PERFORMANCE ANALYSIS OF THE GPS MONITOR STATION TIMING SUBSYSTEM ENHANCEMENT PROGRAM AT THE NAVAL RESEARCH LABORATORY

Ivan J. Galysh, Dwin M. Craig, and Wilson G. Reid
U.S. Naval Research Laboratory, Code 8152
4555 Overlook Ave. SW, Washington, DC 20375, USA

James A. Buisson
Antoine Enterprises, Inc.
Consultant to SFA, Inc.

Abstract

The U.S. Naval Research Laboratory designed, developed, and installed hardware and software for the GPS Monitor Station Timing Subsystem Enhancement (MSTSE) at the GPS Monitor Station (MS) located at the Kaena Point Satellite Tracking Station, Hawaii. From December 1995 to the present as part of the evaluation of the system, the U.S. Naval Observatory (USNO) has been performing time transfers through the Two Way Satellite Time Transfer portion of the MSTSE. It will be shown that the new cesium-beam frequency standard (CFS) HP5071 has been disciplined to the DoD Master Clock by the MSTSE during this period to within ± 3 pp 10^{14}. The phase measurement subsystem, of the MSTSE has, for the first time, allowed independent measurement of the two operational GPS Monitor Station HP5061 CFSs.

During June 1996 a modification was made to the MSTSE to reflect improvements in the system architecture developed during the initial evaluation period. This modification has increased system performance, improved reliability, and facilitated easy integration with future GPS Monitor Station improvements. This paper describes the equipment configuration and the test data collected after the installation of the MSTSE. Results are presented from data collected from June 1996 through October 1996.

INTRODUCTION

The GPS Monitor Station Timing Subsystem Enhancement project provides an improved timing subsystem to the existing GPS Monitor Station in Hawaii. In December 1995 the MSTSE was successfully installed at the Kaena Point Satellite Tracking Station located at Point Waiannae, Hawaii. Independent measurements of the two cesium-beam frequency standards (CFS) already at the Monitor Station have been taking place over the last 10 months. The HP5071 CFS in the MSTSE is the reference clock used for phase measurements of the two HP5061 CFSs. This HP5071 is also interfaced with the Two-Way Satellite Time Transfer (TWSTT) modem to enable remote syntonization of this CFS to the DoD Master Clock. In June of this year upgrades to both hardware and software were made at the Hawaii site. The upgrade reflects improvements achieved subsequent to the initial deployment. The MSTSE now has better communication between the phase measurement system and the TWSTT modem. Network capability has been added that will facilitate easy integration of future GPS Monitor Station upgrades. The Hawaii MSTSE has demonstrated its ability to operate autonomously without operator intervention.

PURPOSE

The purpose of the MSTSE is to provide a very stable frequency source that is syntonized with the frequency of the DoD Master Clock. The MSTSE will provide a consistent frequency source independent of the quality of the cesium frequency standard being used. The stability of the standards varies and the MSTSE eliminates the need to selectively choose a standard.

SYSTEM CONFIGURATION

Figure 1 shows a block diagram of the hardware configuration. The MSTSE receives two 5 MHz signals from the Frequency Standard Element (FSE) rack through a fiber-optic interface. Figure 2 shows the photographs of the FSE rack and the MSTSE rack. The 5 MHz signals from the FSE rack are sent through distribution amplifier modules to the auto switch and to the dual mixer. The primary frequency standard is the HP5071. The 5 MHz signal is sent through a distribution amplifier module to the auto switch, to the dual mixer, and to the TWSTT modem. A 10 MHz signal from the HP5071 is used as a reference for the dual mixer.

The MSTSE configuration was designed to provide an open systems architecture. The system was designed based on the client/server model. Figure 3 shows the software architecture. All communications between client tasks and server tasks are through network sockets. Network capability was added to the system to allow client and server tasks to communicate with each other independently of the computer on which they reside. This is a distributed computing environment.

Server tasks are programs that provide one interface between the hardware it controls and the client tasks. The server tasks have command sets for controlling the hardware and retrieving data. Since each server interfaces with a unique piece of hardware, most of the commands are unique for each server. Each server is assigned a unique network socket port. The servers wait for commands from client tasks by monitoring its network socket port for a command. Three servers currently exist in the MSTSE. They are the auto switch server, the cesium server, and the TWSTT server.

The client tasks are programs that communicate with the servers. The client tasks send and receive information using standard UNIX read and write commands. Establishing a communications interface with the servers is simply a matter of opening a socket port that the server monitors. The clients need only to know the socket port and on which computer the server resides. A configuration file on each computer in the MSTSE contains a list of the servers, where they reside, and their network socket port.

The auto switch is an electronic switch that can redirect any of its three inputs using computer control. An internal oscillator allows smooth transitions when switching from one input source to another. It also filters out any other phase discontinuities that may be generated. A 5 MHz signal from each of the cesium frequency standards is connected to the inputs of the auto switch. The hardware interface between the auto switch and the measurement computer is through the industry standard architecture bus. The auto switch is controlled by the auto switch server. The server has a command set that allows client tasks to switch any of the three inputs to the output. An external control signal from the watchdog timer can do the same thing and override the auto switch server commands. The auto switch itself has the capability to detect signal failures and switch out the failed signal. At this time, the system is designed to cut off the output completely when the primary frequency standard exhibits any type of failure. The auto switch server has other commands to initialize the input channels and to retrieve the auto switch status.

The TWSTT modem has been upgraded from a 386-based computer running DOS to a 486-based computer running a UNIX operating system. A network interface module was added to interface with the measurement computer. The TWSTT modem uses the 5 MHz and 1 pps from the HP5071 for synchronization. It performs time transfers initiated by USNO once a day and passes the results to the measurement computer. The TWSTT is controlled by the TWSTT server. The command set has commands to control the operating modes of the TWSTT modem. Commands are available to retrieve the operating status of the TWSTT modem and all data generated.

The TWSTT modem and the dual mixer use the HP5071 as a frequency reference source. The HP5071 is controlled by the cesium server. The cesium server interfaces with the HP5071 through a serial communications interface. A command set is provided to control the HP5071 and to retrieve data from it.

The dual mixer is made up of three modules. The frequency offset module is a crystal oscillator with its frequency offset 10 Hz from 5 MHz. The crystal signal is mixed with the three 5 MHz signals from the cesium frequency standards in the zero-crossing detector module. A beat frequency of about 10 Hz is generated with each 5 MHz signal and is passed to the event counter module. The event counter counts the number of zero crossings and tags the time the zero crossings occur for each 5 MHz signal. The measurement computer collects the counts and time tags and calculates the phase differences between the MSTSE reference clock and the two HP5061 frequency standards used by the GPS monitor station. The phase differences are collected once an hour.

The computer module is a 486 computer with 16 Mbytes of RAM and a 500 Mbyte hard disk. It has two serial ports, a parallel port, and a built-in video controller. One serial port is used to communicate with the HP5071. The parallel port is used to control the watchdog timer.

The watchdog chassis has a timer circuit that will trip the alarm circuitry if the measurement computer does not send a pulse over the parallel port. The measurement computer under normal conditions sends a pulse once a minute. Another signal from the measurement computer parallel port is used to trip the alarm immediately if an error is detected. When the alarm is tripped, a signal is sent to the auto switch external control port to shutdown the output. The "GO/NOGO" status signal to the Monitor Station is asserted to indicate an error condition in the MSTSE.

VERIFICATION, VALIDATION, AND TESTING

For the MSTSE Project there are two objectives: (1) discipline the frequency of the Monitor Station reference clock to stay within specified limits and (2) determine the quality of performance of the two Monitor Station HP5061 option 004 clocks and the MSTSE HP5071. Two-Way Time Transfer measurements between Hawaii and the DoD Master Clock began on a regular basis on 5 June 1996.

The clock configuration at the Hawaii Monitor Station consisted of the three cesium clocks connected to four channels of the measurement system: the HP5071 frequency standard (NRL S/N 449) in Channel A, an HP5061 frequency standard (AF S/N 281) in Channel B, an HP5061 frequency standard (AF S/N 194) in Channel C, and the same HP5071 frequency standard (NRL S/N 449) in Channel D. Data were observed once per hour. A dual-mixer system was used to measure the phase differences between each cesium clock.

This section compares the behavior of the disciplined HP5071 from two perspectives: (1) from the Two-Way Time Transfer between it and the DoD Master Clock, and (2) from the Linked Common-View Time Transfer between it and the DoD Master Clock. The offset in the latter case was obtained by summing the two data sets: (1) the linked Common-View Time Transfer from the DoD Master Clock to the Hawaii time reference, i.e., the HP5061 connected to Channel B of the clock quality measurement portion of the MSTSE, and (2) the offset between the HP5061 (Channel B) and the HP5071 (Channel A). The period covered by the report is from 5 June to 30 August 1996.

Figure 4 is the offset of the disciplined clock (HP5071 Channel A) from the Hawaii time reference (HP5061 Channel B) with a mean of –4.5 microseconds removed. The residuals of a linear fit to these data are presented in Figure 5, which shows the detailed structure of the data. Figure 6 is the offset of the Hawaii time reference (HP5061 Channel B) from the DoD Master Clock determined by Linked Common-View Time Transfer with a mean of 190 microseconds removed. The time reference at the Defense Imagery and Mapping Agency Monitor Station in Washington D.C. (whose measurements were used in the Linked Common-View Time Transfer) has accumulated a phase bias with respect to the DoD Master Clock as the result of arbitrary steps in the phase due to local station power outages. The detailed structure of these data can be seen in Figure 7, which are the residuals of a linear fit to the data in Figure 6. In summing the two data sets, i.e., the data in Figures 4 and 6, the Hawaii time reference drops out, leaving the offset of the disciplined clock from the DoD Master Clock except, as noted, for an arbitrary bias in the phase.

In Figure 8 is shown the mean residuals of the offset between the disciplined clock and the DoD Master Clock determined by both the Two-Way and the Linked Common-View Time Transfer. A discontinuity of –17 nanoseconds can be seen to have occurred on 15 July 1996 in the data from the Two-Way Time Transfer. USNO replaced a VSAT drawer on that date in the master TWSTT modem which coincides with the 17 nanosecond correction. Using the corrected Two-Way Time Transfer data, the offset of the disciplined clock from the DoD Master Clock obtained from both the Two-Way and the Linked Common-View Time Transfer can be seen in Figure 9 to be very closely correlated except for the second member of a pair of improperly spaced measurements on day 50285.

The four-day average frequency corresponding to the one-hour samples of phase offset obtained from the Linked Common-View Time Transfer is shown in Figure 10. Superimposed on these measurements are estimates of the frequency determined by the MSTSE from fitting a straight line to four successive measurements of the phase offset obtained by Two-Way Time Transfer at nominal 1-day intervals. The correlation between the Two-Way and the Linked Common-View Time Transfer is excellent.

The size and time of occurrence of the frequency tunes made to discipline the HP5071 clock are plotted in Figure 11. The first tune of 2.19 pp 10^{13} was a jam syntonization triggered by initialization of the MSTSE. The tunes clustered in mid-July resulted from the phase discontinuity introduced by the Naval Observatory on 15 July. Twenty-two days can be seen to have elapsed in August during which time no tunes were required.

The estimates of the frequency of the disciplined clock determined by the MSTSE are reproduced in Figure 12 with the tuning goal of ± 3 pp 10^{14} superimposed. Again, the initial frequency is offset by -2.19 pp 10^{13} because of the initialization of the MSTSE. The jam syntonization quickly brings the frequency of the clock to within the tuning goal. For the entire 128 days the frequency remained at or within the tuning goal except for one day in mid-July following the induced phase discontinuity.

Such close agreement between the Two-Way Time Transfer with subnanosecond accuracy and the Linked Common-View Time Transfer with subnanosecond precision provides strong validation of both methods. Furthermore, the precision of the Linked Common-View Time Transfer enabled identification of an anomaly in the Two-Way Time Transfer.

CONCLUSIONS

The first field installation of the MSTSE successfully established feasibility of the concept. The ability to independently measure the currently deployed cesium clocks has provided verifiable data as to the operational health of the existing timing system. The deployed MSTSE is operating without the need for operator intervention. Automated data collection and cesium clock syntonization with the DoD Master Clock have been continuously performed. The MSTSE has provided a disciplined frequency to within ± 3 pp 10^{14} which relates to ± 3 ns in phase. Upgrades in the hardware, software, and network configuration have made the MSTSE ready for any additional Monitor Station implementations.

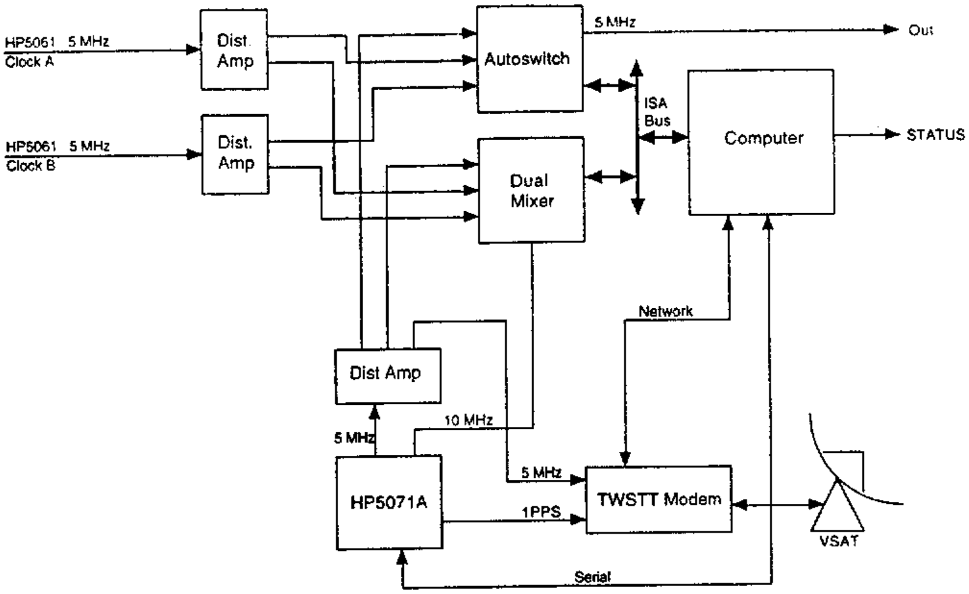
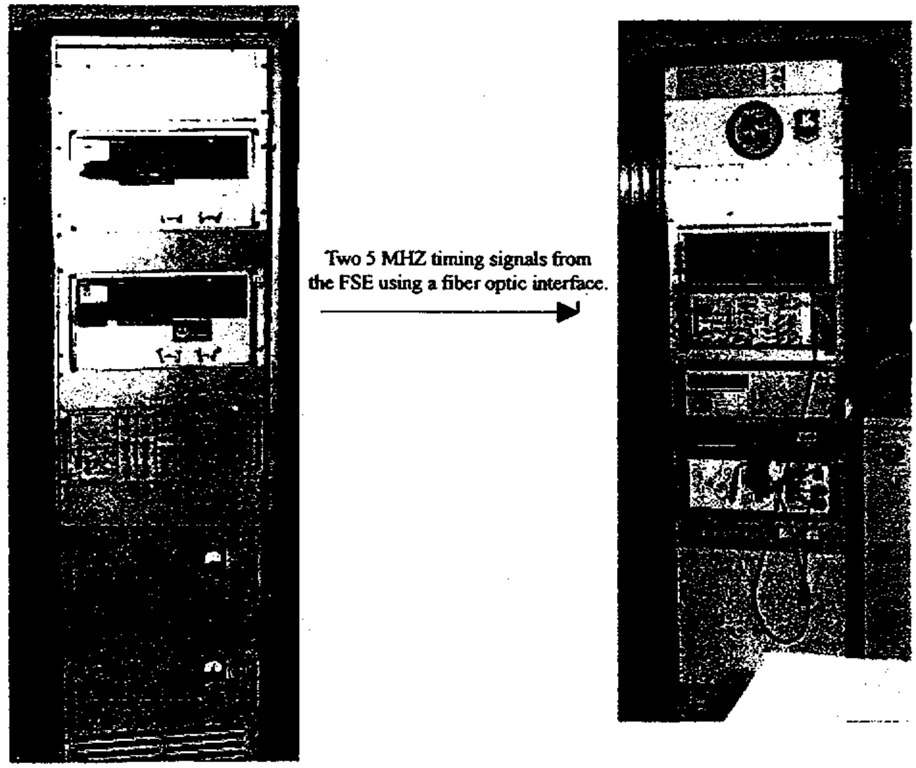


Figure 1. MSTSE hardware block diagram

Existing Frequency Standard Element (A6 Rack) and MSTSE (A12 Rack) at the Hawaii GPS Monitor Station



Two 5 MHZ timing signals from the FSE using a fiber optic interface.

Frequency Standard Element (FSE)
(A6 Rack)

MSTSE
(A12 Rack)

Figure 2. MSTSE rack and frequency stndard element

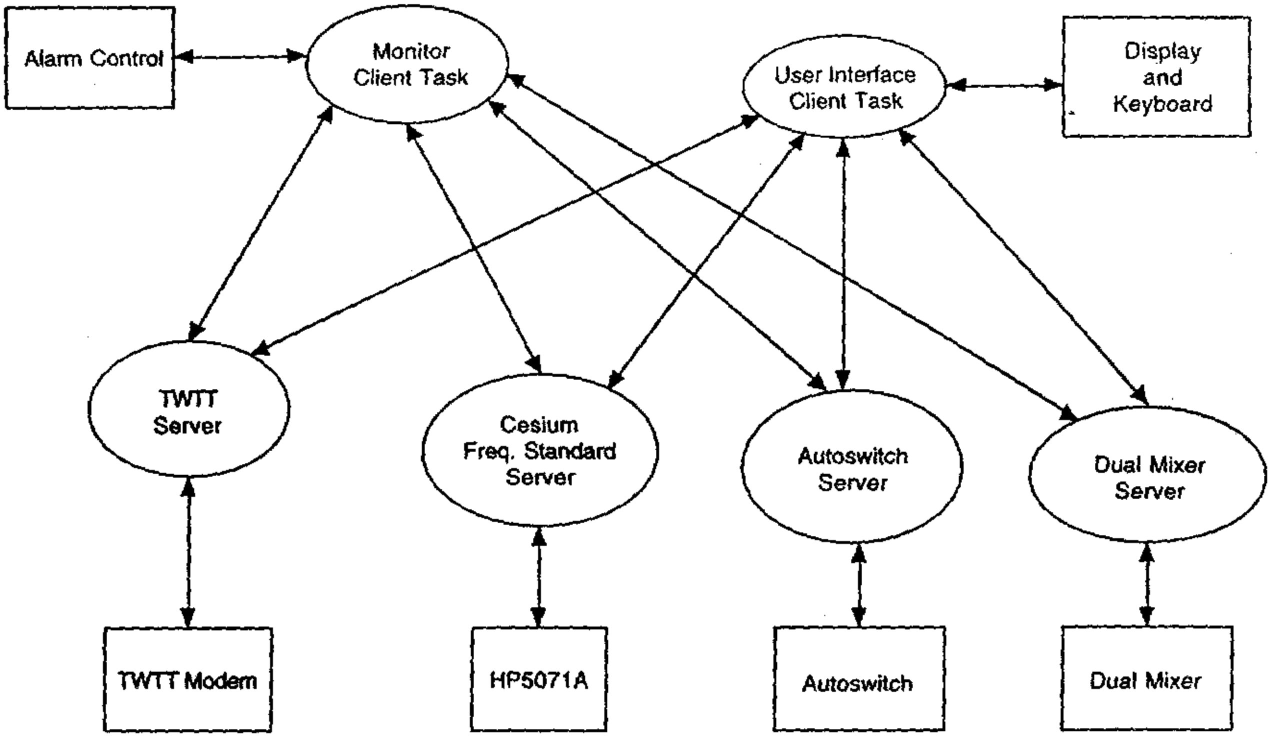


Figure 3. MSTSE software architecture

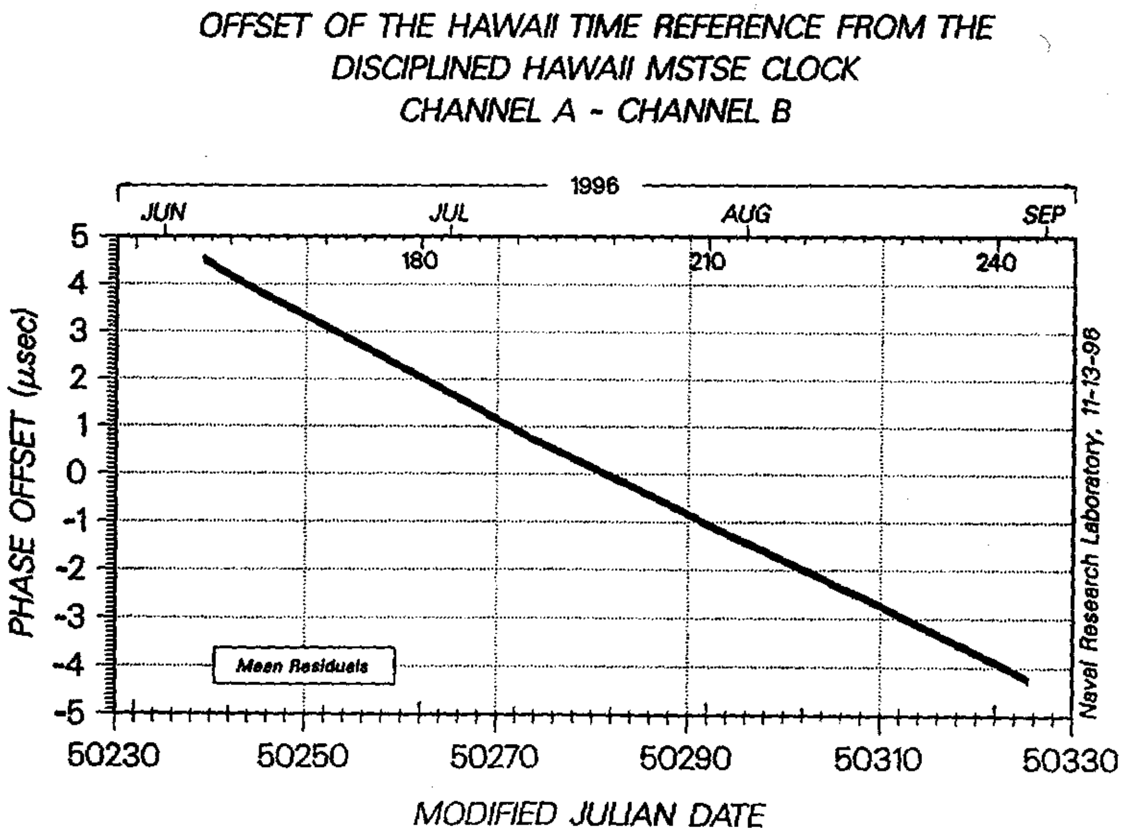

OFFSET OF THE HAWAII TIME REFERENCE FROM THE DISCIPLINED HAWAII MSTSE CLOCK CHANNEL A - CHANNEL B

Figure 4

OFFSET OF THE HAWAII TIME REFERENCE FROM THE
DISCIPLINED HAWAII MSTSE CLOCK
CHANNEL A - CHANNEL B

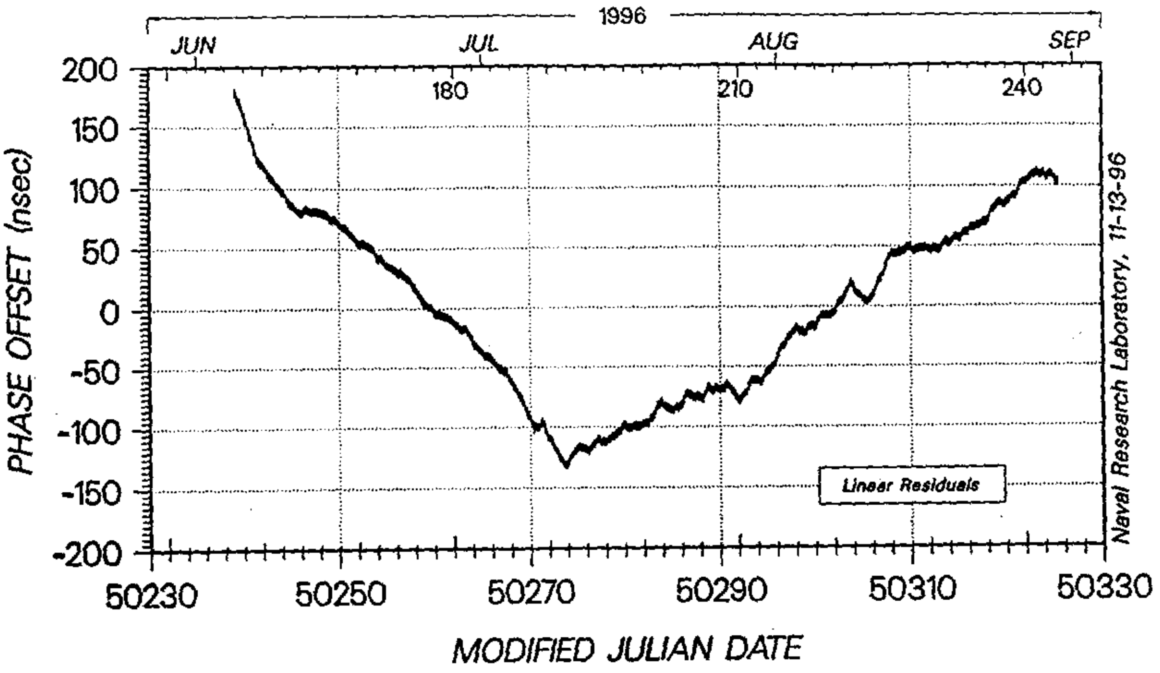


Figure 5

OFFSET OF THE HAWAII TIME REFERENCE FROM THE
DOD MASTER CLOCK USING
LINKED COMMON-VIEW TIME TRANSFER

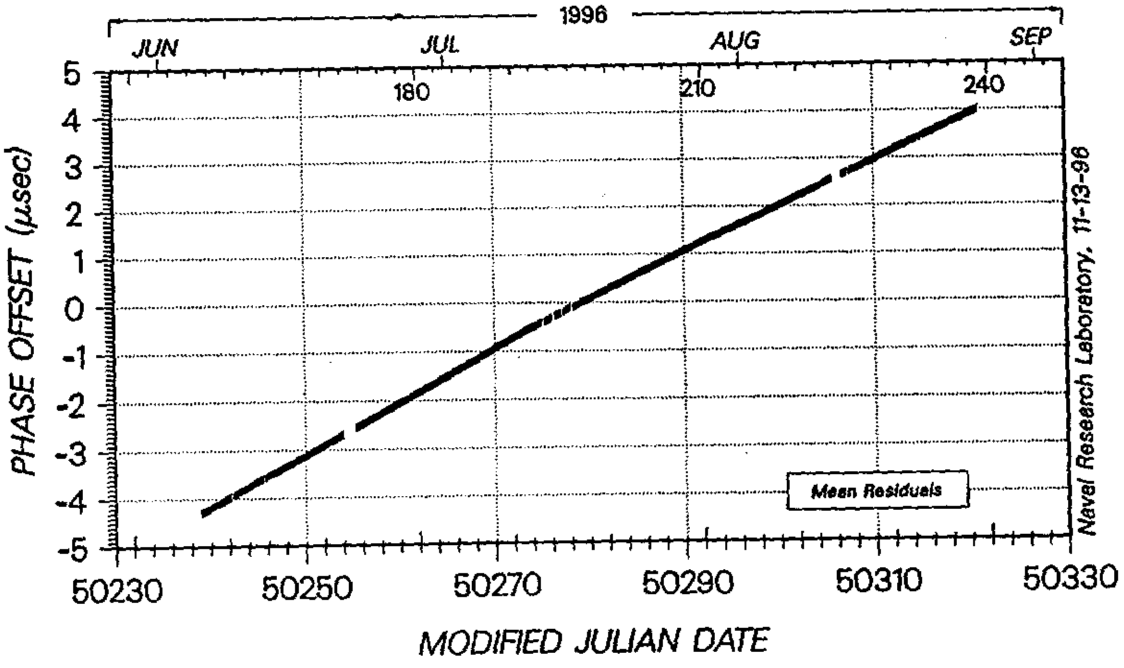
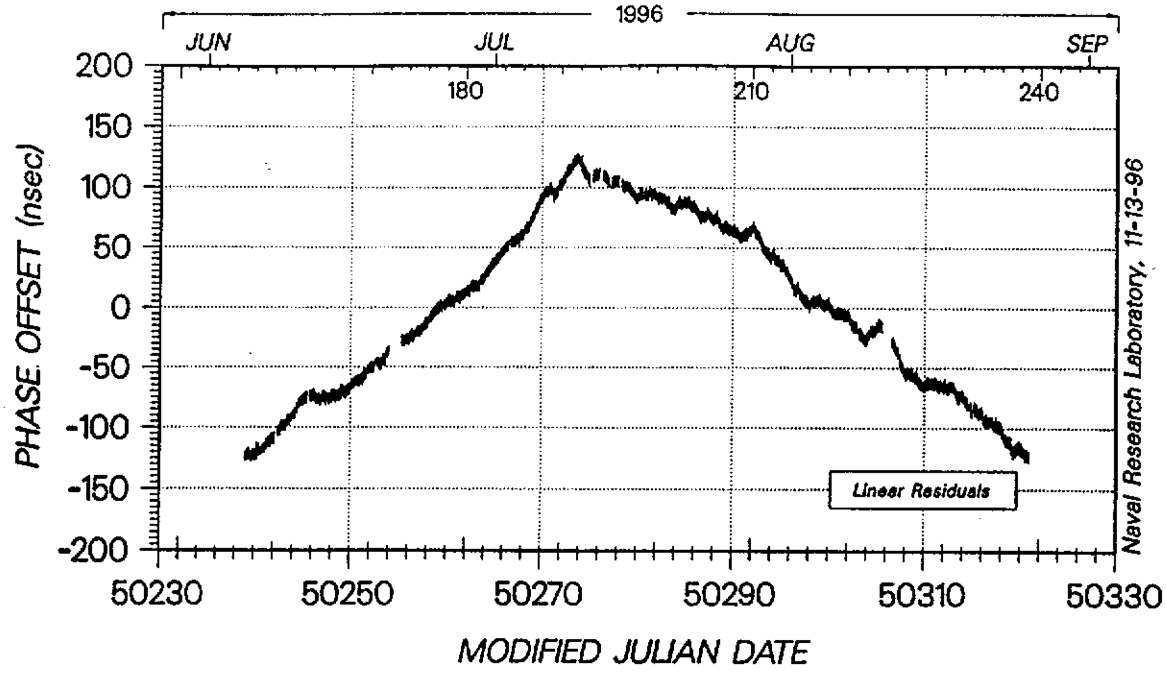
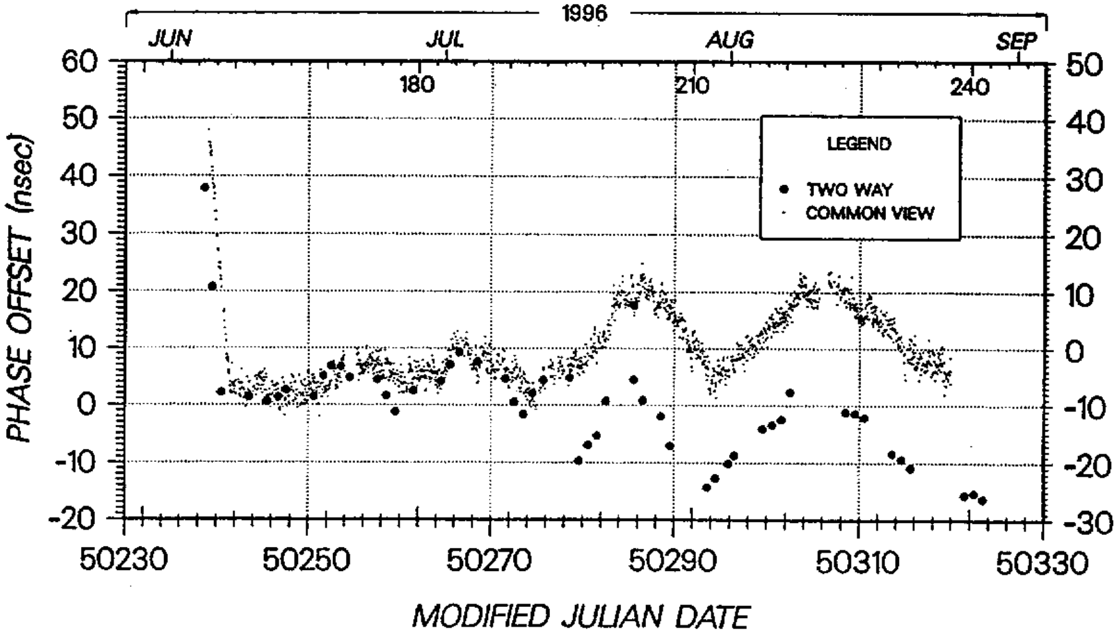


Figure 6



OFFSET OF THE HAWAII TIME REFERENCE FROM THE
DOD MASTER CLOCK USING
LINKED COMMON-VIEW TIME TRANSFER

Figure 7



PHASE OFFSET MEAN RESIDUALS OF DISCIPLINED CLOCK FROM
DOD MASTER CLOCK USING
TWO-WAY TIME TRANSFER AND
LINKED COMMON-VIEW TIME TRANSFER

Figure 8

PHASE OFFSET MEAN RESIDUALS OF DISCIPLINED CLOCK FROM
THE DOD MASTER CLOCK USING
CORRECTED TWO-WAY TIME TRANSFER AND
LINKED COMMON-VIEW TIME TRANSFER

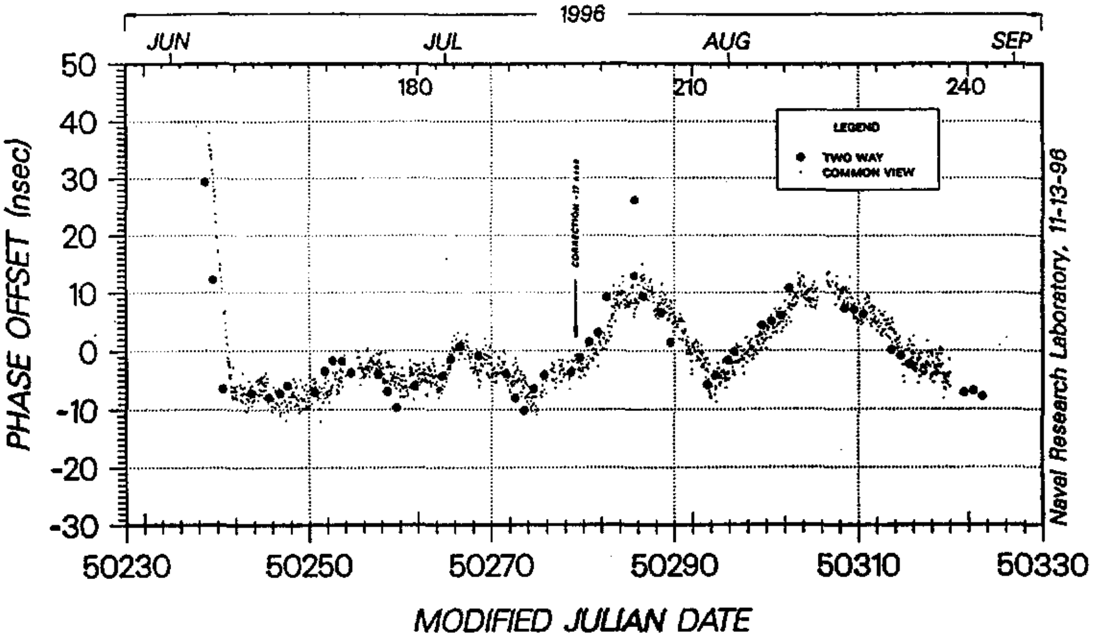


Figure 9

FREQUENCY OFFSET MEAN RESIDUALS OF DISCIPLINED CLOCK FROM
THE DOD MASTER CLOCK USING
TWO-WAY TIME TRANSFER AND
LINKED COMMON-VIEW TIME TRANSFER

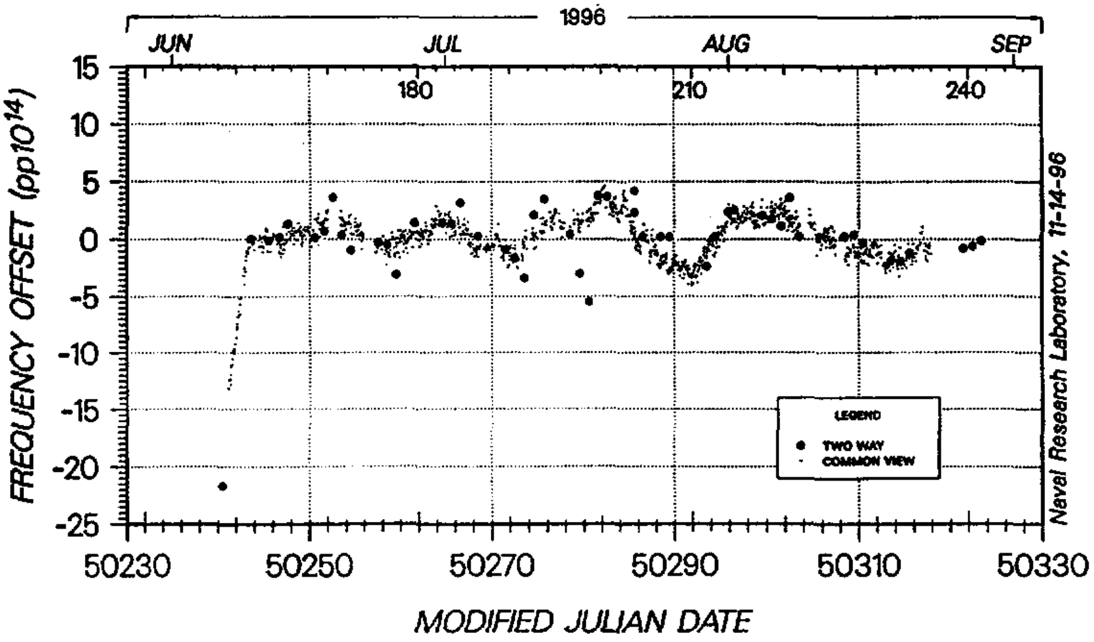


Figure 10

FREQUENCY TUNES MADE TO THE DISCIPLINED HP5071 (S/N 449) DETERMINED FROM TWO-WAY TIME TRANSFER BETWEEN HAWAII AND THE DOD MASTER CLOCK

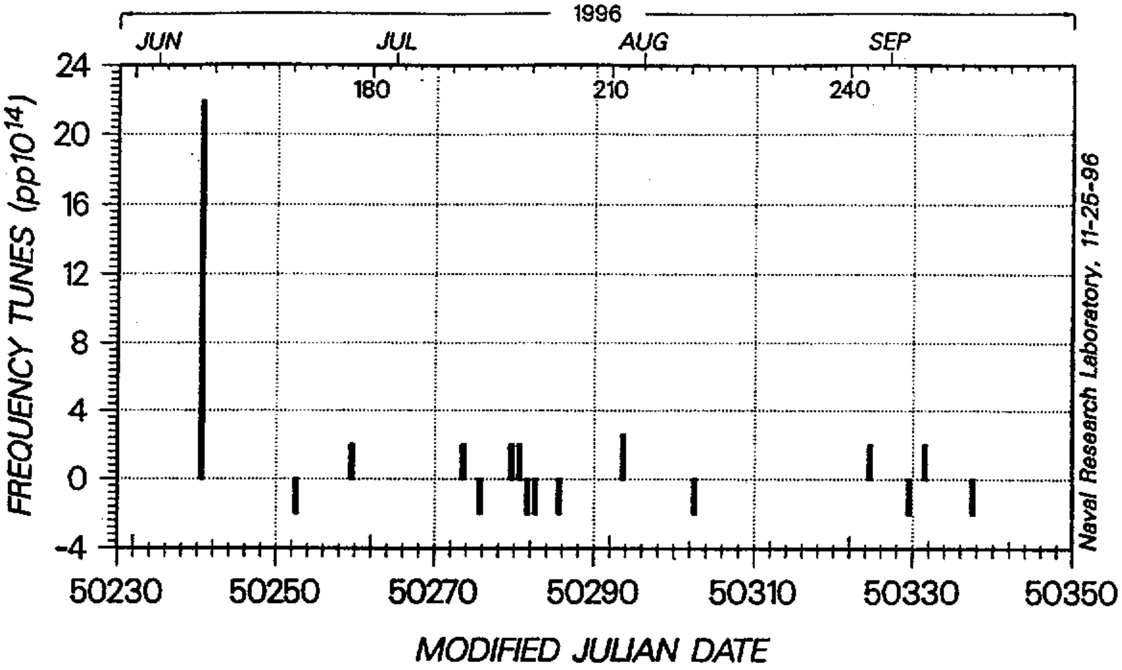


Figure 11

FREQUENCY OFFSET OF THE DISCIPLINED HP5071 (S/N 449) FROM THE DOD MASTER CLOCK DETERMINED BY TWO-WAY TIME TRANSFER

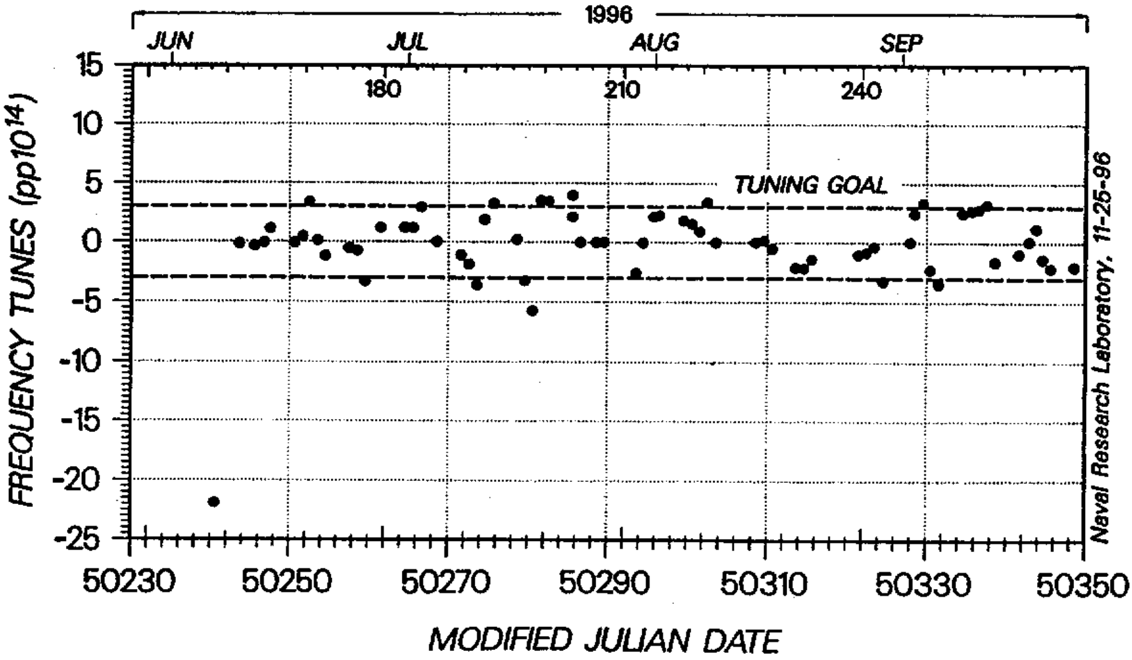


Figure 12

Questions and Answers

PAUL WHEELER (USNO): On your tuning chart, it looks like for every positive tune, the next tune was a negative tune. Was I interpreting that right and do you have an explanation for that?

DWIN CRAIG: No, that was just the way the system ended up. The software at the site, given the criteria that we gave it, generated the tunes. It's a coincidence.