# IONOSPHERIC MODELS AND MEASUREMENTS FOR COMMON-VIEW TIME TRANSFER[*]

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*Abstract* – **We discuss technologies for estimating ionospheric delays in Global Positioning System (GPS) common-view time transfer. Such technologies include the broadcast Klobuchar ionospheric model, the use of ionospheric maps from the International GPS Service (IGS), codeless techniques for measure the ionospheric delay, and using the pseudo-random code on two frequencies. We find that the code receivers we use in this study are excellent references for comparing other ionospheric measurements. Receivers using the Klobuchar model exhibit some with correct values, others with problems. A receiver using a codeless technique appears to have problems. We also find that, because of potential uncertainties in calibrating code receivers, the IGS maps are particularly useful for time transfer.**

***Keywords*** - **codeless ionospheric measurements, common-view time transfer, ionospheric delay, GPS, Klobuchar model**

## I. INTRODUCTION

There are various new commercial common-view time transfer receivers as well as old ones. All use the broadcast Klobuchar ionospheric model [1]. Some also measure the ionosphere either as P/Y code receivers, or using a codeless technique. We consider also the ionospheric maps available from the International GPS Service (IGS). Their use in common-view time transfer was implemented first by the International Bureau of Weights and Measures, in French as the Bureau International des Poids et Mesures (BIPM) [2]. At the National Institute of Standards and Technology (NIST) in Boulder, we look at the IGS maps, a traditional receiver developed when NIST was called the National Bureau of Standards (NBS), and an old NIST Ionospheric Measurement System (NIMS) [3]. At the U.S. Naval Observatory (USNO) we consider three commercial receivers, one of which has a codeless ionospheric measurement system, two pseudo-random code receivers, and the IGS maps. We then look at common-view time transfer between NIST, Boulder and various labs, comparing the use of the broadcast Klobuchar model with IGS maps. One tool we use for characterizing instability due to errors ionospheric delay estimation is the Time Deviation (TDEV).

## II. Receivers at NIST

The IGS maps are consistent, on the average, with both the Klobuchar model of the NBS-type receiver and the NIMS ionospheric measurements. See Figures 1 and 3. The NIMS, however, has significant uncertainties. The model shows diurnal variations with a TDEV of 4 ns using 130 d of data (Figure 2).

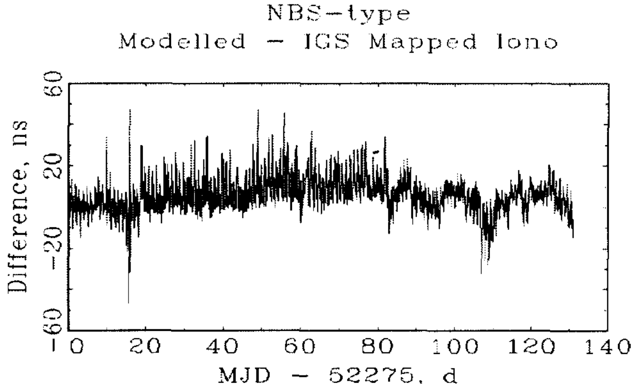

**Figure 1 The Klobuchar ionospheric model from an NBS-type receiver at NIST minus the IGS mapped ionospheric delays. We see apparent systematic diurnal variations that persist for tens of days. The mean of these data is 5.6 ns.**

Figure 3 shows the variations in the NIMS data against the IGS mapped ionosphere at NIST Boulder. TDEV of these data at the shortest time is 13.3 ns coming down with averaging time, $\tau$, as white phase modulation, $\tau^{-1/2}$, to a flicker phase floor of about 1.7 ns from 4 d on.

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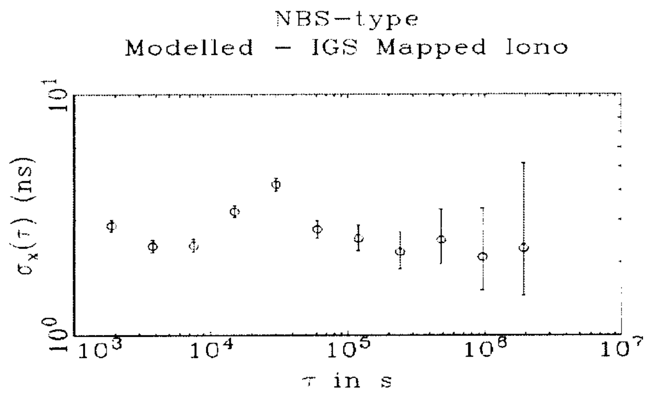

**Figure 2 TDEV of the data in Figure 1. We see a diurnal variation illustrated by a maximum at 0.5 d of over 4 ns.**

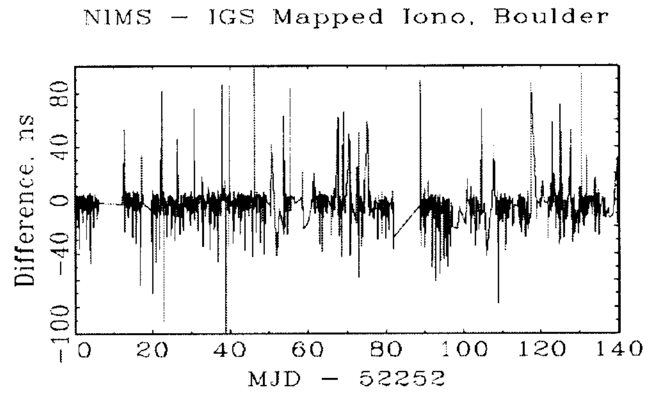

**Figure 3 NIST Ionospheric Measurement System (NIMS) ionospheric delay measurements against the IGS mapped ionosphere. The mean is –3.9 ns, showing consistency with the NIMS calibration uncertainty. The large variation is probably NIMS error.**

## III. RECEIVERS AT USNO

### *A. P/Y Code Receiver Comparisons*

GPS satellites broadcast a code on one frequency L1 which is generally available, and two other codes on two frequencies, L1 and L2, for military use. These codes are the P and Y codes. The Y code is only available for authorized military users. We study ionospheric measurements made with two P/Y code receivers at USNO. We compare the P/Y code receivers with three types of ionospheric measurement systems: IGS maps, P/Y code receivers against each other, and a two-frequency codeless receiver.

The IGS maps are consistent with ionospheric measurements against a P/Y code receiver, which is also consistent with another P/Y code receiver's measurements. See Figures 4 and 6 below.

Figure 5 below shows TDEV of the IGS mapped ionosphere against the P/Y code receiver measurements. As we indicate below, we may assume the deviation values are mostly due to the IGS maps. We have a 6 ns deviation for individual tracks, averaging down as $\tau^{-1/2}$ for about 3600 s, or 1 hour. Then we see a flicker PM floor of about 1.5 ns out to 0.5 d, 43000 s.

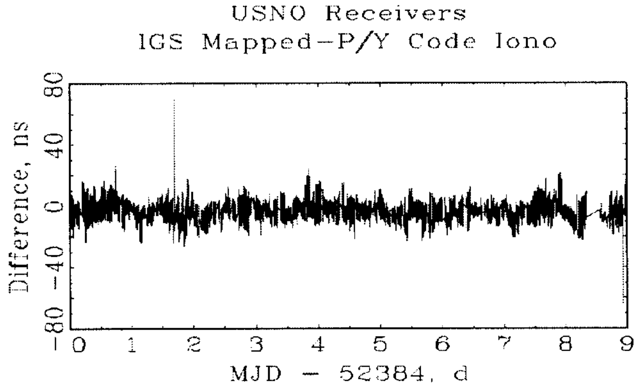

**Figure 4 IGS ionospheric maps minus a P/Y code receiver's ionospheric estimates at USNO. The mean of -3.9 ns is consistent with the estimated receiver calibration uncertainty.**

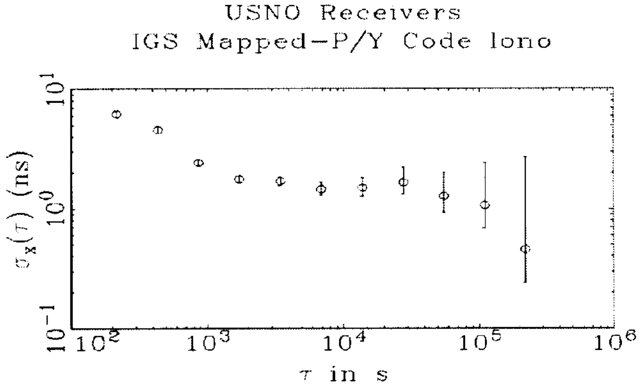

**Figure 5 TDEV of the data in Figure 4. The data are consistent with a White phase modulation (PM) model of 6 ns for individual tracks averaging down to a flicker PM floor of 1.5 ns from 1 hour out to 0.5 d.**

Figure 6 shows the stability and differential accuracy of two P/Y code receivers at USNO. Using a common antenna, we see a stability of 200 ps RMS, and a bias between them of under 2 ns. With separate antennas the stability is 1 ns RMS. We conclude that these receivers are perhaps our best references for comparing other ionospheric measurement systems. Certainly the stability is the best that we currently have.

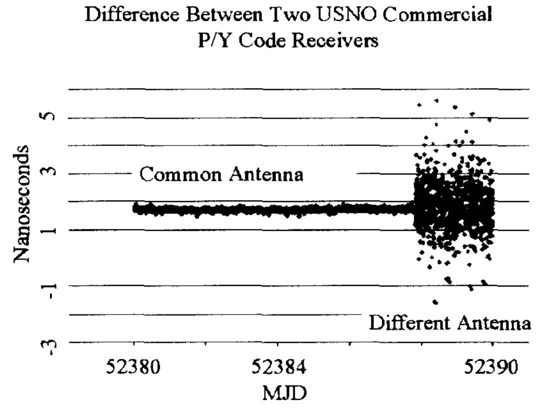

**Figure 6 The difference between the ionospheric measurements of two USNO P/Y code receivers. For the first 75% of the data the two receivers used a common antenna yielding 200 ps RMS. With separate antennas we obtain 1 ns RMS.**

For accuracy, however we have concerns. We estimate the uncertainty in calibrating ionospheric measurements at under 8 ns. We estimate the uncertainty for each channel at 2 ns. The equation for measuring the ionosphere with the phase measurements on L1 and L2 is

$$\text{Iono} = L1 + (L1 - L2)*1.54.$$

Thus, the worst case error of 8 ns occurs if the error in calibrating both L1 and l2 is 2 ns with opposite sign. This suggest that the IGS maps may provide better ionospheric delay estimates for time and frequency transfer, since they are estimated as a global model. It is possible that individual receiver bias errors may be reduced in the global estimation process.

We also compared ionospheric measurements from a two-frequency codeless system with the P/Y code receiver. Unfortunately, these data showed problems with the implementation of codeless system in that commercial receiver. We found a peak to peak variation of over 15 ns in the codeless ionospheric measurements against the P/Y code measurements.

### *B. Klobuchar Model Implementations*

We compare the Klobuchar model computations to each other in four commercial receivers. We denote these receivers as A, B, C, and an NBS-type. We also compare receiver A's results to the P/Y code ionosphere.

Comparing receiver A to a P/Y code receiver we find results consistent with our results from the NBS comparisons with the IGS maps, figures 1 and 2. In particular, we see diurnal variations of 10 – 30 ns, which persist for many days.

Comparisons among the various commercial receivers give mixed results. The commercial receivers A, B, and C are multi-channel receivers, whereas the NBS-type receiver is a single channel receiver. A standard was written for using the ionosphere that was unambiguous with single channel receivers [4,5]. These receivers tracked satellites according to a schedule. Each track was long enough to ensure that ionospheric parameters were decoded once from the satellite during the track. The standard simply ensured that the next track used those parameters for the entire track. Unfortunately, there is no standard way to determine which ionospheric model to use with multi-channel receivers. It is possible to post-process the tracks and use the ionospheric model broadcast during that track for the entire track. This, however, would be inconsistent with the way the model has previously been used.

The comparison between the NBS-type and commercial receiver A show consistency in the implementation of the model, though with differences of about +/- 8 ns at times, probably due to using different parameter sets of the broadcast model. The differences between receivers A and C show similar results, though with +/- 4 ns variations, probably because the data length is much shorter, 10 d compared to 110 d with the NBS-type. Receiver B compared to receiver A shows the same +/- 4 ns variation due to the use of different models, but also a systematic +/- 1 ns diurnal variation. This daily swing suggests a small firmware error in receiver B.

## IV. LONG-BASELINE COMMON-VIEW TIME TRANSFER

We compare IGS mapped ionospheric delays to the results from the broadcast Klobuchar model using two methods. We first give results from time transfer across the continental United States and from Boulder, Colorado, USA to Europe. Next we compare the time transfer from NIST in Boulder, Colorado, USA to the National Physical Laboratory (NPL) in Teddington, England subtracting Two-Way Satellite Time Transfer (TWSTT) data from GPS common-view data.

### *A. GPS Common-View Time Transfer: Model vs. IGS Maps*

We compare the stability of GPS common-view time transfer from NIST, Boulder, Colorado, USA to various other labs, and present the results in tables. First, we show a comparison across the continental United States from NIST in Boulder, Colorado to USNO in Washington D.C. Then we show three comparisons between NIST and labs in Europe.

The tables provide the Time Deviation of the transfer with the model in column 1, and the IGS maps in column 2, and the square root of the difference in column 3. Thus, column 3 gives the contribution of the error due to the modeled ionosphere. Note that the clock noise dominates after several days in all of these time-transfer data. Hence the contribution of the modeled ionosphere becomes obscured.

**Table 1**

TDEV of NIST – USNO

Values are for integration times, $\tau$, of days in powers of 2

i.e. $\tau = 1,2,4,8,16,32,64,128$ days

| Modeled | IGS Mapped | sqrt(Model$^2$ - Map$^2$) |
|---|---|---|
| 1.46 | 0.996 | 1.07 |
| 1.36 | 0.895 | 1.02 |
| 1.22 | 0.898 | 0.824 |
| 1.46 | 1.28 | 0.709 |
| 2.66 | 2.71 | - |
| 7.07 | 7.23 | - |
| 17.8 | 17.9 | - |
| 22.5 | 20.4 | - |

**Table 2**

**NIST - PTB**

Values are for integration times, $\tau$, of days in powers of 2

i.e. $\tau = 1,2,4,8,16,32,64,128$ days

| Modeled | IGS Mapped | sqrt(Model$^2$ - Map$^2$) |
|---|---|---|
| 3.23 | 1.74 | 2.71 |
| 2.91 | 1.62 | 2.41 |
| 2.71 | 1.61 | 2.18 |
| 3.02 | 2.33 | 1.92 |
| 5.55 | 4.67 | 3.01 |
| 12.2 | 9.28 | 7.90 |
| 21.8 | 20.8 | 6.64 |
| 18.4 | 21.5 | - |

**Table 3**

**NIST - OP**

Values are for integration times, $\tau$, of days in powers of 2

i.e. $\tau = 1,2,4,8,16,32,64,128$ days

| Modeled | IGS Mapped | sqrt(Model$^2$ - Map$^2$) |
|---|---|---|
| 3.24 | 1.78 | 2.70 |
| 2.82 | 1.65 | 2.28 |
| 2.60 | 1.74 | 1.94 |
| 2.98 | 2.26 | 1.94 |
| 4.29 | 3.87 | 1.86 |
| 9.03 | 8.36 | 3.40 |
| 19.7 | 17.6 | 8.88 |
| 24.3 | 20.8 | 12.6 |

We see in Table 1 that the ionospheric model contributes about 1 ns for the first few days, a baselineof about 2500 km. Tables 2, 3 and 4 show about 2 ns error contribution from the model over the approximately 7000 km baseline.

**Table 4**

**NIST - NPL**

Values are for integration times, $\tau$, of days in powers of 2

i.e. $\tau = 1,2,4,8,16,32,64,128$ days

| Modeled | IGS Mapped | sqrt(Model$^2$ - Map$^2$) |
|---|---|---|
| 3.12 | 1.74 | 2.58 |
| 2.67 | 1.62 | 2.12 |
| 2.63 | 1.61 | 2.08 |
| 2.57 | 2.33 | 1.10 |
| 3.52 | 4.67 | - |
| 7.96 | 9.28 | - |
| 16.5 | 20.8 | - |
| 21.4 | 21.5 | - |

*B. GPS Common-View minus TWSTT*

Table 5 below gives the results from differencing two different methods of time transfer. This has the advantage of eliminating the clock noise, allowing us to see the error introduced from the Klobuchar model over long integration times. We difference GPS Common-View transfer from NIST in Boulder, Colorado, USA to NPL in Teddington, England. We subtract the TWSTT data from the GPS common-view data. Note that here, the averaging time, $\tau$, is in hours.

**Table 5**

**NIST - NPL, Common-View (C-V) minus TWSTT**

TDEV in ns

$\tau$ in hours

| $\tau$ | C-V with Klob | C-V with IGS | RSS Difference |
|---|---|---|---|
| 8 | 5.971 | 4.105 | 4.336 |
| 16 | 5.520 | 3.672 | 4.122 |
| 32 | 3.060 | 2.162 | 2.165 |
| 64 | 2.648 | 1.855 | 1.890 |
| 128 | 2.405 | 1.787 | 1.610 |
| 256 | 1.798 | 1.459 | 1.051 |
| 512 | 1.661 | 1.133 | 1.215 |
| 1024 | 1.548 | 1.40 | 0.6455 |
| 2048 | 2.668 | 1.758 | 2.007 |
| 4096 | 3.701 | 1.909 | 3.171 |

Here we see that the time transfer error due to the use of the broadcast model persists out past 10 d at the level of about 1 ns.

## V. CONCLUSIONS

We conclude the following:

1. Because code measurements are the most stable, they seem to provide a good reference for ionospheric measurements.
2. There are biases that persist for tens of days in the Klobuchar model, the model broadcast from GPS satellites.
3. Calibration uncertainties of ionospheric measurements in code receivers could be as bad as 8 ns. This suggests that the use of IGS maps may be more consistent for time and frequency transfer.
4. The ionospheric model contributes about 1 ns TDEV instability across the US, and about 2-3 ns from Boulder, CO to Europe
5. The IGS maps improve common-view time transfer TDEV stability over the broadcast model from Boulder, Colorado to England by about 1 ns out to 10 d.

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