COMPARISON OF ATOMIC FREQUENCY STANDARDS AT NIST AND PTB USING CARRIER-PHASE GPS

Lisa Nelson, Judah Levine, and Thomas Parker
National Institute of Standards and Technology
Boulder, CO 80309, USA

Kristine Larson
University of Colorado
Boulder, CO 80309, USA

Peter Hetzel and Juergen Becker
Physicalisch-Technische Bundesanstalt, 38116
Braunschweig, Germany

Abstract

We have constructed a link between Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany and the National Institute of Standards and Technology (NIST) in Boulder, Colorado using carrier-phase Global Positioning System (GPS) receivers. The link will provide a direct measurement of the frequency difference between UTC(PTB) and UTC(NIST), and can also be used to provide a direct comparison between the primary frequency standards at the two laboratories. Based on our previous work with this method, we expect to be able to realize the frequency comparisons with an uncertainty of about 2 X 10^{-15} using one day of averaging. This uncertainty is smaller than the combined uncertainties of the primary frequency standards in both laboratories, and it will therefore support a near-real-time comparison of these primary frequency standards without degrading their capabilities with the noise of the transfer system.

INTRODUCTION

The use of GPS carrier-phase for time transfer on both short (200 m) and long (2400 km) baselines has been previously reported [1-8]. In these experiments GPS carrier-phase time transfer has shown an uncertainty of 100 ps and a frequency uncertainty of 2 parts in 10^{15} for averaging times of a day. Initial short-term comparisons between two-way satellite time transfer (TWSTT) and GPS carrier phase on continental baselines have encouraged the use of carrier phase as a feasible time-transfer method. This paper reports on an experiment to compare UTC(PTB) with UTC(NIST), and CS2 with NIST7, the primary frequency standards at Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany and the National Institute of Standards and Technology (NIST) in Boulder, Colorado, respectively.

As in previous experiments, we will estimate the relative clock behavior at 6-minute intervals using the GPS carrier-phase observations. Details of the geodetic software package and analysis are given in [1-4, 9]. As independent estimates of the performance of our analysis, we will use TWSTT and Circular-T data between NIST and PTB. The limit to the short-term performance of the TWSTT comparison is the nominally 3 times per week observing schedule between the two laboratories. The Circular-T data are a result of postprocessed

Report Documentation Page			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE **DEC 1999**	2. REPORT TYPE		3. DATES COVERED **00-00-1999 to 00-00-1999**
4. TITLE AND SUBTITLE **Comparison of Atomic Frequency Standards at NIST and PTB Using Carrier-Phase GPS**			5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Institute of Standards and Technology,Boulder,CO,80309**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**			
13. SUPPLEMENTARY NOTES **See also ADM001481. 31st Annual Precise Time and Time Interval (PTTI) Planning Meeting, 7-9 December 1999, Dana Point, CA**			
14. ABSTRACT **see report**			
15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

UTC data between various national laboratories and are available monthly, with two–three weeks latency. The UTC difference data between laboratories are published at 5-day intervals and primary frequency data are published every 30 days.

CONFIGURATION

Geodetic quality dual-frequency GPS receivers are installed at NIST and PTB (Figure 1). These receivers produce both pseudorange and carrier-phase measurements at 30 s intervals.

The PTB GPS receiver (PTB1) is supplied with an external 5 MHz reference signal from a hydrogen maser (H2). The primary standard at PTB is called Cesium 2 (CS2). The differences between UTC(PTB) and H2, and CS2 and H2, are reported on an hourly basis. H2 is also the reference for the TWSTT station at PTB. The PTB GPS receiver was installed in July 1999.

The NIST GPS receiver (NIS2) is supplied with an external 5 MHz reference signal from an auxiliary output generator, AOG2. The difference between AOG2 and NIST hydrogen maser one (Maser 1) is reported every two hours. The difference between Maser 1 and NIST7 is reported over a 30-day interval. The output of AOG2 is steered to UTC(NIST), and UTC(NIST) is the reference source for TWSTT. The NIST GPS receiver was installed in its current location in March 1999; however, the antenna cable was changed in September 1999.

The two receivers are approximately 8000 km apart and operated by NIST. The carrier-phase data are compared using geodetic software provided by the Jet Propulsion Laboratory (JPL) using other geodetic receivers that are a part of the International GPS Service (IGS) network [9,10].

NETWORK SELECTION

In order to make a comparison between NIST and PTB it is important to have other receivers in close proximity to each of the comparison sites to help resolve cycle ambiguities (see Figures 2 and 3). The determination of carrier-phase cycles is much more difficult as the baseline length increases.

For this reason we have selected a site near NIST at Table Mountain, Colorado, TMGO. TMGO is located 15 km northeast of NIST and has a rubidium clock reference.

We have also performed the analysis with different sites near PTB: Potsdam, Germany (POTS), Koetzting, Germany (WTZR), and Onsala, Sweden (ONSA). Varying the network sites allows us to see the differences in the clock solution. It is important to note that POTS and WTZR both operate receivers made by the same manufacturer as those at PTB and NIST. ONSA, however, operates a receiver from a different manufacturer. The receiver at POTS is 178 km from PTB and uses its internal clock as its reference. The WTZR receiver is 390 km from PTB and has a hydrogen maser reference clock. ONSA is 575 km from PTB and also has a hydrogen maser reference.

We use intermediate stations to help define the reference frame for the comparison. We have chosen Algonquin, Canada (ALGO) and the United States Naval Observatory (USNO) in Washington, D.C. ALGO is used because of its hydrogen maser reference and well-defined location from Very Long Baseline Interferometry (VLBI). To help resolve cycle ambiguities at ALGO we have chosen the USNO site, 786 km away, which is also referenced to a hydrogen maser. The hydrogen masers have less noise in the short term and therefore provide better determination of the correct carrier-phase ambiguities.

Table 1 shows the different network configurations that are used for this analysis.

OBSERVED DATA AND STATISTICS

Figures 4a-d show the carrier-phase clock estimate solutions for the four different networks. Over this 17-day time period we compare carrier-phase data with TWSTT data. During this time period there are three different continuous time series of carrier-phase data because of jumps in the H2 maser at PTB on Modified Julian Day (MJD) 51453 and MJD 51457. The carrier-phase data have been biased to match the three different data series closest to the TWSTT data between the jumps. In this plot we are comparing H2 to UTC(NIST). The TWSTT data are normally reported as UTC(NIST)-UTC(PTB), so a correction from interpolated hourly H2-UTC(PTB) data has been made to the TWSTT data points in order to make the comparison with the carrier-phase data. Over this time period the carrier-phase clock estimates appear to agree with the TWSTT data in the long term.

Figure 5 shows the fractional frequency differences for the UTC(PTB)-UTC(NIST) carrier-phase solutions from MJD 51447-51464. Over this 17-day time period we compare the carrier-phase data with Circular-T and TWSTT data. An hourly UTC(PTB)-H2 correction has been made to the corresponding hourly carrier-phase data points to make these comparisons. For each of the continuous time series of carrier-phase data, we show the average fractional frequency across the four network solutions as a line covering the range of the data. The fractional frequency for each network during that time series is also shown. The uncertainty for the 5-day Circular-T data is on the order of 1 part in 10^{14}. It appears that the carrier-phase solutions follow the Circular-T and TWSTT solutions with reasonable uncertainty, except for near 51457, where there was a reported jump in the H2 maser at PTB. We are investigating the source of this error.

The fractional frequency differences for the CS2-NIST7 comparison are plotted in Figure 6. The Circular-T data for this difference over this interval is 9 parts in 10^{15}. The first and third series of carrier-phase data seem to match the Circular-T data well, regardless of the network solution used; however, the second series of continuous data has a frequency offset of approximately 8 parts in 10^{15} from this solution. From our initial analysis the uncertainty on this value is on the order of 1 part in 10^{14}, so the frequency step might be real.

Figure 7 shows the Allan Deviation (ADEV) for the carrier-phase data for MJD 51447-51452. The ADEV of the carrier-phase data for MJDs 51453-51456 and 51458-51464 are shown in Figures 8 and 9, respectively. Only the best and worst cases for the four network solutions are plotted to make the charts easier to read. In the time series where we have longer data spans the ADEV approaches 5 parts in 10^{15} at one day.

CONCLUSIONS

From our initial analysis it appears that the carrier-phase data make it possible to measure the differences of CS2-NIST7, and UTC(PTB)-UTC(NIST); however, there are error sources that are not yet fully understood. The effect of the discontinuities in the carrier-phase data combined with corrections made to the data requires further investigation.

REFERENCES

[1] K. Larson and J. Levine, "Time Transfer using the Phase of the GPS Carrier," *IEEE Trans. On Ultrasonics, Ferroelectronics and Frequency Control*, Vol. 45, No. 3, pp. 539-540, 1998.

[2] K. Larson and J. Levine, "Carrier-Phase Time Transfer," *IEEE Trans. On Ultrasonics, Ferroelectronics and Frequency Control*, Vol. 46, No. 3, pp. 1001-1012, 1999.

[3] K. Larson, L. Nelson, J. Levine, T. Parker, and E. Powers, "A Long-term Comparison between GPS Carrier-Phase and Two-Way Satellite Time-Transfer," *Proc. 30th Annual Precise Time and Time Interval Applications and Planning Meeting*, Reston, VA, pp. 247-255, 1998.

[4] K. Larson, J. Levine, L. Nelson, and T. Parker, "Assessment of GPS Carrier-Phase Stability for Time-Transfer Applications," to be published in Special Time and Frequency Publication of IEEE Transasctions on Ultrasonics, Ferroelectronics and Frequency Control.

[5] G. Petit, C. Thomas, "GPS Frequency Transfer using Carrier Phase Measurements," *Proc. 50th IEEE International Frequency Control Symposium*, pp. 1151-1158, 1996.

[6] G. Petit, C. Thomas, and Z. Jiang, "Use of Geodetic GPS Ashtech Z12T Receivers for Accurate Time and Frequency Comparisons," *Proceedings of the 52nd IEEE International Frequency Control Symposium*, pp. 306-314, 1998.

[7] F. Overney, L. Prost, U. Feller, T. Schildknecht, G. Beutler, "GPS Time Transfer using Geodetic Receivers: Middle Term Stability and Temperature Dependence of the Signal Delays," *Proc. 11th European Frequency and Time Forum*, pp. 504-508, 1997.

[8] P. Baeriswl, T. Schildknecht, T. Springer, and G. Beutler, "Time-Transfer with Geodetic GPS Receivers using Code and Phase Observations," *Proc. 10th European Frequency Time Forum*, pp. 430-435, 1996.

[9] S. Lichten and J. Border, "Strategies for High-Precision Global Positioning System Orbit Determination," *Journal of Geophysical Research*, 92, pp. 12,751-12,762, 1987.

[10] G. Beutler, I.I. Mueller, and R.E. Neilan, "The International GPS Service for Geodynamics (IGS): Development and start of official service on January 1, 1994," *Bulletin Geodesique*, 68(1), pp 39-70, 1994.

FIGURES AND TABLES

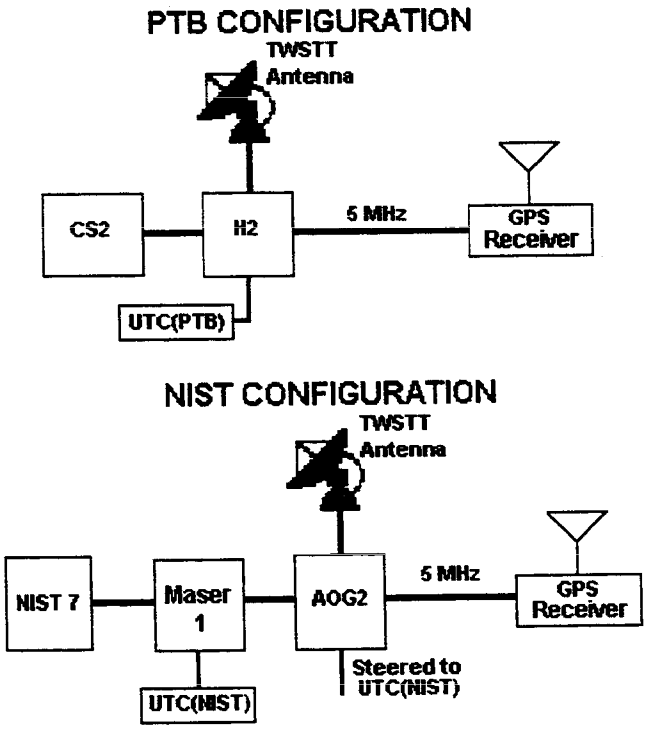

Figure 1: Block Diagram of configurations at NIST and PTB.

Figure 2: Network Station Locations in the United States.

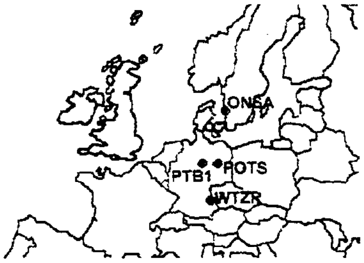

Figure 3: Network Station Locations in Europe.

NETWORK NAME	STATIONS IN NETWORK
A	ALGO,NIS2, PTB1, TMGO, USNO,WTZR
B	ALGO,NIS2, POTS, PTB1, TMGO, USNO
C	ALGO,NIS2, PTB1, ONSA,TMGO, USNO
D	ALGO,NIS2, PTB1, TMGO,WTZR

Table 1: Network names and descriptions.

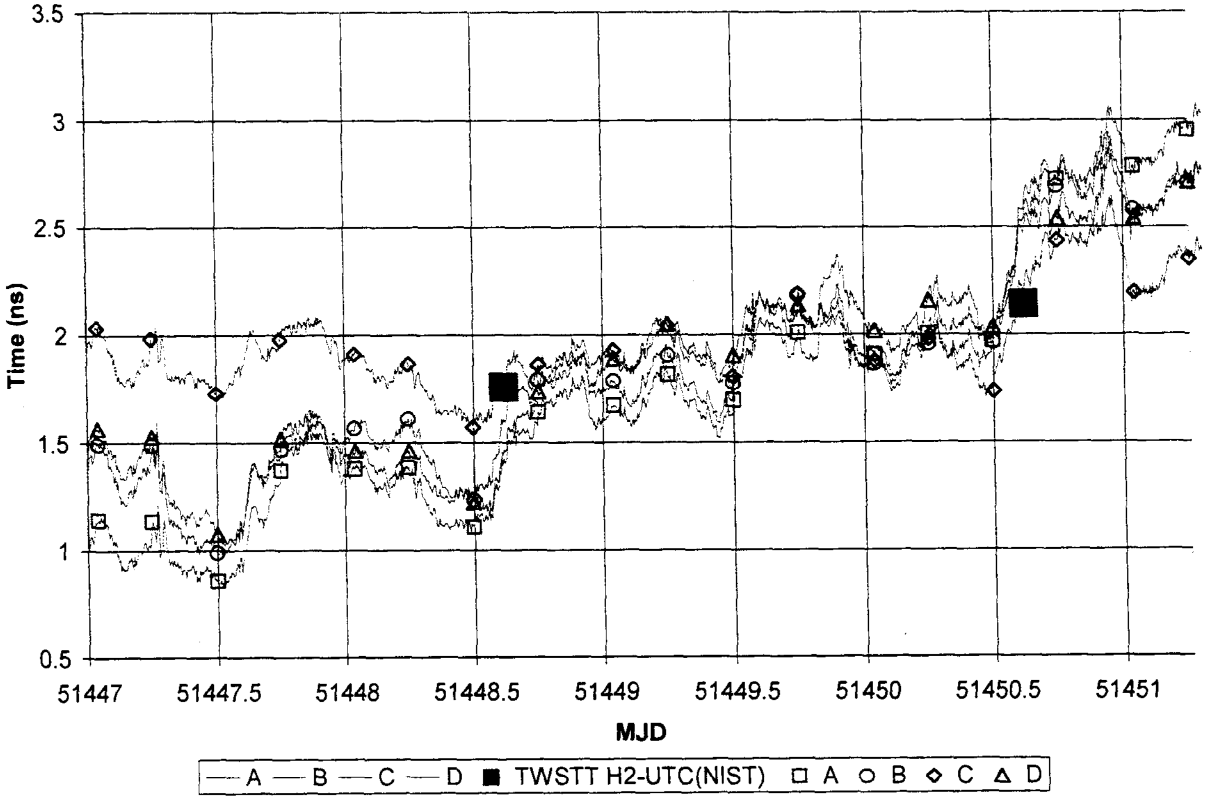

Figure 4a: Carrier-phase and TWSTT H2-UTC(NIST) data. Symbols are added to differentiate the data.

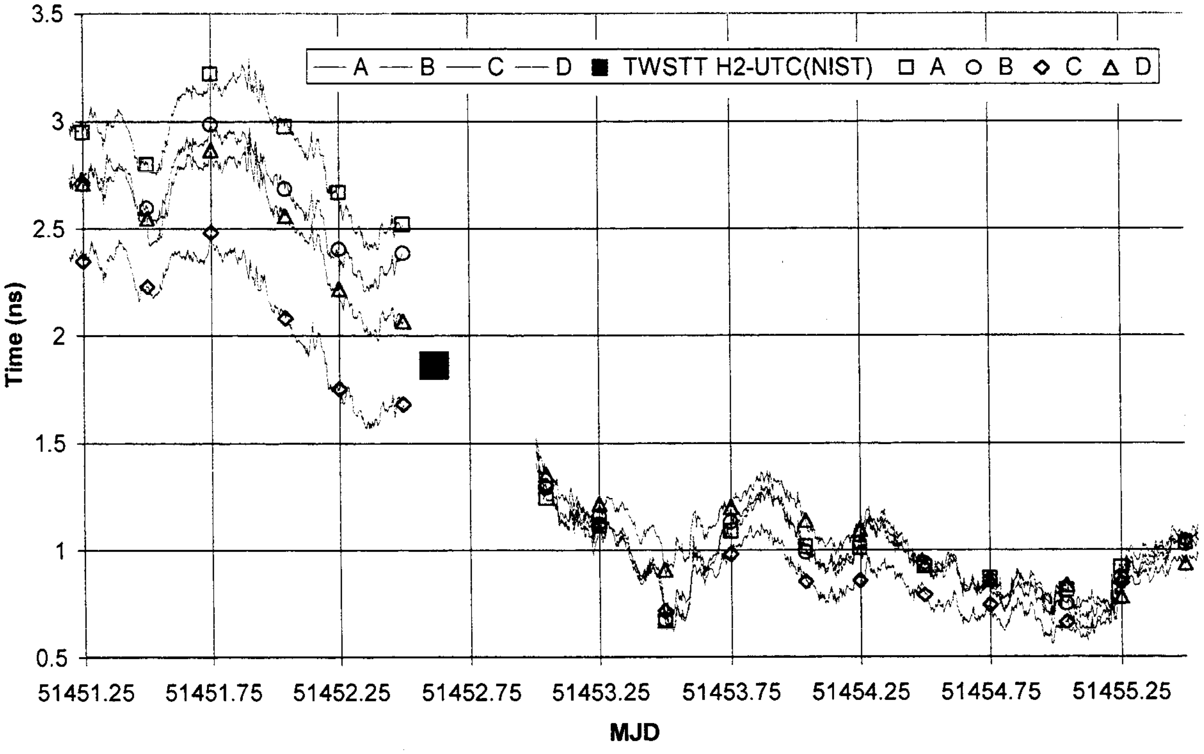

Figure 4b: Carrier-phase and TWSTT H2-UTC(NIST) data.

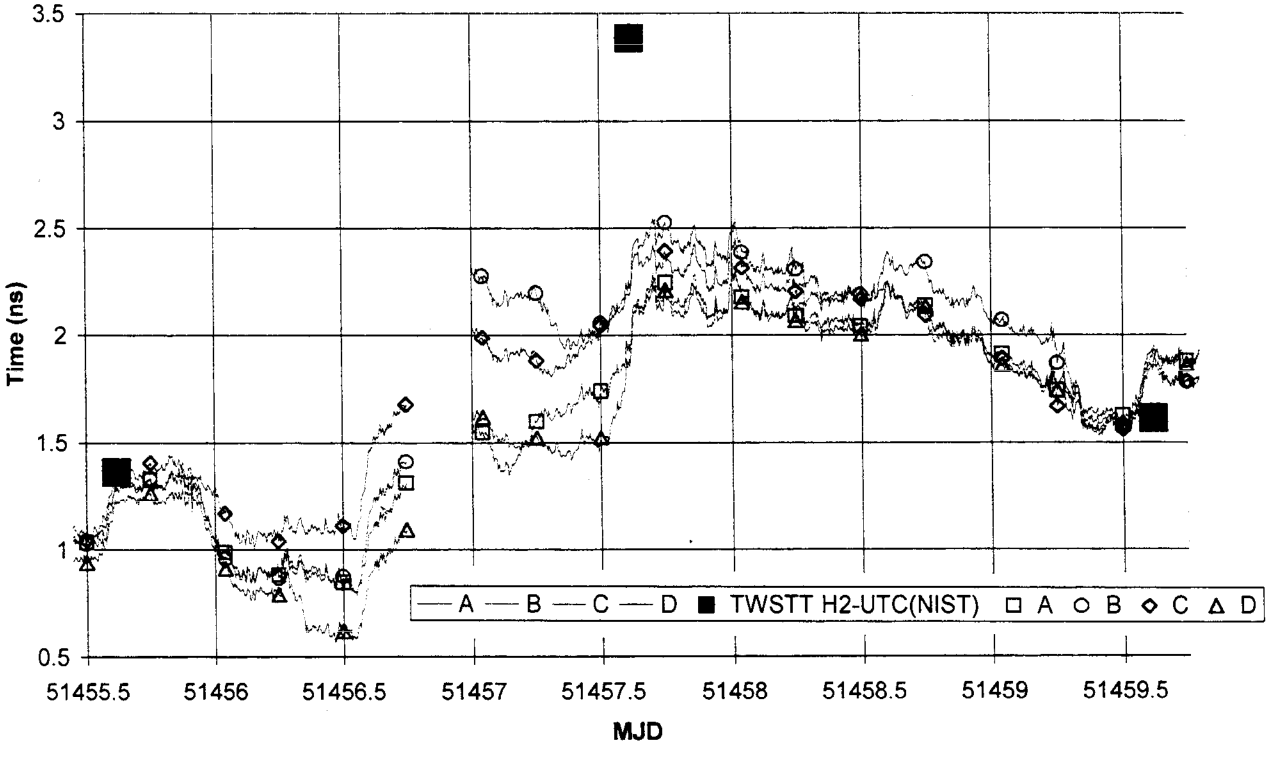

Figure 4c: Carrier-phase and TWSTT H2-UTC(NIST) data.

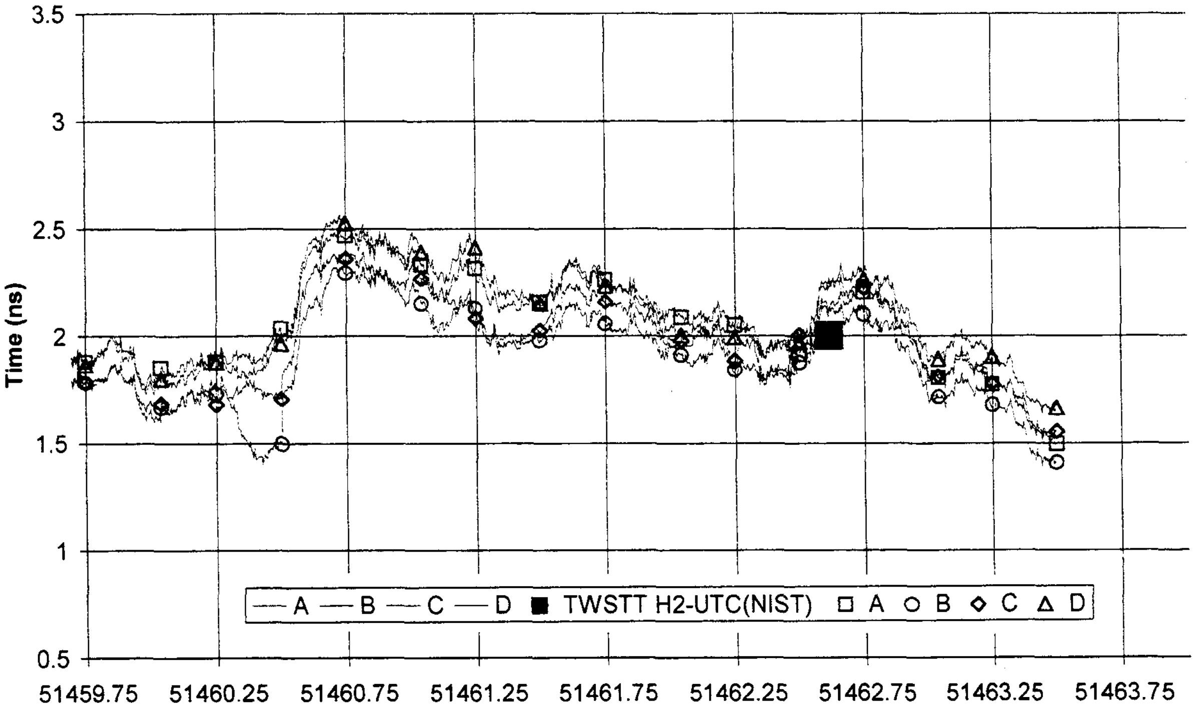

Figure 4d: Carrier-phase and TWSTT H2-UTC(NIST) data.

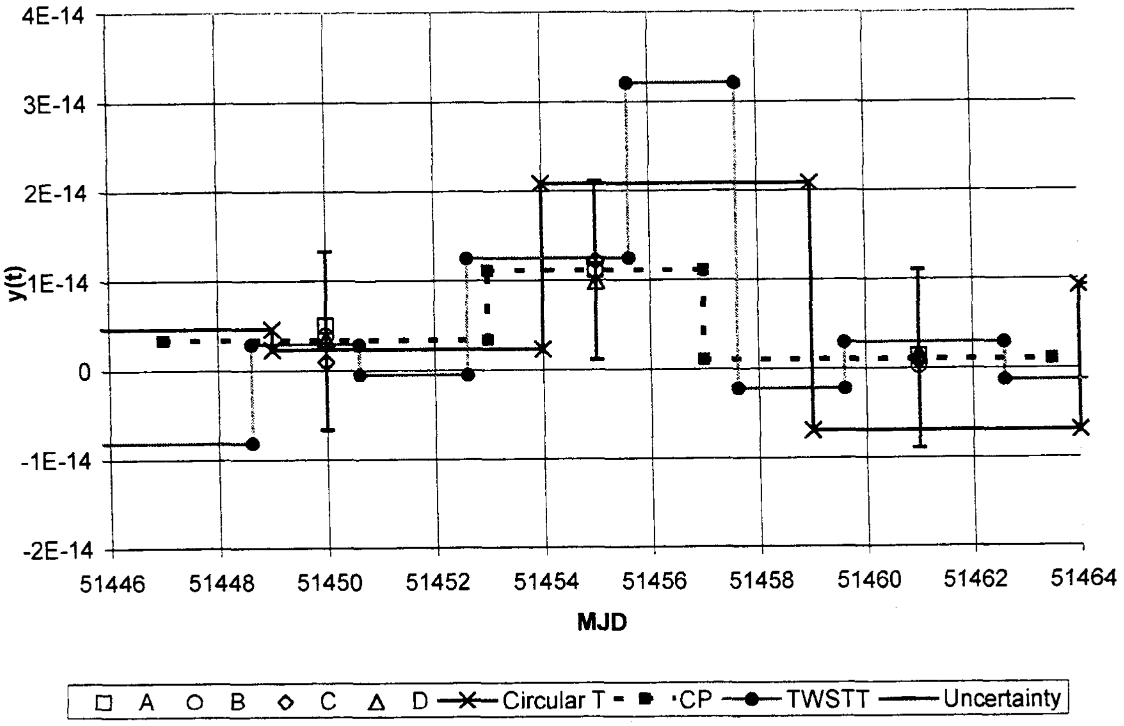

Figure 5: UTC(PTB)-UTC(NIST) Fractional Frequency Difference data.

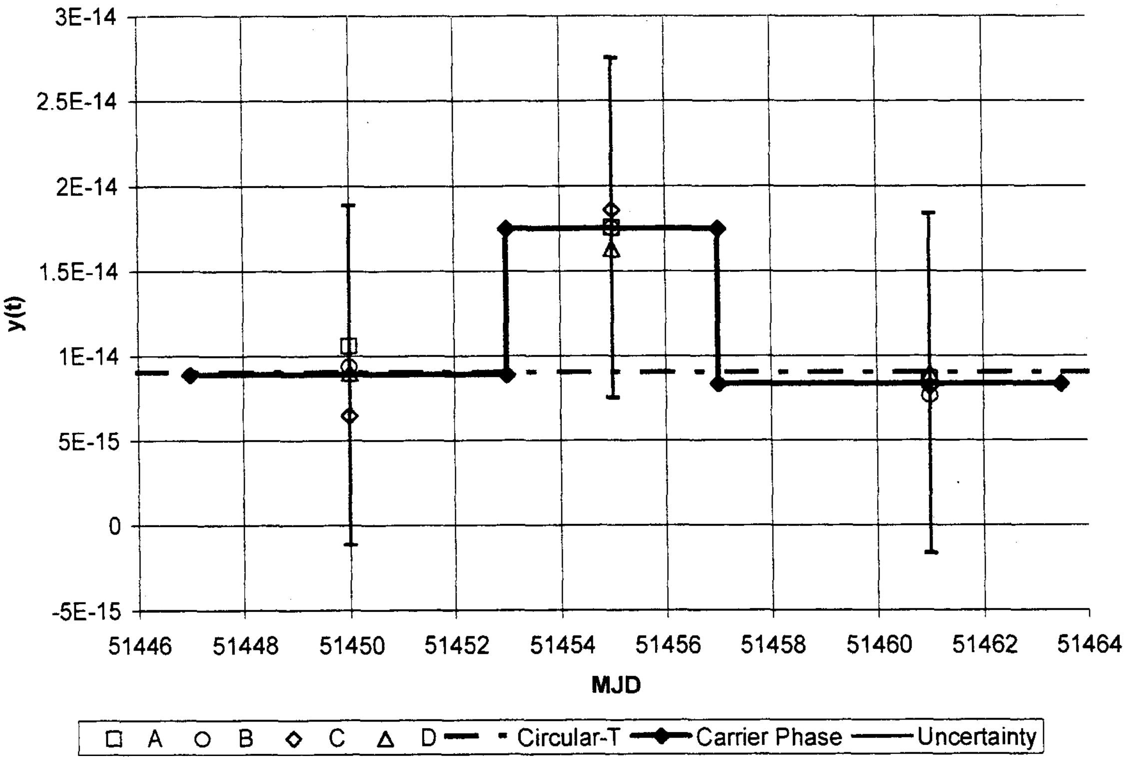

Figure 6: CS2-NIST7 Fractional Frequency Difference data.

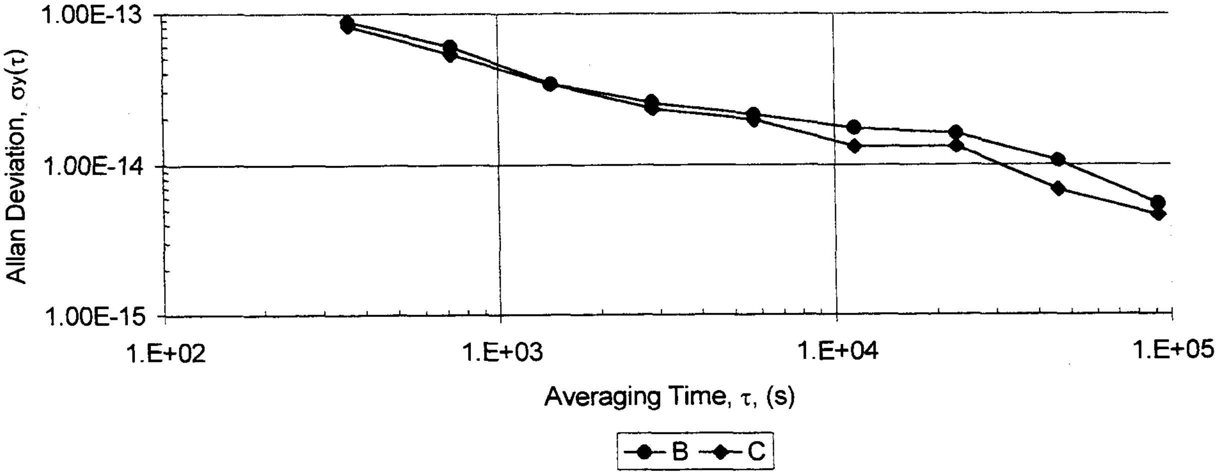

Figure 7: Allan Deviation of the carrier-phase data for MJD 51447-51452.

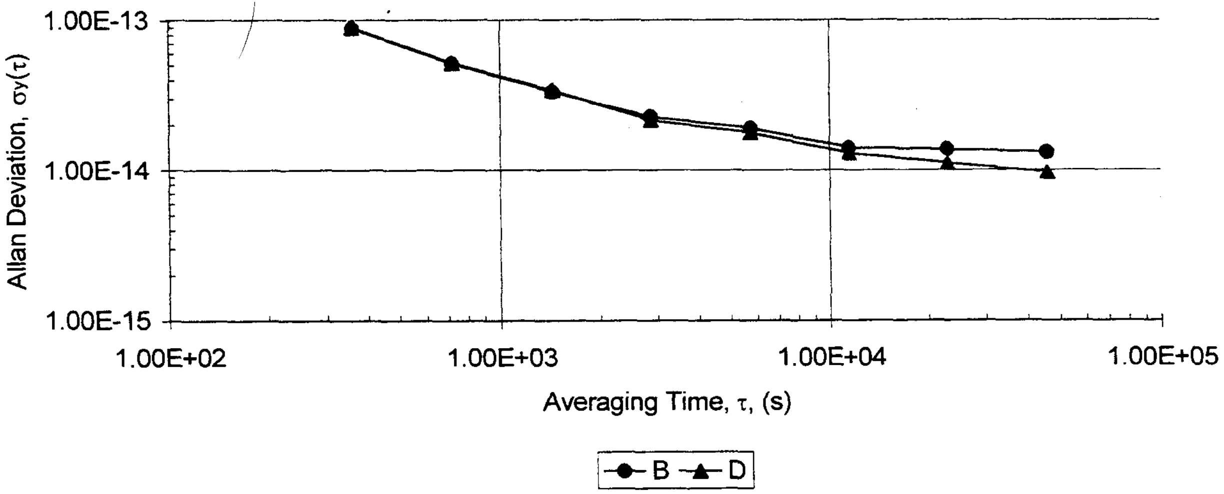

Figure 8: Allan Deviation of the carrier-phase data for MJD 51453-51457.

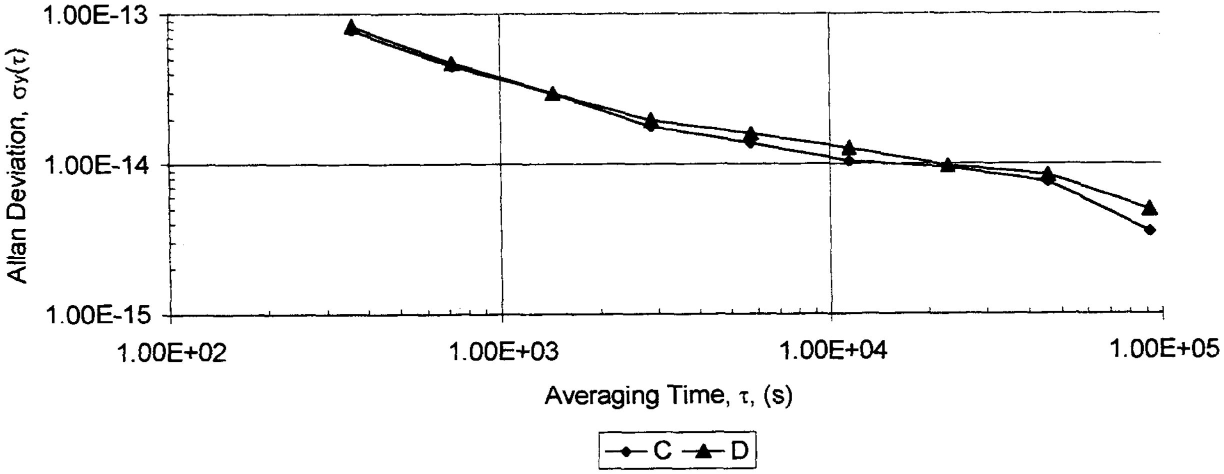

Figure 9: Allan Deviation of the carrier-phase data for MJD 51458-51464.

Questions and Answers

DEMETRIOS MATSAKIS (USNO): I just wondered if you could comment more on the contribution of the clocks to the Allan deviations that you saw there. The contributions of the masers, particularly the maser at the PTB, to the Allan deviations that you showed.

LISA NELSON (NIST): The Allan deviations that I showed at the end, that's the H-2 to UTC (NIST) comparison. You just wanted to know what contribution the H-2 makes to that?

MATSAKIS: Yes, to the clock itself.

NELSON: I'm unsure as to what –

MATSAKIS: Okay, we can talk about it later.

DAVID HOWE (NIST): Lisa, since you use several stations to resolve the phase ambiguity issue and take out those errors, can you give us some idea of how many of those were involved in the whole data run?

NELSON: Do you mean how many biases?

HOWE: Right.

NELSON: Do you mean the hardware resets?

HOWE: Yes.

NELSON: There weren't any hardware resets other than the fact that we have the jump in the H-2 maser at those two different times. As far as I'm aware, the hardware was running continuously through that time.

ED POWERS (USNO): What about these day-boundary discontinuities? Do they give you much trouble?

NELSON: That's one thing with the different blocks of data that we had as far as doing the day boundaries over the 6-day time period where I actually had two different series. Because I do it over a 3- to 4-day run when I do a run of the different networks. We didn't have any problems as far as that goes.