

# GROUND CONTROL SYSTEM FOR THE MIDCOURSE SPACE EXPERIMENT UTC CLOCK

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## Abstract

*One goal of the Midcourse Space Experiment (MSX) spacecraft Operations Planning Center is to maintain the onboard satellite UTC clock [UTC(MSX)] to within 1 millisecond of UTC(APL) (the program requirement is 10 msec). The UTC(MSX) clock employs as its timebase an APL built 5 MHz quartz oscillator, which is expected to have frequency instabilities (aging rate + drift rate + frequency offset) that will cause the clock to drift approximately two to ten milliseconds per day. The UTC(MSX) clock can be advanced or retarded by the APL MSX satellite ground control center by integer multiples of 1 millisecond.*

*The MSX Operations Planning Center is developing software which records the drift of UTC(MSX) relative to UTC(APL) and which schedules the time of day and magnitude of UTC(MSX) clock updates up to 48 hours in advance. Because of the manner in which MSX spacecraft activities are scheduled, MSX clock updates are planned 24 to 48 hours in advance, and stored in the satellite's computer controller for later execution.*

*Data will be collected on the drift of UTC(MSX) relative to UTC(APL) over a three to five day period. Approximately 6 times per day the time offset between UTC(MSX) and UTC(APL) will be measured by APL with a resolution of less than 100 microseconds. From this data a second order analytical model of the clock's drift will be derived. This model will be used to extrapolate the offset of the MSX clock in time from the present to 48 hours in the future. MSX clock updates will be placed on the spacecraft's daily schedule whenever the predicted clock offset exceeds 0.5 milliseconds.*

*The paper includes a discussion of how the empirical model of the MSX clock is derived from satellite telemetry data, as well as the algorithm used to schedule MSX clock updates based on the model.*

## INTRODUCTION

The Midcourse Space Experiment (MSX) spacecraft will have an onboard clock denoted UTC(MSX) which will be used to timetag all data recorded by the satellite. The timebase for UTC(MSX) is an APL built precision 5 MHz quartz crystal oscillator, which is expected to exhibit frequency instabilities (aging rate + drift rate + frequency offset) that will cause the clock to drift approximately two to ten milliseconds per day with respect to UTC(APL). UTC(APL) is the ground based reference clock chosen for use on the MSX program, and is defined as UTC time as maintained by APL's time and frequency laboratory. APL maintains

the traceability of UTC(APL) to UTC time as defined by the United States Naval Observatory [UTC(USNO)].

In this context, clock drift is defined as the rate at which the offset between the UTC(MSX) clock and the UTC(APL) clock is changing, and clock offset is defined as the time interval (in milliseconds) between a UTC(MSX) clock 'tic' and a UTC(APL) clock 'tic'. A clock update refers to advancing or retarding the UTC(MSX) clock in order to reduce the size of its offset from UTC(APL). A Clock Update Maintenance Event is the set of spacecraft commands that perform a clock update to the MSX UTC clock.

In order to maintain the integrity of spacecraft data, the MSX Operations Planning Team (OPT) is required to maintain UTC(MSX) to within 10 milliseconds of UTC(APL). UTC(APL) is maintained by APL's atomic frequency standards, and typically exhibits a clock drift on the order of 10 nanoseconds per day. The Operations Planning Team has as its goal to exceed the 10 millisecond requirement, and maintain UTC(MSX) to within 1 millisecond of UTC(APL).

In order to keep the UTC(MSX) clock within 1 millisecond of UTC(APL), the Operations Planning Team schedules MSX Clock Update Maintenance Events, which consist of a single spacecraft command to advance or retard the onboard clock by an integer multiple of 1 millisecond. Because of the procedure used to schedule MSX spacecraft activities, the commands to execute Clock Update Maintenance Events will be uplinked to the satellite 24 to 48 hours in advance, and stored in the satellite's computer controller for later execution.

Software known as the Time Update Utility, or TUU, is used to plan all MSX clock updates. Because it has to schedule clock updates up to 48 hours in advance, the TUU has to extrapolate the MSX clock offset into the future based on past clock performance. To extrapolate the spacecraft clock's offset, the Time Update Utility derives an analytical model of the offset between UTC(MSX) and UTC(APL) as a second order polynomial of the general form:

$$\text{OFFSET}(t) = Xt^2 + Yt + Z + \text{Updates}(t) \quad (1)$$

where  $t$  = time in milliseconds since the start of the time interval being modelled,  $Z$  = the initial offset of the clock at  $t = 0$ ,  $X$  and  $Y$  are constants, and  $\text{Updates}(t)$  is a time dependent function accounting for all clock updates scheduled during the time interval being modelled.

By design, the Time Update Utility will be run once for each day of the MSX mission. Assume for the purposes of this discussion that Clock Update Maintenance Events for Day  $N$  of the MSX mission are being scheduled. Planning for Day  $N$  will occur early on Day  $N-1$ , giving rise to the requirement that clock maintenance events be scheduled from 24 to 48 hours in advance.

To schedule clock updates for Day  $N$ , the Time Update Utility models five days of clock performance. Days  $N-4$  to  $N-2$  are modelled using measurements of the offset between UTC(MSX) and UTC(APL) recorded by the MSX Mission Control Center. Days  $N-1$  and  $N$  will be modelled using an extrapolation derived by the TUU from the measured data.

## OPERATION OF THE GROUND CONTROL SYSTEM FOR THE MIDCOURSE SPACE EXPERIMENT UTC CLOCK

The UTC(MSX) clock essentially consists of a counter which continuously counts the number 5 MHz cycles output by the oscillator in units of milliseconds. The UTC(MSX) clock drift is entirely due to the frequency instability in the MSX oscillator time base accumulating over time; the digital counting circuit does not contribute to the clock drift. The MSX spacecraft clock will be maintained to its desired accuracy by executing a series of Clock Update Maintenance Events which correct for the measured offset between UTC(MSX) and UTC(APL).

A Clock Update Maintenance Event consists of sending a command to the spacecraft that advances or retards the digital clock counter by an integer number of milliseconds. This means that clock updates have no effect on the 5 MHz oscillator and therefore no effect on clock drift. MSX clock drift and clock updates are considered to be two independent phenomena that, when added together, define the UTC(MSX) clock's total offset from UTC(APL). This allows the TUU to separate the extrapolation of the total clock offset into a clock drift model and a separate clock update model. The MSX oscillator driven drift is modelled using an analytical expression derived from measured clock offset data. Clock Update Maintenance Events will be modelled mathematically as a series of step functions, with a step in the UTC(MSX) clock offset occurring at the time the clock update was executed.

The MSX spacecraft orbit is such that it will pass over APL five to six times per day. During each pass of the spacecraft over APL, the Mission Control Center will measure the offset of UTC(MSX) from UTC(APL) with a resolution of less than 100 microseconds. At the beginning of mission Day N-1, a data file containing measurements of the offset between UTC(MSX) and UTC(APL) versus time from the start of Day N-4 to the end of Day N-2 will be made available to the Time Update Utility by the MSX Mission Control Center; this datafile will also contain a list of all Clock Update Maintenance Events that occurred during the same time period.

When the measured MSX clock offset is plotted, the data will appear similar to the curve labelled "Typical Measured UTC(MSX) Clock Offset" in Figure 1. The discontinuities in the plot are due to clock updates executed during Days N-4 to N-2. The slopes of the continuous portions of the Typical Measured UTC(MSX) Clock Offset curve are due solely to the drift of the UTC(MSX) clock relative to UTC(APL). In order to model the UTC(MSX) clock drift, the Time Update Utility uses the list of Clock Update Maintenance Events that occurred on Days N-4 to N-2 to subtract out the discontinuities from the Typical Measured UTC(MSX) Clock Offset curve, resulting in a continuous curve similar to that labelled "Clock Offset - Clock Updates" in Figure 1.

The TUU performs a second order polynomial fit to the continuous 'Clock Offset - Clock Updates' curve resulting in an analytical expression describing the MSX clock drift of the form:

$$At^2 + Bt + C(N - 4) \quad (2)$$

where  $t$  = time in seconds since the start of Day N-4,  $C(N-4)$  = initial measured clock offset at the start of Day N-4, and  $A$  and  $B$  are constants. The value of  $C(N-4)$  will be obtained

from the measured data received from the Mission Control Center. The model will use the values of A and B derived in this step to extrapolate the clock drift through the end of Day N. During Day N the clock offset model will be of the form:

$$\text{OFFSET}(t) = At^2 + Bt + C(N - 1) + \text{Updates}(t) \quad (3)$$

where  $\text{OFFSET}(t)$  = the predicted UTC(MSX) clock offset at time t, A, B and t are as defined in equation 2,  $\text{Updates}(t)$  = the sum of all clock updates scheduled to occur on Day N prior to time t, and  $C(N-1)$  is a constant to be determined.

$C(N-1)$  is a constant which accounts for both the initial offset of the MSX clock at time  $t=0$ , and for all of the Clock Update Maintenance Events occurring prior to the start of Day N. The initial clock offset,  $C(N-4)$ , is read from the datafile received from the Mission Control Center, as are the magnitudes of all the clock updates executed by the spacecraft during Days N-4 through N-2. At the time the Time Update Utility software will be run for mission Day N, Clock Update Maintenance Events will have already been placed in the spacecraft's Day N-1 daily schedule. (recall that the TUU software is executed for mission Day N at the beginning of Day N-1) The Time Update Utility reads the magnitudes of all clock updates scheduled for mission Day N-1 from the MSX daily spacecraft schedule.  $C(N-1)$  is then set equal to  $C(N-4)$  + the sum of all the clock updates scheduled to occur between the start of Day N-4 and the end of Day N-1.

When summing the magnitudes of the clock updates to calculate  $C(N-1)$ , an update which retards the clock will be added in as a negative offset, and one which advances the clock is added as a positive offset. This definition of  $C(N-1)$  is equivalent to lumping all the Clock Update Maintenance Events occurring prior to the start of Day N into one event occurring at the end of Day N-1 (or the beginning of Day N). Since the Utility is only interested in accurately modelling the clock performance during Day N, this procedure is reasonable.

With A, B and  $C(N-1)$  determined, the Utility extrapolates MSX clock performance and schedules Clock Update Maintenance Events for Day N using the following equation:

$$\text{OFFSET}_N(t) = At^2 + Bt + C_N(t) \quad (4)$$

where  $\text{OFFSET}_N(t)$  = expected clock offset during Day N, t = time since the start of Day N-4 (in milliseconds), and  $C_N(t) = C(N-1) +$  the sum of all clock updates scheduled for Day N prior to time t.

The extrapolation of UTC(MSX) performance through Day N will be an iterative process. Using equation 4, the Time Update Utility propagates the clock's offset from the start of Day N through the first point in time during Day N that the clock offset is predicted to be greater than 0.5 milliseconds. This time is called  $T_i$ , and the TUU places a Clock Update Maintenance Event at a time as close to  $T_i$  as possible on the MSX Day N daily schedule.

Because the spacecraft's schedule will have been previously filled with numerous data collection and data playback events, it is unlikely that the clock update can be scheduled exactly at  $T_i$ .

The TUU therefore scans the current Day N MSX daily schedule and identifies a time  $T_u$ , which is the time closest to  $T_i$  that an event can be scheduled. A Clock Update Maintenance Event completes in seconds, so it can be scheduled in very small gaps of open time. Once  $T_u$  is specified, the TUU substitutes  $T_u$  into equation 4, and solves for the expected clock offset at that time.

The magnitude of the clock update to be scheduled on the spacecraft has to be an integer number of milliseconds, and is determined as follows:

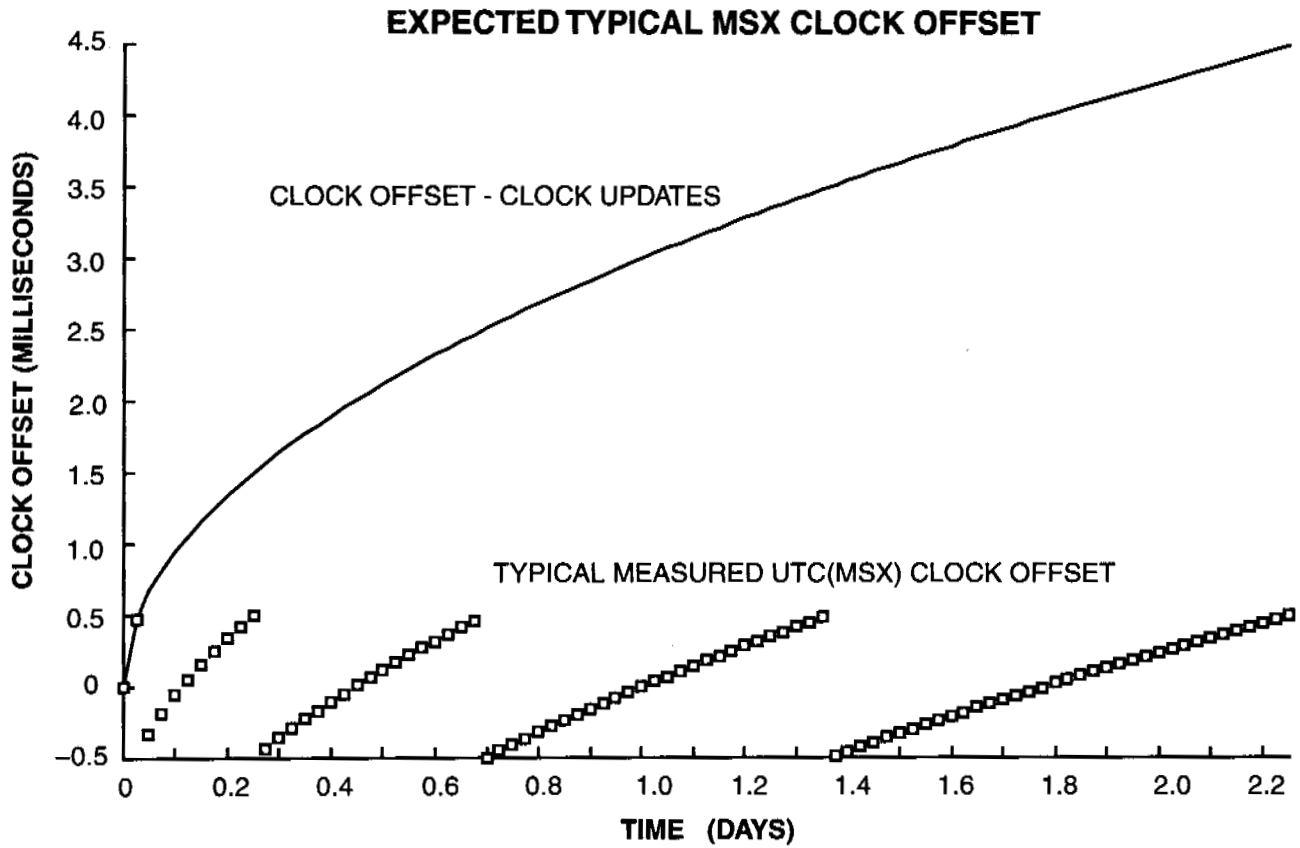
if the expected offset at time  $T_u$  is positive

$$\text{UPDATE}(T_u) = -\text{ROUND}(\text{OFFSET}_n(T_u)) \quad (\text{milliseconds})$$

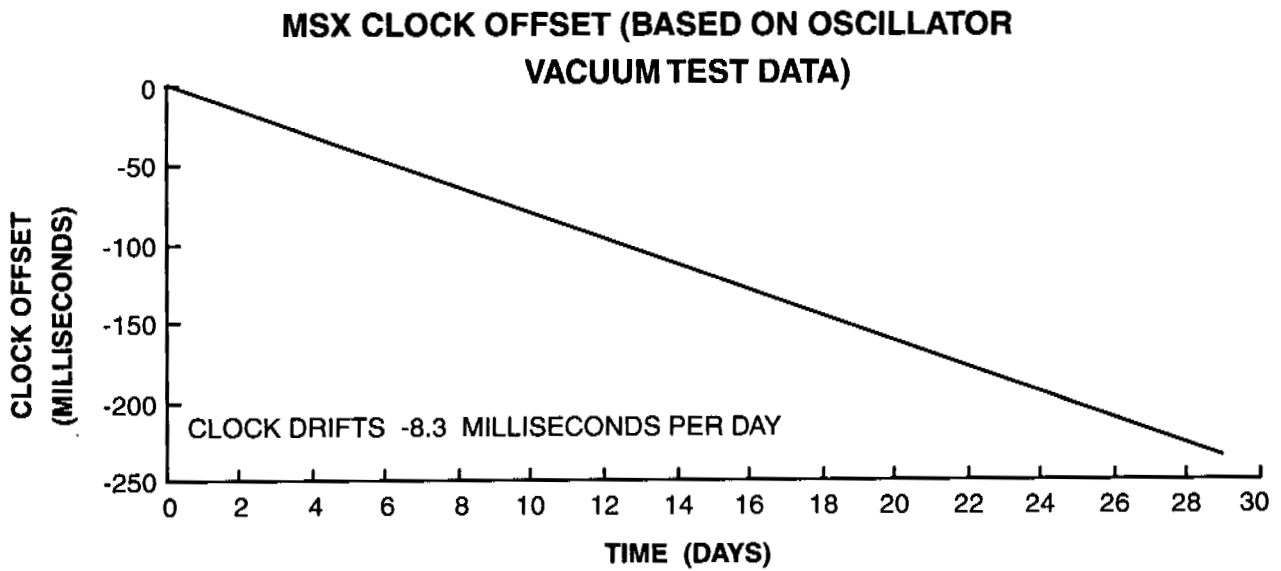
if the expected offset at time  $T_u$  is negative

$$\text{UPDATE}(T_u) = \text{ROUND}(-\text{OFFSET}_n(T_u)) \quad (\text{milliseconds})$$

where the ROUND function simply rounds a decimal number to the nearest integer, UPDATE( $T_u$ ) is the number of milliseconds by which the MSX clock will be advanced or retarded, and OFFSET<sub>n</sub>( $T_u$ ) is the expected clock offset at time  $T_u$ .



**Figure 1**



**Figure 2**