

A CALIBRATION OF GPS EQUIPMENT IN JAPAN*

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Abstract

With the development of common view time comparisons using GPS satellites the Japanese time and frequency standards laboratories have been able to contribute with more weight to the international unification of time under the coordination of the Bureau International de Poids et Measures (BIPM). During the period from June 1 through June 11, 1988, the differential delays of time transfer receivers of the Global Positioning System (GPS) were calibrated at three different laboratories in Japan, linking them for absolute time transfer with previously calibrated labs of Europe and North America. The differential delay between two receivers was first calibrated at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) in Boulder, Colorado, USA. Then one of these receivers was carried to each of the three laboratories: the Tokyo Astronomical Observatory (TAO), the Communications Research Laboratory (CRL), both in Tokyo, and the National Research Laboratory of Metrology (NRLM) in Tsukuba City. At each lab data was taken comparing receivers. Finally the traveling receiver was taken back to NIST for closure of the calibration. On the way back the GPS receiver at the WWVH radio station of NIST in Hawaii was also calibrated. We report here the results of this calibration trip, along with some interesting problems that developed concerning this technique.

Introduction

The motivation for calibrating time transfer receivers of Global Positioning System (GPS) signals has been discussed before (1,2,3). We will summarize the concerns here. The method of clock comparisons using Global Positioning System (GPS) satellites in common view between each pair of stations has become the de facto standard for comparisons of clocks in the major time standards laboratories participating in the international unification of time under the coordination of the Bureau International des Poids et Mesures (BIPM). At least 60 percent of the clocks which enter into the establishment of the International Atomic Time (TAI), as well as all of the primary frequency standards contributing to the length of the second within TAI, are directly linked by GPS.

The BIPM establishes a tracking schedule at regular intervals which ensures that pairs of stations track satellites simultaneously, measuring their local clocks against time as transmitted by the satellites. These measurements are brought together and differenced between pairs of stations to obtain measurements between laboratories. This differencing of common view measurements cancels the GPS clocks and, to a large extent, many of the systematic measurement errors (2). A time transfer accuracy of 10 ns has been expected and apparently realized in many cases. It is difficult to verify this accuracy, since there are no operational time transfer system of equal or greater accuracy. Problems with realizing this accuracy can be divided into three categories:

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- (1) Inaccuracy of the GPS
- (2) Local problems
- (3) Data processing techniques

Errors in time transfer via a single GPS satellite are due to errors in: satellite ephemerides, ionospheric modeling, tropospheric modeling, local antenna coordinates, calibration of delays in local equipment, or due to multipath interference. Inaccuracy of the GPS refers to errors in the satellite ephemerides and ionospheric models as transmitted from the satellites. The tropospheric model is fixed in the receivers and is typically a simple cosecant function of elevation normalized by a function of local height. Errors here might be considered as either part of the GPS system or a problem with the local receiver and environment. Errors in local antenna coordinates or equipment calibration delays or multipath around the antenna are local problems.

A measure of inaccuracy of the GPS is a time transfer closure around the world. The resultant value should be zero. Figure 1 shows the residuals from three common view time transfers: (PTB-NIST), (TAO-PTB), and closing with (NIST-TAO), where PTB is the Physikalisch Technische Bundesanstalt, Braunschweig, Fed. Rep. of Germany. These are residuals over four years: 1985-1988. One can see the maturation of the system. The data over the months of August through November of 1988 are at the end of the plot with a mean of 8.3 ns, and a standard deviation of 7.7 ns. This is consistent with an accuracy estimate of 10 ns for each individual leg. The problem with different data processing techniques is related to the GPS inaccuracy in that there are systematic errors in GPS common view data. A time series of common view measurement differences at one sidereal day intervals with a given satellite can be biased from a similar time series made using a different satellite, or even using the same satellite at a different time (figures 2 and 3)(4,5). The satellites are in 12 hour sidereal orbits. Hence the geometric relationship between the satellite and the ground stations repeats once per sidereal day. For this reason, the tracking schedule prepared by the BIPM sets track times that repeat once per sidereal day. Biases between tracks taken at different times can cause different methods of processing common view data to yield significantly different results.

We discuss the local problems in a little more detail since they are particularly relevant for this paper. The quality of data is degraded by several local sources of errors:

- 1) Wrong calibration of GPS receivers (instrumental delay, antenna cable, connection to the local clock)
- 2) Poor shape of the pulse of the local time reference
- 3) Tropospheric correction error
- 4) Multipath due to signal reflection at the receiving site
- 5) Errors in antenna coordinates

Thus this calibration helps to eliminate an important contribution to GPS time transfer error in Japan. Since Japan is somewhat isolated from other major timing laboratories, GPS common view is an important link for including the Japanese labs in TAI.

We note here that we have tabulated information about the system of generating and comparing UTC using GPS in common view for each of the labs visited. Included is information about the ensemble of clocks and the environmental control for these clocks in table 2, and the local 1 pps in table 3. The coordinates of all three locations in Japan are based on geometric measurements from Tokyo Datum and conversions to WGS-72 and WGS-84. All receivers use the WGS-84 coordinate

system except the on-line receiver at TAO. Since this experiment, as of July 1, 1988 the TAO has been applying the WGS-84 coordinate system to the measured residuals in their own computer, before putting their measurements on the Mark III system. In an experiment at NIST we have seen that the use of the different coordinate systems, WGS-72 versus WGS-84, both to compute satellite position and to convert local antenna coordinates from geodetic to geocentric produced a bias in the calibration of 3.6 ns, and increased the standard deviation from 1.9 to 3.1 ns. This is consistent with our measured standard deviation of 3.3 ns on the on-line receiver at TAO.

Calibrations at NIST

For common view time transfer only the relative delays through receivers are important. To obtain a measure of ref A-ref B we subtract the two measurements against GPS: GPS-ref. Any common delay through the two GPS receivers will cancel. Since we have several GPS receivers at NIST which we monitor carefully, we are able to keep track of their relative delays even when one changes. We have maintained the receiver NBS10 as a standard for measuring relative delays through receivers. For this reason NBS10 has been used as an informal transfer standard for intercomparison of receiver delays between timing laboratories.

The technique for calibrating a remote receiver is to first calibrate a receiver at NIST against NBS10, then carry that calibrated receiver to the remote site and measure tracks in common with the receiver there, and finally bring the receiver back to NIST and close with another calibration against NBS10. The delay between two receivers can be calibrated for time transfer by setting them up to track in common view, at close distances with carefully measured relative coordinates. This allows cancellation of time transfer errors due to satellite ephemeris errors or mis-modeling of the ionosphere. Also, there should be no errors due to incorrect relative coordinates. Differences in measurements due to multi-path still remain. Any instabilities in the receivers become appropriately part of the calibration.

For this trip we first tracked satellites with the receiver NBS23 at NIST in common with tracks on three other receivers, one of which was NBS10. The antenna coordinates of all four receivers were known to within 1 m relative to each other. This was done for weeks. The standard deviations were usually below 2.5 ns. I shall call NBS23 the "traveling receiver" for this calibration trip, since it was the one which was carried. The traveling receiver was then carried to Japan, where it was used to calibrate timing delays of receivers there. Finally, it was returned to the U.S.A. where it was again calibrated against NBS10 for closure. The final calibration showed an offset of 4 ns with a standard deviation under 2.5 ns. To correct for this, all measurements made in Japan have been corrected by 2 ns to obtain an estimate of lab receiver vs. NBS10.

Calibrations at TAO

The traveling receiver was set up the night of June 1. Two receivers of different manufacture were calibrated at TAO. The older receiver is used for data put on the Mark III system for international time comparisons in cooperation with the BIPM. We will call this the "on-line receiver." The second receiver is a newer one which we will call the "back-up receiver." After one day of data we discovered that the 1 pps reference for the back-up receiver had a long rise time, about 50 ns at 90%, since it was coming from old equipment. The people at TAO therefore changed on June 2 to a different digital clock with a fast rise time of about 2 ns. The pulse for both the on-line receiver and the traveling NIST receiver were already coming from this digital clock. After this change both calibrations had standard deviations of 3.5 ns. The calibrated delays are listed in Table 1 below.

Calibrations at CRL

The NIST receiver was set up at CRL on Saturday, June 4, and taken down on June 6. The standard deviation of the data was 13.5 ns. This is large when one considers we are trying to calibrate these delays to within a few ns. CRL has a unique receiver of their own design. It appears to have a large overall delay as compared to other receivers, hence the possibility for more deviations in the measurements. They also use their own ionospheric model. The rise time of the 1 pps to both receivers was of the order of 20–30 ns at 90%. These factors contributed to the large deviation in the data. Coordinate errors were ruled out, both since the two antennae were within 1 m, and since there are deviations of the order of 30 ns on some of the same tracks from one day to the next. The calibration results are listed in Table 1 below.

Calibrations at NRLM

The NBS receiver was set up at NRLM on the afternoon of June 6. Tracks were continued until June 10. NRLM had two GPS receivers NRLMA and NRLMB. These were of a manufacture new to common view time transfer, with software which had not been used before in a timing receiver. In fact the software had been newly issued to NRLM within the previous week to facilitate the common view comparisons of this experiment. In reducing the data we also had a large standard deviation here: 15.5 ns for NLRMA, and 36.6 ns for NRLMB. In this case we found indication of coordinate errors since the day to day deviation of the calibration using a single track was typically under 4 ns, and we had 4 or 5 days of data on most tracks.

The measurement residuals and the elevations and azimuths as recorded from the end of the tracks, resolved to 1 degree, were used to estimate any coordinate change implied by the data. The process is illustrated in figures 4 and 5. Both figures are polar plots of the location of the tracks, indicated by X's, at NRLM in elevation and azimuth. Thus, each X denotes a track which was repeated each day. Next to each X in figure 4 is the residual for that track of the measurements NRLMB–NBS10 after averaging over all the days and then removing the mean of all the measurements. One can see here a large bias in the north south direction. The positioning solution in this case resulted in a 16 m change. Figure 5 shows the residuals after removing the effect of the coordinate change. One can see there is still a large deviation in the residuals.

The coordinate change for NRLMA was rather puzzling. The result was a 3.5 m change largely in the east direction. Yet the antennae themselves were only 2 m apart to begin with. It is possible there was some problem with the software in the receiver. This is reinforced further since the standard deviation of the measurements from NRLMA after correcting for the coordinate change was still 14.6 ns. The coordinate change for the NRLMB receiver was 16.0 m in the north direction, 2.6 m in the east direction, and 0.7 m vertically. A coordinate error here is more plausible in that the antenna for this receiver was somewhat removed to a quieter RF area, and had been surveyed. Though, the residuals after the change still had a standard deviation of 15.2 ns.

| Table 1. Calibration Results Local Receiver-NBS10 | | | | | |
|--|-----------|--|--------------|-------------|-----------------------|
| Lab & Rcvr | Date | No. pts | Mean (ns) | RMS (ns) | Coordinate version |
| TAO on-line | June 1-4 | 47 | -11.7 | 3.3 | WGS-72 |
| TAO back-up | June 1-4 | 44 | +15.0 | 3.5 | WGS-84 |
| CRL | June 4-6 | 34 | -68.1 | 13.5 | WGS-84 |
| NRLM A | June 6-10 | 87 | -61.5 | 15.5 | WGS-84 |
| | | after the estimated coordinate change: | | | |
| | | | -62.3 | 14.6 | WGS-84 |
| NRLM B | June 6-10 | 87 | -169.1 | 36.6 | WGS-84 |
| | | after the estimated coordinate change: | | | |
| | | | -172.2 | 15.2 | WGS-84 |

| Table 2. Clock Ensemble and Local UTC | | | | | | |
|--|--|-----------------------------|--------------------------------|-----------------------|----------------|--|
| Lab i | Clock ensemble | Source of UTC(i) | Point of UTC(i) | temp. control | humid. control | Faraday shield |
| TAO | 8 Comm. Cs. w/ supertubes | 1 Comm. Cs. w/ supertube | Start of time interval counter | yes | yes | yes |
| CRL | 1 lab Cs. 11 Comm. Cs. | Ensemble of 5-6 Comm. Cs. | Start of time interval counter | +/-0.5 deg C | +/-10% | -40dBm |
| NRLM | 3 H-masers 2 HP5061-004 1 HP5061 | 1 HP5061-004 | Start of time interval counter | 23.0 +/- 0.3 deg C | 50% +/- 3% | E field: 120dB B field: linear 20 dB @ 1KHz 110 dB @ 1MHz |

Note: "Comm." is used as an abbreviation of "Commercial"

| Table 3. Shape of the local 1pps | | |
|----------------------------------|--------------------|---------------|
| Lab | 90% Rise Time (ns) | Voltage Level |
| TAO | 4 ns | 0-5 |
| CRL | 25 ns | 0-5 |
| NRLM | 10 ns | 0-5 |

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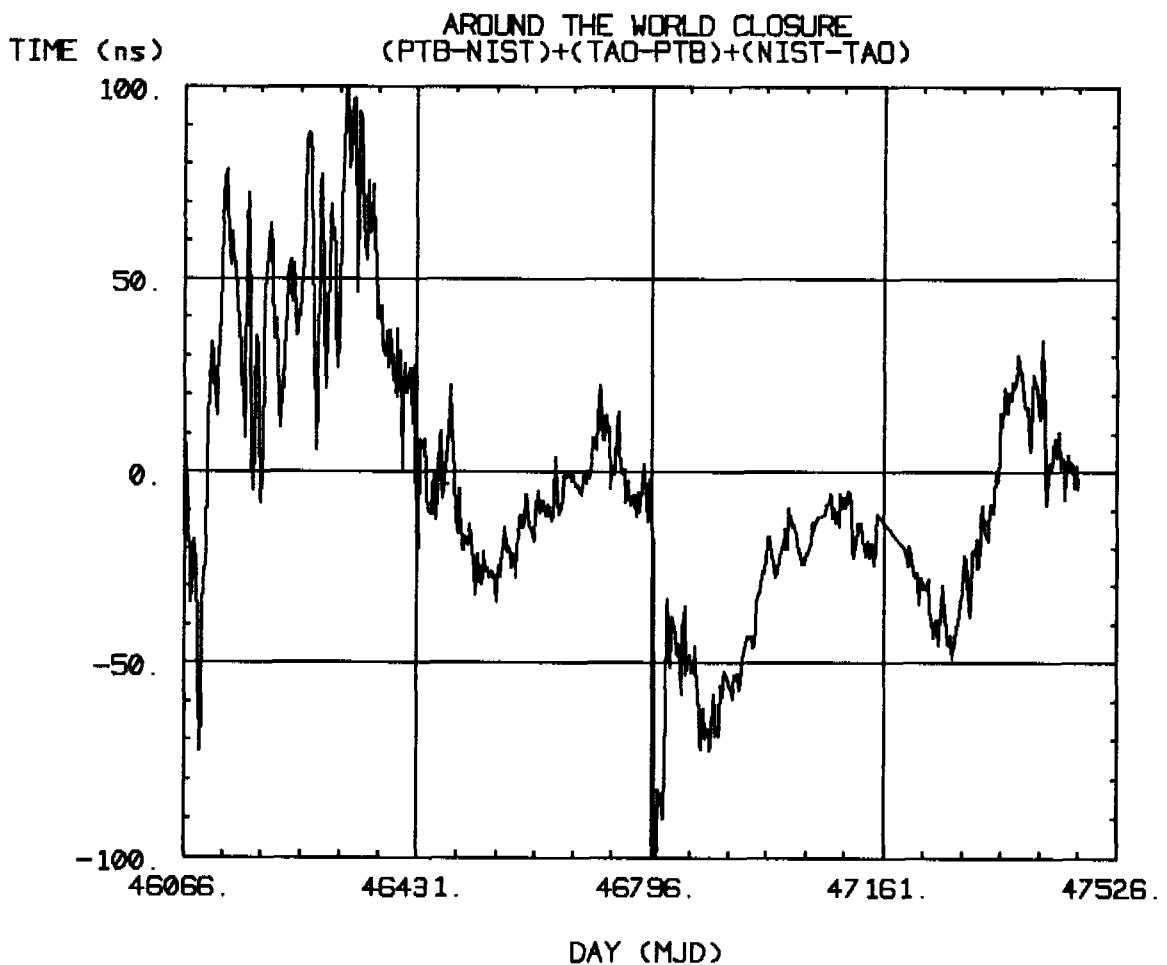


Figure 1: The residuals from three common view time transfers: (PTB-NIST), (TAO-PTB), and closing with (NIST-TAO), over four years: 1985, starting MJD 46067, 1986, starting MJD 46432, 1987, starting MJD 46796, and 1988, starting MJD 47161. One can see the maturation of the system, as the residuals generally decrease and become more well-behaved over the years. The sharp drop in early 1987 coincides with the coordinate change from WGS-72 to WGS-84. The data over the months of August through November of 1988 are at the end of the plot with a mean of 8.3 ns, and a standard deviation of 7.7 ns. This is consistent with an accuracy estimate of 10 ns for each individual leg.

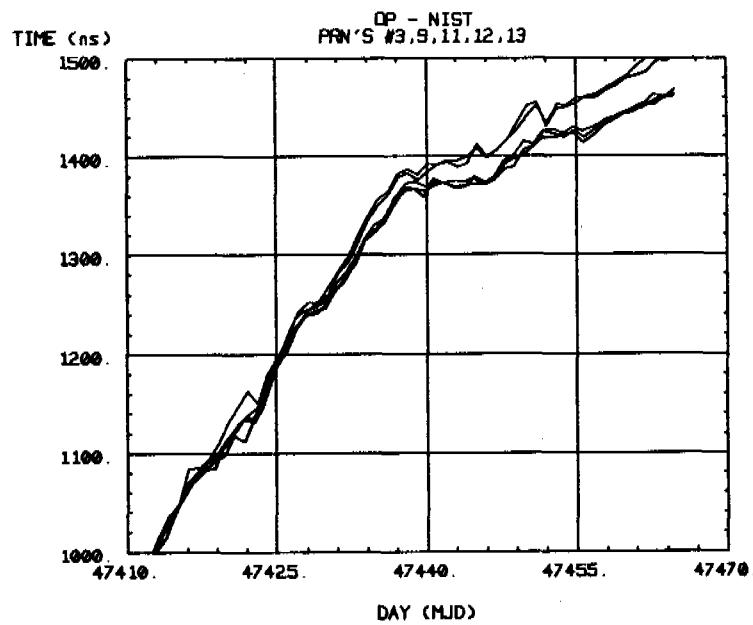


Figure 2: Measurements taken once per sidereal day on satellites in common view between Observatoire Paris, in Paris , France, and NIST, Boulder, Colorado show biases between measurements taken via different satellites. The biases change over time, and can be as large as 40 ns.

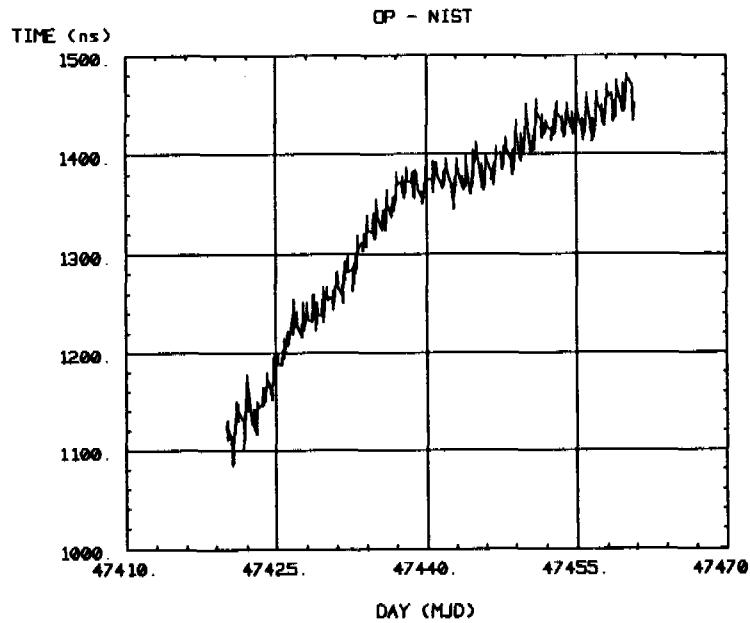


Figure 3: If one uses all common view data available in one chronological time series, the biases appear as noise with a large diurnal signature.

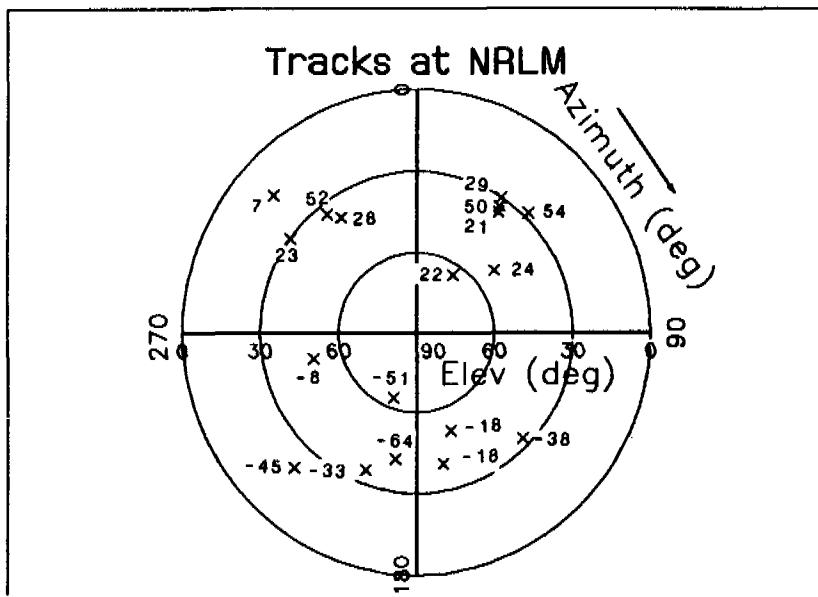


Figure 4: A polar plot of the location of the tracks, indicated by X's, at NRLM in elevation and azimuth. Thus, each X denotes a track which was repeated each day. Next to each X is the residual in ns for that track of the measurements NRLMB-NBS10 after averaging over all the days and then removing the mean of all the measurements. The residuals imply a positioning error of 16 m north, 2.6 m east, and 0.7 m vertical. The positioning error in the north direction can be seen heuristically by noting that the residuals are generally more negative to the south and positive to the north.

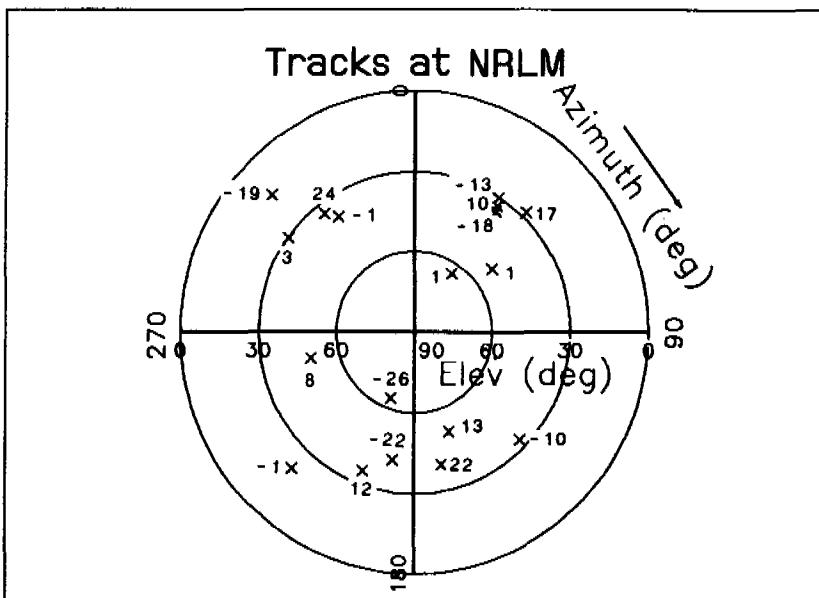


Figure 5: A polar plot of the tracks at NRLM as in figure 3, but now the numbers next to the X's have been adjusted from figure 3 to account for the positioning solution. The standard deviation has dropped from 36.6 ns to 15.2 ns, though this is still quite large.

QUESTIONS AND ANSWERS

JIM SEMLER, INTERSTATE ELECTRONICS: Can you briefly describe the architecture of the receivers that you were calibrating?

DR. WEISS: I am not too familiar with the architecture of all the different receivers, they are quite different designs. They were all operated in a mode that was single-channel, C/A code receivers. I really don't know the different architectures.

DR. GERARD LAPACHELLE, UNIVERSITY OF CALGARY: You mentioned that the multipath reached as much as three nanoseconds. You were lucky because with the chip rate of the code, you could get a delay error as much as 900 nanoseconds. In certain navigation situations, even with the P-code we have seen as much as 30 to 50 nanosecond delay because of multipath. It is possible to combine the code with the carrier to limit this.

DR. WEISS: Yes, if you have a carrier-locked receiver, as long as you do not slip a cycle, the most error that you can get is one cycle. That is the stability of the measurement, you still have the problem of identifying the cycle that you are locking on. The only way to determine the pseudo-range is with the code. You still have to start with a code measurement to identify a cycle. What you mentioned about the deviation due to multipath—a reflected wave can come in as much as 300 meters or 900 nanoseconds out and still in some way influence the integration. The farther out it is, the less that is going to pull the lock of the receiver. There really is a trade-off between how far out it is, in terms of how far it's going to pull the lock, and how much leverage it has in pulling it. Typically what we have seen is errors between 3 and as much as 10 nanoseconds. There have been other studies that indicate more than that, but I haven't seen anything on the order of 30 to 50.