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Remote Clocks Linked by a Fully Calibrated Two—Way Timing Link

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Abstract

Fully calibrated two–way time transfers between the U.S. Naval Observatory (USNO) and the U.S. Naval Observatory Time Service Substation (NOTSS) have become operational. The calibration method employed was the co–located Earth station method. Results concerning timing, stability, comparison of two–way and Global Positioning System (GPS) timing links, and remote clock contribution to local time scale computation will be presented.

PART I: TWO–WAY OPERATIONS

INTRODUCTION

The U.S. Naval Observatory has been experimenting with two–way time transfer since the first communications satellites, i.e. Telstar and Relay–II, were put into operation in the 1960's [1,2]. The ultimate goals of the two–way project have been to improve the USNO's Master Clock of the United States by including remote clocks via the most precise and accurate timing links possible. Three key factors in the support of the USNO Master Clock System addressed by two–way are the direct clock comparisons, timescale comparisons, and the use of remote clocks in a local timescale production. The recent development of low–cost, portable, very small aperture terminals (VSAT) have allowed the two–way time transfer method to finally be put into an operational mode at the U.S. Naval Observatory.

THE PROCEDURE AT USNO

The two–way system employed at the USNO Washington, DC site employes a 4.57 meter satellite terminal and a MITREX model 2500 modem (analog version), while at the NOTSS Richmond, FL site a 1.8 meter VSAT and a MITREX model 2500A modem (digital version) are used. A "flyaway" 1.8 meter VSAT was used for the co-location calibrations and performed by the method discussed in [3]. The USNO Washington, DC reference is the operational USNO Master Clock #2 which is the Sigma Tau hydrogen maser N3 which is steered by small daily frequency changes in its synthesizer, while the NOTSS reference clock is an unsteered HP 5071A cesium beam frequency standard designated as CS152. The Satellite Business System Corporation's SBS-6 at 95 degrees West is the satellite used to make the time transfers. The time transfers are made every working day. The data are transferred daily by ftp via Internet to a central computer located at the USNO Time Service Department in Washington, DC. The appropriate data files are then matched and the final daily time differences are computed and made available, again by ftp.

The formulation used to generate the final time differences is

$$\begin{aligned}\mathrm{UTC(USNO)} - \mathrm{UTC(NOTSS)} \;=\;& 1/2[\mathrm{Ti(USNO)} - \mathrm{Ti(NOTSS)}]\\ & -\Delta\mathrm{Tx(NOTSS)} - \Delta\mathrm{Tx(USNO)}\\ & -\mathrm{d1PPS(NOTSS)} - \mathrm{d1PPS(USNO)}\\ & -S\\ & -R\end{aligned}$$

The first term on the right is the time interval counter differences which are recorded at each site, the second term is the transmit-to-receive delay difference also measured at each site, the third term is the delay from on time of the 1 PPS references as measured at each station, the fourth term is the computed relativistic time delay due to a rotating reference system, and the fifth term is the RF delay as measured by the co-located Earth station method. The ionospheric and tropospheric transmission delays introduced by the Ku band uplink/downlink frequency differences, on the order 100 ps [3] are currently ignored. Any satellite transponder delays are assumed to be reciprocal.

ANALYSIS OF INSTABILITY

Two main noise processes are evident in the instability tests of the frequency behavior of the two-way transfers. From 10^0 to 10^3 seconds white phase noise of the two-way system phase comparisions dominates, i.e. a $\log\tau^{-1}$ slope, (where τ is the sampling time), while from 10^3 to 10^7 seconds white frequency noise originating in the NOTSS cesium reference dominates, i.e. a $\log\tau^{-1/2}$ slope. It is expected, but not currently seen, that beyond 10^7 seconds the long-term steering of the USNO Master Clock will be the dominant "noise" contribution [4].

PART II: THE REMOTE CLOCKS AT NOTSS

INTRODUCTION

When two-way time transfer was begun between the USNO and the NOTSS, the latter had eleven clocks on location for use in its local timescale, and time transfer between these two locations was possible using either two–way or GPS.

PRELIMINARY STUDY AT NOTSS

Starting with the day on which two–way became operational, USNO clocks were incorporated into the NOTSS hourly time scale for a test period of 37 days using both GPS and two–way to determine which method of time transfer gave the better result. (See below for a brief description of the method.) For the period MJD 48983 to 49020 the rms of NOTSS Mean-CS152 was as follows:

NOTSS Mean formed from...	rms
9 local clocks only	± 2ns
9 local clocks plus 11 USNO clocks linked via GPS	± 3ns
9 local clocks plus 11 USNO clocks linked via two–way	± 2ns

It was decided to use two–way because of the smaller noise, but GPS would be an acceptable substitute when necessary. A similar accuracy for GPS as for two–way can only be expected using geodetic receivers, ultra–precise ephemerides, and the common–view technique [5].

THE PROCEDURE AT NOTSS

Every ten days, the difference between the USNO Master Clock and the NOTSS Master Clock at 0 hours UT every day is plotted using both two–way and GPS. This allows a comparison of the two methods and gives the difference between them, so that GPS can be used when two–way becomes unavailable for a lengthy period.

For example, for the period MJD 49150 – 49224, 10.1 nanoseconds would have to be added to the differences obtained using GPS to bring them into coincidence with the differences from using two–way. Over this period, this quantity had a slope of +0.08 ns/day and an rms of ± 4.6 nanoseconds, see Figure 3 . The last nine days were omitted from the plot because the plots overlap. In practice, a value taken from the current ten–day period is used.

The NOTSS GPS system has since been calibrated using the two–way data so that both time transfer methods give the same average result.

USNO hourly clock readings are downloaded at NOTSS and converted to the NOTSS reference system using the two–way data interpolated for 0 hours of each MJD. Another simple interpolation is done for the hours in between. The equation for clock conversion is:

$$\begin{aligned} \mathrm{UTC(NOTSS,MC)-REMOTE} &= [\mathrm{UTC(USNO,MC\#2)-REMOTE}] \\ &+ [\mathrm{UTC(NOTSS,MC)-REF}] \\ &- [\mathrm{UTC(USNO,MC\#2)-REF}] \\ &+ \mathrm{DIFF} \end{aligned}$$

where REMOTE is a clock located at USNO. When using two–way, REF is CS152 and DIFF=0. When using GPS, REF is GPS and DIFF is the difference between the two methods of time transfer.

For the period MJD 48983 to 49229, two–way was used for 232 days of hourly readings and GPS for 15 days.

These resulting (NOTSS - REMOTE) values are then interleaved with the NOTSS readings of its local clocks. The timescale program is rerun with both the local clocks and the remote clocks included to form a NOTSS timescale with several dozen clocks instead of about half a dozen clocks. By using clocks at a remote location, the NOTSS timescale can be better carried through local interruptions in its methodical gathering of hourly clock readings, such as clock vault temperature failures, computer down–time, etc.

CLOCK WEIGHTING

In the NOTSS timescale, the weights given the local clocks are as suggested by Breakiron [6], further modified after studies of the two-pair variances of the various clock types [7]. HP 5061s are given a weight of 0.657 of the HP 5071As. Remote clocks (all of them HP 5071As) were initially given less weight than the local HP 5071As because of expected higher noise due to the time transfer process.

To determine how much noise the two–way time transfer actually adds to the remote clocks, every clock (both local and remote) used in the NOTSS timescale was referenced to the local Sigma Tau hydrogen maser N1 and the rms of the data calculated. A period of time in the range of MJD 49142 to 49227 was chosen for each clock on the basis of having had no rate adjustments during that period. The results were as follows:

Local clocks:
  Single HP 5071A: rms = ± 2ns
  Average of eight HP 5061s: rms = ± 5ns

Remote clocks:
  Average of thirty three HP 5071As: rms = ± 4ns

It thus appears that the two–way time transfer process and the interpolation for the hours in between "degrades" a remote HP 5071A to the noisiness of a local HP 5061. Much of the degradation in the two–way time transfer process is probably related to a problem with the MITREX 2500A modem used at NOTSS, which introduces unmodeled systematics into the timing data. Resolution of this problem awaits a new generation of modems for use in two–way time transfers.

If total clock noise is the basis for determining the clock weights, then the decision to give the remote HP 5071As a weight equal to the local HP 5061s is justified. However, there is no reason to believe that the stability of a remote clock is less than that of a local clock of the same model. A method of making weight more responsive to a clock's past performance may be undertaken at USNO in the future [7].

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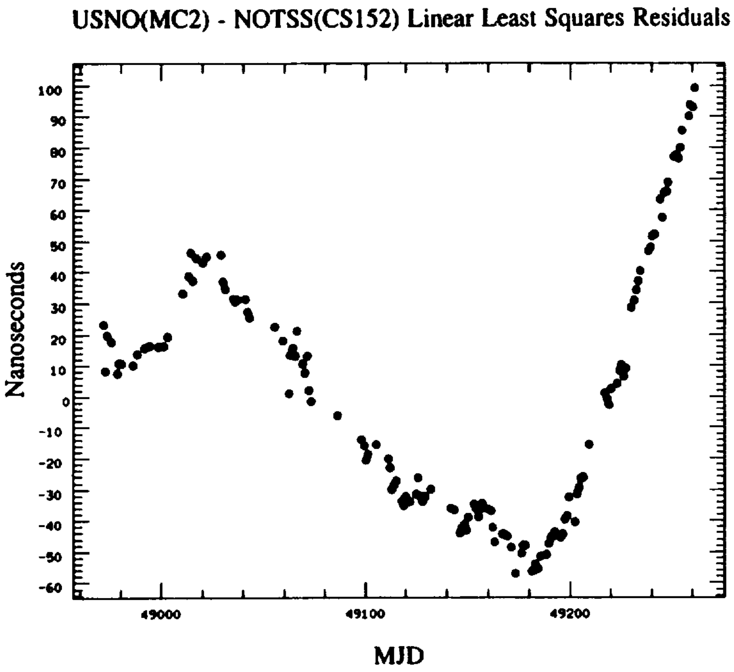

Figure 1. The residuals of the USNO-NOTSS two-way timing link after a linear least squares removal of a 3.89 ns/day slope. Each point is a daily mean generated from 300 to 1500 1-PPS phase comparisons and after application of Equation 1.

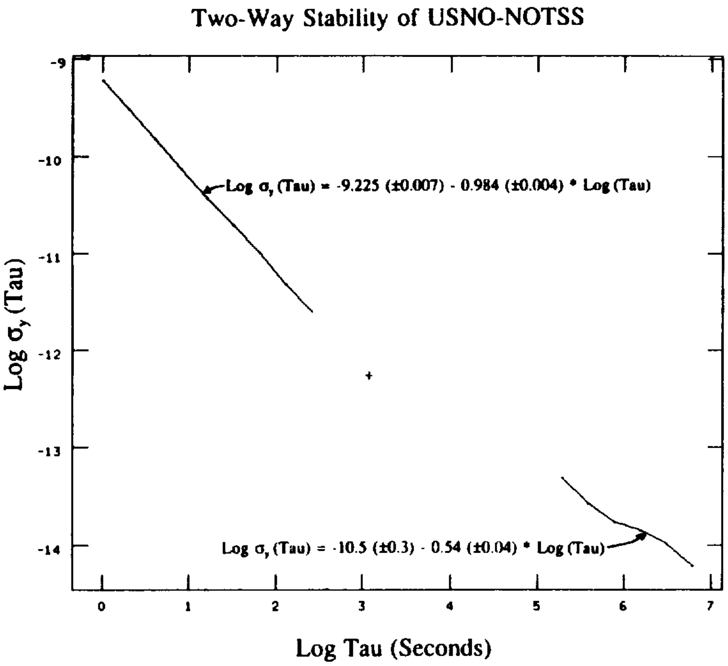

Figure 2. Sigma-tau plot of the USNO-NOTSS time comparisons. A linear least squares fit to the 1-second sample rate phase measurements results in a slope of log tau^{-1} which indicates a white phase noise character for the two-way 1-PPS phase comparisons. The unequally spaced daily data least squares slope indicates a log tau$^{-1/2}$ slope caused by the white frequency noise behavior of the NOTSS HP 5071A cesium clock. A cross-over from white phase noise of the two-way phase comparisons to the white frequency noise of the clock occurs near a tau of 1500 seconds, currently no data is available at that tau, and is indicated in the plot by a "+" symbol.

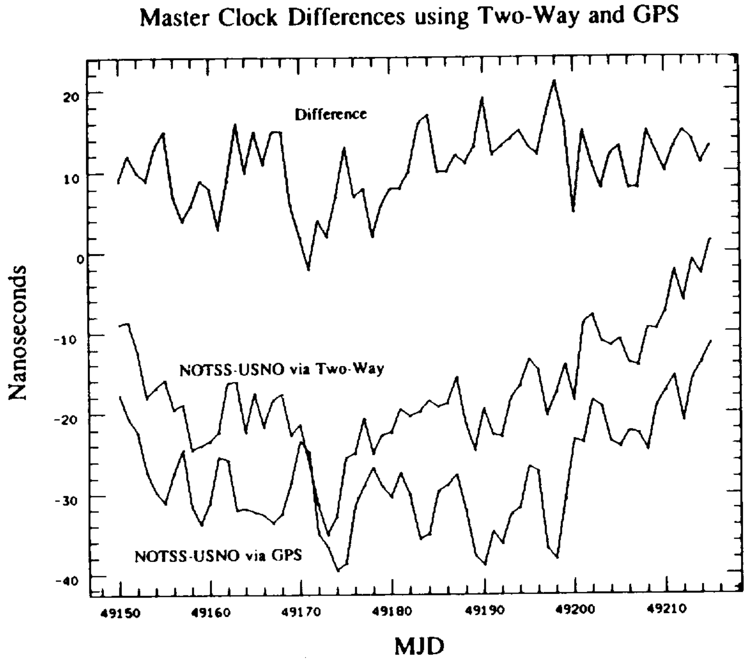

Figure 3. Clock differences as realized by GPS and the two-way timing links.