On-Board Spacecraft Time-Keeping
Mission System Design and Verification

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ABSTRACT

Spacecraft on-board time keeping, to an accuracy better than 1 millisecond, is a requirement for many satellite missions. Scientific satellites must precisely "time tag" their data to allow it to be correlated with data produced by a network of ground and space based observatories. Multiple vehicle satellite missions, and satellite networks, sometimes require several spacecraft to execute tasks in time phased fashion with respect to absolute time. In all cases, mission systems designed to provide a high accuracy on-board clock must necessarily include mechanisms for the determination and correction of spacecraft clock error. In addition, an approach to on-orbit verification of these mechanisms may be required. Achieving this accuracy however need not introduce significant mission cost if the task of maintaining this accuracy is appropriately distributed across both the space and ground mission segments.

This paper presents the mission systems approaches taken by two spacecraft programs to provide high accuracy on-board spacecraft clocks at minimum cost. The first, NASA Goddard Space Flight Center's (GSFC) Extreme Ultraviolet Explorer (EUVE) program demonstrated the ability to use the NASA Tracking and Data Relay Satellite System (TDRSS) mission environment to maintain an on-board spacecraft clock to within 100 microseconds of Naval Observatory Standard (NOS) Time. The second approach utilizes an on-board spacecraft Global Positioning System (GPS) receiver as a time reference for spacecraft clock tracking which is facilitated through the use of Fairchild's Telemetry and Command Processor (TCP) spacecraft Command & Data Handling Subsystem Unit. This approach was designed for a future Shuttle mission requiring the precise coordination of events among multiple space-vehicles.

KEY WORDS

Spacecraft Clock, On-Board Processor, Exterme Ultraviolet Explorer, GPS, Telemetry and Command Processor.

INTRODUCTION

The EUVE satellite, launched in June of 1992, contains an on-board spacecraft clock which is maintained by ground operators using data produced by the NASA/TDRSS mission system. This overall time keeping approach is not new and is also used by GSFC's Upper Atmosphere Research Satellite (UARS) launched in 1991. EUVE's time accuracy requirements were however more stringent than UARS which required a more in-depth clock analysis and verification process. As EUVE's prime spacecraft contractor to GSFC, Fairchild was involved with the satellite's design, manufacture, verification, and in-orbit check-out; including the task of providing a spacecraft clock with verified on-orbit accuracy.

This paper describes the design and verification of the EUVE spacecraft clock and mission time keeping system, including details on how the EUVE project:

a. Uses a simple software based on-board spacecraft clock, and

b. Performed end-to-end verification of the mission level time keeping system as a part of spacecraft test and in-orbit check-out, and

c. Found that spacecraft clock error with respect to ground reference time can be determined/set to within a few tens of microseconds using existing NASA/TDRSS systems, and

d. Demonstrated that the spacecraft clock can be maintained to 100 microsecond accuracy with a reasonable maintenance interval, and

e. Developed an approach for on-orbit clock error measurement which obtains the best possible accuracy using existing NASA/TDRSS mission systems.

This paper will also describe a GPS based approach to spacecraft clock implementation and time keeping. This conceptual system, developed by Fairchild for a future mission, uses a software based clock similar to EUVE, implemented in the spacecraft's computer where it will be periodically compared against accurate "time-stamps" provided by an on-board GPS Receiver. Clock error data from this comparison will be included in spacecraft telemetry and will provide all the information that is required for spacecraft clock maintenance.

Although the GPS based design requires additional spacecraft complexity as compared to the EUVE approach, it significantly reduces the complexity of the mission level time-keeping system and offers the potential for an order of magnitude improvement in clock accuracy. Therefore, this approach will no doubt become more widely used as it is expected that GPS Receivers will be employed by many future spacecraft in support of other functions (orbit determination, navigation, and potentially attitude control).

Both systems rely on low complexity spacecraft hardware and software and simple ground system software. Therefore, these approaches (or hybrid versions) represent viable approaches to onboard time keeping for a variety of future satellites, both large and small.

EUVE SPACECRAFT CLOCK MISSION SYSTEM OVERVIEW

In order to allow scientists to precisely understand when scientific data has been captured by satellite sensors, the EUVE satellite employs an on-board spacecraft clock. This clock is used to "time-stamp" satellite data with Universal Coordinated Time (UTC) prior to it's downlink to the ground. EUVE's mission requirement on data collection time knowledge was established as 1 millisecond. However, the process used on this project to verify and maintain on-orbit spacecraft clock accuracy demonstrated the ability to measure and maintain spacecraft clock time to within 100 microseconds of UTC by integrating various features of the existing TDRSS/NASA mission system.

The EUVE satellite employs a "free-running" clock which is managed by ground controllers to assure that it keeps accurate time with respect to UTC. Ground controllers monitor spacecraft clock error and periodically issue "time adjustment" commands to the spacecraft's clock in order to keep the clock within specified error bounds. Clock error is determined using telemetry "time of arrival" data produced by the TDRSS ground system along with spacecraft tracking (range) data produced by the combined NASA/TDRSS system. Operationally, the only "tool" required to maintain this clock is a ground software algorithm which computes spacecraft clock error, following each spacecraft contact via TDRSS from the available information. This algorithm determines clock error by computing the UTCs at which telemetered spacecraft clock data values were generated on-board the spacecraft and comparing them to the actual time of arrival of the telemetry.

A key feature of the EUVE satellite design with respect to time-keeping is that onboard data acquisition, software processing, and telemetry downlink data are synchronous. As a result, a well defined time relationship exists between any arbitrary reference point in the spacecraft's downlink telemetry stream and onboard events such as data acquisition, and software task execution. Therefore, by knowing what time an arbitrary reference point in a downlink telemetry frame is received on the ground as well as the range delay to the satellite, the on-board clock error can be determined with respect to ground time reference (UTC). This facilitates accurate correlation of onboard event time with ground reference time, both during ground test and in orbit.

During ground test, EUVE's clock error was easily "measured" against a local UTC reference using hardware pulses produced by the spacecraft having a fixed relationship with the spacecraft clock. Determining orbiting satellite clock error with high precision is a bit more challenging. The NASA/TDRSS environment in which EUVE operates is an extremely complex system effectively integrating many organizations in order to provide for precision satellite mission operations. Within this system, however exist all of the elements necessary to measure the difference between on-board spacecraft time and ground reference time. The basic elements needed for this task, although a part of a complex system in the EUVE case, are not themselves complicated and could be provided for any spacecraft mission at reasonable cost.

Figure 1 presents a block diagram depicting the major elements involved in the EUVE mission time keeping system. Satellite control and monitoring is performed from the EUVE Project Operations Control Center (POCC) at the Goddard Space Flight Center (GSFC). The POCC is run by the EUVE Flight Operations Team which shares ground system, computing, and support organization resources with several other satellite POCCs. Radio communications with the satellite are done through the TDRSS via the NASA Ground Terminal (NGT) located at the White Sands Ground Terminal (WSGT). It is at this point where the raw data required for spacecraft clock error determination is formed. After telemetry data has been recovered from the RF downlink signal it is time-stamped with UTC before being sent to the EUVE POCC. In addition, RF and telemetry data processing equipment delays up to this point are also reported to the POCC to facilitate determining the time at which the telemetry actually arrived at the ground station's antenna. TDRSS also provides spacecraft tracking (range) data which allows for the determination of the RF path delay between the spacecraft telemetry antenna and the WSGT antenna as a function of time. This data is provided to the POCC via the GSFC Flight Dynamics Facility.

Satellite telemetry and ground generated data are passed from WSGT/NGT to the EUVE POCC via the NASA Communications Network (NASCOM). Note that this data transmission path has no effect on the ability to determine spacecraft clock error since it is after the point where telemetry is time-stamped. Clock error is determined at the POCC in the Telemetry And Command Processor (TAC) which runs an algorithm after each spacecraft contact via TDRSS to calculate and report spacecraft clock time error in terms of a delta error with respect to UTC. The TAC algorithm uses the time tagged satellite telemetry, satellite range data, ground equipment delay data, and spacecraft hardware delay constant data to compute spacecraft clock error and provide a report to POCC personnel.

GPS / TCP CLOCK SYSTEM OVERVIEW

Mission "X" is a potential future Shuttle mission requiring the precise time coordination of events among multiple space-vehicles over a period of several days. One of these vehicles, the "spacecraft", will employ an on-board clock to provide for the execution of spacecraft stored command sequences at precise times with respect to mission reference time. Just prior to release of the spacecraft from the Shuttle, the spacecraft's clock will be synchronized to mission reference time using the Shuttle's Master Time Unit. After release, the spacecraft's clock will free-run on its own modest reference oscillator. From this point, clock error will be tracked by ground controllers using telemetry data produced from on-board comparison of the spacecraft clock and precise absolute time provided by the spacecraft's GPS Receiver.

The mission does not require that the spacecraft clock keep accurate absolute time, but it does require that ground controllers have precision knowledge about the error between the spacecraft clock and mission reference time. Further, spacecraft clock error accumulation due to reference oscillator frequency error will be slow enough, with respect to required time keeping accuracy (about 5 milliseconds), to allow for error correction by ground operators. Therefore it was decided that spacecraft clock error could be compensated for via adjustment of the execution time "tags" associated with each stored command prior to stored command uplink to the spacecraft. Alternatively, the use of uplink spacecraft clock "delta time" adjustment commands (like EUVE) could provide the ability to keep the spacecraft clock accurate with respect to absolute time.

In this spacecraft the on-board clock is maintained by the Telemetry and Command Processor Unit. The TCP can run the clock from it's internal oscillator or it can be commanded to "slave" the clock to the Shuttle's Master Time Unit during Shuttle In-Bay operations. The TCP also receives regular "time-hacks" from the on-board GPS Receiver. Fairchild determined that it would not be best to directly "slave" the spacecraft's clock to the GPS Receiver's time however. Such a configuration could lead to uncontrolled spacecraft clock accuracy degradation or "glitches" during conditions of "poor geometry" between the spacecraft and the GPS space vehicles or due to GPS signal reception problems arising from spacecraft/ GPS receiver antenna attitude. Further, the spacecraft clock will maintain good accuracy over a reasonable time period in an "open loop" condition. Therefore, it was decided that spacecraft clock error correction is best performed from the ground. Clock error will be tracked from the ground using data provided by the TCP which will "time-stamp" each GPS

Receiver one-pulse-per-second reference output with both spacecraft clock time and GPS Receiver time.

This approach reduces spacecraft clock complexity to a simple hardware oscillator and "sub seconds counter" (provided by the TCP) along with a software "seconds counter". (Note that the GPS Receiver was originally included in the spacecraft design to facilitate precision orbit determination). In addition, use of the GPS Receiver only as a clock measurement tool and not for automatic spacecraft clock update assures that no "glitches" are introduced into the spacecraft clock. The spacecraft clock will simply "free-run" through periods when reception of the required number of GPS satellites is marginal or the geometry of the visible GPS satellites dilutes the precision of the GPS solution (time) data. This mission's spacecraft clock design relies on but a small portion of the TCP's built in time-keeping and system synchronization capabilities, but it demonstrates the ideas behind on-board GPS based high accuracy spacecraft clock time-keeping.

EUVE SPACECRAFT CLOCK DESCRIPTION

In order to minimize hardware, the EUVE spacecraft employs a software clock which is kept by the spacecraft's on-board computer. A single hardware reference oscillator provides regular "time tics" to the software clock function and also controls the satellite's telemetry acquisition and downlink process. Hence, the clock is synchronous with the spacecraft telemetry data acquisition and downlink function.

EUVE's on-board clock algorithm provides two key features that facilitate clock time adjustment and high stability performance. First, clock time can be adjusted via uplink command on a "delta" basis. This allows precise clock time adjustment to be accomplished without regard to uplink path delay and avoids clock time "glitching" or perturbation beyond acceptable limits. Secondly, the algorithm includes a ground commandable clock "drift" compensation parameter to compensate for reference oscillator frequency error. This provides for a clock maintenance interval which is measured in days even though the system is run from a modest on-board reference oscillator.

The clock has a resolution of 1 nanosecond and can be set to an absolute time or adjusted by a delta time via ground command. Further, clock drift rate can be compensated to be less than 4 microseconds per hour via a ground commandable drift compensation parameter. Therefore a clock maintenance interval of 24 hours can assure that on-board clock error is less than 100 microseconds. On-orbit maintenance involves determining on-board clock error relative to ground reference time and performing "delta" time adjustments as necessary.

Figure 2 provides a block diagram of the spacecraft data handling system, highlighting the synchronous relationships between telemetry data collection and downlink process and the spacecraft clock. The system's Central Unit provides a synchronous "heart beat" for all of these activities and is responsible for collecting telemetry data and formation of the downlink telemetry data stream. The CU provides accurate "frame sync" time reference pulses to all spacecraft equipments via Remote Interface Units which are used to acquire spacecraft telemetry data.

EUVE's Onboard Computer is a NASA Standard Spacecraft Computer (NSSC) which runs software Processors (or tasks) on a periodic time slot schedule. Scheduling is performed by the Flight Software Executive which is driven by hardware interrupts from the telemetry system that establish 16 millisecond time slot boundaries. The Flight Software (FSW) Executive executes a particular FSW Processor in each slot of a 64 slot long repetitive sequence which is synchronized with each Downlink Telemetry Major Frame (1.024 sec).

Figure 3 describes the time relationships between data handling system hardware and software related events. This figure provides a time-line picture showing where time is computed, where it is reported in telemetry, and when the first header bit of a telemetry frame leaves the spacecraft antenna. The Spacecraft Clock is maintained (updated) by the "UTC" Processor which is executed during NSSC Scheduler Table Slots #0 and #32 (once every 0.512 seconds). Once every 4 telemetry major frames (every 4.096 sec) full resolution clock time (for the slot #32 clock update) is provided in telemetry to the ground. Note that although the clock is updated by a software process which is only executed every 0.512 seconds, synchronous relationships between the spacecraft computer and data system allow on-board event times to be determined at the ground to microsecond accuracy.

This type of spacecraft clock can be set according to any convenient definition. All that is necessary is to define when the time computed by the clock algorithm will be valid. This definition should be in terms of a reference "point" having a known relationship with spacecraft telemetry to allow correlation of on-board clock time with UTC at the ground. For EUVE the beginning of NSSC slot #33 is referred to as the Spacecraft Time Reference Point. The spacecraft clock is set such that the UTC Processor computes a time that is valid at the beginning of slots #1 and #33. One can think of this as if a "tone" occurs at the beginning of slots 1 & 33 and the UTC Processor announces that "at the tone the time will be blah-blah". Using figure 3, the exact time between these "tones" and the transmission of downlink telemetry bits from the spacecraft antenna can be determined. Since the relevant onboard time relationships are fixed, one can determine the error in the spacecraft clock by comparing the ground arrival time of a given telemetry bit to a ground reference time standard by accounting for all delays between the spacecraft and the point of time stamping at the ground station.

SOFTWARE CLOCK ALGORITHM

Each execution of the EUVE computer UTC Processor causes a value = {0.512 secs +/- a Drift Compensation value} to be added to the current clock time. Determination of the exact time interval between UTC Processor executions is based on the following information:

a. Ref Oscillator Period = T = 1/4.096 MHz (nominal).
b. NSSC Scheduler Table Slot duration = K1 Reference Oscillator cycles = 16 ms nom , K1 = 65536
c. UTC processor executed every K2 NSSC Scheduler Table Slots = 0.512 sec nom, K2 = 32

From this, an algorithm describing spacecraft clock time value versus actual reference time (UTC) is:

```
START
    $N = 0$                                      ;N counts # of times UTC Processor has executed
    $S/C\ Time(0) = t_o$                         ;Initial Time on S/C Clk
    $Ref\ Time(0) = tr_o$                        ;Initial Time on Reference Clk  (UTC)

LOOP
    $Wait\ time = T*K1*K2$                       ; UTC Processor Execution Rate - determined by H/W intrps

    $N = N + 1$
    $S/C\ Time(N) = t_o + N (0.512\ sec + Comp)$    ; New Time computed by spacecraft clock
    $Ref\ Time (N) = tr_o + N(K1*K2*T)$             ; Actual Time per  Ref Time source

Goto LOOP                                        ;Do above in endless loop
```

Notes:
"N" increments synchronously with respect to telemetry (2X per Major Frame)
"Comp" = Drift Compensation value = -M to + M nanosec, where M = integer

The above algorithm describes the discrete time computed by the spacecraft clock at each clock update event and the "actual time" (as reported by a UTC reference) at the time of update. This format allows:

a. Determination of spacecraft clock drift rate with respect to spacecraft reference oscillator frequency,
b. Evaluation of effect of clock drift compensation parameter value changes, and
c. Determination of spacecraft reference oscillator frequency from clock error data.

CLOCK ANALYSIS AND EQUATIONS

Using the algorithm described above, and letting K = K1 * K2, the error in the spacecraft clock time with respect to reference time can be written as:

S/C Clock Error = s/c time(N) - ref time(N)

=[t_o + N(0.512 + Comp)] - [tr_o + N(KT)]

Since t_o and tr_o are constants,

S/C Clock "Drift" Error = N [0.512 + Comp - (KT)]

Let D' = Drift Error over 1 UTC Processor Execution interval (N = 1),

D' = 0.512 + Comp - KT

Next let D = S/C Clock Drift Rate, in sec per sec. Given that 1 UTC Processor interval time = KT,

D = D' x (1/KT) = (1/KT)(0.512 + Comp) - 1

Or, converting D to units of microseconds per hour, then

```
-------------------------------------------------------
| CLOCK DRIFT RATE =                                  |
|     3.6 x 10^9 { (1/KT)(0.512 + Comp) - 1 }         |
-------------------------------------------------------
```

Where: o Drift Rate is in microseconds per hour
o T= 1/ Ref Osc Frequency is in Hz
o Comp is in seconds
o K = 32 x 65535 = 2097152

Rearranging this equation yields:

```
----------------------------------------------------------
| REF OSC FREQUENCY =                                    |
|     { K((D/3.6 x 10^9) + 1 )} / (0.512 + Comp)         |
----------------------------------------------------------
```

Where: "D" = Drift Rate is in microseconds per hour.

To solve for the optimum Drift Comp value, set Drift Rate = 0. This yields:

```
----------------------------
| COMP =                   |
|       KT - 0.512         |
----------------------------
```

EXAMPLES OF EQUATION USE

1) Determine resolution of Drift Compensation Parameter in terms of clock drift rate in microsec / hour :

Using the Drift Rate equation above,
Set Comp = 1 bit = 1 nanosec, and Osc Freq to 4.096 MHz nominal freq.

$$R = 3.6 \text{ x } 10^{9} \{ (4.096 \text{ x } 10^{6}/2097152)(0.512 + 1 \text{ x } 10^{-9}) - 1 \} = 7.2 \text{ uS/Hr}$$

2) Given that data shows a spacecraft clock drift rate = -5.49 uS/Hr and the current drift compensation value is + 7, find the optimum compensation value for Table.

First solve for the Osc Frequency,

$$\text{Osc Freq} = \{ 2097152((-5.49/3.6 \text{ x } 10^{9}) + 1)\} / (0.512 + 7 \text{ x } 10^{-9}) = 4.095999938 \text{ x } 10^{6} \text{ Hz}$$

Then calculate optimum comp value,

$$\text{Comp} = (2097152/4.095999938 \text{ x } 10^{6}) - 0.512 = 7.78 \text{ x } 10^{-9} \text{ sec} = 7.78 \text{ nanosec}$$

Therefore optimum Table drift compensation value = 8

EUVE TIME KEEPING SYSTEM VERIFICATION

The NASA/TDRSS mission system used for EUVE time-keeping is highly complex in terms of the number of organizations, equipment, and software involved. End to end verification of this system was accomplished by a process that began during spacecraft ground test and culminated in an on-orbit "hand-over" of the spacecraft clock to the mission time-keeping system designed to verify the accuracy of clock error reports produced by the system.

In order to allow measurement of spacecraft clock error using only an RF connection to the spacecraft, the relationships between the clock and spacecraft telemetry signals at points both on the spacecraft and in the ground station equipment were measured. This provided the ability to track spacecraft clock time using ground equipment signals up to the point of launch via the RF telemetry link between the spacecraft and the launch site ground system. As a result, spacecraft clock error and drift rate were known to a high degree of accuracy at the time of lift-off. The accuracy of the on-orbit spacecraft clock error determination system was then able to be assessed through a comparison of expected versus reported clock error following launch and hand-over to the mission system.

In fact, initial on-orbit clock error reports produced by the mission time-keeping system differed from what was expected based on the pre-launch data. Tracking down the source of the difference: a) resulted in the correction of inaccurate ground software algorithm parameters, and b) provided insight into how to get more accurate results out of the system as a whole.

PRE-LAUNCH VERIFICATION AND TRACKING

The first step in the spacecraft clock tracking process involved determination of the delays between the clock and the spacecraft's telemetry antenna and any other points on the spacecraft where telemetry is monitored. In order to do this for EUVE, figure 3 was constructed as a means of determining on-board spacecraft timing relationships. During spacecraft I&T, frame sync and "hard-line" telemetry signals, available at a spacecraft test connector, were used as reference signals both to verify certain delays indicated by the figure and as a means of determining telemetry signal processing delays caused by spacecraft Ground Support Equipment (RF and Baseband). This allowed spacecraft clock error to be tracked via the spacecraft's RF downlink link while sitting on the launch vehicle just prior to lift-off.

Figure 4 shows the Pre-launch Equipment System used to measure and track spacecraft clock error at the Cape Canaveral Air Force Station (CCAFS) with respect to the CCAFS cesium clock. This was accomplished by measuring the exact time of receipt of spacecraft telemetry frame sync signals and then accounting for the previously determined delays through the spacecraft, RF Link, and GSE. An IBM PC and custom software was configured to perform this task using input signals available from the spacecraft GSE. The PC was equipped with an event time stamping card which was used to generate a "time stamp" for each spacecraft frame sync event with 1 microsecond resolution. An IRIG-B format time reference signal from the CCAFS cesium clock reference was connected to the time stamp card to provide a high accuracy time reference.

PC software was employed to decommutate the spacecraft clock from the telemetry stream and compare its time to the frame sync event time. The software computed the error between the spacecraft clock and IRIG-B reference time by backing out the appropriate delay times given, a) the fixed relationship between the frame sync and s/c time reference point, b) the knowledge that the GSE delayed telemetry by much less than 1 telemetry minor frame time, and c) that the PC decomm buffered data for 1 major frame. Spacecraft clock error was printed on the PC's display.

ON-ORBIT CLOCK TRACKING & PERFORMANCE

The CCAFS cesium time reference source provided time traceable to Naval Observatory Standard time to 1 usec accuracy. This provided an absolute time reference link with the TDRSS/NGT time stamping reference allowing the EUVE on-orbit time tracking system to be verified using the spacecraft clock as a known time reference source. It was many hours after lift-off before the first clock error reports derived from TDRSS were produced at the EUVE POCC. Initially it appeared that spacecraft clock error was much larger that anticipated based on pre launch clock drift rate. However, after several of days of tracking the clock and scrutinizing the POCC spacecraft clock error software algorithm with the help of many NASA personnel, a couple of conclusions were reached.

First, error was introduced because spacecraft range data is measured at discrete time intervals which don't always coincide with the epoch time of the telemetry data used to determine clock error. The EUVE POCC clock error reports provide a set of spacecraft clock time vs. ground clock time data points, along with corresponding range data points, taken approximately one minute apart. However, the range data used is for exact minute boundaries (ground time) and the clock time samples do not always fall exactly on even minute boundaries. Further, spacecraft range to TDRS changes at rates greater than 4 kilometers per second and every 1 kilometer of spacecraft range data error contributes 3.3 microseconds of error to time calculations. Therefore the "Computed Clock Delta" (error) data points shown in the report can be in error by as much as 30 sec x 4 km/sec x 3.3 uSec/ km = 396 uSec!

In order to combat this problem, and obtain best accuracy, clock error data should be measured at a time when spacecraft range rate is near or equal to zero. This occurs at the spacecraft's "Point of Closest Approach" (PCA) to a TDRS. Figure 5 provides a typical EUVE spacecraft range versus time plot and indicates the PCA region. (Note that EUVE's orbital altitude is about 515 km).

Secondly, it was determined that a delay constant used by the clock error determination software algorithm was in error. It was also found that a sign reversal existed in the way the pre-launch and on-orbit systems reported clock error. Once these were corrected/accounted for, less than 30 microseconds of unexplained error in the spacecraft clock remained! Clearly, this mission system test was well worthwhile as it produced a verified on-orbit spacecraft time-keeping system.

Figure 6 presents a long term EUVE clock error trend plot indicating points where ground commands were issued to null out clock error and change the clock drift compensation parameter. Over the long term a 24 hour periodic perturbation in the error data equal to a few tens of microseconds was noticed. The source of this error was not identified and may represent the accuracy limit for this system of time keeping.

SUMMARY AND CONCLUSION

The EUVE satellite project has demonstrated the ability of a low complexity onboard computer software based clock to keep highly accurate time in the NASA/TDRSS mission environment from an on-board reference oscillator of modest complexity. This paper has shown how this simple clock coupled with careful pre-launch through on-orbit clock tracking procedures provided for verified on-orbit clock performance. Since the cost of the spacecraft hardware and software required to implement this type of spacecraft clock is low, it represents a good approach for any spacecraft mission using the NASA/TDRSS mission environment.

It is expected that GPS based time-keeping approaches will become more widely used as the GPS System becomes fully operational and more and more future spacecraft include on-board GPS Receivers. The inherent advantages of this approach include potentially higher time-keeping accuracy, and freedom from reliance on mission support systems not under the direct control of an individual mission. However, on-board clock systems based on GPS must be implemented with care in order to avoid the introduction of spacecraft clock errors that could result from the potential range of GPS signal conditions/configurations seen by a user receiver. This paper introduced a GPS based spacecraft clock approach that accounts for such problems via ground operations control. This approach was suitable for the brief nature of a Shuttle type mission, however more autonomous on-board approaches will no doubt be devised for future missions.

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