# 3.5 Product Centres
## 3.5.1 Earth Orientation Centre

This section presents activities and main results concerning the Earth Orientation Centre located in Paris Observatory over 2003. General presentation of the IERS Earth Orientation Parameters (EOP), operational activities and yearly analyses are presented at the Web site <http://hpiers.obspm.fr/eop-pc>. According to the IERS terms of reference, the Earth Orientation Centre is responsible for monitoring Earth Orientation Parameters including long term consistency, publications for time dissemination and leap second announcements. It is making available to users different products: long-term and operational series of Polar Motion, Universal Time (UT1), Length of Day (LOD) and Celestial Pole Offsets.

Determination of EOP is in the form of combined solutions derived by the analysis centers of the different techniques. Various solutions are computed: long-term solution (IERS C01), normal values at five and one-day intervals (IERS C02 and C03), and the operational smoothed solution Bulletin B at one-day intervals published monthly and providing EOP with a delay of 30 days with respect to the date of publication. Bulletin B is updated in an operational mode in the IERS C04 which is computed twice weekly. After the presentation of the new interactive tools implemented on our Web site, we will present the different combined EOP solutions available.

### Web interactive tools

On the Web site of the Earth Orientation Centre <hpiers.obspm.fr/eop-pc> has been set up this year interactive tools, mostly written in PHP language, devoted to the EOP time series and most generally to Earth rotation studies.

1) First is devoted to the selection and plot of various EOP time series (“combined”, “long term” and “operational”).
2) Second allows users to compute the Earth orientation matrix at any epoch from EOP time series, and derive associated parameters.
3) Third is devoted to the numerical analysis of long term EOP series (Fast Fourier Transform, periodogram, filter, least square, Singular Spectral Analysis).
4) Fourth enables the mutual comparisons of operational series.
5) Last tools allow to compute the excitation functions associated with Earth rotation irregularities and to compare them to the atmospheric angular momentum functions.

Interactivity is especially interesting for focusing on a given data span or fitting poorly known physical parameter linked with Earth rotation.

## Combined daily series: Bulletin B and EOP(IERS) C 04

Description of Bulletin B is available in the IERS Explanatory Supplement for Bulletin A and Bulletin B (Gambis and Ray, 2003). Since formal uncertainties reported by the contributors are often underestimated, they are calibrated by statistical assessment using the Allan variance analysis in order to reflect the real quality of the data (Gray and Allan, 1974; Gambis, 2002). This procedure leads to an optimal weighting of the individual series entering the combinations (Gambis, 2003). Table 1 gives the estimated accuracy with respect to IERS C04 of these series over 2002–2003 after removal of systematic variations, mainly a bias.

*Table 1: Estimated accuracies of individual solutions entering the combined solutions in 2003.*

| Individual solutions | | Estimated uncertainties | | | | |
|---|---|---|---|---|---|---|
| | | Time | Terrestrial Pole 0.001" | UT1 0.0001s | LOD 0.0001s | Celestial Pole 0.001" |
| **VLBI – 24 h** | | | | | | |
| EOP (AUS) | 01 R 01 | 3-4d | 0.20 | 0.05 | | 0.12 |
| EOP (BKG) | 03 R 04 | 1-4d | 0.22 | 0.05 | | 0.15 |
| EOP (GSFC) | 03 R 06 | 1-4d | 0.16 | 0.04 | | 0.10 |
| EOP (IAA) | 03 R 04 | 1-4d | 0.14 | 0.04 | | 0.08 |
| EOP (MAO) | 03 R 01 | 1-4d | 0.21 | 0.05 | | 0.17 |
| EOP (SPBU) | 03 R 03 | 3-4d | 0.22 | 0.05 | | 0.13 |
| EOP (USNO) | 03 R 04 | 1-4d | 0.15 | 0.04 | | 0.13 |
| **VLBI – Intensive** | | | | | | |
| EOP (BKG) | 03 R 02 | 1-3 d | | 0.13 | | |
| EOP (GSFC) | 03 R 05 | 1-3 d | | 0.12 | | |
| EOP (IAA) | 03 R 03 | 1-3 d | | 0.13 | | |
| EOP (SPBU) | 02 R 01 | 1-3 d | | 0.14 | | |
| **Satellite Laser Trackin** | | | | | | |
| EOP (ASI) | 03 L 02 | 1d | 0.30 | | 2.33 | |
| EOP (CSR) | 95 L 01 | 3d | 0.66 | 1.15 | | |
| EOP (DUT) | 98 L 01 | 3d | 0.56 | | | |
| EOP (IAA) | 02 L 02 | 1d | 0.27 | 0.27 * | 0.13 | |
| EOP (MCC) | 97 L 01 | 1d | 0.30 | | 0.48 | |
| **GPS** | | | | | | |
| EOP (CODE) | 98 P 01 | 1d | 0.06 | | 0.26 | |
| EOP (EMR) | 96 P 03 | 1d | 0.10 | | 0.31 | |
| EOP (ESOC) | 96 P 01 | 1d | 0.13 | | 0.25 | |
| EOP (GFZ) | 96 P 02 | 1d | 0.09 | | 0.29 | |
| EOP (IAA) | 01 P 01 | 1d | 0.24 | | 0.37 | |
| EOP (JPL) | 96 P 03 | 1d | 0.08 | | 0.48 | |
| EOP (NOAA) | 96 P 01 | 1d | 0.25 | | 0.49 | |
| EOP (SIO) | 96 P 01 | 1d | 0.10 | | 0.32 | |

** The satellite techniques provide information on the rate of change of Universal Time contaminated by effects due to unmodelled orbit node motion. VLBI-based results have been used to minimize drifts in UT estimates*

## Predictions

Different methods are used for prediction of the Earth Rotation Parameters.

### Polar Motion

The formalism uses at first a floating period fit (Bevington, 1969) for both the Chandler and annual components estimation over a past time interval of several years. An autoregressive filter is then applied on the short-term residuals series and used for the prediction. The predictions of the celestial pole offsets Dy and De are based on an empirical model (McCarthy, 1996).

### Universal Time

The present formalism used is based on the assumption that the long-term fluctuations (annual and semi-annual) of the preceding year are valid over the next few months. For short-term variations prediction, an autoregressive process is used. Table 2 shows the accuracy of the current EOP solutions and also the skills of the predictions. New procedures for prediction are under investigation, they are based on Singular Spectrum Analysis SSA and Neuronal networks.

*Table 2: Uncertainty of the current solution and the estimated accuracies of the predictions for horizons of 5 days to 1 year for 2003.*

| Solutions | | Terrestrial Pole 0.001" | UT1 0.0001s | Celestial Pole 0.001" |
|---|---|---|---|---|
| Analysis | 1-d | 0.15 | 0.20 | 0.10 |
| Prediction | | | | |
| | 5-d | 3. | 10. | 0.10 |
| | 10d | 6. | 21. | 0.10 |
| | 30d | 12. | 38. | 0.10 |
| | 90d | 40. | 45. | 0.10 |
| | 180d | 60. | 80. | 0.10 |
| | 1-yr | 50. | 120. | 0.10 |

Table 3 gives the agreement and consistencies of the IERS C04 solution with two combined solutions obtained by the IERS rapid service at USNO (Bulletin A) and the JPL. These values reflect the mean precision reached i.e. about 0.05 mas for polar motion and 10 microseconds for UT1. The overall accuracy taking into account the consistency between the terrestrial and celestial frames is in the range of 0.1 mas and 20 microseconds, respectively for Polar Motion and UT1.

## Long-term series: C 01 (1846-2003)

EOP(IERS) C 01 is a series of the Earth Orientation Parameters given at 0.1 year interval from 1846 to 1889 (polar motion only) and 0.05 year interval from 1890 until now (polar motion, celestial pole offsets; UT1–UTC since 1962). For many decades, the observa-

*Table 3: Mean and standard deviation of the differences between various IERS solutions for 2003*

| EOP | Unit | Comb JPL – IERS C04 | | BullA – IERS C04 | |
|---|---|---|---|---|---|
| | | Mean | Standard deviation | Mean | Standard deviation |
| X | mas | –0.19 | 0.07 | –0.03 | 0.05 |
| Y | mas | 0.03 | 0.04 | 0.05 | 0.05 |
| UT1 | 0.1 ms | –0.07 | 0.16 | –0.05 | 0.20 |

tions were made using mostly visual and photographic zenith telescopes. Since the advent of the space era in the 1960s, new geodetic techniques were used for geodynamics. Now, the global observing activity involves Very Long Baseline Radio Interferometry (VLBI), Lunar (LLR) and Satellite Laser Ranging (SLR), Global Positioning System (GPS) and more recently DORIS.

The C 01 series was recomputed in the course of 2003. It is a composite series based on following temporal solutions:

1846–1899: Fedorov *et al*. (1972) polar motion solution derived from three series of absolute declination programs (Pulkovo, Greenwich, Washington).

1900–1961: Vondrak *et al.* (1995) solution derived from optical astrometry analyses based on the Hipparcos reference frame. The series gives polar motion, celestial pole offsets and Universal Time (since 1956).

1962–2003: BIH and IERS solutions (BIH and IERS annual reports).

## Mean Pole with respect to the IERS reference origin

The analyses of the observations of space geodesy require to perform the transformation between both terrestrial and celestial frames via of the Earth Orientation Parameters. Gravity field models include the tesseral coefficients C21 and S21. These terms describe the position of the Earth's figure axis with respect to the Terrestrial Reference Frame. This axis should coincide with the observed position of the rotation pole averaged over the same time period.

The mean polar motion is affected by a long-term drift westward (direction: 70.7 deg West, rate: 4.2 mas/yr). The mean rotation axis with respect to the International Terrestrial Reference Frame, can be considered as the long-term trend obtained after filtering out the Chandler and seasonal terms, every year from 1900 to 2000 (Shiskin *et al.*, 1965). Figure 1 represents the polar motion over 2001–2003 and the path of the mean pole since 1900. The table is available in Conventions 2003 (McCarthy and Petit, 2004) and at the following address: <http://hpiers.obspm.fr/eop-pc/>.

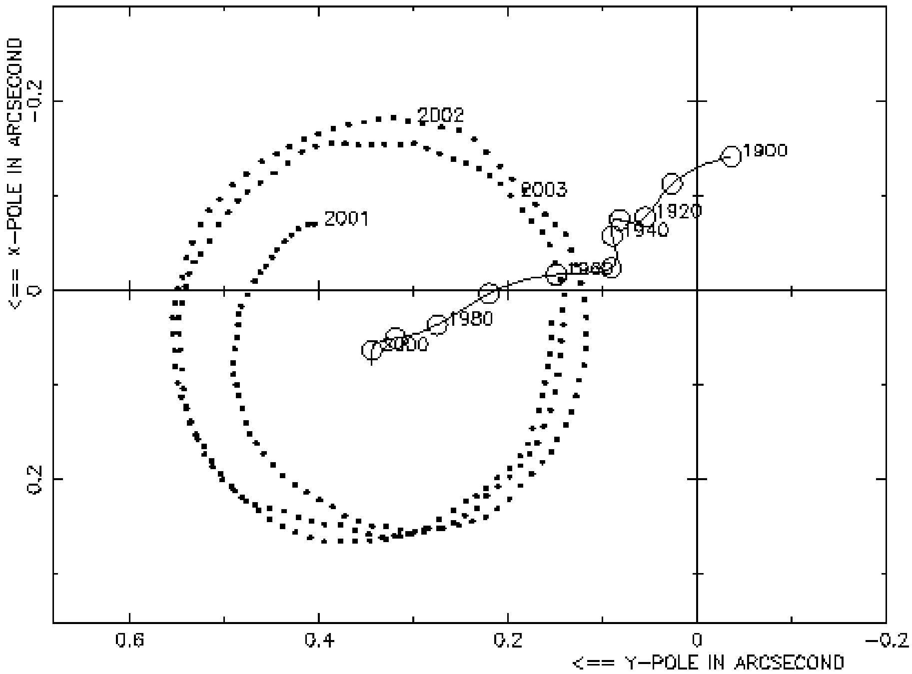


*Fig. 1: Mean polar motion (1900–2003) and IERS C04 polhody over 2001 – 2003.*

## Normal Point Solutions: C 02 (1962-2003), C 03 (1993-2003)

Other series, based on normal points solutions given at various time intervals, are also proposed to users, i.e. C 02 (5-day intervals, polar motion, UT1–UTC, $\delta\psi$, $\delta\varepsilon$), C 03 (one-day intervals, polar motion, UT1–UTC) (Gambis, 1996; Eisop and Gambis, 1997). These series are respectively consistent one to another. They use the full correlation matrix when available. Recently there were new developments in the normal point series C 02 and C 03 in which the estimation of the solution given at the central dates of the n-day interval is made using a least-square fit for all EOP components. Although the L2 estimation has been extensively used for data analysis, it has some drawbacks linked to problems of ill-conditioning and in the non-detection of outliers. Alternative methods based on robust estimators like M-Huber can be used. These estimators are a generalization of both the L1 and L2 class. They have been implemented in our analyses and are now currently used (Bougeard *et al.*, 2000). Table 4 reflects the evolution of the mean uncertainties of C02 solution since 1962.

## Impact of IAU2000 Resolutions on EOP

Resolutions adopted at the 24th General Assembly of the International Astronomical Union recommend the implementation of new procedures concerning the transformation between the celestial and terrestrial reference systems: adoption of a new precession-nutation model (IAU 2000), of a new celestial pole (the Celestial Intermediate Pole) and of a new transformation between the terrestrial and celestial systems defining UT1 as directly proportional to the Earth Rotation Angle.

*Table 4: EOP(IERS) C 02 : Evolution of the mean uncertainty of the normal point solution given at five-day intervals*

| YEARS — Unit | σ(X) — 0.001" | σ(Y) — 0.001" | σ(UT1) — 0.0001s | σ(dψ) — 0.001" | σ(dε) — 0.001" |
|---|---|---|---|---|---|
| 1962–1967 | 30 | 30 | 20 | – | – |
| 1968–1971 | 25 | 25 | 17 | – | – |
| 1972–1979 | 11 | 11 | 10 | – | |
| 1980–1983 | 2 | 2 | 3 | 2 | 1 |
| 1984–1989 | .40 | .40 | .20 | .5 | .2 |
| 1990–2000 | .20 | .20 | .20 | .3 | .1 |
| 2001–2004 | .15 | .15 | .1 | .3 | .1 |

The IERS Workshop held in Paris in April 2002 had the objective to discuss the impact of these resolutions on the various IERS Products (Capitaine *et al*., 2002). The description of all these changes for the IERS is presented in Rothacher (2002). Complete expressions and tables are described in Chapter 5 of the IERS Conventions 2003.

To comply with these resolutions, since 1 January 2003, Bulletin B and IERS C04 are providing new products in addition to those already published. These products include the celestial pole offsets relatively to the new precession-nutation model IAU2000A and using the new formulation described in the following.

## The changes in the EOP

### New parameterisation of the Earth orientation

The most important changes are those introduced by IAU Resolutions B1.6 (IAU 2000 Precession-Nutation Model), B1.7 (Definition of Celestial Intermediate Pole) and B1.8 (Definition and Use of Celestial and Terrestrial Ephemeris Origins). Although it is not directly mentioned in the Resolutions, the new precession-nutation model is accompanied by a new formulation for the transformation between the celestial (*CRS*) and terrestrial (*TRS*) reference systems in the form recommended in the IERS Conventions 2003:

$$[CRS] = Q(t) \cdot R_3(-\theta) \cdot W(t) \cdot [TRS],$$

in which $Q(t)$, $R_3(-\theta)$ and $W(t)$ are time-dependent transformation matrices to account for the precession-nutation, proper rotation of the Earth about the axis corresponding to CIP and polar motion, respectively:

$$Q(t) = \begin{pmatrix} 1 - aX^2 & -aXY & X \\ -aXY & 1 - aY^2 & Y \\ -X & -Y & 1 - a(X^2 + Y^2) \end{pmatrix} \cdot R_3(s), \quad a = \tfrac{1}{2} + \tfrac{1}{8}(X^2 + Y^2)$$

$$W(t) = R_3(-s') \cdot R_2(x) \cdot R_1(y) .$$

The Earth Rotation Angle (ERA) between the CEO and TEO is given as function of UT1 by a simple linear relation:

$\theta(T_u) = 2\pi(0.779\,057\,273\,264\,0 + 1.002\,737\,811\,911\,354\,48\, T_u)$

where $T_u = \mathrm{JD(UT1)} - 2451545.0$ .

Here $X, Y, s$ and $y, y, s'$ describe the position of the Celestial Intermediate Pole (CIP) and the Celestial/Terrestrial Ephemeris Origins (CEO, TEO) in the Geocentric Celestial Reference System (GCRS) and International Terrestrial Reference System (ITRS), respectively (see <http://maia.usno.navy.mil/ch5tables.html>). The novelty are the quantities $X, Y, s$ whose developments into Poisson series, based on the IAU 2000A precession-nutation model, are published by Capitaine et al. (2003). Expressions for the classical transformation based on the new IAU 2000 model have been developed to be equivalent in the new transformation (McCarthy and Petit, 2004).

***Celestial pole offsets***

Precession-nutation is referred to CIP that exhibits, by definition, only long-periodic motions with periods of two days and longer in space. The IERS is now publishing the celestial pole offsets $\delta X_{2000}$, $\delta Y_{2000}$, referred to the new model IAU 2000 following the new formalism and the quantity s. Classical nutation angles, the celestial pole offsets in longitude and obliquity $\delta\Delta y_{2000}$ , $\delta\Delta e_{2000}$. respectively, referred to the new model can be easily derived from ($\delta X_{2000}$, $\delta Y_{2000}$) using equations 23 of Chapter 5 of the IERS Conventions (2003) or the relative Fortran subroutine dXdY_dpsideps included in the package uai2000.package (see next paragraph for its availability). These values $\delta X$, $\delta Y$ are now smaller than 1 mas, reflecting mostly the effect of the Free Core Nutation (FCN) that is not predictable and therefore not incorporated into the new model. The position of the CEO, given by *s*, is insensitive to any small change of the precession-nutation at the level of one mas, so only its model values are to be used (<http://maia.usno.navy.mil/ch5tables.html>). Parallel to these values, the values of 'classical' celestial pole offsets $\delta\Delta_{1980}$, $\delta\Delta e_{1980}$, referred to the old IAU 1976 precession and 1980 nutation model, are also being published for a limited period in Bulletin B and in the operational combined series C04.

***Polar motion***

Polar motion is not affected by adopting the IAU 2000 resolutions. Polar motion contains (relatively small) diurnal and sub-diurnal terms, due to ocean tides and high-frequency nutation terms. These are *not* part of the polar motion values published by the IERS at daily intervals; they are represented by a model (IERS Conventions 2003, Chapters 5 and 8) and should be added after interpolation. The Earth Orientation Centre makes available a Fortran subroutine for such an interpolation (<ftp://hpiers.obspm.fr/eop-pc/models/interp.f>). The position of the TEO, given by *s'*, depends on the actual polar motion, but the value of *s'* is so small that a simple linear approximation (Lambert and Bizouard, 2002) is sufficient:

$s' = -47\ \mu as\ (t - 51544.5) / 36525$ where t is expressed in Modified Julian Days (MJD).

***Universal Time***

UT1–UTC is theoretically not affected by the resolutions. Although UT1 is now directly linked to the Earth Rotation Angle through the linear relation above, the positioning of CEO (represented by the quantity *s*) and IAU2000 expressions between sidereal time and Universal Time UT1 are such that continuity in UT1 is ensured at the epoch of change from the old system.

There are short-periodic (diurnal, semi-diurnal) variations in UT1 due to ocean tides that are treated similarly to polar motion (the IERS publishes the daily values from which these terms have been removed, and they are to be added back after the interpolation).

**Availability of new products and models**

Series of the Earth Orientation Centre, in particular Bulletin B and C04 are being duplicated since January 2003 to give δX and δY in the new formulation in addition to the current issue containing $(\delta psi, \delta eps)_{1980}$.

The new files are available at the following Web/ftp sites:

– Web:
http://hpiers.obspm.fr/eoppc/eop/eopc04/eopc04_IAU2000.02
http://hpiers.obspm.fr/eoppc/eop/eopc04/eopc04_IAU2000.03

– anonymous ftp: hpiers.obspm.fr
files: /eop-pc/eop/eopc04/eopc04_IAU2000.02
/eop-pc/eop/eopc04/eopc04_IAU2000.03

**Fortran subroutines**

1) Transformation of $(\delta X, \delta Y)_{2000}$ to $(\delta psi, \delta eps)_{1980}$ or $(\delta psi, \delta eps)_{2000}$ and inversely are available in Fortran 77/90 at :

– Web:
http://hpiers.obspm.fr/eop-pc/models/models.html#software
files:
– ftp://hpiers.obspm.fr/eop-pc/models/uai2000.package
– ftp://hpiers.obspm.fr/eop-pc/models/uai2000.package.readme

– anonymous ftp: hpiers.obspm.fr
files: /eop-pc/models/uai2000.package
/eop-pc/models/uai2000.package.readme

2) Interpolation of Polar Motion at hourly scale

– Web: http://hpiers.obspm.fr/eop-pc/models/models.html#software
  files:
  – ftp://hpiers.obspm.fr/eop-pc/models/interp.f
  – ftp://hpiers.obspm.fr/eop-pc/models/interp.readme

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