

Earth rotation monitoring, UT1 determination and prediction

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14. ABSTRACT Monitoring the Earth's rotation angle is essential in various domains linked to reference systems such as space navigation, precise orbit determinations of artificial Earth satellites including the Global Navigation Satellite Systems (GNSS), positional astronomy and for geophysical studies on time scales ranging from a few hours to decades. Universal Time UT1 is based on the rotation of the Earth on its axis. Historically it was related to mean solar time on the meridian of Greenwich, sometimes known as Greenwich Mean Time. Monitoring Earth orientation, and in particular UT1, is the primary task of the International Earth Rotation and Reference Systems Service (IERS). The Earth Orientation Center is responsible for monitoring Earth orientation parameters (EOPs) including long-term consistency and leap second announcements. The Rapid Service/Prediction Center is in charge of the rapid, near real-time solution and predictions. These two complementary services of the IERS provide Earth orientation information from results derived predominantly from Very Long Baseline Interferometry with valuable input from GNSS observations and global atmospheric angular momentum for both the combination and prediction of EOPs.					
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Earth rotation monitoring, UT1 determination and prediction

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Abstract

Monitoring the Earth's rotation angle is essential in various domains linked to reference systems such as space navigation, precise orbit determinations of artificial Earth satellites including the Global Navigation Satellite Systems (GNSS), positional astronomy and for geophysical studies on time scales ranging from a few hours to decades.

Universal Time UT1 is based on the rotation of the Earth on its axis. Historically it was related to mean solar time on the meridian of Greenwich, sometimes known as Greenwich Mean Time. Monitoring Earth orientation, and in particular UT1, is the primary task of the International Earth Rotation and Reference Systems Service (IERS). The Earth Orientation Center is responsible for monitoring Earth orientation parameters (EOPs) including long-term consistency and leap second announcements. The Rapid Service/Prediction Center is in charge of the rapid, near real-time solution and predictions. These two complementary services of the IERS provide Earth orientation information from results derived predominantly from Very Long Baseline Interferometry with valuable input from GNSS observations and global atmospheric angular momentum for both the combination and prediction of EOPs.

1. Introduction

By definition UT1 is a linear function of the Earth rotation angle (ERA) [7, 27] selected so that it follows in the long term the 'Greenwich mean solar time'. It is observed using very long baseline interferometry (VLBI), a technique using a quasi-inertial reference system to determine the full set of Earth orientation parameters (EOPs), i.e. polar motion, Universal Time and precession–nutations. Alternatively, the Global Navigation Satellite Systems (GNSS) orbit solutions provide the most significant contribution to the polar motion determination due to the dense and uniform station network and its high precision, but it is limited in providing UT1 and precession–nutations data. It can nevertheless provide valuable information on the variation of these quantities. Section 2 describes techniques that have contributed and/or contribute routinely to estimating UT1 or any quantity connected to UT1, rotation rate or excess of the length of day (LOD).

In section 3, we present the procedure for the data combinations performed by the International Earth Rotation and Reference Systems Service (IERS) Earth Orientation Center to derive the long-term UT1–UTC series, and provide estimates of their precision, accuracy and consistency with respect to the current International Terrestrial Reference

Frame (ITRF) realization. Section 4 is devoted to the rapid combination performed by the Rapid Service and Prediction Center and section 5 deals with predictions. The predictions are performed principally for two applications: short-term forecasts for quasi-real-time applications such as precise orbit determination and telescope pointing and long-term prediction for ephemeris computations and determination of when leap seconds should be introduced in UTC.

2. Data for Universal Time UT1 monitoring

Until the 1970s, UT1 was exclusively monitored by astrometric techniques based on optical instruments such as photographic zenith tubes, meridian refractors and astrolabes. However, as space geodetic observational techniques became more prominent, optical techniques contributed less so that now, optical observations no longer contribute to EOP determination. In the 1970s the emergence of lunar laser ranging (LLR) provided a new means to determine UT0 (UT1 contaminated by the effects of polar motion). In 1975 its accuracy was roughly ± 0.4 ms [3]. Meanwhile VLBI was used to determine UT1 with an accuracy at least ten times better. VLBI, as the only technique referring to a non-rotating

Table 1. Evolution of techniques able to determine Universal Time (UT0 or UT1), LOD or rotation rate. Note that accuracy refers to external validation of the data quality as opposed to internal consistency of the data, which is referred to as precision.

Technique	Since	Parameter	Time resolution	Accuracy
Astrometry	1899	UT1	5 days	1 ms
LLR	1969	UT0	1 day	0.4 ms
SLR	1976	LOD	3 days	200 $\mu\text{s d}^{-1}$
VLBI Standard	1981	UT1	3–4 days	5 μs
VLBI Intensive	1981	UT1	1 day	15 μs
VLBI	1981	LOD	3–4 days	15 $\mu\text{s d}^{-1}$
GPS	1993	LOD	1 day	10 $\mu\text{s d}^{-1}$
Inertial techniques	2000	Ω	1 second to hours	1×10^{-9} relative

celestial reference frame, is nowadays the main contributor to UT1 observations. Satellite techniques such as GNSS and satellite laser ranging (SLR) cannot determine UT1 accurately. Their access to the celestial frame is made via the satellite orbit realizations, which suffer from systematic errors related to modelling the motion of the orbital nodes in space [12]. Still they can provide information on LOD, which is the time derivative of UT1. Consequently LOD can be integrated to provide valuable high-frequency information.

For several years, inertial techniques have been developing and show the potential to determine Earth rotation variations. Let us cite two recent developments based on the Sagnac effect.

Ring laser rotation sensors are currently used in inertial navigation. They have recently been significantly improved (Wetzell Observatory), and show potential as fully independent LOD sensors. By scaling them up in size, they have gained several orders of magnitude over their commercial counterparts, both in sensitivity and stability [34, 35]. Their precision in relative rate is $\Delta\Omega/\Omega \approx 1 \times 10^{-9}$; however, this is not yet comparable to VLBI accuracy.

The gyroscope interferometer based on the atomic interferometry properties developed at Paris Observatory might have more potential [19]. It is about 10 times better than the ring laser. Limitations in the accuracy are due to the instrument noise and the fact that these instruments are susceptible to local effects.

Table 1 shows the evolution and statistics concerning the techniques able to determine quantities linked to Universal Time or Earth rotation rate (Ω).

VLBI observations are made using two different strategies:

- (1) The 24 h R1 and R4 experiments, two 24 h sessions per week, are conducted to provide twice weekly EOP results on a timely basis. The time delay is a maximum of two weeks.
- (2) Intensive sessions. The basic VLBI configuration uses only one pair of VLBI stations widely separated longitudinally to give good sensitivity to UT1 variations [32]. Each so-called ‘Intensive’ session usually observes for about 1 h roughly daily. The positions for the Intensive stations and *a priori* knowledge of the other components of Earth orientation are determined from the 24 h sessions or other sources. According to [31], modelling troposphere delay fluctuations and non-point-like structure in the radio sources are probably the leading residual sources of UT1 error.

The International VLBI Service for Geodesy and Astrometry (IVS) produces a standard UT1 combined series. This series is obtained by averaging the individual results derived by several independent VLBI analysis centres according to a specified algorithm [6]. It is of better quality, i.e. accuracy and consistency, than the individual solutions.

Unlike the combined IVS standard UT1 combination, the IVS does not officially provide any combination of the intensive UT1 series. However, this combination is done as an internal step in the procedures of the IERS Earth Orientation Center. This allows one to identify and remove the systematic errors, and minimize the high-frequency noise.

3. Combination of intensive UT1 series, procedure

The procedure the IERS Earth Orientation Center (EOC) applies is similar to that applied for the general combination leading to the combined C04 [4, 11]. Five individual UT1 intensive solutions are available on a routine basis along with their associated formal errors [30]. These uncertainties are generated from analyses based on least squares or Kalman processes. They thus reflect internal precisions and are usually overoptimistic. Since the combination process requires an estimation of the real accuracy, this is achieved by rescaling the formal uncertainties using an external procedure.

A method that can be used when three time series of similar stabilities and time resolution are available is the Allan variance analysis [16, 38]. This method has been widely applied to estimate instabilities of clocks in the field of time and frequency. The noise of each series can be evaluated, provided that their errors can be assumed to be statistically independent, i.e. that there is no correlation between these series and the covariance is equal to zero. The tests the IERS EOC performed concerning the various analyses sustain this hypothesis. This analysis leads to rescaling individual formal uncertainties.

The combined series is slightly smoothed [39, 40] in order to remove high-frequency variations smaller than 1 day and interpolated at 1-day intervals using a Lagrange polynomial on four points. Residuals of the final combined intensive series with a high-pass filter show a white noise behaviour. This combined ‘Intensive’ solution is utilized in the global combination leading to the C04 computation.

3.1. Use of LOD derived by the GNSS technique

VLBI is unique in its ability to make accurate measurements of Universal Time in a quasi-inertial frame realized through

extragalactic source coordinates. On the other hand, the celestial frame realized through satellite techniques such as SLR and GPS is affected by orbital systematic errors due to the inability to model various perturbations, and is not accurate for UT1 determination.

However, on time scales up to about 20 days, these errors are limited so that the high-frequency signal contained in the GPS UT determination can be used for densification of UT1 derived by VLBI [36]. Different approaches can be used. In the first one [12] the high-frequency GPS LOD estimates are added to the long-term variations of the VLBI series to be integrated in the combined C04 solution as a separate series. This additional contribution is primarily for UT1 densification when intensive VLBI are missing over several days, which happens occasionally, and when estimates obtained from intensive sessions are erroneous; they can sometimes be larger than 100 μ s.

3.2. Method of combined smoothing

An alternative approach is based on the simultaneous combination of UT1 and LOD using the so-called method of ‘combined smoothing’ [41, 42]. It is a generalization of Vondrák smoothing [39, 40]. The method assumes that two relatively smooth curves are available:

- (a) The first one fitting VLBI UT1 estimates
- (b) The second one fitting GPS LOD estimates.

Both curves are tied by the constraint that LOD is the first derivative of UT1,

$$\text{LOD} = -d(\text{UT1} - \text{TAI})/dt.$$

The optimal solution is obtained when minimizing an expression that takes into account the two conditions for two adapted smoothing parameters. These smoothing parameters were determined *a priori* following a series of simulations.

The estimation of the improvement obtained by the use of GPS LOD estimates is not straightforward since no ‘Truth’ series exists for comparison. To discriminate the difference in quality between EOP time series, various authors have suggested using for comparison an external series based on atmospheric excitations of the Earth’s axial angular momentum variations [22]. The tests the IERS EOC made showed that no significant improvement appears and the discrimination of series cannot be made through such a method. The likely reasons for this are that the AAM data are partly derived from models and the quality of the AAM data are not as good as the EOP data. These issues prevent its use in discriminating between the qualities of UT1 series.

Comparisons with an external UT1 combined series like the *Bulletin A* of the Rapid/Prediction Service at USNO (<http://maia.usno.navy.mil/>) or SPACE solution performed at the Jet Propulsion Laboratory, JPL [18], can alternatively give an assessment of the qualities of the series.

3.3. UT1 combination

The combination is performed using mainly the IVS 24h combined solution and the IERS EOC internal combined

intensive solution in addition to the series of UT1 based on the GPS LOD series. It appears that the contribution of GPS LOD either by the current approach using the integration of LOD (GPS) or when applying the combined smoothing leads to a significant improvement of a few microseconds in the weighted root mean square, WRMS, compared with the solution which does not incorporate any LOD(GPS) data [13]. It is also striking that the improvement of the solution is only a few microseconds when Intensive sessions are included.

3.4. Consistency monitoring

The precision of the techniques contributing to IERS Earth orientation series is continually improving. For many applications mostly linked to space geodesy, consistency between the terrestrial reference frame and EOPs is required. The current series of IERS EOPs provides the official transformation between the International Celestial Reference Frame (ICRF) and the ITRF. In order to be consistent with the successive ITRF realizations, the IERS EOP C04 is regularly revised [1]. In particular, to be consistent with the latter realization ITRF2008, changes in the EOP C04 series consist of biases smaller than 50 μ arcsec in both pole components. The change in system of UT1–TAI is on the order of 2 μ s, which is smaller than the level of the WRMS between IVS individual solutions.

Other IERS EOP series (*Bulletin B*, C01, *Bulletin A*) were expressed in this new system consistent with ITRF2008. The Earth rotation parameters associated with ITRF2008 extend until the middle of 2009. Following a strategy that was set up in 2005, the consistency between the current C04 and ITRF realization is monitored by comparison of the two procedures:

- using combination over weekly GPS SINEX and
- using EOP-only derived from the current combination method leading to C04.

A recent comparison shows that the consistency of the pole components of the C04 in the ITRF2008 system is on the order of ± 30 μ arcseconds, smaller than the accuracy of the pole components [5].

3.5. Robust combination

So far, EOP series are derived separately from both the terrestrial and celestial reference frames. We expect that in the near future there will be a strong evolution in that field. EOP solutions and the terrestrial reference frame will be simultaneously derived in a global combination of normal equations derived from the processing of the different techniques. The method has been under investigation for several years [8, 14, 23, 31, 37, 44].

The method is based on the fact that techniques have their own strengths and weaknesses and their combination should benefit from their mutual constraints. Observations derived from the various techniques are processed using unique software. The weighting of the techniques is performed according to Helmert’s method [33]. The main difficulties of the procedure lie in the combination strategy to be applied; in particular the way to ensure stability of reference frames

over successive weekly determinations and the weighting of the various techniques in the combination. It is likely that future generation of EOP and TRF products will be routinely based on rigorous combinations. The method seems promising as well for the study of short-term variations of EOP.

4. Rapid combinations

Since UT1 is required to relate the terrestrial frame to the celestial (inertial) frame, it has a number of practical applications. For instance, GNSS need UT1, along with other EOPs, in order to provide navigation capability. Precision astronomical instruments that need to be pointed with extreme accuracy also need to account for UT1. With these real-world applications comes an inherent need for near-real-time UT1 determinations. These solutions are generically termed ‘rapid combinations.’

To meet the needs of the users of these data, the US Naval Observatory (USNO) serves as the Rapid Service/Prediction Center for the IERS. There are several other institutions that generate rapid combinations including Jet Propulsion Laboratory (JPL), Paris Observatory (OP), and the National Metrological Institute of Russia (VNIIFTRI). Each of these institutions uses a different methodology for creating their solutions such as Kalman filter [17], Vondrak smoothing [11], combination and smoothing [21], and weighted cubic spline [24]. The accuracy of these different algorithms, once systematic errors of the input data are mitigated and appropriate smoothing is applied, is roughly comparable.

Certain data sets play a more prominent role in rapid combinations than others. For instance, the VLBI intensives are designed specifically to make rapid, low latency determinations of UT1. Because of their accuracy and their increasingly quick turnaround due to electronically transferred data, the VLBI intensives are an important part of most rapid combinations. Another data set that plays an important part in rapid combinations is the LOD determinations made by analysis of GPS observations. Since LOD is related to the derivative of UT1, it can be a useful part of rapid combinations as long as the span of GPS data after the last available VLBI data point is not too great.

One of the aspects of rapid combinations that has changed the most over the last decade is the latency of the input EOP data products. For instance, the late 1990s saw the introduction of the International GNSS Service (IGS) Rapid EOP solution that provided polar motion and LOD estimates within one day of the latest observations. The IGS Ultra-rapid solutions, which are provided four times per day, further reduce this latency. The last few years have seen the VLBI intensives undergo a similar transformation. With electronically transferred data being used routinely, the latency of these VLBI sessions is now reduced to under a day. The result is that it is now routine to be able to provide daily EOP combination estimates for UTC midnight within 18 h. This latency is likely to be reduced as the data delivery and analysis process becomes more refined and automated.

An aspect of rapid combinations that is taking on greater importance is the method of data delivery. Historically,

Table 2. Root mean square of the differences between the EOP time series predictions produced by the IERS RS/PC daily solutions for 2010 and the C04 combination solution for UT1 – UTC.

Days in the future	UT1 – UTC/ms
1	0.07
5	0.31
10	0.72
20	2.17
40	5.09
90	7.90

EOP data were disseminated by mail, but with the advent of widespread electronic communication in the 1990s, methods such as e-mail became more prominent. Now, even the popularity of e-mail is diminishing with the majority of data transfers taking place through machine-to-machine (M2M) methods such as file transfer protocol (ftp) and hypertext transfer protocol (http). While the future of electronic communication is always difficult to discern because of the rapidly changing state of the industry, it is reasonable to assume that tomorrow’s communication will look different to today’s. For instance, formats such as extensible markup language (XML) and really simple syndication (rss) may play a more significant part in providing near-real-time EOP data delivery.

5. Predictions

EOP predictions play an essential role in providing data for real-time processes. Since there is an inherent latency in the data dissemination, data analysis, EOP combination and EOP dissemination process, any system that needs real-time EOP data uses EOP predictions. As a result, EOP predictions are likely the most used EOP product [26].

Several methodologies have been used for UT1 prediction with varying degrees of success. Examples include Kalman filters, autoregressive, least-squares and autoregressive (LS + AR), multivariate stochastic methods, neural networks, as well as others. For an example of current prediction capabilities, see [24, 25]. Table 2 provides the root mean square of the differences between the EOP time series predictions produced by the IERS RS/PC daily solutions for 2010 and the 08 C04 combination solution for UT1 – UTC. Note that the prediction length starts counting from the day after the last available observation is made for UT1 – UTC.

5.1. Short-term predictions

The short-term EOP predictions play the critical role of providing the information needed by real-time operational systems to relate terrestrial and celestial reference frames. Most of these systems require relatively high accuracy predictions and so these applications generally drive the need for better prediction capabilities.

While many different UT1 prediction algorithms can be used, one common thread for the improvement of prediction quality is the use of atmospheric angular momentum (AAM) forecasts [10, 15, 20].

AAM fluctuations are caused by variations in the atmospheric pressure and winds from changing weather effects on a variety of time scales and result in dynamical interactions between the atmosphere and the underlying planet. Thus the atmospheric fluctuations are compensated by opposite fluctuations in the solid Earth, and hence in Earth rotation, due to the conservation of the angular momentum of the whole system [2]. In particular, the axial term, related to UT1 and LOD is termed χ_3 (axial), and it can be expressed as the sum of two terms:

- A pressure-term related to the redistribution of the air masses; this term is computed with and without the hypothesis of inverted barometer [9, 29]. In short, the ocean acts to counteract the pressure of the atmosphere above it, with 1 hPa of high atmospheric pressure acting to depress the ocean by approximately 1 cm. To calculate the global effect of this oceanic inverted barometer, the surface pressure of each point of the atmosphere over the ocean is replaced by the mean atmospheric pressure over the world ocean. Thus, the impact of the atmosphere over the world ocean is reduced by the compensation of the ocean mass itself. The regional and temporal variability of the inverted barometer has been studied by [28] and a full discussion of its validity given by [43]. Also, more sophisticated relationships between atmospheric pressure and oceanic height were treated by [9], but it is not feasible to use operationally from data generated by the meteorological centres.
- The wind-term axial term is in effect the relative angular momentum of the atmosphere based on the zonal wind. The highest values of AAM are in the middle latitudes where the large westerly winds dominate. The easterlies in the lowest latitudes contribute negatively to the total AAM, but in total, the angular momentum is positive, so that the zonal winds are in super-rotation about the Earth.

The formulation used to compute the axial atmospheric excitations of LOD based on the pressure and wind terms is based on [2], and updated by [45]:

$$\chi_3 = -0.70 \left[\frac{r^2}{Cg} \right] \int P_s \cos^2 \phi \, dS - 1.00 \left[\frac{r}{\Omega C g} \right] \iint u \cos \phi \, dP \, dS.$$

In this equation, P_s is surface pressure, integrated two-dimensionally over S , the surface of the globe, (ϕ, λ) are latitude and longitude, u is the eastward component of the wind velocity, g is the mean acceleration due to gravity, r is the mean radius of the Earth, C is the axial component of the polar moment of inertia of the solid Earth (mantle + crust), and Ω is the mean angular velocity of the Earth. The χ_3 term is equivalent to the fractional variation of LOD as follows:

$$\frac{\Delta \text{LOD}}{\text{LOD}} = \chi_3.$$

UT1 is obtained by integration of LOD.

Table 3. Estimation of the size of prediction errors in UT1 – UTC as a function of the prediction time performed over the last decade. The mean error does not exceed 300 ms for a four year horizon. The maximum reaches 800 ms for the same prediction time.

Prediction time/year	Prediction error/ms	Maximal error/ms
1	40	150
2	100	300
3	200	470
4	300	800

5.2. Long-term predictions

Long-term predictions can also be used for practical applications, although these applications generally require lower accuracy than the short-term predictions. One example is the generation of ephemerides, which requires the input of ΔT (= Terrestrial Time – UT1). Terrestrial Time is succeeding Ephemeris Time (ET) and is used for deriving the tables of positions of the Sun, Moon and planets. Another use of long-term predictions is for the determination of the occurrence of leap seconds (*Bulletin C*). Table 3 gives the estimation of the size of prediction errors in UT1 – UTC as a function of the prediction time performed over the last decade. Note that statistically the mean error does not exceed 300 ms for a four year horizon.

6. Conclusion

The knowledge of Universal Time UT1 is essential for many applications linked to navigation, reference frame determination and global geophysical properties of both the internal and external parts of the Earth.

As an inertial technique, VLBI is unique in determining UT1. The usual UT1 combination now takes into account the IVS combined solution derived from standard sessions in addition to intensive sessions. The improving accuracy of LOD (GPS) estimates can be valuably employed in the combination. The present UT1 accuracy is about $\pm(3-5) \mu\text{s}$ corresponding to a couple of millimetres on the Earth's surface. Predictions are necessary for various applications, GNSS orbit determinations, and announcement of leap seconds to be introduced in UTC.

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