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Time references in US and UK astronomical and navigational almanacs

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Abstract
An astronomical or navigational almanac can best be thought of as a device for connecting an observer with celestial objects. For an observer with a known position and time the almanac allows the observer to identify the celestial objects. Conversely, if the observer knows what objects he is observing and when, the almanac allows him to determine his position. In either case, knowledge of the time is crucial in providing this link between the celestial objects and the observer through the almanac. This paper summarizes the various time scales used in the astronomical and nautical almanacs produced jointly by the US Naval Observatory and HM Nautical Almanac Office.

1. Introduction

Astronomical and navigational almanacs are designed for use in some straightforward or prescribed manner. One of the objects of these almanacs is to provide accurate coordinates of the celestial objects so that a link can be made between the observer and celestial objects being observed. For an observer with a known position the almanac allows the observer to confirm the identities of the celestial objects. This is the usual objective of an astronomical almanac. Conversely, the objective of a navigational almanac is to allow the observer to use observations of a set of known objects to determine the observer's position. In either case, knowledge of the time is crucial in providing this link between the celestial objects and the observer through the device of an almanac.

Traditionally, almanacs are thought of as paper publications. The two premier joint almanacs of the US Naval Observatory (USNO) and HM Nautical Almanac Office (HMNAO, part of the UK Hydrographic Office) are *The Astronomical Almanac* (AsA) and *The Nautical Almanac* (NA).

Nowadays, almanacs may also be available via other media such as the internet and software. On the internet there is *The Astronomical Almanac Online* [1], the companion to the AsA, and the *Celestial Navigation Data for Assumed Position and Time* [2]. There are software applications such as the *Multiyear Interactive Computer Almanac* (MICA) produced by USNO, and *NavPac*, HMNAO's celestial navigation package. Almanacs may even take the form of software and data that are part of a larger integrated astronomical or navigational system. Separation from the printed page allows users additional freedoms such as receiving positions at non-tabular intervals and allowing higher accuracies than practical in paper publications. However, the principles behind these paperless almanacs are the same as for the published books.

A wide variety of celestial objects may be included in almanacs. For example, the AsA includes sections covering the Sun, Moon, planets, natural satellites of planets, minor planets, comets, stars and stellar systems. However, an astronomical or navigational almanac may also restrict itself to a small number of celestial objects desirable for its particular application.

The time arguments (time references) for each of these almanacs are chosen to economically extract accurate data without significant complications. This choice, of course, also has implications on the precision to which the material is being tabulated.

The contents of almanacs are not static. The contents, time scales and even the titles of the paper almanacs have changed over the centuries. This paper is an overview of the time scales currently used in the almanacs produced by USNO and HMNAO. Detailed definitions are given in the References; particularly Kaplan [3], the glossaries of the AsA and *The Astronomical Almanac Online* [4, 5], Seidelmann *et al* [6], Nelson *et al* [7], the IAU Nomenclature for Fundamental Astronomy 2000 Glossary [8] and IAU Commission 52: Relativistic Glossary for Astronomers [9]. The IAU SOFA Cookbook [11] also has practical explanations and examples.

2. Background

Two fundamentally different types of time scales are used in astronomy and in the almanacs in particular. The first type of time scale is based on atomic clocks, that is coordinate time. The second type is based on the variable rotation of the Earth.

For the almanac producer and users it is necessary to know the relationship between time scales and to understand the relationships between these scales, civil time and the time broadcast via the Global Positioning System, the internet, or radio time signals, i.e. the time the users of the almanacs may employ.

At present, those coordinate time scales that are pertinent to almanacs are Terrestrial Time (TT) and Barycentric Dynamic Time (TDB) (see AsA 2012 Glossary or *The Astronomical Almanac Online* Glossary for definitions [4, 5]). For practical use, these coordinate times must be realized and the proper time is provided by International Atomic Time (TAI) [10]. Those time scales that are based on the rotation of the Earth are Universal Time 1 (UT1) and Greenwich Mean Sidereal Time (GMST).

2.1. Universal time, Earth rotation angle and sidereal time

IAU 2000 Resolution B.1.8 redefined the fundamental relationship between Universal Time (UT1) and the Earth as the Earth rotation angle (ERA). UT1 is the angle of the Earth's rotation about the Celestial Intermediate Pole axis defined by its conventional linear relation to ERA [8]. However, for historical reasons most users tend to think of UT1 as a time rather than an angle. Thus, the ERA connects the origin of the intermediate right ascension to the Terrestrial Intermediate Origin (TIO) and the zero longitude meridian, commonly called the Greenwich meridian.

GMST is now defined in terms of ERA and thus UT1 but also includes the effect of precession, as it relates the equinox with the TIO.

The Earth's rate of rotation varies stochastically. This variation results in both short term changes and a secular change in the rotation rate. Thus, UT1 must be determined observationally from the apparent diurnal motions of celestial bodies, currently from VLBI observations of distant radio sources.

It is useful to remember that Universal Time (UT) is loosely defined as mean solar time. This is also the definition that most users who do not specialize in time scales assume for UT.

2.2. Civil time: UTC and GMT

Coordinated Universal Time (UTC) is the *de facto* worldwide system of civil time, which is tightly synchronized. It is also the time scale broadcast by time signals. UTC is a hybrid time scale as its second (the SI second) is the same as atomic time (TAI) but it is subject to 1 s adjustments to keep it close to alignment with UT1. From inception to the present, UTC has been kept within a specified limit of UT1. Since 1974 the limit is set such that $|\mathrm{UT1} - \mathrm{UTC}| < 0.9$ s. To maintain this limit leap seconds are inserted in UTC [7]. The application of leap seconds is coordinated by the Bureau International des Poids et Mesures. Leap seconds may be inserted at the end of any month, by international agreement, but have always been inserted either at the end of June or December. The application of a leap second is always announced six months before it is implemented.

In many civil applications UTC is often called Greenwich Mean Time (GMT). There is no known legal connection, at least in either the UK or the US, between GMT and UTC. In the UK the name GMT does mean UTC. However, for navigation GMT has meant UT1. Thus, GMT has two meanings that can differ by as much as 0.9 s. For this reason GMT should not be used for precise purposes [6, section 2.521].

Keeping the limit between UT1 and UTC small has meant that almanac producers (in the appropriate circumstances), and navigators in particular, do not need to make a distinction between UT1 and UTC. In fact, many users and applications use UT (or GMT) without specifying UTC or UT1. Should the insertion of leap seconds be abolished, as is currently proposed, both the almanac makers and users will need to be aware of the difference between UT1 and UTC in the future. In all forms of almanac produced by these offices it clearly states that when UT is used it means specifically UT1.

2.3. Time scales used by ephemerides

At present the various ephemerides used in the almanacs, such as the Jet Propulsion Laboratory's (JPL) DE405, and the various USNO minor planet ephemerides are developed in the Barycentric Celestial Reference System, where the time scale is the coordinate time scale TDB. Strictly speaking, the time scale of the JPL ephemerides is T_{eph}. However, T_{eph} is considered to be a practical implementation of TDB. This also applies to USNO minor planet ephemerides [12] that were developed using DE405 as their basis and thus are also compatible with T_{eph} and TDB.

2.4. Terrestrial and Barycentric Dynamic Times

An apparent place, or equivalently the geocentric intermediate right ascension and declination with respect to the CIO and equator of date, is defined in the Geocentric Celestial Reference System where the coordinate time scale is TT. TT is practically related by definition to the proper time TAI by

$$\mathrm{TT} = \mathrm{TAI} + 32.184\ \mathrm{s}.$$

However, the time scale of the barycentric ephemeris of the celestial body for which the apparent place is being calculated is TDB. Thus, a transformation is required so that the ephemeris is evaluated at the correct instant. Section B of the AsA gives the following relationship:

$$\mathrm{TDB} - \mathrm{TT} = +0.001\,657 \sin g + 0.000\,022 \sin(L - L_\mathrm{J})$$

where g is the mean anomaly of the Earth in its orbit around the Sun and $L - L_\mathrm{J}$ is the difference in the mean ecliptic longitudes of the Sun and Jupiter (see AsA 2012 page B7 [4]). This formula for TDB − TT is accurate to about ±30 μs over the period 1980–2050. Both the USNO NOVAS [13] software package and IAU SOFA [14] provide users with more accurate algorithms.

All three high accuracy realizations of TDB mentioned so far, those in NOVAS, SOFA and T_eph, are derived from the algorithm of Fairhead and Bretagnon [15]. The offset between TT and TDB may also be determined from the planetary ephemeris as is done for INPOP08 [16] and EPM2008 [17]. However, the user should be careful because NOVAS and SOFA compute TDB − TT, but INPOP and EPM compute TT − TDB.

The origin for TT is the geocenter while the origin for TDB is the solar system barycenter. However, TDB is defined so that its value remains within 0.002 s of TT for several millennia around the present epoch [18]. As a result, there is a change of scale $\sim 10^{-8}$ in lengths between coordinate systems using TT and those using TDB [19]. Thus, distances in TDB-based ephemerides differ from those in a coordinate system using Barycentric Coordinate Time or TT, and care has to be taken in calculating the positions of solar system bodies. Fortunately, both astronomical and navigational almanacs are concerned almost exclusively with the positions on the plane of the sky, so this change in scale rarely makes a difference in the published quantities. Even more rarely is the difference in scale large enough to be significant.

2.5. Terrestrial Time and Universal Time

For the almanac producer and user who needs to calculate hour angle from apparent or intermediate places it is necessary to know the relationship between TT and UT time scales. The difference TT − UT1, known as ΔT, is dependent on the variable rotation of the Earth, and, hence, is unpredictable. Almanacs must be produced and distributed prior to their use. Thus the unpredictability of ΔT makes it the basic limit to almanac accuracy. Pages K8–K9 of the AsA tabulate observed values of ΔT from 1620 to a time shortly before going to press and estimate values from then to its year of issue and three subsequent years, while the *The Astronomical Almanac Online* gives this information graphically.

This same limitation arising from ΔT applies to electronic as well as printed publications. Thus, some manner of updating the value of ΔT is required in all circumstances. MICA [20], for example, provides periodic updates at its website.

2.6. The time scales TCG and TCB

Neither Geocentric Coordinate Time (TCG) nor Barycentric Coordinate Time (TCB) is used in the US and UK almanacs for different reasons.

TCG is a coordinate time intended for use when the object of interest is within a few Earth radii of the geocenter. However, aside from the Earth itself, the closest object of concern in the almanacs is the Moon, which is located at more than 60 Earth radii from the geocenter. Parameters of interest for the Earth are given in either TDB, e.g. Earth's position with respect to other solar system bodies, or TT, e.g. the Earth's orientation. Thus, there is no current use for TCG in the almanacs.

TCB is a coordinate time based on the SI second with the origin of the reference system at the solar system barycenter. TCB might be used as the time argument for the ephemerides of solar system bodies. To date, however, none of the major, high accuracy solar system ephemerides use TCB as the time argument. Thus, TCB is not currently used in the almanacs.

3. The Astronomical Almanac, TDB, TT and UT

Many of the quantities that are tabulated in the AsA have time argument TT. TT is used because the positions are in a geocentric reference frame and the accuracy of the tabulations means that inclusion of a predicted time scale is not sensible. There are a few tabulations such as the barycentric position and velocity of the Earth where the quantities are tabulated daily at 0 h TDB, as this is the most useful time argument for its use when calculating apparent places.

The AsA tabulates daily at 0 h UT1 the Earth rotation angle, and both Greenwich mean (GMST) and apparent sidereal time (GAST). The definitions for GMST and GAST depend weakly on ΔT; a 1 s change in ΔT in 2012 causes only a 0.1×10^{-6} s change in GMST, which does not affect the tabulated positions.

Section A of the AsA, Phenomena, and many of the tabulations in section F, Satellites of Planets, are tabulated for UT1. For these tabulations a prediction for ΔT is required. The policy of HMNAO and USNO is to adopt a constant value for the whole year, which for the current 2012 edition is 67 s. Times of some phenomena such as lunar perigee and planetary conjunctions are given to the nearest hour, and are not significantly affected by ΔT. Others such as the times of the vernal equinox, Sun and Moon rise and set times, and times of the phases of the Moon are given to the nearest minute, where ΔT may affect the results.

There is always a conflict between the desire to use the latest possible value of ΔT and the fact that the production process, whether for a paper product or software, takes time. A decision cannot be made at the last possible moment as it takes a significant amount of time to produce, check and distribute the product. The AsA, for example is available to users some twelve months before the year of issue and production starts some six to nine months prior to distribution.

Here are four examples of methods used to minimize errors introduced by the *a priori* uncertainty in ΔT:

First, the Besselian Elements in the eclipse data given in section A of the AsA contain a correction term. Thus, given the difference between the most up-to-date value and the value of ΔT adopted for production, the user is able to make the appropriate corrections.

Second, another quantity of interest that is tabulated in various sections of the AsA are the times of ephemeris transit. The times of ephemeris transit are expressed in TT and refer to the transit over the ephemeris meridian, which is a fictitious meridian that rotates independently of the Earth at the uniform rate implicitly defined by TT. This meridian is 1.002 738 ΔT east of the TIO. The practical importance of the ephemeris meridian is that it allows the almanac producer to ignore ΔT, and for the user for most purposes the times may be regarded as giving the Universal Time (UT1) of transit over the zero meridian. However, to the nearest second, the correction that gives the UT1 of transit over the local meridian is

$$\text{time of ephemeris transit } - (\lambda/24) \times \text{first difference},$$

where λ is the east longitude in hours and first difference is the first difference in the time of transit between one day and the next, about 24 hours.

Third, as mentioned above, electronic or online products such as MICA and *The Astronomical Almanac Online* can be provided with data updates to reduce the uncertainties in future values of ΔT.

Navigational products, such as the NA, if tabulated with time argument UTC, which also may be required to be independent of updates, will need predictions of UT1 − UTC to the accuracy of ± 0.9 s or better, made at the time of production and valid over the lifetime of the product.

Fourth, as an alternative to UT1 the user may want to use UTC. UTC has the advantage over UT1 of being more predictable. The application of a leap second is always announced six months before it is implemented. The predictability of UTC comes at the cost of reduced accuracy. Many users of UTC may not even be aware of the difference between the two time scales if their accuracy needs are met.

4. Navigational almanacs, UT and UTC

The purpose of navigational almanacs is to enable navigators to find their longitude and latitude from observations of the positions of celestial objects. In particular, *The Nautical Almanac* (NA) is designed for use with timed sextant observations of various celestial objects, and comparing the results with pre-computed positions. The accuracy of this method gives positions to about $0.2'$ at the best, which is a limitation of using a hand-held sextant on-board a sea-going vessel.

However, $0.2'$ is equivalent to 0.8 s. Hence, even this rather modest accuracy requires knowledge of UT1 to better than a second. The time argument of the NA [21] daily pages is UT1 but it is labelled UT. Although its use has been discouraged (see section 2.2), navigators often still refer to UT1 as GMT (Greenwich Mean Time). The explanation does warn the user that this scale may differ from the broadcast time signals (UTC) by an amount which, if ignored, will introduce an error of up to $0.2'$ in longitude determined from astronomical observations. It continues to explain about leap seconds, and if observations to a precision of better than 1 s are required then the correction DUT1 is also needed since UT1 = UTC+DUT1 to a precision of 0.1 s. Thus, to achieve positions accurate to an arc minute will require the user to make a distinction between UT1 and UTC should the leap second be discontinued.

Table 1. Corrections to longitude due to differences between the time signal and the UT1 tabular argument which is used in *The Nautical Almanac*.

Correction to time signals	Correction to longitude
−0.9 s to −0.7 s	$0.2'$ to east
−0.6 s to −0.3 s	$0.1'$ to east
−0.2 s to +0.2 s	No correction
+0.3 s to +0.6 s	$0.1'$ to west
+0.7 s to +0.9 s	$0.2'$ to west

Alternatively, the longitude, when determined from astronomical observations, may be corrected by the corresponding amount shown in table 1.

Both *The Air Almanac*, produced in the US, and the *UK Air Almanac* also use UT1. The accuracy requirement of *The Air Almanac* is approximately $1.5'$ in hour angle. To reach this accuracy requires a knowledge of UT1 to an accuracy of better than 5 s. The *UK Air Almanac* does not provide information for position-finding as its purpose is for planning.

USNO is currently exploring development of a self-contained automated celestial navigation system. In this case the almanac consists of positional data of a number of stars and the software to determine the observer's position. The design accuracy of the system is $1''$. To achieve this the value of UT1 will need to be known with an accuracy of the order of 0.01 s.

5. Summary

Astronomical and navigational almanacs may tabulate quantities using any time scale as long as the relationships between the various time scales, i.e. those used by the ephemerides, the starting theories or procedure, the rotation of the Earth and civil time are well understood to the precision required.

However, the wide variety of users of our almanacs and products need to be aware of the different time scales that are employed, the time being broadcast (be it over the radio or given by various electronic equipment) and the time argument of the particular tables to ensure that the correct result is produced. It is particularly important that the user understand the relationship between UT1 and other time scales.

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