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THE USE OF IONOSPHERIC DATA IN GPS TIME TRANSFER

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ABSTRACT

With solar activity near maximum, the largest error in the use of the Global Positioning System (GPS) for common-view time transfer can be the correction for ionospheric delay. This paper describes the use of data from two different codeless ionospheric measurement systems to correct common-view time transfer measurements. We first describe the design of the systems, then look at the data. We compare the measured ionospheric values with those from the ionospheric model parameters broadcast from the GPS satellites, computing time transfer values among three time standards laboratories: Observatoire de Paris, Paris, France; National Institute of Standards and Technology, Boulder, Colorado, USA; and Communications Research Laboratory, Tokyo, Japan. Combining these time transfers we can obtain closure around the world. Since this closure should add to zero, we obtain a clear measure of the quality of the overall time transfer system. We make another comparison between these results and ionospheric measurements using a Faraday rotation system.

INTRODUCTION

For most of the last decade, solar activity has been low and the contribution of the ionospheric delay model error to the error budget for GPS common view time transfer has been tolerable [1]. However, since the model accuracy is about 50%, an increase in the overall delay increases the error in using the model. Now that we are approaching a maximum in the approximately 11 year sunspot cycle, the L1 ionospheric delays are approaching 100 ns for the low angles used for intercontinental time transfer. We therefore need to be able to measure the ionospheric delay rather than use the parameters from the transmitted model. Cost and security dictate that we consider only a codeless type receiver, as opposed to a unit that fully decodes the precise code (P-code).

Two such calibrators with somewhat different designs are used in this study. M. Imae built a calibrator with the support of the Bureau International des Poids et Mesures (BIPM) while employed at the Communications Research Laboratory (CRL). The first prototype of these BIPM type calibrators is still operating at the BIPM. An improved commercially available version is located at CRL, Kashima Space Research Center (SRC). Data from both of these were used in this paper. A different calibrator was built at the National Institute of Standards and Technology (NIST), and this design is now being deployed at various locations around the world. For this study, data from the NIST type of calibrator were available primarily from that at NIST, with a small amount of data available from an identical calibrator at the Observatoire de Paris (OP).

For this paper, ionospheric measurements were applied to GPS data from MJD 47886 to 47913, much of the month of January, 1990. For data from Paris, we used the calibrator at the BIPM to correct GPS data from OP. In Japan the ionospheric calibrator was at Kashima SRC and the GPS receiver was at the CRL laboratory at Koganei about 100 km away. In Boulder, both the NIST ionospheric calibrator and a GPS receiver were located at NIST. The GPS data were taken according to the BIPM schedule at each location, thus insuring simultaneous measurements pairwise between locations.

Calibrator Design: The BIPM Calibrator

The BIPM calibrator conceived and built by Michito Imae was the first codeless ionospheric calibrator. It measures the ionospheric delay by measuring the relative delay of the phase of the received P-code clock between the two L-band GPS frequencies, L1 and L2. These frequencies are 1.575 GHz and 1.228 GHz respectively. Since the delay of the P-code through the ionosphere is inversely proportional to the square of the carrier frequency, the total phase delay of the code on either frequency is proportional to the differential phase change between them. We illustrate this below. Let:

dphs1 = the change in phase of the code at L1.
dphs2 = the change in phase of the code at L2.

Since the L1 frequency is 154 times the P-code clock frequency, N = 10.23 MHz, and L2 is 120 times the same frequency, we may write

$$dphs1 = k/(154*N)^2, \quad \text{and} \quad dphs2 = k/(120*N)^2,$$

where k is proportional to the total electron content along the signal path.

If the code starts out in phase between L1 and L2, then we measure (dphs2 - dphs1), the differential phase change. The total delay on L1 then is:

$$dphs1 = [dphs2 - dphs1]/[(154/120)^2 - 1].$$

Thus, the total delay is proportional to the received phase difference. As suggested by MacDoran prior to 1982, the differential phase between the L1 code and the L2 code can be measured without knowing the code itself, since it is the same on both frequencies [2,3,4].

The BIPM calibrator has been described in detail elsewhere [5,6], so we simply outline its construction here. The systems at the BIPM and at CRL both receive the L1 and L2 signals through a directional antenna which provides some gain, cuts back multipath effects, and helps eliminate interference between satellites. The L1 and L2 signals are amplified and multiplied down on separate channels, then are cross-correlated. Two cross correlations are done between the L1 and L2 channels: one direct, and one with a fixed delay in the L1 channel. From these two outputs, the differential delay between the phases of the two codes can be determined.

The system tracks a single satellite for 4 min, taking 1 min to point the antenna and 3 min for measurement. The noise level after 4 minutes of averaging is at the nanosecond level. The system computes total ionospheric delay of the L1 code, as well as the vertical delay. This data is stored in a microcomputer which operates the system. The calibrator tracks based on an entered schedule. The international common view schedule divides the day into 16 min tracks. The common practice is to schedule four, 4 min tracks by the ionospheric calibrator on the satellite being tracked during that 16 min according to the BIPM schedule.

The calibrator is a stand-alone unit. It needs a 5 MHz source with at least the stability of a good quartz oscillator, and an almanac of the GPS satellites no more than about 3 weeks old.

Calibrator Design: The NIST Calibrator

Like the BIPM calibrator, the NIST calibrator also was described in detail elsewhere [6], so we summarize its design here. It is also a codeless ionospheric calibrator that recovers the P-code clock on L1 and L2 and uses the phase difference to compute the L1 ionospheric delay. Major features of the hardware include dual-volute omni-directional antennas on a choke ring ground plane, very low-noise front end, and alternate L1--L2 phase sampling through a common IF channel. S/N of the recovered P-code clocks is typically positive by several decibels in a 100 Hz bandwidth. Signals are processed as 8 bit data, with all satellites in view individually (and simultaneously) tracked in real time to recover the ionospheric delay values. All processing is with an internal 8 bit CMOS microprocessor.

This system differs from the BIPM calibrator both in that it uses an omni-directional antenna, receiving signals from all satellites in view, and it samples the L1 and L2 frequencies sequentially. Instead of correlating the two signals, the NIST calibrator uses a delay-and-multiply operation to recover the P-code clocks for all satellites in view on one of the L-band frequencies, then samples this signal at 250 Hz with 8 bit samples. The software measures the phase of the P-code on that frequency for all satellites as follows. Satellites are separated by their different Doppler shifts and the rates of change of these Doppler shifts. The phases of the P-code clocks are recovered by multiplying the sampled signal by sine(-ωp) and cosine(-ωp) and summing the sine and cosine components for 7.5 s. A four-quadrant arc tangent of the quotient of the sine sum over the cosine sum yields the clock phase. Measurements on L1 and L2 are carried out sequentially; that is, L1 is measured for 7.5 s followed by a 7.5 s measurement of L2. This is analogous to the tau-dither loop in a GPS receiver and provides similar advantages and disadvantages. The major disadvantage is a degradation of the signal-to-noise by 3 dB. Advantages include greater simplicity and stability; since the same narrow-band IF is used for both L1 and L2, the potential for errors due to unequal phase shifts through separate channels is minimized.

To separate satellites and determine their code phases the NIST calibrator needs to know the Doppler shift on each satellite to better than 10 mHz. This cannot be done using the broadcast ephemeris from the satellite. Instead, the NIST calibrator uses a second-order frequency-locked loop. Phase difference from one L1 measurement to the next is used to compute frequency error in (ωp) and close the tracking loop.

When development is complete, the normal mode of operation of the ionospheric calibrator will be in parallel with a GPS coarse-acquisition (C/A) code time transfer receiver, with the measured ionospheric data automatically available to replace the modelled ionospheric data transmitted by the satellite. In this way, the ionospheric calibrator operation will be nearly transparent to the time-transfer user.

The calibrator can also be used as a stand-alone unit for ionospheric measurements, with values of L1 delay for all satellites in view available from one of the two serial ports as often as every 15 s. Also, these data are stored after smoothing for 15 min with a linear fit and are available via modem for up to two weeks, depending on the number of satellites in the system. In this mode, the calibrator must be set on time within ± 1 min and requires a copy of the GPS almanac, updated every 1 to 4 weeks. A stable source of 5 MHz power is required, preferably from a cesium or rubidium standard; however, a crystal oscillator with a drift rate of parts in 10^{-9} per day is satisfactory.

The stability of this ionospheric calibrator is 1-4 ns for 15 saverages with the ultimate limitation to accuracy being multipath interference [8]. The antennas are equipped with choke ring ground planes. The L1 radiation patterns of three ground planes were measured on the antenna test range. The ground planes provided at least 7 dB additional attenuation at 0° elevation, compared to the bare helix. Until now, it has not been determined whether noise figure or multi-path interference reduction is predominant in the measured noise reduction; however, since both a good noise figure and reduced multipath effects are desirable, the calibrators are equipped with choke-ring ground planes. Multipath interference was studied by comparing the measurements between two different calibrators. It was found that by adding microwave absorbent material inside of the inner choke ring, variations between the two systems were reduced to peak-to-peak values of a few nanoseconds.

Comparison Between the BIPM and the NIST Calibrators

In figures 1 and 2 we see three days of ionospheric delay data converted to the vertical delay, taken in Paris by the two calibrators: the NIST calibrator at OP in figure 1 and the BIPM calibrator in figure 2. The conversion assumes that the ionosphere is a spherical shell with uniform electron density. A correction is applied for azimuth and for the curvature of the earth. The NIST data plot vertical delays for many satellites tracked simultaneously at varying elevations and azimuths, thus having different points of intersection with the ionosphere for the vertical delay computation. Since the satellite elevation can vary from 15° to 90°, using a vertical height of 300 km for the ionosphere we see that the ionosphere could be pierced anywhere in a circle of diameter 2000 km. Thus we expect the true vertical delay to have a significant variation among different satellites measured simultaneously, especially near sunrise and sunset. With this in mind, the agreement between the two units seems very good. Some of the variation between measurements is also due to differences in the hardware of the satellites. Our measurement of the ionospheric delay depends on the phase coherence of the code between L1 and L2 at transmission. In fact there are some small unknown delays between these phases which differ among the satellites.

Comparison with Faraday Rotation

Figure 3 shows a comparison between the vertical ionospheric delay from the NIST unit and the corresponding data from the Faraday polarimeter at Boulder. This system records the 136.38 MHz signal from the GOES-3 geosynchronous satellite located near 0° N, 130.1° W. The ray path transits the ionosphere near 36.4° N,109.4° W; the coordinates of Boulder are 40° N, 105.3° W. The plot shows data from the month of January, 1990 averaged daily to give the average diurnal effect. 0 h UT is 5 pm local time. Most of the GPS satellites were up at night during this month. At night the GPS values are higher than the Faraday values. This is to be expected since the Faraday technique is sensitive to electrons up to a height of only about 2000 km, whereas the GPS measurements are affected by electrons up to the height of the satellites [9]. The difference is partly due to the protonospheric content [10], and partly due to the unknown phase delay between the L1 and L2 codes among the various satellites. The discrepancies during the day are probably due to the different geographical locations between the Faraday and the GPS raypaths, as well as the relatively small GPS data samples taken during these times.

GPS Time Transfer with Ionospheric Calibration

Three GPS common-view time transfers were computed using the two types of GPS ionospheric calibrator: UTC(OP) - UTC(NIST),UTC(CRL) - UTC(OP), and UTC(NIST) - UTC(CRL). The GPS data were taken according to the BIPM schedule at each location, thus insuring that there be simultaneous measurements pair-wise between locations. Strict common-view data was used: each measurement needed to be present at each leg of a pair of stations. Each branch was corrected either using the modelled or the measured ionospheric values.

We compared the deviation in time transfer values over each day between those using the GPS modelled ionosphere and the measured. This deviation is due primarily to either satellite ephemeris error, errors in the ionospheric correction applied, or multipath disturbances [1]. Other possible sources of deviation include tropospheric modelling errors, incorrect antenna coordinates, and clock dispersion between measurements. However, we think these latter errors do not contribute significantly here. For the comparison between the modelled and measured ionospheric values we insisted that both forms of common-view data be available before using a point in computations.

We have simply determined if the deviations among daily tracks decrease with the use of measured ionospheric values. We could later study more carefully the sources of these deviations.
Time transfer using a particular satellite and time of day gives a time series of one point per sidereal day. It is possible to study these time series and determine if there is a consistent statistically significant bias, and if the variations around this bias are white.

We present the average daily standard deviations in Table 1 below. The results were surprisingly disappointing. The only time transfer for which there was a decrease in the average daily standard deviation was UTC(NIST) - UTC(CRL) (figures 4 and 5). Looking at the tracks themselves we see that many were at night for each pair of locations. At night the ionospheric delay is much smaller hence variations are smaller and the model is perhaps better. On the other hand, we used the results from these time transfers to compute a closure around the world. For the closure we found a significant improvement using the measured ionospheric values.

Table 1: Average Standard Deviations

From Common-View Time Transfer

Labs	Using Modelled Values	Using Measured Values
UTC(OP) - UTC(NIST)	8.3 ns	10.6 ns
UTC(OP) - UTC(CRL)	7.1 ns	10.1 ns
UTC(NIST) - UTC(CRL)	11.5 ns	8.6 ns

For the path OP - NIST there were seven tracks per day. Of these, six were day tracks at OP and night tracks at NIST, while one was a night track at OP and a day track at NIST. It is surprising that there is not some improvement using the BIPM calibrator since so many tracks were during the day at OP. In a previous report an improvement was found for transfer from OP to the United States Naval Observatory in Washington, DC, USA [6]. One possible explanation is that the BIPM calibrator does not work as well for low elevation angles, and three of the daytime tracks were below 31° at Paris. It is also true that ephemeris error becomes more pronounced with larger baselines. Similarly for the path OP - CRL, all the tracks were at night for OP and five were during the day at CRL. But of these five, three had elevations below 30° at CRL. A previous result showed an improvement for this same path [6], but it was done at a different time when the satellites were in different positions. In addition, in the previous result there were more data. For the path NIST - CRL all the tracks were at night at both locations except one during the day at CRL.

In figure 6 we show the closure around the world using the time transfer values discussed above. The average values and their standard deviations are shown in table 2 below.

Table 2: Closure Around The World

Ionospheric Estimate	Average	Standard Deviation
Modelled	12.7 ns	5.4 ns
Measured	- 4.9 ns	3.4 ns

There is a clear improvement with the use of the measured ionosphere. We must conclude that even though the daily deviations were not lessened for individual time transfers in this experiment, the deviation did drop for the closure, and there was a bias in the use of the GPS ionospheric model.

CONCLUSIONS

We have seen two different ionospheric calibration systems, both giving similar measurements of the ionospheric delay from GPS satellites. We have shown here that the NIST calibrator agrees with Faraday rotation measurements. The same has been shown previously for the BIPM calibrator. We applied these measurements to GPS common-view time transfer, and found that, in this experiment, the standard deviation across the different tracks each day does not generally decrease, though it does in one of the three cases. We do find, however, that combining the three time transfers using the ionospheric measurements to obtain a closure yields an improvement. We conclude that if the baselines are long and many tracks are taken at night, use of the GPS ionospheric model can produce time transfer results which are as self consistent as results which use measured ionospheric values. But the measured values still improve the accuracy of the time transfer. We have also shown that the ionospheric calibration systems can make many measurements of ionospheric delay, and these should be quite useful for studying the ionosphere itself.

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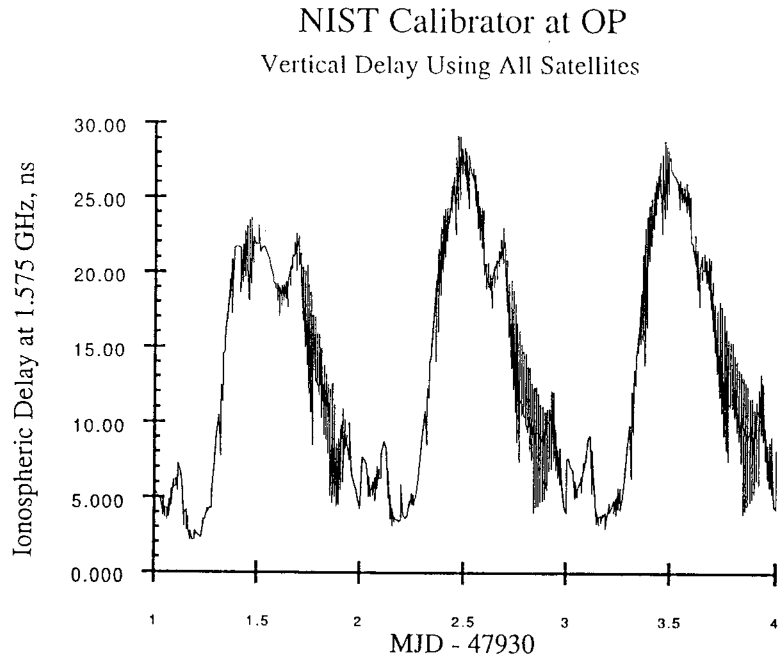

Figure 1: Data from the NIST ionospheric calibrator at OP converted for the vertical delay. Since the calibrator tracks all satellites in view there can be significantly different points of intersection with the ionosphere at one time. Hence there is a spread in the vertical delay at a given time. In addition, there is a variable bias between satellites and perhaps measurement noise.

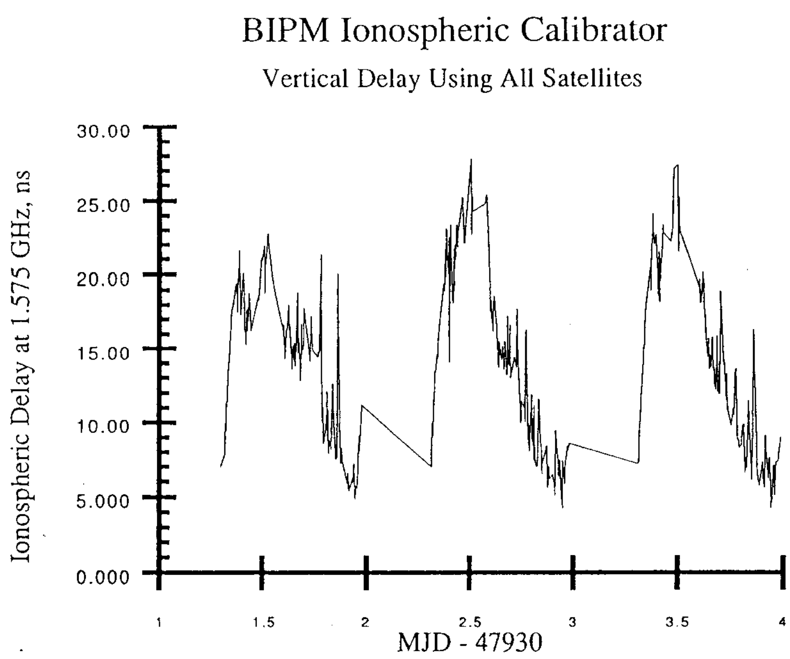

Figure 2: Data from the BIPM ionospheric calibrator. Fluctuations here can be due to the same effects as for the data in figure 1.

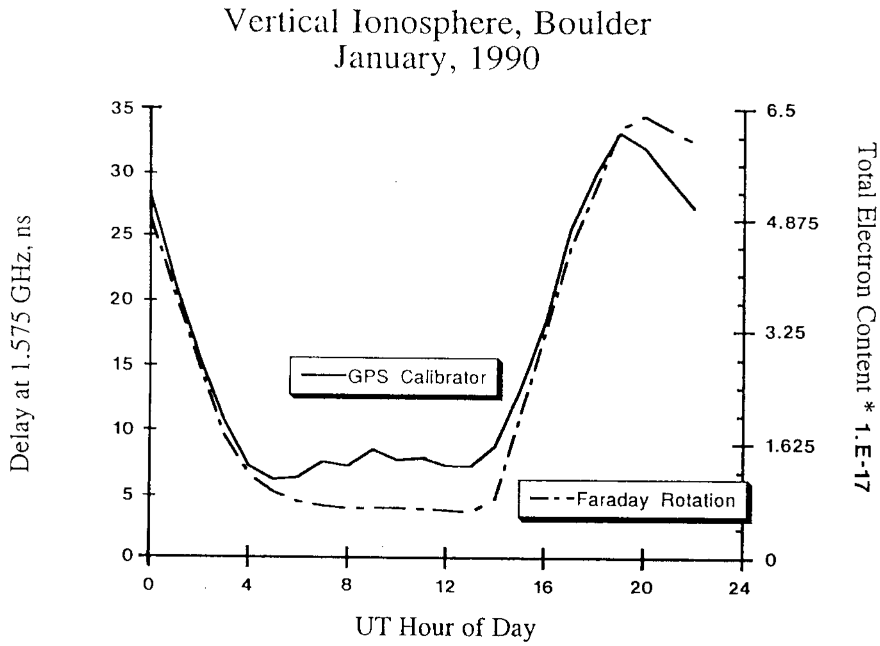

Figure 3: A comparison of measurements of the ionosphere using two different techniques: the NIST/GPS calibrator and Faraday rotation from a GOES satellite. Faraday rotation measures the ionosphere only up to 2000 km. Signals from GPS satellites pierce the ionosphere in different places than that from the GOES satellite. Also, there are biases in data from GPS satellites.

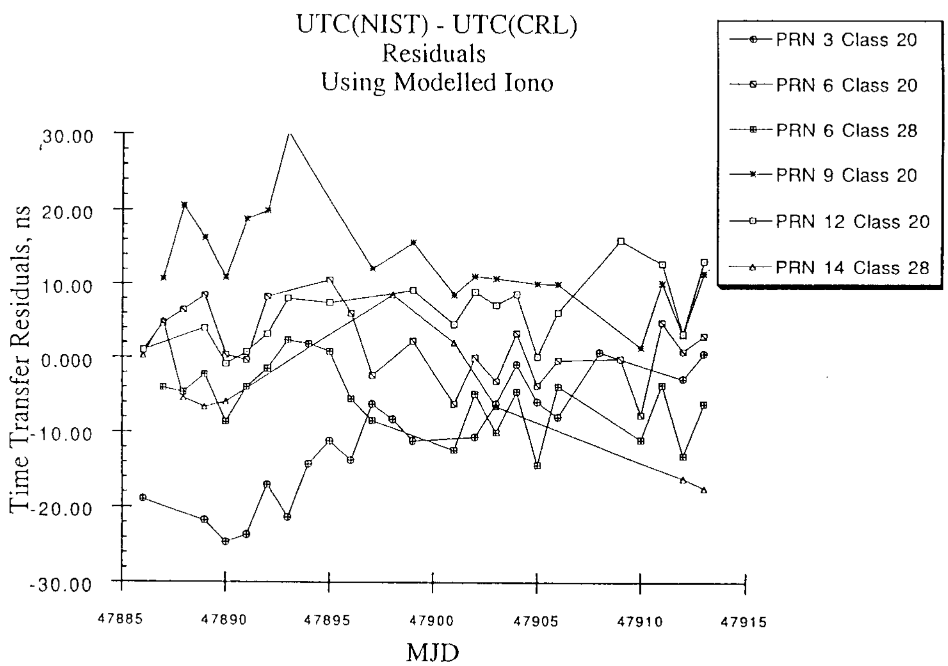

Figure 4: Time transfer residuals from NIST, Boulder to CRL, Tokyo with the data corrected for the ionosphere using the broadcast GPS model parameters.

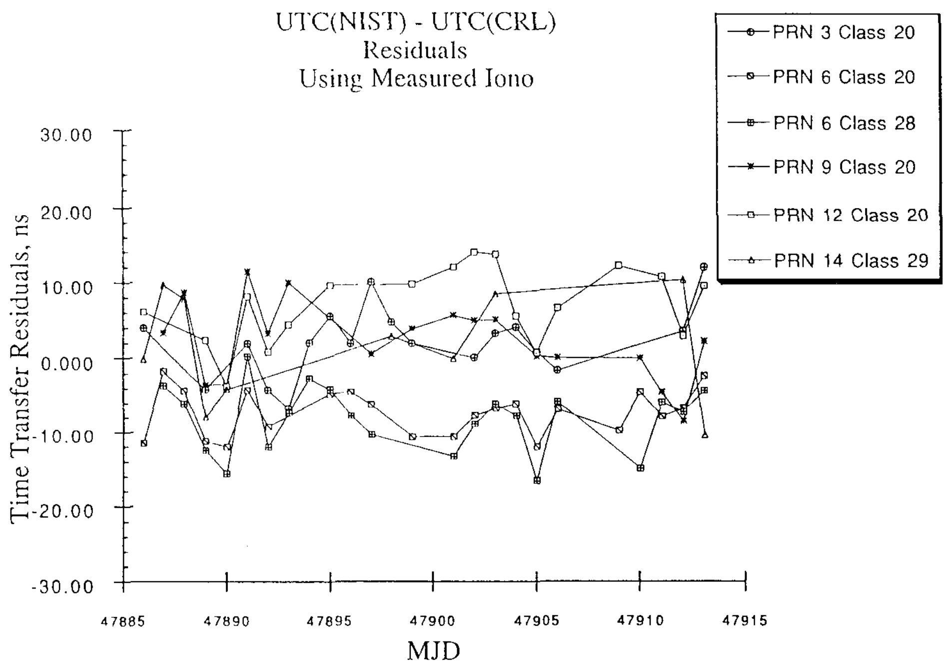

Figure 5: Time transfer residuals from NIST to CRL with the data corrected for the ionosphere using measured values from the NIST type calibrator in Boulder and the BIPM type calibrator in Tokyo.

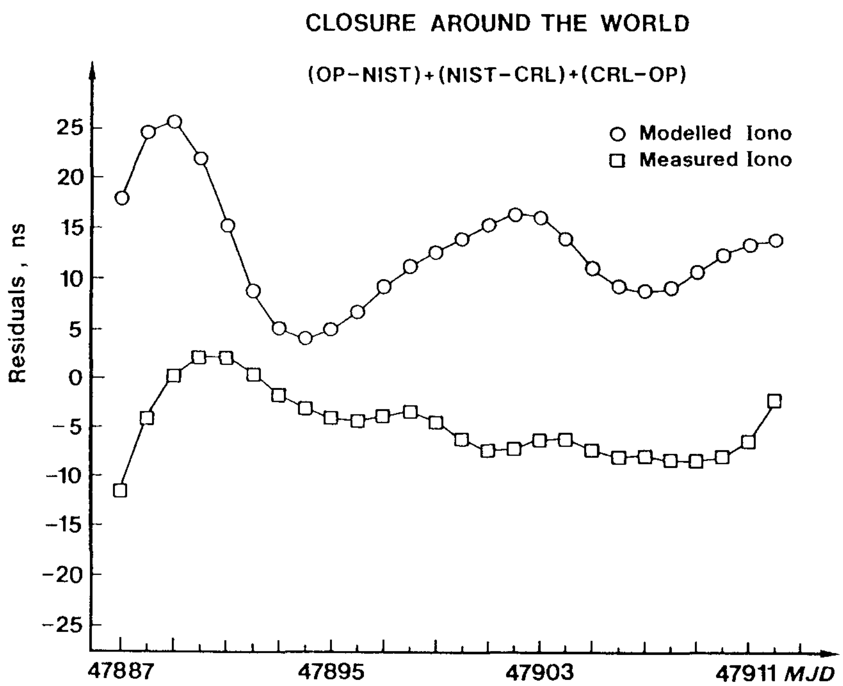

Figure 6: Closure around the world using the time transfer links: UTC(OP)-UTC(NIST) + UTC(CRL)-UTC(OP) + UTC(NIST)-UTC(CRL), computed with measured and modelled ionospheric delays. There is an improvement in the closure using the measured values, a decrease both in the bias and the standard deviation.