A Time Tutorial

Introduction

This chapter aims at collecting brief definitions of the various time systems in use, as well as simple formulae for doing transformations. Information was gleaned from a number of sources, like the *Explanatory Supplement to the Astronomical Ephemeris (1992)*, a paper by Soffel and Brumberg in *Celestial Mechanics and Dynamical Astronomy* ***52****, 355 (1991)*, and several papers in the *Proceedings of the 6th European Frequency and Time Forum* (ESA SP-340, 1992).

The last section describes the time as it is kept in the RXTE FITS tables. Information is available on absolute time calibration in Appendix A.

Time and Date Systems

See also the USNO Time Scales page at http://tycho.usno.navy.mil/systime.html.

1. **TAI (International Atomic Time):** Based on the SI second and derived from a large number of clocks all over the world. Analyzed and published by by BIPM. Reduced to mean sea level.

2. **UTC (Universal Time, Coordinated):** Based on the SI second, it knows days of 86400 and 86401 seconds. The latter are days with a so-called leap second. The objective is to keep UTC within a second of UT1, which is based on the earth's rotation. The offset from TAI is always an integer number of seconds (the accumulated leap seconds).

3. **TT (Terrestrial Time):** An idealized time, for all practical purposes based on TAI, but with a constant offset to provide continuity with Ephemeris Time. Defined on the rotating geoid.

4. **TB (Barycentric Time):** Also known as TDB (Barycentric Dynamical Time). This is basically TT transformed to the solar system barycenter.

5. **TCG (Geocentric Coordinate Time):** A properly relativistic coordinate time, referred to the geocenter. The coordinate time equivalent of TT.

6. **TCB (Barycentric Coordinate Time):** The coordinate time equivalent of TB.

7. **JD (Julian Date):** Number of days since Greenwich mean noon on January 1, 4713 B.C. Note that JD may be used in conjunction with all of the above time systems; whenever the required accuracy dictates this, the time system used should be indicated: e.g., JD (TT).

8. **MJD (Modified Julian Date):** Equals JD - 2400000.5. The same note applies as for JD concerning the time system in use. We shall continue to use MJD notwithstanding the IAU's recent decision not to recognize MJD anymore as an official time unit.

Useful Relations

1. **JD - MJD:**

$$\mathrm{JD} - \mathrm{MJD} = 2400000.5$$

2. **TT - TAI:**

$$\mathrm{TT} - \mathrm{TAI} = 32.184\mathrm{s}$$

3. **TAI - UTC:** Since 1972, an integer number of seconds. Included as an appendix is Table 1 from the IERS UTC document on the history of the leap seconds.

4. **TCB - TCG:**

$$\mathrm{TCB} - \mathrm{TCG} = L_b \times (\mathrm{JD} - 2443144.5) \times 86400 + c^{-2}\mathrm{v}_e \cdot (\mathrm{x} - \mathrm{x}_e) + P\mathrm{s}$$

$$L_b = 1.480813 \times 10^{-8} (\pm 1 \times 10^{-14})$$

The vectors ***xe*** and ***ve*** denote the barycentric position and velocity of the earth's center of mass, and ***x*** is the barycentric position of the observer. The quantity *P* represents periodic terms which can be evaluated using analytical formulae. For observers on the Earth's surface, these are diurnal, with a maximum amplitude of 2.1 microseconds; for spacecraft, they presumably depend solely on the orbit.

The origins of coordinate times have been arbitrarily set so that these times all coincide with TT at the geocenter of 1977.0 (TAI).

5. **TB - TT:**

$$\mathrm{TB} - \mathrm{TT} = 0.001658 \sin g + 0.000014 \sin 2g\,\mathrm{s}$$

$$g = 357.53° + 0.9856003° \times (JD - 2451545.0)$$

6. **TCG - TT:**

$$TCG - TT = L_G \times (JD - 2443144.5) \times 86400s$$

$$L_G = 6.969291 \times 10^{-10} (\pm 3 \times 10^{-16})$$

7. **TCB - TB:**

$$TCB - TB = L_B \times (JD - 2443144.5) \times 86400s$$

$$L_B = 1.550505 \times 10^{-8} (\pm 3 \times 10^{-14})$$

Other Useful Formulae

1. **Relation between time on the geoid (*t'*) and time on a Low Earth Orbit spacecraft (*tL*):**

$$dt_L = \left(1 + \frac{1}{c^2}\frac{GM}{R_e} - \frac{1}{2c^2}v_L^2 - \frac{1}{c^2}\frac{GM}{R_L}\right)dt'$$

This approximates to:

$$dt_L = \left(1 + 6.9534818 \times 10^{-10} - \frac{6.652542 \times 10^{-3}}{R_L}\right)dt'$$

At an altitude of 500 km, the clock would loose approximately 8.5 ms per year, unless its frequency were adjusted.

RXTE FITS Tables

The time stamps presented by RXTE FITS tables as generated by XFF will be in TT.

It has been agreed that the **Spacecraft Clock Seconds (SCCS)**, or **Mission Elapsed Time (MET)**, will represent true elapsed seconds since January 1, 1994, at 0h0m0s UTC, which corresponds to MJD = 49353.0 (UTC).

Raw time stamps in the FITS tables created by XFF will be on this (SCCS or MET) time system. However, FITS times are to be taken as the sum of a Time value and the values of the `MJDREF` and `TIMEZERO` keywords. The `MJDREF` keyword will incorporate the transformation from UTC, via TAI, to TT (equaling an offset of 60.184 s). Thus, for January 1, 1994, at 0h UTC:

MJD (Jan 1, 1994, 0h UTC) = 49353.0 (UTC) = 49353.000696574074 (TT)

The `TIMEZERO` keyword will provide a nominal clock correction that ensures an absolute accuracy of TBD (nominally 1) ms for the time stamps. The exact value of the tolerance will be based on experience in orbit; the goal is to provide reasonably accurate absolute time with a minimum effort. Generically, the value of `TIMEZERO` may be described as "the fractional part of UTCF".

[UTCF is an institutional dinosaur that can be found in the telemetry. Its purpose is to provide a conversion to UTC: when the sum of SCCS and UTCF is divided by 86400, the integer part of the result provides the number of UTC days since January 1, 1993, at 0h UTC, while the fractional part indicates the current UTC. Thus, UTCF is the sum of the number of seconds in 1993 (31,536,001) and the clock correction, minus the number of leap seconds since January 1, 1993.]

To summarize the times in the FITS tables:

- Raw time stamps are in SCCS.
- Time stamps plus `TIMEZERO` provide time in TAI, as seconds since January 1, 1994, at 0h 0m 28s (TAI).
- Time stamps plus `TIMEZERO` plus `MJDREF` provides absolute time in TT.
- All time-related quantities are in seconds, except for `MJDREF` which is in days.

An Ftools filter will be provided that can either determine a more accurate value for `TIMEZERO`, or insert a column with corrections for all time stamps, depending on the desired precision. The maximum attainable absolute time precision, using this procedure, is TBD (nominally 10) microseconds.

It may be possible to reach even higher accuracies, to the level of a few microseconds, but this will require a knowledgeable guest observer fine-tuning the clock corrections "by hand". No SOC support will be extended for this, beyond providing the guest observer with all data readily available to the SOC.

The relevant FITS table keywords are summarized below:

```
Keyword       Value               Unit   Comment

TTYPE1       'TIME'                s     Column 1 contains raw time in SCCS
TIMESYS      'TT'                        Defines TT as fundamental time system
MJDREF       49353.000696574074    d     1994.0 (UTC) in TT
TIMEZERO     frac(UTCF)            s     Clock correction
```

Various transformations between MET, TT, and UTC in a variety of formats (seconds, calendar date/time, year-day-time, JD, MJD) can be performed using the xTime web tool.

***A Time Tutorial* was written by Arnold Rots of the RXTE GOF.**

- Introduction
- Time and Date Systems
- Useful Relations

Appendix A: RXTE Absolute Timing Accuracy

Definition of Terms

To properly understand the various elements involved in establishing absolute time, one has to be aware of the different components and time systems. In the RXTE FITS files, one will find the following quantities, either as header keywords or table columns.

```
Time          Time stamp, in MET seconds (i.e., the spacecraft clock reading)
TIMEZERO      First order clock correction (~3.4 s)
MJDREF        The MJD(TT) of 1994.0(UTC): 49353 d + 60.184 s
TIMESYS       Time system; either TT or TDB
CLOCKAPP      Boolean: any correction applied?
TIERABSO      Absolute time accuracy
TIMEPIXR      Relative position of time stamp in bin
```

Time systems:

```
TT            Terrestrial Time
TDB           Barycentric Dynamical Time
TCG           Geocentric Coordinate Time
TCB           Barycentric Coordinate Time
```

MET (Mission Elapsed Time) is counted as elapsed seconds since 1994.0 (UTC). MJD (Modified Julian Day) is defined as JD - 2400000.5. A more detailed description of time scales and time systems can be found in the RXTE Time Tutorial.

Time can be expressed in the following ways:

```
MET (accuracy 4 s)       Time
MET (accuracy 100 µs)    Time + TIMEZERO
MET (accuracy 5 µs)      Time + TIMEZERO + clockCorr;
MJD(UTC)                 MET + 49353 d - leap seconds
MJD(TT)                  MET + 49353 d + 60.184 s
MJD(TDB)                 TT + baryCorr(TDB) = TT + tau + (TDB - TT)
MJD(TCB)                 TT + baryCorr(TCB) = TT + tau + (TCG - TT) + (TCB - TCG)
```

MOC Clock Calibration

The MOC (Missions Operations Center) performs clock calibrations several times a day. It uses the USCCS method which involves tagging of a round-trip signal, claiming an accuracy of 1 μs, deteriorated to 5 μs by uncertainties in the White Sands ground clock.

For various reasons, we believe this technique to have yielded an accuracy of 8 μs for RXTE observations made prior to 1997-04-29 (mission day 1214). From that day onward, a formal accuracy of 5 μs is appropriate.

Scientific Verification

Using the pulsars PSR B1509-58 and PSR B0531+21 (the Crab pulsar), we have verified the MOC's absolute clock calibration to an accuracy of 1 ms. This the best that can be done, using cosmic sources. Hence, we feel justified in accepting the clock calibrations by the MOC to the quoted accuracy of 5 or 8 μs (see above).

In addition, the RXTE instruments have intrinsic delays which need to be included in high-precision clock corrections. These are:

```
PCA:        16 - 20 μs
HEXTE:       0 -  1 μs
```

Barycenter Corrections

The pathlength corrections (tau) applied by the Ftool fxbary are based on inherited software and ephemeris; they are accurate to better than 1 μs. The pathlength correction calculation in fasebin uses new software, based more directly on the JPL DE-200 ephemeris, and is accurate to a fraction of a μs.

The values for TDB-TT that these tools derive are not to be trusted to better than a few μs. However, if one were to improve on these, one should really switch from using TDB to TCB.

Clock Correction Tools

If an absolute timing accuracy of 100 μs is sufficient, the FITS files contain all that is needed, provided that CLOCKAPP is true and TIMEZERO is non-zero.

If one needs to do better than that, there are two XTE-GOF tools that incorporate the higher accuracy:

1. The Ftool fasebin automatically applies high-accuracy clock corrections, provided that it has access to a current version of the file tdc.dat.

2. The web tool xTime always provides all clock corrections, whenever it does a time conversion.

If one is using one's own software, one can obtain a C function that calculates the clock correction. xCC.c is available through the web.

All these tools rely on the same ASCII file, tdc.dat, which contains the clock correction coefficients and needs to be kept up-to-date.

Sampling and the Position of Time Stamps

In RXTE FITS files, three types of data are encountered:

1. **Integrated data.**

   Also histogram or binned data. All science data (including event lists) belong to this category. A certain quantity, such as an event count, is integrated over a specific time range (bin). In binned modes, a histogram is presented with contiguous time bins. In event modes, individual time bins are enumerated, each with an implied event count of 1 and a width equal to the time resolution.

   The keyword TIMEPIXR indicates the relative position of the time stamp in the bins: a value of 0.0 indicates that the time stamp refers to the beginning of the bin; 0.5 the center of the bin; 1.0 the end of the bin. If TIMEPIXR is absent, a value of 0.5 is to be assumed, conform the FITS standard. RXTE FITS files always have TIMEPIXR=0.0; i.e., for RXTE, the time stamps always refer the the start of the bin.

2. **Sampled data with known sampling interval**

   A physical quantity, like a voltage or a temperature, or a bit mask, such as a command, is sampled at regular, fixed, and known intervals. This is the case for housekeeping files (particularly instrument housekeeping files) that have a non-zero value for the keyword DELTAT. All that can be said is that the reading took place in the time interval of DELTAT seconds following the time stamp.

3. **Sampled data with unknown sampling interval**

   A physical quantity, like a voltage or a temperature, or a bit mask, such as a command, is sampled at unknown intervals. This is the case for housekeeping files (particularly spacecraft housekeeping files) that have a zero value for the keyword DELTAT. All that can be said is that the reading took place in the time interval between the previous and the current time stamp. In retrospect, a value of 1.0 might have been more appropriate for TIMEPIXR, in this case.

In the last two cases, it may be possible to be more precise, but this requires detailed knowledge of the subsystem, as well as particulars of the data, and no general rule can be given.

Appendix B: Table 1---Leap Second

Table 1. RELATIONSHIP BETWEEN TAI AND UTC, UNTIL 31 MAY 1998

Limits of validity (at 0h UTC)		**TAI - UTC**
1961 Jan. 1 -	1961 Aug. 1	1.422 818 0s + (MJD - 37 300) x 0.001 296s
Aug. 1 -	1962 Jan. 1	1.372 818 0s + ""
1962 Jan. 1 -	1963 Nov. 1	1.845 858 0s + (MJD - 37 665) x 0.001 123 2s
1963 Nov. 1 -	1964 Jan. 1	1.945 858 0s + ""
1964 Jan. 1 -	April 1	3.240 130 0s + (MJD - 38 761) x 0.001 296s
April 1 -	Sept. 1	3.340 130 0s + ""
Sept. 1 -	1965 Jan. 1	3.440 130 0s + ""
1965 Jan. 1 -	March 1	3.540 130 0s + ""
March 1 -	Jul. 1	3.640 130 0s + ""
Jul. 1 -	Sept. 1	3.740 130 0s + ""
Sept. 1 -	1966 Jan. 1	3.840 130 0s + ""
1966 Jan. 1 -	1968 Feb. 1	4.313 170 0s + (MJD - 39 126) x 0.002 592s
1968 Feb. 1 -	1972 Jan. 1	4.213 170 0s + ""
1972 Jan. 1 -	Jul. 1	10s
Jul. 1 -	1973 Jan. 1	11s
1973 Jan. 1 -	1974 Jan. 1	12s
1974 Jan. 1 -	1975 Jan. 1	13s
1975 Jan. 1 -	1976 Jan. 1	14s
1976 Jan. 1 -	1977 Jan. 1	15s
1977 Jan. 1 -	1978 Jan. 1	16s
1978 Jan. 1 -	1979 Jan. 1	17s
1979 Jan. 1 -	1980 Jan. 1	18s
1980 Jan. 1 -	1981 Jul. 1	19s
1981 Jul. 1 -	1982 Jul. 1	20s
1982 Jul. 1 -	1983 Jul. 1	21s
1983 Jul. 1 -	1985 Jul. 1	22s
1985 Jul. 1 -	1988 Jan. 1	23s
1988 Jan. 1 -	1990 Jan. 1	24s
1990 Jan. 1 -	1991 Jan. 1	25s
1991 Jan. 1 -	1992 Jul. 1	26s
1992 Jul. 1.-	1993 Jul 1	27s
1993 Jul. 1 -	1994 Jul. 1	28s
1994 Jul. 1 -	1996 Jan. 1	29s
1996 Jan. 1 -	1997 Jul. 1	30s
1997 Jul. 1.-		31s