COMBINATION OF EOP FROM DIFFERENT TECHNIQUES

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ABSTRACT. We describe the state of the art of the combination of the Earth Orientation Parameters at Paris Observatory/IERS Earth Orientation Centre. We sum up the characteristics of the classical C04 combination. After the algorithm's description, we try to assess its accuracy by comparison with other EOP series. Then the multi-technique combination "GINS-DYNAMO" is presented. We assess its capability to contribute to C04 in the future and its performances for high frequencies determination of the Earth Orientation.

1. INTRODUCTION

The Earth Orientation Parameters (EOP) describe the irregularities of the Earth rotation with respect to a non-rotating reference frame. Two parameters (dPsi, dEps), the celestial pole offsets, correct the precession-nutation model of the celestial pole, one parameter (UT1-UTC) gives the irregularities of the rotation angle, and the two last one (x,y) describe the polar motion with respect to the crust. They give the full transformation between the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference Frame (ICRF). The reference EOP series computed at the Earth Orientation Centre at Paris Observatory is obtained from the combination of "operational" EOP series derived from the various astro-geodetic techniques : Laser Ranging to the Moon (LLR) and to dedicated artificial satellites (SLR), Very Long Baseline Interferometry on extra-galactic sources (VLBI) and more recently from Global Positioning System (GPS) and Doppler Orbitography by Radio-positioning Integrated on Satellite (DORIS) (Gambis, 2004). The objective of this paper is threefold : 1) present the C04 combination procedure and the recent improvements brought in the software code; 2) present the new EOP C04 solution, its accuracy, and how it is made consistent with ITRF 2005; 3) present multi-technique combination implemented recently at Paris Observatory and the way it could contribute to the future C04 combination.

2. DESCRIPTION OF THE PROCEDURE

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 analysis centres which are used in our combinations. In some cases of inaccuracy or instability of some specific series, individual series have been privileged as long as problems have not been solved. This was 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 1 gives the list of the contributed series relatively to the EOP components used as of 1 January 2009.

Step 2 - Computation of the differences between operational and 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 preliminary remove a known reference containing most of the signal, from the operational EOP series. 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

EOP	x, y, LOD	$UT1$	dX, dY
	EOP (IGS) 07 P 01	EOP (IVS) 07 R 01	EOP (IVS) 07 R 01
	EOP (IGS) 96 P 02	intensive VLBI solutions	Individual standard
	EOP (IVS) 07 R 01	UT(GPS)	VLBI solutions
	EOP (ILRS) 05 L 01		

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

diurnal/sub-diurnal information due to ocean tides. Concerning the offsets of nutation, the parameters of the reference series are dPsi and dEps referred to IAU 2000 precession-nutation model. Therefore all operational celestial pole offsets are transformed into (dX, dY)/IAU 2000, before constituting the difference.

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 on orbits 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 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 (sometimes 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 & Cepek, 2000). 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.

Step 4 - Sorting by increasing dates. For each EOP, the whole set of values of the different series are sorted by chronological dates.

Step 5 - Running average. Data are averaged over successive time intervals of 0.5 day. 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 6 - 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. The community of Time and frequency uses a variety of stability metrics in order to characterize frequency standards, clocks and oscillators. Allan variance (Gray & 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 Allan variance analysis was applied to the field of earth orientation metrology (Gambis, 2002). 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 concerning the various analyses we made (not in the present note) are sustaining this hypothesis. This procedure provides an estimation of a scaling factor of the formal error on which the weighting of the combined individual results is based.

Step 7 - High frequency filtering. Vondrák smoothing (Vondrák & Cepek, 2000) is applied in order to remove high frequency variations. Characteristics of the smoothing, according to the epoch of the solution, are reported in Table 2. It is remarkable that nowadays in view of the accuracy reached by the EOP the smoothing is extremely weak.

Time interval		x,y	UT1	LOD	dPsi, dEps
1984-1993	Smoothing coefficient	10^2	$10^{0.7}$		$10^{0.5}$
	1% remaining amplitude	2.9 d	4.8 d		5.2 d
	99% remaining amplitude	6.2 d	10.3 d		11.2 d
1994-1999	Smoothing coefficient	10^5	10^2	10^2	$10^{0.5}$
	1% remaining amplitude	0.92 d	1.3 d	1.3 d	2.4 d
	99% remaining amplitude	2 d	6.3 d	6.3 d	11.2 d
2000-2008	Smoothing coefficient	10^5	10^5	10^3	$10^{0.5}$
	1% remaining amplitude	0.92 d	0.92 d	2 d	2.4 d
	99% remaining amplitude	2 d	2 d	4.3 d	11.2 d

Table 2: Characteristics of the smoothing coefficient (Vondrak, 1977) adopted for EOP (IERS) 05C 04. Specific percentage of the signal relatively to 1% and 99% remaining amplitude are given.

Step 8 - Interpolation. The filtered series are interpolated at 1 day intervals using a Lagrange polynomial on four points. This step is extremely critical to avoid to deteriorate the accuracy of the estimates.

Step 9 - Adding back the intermediate series. The final values are obtained by adding to the filtered and interpolated values the "intermediate" reference series, which was removed in step 2 as well as the removed models (zonal tides on UT1-TAI/LOD, precession-nutation offsets).

Step 10 - Archiving in the database. The final 05C04 is archived in the ORACLE database and made available to users via ftp/web processes.

3. RESET OF THE C04 COMBINED SOLUTION IN THE ITRF REFERENCE FRAME.

One of the main tasks of the Earth Orientation Centre 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 systems, realized by the Analysis Centres. This inconsistency of the EOP series with respect to the ITRF and ICRF produce systematic shift between series (Zhu & Mueller, 1983). Due to the separate determination of both celestial and terrestrial reference frames and EOP, there had been 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 of satellite techniques (the International GNSS Service, IGS, the International Laser Ranging Service, ILRS and the International Doris Service, IDS) and in a daily (VLBI session-wise) basis by the International VLBI Service, IVS. 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 IRTF 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 offsets (UT1, dPsi, dEps) 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 have to model them as broken lines, i.e. as consecutive linear trends using a Least

EOP	Time interval	Reference Series
UT1/ dX / dY	1984-1993	IVS combined solution
	1994-2008	id
x,y	1984-1993	Former C04 solution
	1994-2007	EOP ITRF 2005 (IGN)

Table 3: Reference series used according the epoch of the solution.

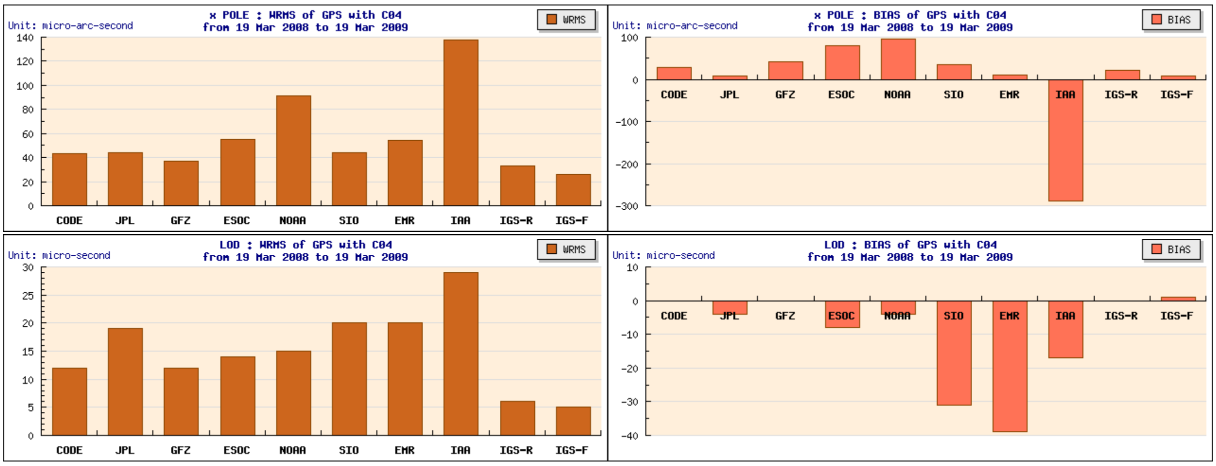

Figure 1: The agreement of C04 EOP with individual GPS solutions is illustrated for x pole coordinates and LOD.

Square fit. For each operational series linear drifts (bias + trend) are estimated according to Table 3. The estimated drifts are then removed from the operational EOP, then consistent with the ITRF and ICRF, and ready to be combined.

4. OTHER IMPROVEMENTS

The description of the previous algorithm leading to the combined C04 EOP series was presented in Gambis (2004). The numerical code was recently upgraded (Bizouard & Gambis, 2009) to take advantage of the evolution of the precision of EOP derived from the various techniques as well as to benefit from the dramatic improvement of computational resources: i) the model for nutation and UT1/LOD tidal variations have been updated according to the last IERS Conventions 2003 ii) the 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 iii) the formal errors associated with the computed EOPs are estimated and made available. Performances are 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 20 years leads to an improved consistency and long-term stability of the solution.

5. COMBINATION STRATEGY AND COMPARISONS WITH OTHER 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. It should be noticed that between 2000.0 and 2006.0, C04 solution for x-pole and y-pole almost corresponds to the EOP ITRF 2005. This was achieved by weighting the ITRF 2005 polar motion about 10 times larger than other operational series. Starting at 2006.0 we attributed a regular weighting to ITRF 2005 polar motion. In the initial C04 solution, instabilities in the IVS combined solution prevented us to use it until the solution was available in SINEX format where EOP and terrestrial frame is present. It appeared that the IVS solution greatly improved. Since, it is used in our combinations. We do not combine exclusively IGS or IGS-R (rapid) solutions because the last IGS-R values are available with a one day delay. The CODE and GFZ provide the pole coordinates and LOD for the quasi real-time preliminary solution. To investigate the accuracy of the C04 solution, we can compute the difference of that solution with other operational series, of which are computed WRMS and biases. The results are illustrated over 1 year by figure 1 for

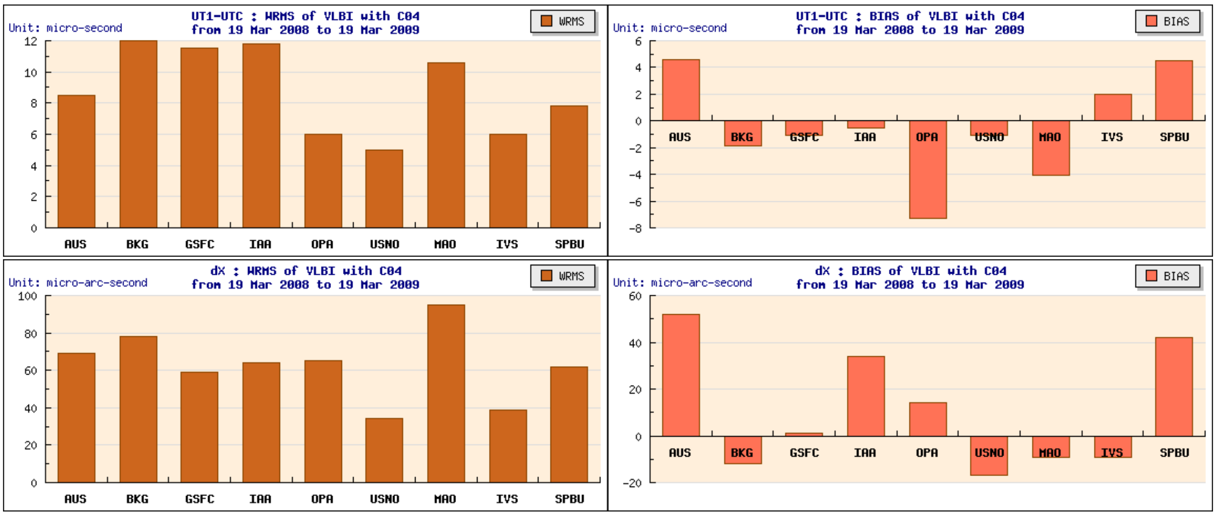

Figure 2: The agreement of C04 EOP with individual VLBI solutions is illustrated UT1 and celestial pole offset dX.

pole coordinates (x) and LOD. The typical WRMS is 40 μas for pole coordinates and 20 μs for LOD. According to the figure 2 the typical WRMS for UT1 is 10 μs and 40 μas for nutation offsets.

6. THE MULTI-TECHNIQUE COMBINATION

The determination of Earth Orientation is now considered in a more global way, incorporating any geodetic observations, related to the parameters to be estimated. What are combined are the normal equations associated with all parameters needed for modelling the observations obtained by VLBI, GPS, SLR and DORIS techniques. After forming a set of normal equations, it is inverted for obtaining the parameters in which we are interested in. The normal equations are produced using a common software and a common set of standard and models, related to the instruments and the propagation of the electromagnetic signal in the atmosphere. That procedure has been set up in France by the GRGS, as an extension of the GINS software initially designed for orbitography. To the 4 techniques and the related production of their normal equations are also assigned 4 different teams : G. Bourda, P. Charlot (Bordeaux Observatory) for VLBI, S. Loyer, F. Perosanz (CNES, CLS, Toulouse) for GPS, F. Deleflie, P. Exertier (OCA, Grasse) for SLR, L. Soudarin (CNES, Toulouse) for DORIS. The GRGS is now organized for a routine production of weekly SINEX files since 2005, which are stored at IERS as inter-technique products. In 2007 the processing has been upgraded and includes common tropospheric biases. At Paris Observatory is set up the inversion of the normal equation, for determining EOP as well as terrestrial station coordinates (software DYNAMO). Our multi-technique combination, based upon the whole sets of VLBI, GPS, SLR, and DORIS observations over the period 2005-2008, does not reach the performance of the "classical" series. However the DYNAMO procedure, restricted to GPS observations, give pole coordinates of quality comparable of the best EOP series (results of March 2009). What may be the most interesting feature of the multi-technique combination is its time resolution of 6 hours. As shown in figure the spectrum of the obtained pole coordinates (GPS combination) shows, besides the retrograde diurnal oscillation corresponding to classical nutation offset, extra peaks both in retrograde and prograde bands to be validated. If validated those series will be a powerful mean for investigating atmospheric-oceanic excitation at diurnal and sub-diurnal scale. For instance in the prograde band the daily prograde peaks stress either defect in the model of the oceanic tidal effect or atmospheric effect to be estimated. Another advantage of GRGS series is that they allow us to densify nutation offsets, which are usually determined at 5-day mean interval.

7. CONCLUSIONS

Over these last years Paris Observatory / IERS Earth Orientation Centre has improved the combined C04 solution. Pole motion and LOD accuracies are 50 μas for pole motion, 10 μs for UT1, 20 μas for LOD and 60 μas for nutation offsets. It is consistent with ICRF and ITRF 2005 to less than 30 μas for pole components, less than the real accuracy. In the future multi-technique combination GINS-DYNAMO

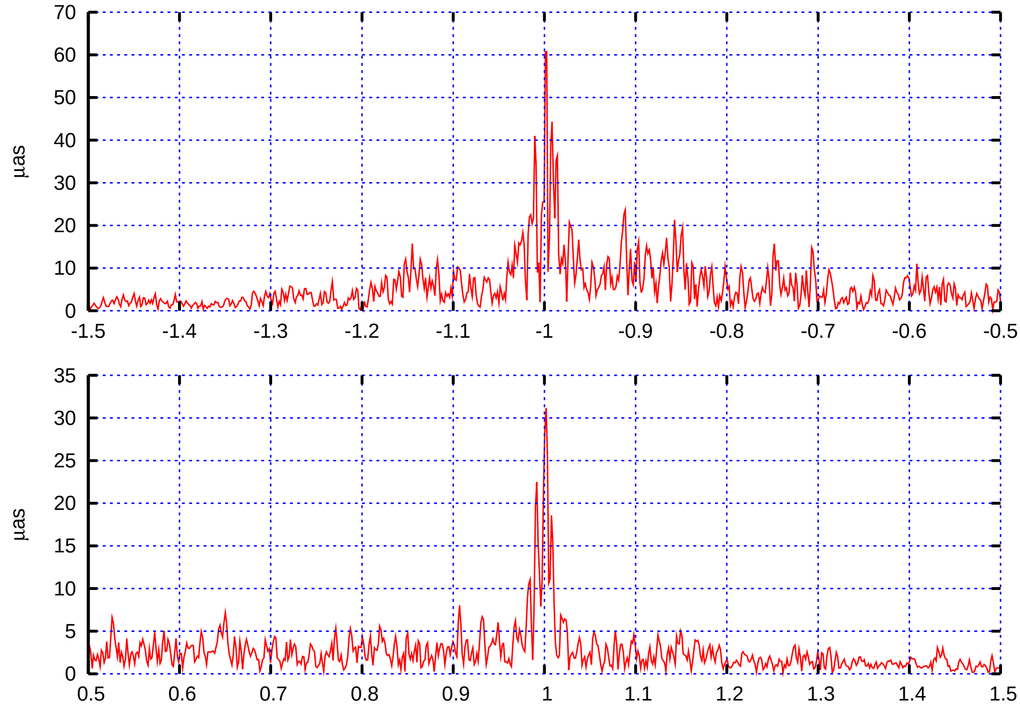

Figure 3: Complex spectrum of the GRGS pole coordinates determined by GPS intra-technique combination over [2007.0, 2009.0]. Notice the several diurnal peaks to be validated by independent solution and further tests of the GINS-DYNAMO procedure.

could become the future realisation of C04 solution and give 6 hourly pole coordinates and daily UT1 and celestial pole offsets.

8. REFERENCES

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