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A technique to improve the accuracy of Earth orientation prediction algorithms based on least squares extrapolation

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ABSTRACT

We present a technique to improve the least squares (LS) extrapolation of Earth orientation parameters (EOPs), consisting of fixing the last observed data point on the LS extrapolation curve, which customarily includes a polynomial and a few sinusoids. For the polar motion (PM), a more sophisticated two steps approach has been developed, which consists of estimating the amplitude of the more stable one of the annual (AW) and Chandler (CW) wobbles using data of longer time span, and then estimating the other parameters using a shorter time span. The technique is studied using hindcast experiments, and justified using year-by-year statistics of 8 years. In order to compare with the official predictions of the International Earth Rotation and Reference Systems Service (IERS) performed at the U.S. Navy Observatory (USNO), we have enforced short-term predictions by applying the ARIMA method to the residuals computed by subtracting the LS extrapolation curve from the observation data. The same as at USNO, we have also used atmospheric excitation function (AEF) to further improve predictions of UT1-UTC. As results, our short-term predictions are comparable to the USNO predictions, and our long-term predictions are marginally better, although not for every year. In addition, we have tested the use of AEF and oceanic excitation function (OEF) in PM prediction. We find that use of forecasts of AEF alone does not lead to any apparent improvement or worsening, while use of forecasts of AEF + OEF does lead to apparent improvement.

1. Introduction

Earth orientation parameters (EOPs) are used to describe the time-variable orientation of the Earth represented by the International Terrestrial Reference Frame (ITRF) with respect to the space represented by the Geocentric Celestial Reference Frame (GCRF) with the help of the Celestial Intermediate Pole (CIP). Precession–nutation describes the orientation of the CIP with respect to the GCRF. Polar motion (PM) describes the orientation of the CIP with respect to the ITRF. UT1-UTC describes the variation of rotation angle of the ITRF with respect to the GCRF in the equator of the CIP (McCarthy and Luzum, 2010).

Real-time high precision EOPs are needed in a variety of sciences and applications such as geodesy, astronomy, navigation, and time-keeping. One example is accurately predicted EOPs are needed to generate the broadcast orbits to be uploaded to the Global Positioning System (GPS) satellites. Rapid solutions in the very recent past and predictions for a year into the future in daily interval are performed and updated weekly by the International Earth Rotation and Reference Systems Service (IERS) Rapid Service/Prediction Center (RS/PC) operated by the U.S. Navy Observatory (USNO)[1] (Luzum et al., 2009; Stamatakos et al., 2011), and published in the IERS Bulletin A. In addition, USNO is also providing daily interval predictions for 90 days in the future, which are updated daily. A similar task is also routinely performed at NASA's Jet Propulsion Laboratory (JPL), updated daily with predictions for 83 days into the future[2] (e.g., Chin et al., 2009).

As precession–nutation are predicted much more accurately than PM and UT1-UTC (e.g., Niedzielski and Kosek, 2008), current efforts of EOP predictions are mostly devoted to the predictions of PM and UT1-UTC, which is also the focus of this work. Hence, we restrict EOPs to include PM and UT1-UTC only hereafter. Furthermore, we follow the convention in EOP prediction to assume that the values of EOPs determined from observations and to be predicted have a daily interval, which implies that the EOP time series

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[1] http://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html.
[2] ftp://euler.jpl.nasa.gov/keof/predictions/.

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include only variations with periods equal to or longer than a couple of days, while variations with shorter periods are assumed to have been smoothed out.

Temporal variations of the EOPs are caused by a number of geophysical processes (e.g., Gross, 2007): (a) tides; (b) non-tidal atmospheric and oceanic processes, which are modeled in atmospheric (AGCMs) and oceanic (OGCMs) general circulation models; (c) the glacial isostatic adjustment (GIA); (d) land water (also including snow, glacier and ice sheet) mass variations; (e) processes in the Earth's core; and (f) other geophysical processes of relatively minor importance including plate tectonic motions, Earthquakes, to name a few. The processes (a) and (b) are most relevant to EOP predictions.

Tides mainly influence UT1-UTC. Tide-induced UT1-UTC variations mainly include a series of sinusoidal variations with periods ranging from about 5.6 days to 18.6 years, which are well modeled, determined and predicted (e.g., Yoder et al., 1981; McCarthy and Luzum, 2010). Another well determined and predicted major component of UT1-UTC variations is the seasonal variation, which is mainly caused by atmospheric processes, with minor contribution from oceanic processes and land water mass variations. Hence, in UT1-UTC predictions, the above mentioned tidal and seasonal variations are, based on IERS models (McCarthy and Luzum, 2010), removed from past data and predicted for the future. Leap seconds are also removed in UT1-UTC for predictions. As a result, what is predicted in reality is UT2R-TAI, the variation of which is dominated by a linear trend mainly caused by tidal dissipation and glacial isostatic adjustment (GIA—the effect is a trend on the order of a 100 years), and some minor periodical variations with periods ranging from a fraction of a year to several decades (e.g., Tissen et al., 2010), which are either related to atmospheric and oceanic processes, or core processes (e.g., Gross, 2007).

PM is dominated by the annual (AW) and Chandler (CW) wobbles, both mainly driven by atmospheric and oceanic processes combined (e.g., Gross, 2007). The former is a forced mode with a period of 1 year, the latter a normal mode with a period of 1.18 years. Other PM constituents are extremely minor, including a linear drift mainly caused by GIA, and a number of wobbles with periods ranging from the order a fraction of a year (fourth of a year, third of a year, half a year, half of the CW period) to the order as long as interannual, decadal and longer time scales (e.g., Stamatakos et al., 2007; Höpfner, 2003; Gross, 2007), which are also either related to atmospheric and oceanic processes, or core processes (Gross, 2007).

While the characteristics listed in the above two paragraphs are the main features of EOP variations, variations exist across the whole spectrum. After removing those main constituents, the residual EOP time series are normally considered stochastic for predictions, in which there exist highly oscillatory variations very crucial for near-term predictions. These highly oscillatory variations are mainly caused by non-tidal atmospheric and oceanic processes, which are related to EOP variations through the atmospheric (AEF) and oceanic (OEF) excitation functions (EFs), which can be computed from the mass redistribution and velocity field of AGCMs and OGCMs (e.g., Barnes et al., 1983). Theoretically, forecasts of AEF and OEF could be used in EOP predictions. At present, AEF forecasts are successfully used in UT1-UTC predictions at both USNO and JPL, since data showed that UT1-UTC can be explained almost completely by AEF with a practically negligible contribution from OEF, and there exist AEF forecasts accurate enough to improve UT1-UTC predictions (e.g., Freedman et al., 1994; Johnson et al., 2005; Gross et al., 2007a,b; Gambis et al., 2011). Recently, it has also been reported that PM predictions may be improved by using forecasts of AEF, OEF, and hydrological EF (HEF) (Dill and Dobslaw, 2010). However, this is a hindcast study, and forecasts of AEF and/or OEF, HEF have not been used for practical PM predictions. The major reason may be that reasonably accurate forecasts of OEF are not yet available in real time.

Different methodologies are adopted at USNO and JPL, where EOP predictions are regularly delivered. Empirical approaches are used at USNO (McCarthy and Luzum, 1991; Stamatakos et al., 2007; Gambis and Luzum, 2011). UT1-UTC (or actually, UT2R-TAI) is predicted using forecasts of AEF for the nearest future. After that, the prediction is based on a simple differencing, as the influence of the periodic variations is small. The results from differencing are then smoothed, with short-term predictions less smoothed than long-term predictions. PM predictions are made by least squares (LS) extrapolation using a curve consisting of the CW, as well as annual, semiannual, terannual and 1/4 annual periodical signals, of which the idea can be traced back to Zhu (1982). The near-term predictions are enhanced by applying an autoregressive (AR) forecast method to the residual time series obtained by subtracting the LS extrapolation curve from the observed PM, of which the idea can be traced back to Chao (1984). At JPL, a Kalman-filter (KF) technique is used to combine different observations and to predict EOPs (Chin et al., 2004, 2009; Petrov et al., 1995; Gross et al., 1998). Recently, forecasts of AEF are also incorporated into the KF for predicting UT1-UTC (Freedman et al., 1994; Gross et al., 2007a,b).

In addition to the AR method applied to PM prediction at USNO, various other stochastic methods have also been applied to PM and/or UT1-UTC predictions, e.g., autocovariance (AC) (Kosek et al., 1998; Kosek, 2002), artificial neural network (NN) (Schuh et al., 2002; Liao et al., 2012), multivariate autoregression (MAR) (Niedzielski and Kosek, 2008), autoregressive moving average (ARMA) and autoregressive integrated moving average (ARIMA) (Luzum et al., 2001; Kosek et al., 2004). The stochastic methods are actually applied to the residual time series after removing a polynomial–sinusoidal curve used for LS extrapolation. Hereafter, the combination of LS extrapolations and a stochastic method is referred to as LS + stochastic. Besides the LS + stochastic approach, other approaches have also been used, e.g., the wavelets and fuzzy approach (Akyilmaz et al., 2011). A list of most contemporary methods and their comparison can be found in Kalarus et al. (2010).

In this work, we present a technique to improve the LS extrapolation of the LS + stochastic approach. As usual, we use, for LS extrapolation, a curve consisting of a polynomial and a few sinusoids, which is referred to as polynomial–sinusoidal curve. The idea is to consider the last observed EOPs to be exact in the computation of the parameters of the polynomial–sinusoidal curve by LS fitting, i.e., to fix the last observed EOPs on the LS extrapolation curves. We also attempt to find the optimal choices of the parameters used, including length of observations used for predictions, order of the polynomial, and number of sinusoids and their periods. Based on the results of various tests, we did confirm improvement by assuming the last observed EOPs to be exact.

Besides the improvement in LS extrapolation, we have attempted to improve near term predictions by applying the ARIMA method to the residual time series after removing the LS extrapolation curve. Furthermore, we have also tested the use of AEF and OEF forecasts to improve near term predictions. For UT1-UTC, as the AEF is dominant over OEF (e.g., Johnson et al., 2005), we have tested only the use of AEF forecasts. For PM, we have tested the use of both AEF forecasts and AEF + OEF forecasts. Two approaches have been used to include forecasts of AEF and OEF in EOP predictions. The first approach is to directly integrate the AEF or AEF + OEF to compute EOP for the first few days when their forecasts are available, and then use the ARIMA method after. The second approach is to use a KF.

Actually, what we did is a hindcast to test our methods. We used the USNO (i.e., IERS RS/PC) data of UT1-UTC and PM, which date back to modified Julian date (MJD) 41,684.00 (0 UTC, January 2, 1973). We have extended the UT1-UTC data back to MJD 37,684.00