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UTC AND THE HUBBLE SPACE TELESCOPE FLIGHT SOFTWARE

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Many scientific spacecraft include on-board computers whose flight software implicitly assumes a correspondence between the UT1 and UTC time scales. Using the Hubble Space Telescope flight software as an example, we examine the aspects of on-board computer flight software that may make use of these time scales, and consider how the software may be impacted by allowing the two time scales to diverge.

INTRODUCTION

Since the early days of the Space Age, many artificial satellites have been equipped with on-board computers. The software that runs on spacecraft on-board computers, called *flight software*, may serve a number of functions, such as:

- Spacecraft attitude determination and control;
- Autonomous commanding to the spacecraft hardware while out of ground contact;
- Spacecraft health and safety checks; and
- Scientific instrument support.

On-board computers have the advantage of providing a great deal of flexibility to a mission, since the flight software may be re-programmed at any time to compensate for hardware failures or adapt to changing mission requirements.

The Hubble Space Telescope (HST) is an example of a modern scientific spacecraft employing on-board computers. In addition to some dedicated microprocessors, the HST spreads its computational work among *two* general-purpose on-board computers: a 486 computer (used for attitude determination and control and spacecraft health and safety monitoring), and an NSSC-I (NASA Standard Spacecraft Computer I) used to support the scientific instruments. The two computers are capable of communicating with each other so that, for example, the 486 computer can signal the NSSC-I to safe its scientific instruments if a dangerous spacecraft attitude it detected.

Among the calculations performed by HST's 486 attitude-control computer are the calculation of ephemerides for the Sun, the Moon, the HST spacecraft, and the Tracking and Data Relay Satellites (TDRS) used for communication with the ground. The 486 computer also computes a geomagnetic field model as backup to the on-board magnetometers for use in its attitude control algorithm. Such

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calculations are typical of computations done in attitude-control computers of scientific spacecraft, and implicitly assume a close correspondence between the UT1 and UTC time scales. Here we'll examine some of the details of such calculations, and how they might be impacted by a proposed change in the definition of the UTC time scale that would eliminate leap seconds and allow UTC to drift with respect to UT1.

SPACECRAFT CLOCKS

Scientific spacecraft generally include an on-board clock driven by a crystal oscillator. The flight software can track oscillations of the on-board clock in the form of a simple counter, which serves as the basis of time calculations in the software. For example, the ground can provide a set of clock calibration coefficients to allow the flight software to convert the on-board clock counter to units of SI seconds elapsed from some specified epoch such as J2000,* and this calibrated clock can then be used as input to the ephemeris and geomagnetic field calculations. The on-board clock calibration coefficients need to be updated from the ground periodically to allow for drift in the crystal oscillator.

The flight software generally places the clock counter into the downlinked telemetry stream, where software on the ground can convert it to UTC using a similar set of calibration coefficients. This ground-calibrated clock is used to time-tag the received telemetry.

SOLAR EPHEMERIS

Scientific spacecraft may compute solar ephemerides for a number of reasons. A solar observatory, for example, may compute the position of the Sun at frequent intervals to ensure that the instruments stay correctly pointed directly at the Sun's disk. Many spacecraft contain solar arrays as their primary source of electric power, and these arrays must be kept pointed normal to the Sun's direction. If the solar arrays are steerable, then a knowledge of the direction of the Sun allows the on-board computer to keep the arrays properly oriented.

For an astronomical observatory like HST, the Sun is something to be avoided: the sensitive instruments can be permanently damaged if they are exposed to direct sunlight. In this case a safing test can be written to place the entire observatory into a safe condition if the instruments are pointed too close to the Sun.

Another reason for computing the position of the Sun in flight software is to correct the true position of astronomical targets for velocity aberration effects. By calculating both velocity aberration and parallax corrections, the flight software can correct the true position of an astronomical target to its *apparent* position, so that it can be located by the scientific instruments.

It is a relatively straightforward task to compute the position of the Sun using a low-precision analytical model.[1] Beginning with the time n (measured in days from epoch J2000 in the UT1 time scale),

$$n = \mathrm{JD} - 2451545.0 \tag{1}$$

where JD is the Julian day, we compute the mean longitude L and mean anomaly g of the Sun from

$$L = 280^{\circ}\!.460 + 0^{\circ}\!.985\,6474\,n \tag{2}$$

$$g = 357^{\circ}\!.528 + 0^{\circ}\!.985\,6003\,n. \tag{3}$$

*J2000 is the instant of January 1, 2000, at 12:00:00 TDB.

We then find the ecliptic longitude λ and ecliptic latitude β, taking the latter to be 0° since the Sun lies in the ecliptic plane:

$$\lambda = L + 1^\circ\!.915 \sin g + 0^\circ\!.020 \sin 2g \tag{4}$$
$$\beta = 0^\circ. \tag{5}$$

The Earth-Sun distance in astronomical units may be found from the mean anomaly g using

$$R = 1.000\,14 - 0.016\,71 \cos g - 0.000\,14 \cos 2g. \tag{6}$$

Here λ, β, and R form a set of spherical polar coordinates of the Sun. We can convert the ecliptic coordinates to equatorial coordinates referred to the plane of the equator using

$$\tan \alpha = \tan \lambda \cos \varepsilon \tag{7}$$
$$\sin \delta = \sin \lambda \sin \varepsilon, \tag{8}$$

where α is the right ascension, δ is the declination, and ε is the obliquity of the ecliptic for epoch J2000, $\varepsilon = 23^\circ\, 26'\, 21''\!.448$. Converting from spherical to cartesian coordinates gives the geocentric cartesian coordinates of the Sun:

$$x = R \cos \alpha \cos \delta \tag{9}$$
$$y = R \sin \alpha \cos \delta \tag{10}$$
$$z = R \sin \delta \tag{11}$$

which is typically what is required for on-board safety check and velocity aberration calculations. This analytical formula for the position of the Sun is accurate to about 1 minute of arc.

LUNAR EPHEMERIS

Not all spacecraft require the calculation of an on-board lunar ephemeris, but sometimes it is required. For the Hubble Space Telescope, for example, the full Moon is sufficiently bright to pose a potential danger to the sensitive scientific instruments. A lunar ephemeris is therefore required to implement a Moon-pointing safing test, which will command the instruments to a safe state if the Telescope ever points too close to the Moon. The lunar ephemeris is also required to calculate the *velocity* of the Moon, which is a (small) part of the velocity aberration corrections described earlier.

The position of the Moon is much more difficult to calculate to high accuracy than the position of the Sun. While the solar ephemeris calculation is essentially a two-body (Earth-Sun) problem to good accuracy, the lunar ephemeris calculation forms a *three*-body (Earth-Moon-Sun) problem. In calculating the position of the Moon, one must be realistic in assessing how much accuracy is required: calculating the position of the Moon to high accuracy is a difficult problem, and may consume too much of the on-board computer's resources. For a safing test, an accuracy on the order of the lunar diameter ($\sim 0.5^\circ$) is usually adequate, and any errors in the calculation of the position may be absorbed in an extra "buffer zone" around the Moon's position.

A lunar ephemeris calculation typically used in flight software is an analytical model[1] based on Brown's lunar theory.[2,3] One begins by computing the time T in Julian centuries elapsed from epoch J2000 (with fractions of a day being on the UT1 time scale):

$$T = \frac{\mathrm{JD} - 2451545.0}{36\,525}, \tag{12}$$

where JD is the Julian day. One then computes the ecliptic coordinates of the Moon (λ, β) and the horizontal parallax π directly from

$$\begin{aligned}
\lambda = {} & 218\overset{\circ}{.}32 + 481\,267\overset{\circ}{.}881\,T \\
& + 6\overset{\circ}{.}29 \sin(135\overset{\circ}{.}0 + 477\,198\overset{\circ}{.}87\,T) - 1\overset{\circ}{.}27 \sin(259\overset{\circ}{.}3 - 413\,335\overset{\circ}{.}36\,T) \\
& + 0\overset{\circ}{.}66 \sin(235\overset{\circ}{.}7 + 890\,534\overset{\circ}{.}22\,T) + 0\overset{\circ}{.}21 \sin(269\overset{\circ}{.}9 + 954\,397\overset{\circ}{.}74\,T) \\
& - 0\overset{\circ}{.}19 \sin(357\overset{\circ}{.}5 + 35\,999\overset{\circ}{.}05\,T) - 0\overset{\circ}{.}11 \sin(186\overset{\circ}{.}5 + 966\,404\overset{\circ}{.}03\,T) \qquad (13) \\
\beta = {} & +5\overset{\circ}{.}13 \sin(93\overset{\circ}{.}3 + 483\,202\overset{\circ}{.}02\,T) + 0\overset{\circ}{.}28 \sin(228\overset{\circ}{.}2 + 960\,400\overset{\circ}{.}89\,T) \\
& - 0\overset{\circ}{.}28 \sin(318\overset{\circ}{.}3 + 6003\overset{\circ}{.}15\,T) - 0\overset{\circ}{.}17 \sin(217\overset{\circ}{.}6 - 407\,332\overset{\circ}{.}21\,T) \qquad (14) \\
\pi = {} & +0\overset{\circ}{.}9508 \\
& + 0\overset{\circ}{.}0518 \cos(135\overset{\circ}{.}0 + 477\,198\overset{\circ}{.}87\,T) + 0\overset{\circ}{.}0095 \cos(259\overset{\circ}{.}3 - 413\,335\overset{\circ}{.}36\,T) \\
& + 0\overset{\circ}{.}0078 \cos(235\overset{\circ}{.}7 + 890\,534\overset{\circ}{.}22\,T) + 0\overset{\circ}{.}0028 \cos(269\overset{\circ}{.}9 + 954\,397\overset{\circ}{.}74\,T) \qquad (15)
\end{aligned}$$

The horizontal parallax π is directly related to the Earth-Moon distance R:

$$R = \frac{R_\oplus}{\sin \pi}, \qquad (16)$$

where $R_\oplus$ is the radius of the Earth. Knowing the ecliptic coordinates and Earth-Moon distance, one then computes the geocentric cartesian coordinates of the Moon using Eqs. (7–11). The error in the Moon's position with this model is about $0\overset{\circ}{.}4$, which is comparable to the diameter of the lunar disk.

SPACECRAFT EPHEMERIS

Many spacecraft flight software systems require a computation of the position of the spacecraft at any given time. This may be necessary for computing a parallax correction to the apparent position of an astronomical target, or for computing a position vector to a TDRS communications satellite. A number of methods have been used to compute a spacecraft ephemeris in flight software; a typical method is the two-body Keplerian orbit propagator described here, which is used for the Hubble Space Telescope.

In a two-body ephemeris calculation,[4] one calculates the position of the spacecraft from a known set of orbital elements, which are stored on-board in the flight software. New values of these elements must be uplinked periodically: since the Earth is not a perfect point mass and the spacecraft is subject to perturbations due to the Sun and Moon, the orbital elements change will change with time.

Beginning with a time t measured in days from some epoch time T_0, we begin by finding the mean anomaly M of the spacecraft at time t:

$$M = M_0 + 2\pi N(t - T_0), \qquad (17)$$

where M_0 is the mean anomaly at the epoch time T_0, and N is the mean daily motion in rev/day. Knowing the mean anomaly M and orbit eccentricity e, one then solves Kepler's equation to find the eccentric anomaly E:

$$M = E - e \sin E. \qquad (18)$$

Elaborate iterative methods for solving Kepler's equation may not be appropriate, since the computer time available for computing a spacecraft position will be limited in flight software. Instead, a direct method (such as a truncated series expansion via the equation of the center[5]) may give a quick solution to sufficient accuracy, especially for spacecraft in near-circular orbits.

From the eccentric anomaly E, the next step is to compute the true anomaly f of the spacecraft:

$$\tan\left(\frac{f}{2}\right) = \left(\frac{1+e}{1-e}\right)^{1/2} \tan\left(\frac{E}{2}\right), \tag{19}$$

and the Earth-spacecraft radial distance r:

$$r = a(1 - e\cos E). \tag{20}$$

The coordinates (r, f) form the plane polar coordinates of the spacecraft position in the plane of the orbit; the remaining calculations convert these coordinates to geocentric cartesian coordinates. To accomplish this, we begin by updating the longitude of ascending node Ω and argument of perigee ω to correct for perturbations in the orbit:

$$\Omega = \Omega_0 + \dot{\Omega}(t - T_0) \tag{21}$$

$$\omega = \omega_0 + \dot{\omega}(t - T_0). \tag{22}$$

We then compute the argument of latitude u,

$$u = \omega + f, \tag{23}$$

and finally compute the geocentric cartesian coordinates of the spacecraft from

$$x = r\cos u\cos\Omega - r\sin u\sin\Omega\cos i \tag{24}$$

$$y = r\cos u\sin\Omega + r\sin u\cos\Omega\cos i \tag{25}$$

$$z = r\sin u\sin i. \tag{26}$$

An ephemeris for the TDRS communications satellite may be computed in the same fashion, or a simplified model may be used that takes advantage of the fact that the TDRS spacecraft will always be stationed at the same longitude and directly over the equator.

GEOMAGNETIC FIELD MODEL

On many spacecraft, a set of electromagnets called *magnetic torquer bars* is placed on the spacecraft body which can generate magnetic fields that interact with the Earth's magnetic field. When the spacecraft's reaction wheels have spun up to their limiting rate, they may be slowed down by applying a torque to them while simultaneously using the torquer bars to "push" against the Earth's magnetic field to keep the spacecraft stationary. In effect, excess angular momentum in the reaction wheels is thus transferred to the Earth. Doing this requires a knowledge of the geomagnetic field vector at the spacecraft position, which can be found from magnetometer data and the spacecraft's orientation. But if the magnetometer data is not available, the flight software may incorporate a geomagnetic field model as a backup.

The geomagnetic field vector is traditionally found by expanding the geomagnetic scalar potential V into a spherical harmonic series:[6]

$$V(r,\theta,\lambda) = a\sum_{n=1}^{k}\left(\frac{a}{r}\right)^{n+1}\sum_{m=0}^{n}\left[g_n^m\cos m\lambda + h_n^m\sin m\lambda\right]P_n^m(\cos\theta), \tag{27}$$

where a is the radius of the Earth, r is the distance of the spacecraft from the center of the Earth, λ is the longitude of the spacecraft subsatellite point, θ is the co-latitude of the subsatellite point, and P_n^m are Schmidt-normalized associated Legendre polynomials of the first kind. The coefficients g_n^m and h_n^m are published as the International Geomagnetic Reference Field (IGRF), and are updated every five years to correct for time variations in the field.

The geomagnetic field vector $\mathbf{B}$ at the spacecraft position is found from the gradient of the scalar potential:

$$\mathbf{B}(r, \theta, \lambda) = -\nabla V. \tag{28}$$

This gives the geomagnetic field vector at the spacecraft position, knowing the spacecraft radial distance r and the longitude λ and co-latitude θ of the sub-satellite point. But the on-board ephemeris gives the spacecraft position in the inertial geocentric cartesian frame, so we need to know where the Earth is in its rotation to convert between the inertial frame and the frame rotating with the Earth. The angle between the prime meridian and the vernal equinox is called the *sidereal time at Greenwich* (GST), and is given by the formula[7]

$$\begin{aligned} \mathrm{GST} = {} & 280\overset{\circ}{.}460\,618\,37 + 360\overset{\circ}{.}985\,647\,366\,29\,(\mathrm{JD} - 2451\,545.0) \\ & + 0.000\,387\,933\,T^2 - T^3/38\,710\,000, \end{aligned} \tag{29}$$

where JD is the Julian day (including any fractional day, in UT1) and T is given by Eq. (12).

DISCUSSION

Currently, leap seconds are introduced into the UTC time scale in order to keep UTC to within 0.9 seconds of UT1, a time scale based on Earth rotation. The proposed change in the definition of the UTC time scale would eliminate leap seconds, causing the UTC and UT1 time scales to diverge beginning in 2018.

We can estimate the magnitude of this drift using historical data. Stephenson and Morrison[8] have found that the difference between terrestrial time (TT) and universal time (UT1) over several centuries can be fit to a mean parabola given by

$$\mathrm{TT} - \mathrm{UT1} \approx 0.003086y^2 - 11.23y + 10199 \quad \mathrm{sec}, \tag{30}$$

where y is the year. To find the predicted difference between the "new" UTC and UT1, note that terrestrial time (TT) is related to atomic time (TAI) through

$$\mathrm{TT} = \mathrm{TAI} + 32.184\,\mathrm{sec}. \tag{31}$$

If we estimate roughly four leap seconds will occur between 2011 and 2018, then beginning in 2018 UTC and TAI would be related by

$$\mathrm{TAI} \approx \mathrm{UTC} + 38 \quad \mathrm{sec}. \tag{32}$$

Combining Eqs. (30) through (32) gives a relation for the estimated long-term difference between UTC and UT1, if the proposed change to UTC is implemented in 2018:

$$\Delta \equiv \mathrm{UTC} - \mathrm{UT1} \approx 0.003086y^2 - 11.23y + 10129 \quad \mathrm{sec}. \tag{33}$$

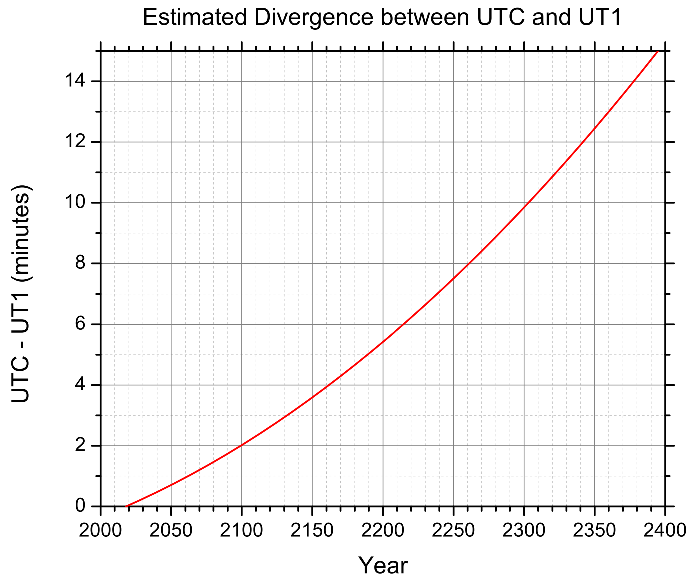

Figure 1. Predicted divergence of UTC and UT1 time scales, if the proposed change to UTC is adopted beginning in 2018. The predicted rate of change is based on the mean parabola fit to historical data given by Reference 8.

The *rate* at which the two time scales would diverge is therefore given approximately by

$$\frac{d\Delta}{dy} = 0.006173y - 11.23 \quad \text{sec/year.} \tag{34}$$

The predicted divergence of the UTC and UT1 time scales based on the mean parabola is shown in Figure 1.

Assuming these rates of divergence of the two time scales, it is possible to estimate the corresponding errors in the calculation of solar and lunar ephemerides *if UTC continues to be used in place of UT1*. From the rates of apparent motion of the Sun, Moon, and HST spacecraft relative to the Earth, we find the results shown in Figure 2.

As shown in the figure, the solar ephemeris would be least affected by an error in using a re-defined UTC time scale instead of UT1, with the error approaching the model error of $0\overset{\circ}{.}01$ after roughly 400 years. The error in the lunar ephemeris accumulates more rapidly, but the lunar ephemeris model also has a higher inherent error; if a re-defined UTC time scale were used in place of UT1 in the lunar ephemeris, the resulting accumulated error would roughly equal the model error in about the same time, 400 years.

A more significant issue is the spacecraft ephemeris. In this case the position of the spacecraft is computed from an algorithm that uses the number of seconds elapsed since an epoch time. The epoch time is one of several orbital elements that are derived from observations of the spacecraft position. If the time scale used in computing the orbital elements is the same time scale used on-board to compute the spacecraft ephemeris, then there should be no difficulty with the spacecraft ephemeris calculation. But if the on-board ephemeris calculation and the derivation of the orbital elements are computed using two *different* time scales (i.e. one with UT1 and the other with re-defined UTC), then there is the potential for errors to accumulate rapidly—perhaps approaching the

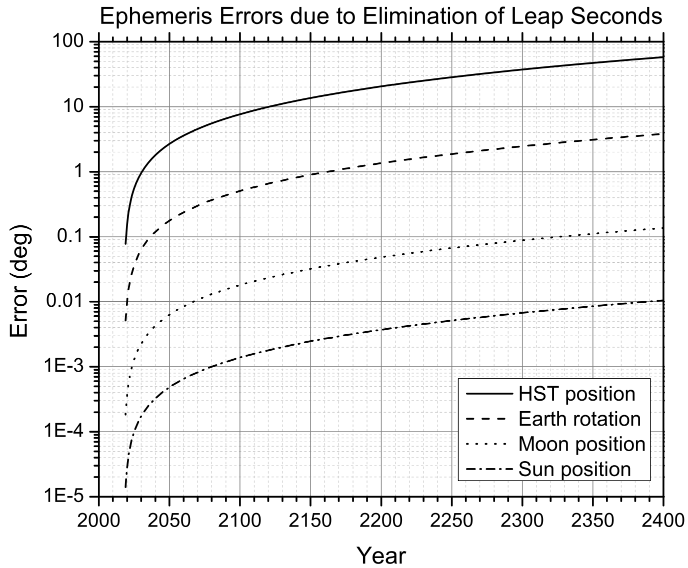

Figure 2. Predicted errors in ephemeris calculations, if UTC the proposed UTC change is adopted and ephemeris calculations continue to use UTC as their time basis. The errors shown for the HST spacecraft are the expected errors if the spacecraft orbital elements are not derived from the same time scale as is being used for the on-board ephemeris. The "Earth rotation" curve applies to error in calculating the position of a geosynchronous communications satellite (e.g. TDRS).

model error in less than five years (Figure 2). Since the orbital elements are typically produced by a different group than the flight software team, there is potential for confusion over which "universal" time scale is being used.

Some spacecraft flight software systems (such as HST's) maintain ephemerides for several geosynchronous communications satellites, in order to properly point the high-gain antennas. Since geosynchronous satellites rotate with the Earth, it is necessary to maintain either a UT1 clock or a calculation of Greenwich Sidereal Time on-board to properly track the Earth's rotation. If a UTC clock is used in place of a UT1 clock, errors would accumulate at the "Earth rotation" rate shown in Figure 2. This would lead to ephemeris errors on the order of the model error in a few decades.

For the geomagnetic field model, the error in the magnetic field vector depends in a complex way on the error in Earth rotation, but the latter should amount to less than 1° for several decades.

CONCLUSIONS

Spacecraft flight software systems making use of the solar, lunar, and spacecraft ephemeris models and geomagnetic field model described here implicitly assume the use of the UT1 time scale, although the on-board clock is typically calibrated to UTC. As seen in Figure 2, if UTC without leap seconds is used in place of UT1, the error in the calculated solar position due to the omission of leap seconds will approach the error in the solar ephemeris model ($0\overset{\circ}{.}01$) after roughly 400 years. For the Moon, the error accumulates more quickly, but the model error is also larger ($0\overset{\circ}{.}4$); the error in time would approach the modeling error at around the same time.

Spacecraft ephemeris calculation errors would grow much more rapidly, approaching the model error in much less time, from five years or less for the ephemeris of a low-Earth orbiting spacecraft like HST to a few decades for a geosynchronous spacecraft. But even if the accumulated errors do not approach the model error during the expected lifetime of the mission, one must consider the issue of *software reuse*: many flight software systems use software adapted from earlier missions to help lower software development costs. Failing to replace UTC with UT1 where appropriate in today's flight software systems could then cause an unexpected accumulation of errors in future missions that inherit today's software.

Another issue to consider is the time-tagging of the telemetry stream. Some missions (like HST) insert time tags into the telemetry stream by simply downlinking the on-board clock counter. In this case, the ground software could continue to convert the clock counter to UTC as before. But if an on-board UTC clock calculation is required (as in the Extreme Ultraviolet Explorer flight software), a flight software change may be required to allow the flight software to maintain separate UT1 and UTC clocks on-board.

Of course, the simplest scenario is to maintain the *status quo*, where the UTC time scale continues to be maintained in synchronization with UT1 via the insertion of leaps seconds. A change in the definition of UTC would require a mission-by-mission consideration of the possible impacts on the flight software systems, such as have been described here.

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