The combined Earth Orientation solution C04

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Version 5 June 2009

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Introduction

Activities in fields of navigation, astronomy and global geodesy require the accurate knowledge of the orientation of the Earth in a non-rotating or quasi inertial reference frame. Earth Orientation Parameters (EOP) allow the transformation between a terrestrial reference system tied to the earth and materialized by the International Terrestrial Reference Frame ITRF (Altamimi et al., 2007) with respect to a celestial reference system realized by the International Celestial Reference Frame ICRF (Ma et al., 1998). One of the main tasks of the Earth Orientation Centre is to collect the various temporal series linked to the Earth orientation variations from the different technique centres relative to the geodetic techniques and to analyse them in order to derive and make available optimal combined solutions to the international community. This includes the monitoring of earth orientation parameters including long term consistency, publications for time dissemination and leap second announcements.

The Earth Orientation Parameters (EOP) describe the irregularities of the Earth rotation. Two parameters correct the precession-nutation model of the celestial pole dX, dY, UT1 − UTC gives the irregularities of the rotation angle, and the two last parameters (x-pole and y-pole) describe the pole motion with respect to the crust. The reference EOP series computed at the Earth Orientation Center at Paris Observatory is currently obtained from the combination of operational EOP series routinely derived from the various astro-geodetic techniques: Laser Ranging to the Moon (LLR) and to dedicated artificial satellites (SLR), Very Large Baseline Interferometry on extra-galactic sources (VLBI) and more recently from GPS and DORIS systems.

The analyses of the observations obtained from these techniques allow to derive all or a part of products linked to the reference systems and Earth orientation. Their complementarities and in some sense their redundancies sustain the concept of performing combined optimal solutions taking advantage of their respective strengths and minimizing their weaknesses.

It is fundamental to ensure consistency between the ITRF, the International Celestial Reference Frame ICRF and EOP connecting these two frames. So far the EOP time series solution and the ITRF are computed separately; this naturally led to an increasing inconsistency between both of them. At the end of 2005, the discrepancy was about 300 microarcseconds for polar motion, which is small but significant with respect to the current accuracy below 100 microarcseconds. In order to make available to users a homogeneous EOP set, it has been necessary to recompute the C04 in order to reset it to the ITRF reference. This was done after the release of the ITRF2005. Since, regularly, the ITRS centre and the EOP PC have agreed to regularly monitor the consistency using a comparison between the upgraded procedure implemented at EOP PC and CATREF combination which incorporates the routinely available SINEX files derived by the technique centres.

The purpose of this technical note is

1) To describe the combination procedure, its recent improvements mostly due to significant changes in the software code. We also present the re-computations which were carried on to make the series consistent with the EOP associated to the newly release ITRF2005.

2) To give the characteristics of the new EOP C04 solution, its accuracy, and how we proceed to monitor its consistency with the current realization of the ITRF reference frame.

KEYWORDS

Earth Rotation, combination, prediction, reference frames consistency

I Definitions and IERS conventions

1. The International Celestial and Terrestrial Reference Systems

The International Celestial and Terrestrial Reference Systems (respectively ICRS, ITRS) are defined by their origins, directions of axes and, in the case of the ITRS, length unit.
The ICRS is described by Arias et al. (1995). Its origin is at the barycenter of the solar system. The directions of its axes are fixed with respect to the quasars to better than +/- 20 micro-arcseconds. They are aligned with those of the FK5 within the consistency of the latter (+/- 80 milliarcseconds at epoch J1991.25 (van Leeuwen et al., 1997). The ICRS is realized by estimates of the coordinates of a set of extragalactic sources: the International Celestial Reference Frame (ICRF) (Ma and Feissel, 1997; Ma et al., 1998). According to Resolution B2 of the International Astronomical Union (IAU) 23rd General Assembly (Kyoto, 1998), after 1 January 1998 the IAU celestial reference system is the International Celestial Reference System (ICRS) as defined by the International Earth rotation and Reference systems Service (IERS), and the corresponding fundamental reference frame is the ICRF constructed by the IAU Working Group on Reference Frames.

The ITRS origin is at the center of mass of the entire Earth system, including the oceans and the atmosphere. Its length unit is the meter (SI), consistent with the TCG time coordinates for a geocentric local frame. The orientation of its axes is consistent with that of the BIH System at 1984.0 within +/- 3 milliarcseconds. The International Reference Meridian (IRM) is implicitly defined through the adoption of the set of coordinates of stations realizing the ITRF.
Its time evolution in orientation is such that it has no residual rotation relative to the Earth's crust. The ITRS is realized by estimates of the coordinates and velocities of a set of observing stations, the International Terrestrial Reference Frame (ITRF). For more details, see the IERS Conventions (McCarthy and Petit, 2004). The current ITRF realization is ITRF2005 (Altamimi et al., 2007).

2. IERS constants and models

The IERS Conventions (McCarthy and Petit, 2004) are a set of constants and models used in the analyses of observations derived from the various astro-geodetic techniques.

The values of the constants are adopted from recent analyses. In some cases, they differ from the current IAU and International Association of Geodesy conventional ones. The models are, in general, the best estimates of the specialists in the field. The IERS Earth Orientation Parameters (EOP) describe the rotation of the ITRS relative to the ICRS, in conjunction with the conventional precession nutation model.

3 The Earth Orientation Parameters, current definitions

Combined EOP series derived are in agreement with resolution adopted at the 24th general assembly which was held in Manchester in August 2000.

3.1 Pole coordinates

Pole coordinates give the terrestrial position of the Celestial Intermediate Pole (CIP). The x-axis is in the direction of the IERS Reference Meridian (IRM), the y-axis is in the direction 90 degrees West longitude. It contains relatively small diurnal and sub-diurnal terms, due to ocean tides and high-frequency nutation terms. As recommended in IERS Gazette #13 (McCarthy and Gambis, 1997), these are not part of the polar motion values published by the IERS at daily intervals; they are represented by a model (McCarthy and Petit, 2004) and should be added after sub daily interpolation.

The Earth Orientation Centre makes available a FORTRAN subroutine for such an interpolation (ftp://hpiers.obspm.fr/eop-pc/models/interp.f).

3.2 Universal Time

UT1 is the rotation angle about the celestial intermediate pole. It is related to the Greenwich mean sidereal time (GMST) by a conventional relationship (Aoki et al., 1982). It gives access to the direction of the International Reference Meridian (IRM) in the ICRS, reckoned around the CIP axis. It is expressed as the difference UT1-TAI or UT1-UTC. TAI is the atomic time scale calculated by the BIPM. Its unit interval is exactly one SI second at mean sea level. The origin of TAI is such that UT1-TAI was approximately 0 on 1 January 1958. The instability of TAI is about six orders of magnitude smaller than that of UT1.

Universal time Coordinated UTC

UTC is defined by the International Radio Consultative Committee (CCIR) Recommendation 460-4 (CCIR, 1986). It differs from TAI by an integral number of seconds in such a way that UT1-UTC remains smaller than 0.9 s in absolute value. The decision to introduce a leap second in UTC to meet this condition is the responsibility of the IERS; it is announced in Bulletin C. According to the CCIR Recommendation, first preference is given to opportunities at the end of June and December and second preference to those at the end of March and September. Since the system was introduced in 1972, only dates in June and December have been used.

DUT1 is the difference UT1-UTC expressed with a precision of +/- 0.1s; it is broadcast with the time signals and announced in Bulletin D. The changes in DUT1 are announced by the IERS.

The difference between the astronomically determined duration of the mean solar day (D) and 86400s of TAI is called the excess of the length of day denoted LOD. Its relationship with the angular velocity of the Earth, ω, is at the first order:

$\omega = \Omega_N \left(1 - \frac{LOD}{T}\right)$ where $\Omega_N = 72921151.467064 \cdot 10^{-12}\, rd/s$ is the nominal rotation rate and T the associated duration of the mean solar day (T = 86400 s TAI, D = LOD + T)

UT1, hence LOD and Omega are subject to variations due to zonal solid earth tides which can be accurately modeled. The model, which is a part of the IERS Conventions 2003, includes periodic components with periods ranging from 5.64 days to 18.6 years. UT1 − UTC is produced at daily intervals and do not include the effects of semidiurnal and diurnal variations mainly due to ocean tides.

3.3 Nutation

Precession-nutation is referred to CIP which exhibits, by definition, only long-periodic motions with periods greater than two days in space. The IERS is now publishing the celestial pole offsets δX_{2000} and δY_{2000} referred to the new model IAU 2000 following the new formalism recommended in the IERS 2003 Conventions. Classical nutation angles, the celestial pole offsets in longitude and obliquity ($\delta\Delta\psi_{2000}$, $\delta\Delta\varepsilon_{2000}$), respectively, referred to the new model can be easily derived from (δX_{2000}, δY_{2000}) using equations 23 in Chapter 5 of the IERS Conventions 2003 or the relative Fortran subroutines DPSIDEPS2000_DXDY2000 included in the package, uai2000.package (see next paragraph for its availability). However, they should not be anymore used. The values δX_{2000} and δY_{2000} 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.

II Description of the EOP combination algorithm

To date, various techniques allow the determination of all or a part of the Earth Orientation Parameters: Laser Ranging to the Moon (LLR) and to dedicated artificial satellites (SLR), Very Large Baseline Interferometry on extra-galactic sources (VLBI) and more recently GPS and DORIS systems. Over the last fifteen years, these techniques were independently organized into international services IGS, ILRS, IVS and IDS respectively in 1994, 1998, 1999 and 2003.
These geodetic techniques have however their own strengths and weaknesses. The analyses of their observations allow to derive all or a part of products linked to the reference systems and Earth orientation (Table 1). According to the technique, the EOP individual time series have different temporal resolution, precision, accuracy and stability. Their complementary and in some sense their redundancy sustain the concept of performing combined optimal solutions.

TABLE 1. Contributions of the different techniques to various products derived within the IERS. The number of stars (*) roughly matches their relative contribution to the corresponding product.

PRODUCTS SLR GPS DORIS	LLR	VLBI	SLR	GPS	DORIS
Extragalactic ref. Frame		***			
Tie to solar system	***	*			
Tie to Earth					
Precession-nutation	**	***	*	*	
Universal Time	*	***			
Earth Rotation					
High-frequency UT		***	*	**	
Polar Motion		**	**	***	*
Terrestrial Reference Frame					
Network coverage		*	*	***	***
Long-term geocenter			**	**	**
Tectonic plate motion		***	**	***	***
Densification		*	*	***	***

In the following, we describe the procedure developed and currently applied at the Earth Orientation Centre of the IERS for the combination of EOP series. The following successive steps leading to the 05C04 combined solution are detailed. The 05C04 time series is the scientific reference solution used for various applications, mostly in the fields of astronomy, space geodesy, and geophysics. It is maintained fixed for epochs extending to date – 30 days back. After this epoch, preliminary estimates updated regularly are given.

Step 1 - Selection of a set of operational series
In the past, EOP combined series were based on individual solutions derived by the analysis centres for the different techniques. Nowadays, Technique Centres, i.e. IVS, ILRS, IGS and IDS are deriving combined solutions based on individual analysis centres. These combined series are themselves used in our combinations in which individual solutions are usually excluded. In some cases of inaccuracy or instability of some specific series, individual series have been privileged as long as problems have not been solved with the technique centres combined series. This was for example the case for the IVS combined solution for UT1 and nutation offsets which were initially not used on contrary to individual VLBI series. The IVS solution is now currently used since it is based on SINEX combinations. Table 2 gives the list of the contributed series relatively to the EOP components used as of 1 January 2009.

EOP component	EOP series used in the combination
Pole components and LOD	IGS Final Combined IGS Rapid Combined IVS Combined ILRS Combined
UT1	IVS Combined and intensive VLBI solutions UT(GPS) derived from GPS LOD-based series
Nutation	IVS Combined and Individual standard VLBI solutions

Table 2 - EOP series currently used in the combination as of 1 January 2009

Step 2 - Computation of the differences between operational – intermediate reference series.
We do not directly combine the values of the series. The more these values will present large variations, the larger will be the errors introduced in the successive steps: interpolation, filtering in addition to any instability in the numerical computations. Therefore, we previously remove a known reference from the operational EOP series which is containing most of the signal. This reference is nothing else that the former combined solution previously obtained and extended by preliminary values extrapolated by predictions. To achieve this, the reference series is interpolated at each date of the operational series applying a Lagrange interpolation over 4 points. The difference between operational series and reference series is then computed. The combinations are applied on these differences. Let us remind, by the way, that the combined C04 solution is so far given at one-day intervals and does not contain any diurnal/sub-diurnal information due to ocean tides. For applications requiring the full EOP, an ocean tide model has to be used (IERS Conventions, 2003).

Concerning the offsets of nutation, the parameters of the reference series are dX, and dY relatively to the IAU 2000 model. For users requiring the old definition, dX and dY are transformed back to dPsi and dEps referred to IAU 2000 precession-nutation model.

Step 3 – UT1 and LOD computation
VLBI is unique technique in its ability to make accurate measurements of Universal Time in a quasi-inertial frame realized through extragalactic sources coordinates. On the other hand, the celestial frame realized through satellite techniques like SLR and GPS are linked to orbits systematic errors and is not accurate for UT1 determination. Still, on time scales limited to a couple of weeks, errors in the orbit are limited so that the high-frequency signal contained in the GPS UT determination can be used for densification of UT1 derived by VLBI (Gambis et al, 1993). High frequency GPS LOD estimates calibrated by VLBI are thus integrated in the combined 05C04 solution as a separate series. This additional contribution is of main importance for UT1 densification when intensive VLBI are missing, what happens from time to time over several days and as well when estimates obtained from intensive sessions are erroneous (they can sometimes be larger than 100 microseconds).

An alternative approach which is now successfully applied is based on the simultaneous combination of UT1 and its rate LOD using a method of combined smoothing (Vondrák & Gambis, 2000; Vondrák & Čepek, 2000; Bizouard and Gambis, 2009). The method of combined smoothing assumes that two relatively smooth curves are available:

- a) One fitting well to VLBI UT1 estimates
- b) The second one fitting well to GPS LOD estimates

Both curves are tied by constraints: the latter one is the first derivative of the former one. There is a compromise between these three conditions. This approach of using LOD derived by GPS can be used for determining quasi-real time estimates from the last VLBI intensive epoch to now. It leads to a fair consistency level between UT1 and LOD (Figure 1).

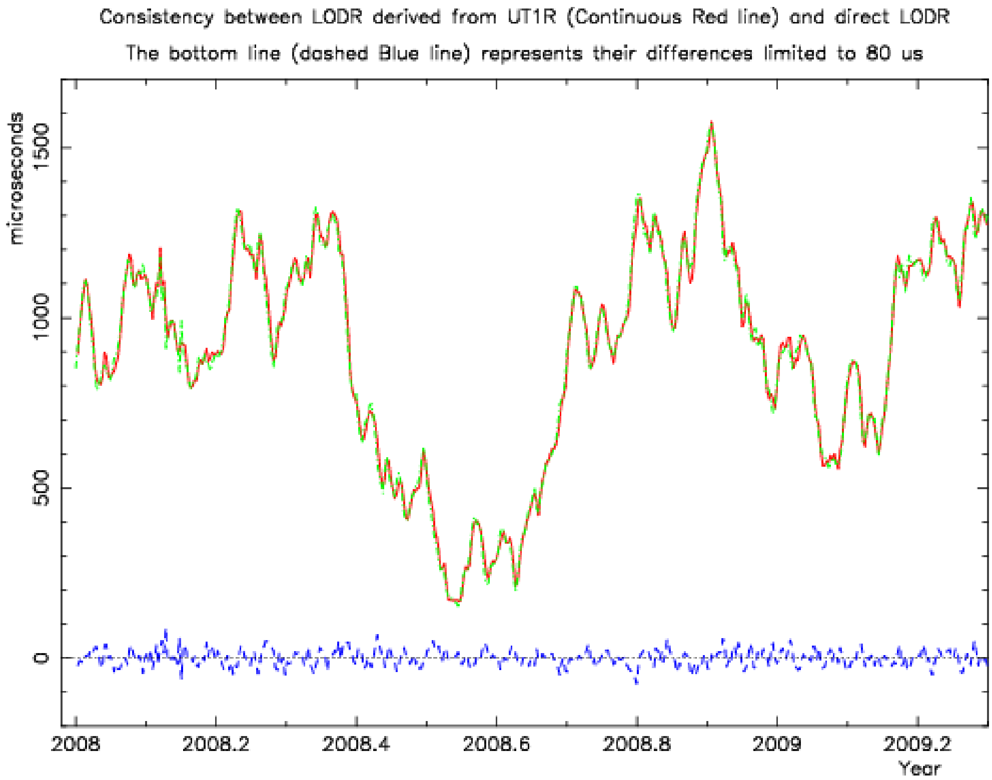


Figure 1 – Consistency of the direct LODR (dashed Green line) and LODR derived from UT1R (Continuous Red line). The bottom line represents the difference of these two series which is limited to 80 microseconds.

As a control, to test the impact of the GPS LOD estimates, a separate analysis was made. Combinations have been compared to an independent time series of atmospheric excitations of the Earth's axial angular momentum variations. Although this approach does not give any significant results by the fact that AAM data are partly derived from models, it gives anyway some indication of the quality of the EOP series.

Step 4 - Running average.
Data are averaged over successive time intervals of 0.5 day. The 0.5 day binning is justified by the data input, daily sampling for pole components derived from GPS and for UT1 derived from standard and intensive VLBI sessions. By using Lagrange interpolation we propagate the observed values to the averaged date. The average is weighted by the formal errors of the observed values. The averaged error or weight is also calculated.

Step 5 - Weighting change.
EOP estimated for the combinations are available with associated formal errors. These errors are issued from analyses based for instance on least square or Kalman processes. They are thus reflecting internal precisions and consequently are usually not realistic. Most of the time, they are optimistic (better than real). Still, the combination process requires an estimation of the real accuracy (or inaccuracy). This can be achieved by rescaling the formal uncertainties using an external procedure.

One method which can be used when three time series of similar stabilities are available is the three cornered hat (Gray and Allan, 1974, Vernotte et al., 2004). This method has been widely applied to estimate instabilities of clocks in the filed of Time and Frequencies. More recently, it has been applied to EOP time series since the 1980's (BIH Annual reports).
Considering three or more time series of similar quality and time resolution, the noise of each series can be evaluated, provided that their errors are assumed to be statistically independent. It means that there is no correlation between these series (the covariance is equal to zero). Tests we performed concerning the various analyses are sustaining this hypothesis. Figure 2 represents the typical correlation for x-pole and y-pole between two series, GPS and VLBI, where the level of correlation is smaller than 0.1.

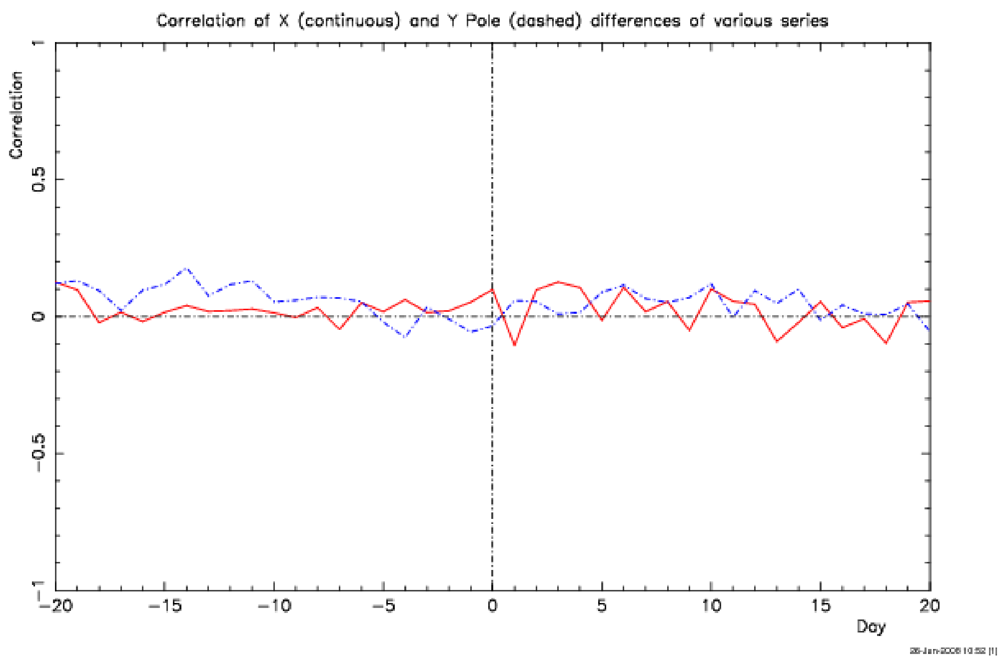


Figure 2 – Correlation of X-pole (Red continuous) and Y-Pole (Blue dashed line) differences between two current series GPS and VLBI. The level of correlation is smaller than 0.1.

Let us consider three independent EOP time series with similar stabilities, a, b and c. We can form their differences with the help of interpolation when necessary. The first assumption lies in the hypothesis of non correlation between the three series. With such an assumption, variances of pair differences can be expressed as:

$\sigma^2_{ab} = \sigma^2_a + \sigma^2_b$

$\sigma^2_{ac} = \sigma^2_a + \sigma^2_c$

$\sigma^2_{bc} = \sigma^2_b + \sigma^2_c$

The individual variances may be deduced according to:

$\sigma^2_a = ½ [\sigma^2_{ab} + \sigma^2_{ac} - \sigma^2_{bc}]$

$\sigma^2_b = ½ [\sigma^2_{ab} + \sigma^2_{bc} - \sigma^2_{ac}]$

$\sigma^2_c = ½ [\sigma^2_{ac} + \sigma^2_{bc} - \sigma^2_{ab}]$

The variance leads to the RMS, the ratio of this RMS σ_a to the mean formal error of the series σ_m gives the scaling factor $f = \sigma_a / \sigma_m$ which is to be multiplied by the formal error of each measurement to give a realistic error.

Another approach uses the Allan Variance (AV) .The community of "Time and frequency" uses a variety of stability metrics in order to characterize frequency standards, clocks and oscillators. Allan variance (Gray and Allan, 1974) is currently used for estimation of the stability of primary frequency standards. It is also applied in the time domain for characterization of the stability of atomic time scales. More recently, the AV analysis was applied to the field of earth orientation metrology (Gambis, 2002).

The AV is a measurement of stability in time series. It is also known as the two-sample variance. It is defined as one half of the time average of the squares of the differences between successive readings of the fractional error sampled over the sampling period.

The AV depends on the time period used between samples: therefore it is a function of the sample period, as well as the distribution being measured, and is displayed as a graph rather than a single number. A low Allan variance is a characteristic of a time series with good stability over the measured period

For various theoretical and practical reasons the definition advised by Allan is:

$< \sigma_y^2(N = 2, T = \tau, \tau) >$. It reads $< \sigma_y^2(2, \tau, \tau) > = < \frac{(\overline{y_{i+1}} - \overline{y_i})^2}{2} > \equiv \sigma_y^2(\tau)$

where $\overline{y_i} = \overline{y(t_i)}$ and $\overline{y_{i+1}} = \overline{y(t_{i+1})}$

To estimate $\sigma_y^2(\tau)$ we perform a simple mean from a finite number m of y_i estimates.

$$\sigma_y^2(\tau) \approx \frac{1}{m}\sum_{i=1}^{m}\frac{(y_{i+1} - y_i)^2}{2}$$

The advantage of the AV over the classical variance is that it converges for most of the encountered types of noise, whereas the classical variance does not always converges to a finite value.

The ratio $\sigma_y(\tau)/\sigma_f$ where σ_f is the mean formal error of the series allows to derive a scaling factor used to multiply the individual formal error to make it realistic.

It is convenient to represent $\sigma_y^2(\tau)$ as consecutive power function exponent τ^μ where μ characterizes the type of noise (white, flicker, random) present in the time series. Then, it is graphically more convenient to plot $\log\sigma_y^2(\tau)$ versus log(τ). In this log - log representation, the general slope μ allows to describe the type of noise, i.e. -1 for white noise, 0 for flicker noise and +1 for random walk noise. Figures 3 and 4 show this log - log representation for respectively x-pole and UT1-UTC components : differences between both the IGS and IVS combined relatively the 05C04. The parameter τ varies from a few days to about 3 years. White noise behavior appears (slope is about -1).

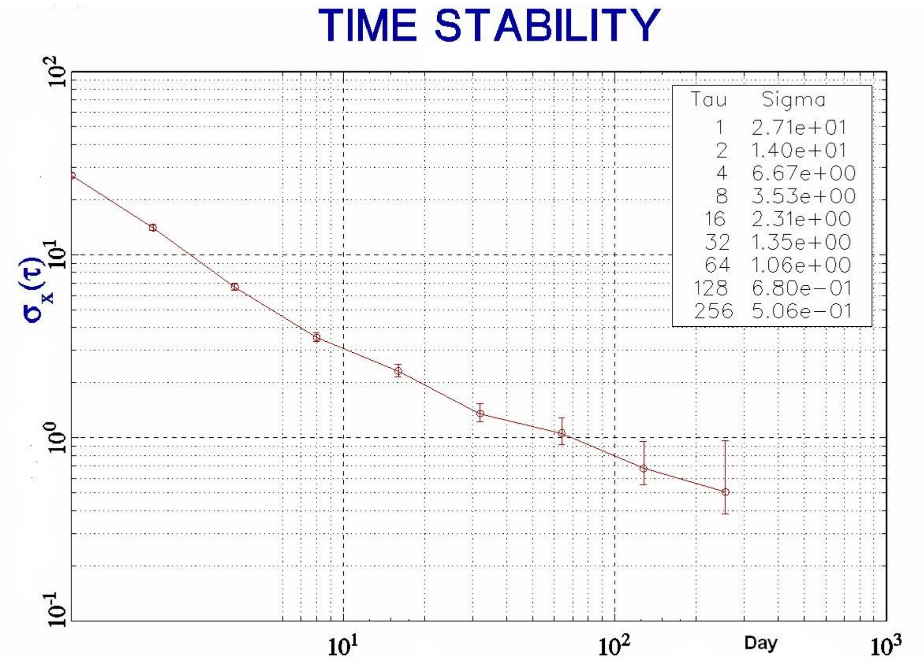


Figure 3 - The Allan variance analysis onto the x-pole residuals IGS00 - 05C04 reveals also a white noise behaviour characterized by a negative slope of about − 1.

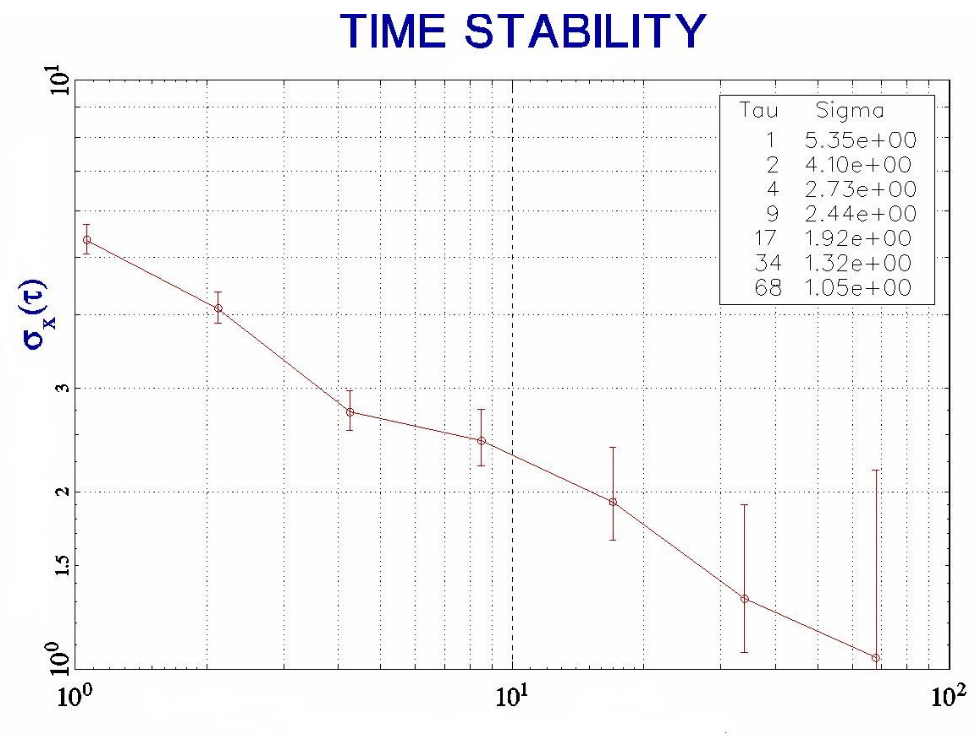


Figure 4 - The Allan variance analysis onto the UT1 residuals IVS Combined - 05C04 reveals also a white noise behaviour characterized by a negative slope of about − 1.

Step 6– Filtering
High frequency filtering Vondrák smoothing (Vondrák 1969; Vondrák 1977) is applied in order to remove high frequency variations. It is of prime importance that the smoothing characteristics be such that the residuals of the raw data to this smoothing are mostly white noise. Characteristics of the smoothing, according to the epoch of the solution, are reported in Table 2. A series of tests with different smoothing parameters was made in order to determine the optimal parameters (Figure 5 for X-pole and Figure 6 for UT1−UTC). These tests show that the optimal values are 10^5 for both polar components and UT1−UTC. It is remarkable that nowadays the smoothing is extremely weak in view of the accuracy reached by the EOP. Figure 7 shows the residuals Raw values − Smoothed values show a clearly a white noise behaviour.

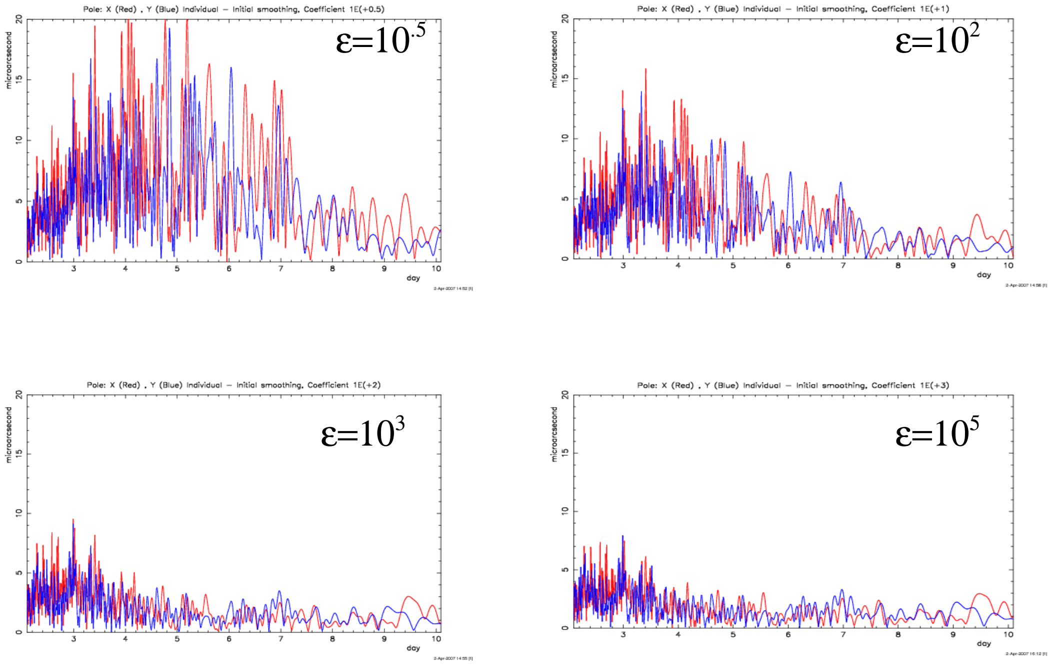


Figure 5 – Periodograms for C04 pole components of differences Raw values − Smoothed values for different smoothing parameters (Vondrak's smoothing) from 2 to 10 days. X_Pole (Red) and Y_Pole (Blue). The optimal values are obtained for a very weak smoothing corresponding to 10^5 (see table 2).

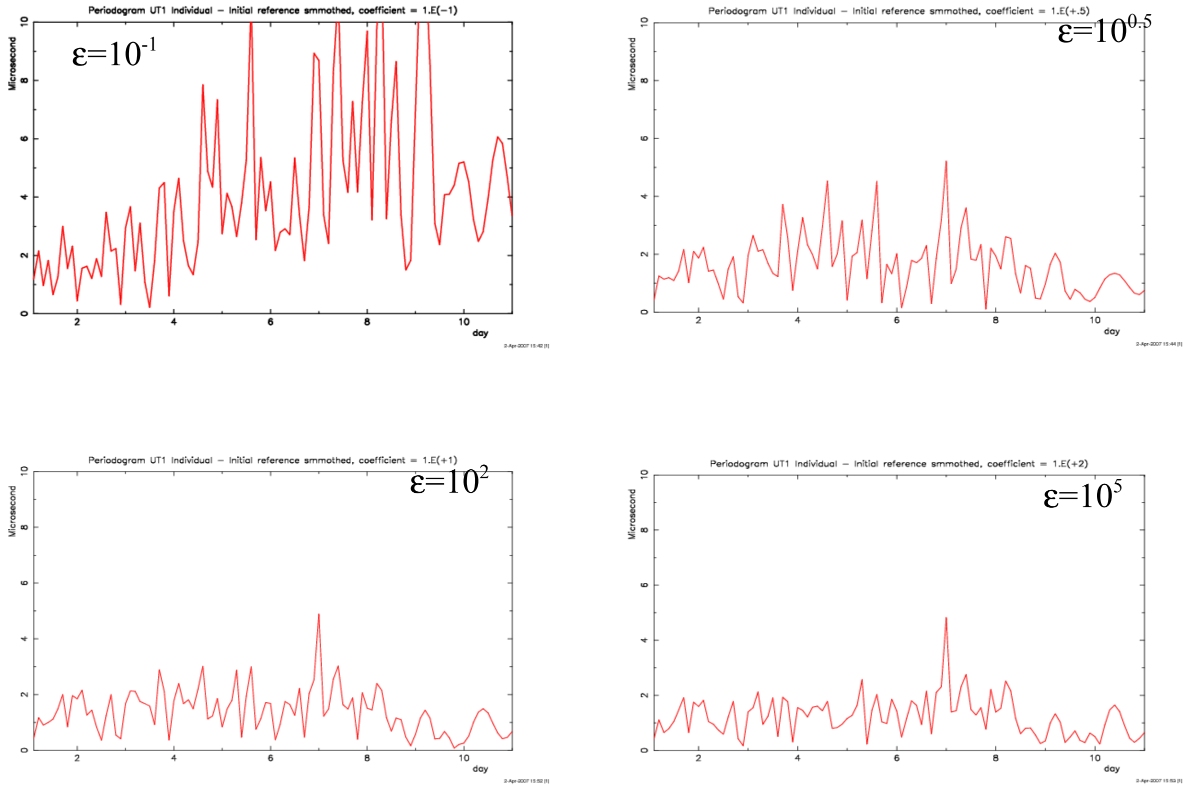


Figure 6 – Periodograms for C04 UT1−UTC of differences Raw values − Smoothed values for different smoothing parameters (Vondrak's smoothing) from 2 to 10 days. The optimal values are obtained for a very weak smoothing corresponding to 10^5 (see table 2).

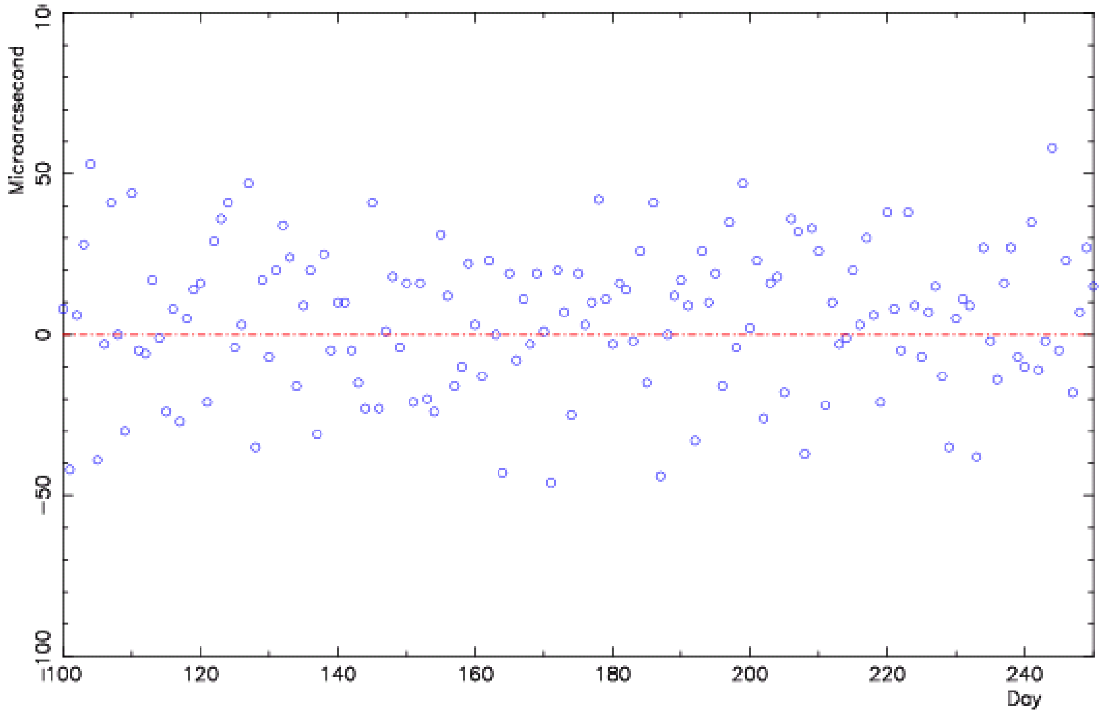


Figure 7 – X-Pole, difference of the raw combined series – smoothed series obtained with the Smoothing parameter ε=10^5. Residuals show a clearly white noise behaviour.

Step 7 - Interpolation
The filtered series are interpolated at 1 day intervals using a Lagrange polynomial on four points. This step of "data transportation" is critical in the sense it may slightly deteriorate the real accuracy of the estimates.

Step 8 - Adding back the intermediate series.
The final values are obtained by adding the intermediate reference series (removed in step 2 as well as the removed models ("zones tides" on UT1-TAI/LOD, precession-nutation o□sets) to the filtered and interpolated values.

Step 9 - Archiving in the database.
The final 05C04 is archived in the ORACLE database and made available to users via e-mailing and ftp/web protocols.

Table 2 - Characteristics of the smoothing coefficient (Vondrak, 1969 and 1977) adopted for EOP (IERS) 05 C04. Specific percentage of the signal relatively to 1% and 99% remaining amplitude are given. The choices of the intervals are determined by the stability of the different techniques over these intervals.

Time span		Pole components	UT1	LOD	Nutation offsets
1984-1993	Smoothing coefficient 1% remaining amplitude 99% remaining amplitude	10^2 2.9d 4.3d	$10^{0.7}$ 4.8d 10.3d		$10^{0.5}$ 5.2d 11.2d
1994-1999	Smoothing coefficient 1% remaining amplitude 99% remaining amplitude	10^5 0.92d 2d	10^2 2.9d 4.3d	10^2 2d 4.3d	$10^{0.5}$ 5.2d 11.2d
2000-2008	Smoothing coefficient 1% remaining amplitude 99% remaining amplitude	10^5 0.92d 2d	10^5 0.92d 2d	10^3 2d 4.3d	$10^{0.5}$ 5.2d 11.2d

Other improvements

The description of the previous algorithm leading to the combined C04 EOP series was presented in Gambis (2004). Recently the numerical code was upgraded to take advantage of the evolution of the precision of EOP derived from the various techniques and to benefit from the dramatic improvement of computational resources and for optimization (Bizouard and Gambis, 2009). We present thereafter the improvements that have been achieved:

- Model for nutation and UT1/LOD tidal variations have been updated according to the last IERS Conventions 2003. MHB 2000 is used for precession-nutation, Dehant-Defraigne's model for tidal variation in UT1/LOD.
- Dimensions of tables have significantly been increased and double precision generalized to all parameters. This allows solutions to be performed over 30 years in one run.
- Formal errors associated with the computed EOPs are estimated.

By the way, performances were significantly improved. This is illustrated by better RMS agreements of the differences between individual and the combined solutions. We gain about 3−4 µs for UT1, and 50 µas for nutation offsets.
The possibility to make long-term computation over 30 years led to an improved consistency and long-term stability of the solution.

III Analyses of the combined 05 C04 solution, comparisons with individual and other combined series

The C04 series is maintained fixed from 1962.0 to the date of today – 30 days back. The recent 30 days are regularly updated twice a week. They are considered as preliminary values. For quasi-real time EOP determination, we have used the IGS ultra rapid data.
(http://igscb.jpl.nasa.gov/components/prods.html)

The agreement of the different operational series entering or not the combinations is characterized by the following plots:

- Histograms of residuals respectively for x-pole and UT1 between IGS combined, IVS combined and the reference C04. Residuals histogram is quasi-gaussian (Figure 8 and Figure 9)
- Technique centres (IGS, IVS, ILRS) solutions in term of WRMS and biases for pole components (Figure 10).
- Agreement with combined solutions NEOS BulletinA (USNO) rapid service and predictions and SPACE 2008 (JPL) in term of WRMS and biases (Figure 11)
- Agreement with independent series is given in appendix. These plots and histograms are currently produced are made available to IERS users

(see http://hpiers.obspm.fr/eop-pc/products/combined/verif.html)

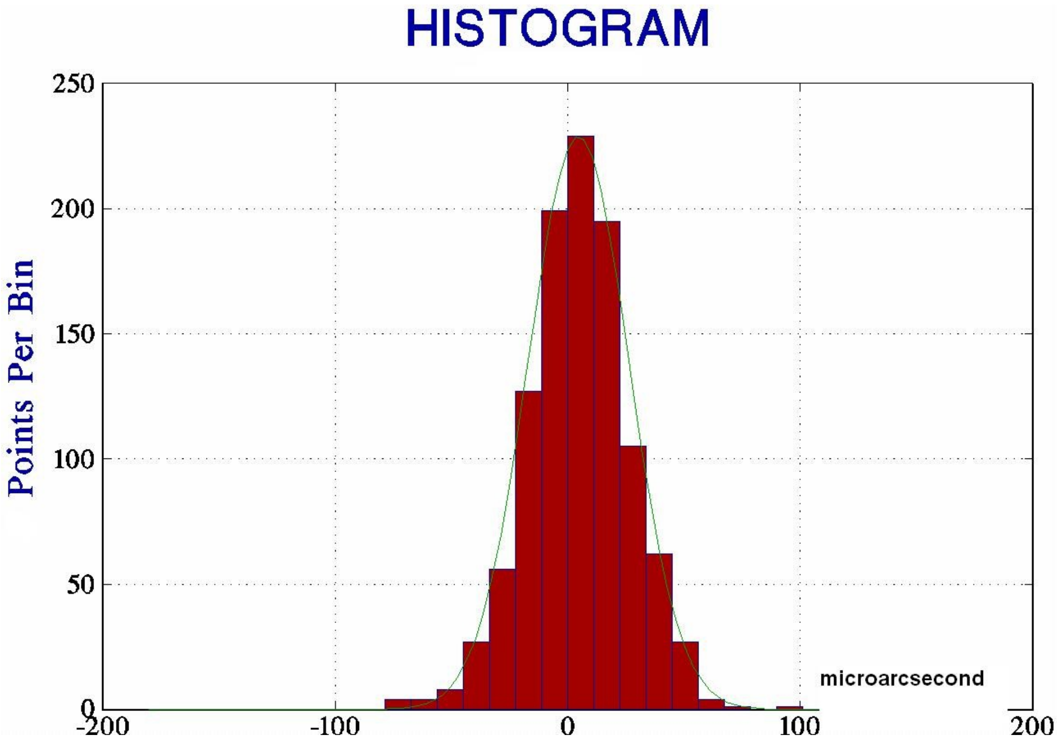


Figure 8 - Histogram for x-pole component of residuals IGS00P03 − 05C04 over 2006-2008. It appears that residuals have a gaussian distribution revealing white noise

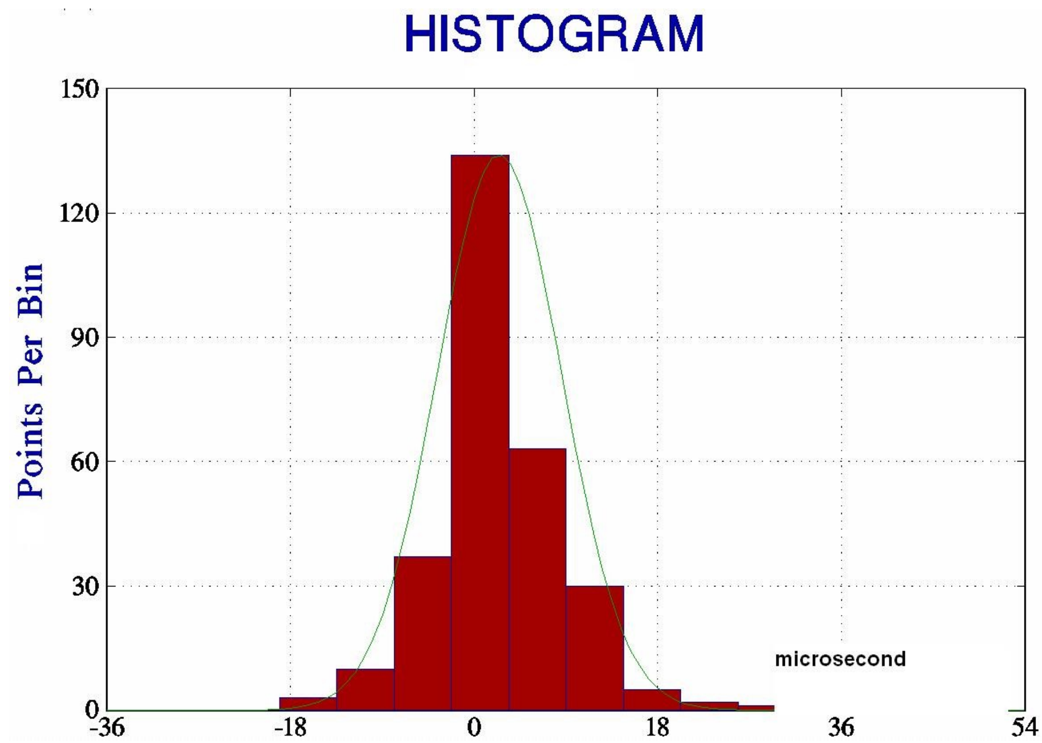
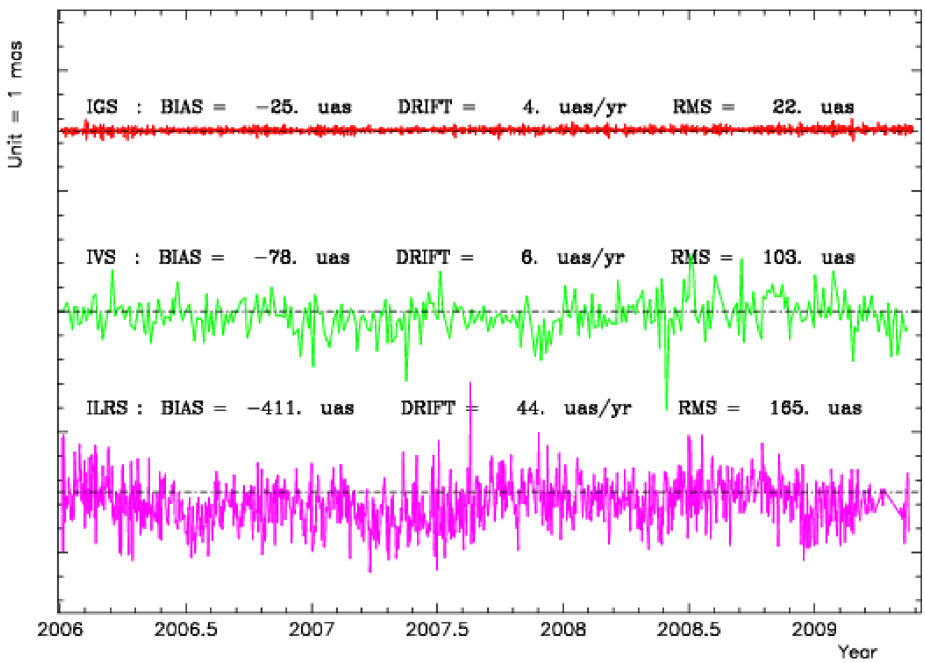


Figure 9 - UT1 residuals IVS Combined – 05C04. Gaussian distribution reveals white noise behaviour



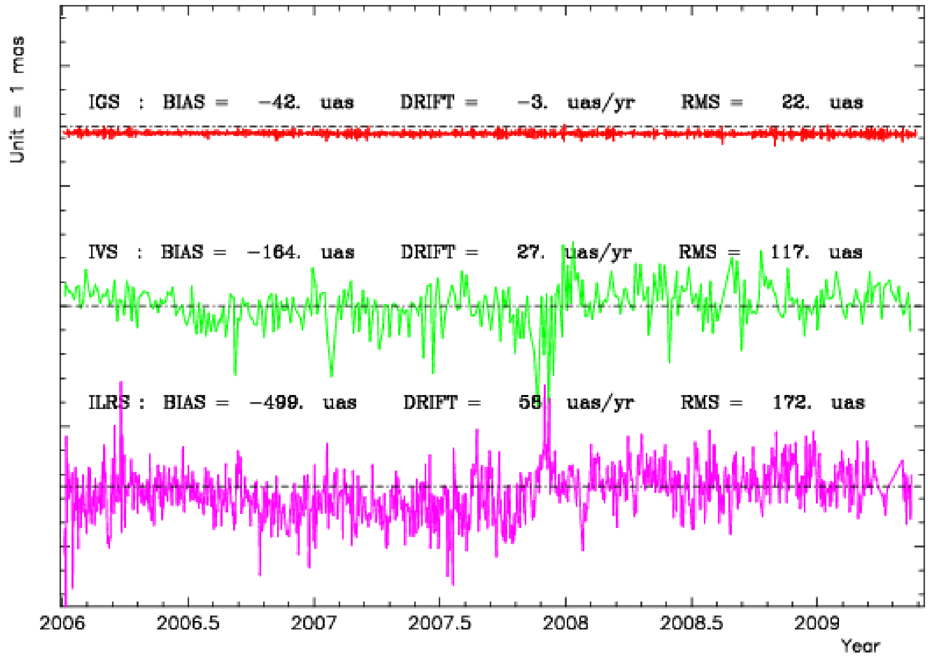
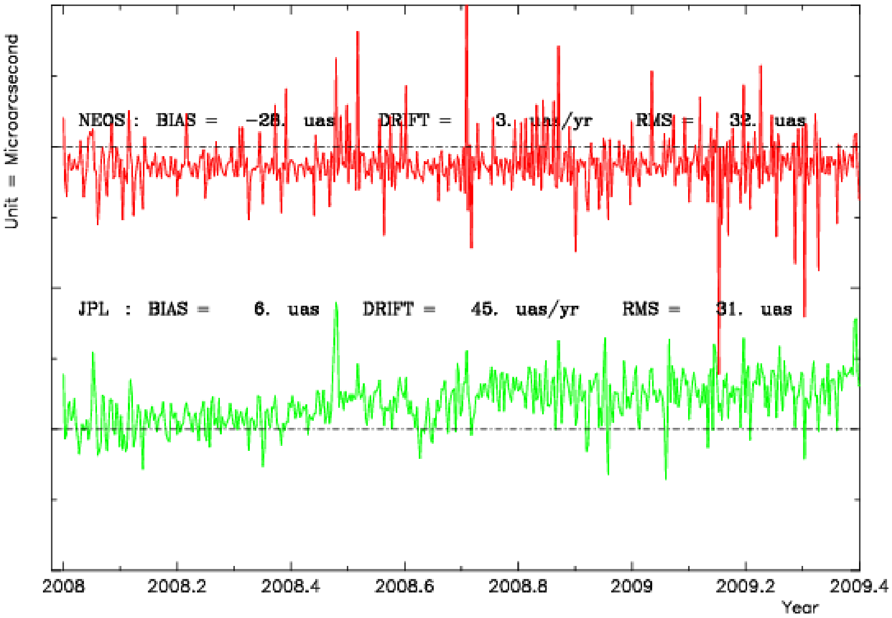
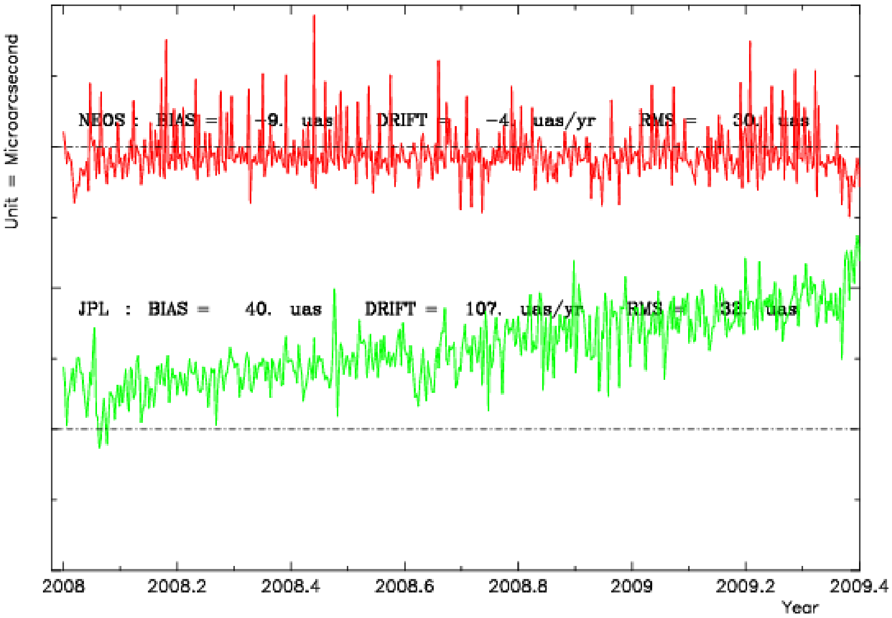


Figure 10 – Differences for X-Pole and Y-pole between the combined C04 and the techniques centres series (IGS, IVS and ILRS combined). Statistics biases, drifts and WRMS are given


Unit = Microarcsecond
NEOS : BIAS = -28. uas DRIFT = 3. uas/yr RMS = 32. uas
JPL : BIAS = 6. uas DRIFT = 45. uas/yr RMS = 31. uas
2008
2008.2
2008.4
2008.6
2008.8
2009
2009.2
2009.4
Year


Unit = Microarcsecond
NEOS : BIAS = -9. uas DRIFT = -4. uas/yr RMS = 30. uas
JPL : BIAS = 40. uas DRIFT = 107. uas/yr RMS = 32. uas
2008
2008.2
2008.4
2008.6
2008.8
2009
2009.2
2009.4
Year

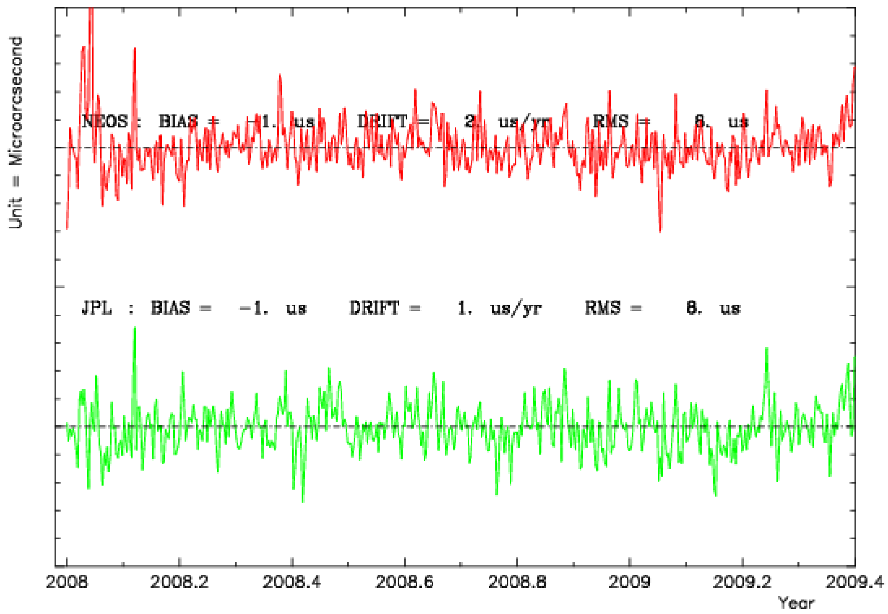


Figure 11 - Differences for X-Pole, Y-Pole components and UT1−UTC between the combined C04 and the combined external solutions (Bulletin A final and SPACE series). Statistics biases, drifts and WRMS are given

IV Reset of the C04 combined solution in the ITRF reference frame

One task of the Earth Orientation Center is to produce EOP consistent with both the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF). The operational series are not perfectly aligned with the ITRF and ICRF since they are referred to different terrestrial and celestial frames, realized by the Analysis Centers. This inconsistency of the EOP series with respect to the ITRF and ICRF produce systematic shift between series (Zhu and Mueller, 1983).
Due to the separate determination of both celestial and terrestrial reference frames and EOP, there had been around 2005/2006 a slow degradation with time of the overall consistency. For instance, for pole components, in the late 2005, discrepancies at the level of 300 micro-arc-seconds were present between the current IERS C04 and the ITRF realization. This was solved in the new solution by re-aligning the C04 on the system linked to the newly issued ITRF2005 (Altamimi et al., 2007).

Historically, for the first time, the ITRF2005 input data were time series solutions, provided in a weekly production by the IAG International Services. Each intra-technique time series is indeed a weekly combination of the individual Analysis Centre (AC) solutions of the technique, except for DORIS for which two individual analysis centre time series were submitted for the ITRF2005 computation. Local tie vectors at about 87 sites were used in the ITRF2005 combination allowing the connection between the four techniques. The ITRF2005 is composed of 608 stations located at 338 sites, with an imbalanced distribution between the northern (268 sites) and the southern hemisphere (70 sites).

The 05C04 series is supposed to be consistent with the current ITRF as well as ICRF realization. Therefore, before the process of combination of EOP, all series have to be translated into the system consistent with ITRF. For this purpose, we assume that some specific series are already consistent with ITRF and ICRF:

- The celestial pole o sets (UT1, dX, dY) provided by the IVS are consistent with the ICRF from 1984 to 2006.

- The polar motion components associated with the ITRF 2005 solution gives the direction of the CIP in the ITRF without any linear trend since 1993.

The trends between ”ITRF/ICRF consistent series” and operational series are not perfectly linear over several years, and we had to model them as broken lines, i.e. as consecutive linear trends using a Least Square fit.
For each operational series linear drifts (bias + trend) were estimated according to Table 3. The estimated drifts were then removed from the operational EOP, then consistent with the ITRF and ICRF, and ready to be combined.

EOP	Time interval	Reference Series
UT1 / dPsi / dEps	1984-1993 1994-2006	IVS combined solution
Pole components	1984-1993 1994-2006	Former C04 solution EOP ITRF 2005 (IGN)

Table 3– Reference series used according the epoch of the solution. The choices of the intervals were determined by the stability of the different techniques over these intervals.

Figure IV_1 represents differences between ITRF2005 (IGN) EOP solution and the 05C04 solution until 2006.0 and the extension over 2007.

V Maintenance of the consistency with respect to ITRF with time

The ITRF is realized at intervals of a few years. It is essential for many geodetic applications to ensure the consistency between the C04 and the ITRF with a good accuracy. For that purpose, with the ITRS Product Centre, we have implemented a strategy ensuring the ITRF2005 and IERS 05 C04 consistency with time. The two IERS product centres agreed to assess the extension of the series in two ways: using (1) the EOP PC upgraded procedure and (2) CATREF combination incorporating the routinely available SINEX files by the technique services. The procedure of the EOP Product Centre at Paris Observatory is routinely performed whereas the CATREF combination is to be done at regular interval (let us say every 6 months). Both results were compared on this time scale in order to evaluate the level of their consistency. In order to illustrate the current level of consistency between the two computations, Figure 12 shows the polar motion di erences, including the extended period of about two years of data after the end of ITRF2005 series (i.e. epoch 2006.0). A particular feature could easily be seen from Figure 12 that is, the small but distinguishable jump around the end of 2006. This jump curiously coincides with the time where the IGS switched from relative to absolute model of antenna phase centre variations which normally impacts mostly station vertical components. Still, this jump is largely within the current GPS polar motion performance estimated to be at the level of 50 μ as.

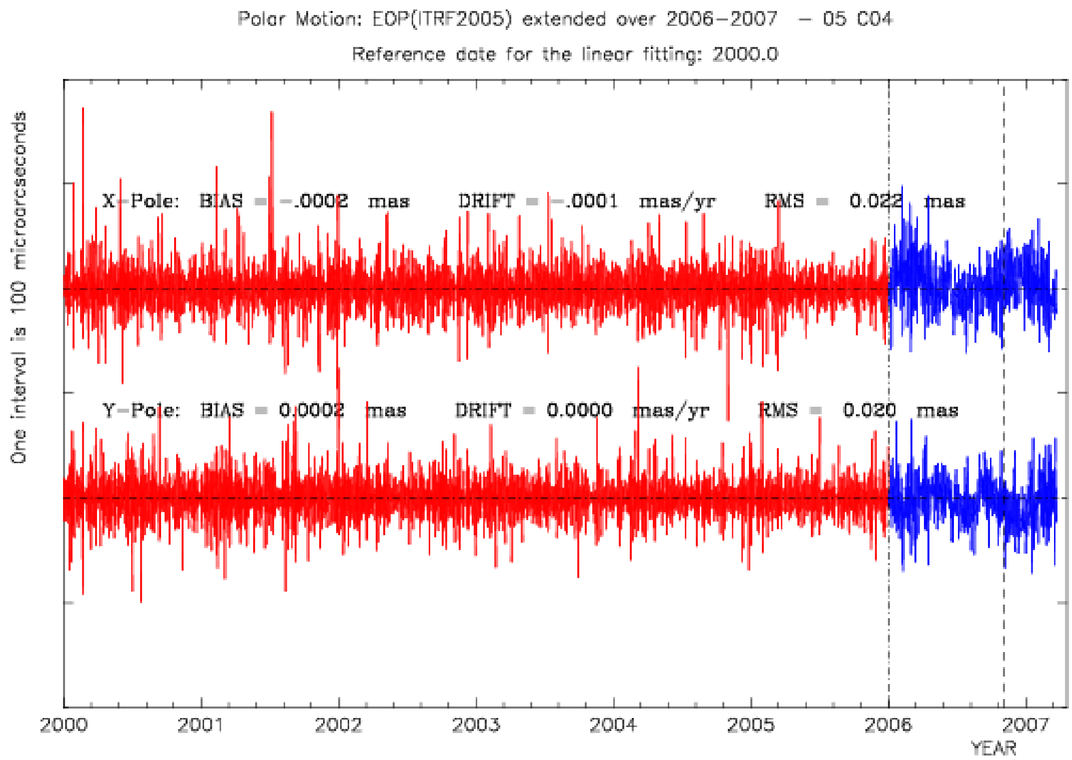


Figure 12 – Pole components differences between the C04 and the pole components derived together with the ITRF2005. The C04 was fitted to the ITFR2005 frame over 2000−2006. In order to monitor the consistency after while the comparison of the independently derived C04 and the EOP solution derived from CATREF SINEX combination is maintained at the level of 30 microarseconds, smaller than the pole components inaccuracy.

VI Predictions

VI.1 Current predictions

Prediction of earth orientation parameters is one of the tasks of the IERS rapid service and predictions at USNO which currently makes available the IERS reference solution. Still the EOC is in charge of the announcement of leap seconds to be introduced in UTC and performing an alternative prediction for different space agencies (ESA, CNES). Different approaches are used to predict the Earth rotation parameters.

a) 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.
b) 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 the prediction, of short-term variations, an autoregressive process is used. The prediction of UT1-UTC is essential for the announcement of the leap second introduced irregularly in order to maintain the difference UT1-UTC smaller than .9 s. The occurrences and non-occurrences of this event are announced in the Bulletin C.
c) Nutation offsets $d\psi$ and $d\varepsilon$ the predictions were until December 2002 based on an empirical model (Conventions 1996). With the adoption of the new precession-nutation model MHB2000, new quantities dX and dY are below 1 mas (mainly the effect of the free core nutation), so that their prediction is not critical for geodetic purposes. However, the empirical model of the FCN can be used, allowing predicting dX and dY at the 100 μas level.

The inaccuracy of the prediction can be statistically assessed afterwards by comparing predicted values to real one (Table 5).

Table 5: Uncertainty the estimated accuracies of the predictions for horizons of 1 day to 1 year for the period 2004-2008.The use of AAM according to section VII-2 improves significantly the quality of the prediction by about 50%

Solutions		Polar motion milliarcsecond	UT1 Classical procedure millisecond	UT1 Procedure using AAM millisecond	Celestial Pole Offset relatively to MBH2000 milliarcsecond
Prediction					
	1-d	0.6	0.05	0.04	0.10
	4d	1.7	0.30	0.20	0.10
	10d	3.7	0.80	0.50	0.10
	40d	10.2.	4.50	-	0.10
	180d	60.	7.5	-	0.10
	1-yr	50.	12.	-	0.10

VII-2 Predictions based on atmospheric angular momentum

Real-time orbit determination and interplanetary navigation require accurate predictions of Universal Time UT1. Below 10 days, variations in earth rotation are mostly due to atmospheric effects. Therefore, the axial Atmospheric Angular Momentum (AAM) series can be used as a proxy index to predict UT1.

In the present work, we have been using AAM forecasts derived by three independent centres, i.e. U.S. National Centres for Environmental Prediction (NOAA/NCEP, formerly NMC), the Japanese Meteorological Agency (JMA) and the United Kingdom Meteorological Office (UKMO). An adaptive procedure is being applied on a real-time basis in the frame of the EOP Prediction Campaign (Schuh et al 2008). We give the statistics concerning the prediction performances we have obtained (Gambis et al. 2008). They are in the range of respectively 300 and 600 microseconds for a horizon of 5 and 10 days which is a roughly twice better than the current predictions directly based on statistical procedures applied onto the C04 time series.

Atmospheric Angular Momentum (AAM) fluctuations are generated by dynamical interactions between the atmosphere and the underlying planet. It is well known that these fluctuations are compensated by opposite fluctuations in the earth rotation when assuming the conservation of the angular momentum of the whole system atmosphere + solid earth. $\chi 3$ the axial Atmospheric Angular Momentum (AAM) functions can be expressed as the sum of two terms:

- A pressure-term related to the redistribution of the air masses.
- A wind-term related to the relative angular momentum of the atmosphere

$$\chi_3 = -0.70\left[\frac{r^2}{Cg}\right]\int P_S \cos^2\phi \; dS - 1.00\left[\frac{r}{\Omega\, Cg}\right]\iint u \cos\phi \; dPdS$$

P is the pressure, ∫dS is the surface integral over the globe, (φ, λ) are latitude and longitude, u, v are the eastward and northward components of the wind velocity, PS is the surface pressure, g is the mean acceleration of gravity, r is the mean radius of the earth, C is the polar moment of inertia of the solid earth, C is the axial moment of inertia, and Ω is the mean angular velocity of the earth.

The Length-of-day variation can be directly expressed as:

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

UT1 is obtained by the integration of LOD

The forecasts of weather centres are based on advancing the equations of motion of the atmosphere according to physical principles, and so the sophistication of the various models contained within the weather forecast systems are of paramount importance to the quality of the forecasts. For example for the National Centres for Environmental Prediction latest improvements, new radiation schemes are available for the model physics, a three dimensional variation approach is now used, an improved vertical coordinate system is in place, and new observing systems are available. We will mention the relevance of such developments to the predictions related to AAM.

Data set
JMA : Since early 1993, the AAM functions computed from the JMA global analysis data at 00UTC, 06UTC, 12UTC and 18UTC have been provided operationally.
NCEP: AAM forecasts are computed at 12 hour intervals over 5 days
UKMO: AAM forecasts are computed at 24 hour intervals over 6 days

Procedure used
1 - Predicted values of AAM are transformed into a LODR series using both pressure and wind terms
2 – The AAM-derived LODR is then integrated into a 10-day UT1R prediction
3 - The method is adaptive, i.e. the bias error on LOD (linear drift on UT1) computed on the previous 10-day interval is used for the following real time forecast
4 - The process is done each week on Thursdays for each series JMA, NCEP and UKMO
5 – Since the individual AAM series are given for different time spans (5 to 8 days depending on the AAM Analysis Centre) a linear extrapolation is made to give a 10-day forecast required by the EOP Prediction Campaign.
6 - A combined mean solution based on the three independent solutions is then performed

7 – Every week the difference between this atmospheric based UT1R series and the 05C04 series is performed.
8 – Absolute mean errors of differences are given from 1 to 10 days for the 4 series. This mean error gives the quality of the forecasts performances.

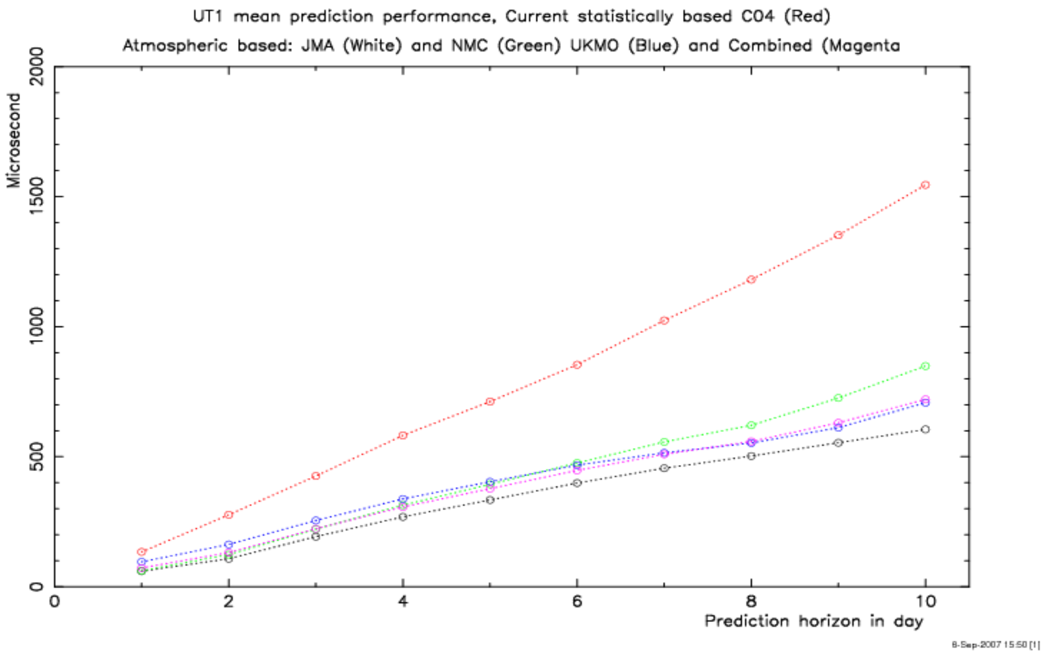


Figure 13 – UT1-UTC mean prediction skill based on the integration of the axial angular momentum prediction derived from various centres, i.e. JMA (Black), NCEP (Green), UKMO (Blue) , their combination (Blue). In red: the current prediction based on pure statistical processes. An improvement of a factor 2 can be noted.

The Prediction Comparison Campaign was a good opportunity to check the performance of the procedure of used AAM-based UT1 on a real-time basis. Mean errors over a time span of 6 months are in the range of 300 and 600 microseconds for a horizon of respectively 5 and 10 days (Figure 13). All centres forecasts have approximatively the same quality and the combined solution does not lead to any improvement. The use of AAM leads to an improvement of more than 50% compared to usual statistical predictions.

VII Conclusions

The C04 solution has been dramatically improved. Pole motion and LOD accuracies are better than 50 μas for pole motion, 4 μs for UT1, 20 μas for LOD and 60 μas for nutation offsets. For polar motion, it is consistent with ICRF and ITRF 2005 to less than 30 μas for pole components, smaller than the real accuracy.

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IX Annexes

Plots and histograms (see http://hpiers.obspm.fr/eop-pc/products/combined/verif.html)

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