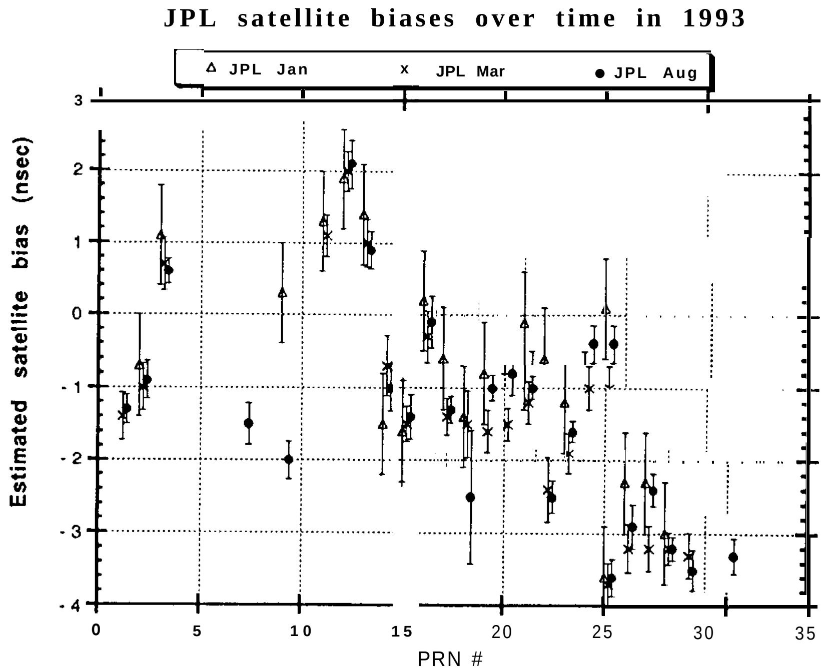

Figure 7 — Estimates of satellite biases for three periods in 1993. The data are consistent with the claim that the satellite biases are constant in time. The Mar - Aug differences have a mean of -0.1 ns and an RMS of 0.4 ns.

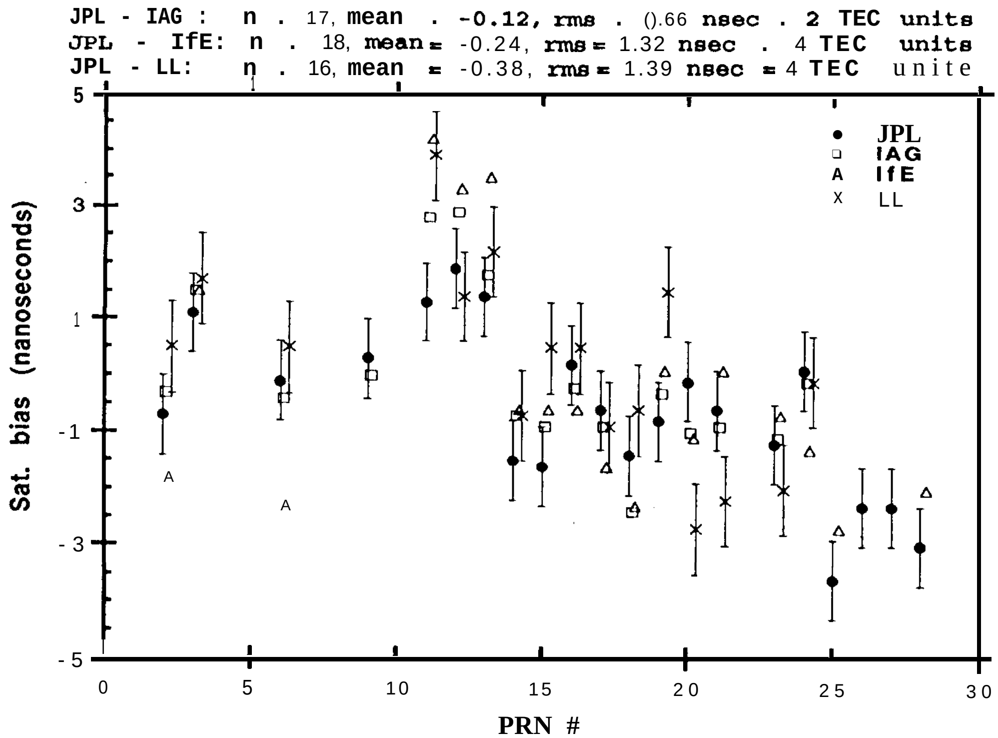

Figure 8 — A comparison of estimated satellite biases reported by four research groups. Our values are closest to IAG's values (RMS of differences = 2 TECU), and not very close to IfE and LL (4 TECU).

multipath error would have to be held below 0.1 ns and the satellite bias uncertainty below 0.25 ns. To push the uncertainty in the satellite biases that low, further improvements in the TRIN ionosphere mode] will be required.

Error Source	Error (ns)
Carrier phase noise (30 Sec integration)	≤0.01
Antenna phase center offset (L 1 vs. L2) in both receiver and satellite	<0.04
Uncertainty in leveling the carrier due to pseudorange multipath noise	0.1 -0.3
Receiver bias uncertainty	0.2
Satellite bias uncertainty	0.5
RSS	0.55 - [illegible]

Figure 9 — A preliminary error budget for line-of-sight TEC measurements derived from GPS differential delay measurements.

Conclusions

The problem of estimating the instrumental biases in the GPS satellites using the GPS data itself is difficult because onc must simultaneously estimate the TEC using a model of the ionosphere. We have been able to reduce the day-to-day scatter in our estimates of the satellite biases from around 1.0 ns to below 0.5 ns by improving our ionosphere model and estimation strategy. This suggests that the biases are in fact constant in time at the level of 0.5 ns. We anticipate that we can reduce the scatter further by continuing to improve the TRIN ionosphere model.

The disagreement between the reported bias values of various groups is not surprising in view of the various estimation strategies employed and the preliminary nature of the comparison. More direct comparisons are needed to reconcile the differences. A definitive answer to the difficult bias estimation problem may require that we abandon the two-dimensional approximation of a shell model in favor of a full three-dirnensional mode} in which the GPS observable is correctly modeled by integrating ionospheric densities along the line of sight.

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