European Space Agency
Research and Scientific Support Department
Planetary Missions Division

Time Standards Overview

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CHANGE RECORD SHEET

Date	Iss.	Rev.	Description/Authority
25th June, 03	1	-	Creation of the Time Standards technical note for planetary missions
1st July, 03	1	1	Modification in the chapter 6, Time Standards in PDS, to correct and clarify it. These changes were suggested by Anne Raugh (PDS Small Bodies Node; University of Maryland) and Detlef Koschny.
2nd July, 03	1	2	Correction of the footprint 1. Modification in the chapter 1.3, 2.3 and 2.4.3 to include some suggestions from Jens Biele (Institut fuer Raumsimulation, Germany).
8th July, 03	2	1	A new chapter was included, 2.5, about Coordinate Time, also suggested by J. Biele.

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1 Introduction

1.1 Purpose

The main purpose of this document is to give a clear and comprehensive overview of all the different time standards used in the different phases of the planetary missions. This document does not follow a chronological sorting in the definition of the concepts involved. The definition will be done from the more precise terms, from those that are defined by themselves, to those that needs other terms or definitions explained forehand.

Finally some specific details will be explained in order to clarify some aspects related with different issues, such as the Planetary Data Systems Standards (PDS) or the Data Delivery System (DDS) used in several phases on the planetary missions.

1.2 Intended Readership

SOC Teams: Science Operation Center Teams

1.3 Naming Conventions

Since it is possible to use both, TT and TDT, to refer to the Terrestrial Dynamical Time, in this document we will use TDT. As it is also possible to use TB and TDB to refer to the Barycentric Dynamical Time, we will use TDB.

1.4 Acronyms

The following table shows a list with the acronyms used in this document.

BIPM	Bureau International des Poids et Measures
CCIR	Consultative Committee for Radio
CCIR	International Radio Consultative Committee
DDS	Data Delivery System
ET	Ephemeris Time
GMAT	Greenwich Mean Astronomical Time
GMT	Greenwich Mean Time
GPS	Global Positioning System
IAU	International Astronomical Union
IERS	International Earth Rotation Service
IRP	IERS Reference Pole
JD	Julian Date
MJD	Modified Julian Date
PDS	Planetary Data System
SI	International System of Units
SOC	Science Operations Center
TAI	International Atomic Time
TB	Barycentric Dynamical Time
TCB	Barycentric Coordinate Time
TCG	Geocentric Coordinate Time
TDB	Barycentric Dynamical Time
TDT	Terrestrial Dynamical Time

TT	Terrestrial Dynamical Time
UK	United Kingdom
UT	Universal Time
UT0	Universal Time Observed
UT1	Universal Time 1
UT2	Universal Time 2
UTC	Coordinated Universal Time

2 Atomic Time Standards

2.1 Introduction

There are two widely used types of time standards. Those related with the rotation of the earth, and those related with the frequency of atomic oscillations (mainly the cesium-133 atom).

The earth rotation is not uniform, therefore the rate of the clocks referenced to the rotation exhibit both periodic changes and long term drifts of the order of a second per year. Atomic standards are the closest approximations we currently have to a uniform time with accuracy on the order of microseconds per year.

2.2 TAI – International Atomic Time

TAI is a uniform and stable scale established by the BIPM on the basis of atomic clock data. This is result of statistically combining the input of many clocks around the world, each corrected for known environmental and relativistic effects. These clocks have different weighting factors in the TAI.

TAI is a scale that does not keep in step with the slightly irregular rotation of the Earth, therefore for public and practical purposes it is necessary to have another scale that, in long term, does. In relativistic terms TAI is an Earth-based time since it is defined for a gravitational potential and inertial reference on the surface of the earth, i.e. in another reference frame TAI would be different.

TAI is the standard for the SI second defined as the duration of 9,192,631,770 cycles of radiation corresponding to the transition between two hyperfine levels of the ground state of cesium 133.

Although TAI was officially introduced in January 1972, it has been available since July 1955. Its epoch was set so that TAI was in approximate agreement with UT1 on 1 January 1958.
TAI is made available every month in the BIPM "*Circular T*" at their web site in the following address: ftp://62.161.69.5/pub/tai/publication.

2.3 UTC – Coordinated Universal Time

UTC is the time scale based on the second (SI), as defined and recommended by the CCIR, and maintained by the BIPM. It follows TAI exactly except for an integer number of seconds, called leap seconds since 1st January 1972, which have been introduced to keep solar noon at the same UTC (averaged over the year) even though the rotation of the Earth is slowing down. Before 1972, UTC was also adjusted, but following a different and more complicated protocol that was changed to the actual one. The offset is changed as needed to keep UTC within about 0.9 seconds of Earth rotation time or UT1. Leap seconds are typically added once per year at the last second of December 31 or June 30, but they can be added (or subtracted) at other designated times throughout the year, on the advice of the IERS. The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series and the information about all the historical leap seconds is available in ftp://maia.usno.navy.mil/ser7/tai-utc.dat.

UTC is the standard time common to every place in the world. Formerly and still widely known as GMT, UTC nominally reflects the mean solar time along the Earth's prime meridian. UTC forms the basis of a coordinated dissemination of standard frequencies and time signals. It is distributed with standard radio stations that broadcast time, but it can also be obtained readily from the GPS satellites (but note the details given in 5.2.7).

UTC is used also in plane and ship navigation, where it is also known as Zulu time.

2.4 Dynamical Time

2.4.1 Introduction

Dynamical time is the independent variable in the theories that describe the motion of the bodies in the solar system. This concept corresponds to the concept of the inertial time, i.e. the time scale that fulfills exactly the equation of motion of celestial bodies. Therefore, every time that an ephemeris is used, the date and time must be in terms of one of the dynamical times.

These time scales are necessary because no other time scales satisfy the objectives of the dynamical ones. UTC would clearly be unsuitable as the argument of an ephemeris because of leap seconds. A solar-system ephemeris based on an Earth rotation based time scale would somehow have to include the unpredictable variations of the Earth's rotation. TAI would work, but eventually the ephemeris and the ensemble of atomic clocks would drift apart. Only two of the dynamical time scales are of any great importance for planetary missions, TDT and TDB.

2.4.2 TT or TDT – Terrestrial Dynamical Time

TDT is the independent argument for apparent geocentric ephemeris of solar system bodies, defining a theoretical time scale. In principle, it applies to an earthbound clock at sea level, and for practical purposes it is tied to TAI, and its unit of duration is a day of 86400 SI seconds on the geoid.

TDT is used as the time scale of ephemeris for observations from Earth's surface. TDT replaced ET when the IAU 1976 System of Astronomical Constants was implemented in the *Astronomical Almanac* in 1984. This time, as it is referred to the geocenter, is the *Proper Time* with periodic variations up to 1.6 milliseconds, but common between Earth and objects within the earth's gravity field.

TDT was renamed simply Terrestrial Time (TT) in 1991, when it acquired the actual time unit, the SI second at mean sea level. That is important for precise time keeping because, according to general relativity, the rate of passage of time depends on the gravitational potential.

2.4.3 TB or TDB – Barycentric Dynamical Time

TDB is the independent argument for orbital motions referenced to the center of mass of the solar system, the origin of this reference frame. It is as close a possible to an inertial reference frame in the gravitational theory, thus it fulfills exactly the equation of motion of the celestial bodies.

TDB is derived from orbital motions referred to the barycenter of the solar system. This time is the coordinated time in terminology of General Relativity.

TDB differs from TDT by an amount that cycles back and forth by a millisecond or two due to relativistic effects, related with variations in the gravitational potential around the Earth's orbit combined with velocity terms. The maximum of these variations is about 1.6 milliseconds and they are periodic with an average of zero. The variation is negligible for most purposes, but unless taken into account would swamp long term analysis of pulse arrival times from the millisecond pulsars. It is a consequence of the TDT clock being on the Earth rather than in empty space. The ellipticity of the Earth's orbit means that the TDT clock's speed and gravitational potential vary slightly during the course of the year, and as a consequence its rate as seen from an outside observer varies due to transverse Doppler effect and gravitational redshift.

TDB is used as a time scale of ephemeris referred to the barycenter of the solar system that employs the fundamental equations of motions, and therefore it is subject to the inadequacies of those analytical theories. TDB replaced ET when the IAU 1976 System of Astronomical Constants was implemented in the *Astronomical Almanac* in 1984, to use in this type of ephemeris. When the difference between TDT and TDB is not important, e.g. for ephemeris about near earth objects, both can be used indistinctly.

2.5 Coordinate Time

2.5.1 Introduction

In 1991, the General Theory of Relativity was introduced as the theoretical background for the definition of the celestial space-time reference frame. With this theory, the definition of TDT and TDB had distinct theoretical flaws: in fundamental astronomy TDB is strictly periodic, and the presence of long-period and secular terms made a rigorous definition of TDB impossible. As a consequence, the spatial coordinates in the barycentric frame had to be re-scaled to keep the speed of light unchanged between the barycentric and the geocentric frames. Moreover, by applying only the periodic component, the unit of time had been implicitly changed, with potential consequences for the physical interpretation of observations. This led the IAU to devise tighter definitions, and to introduce the new time scales TCG and TCB.

In these terms, it is possible to consider TDB as an obsolete term, but it remains as a practical tool (not as a concept of atomic time) to compute ephemeris. TCG and TCB are needed depending on the level of accuracy one is dealing with, and must be used to compute high accuracy orbits and ephemeris.

2.5.2 TCB – Barycentric Coordinate Time

TCB is the most fundamental time scale that can be defined. Essentially, it is the proper time measured by an asymptotic observer, i.e. one located infinitely far away, at rest with respect to the solar system. More precisely, it is the time coordinate of a space-time coordinate system that is centered in space on the barycenter of the solar system and non-rotating with respect to distant galaxies. TCB tends asymptotically to the proper time of an observer at rest with respect to the coordinate system.

TCB differs from TDB in a constant rate. This constant reflects the gravitational redshift caused by the Sun's attraction, the time dilations produced by the Earth's movement around the Sun, the gravitational redshift caused by the Earth's own attraction and other effects such as the other planets' influence.

TCB and TDB were synchronized on 1st January 1977 at 00:00:00 TAI.

Because of the form of the metric, time transformations and the realization of coordinate times in the barycentric system are not specified at the c^{-4} level (c is the speed of light in vacuum, $c = 299792458$ m/s), i.e. at a level of a few parts in 10^{16} in rate, using the following approximation:

$$TCB - TDB = L_B * (JD - 2443144.5) * 86400,$$
$$L_B \approx 1.550505 * 10^{-8}$$

where JD is the Julian Day. Since JD is not specified to be a particular time scale this constant was not properly defined, but it is advised to use JD with TAI time scale to allow a consistent definition.

A full 4-dimensional transformation is required for further precision.

2.5.3 TCG – Geocentric Coordinate Time

TCG is the proper time measured by an asymptotic observer, i.e. one located infinitely far away, at rest with respect to the gravitational field of the Earth. It is the time coordinate of a space-time coordinate system that is centered in space on the center of mass of the Earth. Thus, TCG coincides with TDT except insofar as it omits the gravitational effect of the Earth itself and the time dilation caused by its rotation.

TCG and TDT were synchronized on 1st January 1977 at 00:00:00 TAI.

TDT differs from TCG by a constant rate. Because of the form of the metric, time transformations and the realization of coordinate times in the geocentric system are not specified at the c^{-4} level (c is the speed of light in vacuum, $c = 299792458$ m/s), i.e. at a level of a few parts in 10^{16} in rate, using the following approximation:

$$TCG - TDT = L_G * (JD - 2443144.5) * 86400,$$
$$L_G \approx 6.969291 * 10^{-10}$$

where JD is the Julian Day. Since JD is not specified to be a particular time scale, this constants were not properly defined, but it is advised to use JD with TAI time scale, to allow a consistent definition.

A full 4-dimensional transformation is required for further precision.

2.5.4 Relationship between TCB and TCG

This relation is the scope of General Relativity and it depends on the point in space where the comparison is made. This is because a terrestrial observer and one at the center of the solar system might not agree about whether two events are instantaneous. The relation of TCG to TCB has three kinds of terms: a secular term, periodic terms and a term dependent on the observer's position.

The ratio of TCG to TCB tends to $1 - L_C$[1] at infinity. This constant reflects the gravitational redshift caused by the Sun's attraction, the time dilations produced by the Earth's movement around the Sun and other effects such as the other planets' influence. These effects are present in TCG but not in TCB.

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[1] The actual computation of L_C requires the integration of solar system ephemeris and the specification of an averaging duration, and this process may be applied to the utmost accuracy, after a choice of ephemeris and averaging duration, e.g. in the IAU 24th General Assembly resolutions L_C is defined as $L_C = 1.48082686741 * 10^{-8} \pm 2 * 10^{-17}$. However, no completely unambiguous definition may be provided for L_C because they always depend on the ephemeris and time span used for their computation. Therefore, the use of this constant is not advised to formulate time transformations when it would require knowing their value with an uncertainty of order 10^{-16} or less.

The periodic terms can amount up to slightly less than 2 milliseconds. The leading periodic term has period one year and amplitude 1657 microseconds. It is currently maximal in the beginning of April making TCB ahead of TCG by about 1.7 milliseconds more than in the beginning of January due to the ellipticity of the Earth's orbit.

The term dependent on the observer's position is, at most, in the order of 2 microseconds for an observer on the Earth's surface. TCB is ahead of TCG by about 2 microseconds more for an observer situated on the equator, at sunrise, on the summer or winter solstice, than for the center of the Earth, because such an observer is ahead of the Earth's revolution. This term cancels if the observer is at the center of the Earth, by convention, in the sense that the terms at the center of the Earth are the terms already mentioned above.

Because of the form of the metric, time transformations and the realization of coordinate times in the geocentric system are not specified at the c^{-4} level (c is the speed of light in vacuum $c = 299792458$ m/s), i.e. at a level of a few parts in 10^{16} in rate, using the following approximation:

$$TCB - TCG = L_C * (JD - 2443144.5) * 86400 + \frac{v_E^i r_E^i}{c^2} + P$$

$$L_C \approx 1.480813 * 10^{-8}$$

where JD is the Julian Day. Since JD is not specified to be a particular time scale, this constants were not properly defined, but it is advised to use JD with TAI time scale, to allow a consistent definition. P represents the periodic terms. v_E^i is the barycentric coordinate velocity of the geocenter, $r_E^i = x^i - x_E^i$ with x^i the barycentric position of the observer and x_E^i the barycentric coordinate position of the geocenter. c is the speed of light in vacuum.

A full 4-dimensional transformation is required for further precision.

3 Earth Rotation Time Standards

3.1 Introduction

Several important time scales still follow the rotation of the Earth, most notably civil times, but some of these are now derived from atomic time through a combination of Earth rotation theory and actual measurements of the Earth's rotation and orientation.

3.2 UT – Universal Time

3.2.1 Introduction

The atomic times gives us the interval of time between two different events, but they do not give us the hour angle of the Sun, i.e. the position of the Sun in the sky. The required time scale for this purpose is the UT, and is for most purposes, the same as UTC.

However, for very precise work there are several subtly different varieties of UT. When a precision of a second or better is needed, it is necessary to be more specific about the variety of UT that is being used.

Normally, the instant of time at which events are observed should be recorded and reported in UTC. Of course, if the observation is not made with a precision better than a second, it is not possible to distinguish between the various versions of UT, and the time recorded should be

UT. To say UTC under such circumstances is the pretend to a greater precision that was actually achieved. Nevertheless the two terms are often used loosely to refer to time kept on the Greenwich Meridian, as well GMT.

3.2.2 UT1

UT1 is a measurement of the actual rotation of the Earth, independent of observing location. UT1 is essentially the same as the not well defined GMT. It is the observed rotation of the Earth with respect to the mean sun corrected for the observer's longitude with respect to the Greenwich Meridian and for the observer's small shift in longitude due to polar motion[2].

Since the Earth's rotation is not uniform, the rate of UT1 is not constant, and its offset from atomic time is continually changing in a not completely predictable way. This variation in UT1 is dominated by seasonal oscillations due primarily to the exchange of angular momentum between the atmosphere and the solid earth and seasonal tides.

Since UTC is intentionally incremented by integer seconds (leap seconds) to stay within 0.9 seconds of UT1, the difference between UT1 and UTC is never greater than this. This difference is published weekly in IERS Bulletin A along with predictions for a number of month into the future.

In astronomical and navigational usage, UT1 is commonly referred as UT.

3.2.3 UT0 – Universal Time Observed

UT0 is an observatory specific version of UT1 in the sense that UT0 contains the effect of polar motion[2] on the observed rotation of the Earth. Since UT1 is now determined from observations from an ensemble of observatories, the practical use of UT0 has dwindled. The conversion from UT1 to a local observatory time with respect to the mean sun or stars is now done as a set of coordinate rotations that do not explicitly use UT0 as an intermediate step, as before.

3.2.4 UT2

UT2 is UT1 with annual and semiannual variations in the Earth's rotation removed. UT2 is obtained by applying an adopted formula that approximates the seasonal oscillations in the Earth's rotation. However, due to other variations including those associated with the secular effects of tidal friction (the Earth's spin is continually but gradually slowing down), high frequency tides and winds, and the exchange of angular momentum between the Earth's core and its shell, UT2 is also not a uniform time scale.

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[2] Because of internal motions and shape deformations of the earth, an axis defined by the locations of a set of observatories on the surface of the earth is not fixed with respect to the rotation axis that defines the celestial pole. The movement of one axis with respect to the other is called polar motion. For a particular observatory, it has the effect of changing the observatory's effective latitude as used in the transformation from terrestrial to celestial coordinates. The International Earth Rotation Service definition of the terrestrial reference frame axis is called the IERS Reference Pole (IRP) as defined by its observatory ensemble.

The dominant component of polar motion, called Chandler wobble, is a roughly circular motion of the IRP around the celestial pole with an amplitude of about 0.35 arcseconds (with a peak to peak value of 0.7 arcseconds) and a period of roughly 14 months.

The other important periodic component in the polar motion is the annual variation and the variations with periods shorter that one year that are mainly due to the interactions between the atmosphere, the hydrosphere and the solid Earth. These variations produce an elliptical motion in the IRP around the celestial pole with amplitude of about 0.2 arcseconds.

Polar motion has diurnal and semi-diurnal variations with amplitudes of a fraction of millisesond of arc (mas) that are due to the oceanic tides.

3.3 GMT – Greenwich Mean Time

GMT is a time scale based on the apparent motion of the mean sun with respect to the meridian through the Old Greenwich Observatory. The mean sun is used because time based on the actual or true apparent motion of the sun does not tick a constant rate, hence at different times of the year the sun appears to move faster or slower in the sky. So if the mean sun is directly over the Greenwich meridian, it is exactly 12:00 GMT.

GMT is formerly used as a basis for every world time zone that sets the time of day and is at the center of the time zone map. GMT is the average time that the Earth takes to rotate from noon-to-noon. GMT is fixed all year and does not switch to daylight saving times.

Prior to 1925, astronomers reckoned mean solar time from noon so that when the mean sun was on the meridian, it was actually 00:00 GMT. This practice arose so that, astronomers would not have a change in date during a night's observation. This reckoning of GMT is now called GMAT (Greenwich Mean Astronomical Time) and it no longer used.

Today, GMT is used as the UK's civil time, or UTC. But to navigators, GMT has referred to UT1, which directly corresponds to the rotation of the Earth, and is subject to that rotation's slight irregularities. It is the difference between UT1 and UTC that is kept below 0.9 seconds by the application of leap seconds, and this gives the inconsistency in the GMT definition. GMT can be used as a reference frame if the accuracy is lower that a second, but if it is greater, and due the different meanings that GMT has, this term is ambiguous.

3.4 ET – Ephemeris Time

For much of the twentieth century, ET was the time scale used for theoretical ephemeris calculations.

The first time scales were based on the rotation of the Earth. However, as clocks became more precise, it became clear that the rotation of the earth was not constant, explaining the errors in the calculation of the celestial positions of planets. ET was based not on the irregularly rotating Earth, but in principle on the motion of Earth in its orbit around the Sun, which was presumed to be uniform. In practice, ET was calculated from observations of occultation of stars by the Moon, the motion of the Moon in its orbit being supposed to be calculated using a uniformly flowing ET. ET, however, did not include relativistic effects, such as corrections for the gravitational potential and velocity, required by advances in the accuracy, and therefore, in 1984 it was replaced by TDT/TDB.

ET had a unit of time, called mean tropical year whose duration is 31,556,925.9747 seconds, and an initial epoch, 1900 January 0^d 12^h. ET closely matches UT in the 19th century, but in the 20th century ET and UT have been diverging more and more. Currently, ET is running almost precisely one minute ahead of UT.

ET had two shortcomings. One was that the ephemeris second was based on a standard that could never be measured again. Current years are not the same length as the year in 1900, since years are getting shorter by about half a second per century. The other was that for some users, a time scale which every second is just the same as every other, and hence that is not based on the Earth's rotation, is not ideal.

4 Standard dating methods used in Space Science

4.1 JD – Julian Date

Julian Day or Julian Date is a continuous count of days and fractions, started in January 1st, 4713 BC (-4712 in the astronomical almanac) at Greenwich mean noon (12^h UT). Astronomers use this method in order to avoid the complexity of the other calendars.

Julian dates assign a unique number to each calendar day. Hours, minutes and seconds are counted as fractions of a day since the last noon. Note that the JD is always determined from an universal time standard (i.e. UTC, TDT, TAI…) but never Local Time.

JD is very useful because it makes easy to determine the number of days between two events by simply subtracting their JD numbers. Such a calculation is difficult for the standard (Gregorian) calendar, because days are grouped into months, which can contain a variable number of days, and there is the added complication of Leap Years.

Astronomers use certain JD values as important reference points, such as J2000, that is the JD for 1st January 2000 at 12:00 UTC.

4.2 MJD – Modified Julian Date

MJD is an abbreviated version of the JD dating methods. It was introduced by space scientists in the late 50's. It is based on a shift of the JD so its origin occurs at midnight on 17th November 1858. The MJD differs from the JD by exactly 2400000.5, therefore the computation of the MJD is easily done from the JD using the following formula:

$$MJD = JD - 2400000.5$$

The half-day is subtracted so that the day starts at midnight in conformance with civil time reckoning. Various international commissions such as IAU, CCIR and others have sanctioned this MJD, because they recommend it as a decimal day count, which is independent of the civil calendar in use.

The MJD is always referred to as a time reckoned in UT, or UTC, TAI or TDT.

MJD is a convenient dating system with only 5 digits, sufficient for most modern purposes. The days of the week can easily be computed because the same weekday is obtained for the same remainder of the MJD after division by 7.

The MJD has been officially recognized by the IAU and by the CCIR.

4.3 UNIX Time

The UNIX Time is the number of seconds since 00:00:00 UTC on January 1st, 1970. This is a method of encoding time used by low-level UNIX commands.

5 Relationship between different Time Standards

5.1 Between TAI and other Time Standards

5.1.1 TAI and UTC

The difference between TAI and UTC is due to the leap seconds. This offset changes each time a leap second is added or subtracted to UTC. This difference is nowadays 32 seconds. The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

$$TAI = UTC + (leapsec)\ seconds$$

5.1.2 TAI and TDT/ET

The difference between TAI and TDT/ET is defined by the offset existing between ET and TAI when this was defined in January 1st, 1977. This difference is fixed and its 32.184 seconds.

TDT/ET = TAI + 32.184 seconds.

5.1.3 TAI and TDB

The difference between TAI and TDB is computed using the following formula, based in the difference of TDB and TDT, and related with the JD.

TDB = TAI + 32.184 + 0.001658 sin (g) + 0.000014 sin (2g) seconds

where g = 357.53 + 0.9856003 (JD – 2451545.0) degrees

5.1.4 TAI and UT1

The difference between UTC and UT1 (DUT1) is monitored by the IERS and published weekly in the IERS Bulletin A along with predictions for a number of months into the future. Therefore, to calculate the difference between TAI and UT1 the leap seconds and this difference are required:

UT1 = TAI – (leapsec) + DUT1 seconds

The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series

5.1.5 TAI and UT0

The difference between TAI and UT0 is based on a formula that relates UT0 and UT1:

$$UT0 = TAI - (leap\sec) + DUT1 + \tan(lat) * (x * \sin(long) + y * \cos(long)) \text{ seconds}$$

where *x* and *y* are the pole offsets published in IERS Bulletin A, and *lat* and *long* are the observatory's nominal station coordinates. DUT1 is also published weekly in the IERS Bulletin A and the information on the leap second is available in ftp://tycho.usno.navy.mil/pub/series

5.1.6 TAI and UT2

The difference between TAI and UT2 is based a formula that relates UT2 and UT1:

$$\begin{aligned} UT2 = TAI - (leap\sec) + DUT1 + 0.022\sin(2Tp) - 0.012\cos(2Tp) \\ - 0.006\sin(4Tp) + 0.007\cos(4Tp) \end{aligned} \quad \text{seconds}$$

where $T = 2000.0 + \dfrac{(MJD - 51544.03)}{365.2422}$, is the Besselian day fraction. DUT1 is published weekly in the IERS Bulletin A and the information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.1.7 TAI and GMT

The difference between both standards depends on the definition given to GMT. If we consider GMT as UTC, then the difference between TAI and GMT is the same as TAI and UTC. On the other hand, if we consider GMT as UT1, the difference between them is the same as TAI and UT1.

5.1.8 TAI and GPS

The GPS epoch is January 6, 1980 and is synchronized to UTC. GPS is not adjusted for leap seconds. The difference between TAI and GPS is therefore fixed:

TAI = GPS + 19 seconds

5.2 Between UTC and other Time Standards

5.2.1 UTC and TDT/ET

The difference between UTC and TDT/ET is defined by the offset between TAI and TDT/ET and corrected for the leap seconds. This difference is given by the following formula:

TDT/ET = UTC + (leapsec) + 32.184 seconds

The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.2.2 UTC and TDB

The difference between UTC and TDB is computed using the following formula, based in the difference of TDB and TDT, and related with the JD and the offset between TAI and TDT.

TDB = UTC + (leapsec) + 32.184 + 0.001658 sin (g) + 0.000014 sin (2g) seconds

where g = 357.53 + 0.9856003 (JD – 2451545.0) degrees. The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.2.3 UTC and UT1

The difference between UTC and UT1 (DUT1) is monitored by the IERS and published weekly in the IERS Bulletin A along with predictions for a number of months into the future.

UT1 = UTC + DUT1 seconds

5.2.4 UTC and UT0

The difference between UTC and UT0 is based on a formula that relates UT0 and UT1:

$$UT0 = UTC + DUT1 + \tan(lat) * (x * \sin(long) + y * \cos(long)) \text{ seconds}$$

where *x* and *y* are the pole offsets published in IERS Bulletin A, and *lat* and *long* are the observatory's nominal station coordinates. DUT1 is also published weekly in the IERS Bulletin A.

5.2.5 UTC and UT2

The difference between TAI and UT2 is based a formula that relates UT2 and UT1:

$$\begin{aligned} UT2 = UTC + DUT1 + 0.022\sin(2Tp) - 0.012\cos(2Tp) - 0.006\sin(4Tp) \\ + 0.007\cos(4Tp) \end{aligned} \text{ seconds}$$

where $T = 2000.0 + \frac{(MJD - 51544.03)}{365.2422}$, is the Besselian day fraction. DUT1 is published weekly in the IERS Bulletin A.

5.2.6 UTC and GMT

The difference between both standards depends on the definition given to GMT. If we consider GMT as UT1, the difference between them is the same as UTC and UT1, otherwise both standards are the same, by definition.

5.2.7 UTC and GPS

The GPS epoch is January 6, 1980 and is synchronized to UTC. GPS is not adjusted for leap seconds. The difference between UTC and GPS depends therefore on the number of leap seconds:

GPS = UTC + leapsec – 19 seconds

The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.3 Between TDT/ET and other Time Standards

5.3.1 TDT/ET and TDB

The difference between TDT/ET and TDB are due to relativistic corrections to move the origin to the solar system barycenter. The relationship between them is given by the following formula:

TDB = TDT/ET + 0.001658 sin (g) + 0.000014 sin (2g) seconds

where g = 357.53 + 0.9856003 (JD – 2451545.0) degrees

5.3.2 TDT/ET and UT1

The difference between UTC and UT1 (DUT1) is monitored by the IERS and published weekly in the IERS Bulletin A along with predictions for a number of months into the future. Therefore, to calculate the difference between TDT/ET and UT1 the leap seconds and this difference are required.

UT1 = TDT/ET – (leapsec) + DUT1 – 32.184 seconds

The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.3.3 TDT/ET and UT0

The difference between TDT/ET and UT0 is based on a formula that relates UT0 and UT1:

$$\begin{aligned} UT0 &= TDT/ET - (leap\sec) - 32.184 + DUT1 \\ &\quad + \tan(lat) * (x * \sin(long) + y * \cos(long)) \end{aligned} \quad \text{seconds}$$

where *x* and *y* are the pole offsets published in IERS Bulletin A, and *lat* and *long* are the observatory’s nominal station coordinates. DUT1 is also published weekly in the IERS Bulletin A and the information on the leap second is available in ftp://tycho.usno.navy.mil/pub/series

5.3.4 TDT/ET and UT2

The difference between TDT/ET and UT2 is based a formula that relates UT2 and UT1:

$$\begin{aligned} UT2 &= TDT/ET - (leap\sec) - 32.184 + DUT1 + 0.022\sin(2Tp) \\ &\quad - 0.012\cos(2Tp) - 0.006\sin(4Tp) + 0.007\cos(4Tp) \end{aligned} \quad \text{seconds}$$

where $T = 2000.0 + \frac{(MJD - 51544.03)}{365.2422}$, is the Besselian day fraction. DUT1 is published weekly in the IERS Bulletin A and the information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.3.5 TDT/ET and GMT

The difference between both standards depends on the definition given to GMT. If we consider GMT as UTC, then the difference between TDT/ET and GMT is the same as TDT/ET and UTC. On the other hand, if we consider GMT as UT1, the difference between them is the same as TDT/ET and UT1.

5.3.6 TDT/ET and GPS

The GPS epoch is January 6, 1980 and is synchronized to UTC. GPS is not adjusted for leap seconds. The difference between TDT/ET and GPS is therefore fixed:

TDT/ET = GPS + 51.184 seconds

5.4 Between TDB and other Time Standards

5.4.1 TDB and UT1

The difference between UTC and UT1 (DUT1) is monitored by the IERS and published weekly in the IERS Bulletin A along with predictions for a number of months into the future.The difference between UT1 and TDB is computed using the following formula, based in the difference of TDB and TDT, and related with the JD and the offset between TAI and TDT.

UT1 = TDB + DUT1 – (leapsec) – 32.184 – 0.001658 sin (g) – 0.000014 sin (2g) seconds

where g = 357.53 + 0.9856003 (JD – 2451545.0) degrees. The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.4.2 TDB and UT0

The difference between TDB and UT0 is based on a formula that relates UT0 and UT1:

$$\begin{aligned} UT0 = TDB - (leap\,\mathrm{sec}) - 32.184 + DUT1 - 0.001658\sin(g) \\ - 0.000014\sin(2g) + \tan(lat) * (x * \sin(long) + y * \cos(long)) \end{aligned} \quad \text{seconds}$$

where g = 357.53 + 0.9856003 (JD – 2451545.0) degrees, *x* and *y* are the pole offsets published in IERS Bulletin A, and *lat* and *long* are the observatory's nominal station coordinates. DUT1 is also published weekly in the IERS Bulletin A and the information on the leap second is available in ftp://tycho.usno.navy.mil/pub/series

5.4.3 TDB and UT2

The difference between TAI and UT2 is based a formula that relates UT2 and UT1:

$$\begin{aligned} UT2 = TDB - (leap\,\mathrm{sec}) - 32.184 + DUT1 - 0.001658\sin(g) - 0.000014\sin(2g) \\ + 0.022\sin(2Tp) - 0.012\cos(2Tp) - 0.006\sin(4Tp) + 0.007\cos(4Tp) \end{aligned}$$

seconds

where g = 357.53 + 0.9856003 (JD – 2451545.0) degrees, $T = 2000.0 + \frac{(MJD - 51544.03)}{365.2422}$, is the Besselian day fraction. DUT1 is published weekly in the IERS Bulletin A and the information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.4.4 TDB and GMT

The difference between both standards depends on the definition given to GMT. If we consider GMT as UTC, then the difference between TDB and GMT is the same as TDB and UTC. On the other hand, if we consider GMT as UT1, the difference between them is the same as TDB and UT1.

5.4.5 TDB and GPS

The GPS epoch is January 6, 1980 and is synchronized to UTC. GPS is not adjusted for leap seconds. The difference between TDB and GPS is computed using the following formula, based in the difference of TDB and TDT, and related with the JD.

TDB = GPS + 51.184 + 0.001658 sin (g) + 0.000014 sin (2g) seconds

where g = 357.53 + 0.9856003 (JD – 2451545.0) degrees

5.5 Between UT1 and other Time Standards

5.5.1 UT1 and UT0

The difference between UT0 and UT2 is due to the corrections for the effect of the polar motion, i.e. corrections for the latitude and longitude of observatory's points on the Earth's surface with respect to the Earth's instantaneous rotation axis. The difference is based on the following formula:

$$UT0 = UT1 + \tan(lat) * (x * \sin(long) + y * \cos(long)) \text{ seconds}$$

where *x* and *y* are the pole offsets published in IERS Bulletin A, and *lat* and *long* are the observatory's nominal station coordinates.

5.5.2 UT1 and UT2

The difference UT1 and UT2 is due to the correction for the annual and semiannual variations in the Earth's rotation. This difference is based on the following formula:

$$\begin{aligned} UT2 = UT1 &+ 0.022\sin(2Tp) - 0.012\cos(2Tp) - 0.006\sin(4Tp) \\ &+ 0.007\cos(4Tp) \end{aligned} \text{ seconds}$$

where $T = 2000.0 + \frac{(MJD - 51544.03)}{365.2422}$, is the Besselian day fraction.

5.5.3 UT1 and GMT

The difference between both standards depends on the definition given to GMT. If we consider GMT as UTC, then the difference between UT1 and GMT is the same as UT1 and UTC, otherwise both standards are the same, by definition.

5.5.4 UT1 and GPS

The GPS epoch is January 6, 1980 and is synchronized to UTC. GPS is not adjusted for leap seconds. The difference between UTC and UT1 (DUT1) is monitored by the IERS and published weekly in the IERS Bulletin A along with predictions for a number of months into the future. Therefore, to calculate the difference between GPS and UT1 the leap seconds and this difference are required:

UT1 = GPS – (leap seconds) + DUT1 + 19 seconds

The information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series

5.6 Between UT0 and other Time Standards

5.6.1 UT0 and UT2

The difference between UT0 and UT2 is due to the corrections for the effect of the polar motion, i.e. corrections for the latitude and longitude of observatory's points on the Earth's surface with respect to the Earth's instantaneous rotation axis, and the annual and semiannual variations in the Earth's rotation. The difference is based on the following formula:

$$\begin{aligned} UT0 = {} & UT2 + \tan(lat) * (x * \sin(long) + y * \cos(long)) - 0.022 \sin(2Tp) \\ & + 0.012 \cos(2Tp) + 0.006 \sin(4Tp) - 0.007 \cos(4Tp) \end{aligned} \quad \text{seconds}$$

where $T = 2000.0 + \frac{(MJD - 51544.03)}{365.2422}$, is the Besselian day fraction, *x* and *y* are the pole offsets published in IERS Bulletin A, and *lat* and *long* are the observatory's nominal station coordinates.

5.6.2 UT0 and GMT

The difference between both standards depends on the definition given to GMT. If we consider GMT as UTC, then the difference between UT0 and GMT is the same as UT0 and UTC. On the other hand, if we consider GMT as UT1, the difference between them is the same as UT0 and UT1.

5.6.3 UT0 and GPS

The GPS epoch is January 6, 1980 and is synchronized to UTC. GPS is not adjusted for leap seconds. The difference between GPS and UT0 is based on a formula that relates UT0 and UT1:

$$UT0 = GPS - (leap\,\mathrm{sec}) + DUT1 + 19 + \tan(lat) * (x * \sin(long) + y * \cos(long))$$

seconds

where *x* and *y* are the pole offsets published in IERS Bulletin A, and *lat* and *long* are the observatory's nominal station coordinates. DUT1 is also published weekly in the IERS Bulletin A and the information on the leap second is available in ftp://tycho.usno.navy.mil/pub/series

5.7 Between UT2 and other Time Standards

5.7.1 UT2 and GMT

The difference between both standards depends on the definition given to GMT. If we consider GMT as UTC, then the difference between UT2 and GMT is the same as UT2 and UTC. On the other hand, if we consider GMT as UT1, the difference between them is the same as UT2 and UT1.

5.7.2 UT2 and GPS

The GPS epoch is January 6, 1980 and is synchronized to UTC. GPS is not adjusted for leap seconds. The difference between GPS and UT2 is based a formula that relates UT2 and UT1:

$$\begin{aligned} UT2 = GPS - (leap\,\sec) + DUT1 + 19 + 0.022\sin(2Tp) \\ - 0.012\cos(2Tp) - 0.006\sin(4Tp) + 0.007\cos(4Tp) \end{aligned} \quad \text{seconds}$$

where $T = 2000.0 + \frac{(MJD - 51544.03)}{365.2422}$, is the Besselian day fraction. DUT1 is published weekly in the IERS Bulletin A and the information on the recent leap second is available in ftp://tycho.usno.navy.mil/pub/series.

5.8 Between GMT and GPS

The difference between both standards depends on the definition given to GMT. If we consider GMT as UTC, then the difference between GPS and GMT is the same as GPS and UTC. On the other hand, if we consider GMT as UT1, the difference between them is the same as GPS and UT1.

6 Time Standards in PDS

PDS, in the newest version 3.5, has adopted the use of UTC for expressing time, using the format HH:MM:SS.sss. UTC is required for all observational times, as the astronomical time standard. Note that the hours, minutes, and integral seconds fields must contain two digits. The seconds field may include a fractional part if appropriate.

Optionally, and for terrestrial activities such as archiving time or data producing time, the “Z” civil time zone designator can be employed, appended to the end of the time format, i.e. HH:MM:SS.sssZ, to indicate Greenwich time zone. All the other time zones must be indicated by the offset hour from the Greenwich meridian one, i.e. HH:MM:SS.sss ±n, where n is the number of hours from UTC.

Because of historical confusion involving the terrestrial time zone indicator "Z", Greenwich Mean Time and Coordinated Universal Time, there are many legacy data sets in the PDS that use the "Z" time zone indicator even though the times recorded are actually in UTC. By convention, PDS assumes that in its own datasets archived prior to 2003 any time recorded with a "Z" zone indicator is, in fact, a UTC time, not a terrestrial time.

7 Time Standards in the DDS files

For Requests: UTC with the letter designator “Z”. This format is used in all requests done to DDS.

Packet Headers: Sun Modified Julian Time (Sun MJT or UNIX Time) referred to Coordinated

Universal Time (UTC). Sun Modified Julian Time is the name given in the DDS to the UNIX Time. The headers of the following packets must use this standard format:

Telemetry Data

Command History Packets

Auxiliary Data

Auxiliary Data Packets use the following time standards:

Orbit & Attitude Files: Barycentric Dynamical Time (TDB)

Event Files & Lander: Coordinated Universal Time (UTC)