MESSENGER Onboard Timekeeping Accuracy during the First Year in Orbit at Mercury

Stanley B. Cooper, J. Robert Jensen, and Gregory L. Weaver

The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA

Stanley.B.Cooper@jhuapl.edu

Abstract—The NASA MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission to Mercury, launched in 2004, utilizes a timekeeping system that consistently provides accurate post-processed time knowledge between the spacecraft and ground operations to within 150 µs. The main constituent of this observed error, when the round-trip light time is computed directly from the geometrical distance traveled, has been attributed to the Shapiro delay. One means that is used to monitor the accuracy of MESSENGER timekeeping is a series of in-flight tests. We typically refer to these as "Latch MET" tests because the primary feature of these tests is the latching of the onboard mission elapsed time (MET) counter value in response to specific "Latch MET" commands transmitted from a Deep Space Network station.

In 2011, we increased the nominal in-orbit cadence of Latch MET tests to once per week in order to characterize the relationship between the observed MESSENGER time accuracy and the Shapiro delay. Here we provide details on the collection and analysis of these results and their relevance to operating deep-space clock systems dominated by relativistic effects.

Key words: deep-space timekeeping, orbit determination, Shapiro delay

I. INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is funded by the NASA Discovery Program and is led by its principal investigator, Sean C. Solomon, of the Carnegie Institution of Washington and the Lamont-Doherty Earth Observatory, Columbia University. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) designed and built the MESSENGER spacecraft and continues to provide project management and mission operations. The MESSENGER spacecraft was launched on 3 August 2004 and on 18 March 2011 became the first spacecraft to enter orbit about Mercury. Since that milestone, the MESSENGER spacecraft has completed its one-year primary science mission and has moved forward into an extended science mission phase expected to end in early 2013.

During MESSENGER's Primary Mission the spacecraft met all mission objectives, which were focused on answering these six key questions about Mercury [1]:

- Why is Mercury so dense?
- What is the geologic history of Mercury?
- What is the nature of Mercury's magnetic field?
- What is the structure of Mercury's core?
- What are the unusual materials at Mercury's poles?
- What volatiles are important at Mercury?

The MESSENGER spacecraft carries seven instruments in its science payload to provide imaging, compositional analysis, magnetic field assessment, and planetary topography. In addition, a radio science Doppler ranging experiment is supported to make gravitational measurements for the determination of planetary interior structure. To assure the sustained delivery of the science data products, the MESSENGER spacecraft design integrates a system of power generation, propulsion, thermal management, communications, and guidance-and-control features, depicted in Fig. 1. As should be clearly appreciated, mission operations in continuous orbit at Mercury must account for a severe heat and radiation environment. Additionally, dynamic perturbations caused by solar influence place unique challenges on maintaining the desired orbital working position of the spacecraft [2].

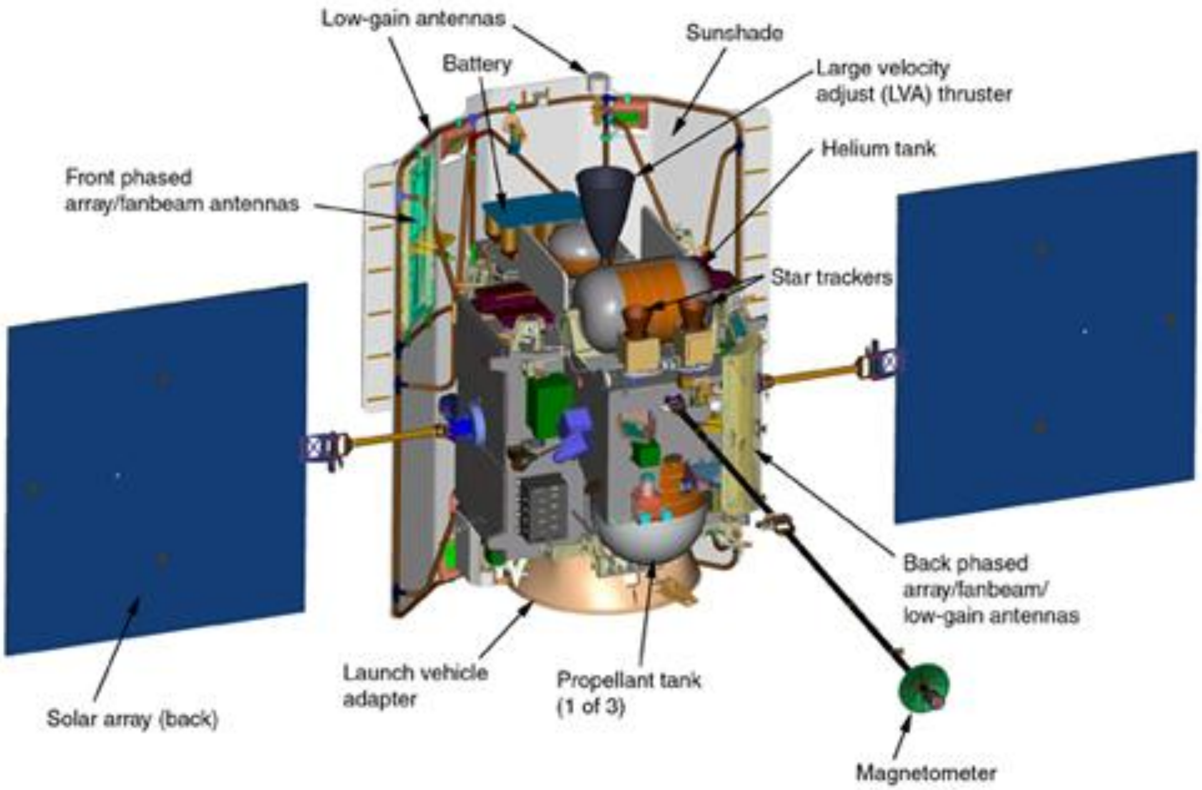

Figure 1. Arrangement of MESSENGER spacecraft operational systems.

Overarching the spacecraft's key system design features is the Integrated Electronics Module (IEM), which acts as the command and data handling subsystem. The IEM consists of a 25 MHz main processor and a 10 MHz fault protection processor that collect, monitor, store, and administrate functional processing for all spacecraft operations. Two fully redundant IEMs are integrated into the spacecraft for back-up contingency. Within the IEM processing functions, the MESSENGER timekeeping system (TKS) supports the functions of navigation guidance and control, command execution sequencing and telemetry communication, and the distribution of time information to the science instruments for chronological recording. The MESSENGER TKS performance requirements are therefore derived from the synthesis of these operational needs.

Of the ensemble of MESSENGER TKS-dependent systems, the Mercury Laser Altimeter (MLA) developed by the NASA Goddard Space Flight Center drives the accuracy requirement of the TKS to maintain ± 1 ms of Terrestrial Dynamical Time (abbreviated TDT or TT), after ground-based post-processing. MLA is a time-of-flight reflective ranging instrument that maps the surface topography of Mercury at a wavelength of 1064 nm [3], and the TKS is used to determine time stamps for the MLA observations. The data collected by the MLA are used to track the planet's slight libration about its spin axis, the amplitude of which constrains the radius of Mercury's liquid outer core. MLA data, combined with the radio science Doppler experiment, are also used to map the planet's gravitational field. The performance of the MESSENGER TKS has been critical to many of MESSENGER's science results, including the recent confirmation of the existence of water ice deposits within permanently shadowed craters located at Mercury's far northern latitudes [4].

This paper will show the post-processed MESSENGER TKS performance as recovered for the first year of orbital operations at Mercury. We will discuss the method of measurement and validation used to determine this performance, which yielded timekeeping accuracy to TT of better than 150 µs, well within the MLA ±1 ms requirement. We also will show an apparent correlation of the TKS performance with the expected Shapiro delay coincident with the Earth-probe-Sun angle as the MESSENGER spacecraft progressed through three solar conjunctions.

In our experience, the high degree of agreement between the apparent MESSENGER TKS error relative to TT and the expected amount of Shapiro delay are examples of emergent measurement capabilities arising from a better-than-required clock. It has been reported that the oscillators on the New Horizons spacecraft en route to Pluto likely detected the incidence of heavy particles at Jupiter's magnetopause earlier than the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) instrument [5]. The revelation that the New Horizons TKS is an in-situ radiation detector was not a total surprise given the known behavior of quartz resonators in space application, but our ability to resolve such very low particle flux densities made it regrettable that quartz radiation sensitivity was never characterized for the New Horizons TKS. In this paper, we revisit the performance of the New Horizons TKS in the observation of the Shapiro delay and how this observation influenced our TKS validation test with MESSENGER after orbit insertion.

II. THE MESSENGER TIMEKEEPING SYSTEM

The purpose of the MESSENGER TKS is to provide knowledge of the relationship between time onboard the MESSENGER spacecraft and Earth time. The mechanism for achieving that knowledge makes use of the telemetry downlink from the spacecraft to NASA Deep Space Network (DSN) stations on Earth [6].

A. Description of Operation

The spacecraft contains multiple representations of time, all referenced back to the value of a mission elapsed time (MET) counter. This 48-bit counter consists of two parts: a 28-bit integer seconds counter and a 20-bit sub-seconds counter with a least significant bit resolution of 1 µs. The sub-seconds counter counts to 999,999 µs before it "overflows," causing the integer seconds counter to increment by 1 s. That "overflow" also results in the generation of a nominally 1 Hz pulse that we call the "1 pulse per second" (1 PPS) signal. For this mission, the leading edge of the 1 PPS is coincident with the overflow of the sub-seconds counter and is the time reference to which the time of every other event on the spacecraft (and every instrument observation) is referred.

MESSENGER downlink frames conform to a standard for frame formats, called the CCSDS transfer frame structure, defined by the Consultative Committee for Space Data Systems, and include both a primary frame header and a secondary frame header. Each MESSENGER downlink frame includes in the secondary frame header the 48-bit MET of the transmission time of a previous frame. When the frame is received at a DSN station, the downlink-frame time-reference bit edge is time-stamped with Coordinated Universal Time (UTC) and that Earth-received time (ERT) is associated with that frame as metadata. The frame with all metadata is further packaged into a DSN standard formatted data unit (SFDU), and that SFDU is transmitted to the MESSENGER Mission Operations Center (MOC) at JHU/APL.

At the MOC, automated ground timekeeping software daily processes selected sets of received frames. Fig. 2 is a sketch of that process. The ERT is adjusted by subtracting the downlink one-way light time (OWLT) from the spacecraft to the DSN station, to give the time at which the downlink-frame time-reference bit edge was transmitted from the spacecraft antenna. Computation of OWLT utilizes the spacecraft predicted ephemeris. Known delays through the spacecraft are then subtracted to give the estimated Earth time at which the corresponding 1 PPS time-reference edge occurred. The appropriate MET from downlink frame headers is identified, giving the correlation between the integer seconds component of MET and Earth time. MET, in this sense, is a representation of the time of the 1 PPS time-reference edge.

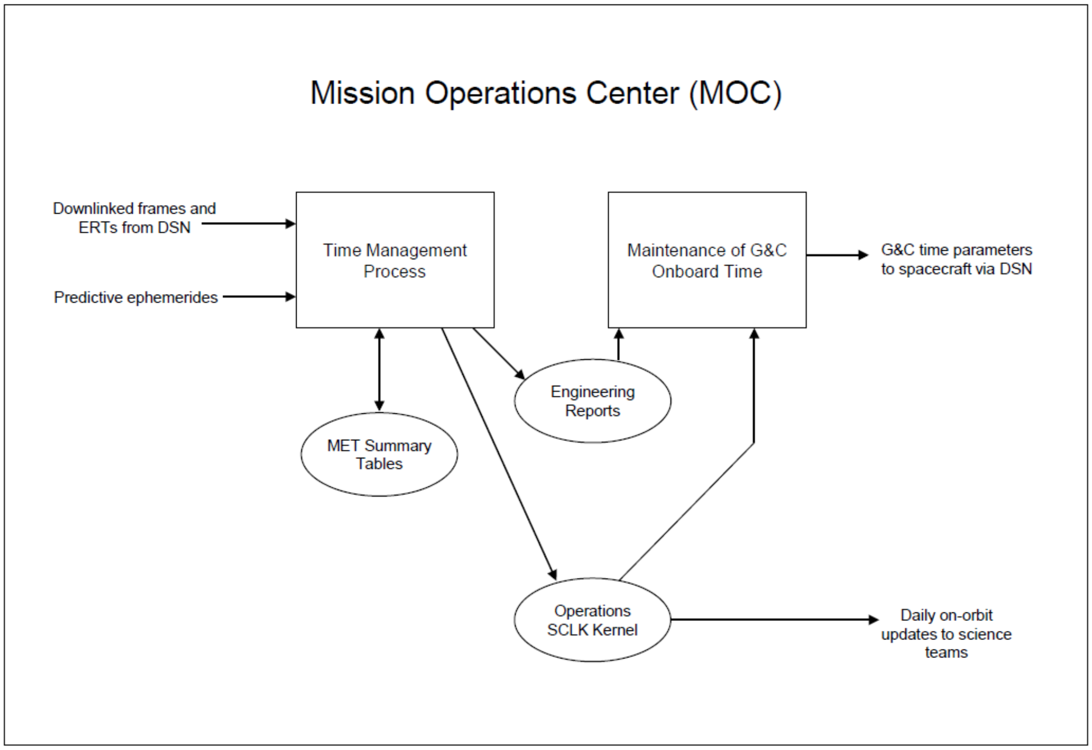

Figure 2. Framework for the MESSENGER Timekeeping System ground component.

B. JPL SPICE and the APL Operations SCLK Kernel

The MOC timekeeping software packages the MET–Earth time correlation into a text file called a Spacecraft Clock (SCLK) kernel. In doing so, it utilizes a package of software developed and maintained by the Jet Propulsion Laboratory (JPL) Navigation and Ancillary Information Facility (NAIF), called Spacecraft Planet Instrument C-matrix Events (SPICE.) The NAIF SPICE software uses a number of data files, called kernels, to enable computation of a variety of parameters of interest, such as OWLT. SPICE uses SCLK kernels to represent time correlations and other types of kernels to represent planetary and spacecraft ephemerides and other types of mission-specific data.

The SPICE SCLK kernel is a text file that contains a table of time records, each including three fields:

- an encoded representation of MET,
- the estimated Earth time at which that MET occurred, in the TT timescale standard, and
- the rate of change of TT with respect to MET in TT seconds per MET second, which is routinely referred to as TDTRATE.

TT is related to UTC but does not include leap seconds. SPICE estimates correlations between arbitrary MET values and TT using linear extrapolation from the most recent past time record. JHU/APL takes that one step further and updates TDTRATE when new data become available, providing the improved accuracy needed for this mission. The JHU/APL version of the SCLK kernel is called the Operations SCLK Kernel and conforms to the standard format definition of SPICE SCLK kernels.

C. In-flight tests and the Latch MET Command

The post-processed ±1 ms requirement mentioned above, on the accuracy of the correlation between the time of an MLA observation (in terms of MET) and Earth time, is tighter than the time accuracy requirements that apply to other deep-space missions of which we are aware. One additional requirement defined early in the MESSENGER mission was to have a mechanism for verifying in-flight that this high level of accuracy is achieved. The mechanism for in-flight time accuracy verification developed is called a "Latch MET" test, so named because it involves latching the value of MET in response to a Latch MET command sent from the DSN ground station.

The Latch MET test involves several components. First, a Latch MET command is sent from a DSN station to the spacecraft, and the time of radiation of that command is reported, with very high accuracy, to the MOC by the DSN station. The novel scheme for accurately reporting the command radiation time was devised by Jeffrey Berner of DSN and developed over a period of several years with the support of DSN personnel, including Richard Benson, Daniel Finnerty, and Alvin Hewitt. It has been used for in-flight tests on MESSENGER and also for the New Horizons mission. The Latch MET command, when detected by the spacecraft, causes the current value of the 48-bit MET counter to be captured, or "latched." That MET value, along with an identification parameter contained in the Latch MET command, is reported by flight software in a special "Latch MET" telemetry packet. The uplink OWLT is computed on the ground using SPICE and is added to the reported command radiation time together with known delays through the spacecraft, giving an estimate of the Earth time that corresponds to the latched MET. Note that this process gives a correlation between MET and Earth time (TT or UTC) that is not subject to clock (MET) drift.

The next step in this process involves mapping that same latched MET value through the Operations SCLK Kernel to obtain an estimated TT from telemetry downlink. The mapping through the Operations SCLK Kernel is based on the spacecraft predicted ephemerides. Then, the difference between the two estimates of TT is taken to estimate the error in the time correlation provided by the Operations SCLK Kernel:

$$TT\text{ [downlink, SCLK Kernel predicted]} - TT\text{ [uplink, from Latch MET test, using predicted OWLT]} \tag{1}$$

After the one-year in-orbit Primary Mission of MESSENGER, a reconstructed spacecraft ephemeris became available and was used to improve that estimate, as:

$$TT\text{ [downlink, SCLK Kernel predicted]} - TT\text{ [uplink, from Latch MET test, using reconstructed OWLT]} \tag{2}$$

D. In-flight Tests

In-flight Latch MET tests were conducted on both the MESSENGER and the New Horizons missions.

We began our campaign of New Horizons in-flight Latch MET tests on 26 July 2006, and we determined that the estimated error in the Operations SCLK Kernel at that time was 133 μs, more than an order of magnitude better than what was required for New Horizons. A second test a month later, on 23 August, gave an estimated error of 158 μs. The next test, on 30 November 2006, resulted in an estimated error in the Operations SCLK Kernel correlation of 273 μs, more than double the July result, yet still more than an order of magnitude better than the requirement. At this point, it was unclear if there was a problem with the New Horizons TKS, and we did not know if the error would continue to grow. Another test was performed two weeks later and, as shown in Fig. 3, the error decreased slightly, and yet another test two weeks after that again showed a decrease in error. Finally, a test on 3 February 2007 gave an estimated error of 123 μs, a value comparable to the July result.

The increase in the error accompanied the onset of superior solar conjunction as the Sun came between Earth and the spacecraft. Solar conjunction could affect the measurement only through the introduction of relativistic effects. In particular, the increase in the error was attributed to the Shapiro delay [7]. The

Shapiro delay is an increase in the travel time (the OWLT) of a signal passing through the gravitational field of a massive body, in this case the Sun. It was first confirmed by Irwin Shapiro in the 1960s using measurements of radar distances to Venus and Mercury [7]. The Shapiro delay is important not only to the timekeeping as discussed here, but as a consideration in the orbit determination process itself for all deep-space missions. Both the radiometric range measurements and the Doppler velocity measurements are markedly affected by the Shapiro delay, so this delay is routinely included in deep-space navigation calculations. This effect is important for all portions of these missions; it is not limited to solar conjunctions, but it is more pronounced near those events.

The error estimates for the New Horizons tests are shown again in Fig. 4 together with a prediction of Shapiro delay. The Shapiro delay peaks once a year because a solar conjunction occurs once a year as a result of the motion of Earth around the Sun. The agreement between the Shapiro-delay prediction and the test results is fairly good. We conducted a few more Latch MET tests after 2007 (Fig. 4) during times when New Horizons was awakened from its hibernation phases, and the results continued to suggest a possible correlation between those results and Shapiro delay.

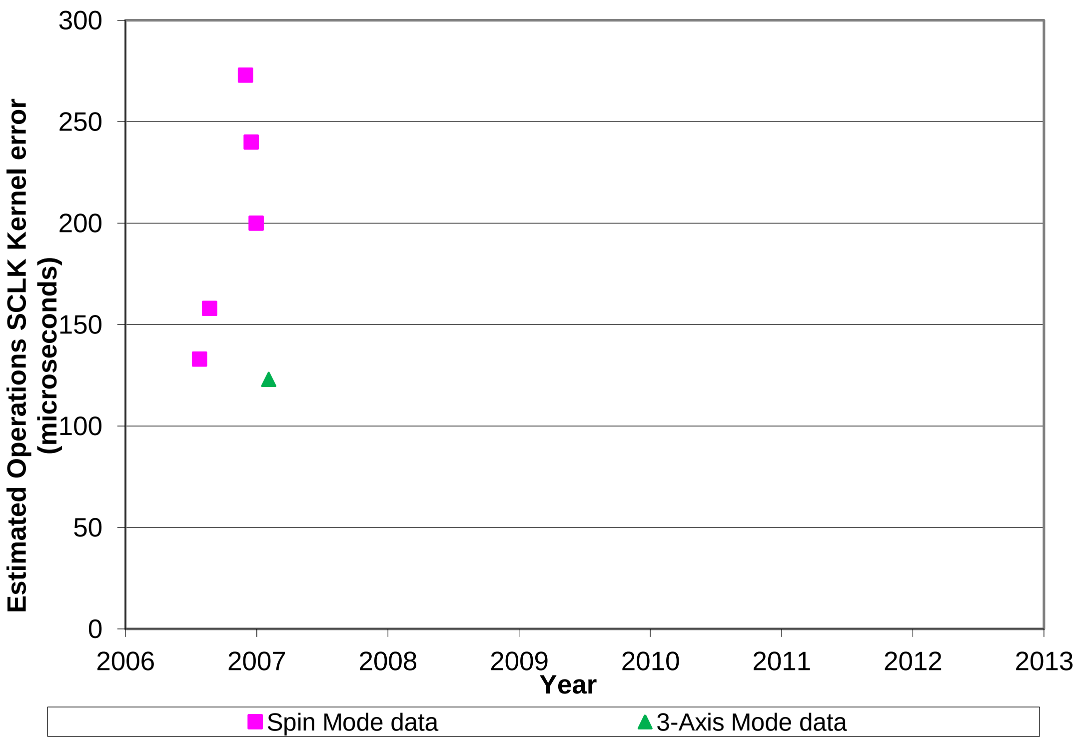

Figure 3. Initial results of New Horizons Latch MET tests.

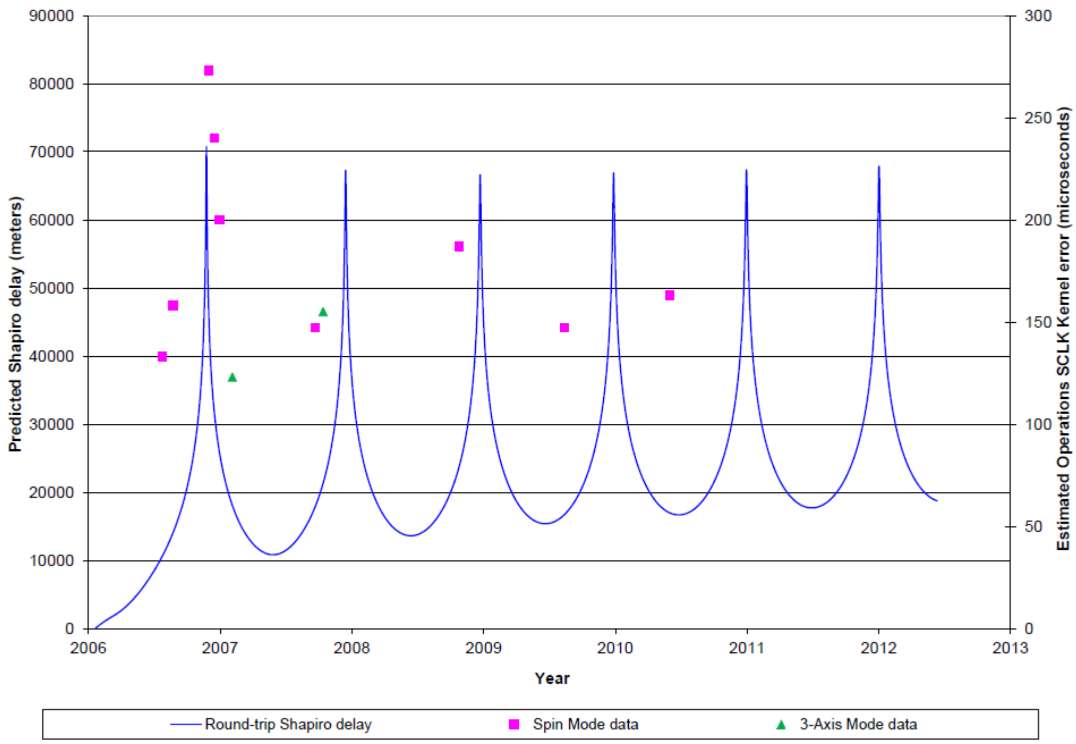

Figure 4. New Horizons Latch MET tests and predicted Shapiro delay.

III. THE MESSENGER LATCH MET CAMPAIGN AND THE SIGNIFICANCE OF SHAPIRO DELAY

During the period of the New Horizons tests, MESSENGER continued on its journey toward Mercury. Occasional Latch MET tests were conducted to confirm that MESSENGER timekeeping continued to be accurate, with the plan to increase the cadence of these tests to once a month for the one-year Primary Mission. Fueled now with the expectation that there was likely a relation between the errors in the MESSENGER Operations SCLK Kernel time correlations and the Shapiro delay, we decided to increase that in-orbit cadence to weekly whenever it was feasible to do so. The results are shown in Fig. 5. A total of 28 Latch MET tests were conducted during the one-year Primary Mission; each test involved sending 30 Latch MET commands, spaced 20 s apart, to the spacecraft. It appears from these data that the Shapiro delay is a lower bound on the accuracy of Operations SCLK Kernel correlation errors.

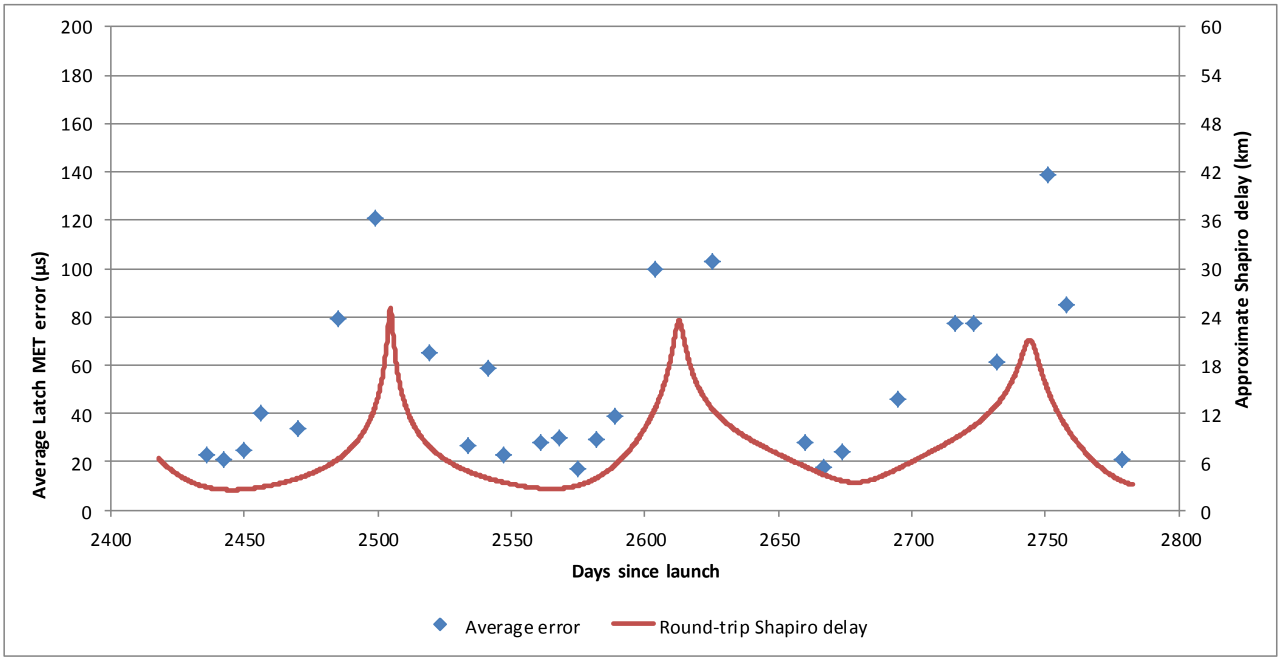

Figure 5. Summary of MESSENGER in-orbit Latch MET test results, for the first year in Mercury orbit.

The SPICE computation used in determining the downlink OWLT for Operations SCLK Kernel correlations and the SPICE computation used in determining the uplink OWLT for Latch MET tests do not account for the Shapiro delay. However, the Shapiro delay does in fact cause the actual OWLT to be larger than computed by SPICE, for both downlink OWLT and uplink OWLT. For that reason, it is the round-trip Shapiro delay that correlates with our results.

Note also that in both Figs. 4 and 5, the Shapiro delay never diminishes to zero; the Sun's gravitational field continues to influence OWLT at all times. We would expect to see that same effect for any transfer of time information across the Solar System.

Following [7] and using the distances and angles defined in Fig. 6, the Shapiro delay is found as:

$$r \sim \left(\frac{2GM}{c^2}\right)\left\{\ln\left(\frac{X_1+\sqrt{X_1^2+R^2}}{R}\right)+\ln\left(\frac{X_2+\sqrt{X_2^2+R^2}}{R}\right)\right\} \tag{3}$$

In terms of the angles defining the Earth-Sun-spacecraft geometry, equation (3) can be expressed as:

$$r \sim \left(\frac{2GM}{c^2}\right)\left\{\ln\left(\cot\left(\frac{SEP}{2}\right)\cot\left(\frac{SPE}{2}\right)\right)\right\} \tag{4}$$

where r is the estimate of Shapiro delay, G is the gravitational constant, M is the mass of the Sun, c is the speed of light, SEP is the Sun-Earth-probe angle, and SPE is the Sun-probe-Earth angle.

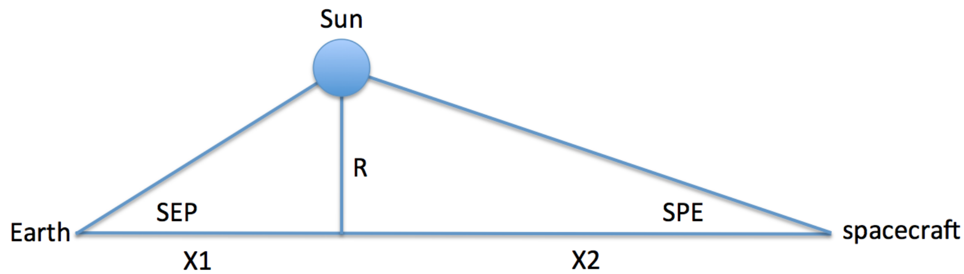

Figure 6. Distances and angles for the Shapiro delay calculation.

How large can the Shapiro delay be for a spacecraft at Mercury? According to Rindler [7], the round-trip Shapiro delay can be up to 66 km or 220 μs at Mercury. So the one-way Shapiro delay can cause an error in the Operations SCLK Kernel mapping of up to 110 μs, still well within the large margin designed into the ±1 ms time error budget.

IV. CONCLUSIONS

Verification of the MET timekeeping performance to mission requirements for the MESSENGER and New Horizons onboard TKS has been shown to be effectively determined by the Latch MET method. The timekeeping system itself takes advantage of a JHU/APL augmentation of the JPL SPICE SCLK kernel processing application, called the Operations SCLK Kernel. The Operations SCLK Kernel offers enhanced precision in the resolution of TDTRATE, the estimated run between the post-processed MET and TT. From the post-processed MESSENGER TKS data accumulated over the first year of science operations at Mercury, the largest measured error in MET was determined to be within 150 μs of TT, showing ample performance margin to the ± 1 ms requirement driven by the MLA.

Given our experience with the New Horizons MET measurements, we anticipated that the greatest contribution to the apparent MESSENGER TKS MET error might be attributable to the uncorrected Shapiro delay. The correlation shown in this paper clearly demonstrates an affirmation of this expectation. Other potential sources of error, such as large deviations in accuracy due to oscillator aging, radiation, or temperature/voltage effects, did not markedly influence the Latch MET results. Moreover, Shapiro delay appears as a lower bound on the non-compensated accuracy of the MESSENGER TKS. This statement is true for any TKS whose time is observed across the Solar System. Deep-space radiometric navigation routinely accounts for the Shapiro delay, and these results make us confident that the TKS can compensate in a complementary manner.

MESSENGER TKS measurement of the Shapiro delay is an example of beneficial science emergent from better-than-expected clock performance. Our confidence in this assertion is based on the stability of the onboard oscillator and the capability to resolve, with high precision, the performance of the MESSENGER TKS using the Latch MET method. Although fitting the clock performance with its cost and physical resource needs in consideration of the most demanding timekeeping and/or frequency stability requirement is often an obvious economic trade in space systems engineering, it has been our experience that allowing for a better clock can reveal unplanned enhancement to science collection results after operations begin.

REFERENCES

[1] "Mercury: The Key to Terrestrial Planet Evolution," The Johns Hopkins University Applied Physics Laboratory, accessed Dec. 6, 2012, http://messenger.jhuapl.edu/why_mercury/index.html.

[2] D. R. Stanbridge et. al., "Available force model accuracies for MESSENGER in Mercury orbit," Astrodynamics Specialist Conference, American Astronautical Society/ American Institute of Aeronautics and Astronautics, Girdwood, AK, Jul. 31 – Aug. 4, 2011, paper AAS 11-548, 19 pages.

[3] J. F. Cavanaugh et al., "The Mercury Laser Altimeter instrument for the MESSENGER mission," Space Sci. Rev., 131, 2007, pp. 451-479. doi:10.1007/s11214-007-9273-4.

[4] G. A. Neumann et. al., “Bright and dark polar deposits on Mercury: evidence for surface volatiles,” *Science Express*, Nov. 29, 2012, downloaded from *www.sciencemag.org* on Dec. 6, 2012, *http://www.sciencemag.org/content/early/recent/29 November 2012/page1/10.1126/scince.122974*, 6 pages. doi:10.1126/science.1229764.

[5] J. R. Jensen, G. L. Weaver, “The in-flight frequency behavior of two ultra-stable oscillators on-board the New Horizons spacecraft,” Proc. 39th PTTI Meeting, pp. 79–93, November 2007.

[6] S. B. Cooper, “From Mercury to Pluto: a common approach to mission timekeeping,” IEEE Aerospace and Electronic Systems Magazine, 21 (10), Oct. 2006, pp. 18-23.

[7] W. Rindler, Relativity – Special, General, and Cosmological, Oxford University Press, Oxford, 2006, p. 237.