TIME MAINTENANCE SYSTEM FOR THE BMDO MSX SPACECRAFT

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Abstract

The Johns Hopkins University Applied Physics Laboratory (APL) is responsible for designing and implementing a clock maintenance system for the Ballistic Missile Defense Organizations (BMDO) Midcourse Space Experiment (MSX) spacecraft. The MSX spacecraft has an on–board clock that will be used to control execution of time–dependent commands and to timetag all science and housekeeping data received from the spacecraft. MSX mission objectives have dictated that this spacecraft time, UTC(MSX), maintain a required accuracy with respect to UTC(USNO) of $\pm$ 10 ms with a $\pm$ 1 ms desired accuracy. APL's atomic time standards and the downlinked spacecraft time were used to develop a Time Maintenance system that will estimate the current MSX clock time offset during an APL pass and make estimates of the clock's drift and aging using the offset estimates from many passes. Using this information, the clocks accuracy will be maintained by uplinking periodic clock correction commands. The resulting Time Maintenance system is a combination of Offset Measurement, Command/Telemetry, and Mission Planning hardware and computing assets. All assets provide necessary inputs for deciding when corrections to the MSX spacecraft clock must be made to maintain its required accuracy without inhibiting other mission objectives. This paper describes the MSX Time Maintenance system as a whole and details the clock Offset Measurement subsystem, a unique combination of precision time maintenance and measurement hardware controlled by a Macintosh computer. Simulations show that the system estimate the MSX clock offset to less than $\pm$ 33 μs.

TIME MAINTENANCE OVERVIEW

The Midcourse Space Experiment (MSX) Time Maintenance system is composed of four subsystems: the spacecraft clock, the Offset Measurement (OM) subsystem, the Command/Telemetry subsystem, and the Operations Planning Center (OPC). Figure 1 shows a top–level view of the system and its major components. Spacecraft time, UTC(MSX), is telemetered in the spacecraft housekeeping data stream, passes through the APL Satellite Tracking Facility (STF) and Mission Control Center (MCC) downlink hardware, and is compared to a locally maintained time, UTC(MCC), in the OM subsystem. In order to accurately estimate the clock offset, the OM subsystem also receives propagation delays and the scheduled clock corrections from the MCC computer network. The computed clock offset, drift, and aging are then passed to the

network from which they get distributed to the MSX community, including the OPC. The OPC has software that will schedule and generate the necessary clock correction commands. These are sent back to the MCC computer network for uplinking to the spacecraft through the MCC uplink or the Onizuka Air Force Base Test Support Complex (TSC). The Time Maintenance system is also required to disseminate the UTC(MSX) offset (error) and characteristics to the MSX community, to set and characterize the MSX clock during spacecraft integration and test, and to set the clock just before launch.

Spacecraft Clock

The MSX spacecraft clock, UTC(MSX), is actually a software–maintained, 35 bit integer with 1 ms resolution representing the number of milliseconds into the current year. This counter increments by 1000 ms every time it receives the spacecraft 1 pulse/s (1 PPS) time epoch. This time epoch is obtained by direct division of one of the two APL–built ultrastable 5 MHz quartz crystal oscillators, so its drift and aging characteristics are determined solely by the oscillator's frequency offset and drift. For these oscillators, the deviation from the nominal frequency, or frequency error, at any time, $f_{err}(t)$, can be modeled by a simple linear equation,

$$f_{err}(t) = f_{err}(0) + \Delta f_{err}[t - t_0] \tag{1}$$

where $f_{err}(t)$ is the frequency drift. Integrating this frequency error over time with respect to the nominal oscillator frequency, f_n, yields a simple quadratic equation for modelling the UTC(MSX) clock offset versus time, $Y(t)$,

$$Y(t) = Y(t_0) + [f_{err}/f_n][t - t_0] + [\Delta f_{err}/f_n][t - t_0]^2/2 \tag{2}$$

The oscillator specifications call for a normalized frequency error of less than 5×10^{-8} and a drift rate of less than 1×10^{-10}/day. To compensate for these oscillator frequency instabilities, the spacecraft command system has implemented a 1 ms resolution clock offset command that is added to the software–maintained UTC(MSX).

The UTC(MSX) time is downlinked in real time in each major frame of the 16 kbps housekeeping telemetry stream. The major frame epoch of this stream is coherent with the spacecraft 1 PPS epoch. From this epoch and time, the UTC(MSX) offset can be determined with a high degree of accuracy.

Command/Telemetry

The Command/Telemetry downlink receives the telemetry signal, separates out the 16 kbps housekeeping, and sends it to the Offset Measurement subsystem. The telemetry portion of the Command/Telemetry subsystem consists of the necessary RF and digital downlink hardware to receive, downconvert, and demodulate the S–band spacecraft signal to separate out the digital housekeeping stream. The uplink portion contains the hardware and software to format, modulate, and upconvert the clock correction command. The MCC computer network provides

the OM with the needed spacecraft telemetry propagation delays and the previous clock corrections for each APL pass.

Operations Planning

The scheduling software in the OPC contains a time update utility that uses the current estimated clock offset and characteristics to determine when a clock update should be sent. The oscillator specifications stated above translate to an maximum clock drift of 5 ms/day, requiring a maximum of five corrections per day to remain within the desired accuracy.

Because of the manner in which the OPC schedules its many events, the scheduling software must schedule events up to 2 days in advance. The time update utility will predict the clock offset ahead for 2 days and, whenever this predicted offset is greater than ± 0.5 ms, an attempt will be made to schedule a clock correction. If data will not be corrupted by the correction, a correction of 1 ms will be made. Thus ideally the offset versus time would be a sawtooth fluctuating between +0.5 ms and −0.5 ms. However, the realities of scheduling may, very likely, force a slightly larger error on occasion. To accommodate this offset prediction capability, the Time Maintenance system has a goal of 2 day prediction errors of less than ± 100 μs.

Offset Measurement Subsystem

The heart of the Time Maintenance System is the OM subsystem, and the remainder of this paper will be devoted to detailing its operation. This subsystem is composed of specialized offset measurement hardware, a Macintosh time management unit (TMU), and custom time and frequency generation (T&F) equipment. For the purposes of this paper the OM subsystem will be broken into four parts: UTC(MCC) time generation; Delta measurement; offset estimation; and drift and aging estimation. Figure 2 shows an overview of the OM subsystem.

All measurements of the spacecraft clock offset will be made with respect to a reference UTC(MCC) 1 PPS epoch. Obviously, this epoch is not exactly the UTC(USNO) 1 PPS time epoch; thus the accuracy of any estimate of the spacecraft offset will depend greatly on the accuracy of this reference clock and the reference frequency. Therefore, a critical requirement of the OM subsystem is to provide precise time and frequency to the offset measurement hardware.

UTC(MCC) Time Generation

Figure 3 details the methodology for time transfer to the OM. The APL Time and Frequency Standards Laboratory (T&FSL) maintains atomic time and frequency standards. UTC(APL) is consistently maintained to within 2 μs of UTC(USNO)[1]. The STF receives time and frequency standards over fiber optics from the T&FSL in the form of IRIG B, 1 PPS, and 5 MHz. The STF regenerates the IRIG B and 1 PPS, both to account for the signal delay to the STF (the T&FSL is about 0.5 mile away) and to allow stand–alone capability should the T&FSL signal drop out. The STF phase–locks a 1 MHz disciplined crystal frequency standard to the incoming T&FSL 5 MHz, allowing for the long–term stability of the 5 MHz while cleaning up the transmitted frequency reference for better short–term stability. This 1 MHz is used as the

STF time code generator (TCG) time base. Informal round–trip testing with the T&FSL and comparison with a local GPS receiver has shown the STF time output to be consistently within ± 10 μs of UTC(USNO). The STF T&F outputs are the OM T&F inputs.

The OM does a similar time regeneration to allow for stand–alone operation and to produce a stable time output. The 5 MHz from the STF is input to a 10 MHz rubidium (Rb) PLL followed by a 10 to 5 MHz scaler and a 5 MHz buffer/isolator. This allows for the OM 5 MHz reference to be phase–locked to the APL 5 MHz reference when it is present and to be derived from the stable Rb oscillator when it is not. Because the Rb has specifications about 2 orders of magnitude better than the spacecraft oscillator, for a short period of time the Time Maintenance operation could continue with the Rb as its time base.

A buffered 5 MHz output is the time base for the TCG, whose output is UTC(MCC). This custom TCG will initially synchronize to the IRIG B and 1 PPS time standards with less than 1 microsecond error. Then the synchronization software will be turned off and the TCG will free run off its 5 MHz reference. This is to prevent the TCG from trying to track any noise in the IRIG B and 1 PPS inputs. Because UTC(MCC) is generated from a direct division of the 5 MHz reference, the long–term stability of UTC(MCC) will be the same as the 5 MHz reference. While no longer synchronizing to its reference inputs, the TCG monitors the difference between its 1 PPS output and the reference inputs (again to sub–microsecond accuracy) to ensure that UTC(MCC) does not drift from UTC(STF). This difference is queried by the TMU and triggers an alarm if greater than 5 μs. The OM also monitors the distributed UTC(MCC) IRIG B, 1 PPS, and 5 MHz outputs via status lines sent to the TMU parallel board from the distribution units.

Delta Measurement

The critical offset measurement signal is the transmitted spacecraft 16 kbps major frame epoch, which occurs nominally once per second. It is this signal that contains the precision information about the spacecraft time epoch and oscillator performance. Once per second during an APL pass the OM makes a measurement of the time interval, Delta, between the local UTC(MSX) 1 PPS reference and the recovered spacecraft epoch. Figure 4 details the Delta measurement hardware. The spacecraft epoch is recovered by the frame synchronizer/demux (FS/D) using the first bit transition of the major frame sync word as the epoch edge. Calibration tests have shown that the offset between this recovered epoch and the actual major frame epoch is consistent and measurable and can thus be accounted for. Every second, the Time Interval Measurement Unit (TIM) is set up by the TMU to measure the time interval between the recovered epoch and the 1 PPS reference edge. For accuracy, the TIM uses the 5 MHz reference as its timebase.

The FS/D will send six of the housekeeping telemetry words to the TMU parallel I/O board. These words contain the UTC(MSX) time, the mission elapsed time (MET), and the spacecraft oscillator being used. Once the MCC has acquisition of signal (AOS) for the 16 kbps telemetry (which the TMU determines from the FS/D status signal), the TMU will first empty the FS/D buffer and get major frame synchronization using an end of frame (EOF) signal. Then the sequence of events for each second is as follows:

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1. The TMU sets up the TIM to make a Delta measurement.
2. The TMU waits until the TIM reports that a measurement is complete.
3. The TMU reads the UTC(MSX) time from the TCG (only concerned with second accuracy because, by definition, the 1 PPS occurs on a 1 s boundary).
4. The TMU reads the Delta measurement.
5. The TMU reads the FS/D buffer to get the UTC(MSX) of the next epoch.

This sequence is repeated until loss of signal (LOS). Hardware is controlled and data are retrieved over a local GPIB bus controlled by the TMU.

When the received spacecraft epoch approaches coincidence with the 1 PPS rising edge, the TMU will automatically command the TIM to measure from the 1 PPS falling edge. This prevents noise from generating an ambiguity in the time difference measurements around even second intervals. This switching will take place after a pass is complete. Calibration of the 1 PPS duty cycle allows the approximate 0.5 s bias to be accounted for.

Offset Estimation

The UTC(MSX) Offset estimation takes place in the TMU. At any given time, t_0, this offset has been defined to be

$$T(t_0) = \text{UTC(USNO)}_0 - \text{UTC(MSX)}_0 \tag{3}$$

However, this offset is not simply the Delta measured by the TIM. Both biases and noise must be accounted for to the greatest degree possible. Figure 5 illustrates the offset measurement biases. These biases are measured before launch (for spacecraft biases) and periodically during the mission (for ground station biases). The propagation delays, td4, are computed for each second in the MCC Computer Network based on the estimated MSX orbit and sent to the TMU prior to every APL pass. With this bias data, the TMU has the information necessary to compute the offset for any given second during the pass using the equation,

$$Y(t_0) = \text{UTC(MCC)}_1 + \text{Delta} - [\text{UTC(MSX)}_0 + \sum \text{td}(1-8)] + \sum td(9,10) \tag{4}$$

Each of these offset samples is contaminated with the noise of the downlink, so the samples from each pass will be condensed to a single offset estimate to reduce the random error. The time of closest approach (CA) was chosen as the best time to estimate the offset because this is where the range error effects would be least. The offset samples are also windowed about CA to further minimize the range error effects. Since the oscillator drift is very linear over the period of a pass (5 to 15 minutes), a first–order least squares regression is used to estimate the single pass offset estimate. A higher order estimate may attempt to fit the range error curve or noise. The general first–order linear equation is,

$$Y_1 = \beta_0 + \beta_1 X_1 + \epsilon_1 \tag{5}$$

where X_i are the time of the offset samples: Y_i are the actual offset samples; β_n are the actual offsets and drift; and b_n are the estimates of β. The fitted equation, Equation 6, is used to estimate the offset:

$$\hat{Y} = \bar{Y} + b_1(X - \bar{X}) \tag{6}$$

where

$$b_1 = \frac{\sum(X_i - \bar{X}(Y_1 - \bar{Y}))}{\sum(X_i - \bar{X})^2} \tag{7}$$

For a given estimate, $\hat{Y}_h$, the standard deviation is

$$\sigma_h = \sigma_i \left[\frac{1}{n} + \frac{(X_h - \bar{X})}{\sum(X_i - \bar{X})^2} \right]^{\frac{1}{2}} \tag{8}$$

when $X_h = \bar{X}$, σ_h is minimized and the offset estimate is $\hat{Y}_h = \bar{Y}$.

This shows that if the offset samples are windowed about CA, the standard deviation of the estimate will be minimized at CA and the offset estimate is just the average of the offset samples. As an independent verification of the estimated offset, the TSC has agreed to make their own spacecraft offset estimations. These will be used to detect errors in the Time Maintenance system.

Drift and Aging Estimation

From Equation 2 we know that these offset estimates over time can be approximated by a simple quadratic. So, after an offset estimate has been made for at least three passes, the UTC(MSX) drift and aging will be solved for by using the offset estimates from each pass in a second–order least squares regression. Only the offsets from the previous week or so will be used so that the estimates are not too heavily weighted with old data and are able to respond to new oscillator trends. Equation 2, written in a slightly different format and notation (to avoid difficulties of inverting the $X'X$ matrix), is

$$Y_i = \beta_0 + \beta_1 x_i + \beta_1 x_i^2 + \epsilon \tag{9}$$

or in matrix form, $\mathbf{Y} = \mathbf{x}\beta + \epsilon$, where X_i are the time of the offset estimate from each pass; Y_i are the actual offset estimates from each pass; β_n are the actual offset, the drift, and the aging; b_n are the least squares estimates of b using x; B_n are the least saquares estimates of b using X; and $x_i = X_i - \bar{X}$. The least squares estimators, b, of β are

$$b = (x'x)^{-1}x'Y \qquad (10)$$

The least squares estimators, B, of β are

$$
\begin{aligned}
B_0 &= b_0 - b_1\bar{X} + b_{11}\bar{X}^2 \\
B_1 &= b_1 - 2b_{11}\bar{X} \\
B_{11} &= b_{11}
\end{aligned}
$$

These equations allow one to solve for clock drift, B_1, and aging, $2B_{11}$. A complete history of the UTC(MSX) characteristics will be maintained for the mission duration for each of the spacecraft oscillators.

An analysis of the offset measurement error sources show components of both a "fixed" (such as the UTC(MCC) error) and a "variable" (such as the telemetry propagation time errors and thermal noise) nature with respect to a time period of a pass or longer. The fixed errors are effectively an unknown bias and, as such, will directly affect the ability to estimate and predict the clock offset. The variable errors can be effectively reduced by the regression analysis. Simulations were run using worst–case fixed errors of $\pm$ 12 μs, variable errors of $\pm$ 3 μs rms, and $\pm$ 2 μs range errors. These showed that with the data from only six passes, the estimation error of the current pass offset is less than 14 μs and the 2 days prediction error is less than 30 μs.

The TMU uses LabVIEW software to perform the hardware control, data acquisition, data processing, data display, and user interface functions. LabVIEW is a graphical programming language with a graphical user interface and lends itself readily to the requirements of real–time offset sample display and pass estimate graphing.

Correction Verification

When the scheduling software schedules a spacecraft clock correction, it reports the time and magnitude of this scheduled offset to the TMU. Since the uncertainty of a pass offset estimate is much less than the magnitude of the corrections, the TMU is able to verify that each of the scheduled corrections actually took place. For each pass, the TMU will predict what the expected clock offset should be based on the last pass offset, the clock drift and aging rates, and the scheduled clock corrections. If the two agree within a specific tolerance, the offset is "verified" and added to the history of previous offsets for use in the second order regression. Before the regression is done, however, the clock corrections must be subtracted out as the regression needs uncorrected offset estimates to model the oscillator characteristics.

Control/Status and Data Transfer

The Offset Measurement subsystem is an automated subsystem driven by commands from the MCC computer network via the MCC configuration control computer over its separate GPIB

bus. Satellite alerts driven software will tell the TMU to go into a data collection mode just before the pass starts, to terminate data collection when the pass is complete, and to process the pass samples after the pass. The OM also reports subsystem status, mode, and errors over this bus.

Once the OM data processing is completed, the clock characteristics must be transferred to the MCC computer network for distribution to the MSX community. To accomplish this, the TMU runs software that makes it a DECNET end–node on the MCC Ethernet network. This makes it possible for the MCC computer network to write the needed propagation delay and scheduled correction data on the TMU hard disk before each pass and to read the clock characteristics results from the TMU hard disk after each pass. A handshake file on the TMU hard disk lets the network know the current progress of the TMU collection and processing.

Test and Calibration

The spacecraft simulation capability is an important aspect of the OM subsystem for testing and calibration. This simulation capability consists of a telemetry simulator driven by a frequency synthesizer. The simulator puts out a 16 kbps housekeeping stream containing the normal UTC(MSX) clock words that can be synchronized to UTC(MCC) plus a known bias. The synthesizer is driven by the same MCC 5 MHz reference that drives UTC(MCC). Thus, if the synthesizer is set to the nominal oscillator frequency, the simulator offset should not vary over time with respect to UTC(MCC). Once this synchronization bias has been measured, the simulated data stream can be fed into the normal telemetry path and the downlink delays can be calibrated. This is done before every cluster of passes over APL to verify both that the delay has not changed (indicating a possible problem) and that the OM subsystem is operational. The simulator is also used to calibrate the duty cycle of the 1 PPS by changing the Delta measurement trigger edge and calculating the difference in measured offset.

For additional testing capabilities, the TMU can change the synthesizer frequency. A programmed frequency offset will simulate a clock drift, and varying this offset linearly over time will simulate clock aging. The synthesizer is of the direct digital synthesis variety, so it is possible to make these frequency changes without causing phase discontinuities in the output. It also has 1 μHz resolution, making it possible to simulate range error effects for more accurate pass simulations.

Reference

[1] Suter, J. J., "*Performance of APL Atomic Clocks as Analyzed by the Bureau International des Poids et Mesures and the National Institute of Standards and Technology*", JHU Applied Physics Laboratory, S2R–92–108, April 10, 1992.
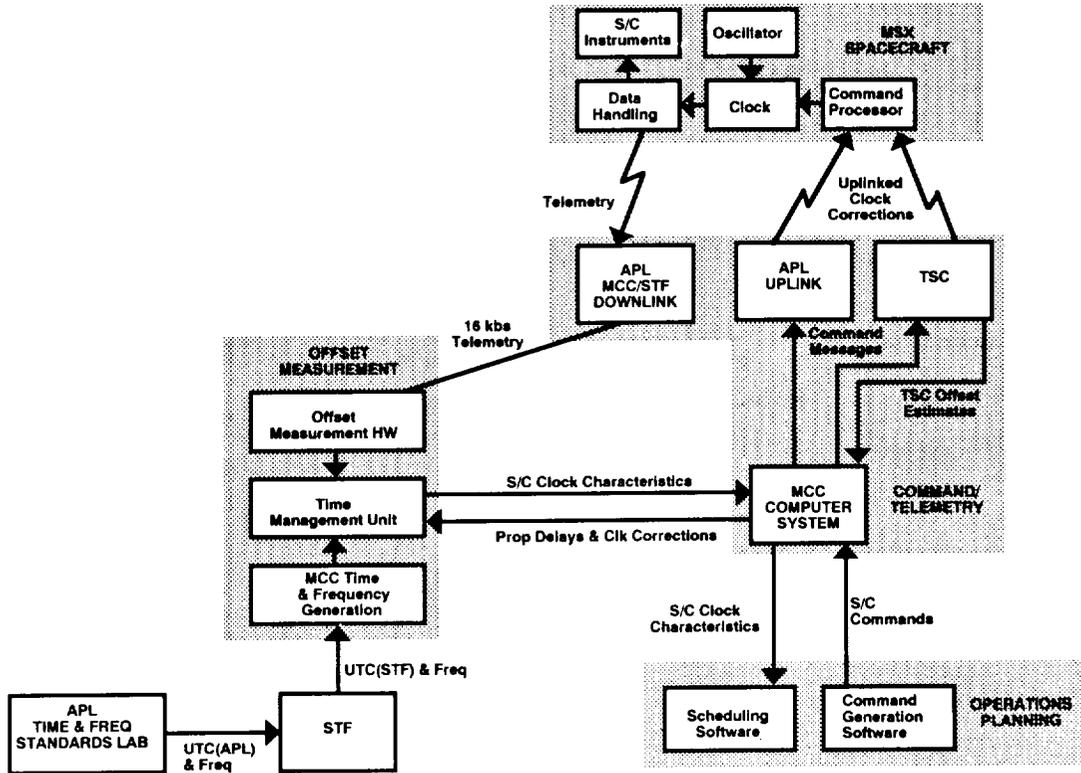
Figure 1   Time Maintenance Overview
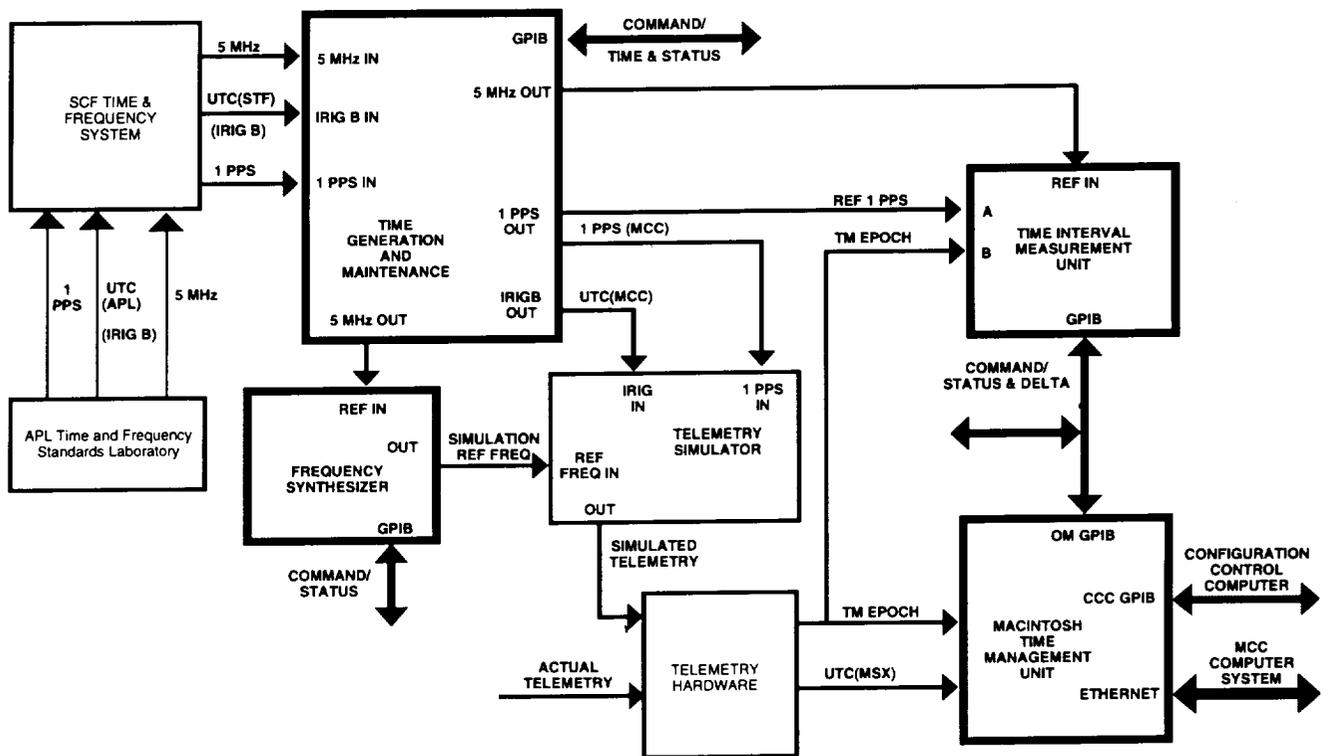
Figure 2   Offset Measurement Subsystem

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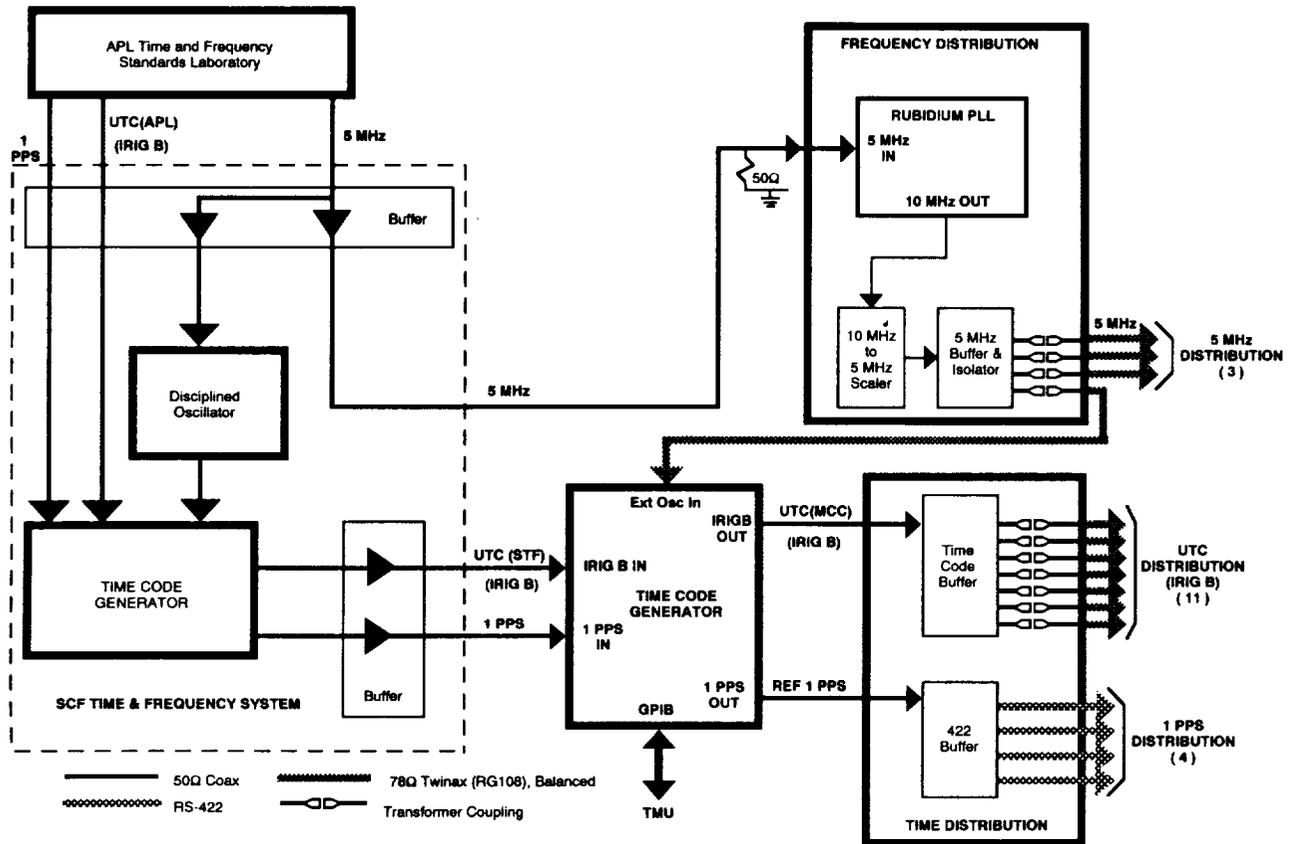
**Figure 3 MCC Time Generation and Maintenance**
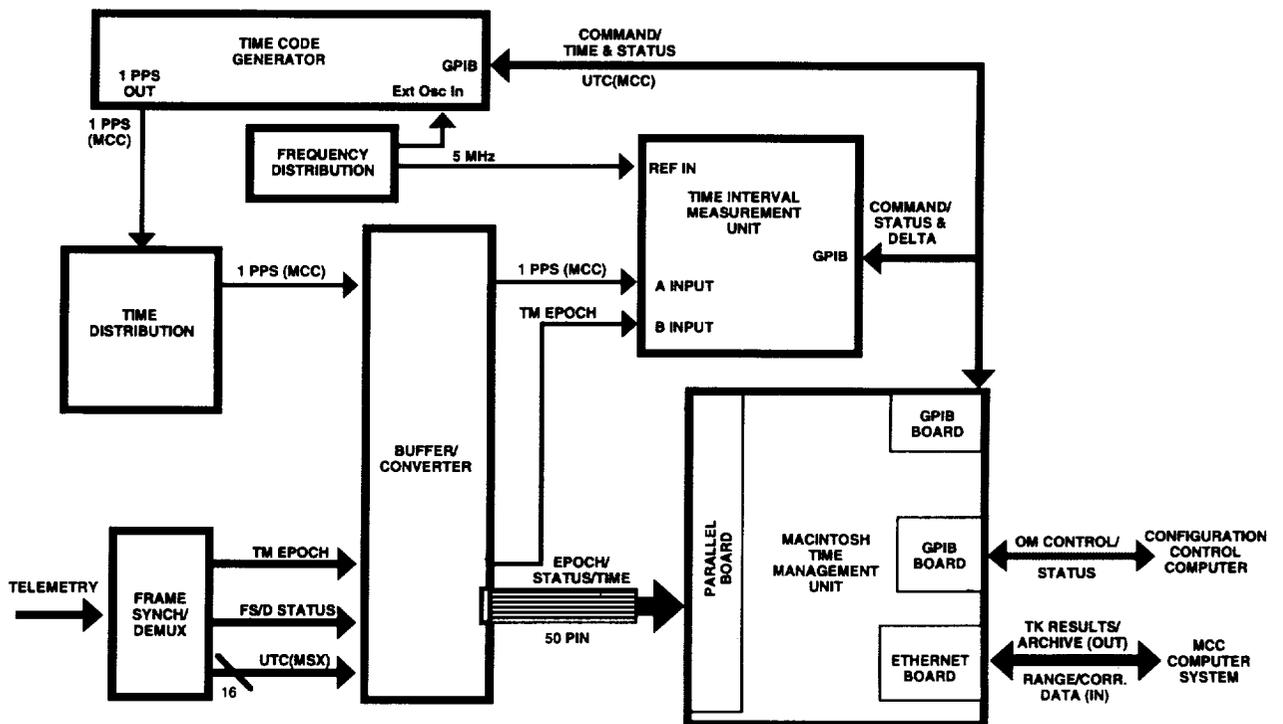
Figure 4 Delta Measurement Hardware

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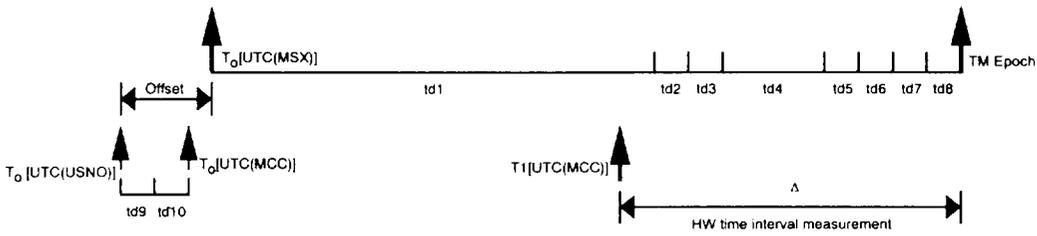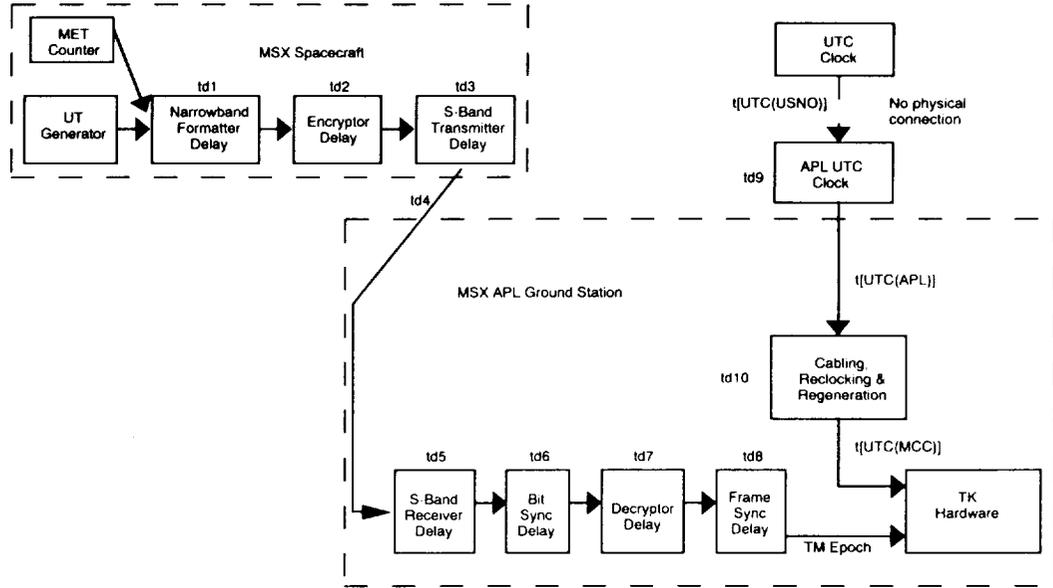
Figure 5   Offset Measurement Biases