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To: Distribution

From: S. B. Cooper

Subject: Revised Relativistic Interpretation of Operations SCLK Kernels

The MESSENGER, New Horizons, STEREO and Van Allen Probes (RBSP) missions use a simple algorithm to determine the estimates of Earth time that are included in each mission's Operations SCLK Kernel. Solar Probe Plus will also use that same algorithm for its Operations SCLK Kernel. The Operations SCLK Kernel relates spacecraft time to Earth time.

This memo describes that algorithm and the computational error resulting from relativistic effects in its use. The error, it turns out, is too small to be of concern for these missions. An earlier analysis [b] was incorrect and greatly overestimated the magnitude of this error. That analysis was based on an incorrect application of special relativity.

First, some background on how Earth time is represented in the Operations SCLK Kernel: An SCLK kernel is a time data text file in a generic format defined by the Navigation and Ancillary Information Facility (NAIF) of NASA's Jet Propulsion Laboratory (JPL) for use with their SPICE software [c]. An Operations SCLK Kernel is an SCLK kernel with improved time accuracy resulting from recalculation of past clock drift. The Operations SCLK Kernel was "invented" at APL specifically to provide the enhanced accuracy required for the MESSENGER mission. All our current deep space missions and the Earth-orbiting Van Allen Probes mission produce Operations SCLK Kernels.

Each SCLK kernel includes "time records" or "time coefficients triplets," each of which contains three fields. The first of these fields is the primary representation of time onboard each spacecraft which, for these missions, is called "Mission Elapsed Time" or "MET." The second field is called "Terrestrial Dynamical Time" or "TDT," which is a time system used to represent Earth time. The third field is the rate of change of TDT with respect to MET, as defined in [c]. The purpose of those time records is to provide correlations between MET (i.e., spacecraft time) and TDT (i.e., Earth time).

One minor note about the terminology: Terrestrial Dynamical Time (TDT) was defined in 1976 by the International Astronomical Union (IAU). It is closely related to standard world time UTC but does not include UTC leap seconds: TDT = UTC + leap seconds + 32.184 seconds, approximately. The IAU later redefined TDT and renamed it "Terrestrial Time" or "TT." APL SCLK kernels, as well as NAIF SPICE documentation, have traditionally used the TDT nomenclature and we will continue to use TDT here.

The algorithm used in the mission timekeeping system ground software to compute the TDT for the Operations SCLK Kernel is

(1) $TDT(G) = TDT_{DSN} – OWLT – TD_{SC} – TF_{OFFSET}$, where

TDT(G) is the ground estimate of the TDT corresponding to the onboard time reference event ("1 Pulse-Per-Second" or "1 PPS" event occurring at the 1-second increment of the MET counter),
TDT_{DSN} is the TDT equivalent to the UTC downlink telemetry frame Earth Received Time (ERT) reported by the receiving Deep Space Network (DSN) station or other ground station,
OWLT is the one-way-light-time from the spacecraft antenna to the receiving ground station, as computed by SPICE using the predictive spacecraft ephemeris
TD_{SC} is the transmission delay of the first bit of the downlink frame through the spacecraft, from the time the MET value is latched, and
TF_{OFFSET} is the offset from the 1 PPS reference event to the time the MET value is latched.

The term TDT_{DSN} is in an Earth centered frame of reference. However, it turns out that SPICE computes OWLT in a solar barycentric frame of reference. Combining the two as shown in the above equation is not strictly correct and results in some error in TDT(G), which is intended to be in an Earth centered frame of reference. The amount of that error is small and it is the purpose of this memo to document that detail.

The correct formulation, in terms of the time system "Terrestrial Barycentric Time" or "TDB," would be

(2) $TDB(G) = TDB_{DSN} – OWLT_{TDB} – TD_{SC} – TF_{OFFSET}$, where

TDB(G) is the ground estimate of the TDB corresponding to the onboard time reference event ("1 PPS" event occurring at the 1-second increment of the MET counter); TDT(G) would be obtained from TDB(G) using a standard SPICE conversion,
TDB_{DSN} is the TDB equivalent to the UTC downlink telemetry frame Earth Received Time (ERT) reported by the receiving DSN or other ground station,
$OWLT_{TDB}$ is OWLT as defined above, with the "TDB" notation added to emphasis that it is in the same reference frame as TDB_{DSN}, and
TD_{SC} and TD_{OFFSET} are as defined above; frame of reference errors in these are negligibly small.

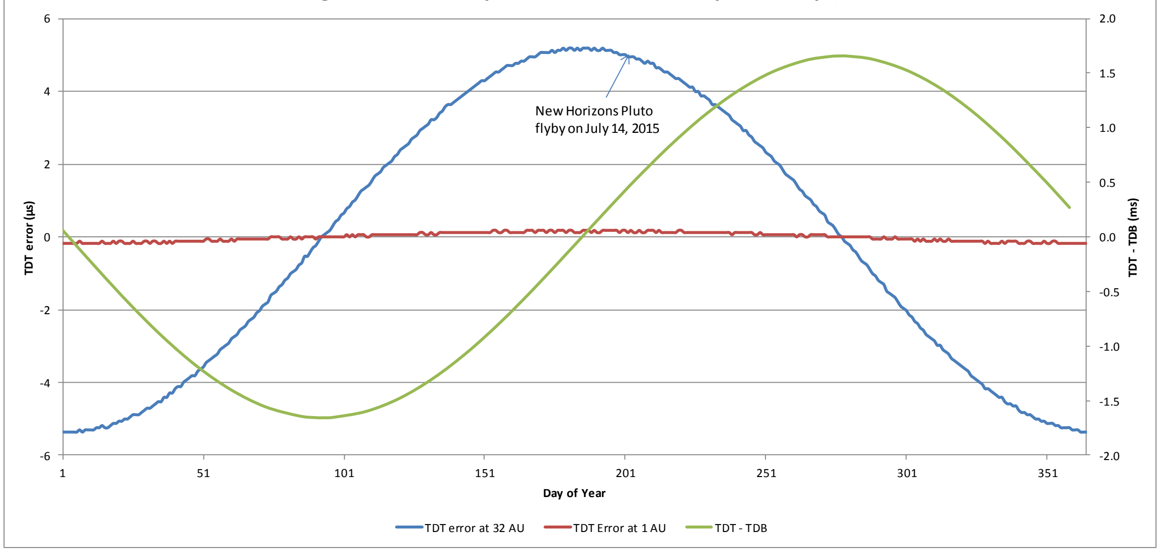

Figure 1: TDT computation error due to Eq. (1) vs. Eq. (2)

Figure 1 shows the error in TDT(G) computed with SPICE using Equation (1) compared to TDT(G) computed with SPICE using Equation (2), for assumed distances of 32 AU (the New Horizons Pluto flyby distance) and 1 AU. The error for New Horizons will be less than 6 µs through the Pluto flyby and the error for all our other missions is less than 0.2 µs. The error is a function of how far the spacecraft is from the Earth and also a function of the day of the year because the relationship between TDT and TDB depends on the day of the year. We conclude from Figure 1 that the use of Equation (1) to estimate TDT(G) does not contribute a significant amount of error.

However, there is a much larger relativistic error that is not accounted for in either Equation (1) or Equation (2), namely, Shapiro delay. This effect is described in Reference [e] for New Horizons and MESSENGER and can contribute a hundred microseconds or more in TDT error.

The calculation of TDT relies on the SPICE computation of $OWLT_{TDB}$. However, that computation does not include Shapiro delay and so is in error by that amount and TDT is correspondingly in error by that amount. There are some other small errors in the calculation of TDT but Shapiro delay is generally the most significant of those computational errors as observed on New Horizons and MESSENGER and reported in [e].

For completeness, here are the other systemic calculation errors that have been identified in determination of TDT.

1. Our mission timekeeping software uses the SPICE function "LTIME" to compute OWLT. The error in this computation is of the order of one nanosecond for computation of OWLT in a solar barycentric frame of reference. The LTIME result is a Newtonian computation of OWLT and does not include relativistic Shapiro delay.

2. According to the Astronomical Almanac [f], the standard formula for conversion between TDT and TDB is accurate to ±30µs. A conversion from TDT to TDB and later back to TDT is understood to cancel almost all of that error, so the 30µs is a "one-way" error.

3. SPICE uses an approximation to the standard formula (see Equation [1] in [d]) for conversion between TDT and TDB that can result in an additional error of less than 30 microseconds. A conversion from TDT to TDB and later back to TDT again cancels almost all of that error. This is relevant to the computations of Figure 1.

4. The definition of the Operations SCLK Kernel, an APL "Generic SCLK Kernel" [a], includes a specification of the rate of change of TDT with respect to MET that allows a quantization error of less than one microsecond per day when used to extrapolate the MET-TDT correlation in a time record to a later time.

There are other sources of error in TDT(G) that are not due to the calculations themselves and are treated in mission-specific documentation. These include the accuracy of the ground station determination of downlink telemetry frame ERT, the stability of the oscillator that drives the MET counter and the prediction of future MET counter drift relative to UTC. Such issues are outside the scope of this memo.

Summary

This memo describes errors in computation of the TDT values that are placed into APL Operations SCLK Kernels for the MESSENGER, New Horizons, STEREO, Van Allen Probes and Solar Probe Plus missions. Those errors are dominated by relativistic Shapiro delay, which is not accounted for in SPICE calculation of OWLT. The computational errors are too small to be of concern for current APL missions.

Additional errors in determination of TDT, such as the ground station reporting of downlink frame received times, are outside the scope of this discussion and are presented in mission-specific documentation.

References

[a] S. B. Cooper, "Generic SCLK Kernel Format to Support Deep Space Missions," JHU/APL memo SEA-2003-024, May 27, 2003

[b] S. B. Cooper, "Relativistic Interpretation of SCLK Kernels for the MESSENGER, New Horizons, STEREO and G-RBSP Missions," JHU/APL memo SEA-2007-010, February 12, 2007

[c] "SCLK Required Reading," Jet Propulsion Laboratory, NAIF/SPICE Toolkit online documentation, May 27, 2010 - http://naif.jpl.nasa.gov/pub/naif/toolkit_docs/C/req/sclk.html

[d] "Time Routines in CSPICE, Appendix A" Jet Propulsion Laboratory, NAIF/SPICE Toolkit online documentation, April 9, 2009 - http://naif.jpl.nasa.gov/pub/naif/toolkit_docs/C/req/time.html

[e] S. B. Cooper, J. R. Jensen, G. L. Weaver, "MESSENGER Onboard Timekeeping Accuracy During the First Year in Orbit at Mercury," Proceedings of the 44th Annual Precise Time and Time Interval Systems and Applications Meeting, Reston, Virginia, November 2012, pp. 361-370

[f] "The Astronomical Almanac for the Year 2009," U. S. Government Printing Office, 2009

APPENDIX A

Glossary of timekeeping terms and acronyms

1 PPS	“1-Pulse-Per-Second” signal occurring at a 1 Hz rate
APL	Same as JHU/APL
C&DH	Command and Data Handling Subsystem
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
DSN	Deep Space Network system of NASA ground communication stations
Encoded SCLK	Continuous mission timeline in the SCLK kernel, mapped from possibly discontinuous MET (cf. SCLK)
ERT	Earth Received Time, the time at which a downlink frame reference edge is received at the ground station
iMET or IMET	Integer seconds component of MET
JHU/APL	The Johns Hopkins University Applied Physics Laboratory
MESSENGER	“MErcury Surface, Space ENvironment, GEochemistry and Ranging” mission to Mercury
MET	Mission Elapsed Time counter on the spacecraft
OWLT	One-way-light-time, used here to refer to the time for a telemetry frame to travel from the spacecraft to a ground station
PPS	Same as 1 PPS
RBSP	Radiation Belt Storm Probes mission, renamed after launch to “Van Allen Probes”
SCLK	A text representation of spacecraft time 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 en-coded SCLK (cf. MET) and TDT(G)
Spacecraft clock	The onboard representation of time that is distributed to the science instruments, but sometimes instead refers to the full-precision MET counter value in the C&DH Subsystem
SPICE	"Spacecraft Planet Instrument C-Matrix Events" system of software tools developed by the Jet Propulsion Laboratory
SPP	Solar Probe Plus mission
STEREO	"Solar TErrestrial RElations Observatory" mission
TDB	Terrestrial Barycentric Time
TDT	Terrestrial Dynamical Time
TDT(G)	Ground estimate of the TDT of the onboard reference event represented by the 1 PPS reference edge
TDT(S)	Onboard estimate of the TDT of the onboard reference event represented by the 1 PPS reference edge
UTC	Coordinated Universal Time
vMET or VMET	Sub-seconds component of MET

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