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Principles of Timekeeping for the NEAR and STEREO Spacecraft

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Abstract—**This paper discusses the details of the inherently different timekeeping systems for two interplanetary missions, the NEAR Shoemaker mission to orbit the near-Earth asteroid 433 Eros and the STEREO mission to study and characterize solar coronal mass ejections. It also reveals the surprising dichotomy between two major categories of spacecraft timekeeping systems with respect to the relationship between spacecraft clock resolution and accuracy. The paper is written in a tutorial style so that it can be easily used as a reference for designing or analyzing spacecraft timekeeping systems.**

Index terms—**NEAR, NEAR Shoemaker, 433 Eros, Discovery Program, STEREO, Sun–Earth Connections Program, Spacecraft timekeeping, Spacecraft time maintenance, Spacecraft clock**

I. INTRODUCTION

The Near Earth Asteroid Rendezvous (NEAR) spacecraft, designed, built, and managed by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) under the sponsorship of the National Aeronautics and Space Administration (NASA), was launched on February 17, 1996, aboard a Delta II-7925 rocket. It was inserted into orbit about the near-Earth asteroid 433 Eros on February 14, 2000, becoming the first spacecraft ever to orbit any small planetary body. Renamed NEAR Shoemaker in March 2000 in honor of the late planetary scientist Eugene M. Shoemaker, it was the first space vehicle in the NASA Discovery Program. The Solar Terrestrial Relations Observatory (STEREO) Mission, part of NASA's Sun–Earth Connections Program, is presently in the early stages of mission planning at JHU/APL. STEREO will study and characterize solar coronal mass ejection (CME) disturbances using two identical Sun-pointing spacecraft.

In late February 1998, I was asked to lead the effort to automate a system to correlate time received from the NEAR spacecraft to Coordinated Universal Time (UTC). In mid-1999 I was asked to lead the effort to define a suitable timekeeping system for the STEREO Mission. It quickly became apparent that the principles governing a timekeeping system for STEREO, given the constraints under which STEREO would have to be designed, would have to differ substantially from the principles on which the NEAR timekeeping system is based. The discussion here involves timekeeping as it relates to the spacecraft system clock, which is generally a component of the spacecraft Command and Data Handling (C&DH) system. *Distribution* of time to the instruments and throughout the spacecraft is outside the scope of this paper.

The primary goal of spacecraft timekeeping is to establish knowledge of the time of an onboard reference event with respect to which the time of every other event on the spacecraft can be measured. The means of establishing such knowledge differs from spacecraft to spacecraft. Typically, that reference event is the reference edge of a pulse that defines the fundamental timing cycle of the spacecraft C&DH system. There are several major types of spacecraft timekeeping systems, distinguished by the method used to establish knowledge of the time of the reference event. For reference, we establish the following spacecraft timekeeping categories:

Category 1 includes timekeeping systems in which transmission of the downlink telemetry transfer frames is synchronized to the reference event of the spacecraft C&DH system and in which correlation of the C&DH spacecraft clock to a standard time system (such as UTC) requires ground support. The NEAR spacecraft timekeeping system is an example of this category, in which downlink telemetry frames are synchronized to the fundamental

C&DH 1-Hz or 1-s timing cycle, and correlation to a standard time system (Terrestrial Dynamical Time, TDT) equivalent to UTC is accomplished on the ground.

Category 2 includes timekeeping systems in which transmission of the downlink telemetry transfer frames is *not* synchronized to the reference event of the C&DH and in which correlation of the C&DH clock to a standard time system requires ground support. The planned configuration of the STEREO timekeeping system is an example of this category, in which downlink telemetry frames are not synchronized to the fundamental C&DH timing cycle, and correlation to a standard time system (UTC in this case) requires ground support.

Category 3 includes all other varieties of spacecraft timekeeping systems. An example is the timekeeping system used in the JHU/APL-designed and built Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite, in which time (Global Positioning System [GPS] time) equivalent to UTC is normally provided to the C&DH directly from signals received from GPS satellites.

This categorization reveals an interesting dichotomy in the relationship between spacecraft clock resolution and timekeeping system accuracy. The clock resolution and timekeeping accuracy for a Category 1 system are totally independent of each other. For a Category 2 system, on the other hand, timekeeping system accuracy is limited by the spacecraft clock resolution. For example, the Category 1 NEAR system meets an accuracy requirement of 20 ms with respect to UTC with a spacecraft clock resolution of 1 s. Contrary to this, the much looser system accuracy requirement of 0.5 s for the Category 2 STEREO timekeeping system cannot be satisfied with a spacecraft clock resolution of 1 s.

Category 1 and Category 2 timekeeping systems may be "open-loop," in which the spacecraft clock is free-running and never corrected by ground control, or "closed-loop," in which the spacecraft clock is controlled and corrected by uplinked commands. Table I lists a few space missions (all designed or in planning at JHU/APL) illustrative of these various classifications.

Table I
Examples of spacecraft timekeeping systems

	Open-Loop	**Closed-Loop**
Category 1	NEAR [1] (launched 1996)	MSX [2][3] (launched 1996)
Category 2	CONTOUR [4], MESSENGER [5] (future)	STEREO [6] (future)

Note: The Midcourse Space Experiment (MSX) is an Earth-orbiting satellite sponsored by the Ballistic Missile Defense Organization. The Comet Nucleus Tour (CONTOUR) and the Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) mission are, like NEAR, interplanetary missions in NASA's Discovery Program.

Once the Category 1 or Category 2 nature of a timekeeping system is recognized and accounted for, the general formalism introduced in this paper can be used to analyze either type. Whether the system is open-loop or closed-loop then becomes the driving issue in design and analysis of the system, particularly with regard to determination of the system time accuracy.

All the interplanetary spacecraft listed in Table I require onboard knowledge of Earth time in order to be able to point a communication antenna toward Earth. This is accomplished in the "open-loop" systems of Table I by adding a bias to the spacecraft clock. The bias is provided by uplinked commands as often as necessary to ensure the accuracy of onboard knowledge of Earth time satisfies mission requirements. In this sense, all the "open-loop" systems listed have a "closed-loop" component that is important to understand for analysis of the accuracy of the onboard knowledge of Earth time.

II. GENERAL OVERVIEW OF TIMEKEEPING

The primary goal of spacecraft timekeeping, as noted earlier, is to establish accurate knowledge relative to a standard time system such as UTC of the time of an onboard reference to which all spacecraft events can be referred. Establishing this goal has the following purposes:

- Time is needed by the spacecraft itself so that "time-tagged" commands uplinked from the ground, which must be executed at specific times, can be properly serviced. The spacecraft C&DH system may also schedule actions to be taken at specific absolute times.
- Time is needed by the spacecraft instruments and other sources of downlink telemetry data so that information about internal or external events can be properly time-tagged for later correlation with other instruments (on the same or different spacecraft) or with other external events.

A. Standard Time Systems

Each spacecraft discussed in this paper (NEAR Shoemaker, STEREO, TIMED) establishes time of the reference event with respect to a different time system. A great many scales or systems for defining time intervals have been invented over the centuries. Many are based on the motions of the planets and the moon or the rotation of the Earth. These include the several "Universal Time" systems UT0, UT1 and UT2; the now-redefined Ephemeris Time (ET) and Greenwich Mean Time (GMT) systems; and other lesser-known systems. (According to [7], UT1 and GMT were identical before GMT was redefined.) In the latter half of the 20th century, new timescales were defined based on the Systéme International (SI) second (s), a time interval determined by a collection of atomic frequency standards that represents time at mean sea level [7,8]. These "atomic times" include TAI (International Atomic Time), UTC (Coordinated Universal Time) and TDT or TT (Terrestrial Dynamical Time). The simple relationships between these time systems are

$$\mathrm{TDT} = \mathrm{TAI} + 32.184\ \mathrm{s}, \tag{1}$$

$$\mathrm{UTC} = \mathrm{TAI} - (\text{number of leap seconds}). \tag{2}$$

In addition, TDB (Barycentric Dynamical Time) is an important system commonly used in astronomy and equals TDT except for relativistic corrections [9]. According to [9], Ephemeris Time (ET) was replaced by TDT in 1984. As currently used, however, ET may refer to either TDT or to TDB (see [10], for example).

Another important and commonly used "atomic time" is GPS time, which is related to UTC as

$$\text{GPS time} = \mathrm{UTC} + (\text{leap seconds since January 1980}). \tag{3}$$

On January 1, 2000, GPS time = UTC + 13 s.

In current usage, UTC and GMT are identical; this is the time system used for everyday timekeeping by most of the world's population. It is the only time system considered here that involves leap second corrections; leap seconds are inserted to keep the difference $\Delta\mathrm{UT} = \mathrm{UT1} - \mathrm{UTC}$ to within 0.9 s [11][12][13]. The acronym UT is often used to refer to UTC but still sometimes refers to UT1 [12] and, because of that ambiguity, I have avoided using that acronym. The estimate of UTC provided by the United States Naval Observatory's (USNO's) Master Clock [8] is the UTC value generally used for U.S. space missions. We refer to that value as UTC(USNO) or, simply, UTC.

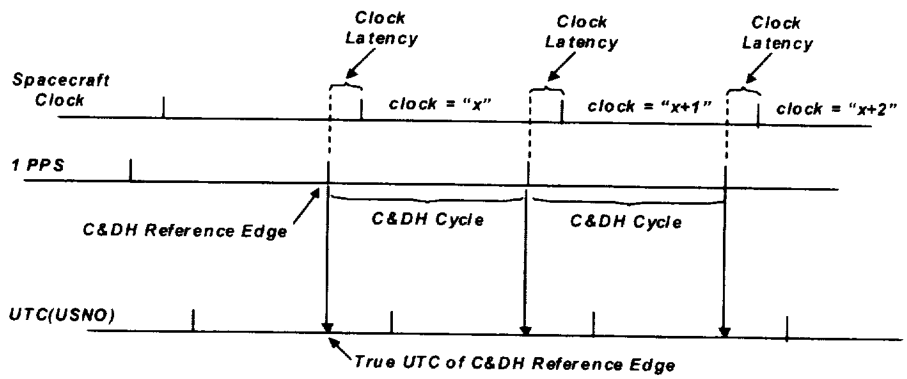

Fig. 1. Example of spacecraft clock based on 1-s C&DH cycle

B. Knowledge of the Time of the Reference Event

For the NEAR Shoemaker, STEREO, and TIMED spacecraft, the reference event to which the time of every other event is measured is the reference edge of a 1-pulse-per-second (1-PPS) signal that defines the beginning of the fundamental timing cycle of the C&DH system.

Figure 1 is an example of a spacecraft clock based on a 1-PPS reference edge, in which knowledge of the time of the reference edge with respect to UTC is desired. The 1-PPS signal defines a 1-s C&DH cycle (or "tick") that includes incrementing of the spacecraft clock once per second. The spacecraft clock provides an estimate of the time of the C&DH reference edge. In the special case in which the spacecraft clock is itself expressed in terms of UTC, such as the clock on STEREO, the clock value is an approximation to the true UTC of the C&DH reference edge. More generally, the clock is expressed in terms of some other timescale; commonly, the clock is a simple binary counter of the number of seconds since launch or since the clock was reset.

TIMED is an example of an Earth-orbiting satellite that uses the GPS's Earth-orbiting satellites to estimate the GPS time of the C&DH reference edge. This Category 3 timekeeping system does not depend on Earth-based estimates of spacecraft time derived from downlink telemetry. However, Category 1 and 2 timekeeping systems like those used on NEAR and STEREO and other interplanetary missions do depend on Earth-based estimates derived from downlink telemetry. For these systems, each downlink telemetry frame contains the value of the spacecraft clock corresponding to a specific C&DH reference edge which occurred at a particular value of UTC(USNO). Depending on the downlink data rates involved, multiple telemetry frames can include the same clock value referencing the same C&DH reference edge. On Earth, the time of the C&DH reference edge is not known but is estimated as

$$UTC_{PERCEIVED} = UTC_{GRT} - OWLT - TD_{SC} - TF_{OFFSET}\text{, where} \quad (4)$$

$UTC_{PERCEIVED}$ = the estimate on Earth of UTC corresponding to the C&DH reference edge;
UTC_{GRT} = the ground received time (GRT) in terms of UTC, which the receiving NASA Deep Space Network (DSN) station appends to the received telemetry transfer frame [14];
OWLT = one-way light time; that is, the signal transit time from the spacecraft to Earth;
TD_{SC} = encoding and transmission delay of a the first bit of a downlink telemetry frame through the spacecraft; and
TF_{OFFSET} = the offset from the C&DH reference edge to the beginning of encoding and transmission of the first bit of a downlink telemetry frame.

For a Category 1 timekeeping system, TF_{OFFSET} is a known value (other than some small and generally negligible jitter), and the uncertainty in TF_{OFFSET} is essentially zero. This is because the time of transmission of each downlink telemetry frame is synchronized to the C&DH reference edge. If the uncertainties in UTC_{GRT}, OWLT, and TD_{SC} can be kept small, then the uncertainty U_0 in $UTC_{PERCEIVED}$ can be kept small, regardless of the resolution of the spacecraft clock.

For a Category 2 timekeeping system, the time of transmission of each downlink telemetry frame is not synchronized to the C&DH reference edge, and the uncertainty in TF_{OFFSET} depends on the resolution of the clock. Suppose the spacecraft clock resolution is 1 s and each telemetry frame contains the clock value corresponding to a C&DH reference edge. That allows us on the ground to determine the time of transmission of the first bit of the telemetry frame to within the 1-s window defined by the spacecraft clock. We could choose TF_{OFFSET} to be any value within a 1-s window. It's likely we would choose it to be at the center of that window to minimize the maximum error in TF_{OFFSET}, so the uncertainty in TF_{OFFSET} would be ≥ 0.5 s. That, in turn, means the uncertainty in the estimate $UTC_{PERCEIVED}$ of UTC would be $U_0 > TF_{OFFSET} \geq 0.5$ s.

U_0 is an important figure of merit for Category 1 and Category 2 systems and an important tool for designing spacecraft timekeeping systems. Some examples illustrate this point.

For the NEAR Shoemaker Category 1 timekeeping system, the uncertainty in TD_{SC}, the transmission delay of a telemetry frame through the spacecraft, varies as a function of downlink telemetry data rate. By using only telemetry downlinked at the highest four data rates, we have kept $U_0 < 2$ ms. This, in turn, allows the NEAR timekeeping system to meet mission requirements.

The Category 2 timekeeping system originally proposed for STEREO is based on a 1-s clock resolution and results in $U_0 > TF_{OFFSET} \geq 0.5$ s. This means the estimate of $UTC_{PERCEIVED}$ of the UTC of the C&DH reference edge could be in error by as much as 0.5 s, which will not satisfy the mission requirements described below. In order to satisfy mission requirements in this case, it is necessary to somehow reduce TF_{OFFSET}. The method now planned for STEREO involves addition of a subsecond "vernier" counter on the RF downlink card, properly synchronized to the 1-PPS signal which defines the C&DH reference edge and inserted together with the spacecraft clock value into each downlink telemetry frame. This results in an uncertainty in TF_{OFFSET} of less than 2 ms and allows us to achieve a U_0 value of better than 30 ms, which will allow mission requirements to be met.

The backup timekeeping system for the Earth-orbiting TIMED satellite, to be used if the primary GPS system fails, is also a Category 2 system with $U_0 > TF_{OFFSET} \geq 0.5$ s. The method planned for establishing $UTC_{PERCEIVED}$ relies on an interesting but complex ground system technique that depends on the availability of high-data-rate downlink telemetry. At the highest downlink rate, the interval between the first bit of two consecutive frames is only a few milliseconds. Many frames containing the same spacecraft clock value are downlinked per second. The ground system monitors the spacecraft clock value provided in each telemetry frame until it observes a change in that value due to the C&DH 1-PPS reference edge. Since the time between the first bit of consecutive frames is only a few milliseconds, the effective uncertainty in the value of TF_{OFFSET} for the first frame downlinked after the clock has incremented can be reduced to a few milliseconds, and the value of U_0 reduced correspondingly.

To recapitulate, the following categories relevant to establishing knowledge of the time of the reference event have been identified in this paper:

Category 1: Knowledge of the time of the C&DH reference edge depends on downlink telemetry synchronized to that reference edge.

Category 2: Knowledge of the time of the C&DH reference edge depends on downlink telemetry that is not synchronized to that reference edge.

Method 1: Unaided (e.g., original STEREO proposal)
Method 2: Vernier-aided (e.g., revised STEREO approach)
Method 3: Ground resynchronization-aided (e.g., TIMED backup mode)

Category 3: All other systems (e.g., TIMED GPS mode)

C. *Timekeeping System Figures of Merit*

The figure of merit U_0 was introduced in the previous section. This value is a measure of the *observability* of the spacecraft clock relative to a standard time system. Several other figures of merit (commonly called FOMs in the engineering community) also are important for spacecraft timekeeping systems.

Reference [15] provides the definition *"Accuracy: the degree of conformity of a measured and/or calculated value to some specified value or definition."* In this paper we discuss the end-to-end system accuracy S_0 and the spacecraft clock accuracy or "extended clock" accuracy $A_0 < S_0$, each with respect to a specified standard time system. It should be clear that we must have $U_0 \leq A_0 < S_0$ for any Category 1 or Category 2 system.

Controllability of the spacecraft clock is an issue for closed-loop timekeeping systems. In this paper, we describe this FOM as the maximum allowable interval Δt_{CL} between clock corrections. It will be seen that Δt_{CL} is a function of U_0, A_0, spacecraft clock drift, and the short-term predictability of spacecraft clock drift.

III. THE NEAR TIMEKEEPING SYSTEM

The NEAR Mission came to an end in February 2001 with the successful landing of the spacecraft on 433 Eros. During the mission, the NEAR Mission Operations Center at JHU/APL was the primary source of information about system time maintained onboard the NEAR spacecraft. It had the responsibility of correlating that system time with UTC [16]. The algorithm described here for computing that correlation was fully implemented and automated and was in daily use at the NEAR Mission Operations Center.

A. *The NEAR System Clock (MET)*

The NEAR Shoemaker spacecraft maintains an onboard clock called the Mission Elapsed Time (MET). Correlation of MET with UTC requires an understanding of the delays and of the uncertainties in the delays to which NEAR telemetry is subject.

The NEAR C&DH system contains redundant Command and Telemetry Processors (C/TP), called C/TP 1 and C/TP 2. Throughout the mission, C/TP 1 has been the active, or primary, C/TP responsible for control of telemetry generation, the onboard data recorders, and the C&DH 1553B data bus.

In the telemetry, the primary C/TP is generally designated the BC (for 1553B bus controller), and the secondary or backup C/TP is designated RT (for 1553B remote terminal). The BC and RT C/TPs each maintain a 32-bit unsigned integer software counter called MET, with resolution of one count per second. In addition, several other MET counters are maintained in other subsystems of the spacecraft. The MET that concerns us here is that maintained by the primary (i.e., BC) C/TP. This MET is sometimes called the "system MET" or "spacecraft clock" to distinguish it from the other MET counters maintained on the spacecraft.

In addition, each NEAR telemetry frame can contain numerous entries for the various MET counters, including even more than one entry for the system MET. The primary C/TP increments its MET counter at a fixed latency relative to the reference edge of a 1-PPS signal generated by a hardware divide chain driven by a crystal oscillator. The interval between successive 1-PPS reference edges is called a time tick. Each time tick corresponds to a different value of system MET. Tick x is the time tick in which the NEAR telemetry "transfer frame" is built or assembled. The corresponding system MET value (which is placed in the transfer frame secondary header [17]) is the value that appears most suitable for determining the correlation between MET and UTC. Actual transmission of the NEAR telemetry transfer frame to Earth occurs in the next tick, which is called tick $x + 1$ here.

NEAR telemetry is stored at the Mission Operations Center in an Oracle database called the Assessment Database. It is of interest that the Assessment Database contains more than 100 distinct names referring to entries for the various MET counters. Identifying the one name that properly references the "system MET" counter at the appropriate time tick was critical in implementation of the algorithm discussed here.

The 1-PPS reference edges define the fundamental NEAR C&DH timing cycle of 1 Hz or 1 s. Downlink telemetry transfer frame transmissions are synchronized to the C&DH 1-Hz timing cycle. We therefore call the NEAR timekeeping system a Category 1 system as defined in the Introduction. This classification is reflected in the algorithm used for correlation to UTC.

B. Correlating MET to UTC

Given the MET corresponding to tick x, the corresponding UTC, ignoring leap seconds, is perceived on Earth as having the value $UTC_{PERCEIVED}$ defined by equation (4), rewritten here in a slightly different form reflecting common usage:

$$UTC_{PERCEIVED} = UTC_{GRT} - OWLT - \Delta_{SC} - REF_{1PPS}\,, \tag{5}$$

where

- $UTC_{PERCEIVED}$ is the estimate on Earth of UTC corresponding to the C&DH reference edge;
- OWLT is the one-way light time, or the time it takes an electromagnetic wave (light or radio frequency emissions) to travel in free space from the NEAR antenna to the DSN station on Earth;
- Δ_{SC} is the time interval between the C&DH reference edge just prior to the transmission of a downlink telemetry frame and the radiation of the first bit of that frame from the NEAR antenna; and
- REF_{1PPS} is the "time reference offset".

Software employing the SPICE[1] system is used at the NEAR Mission Operations Center to compute OWLT, given the DSN ground received time UTC_{GRT}, the location of the receiving DSN station, and the spacecraft and Earth ephemerides.

The parameter Δ_{SC} in these calculations is the time delay between the 1-PPS reference (leading) edge for tick $x + 1$ and the radiation of the first bit of the telemetry transfer frame from a NEAR antenna. (The exact antenna used and the exact path through the NEAR telecommunications system do vary [18].)

Table II gives values for Δ_{SC} for various telemetry data rates and convolutional encoding rates. The table does not include possible delays of less than 2 or 3 μs through the telecommunications downlink hardware; such delays are negligible compared with the known delays and uncertainties.

Table II provides values of spacecraft delay with respect to the 1-PPS reference edge for tick $x + 1$ (Fig. 1), but the MET value available in the transfer frame secondary header is defined with respect to the 1-PPS reference edge for tick x. The parameter REF_{1PPS} in equation (5) accounts for that difference in reference edges and always has the value +1 s. This is sometimes called the system MET "buffering delay." With that definition, the quantity $(OWLT + \Delta_{SC} + REF_{1PPS})$ is the total time delay from the 1-PPS reference edge that begins the time tick during which a NEAR telemetry transfer frame is assembled until receipt of the first transfer frame bit at a DSN ground station. Also, $\Delta_{SC} + REF_{1PPS} = TD_{SC} + TF_{OFFSET}$ is the delay from that 1-PPS reference edge to radiation of the first bit of the transfer frame from the NEAR antenna.

[1] The Navigation and Ancillary Information Facility (NAIF) of NASA's Jet Propulsion Laboratory (JPL) has developed and maintains an extensive collection of software tools called SPICE (an acronym taken from "Spacecraft Planet Instrument C-matrix Events"). SPICE data files, called kernels, provide parameters important for calculations relevant to space missions and include, for example, NEAR ephemeris and UTC leap seconds. The NEAR Mission Operations Center generates a SPICE spacecraft clock kernel (SCLK kernel) to define known relationships between NEAR MET and TDT. All computations internal to SPICE utilize TDB. However, SPICE includes a variety of tools that readily convert between TDB and other time systems.

Table II

Total spacecraft delay, Δ_{SC}, for various telemetry data rates and convolutional encoding rates. Possible delays of less than 2 or 3 μs through the telecommunications downlink hardware are not included; such delays are negligible compared with the known delays and uncertainties.

Data Rate	Mode	Frames per second	Average C&DH Delay, ms*	Uncertainty in C&DH Delay, ms	Reed-Solomon Encoded Rate, bps	Convolutional Encoding Rate R	TCU** Delay, ms	Total Spacecraft Delay Δ_{SC}, ms*
26.496 kbps	Normal	3	0.412	±0.132	30336.00	R = 1/2	0.0041	0.4 ± 0.13
						R = 1/6	0.0014	0.4 ± 0.13
17.664 kbps	Normal	2	0.618	±0.198	20224.00	R = 1/2	0.0062	0.6 ± 0.20
						R = 1/6	0.0021	0.6 ± 0.20
8.832 kbps	Normal	1	1.236	±0.396	10112.00	R = 1/2	0.0124	1.2 ± 0.40
						R = 1/6	0.0041	1.2 ± 0.40
4.416 kbps	Normal	1/2	2.472	±0.791	5056.00	R = 1/2	0.0247	2.5 ± 0.79
						R = 1/6	0.0082	2.5 ± 0.79
2.944 kbps	Normal	1/3	3.708	±1.187	3370.67	R = 1/2	0.0371	3.7 ± 1.2
						R = 1/6	0.0124	3.7 ± 1.2
1.104 kbps	Normal	1/8	9.889	±3.165	1264.00	R = 1/2	0.0989	10.0 ± 3.2
						R = 1/6	0.0330	9.9 ± 3.2
39.4286 bps	Emergency	1/224	276.898	±88.607	45.143	R = 1/2	2.7690	279.7 ± 88.6
						R = 1/6	0.9230	277.8 ± 88.6
9.8571 bps	Emergency	1/896	1107.590	±354.429	11.286	R = 1/2	11.0759	1118.7 ± 354.4
						R = 1/6	3.6920	1111.3 ± 354.4

*For 26.496 kbps data rate, add 1/3-s delay for second transfer frame, 2/3-s delay for third transfer frame.
For 17.664 kbps data rate, add 1/2-s delay for second transfer frame.
**Telemetry Conditioning Unit.

C. Using TDT for MET Correlation

The use of UTC-based parameters in equation (5) ignores leap seconds. There are many alternatives to this form that involve conversion between UTC and other time systems, incorporating leap seconds into the conversion instead of in evaluation of the equation itself. The algorithm provided to the NEAR Mission Operations Center for correlation of MET with UTC actually uses TDT. The relationship between TDT and UTC is

$$\mathrm{TDT} = \mathrm{UTC} + 32.184\ \mathrm{s} + n, \tag{6}$$

where n is the number of leap seconds. The equation for correlation of MET with UTC then becomes

$$\mathrm{TDT}_{\mathrm{PERCEIVED}} = \mathrm{TDT}_{\mathrm{GRT}} - \mathrm{OWLT} - \Delta_{SC} - \mathrm{REF}_{\mathrm{1PPS}}. \tag{7}$$

Because of equation (6), we refer to both $TDT_{PERCEIVED}$ and $UTC_{PERCEIVED}$ as the "UTC estimator."

D. Uncertainty in the UTC Estimator

Equation (7) shows that the uncertainty $\eta(UTC_{PERCEIVED}) = U_0$ in our knowledge of the TDT or UTC of the 1-PPS reference edge corresponding to values of MET is composed of the uncertainties $\eta(UTC_{GRT})$ in TDT_{GRT}, $\eta(OWLT)$ in OWLT, and $\eta(\Delta_{SC})$ in Δ_{SC}. (The uncertainty in REF_{1PPS} is not zero but is limited to the jitter in the 1-PPS signal, which is negligible for this application.) The uncertainty $\eta(UTC_{GRT})$ is given by Reference [14] as bounded[2] by ±0.1 ms. Because of ephemeris uncertainties and relativistic effects that the SPICE software does not account for, we believe that SPICE computes OWLT with an uncertainty of ±1 ms, uniformly distributed. The uncertainty in Δ_{SC}, taken from Table II, is also uniformly distributed. That gives

$$\eta(UTC_{PERCEIVED}) = f\{\eta(UTC_{GRT}), \eta(OWLT), \eta(\Delta_{SC})\}, \tag{8}$$

which expresses $U_0 = \eta(UTC_{PERCEIVED})$ as some undefined function of the component uncertainties. UTC_{GRT} and OWLT are correlated since SPICE computation of OWLT uses UTC_{GRT} but Δ_{SC} is independent of OWLT and UTC_{GRT}. Table III summarizes our knowledge of the uncertainties in the estimator $TDT_{PERCEIVED}$ or $UTC_{PERCEIVED}$. Neither the root-sum-squares (RSS) summation nor the total summation of component uncertainties is a completely satisfactory description of the uncertainty in the UTC estimator, but these values do provide rough estimates of that uncertainty.

Table III
Uncertainties in the NEAR UTC estimator

Data Rate	Ground Received Time UTC_{GRT}, ms	Spacecraft–Earth Signal Transit time OWLT, ms	Total Spacecraft Delay Δ_{SC}, ms	RSS	SUM
26,496 kbps	±0.1	±1.	±0.132	±1.0	±1.2
17,664 kbps	±0.1	±1.	±0.198	±1.0	±1.3
8,832 kbps	±0.1	±1.	±0.396	±1.1	±1.5
4,416 kbps	±0.1	±1.	±0.791	±1.3	±1.9
2.944 kbps	±0.1	±1.	±1.187	±1.6	±2.3
1.104 kbps	±0.1	±1.	±3.165	±3.3	±4.3
39.4286 bps	±0.1	±1.	±88.607	±89	±90
9.8571 bps	±0.1	±1.	±354.429	±354	±356

David Tillman of JHU/APL, who did an outstanding job programming the Mission Operations Center component of the NEAR timekeeping system, has observed that the performance of the NEAR timekeeping system is very sensitive to the uncertainty $\eta(OWLT)$ in the spacecraft ephemeris. The Jet Propulsion Laboratory (JPL) provides to the NEAR Mission Operations Center at JHU/APL the SPICE ephemeris kernel for the NEAR spacecraft and provides improved versions of that kernel as the mission progresses. Different versions of the SPICE ephemeris kernel provide different estimations and predictions of spacecraft ephemeris, with differing levels of $\eta(OWLT)$ for any particular period of time; Mr. Tillman has worked out procedures to ensure that the Mission Operations Center uses only those available ephemeris kernels which are expected to provide the best estimates of ephemeris.

E. Prediction of Future MET Drift

Given MET and $TDT_{PERCEIVED}$, we can create a plot showing the correlation between MET and TDT or UTC for all *past* values of MET. This is useful but is not all we want. We wish to be able to predict the value of the MET counter at any given future time defined by a value of UTC or TDT.

[2] This is an upper bound on UTC_{GRT} accuracy imposed by calibration limits of the DSN time-stamping system.

The method for making this prediction at the NEAR Mission Operations Center is simple: the predicted future rate of drift of the MET counter relative to TDT is assumed to be equal to its measured short-term rate of drift. Over periods of a few days to a few weeks, this method works surprisingly well for the required NEAR total system timing accuracy of ±20 ms. The MET clock drift has been observed to vary from about 16 to 38 ms per day relative to TDT, but the change in drift is generally small from day to day.

Note that since we are concerned with determining the relationship between spacecraft MET and Earth-based UTC, any relativistic effects on the spacecraft MET oscillator due to its environment may be viewed from the Earth as components of oscillator (MET) drift. Thus we need not explicitly compute the magnitude of those relativistic effects.

F. Dissemination and Accuracy of NEAR Time

Time is known on the NEAR spacecraft only in terms of the system MET clock. The NEAR Mission Operations Center at JHU/APL disseminates time to the scientific community by means of a SPICE spacecraft clock (SCLK) kernel, which describes known and predicted relationships between NEAR MET and TDT.

The SCLK kernel includes a table of time intervals, each specified as a time "coefficients triplet" consisting of MET at the beginning of the time interval, the corresponding $TDT_{PERCEIVED}$ computed from equation (7), and the predicted rate of change of TDT with respect to the MET counter during that interval [19]. Table IV illustrates a portion of the time coefficients triplet table of an SCLK kernel obtained from Reference [20]. It includes, as well, the equivalent rate of drift of the MET counter with respect to TDT or UTC. Note that the rate of change given in the SCLK kernel indicates that the spacecraft MET counter increments faster than once per TDT (SI) second.

Table IV

Portion of a recent NEAR Shoemaker SCLK kernel with equivalent MET drift rates.

------------------- SCLK COEFFICIENTS TRIPLET -------------------			MET Drift Rate (ms/day)
Actual MET (ms)	Earth Time (TDT)	Rate of Change (TDT s/ MET ms)	
1.2301577300e+11	@11-JAN-2000-15:46:52.289	9.9999966231e-04	29.2
1.2378214600e+11	@20-JAN-2000-12:39:45.036	9.9999966955e-04	28.6
1.2474293600e+11	@31-JAN-2000-15:32:54.713	9.9999966406e-04	29.0
1.2593273100e+11	@14-FEB-2000-10:02:49.319	9.9999966865e-04	28.6
1.2855638600e+11	@15-MAR-2000-18:50:23.455	9.9999967057e-04	28.5
1.3043917100e+11	@06-APR-2000-13:50:07.829	9.9999966756e-04	28.7
1.3118129200e+11	@15-APR-2000-03:58:48.577	9.9999966077e-04	29.3
1.3285501400e+11	@04-MAY-2000-12:54:10.014	9.9999966383e-04	29.0
1.3328877800e+11	@09-MAY-2000-13:23:33.874	9.9999967655e-04	27.9
1.3414737700e+11	@19-MAY-2000-11:53:32.591	9.9999967025e-04	28.5
1.3458302500e+11	@24-MAY-2000-12:54:20.442	9.9999965803e-04	29.5
1.3527066600e+11	@01-JUN-2000-11:55:01.201	9.9999965024e-04	30.2

Notes:

1) For the time period shown, TDT is larger than UTC by 64.184 s [12].

2) These data are taken from NEAR Shoemaker SCLK kernel "near_154.tsc," dated June 1, 2000.

Linear interpolation can be used between entries to estimate the correlation between TDT (or UTC) and MET. For times later than the last time coefficients triplet entry in the SCLK kernel, linear extrapolation is used to predict future correlation between MET and TDT. Let MET_0, $rate_0$, and TDT_0 constitute the last entry in the SCLK kernel and let $MET_i = MET_0 \times 10^{-3}$ represent MET in seconds; $rate_i = rate_0 \times 10^3$; and $TDT_i = TDT_0$. The predicted relationship is

$$\mathrm{TDT} = \mathrm{TDT}_i + (\mathrm{rate}_i)(\mathrm{MET} - \mathrm{MET}_i), \tag{9}$$

or

$$\mathrm{MET} = \mathrm{MET}_i + (\mathrm{TDT} - \mathrm{TDT}_i)/\mathrm{rate}_i. \tag{10}$$

As new telemetry is received from the spacecraft, the NEAR Mission Operations Center compares the predicted MET drift with the actual MET drift for selected downlinked telemetry frames, chosen using a complicated data-quality filter, and adds a new time coefficients triplet to the SCLK kernel whenever the difference between the predicted and actual values is too great. Given a new value MET_n of MET from telemetry and a new $\mathrm{TDT}_n = \mathrm{TDT}_{\mathrm{PERCEIVED}}$ computed from equation (7), the (perceived) error in the prediction of MET drift is E_D = predicted MET drift – observed MET drift = $[(\mathrm{TDT}_n - \mathrm{TDT}_i)/\mathrm{rate}_i - (\mathrm{TDT}_n - \mathrm{TDT}_i)] - [(\mathrm{MET}_n - \mathrm{MET}_i) - (\mathrm{TDT}_n - \mathrm{TDT}_i)]$, or

$$E_\mathrm{D} = (\mathrm{TDT}_n - \mathrm{TDT}_i)/\mathrm{rate}_i - (\mathrm{MET}_n - \mathrm{MET}_i), \tag{11}$$

and the perceived error in the prediction of TDT_n is

$$\begin{aligned} E_\mathrm{P} &= \mathrm{rate}_i \times (\mathrm{MET}_n - \mathrm{MET}_i) - (\mathrm{TDT}_n - \mathrm{TDT}_i) \\ &= -\,\mathrm{rate}_i \times E_\mathrm{D} \sim -E_\mathrm{D}, \text{ since } \mathrm{rate}_i \sim 1. \end{aligned} \tag{12}$$

The NEAR end-to-end system accuracy requirement is $S_0 = 20$ ms. This means the magnitude of the error in the estimate of TDT at the instruments as computed using the SCLK kernel must be less than S_0. There exists an E_MAX such that, so long as $|E_\mathrm{P}| < E_\mathrm{MAX}$, the system error requirement $S_0 = 20$ ms is satisfied. Whether or not that requirement is satisfied throughout the entire interval $\mathrm{TDT}_n - \mathrm{TDT}_i$ is unknown, since we do not generally have telemetry available for the entire interval. For convenience, we used E_D as our test parameter, which is valid since $|E_\mathrm{P}| = \mathrm{rate}_i \times |E_\mathrm{D}| < |E_\mathrm{D}| < E_\mathrm{MAX}$ and since $|E_\mathrm{D}| - |E_\mathrm{P}|$ is negligible.

The NEAR system time error budget, excluding the prediction of MET drift relative to UTC or TDT, consists of these components:

- DSN timing errors and range uncertainty = ±1.1 ms = $\eta(\mathrm{UTC}_\mathrm{GRT}) + \eta(\mathrm{OWLT})$
- C/TP to transmitter time synchronization = see Table II = $\eta(\Delta_\mathrm{SC})$
- C/TP to Imager time synchronization = ±0.001 ms
- Imager Shutter time control uncertainty = ±0.1 ms
- C/TP to Guidance & Control (G&C) synchronization = ±5 ms
- G&C to attitude snapshot synchronization = ±2 ms

Referring to Table II, we see that the C/TP to transmitter time synchronization varies from ±0.13 to ±354.4 ms, depending on telemetry data rate. How do we combine all these sources of error with the allowable limit on total system timing error of ±20 ms to determine a limit E_MAX on allowable MET drift prediction error? If all the error sources are uncorrelated, we could combine all these sources using the common RSS technique which, using only the six highest data rates (because $\eta(\Delta_\mathrm{SC})$ at the two lowest rates exceeds $S_0 = 20$ ms), would give $E_\mathrm{MAX} = 18.7$ ms. However, since we did not know the statistical distributions of all the component terms, it was not clear when planning the NEAR timekeeping system if that would be a valid approach. Instead, we chose to take a more conservative direction and used a straight summation of the component terms. We also chose to use only the four highest data rates, so the variation in C/TP to transmitter time synchronization is limited to the range ±0.13 to ±0.79 ms. (This also has the effect of providing the bound $U_0 < 2$ ms, as can be seen in Table III.) This leads to an upper bound on composite system error, exclusive of the prediction of MET drift, of ±9.0 ms, and the bound on allowable MET drift prediction error becomes $E_\mathrm{MAX} = \pm 11.0$ ms.

As stated previously, if $|E_\mathrm{D}| < E_\mathrm{MAX}$, the system accuracy requirement $S_0 = 20$ ms is believed to be satisfied. However, in deciding whether or not to add a new time coefficients triplet to the SCLK kernel, we must consider as well whether or not we expect $|E_\mathrm{D}| < E_\mathrm{MAX}$ to remain true until the next opportunity to examine telemetry from the spacecraft. Therefore, the Mission Operations Center adds a new triplet to the kernel whenever $|E_\mathrm{D}| > E_\mathrm{MAX} - M_\mathrm{T}$, where the margin M_T is a somewhat arbitrary value chosen to allow for possible increase in $|E_\mathrm{D}|$ until the next examination of telemetry 1 or 2 days later. As noted, the MET clock drift per day has been observed to vary by more than $S_0 = 20$ ms over the entire mission, so the selection of M_T is made with the assumption that the drift will not change much over 1 or 2 days. If the temperature environment of the oscillator, a temperature compensated crystal oscillator (TXCO), remains fairly stable, then it is likely the drift in MET relative to TDT will not vary greatly. M_T also accounts for the +/-0.5 ms uncertainty due to rounding the value of TDT to 1 ms in the SCLK kernel. The implementation of the Mission Operations Center portion of the NEAR timekeeping system actually uses $M_T = 6$ ms, so the decision is made to add a new time coefficients triplet to the SCLK kernel whenever

$$|E_D| > E_{MAX} - M_T = 11 - 6 \text{ ms} = 5 \text{ ms}. \tag{13}$$

Our operational experience with this threshold value has been very satisfactory, resulting in less than one additional SCLK time coefficients triplet per week on average. Of course, whenever a new triplet is added, the extended SCLK kernel must be distributed to the user community; thus, fewer changes to the kernel mean a lower incidence of logistical problems in performing such distributions.

One question not answered by the time triplets in the SCLK kernel is whether or not $|E_D| < E_{MAX}$ when a triplet was added, so the scientific community has no way of knowing how probable it is that the system accuracy requirement was satisfied at that point in NEAR system time. In retrospect, it would have been useful to create an additional product (distributed on the World Wide Web through [20], where the NEAR SCLK kernel is also available) which does provide that information. Alternatively, an extended form of the SCLK kernel could include that information, but that is not available in the current implementation.

G. *Alternative Perspectives on NEAR Accuracy*

We can define a NEAR "extended clock" consisting of the SCLK kernel, the spacecraft MET counter, and the spacecraft oscillator that drives the MET counter. This is a generalization of the spacecraft clock, which consists of the MET counter and the spacecraft oscillator that drives the counter. We can then talk about the accuracy $A_0 < S_0$ of the extended clock and the clock error $E_C = \text{TDT}_{\text{PREDICTED}} - \text{TDT}_{\text{ACTUAL}}$, which must satisfy $|E_C| < A_0$ in order that the system accuracy S_0 be satisfied. We do not know $\text{TDT}_{\text{ACTUAL}}$, the actual time of the 1-PPS reference edge, when we receive a new downlink telemetry frame containing a new value of MET but can only estimate it with $\text{TDT}_{\text{PERCEIVED}}$ computed from equation (7). We can therefore only estimate E_C by the perceived error E_P in the prediction of TDT provided by equation (12), where $E_P = E_C \pm U_0$, because $\text{TDT}_{\text{PERCEIVED}} = \text{TDT}_{\text{ACTUAL}} \pm U_0$. We then require that $|E_P| < A_0 - U_0$ to ensure $|E_C| < A_0$. Since we require $|E_P| < E_{MAX}$, we might assume $E_{MAX} = A_0 - U_0$, but that is not obvious. However, a look at the NEAR system time error budget does support this relationship. Then $A_0 = E_{MAX} + U_0 \sim 11 + 2$ ms = 13 ms. This tells us that the extended clock which includes the SCLK kernel can predict the TDT or UTC time of the NEAR 1-PPS reference edge to within $A_0 \sim 13$ ms. The value $I_0 = S_0 - A_0 \sim 7$ ms is the portion of the system error budget allocated to error sources external to the extended clock, as detailed in the system time error budget given earlier. Note that I_0 accounts for all uncertainties in distribution of time from the C/TP to the Imager and to the G&C system.

We might ask if S_0 can be chosen smaller for future missions using an open-loop timekeeping system similar to that used on NEAR. The error component I_0 depends on the instrument suite and cannot be readily influenced by design of the "extended clock." However, the extended clock accuracy A_0 can be improved (i.e., error can be reduced) by appropriate spacecraft clock design, including selection of the oscillator. The minimum value of A_0 depends on U_0 and also depends on a trade-off between the interval between updates of the SCLK kernel and the uncertainty in the spacecraft clock drift rate. Suppose the interval between SCLK kernel updates is Δt_{OL} and suppose that must be no less than some minimum value Δt_{MIN}, perhaps due to a limitation on the frequency of ground contacts. Suppose also that the uncertainty in our prediction of the drift rate of the spacecraft MET counter with respect to the standard time system (such as TDT or UTC) is δR. Whenever a new time coefficients triplet is added to the SCLK kernel, the new estimate TDT_i of the TDT of the 1-PPS reference edge may be in error by as much as $E_{\text{UPDATE}} = U_0$, the uncertainty in the computation of TDT by equation (7). The clock drift rate, rate_i, from the SCLK kernel may be in error by as much as δR, so the error of the extended clock is bounded by $E_C = (\Delta t_{OL})(\delta R) \pm E_{\text{UPDATE}} = (\Delta t_{OL})(\delta R) \pm U_0$. The perceived error in the extended clock is $E_P = E_C \pm U_0 = (\Delta t_{OL})(\delta R) \pm 2U_0$. The decision threshold, as used above, is $A_0 - U_0 - M_T > |E_P| = |(\Delta t_{OL})(\delta R) \pm 2U_0|$. Using the maximum value of $|E_P|$,

$$A_0 > (\Delta t_{OL})(\delta R) + 3U_0 + M_T > (\Delta t_{MIN})(\delta R) + 3U_0 + M_T \tag{14}$$

is the lower bound on the accuracy A_0 of the extended clock, that is, of the prediction of the time of the onboard reference event with respect to the standard time system. Note, however, that $M_T \geq (\Delta t_{MIN})(\delta R) + Q$, where Q is the additional uncertainty due to the precision of TDT in the SCLK kernel, so

$$A_0 > 2(\Delta t_{MIN})(\delta R) + 3U_0 + Q. \tag{15}$$

Equation (15) is particularly interesting because it reveals the explicit dependence of the minimum value of A_0 on Δt_{MIN}, δR, and U_0. While Δt_{MIN} is probably determined by mission constraints, U_0 depends on design of the C&DH and downlink telemetry systems and δR depends on the oscillator used, the temperature regime to which the oscillator will be exposed and the amount of variation in oscillator frequency due to such design issues as power system regulation. There is also a dependence of δR on U_0 when the predicted clock drift rate is determined using an estimate of past drift.

We can do even better than equation (15) if the SCLK kernel is updated with every ground contact instead of when a telemetry-based decision rule is satisfied, but that may present a logistics challenge in handling more frequent distribution of larger SCLK kernels. The decision rule method selected for NEAR allowed us to limit both the size of the kernels and the frequency of the distribution of time kernels to the user community while satisfying the bound on system timing error. Other approaches are available, as well, to provide much better accuracy of the extended clock. Use of reconstructed spacecraft ephemerides (to minimize the uncertainty in OWLT) and use of interpolation (to reduce the effect of δR) are two techniques that can improve the accuracy of the clock. The MESSENGER mission, for example, is currently planning to use both interpolation and reconstructed ephemerides to achieve a spacecraft system time accuracy of +/-1 ms.

One last issue that often causes confusion in planning a timekeeping system is whether or not to use statistical methods. While NEAR used the simple relationship $S_0 = I_0 + A_0$, if we have sufficient knowledge of the statistics of the error sources it may be appropriate to instead use a lower value for S_0 computed with the RSS method. Use of the RSS method requires (1) that the error sources be uncorrelated and (2) that each component of the end-to-end system time error budget be expressed in exactly the same statistical terms. Suppose, for example, that we require an end-to-end system accuracy $S_0 = 10$ ms 3σ, in the Gaussian sense, meaning that we require time at the instruments to be known 99.87% of the time to within $S_0 = 10$ ms of UTC. For clarity, we might write $S_{3\sigma} = 10$ ms as the system accuracy requirement. We must then express I_0 and A_0 in equivalent terms. If the components of the (instrument) error sources comprising I_0 are all Gaussian, then $I_{3\sigma}$ is unambiguous. However, the components of A_0 are generally not Gaussian and we may not even know the statistical nature of those parameters. If we do know the 3σ extended clock accuracy $A_{3\sigma}$, then $S_{3\sigma} = [(I_{3\sigma})^2+(A_{3\sigma})^2]^{1/2}$ is the end-to-end system accuracy possible.

IV. THE STEREO TIMEKEEPING SYSTEM

The STEREO Mission includes two spacecraft scheduled to be launched in 2005. These spacecraft will provide measurements and images of coronal mass ejections (CMEs)[3] with particular emphasis on studying CMEs that affect the Earth. They will be in heliocentric orbits, one leading the Earth and slightly closer to the Sun and the other lagging the Earth and slightly farther from the Sun.

The STEREO timekeeping system will include a space segment consisting of the two spacecraft and a ground segment. The ground segment will be a component of the STEREO Mission Operations Center at JHU/APL, which will communicate with the elements of the space segment via NASA's DSN. The two spacecraft in the space segment will operate independently of each other and will not communicate with one another.

Some of the images taken by the two STEREO spacecraft will be combined during post-processing into stereo images of CMEs. It will be necessary to correlate the times of the images taken by the two spacecraft to within ±1 s. To accomplish this, the time of each image will need to be known to within ±0.5 s of a standard time system.

[3] As explained in [21], CMEs are distinct from solar flares and generally do not occur in conjunction with flares.

UTC has been chosen as that time system for convenience, particularly since one mission requirement is that the spacecraft bus provides an estimate of UTC to the instruments. In order to meet mission requirements in a way compatible with the system timekeeping error budget, a spacecraft clock accuracy of ±0.35 s of UTC is being used.

The STEREO timekeeping system must support a primary mission of 2 years and a possible extended mission of 5 years. The significance of these requirements will be clear when we discuss the effect of oscillator aging.

A. The STEREO System Clock

The STEREO spacecraft system clock must be accurate to within $A_0 = 0.35$ s of UTC. Mission design constraints establish the time reference event as the reference edge of a 1-PPS signal derived from the RF downlink oscillator. This is again called the C&DH reference edge (Fig. 1). The clock will be maintained to establish knowledge of the time of the C&DH reference edge to within ±0.35 s of UTC. Note that the 1-PPS signal is free-running and, unlike some spacecraft timekeeping systems [22], is never adjusted to meet the accuracy requirement. Rather, it is only knowledge of the time of the C&DH 1-PPS reference edge that is maintained to within ±0.35 s of UTC. This estimate of the UTC of the reference edge is called the spacecraft UTC clock.

Owing to mission design constraints, the STEREO timekeeping system will use a 32-bit unsigned integer MET counter with resolution of 1 s, which is incremented once per second by the 1-PPS pulse. The counter value drifts with respect to Earth time, because the 1-PPS pulse does not occur at intervals of exactly 1 s. To provide a spacecraft UTC clock that is accurate to within ±0.35 s of UTC, the MET value is mapped via a "UTC correlation register" (commonly called "UTCF" or "UT correction factor") to the spacecraft UTC clock. The UTCF value is adjusted by the STEREO Mission Operations Center using an uplink command when needed to maintain $A_0 = 0.35$. Consideration was given to having the onboard software automatically update the UTCF value based on expected clock drift, but that approach was rejected because of the instrument teams' desire to minimize the number of adjustments to the UTC clock. Consideration was also given to scaling MET to reduce the effective clock drift rate and thereby extending the time between clock adjustments but that complication is not necessary for the clock performance needed for STEREO. Instead, the UTC clock value will be computed as MET + UTCF.

B. Accuracy of the Spacecraft UTC Clock

The UTC clock onboard each spacecraft provides an estimate $\mathrm{UTC_{APPROXIMATE}}$ of the time of the C&DH reference edge. To maintain that estimate to within ±0.35 s of UTC, the STEREO Mission Operations Center will use downlinked telemetry to establish an estimate $\mathrm{UTC_{PERCEIVED}}$ of when the C&DH reference edge actually occurred. Combining that information with the expected clock drift, Mission Operations will schedule uplink commands to correct the C&DH UTCF register. This estimate will be computed using equation (4), which is repeated here:

$$\mathrm{UTC_{PERCEIVED}} = \mathrm{UTC_{GRT}} - \mathrm{OWLT} - \mathrm{TD_{SC}} - \mathrm{TF_{OFFSET}}. \tag{16}$$

Unlike NEAR, the STEREO downlink telemetry system is constrained to use telemetry frames *not* synchronized to the C&DH reference edge, so STEREO timekeeping is a Category 2 system. This means that the time of transmission of each downlink telemetry frame could occur at any time within a 1-s window. That, in turn, means the uncertainty in $\mathrm{TF_{OFFSET}}$ must be at least 0.5 s, so the uncertainty $\pm U_0$ in $\mathrm{UTC_{PERCEIVED}}$ is $U_0 > S_0 = 0.5 \text{ s} > A_0 = 0.35$ s, and therefore the requirement to maintain the spacecraft UTC clock to within $A_0 = 0.35$ s of UTC cannot be satisfied. Such an approach was mentioned earlier as the "unaided" Method 1 for Category 2 systems.

This issue is resolved on STEREO by effectively extending the MET counter with an 8-bit vernier counter maintained on the downlink RF card and incremented at a rate very close to 256 Hz, derived from the 1-PPS signal. This is the "vernier-aided" Method 2 for Category 2 systems. The vernier counter is reset to zero with each 1-PPS signal. Both the MET value and the 8-bit vernier counter value are "jammed" into the downlink telemetry frame secondary header just before the telemetry frame is encoded and transmitted. This reduces the uncertainty in $\mathrm{TF_{OFFSET}}$ to about 4 ms in the worst case or 2 ms in the best case. Only the 32-bit integer value is used in the mapping from MET to spacecraft UTC.

The uncertainty in OWLT (the one-way light time) is determined primarily by the uncertainty in knowledge of the spacecraft ephemeris. STEREO ephemeris will be known to within ±7500 km in all directions, an upper bound set by image resolution requirements. This translates to ±25 ms uncertainty in OWLT. The standard DSN service provided to NEAR by the DSN gives UTC_{GRT} to within ±0.1 ms, and it can be assumed that the same degree of service will be available for STEREO. The uncertainty in TD_{SC} is also expected to be very small. With these values, an upper bound for the uncertainty in $UTC_{PERCEIVED}$ is $U_0 \sim 30$ ms. It is likely that the requirement on spacecraft ephemeris will be refined to a much lower value resulting in a lower U_0 but 30 ms is the level being used in the current planning phase.

C. Spacecraft UTC Clock Drift

The spacecraft UTC clock drifts because the 1-PPS signal does not occur at intervals of exactly 1 s; that, in turn, occurs because the RF downlink oscillator frequency differs from its nominal output frequency of 30.6 MHz. The specifications for the High Stability Oscillator (HSO) to be used on STEREO are

- Nominal output frequency of 30.6 MHz
- Initial setting accuracy of $\pm 5 \times 10^{-8}$
- Aging rate of $< 5 \times 10^{-10}$ per 24 hours
- Frequency as a function of temperature of 1×10^{-11}/°C over the oscillator operating range of –5° to +25°C

The time Δt_{μ} in microseconds gained or lost by a clock driven by this oscillator is given approximately by the equation (from Reference [23]):

$$\Delta t_{\mu} = 8.64[(\Delta f/f)t + (k/2)t^2], \qquad (17)$$

where

$\Delta f/f$ is the oscillator reference offset (setting offset) in parts in 10^{-10};
k is the oscillator aging or drift rate in parts in 10^{-10}/day; and
t is the elapsed time in days.

Using equation (17), the spacecraft UTC clock drift rate works out to

- 4.3 ms/day at the start of the mission
- 35.9 ms/day worst case after 2 years
- 83.2 ms/day worst case after 5 years

Variation in temperature is expected to be the major contributor to the uncertainty of clock drift. The uncertainty of clock drift due to temperature variations is $(1 \times 10^{-11}/°C) \times 30°C = 0.33 \times 10^{-9} = 0.026$ ms/day.

D. Clock Correction Interval

The STEREO Mission Operations Center will uplink a command to adjust the UTCF value in order to correct the spacecraft UTC clock whenever necessary to guarantee that the clock remains accurate to within $A_0 = 0.35$ s of UTC. It is important to understand what the interval (Δt_{CL}) between adjustments would be in the worst case. There are three factors to consider: (1) uplink clock correction insertion error E_{INS}, (2) false error due to overestimate of clock error estimator, and (3) spacecraft clock drift.

1) Clock insertion error

Equation (4) introduced $UTC_{PERCEIVED}$, the estimate on Earth of the UTC corresponding to the C&DH reference edge. We can express this estimate as $UTC_{PERCEIVED} = UTC(USNO) \pm U_0$, so a clock correction effective at time t_2 based on $UTC_{PERCEIVED}$ determined for time t_1 could be in error by U_0 plus some uncorrected clock drift for the interval $t_2 - t_1$. In the worst case, the clock correction insertion error is $E_{INS} = U_0 + D_{INS} = U_0 + (R_U)(t_2 - t_1)$, where R_U is the worst-case uncertainty in clock drift rate and D_{INS} is the uncertainty in clock drift for the interval $t_2 - t_1$. If clock correction uplink commands are scheduled a week in advance, then in the worst case, the uncorrected clock error due to possible temperature variations would be $D_{INS} = 0.026$ ms/day × 7 days ~ 0.2 ms. The aging effect over 7 days would be ~ 0.3 ms and R_U would need to account for that. R_U also depends on how well we predict the rate of clock drift and that in turn depends on the specific method used for the prediction.

2) False error due to overestimate in E_P

The error in the spacecraft UTC clock value $\mathrm{UTC}_{\mathrm{APPROXIMATE}}$ is $E_C = \mathrm{UTC}_{\mathrm{APPROXIMATE}} - \mathrm{UTC(USNO)}$, where UTC(USNO) is the actual but unknown time of the C&DH reference edge identified by $\mathrm{UTC}_{\mathrm{APPROXIMATE}}$. At the Mission Operations Center, the time of the C&DH reference edge is estimated as $\mathrm{UTC}_{\mathrm{PERCEIVED}}$, so the perceived error in the spacecraft UTC clock is $E_P = \mathrm{UTC}_{\mathrm{APPROXIMATE}} - \mathrm{UTC}_{\mathrm{PERCEIVED}} = \mathrm{UTC}_{\mathrm{APPROXIMATE}} - \mathrm{UTC(USNO)} \pm U_0 = E_C \pm U_0$. As long as $|E_P| < A_0 - U_0$, we know $|E_C| < A_0 = 0.35$ s, so the clock accuracy requirement is satisfied.

Suppose now that $A_0 - U_0 < |E_P| < A_0 + U_0$. Since the criterion $|E_P| < A_0 - U_0$ is not satisfied, we might conclude that $|E_C| > A_0$ even if $|E_C| < A_0$. The maximum actual clock error that can be tolerated using the decision rule $|E_P| < A_0 - U_0$ without falsely concluding that the spacecraft clock is less accurate than A_0 relative to UTC is $|E_C| < A_0 - 2U_0$. In other words, if $|E_C| < A_0 - 2U_0$ is satisfied, then $|E_P| < A_0 - U_0$ will *always* be satisfied, and the Mission Operations Center will conclude that the clock error satisfies the accuracy requirement $|E_C| < A_0 = 0.35$ s.

3) Effect of clock drift on the interval between clock corrections

The MET counter value (and the UTC clock value to which MET is mapped) drifts with respect to Earth time because the 1-PPS pulse does not occur at intervals of exactly 1 s. Suppose $R(t)$ is the clock drift rate and varies with time, and $R_{WC} \geq |R(t)|$ is the worst-case clock drift for some time interval of interest. Suppose also that Δt_{CL} is the worst-case allowable interval between clock corrections. The worst-case spacecraft UTC clock error is then $|E_C| = E_{INS} + R_{WC} \times \Delta t_{CL}$. In the previous section we determined that $|E_C| < A_0 - 2U_0$ is necessary to ensure the decision rule $|E_P| < A_0 - U_0$ is satisfied. That provides the result

$$\Delta t_{CL} < (A_0 - 2U_0 - E_{INS})/R_{WC} . \tag{18}$$

Using $A_0 = 0.35$ s, $U_0 = 30$ ms, and $D_{INS} \sim 10$ ms, with the clock drift rates R_{WC} computed from equation (17), the maximum allowable interval between clock corrections is

- $>$ 1 month at the start of the mission
- $\sim$ 7 days after 2 years
- $\sim$ 3 days after 5 years

V. TIMEKEEPING SYSTEM DESIGN TRADE-OFFS AND GUIDELINES

Equation (4), repeated as equation (19), provides insight into the design of Category 1 and Category 2 timekeeping systems:

$$\mathrm{UTC}_{\mathrm{PERCEIVED}} = \mathrm{UTC}_{\mathrm{GRT}} - \mathrm{OWLT} - \mathrm{TD}_{\mathrm{SC}} - \mathrm{TF}_{\mathrm{OFFSET}} . \tag{19}$$

The uncertainty in $\mathrm{UTC}_{\mathrm{GRT}}$ is determined by the DSN or other ground receiving system employed and is not generally a mission parameter that can be controlled. When DSN is used, a bound of ±0.1 ms on the uncertainty can be provided.

The uncertainty in OWLT depends on the uncertainty in our knowledge of the spacecraft ephemeris. For NEAR, the best available ephemeris information can in theory provide a level of OWLT uncertainty of ±1 ms. However, the ephemeris information is sometimes not that good. For STEREO, the science imaging requirements impose an ephemeris accuracy of no worse than ±7500 km, equivalent to 25 ms in OWLT uncertainty. Actual STEREO ephemeris accuracy may be much better than this, perhaps even at the level of ±200 km or < 1 ms in OWLT uncertainty. The NASA-sponsored Deep Space Systems Technology (DSST or X2000) program at JPL aims at determining OWLT to within ±30 ns (10-m range uncertainty). Earth-orbiting satellites would be expected to have OWLT of only a few milliseconds and uncertainty in OWLT of << 1 ms.

The uncertainty U_{SC} in $\mathrm{TD}_{SC} + \mathrm{TF}_{\mathrm{OFFSET}}$ is directly affected by the design of the C&DH and downlink telemetry systems. Let ${}_1U_{SC}$ be the value of U_{SC} for a Category 1 timekeeping system and ${}_2U_{SC}$ the value of U_{SC} for a Category 2 system. For a specific mission with given uncertainty of OWLT, the observability U_0 of the spacecraft clock relative to a standard time system depends on U_{SC}, so we would like to choose a timekeeping system category based on which of ${}_1U_{SC}$ or ${}_2U_{SC}$ can be made smaller. However, other spacecraft design considerations may dominate. Downlink telemetry rates, especially for interplanetary missions, are constrained by a number of issues independent of timekeeping, and it may be difficult to choose downlink telemetry frame sizes to enable synchronization at those rates to the C&DH reference edge. The "streaming" downlink telemetry used with Category 2 systems decouples the downlink rates and frame sizes, and such systems must provide some method (such as the STEREO vernier-aided method) for establishing accurate knowledge of the time of the C&DH reference edge, which is typically the reference event to which the time of all other events on the spacecraft can be referred.

The choice between an open-loop timekeeping system in which the spacecraft clock is free-running and never corrected by ground control and a closed-loop system in which the spacecraft clock is controlled and corrected by ground command is not always obvious. This issue was extensively debated for STEREO, which must compare data from two spacecraft, and a closed-loop system was the method adopted. From a Mission Operations Center perspective, use of a free-running spacecraft clock requires not only that correlation of the clock to UTC or some other standard time system be established on the ground but that clock correlation and prediction information for each spacecraft be disseminated and made available promptly to the user community. This dissemination may involve a considerable logistics effort. For such a system, the observability U_0 of the clock and stability of clock drift are important. Clock correlation and prediction information can be updated whenever necessary, provided that the clock drift is such that the frequency of updates is low enough to be logistically feasible and high enough that the behavior of the clock is known to sufficient accuracy between updates. For a closed-loop system, the maximum allowable interval Δt_{CL} between clock corrections is a critical parameter, as is the effective clock drift rate. These parameters must ensure that control of the spacecraft clock by the Mission Operations Center is practicable, and they are dependent on required clock accuracy A_0, clock observability U_0, and clock drift characteristics.

A major advantage of open-loop timekeeping versus closed-loop is that timekeeping errors in an open-loop system can be corrected after the fact, whereas a closed-loop timekeeping system that has already time-tagged spacecraft and instrument data with inaccurate times cannot easily correct that error.

It is informative to compare open-loop system accuracy with closed-loop system accuracy. Given the same instrument suite with time error budget I_0, the end-to-end system accuracy S_0 depends on the clock accuracy A_0. The accuracy of the extended clock of a NEAR-type open-loop system is given by equation (15), which is repeated here:

$$A_{OL} = A_0 > 2(\Delta t_{MIN})(\delta R) + 3U_0 + Q, \tag{20}$$

and the accuracy of the spacecraft clock of a STEREO-type closed-loop system, rewriting equation (18) and using the worst-case relationship $E_{INS} = U_0 + D_{INS}$, is

$$A_{CL} = A_0 > (\Delta t_{CL})(R_{WC}) + 3U_0 + D_{INS} \,. \tag{21}$$

The most notable difference between these two equations is the dependence of A_{OL} on the uncertainty δR of spacecraft clock drift rate versus the dependence of A_{CL} on the worst-case spacecraft clock drift rate R_{WC}. Note that U_0 is the same in both equations and applies to both Category 1 and Category 2 timekeeping systems.

The dependence of A_0 on $3U_0$ in (20) and (21) is due to the use of a telemetry-based decision rule to determine when to adjust the spacecraft clock component of a closed-loop system or to adjust the extended clock SCLK kernel (or equivalent) of an open-loop system. The decision rule bounds the error E_P perceived from downlink telemetry to $|E_P| < A_0 - U_0$ to ensure the actual clock error is bounded by $|E_C| < A_0$. When the interval between clock adjustments is instead determined by some a priori rule, such as once per ground contact or once per week, the dependence of A_0 becomes U_0. However, telemetry could then confirm the accuracy of the clock only to the level $A_0 + 2U_0$ because E_C cannot be observed directly. For some applications, it may be appropriate to define a slightly larger A_0 which depends on $3U_0$ and which can be directly verified through downlink telemetry.

Techniques are available to provide better accuracy than available with the NEAR-type design (equation 20) or with the STEREO-type design (equation 21). It was mentioned in the discussion of the NEAR extended clock that several methods could provide better accuracy for open-loop systems. Closed-loop systems, as well, can be designed to be more accurate through several approaches. If the mapping from MET to the onboard estimate of UTC includes a scaling factor to account for the drift of MET relative to UTC(USNO), the clock drift rate in equation 21 is replaced by the "error" or uncertainty δR in prediction of the drift rate of the spacecraft MET counter. Note that δR must account for any oscillator frequency variation due to temperature or voltage changes or any other environmental effects. Combining scaling with periodic clock adjustments gives

$$A_{CL} = A_0 > (\Delta t_{CL})(\delta R) + U_0 + D_{INS}\,. \tag{22}$$

One important issue that should not be overlooked in design of a space mission timekeeping system is the question of how to test the performance of the system. Since the ground segment of the NEAR timekeeping system was automated only after launch, it has not been possible to perform a "ground truth" verification of the performance of the end-to-end NEAR timekeeping system. Measurements taken by the NEAR X-Ray/Gamma-Ray Spectrometer have been independently verified to be accurate to within 100 ms of UTC, but the mission goal of system end-to-end accuracy of S_0 = 20 ms has never been verified. (Note, however, that the performance of the NEAR Shoemaker timekeeping system has been completely satisfactory; see [24], for example.) Since STEREO is planned for a future launch, the opportunity exists to perform "ground truth" verification both on the ground and during the month or so after launch, when the spacecraft are flying essentially the same trajectory toward the moon and before they separate into heliocentric orbits leading and lagging the Earth.

VI. FUTURE DIRECTIONS: FORMATIONS

With current interest in collections of interplanetary spacecraft flying in formation [25] and in constellations about planetary bodies [26], the extension of the ideas presented in this paper to such applications is of interest. In general, we will want to know the relative biases between the clock on one spacecraft and the clocks on the other spacecraft in a formation or constellation of space vehicles. We are concerned here with spacecraft that communicate directly with each other.

We can easily generalize equation (4) to the transfer of telemetry between two spacecraft. Suppose spacecraft A sends to spacecraft B the value ${}_1C_A$ of its clock at time t_1 and spacecraft B responds by sending to spacecraft A the value ${}_2C_B$ of its clock at time t_2 as well as the clock time ${}_1C_{BRT}$ at which spacecraft B received the transmission from spacecraft A and the offset value TF_{SCA} for the telemetry frame spacecraft B received from spacecraft A. It follows directly from equation (4) that

$${}_1E_{AB} = {}_1C_A - {}_1C_{BRT} + OWLT_{AB} + TD_{SCA} + TF_{SCA} \tag{23}$$
$${}_2E_{BA} = {}_2C_B - {}_2C_{ART} + OWLT_{BA} + TD_{SCB} + TF_{SCB}, \tag{24}$$

where

- ${}_1E_{AB}$ is an *estimate* of the bias ${}_1C_A - {}_1C_B$ of the clock on spacecraft A relative to spacecraft B;
- ${}_2E_{BA}$ is an *estimate* of the bias ${}_2C_B - {}_2C_A$ of the clock on spacecraft B relative to spacecraft A;
- ${}_iC_j$ is the time of the clock on spacecraft j (= A or B) at time t_i;
- ${}_1C_{BRT}$ is the time of the clock on spacecraft B representing the time of receipt of the transmission from spacecraft A;
- ${}_2C_{ART}$ is the time of the clock on spacecraft A representing the time of receipt of the transmission from spacecraft B;
- $OWLT_{ij}$ is the one-way light time (signal transit time) from spacecraft i to spacecraft j;
- TD_{SCi} is the telemetry transmission delay through spacecraft i; and
- TF_{SCi} is the time offset of a telemetry frame relative to the C&DH reference edge of spacecraft i.

If the total transaction time $\Delta t_T = {}_2C_{ART} - {}_1C_A$ for the two-way communication is small, perhaps a few seconds, then the change in bias between the two spacecraft clocks will be very small. As an extreme example, suppose the two clocks are drifting rapidly with respect to each other at the rate of about 100 ms/day; then, the change in clock bias $\delta_{BIAS} = {}_2E_{AB} - {}_1E_{AB}$ over a few seconds would be a few microseconds. The approximation $\delta_{BIAS} = 0$ will be a good estimate for some missions.

Let $\delta_{OWLT} = OWLT_{BA} - OWLT_{AB}$. If the radial distance between the two spacecraft is changing slowly, then, for many applications, for a sufficiently small two-way transaction time Δt_T, we can assume $\delta_{OWLT} \sim 0$.[4] Defining $\delta = \delta_{BIAS} + \delta_{OWLT}$, $\nu = TD_{SCA} - TD_{SCB}$, and $\phi = TF_{SCA} - TF_{SCB}$ and solving equations (23) and (24),

$$\begin{aligned} {}_1E_{AB} &= \tfrac{1}{2}[({}_1C_A - {}_1C_{BRT}) - ({}_2C_B - {}_2C_{ART}) + \phi + \nu - \delta] \\ &\sim \tfrac{1}{2}[({}_1C_A - {}_1C_{BRT}) - ({}_2C_B - {}_2C_{ART}) + \phi + \nu], \text{ for } \delta \sim 0. \end{aligned} \tag{25}$$

This offers a simple approach to estimating the biases between spacecraft clocks for a collection of spacecraft flying in formation, without explicit knowledge of the range between spacecraft, and allows meaningful definition of a "formation time" or "constellation time" [27] suitable for time-tagging events observed by any of the spacecraft in the formation. Solving equations (23) and (24) for OWLT can also provide a coarse estimate of range between spacecraft.

Remembering the earlier statement that "The primary goal of spacecraft timekeeping is to establish knowledge of the time of an onboard reference event with respect to which the time of every other event on the spacecraft can be measured," we should ask to what reference event is the above "formation time" measured? The answer is not straightforward, and may be one of several possible answers. A simple approach is to set the formation time equal to the clock time of one of the spacecraft, implicitly defining the "reference event" as the C&DH reference edge for that particular spacecraft. That leaves unanswered the engineering question of what to do when the clock of that particular spacecraft fails. Another approach, similar to [27], is to define the formation time as an "ensemble time" that somehow combines the values of the clocks of all the spacecraft. How to define such an ensemble time and how (or whether) to relate that to a "reference event" may be a fruitful area for future study. Such an ensemble approach does provide a more robust and reliable system for defining formation time than depending on the health of a particular spacecraft clock.

VII. SUMMARY

This paper introduced the concept of Category 1 and Category 2 spacecraft timekeeping systems and discussed the dichotomy between such systems in terms of the relationship between spacecraft clock resolution and accuracy. The similarities between the two categories were discussed, and equation (4) for estimating the time of the onboard reference event was applied to both. Distinctions between open-loop systems and closed-loop systems were examined and the various factors that influence the accuracy of such systems were discussed. Trade-offs and guidelines for designing spacecraft timekeeping systems were suggested, and the importance of "ground truth" verification noted. Finally, a possible extension of these ideas to spacecraft flying in formation was introduced.

Successful application of these principles to the NEAR Shoemaker timekeeping system was described, as was the proposed implementation of the STEREO timekeeping system.

[4] For example, for Deep Space 3 (DS3) [25], spacecraft separations will be no more than 1 km, so we would expect $\delta_{OWLT} < 1\ \mu s$. For the Mars constellation described in [26], spacecraft separations would be ~ 3000 km, so we would expect $\delta_{OWLT} \ll 1$ ms.

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13. ABSTRACT *(Maximum 200 words)*

This paper discusses the details of the inherently different timekeeping systems for two interplanetary missions, the NEAR Shoemaker mission to orbit the near-Earth asteroid 433 Eros and the STEREO mission to study and characterize solar coronal mass ejections. It also reveals the surprising dichotomy between two major categories of spacecraft timekeeping systems with respect to the relationship between spacecraft clock resolution and accuracy. The paper is written in a tutorial style so that it can be easily used as a reference for designing or analyzing spacecraft timekeeping systems.

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