DUAL FREQUENCY P-CODE TIME TRANSFER EXPERIMENT*

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ABSTRACT

The Clock Evaluation and Time Keeping Experiment was the cooperative effort of Applied Research Laboratories, the National Bureau of Standards, and the United States Naval Observatory. It was designed to collect a dense Global Positioning System (GPS) data set for evaluating methods of monitoring a ground-based atomic clock with on-site data alone, and of investigating improved methods of time setting and time transfer using GPS data. The experiment collected two-frequency, P-code, pseudorange and Doppler data for five weeks at three sites; Austin, Texas; Boulder, Colorado; and Washington, D.C. All sites used two-frequency receivers on cesium oscillators. A time history of the cesium oscillators against hydrogen masers also was recorded at two of the sites.

Comparison of the range residuals for the broadcast and the precise ephemerides shows a difference of up to 50 ns, with a pattern that was generally repeated each day during the experiment. The pattern is likely due to the broadcast ephemeris. Clock recovery using such data should be possible at the 30 ns level, but recovery of frequency information will require several days' data. The behavior of the cesium oscillators was well tracked by the range residuals over the five weeks of the experiment. Residuals of Doppler data were strongly correlated across stations. This implies that time transfer with accuracy approaching 1 ns looks promising over the time period of one satellite pass. With a full GPS constellation, continuous use of phase data could significantly improve time transfer via GPS.

I. INTRODUCTION

Applied Research Laboratories, The University of Texas at Austin (ARL:UT), was responsible for the design, development, and deployment of the Defense Mapping Agency (DMA) GPS monitor sites. One of the functions of these sites is to provide data which, in addition to that from the GPS Operational Control Sites (OCS), are used to produce a precise ephemeris. The quality of a GPS orbit is highly dependent on the quality of the clocks used as a reference in collecting the data[1],[2],[3]. A single commercial, high performance cesium atomic clock is deployed at each of these sites. The ensemble of orbiting clocks will be used to monitor the quality of each station clock. An experiment was designed with the intent of helping to develop techniques to perform this monitoring.

This experiment, called the Clock Evaluation and Time Keeping Experiment (CETKE), was performed between 20 March and 24 April 1987. This was a cooperative experiment between ARL:UT, the U.S. Naval Observatory (USNO), and the National Bureau of Standards (NBS). The objectives of this experiment were: to determine ways to monitor a cesium oscillator at a GPS data site with only on-site data, to evaluate multi-station strategies for monitoring clock behavior, to evaluate systematic errors in clock measurements, and to investigate improved time transfer/time setting strategies using GPS data. Daily on–site analysis was deemed essential to timely equipment monitoring at the DMA monitor sites. This requires the use of the broadcast ephemeris and one station's data. This differs from most other current GPS high precision timing work, which has focused on time transfer. In time transfer the differencing of data between stations causes many errors to cancel.

Three TI 4100 GPS* receivers, identical to the ones at the DMA GPS monitor sites, were used in the experiment. These were located at ARL:UT in Austin, Texas, USNO in Washington, D.C., and NBS in Boulder, Colorado. The baselines were 2400 km (USNO- NBS), 2100 km (USNO-ARL) and 1265 km (NBS-ARL:UT). The receivers had commercial high performance clocks for frequency standards. These clocks were in a laboratory environment similar to the environments at the DMA monitor sites. NBS and USNO provided measurements of the time history of these clocks against hydrogen masers at those sites. The hydrogen masers and laboratory clock ensembles served as the references against which the GPS measurements were judged.

The data were collected from all satellites on atomic oscillators at the time of the experiment (PRNs 3,6,9,11,12,13). Most of the data were acquired late at night. Two satellites, 9 and 12, had short daytime passes. The data consisted of simultaneous integrated Doppler phase and pseudorange on both L1 and L2 on up to 4 satellites. The data were acquired at 60 s intervals over most of the experiment. During weekends a 120 s data interval was used. At intervals of two weeks, one hour of 6 s data was taken on Tuesday and Wednesday nights. This gave three sets of higher speed data, which were used for the analysis of multipath.

Residuals of measurements are the quantities reported here. These contain the local clock error, along with other errors. The pseudorange residual, r, will be given by

$$\begin{aligned} r &= \rho - |\vec{x}_{SV} - \vec{x}_g|, \\ &= \rho_0 - |\vec{x}_{SV} - \vec{x}_g| + c\tau + \epsilon_r + \epsilon_M. \end{aligned} \tag{1}$$

where

ρ is the measured pseudorange,
ρ_0 is the true range,
τ is the clock error (ground plus satellite),
c is the speed of light,
$\vec{x}_g$ is the station position,
$\vec{x}_{SV}$ is the satellite position,
ϵ_r is the receiver noise, and
ϵ_M is the multipath error.

This quantity contains the ground clock error in τ. Use of multiple satellites helps in isolating ground clock error.

In the current case, the value of several of the other errors is known or can be estimated. The uncertainty due to the receiver has been measured to be less than 60 cm for pseudorange and less than 1 cm for phase measurements[4]. The errors in the ground positions should be on the order of 3 m or less. All sites were established with transit surveys. The NBS site is near, and well connected to, the site used by NBS for their GPS time transfer[5]. The receiver antenna has sensitivity down to the horizon[6] and is susceptible to multipath. This error will be bounded by 30 m (1 p-code chip) for pseudorange and one

* Mention of a commercial product does not imply an endorsement.

wavelength (20 cm at L1 and 25 cm at L2) for phase. Multipath is usually only a small fraction of these maxima[7], and has been estimated from the residuals of this experiment to be less than 3.5 m for pseudorange at ARL:UT, 4.2 m at USNO, and 3.8 m at NBS.

The major remaining non–clock error is the satellite position, $\vec{x}_{SV}$. This ephemeris error will be the major unknown quantity in this study and is addressed in detail. Only a fraction of the residuals and results obtained will be presented here. The emphasis will be on the comparison of the precise ephemeris to the broadcast ephemeris (and hence a rough estimate of the error in the broadcast ephemeris) and on the use of phase residuals.

In order to magnify critical details, a line has been removed from all the residuals shown here. A single slope was determined for each station clock and used for all residuals throughout the experiment. The bias value is different for each figure; in some cases, where noted below, it varies for different lines on the same graph. The horizontal axis in every case is in days–of–the–week for GPS week 375 (beginning 15 March 1987). This scale continues beyond 7 days to give a continuous monotonic time scale.

II. PSEUDORANGE RESULTS

Range residuals for PRN 9 observed at USNO over one week are shown in Fig. 1. In this figure an offset of −40 ns has been added to the broadcast ephemeris residuals, and +40 ns to the precise ephemeris residuals. Results from both broadcast and precise ephemerides are given. PRN 9 had both a day and a night pass. The difference between the residuals in the two passes is large when the broadcast ephemeris is used, but it almost disappears in residuals for which the precise ephemeris was used. This indicates that the error in single station time setting due to use of the broadcast ephemeris could be as large as 50 ns.

Also in Fig. 1, comparing the residuals for the two ephemerides shows definite daily signatures in the broadcast ephemeris residuals. This implies that using residuals at the same sidereal time each day will reduce the variations significantly. However, this strategy is dependent upon characteristics of broadcast ephemeris error, which are not necessarily consistent over long periods of time. (Fig. 1 also indicates that the OCS is within the operating specifications.)

Figure 2 shows an expanded view of the comparison of the precise ephemeris residuals at all three stations, during a single pass. An offset of +30 ns was added to the NBS results, −30 ns to those of USNO. Because of the uncertainty in determining the slopes that were removed from these curves, the curves could be somewhat tilted. Even in pseudorange residuals some short–term errors are highly correlated.

A comparison of the timing errors from broadcast and precise ephemerides is shown in Figs. 3 and 4 over the entire 5 week experiment period. Two weeks of the precise ephemeris residuals are yet to be processed. Here the residuals from two satellites are plotted along with the measurement of the cesium behavior with respect to the hydrogen maser. For clarity, the PRN 9 and 11 residuals have been offset by 100 ns relative to each other. The residuals from the precise ephemeris in Fig. 4 are more compact than the broadcast ephemeris residuals in Fig. 3. The same slope has been removed from both the reference line and the residuals.

The gross features of the cesium behavior are easily seen in both figures. In particular the frequency shifts at 20 and 29 days are clearly evident. The slight shift at about 23 days can also be seen. Detecting these features with the eye and with a computer algorithm are very different problems. In the presence of the daily signatures from the broadcast ephemeris, either some collapse of the signature (via constant sidereal day sampling) or several days of residuals, or both, will be required to detect these frequency shifts. Work on this algorithm is in progress.

III. PHASE DATA

Another approach to this problem is to examine the integrated Doppler data available at the DMA monitor sites. This data has a much lower noise level—about 1 cm—but can only give information about range differences from the time since signal acquisition. The integral of the Doppler frequency is the range difference over the time of integration:

$$\begin{aligned}\int_{t_1}^{t_2} f_{d_0}\, dt &= -\int_{t_1}^{t_2} \frac{Rf_0}{c}\, dt, \\ &= -\frac{1}{\lambda}\Big[R(t_2) - R(t_1)\Big],\end{aligned} \tag{2}$$

where f_{d_0} is the carrier frequency, λ is the carrier wavelength, and R is the range. The measured Doppler frequency, f_d, is the sum of range time derivative and clock error,

$$f_d = f_{d_0} + \dot{r}. \tag{3}$$

Although these data are weaker in geometric information than the pseudorange data, they can give information about frequency.

The phase residuals for a single pass, as observed at all three sites, are shown in Fig. 5. As before, a slope has been removed from the residuals at each site, and constant offsets have been added. This means that each curve could be translated vertically and tilted for a best fit. Clearly there is a very high degree of correlation between the ARL:UT and USNO residuals. With a slight change of slope the NBS residuals will match very well.

This figure implies that phase data taken simultaneously at remote sites will have correlated errors at the 1 ns level. Therefore over the time span of one pass, time comparison stabilities with a precision of 1 ns or better look promising. When the full constellation is in orbit, one could go from one satellite to another with phase measurements and obtain time shifts at this level over many days. This would require overlapping data segments between satellites. Receivers that record phase from multiple satellites would facilitate this procedure.

IV. CONCLUSIONS

This experiment has obtained a dense data set for the purpose of evaluating methods of on–site clock evaluation. It has been shown that there are significant signatures in the residuals using the broadcast ephemeris and that these are probably ephemeris–related. These signatures repeat daily; but this is not an assured process, as it depends on the consistency of processing methods and data input at the OCS. These signatures are present in both the phase and range residuals and make short–term (one day) estimates of frequency difficult or meaningless.

It appears that, using multiple satellites and the broadcast ephemeris, clock recovery should be possible at the 30 ns level (one–third of the system specification). Initially, the recovery of frequency information will require several days of data collection. If the signature of the station residuals is constant, ongoing frequency estimates could be made on a daily basis after initial data have been taken.

The use of phase residuals to compare time at the few ns level appears very promising. In the future when more satellites are in orbit, continuous use of phase data could significantly improve time difference comparisons via GPS.

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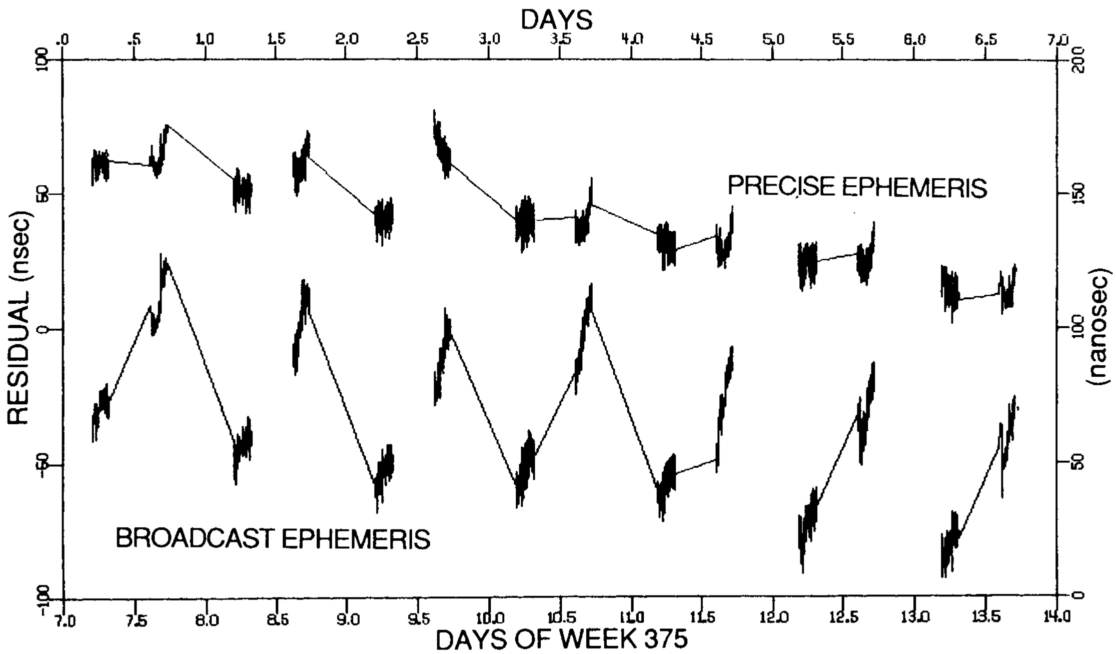
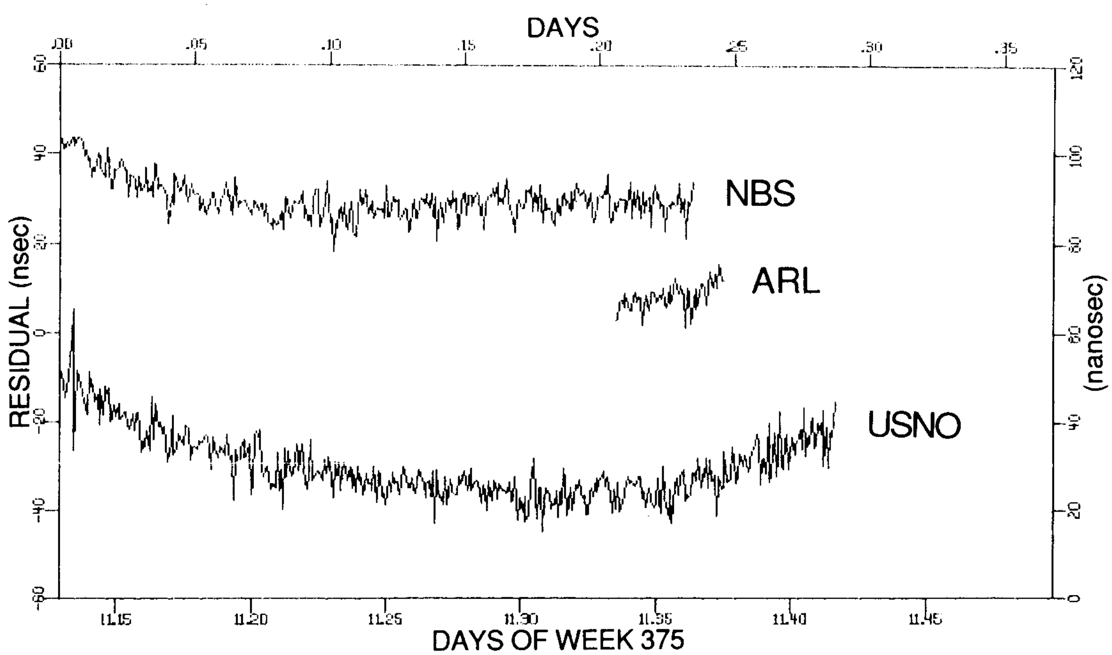


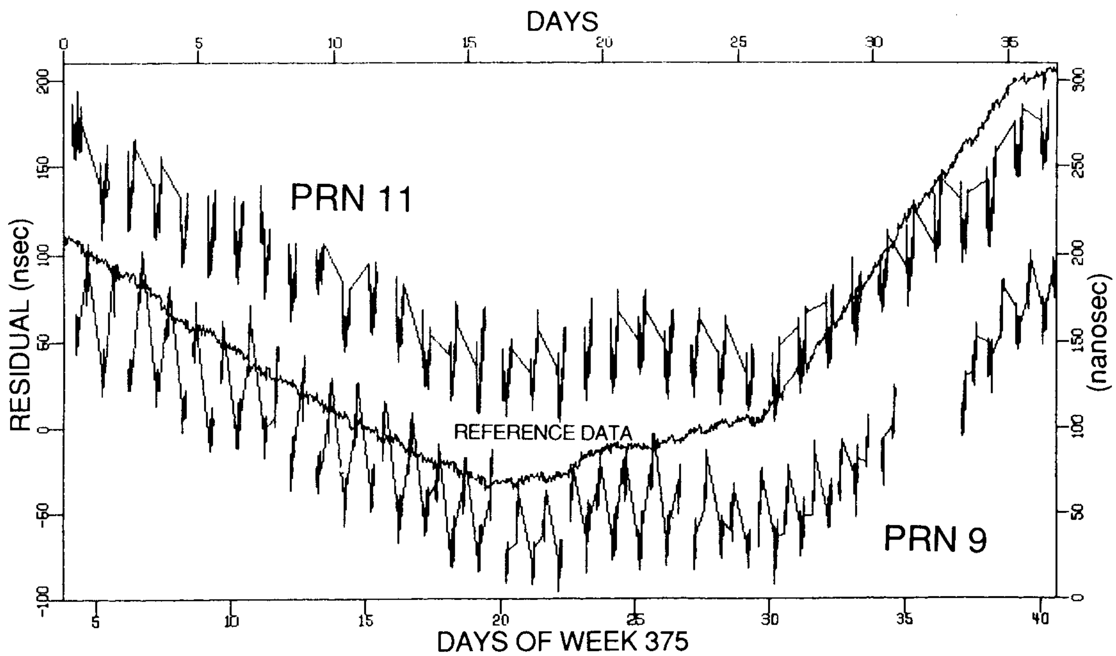
CETKE RANGE RESIDUALS
PRN9 UNSO GPS Week 376

Figure 1



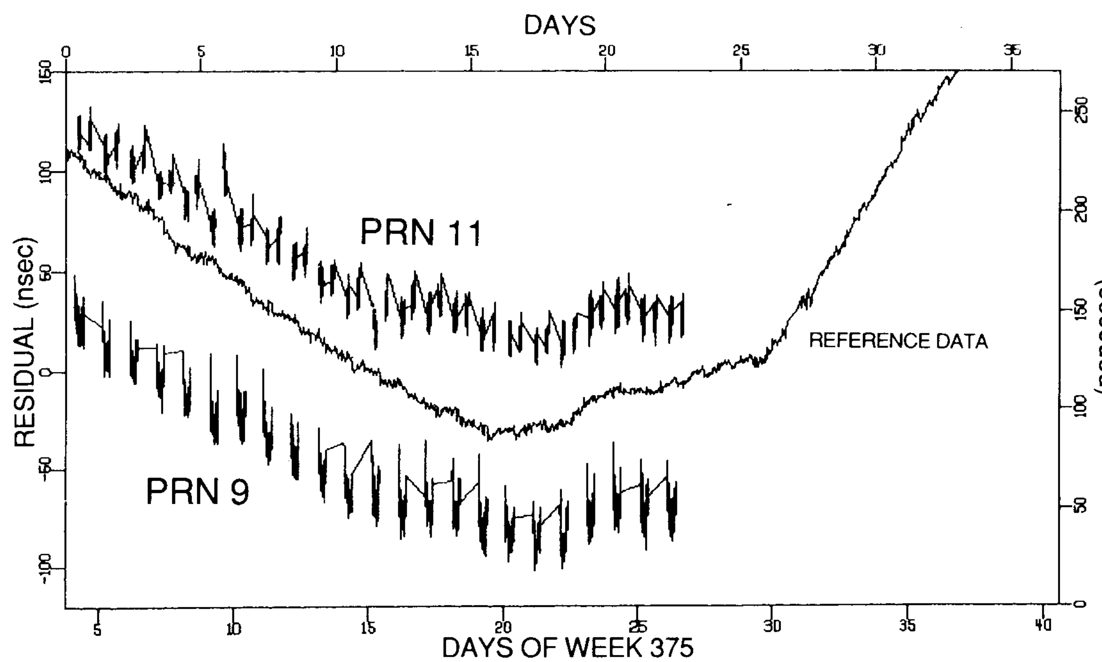
CETKE RANGE RESIDUALS
Precise Ephemeris PRN 11

Figure 2



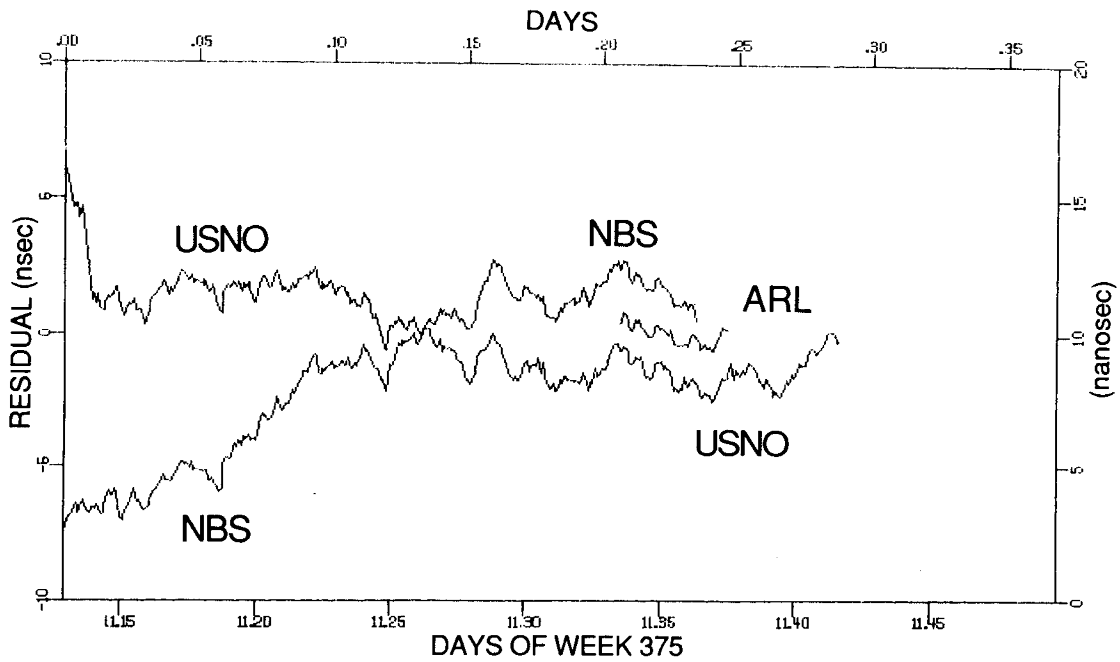
CETKE RANGE RESIDUALS WITH REFERENCE
USNO Broadcast Ephemeris PRN 9 and 11

Figure 3



CETKE RANGE RESIDUALS WITH REFERENCE
USNO Precise Ephemeris PRN 9 and 11

Figure 4



CETKE PHASE RESIDUALS
Precise Ephemeris PRN 11

Figure 5