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THE IERS BULLETIN C AND THE PREDICTION OF LEAP SECONDS

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The Earth Orientation Product Center of the IERS is responsible for the prediction and announcement of the leap second (Bulletin C) and the value of DUT1 truncated at 0.1s for transmission with time signals (Bulletin D). Bulletin C is issued twice a year and announces six months in advance the event or non-event of a leap second to be introduced in UTC. Two surveys, in 2002 and 2011, were conducted by the Earth Orientation Center. Results have shown that a large majority of users of the IERS Bulletin C favor the current definition of UTC, with the occasional introduction of leap seconds to maintain UTC close to UT1. However, a number of users satisfied with the current definition of UTC, stressed the need for a longer prediction interval as compared to the six-month announcement which is currently made. In the present paper we analyze the feasibility to extend the prediction announcement to a longer range, between 2 to 10 years. The limitation of an accurate prediction comes from the difficulty to predict the so-called decadal fluctuation attributed to the core-mantle coupling. Simulations performed using data over the last 40 years show that, at the 95% confidence level, it is possible to extend the prediction interval to 2.5 years. An alternative method, based on an artificial neural network, shows so far similar results.

INTRODUCTION

The legal time scale UTC (Universal Time Coordinated) is derived from TAI (*Temps Atomique International*) by the occasional insertion of leap seconds in order to maintain UTC within 0.9 s of the time scale based on the Earth's rotation UT1, *i.e.* |UT1-UTC| < 0.9 s. This system was introduced in 1972 and so far has turned out to be globally satisfactory. About 15 years ago, various communities involved particularly in telecommunication and navigation systems proposed a revision of the UTC definition aiming to eliminate leap seconds in order to have a continuous time scale. This has been since the topic of discussions among the different communities requiring accurate timing.

In order to question users about a possible redefinition of UTC, the Earth Orientation Product Center of the IERS conducted two surveys in 2002 and in 2011.[1, 2] Results showed that a large majority of users in different communities are satisfied by the current UTC system. However, amidst the answers as the *status quo*, many users expressed their preference to have a longer prediction interval at their disposal. We have investigated here the capability of extending the leap-second prediction interval by applying the current method based on a Least Squares process and

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Autoregressive filtering and, in addition, on an alternative method based on a neural network which is under investigation at our institute.

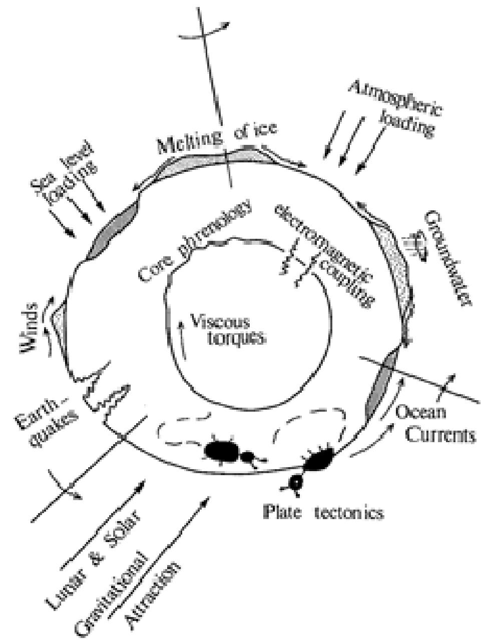

Figure 1. Schematic illustration of the phenomena perturbing the Earth rotation (courtesy of K. Lambeck, Nature 286, p. 104, 1980)

Table 1. Scales ranging from a few hours to decades as well as secular drift

Time scale	Phenomena	Amplitude
Secular drift	Tidal dissipation Post-glacial rebound	1.8 ms/century -0.5 ms/century
Decadal fluctuations	Core/mantle torque Global ocean-atmosphere processes	5 ms << 0.5 ms
Variations from a few days to about 2 years	Atmosphere motions(zonal winds)	1 ms
Diurnal and sub-diurnal variations	Ocean tides	~200 μs

UNIVERSAL TIME AND EXCESS OF THE LENGTH OF DAY OVER 86400 (LOD)

UT1 is the time scale based on solar time. It is strictly proportional to the Earth Rotation Angle (ERA) around the moving rotation axis (IAU 2000). LOD, time derivative of UT1, is the excess of the Length of the day over 86400 s. LOD is easier to represent than UT1−UTC and is more often used by geophysicists in their analyses. Different phenomena affecting the Earth rotation contribute to variations at different time (Figure 1).[3] The effects of these phenomena cannot be modeled and consequently the Earth rotation rate as well as the other Earth rotation parameters needs to be permanently observed.

The effects of the phenomena have for LOD different signatures and magnitudes (Table 1). In the present paper, we are particularly concerned with the long-term variations in UT1 (or LOD), including the secular drift due to the lunar torque. These variations are an important factor in driving UT1 apart from UTC, in addition to the effect of the choice of the atomic second in 1967. The atomic second was derived from the ephemeris second, which itself was based on the mean solar day of 1820, which was 86400s long with the epoch precision. In other words, more comprehensively, the atomic second is “a bit too short” with respect to the $^{1}/_{86400}$ part of the present solar day, which leads to a daily increase of the integrated quantity UT1−UTC.

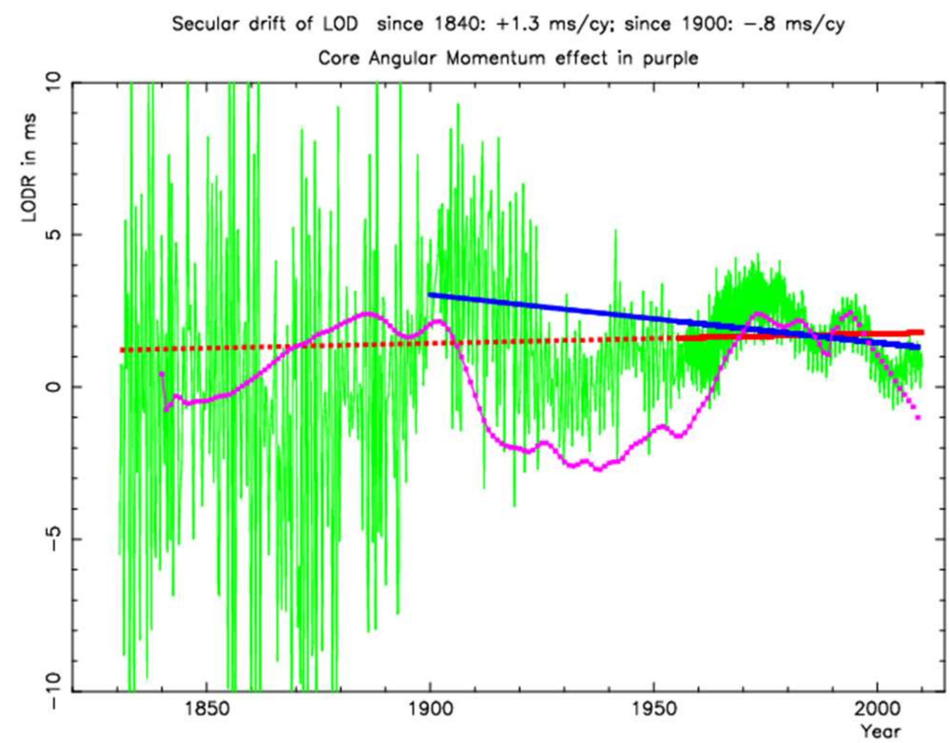

Figure 2. Composite LOD series based on eclipses, occultations of stars by the Moon (after 1860) and optical observations until 1972, lunar laser ranging since 1969 and now mostly the VLBI technique, unique in giving access to a quasi-inertial frame realized by the positions of extra-galactic sources. In the solid magenta line, the so-called “decadal variations” appear. They are attributed to the core mantle interaction due to the Earth magnetic field.[4] The dashed red line corresponds to the secular drift (about 1.3 ms/cy) slowing down the Earth rate of rotation. Looking to the interval 1900 until now, it appears that the Earth is accelerating (blue line).

Figure 2 represents a series of LOD derived from different types of observations: in the past palaeontology (coral growth, bivalve’s growth, sedimentation), ancient eclipses after 700 BC, occultation of stars by the Moon (after 1860) and optical observations until 1972.[5] Nowadays, beside the Lunar Laser Ranging which yields scarce UT0 estimates with poor accuracy, the only technique able to estimate UT1 is the VLBI (Very Long Baseline Interferometry) observing extra-galactic sources realizing the non-rotating reference frame and this via a worldwide network of radio telescopes. Within the past few years, VLBI UT1 estimates are complemented by high-frequency signal derived from GNSS techniques. UT1 accuracy is currently at the level of 5 microseconds of time.[6, 7]

BULLETIN C AND THE NEW UT1−UTC TIME SERVICE

The various irregular fluctuations which were progressively detected in the Earth rotation rate of the Earth led in the 1970's to the replacement of UT1 as the reference time scale. However, it was desired by the scientific community to maintain the difference UT1−UTC smaller than 0.9 seconds to ensure agreement between the physical and astronomical time scales. Since the adoption of this system in 1972, partly due to the initial choice of the value of the second ($^{1}/_{86400}$ mean solar day of the year 1820) and secondly to the general slowing down of the Earth's rotation, it has been necessary to add 25 s to UTC. As of 1 July 2012, 00:00:00 UTC is 35 seconds behind TAI (TAI − UTC = 35 s). Figure 3 shows the occurrence and number of leap seconds per year between 1972 and 2010.[8] It appears that, since the year 2000, the Earth is relatively speeding up, and the rate of introduction of leap seconds has significantly decreased.

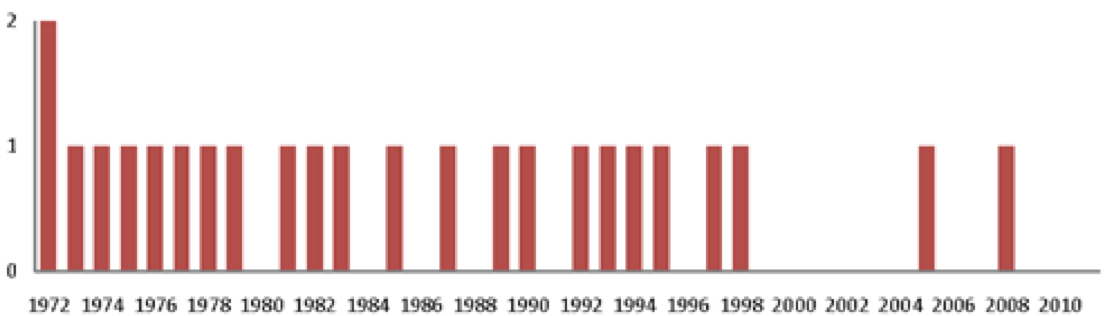

Figure 3. Leap seconds per year between 1972 and 2010 (courtesy of W. Dick[8], 2011)

The fields of activities of Bulletin C users extend over various communities, mainly: astronomy, astrophysics, geodesy, precise orbit determination, geophysics, time-service laboratories, computer centers, radio-signal laboratories, radio-astronomy activities, radio stations, post and telecommunication, hydrographic and oceanographic labs, surveying and mapping institutes, civil engineering, and space research. As of July 2013, there were 2800 subscribers.

The New UT1−UTC Time Service

Information concerning UT1−UTC and the occurrence of the leap seconds are currently made available via IERS bulletins (Bulletins D and C) sent to users in ASCII format. However, this procedure does not satisfy automatic systems. We have investigated the way to develop a new service based on the concept of Virtual Observatory (VO).[9] This concept, provided by the International Virtual Observatory Alliance (IVOA), allows scientists and the public to access and retrieve UT1−UTC information using on-line distributed computational resources. The UT1 service described is now operational via the following URLs:

http://hpiers.obspm.fr/iers/eop/eopc04/eopc04_IAU2000.62-now_VOtable.xml.txt

http://hpiers.obspm.fr/iers/eop/eopc04/eopc04.62-now_VOtable.xml.txt

ftp://hpiers.obspm.fr/iers/eop/eopc04/eopc04_IAU2000.62-now_VOtable.xml

ftp://hpiers.obspm.fr/iers/eop/eopc04/eopc04.62-now_VOtable.xml

These files are available in the XML-based VOTable format. In addition, a simple ASCII file giving the dates of insertion of leap seconds is available on the front page of the IERS EOP product Center at http://hpiers.obspm.fr/iers/bul/bulc/Leap_Second_History.dat.

CURRENT PREDICTION METHOD

The prediction of UT1 is the superposition of four components: a secular drift due to the tidal torque, a decadal fluctuation due to the core mantle interaction, seasonal variation that is relatively stable, and irregular variations. The seasonal variations can be reasonably well modelled by both an annual and semi-annual term, the irregular component by an autoregressive filtering considering the residual signal is statistically stationary, which is an approximation leading to limited errors. The main errors in the prediction come from the decadal fluctuation which varies slowly but which may undergo unsuspected changes within a few years.

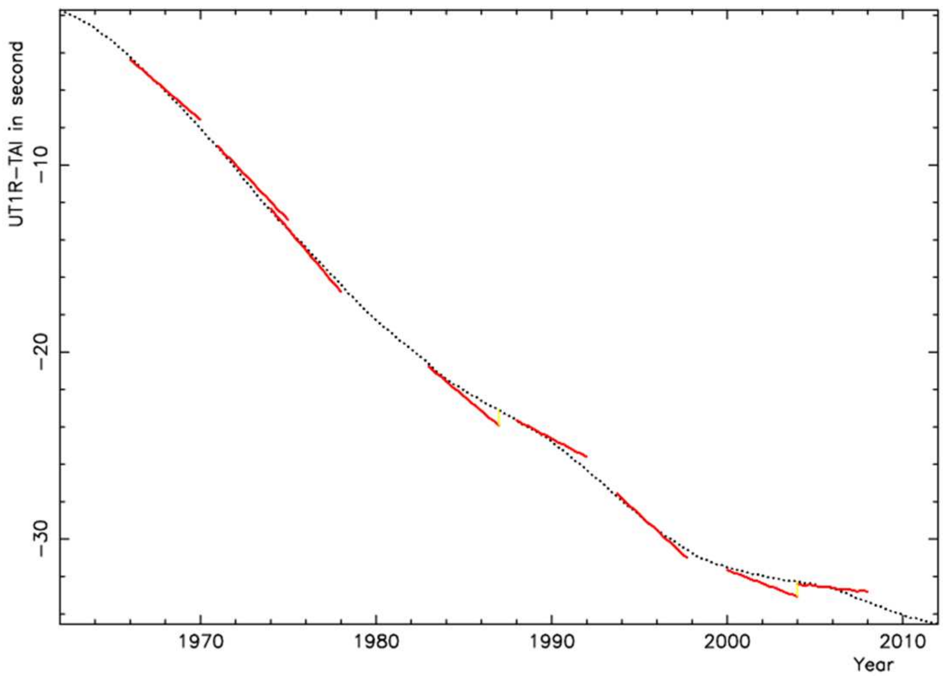

Figure 4. Simulation: forecasting UT1-UTC from 1 to 15 years. The prediction (in red) is compared to the actual estimates of the C04, available afterwards. The simulation was performed on successive intervals, each one shifted from the preceding one by one year.

SIMULATIONS

Procedure

We have conducted here a series of simulations. The simulation procedure is performed directly on UT1−UTC, the integration of LOD, where the trend due to decadal fluctuations is dominating. It takes into account the predictions of three parameters:

- the seasonal term using Least Squares fitting,
- the sum of the secular drift and the decadal variation considered as a trend over a few years, and

- irregular variations based on an autoregressive filtering.

A series of simulations shifted by one year were performed over the interval 1962 to now, searching for the maximal prediction interval to reach to get a prediction accurate to 0.9 s. The predicted estimates are compared to the past values C04 series considered to be the truth (Figure 4).

Results

Results are given in the form of statistics. Table 2 shows the rate of success in maintaining prediction accuracy within |0.9 s| versus the prediction length in years. It appears that such a precision is reachable at 95% confidence level for a prediction interval of less than 3 years.

Table 2. Rate of success maintaining prediction accuracy < |0.9 s| over prediction intervals of *n* years.

Prediction interval (*n*, years)	Simulation success (%)
2.5	95%
3	85%
4	75%
8	25%
12	10%

Over the last decade (2000–2012), where fewer leap seconds were introduced due to the relative acceleration of the Earth rotation rate, the performance of the prediction algorithm is better (Table 3).[10]

Table 3. Estimation of the size of prediction errors in UT1−UTC as a function of the prediction time over the last decade. Note that statistically the mean error does not exceed 300 ms for a four year horizon over the interval 2000-2010.

Prediction interval (*n*, years)	Prediction error, average (ms)	Maximal error (ms)
1	40	150
2	100	300
3	200	470
4	300	800

PREDICTION USING THE ARTIFICIAL NEURAL NETWORK (ANN)

An alternative predictive method based on artificial neural networks (ANN) is being carried out in our group. This approach has already been successfully applied to pattern recognition, sunspots[11] and the prediction of stock prices.[12] The method was first studied by Egger (1992).[13] It was then implemented by various authors for EOP predictions.[14, 15] New and more efficient algorithms are now available. That encouraged us to re consider applying this method.[16] In this study, two approaches are under investigation:

1) "PERCEPTRON": standard feed forward network that fits a relationship between input and target. The results obtained are similar to those obtained by the purely statistical methods.
2) "NARX": Nonlinear autoregressive with external input; learns to predict future values of a time series based on the past values of the same series. It uses n delays, *i.e.* n points of the time series to predict the next value. This method is being implemented. The effects of different critical parameters have to be preliminary studied in sensitivity simulations before an exhaustive statistics and comparisons with the current methods be given.

SUMMARY

We have investigated the possibility to extend the six-month time prediction for leap seconds according to the request of a number of users requiring accurate time scale for different applications: ephemeris, telescope pointing or orbit determination. Predicting the leap second with a 2-½ year time interval is possible at 95% confidence level using the current statistical method based on least-squares and autoregressive methods. 100% of success is reachable for a 4-year prediction for the last decade due to the recent speeding up of the Earth rotation which leads to more space introduction of leap seconds. Improvements will likely come from a better knowledge of the decadal fluctuation due to the interaction between the core and the mantle of the Earth.

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