General Combination of EOP Series

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Summary: The objective of the session was twofold: first to present the impacts of the IAU Resolutions on IERS products, and in particular those concerning the Earth Orientation Parameters (EOP); and secondly to review the variety of current methods used for combining Earth Orientation Parameters time series (Polar motion, Universal Time, and precession-nutation).

The impact of IAU 2000 Resolutions on all IERS Products was thoroughly discussed at the previous IERS Workshop (Paris, April 2002). The problem has been addressed from many points of view, and described in detail in the presented papers contained in the Proceedings of the Workshop (Capitaine et al. 2002). Future products of the IERS will be affected by the changes that have been adopted by the IERS Directing Board at its 35th Meeting that immediately followed the Workshop; the description of all these changes is covered by Position paper by Rothacher (2002). This topic is transferred to another chapter of the present publication.

1 Background

Until 1972, astrometry based on a network of optical instruments was the only technique able to monitor the Earth Orientation (polar motion coordinates, Universal Time UT1, and nutation). Since, various techniques have shown their capability to give all or a part of these parameters: Doppler observations of navigation satellites, laser ranging to the Moon and to dedicated artificial satellites, Very Large Baseline Interferometry (VLBI) and more recently GPS and DORIS. Other techniques, like inertial one (optical and cold atoms gyroscopes) might give contributions in the future. The life time of observational techniques is limited (technology evolution, agencies funding priority, etc…). It is fundamental that new techniques be introduced to replace those that are disappearing. At least 3 independent techniques are necessary for complementarities (none of the techniques being able to derive all EOP) and redundancy aspects linked in particular to systematic errors determination. The Earth's orientation needs to be monitored over the long-term for reference frames metrology. Whereas, space geodesy for geophysical researches and operational requirements (e.g. Space probes orbits, GPS orbits and reference frames monitoring) require higher sample rates. This is for EOP predictions as well as solutions.

The different Earth Orientation Parameters (EOP) series currently derived from the individual techniques are inhomogeneous in their temporal length, quality, and temporal resolution. This fact supports the concept of long-term equally spaced combined solutions benefiting from the individual contributions at the various time scales. In the process of EOP time series combination, various points should be considered. A non-exhaustive list of these points would include: individual time series characteristics (temporal resolution, internal precision, internal stability at various time scales as well as the corrections for bias, rate, and seasonal variability); statistical analysis (proper scaling of individual series, weighting, smoothing, and interpolation); comparisons; and checks of the final combined solution: with respect to individuals series and between combined series derived by independent centres.

2 What does “combinations” mean?

The word “combinations” can have different meanings:

- Intra-technique combinations refers to the production of a single time series using results from different analysis centres of a same technique, like GPS, made available at identical dates. We are faced with a weighted averaging. The critical points are the real error estimation of data, stability, and systematic error evaluation.
- Multi-technique combination refers to the production of a single time series using various time resolutions, various internal precision, systematic errors / deviations, weighting, interpolation, smoothing as well as the use of different procedures to produce the combination.
- “Rigorous” Global Combinations at different levels refers to the examination of observations processing, covariance matrices analysis, or simultaneous combination of terrestrial frame and EOP.

In the present session we will restrict to the 2 first items. “Rigorous” combinations will be discussed in another session.

Characteristics of ideal combined EOP solutions

An ideal combined EOP solution should have the following characteristics: be continuous, given at equidistant intervals without any gap, homogeneous, stable at the various time scales (reference system maintenance) with negligible systematic errors. It can be slightly smoothed to remove the high-frequency noise and able to handle the introduction of new series while maintaining the stability of the system.

Statistical analysis

In the process of combination, different critical steps should be considered. Formal errors are an internal value derived by each analysis centre. These errors may not be realistic and should be rescaled by an external procedure. This leads to a value used for weighting the various series in the course of combinations. The different approaches are used for interpolation and smoothing. These approaches include: Vondrak algorithm, Fourier, and spline. An alternative method uses a Kalman filter to produce a single time series. The Kalman filter approach requires accurate modelling of the errors for each of the techniques used in the combination.

Current characteristics of EOP estimates, precision, accuracy

Precision gives an estimation of the agreement of various individual solutions with respect to combined solutions (Earth Orientation Center, Rapid Service/Prediction Center, and JPL). This agreement is 50–100 µas for Polar motion, 4–10 µs for Universal Time, and 200 µas for nutation offsets. Accuracy reflects the real uncertainties of a solution taking into account the inconsistency and systematic errors of the EOP system with respect to the terrestrial and celestial frames. These inconsistencies and systematic errors are more critical than precision. It appears that so far the accuracy level is above the precision, for Polar motion (150–200 µas), Universal Time (15–20 µs), and nutation offsets (200 µas).

Check and comparisons of the EOP combined solutions

Different approaches are used for assessing the quality of the EOP combined solutions: its internal consistency, their differences with individual solutions, differences between series derived by the same centre using different routines, and differences between independent solutions (Earth Orientation Center, NEOS, and JPL).

The different current methodologies for EOP combinations

We present thereafter the procedure approaches of the current groups which are currently deriving combined temporal series of earth orientation parameters, i.e. the Earth Orientation Center at Paris Observatory, France; the Rapid Service/Prediction Center at USNO, Washington, USA; JPL, Pasadena, USA; and Astronomical Institute, Prague, Czech Republic.

Improvements and prospects

The increasing precision reached by the various techniques in the determination of EOPs allows better combination series. Improvements have been currently developed in different statistical processed involved: weighting, interpolation, smoothing, and outliers detection. New approaches for instance based on combined smoothing (Vondrak) or non-linear algorithms are under investigation. Other products of interest are or will be also introduced, i.e. se of GPS LOD for near-real time UT1 extrapolation, AAM estimates for near-real time UT estimation, pole rates for interpolation, and GPS nutation rates for densification. In order to better assess the systematic corrections, pre-intra-technique combination solutions are computed. New predictions algorithms based on non-linear processes (chaotic, SSA, neuronal network) are under investigation. Deriving more consistent and accurate products is a permanent challenge in the EOPs monitoring. This can be done by consistency studies of the EOP system with respect to both terrestrial and celestial frames, or using the rigorous approach based on a simultaneous determination of EOPs and the terrestrial frame.

3 The various EOP combinations currently performed

3.1 Combination of EOP series at the IERS Earth Orientation Center

General presentation of the IERS Earth Orientation Parameters (EOP), operational activities and yearly analyses are presented in the web site <[1]>. Determination of EOP is in the form of combined solutions derived from the individual series. 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 solutions at one-day intervals in Bulletin B published with a delay of thirty days between the date of publication and the last date of the standard solution. Bulletin B is updated in the IERS C04 computed twice weekly.

The Earth Orientation Center is collecting on two modes operationally and yearly for long-term analyses, EOP time series derived by analysis centers of the various techniques (VLBI, SLR, GPS, DORIS).

We present the state of the art and future prospects concerning the multi-technique EOP combined solution made at IERS Earth Orientation Center.

Procedure for IERS C04 computation

The first step in the general procedure for deriving the IERS multi-technique combined solution is the evaluation for each solution of the correction of systematic errors, bias and drift in order to translate it into the IERS system. The formal uncertainties estimated by the analysis centers being an internal consistency value, an external calibration has usually to be made in order to reflect the real uncertainty of the estimates. This is done using the Allan variance analysis (Gray and Allan, 1974; Gambis, 2000) of the differences between series without any reference to a combined series. When three or more series of similar quality and time resolution can be differenced, the pair vari-

[1] http://hpiers.obspm.fr/eop-pc

ance of the noise of each series can be evaluated, provided that their errors are assumed to be statistically independent. The pair variance thus obtained is used as an estimate of the uncertainty of a single determination in a given series; its ratio with the rms formal uncertainty over the same period provides a scaling factor, on which the weighting of the combined individual results is based. In order to work on small quantities, a reference series is used. Currently the reference is the C04 slightly smoothed. This reference is interpolated for the dates of the individual series using for instance Lagrange's polynomials and then removed from these individual series. Since the reference is in fact added back at the end of the combination process, its choice is arbitrary and does not pollute the final solution. After a chronological merging of the data, all data within an predefined interval are averaged, this interval is [-0.5d, 0.5d]. The series is slightly smoothed (the frequency cutoff is about 2 days). This smoothing allows the elimination of erroneous data using the 2.57 sigma criteria. This series is added back to the reference in order to give the final combined solution. For universal time, zonal tides with periods smaller than 35 days are previously removed. For nutation, terms between 3 and 20 days (MHB 2000) are in a first step removed.

Regular improvements were implemented in the combination procedures or for predictions, for example:

- Use of Atmospheric Angular Momentum for UT1 short-term predictions (Gambis, 1988),
- Intra-technique pre-combined solutions for a better estimation of systematic errors,
- Use of GPS LOD estimates for near-real time UT1 determination (the improvement of the solution is a factor 8 for 1 week and respectively 16 and 24 for 2 and 3 weeks compared to usual predictions based on VLBI data) (Gambis, 1998), and
- Use of Ultra rapid EOPs for real-time estimations.

New developments under investigation include:

- Use of pole rates for the interpolation of GPS series,
- Method of combined smoothing (Vondrák & Gambis, 2000; Vondrák & Čepek, 2000), and
- Analysis of high-frequency EOP variations.

Predictions

Different approaches 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. For the nutation offsets $d\psi$ and $d\varepsilon$, the predictions are based on an empirical model (Conventions 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 the prediction, of short-term variations, an autoregressive process is used. New procedures for this prediction that are linked to Singular Spectrum Analysis (SSA) (Bougeard et al., 2002) and neuronal networks are under investigation.

Long-term series: C 01 (1846–2002)

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 observations were made using mostly visual and photographic zenith telescopes. Since the advent of the space era in the 1960's, 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 2001 to take into account, from 1900 to 1961, the series recomputed by J. Vondrak (1995) is based on the processing of optical data using Hipparcos catalogue as the celestial frame. The C01 series is a composite series based on the following 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).

1962–2001: BIH and IERS solutions (BIH and IERS annual reports).

Normal point solution: C 02 (1962–2002), C 03 (1993–2001)

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, $d\psi$, $d\varepsilon$), C 03 (one-day intervals, polar motion, UT1–UTC) (Gambis, 1996; Eisop and Gambis, 1997). These series use the full correlation matrix when available. The initial processes of weighting using Allan's variance and systematic errors to refer to the IERS systems are similar to C04. In this solution the data are transported to the central date of an interval of 5 or 1 day (respectively for C02 and C03). The projection is made according to the reference (i.e. C04). A linear equation system is solved using a least-square process. 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; Gambis et al., 2002). A better detection of outliers is gained.

Consistency of IERS EOP series with ITRF and ICRF

Individual EOP series determined from the analyses of the various techniques present mutually systematic errors, generally limited to biases and drifts which can be attributed to the adoption of different references frames CRF and TRF. Consequently, the determination and the maintenance of a reference EOP solution is essential. Monitoring of the consistency is currently performed at the Earth Orientation Center in the IERS Annual Reports since 1991. The mean consistency is regularly improving for the different techniques. So far the mean estimated values are about 0.1 mas for polar motion and 20 microseconds for UT1 (IERS Annual Reports). There are different approaches to estimate the consistency of the IERS EOP system with respect to both terrestrial and celestial reference frames (Bizouard et al., 2002, Gambis et al., 2002). The topic of consistency monitoring is more directly concerned in session 4.

3.2 Combination of EOP series at the Rapid Service / Prediction Center at USNO

IERS Rapid Service Techniques

The algorithm used by the IERS Rapid Service / Prediction Center for the determination of the quick-look Earth orientation parameters is based on a weighted cubic spline with adjustable smoothing fit to contributed observational data (McCarthy & Luzum, 1991a). Contributed data are corrected for possible systematic differences. Biases and rates are determined with respect to the C04 system of the IERS Earth Orientation Center (EOC). Statistical weighting used in the spline is proportional to the inverse square of the estimated accuracy of the individual techniques. Minimal smoothing is applied, consistent with the estimated accuracy of the observational data. Weights in the algorithm may be either an a priori values estimated by the standard deviation of the residual of the techniques or based on the internal precision reported by contributors.

Operationally, the weighted spline uses as input the epoch of observation, the observed value, and the weight of each individual data point. The software computes the spline coefficients for every data point which are then used to interpolate the Earth orientation time series so that x, y, UT1–UTC, $d\psi$, and $d\varepsilon$ values are computed at the epoch of zero hours UTC for each day. The only data points that are excluded from this process are points whose errors, as reported by the contributors, are greater than three times their average reported precision or those points that have a residual that is more than four times the associated a priori error estimate. Since all of the observations are reported with the effects of sub-daily variations removed, no processing is done to account for these effects (see IERS Gazette No. 13, 30 January 1997).

The daily values errors listed in Bulletin A are derived from the quality of the spline fit in the neighborhood of the day in question. Comparisons of the accuracies of three different Rapid Service / Prediction Center products compared to the C04 series maintained by the IERS EOC at the Paris Observatory show mean differences of less than 0.07 mas for polar motion and less than 0.005 ms for UT1–UTC. The standard deviations of these differences were less than or equal to 0.017 mas and less than 0.080 ms for polar motion and UT1–UTC, respectively. The agreement between the weekly Bulletin A Rapid solution and the Bulletin Daily solution with the IERS EOC solutions are quite good.

USNO's Prediction Techniques

Polar motion predictions are based on the extrapolation of an annual and semiannual ellipse and a Chandler circle fit to the previous 400 days of observed values of x and y (McCarthy and Luzum, 1991b). The differences between the last observed pole position and rate and those of the curve are computed. These differences are then used to adjust the extrapolated curve by an amount that decreases with the length of the forecast. In February 1998, the near-term polar motion predictions (less than about 30 days) were improved significantly by modifying the transition process from the last observed polar motion result to the long-term predictions. Continuity in the first derivatives was enforced placing great weight on the observed polar motion rate reported by the IGS in their Rapid series. The improvement was most pronounced for the shortest prediction intervals. The procedure for UT1–UTC involves a simple technique of differencing (McCarthy and Luzum, 1991b).

The very near-term UT1–UTC prediction is strongly influenced by the observed daily Universal Time estimates derived at USNO from the motions of the GPS orbit planes reported by the IGS Rapid service. The IGS estimates for LOD are combined with the GPS-based UT estimates to constrain the UT1 rate of change for the most recent observational day. For the 5 days after the latest observed day, AAM-based predictions of LOD excitation are combined smoothly with the longer-term UT1 predictions described above.

Errors of the estimates are derived from analyses of the past differences between observations and the published predictions. Formulas published in Bulletin A to extend the tabular data. The prediction of $d\psi$ and $d\varepsilon$ is based on the KSV_1996_3 model (McCarthy, 1996). Recent prediction performance in UT1–UTC has been improved by 42% at 10 days into the future by the addition of a UT1-like data product derived from NCEP AAM (UTAAM) to the combination and prediction routine (Johnson et al., 2002). This estimate of improvement was determined by examining one year of daily solutions that used UTAAM in the combination and prediction solutions.

Rapid Service Research and Improvements

The Center is continuously evaluating its products and researching possible improvements. The Center is currently working on meeting the resolutions passed at the 24th General Assembly of the International Astronomical Union recommend the implementation of a number of new procedures concerning the transformation between the celestial and terrestrial reference systems. Information regarding these changes is available in Chapter 5 of the IERS Conventions 2000. The Center is also working to include VLBI data from USNO and the IVS combination series. These modifications and additions to the Rapid service and prediction products should be completed by January 1, 2003. The Center is also working on an improvement to the bias and rate estimation techniques by April of 2003.

Current research efforts are focused in a few areas. These include: improving the UT1-like data products estimated from GPS and AAM, the usefulness of other global geophysical fluid models, improved error estimates, and the automation of more Bulletin processes.

Availability of Rapid Service

The data described above are available from the Center in a number of forms. You may request a weekly machine-readable version of the IERS Bulletin A containing the current ninety days worth of predictions via electronic mail form at <[1]> or <[2]>. Internet users can also direct an anonymous FTP to <[3]> and change to the ser7 directory where they can access the IERS Bulletin A or more complete databases. World Wide Web access is available at <[2]>.

3.3 Combination of EOP series at the JPL (CRC)

In support of tracking and navigation of interplanetary spacecraft, a Kalman filter has been used at the Jet Propulsion Laboratory (JPL) for more than a decade to combine independent measurements of the Earth’s orientation. A Kalman filter has a number of properties that make it an attractive technique for combining Earth orientation measurements (Gross et al., 1998). Changes in the Earth’s orientation can be described as a randomly excited stochastic process. Consequently, between successive measurements of the Earth orientation parameters, the uncertainty in the knowledge of their values grows and rapidly becomes much larger than the uncertainty in the measurements. Thus, it is important to analyse each measurement at its measurement epoch, rather than at some “nearby”, regularized epoch as is commonly done in normal-point methods of combining data sets. Kalman filters are an effective means of dealing with irregularly spaced data sets since the state vector and state

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[1] ser7@maia.usno.navy.mil
[2] http://maia.usno.navy.mil/
[3] ftp://maia.usno.navy.mil

covariance matrix can be propagated to the measurement epoch regardless of whether or not the measurements are equi-spaced.

Due to this growth in the uncertainty of the Earth Orientation Parameters between measurements, when intercomparing data sets in order to evaluate their relative accuracies (and hence to set relative weighting factors), it is important to compare independent measurements whose epochs are as close as possible to each other. This argues for comparing an individual data set against a combination of all other independent data sets (rather than against some other individual series) so that the difference in the epochs of the measurements being compared is minimized. Since it is unlikely that independent measurements will be given at exactly the same epoch, it is important that the interpolation procedure used in generating the combined series accounts for the growth in the uncertainty of the Earth orientation parameters between measurements. The JPL Kalman Earth Orientation Filter does this in an objective manner by employing realistic stochastic models of the uncertainty growth between measurements.

Finally, the degree of smoothing applied to the measurements should vary with both the precision and the sampling interval of the measurements. As improvements have been made to the measurement systems, the precision with which the measurements have been made has dramatically improved, and the sampling interval has gotten dramatically smaller. With a Kalman filter, the degree of smoothing applied is a function of both the precision of the measurements and the time span over which the state vector and covariance matrix must be propagated, that is, of the sampling interval of the measurements. Thus, with a Kalman filter, the degree of smoothing is automatically adjusted as the precision and sampling interval of the measurements change.

For these, and other reasons, a Kalman filter was chosen to combine Earth orientation measurements at JPL. Reference series of Earth orientation parameters obtained by combining the most accurate available measurements of the Earth's orientation are generated annually at JPL. These series, the most recent of which are SPACE2001, COMB2001, and POLE2001 (Gross, 2002), can be obtained by anonymous ftp to <[1]>. In addition, updates to these reference series, including short term predictions, are generated twice-per-week in a rapid service mode. These rapidly combined and predicted Earth orientation series can be obtained by anonymous ftp to <[2]>. As part of an operational program, it is anticipated that such annual reference combinations and rapid service-style updates will continue to be generated indefinitely.

3.4 Combination of EOP series at the Prague CRC

Some of the Earth Orientation Parameters (namely those that are referred to celestial reference system, i.e., Universal Time and celestial pole offsets) are observed by VLBI, while their time derivatives (length-of-day, celestial pole offset rates) are observed by satellite techniques (GPS, SLR).

Satellite methods, unlike the VLBI, measure the orientation of the Earth with respect to satellite orbits, and therefore are not capable of measuring directly the Earth's orientation with respect to the International Celestial Reference System (ICRS). Because the modeling of satellite orbits in space is a complicated task (their motion is subject to many influences, both gravitational and non-gravitational) and some of the orbital elements are correlated with some EOP, the exact and stable tie to ICRS is very difficult. Therefore, the satellite methods can provide only the time derivatives of those Earth Orientation Parameters that are sensitive to ICRS (i.e., Universal Time and precession-

[1] ftp://euler.jpl.nasa.gov/keof/combinations/2001
[2] ftp://euler.jpl.nasa.gov/keof/predictions

nutation). Satellite observations can thus deliver unique contribution to the spectrum in the high frequency range only (up to 14 days).

This is a typical example when the recently proposed method of combined smoothing, introduced shortly by Vondrák & Gambis (2000) and described in detail by Vondrák & Čepek (2000) can be used. The solution is based on two independent series of measurements:

- Series of function values;
- Series of time derivatives;

of the same time function whose analytical expression is unknown. We are looking for a smooth curve that fits both observed series well, by minimizing a weighted sum of three parameters S, F and $\overline{F}$, expressing the smoothness

$$Q = S + \varepsilon F + \overline{\varepsilon}\overline{F} = \min.$$

$$\Rightarrow \quad \frac{\partial Q}{\partial y_i} = 0, \quad i = 1, 2, \ldots N.$$

of the curve and its fidelity to both series, respectively:

The 'coefficients of smoothing' $\varepsilon, \overline{\varepsilon}$ act as weighting factors, expressing the relative importance of the three parameters: the larger these coefficients, the better the fit to observations but the rougher the curve. The choice of the numerical values of coefficients of smoothing, based on numerous experiments with simulated data, led to the following conclusion:

- Provided the minimum period $P_{\min}$ of the signal is known and the resolution of observations is 7 days for function values, 1 day for time derivatives, the optimal choice is

$$\varepsilon = \left(\frac{12.6}{P_{\min}}\right)^6, \quad \overline{\varepsilon} = \left(\frac{16.9}{P_{\min}}\right)^4.$$

This choice assures that the smoothing is sufficiently weak not to suppress the signal contained in both series of the input data, and at the same time sufficiently strong to suppress the high frequency noise of the observations.

However, the straightforward use of the method does not lead to an optimal result; there are large systematic errors in long-period part of the spectrum in GPS data (the dominant period is around 60 days, with amplitude of about 0.1 mas / day). Therefore, it is necessary to 'calibrate' the GPS data with respect to VLBI (that is more stable in long-periodic sense), prior to combination.

The method was used to combine VLBI and GPS observations, both UT1 / LOD and celestial pole offsets / celestial pole offset rates (Vondrák et al., 2002a, b, 2003). Most recently, the following combinations have been worked out:

- Combination of UT1 / LOD in the interval 1997.1 – 2002.1, based on the series of:
  - UT1, given at unequally spaced intervals (from 1 to 7 days) in the most recent IVS combined solution `ivs02002.eops`;
  - LOD, given at strictly 1-day intervals in the IGS combined solution `igs00p02.erp` (these values have already been calibrated against VLBI by the IGS).

The coefficients of smoothing $\varepsilon = 34\,\mathrm{days}^{-6}$, $\overline{\varepsilon} = 34\,\mathrm{days}^{-4}$ (calculated for $P_{\min} = 7\,\mathrm{days}$) were used. The statistics of the combination yields the *a posteriori* average uncertainties (computed from the residuals of both series from the combined curve) that are quite comparable to the *a priori* values (reported by the IVS and IGS), as can be seen from Table 1.

Table 1 Average uncertainties in UT1 and LOD

Average uncertainties in	UT1 [µs]	LOD [µs]
a priori	2.8	10.4
a posteriori	4.0	8.9

- Combination of celestial pole offsets in the interval 1994.3 – 2002.0, based on the series of:
  - Celestial pole offsets, given at unequally spaced intervals (from 1 to 7 days) in the same IVS combined solution as above, i.e. `ivs02002.eops;`
  - Celestial pole offset rates at 1-day intervals, given in the GPS solution made at CODE in Berne. These values had to be first calibrated to VLBI in order to remove the long-periodic (periods longer than about a month) large systematic errors due to GPS orbit mismodeling. This was assured by computing the offset of the integrated GPS rate (over three consecutive VLBI intervals, i.e., 3 – 20 days) from the difference of VLBI data at the two endpoints, and removing the offset from GPS data.

The same coefficients of smoothing as above were used. The comparison of average *a posteriori* and *a priori* uncertainties is given in Table 2.

Table 2 Comparison of average *a posteriori* and *a priori* uncertainties

Average Uncertainties in	VLBI $\Delta\psi$ [mas]	GPS $\Delta\dot{\psi}$ [mas/day]	VLBI $\Delta\varepsilon$ [mas]	GPS $\Delta\dot{\varepsilon}$ [mas/day]
a priori	0.101	0.079	0.041	0.033
a posteriori	0.125	0.151	0.042	0.056

The *a priori* and *a posteriori* uncertainties are more or less equal in case of VLBI observations, but substantially different for GPS rates – the latter are about two times larger than the former. It seems that the formal GPS uncertainties are highly underestimated in this case.

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