CLOCK MANAGEMENT DATA ANALYSIS FOR SATELLITE COMMUNICATIONS

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***Abstract*— The U.S. Naval Research Laboratory has installed GPS-based timing systems in several Defense Satellite Communication System (DSCS-III) satellite communication facilities to support the Single Channel Transponder (SCT) program. The goal of these systems was to manage the satellite crystal oscillators to 25 microsecond accuracy and ground cesium clocks to 5 microsecond accuracy. A Windows-compatible computer program was written to facilitate the clock management of these oscillators. This paper will describe these systems, as well as give detailed data analysis of the time management for the satellite oscillators.**

I. INTRODUCTION

The Daymark Clock Management system is a hardware and software compilation developed by the U.S. Naval Research Laboratory (NRL) for the Air Force Space and Missile Systems Center to manage timing of the Single Channel Transponder (SCT) satellite communications system residing on the DSCS-III satellites. Because the SCT is a frequency hopping system, timing is critical. The SCT Injection System (SCTIS) on the ground must provide signals with the frequency hopped exactly at the expected times. In addition, the satellite must receive the signals exactly at the expected times; otherwise, communications with the satellite fail.

Accurate site timing allows for robust operation of the SCT independent of time checking via the satellite beacon signal. Accordingly, the controller sites must manage the onboard Satellite Time Generator (STG) time accuracy via an internal crystal oscillator and the sites' own cesium clock time accuracy. Maintaining STG time accuracy requires small frequency adjustments made to the satellite oscillator to account for the drifting oscillator frequency. These small frequency adjustments do not cause a communications loss. However, time adjustments or large frequency adjustments could disrupt communications, jolting a user off the satellite system due to a sudden inability to follow the time intervals of the frequency hopping. The cesium clock accuracy is maintained through microsecond time adjustments and small frequency adjustments. For accurate time, all oscillators are compared to a common reference to all users, such as GPS.

The goal of the Daymark system is to provide the means of keeping an accurate, stable, reliable, and survivable local time and frequency reference for user systems. To meet the accuracy requirements, the system has a nominal system error budget of 25 microseconds from Universal Coordinated Time as determined by the U.S. Naval Observatory UTC(USNO) [1], to be shared by the satellite's STG and the cesium frequency standard at the ground SCTIS terminal sites.

Over the past several years, the supporting contractor from L-3 Titan has traveled to all supported sites several times installing new system software and holding many training sessions during all work shifts to make sure site operators are properly informed in utilizing Daymark. In addition, all data recorded is emailed to NRL and Titan at the beginning of each month. If any problems are found, the site is contacted and solutions are determined. There have been many problems with operator turnover, because Army and Air Force personnel at the sites change out so frequently. Therefore, it has been difficult to keep trained personnel onsite and using the software continuously. To resolve this problem, over the past year the STG data has been analyzed to determine the percentage of time each oscillator spends outside of the error limits, then sent to every STG site for comparison purposes. By publishing a single report of all STG error percentages, each site can see how its results compare to other sites.

At PTTI 2002, the initial system and new computer program design were presented [2]. In the following sections, we will display two different groups of data analysis from the upgraded system, one extending from July 2000 through July 2004, and a follow-up extending from July 2004 through July 2005.

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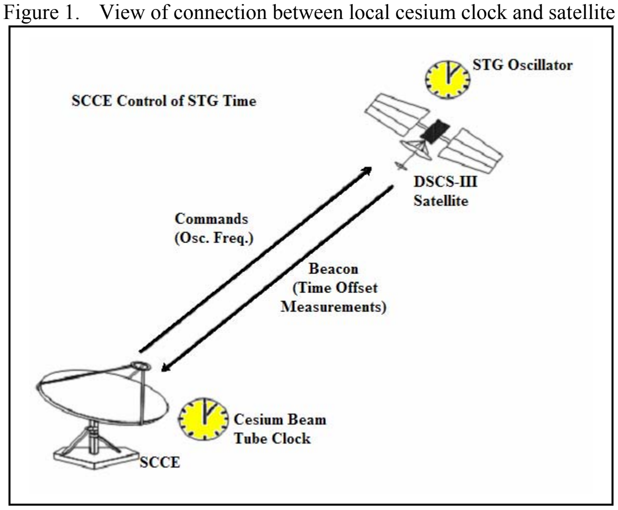
II. SITE OSCILLATORS

The SCT system (Figure 1) is comprised of two main timing elements kept within an error budget of 25 microseconds. The ground terminal cesium clocks are used as the timing references for the entire site. In addition, the STG oscillator on the satellite is responsible for communication.

Figure 1. View of connection between local cesium clock and satellite oscillator.



A. Terminal Cesium Clocks

As the timing reference for the entire site, cesium beam tube atomic clocks are the more stable of the two oscillators, even when not routinely managed. When the system was originally installed, the main cesium clock implemented at the various sites was the Hewlett Packard HP5061(A and B). Though the frequency stability is a part in 10^{-13}, this clock is difficult to frequency adjust. In the last few years, these clocks are slowly being replaced by HP5071's. The frequency stability for these clocks has approached a part in 10^{-14}, with a more user-friendly interface. At the sites, the clocks can generally now go for 6 – 12 months without needing a frequency adjustment.

B. STG Oscillators

The DSCS-III STG is driven by a high quality, space-qualified quartz crystal oscillator with a good temperature coefficient and a low frequency drift rate on the order of less than 1×10^{-11} per day. The oscillator is capable of remote frequency adjustments through a D/A converter. Four-digit (12 bit) frequency "words" are sent to the satellite, which the D/A converter converts into voltages used to adjust the oscillator frequency. However, due to the implementation of the voltage controlled oscillator, the relationship between the frequency words and the voltage adjustment is nonlinear.

Time-of-day is adjusted in the STG, independent of the oscillator. Normally, the time is only adjusted when a leap second is implemented, because a time offset jump can easily cause communication problems for users of the satellite system and other sites. Instead, STG time offsets are improved by adjusting the frequency. By keeping control of the frequency drift, the STG time can stay within the specified error bounds much longer. When properly adjusted, the STG may stay in the error bound of +/- 25 microseconds for over a month.

III. CLOCK MANAGEMENT SYSTEM

A. Introduction

Before the Daymark system was developed, the terminal cesium clocks were supported by USNO directly, with the STG oscillators referenced to the cesium clocks. In 1996, when the USNO support for DSCS site timing ended, NRL was sponsored to create a new clock management system. To keep site timing accurate, NRL developed the Daymark system and software, which compares the oscillators against a commonly accessible reference. For a time reference, the system uses the USNO-derived UTC Master Clock via GPS. The cesium clock time offset compared to UTC(USNO) is measured daily and sustains an accuracy of better than 0.1 microseconds monthly. When managed, the STG time offset measured three times a day sustains an accuracy of 1 microsecond daily.

The Daymark system aims to keep the system oscillator time within the specified error budget for as long as possible, reducing the reliance on GPS. To accomplish this, NRL installed measuring equipment at most SCTIS field sites. Using this equipment, time offset measurements from UTC(USNO) are taken regularly. The Daymark Clock Management software proposes time and frequency adjustments for the cesium clocks and frequency adjustments for the STG oscillator necessary to keep the time-offsets within their respective error limits for as long as possible (generally, at least a few months). The official message from the Defense Satellite Communications System (DSCS) Network Manager requiring the Daymark system to be used was distributed DTG 292143Z MAR 99.

B. Original Site Equipment

The Daymark system was built around the timing of several key pieces of equipment currently present at all SCTIS-enabled facilities. High-resolution site timing for each site is maintained via one pulse per second (1PPS) signals from the primary local cesium clock. The accurate standard frequencies provided by the local cesium clock are used for all site systems and measuring equipment needing occasional time and frequency adjustments. At each site, there are two local cesium clocks, an active and a backup. A Disciplined Frequency Standard (DFS) chooses which clock to use as the active clock, then adjusts its internal oscillator accordingly, distributing needed frequencies to the site. If the active clock fails, the backup cesium clock takes over.

C. Equipment Modifications

Figure 2 illustrates the original site equipment plus the modifications made by NRL for the Daymark system.

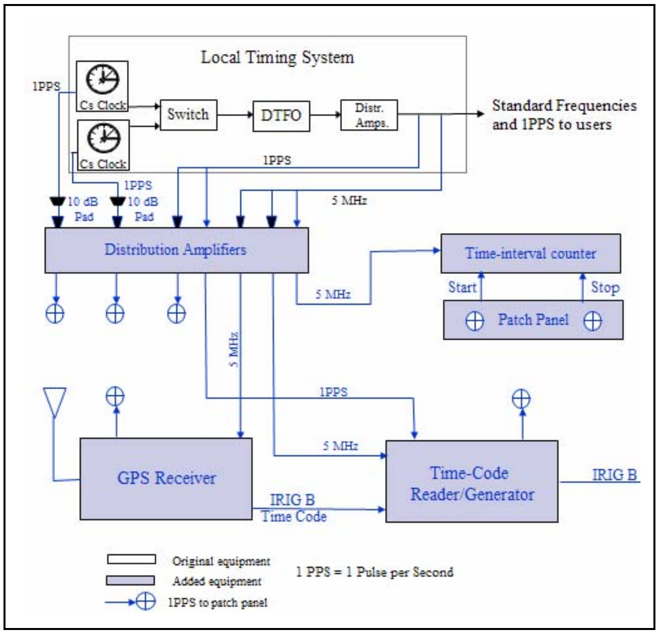


Figure 2. Equipment modifications made to the local timing system.

To implement the Daymark system, NRL installed a set of time measuring equipment at each site. First of all, to provide an interface between the original and added site equipment, a distribution amplifier was provided, so that a failure in NRL's equipment would not interfere with ongoing site operations. A GPS receiver and antenna with a fiber optic cable were installed to supply the system with a highly accurate 1PPS UTC(USNO) reference available anywhere in the world. A time interval counter was also added, to compare the signal from a particular oscillator with this reference signal from the GPS receiver. Subtracting the time of the oscillator signal from the reference with a 1PPS signal gives us a time offset. The slope of these time offsets taken over time is the frequency offset. By looking at how this changes over time, we can determine the best frequency changes to command to the oscillator.

NRL also included system components to better adapt to the site configuration. When a leap second is decided upon, GPS implements it immediately, but the Defense Information Systems Agency (DISA) sometimes does not. If an operator sees this one second offset in the clock oscillators, they may be tempted to adjust their oscillators, causing a large time jump for their entire system. This large time jump can cause communication loss for the site. Therefore, a time code generator initially set on time with the GPS receiver maintains time with distributed 5 MHz and 1PPS and holds time when a leap second occurs, until DISA implements it. One other problem the sites have is setting time accurately on different devices around the equipment racks. A remote time display supplies time of day at other local equipment with a 5 MHz signal from the GPS receiver through the distribution amplifier, so the time may be set with greater precision.

This equipment is user managed instead of computer controlled. Measurements are logged by hand on paper, and the user must manually switch between viewing particular oscillators' time errors. This was originally done to make sure users knew the offset of the clock at all times. In the future, it would be more beneficial to provide a computer system that automates these measurements.

D. Daymark Clock Management Software

The Daymark Clock Management software provides a straightforward method of adjusting the frequency and time of the site oscillators as minimally as possible, based on time offset measurements from the hardware. A separate log file with date, time, and time offset entries may be created for each oscillator present in the system. Each oscillator also has a separate log of all time and frequency changes made to the oscillator during the range of data logging. For the STG oscillator, this log also includes parameters characterizing the D/A converter non-linearities: a voltage regulation factor and a Hertz per count factor, where a count is a +/- 1 change in the 4-digit frequency word commanded to the satellite to define the current satellite oscillator frequency. The Daymark program has the capability of determining these parameters, by looking at the results of weak and strong frequency changes commanded to the satellite. This characterization is done for each STG when the site takes control of it, plus should be done every few years hence. With these log files, Daymark provides modeling of the oscillator time offsets. The STG has a parabolic curve fit to its time offset data due to the satellite crystal oscillator frequency drift rate. The local cesium clock has a linear line fit to its time offset data because its frequency drift rate may be considered negligible. Based on these models, Daymark provides a prediction of necessary frequency adjustments to the STG in the form of the number of counts that the frequency word commanded to the satellite must change, and a prediction of the necessary time and frequency adjustments to the cesium clock.

The operation of the measurement-taking system is fairly straightforward. Measurements of an oscillator's time-offset from UTC (USNO) are taken at regular intervals and logged (three times daily for the STG, daily for the cesium clocks). If a time or frequency adjustment has been made, that too is recorded in the appropriate log. Manual data entry into the program is performed daily for the STG and monthly for cesium clocks. After the program is started, the operator may call up the desired oscillator's data file. The program then displays the data plus a model of the clock's performance over a specified period of time. The operator may enter new data from the log and save the new data to the open file. Time and frequency adjustments are entered and saved in the current satellite's change file. Finally, the operator may enter a proposed data and time for an oscillator adjustment. Daymark advises on the frequency (and time adjustments for cesium clocks) adjustments to make at the specified time. For the STG, the program can also predict the best date, time, and frequency change for the oscillator.

This process may be repeated for all cesium clocks or STGs present in the system.

Due to an extension in the lifetime of the SCTIS mission, modifications to the system components have become necessary. To improve our user interface, we have upgraded the system software and documentation for a faster, more intuitive program. The system documentation has been turned into step-by-step graphical walkthroughs for most aspects of program operation. In addition, we have included searchable help file entries that are accessible during normal program operation, so the documentation no longer strikes the users as intimidating. The program itself was upgraded from the original DOS version to a Windows version in 2002. Since most new users are more comfortable with graphical user interfaces, the DOS-based approach was no longer adequate. In addition, the DOS version was not compatible with Windows XP or Windows 2000. By solving these issues, we have had a great deal more success convincing users to continuously use our system.

In the future, we have several more upgrades we would like to make to the system, due to the overwhelming success of our current improvements. As mentioned earlier, we would like to automate our data-taking schema. This would involve changing our hardware to devices controllable by GPIB or RS-232 interfaces, and updating the software to provide active control as opposed to passive computation. The system will never be allowed to change the oscillators' time and frequency itself; this will always be the operator's job, due to the need to oversee the critical nature of timing in the oscillators.

IV. Data Analysis

The data collected and stored by the operators of the Daymark system reveals much about the health of the SCTIS system. Many supervisory boards are extremely interested in the clock management involved in this system; therefore, the final analysis of the present and future performance of each oscillator is very important. To this end, we have recently begun showing STG site managers comparisons of their oscillator performance versus other sites performance. This has been one of the most motivational approaches to convincing site personnel to continuously use the Daymark system. Previously, we reported the amount of time their systems were out of the acceptable range. Now, we give each site a comparative score. Thus, when compared with all other STG operator sites in front of higher-up personnel, sites are much more motivated to improve their performance.

A. First Data Analysis: July 2000 through July 2004

In July, all available data for the previous four years from each satellite was compiled for supervisory boards. The number of times and percentage of time each satellite had gone outside of the +/- 25 microsecond error bounds was calculated, in the maximum length interval with available data. Each site in control of an STG was given a comparable score, to highlight good and bad practices and mark improvement.

The following table gives a summary of these results. Percentages are considered acceptable when less than 7% for the given period. Unacceptable percentages are where the oscillator was out of tolerance for more than 30% of the time. Further results can also be seen by viewing the graphs of satellite time offsets compiled for each site (Figs. 4-7).

TABLE I. First Data Analysis

Site	Sat. #	# Times Out of Error Bounds	Percentage Out of Error Bound	Length of Interval
Buckner	0712	15 times	23.18%	101.40 days
	1708	110 times	11.30%	702.90 days
Detrick	3676	63 times	30.22%	274.83 days
	4487	99 times	25.78%	394.00 days
	7314	15 times	6.09%	239.02 days
Landstuhl	7314	13 times	3.23%	46.74 days
	9940	14 times	26.09%	46.69 days
Meade	4524	176 times	30.70%	451.38 days
	1172	167 times	33.13%	789.17 days
	0712	4 times	0.14%	33.66 days
	7314	106 times	36.76%	390.84 days
Roberts	1708	46 times	2.17%	283.88 days
	2413	29 times	6.34%	281.32 days

STG Oscillator Analysis, July 2000 through July 2004

Looking at the table, we can clearly see that the Roberts site has by far been taking the best care of their oscillators, with around 5% error in two/thirds of a year. By the same token, the Meade site needs the most improvement, with over 30% error in three satellites. Overall, more than half of the satellites had been out of bounds over 25% of their control period, suggesting that the system was not being used efficiently. For the next year, we increased the number of site visits and training time, plus began sending out quarterly reports containing updated error percentages.

B. Yearly Update Analysis: July 2004 through July 2005

In July 2005, we produced a compilation of each site's progress over the prior year. Table II summarizes the percentages calculated, as well as indicates whether the percentage increased or decreased from the last report.

TABLE II. Second Data Analysis

Site	Sat. #	# Times Out of Error Bounds	% Out of Error Bound		Length of Interval
Buckner	0712	32 times	2.12%	↓	364.93 days
	1708	14 times	7.37%	↓	79.83 days
Detrick	3676	31 times	1.83%	↓	364.83 days
	4487	31 times	4.59%	↓	273.83 days
	2413	50 times	4.73%		341.33 days

Landstuhl	9940	44 times	12.71%	↓	364.98 days
Meade	1172	44 times	4.83%	↓	364.81 days
Roberts	1708	34 times	3.11%	↑	262.50 days
	2413	43 times	3.99%	↓	364.83 days

STG Oscillatory Analysis, July 2004 through July 2005

Between 2004 and 2005, with our renewed training efforts and reports detailing site activities to supervisory committees, we have seen percentages outside of error bounds drop drastically from 25% to under 5%. The number of times outside of the error bounds for each STG still seems high; however, most of these occurrences are one-time-only or very short. Therefore, they are not particularly worrisome. In the past several months, we have had continuing problems with sites delaying their sending of data. With more oversight, even the 5% errors can be dropped to a range more within the capabilities of these oscillators. Figs. 4-7 show each STG's readings for each time period.

V. CONCLUSION

By alerting the proper personnel to site deficiencies, installing the new Windows software at all sites, and training the majority of site operators possible, we have solved a great deal of our clock management problems identified in the previous paper [2].

In the near future, we have several upgrades we would like to make to the Daymark Clock Management system. We believe one of the most beneficial additions would be automating data collection to avoid delay in adding new points to the models. This would keep the clocks from going out of bounds as often, plus would help in the training necessary for the high level of turn over at the involved sites.

This improvement would involve several new pieces of hardware capable of interfacing through GPIB or RS232, plus a program revision to handle automation procedures. Our current goal is to acquire funding for this venture as soon as possible.

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[2] R. Evans and J. White, 2003, "Time of Day Management for Satellite Communications," Proceedings for PTTI '02, December 2002, Reston, VA, USA.

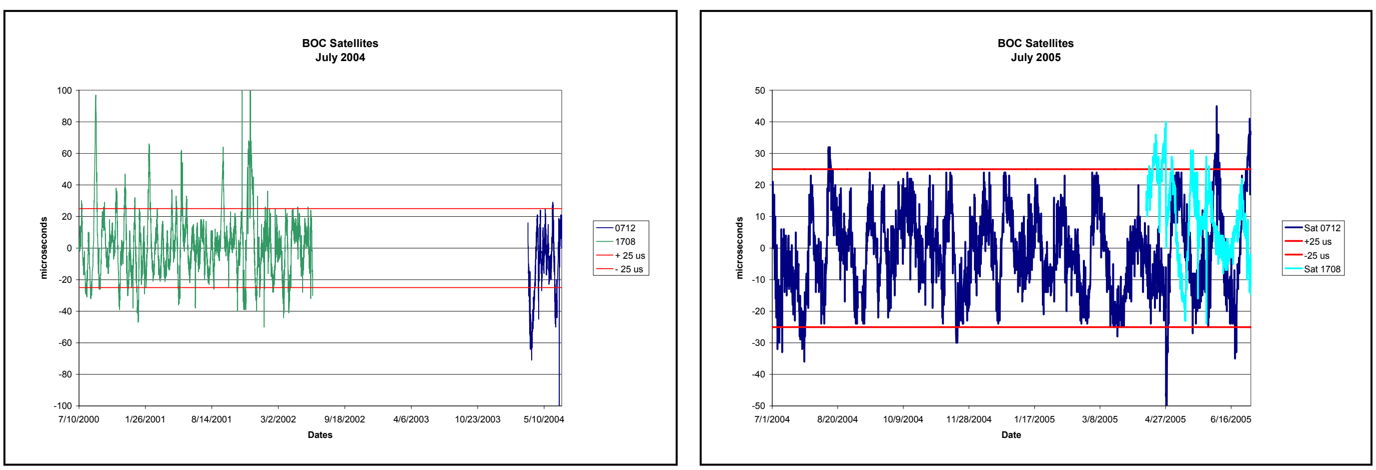

Figure 3. Buckner STGs, July 2004 versus July 2005

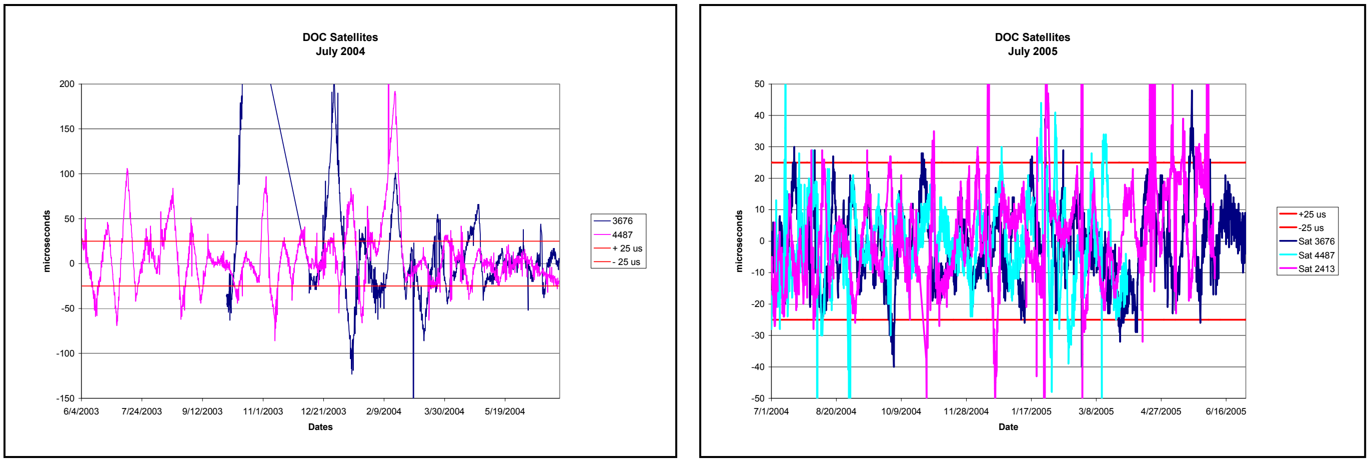

Figure 4. Detrick STGs, July 2004 versus July 2005

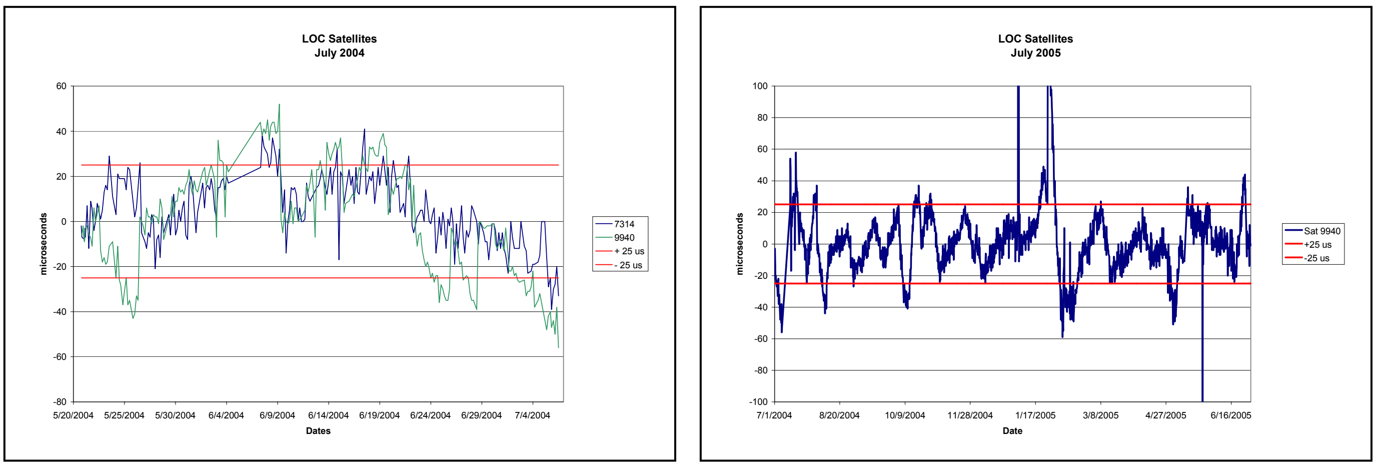

Figure 5. Landstuhl STGs, July 2004 versus July 2005

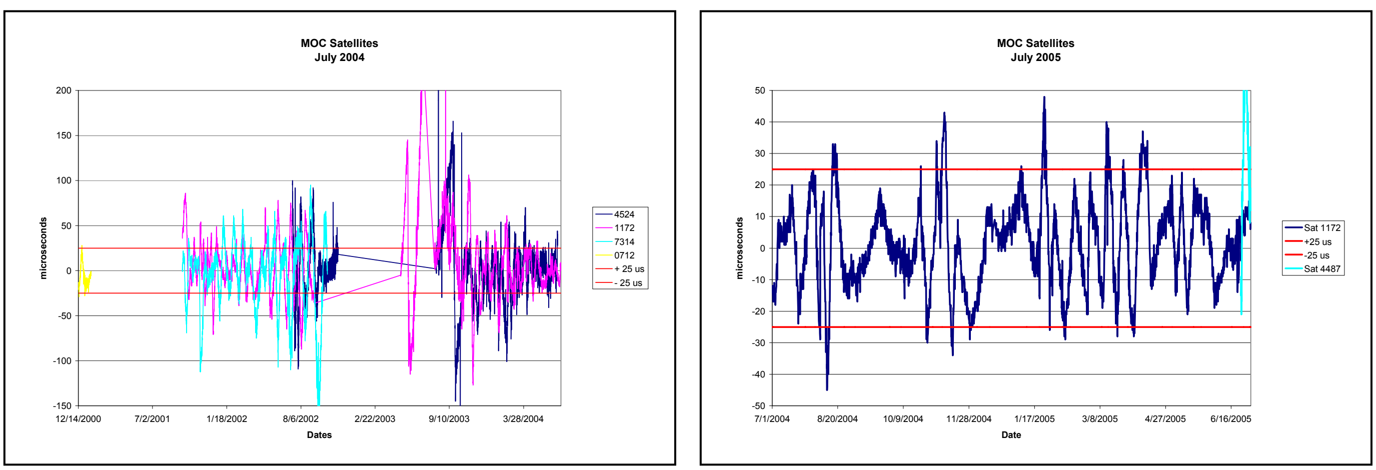

Figure 6. Meade STGs, July 2004 versus July 2005

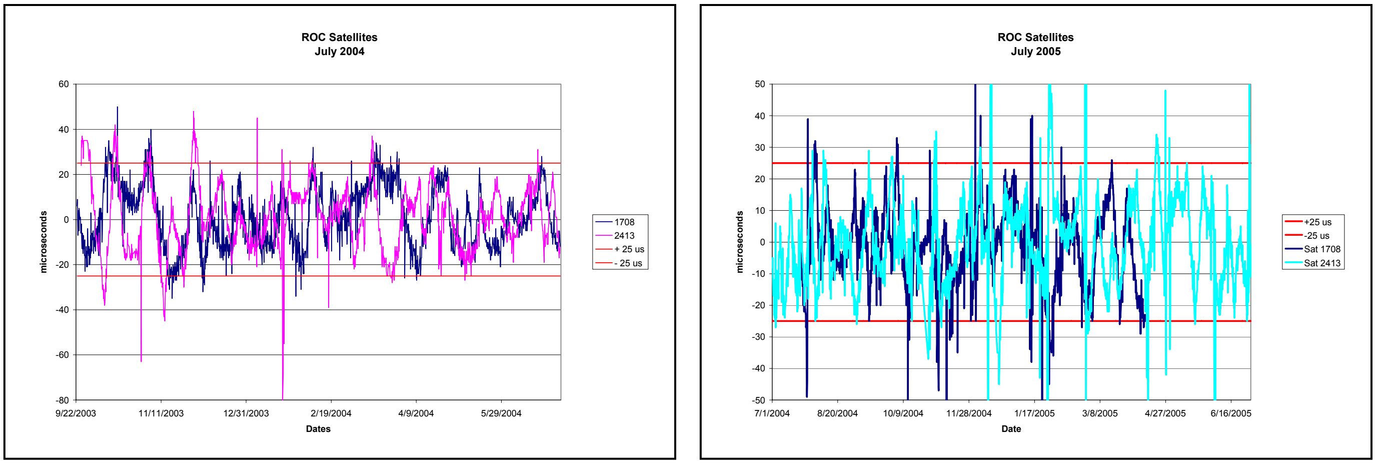

Figure 7. Roberts STGs, July 2004 versus July 2005