IMPROVING THE NIST IONOSPHERIC MEASUREMENT SYSTEM[1]

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ABSTRACT

Two problems of the NIST Ionospheric Measurement System have been addressed. A new software lock on the received satellite frequency allows the system to lock more robustly in the presence of selective availability. We obtain about 30% more measurements. Also, biases in the measurements largely come from the front end antenna system. Preliminary results indicate that for the most part the problem is neither due to multi-path interference nor phase center offsets in the antennas, as was previously thought. There is indication that some of the effect is due to an interaction between the two quadrafiler helix antennas.

INTRODUCTION

Measurements of the delay of GPS timing signals through the ionosphere are important for common-view time transfer. The longer the baseline, the more important that real measurements be used in place of an ionospheric model. The NIST Ionospheric Measurement System (NIMS) is used routinely for international time transfer for the generation of international atomic time (TAI) [1]. Measurements from various NIMS's and other ionospheric measurement systems have been shown to significantly improve international time transfer, especially during periods of maximum solar sunspots [2].

The NIMS measures the relative phase of the pseudo-random code called the P-code as received between the two frequencies L1, 1.6 GHz, and L2, 1.2 GHz, transmitted by the Global Positioning System (GPS) satellites [3]. The P-code is transmitted coherently on the two frequencies.[4] Since the group delay of the code is inversely proportional to the square of the carrier frequency, the differential arrival time is a measure of the ionospheric delay on the signals. The NIMS measures the differential arrival time of the P-code between the L1 and L2 signals using a codeless technique [1,5,6]. The system does not use the actual P-code, rather it determines the relative phase of the code using a delay-and-multiply technique. Since we do not track the pseudo-random codes per se, we must find some way to differentiate among the GPS satellite signals received, since they are all nominally on the same frequency. The differences of the received frequencies are due to Doppler shifts of the received signals resulting from the motion of the satellites. We use the frequency offsets of the satellites and the rates of change of these offsets due to satellite motion to discriminate among satellites. The NIMS software tracks each satellite by using individual frequency-locked loops to each satellite.

The GPS signals are deliberately corrupted using a process called selective availability (SA) to deny the full accuracy of the system from users who are not authorized by the U.S. military. SA causes the received frequencies to fluctuate so rapidly that the original NIMS frequency-locked loop was unable to maintain lock consistently. We have redesigned and implemented a new loop, increasing the bandwidth. In the redesign we now implement a frequency lock on both the L1 and L2 signals instead of only the L1 signal. Since we receive the signals sequentially, dwelling 7.5 s on each, we now have lock information every 7.5 s instead of every 15 s. Unfortunately, this does not double the bandwidth. Because the frequency average is a difference of the measured phase now minus the measured 15 s ago, the frequency measurement on L1 at time T is correlated with the correction applied based on the measurement on L2 at time T-7.5s. Yet the increase in bandwidth is significant enough to provide consistent locking on GPS satellites with approximately a 30% increase in available data.

Another problem with the NIMS has been biases in measurements of the order of ±6 ns. Measurements of the delay from the same satellite at the same time with two different receivers show such offsets, which repeat each day. Research suggests that averaging these biases over all satellites tracked in one hour by correcting the received delay for the vertical ionosphere shows an agreement with Faraday rotation measurements of the

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ionosphere at about the 3 ns level [7,8].

Our studies suggest that the biases come from the front end antenna system. While at first glance the problems seem to relate to the geometric relationship of the receiver to the satellites and multi-path interference, our study indicates that for the most part this is not so. Therefore, the problem is probably neither due to multi-path interference nor phase center offsets in the antennas, as was previously thought. There is indication that some of the effect is due to an interaction between the two quadrafiler helix antennas.

THE NEW TRACKING LOOP

A complete description of the NIMS has been published elsewhere. We describe here three functional portions of the design relevant to our discussion. The front end mixes a signal from either L1 or L2 with a frequency midway between them. The system sequentially locks on L1 for 7.5 s and L2 for 7.5 s. This design allows both frequency channels to follow the same paths after the first mixer. This is an important feature for stability and accuracy of the NIMS.

The codeless phase measurement is based on a delay-and-multiply technique. Both the L1 and L2 signals carry a pseudo-random code called the P-code, with a chip rate of 10.23 MHz. The NIMS recovers this 10.23 MHz clock by delaying the signal by half of one chip, about 50 ns, multiplying the delayed signal by the direct one, then band-limiting the result. We now have a signal consisting of a sum of sine waves coherent with the 10.23 MHz clocks from the satellites. This signal is then mixed down so the central frequency is approximately 78.74 Hz. The Doppler offsets vary about ± 25 Hz. This signal is sampled at 250 Hz by a 8 bit A/D converter and passed into a microprocessor.

The microprocessor tracks each satellite in the 250 Hz bit stream using a frequency lock loop as well as deriving the ionospheric delay for each satellite on the L1 signal. We process the 250 Hz data for 7.5 s, obtain a phase of the P-code on the received L-band, then switch to the other L-band for the next 7.5 s. The 250 Hz data are processed as follows. At each 250th of a second, we compute, for a given satellite, a sine and cosine value based on an estimate of the satellite's P-code received frequency and rate-of-change of the frequency. We sum for the entire 7.5 s the product of the sine value and the received data, as well as summing the product of the cosine value and the data. The arctangent of the ratio of the sine product sum divided by the cosine sum gives us a phase of the P-code for the 7.5 s interval for the received L-band.

Thus for each satellite, we have a sequence of P-code phases, one every 7.5 s, alternating between L1 and L2. Let us label phases as Φ^1_1, Φ^2_1, Φ^1_2, Φ^2_2, Φ^1_3, Φ^2_3, ..., where the superscript refers to the L band frequency, and the subscript is a sequential count of the phases. The difference between neighboring phases, such as Φ^2_1-Φ^1_1, Φ^2_1-Φ^1_2, give us our measurements of the ionospheric delay. The difference $\Phi^1_2 - \Phi^1_1$, being the change in the relative L1 phase over 15 s, is a measure of the offset in our estimate of received frequency for this satellite. The change in the relative L2 phase over 15 s, $\Phi^1_2 - \Phi^1_1$, also measures our estimate of received frequency for this satellite.

We report here that we now use both the change in the relative L1 phase over 15 s, $\Phi^1_2 - \Phi^1_1$, and the relative L2 phase over 15 s, $\Phi^2_2 - \Phi^2_1$ in the frequency-locked loop. Previously we used only the change in L1 phase over 15 s to close the frequency lock loop. This was done for two reasons. First of all, it was enough to allow us to lock consistently on satellites before the advent of SA. Secondly, the L2 change in phase is coupled with the L1 change in phase, so that using both measures does not double the information over using one of them. In addition, the signal power of L2 is specified to be 6 dB lower than L1. The L2 and L1 phase changes are coupled because we alternate measurements of phase on L1 and L2. Hence between consecutive L1 phase measurements there is an L2 phase measurement, and vice versa. If we adjust our received frequency estimate after an L1 phase measurement using $\Phi^1_2 - \Phi^1_1$, then the phase change $\Phi^2_2 - \Phi^2_1$, will be corrupted by that adjustment, since the steering will have occurred midway through the $\Phi^2_2 - \Phi^2_1$ measurement.

We implemented a tracking loop which adjusts the L2 phase difference measurement by subtracting 1/2 of the previous phase correction which had been applied midway through the L2 measurement. So if A1 was the previous phase correction applied after the L1 measurement, we now use

$$A2 = \Phi^2_2 - \Phi^2_1 - \tfrac{1}{2}A1$$

as the phase applied to close the frequency lock loop after this L2 measurement. Similarly, after the next L1 7.5 s measurement, we now use

$$A3 = \Phi^1_3 - \Phi^1_2 - \tfrac{1}{2}A2.$$

The factor of 1/2 comes since the rate adjustment from the previous cycle occurred half-way through the current one.

The result of the new lock loop is that the receiver takes about 30% more data. As a result, the effect of SA seems no longer to interferes with the operation of the receiver. Since measurements of the ionospheric delay must be made nearly simultaneously with GPS common-view measurements in order to correct the common-view measurements, this will allow for less noise in international time transfer.

MEASUREMENT BIASES

If we measure ionospheric delays using two NIMS's and difference these values, biases appear. For a given satellite we found a non-constant bias pattern that repeats with each pass, once per sidereal day. Examples of this are shown in figures 1a and 1b. Each point is the difference of midpoints to 15 minute linear fits to the 7.5 s ionospheric measurements. Note that the pattern is different for different satellites, even if they are tracked at common times.

We wish to point out that even with these biases, agreement with measures of the vertical delay through the ionosphere using Faraday rotation is approximately at the 3 ns level [4]. This level of agreement requires averaging all NIMS data taken over one hour after correcting them for the vertical delay.

Because we are using a codeless technique, we expected that multi-path interference would be a significant cause of biases. We decided to attempt to reduce these biases by physically rotating the antenna. We hoped rotation would reduce multipath corruption since measurements of the antenna pattern of one such antenna showed a field reversal with a rotation of 180 degrees of azimuth.

Figure 2 shows how the two NIMS antennas are offset from each other and surrounded by a choke ring ground plane. For simplicity we decided to rotate the entire unit and look for a reduction in the changing biases. Though this rotation was less than optimum since it meant that the antennas moved as well as rotated, we felt this should serve to demonstrate the possibility. Figure 3 illustrates the system built for rotating the entire front end antenna system. We built two rotators, one for NIMS#106 and one for #110. They both rotated coherent with the 7.5 s measurement sequence of their respective NIMS processor. The antenna with NIMS#106 rotated in 7.5 s in one direction, then reversed for the next 7.5 s. The antenna system with NIMS#110 rotated in 22.5 s in one direction, then revered direction for the next 22.5 s. Thus in one direction we measure sequentially L1, L2, then L1 each for successive 120° intervals, then reverse and measure L2, L1, then L2 in the opposite 120° intervals. For the 15 minute linear fits, these should average appropriately.

The results of rotating the antenna are null. We see no significant change in the pattern of biases. Compare the data in figures 4a and 4b, the biases while rotating, with the data in figures 1a and 1b. The two satellites chosen for these figures display biases whose day-to-day variances are typical. The patterns themselves and the peak-to-peak changes in the biases vary among satellites. The fact that rotating the antenna produced a null result suggests that the biases may not be a function of the geometry of the received signal and any multipath interference. In particular, the orientation of the antenna systems does not seem to contribute to the biases we are measuring, or we would expect to find a significant change in the biases after rotating the antenna system continuously. From this we conclude that a potential phase center offset between the antennas does not significantly contribute to the problem represented in figures 1a and 1b.

Two other simple experiments were done. In the first one, the antennas and front end electronics were swapped between the two rotating NIMS units. Thus the systems consisting of L1 and L2 antennas, choke ring ground plane, and front end electronics were reversed between their positions on the roof, and connected to the opposite systems of cables, rotators, and the electronics in the lab. The result of this reversal was a reversal in the sign of the biases, keeping data associated with the laboratory electronics. The values of the biases were apparently the same within the uncertainty, but with the opposite sign. This result suggests that the biases are not associated with antenna position. That is, the differential biases we measure are not associated with the differential multipath interference associated with position, but rather with biases associated with differences in the specific front end antenna systems.

A second experiment added another piece to this puzzle. The L1 antenna on one of the NIMS antenna systems was rotated by 45°. The resultant change in the biases was large. Figures 5a and 5b show the biases for the satellites of 4a and 4b after this rotation. We want to emphasize that though the peak-to-peak values in figures 5 are small, they represent the differential biases between the two systems. We have no information about the biases in either single system.

CONCLUSIONS

We have discussed work on two problems of the NIMS. For the problem of loss of lock because of SA we developed a new frequency lock. The new loop has largely eliminated the problem caused by SA. We now reliably lock on most satellites. The problem of biases in the ionospheric measurements was not solved, but substantial progress has been made toward discovering their cause. At this time the most probable cause lies in the relationship between the two quadrafiler antennas for receiving the L1 and L2 signals. These results on biases are preliminary, and more research is necessary.

BIBLIOGRAPHY

[1] B. Guinot and C. Thomas, "Establishment of international time," BIPM Annual Report, Part D, pp. D1-D22, 1988.

[2] W. Lewandowski, G. Petit, C. Thomas, "Precision and accuracy of GPS time transfer," *IEEE Trans. Instrum. Meas.*, v. 42, pp. 474-479, April, 1993.

[3] D. Davis, M.A. Weiss, M. Vidmar, "A Codeless ionospheric calibrator for time

transfer applications," *Proc. Institute of Navigation, Satellite Division*, 2nd International Meeting (ION GPS-89), 1989.

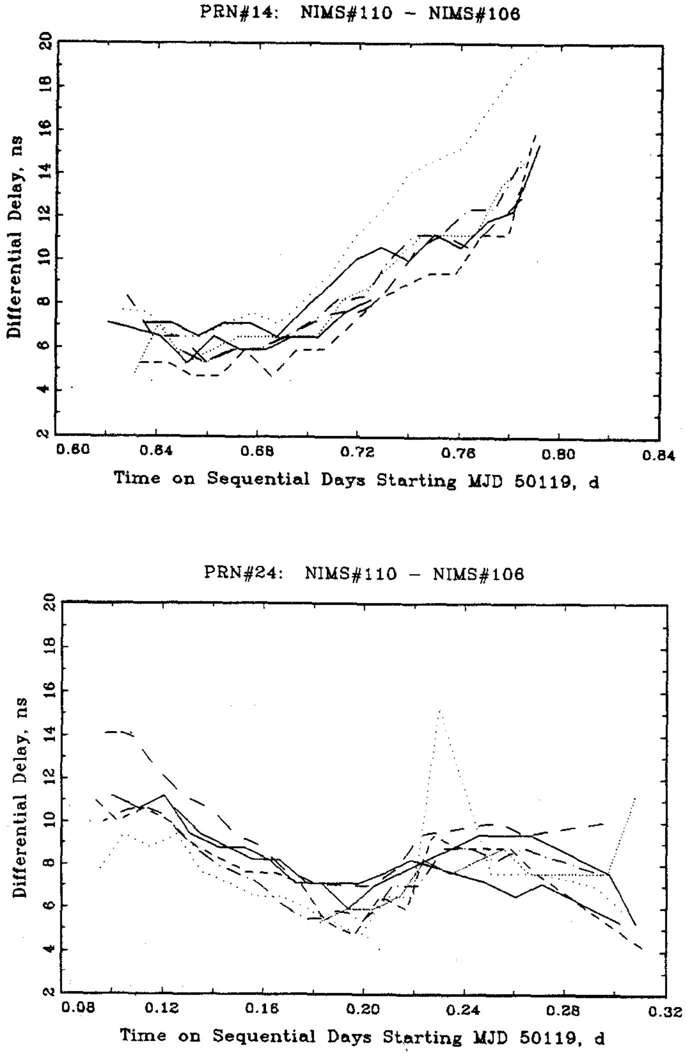
[4] B. W. Parkinson, S. W. Gilbert, "NAVSTAR: Global positioning system--ten years later," *Proc. IEEE*, v. 71, pp.1177-1186, Oct. 1983.

[5] P. MacDoren et al, U.S. Patent 4,797,677, Jan. 10, 1989.

[6] M. Imae, M. Miranian, W. Lewandowski, and C. Thomas, "A dual-frequency codeless GPS receiver measuring ionospheric effects and its application to time comparison between Europe and USA," *Proc. 3rd European Time and Frequency Conf.*, pp.89-93, 1989.

[7] K. Davies, "Comparison of Hourly Total Electron Contents from GPS and GOES-2," *Proc. International Beacon Satellite Symposium*, Aberystwyth, United Kingdom, 11-15 July, 1994.

[8] D. Davis, M.A. Weiss, K. Davies, G. Petit, "Improving GPS Time Transfer Accuracy with the NIST Ionospheric Measurement System," *Proc. Institute of Navigation, Satellite Division*, 4th International Meeting (ION GPS-91), 1991.



Figures 1a and 1b: The difference of ionospheric measurements from NIMS#110 minus NIMS#106 made at the same time on the same satellites. The two units were not rotating during these measurements. Curves represent data taken on successive days, and adjusted for the approximately 4 min/d shift of the satellite ground track. We see that there is a repeated changing bias in the offset between the two systems.

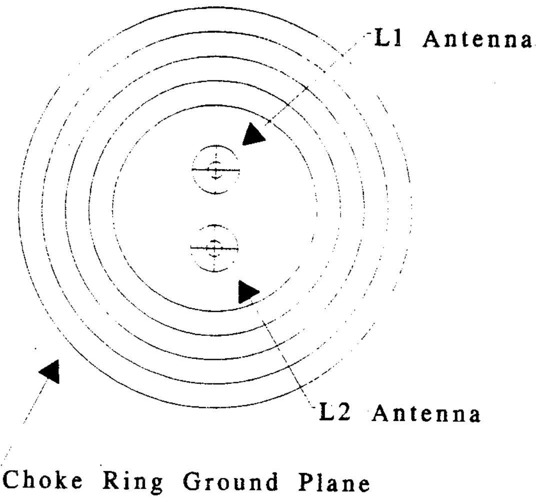


Figure 2: Shows the geometric relationship among the two antennas of the NIMS, L1 and L2, and the choke ring ground plane. The rotation system rotates the entire system around its center.

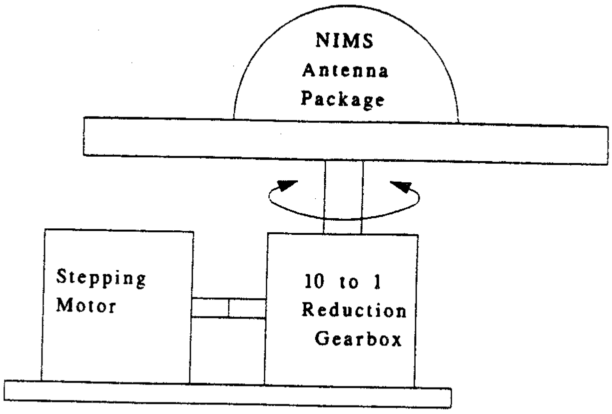
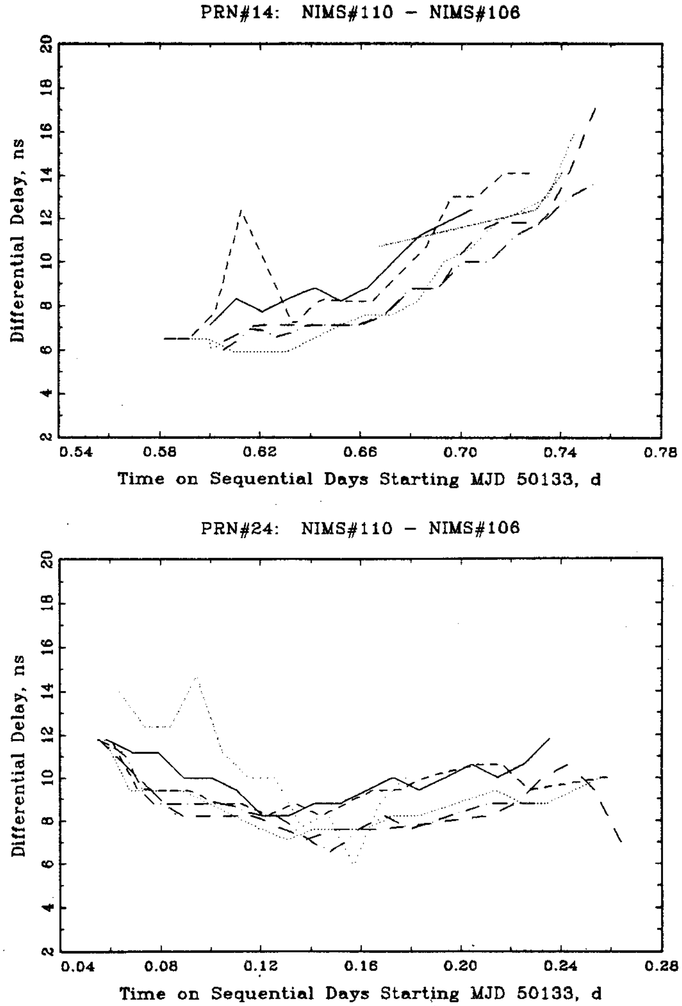
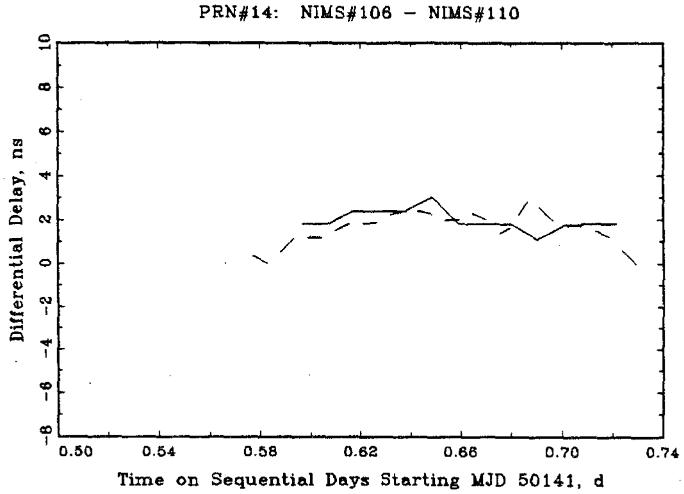
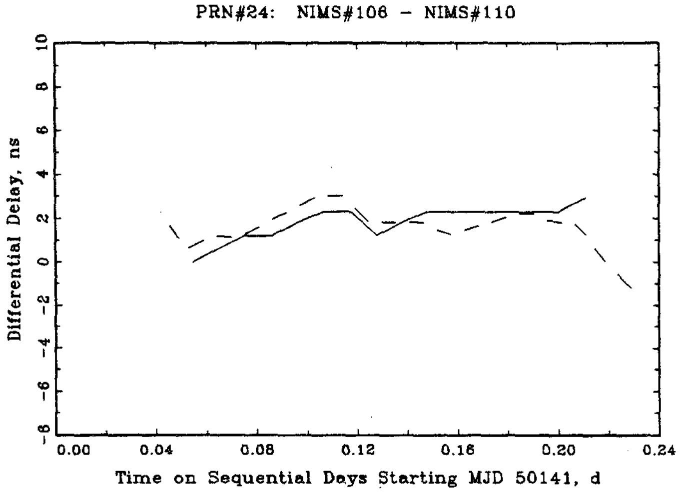


Figure 3: An illustration of the NIMS rotation system. One system, NIMS#106, rotated each direction in 7.5 s, coherent with the NIMS measurements. The other, NIMS#110 rotated each direction in 22.5 s, also coherent with the measurements.



Figures 4a and 4b: As in figures 1, the difference of ionospheric measurements from NIMS#110 minus NIMS#106 made at the same time on the same satellites. In this case the two units were rotating during these measurements. Curves represent data taken on successive days, and adjusted for the approximately 4 min/d shift of the satellite ground track. The repeated changing bias in the offset between the two systems does not seem to have changed.





Figures 5a and 5b: As in figures 1 and 4, the difference of ionospheric measurements from NIMS#110 minus NIMS#106 made at the same time on the same satellites. The antenna packages have been reversed between the units, and the L1 antenna for the unit #110 as been rotated by 45°. The two units were rotating during these measurements. Curves represent data taken on successive days, and adjusted for the approximately 4 min/d shift of the satellite ground track. The repeated changing bias in the offset between the two systems seems to have changed significantly. Note that a reduction in the differential bias does not necessarily imply that the bias itself has been reduced.