

# A VERY-SHORT-BASELINE TIME TRANSFER EXPERIMENT USING TWO GEODETIC- QUALITY GPS RECEIVERS AND CARRIER PHASE TECHNIQUES

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## Abstract

*For over 10 years primary timing laboratories have used signals from the Global Positioning System (GPS) to compare atomic timescales. The method used, the common-view of GPS satellites, does not use the GPS system to its full potential. Recently, there has been much interest in using geodetic-quality GPS receivers for time transfer. The result has been a substantial improvement in the precision of the resulting time and frequency transfers.*

*In this paper, a detailed account is presented of common-clock comparisons made at NPL between a recently purchased Ashtech Z12-T receiver and an older Allen Osborne Associates (AOA) TTR-4P receiver. Data collected from these geodetic-quality GPS receivers were processed using analytical software developed at NPL. Direct comparisons are made between the two receivers using both P1 and P2 coded signals, and L1 and L2 phase measurements. Measured ionospheric delays were obtained from both receivers and compared. Multipath is one of the major causes of errors in the surveying applications of geodetic GPS receivers. Code-phase differences were used to estimate the magnitude of code multipath present in both receivers. The principal sources of error present in the common clock measurements are discussed and possible improvements are considered. The future direction of geodetic time transfer work at NPL is also outlined.*

## 1 INTRODUCTION

The application of geodetic GPS techniques to frequency and time transfer has produced some very impressive results [1],[2]. These results have increased the interest in using geodetic GPS time transfer for international comparisons between primary timing laboratories. One recent development has been the formation of a joint BIPM/IGS pilot project to coordinate studies in the field [3].

The quality of geodetic GPS frequency and time transfers will, however, be limited by the delay stability of both the GPS receiver's instrumentation and that of the associated measurement systems [4]. Other local environmental considerations, for example the susceptibility of the receiver's antenna to multipath, will also limit the receiver's performance.

The post-processing of geodetic GPS data is more complicated than the processing of data collected by other high precision time transfer methods. Only a few primary timing laboratories have the capability to postprocess their own geodetic GPS data, and those who do usually use commercial software.

In this paper the results of a very-short-baseline common-clock experiment between NPL's Ashtech Z12-T and AOA TTR-4P geodetic-quality GPS receivers are presented. NPL's development of analysis software from first principles is described. The relative performance of NPL's GPS receivers is evaluated by using the analysis software to compare both the code and phase data available from both receivers. By combining these data with the broadcast GPS almanac data, a detailed evaluation was possible, including an examination of the physical processes limiting the receivers' performance.

## **2 GEODETIC GPS HARDWARE AT NPL**

NPL possesses two geodetic quality GPS receivers, an Ashtech Z12-T and an AOA TTR-4P. The hardware configuration is shown in Figure 1. The Ashtech Z12-T is a modified version of the Ashtech Z12 receiver, where the internal oscillator is replaced by a 20 MHz external reference signal. The receiver provides 1 PPS input and output signals, which lock the receiver's internal clock. The TTR-4P is an older receiver widely used in primary timing laboratories. The two receivers' antennas are located approximately five meters apart. Standard frequency and 1 PPS reference signals for the two receivers originate from common frequency distribution and 1 PPS generation units. All the receivers' input signals are referenced to NPL's Sigma Tau Active Hydrogen Maser.

## **3 DATA SETS EXTRACTED FROM THE RECEIVERS**

Several data sets were extracted from the receivers. RINEX data were extracted from the Ashtech Z12-T receiver. Although in principle available, similar RINEX data could not be obtained from the TTR-4P receiver; however, code and phase measurements were obtained from the receiver using its "block 015" data. Both data sets were collected with a measurement epoch of 30 seconds synchronized to GPS time. The GPS almanac data were also extracted from the Ashtech Z12-T receiver, which was used in NPL's postprocessing software.

## **4 POSTPROCESSING SOFTWARE DEVELOPED AT NPL**

The baseline between NPL's two geodetic GPS receivers is 5 m. With this limited baseline extensive data post processing is still required to compute comparisons between the two receivers with a measurement precision of 10 picoseconds.

Several distinct operations are performed by the analysis software:

- 1) Each day's data are processed separately. The software's data input included code and phase variables from each receiver, along with the GPS almanac data and approximate receiver coordinates. The data are processed in 30 s blocks, which corresponds to the measurement epoch.
- 2) The GPS almanac is decoded to obtain satellite coordinates, at each measurement epoch, which were then used to calculate accurate satellite azimuth and elevation values. Satellite azimuth and elevation angles are generated in the Ashtech Z12-T and TTR-4P output data sets, but only with a precision of  $1^\circ$ , which is not adequate for the comparison of the receivers' clocks with 10-picosecond precision.
- 3) A first calculation is made of the relative coordinates between the phase centers of the two antennas, using only the code variables P1 and P2, and the satellite azimuth and elevation values calculated in step 2. A separate estimate is made at each measurement epoch by calculating the pseudo-range differences  $(P1_{(TTR-4P)} - P1_{(Ashtech\ Z12-T)})$  and  $(P2_{(TTR-4P)} - P2_{(Ashtech\ Z12-T)})$  using each satellite. The antennas' relative coordinates are then optimized to minimize the scatter between pseudo-range differences calculated from each satellite in view. This calculation is repeated for each measurement block, and finally a mean value for the relative coordinates is determined.
- 4) Phase data are now introduced into the analysis. Step (3) is repeated using phase rather than code measurements. Phase ambiguities are corrected by adding integer cycles to the L1 and L2 measurements. With these very short baselines, resolving the phase ambiguities is relatively straightforward. Using a single day's data, the coordinate differences between the two antennas could be determined with sub-centimeter precision. Separate relative coordinates are calculated for the L1 and L2 frequencies to reflect the slightly different phase centers in the antennas.
- 5) The software is then used to generate a wide range of output parameters using the optimized relative coordinates in the processing. These include: measured code and phase differences between the two receivers, ionospheric delay measurements, and receiver code/phase differences used in the study of code multipath.

## 5 DIRECT COMPARISONS BETWEEN THE TWO RECEIVERS

P1 code differences, calculated between the two receivers are shown in Figures 2 and 3. P2 code differences were also calculated but are not shown here. Figure 2 shows individual satellite tracks, while the mean value calculated from all satellites simultaneously tracked by both receivers is shown in Figure 3. The P1 and P2 code differences showed no obvious correlations. There is a scatter of several nanoseconds within individual tracks; this decreases to (1-2) nanoseconds ( $1\sigma$ ) for the mean value

averaged over all satellites. The scatter in the data appeared asymmetric, with notable outliers. The majority of these were attributed to multipath occurring within the AOA TTR-4P receiver, often when the satellite is at low elevation angles. The data scatter reduces with satellite elevation angle, due in part to the increased gain of the antenna at these angles. There was no obvious correlation between individual satellite tracks. The scatter on the P2 data is approximately twice that on the P1 data. This is consistent with the lower levels of received P2 signals.

The phase differences between the two receivers are shown in Figures 4 and 5. The scatter on the phase data is noticeably lower than that from the code data, typically 10-picosecond scatter between successive measurements on the same satellite track. The long-term variations show no obvious correlation with long-term variations in the code measurements. Individual satellite tracks correlated extremely well (Figure 4), with a typical 20-picosecond RMS scatter ( $1\sigma$ ) between all the tracks measured in the same epoch. This shows that the majority of the phase instabilities are correlated between measurements from all of the satellites. The phase differences observed at L1 and L2 frequencies also agreed well (Figures 5), although there were variations of up to 60 picoseconds in the L1-L2 phase differences (Figure 6). The short-term instabilities in the phase differences correlate with temperature cycling in the room containing the receivers; this cycling has a period of approximately 30 minutes (See Figures 4,5, and 6). The Ashtech Z12-T receiver temperature is included in Figure 5. There was no obvious correlation with outdoor temperature. More detailed studies are planned to isolate the causes of the phase instabilities.

## 6 IONOSPHERIC DELAY MEASUREMENTS

Over a longer baseline a geodetic GPS time transfer will be limited by the effectiveness of the ionospheric delay correction. Three different methods of measuring the L1 ionospheric correction are shown here: (i) using code  $\alpha(P1-P2)$  differences (Figure 7); (ii) using phase  $\alpha(L2-L1)$  differences (Figure 8); and (iii) using single frequency code-phase  $0.5(P1-L1)$  differences (Figure 9) calculated at the L1 frequency. ( $\alpha = F_2^2/(F_2^2 - F_1^2)$  where  $F_1$  and  $F_2$  are the transmission frequencies of L1 and L2 respectively). Absolute values of the ionospheric delay may be obtained from the code measurements; however, only relative ionospheric delay changes may be obtained using the phase measurements, and the code-phase differences. Good agreement is obtained between all three methods. The phase measurements clearly demonstrated far less noise than on the code measurements; this was in part due to the encryption of the GPS P-code, and in part due to phase measurements being intrinsically less noisy. The noise on the code measurements obtained from the AOA TTR-4P receiver was approximately half the level of noise obtained from the Ashtech Z12-T receiver. There was no obvious bias between code measurements obtained from different receiver channels or from different GPS satellites; however, there was a bias of 30 nanoseconds between the coded ionospheric measurements obtained from the Ashtech Z12-T and AOA TTR-4P receivers. The single frequency code-phase differences are shown to be effective in

determining ionospheric delay changes.

The differences between ionospheric phase measurement obtained from the Ashtech and AOA TTR-4P receivers are shown in Figure 10. Variations in these plots of up to 100 picoseconds were observed which correlate with satellite elevation. This may be due to the different relative phase patterns of the two antennas. A simple alternative explanation is that the height component of the antenna coordinate differences may be slightly in error.

## 7 MEASUREMENT OF CODE MULTIPATH

A major limitation to the use of geodetic GPS receivers for positioning applications is multipath. Phase multipath is typically a thousand times smaller than code multipath. The quality of the GPS code measurements is vital for the analysis of geodetic GPS data, which may be severely degraded by code multipath. Measuring code-phase differences from individual satellite tracks is an excellent way to identify code multipath. The repeating GPS constellation each sidereal day enables multipath to be observed through the repeating delay changes observed in the code phase differences. Examples are shown in Figure 11 for data obtained from NPL's Ashtech Z12-T receiver. The repeating code phase difference patterns were observed at both L1 and L2 frequencies. The patterns observed were noticeably different at the two frequencies, because multipath effects are frequency-dependent (Figures 11 and 12). The origin of much of this multipath may well be a copper dome on NPL's laboratory roof. The Ashtech Z12-T antenna has recently been moved; the new site will be examined for residual code multipath.

## 8 FUTURE WORK

NPL has an active program to develop its geodetic GPS installation. NPL intends to purchase another geodetic-quality GPS receiver, enabling "three-cornered-hat" comparisons in future. Also NPL has a 3S Navigation combined GLONASS/GPS receiver from which the L1 CA code GPS channels may be used for direct comparisons with geodetic GPS receivers. Instrumentation delay instabilities may be reduced through temperature control of the GPS receivers, antennas, and connecting cables. Work is underway to improve the frequency distribution system from NPL's Active Hydrogen Maser.

NPL is in the process of upgrading its geodetic GPS installation to meet the requirements of an IGS station. NPL is also playing an active part in comparisons between geodetic GPS and other high precision time transfer methods, including TWSTFT and GLONASS time transfer.

## **9 CONCLUSIONS**

This paper has demonstrated that short-baseline common-clock experiment using geodetic GPS receivers may be analyzed from first principles using relatively straightforward software. This type of analysis may be usefully performed by primary timing laboratories to obtain an insight into the performance of their geodetic GPS timing receivers.

A major source of errors is due to delay instabilities within the receiver instrumentation. The analysis described in this paper has identified the magnitude of both the code and phase instabilities occurring between NPL's geodetic GPS timing receivers. Other physical processes limiting geodetic GPS time transfer, including ionospheric delay determination, code multipath, and antenna phase dispersion, have been examined. Future work is required to optimize the receiver's performance.

## **10 REFERENCES**

- [1] K. M. Lawson and J. Levine, "Time transfer using GPS carrier phase methods," Proceedings of the 29 th PTTI meeting, pp. 221-228, December 1997.
- [2] F. Overney, L. Prost, G. Dudle, Th. Schildknecht, G. Beutler, J. A. Davis, J. M. Furlong, and P. Hetzel, "GPS time transfer using geodetic receivers (GeTT): Results on European baselines," Proceedings 12 th EFTF, pp. 94-99, March 1998.
- [3] J. Ray, "The IGS/BIPM pilot project to study accurate time and frequency comparisons using GPS phase and code measurements," Proceeding of the 30 th PTTI meeting (these Proceedings), December 1998.
- [4] F. Overney, Th. Schildknecht, G. Beutler, L. Prost, and U. Feller, "GPS time transfer using geodetic receivers: Middle term stability and temperature dependence of the signal delays," Proceedings of the 11 th EFTF, pp. 504-508, March 1997.

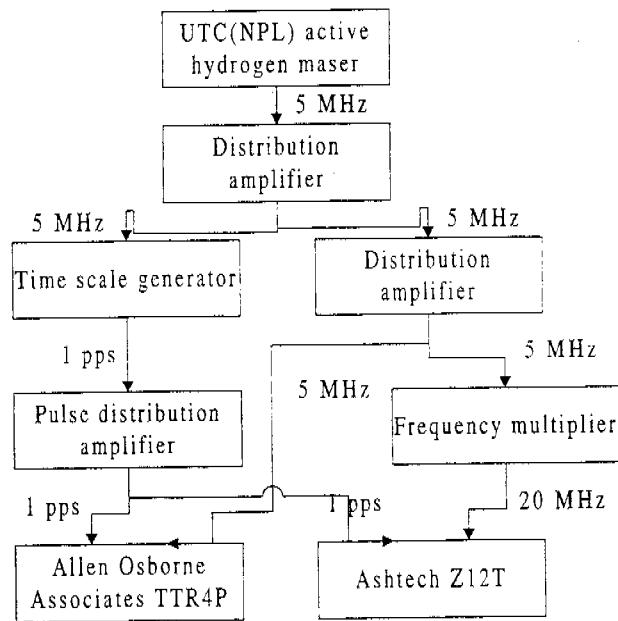


Figure 1: Ashtech Z12-T and AOA TTR-4P receiver hardware configuration.

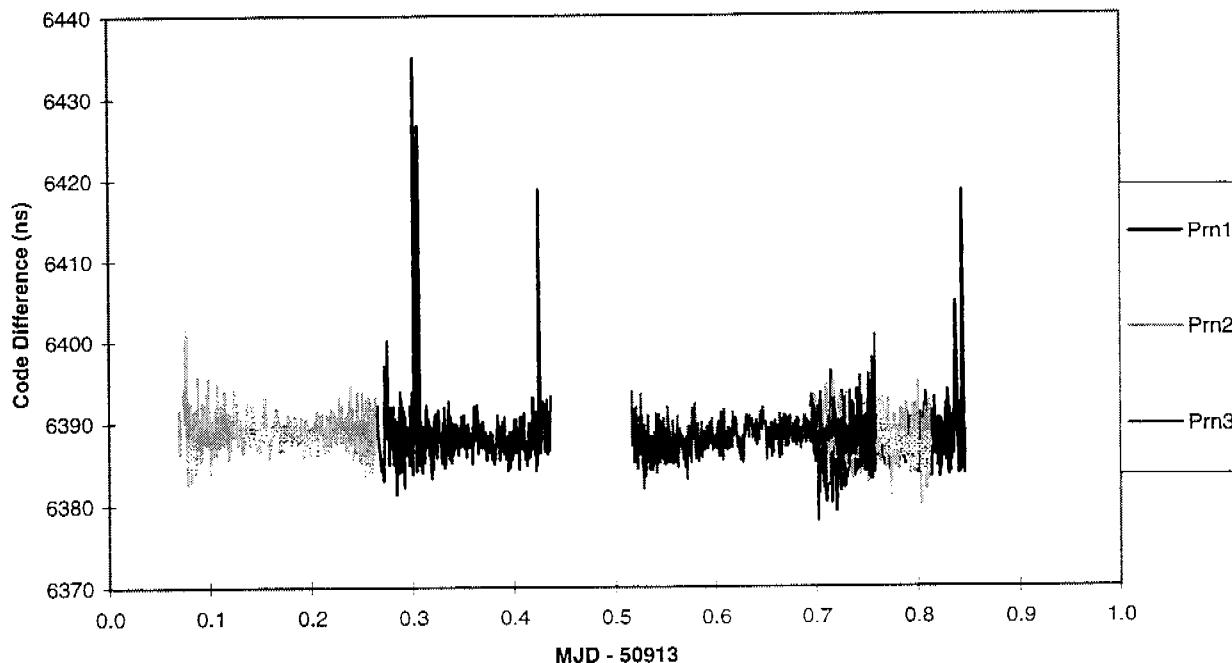


Figure 2: P1 code comparisons (AOA TTR-4P - Ashtech Z12-T), individual satellite tracks.

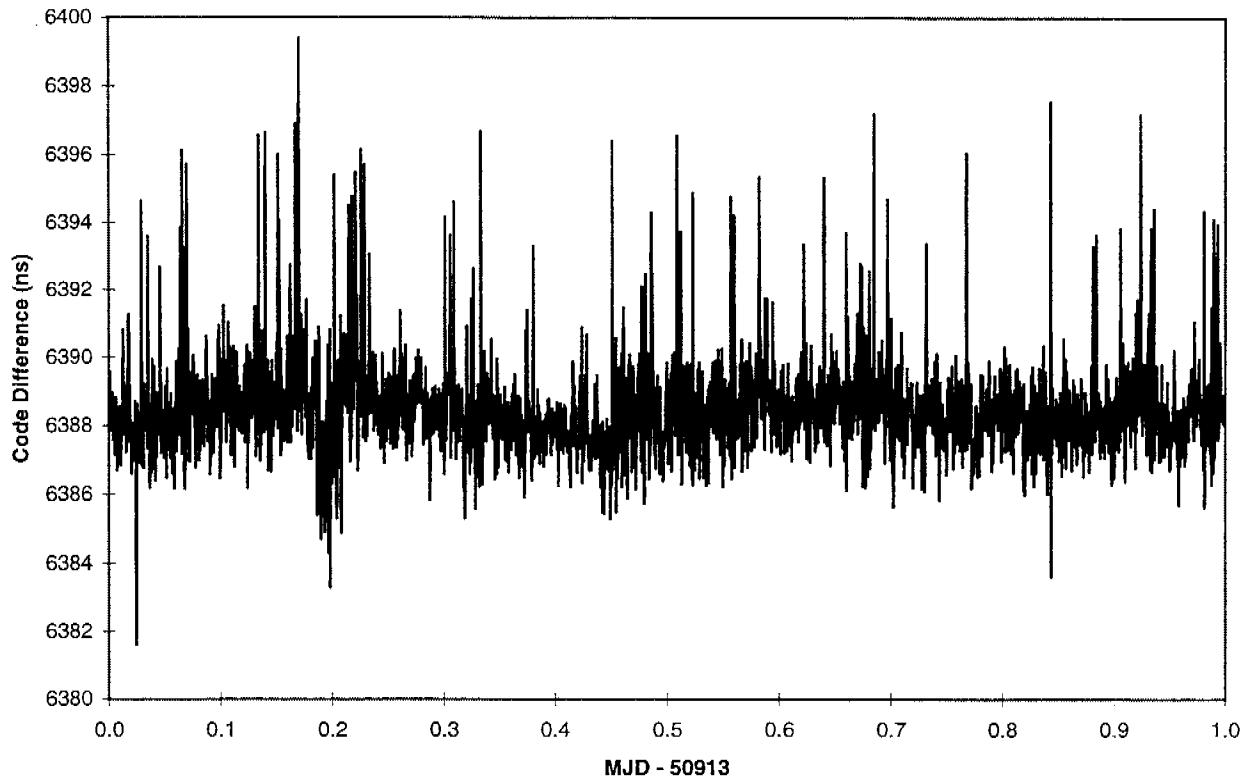


Figure 3: P1 code comparisons (AOA TTR-4P - Ashtech Z12-T), mean values.

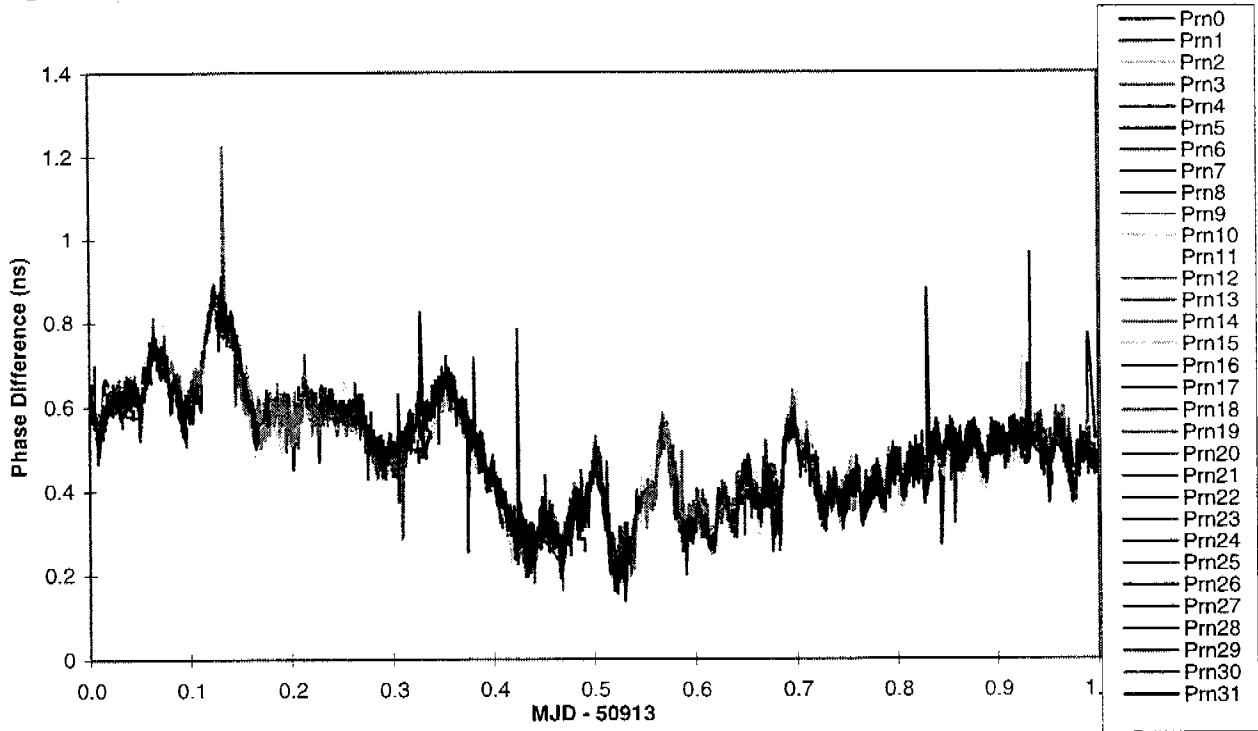


Figure 4: L2 phase comparisons (AOA TTR-4P - Ashtech Z12-T), individual satellite tracks.

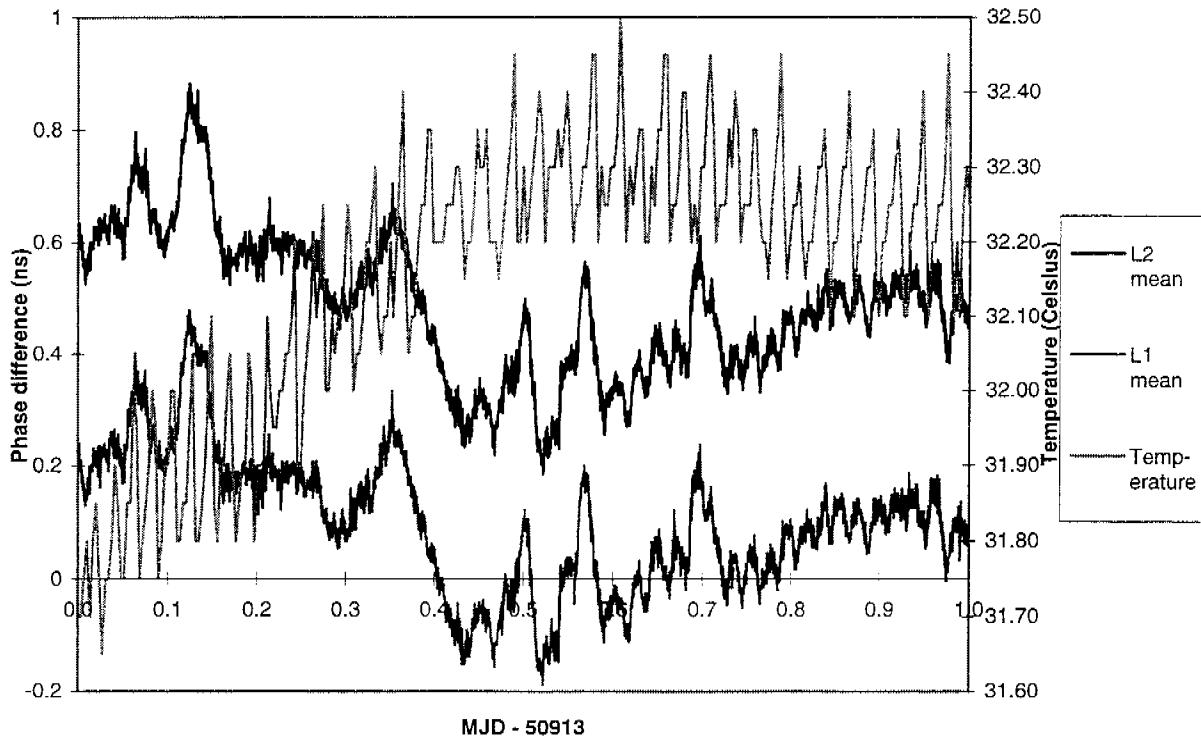


Figure 5: L1 and L2 phase comparisons (AOA TTR-4P - Ashtech Z12-T), mean values.

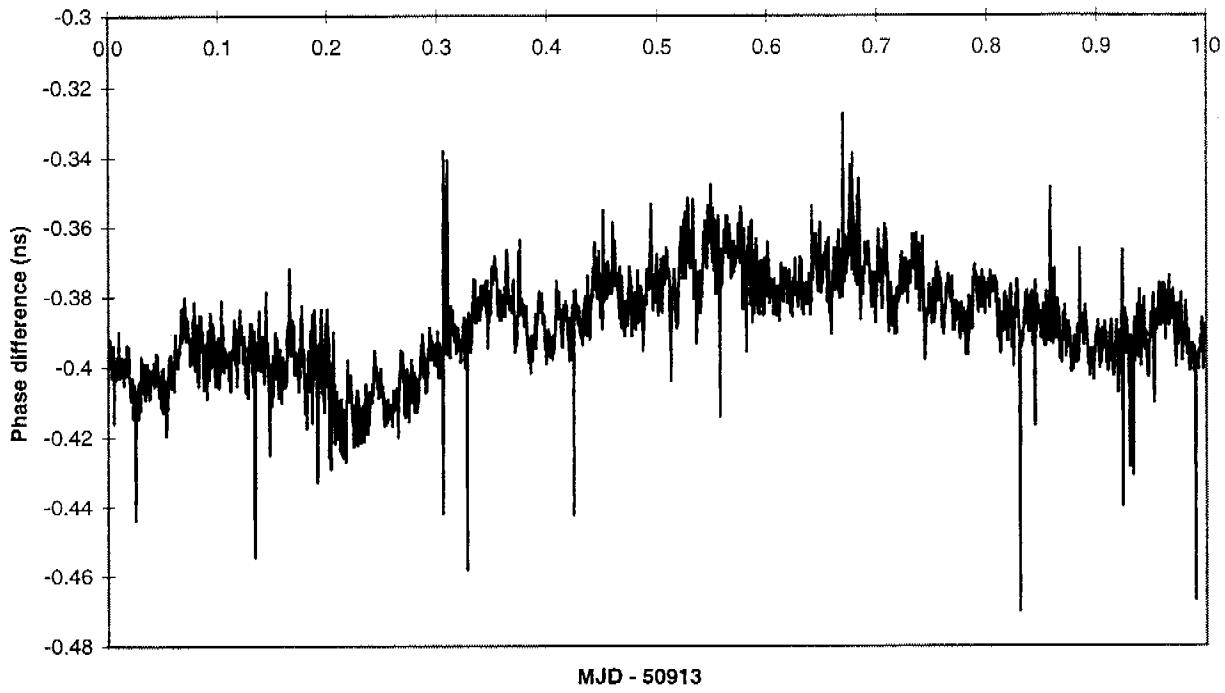


Figure 6: Phase comparisons (AOA TTR-4P - Ashtech Z12-T), L1 - L2 differences.

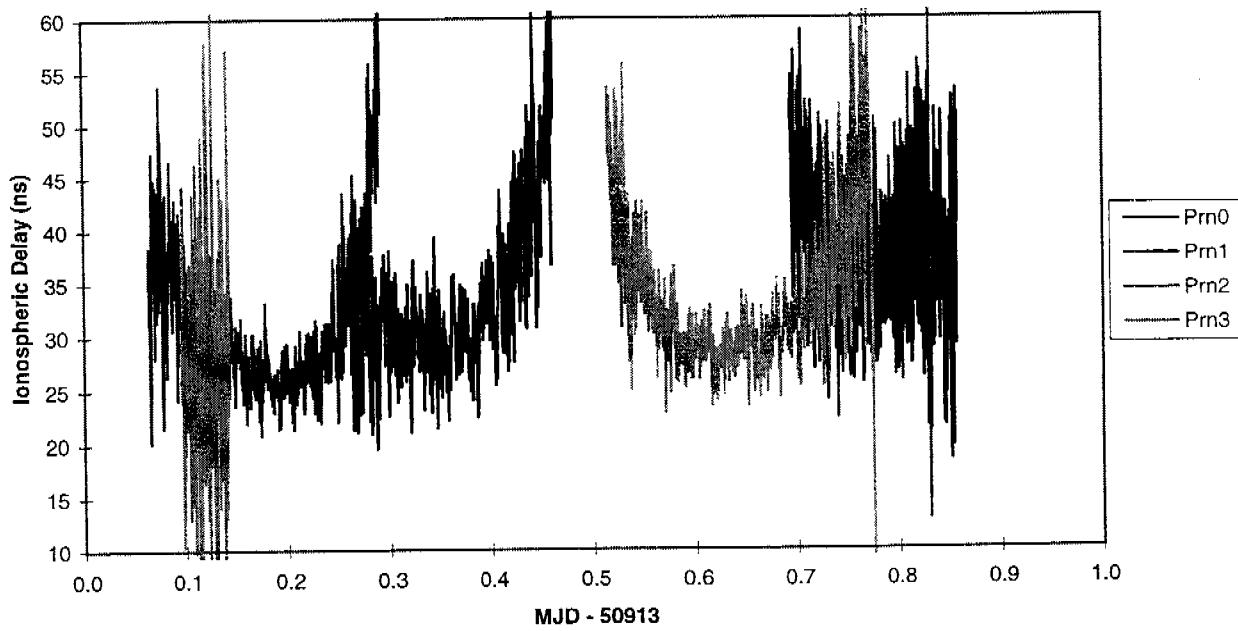


Figure 7: Code ionospheric delay measurements, individual satellite tracks, Ashtech Z12-T receiver.

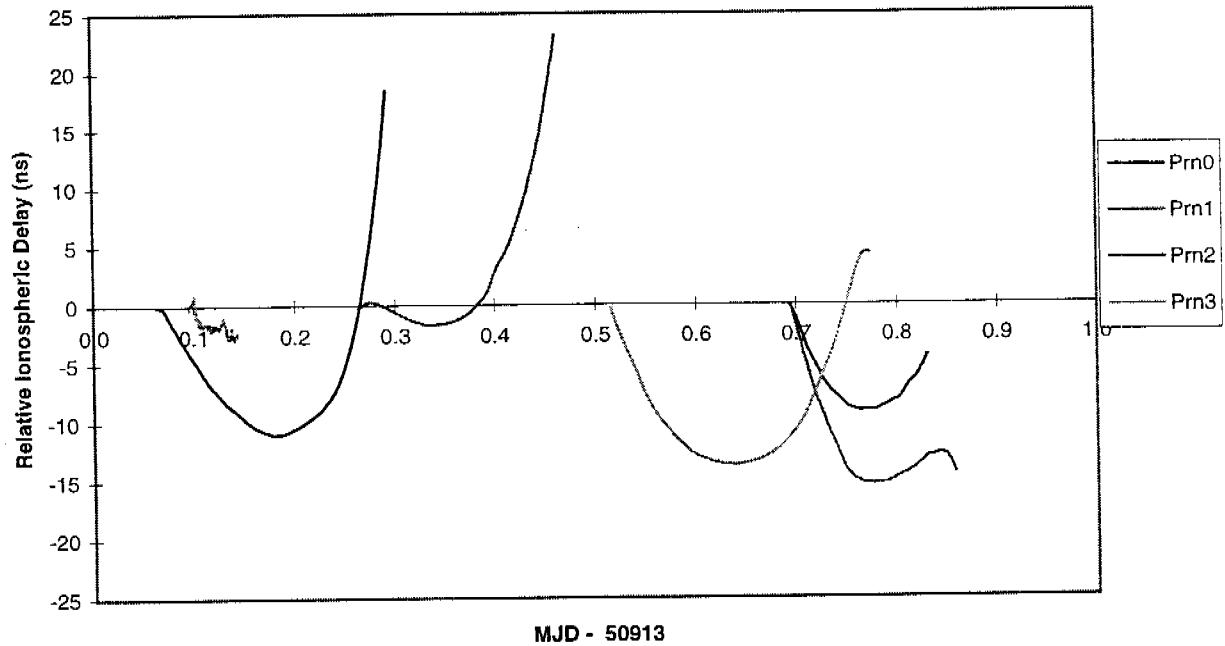


Figure 8: Phase ionospheric delay measurements, individual satellite tracks. Ashtech Z12-T receiver.

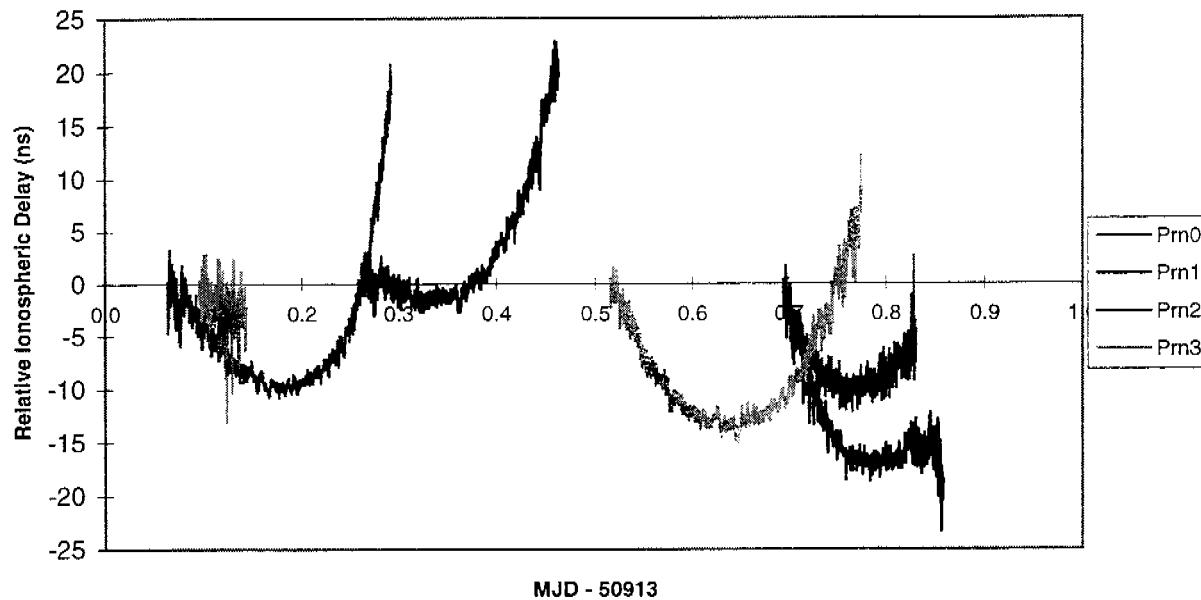


Figure 9: L1 single frequency ionospheric delay measurements, individual satellite tracks. Ashtech Z12-T receiver.

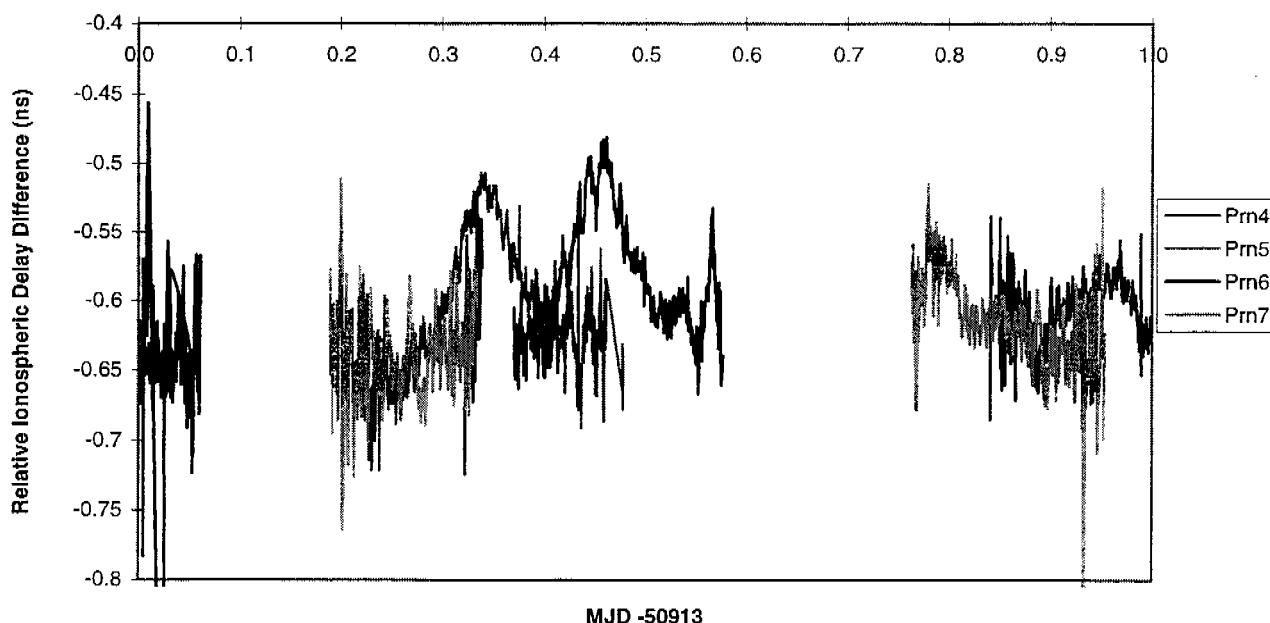


Figure 10: Phase ionospheric delay measurements, individual satellite tracks, (AOA TTR-4P - Ashtech Z12-T) phase differences.

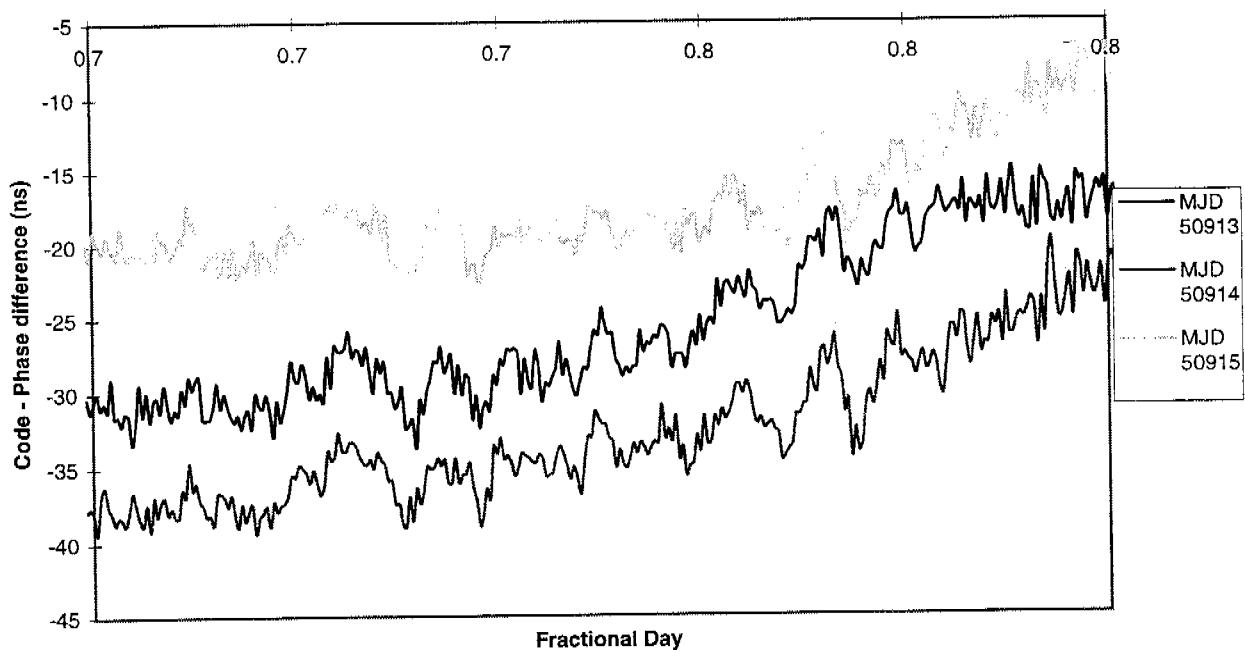


Figure 11: P1-L1 code-phase differences, PRN 31, MJD 50914 and 50195 data offset by four and eight minutes respectively, Ashtech Z12-T receiver.

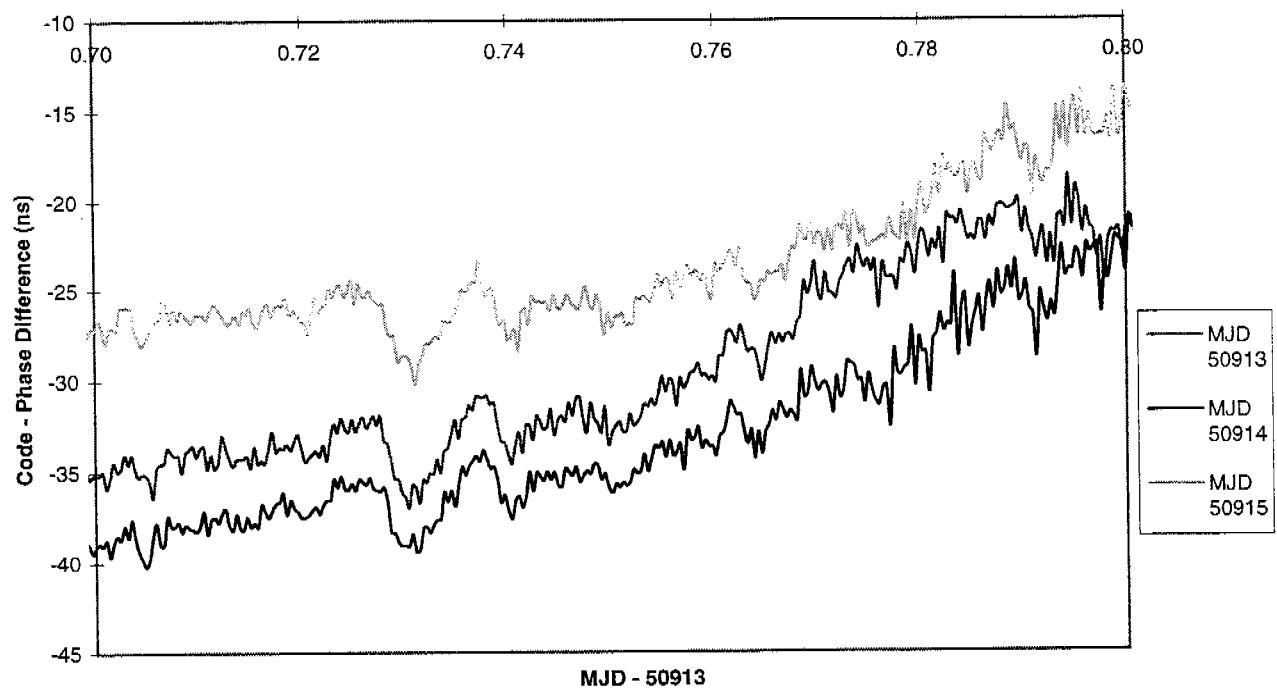


Figure 12: P2-L2 code-phase differences, PRN 31, MJD 50914 and 50195 data offset by four and eight minutes respectively, Ashtech Z12-T receiver.

## Questions and Answers

MIHRAN MIRANIAN (USNO): On the TTR4-P, were you using any kind of an elevation mask for the ionosphere? Because it is notoriously bad for ionospheric measurements.

JOHN DAVIS (NPL): No, we were not. We were using everything that we could collect from the TTR4-P because the Ashtech had more channels (12); the TTR4-P had eight. Also, we discovered that the TTR4-P found it slightly harder to lock onto satellites. So in reality, everything was used. Where there was a TTR4-P track, there was always an Ashtech. We did not use a mask. In those P-1 measurements, everything has been included, wherein after the average including the low-elevation satellites was measured, we could put a mask on.

MIHRAN MIRANIAN: Yes, we use them at the Observatory, and we found that anything below about 25 degrees is really useless.