GPS MONITOR STATION UPGRADE PROGRAM AT THE NAVAL RESEARCH LABORATORY

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Abstract

One of the measurements made by the GPS Monitor Stations is to measure the continuous pseudo-range of all the passing GPS satellites. The pseudo-range contains GPS satellite and Monitor Station clock errors as well as GPS satellite navigation errors. Currently the time at the GPS Monitor Station is obtained from the GPS constellation and has an inherent inaccuracy as a result. Improved timing accuracy at the GPS Monitor Stations will improve GPS performance.

The U.S. Naval Research Laboratory (NRL) is developing hardware and software for the GPS Monitor Station Upgrade program to improve the Monitor Station clock accuracy. This upgrade will allow a method independent of the GPS satellite constellation of measuring and correcting Monitor Station time to U.S. Naval Observatory (USNO). The hardware consists of a high-performance atomic cesium frequency standard (CFS) and a computer which is used to ensemble this CFS with the two CFSs currently located at the Monitor Station by use of a dual-mixer system. The dual-mixer system achieves phase measurements between the high-performance CFS and the existing Monitor Station CFSs to within 400 femtoseconds.

Time transfer between USNO and a given Monitor Station is achieved via a two-way satellite time-transfer modem. The computer at the Monitor Station disciplines the CFS based on a comparison of one pulse per second sent from the master site at USNO. The Monitor Station computer is also used to perform housekeeping functions, as well as recording the health status of all three CFSs. This information is sent to USNO through the time-transfer modem.

Laboratory time synchronization results in the sub-nanosecond range have been observed and the ability to maintain the Monitor Station CFS frequency to within 3.0×10^{-14} of the master site at USNO.

INTRODUCTION

The GPS Monitor Station Timing Subsystem Enhancement (MSTSE) project will provide a timing subsystem to the existing GPS Monitor Stations in Hawaii, Kwajalein Island, Ascension Island, and Diego Garcia. The new timing subsystem will provide uninterrupted frequency output that is syntonized to Universal Time Coordinated from the U.S. Naval Observatory, UTC (USNO), via a Two-Way Satellite Time Transfer modem (TWSTT). A new cesium-beam frequency standard (CFS) will be ensembled with the existing clocks, which will increase reliability and stability. If one of the clocks at the Monitor Station (MS) site begins to fail, the KAS-2 (Kalman Filter Algorithm for Time Scale Computation) software will automatically deweight that CFS out of the system. This upgrade will also allow remote monitoring of the health and performance of the clocks in the ensemble. This will allow an independent means to confirm the subsystems performance and the quality of the timing reference available to each MS. All of these functions will be automated and not require operator intervention.

The GPS Monitor Stations measure the continuous pseudo-range of all the passing GPS satellites. These data are sent to the Master Control Station (MCS) over a communications link. At the Monitor Stations there are three components that contribute to major errors in the pseudo-range measurements, errors from the clock in the space vehicle, errors in the ground receiver, and errors in the ground clock. If the problem involves the CFS, then the system must be switched over to the backup CFS. This manual switchover by the operator at the MCS may cause a phase discontinuity which can appear as a data anomaly. At the MCS the data that have been collected is preprocessed and input to the system Kalman filter. Recently measurements taken from the satellite constellation have been used to improve these error models, and system performance has improved. The purpose of the GPS MSTSE is to improve the reliability of the present system and to provide an independent method of measuring the clock performance of the ground station clocks, thus making possible improvements in the clock models and reducing noise from the ground clocks for the Kalman filter calculations.

OBJECTIVES

The GPS Monitor Station Timing Subsystem Enhancement Project has the following objectives: to non-obtrusively enhance the existing Monitor Station systems using existing interfaces, to provide a higher degree of reliability at each monitor site, to syntonize the Monitor Station frequency to the USNO Master Clock, to provide an independent means to measure Monitor Station performance, and to provide for remote unmanned operation.

MONITOR STATION INTERFACE

The new timing subsystem will appear, to the existing hardware interface at the GPS MS, as one of the CFSs already installed at the monitor site. The output from the MSTSE will be provided into the existing MS hardware as if it were the output of a single CFS. The MSTSE will also provide a clock health status signal into the existing hardware interface. Figure 1 is a diagram showing the way in which the MSTSE is integrated into the existing system.

HARDWARE CONFIGURATION

As shown in Figure 2, the MSTSE hardware configuration consists of an HP5071 CFS, a dual-mixer phase measurement system, an autoswitch, a TWSTT, a system computer, a backup power system, and a watchdog timer. The equipment is contained in a single rack, excluding the Very Small Aperture Terminal (VSAT) for the TWSTT. The rack layout is shown in Figure 3. The HP5071 Primary Frequency Standard has the high-performance cesium beam tube option, which allows for time domain stability of 2.0×10^{-14} seconds in a 30-day period. This CFS has a microprocessor-controlled Voltage-Controlled Crystal Oscillator (VCXO) which is corrected several times a second so that it remains locked to the cesium transition frequency. The HP5071 can be accurately disciplined by ensemble software and the TWSTT modem.

To measure clock quality, a four-channel dual-mixer system is being employed. Measurements between the two existing HP5061 CFSs and the new HP5071 CFSs will be performed with precision in the 400 femtosecond range. The measurements are collected hourly. These data are then applied to the KAS-2 ensembling software[1]. The resulting ensemble output is then used to discipline the HP5071 CFS.

The dual-mixer hardware consists of three elements, an offset reference oscillator, a crossover detector, and an event timer. The dual-mixer hardware uses a Guide Technology 401 event-timing controller. The GT401 has its own on board microprocessor and the ability to time-tag an event on any of four channels to 0.4 μs accuracy. This card has a real-time clock which takes an external 10 MHz input supplied by the reference HP5071 CFS. This real-time clock is then the baseline reference for the time-tag generation. The 5 MHz outputs of the three CFS are fed into the distribution amplifier (DA). The outputs from the DA are then mixed with the output from the offset reference oscillator, thus providing the heterodyne effect, and is then sent to the event counter (GT401 Event-Timing Controller Monitor) for phase crossover detection and time-tagging. A more detailed description of the dual-mixer phase measurement system can be found in [2]. The dual-mixer software processes the time-tagged data and then outputs phase data on the different CFSs. The data generated by the dual mixer are integrated into the daily TWSTT message and sent during every time transfer.

The function of the autoswitch is to shut off the 5MHz RF signal to the MS in the event of a major failure; this is a failsafe feature. The existing MS system detects clock failure as a loss of signal and switches to the secondary CFS. The autoswitch hardware monitors the signal level and phase of the 5 MHz signals on all three CFS channels. The autoswitch has frequency drift and signal amplitude detection hardware. The autoswitch continuously tests the incoming signals. A comparison between all three inputs is done and a majority vote is taken to determine if any of the CFS outputs is drifting off frequency compared to the other two clock channels. If a CFS output frequency has drifted too far from the other CFSs, then that channel is shut down by the autoswitch. This provides a safeguard against a poorly performing CFS providing a bad frequency signal from the MSTSE.

The Two-Way Time Transfer modem is capable of precise time transfer with sub-nanosecond precision using commercial communications satellites. This modem allows for frequency syntonization of the HP5071 to the USNO Master Clock. This modem consists of a commercial PC/AT computer in an industrial chassis, an analog transmitter section, and a VSAT communications antenna. The system was developed at NRL and Allen Osborne Associates during the last 4 years[3]. The digital section of the modem is connected to the system computer using an RS-232 serial connection. The TWSTT modem can then not only send time-transfer results to the main system computer, but also CFS measurement data back through the modem. The TWSTT modem is configured as a target at the remote site, with USNO operating as the master station. The modem is configured for automated operation and will automatically perform a time transfer when initiated from the master site.

The system computer section of the timing subsystem is an PC in an industrial chassis. The computer has RS232 port connections to the Two-Way Time Transfer modem and the HP5071 CFS. The computer module also contains the dual-mixer hardware and the autoswitch module connected via its Industry Standard Architecture passive backplane. Along with the computer's power supply is a battery charger and voltage regulator for keeping the emergency batteries charged. The centronics parallel output of the computer is connected to a watchdog timer module. The watchdog timer is another failsafe feature of the timing subsystem. It controls the System Health Status line to the MS system and the MCS. A health status message will be indicated to the Monitor Station and the output of the autoswitch cut off if the system computer fails.

SOFTWARE

The system computer operates under a multitasking operating system, with operations handled by small independent routines. There are separate routines to handle each portion of the timing subsystems' functionality. Tasks communicate to each other via files or pipelines. The operating system is Linux, which is a POSIX-compliant implementation of the UNIX operating system. Linux is an ideal operating system for implementation of the timing subsystem, and will accommodate possible future integration into a new MS open system architecture.

The MSTSE software consists of five software modules controlling the various parts of the data collection and control functions of the MSTSE, as shown in Figure 4. The five major software modules are: the control program, the dual mixer task, the autoswitch task, the cesium task, the modem task, and the watchdog task. Figure 4 illustrates the lines of communication between the different software modules.

The control program initializes all of the other software modules when the system first boots up. This program provides a display interface to the video output which shows the status of the autoswitch. This module also communicates with the cesium task to get status information from the HP5071 CFS. The control program provides a quick way to determine the health and status of the HP5071 CFS and the autoswitch.

The Dual Mixer task processes the dual-mixer data to provide the phase relationship between the Master Clock (HP5071) and the two existing HP5061s at the Monitor Station. The dual-mixer hardware collects hourly time-tagged data on four channels. The first channel is the reference HP5071, and the second and third channels are the two HP5061s. The fourth channel measures the reference HP5071 against itself as a noise channel and an extra check of dual-mixer performance. The GT401 event-timing controller monitor ISA bus card is checked continuously by the dual-mixer task to maintain the proper relationships between collected data. After data collection is complete, the dual-mixer software begins to perform postprocessing, which involves providing the correct time tags for each phase measurement. The dual-mixer task provides clock quality data to the modem task for inclusion into the daily time transfer.

After the phase data processing is complete, the dual-mixer task calls the KAS-2 software which generates the ensemble. The cesium task output then receives these data from the KAS-2 software for determination of the correct output frequency.

The autoswitch task monitors the autoswitch every 5 seconds and updates a status file. This software routine queries the hardware in the autoswitch to monitor the signal level and phase quality of the signals coming from the CFSs on all three channels.

The cesium task monitors and controls the HP5071 CFS. Every minute it checks the operating status of the HP5071. Once an hour the task collects the operating parameters from the CFS. The current discipline value generated by analysis of the TWSTT data is provided to the cesium task, which then disciplines the HP5071. In this way the reference HP5071 is syntonized to UTC (USNO).

The modem task monitors the operation of the TWSTT. After the time transfer has been initiated by USNO, the modem task collects the results of the transfer. The data from the transfer are then sent to the clock discipline task, where a calculation in the discipline algorithm determines if a command should be sent to the HP5071. The purpose of discipline task is to syntonize the reference HP5071 CFS to UTC (USNO). The disciplining algorithm estimates the frequency offset of the reference CFS to UTC (USNO) by using the slope of the data from a linear fit to the frequency data. The slope is calculated from a minimum of three time-transfer measurements and is compared to a predetermined threshold. The threshold is preset. When the system is in the initialization process, a jam syntonization occurs between the reference CFS and USNO. This is a one-time gross adjustment of the remote clock after the first three time-transfer measurements are gathered. After the jam sync of the reference CFS, the discipline commands are limited to a maximum frequency value of 2 parts in 10^{-14}. Discipline commands in this range should be well below the measurement threshold of the existing MS equipment and, therefore, transparent to its operation. The modem task also controls the packing task, which prepares the last three days of clock quality data to be sent to USNO during the transfer.

The watchdog task sends a reset signal to a watchdog timer every 60 seconds; failure to do so changes the health status message to the Monitor Station Frequency Standard Element and turns off the autoswitch. The MS system then switches to the secondary (backup) HP5061 as the frequency reference to the Monitor Station. This final switching occurs externally to the MSTSE.

PERFORMANCE EVALUATION

Clock Quality

Performance of the MSTSE software and hardware configuration was tested against the time and frequency reference systems at the NRL Precise Clock Evaluation Facility[4]. The time and frequency reference used at the NRL Precise Clock Evaluation Facility contains two Sigma Tau hydrogen masers. These masers produce 1PPS and 5MHz signals that are synchronized to UTC (USNO). The test configuration assigned each system under test consisted of one HP5071 as the primary or reference CFS. The other two CFS in the systems were two other HP5071s, which were also monitored by the precise clock evaluation facility's long-term clock measurement system. All three clocks have their 5MHz outputs routed into the Precise Clock Evaluation Facility's long-term measurement system. This dual-mixer system is capable of measuring 48 clocks simultaneously with a τ-interval of one hour and a noise floor of $6 \times 10^{-12}/\tau$.

A test was run over a four-day period in which measurements of the three clocks were taken by the MSTSE system and NRL's precise clock evaluation facility. Figure 5 is a plot comparing the two systems. There is a intentional 1-nanosecond offset in the data to allow for easier comparison of the two phase plots. The correlation between the two sets of measurements is very good, as can be seen. Consequently the measurement precision and accuracy was verified.

Two-Way Satellite Time Transfer

At NRL a test configuration was set up to verify the performance of the TWSTT that will be installed in the MSs. Two different configurations were used to evaluate the performance of the TWSTT. The first configuration tested involved taking two modems and connecting them directly without a using a satellite antenna. The second performance evaluation involved using a satellite link.

The first data plot (Figure 6) shows 16 days of data. As can been seen in the data, the original jam syntonization is on the order of 18 parts in 10^{-14}. After this initial frequency correction, the reference CFS has very little drift in the next 13 days. The discipline algorithm doesn't sent a command to the CFS because the threshold frequency drift has not been crossed.

The second data plot (Figure 7) shows the modem performance using the satellite in the test configuration. Again, a jam sync occurs after the first three time transfers have occurred. After 33 days the CFS frequency drifted over the threshold set by the discipline algorithm and a command was sent to the cesium task to provide a correction. This demonstrates that the algorithm worked, and that the CFS can be syntonized remotely.

CONCLUSIONS

The system improves performance at the monitor site by providing a very stable frequency standard with the HP5071. It allows measurement of the existing CFS against the new CFS and disciplines the new CFS to the UTC time provided by USNO. This upgrade will provide composite clock capability, which until now has only been available at the MCS. Greater reliability is realized through multiple safeguards to ensure continuous monitored performance at each ground site.

REFERENCES

[1] S. Stein 1995, *"KAS-2: Algorithm for time-scale computation and control of real-time clocks,"* Report No. TS95.0046 Rev. 1 (Timing Solutions Corporation Boulder, Colorado).

[2] S. Stein, D. Glaze, J. Levine, J. Gray, D. Hilliard, D. Howe, and L. Erb 1982, *"Performance of an automated high accuracy phase measurement system,"* Proceedings of the 36th Annual Symposium on Frequency Control, 2-4 June 1982, pp. 314-320 = NIST Tech. Note 1337, pp. 241-247.

[3] G.P. Landis, I.J. Galysh, G. Gifford, and A. Osborne 1992, *"A new two-way time transfer modem,"* Proceedings of the 23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1991, Pasadena, California, pp. 247-257.

[4] E.C. Jones, E.D. Powers, A.H. Frank, and J.A. Maury 1995, *"Static timing tests of the R-2332/AR, R2331/URN, MANPACK (RPU-1), and the Texas Instrument MANPACK AN/PSN-9 NAVSTAR Global Positioning System user equipment at the Naval Research Laboratory,"* NRL MR/8150-95-7754 (Naval Research Laboratory, Washington, D.C.). A more up-to-date report will be forthcoming shortly.

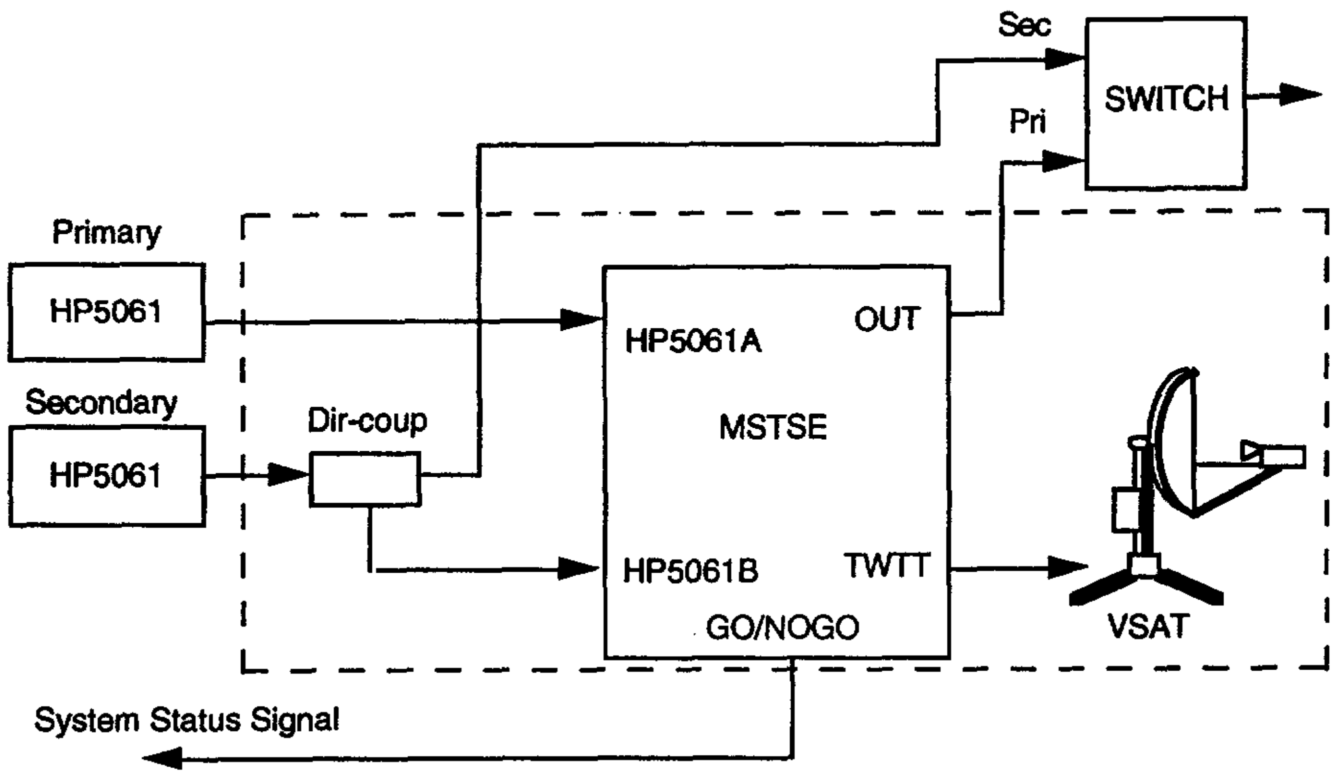

Sec
SWITCH
Pri
Primary
HP5061
Secondary
HP5061
Dir-coup
HP5061A
OUT
MSTSE
HP5061B
TWTT
GO/NOGO
VSAT
System Status Signal

Figure 1

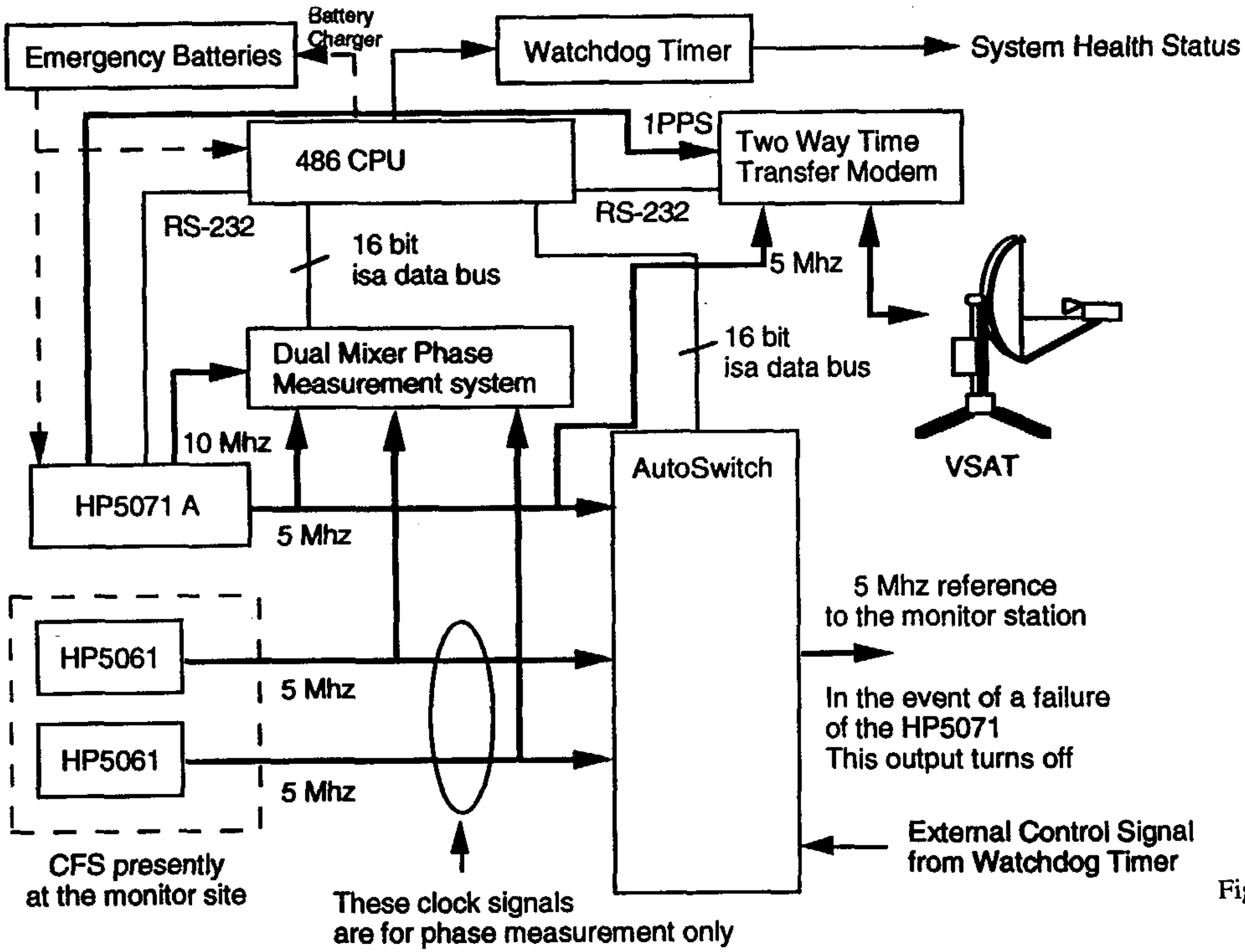

Emergency Batteries
Battery Charger
Watchdog Timer
System Health Status
1PPS
486 CPU
Two Way Time Transfer Modem
RS-232
RS-232
16 bit isa data bus
5 Mhz
16 bit isa data bus
Dual Mixer Phase Measurement system
10 Mhz
VSAT
HP5071 A
5 Mhz
AutoSwitch
5 Mhz reference to the monitor station
HP5061
5 Mhz
HP5061
5 Mhz
In the event of a failure of the HP5071 This output turns off
External Control Signal from Watchdog Timer
CFS presently at the monitor site
These clock signals are for phase measurement only

Figure 2

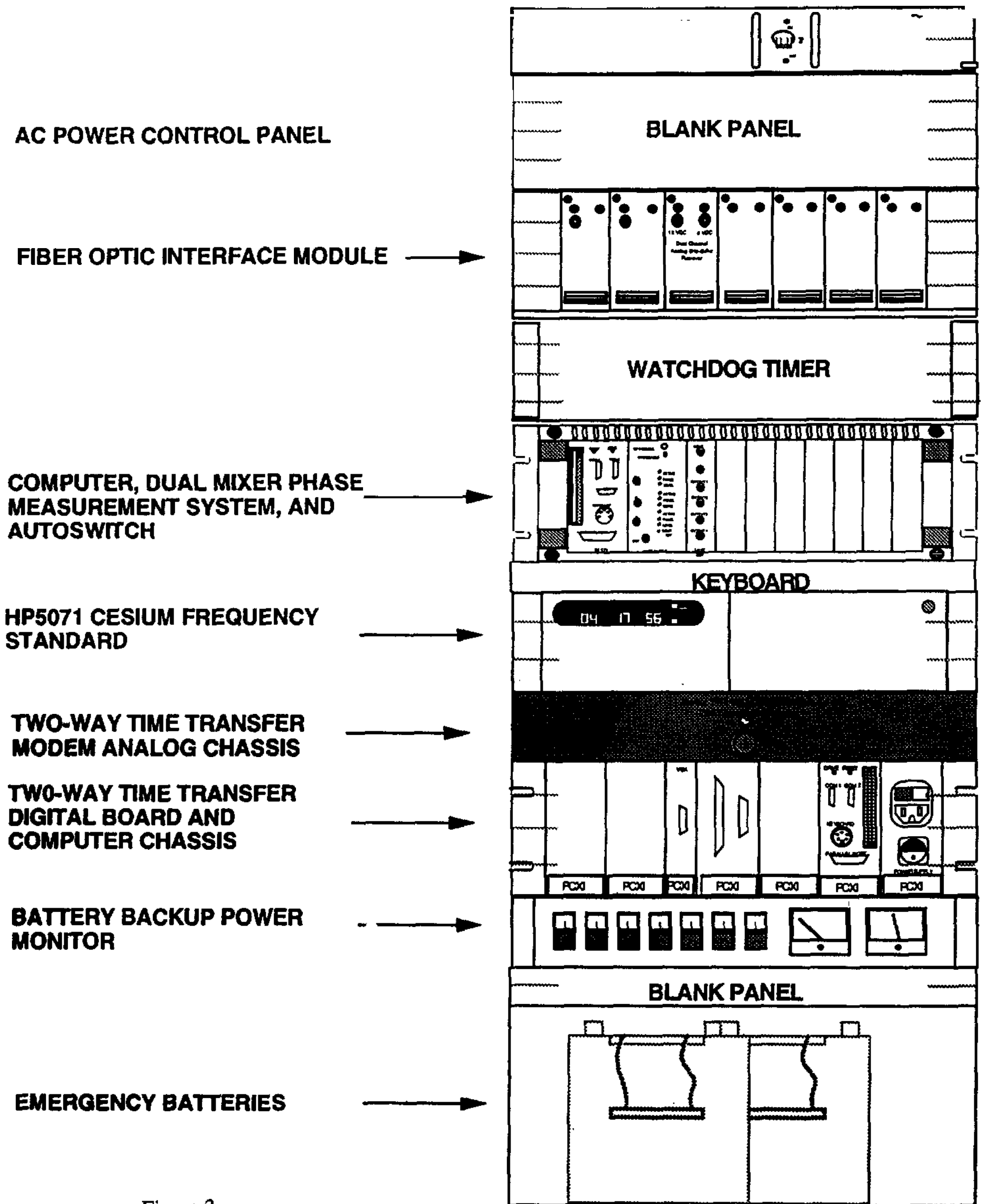

AC POWER CONTROL PANEL
BLANK PANEL
FIBER OPTIC INTERFACE MODULE
WATCHDOG TIMER
COMPUTER, DUAL MIXER PHASE MEASUREMENT SYSTEM, AND AUTOSWITCH
KEYBOARD
HP5071 CESIUM FREQUENCY STANDARD
04 17 56
TWO-WAY TIME TRANSFER MODEM ANALOG CHASSIS
TW0-WAY TIME TRANSFER DIGITAL BOARD AND COMPUTER CHASSIS
PCXI
PCXI
PCXI
PCXI
PCXI
PCXI
PCXI
BATTERY BACKUP POWER MONITOR
BLANK PANEL
EMERGENCY BATTERIES

Figure 3

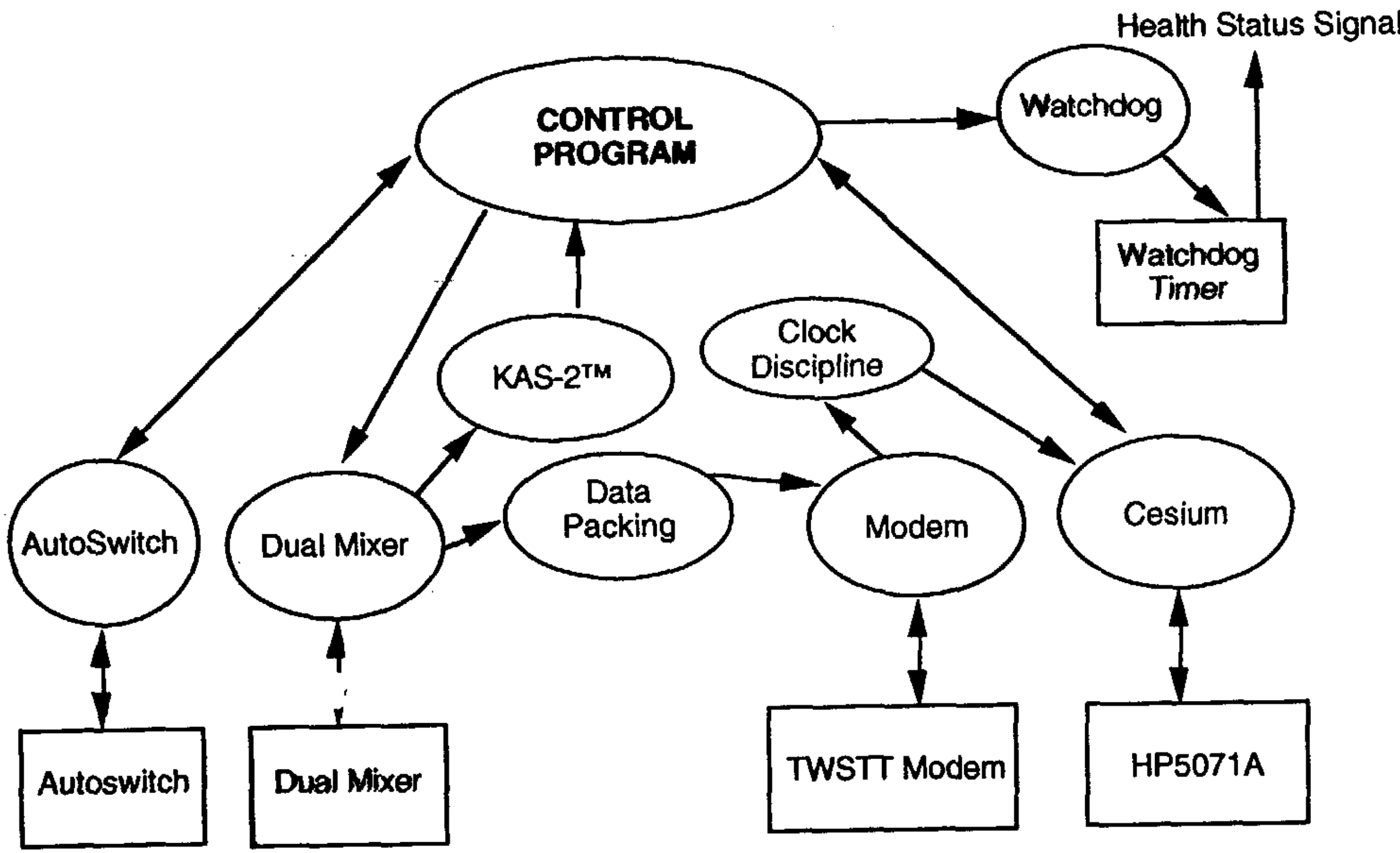

Health Status Signal
CONTROL PROGRAM
Watchdog
Watchdog Timer
KAS-2™
Clock Discipline
Data Packing
AutoSwitch
Dual Mixer
Modem
Cesium
Autoswitch
Dual Mixer
TWSTT Modem
HP5071A

Figure 4

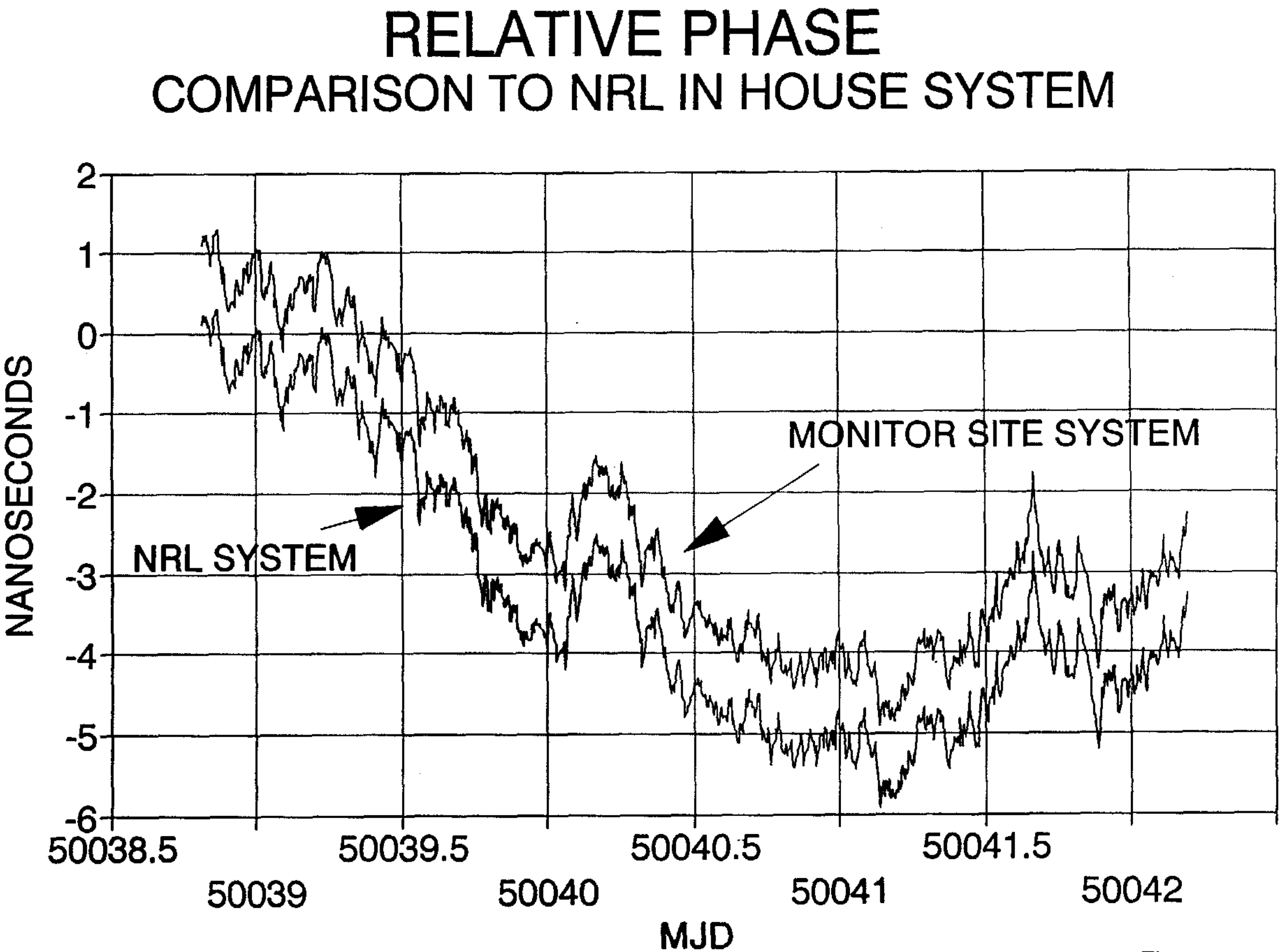
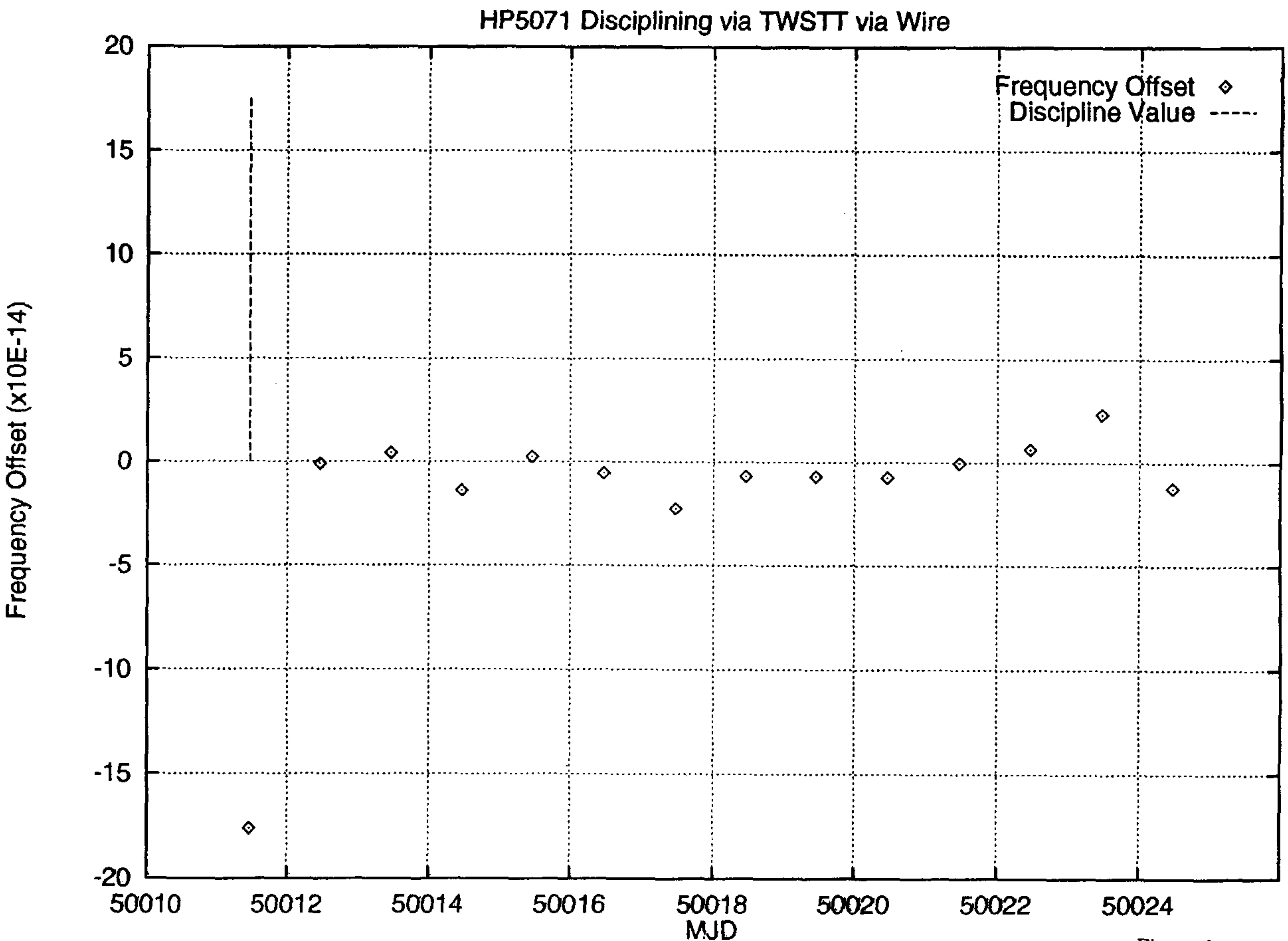
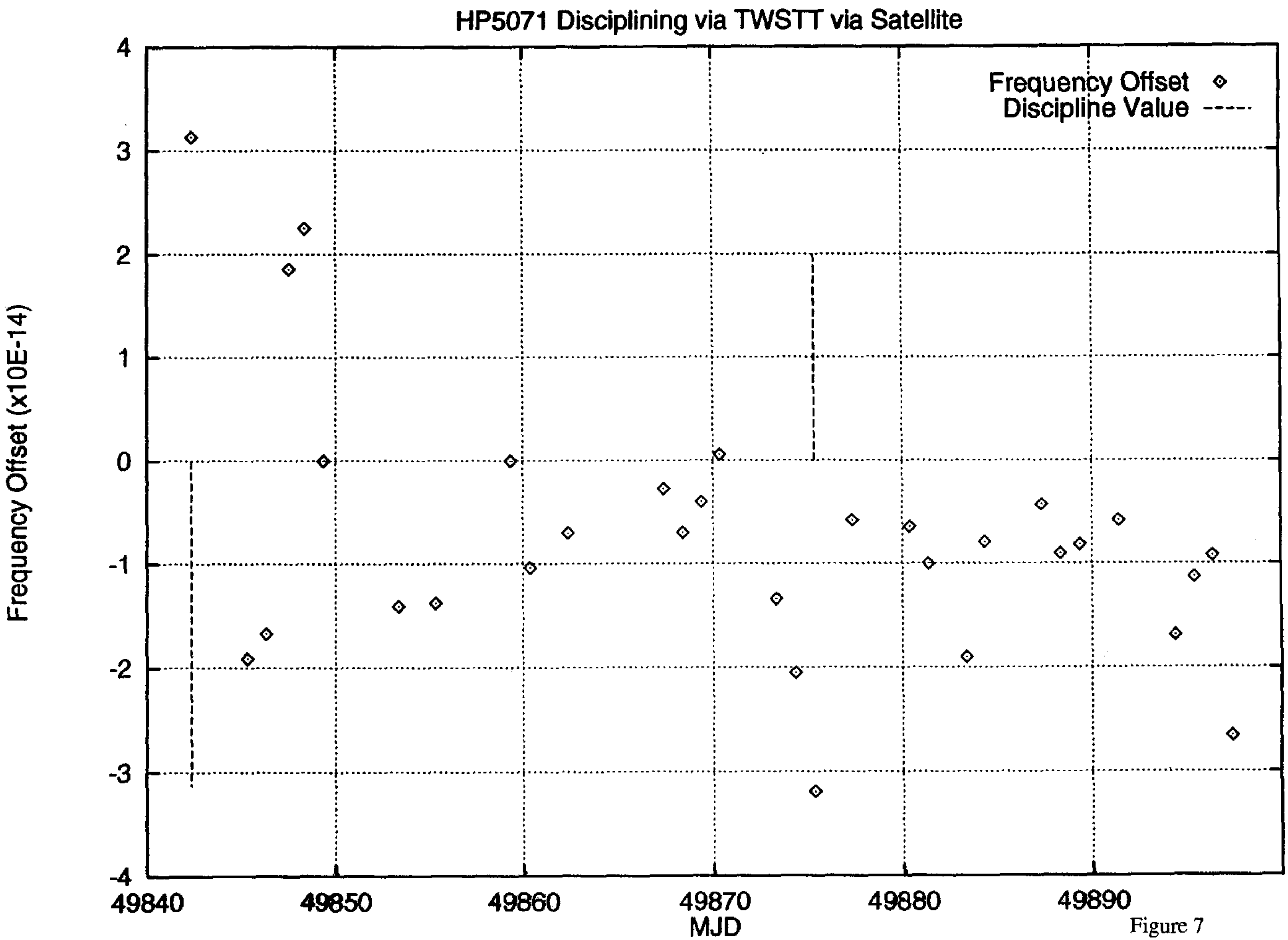

RELATIVE PHASE
COMPARISON TO NRL IN HOUSE SYSTEM
NANOSECONDS
2
1
0
-1
-2
-3
-4
-5
-6
50038.5
50039
50039.5
50040
50040.5
50041
50041.5
50042
MJD
MONITOR SITE SYSTEM
NRL SYSTEM

Figure 5



HP5071 Disciplining via TWSTT via Wire
Frequency Offset
Discipline Value
Frequency Offset (x10E-14)
MJD
20
15
10
5
0
-5
-10
-15
-20
50010
50012
50014
50016
50018
50020
50022
50024

Figure 6



HP5071 Disciplining via TWSTT via Satellite
Frequency Offset
Discipline Value
Frequency Offset (x10E-14)
MJD
4
3
2
1
0
-1
-2
-3
-4
49840
49850
49860
49870
49880
49890

Figure 7

Questions and Answers

CAPT. STEVEN T. HUTSELL (USAF): If my understanding of the proposal is current, the recalculation of the disciplining commands is going to be done once per day. Is that correct or is that current to your understanding?

DWIN CRAIG (NRL): There will be calculations going on after every time transfer.

CAPT. STEVEN HUTSELL (USAF): And is that going to be done once a day still?

DWIN CRAIG (NRL): My understanding is now for the operational deployment it should be a daily transfer.

CAPT. STEVEN HUTSELL (USAF): Because operationally one could make a safe argument that it would be disadvantageous to even do disciplining at all, and the reason for that is very simple. Disciplining, using a sampling of once per day, as far as we're concerned operationally, though it may improve the long-term stability of the frequency standard or the timing system at the monitor station, that's based on a sacrifice in the short term. By "short term" I mean that tau equal to or less than one day.

The real problem in this is currently MSTSE does not have any means to electronically notify the GPS composite clock that there are transients, if you will, being introduced that are completely independent of the natural noise that's occurring for that particular day. In other words, it's based off of information from previous days. I think one could make a safe argument that it would benefit us maybe not to consider disciplining the MSTSE.

In spite of that, we're very interested in the prospects of this. If we can have 5071s along with this ensemble algorithm at all of our sites, that would greatly benefit us. I'd like your comments on that.

DWIN CRAIG (NRL): Well, there are a lot of things that you could envision using this technology after it's been deployed. I personally look at it as an investment in infrastructure. And you're correct, a lot of your comments are correct. There have been some safeguards written into the software that performs the disciplining.

There's a gentleman here named Bill Reid who would be a good person to talk to concerning that. I did not write the disciplining algorithm, and that's why I don't think it's appropriate for me to go into depth.

DR. GERNOT WINKLER (USNO, RETIRED): I would like to make a comment to that. Look at Paper 21, which will begin tomorrow afternoon. The concern expressed by the question about degrading the stability of the local standard, it's just a question of how the servo loop is designed. You can completely avoid that if your main concern is the long-term correction. I would suggest looking at that after Paper 21 is given.

DWIN CRAIG (NRL): You're absolutely correct, Dr. Winkler. There's no debate about that at all. You're absolutely correct. Those things were taken into consideration. But again, I'm not the expert in depth on that particular algorithm.

I hope that I didn't leave anyone with the impression that there was going to be a discipline sent to the clock on a very regular basis. If I did, I apologize. That's not the way the system operates.

CAPT. STEVEN HUTSELL (USAF): When we're talking about short-term versus long-term stability, it's important to point out that long-term stability is nice, but our primary concern is what I call "short-term stability," tau equals one day or less. The reason for that is because we update the navigation message in all of our satellites normally, as often as once per day or more. We're concerned about the predictability up to tau equals one day.

Yes, long-term stability is nice, but if we're making a sacrifice to short-term stability to maintain that, we could argue that well, it's maybe not as important as we'd like to think.

DWIN CRAIG (NRL): I agree with you, Sir. And I think one feature of the system that could actually contribute to helping you at the MCS would be the fact that you get the daily phase measurement data back, independent of the system as it exists now. That will provide you a second data source, sort of a sanity check on how the system is performing on a day-to-day basis.