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To: R. L. Henderson

From: S. B. Cooper

Subject: Relativistic Interpretation of SCLK Kernels for the MESSENGER, New Horizons, STEREO and G-RBSP Missions

Reference:

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

The Reference describes a common file type for tabulating the correlation between time on a spacecraft and time on the ground. This file type is called an “SCLK kernel.” The MESSENGER, New Horizons and STEREO missions use these SCLK kernels and the G-RBSP mission, which has not yet been fully defined, may use them as well.

We’ve learned this past year, since the launch of New Horizons, that the relativistic frame of reference assumed by the user of the various mission timekeeping systems affects the accuracy of the correlations in the SCLK kernels.

For STEREO and G-RBSP, the magnitudes of the time errors that would occur if the user assumes a frame of reference different from that used by the SCLK kernel are small enough to be absorbed into the time error budgets. As a result, the users of time for the STEREO and G-RBSP missions do not need to be aware of or concerned with what frame of reference they are assuming.

For MESSENGER and New Horizons, however, it is important that the user understand in which frame of reference time is being represented. All MESSENGER and New Horizons SCLK kernels represent the correlation between spacecraft time (MET) and the time (TDT) of an ideal clock on the surface of the Earth as it would appear to an observer at the solar system barycenter. That means that to an observer at the solar barycenter, the MET value (time on the spacecraft) given in the SCLK kernel and the corresponding TDT value (time of an ideal clock on the surface of the Earth) given in that same record (line) of the SCLK kernel would appear to occur simultaneously. An important consequence of that is that the MET value and the TDT value would not appear to be simultaneous to an observer on the surface of the Earth. This is a fundamental result of the Theory of Special Relativity.

If that Earth-based observer assumes that the SCLK kernel represents correlations in an Earth-based frame of reference, the resulting error can be many times larger than the MESSENGER or New Horizons science time error budgets.

It is important that all users of MESSENGER and New Horizons time understand this. The error in assuming an Earth-based frame of reference is

(1) $$E \approx \underline{d} \bullet \underline{v} / c^2$$, where

$\underline{d}$ is a (solar system barycentric) vector from the spacecraft to the DSN station that receives spacecraft telemetry, with magnitude equal to the distance traveled by a downlink telemetry frame transmitted from the spacecraft and received at the DSN station at a specific time,
$\underline{v}$ is the (solar system barycentric) velocity vector of the DSN station, and
c is the speed of light

This error can be substantial. For example, for a spacecraft approaching Pluto at about 30 AU from the Earth, this value can approach 1.5 seconds or can be close to zero, depending on the dot product of the DSN station velocity vector and the distance vector. Equation (1) is only an approximation because the vector directions change during the transit of a frame from the spacecraft to the DSN station.

As long as the user of MESSENGER or New Horizons time interprets the time correlation from the SCLK kernel as being in a solar barycentric frame of reference, the relevant mission timekeeping system accuracy will be satisfied. When it is necessary to use an Earth-based frame of reference, a correction corresponding to equation (1) will be needed.

The frame of reference of the SCLK kernel correlations is determined by the frame of reference of the ephemerides used to compute those correlations. The onboard ephemerides used by the G&C Subsystems of the MESSENGER, New Horizons and STEREO missions are in the same frame of reference as the ephemerides used to compute the SCLK kernel correlations. The onboard computation of time for these missions uses parameters taken from the SCLK kernels, so the onboard time and the G&C ephemerides are in the same frame of reference. In other words, there is no error introduced by the frame of reference used by the onboard G&C Subsystem in any of these missions.

Acknowledgement

Shortly after the January 2006 launch of New Horizons, Bob Jensen noticed that the spacecraft USO frequency reported by the New Horizons non-coherent navigation system differed slightly from that reported by the mission timekeeping system. That difference was very small (a few parts per billion) but larger than expected. As months went by, the magnitude of that difference changed. Bob painstakingly studied that result and, through a number of refinements of his frequency model and diligent pursuit of the underlying theory, finally came to the conclusion that his frequency model and the mission timekeeping system were reporting frequency in different relativistic frames of reference. Bob's work also led to equation (1) that has been used, with the help of Scott Turner, to determine the numerical conclusions of this memo.

Summary

The SCLK kernels for the MESSENGER and New Horizons missions have been determined to be in a relativistic solar system barycentric frame of reference. That has been verified through confirmation that the ephemerides used to compute the SCLK kernel correlations are in a solar barycentric frame. It is critically important that the users of MESSENGER and New Horizons time be aware of this and that they properly interpret the time correlations in the SCLK kernels.

Users of STEREO and G-RBSP time do not need to be concerned with this issue because the time error budgets for these missions will absorb the ambiguity in the SCLK kernel that results from this effect of Special Relativity.

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sbc/s

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Glossary of timekeeping terms and acronyms

AU	Astronomical Unit; the mean distance between the Earth and the sun. 1 AU ~ 93,000,000 miles ~ 150,000,000 km
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
DSN	NASA Deep Space Network
Encoded SCLK	Continuous mission timeline in the SCLK kernel, mapped from possibly discontinuous MET (cf. SCLK)
ERT	Earth Received Time
Extended clock	A clock consisting of an oscillator, MET counter value and an SCLK kernel, providing a clock readout in terms of TDT or UTC
G&C	Guidance and Control Subsystem
G-RBSP	Geospace Radiation Belt Storm Probes mission (same as RBSP)
GRT	Ground Received Time, used on NEAR mission
IEM	Integrated Electronics Module
iMET	Integer seconds component of MET
JHU/APL	The Johns Hopkins University Applied Physics Laboratory
JPL	NASA's Jet Propulsion Laboratory, managed by the California Institute of Technology
MESSENGER	"MErcury Surface, Space ENvironment, GEochemistry, and Ranging" mission to Mercury
MET	Mission Elapsed Time counter on the spacecraft (cf. encoded SCLK). An alternative meaning sometimes used in a MOC is

	the time elapsed since launch. Context will generally distinguish between these meanings.
MOC	Mission Operations Center
NAIF	Navigation and Ancillary Information Facility of JPL
OWLT	One Way Light Time
RBSP	Geospace-Radiation Belt Storm Probes mission (same as G-RBSP)
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.
SPICE	“Spacecraft Planet Instrument C-matrix Events” system of software tools developed by NAIF at JPL
STEREO	“Solar Terrestrial Relations Observatory” mission
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
USO	Ultra-Stable Oscillator
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 component of MET