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Subject: Design of the MESSENGER Timekeeping System

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This note describes the design of the timekeeping system for the MESSENGER mission to Mercury. This design is currently being used as the basis for implementation and ground test of the mission timekeeping system. It is also being used as the basis for development of a Concept of Operations (CONOPS) for operation of the mission timekeeping system. The design was presented at the MESSENGER Timekeeping System Design Review in January 2002 and was summarized at the MESSENGER Critical Design Review in March 2002. The numerical details have since changed due to new information about the precision oscillator performance and operating environment. In addition, some changes have been made to the design to simplify the utilization of information gathered from downlink telemetry.

Accuracy requirements

Table 1: MESSENGER Timekeeping Accuracy Requirements

Item	***Onboard knowledge of time***		***Ground knowledge of time***			
	G&C knowledge of Earth time		***Quick-look ("immediate") correlation accuracy between data time tag and UTC***			***After-the-fact correlation accuracy between data time tag and UTC ****
	Coarse oscillator	***Precision oscillator***	***Coarse oscillator***	***Precision oscillator***		***Precision oscillator *****
	First 60 days on cruise, plus safe modes	***Cruise and on-orbit***	***First 60 days on cruise, plus safe modes***	***Cruise***	***On-orbit***	***On-orbit***
Command execution (extrapolated one week forward)			**+/-100 seconds**	**+/-0.5 second**		
G&C attitude control	**+/-3 hours (to find Earth)**					
		+/-100ms (OpNav, MOI & on-orbit)				
Attitude data time tags						+/-10ms (for MLA)
MDIS for OpNav				+/-1000ms (approach), +/-100ms at 10 days later	**+/-25ms ** (landmark tracking)**	+/-3ms
Other MDIS				+/-1000ms (flybys & on-orbit)		+/-10ms (for stereo)
MLA						**+/-1ms**
MLA goal						+/-0.5ms
GRNS						+/-1000ms
MAG						+/-1250ms
EPPS						+/-50ms
XRS						+/-500ms
MASCS						+/-500ms
* Jitter in delivery of MET from DPU to instruments shall be < 1ms between instruments						
**** Assuming no more than 2 days between telemetry downlinks**						

Table 1 is taken from the MESSENGER System Requirements Document (SRD) section 3.3.6.3 [1] and summarizes all the accuracy requirements for the MESSENGER timekeeping system. The requirements for the precision oscillator begin to apply only when the high gain antenna (HGA) is first used, about two to three weeks after launch.

As stated in the SRD, the MESSENGER spacecraft will include two Integrated Electronics Modules (IEM) and each will maintain spacecraft Mission Elapsed Time (MET) and an estimate of Earth time. Each IEM will use an internal coarse oscillator and, in addition, a precision oscillator in a package external to the IEM to increment each MET counter. Note that Table 1 includes different time accuracy requirements when the coarse oscillator is used to increment the MET counter as compared to the time accuracy requirements when the precision oscillator is in use.

Design philosophy

Table 1 reflects a number of distinct requirements that must be satisfied during different phases of the mission by the MESSENGER timekeeping system. In order to keep the implementation, use and, especially, testing of the system as simple as possible, the timekeeping system will be designed to satisfy the same accuracy constraints throughout the mission. This should enhance the reliability of the system by minimizing the overall complexity of the design.

The JHU/APL Space Department recommends that designs incorporate both a “worst case” design philosophy and also include a suitable design margin to accommodate unanticipated or unknown effects that could compromise performance [13]. As stated by the Space Department Chief Engineer, “The Space Department mandates certain minimum system level margins in addition to utilizing a ‘worst case’ design philosophy. This conservative approach has contributed over the years to APL’s enviable record of mission success.” The MESSENGER timekeeping system design follows this recommendation and includes appropriate design margins as well as a worst case approach.

The accuracy requirements in Table 1 fall into three distinct categories, namely, (1) onboard knowledge of Earth time for Guidance and Control (G&C) Subsystem pointing control, (2) “quick-look” correlation accuracy between MET/data time tags and UTC primarily for spacecraft control and OpNavs and (3) “after-the-fact” correlation accuracy between MET/data time tags and UTC for precise science measurements.

Onboard knowledge of Earth time

When the precision oscillator is in use, onboard knowledge of Earth time will be maintained to ±100 ms relative to Earth time at all times that it is possible to do so and to ±3 hours at all other times. Earth time onboard the spacecraft will be kept in terms of the Earth time system called Terrestrial Dynamical Time (TDT or TT), described in Reference [2]. Numerically,

$$\text{TDT} = \text{UTC} + 32.184 \text{ seconds} + (\text{leap seconds}) \quad (1)$$

For the past several years, the number of leap seconds has been 32, so TDT = UTC + 64.184 seconds. In other words, today when the time was 12:00:00.000 UTC the time in terms of TDT was 12:01:04.184 TDT. TDT will be used by the G&C Subsystem as an approximation to Barycentric Dynamical Time (TDB) [2] to access onboard ephemeris data for spacecraft pointing control. The difference between TDT and TDB is always less than 2 ms, which is generally considered negligible for this application. When the coarse oscillator is being used for timekeeping, onboard knowledge of Earth time will be maintained to an accuracy better than ±3 hours.

Quick-look correlation accuracy

When the precision oscillator is in use, the accuracy of the ground-based knowledge of the Mercury Dual Imaging System (MDIS) data time tags relative to Earth time will be maintained to ±25 ms at all times that it is possible to do so to support OpNavs throughout the mission. The actual requirement, as specified in Table 1, is ±1 second during cruise (including Mercury orbit insertion) and ±25 ms while on orbit around Mercury. However, the timekeeping design will not distinguish between the two and will attempt to maintain ±25 ms accuracy at all times. This level of accuracy will apply for at least two days, which is expected to include the interval between the beginnings of consecutive DSN contacts[1] in most relevant cases. In addition, to support spacecraft command execution, the correlation between MET and TDT (or UTC) extrapolated one week in the future will be within ±0.5 second. This is derived from the requirement to predict the time of future burns to within ±1 second one week in the future, with the constraint that the resolution of command time tags is one second. When the coarse oscillator is used for timekeeping, the correlation between MET and TDT extrapolated one week in the future will be within ±100 seconds.

After-the-fact correlation accuracy

While on orbit around Mercury, only the precision oscillator will be used for satisfying science precision time requirements. When the coarse oscillator must be used, the default is that science will not be fully supported. The accuracy of the ground-based knowledge of the Mercury Laser Altimeter (MLA) data time tags relative to Earth time (TDT or UTC) will be maintained to ±1 ms for all times that it is possible to do so. This level is specifically needed to support MLA investigations into whether or not Mercury has a liquid outer core. The goal in

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[1] The terms DSN "contact", "pass" or "track" are all used in this note to mean a continuous period of time during which the spacecraft is communicating with the Earth through the Deep Space Network (DSN). It may include handoffs between DSN stations but includes the total period of communication with <u>all</u> DSN stations.

vestigations into whether or not Mercury has a liquid outer core. The goal in Table 1 of providing ±0.5 ms accuracy of MLA data time tags will remain a goal but does not appear to be achievable near solar maximum, when the spacecraft will be orbiting Mercury, with the expected precision oscillator performance.

Table 1 summarizes the accuracy constraints that have been adopted to guide design of the MESSENGER spacecraft timekeeping system. It is important to note that the timing accuracy requirements in Table 1 for the Attitude Subsystem and the GRNS, MAG, EPPS, XRS and MASCS instruments are the responsibility of the attitude and instrument teams and have not been specifically addressed in the design of the spacecraft timekeeping system.

The spacecraft architecture treats all the instruments as being part of a single Payload package which interfaces with the spacecraft through the redundant Payload Data Processing Units (DPUs). The requirement in Table 1 on time jitter between instruments relates to the handling of time internally to the Payload.

Design overview

The MESSENGER mission timekeeping system consists of a flight component and a ground component. The ground component operates within the Mission Operations Center (MOC). Figure 1 is a sketch of the general framework of the timekeeping system design logic.

Each mission timekeeping system includes certain characteristics that are distinctive. In the case of MESSENGER, the environment offers a particular challenge in satisfying the requirements of Table 1. The effect of solar maximum radiation and wide temperature excursions on the precision oscillator give major contributions to the time error budgets. Long solar conjunctions, particularly just prior to Mercury orbit insertion (MOI) and on orbit around Mercury, also stress the design of the timekeeping system.

The flight component

The timekeeping system flight component physically consists of a “Main Processor” (MP) board, an Interface (“I/F”) board and a precision oscillator. The MP and I/F boards are packaged as part of the IEM and the precision oscillator is packaged separately from the IEM. The MP runs the Command and Data Handling (C&DH) and G&C software as a single CSCI or program. The I/F board contains the coarse oscillator, the 48-bit MET register and other registers that can be read by the MP. The MET is actually composed of two cascaded registers: a 20-bit sub-seconds binary register with 1-microsecond resolution and a 28-bit unsigned binary integer seconds register with 1-second resolution. The sub-seconds counter is called “vMET” in this document and the integer seconds counter is called “iMET” [18]. The I/F board provides to the MP a “one-pulse-per-second” (1 PPS) interrupt that the MP uses to establish a 1-second cycle and a 50 Hz interrupt that the MP uses to establish 20 ms frames. The 50 Hz and 1 PPS interrupts are synchronized so that they are coincident once per second. When the 50 Hz and 1 PPS interrupts are coincident, the C&DH designates the corresponding new frame as frame 0. During frame 0, the C&DH reads the 28-bit iMET integer seconds value from the I/F board; that is the only instance at which the current MET value is read by the MP. For error checking, the C&DH may also read the 20-bit sub-seconds component of MET to ensure there are no unexpected jumps in the 48-bit MET value. The CSCI uses the integer seconds iMET value to compute the onboard estimate of TDT corresponding to the reference edge of the 1 PPS signal using:

$$\text{(2)} \qquad TDT(S) = (iMET - MET1) \times TDTRATE + TDT1$$

The TDT(S) value computed is used by the G&C software to access onboard ephemerides that are expected to be expressed in terms of the TDB Earth time system, which is closely related to TDT and differs from TDT by less than 2 ms. The G&C software can use these ephemerides to control spacecraft attitude and antenna pointing. The values TDT(S), iMET, MET1, TDTRATE and TDT1 will be provided in G&C Time Packets, APID x41F, at a nominal rate[2] of once per hour while in communication with the DSN.

During any of the fifty 20 ms-frames (frames N=0 through N=49), the G&C software uses the equation

$$\text{(3)} \qquad TDT(G\&C) = TDT(S) + (20\ \text{ms})(N)$$

to estimate the time of the beginning of that frame.

The 28-bit integer seconds component of MET is incremented approximately once per second coincident with the reference (leading) edge of the 1 PPS pulse. This value is loosely referred to as “the spacecraft clock.” With this definition, the spacecraft clock or 28-bit iMET is a representation of the time of the reference edge of the 1 PPS signal. The 28-bit spacecraft clock value is distributed to all onboard users of time.

The 48-bit MET counter is incremented every microsecond by a signal from a divide chain derived from the 5 MHz oscillator frequency output. When the precision oscillator is available the divide chain is derived from that oscillator but, when the precision oscillator is not available, the divide chain is derived from the coarse oscillator on the I/F board. The expected oscillator performance re-

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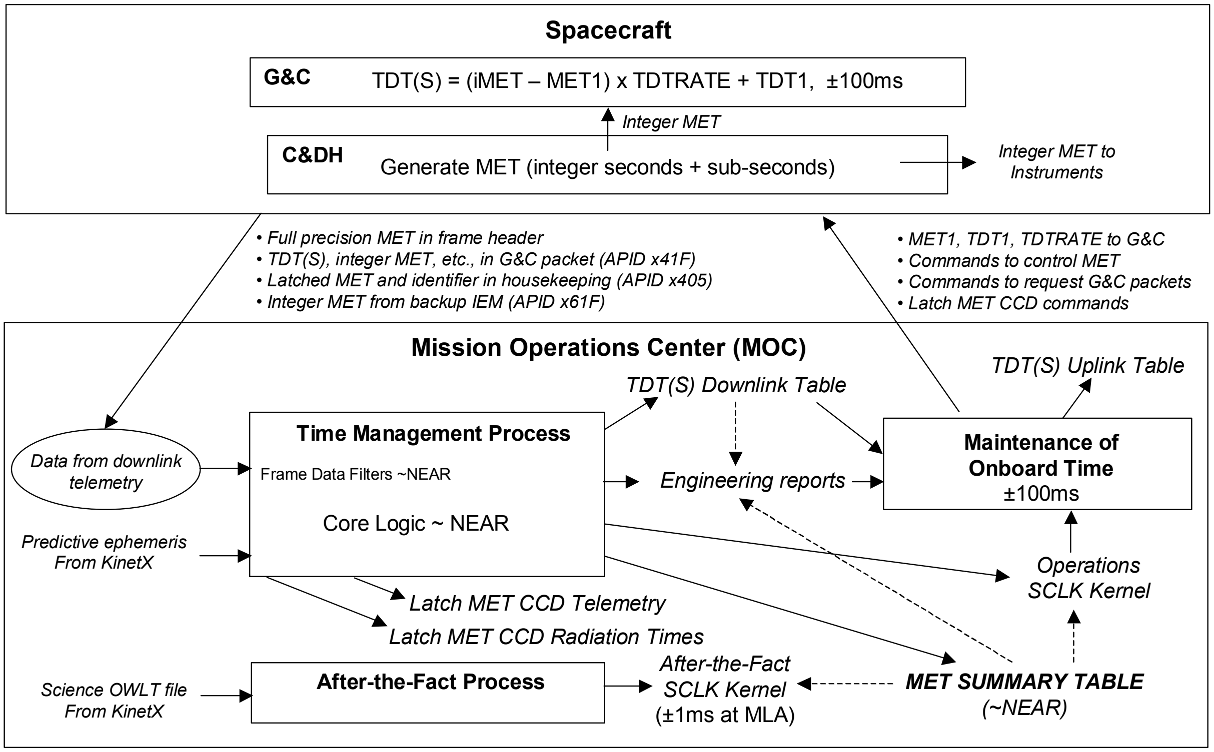
[2] This frequency may be relaxed as the mission progresses and we gain confidence in how well TDT(S) performs.

lated to timekeeping is detailed in later sections of this note. Table 1 reflects the differing accuracy levels required when either oscillator is used. The coarse oscillator is used whenever power is too low to support the precision oscillator or during certain spacecraft safe mode conditions when it is important to reduce the amount of power used. At launch and for several weeks afterward, the coarse oscillator will be used. The precision oscillator is necessary to support mission science measurement requirements.

To summarize the above, the flight component maintains two representations of time, namely, TDT and MET. When the sub-seconds part of MET is zero, the integer seconds value of MET is a representation of the time of the reference edge of the 1 PPS signal. The onboard estimate TDT(S) of TDT is a second representation of the time of that same reference edge. The value TDT(G&C) is related to TDT(S) by equation (3) and is an approximation to the TDT of the time of the 50 Hz interrupt which marks the beginning of a 20 ms-frame.

Figure 1: Framework of the MESSENGER Timekeeping System



Downlink telemetry is not synchronized to the 50 Hz or 1 PPS signals. Timekeeping systems that are constrained to use downlink telemetry that is not synchronized to the 1 PPS are described in Reference [2]. The I/F board provides to the MP a “Downlink Frame Interrupt” which is not synchronized to the 50 Hz or 1 PPS interrupts. The Downlink Frame Interrupt represents the time that the leading edge of the first bit of the primary header of the turbo-coded telemetry frame currently being downlinked is being fed by the I/F board to the transponder, adjusted to account for delays through the transponder.[3] The I/F board latches the 48-bit MET value representing that time. The MP software reads that 48-bit latched value and inserts it into the secondary header of the next downlink frame. In other words, the MET in the downlink frame secondary header is the MET of the leading edge of the first bit of the primary header of the previous turbo-coded downlink frame.

Including the primary and secondary headers and the “Frame Error Control Field” (FECF) [5], each downlink frame will contain either 8920 bits or 1784 bits. The actual length of each frame will depend on whether turbo coding, convolutional coding or “no coding” is used and will be greater than the 8920-bit or 1784-bit information block length, but every physical frame downlinked will begin with a sync pattern. The current mission plan is to use only rate 1/6 turbo-coded downlink telemetry frames. Rate 1/6 turbo coding preceeds each frame with 192 sync symbols equivalent to 32 bit times, and appends to the end of each frame “trellis termination” symbols equivalent to 4 bit times. In other words, turbo coding adds the equivalent of 36 bits to each downlink frame so that the 8920-bit frame “uses” 8956 bit times and the 1784-bit frame “uses” 1820 bit times.[4]

More than 80,000 downlink data rates are available from 10 bits per second (bps) to 104,166.7 bps, although a specific set of 212 rates have been chosen to be explicitly tested during I&T. Appendix C contains a table provided by Karl Fielhauer that provides additional information about the range of downlink data rates available.

In-flight verification of timekeeping accuracy and ground I&T testing of the timekeeping system will utilize a “Latch MET” critical command. Whenever a Critical Command Decoder (CCD) on the I/F board receives an uplinked Latch MET CCD command through one of the transponders, the 48-bit MET value is latched into a “MET at CCD Command” register together with an 8-bit parameter contained in the command itself. The contents of that register and the 8-bit parameter value are placed by the C&DH software once each second into the Spacecraft Housekeeping Packet.

One major function of the flight component is distribution of time to the redundant Payload DPUs that, in turn, provide time to all the science instruments. The value of current 28-bit integer seconds MET read by the C&DH at the 1 PPS

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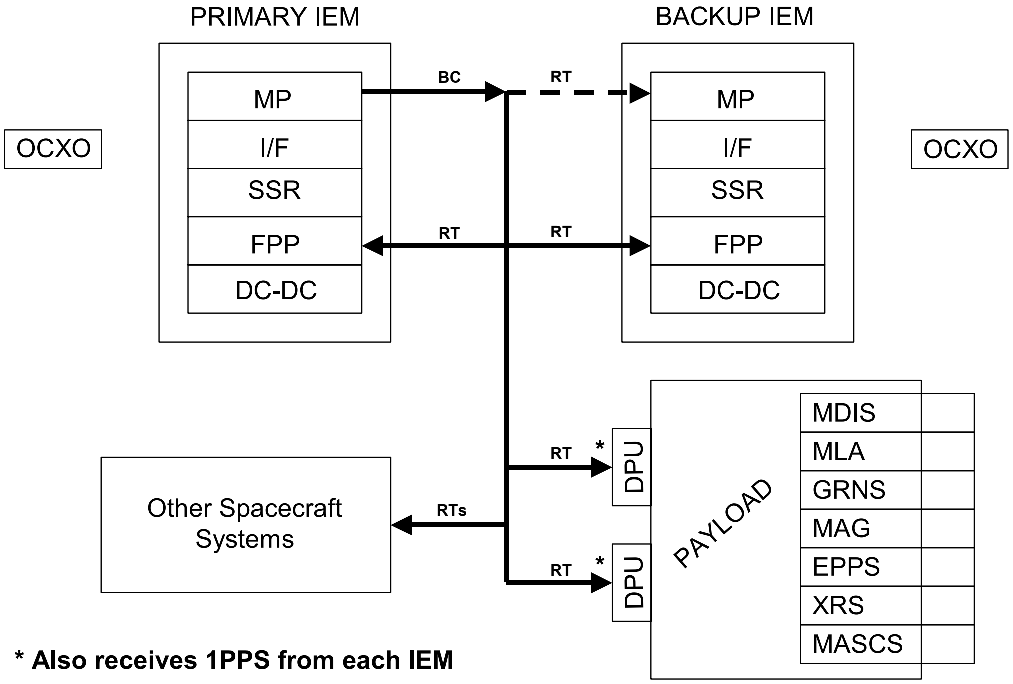
[3] During I&T, we will attempt to confirm that this data rate dependent adjustment is performed correctly.

[4] Convolutional coding increases the frame size only by a preceeding 32-bit sync word.

MP interrupt is modified (by the addition of one second) and transmitted to a DPU via the MIL-STD-1553B data bus. After the next 1 PPS MP interrupt, a "sync-with-data-word" message is sent to the DPU to mark the time to which that MET value corresponds. For the greater accuracy required by some of the instruments, the 1 PPS signal is also provided to each DPU from each IEM I/F board. MDIS processing is included in the DPU but MET is further distributed by the DPU to all the other instruments. For those instruments that require very accurate time, the 1 PPS signal is provided from each DPU to the instruments to mark the time to which the distributed MET corresponds.

Figure 2: Distribution of MET via the MIL-STD-1553B Bus



As shown in Figure 2, the spacecraft contains two IEMs (designated the "primary" or active IEM and "secondary" or backup IEM), each with an associated but separately packaged OCXO. Each IEM [1] [6] contains five boards, namely, the MP and I/F boards, a DC-DC converter board, a Solid State Recorder board and a Fault Protection Processor (FPP). The MP in the primary IEM is designated the primary MP and is the MIL-STD-1553B "Bus Controller" (BC). All other devices attached to the 1553 bus are "Remote Terminals" (RTs). Once per second, the primary MP distributes 28-bit integer seconds iMET on the 1553 bus not only to the two payload DPUs but also to other RTs including the backup MP (when powered) and to the two FPPs [7]. It also once per second sends a "sync-with-data-word" message to each RT; there will be no retransmission of any sync-with-data-word message to prevent ambiguity in knowledge of the time of the 1 PPS.

The I/F (Interface) board in the backup IEM is always powered and the 48-bit MET counter on that board is always counting.

The ground component

The accuracy requirements of Table 1 are, as described earlier, divided into the three major categories “onboard knowledge of Earth time,” “quick-look correlation accuracy” and “after-the-fact correlation accuracy. The Earth time actually used as the basis for all MESSENGER timekeeping is TDT which, as noted earlier, is related to UTC according to equation (1). Note in particular that TDT differs from UTC only by a fixed offset as long as the number of leap seconds does not change, so any accuracy specification or drift rate in terms of either TDT or UTC applies equally to the other.

Design of the ground component is organized around the above three categories of accuracy requirements, as illustrated in Figure 1. At the end of each spacecraft track, which may involve multiple DSN stations, a Time Management Process will be run in the MESSENGER Mission Operations Center (MOC)[5]. The Time Management Process will assess the health (accuracy) of both quick-look ground-based MET-TDT correlation and the onboard estimate of TDT. The After-the-Fact Process is run only when a new “Science OWLT File” is received from the KinetX navigation team.

The Time Management Process performs, basically, six functions. The most critical function is to ensure that no bad downlink telemetry information is used for any other timekeeping functions. The processing functions are

a) Read downlink telemetry data and associated information,
b) Filter out any apparent or potential bad data,
c) Create one or more new entries in the MET Summary Table,
d) Update and distribute the Operations SCLK kernel,
e) Update the TDT(S) Downlink Table
f) Create engineering reports and other related products

Each downlinked telemetry frame is provided by DSN packaged in a “Standard Formatted Data Unit” (SFDU) [8], which contains additional information

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[5] During continuous 24-hour tracks that may happen during critical activities, the Time Management Process will nominally be run once per day. However, that can be increased to three times per day if required. Some special provisions may be necessary to ensure the apparent timeline is not disrupted during such critical operations.

including the “Earth Received Time” (ERT) at which the leading edge of the first bit of the primary header of the turbo-coded frame was received at the DSN station. The Time Management Process will include filters that examine not only data in the telemetry frame itself but also other data in the SFDU. The NEAR timekeeping processing included two such filters, one that blocked short-lived errors lasting only a frame or two and one that blocked longer-term errors. It was observed during NEAR that “Ground Received Time” (GRT), which is what the time of receipt at the DSN station was then called, sometimes was in error by from 50 ms to 20 seconds over a period of some minutes, and the filter to block longer-term errors prevented that problem from corrupting other timekeeping system functions.

At least two bad-data filters will be needed. One will require a number of consecutive good frames with consistent values for MET and ERT and will choose a single pair of consecutive frames from which to extract data, to avoid single-frame errors. The only data extracted from the second of these two frames will be the MET of the first frame. The other filter will ensure that the MET and ERT for the chosen frames are consistent with possible MET drift rates so that the type of error in ERT observed on NEAR will be blocked.

The MET Summary Table, identical in concept to the MET Summary Table used for NEAR processing, will include one record (“row”) for each set of downlink frames used, including all input parameters and computed parameters. The Time Management Process will both use data from this Table and create and populate rows as needed. If, for example, downlinked telemetry frames were examined once per hour for the times included in a DSN track, one row would be added to the Table each hour.

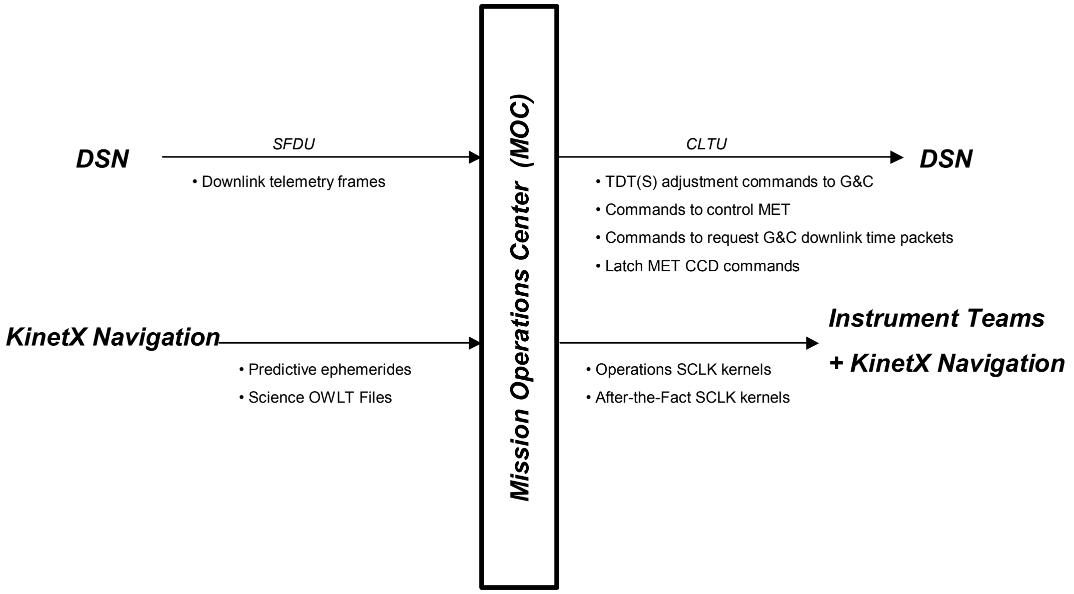
The MET Summary “Table” is actually being implemented in MESSENGER ground software as a collection of tables. It was implemented for the NEAR mission as a single table in an Oracle database. A more appropriate name might be “MET Summary Data Repository” or “MET Summary Data Store”. This document will continue to use the term “MET Summary Table” to be consistent with past usage.

The Operations SCLK kernel is essentially an extension of the MET Summary Table and will allow the Mission Operations onboard time maintenance function to utilize standard SCLK kernel tools to access information available in the Table. These standard tools will be used as well to plan the times of execution of onboard time-tagged commands. The Operations SCLK kernel will also be distributed outside the MOC to support OpNavs and science planning.

The TDT(S) Downlink Table contains one row for each TDT(S), iMET pair received from the spacecraft in downlink telemetry packets. It will contain accompanying information contained in those packets such as TDT1, MET1 and TDTRATE to allow quick evaluation of any operational problems observed. The error in TDT(S) is automatically estimated for the given integer seconds iMET by comparison with the estimate of TDT for that iMET computed by interpolation between entries in the Operations SCLK kernel.

The onboard time maintenance function concerns itself with ensuring that the onboard estimate TDT(S) of TDT satisfies the accuracy constraint of Table 1. Whenever necessary it computes new values for TDT1, MET1 and TDTRATE and provides that to Mission Operations staff for uplink to the spacecraft. Mission Operations onboard time maintenance also maintains a “TDT(S) Uplink Table” which contains one row for each new upload of time parameters to the G&C and includes all related parameters taken from the Operations SCLK kernel and computed parameters such as the estimated error in TDT(S). The Operations Time Engineering File and the Backup IEM Time Engineering File, both products of the Time Management Process, support the operator in monitoring and controlling the behavior of onboard time.

Figure 3: MOC External Timekeeping Interfaces



The After-the-Fact process is run each time a new Science OWLT File is received from KinetX, at least once every two weeks. It extracts data from the MET Summary Table to update the After-the-Fact SCLK kernel. At least one new SCLK kernel entry is made for each DSN track so that the requirements of Table 1 are satisfied.

Figure 3 is a summary of the various Mission Operations Center external timekeeping interfaces. Inputs include downlink telemetry received via the Deep

Space Network (DSN) and spacecraft predictive ephemerides SPICE kernels and Science OWLT Files from KinetX Navigation. Outputs include commands to the spacecraft sent via DSN and the Operations and After-the-Fact SCLK kernels distributed to the instrument teams and to KinetX Navigation. Some supplementary output products may be posted on the Web.

Formats

This discussion involves a number of items including the timekeeping output products, input data, downlink frames and packets and the contents thereof and parameters uplinked to the spacecraft. It includes the MET Summary Table, the TDT(S) Downlink Table and the TDT(S) Uplink Table. ***One area not addressed here is the format of any display of timekeeping information such as MET or UTC/TDT at the MOC; that's largely an issue for the MOC to define and design.***

Mission Operations output products

Mission Operations timekeeping software output products include the following:

a) Operations SCLK kernel
b) After-the-Fact SCLK kernel
c) Operations Time Engineering File
d) Backup IEM Time Engineering File
e) MET Summary Table
f) TDT(S) Downlink Table
g) TDT(S) Uplink Table
h) TDT1, MET1 and TDTRATE for Mission Operations command uplink
i) Latch MET CCD command
j) Latch MET CCD downlink telemetry log
k) Latch MET CCD command radiation time log

SCLK kernels

The SCLK kernel is described in Reference [18]. The heart of each SCLK kernel is the “time coefficients triplet” or “time record” as also described in [18]. A typical time coefficients triplet for MESSENGER is

126247369000000 @18-MAR-2006-00:33:32.495123 0.99999912345

Each of these fields is explained in Reference [18]. They are the encoded SCLK corresponding to the 1 PPS reference event, the estimate of the TDT(G) of that 1 PPS and the clock rate of change of TDT with respect to MET.

For MESSENGER, encoded SCLK is in terms of the count of spacecraft "ticks" or (MET) microseconds since launch. Since encoded SCLK is defined to represent the time of the 1 PPS reference event that defines the integer seconds iMET, the least significant six digits of encoded SCLK will always be zero. In the example above, "126247369000000" represents 126247369 seconds since launch as measured by the MET counter.

The clock change rate, in TDT seconds per MET second, is given as 12 digits including 11 digits to the right of the decimal point. The least significant bit weight of 10^{-11}, when used to extrapolate to a later time than represented by the current record, contributes an error of less than 1 μs per day.

a) Operations SCLK kernel

The Operations SCLK kernel is the "clock kernel" used by Mission Operations to support command time prediction and maintenance of G&C onboard time. It is provided to KinetX to support their optical navigation (OpNav) activity and is also made available to instrument teams and all other users of time.

The change rate in the most recent time coefficients triplet of the Operations SCLK kernel is a prediction of future clock drift behavior and is intended to support linear extrapolation of MET-TDT correlation at least until the next DSN contact. Standard SPICE tools use the clock change rate to extrapolate to later times from an earlier time coefficients triplet, even if a later time coefficients triplet is available.

For all but the most recent time coefficients triplet in the Operations SCLK kernel, the change rate in TDT seconds per MET seconds is determined by linear interpolation between the encoded SCLK and TDT(G) in the same time coefficients triplet and the encoded SCLK and TDT(G) in the next time coefficients triplet. This allows the standard SPICE (extrapolation) tools to provide a more accurate mapping between MET and TDT.

Suppose two consecutive time records (time coefficients triplets) in the Operations SCLK kernel contain the values MET1[6], TDT1, RATE1 and MET2, TDT2, RATE2. Existing tools for reading SCLK kernels would estimate any TDT corresponding to an MET between MET1 and MET2 as the extrapolation

$$\text{TDT}_{\text{PREDICTED}} = \text{TDT1} + (\text{MET} - \text{MET1})(\text{RATE1}). \qquad (4)$$

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[6] Technically, the SCLK kernel records contain encoded SCLK and not MET. However, for simplicity this discussion treats those records as though they instead contain MET.

In order to use the same tools to use linear interpolation between lines of the After-the-Fact SCLK kernel, the rate inserted in the kernel is computed as

$$\text{RATE1} = (\text{TDT2} - \text{TDT1}) / (\text{MET2} - \text{MET1}), \tag{5}$$

so that the same "extrapolation" tools can give us the interpolated value

$$\begin{aligned} \text{TDT}_{\text{INTERPOLATED}} &= \text{TDT1} + (\text{MET} - \text{MET1})(\text{RATE1}) \\ &= \text{TDT1} + (\text{TDT2} - \text{TDT1}) \times (\text{MET} - \text{MET1}) / (\text{MET2} - \text{MET1}). \end{aligned} \tag{6}$$

One new time coefficients triplet is added for each DSN track, more for continuous tracks. This will produce a final Operations SCLK kernel containing less than 3000 time records (about 240,000 bytes), which is well within the capability of SPICE. (SPICE was recently modified to allow up to 10,000 time records in an SCLK kernel.)

b) After-the-Fact SCLK kernel

The After-the-Fact SCLK kernel is designed to support science accuracy requirements and is also distributed to all users of time.

The format of the After-the-Fact SCLK kernel is identical to the above with the following exceptions: The last time coefficients triplet in the After-the-Fact SCLK kernel will have an entry of zero for the change rate. This is because the change rate entries are computed based strictly on linear interpolation between the times of two consecutive time records and there is no record following the last time record. In addition, the last entry in the SCLK kernel array SCLK_PARTITION_END will be changed each time a new time coefficients entry is added to the After-the-Fact SCLK kernel to prevent extrapolation past the last time in the kernel, because such extrapolation could not satisfy the after-the-fact high-accuracy MET-TDT correlation requirement.

With this definition, the direct contribution of the SCLK kernel format to timekeeping error, using the same tools used to access the Operations SCLK kernel, is no worse than Q = 2 microseconds. This includes less than 1 μs error per day using the 12-digit change rate.

As with the Operations SCLK kernel, one new time coefficients triplet is added for each DSN track, more for continuous tracks. This will produce a final After-the-Fact SCLK kernel about the same size as the final Operations SCLK kernel.

c) *Operations Time Engineering File*

This file will support monitoring the performance and accuracy of the time-keeping system and may be posted on internal or external Web sites. It will be updated after each period of communication with the Deep Space Network. This file will be used by Mission Operations to monitor the clock drift rate, error in TDT(S) and other parameters important for monitoring and control of the time-keeping system. When necessary, Mission Operations can also use the MET Summary Table, Operations SCLK kernel or TDT(S) Downlink Table for these purposes. There will be one file for the entire mission, containing one record of time information for each DSN pass. Each record will contain a number of fields:

- Encoded SCLK in units of s/c “ticks”. This is exactly the same as the corresponding entry in the Operations SCLK kernel.
- Corresponding iMET, in integer seconds.
- TDT(G) in calendar format. This is exactly the same as the corresponding entry in the Operations SCLK kernel.
- SPICE numeric representation of TDT(G), in seconds since epoch.
- E_P since last TDT(G) in Operations SCLK kernel, in milliseconds. See Reference [2].
- Initial computed clock change rate in TDT seconds per MET second, based on past data.
- Estimated MET drift rate in milliseconds per day.
- DSN station identifier.
- One-way-light-time (OWLT) in seconds.
- SCLK kernel MET partition.
- Turbo (T) or convolutional (C) coding or no coding (N).
- Computed downlink data rate, in bits per second, based on delta MET between frames. This is an estimate of the commanded data rate and does not reflect any deviation due to oscillator frequency offset.
- SPICE numeric representation of TDT(S), in seconds since epoch, from a recent G&C Time Packet, APID x41F.
- TDT(S) in calendar format.
- Corresponding iMET, in seconds.
- Estimated error in TDT(S), in milliseconds.
- Error threshold, in milliseconds.
- Error alarm setting, in milliseconds.
- G&C parameter MET1 used to compute TDT(S), in integer seconds, from G&C Time Packet.
- SPICE numeric representation of TDT1 used to compute TDT(S), in seconds since epoch, from G&C Time Packet.
- G&C parameter TDT1 in calendar format.
- G&C parameter TDTRATE used to compute TDT(S), in TDT seconds per MET second, from G&C Time Packet.
- Active oscillator, coarse (C) or precision/OCXO (P).

- Active IEM (A or B).
- MOC processing time (UTC).
- Warning message to indicate when TDT(S) exceeds the error alarm setting. If downlink telemetry is not turbo coded, this warning message instead provides that information.

d) Backup IEM Time Engineering File

This file will provide information about the performance of the coarse oscillator in the backup IEM. One particular use will be computation of parameters to be uplinked to the backup MP for potential TDT(S) computation by the G&C Subsystem if the backup IEM ever becomes the primary IEM. Each record in this file will contain the integer seconds iMET from the backup IEM and the corresponding integer seconds iMET from the primary IEM, as well as an indication of which is the backup IEM. The method used to report the backup iMET together with the fact that the METs in the two IEMs are not synchronized results in an accuracy of ±2 seconds in correlation between the two iMET values in the record.

e) MET Summary Table

Conceptually, the “Table” will include a number of functional tables. These have evolved during ground software development into this collection of tables defined in Reference [19]:

- RawTelemetry Table
- OperationsSCLKKernelParms Table
- OperationsTimeEngrFileParms Table
- AfterTheFActSCLKParms Table
- GuidanceAndControlTime Table

These tables may not be in a formal database but that has not yet been decided. However, it is convenient to describe them as though they are components of a database so each table will have a “primary key”. For the first four tables in the above list, the primary key will be a compound key consisting of DSN station identifier plus Earth Received Time (ERT). For the last table, the primary key will be the time (UTC) at which the data was processed in the Mission Operations Center.

<u>The RawTelemetry Table</u> is central to creation of the SCLK kernels. There will be one “row” (record) added to the table roughly once per hour of a DSN pass (which may consist of multiple DSN stations).

Each row will be developed from two consecutive downlink frames (of any available type, i.e., real-time or playback). One underlying understanding is that the frame headers of both real-time and playback frames are constructed in the same manner so that the information in any frame header is always "fresh" and not taken from the Solid State Recorder (SSR). For descriptive purposes, we will refer to the earlier of the two consecutive frames as the "target" frame and the latter of the two frames as the "supplemental" frame. It was noted earlier in the description of the flight system that the 48-bit MET in the secondary frame header of the supplemental frame is actually the MET that represents the time of the leading edge of the first bit of the primary header of the target frame.

Each row of the RawTelemetry Table will contain:
- Full 48-bit MET obtained from the target frame (for frame filters)
- ERT obtained from the SFDU for the target frame (part of primary key)
- Full 48-bit MET obtained from the supplemental frame
- ERT obtained from the SFDU for the supplemental frame (for frame filters)
- Encoding method (turbo or convolutional), from SFDU of target frame
- DSN station identifier, from SFDU of target frame (part of primary key)
- Additional items needed for processing

The OperationsSCLKKernelParms Table supports creation of the Operations SCLK kernel. One row (record) will be added corresponding to each row of the RawTelemetry Table and will contain the corresponding primary key.

Each row of the OperationsSCLKKernelParms Table will contain:
- Target ERT (part of primary key)
- DSN station identifier (part of primary key)
- Current MET partition number
- Encoded SCLK obtained from MET extracted from supplemental frame
- TF_{OFFSET} obtained from MET extracted from supplemental frame
- TD_{SC} used to compute TDT(G)
- One-way-light-time (OWLT) computed from spacecraft ephemeris kernel and used to compute TDT
- Estimated (“initial”) TDT(G) (computed using ERT from target frame)
- Predicted clock change rate (actual entry for Operations SCLK kernel)
- Interpolated clock change rate
- Computed downlink bit data rate
- Additional items needed for processing

The OperationsTimeEngrFileParms Table, together with the OperationsSCLKKernelParms Table and the GuidanceAndControlTime Table, supports creation of the Operations Time Engineering File. One row (record) will be added corresponding to each row of the RawTelemetry Table and will contain the corresponding primary key.

Each row of the OperationsTimeEngrFileParms Table will contain:
- Target ERT (part of primary key)
- DSN station identifier (part of primary key)

- Perceived error E_P due to previous record in Operations SCLK kernel
- MET drift rate computed from "predicted" clock change rate (not from actual entry in Operations SCLK kernel)
- Packet MET from selected record of the GuidanceAndControlTime Table
- Additional items needed for processing

The GuidanceAndControlTime Table supports creation of the TDT(S) Downlink Table. One record will be added for each Guidance and Control Time Packet APID x41F received.

Each row will contain:

- TDT(S) computed by the G&C Subsystem
- The iMET used to compute TDT(S)
- The MET1 used to compute TDT(S)
- The TDT1 used to compute TDT(S)
- The coarse oscillator TDTRATE parameter for TDT(S) computation
- The precision oscillator TDTRATE parameter for TDT(S) computation
- The active oscillator identification (coarse or precision)
- The active IEM identification (A or B)
- The estimated error in TDT(S)
- Packet MET from Guidance and Control Time Packet APID x41F
- Mission Operations Center processing time (UTC), as primary key
- Additional items needed for processing

The AfterTheFactSCLKParms Table supports creation of the After-the-Fact SCLK kernel. It will contain one record for each DSN contact or more than one record for continuous 24-hour DSN station communication. The *baseline plan* is that one record will be created corresponding to each record of the Operations SCLK kernel and so will have a primary key corresponding to that record. That decision may be revisited if necessary.

Each row of the AfterTheFactSCLKParms Table will contain:

- Target ERT (part of primary key)
- DSN station identifier (part of primary key)
- Selected encoded SCLK
- TF_{OFFSET}
- TD_{SC}
- Improved one-way-light-time (OWLT) obtained from Science OWLT File
- Improved TDT(G)
- Improved interpolated clock change rate
- Additional items needed for processing

f) TDT(S) Downlink Table

This table contains the TDT(S) and corresponding spacecraft clock values received in G&C downlink telemetry packets and also includes the TDT1, MET1 and TDTRATE values contained in those packets. One row of the table will be added for each new G&C Time Packet, APID x41F, received.

The contents of each row are:

- TDT(S) computed by the G&C Subsystem
- The iMET used to compute TDT(S)
- The MET1 used to compute TDT(S)
- The TDT1 used to compute TDT(S)
- Actual TDTRATE used to compute TDT(S)
- The estimated error in TDT(S)
- Mission Operations Center processing time (UTC)

g) TDT(S) Uplink Table

This table contains the TDT1, MET1 and TDTRATE values sent to the spacecraft in uplink telemetry. It also contains any information extracted from the Operations SCLK kernel or TDT(S) Downlink Table to support the computations and decisions made.

The contents of each row are:

- Identity of IEM to which parameters were sent (IEM A or IEM B)
- MET1
- TDT1
- TDTRATE for coarse and precision oscillator
- Current estimated error in TDT(S), from Operations Time Engineering File
- E_{ALARM}, from Operations Time Engineering File
- Interval since last G&C time parameter upload to this IEM
- Reason for this upload (“routine” or “alarm”), provided by the operator

h) Uplink command parameters for onboard TDT(S) computation

TDT1 and MET1 provide the initial values for onboard computation of TDT(S) using equation (2), such that TDT(S) = TDT1 when the 28-bit integer seconds iMET numerically satisfies iMET = MET1. TDTRATE is the third parameter needed for that computation. The Timekeeping Concept of Operations (CONOPS) for this mission is that TDTRATE for the coarse oscillator and TDTRATE for the precision oscillator in the same IEM will be identical at all times. The reason for this can be seen from equation (2), which is repeated here:

(7) $\text{TDT(S)} = (\text{iMET} - \text{MET1}) \times \text{TDTRATE} + \text{TDT1}$

If we used a different TDTRATE for the two oscillators then, when switching between the two oscillators in the same IEM, we would have an artificial jump in the onboard estimate TDT(S) because

(8) $(\text{iMET} - \text{MET1}) \times \text{TDTRATE}_{\text{COARSE}} \neq (\text{iMET} - \text{MET1}) \times \text{TDTRATE}_{\text{PRECISION}}$

We understood this only after the G&C Subsystem flight software was committed to using separate TDTRATE values for the two oscillators and that is why any upload of G&C time parameters must specify both values.

The values that will be uploaded, all as 64-bit double precision floating point numbers, will be

- MET1 (integer seconds)
- TDT1 corresponding to MET1
- $\text{TDTRATE}_{\text{PRECISION}}$
- $\text{TDTRATE}_{\text{COARSE}}$

i) Latch MET CCD command

The CLTU that includes the Latch MET CCD command will contain a single Latch MET command. The CLTU format is

- 16-bit sync pattern (EB90 or 146F)
- 64-bit code block
- 64-bit tail sequence

The 64-bit code block is broken down as

- 40-bit header (common to all CCD commands)
- 16-bit Latch MET command
- 8-bit BCH error detection field (based on previous 56 bits)

The 16-bit Latch MET CCD command consists of

- Identifier (an arbitrary 8-bit value) (bits 15-8)
- Not used (4 bits) (bits 7-4)
- Op Code (4 bits) (bits 3-0); binary 1010 for the Latch MET Op Code

j) Latch MET CCD downlink telemetry log

When the Latch MET CCD command is detected in flight hardware, the current 48-bit MET value is latched as well as the 8-bit command identifier. These values are reported in the Spacecraft Housekeeping Packet, APID x405, and are captured in this log file. This packet is normally available only in long (8920-bit) frames and not in the short (1784-bit) frames used at the lowest downlink rates. However, if Latch MET CCD commands are sent while only short frames are being downlinked, the last latched MET and command identifier will be reported in APID x405 once long frames are again being sent and that will be captured in this log file.

The log file is being designed to filter out duplicate entries and include only one record for each MET/identifier pair. A single log file will be maintained for I&T and a single, separate log file for flight.

k) Latch MET CCD command radiation time log

As described in Reference [14], the DSN station that sends a Latch MET CCD command to the spacecraft will report the radiation time of that command to APL. The details of the communication between the DSN and APL have not been finalized but are being worked. The radiation time of the uploaded command will be captured in this log file.

Input data

Data input to the ground system include:

a) Downlink telemetry frame headers and SFDU contents
b) Downlink housekeeping and special time packets
c) Predictive spacecraft ephemeris
d) Science OWLT File

In addition, operator-editable Configuration Files will contain parameters necessary to control execution of the timekeeping system ground software [19]. The Configuration Files are not fully defined at this time.

a) Downlink telemetry frame headers and SFDU contents

As described earlier, the secondary header of each downlink telemetry frame will contain the 48-bit MET corresponding to the time of the previous frame. Additional information such as ERT will be available in the SFDU associated with each downlink frame. The ERT is specified in the Detailed Mission Requirements (DMR) agreement with DSMS as being referenced to the leading edge of the first bit of telemetry data contained in the SFDU with an accuracy of

±25 μs 1σ[7]. The format of ERT and other parameters contained in the SFDU is given in Reference [8].

b) Downlink housekeeping and special time packets

As noted earlier, the values TDT(S) and associated 28-bit iMET, together with the MET1, TDT1 and TDTRATE used to compute TDT(S), will be provided in downlink G&C Time Packets, APID x41F, at a nominal rate of once per hour during communication with the DSN. As with all packets, the downlink rate is controlled by Mission Operations.

To support in-flight verification and ground I&T, the contents of the "MET at CCD Command" register which contains the 48-bit MET at which a Latch MET CCD command was received and the corresponding latched 8-bit parameter value are placed by the C&DH software once each second into the Spacecraft Housekeeping Packet, APID x405. The relevant telemetry mnemonics are HSK_CCD_CMD_MET and HSK_CCD_CMD_ID_MET.

When the backup MP is powered, the backup IEM 28-bit iMET value will be available together with the primary 28-bit MET value in the Boot (Backup) MP Housekeeping Packet, APID x61F. The relevant telemetry mnemonics are BOOTBMP_LOCAL_MET_SEC_61F for the iMET from the backup IEM I/F card and BOOTBMP_SH_TIME_61F, the iMET in the packet header, for the iMET from the primary IEM. (Telemetry parameter BOOTBMP_MET_61F is identical to BOOTBMP_SH_TIME_61F.)

c) Predictive spacecraft ephemeris

Timekeeping will use the same predictive spacecraft SPICE ephemeris information provided by KinetX for navigation. Our agreement with KinetX is that KinetX will send to the MOC at least once every two weeks during cruise and more often on-orbit a new spacecraft predictive ephemeris SPICE ("SPK") kernel (file). The file will provide spacecraft ephemeris accurate to no worse than ±400 km peak (equivalent to roughly ±1.334 milliseconds one-way-light-time or OWLT accuracy) when the file is two weeks old.

d) Science OWLT File

The KinetX navigation team for MESSENGER has agreed to provide a spacecraft "Science OWLT File" with each predictive spacecraft ephemeris kernel. This after-the-fact Science OWLT File will include OWLT from the spacecraft to each individual DSN station, with an accuracy of ±10 microseconds peak. Relativistic effects are accounted for in this number. The Science OWLT File al-

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[7] This is relative to the local DSN station clock. That UTC clock is maintained to be accurate to within ±20 μs 3σ of UTC(NIST), resulting in an ERT accurate to ±95 μs 3σ of UTC(NIST).

ways provides OWLT for past times and the delivered file has a latency of one week. This means the most recent time in the Science OWLT File will be no more than one week old at the time the Science OWLT File is delivered to the MOC. Note that this “Science OWLT File” provides OWLT only for past times and is different from the “Light Time File” used for Mission Operations planning.

Design details and analysis

The numerical details related to MESSENGER timekeeping depend on the characteristics of the precision and coarse oscillators. These are the relevant specifications pertinent to the two oscillator types:

a) Coarse oscillator

- frequency-temperature stability of ±50 ppm over entire oscillator temperature range
- frequency stability of ±5 ppm over the full range of all other environmental factors such as voltage and radiation
- aging of no more than ±5 ppm/year
- initial accuracy at 23°C of ±15 ppm
- negligible frequency sensitivity to solar radiation

b) Precision (OCXO) oscillator

- frequency-temperature stability of 4 ppb over entire 40°C oscillator temperature range (That is, 0.1 ppb per degree C over the 40°C range of precision operation.)
- frequency-temperature stability of 1 ppb total over any 10°C temperature interval for the entire oscillator temperature range (This is based on a maximum predicted change in OCXO temperature over two days between the beginnings of two DSN contacts of no more than 10°C.)
- frequency-voltage stability of ±0.2 ppb over entire oscillator supply voltage range (Note that the load is expected to not vary so the frequency-load sensitivity is not important.)
- aging of less than ±0.05 ppb/day, 30 days after turn-on
- aging of less than ±9 ppb/year
- initial accuracy at 25°C of ±0.1 ppm
- frequency radiation stability of 0.1 ppb/rad (SI) proton radiation
- OCXO warm-up (oven power stabilized) at end of one hour after turn-on

The precision oscillator vendor will commit only to a daily aging specification at 30 days after turn-on and that does not allow us to evaluate the time error budgets earlier than that. We do have some estimates (but not commitments) from the vendor regarding the daily aging rate:

<10 ppb/day	after warm-up
<8 ppb/day	at 1.5 days after turn-on
<5 ppb/day	at 3.0 days after turn-on
<1 ppb/day	at 7.0 days after turn-on
<0.5 ppb/day	at 14 days after turn-on

These numbers are important for evaluating performance when a cold OCXO is turned on. Actual test data received from the vendor for the two OCXO units that have been selected for flight indicates that we should achieve a daily aging rate of <1 ppb/day at 1 day after turn-on.

Part of the mission, including while in orbit about Mercury, will occur during solar maximum when proton radiation from the Sun is high. During major radiation events the oscillator could experience up to perhaps 1500 rads (SI) of proton radiation over a period of a few hours to a few days two or three times a year. The precision oscillator specification given above is frequency-radiation stability of 0.1 ppb/rad (SI) proton radiation so there could be a fairly rapid shift of OCXO frequency of +/-150 ppb. At other times, we expect the background radiation will not exceed 0.0036 rad/min (SI) of proton radiation so (again using 0.1 ppb/rad (SI) proton radiation) the apparent oscillator frequency aging due to background radiation during solar maximum would be no more than 0.518 ppb/day. This is an order of magnitude greater than the normal non-radiation aging of the OCXO.

In considering the effects of oscillator frequency stability and frequency aging, it is important to understand the interval over which these effects occur. With this timekeeping system design that is generally the interval between the beginnings of two consecutive DSN downlink passes. During the launch phase (L to L+15 days) and critical operations this will be at least once per day. During the cruise phase, downlinks will be twice per week but the spacing between two consecutive contacts may be as much as five or more days between. However, during solar conjunctions and DSN station outages the interval between downlink contacts will increase.

The spacecraft will orbit Mercury once every 12 hours, providing the opportunity to begin a new DSN track[8] once every 12 hours. The on-orbit plan is to provide one DSN downlink every 24 hours. However, it will at times be necessary to vary that interval to either 12 hours or 36 hours. Rarely, as when a DSN contact is missed, the interval could be as much as 48 hours and that is the interval used in designing the timekeeping system to meet the requirements of Ta-

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[8] As noted earlier, DSN "track", "pass" and "contact" are used interchangeably and sometimes refer to communication with a single DSN station and sometimes sequential communication with multiple DSN stations. In this memo, these terms all refer to the total period of communication with all DSN stations.

ble 1. That will account for the intervals between most on-orbit downlinks that are not delayed by solar conjunctions.

These are the longest solar conjunctions with Sun-Earth-Probe (SEP) angle $< 3^{o}$ as well as some that are close to critical events:

For the primary mission,

- Longest conjunction on cruise: 19.62 days
- Longest conjunction on orbit: 9.55 days
- Conjunction of 1.90 days starts 21 hours after Mercury flyby #2
- Conjunction of 5.07 days ends 2.9 days before Mercury Orbit Insertion

For the backup mission,

- Longest conjunction on cruise: 45.59 days
- Longest conjunction on orbit: 10.1 days
- Conjunction of 2.2 days starts 4 days after Mercury flyby #1
- Conjunction of 4.3 days starts 6 days after Mercury Orbit Insertion

The remainder of this discussion of design details and analysis is organized around the three categories of timekeeping requirements of Table 1. The time accuracy requirements in Table 1 for G&C attitude control and for command execution time prediction will be supported through Mission Operations use of the **Operations SCLK kernel**. The time accuracy requirement for optical navigation will also be supported by the **Operations SCLK kernel**, which is provided to the KinetX navigation team. The instrument teams can also use the Operations SCLK kernel as a planning tool for science observations. The **After-the-Fact SCLK kernel** will support all the after-the-fact correlation accuracy requirements of Table 1, although the Operations SCLK kernel would also be adequate to support some of the less demanding requirements.

a) MET-UTC/TDT correlation accuracy

Mission timekeeping is based on information received in downlink telemetry frames and accompanying information provided by the receiving NASA Deep Space Network (DSN) stations. Equation (4) of Reference [2] is rewritten and modified here using TDT instead of UTC and provides an estimate on Earth of the time of the reference edge of the onboard C&DH 1 PPS signal:

(9) $\mathrm{TDT(G)} = \mathrm{TDT}_{\mathrm{ERT}} - \mathrm{OWLT} - \mathrm{TD}_{\mathrm{SC}} - \mathrm{TF}_{\mathrm{OFFSET}}$, where

TDT(G) is the estimate on Earth of the TDT corresponding to the 1 PPS reference edge

$\mathrm{TDT}_{\mathrm{ERT}}$ is the Earth Received Time (ERT) that the receiving NASA DSN station appends to the received downlink telemetry frame [8], expressed in terms of TDT

OWLT is one-way-light-time, the signal transit time from the spacecraft antenna to Earth

TD_{SC} is the transmission delay of the first bit of the downlink telemetry frame through the spacecraft, from the time the 48-bit MET is latched by the downlink hardware, and

TD_{OFFSET} is the offset from the 1 PPS reference edge to the time the 48-bit MET is latched

Note that the 48-bit MET corresponding to the computed TDT(G) is contained not in the header of the frame for which TDT(G) is computed but in the secondary header of the next downlink frame.

For each time coefficients triplet in any of the SCLK kernel types, Equation (9) is used to compute the TDT(G) corresponding to the 28-bit integer seconds iMET obtained from the downlink telemetry frame secondary header. For the Operations SCLK kernel, OWLT in Equation (9) is computed using the predictive spacecraft ephemeris SPICE kernel. For the After-the-Fact SCLK kernel, a more accurate OWLT is obtained from the Science OWLT File providing a more accurate estimate of the TDT(G) corresponding to the 28-bit iMET.

We see from Equation (9) that the uncertainty η(TDT(G)) in our estimate of the TDT or UTC corresponding to the 28-bit iMET received in a downlink telemetry frame header is composed of the uncertainties $\eta(TDT_{ERT})$ in TDT_{ERT}, η(OWLT) in OWLT and $\eta(TD_{SC})$ in TD_{SC}, as well as a contribution $\eta(TF_{OFFSET})$ in TF_{OFFSET}. The SPICE computation of OWLT from the predictive spacecraft ephemeris kernel uses TDT_{ERT} so OWLT and TDT_{ERT} are correlated and therefore $\eta(TDT_{ERT})$ and η(OWLT) cannot be combined using root-sum-square (RSS) summation. In general, we take the conservative approach (in conformance with Reference [13]) and use the straight summation

$$(10)\quad U = |\eta(TDT(F))| = |\eta(TDT_{ERT})| + |\eta(OWLT)| + |\eta(TD_{SC})| + |\eta(TF_{OFFSET})| + P,$$

where $P < 1$ μs is the loss of precision in the SCLK kernel representation of TDT(G).

The uncertainty U in our estimate of TDT(G) depends on η(OWLT) which varies according to the source from which OWLT is obtained. We shall use the naming convention throughout this document that $U = U_0$ whenever OWLT is computed from a spacecraft ephemeris kernel and $U = U_1$ whenever a more accurate OWLT is obtained from a Science OWLT File. U_0 is the uncertainty in the TDT(G) value in time coefficients triplets in the Operations SCLK kernel while $U_1 < U_0$ is the uncertainty in the TDT(G) value in time coefficients triplets in the After-the-Fact SCLK kernel.

We expect that $|\eta(TDT_{ERT})| \leq 100$ μs, $|\eta(TD_{SC})| \leq 1$ μs and that $|\eta_{PRECISION}(TF_{OFFSET})| \leq 2$ μs for the OCXO or $|\eta_{COARSE}(TF_{OFFSET})| \leq 76$ μs for the coarse oscillator.[9] However, there are considerations that may increase these numbers: (1) We may not be able to measure TD_{SC} to this level and (2) radiation may increase TD_{SC} during the mission and so increase our uncertainty in this number. With these considerations, η_F = 120 µs seems a reasonable allowance for the summation of these effects when the precision oscillator is used or η_F = 200 µs when the coarse oscillator is used. Then $U = |\eta(OWLT)| + \eta_F$. In the earlier discussion of formats, it was noted that $\eta(OWLT) = \pm 10$ µs when OWLT is obtained from a Science OWLT File, so $U_1 \sim 130$ µs with the precision oscillator. When downlink OWLT is computed from a predictive spacecraft ephemeris kernel, accurate to no worse than ±400km, $\eta(OWLT) = \pm 1.334$ ms so $U_0 \sim 1.5$ ms.

Operations SCLK kernel

To reiterate, $\pm U_0$ is the uncertainty in the mapping of the encoded SCLK (MET) value to TDT(G) in each time coefficients triplet of the Operations SCLK kernel. The “observability” or “measurement uncertainty” U_0 of the Earth time corresponding to an MET was introduced in Reference [2] and is an important figure of merit for the analysis and design of many timekeeping systems.

In order to determine the maximum potential error in mapping from any other MET to TDT or UTC, we must consider the additional error that may be introduced through use of the change rate, the third component of each time coefficients triplet. As noted earlier, the Operations SCLK kernel will support the time accuracy requirements of Table 1 for G&C attitude control and for command execution time prediction. Let’s look at these two items one at a time.

--- Time accuracy for G&C attitude control with the precision oscillator

The requirement of Table 1 when the precision oscillator is in use is to maintain onboard knowledge of Earth time to ±100 ms relative to Earth time at all times that it is possible to do so and to ±3 hours at all other times.

Equation (2) defines the method used onboard the spacecraft to compute an estimate TDT(S) of the Earth time of the reference edge of the 1 PPS signal, and is repeated here:

(11) TDT(S) = (iMET – MET1) x TDTRATE + TDT1, where

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[9] We will use the estimate $TF_{OFFSET} \sim (vMET + 0.5) * (1\ \mu s)$, where MET = (iMET,vMET) introduced earlier defines the sub-seconds counter vMET. This introduces an error less than 1 µs due to the maximum expected OCXO fractional frequency offset of 1 ppm or less than 75 µs due to the maximum expected coarse oscillator fractional frequency offset of 75 ppm (both described later in this document) plus an uncertainty 0.5 µs due to the precision of vMET.

iMET is the 28-bit spacecraft clock value in integer seconds,
MET1 is a parameter uploaded from Mission Operations,
TDTRATE is a scaling parameter (estimated clock change rate in TDT seconds per MET second) uploaded from Mission Operations,
TDT1 is another parameter uploaded from Mission Operations and is the value of TDT(S) when MET = MET1.

The precision oscillator requirement of Table 1 is that the error |TDT(S) – true TDT| < 100 milliseconds in the estimate TDT(S) of the Earth time corresponding to the reference edge of the 1 PPS that set iMET to its specific value. For a given TDT(S), integer iMET pair downlinked in telemetry from the spacecraft, we can estimate the true TDT corresponding to that MET using the Operations SCLK kernel and that is, in fact, exactly what we will use to occasionally monitor the error in the onboard TDT(S) value. This information is downlinked in G&C Time Packet APID x41F.

The process by which the accuracy of TDT(S) is provided for by Mission Operations was described earlier in the design overview section. After modifications to the MET Summary Table and Operations SCLK kernel have been completed, the Time Management Process searches the TDT(S) Downlink Table for the most recent TDT(S) and 28-bit iMET from downlink housekeeping packets and compares TDT(S) with the estimate $TDT_{ESTIMATED}$ obtained from the Operations SCLK kernel for that same iMET. The iMET used to obtain $TDT_{ESTIMATED}$ must be earlier than the last iMET (encoded SCLK) in the Operations SCLK kernel to bound the uncertainty in $TDT_{ESTIMATED}$.

If we incorporate a design margin of 20% = 20 ms for this design, then what we really require is $|TDT(S) – true\ TDT| < A_0 = 80$ milliseconds. For a given MET the corresponding TDT obtained from the Operations SCLK kernel is related to the true TDT as $TDT_{ESTIMATED} = true\ TDT \pm U_X$. Rewriting this, $true\ TDT = TDT_{ESTIMATED} \pm U_X$. Then our requirement is $|TDT(S) – TDT_{ESTIMATED} \pm U_X| < A_0 = 80$ milliseconds or $|E_P \pm U_X| < A_0 = 80$ milliseconds where the error we perceive on the ground is $E_P = TDT(S) – TDT_{ESTIMATED}$. This must hold for all possible values of $E_P \pm U_X$ including the largest of such values, so $|E_P| + U_X < A_0 = 80$ ms or $|E_P| < A_0 – U_X = E_{THRESHOLD}$ will satisfy the requirement of Table 1.

What is the value of $\pm U_X$, the uncertainty in our estimate $TDT_{ESTIMATED}$ of TDT mapped from a particular MET through use of the Operations SCLK kernel? For a given iMET, which must be earlier than the last iMET (encoded SCLK) in the Operations SCLK kernel, the definition of that SCLK kernel provides an estimate of TDT based on interpolation so $U_X = U_0$ + uncertainty due to the normal frequency variation of the OCXO. Using the OCXO stability and effective aging information presented earlier, $U_X \sim 8$ ms is a conservative estimate[10] for the en-

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[10] This assumes daily telemetry downlinks and non-radiation aging of ±10 ppb/day for the first week after OCXO turn-on (K = ±10.518 ppb/day), weekly

tire mission, excluding solar conjunctions. Then $E_{THRESHOLD} = A_0 - U_X \sim 80ms - 8ms = 72$ ms.

The error components that contribute to the perceived error $E_P = TDT(S) - TDT_{ESTIMATED}$ are, considering Equation (11),

- the uncertainty in $TDT_{ESTIMATED}$
- the uncertainty in TDT1
- uncertainty due to error in TDTRATE as estimate of clock change rate

The final item in this error budget is expected to be the major contributor to the budget.

A major radiation event of 1500 rads proton radiation (as discussed earlier) can modify the actual clock change rate by roughly 13 ms/day, which could cause the error budget to be violated quickly. Smaller radiation events could similarly violate the error budget. For this reason, the "CONOPS" or MOC Concept of Operations is to maintain the onboard estimate of TDT(S) through use of "real-time" commands rather than through time-tagged commands, so that MOC can quickly react to unexpected jumps in the error.

We'll now examine several variations in the error budget for $E_{THRESHOLD}$ = 72 ms. For normal operations when we do not encounter a major radiation event or solar conjunction or DSN outage, we have the "TDT(S) precision oscillator error budget":

- 8 ms = U_X = bound on error in estimate of true TDT (for monitoring error in TDT(S)) using Operations SCLK kernel change rate based on interpolation
- 1.5 ms = U_0 = uncertainty in TDT1 when TDT1 is taken from the last Operations SCLK kernel entry
- error in TDT(S) due to OCXO frequency stability
- error in TDT(S) due to effective OCXO frequency aging
- error in TDT(S) due to prediction of the clock change rate TDTRATE

The spacecraft clock (MET) does not perfectly track Earth time in TDT or UTC. In other words, the 1 PPS pulses that increment the 28-bit component of MET are not spaced exactly one UTC second [2] apart. The value TDTRATE represents the Mission Operations estimate of the number of UTC or TDT seconds per MET "second". If the true drift of the spacecraft clock (MET) with respect to UTC remained constant and if we could perfectly measure the past clock change rate, then the TDTRATE scaling performed by Equation (11) would perfectly map the change in MET to the change in TDT. Our worst-case design

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downlinks and non-radiation aging of ±1 ppb/day after the first week (K = ±1.518 ppb/day).

must assume the clock drift rate does not necessarily remain constant and, in addition, our ability to measure the past clock change rate is limited by the "observability" or "measurement uncertainty" U_0 = 1.5 ms.

Notice that TDTRATE in Equation (11) is taken from the last time coefficients triplet of the Operations SCLK kernel.

From Appendix B, we see that the error in estimating the average change in MET per change in TDT using past values of MET and TDT(G) as simply TDTRATE = ΔTDT/ΔMET depends on U_0 and on the effective OCXO frequency aging rate K, as well as on the magnitude T = ΔTDT. It was noted earlier that the effective aging rate depends on both the background radiation (±0.518 ppb/day) and on how recently the OCXO was turned on. When the OCXO is first turned on we do not have good information about the rate TDTRATE. Also, we expect that adjustments to the parameters TDT1 and MET1 of Equation (11) can be done daily or near daily for the first week after the OCXO is powered, so the accuracy of the TDTRATE used is not particularly critical. After the first week, the OCXO non-radiation aging rate, as noted earlier, drops to ±1 ppb/day, so K = ±1.518 ppb/day ~ ±131 μs/day/day. The error E is minimized for these numbers at T = 6.8 days and is approximately ±0.9 ms/day. For other intervals T,

- |E| < 3.07 ms/day if T = 1 day
- |E| < 1.64 ms/day if T = 2 days
- |E| < 1.20 ms/day if T = 3 days
- |E| < 1.02 ms/day if T = 4 days
- |E| < 0.93 ms/day if T = 5 days
- |E| < 0.90 ms/day if T = 6 days
- |E| < 0.89 ms/day if T = 7 days
- |E| < 0.90 ms/day if T = 8 days
- |E| < 0.93 ms/day if T = 9 days
- |E| < 0.96 ms/day if T = 10 days
- |E| < 1.00 ms/day if T = 11 days
- |E| < 1.04 ms/day if T = 12 days
- |E| < 1.09 ms/day if T = 13 days
- |E| < 1.14 ms/day if T = 14 days
- |E| < 1.19 ms/day if T = 15 days

As long as 3 days $\leq$ T $\leq$ 15 days, |E| < 1.2 ms/day, approximately. We should recognize that this average clock change rate really applies only at the beginning of the next prediction interval (see Appendix B) since the oscillator frequency will continue to age over that interval and because the actual clock change rate will vary due to OCXO temperature and voltage changes.

The uncertainty in TDT(S) due to OCXO frequency temperature and voltage stability, based on the OCXO parameters specified earlier is ±4.4 ppb ~ ±380 µs/day. The potential error in TDT(S) due to the effective aging rate K = ±1.518 ppb/day ~ 131 µs/day/day is $(K/2)t^2$ for an interval of t days. With these numbers the "TDT(S) precision oscillator error budget" for "t" days is

- 8 ms ~ U_X = bound on error in estimate of true TDT (for monitoring error in TDT(S)) using Operations SCLK kernel change rate
- 1.5 ms = U_0 = uncertainty in TDT1 when TDT1 is taken from the last Operations SCLK kernel entry
- 3.8 ms uncertainty in TDT(S) due to OCXO frequency stability (±4.4 ppb)
- 6.6 ms uncertainty in TDT(S) due to OCXO frequency aging (±1.518 ppb/day)
- 12.0 ms uncertainty in TDT(S) due to estimate of TDTRATE

~ 31.9 ms expected maximum TDT(S) error over t = 10 days[11]

- 8 ms ~ U_X
- 1.5 ms = U_0
- 5.7 ms uncertainty in TDT(S) due to OCXO stability
- 14.8 ms uncertainty in TDT(S) due to OCXO aging
- 18.0 ms uncertainty in TDT(S) due to TDTRATE estimate

~ 48.0 ms expected maximum TDT(S) error over t = 15 days

- 8 ms ~ U_X
- 1.5 ms = U_0
- 7.6 ms uncertainty in TDT(S) due to OCXO stability
- 26.3 ms uncertainty in TDT(S) due to OCXO aging
- 24.0 ms uncertainty in TDT(S) due to TDTRATE estimate

~ 67.4 ms expected maximum TDT(S) error over t = 20 days

- 8 ms ~ U_X
- 1.5 ms = U_0
- 9.5 ms uncertainty in TDT(S) due to OCXO stability
- 41.0 ms uncertainty in TDT(S) due to OCXO aging
- 30.0 ms uncertainty in TDT(S) due to TDTRATE estimate

~ 90.0 ms expected maximum TDT(S) error over 25 days, exceeding $E_{THRESHOLD}$

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[11] It is sometimes possible to combine the component uncertainties using a root-sum-squared method but that requires careful application to avoid misleading results and is not always applicable. The simple summation approach is more conservative and can always be used.

- 8 ms ~ U_X
- 1.5 ms = U_0
- 19.0 ms uncertainty in TDT(S) due to OCXO stability
- 164.0 ms uncertainty in TDT(S) due to OCXO aging
- 60.0 ms uncertainty in TDT(S) due to TDTRATE estimate

~ 252.5 ms maximum TDT(S) error over t = 50 days, exceeding $E_{THRESHOLD}$

The CONOPS for normal operations is to upload new parameters for on-board computation of TDT(S) to the spacecraft based on downlink telemetry received just two or three days prior to the uplink. If Mission Operations does a weekly upload of new parameters, then the error in TDT(S) would be less than the 15-day precision error budget of 48 ms even allowing for an occasional DSN outage. For normal operations if we set an alarm threshold slightly higher than this, perhaps at E_{ALARM} = 50 ms, then E_{ALARM} should never be exceeded as long as new parameters for computing TDT(S) are uploaded at least weekly. If it ever happens that the perceived error $|E_P|$ in TDT(S) does exceed E_{ALARM} then it is likely a significant solar radiation event has caused a substantial jump in the clock change rate. In that case we would have perhaps ($E_{THRESHOLD}$ – E_{ALARM})/(13 ms/day) = 22 ms/(13 ms/day) ~ 2 days after the downlink telemetry is received to upload new parameters for computing TDT(S) before the error budget $E_{THRESHOLD}$ = 72 ms is violated. This is based on very conservative numbers and on a conservative design margin of 20% = 20 ms.

How should Mission Operations proceed if $|E_P| > E_{ALARM}$? First, to be sure the alarm is not just caused by a transient data glitch, $|E_P| > E_{ALARM}$ should be satisfied for at least two observations during the downlink pass, spaced apart sufficiently to ensure data from the two observations are uncorrelated. Uplink parameters TDT1 and MET1 can be determined as usual from the Operations SCLK kernel. Uplink parameter TDTRATE is more difficult to determine since that is exactly the parameter that has been placed in question by the alarm. Since the radiation event has likely raised for the short-term the level of background proton radiation, the guidelines above for limiting the error in computing TDTRATE = ΔTDT/ΔMET no longer apply. I recommend that the predictive TDTRATE value that was computed automatically for the Operations SCLK kernel be used as it normally is for the first parameter correction upload after the alarm and that additional parameter uploads be performed every few days thereafter until the downlinked values of TDT(S) again behave normally. In that way, the error in TDT(S) is not likely to grow very large between parameter uploads. Of course, that error will need to be carefully monitored to ensure it does not grow too rapidly.

On NEAR, new parameters for computing TDT(S) were uplinked as part of the preparation for each critical maneuver so clock drift was not a major issue for those times. MESSENGER CONOPS will likely follow a similar procedure. In addition, long solar conjunctions are possible during the mission and for those it would also seem prudent to upload new TDT(S) computation parameters just prior to those conjunctions. The TDT(S) precision oscillator error budget given above can serve as a guideline for determining the maximum error in TDT(S) during long conjunctions.

--- Time accuracy for G&C attitude control with the coarse oscillator

The requirement of Table 1 when the coarse oscillator is in use is to maintain onboard knowledge of Earth time to within ±3 hours at all times.

The uncertainty in TDT(S) due to oscillator frequency temperature and voltage stability, based on the coarse oscillator parameters specified earlier is ±110 ppm ~ 9.5 seconds/day. The potential error in TDT(S) due to the effective aging rate K = ±5 ppm/year ~ 158 seconds/year/year is $(K/2)t^2$ for an interval of t years. The initial error |E| in the estimate of TDTRATE is dominated by the aging rate and is

- |E| ~ 5 ms/day if T = 1 day
- |E| ~ 16 ms/day if T =7 days

With these numbers the "TDT(S) coarse oscillator error budget" for 100 days is

- 67 seconds ~ U_X = bound on error in estimate of true TDT (for monitoring error in TDT(S)) using Operations SCLK kernel change rate
- 1.5 ms = U_0
- 950 seconds uncertainty in TDT(S) due to oscillator stability
- 9 seconds uncertainty in TDT(S) due to oscillator aging
- 2 seconds uncertainty in TDT(S) due to TDTRATE estimate

~ 20 minutes expected maximum TDT(S) error over t = 100 days

As with all our discussions of oscillator behavior, this is based on an oscillator model that includes certain assumptions such as linear oscillator aging over time. However, it is clear from this discussion that use of the coarse oscillator should easily satisfy the ±3 hours requirement provided a reasonable estimate of TDTRATE is used.

--- Command execution time prediction accuracy with the precision oscillator

Now let's consider the ±0.5 second MET-UTC time correlation requirement for the prediction of engine burn command execution time one week in the future. The source of this requirement is that command execution start times need to be controlled for burns to within ±1 second. The response to Action Item #1 (Reference [10]) from the MESSENGER Timekeeping System Design Review determined that, because command time tag resolution is 1 second, the burn time accuracy can be achieved if MET-UTC time correlation is predicted to within ±0.5 second.

Given that we want a command to be executed at a certain future UTC, we use the Operations SCLK kernel to map that UTC (after conversion to TDT) to the onboard iMET that needs to be specified as the execution time for that command. This mapping will generally involve the last time coefficients triplet of the SCLK kernel. We noted earlier that we would set the change rate in that last time coefficients triplet to the same value used above for the onboard value of TDTRATE that the G&C processor uses for maintaining an estimate of Earth time. From the discussion above, the estimate of TDTRATE with the OCXO may be in error throughout the mission by ±1.2 ms/day. The error budget (at least one week after the OCXO is turned on and during normal solar maximum background radiation) to consider is then

- 100 ms = 20% design margin
- 1.5 ms = U_0 = initial TDT/iMET mapping uncertainty when TDT is taken from the last entry in the Operations SCLK kernel
- 2.7 ms uncertainty due to OCXO frequency stability (±4.4 ppb over 7 days)
- 3.3 ms uncertainty due to OCXO frequency aging (K = ±1.518 ppb/day)
- 8.4 ms = the uncertainty over one week due to estimation error in TDTRATE

which totals 116 ms and satisfies the ±0.5 second accuracy requirement. Technically, we should add another $2U_0$ = 3 ms to the error budget [2] if we use downlink telemetry to verify that the ±0.5 second is achieved, but even then the error budget is satisfied.

When a major solar proton radiation event occurs, the above error budget will not apply. The radiation model being used expects the OCXO to be exposed to a total of 5190 rads (SI) solar proton radiation over the 2.75 solar maximum years of the mission, most of which arrives during several major radiation events. The maximum of 1500 rads per event is just a ballpark number that is being used here because we do not know what the actual maximum dose could be during any particular event. It was noted earlier that an event of 1500 rads could cause a fairly rapid shift (over several days) of OCXO frequency of ±150 ppb or about 13 ms/day. Over 7 days that would total 91 ms or so; let's use 100 ms since our model of the maximum radiation per event is just an estimate. That brings the error budget in predicting over one week the MET corresponding to a particular TDT for creating a time-tagged command to about 216 ms, which still satisfies the ±0.5 second requirement.

When the OCXO is first turned on, the aging rate will be much higher and will contribute perhaps an additional 10 ms or so to the error budget. However, we will not have a good estimate of TDTRATE so prediction of the MET corresponding to a particular TDT over a period of a week would be a risky thing to do.

It would probably be best to not schedule time-tagged commands during the first week after the OCXO is turned on if MET is driven by that OCXO. If it is necessary to schedule time-tagged commands with the MET driven by an OCXO that has just been turned on, we could use TDTRATE = 1. The maximum error in prediction of MET would be ~86 ms/day because the maximum OCXO fractional frequency offset by the end of the mission is expected to be less than ±1 ppm, as explained later in the section on oscillator switching scenarios. To satisfy the ±0.5 second MET command execution prediction time of Table 1 required with the precision oscillator would necessitate reducing the extrapolation interval to a period shorter than the week specified in Table 1. Based on the error budget above, that period would have to be bounded at about three days.

--- *Command execution time prediction accuracy with the coarse oscillator*

The requirement in Table 1 for MET-UTC time correlation requirement for the prediction of engine burn command execution time one week in the future is ±100 seconds.

As above, given that we want a command to be executed at a certain future UTC, we use the Operations SCLK kernel to map that UTC (after conversion to TDT) to the onboard MET that needs to be specified as the execution time for that command. This mapping will involve the last time coefficients triplet of the SCLK kernel. We noted earlier that we would set the change rate in that last time coefficients triplet to the same value used above for the onboard value of TDTRATE that the G&C processor uses for maintaining an estimate of Earth time.

From the earlier discussion, the estimate of TDTRATE may be in error throughout the mission by ±16 ms/day or so. The error budget is then

- 20 seconds = 20% design margin
- 1.5 ms = U_0 = initial TDT/MET mapping uncertainty when TDT is taken from the last entry in the Operations SCLK kernel
- 66.5 seconds uncertainty due to coarse oscillator frequency stability (±110 ppm over 7 days)
- 106 ms uncertainty due to frequency aging (estimated $|K| < 0.05$ ppm/day)
- 112 ms = the uncertainty over one week due to estimation error in TDTRATE

which totals 87 seconds and satisfies the ±100 seconds requirement. Technically, we should add another $2U_0$ = 3 ms to the error budget [2] if we use downlink telemetry to verify that the ±100 seconds is achieved but that adjustment is negligible.

When the coarse oscillator is first turned on, we will not have good knowledge of TDTRATE and should assume TDTRATE = 1, which is the same as assuming zero drift in MET relative to Earth time. The error in that assumption is described later in the section on oscillator switching scenarios and is expected to be no more than ±75 ppm or ±6.5 seconds/day in prediction of MET. Referring back to the error budget above, we would have to bound the period over which MET is extrapolated to about 4½ days in order to not exceed the ±100 seconds requirement of Table 1.

--- *Quick-look ground knowledge of time to support OpNavs*

In addition to the functions described above, the Operations SCLK kernel provides correlations between MET and TDT to support the optical navigation (OpNav) activity of the KinetX navigation team when the precision oscillator is being used. From Table 1, the requirement that needs to be satisfied by the Operations SCLK kernel is ±25 milliseconds accuracy in correlation between MET and TDT/UTC. This requirement applies strictly only when the spacecraft is on orbit around Mercury but we expect the Operations SCLK kernel to satisfy this for the entire mission. The OpNav process requires knowledge of the mapping between the spacecraft MET clock and TDT or UTC for those MET values associated with images that have already been taken and have been received in downlink telemetry and forwarded to the KinetX navigation team. However, newly downlinked OpNav images may be sent to KinetX before a newly updated Operations SCLK kernel is available. That means it is necessary that the accuracy requirement be satisfied by the Operations SCLK kernel at least until the next telemetry downlink so that any OpNav images taken during that period can have their MET values accurately mapped to TDT or UTC.

Let's reuse parts of the error budget developed earlier in the section on precision oscillator command time prediction:

- 5 ms = 20% design margin
- 1.5 ms = U_0 = initial TDT/iMET mapping uncertainty when TDT is taken from the last entry in the Operations SCLK kernel
- 2.7 ms uncertainty due to OCXO frequency stability (±4.4 ppb over 7 days)
- 3.3 ms uncertainty due to OCXO frequency aging (K = ±1.518 ppb/day)
- 8.4 ms = the uncertainty over one week due to estimation error in TDTRATE

which totals ±20.9 ms and satisfies the ±25 ms accuracy requirement over an interval of 7 days. Since a radiation event could increase this error due to a change in clock drift rate, it would be prudent to have more frequent DSN contacts during any period that an OpNav will be performed.

After-the-Fact SCLK kernel

Achievement of the $\pm S_1 = \pm 1$ ms after-the-fact accuracy requirement for MLA data time tags relies on a new approach to using existing tools. The reader should note this approach may not have been used before. This accuracy requirement applies only when the spacecraft is on orbit around Mercury and only when the precision oscillator is used and does not apply when the coarse oscillator is in use.

The approach used is linear interpolation between time coefficients triplets in the After-the-Fact SCLK kernel together with improved knowledge of one-way-light-time (OWLT) used to compute the time coefficients triplets.

We have decided to use the SPICE SCLK kernel scheme to support maintenance of after-the-fact timekeeping in order to utilize the same tools used to access the Operations SCLK kernels. We plan to use the “Science OWLT File” from KinetX described earlier, providing downlink OWLT accurate to ±10 μs. From our earlier discussion, U_1 = 130 μs.

Provided the precision oscillator has been on at least 30 days and assuming no more than two days between the start of two consecutive DSN contacts, the after-the-fact time error budget is

11 μs = allowance for MLA instrument time uncertainties
10 μs = allowance for uncertainty due to distribution of 1 PPS to MLA
130 μs = U_1 = bound on interpolation error due to measurement uncertainty U_1
9 μs = bound on interpolation error due to aging (K = 0.05 ppb/day, 30 days after turn-on)
90 μs = bound on interpolation error due to background radiation (0.518 ppb/day)
44 μs = bound on interpolation error due to relativistic effects on oscillator [16]
242 μs = bound on interpolation error due to OCXO temperature/voltage effects
2 μs ~ Q = bound on computation error due to precision of After-the-Fact SCLK kernel change rate

This adds up to ±538 μs, leaving a margin exceeding 40% of the ±1 ms accuracy requirement. This applies only during “quiet” times with the solar maximum background proton radiation level and at least 30 days after the precision oscillator has been turned on.

When oscillator switching occurs and a cold OCXO is turned on, it is likely that telemetry downlinks will occur daily and not at the maximum two days between downlinks that we normally provide for. With daily downlinks and using the higher OCXO aging rate that applies shortly after turn-on, the after-the-fact time error budget becomes

11 μs = allowance for MLA instrument time uncertainties
10 μs = allowance for uncertainty due to distribution of 1 PPS to MLA
130 μs = U_1 = bound on interpolation error due to measurement uncertainty U_1
432 μs = bound on interpolation error due to aging (K = 10 ppb/day after warm-up)
23 μs = bound on interpolation error due to background radiation (0.518 ppb/day)

<44 μs = bound on interpolation error due to relativistic effects on oscillator
121 μs = bound on interpolation error due to OCXO temperature/voltage effects
1 μs ~ Q = bound on computation error due to precision of After-the-Fact SCLK kernel change rate

This adds up to ±772 μs, leaving a margin exceeding 20% of the ±1 ms accuracy requirement.

About a week after a cold OCXO is turned on, if we again assume the maximum two days between downlinks and note that the OCXO aging rate has rate has decreased, the after-the-fact time error budget becomes

11 μs = allowance for MLA instrument time uncertainties
10 μs = allowance for uncertainty due to distribution of 1 PPS to MLA
130 μs = U_1 = bound on interpolation error due to measurement uncertainty U_1
173 μs = bound on interpolation error due to aging (K = 1 ppb/day, 7 days after turn-on)
90 μs = bound on interpolation error due to background radiation (0.518 ppb/day)
44 μs = bound on interpolation error due to relativistic effects on oscillator
242 μs = bound on interpolation error due to OCXO temperature/voltage effects
2 μs ~ Q = bound on computation error due to precision of After-the-Fact SCLK kernel change rate

This adds up to ±702 μs, leaving a margin of 30% of the ±1 ms accuracy requirement.

If downlink contact intervals are such that we expect no more than 1.5 days between downlinks, the after-the-fact time error budget a week after a cold OCXO is turned on becomes

11 μs = allowance for MLA instrument time uncertainties
10 μs = allowance for uncertainty due to distribution of 1 PPS to MLA
130 μs = U_1 = bound on interpolation error due to measurement uncertainty U_1
98 μs = bound on interpolation error due to aging (K = 1 ppb/day, 7 days after turn-on)
51 μs = bound on interpolation error due to background radiation (0.518 ppb/day)
<44 μs = bound on interpolation error due to relativistic effects on oscillator
182 μs = bound on interpolation error due to OCXO temperature/voltage effects
2 μs ~ Q = bound on computation error due to precision of After-the-Fact SCLK kernel change rate

This adds up to ±528 μs, leaving a margin of more than 40% of the ±1 ms accuracy requirement.

The various margin values noted above will be important in the discussion of in-flight verification of timekeeping accuracy.

If a major solar proton radiation event occurs, the error budget will not be satisfied until after that event because of the potentially significant change in oscillator frequency offset and resultant jump in MET counter drift rate.

Oscillator switching scenarios

Each of the two IEMs can use either a coarse oscillator or a precision oscillator (OCXO) to drive the divide chain which increments the MET counter and generates the 1 PPS signal, so any one of four oscillators may be the source of spacecraft MET. We will launch using the coarse oscillator in the primary IEM and switch several weeks later to the precision oscillator in that same IEM. The mission CONOPS is to then operate with that precision oscillator for the rest of the mission. However, various possible safing scenarios can cause us to switch back to the coarse oscillator in the same IEM or to switch to the other IEM. We can switch from any one of the four oscillators to any one of the others with only one restriction: We will switch to a precision oscillator only from the coarse oscillator in the same IEM and not from either oscillator in the other IEM.

There are two primary timekeeping issues to deal with when switching oscillators or IEMs: (1) a potential artificial jump in the onboard G&C estimate TDT(S) of Earth time and (2) discontinuity in the SCLK kernels. Let’s examine these one at a time.

--- Artificial jump in TDT(S)

The G&C software in each IEM computes an estimate of Earth time with Equation (11), which is repeated here:

$$\text{TDT(S)} = (\text{MET} - \text{MET1}) \times \text{TDTRATE} + \text{TDT1} \tag{12}$$

The parameters MET1, TDT1 and TDTRATE are uploaded from Mission Operations. When we switch from one oscillator in the primary IEM to the other oscillator in that same IEM without rebooting the MP, if we continue to use the same MET1 and TDT1 values but change TDTRATE to reflect use of a different oscillator we will see an artificial jump in the estimate TDT(S). This could cause the estimate TDT(S) to become insufficiently accurate to support G&C functions.

What can we do to prevent this jump in TDT(S)? There are several possible approaches. The two oscillators are not synchronized but the MET value will jump by only a few hundred nanoseconds due to the way the hardware is implemented so that is not an issue. We could autonomously adjust TDT1 given a new TDTRATE to ensure there is no large jump in TDT(S). However, we will generally not know what the actual clock change rate is. *<u>The simplest approach when switching between oscillators in the same IEM is to continue to use the</u>*

same values for MET1, TDT1 and TDTRATE. The jump in TDT(S) is then only a few hundred nanoseconds. Since one of the two oscillators is the coarse oscillator, the Table 1 accuracy requirement with which we are concerned is ±3 hours, which should be easy to maintain even if the next DSN contact is a week or more away.

Let's look at the details. The coarse oscillator specifications are initial accuracy of ±15 ppm and aging of ±5 ppm/year so the frequency offset at the end of the mission (allowing a maximum of 12 years ground test plus flight) could be ±75 ppm which is equivalent to ±6.5 seconds/day of MET drift relative to UTC or TDT. The coarse oscillator offset is apparently not significantly affected by solar radiation. The precision OCXO specifications are initial accuracy of ±100 ppb and aging of ±9 ppb/year[12] so the frequency offset at the end of the mission could be ±208 ppb. In addition, the OCXO will be exposed to roughly 5200 rads (SI) of proton radiation over the several years of solar maximum and that can cause an additional frequency offset of 520 ppb so the frequency offset at the end of the mission would be less than ±1 ppm. In switching from one oscillator to the other with the same IEM, the maximum error due to continuing to use the same value for TDTRATE would be about ±76 ppm ~ ±6.6 seconds/day of MET drift relative to UTC or TDT. The error over 100 days would be roughly 660 seconds which, when combined with the "TDT(S) coarse oscillator error budget" presented earlier, results in a maximum error in TDT(S) of less than half an hour, well within the ±3 hours accuracy requirement of Table 1. *That means that, even through the longest solar conjunctions, continuing to use the same values for MET1, TDT1 and TDTRATE when the IEM switches between its two oscillators will maintain TDT(S) accurate to within ±3 hours of UTC or TDT.*

The situation is similar if we switch from the precision oscillator to the coarse oscillator in the same IEM because the MP has been rebooted, as long as the parameters MET1, TDT1 and TDTRATE are retained (in non-volatile memory) through the reboot.

When we switch IEMs, the estimate TDT(S) in the new primary IEM MP will differ ("jump") relative to the last estimate TDT(S) in the old primary IEM MP. The backup IEM will have in non-volatile memory values for the parameters MET1, TDT1 and TDTRATE that were uploaded from Mission Operations the last time the backup MP was turned on based on previous downlinks of the Boot MP Housekeeping Packet. Those parameter values may be based on downlinks that are many months old. The CONOPS for the backup MP is that it will be turned on only once every few months for a few hours. Suppose the backup MP was turned on every three months prior to switching to that IEM, so the MET1, TDT1 and TDTRATE values could be based on data that is no more than six months

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[12] Vendor test data does not support this number. However, the test data does give an upper bound of better than ±25 ppb/year and that does not change the conclusion of this analysis.

old. In the worst case, we would have no reasonable information about TDTRATE and could use, perhaps, TDTRATE = 1. From the discussion above, the frequency offset at the end of the mission could be ±75 ppm, which is equivalent to ±6.5 seconds/day of MET drift relative to UTC or TDT. Over six months the error in TDT(S), following the budget presented earlier, could be

- 67 seconds ~ U_X
- 1.5 ms = U_0
- 1739 seconds uncertainty in TDT(S) over six months due to oscillator stability
- 20 seconds uncertainty in TDT(S) due to oscillator aging
- 1190 seconds uncertainty in TDT(S) due to use of TDTRATE = 1

~ 3016 seconds < 1 hour expected maximum error in TDT(S) over six months

In other words, TDT(S) computed by the new primary IEM MP will be in error by less than 1 hour as compared to the error of less than 20 minutes that had been computed by the old primary IEM MP. The "jump" in TDT(S) when switching IEMs will then be less than 1 hour 20 minutes.

In summary, a viable approach to maintaining TDT(S) accurate to within ±3 hours of UTC or TDT through all planned oscillator switching scenarios is the following: When switching between the two oscillators in the same IEM, continue to use the same MET1, TDT1 and TDTRATE values. This results in a jump in TDT(S) of a few hundred nanoseconds. When switching IEMs, use TDTRATE = 1 and the last MET1, TDT1 values uploaded to the backup MP from Mission Operations. As long as the backup IEM MET1 and TDT1 values are based on downlink telemetry from Boot MP Housekeeping Packets no more than six months old (due to MET1, TDT1 uploads every three months), then the "jump" in TDT(S) will be less than 1 hour 20 minutes and the ±3 hour requirement will be satisfied.

--- Discontinuity in the SCLK kernels when switching primary IEM oscillators

Let's first look at the Operations SCLK kernel. When we switch from one oscillator in the primary IEM to the other oscillator in that same IEM, the jump in MET of several hundred nanoseconds will be of no consequence since the mapping from MET (encoded SCLK) to TDT(G) is accurate to only U_0 ~ 1.5 ms. However, by switching from one oscillator to the other the actual oscillator frequency offset and resultant clock change rate suddenly jumps. The clock change rate that is automatically computed and used as the third component of the new time coefficients triplet in the Operations SCLK kernel will not be a good estimate of the new actual clock change rate. For that reason, special care should be taken in determining the execution time for time-tagged commands based on that new entry. Additional DSN contacts are needed before the computed clock change rate is accurate enough to use to extrapolate command execution times one week in the future, as required by Table 1.

The After-the-Fact SCLK kernel will also include a clock change rate that is not accurate between the DSN downlink that immediately preceded the oscillator switching and the next DSN downlink. Since the clock change rate is always computed from two consecutive lines of the kernel that inaccuracy will exist only for that interval between DSN downlinks. Note that the mapping from MET to TDT(G) is accurate only to U_1 ~ 130μs so the jump in MET of a few hundred nanoseconds is again of no consequence.

--- Discontinuity in the SCLK kernels when switching IEMs

When we switch from the primary IEM to the backup IEM, the MET value jumps either forward or backward and possibly by a significant amount. In terms of SCLK kernels, we say that MET has entered a new “partition” [12]. The encoded SCLK value, however, continues to monotonically increase. The entering of a new partition into each type of SCLK kernel will likely require manual intervention. The standard tools being developed for reading and using the SCLK kernels are required to properly handle partitions. When the IEMs do switch we will generally not know the frequency offset of the new oscillator and so will not know the new clock change rate. Use of the value “change rate = 1” is appropriate for the Operations SCLK kernel for the first new time coefficients triplets after the IEM switching has occurred, that is, for the first time coefficients triplets of the new MET partition. As before, additional DSN contacts are needed before the computed clock change rate in the Operations SCLK kernel is accurate enough to use to extrapolate command execution times. The clock change rate automatically computed for the last time coefficients triplet prior to the switching will not be correct in any of the SCLK kernel types.

In-flight verification

We are concerned with how to verify during flight that the downlink-based mission timekeeping system meets the accuracy requirements of Table 1. Of particular concern is the ±1 ms requirement on correlation of MLA data time tags to UTC. The approach proposed is to utilize known command uplink timing to verify timekeeping system accuracy.

The MLA ±1 ms time error budget includes a number of error components such as uncertainty in knowledge of clock drift due to temperature, radiation and relativity and includes a margin depending on the state of the OCXO and on environmental factors. The level of this margin was discussed earlier and is summarized here:

- ~ 462 μs margin with solar maximum background radiation provided the OCXO has been powered at least 30 days, downlinks spaced no more than two days apart

- ~ 228 μs margin with solar maximum background radiation the first week after the OCXO is turned on, downlinks spaced no more than one day apart
- ~ 298 μs (downlinks spaced no more than two days apart) or 472 μs (downlinks spaced no more than 1.5 days apart) margin with solar maximum background radiation provided the OCXO has been powered at least one week
- less margin, if any, following a solar proton radiation event

If the uncertainty in command uplink timing is less than the margin then we can use command uplink timing to verify that the ±1 ms requirement is satisfied.

This command uplink timing method utilizes a “Latch MET CCD” command that is recognized by an IEM Critical Command Decoder (CCD). When one of the CCDs on the IEM Interface (I/F) board detects the Latch MET command (at the leading edge of the CLTU tail sequence) it latches the current 48-bit MET value into the “MET at CCD Command” register together with an 8-bit parameter contained in the command. Each in-flight verification test would include a single Latch MET CCD command wrapped in a standard CLTU. The components of Latch MET CCD command uplink timing uncertainty are

1. Knowledge of the radiation time of the command from the DSN antenna
2. Knowledge of one-way-light-time
3. Knowledge of the uplink uncertainties through the spacecraft
4. Jitter in latching the 48-bit MET and 8-bit parameter

Let’s consider these components one at a time:

1. Command radiation time: We worked for more than a year with Rich Benson and Jeff Berner of DSMS to develop a method for accurately reporting the DSN station radiation time of the Latch MET CCD command. Figure 4 illustrates the method proposed by Jeff Berner using a second “downlink” telemetry channel to report in an SFDU the radiation time of a bit in the Latch MET CCD CLTU. The acronyms in Figure 4 represent standard DSN hardware components such as the LNA or “low noise amplifier”. The method will allow determination of first-bit radiation time for a 500 bps command uplink with an accuracy[13] of

- ±11 μs 1σ for a 500 bps command uplink rate
- ±41 μs 1σ for a 125 bps command uplink rate
- ±162 μs 1σ for a 31.25 bps command uplink rate
- ±1022 μs 1σ for a 7.8125 bps command uplink rate

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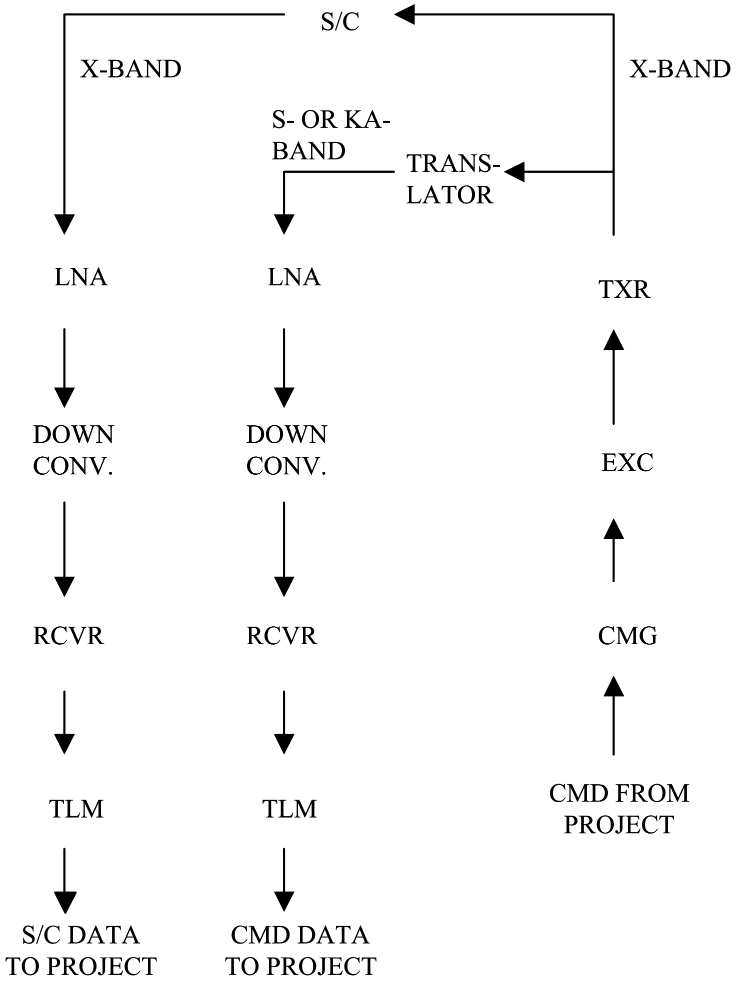
[13] Relative to the local DSN station clock.

The 7.8125 bps emergency uplink rate would probably not be used for in-flight verification. Whether or not this baselined measurement method will work remains to be determined.

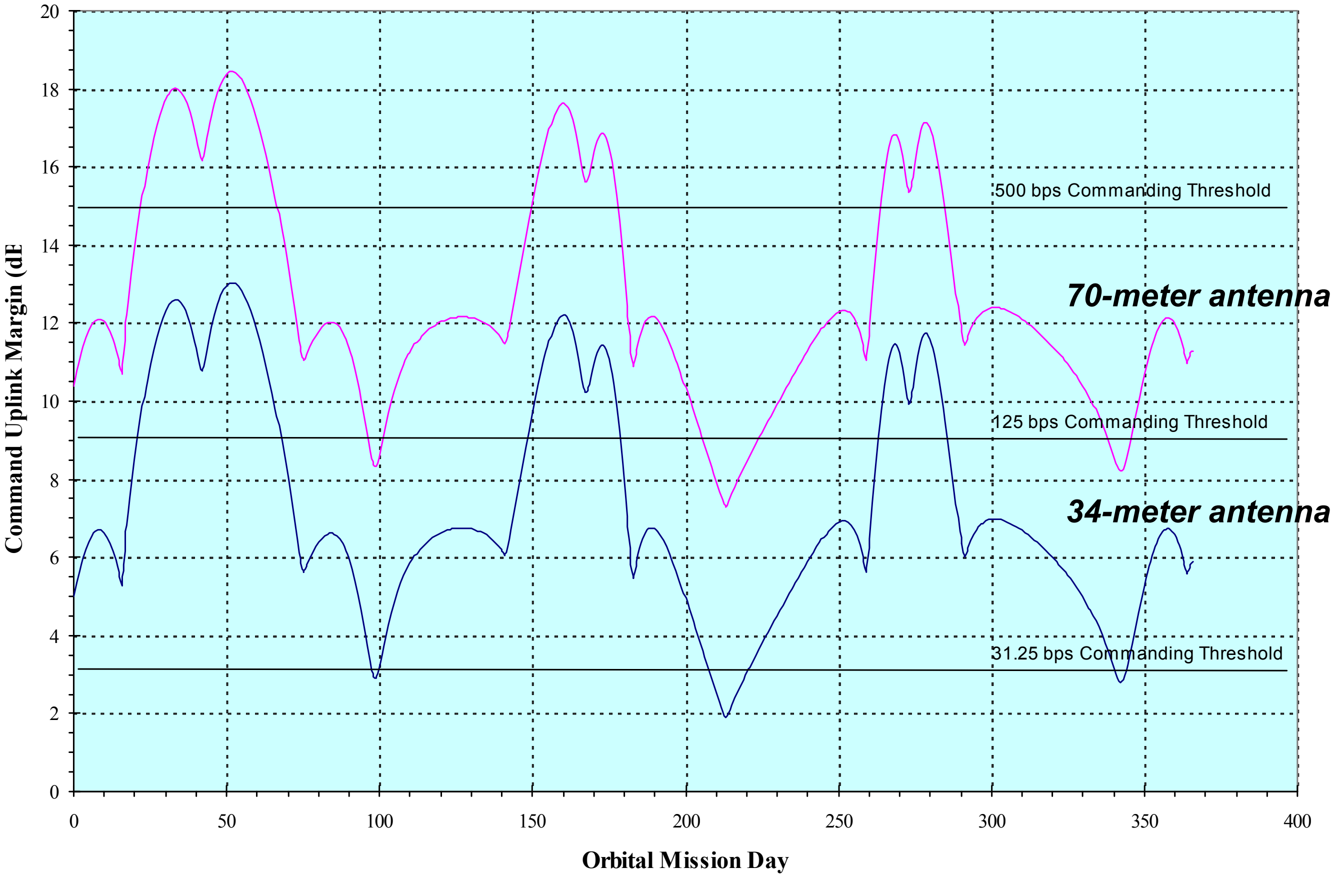
While we would prefer to always use the 500 bps uplink rate for in-flight time accuracy verification because that gives the least uncertainty in command uplink timing, only the 125 bps and 31.25 bps rates will be available for much of the mission. On orbit we expect to use primarily a 34-meter DSN antenna which, as illustrated in Figure 5, will not provide any 500 bps opportunities. If necessary, perhaps after a solar proton radiation event, we can request DSN support with a 70-meter antenna to provide the higher 500 bps or 125 bps rate.

Figure 4: Proposed Radiation Time Measurement



2. One-way-light time (OWLT): When the Science OWLT File is used, the command uplink OWLT will be known with an accuracy of ±10 μs peak. This is the approach that must be used to confirm that the ±1 ms time error budget is satisfied. For other time accuracy requirements in Table 1, however, we can use the spacecraft predictive ephemeris kernel with an accuracy of ±400 km peak worst case to provide uplink OWLT accurate to ±1.334 ms. The ephemeris kernel has the advantage of being available at the time of the in-flight verification test while the Science OWLT File is available only weeks later. Both approaches can be used so that a measure of timekeeping system accuracy can be established shortly after the pass and the Science OWLT File used later to verify the earlier results.

Figure 5: On-orbit command uplink margin



3. Uplink uncertainties through the spacecraft: Uncertainties in the uplink time delay through the spacecraft transponder accounts for most of this item with additional uncertainty of the order of a microsecond or so through the rest of the RF system. At the 500 bps uplink rate, the transponder uncertainty (jitter) is expected to be ±25.8 μs 1σ (at E_b/N_0 = 13.5 dB) or better, depending on the command uplink link margin. The following list summarizes the 1σ uncertainties at the various uplink rates:

- ±25.8 μs at 500 bps with E_b/N_0 = 13.5 dB
- ±84.5 μs at 125 bps with E_b/N_0 = 14.5 dB
- ±103.5 μs at 125 bps with E_b/N_0 = 13.5 dB
- ±268.4 μs at 31.25 bps with E_b/N_0 = 16.5 dB
- ±414.2 μs at 31.25 bps with E_b/N_0 = 13.5 dB

The vendor has stated that the transponder exhibits unpredictable jumps in uplink time delay but has not been able to characterize the nature of those jumps nor how often those jumps could occur. As long as those jumps occur not too frequently, that will not affect our results since we can simply exercise the Latch MET CCD command multiple times. This phenomenon continues to be investigated.

4. Jitter in latching MET and 8-bit parameter: This should be negligible compared to the above numbers.

Combining the above numbers using the RSS method and treating the OWLT uncertainty as “better than” 3σ, with OWLT from the Science OWLT File, gives the uncertainty in the time at which the Latch MET CCD command is detected by the IEM and the MET latched at 500 bps and E_b/N_0 = 13.5 dB as

±11 μs 1σ accuracy of reported command radiation time
±20 μs 3σ accuracy of DSN station time offset relative to UTC(NIST)
±10 μs 3σ accuracy of OWLT from Science OWLT File
±25.8 μs 1σ uncertainty in transponder uplink delay

for a total uncertainty of ±88 μs 3σ in Latch MET CCD command uplink timing. Table 2 summarizes these results for various uplink rates and E_b/N_0 values:

Table 2: 3σ uncertainty in Latch MET CCD command uplink timing

Uplink bit rate	Eb/No (dB)	Using Science OWLT File	Using Predictive Spacecraft Ephemeris
500 bps	13.5	±88 μs	±1337 μs
125 bps	14.5	±283 μs	±1363 μs
125 bps	13.5	±335 μs	±1375 μs
31.25 bps	16.5	±941 μs	±1632 μs
31.25 bps	13.5	±1335 μs	±1887 μs

Comparing these with the timekeeping system margins given above, it appears we can confirm that the ±1 ms error budget is satisfied using the 500 bps uplink regardless of when the OCXO was turned on. Using 125 bps with E_b/N_0 = 14.5 dB would require that the OCXO had been turned on at least one week earlier. The configuration 125 bps and E_b/N_0 = 13.5 dB can also be used when the margin is sufficient. It's also clear that the 31.25 bps uplink rate could not be used to verify the ±1 ms error budget but could be used to verify other time accuracy requirements of Table 1.

Note that we can always use the 125 bps uplink rate but will not always be assured a priori that a negative result is meaningful. For example, if we have just switched to the OCXO (timekeeping system margin of the order of 228 μs) and use 125 bps with E_b/N_0 = 13.5 dB then we can determine the accuracy of the timekeeping system to within ±335 μs. If our in-flight verification test results in a difference between the measured time and the time predicted by an SCLK kernel of, say 500 μs then we believe the predicted time is accurate to 500 μs ± 335 μs, which is always less in magnitude than 1 ms. If instead we determine the difference is 750 μs and the predicted time accurate to 750 μs ± 335 μs then we do not know whether or not the timekeeping system satisfies the ±1 ms requirement. Use of the RSS method to combine the 750 μs and 335 μs numbers may not be appropriate here.

These are preliminary conclusions and guidelines that may change as we learn more about the expected delay uncertainties.

When the 48-bit MET is latched by the IEM CCD in response to the Latch MET CCD command, the flight software reports the new latched MET value and latched 8-bit parameter value in the Spacecraft Housekeeping Packet, APID x405.[14] At Mission Operations, that MET will be mapped to TDT/UTC through

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[14] The Spacecraft Housekeeping Packet, APID x405, is downlinked only when the long downlink frame length is used. The long frame length is not used at the lowest downlink bit rates.

the appropriate SCLK kernel and the result compared to the UTC computed using the uplink path. As long as the difference plus or minus the uncertainty of the command uplink path is less than the appropriate error budget (±1 ms for the MLA), the error budget will be satisfied. For additional details, see Reference [14].

Nominally, in-flight verification utilizing the Latch MET command will be planned for roughly one pass per month and would involve the sending of some number of Latch MET CCD command CLTUs during that pass.

Ground test

This section provides an overview of the tools and methods we expect to use for ground test. Reference [17] describes the preliminary test plan.

The MESSENGER timekeeping system includes flight hardware and software components and ground software. Testing of the flight hardware components includes such issues as ensuring the MET counter does count correctly and increments once per microsecond and does synchronize with the 1 PPS and does count through all possible values. That level of detailed hardware testing is the responsibility of the IEM Lead Engineer and is not covered in this note. The issue discussed here is how to verify on the ground during I&T that the timekeeping system satisfies the accuracy requirements of Table 1.

--- *Testing requirements*

We must verify through ground test that the timekeeping system extended clocks[15], using each of the SCLK kernels, are sufficiently accurate to support the time accuracy requirements of Table 1. We must also verify through test that the G&C onboard estimate TDT(S) of TDT is properly maintained. This applies both to the coarse oscillator and to the precision oscillator.

End-to-end testing is required to verify the accuracy of the data/image time tags for the MDIS and MLA instruments and the Attitude Subsystem to support the optical navigation and science requirements of Table 1. This means that each instrument/subsystem, after integration with the spacecraft, will be included in one or more end-to-end tests that incorporates mapping of the data time tags through the appropriate SCLK kernels to ensure the data time tags are correct and are accurately mapped to Earth time. Planning for these tests is ongoing at this time.

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[15] An "extended clock" consists of a primary IEM oscillator, the MET counter in the primary IEM and an SCLK kernel.

End-to-end testing on the spacecraft is not required for the other instruments, specifically GRNS, MAG, EPPS, XRS and MASCS. What this means is that the time accuracy performance of each instrument will be determined by the appropriate instrument team, preferably by test, and the individual instrument team will be responsible for certifying that the instrument satisfies its component of the relevant time error budget.

To the extent that it is reasonable to do so, testing should be done over the full range of temperatures planned for this mission.

--- *Testing methodology*

A number of tools are available to support testing of the timekeeping system including four test signals and the MIL-STD-1553B bus available through the spacecraft test connector, time uplink commands and resulting downlink information and a stand-alone 1553 bus analyzer (“PASS”) having IRIG-B capability.

The four discrete test signals coming through the spacecraft test connector are

1. Oscillator test point (5MHz divided down to 5MHz/256)
2. Downlink Frame Interrupt[16] test point
3. “CCD_MET_Latch”, indicating detection of the Latch MET CCD command
4. 1 PPS test point

The Oscillator test point may be used to monitor the output frequency of the oscillator used to generate the 1 PPS signal and to drive the MET counter. This will be especially useful during thermal vacuum (TV) testing to help us to understand the behavior of the 1 PPS signal and the MET counter.

We will use the Latch MET critical command to independently verify the accuracy of the timekeeping system extended clocks. The time of the Latch MET test signal can be measured by the I&T testbed time code reader to < 2 μs relative to a facility IRIG-B signal. We can then map the latched MET through each SCLK kernel to TDT to verify the extended clock accuracy.

To use the Latch MET method, we must actually send to the spacecraft a Latch MET CCD command, which may interfere with other processing particularly during mission simulations. To some limited extent, we can passively monitor the 1 PPS and Frame Interrupt signals with a time code reader to do similar testing but the large quantity of test data produced may be difficult to analyze. At the lowest downlink bit rates we will have to utilize the Downlink Frame Interrupt test signal since the flight software reports the results of the Latch MET CCD

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[16] This is the signal that latches the MET as the first bit of a downlink frame is fed to the transponder and is also the signal which interrupts the MP to assemble a new downlink frame.

command detection in the Spacecraft Housekeeping Packet, APID x405, which is not available in the shorter frames downlinked at those bit rates.

We can use the 1553 PASS to passively monitor the 28-bit MET integer seconds value being passed to the 1553 remote terminals. We can first measure the delay and jitter between the 1 PPS test signal and the 1553 sync-with-data-word message; that jitter could be as little as roughly 150 μs, depending on how the 1553 bus controller software handles scheduling of that message. We expect to be able to measure the 1 PPS to sync-with-data-word message delay using the I&T testbed 1553 card to report the sync-with-data-word time and the I&T testbed time code reader to report the 1 PPS time. By mapping the distributed MET to TDT through the SCLK kernels, backing out the latency between the 1 PPS and the sync-with-data-word message and measuring the time of the external 1 PPS test signal, we can determine if the correct 28-bit MET value is being distributed on the 1553 bus.

Summary

The MESSENGER timekeeping system is designed to satisfy the accuracy requirements of Table 1 using the framework sketched in Figure 1. The timekeeping system consists of a flight component and a ground component that is part of the MESSENGER Mission Operations Center (MOC). The flight component is based on a 1-second cycle synchronized to the reference edge of a 1 PPS signal. The time of that reference edge is represented onboard both by the 28-bit integer seconds portion of an MET counter and by an estimate TDT(S) of the Earth time TDT. The ground component includes a Time Management Process that is run at the MOC at the end of each spacecraft track, which may involve multiple DSN stations. That Time Management Process uses downlink telemetry to update the MET Summary Table and to maintain the Operations SCLK kernel. These products are used to maintain the accuracy of the onboard estimate TDT(S) of Earth time, to plan the execution time of onboard commands and to support OpNav image time correlation. We expect the Time Management Process to be completed within three hours after a spacecraft track. Whenever a new Science OWLT File is received from KinetX Navigation, the MOC performs after-the-fact processing to update the After-the-Fact SCLK kernel, which is used primarily to support science time correlation requirements.

We continue to work with DSMS to develop a method for in-flight verification of timekeeping system accuracy.

At this writing, the I&T timekeeping system tests identified by Reference [17] have not yet been performed.

References

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[19] “Detailed Design Review of the Common Timekeeping Data Manager CSC,” Michael Reid and Leeha Herrera, JHU/APL memo SIG-03-022, May 9, 2003

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sbc/s

Distribution
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RGShelton
DESibol
DDStott
WCStratton
XSun, NASA/GSFC
DSTillman
SEA File
Archives

Appendix A: The Last NEAR SCLK Kernel

```
KPL/SCLK
\begintext

LABEL_START
FILENAME ="near_171.tsc"
MISSION_NAME ="NEAR"
ORGANIZATION = "JHU/APL"
AUTHOR ="SCLK update program"
CONTACT ="david.tillman@jhuapl.edu"
TYPE ="SCLK"
CREATION_DATE ="12-Feb-2001"
TARGET ="N/A"
START_UTC ="1996-02-17T20:43:29"
END_UTC ="N/A"
END_DET_UTC ="N/A"

SOURCE_FILES ={de403.bsp,
eros9845.bsp,
near_1998356_2000045_v01.bsp,
near_2000045_2000125_v02.bsp,
near_2000121_2000189_v01_noburn.bsp,
near_2000181_2000242_v01.bsp,
near_2000223_2000270_v01.bsp,
near_2000265_2000298_v01.bsp,
near_2000294_2000309_v01_noburn.bsp,
near_2000302_2000341_v01.bsp,
near_2000336_2001028_v01.bsp,
near_2001026_2001043_v01.bsp,
near_2001035_2001043_v01.bsp,
naif0007.tls,
pck00006.tpc,
near_170.tsc}

MERGED_FILES ="N/A"

NUMBER_VERTICES ="N/A"
NUMBER_PLATES ="N/A"

DESCRIPTION ="

This kernel uses a least-squares fit to the clock data from Nov. 1996
to December 1997, using a constant drift rate of -0.0164 seconds/day.
Coefficients covering the period January 1998 through end of mission
are produced by the SCLK Kernel Update utility on an automatic basis.

This kernel also includes the effects of time changes sent to the
spacecraft clock during a test on May 30, 1997, and during the
Mathilde flyby on June 27, 1997.  All of these time changes were
cancelled by later time changes, so that the spacecraft clock was
set back to its original timeline.
```

```
For the final touchdown of NEAR on Eros on 12 Feb 2001, the clock
was set backwards 17 seconds.  A new partition was added to
reflect this.

This will be the final kernel produced for the NEAR mission.  "

LABEL_END
FREE FORM COMMENTS:


Specification for a type 1 SCLK...
Model the SCLK against the time system TDT (terrestrial
dynamical time) TIME_SYSTEM = 2; variable names
indicate NEAR (ID -93).



This kernel was rebuilt on Tue Dec  8 20:22:10 1998
starting from encoded SCLK: 59023003498 as build number: 1


This kernel was rebuilt on Thu Jan 28 14:59:12 1999
starting from encoded SCLK: 92272635009 as build number: 2

\begindata
SCLK_KERNEL_ID           = ( @2001-02-12T19:00:03 )
SCLK_DATA_TYPE_93        = (        1 )
SCLK01_TIME_SYSTEM_93    = (        2 )


\begintext
For NEAR, Use a single field which represents milliseconds past
mission start time; moduli set well beyond end of mission.

\begindata
SCLK01_N_FIELDS_93       = (        1 )
SCLK01_MODULI_93         = (  2.0e+12 )
SCLK01_OFFSETS_93        = (        0 )
SCLK01_OUTPUT_DELIM_93   = (        1 )


\begintext
Supply the partition information.  If needed,
(e.g., switch to backup bus controller occurs), can
add additional records (lines) to following variables to
define new partitions; generally, the start of the
new partition should coincide with the end of the
previous one.

\begindata
SCLK_PARTITION_START_93  = ( 0.0000000000e+00
                             4.0409661942e+10
                             4.0429229946e+10
                             4.2793916398e+10
                             4.2808703400e+10
                             4.2831583405e+10
```

```
                      1.5741315200e+11
                     )

SCLK_PARTITION_END_93      = ( 4.0409721942e+10
                      4.0429169946e+10
                      4.2793906398e+10
                      4.2808704400e+10
                      4.2831592405e+10
                      1.5741316900e+11
                      2.0000000000e+12
                     )

\begintext
Finally, define coefficients for starting MET (millisec),
starting TDT (expressed in terms of date/time string
@dd-mmm-yyyy-HH:MM:SS) and rate of change between the
spacecraft clock and TDT, having the following property:

   rate = TDT (sec) / most significant count (millisec)

For NEAR, the most significant count corresponds to 1/1000 of
a second, giving a rate of 0.001 sec/millisec in the absence
of clock drift; in general, rate is related to the MET drift
rate of the spacecraft clock (in millisec/sec) as follows:

   rate = {1+MET drift rate (millisec/sec)/1000} / 1000

The following are preliminary data; additional records (lines) should
be added as needed to account for changes in clock drift over time;
the new records must ensure a continuous and monotonically
increasing relationship between MET and TDT.

\begindata
SCLK01_COEFFICIENTS_93     = (

0.0000000000e+00   @17-FEB-1996-20:44:30.960       9.9999980900e-04
4.0409721942e+10   @30-MAY-1997-13:39:45.184       9.9999980900e-04
4.0429229946e+10   @30-MAY-1997-19:04:53.184       9.9999980900e-04
4.2793906398e+10   @27-JUN-1997-03:56:09.184       9.9999980900e-04
4.2808694400e+10   @27-JUN-1997-08:02:37.184       9.9999980900e-04
4.2831583405e+10   @27-JUN-1997-14:24:06.184       9.9999980900e-04
6.0125985000e+10   @13-JAN-1998-18:24:04.310       9.9999979941e-04
6.0212390000e+10   @14-JAN-1998-18:24:09.280       9.9999965456e-04
6.0515927000e+10   @18-JAN-1998-06:43:06.180       9.9999967129e-04
6.0760157000e+10   @21-JAN-1998-02:33:36.105       9.9999969185e-04
6.1092948000e+10   @24-JAN-1998-23:00:07.008       9.9999970879e-04
6.1253334000e+10   @26-JAN-1998-19:33:12.956       9.9999967631e-04
6.1373467000e+10   @28-JAN-1998-04:55:25.916       9.9999966669e-04
6.1594465000e+10   @30-JAN-1998-18:18:43.841       9.9999966090e-04
6.6859033000e+10   @01-APR-1998-16:41:29.880       9.9999962751e-04
7.2308626000e+10   @03-JUN-1998-18:28:01.519       9.9999975022e-04
7.4721547000e+10   @01-JUL-1998-16:43:21.823       9.9999971165e-04
7.5132721000e+10   @06-JUL-1998-10:56:15.686       9.9999966728e-04
7.5328509000e+10   @08-JUL-1998-17:19:23.626       9.9999969335e-04
7.7738193000e+10   @05-AUG-1998-14:40:46.895       9.9999969645e-04
7.8777422000e+10   @17-AUG-1998-15:21:15.572       9.9999968889e-04
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7.8952916000e+10    @19-AUG-1998-16:06:09.527      9.9999974263e-04
7.9588468000e+10    @27-AUG-1998-00:38:41.368      9.9999975051e-04
8.0154353000e+10    @02-SEP-1998-13:50:06.221      9.9999974042e-04
8.1317059000e+10    @16-SEP-1998-00:48:31.925      9.9999974566e-04
8.1805260000e+10    @21-SEP-1998-16:25:12.798      9.9999973960e-04
8.2139807000e+10    @25-SEP-1998-13:20:59.695      9.9999969034e-04
8.2432241000e+10    @28-SEP-1998-22:34:53.609      9.9999970785e-04
8.3004321000e+10    @05-OCT-1998-13:29:33.450      9.9999972196e-04
8.3637554000e+10    @12-OCT-1998-21:23:26.279      9.9999972994e-04
8.4815021000e+10    @26-OCT-1998-12:27:52.954      9.9999972383e-04
8.5429701000e+10    @02-NOV-1998-15:12:32.778      9.9999971380e-04
8.5598364000e+10    @04-NOV-1998-14:03:35.735      9.9999974401e-04
8.6208312000e+10    @11-NOV-1998-15:29:23.584      9.9999975251e-04
8.6810662000e+10    @18-NOV-1998-14:48:33.426      9.9999973864e-04
8.7836239000e+10    @30-NOV-1998-11:41:30.153      9.9999973342e-04
8.8228097000e+10    @05-DEC-1998-00:32:28.043      9.9999971986e-04
8.8438735000e+10    @07-DEC-1998-11:03:05.977      9.9999968567e-04
8.8723522000e+10    @10-DEC-1998-18:09:32.894      9.9999970990e-04
8.9167446000e+10    @15-DEC-1998-21:28:16.770      9.9999972121e-04
8.9826627000e+10    @23-DEC-1998-12:34:37.577      9.9999970657e-04
9.0351015000e+10    @29-DEC-1998-14:14:25.418      9.9999969656e-04
9.0508753000e+10    @31-DEC-1998-10:03:23.364      9.9999965725e-04
9.0804879000e+10    @03-JAN-1999-20:18:49.254      9.9999963003e-04
9.0891284000e+10    @04-JAN-1999-20:18:54.125      9.9999850403e-04
9.1051108000e+10    @06-JAN-1999-16:42:38.180      1.0000003417e-03
9.1137521000e+10    @07-JAN-1999-16:42:51.150      9.9999965120e-04
9.1643374000e+10    @13-JAN-1999-13:13:43.967      9.9999963823e-04
9.2098885000e+10    @18-JAN-1999-19:45:34.837      9.9999971539e-04
9.2272972000e+10    @20-JAN-1999-20:07:01.780      9.9999967241e-04
9.2989875000e+10    @29-JAN-1999-03:15:24.550      9.9999967956e-04
9.3630426000e+10    @05-FEB-1999-13:11:15.352      9.9999969096e-04
9.3889558000e+10    @08-FEB-1999-13:10:07.278      9.9999971539e-04
9.4235104000e+10    @12-FEB-1999-13:09:13.188      9.9999974051e-04
9.4507432000e+10    @15-FEB-1999-16:48:01.123      9.9999975952e-04
9.5913077000e+10    @03-MAR-1999-23:15:25.732      9.9999972150e-04
9.6661855000e+10    @12-MAR-1999-15:15:03.495      9.9999968374e-04
9.7087768000e+10    @17-MAR-1999-13:33:36.369      9.9999970449e-04
9.7259103000e+10    @19-MAR-1999-13:09:11.324      9.9999973601e-04
9.8124119000e+10    @29-MAR-1999-13:26:07.102      9.9999974347e-04
9.8740823000e+10    @05-APR-1999-16:44:30.949      9.9999975168e-04
9.9332844000e+10    @12-APR-1999-13:11:31.797      9.9999974315e-04
1.0115632000e+11    @03-MAY-1999-15:42:47.324      9.9999974035e-04
1.0192592400e+11    @12-MAY-1999-13:29:31.118      9.9999973302e-04
1.0270511600e+11    @21-MAY-1999-13:56:02.905      9.9999972622e-04
1.0330746400e+11    @28-MAY-1999-13:15:10.735      9.9999971703e-04
1.0357738900e+11    @31-MAY-1999-16:13:55.653      9.9999969744e-04
1.0428957000e+11    @08-JUN-1999-22:03:36.432      9.9999968955e-04
1.0495320300e+11    @16-JUN-1999-14:24:09.232      9.9999969796e-04
1.0563745000e+11    @24-JUN-1999-12:28:16.031      9.9999970644e-04
1.0615676900e+11    @30-JUN-1999-12:43:34.873      9.9999969499e-04
1.0759866100e+11    @17-JUL-1999-05:15:06.407      9.9999967686e-04
1.0931735300e+11    @06-AUG-1999-02:39:57.784      9.9999963727e-04
1.0988321800e+11    @12-AUG-1999-15:51:02.573      9.9999962675e-04
1.1160191700e+11    @01-SEP-1999-13:16:00.888      9.9999960134e-04
1.1274866800e+11    @14-SEP-1999-19:48:31.393      9.9999956861e-04
1.1444949000e+11    @04-OCT-1999-12:15:32.636      9.9999955513e-04
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1.1661321300e+11    @29-OCT-1999-13:17:34.680        9.9999955809e-04
1.1989633300e+11    @06-DEC-1999-13:16:13.361        9.9999959823e-04
1.2007520000e+11    @08-DEC-1999-14:57:20.294        9.9999962694e-04
1.2076756000e+11    @16-DEC-1999-15:16:40.048        9.9999964471e-04
1.2301577300e+11    @11-JAN-2000-15:46:52.289        9.9999966231e-04
1.2378214600e+11    @20-JAN-2000-12:39:45.036        9.9999966955e-04
1.2474293600e+11    @31-JAN-2000-15:32:54.713        9.9999966406e-04
1.2593273100e+11    @14-FEB-2000-10:02:49.319        9.9999966865e-04
1.2855638600e+11    @15-MAR-2000-18:50:23.455        9.9999967057e-04
1.3043917100e+11    @06-APR-2000-13:50:07.829        9.9999966756e-04
1.3118129200e+11    @15-APR-2000-03:58:48.577        9.9999966077e-04
1.3285501400e+11    @04-MAY-2000-12:54:10.014        9.9999966383e-04
1.3328877800e+11    @09-MAY-2000-13:23:33.874        9.9999967655e-04
1.3414737700e+11    @19-MAY-2000-11:53:32.591        9.9999967025e-04
1.3458302500e+11    @24-MAY-2000-12:54:20.442        9.9999965803e-04
1.3527066600e+11    @01-JUN-2000-11:55:01.201        9.9999965024e-04
1.3630773500e+11    @13-JUN-2000-11:59:29.843        9.9999965527e-04
1.3761435000e+11    @28-JUN-2000-14:56:24.387        9.9999965118e-04
1.3933430600e+11    @18-JUL-2000-12:42:19.795        9.9999965580e-04
1.3970032500e+11    @22-JUL-2000-18:22:38.674        9.9999966990e-04
1.4036837700e+11    @30-JUL-2000-11:56:50.448        9.9999966240e-04
1.4096962100e+11    @06-AUG-2000-10:57:34.240        9.9999965383e-04
1.4165723100e+11    @14-AUG-2000-09:57:43.997        9.9999964633e-04
1.4469710800e+11    @18-SEP-2000-14:22:19.927        9.9999964801e-04
1.4625519300e+11    @06-OCT-2000-15:10:24.373        9.9999964470e-04
1.4869368300e+11    @03-NOV-2000-20:31:53.512        9.9999964684e-04
1.4935705700e+11    @11-NOV-2000-12:48:07.273        9.9999963914e-04
1.5033180800e+11    @22-NOV-2000-19:33:57.927        9.9999964463e-04
1.5385793000e+11    @02-JAN-2001-15:02:38.679        9.9999964612e-04
1.5473045800e+11    @12-JAN-2001-17:24:46.375        9.9999965195e-04
1.5579406100e+11    @25-JAN-2001-00:51:29.000        9.9999964722e-04
1.5682978300e+11    @06-FEB-2001-00:33:30.629        9.9999964217e-04
)
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Appendix B: Estimation of clock drift rate prediction error

Suppose at time t1 the oscillator fractional frequency offset is $\Delta f1/f$ and at time t2 the fractional frequency offset is $\Delta f2/f = \Delta f1/f + K\Delta t$, where $\Delta t = t2 - t1$ and K is the frequency aging rate. It is common practice to assume oscillator frequency does age linearly over short periods.

Now suppose the MET counter driven by this oscillator drifts by an amount Δh over the period Δt. If the oscillator fractional frequency offset were zero, the MET counter would not drift and the counter value would change by Δt over the period Δt. Instead, the fractional frequency offset is not zero and the MET counter value changes by $\Delta t + \Delta h$ over the period Δt. Linear frequency aging gives

$$\Delta h = (\Delta f1/f)(\Delta t) + (K/2)(\Delta t)^2 \,, \tag{13}$$

corresponding to Equation (17) of Reference [2]. If we estimated the drift rate of the MET counter relative to Δt as

$$\Delta h/\Delta t = \Delta f1/f + (K/2)(\Delta t) \,, \tag{14}$$

the error in our estimate of drift rate at time t2 would be $(K/2)(\Delta t)$ because the MET counter drift rate at time t2 is the oscillator fractional frequency offset $\Delta f2/f = \Delta f1/f + K\Delta t$.

Since there is an uncertainty U_0 in our observation of the time corresponding to the MET counter value at t1 and again at t2, we actually observe an apparent drift in MET counter value of $\Delta h' = \Delta h \pm 2U_0$. We could do a simple estimation of the clock drift rate at time t2 as

$$\Delta h'/\Delta t = \Delta h/\Delta t \pm 2U_0/\Delta t = \Delta f1/f + (K/2)(\Delta t) \pm 2U_0/\Delta t, \tag{15}$$

giving us a total error in estimation of clock drift rate at t2 of

$$E = (K/2)(\Delta t) \pm 2U_0/\Delta t \,. \tag{16}$$

With the values U_0 = 2 ms and K = 1.74 ppb/day, the error is minimized at Δt = 7.3 days where the prediction error is ±1.1 ms/day.

It's easy to show that $|E| < 2$ ms/day if 3 days $\leq \Delta t \leq$ 7 days.

Appendix C: MESSENGER Downlink Modes and Data Rates

This table provides general guidance regarding the range of downlink rates available and details of how these rates will be used.

Bit Rate (bps)	Symbol Rate (sps)	Peak Mod. Index (rad)	Applicable Mission Phase	Modulation & Coding	Transfer Frame Length (bits)	Notes
9.99968	59.998	0.9	Emergency	NRZ-L on 25 kHz square-wave subcarrier Turbo rate 1/6	1784	Emergency mode bit rate
39.9987	239.992	0.6 or 1.23	Cruise			Minimum expected cruise bit rate. Lower mod. index for 34m BWG use. Higher mod. index for 34m HEF use.
200.032	1200.192	1.23			8920	Intermediate cruise bit rate
600.384	3602.305	1.23		Biphase-L direct on carrier Turbo rate 1/6		Intermediate cruise bit rate
2012.882	12,077.295	1.23	Cruise & Science			Highest expected cruise bit rate Useful low rate for science return
9057.971	54,347.826	1.23	Early Ops & Science			Slightly > 1 frame/second
16,025.641	96,153846	1.23	Science			Intermediate science return rate. Close to uplink subcarrier frequency (check for interference)
41, 666.667	250,000.000	1.23				Intermediate science return rate
104,166.667	625,000.000	1.23				Maximum mission bit rate
9057.971	54,347.826	1.23	Test Case	Biphase-L direct on carrier Conv. rate 1/2	8920	Backup to Turbo coding.
9057.971	54,347.826	1.23	Test Case	Biphase-L direct on carrier Conv. rate 1/6	8920	Backup to Turbo coding

Notes:

1. Exact bit rates are calculated from $R_b = \frac{5 \times 10^6}{12\,(N+1)}$ bps, where N is an integer between 3 and 41,667.
2. Downlink data is randomized as per CCSDS requirements (Ref. 6)

3. Transfer frame length does not include frame sync word (32 bits for either turbo coding or convolutional coding). It also does not include the 4 trellis termination bits for turbo coding.

4. Frame sync word is 25D5C0CE8990F6C9461BF79CDA2A3F31766F0936B9E40863 for Turbo-coded frames (192 symbols). The sync word is not randomized.

5. Frame sync word is 1ACFFC1D for convolutional-coded frames (32 bits). The sync word is not randomized.

Appendix D: Glossary of MESSENGER acronyms

1 PPS	"1-Pulse-Per-Second" signal occurring at 1 Hz rate on I/F board
BC	MIL-STD-1553B bus Bus Controller
C&DH	Command and Data Handling Subsystem
CCD	Critical Command Decoder in IEM
Clock change rate	The number of UTC (or TDT) seconds per MET second
Clock drift rate	A measure of MET drift relative to UTC defined as clock drift rate = (1/clock change rate) – 1, usually scaled to ms/day
CLTU	Command Link Transmission Unit sent to the spacecraft
CSCI	Computer Software Configuration Item, i.e., a program
DMR	Detailed Mission Requirements agreement with DSMS
DPU	Payload Data Processing Unit
DSMS	Deep Space Mission System organization of JPL
DSN	NASA Deep Space Network, part of DSMS
Encoded SCLK	Continuous mission timeline in the SCLK kernel, mapped from possibly discontinuous MET (cf. SCLK)
EPPS	Energetic Particle and Plasma Spectrometer instrument
EPU	Instrument Event Processing Unit
ERT	Earth Received Time
Extended clock	A clock consisting of an oscillator, 28-bit or 48-bit MET value and an SCLK kernel, providing a clock readout in terms of TDT or UTC
FECF	Frame Error Control Field in downlink telemetry frame
FPP	Fault Protection Processor in the IEM
G&C	Guidance and Control Subsystem
GRNS	Gamma-Ray and Neutron Spectrometer instrument

GRT	Ground Received Time, used on NEAR mission; also used in MESSENGER ground software to represent ERT
HGA	High Gain Antenna
IEM	Integrated Electronics Module
IRIG-B	A commonly used time code format developed by the Inter-Range Instrumentation Group (IRIG)
I/F	Interface board in the IEM
iMET	Integer seconds component of MET (cf. spacecraft clock)
I&T	Integration and Test (including "mission simulations")
JHU/APL	The Johns Hopkins University Applied Physics Laboratory
JPL	NASA's Jet Propulsion Laboratory, managed by the California Institute of Technology
MAG	Magnetometer instrument
MASCS	Mercury Atmospheric and Surface Composition Spectrometer
MDIS	Mercury Dual Imaging System instrument
MESSENGER	"Mercury Surface, Space Environment, Geochemistry, and Ranging" mission to Mercury
MET	Mission Elapsed Time (cf. encoded SCLK). An alternative meaning sometimes used in a MOC is the time elapsed since launch. Context will generally distinguish between these meanings.
MLA	Mercury Laser Altimeter instrument
MOC	Mission Operations Center
MOI	Mercury Orbit Insertion maneuver
MP	Main Processor in the IEM
NAIF	Navigation and Ancillary Information Facility of JPL
NEAR	Near Earth Asteroid Rendezvous Shoemaker mission
OCXO	Oven Controlled Crystal Oscillator
OpNav	Optical Navigation supported by KinetX navigation team
OWLT	One Way Light Time

ppb	“parts per billion”
ppm	“parts per million”
RT	MIL-STD-1553B bus Remote Terminal
SCLK	A SPICE text representation of time on a spacecraft generally in the form “partition/<time string>”, where <time string> may be “iMET” or “iMET:vMET” or various similar forms
SCLK kernel	Spacecraft clock data file containing correlations between encoded SCLK (cf. MET) and TDT(G)
SFDU	Standard Formatted Data Unit provided by DSN
Spacecraft clock	This is an ambiguous term that can refer to various representations of time on a spacecraft such as MET, iMET, SCLK or other forms. For MESSENGER, this generally refers to the integer seconds iMET distributed to all onboard users of time.
SPICE	“Spacecraft Planet Instrument C-matrix Events” system of software tools developed by NAIF at JPL
SRD	MESSENGER System Requirements Document
SSR	Solid State Recorder in the IEM
TBD	“To Be Determined”
TDB	Terrestrial Barycentric Time
TDT	Terrestrial Dynamical Time
TDT(G)	Ground estimate of the TDT of the 1 PPS reference edge
TDT(S)	Onboard estimate of the TDT of the 1 PPS reference edge
UTC	Coordinated Universal Time
UTC(NIST)	The UTC supplied by the National Institute of Standards and Technology (NIST), to which DSN station time is referenced
vMET	Sub-seconds (“vernier”) component of MET
XRS	X-ray Spectrometer instrument