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Analyzing the sets of the VLBI-based Celestial Pole positions (1984–2005) by the numerical theory of the Earth rotation ERA-2005

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Г. А. Красинский. Анализ рядов РСДБ определений положния небесного полюса (1984–2005) с использованием численной теории вращения Земли ERA-2005.

Ключевые слова: Ключевые слова.

Ряды GSFC, USNO, BKG, IAA, MAO, AUS положений небесного полюса на временном интервале 1984, январь – 2005, октябрь, полученные в шести центрах анализа РСДБ данных, обработаны с использованием численной теории вращения деформируемой Земли с двухслойным жидким ядром. Соответствующие дифференциальные уравнения приведены в работе (Krasinsky, 2005a); в работе (Krasinsky, 2005b) описан первый опыт их использования при анализе ряда GSFC. В настоящее время математическая основа численной теории подверглась дальнейшему уточнению и с улучшенной моделью (обозначение ERA-2005) были изучены все доступные ряды РСДБ данных о положении небесного полюса для оценивания их точности, особенностей и взаимной согласованности. Показано, что среднеквадратические ошбки невязок $\sigma(d\theta)$, $\sin\theta\sigma(d\phi)$ углов нутации θ и прецессии ϕ для численной теории существенно меньше соответствующих величин для принятой модели MAC 2000 прецессионно-нутационного движения. Так, например, значения $\sigma(d\theta)$, $\sin\theta\sigma(d\phi)$ ряда GSFC равны 0.136 mas и 0.129 mas, в то время как с моделью MAC 2000 они равны соответственно 0.197 mas и 0.161 mas. Это позволило получить объективную оценку качества всех рассматриваемых рядов. Сравнение теорий вращения Земли ERA-2005 и MAC 2000 на интервале 1984–2010 показадо что к 2009 г. расхождения в угле прецессии достигнут величины 1.7 mas и после этой даты увеличение расхождений продолжится. Поскольку невязки MAC 2000 за последние годы измерений показывают явное ухудшение (в отличие от невязок для ERA-2005) мы полагаем, что этих расхождения должны быть приписаны дефектам модели MAC 2000.

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Keywords: Earth rotation, VLBI observations.

The current VLBI-based offsets of the Celestial Pole positions provided by Analysis Centers GSFC, USNO, BKG, IAA, MAO, AUS (time interval 1984, January 1 – 2005, October 20) are discussed applying the Earth's rotation theory constructed by numerical integration of differential equations of rotation of the deformable Earth with the two-layer fluid core. The equations are documented in paper (Krasinsky, 2005a); in paper (Krasinsky, 2005b) their usage for the analysis of the GSFC series is described. Since then the mathematical grounds of the theory has undergone further refinements and with the improved model (denoted ERA-2005) we have studied all the available series of the VLBI based Celestial Pole positions to estimate their quality, peculiarities and compatibility. It appears that Weighted Random Mean Square (WRMS) errors of the residuals $\sigma(d\theta)$, $\sin\theta\sigma(d\phi)$ of the angles of nutation θ and precession ϕ of the numerical theory are significantly less than those for the adopted model IAU 2000. For instance, the GSFC values of $\sigma(d\theta)$, $\sin\theta\sigma(d\phi)$ are 0.136 mas and 0.129 mas, while for the IAU 2000 model they are 0.172 mas and 0.165 mas, respectively. That made it possible to estimate objectively the quality of all the series. Comparison of the Earth rotation theories ERA-2005 and IAU 2000 for the time span 1984–2010 shows that in 2009 the discrepancies in the precessional angle have reached 2 mas and will keep increasing. Because the residuals of IAU 2000 with the VLBI data for the recent years do demonstrate some deterioration (unlike those of ERA-2005 model) we believe that these discrepancies have to be attributed to IAU 2000, but not to ERA-2005.

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Contents

1. Introduction

The adopted precession-nutational theory IAU 2000 (Mathews et al., 2002) provides much better modeling of the VLBI based positions of the Celestial Poles as compared with the previous model IAU 1980. However, in our paper (Krasinsky, 2005a) some theoretical drawbacks of IAU 2000 were noted and a theory of rotation of the non-rigid Earth with the two-layer fluid core was constructed by numerical integration fitted then to the Celestial Pole positions on the time interval January, 1984– May 2005 (the GSFC series). The analysis of the VLBI data applying both models has revealed rather large systematic errors of IAU 2000 after J2000. Moreover, the Celestial Pole positions after 2007, calculated with the numerical theory, predict increasing deterioration of IAU 2000. The recent VLBI data (continued up to the end of October, 2005) confirm this conclusion; see Fig 1 where the solid line shows the predicted biases of IAU 2000. While at present the divergence of IAU 2000 with observations reaches 1 mas in the angle ϕ of precession, it is expected that by 2009 the discrepancies will exceed 2 mas which value is not only too large for geodynamic applications but even for publications in Astronomical Yearbooks.

For comparison, the analogous plots of residuals are presented for the numerical theory in Fig 2. One can see that the amplitudes of the free oscillations have considerably diminished, and in the numerical theory there are no more long-term systematic errors which are noticeable in Fig 1 for IAU 2000. As the second illustration, in Figs 3 and 4 there are presented the residuals of $d\theta$ and $\sin\theta d\phi$ (the GSFC series) both for IAU 2000 and the numerical theory for the whole time span 1984–2005. (Note that in the numerical theory the variables θ, ϕ have meaning of the Euler's angles of nutation and precession of the instant Earth's equator referred to the ecliptical inertial frame J2000 and ϕ includes both precessional and nutational motions). One can see that the numerical theory describes the main part of the Free Core oscillations, in spite of their complicated time behavior. It appears that such behavior is a result of beating of the two modes of free oscillations with close periods. The first of them is the well-known FCN period, the second one (about 420 days) is the period FICN of the free oscillations of the inner part of the fluid core (see Krasinsky, 2005a). The current version of the numerical theory is designated ERA-2005, implying that it provides Earth Rotation Angles, is based on the VLBI data up to the end of 2005, and is built into the programming

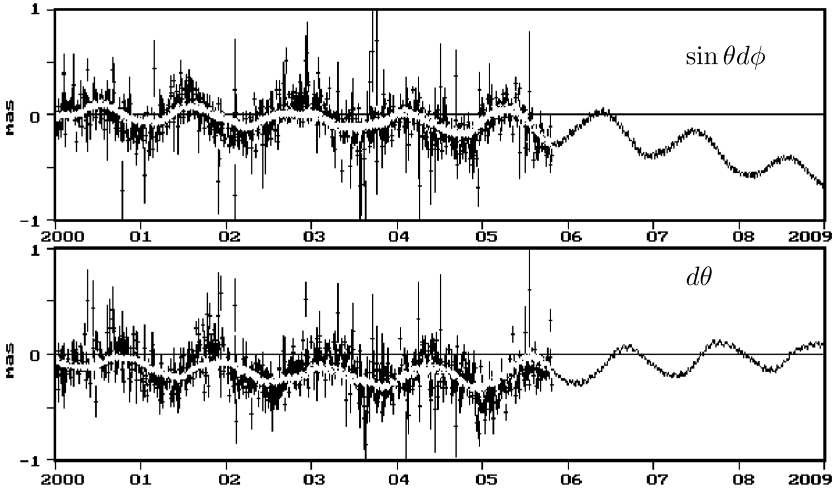

Figure 1. Observed and predicted corrections to IAU 2000, GSFC series.

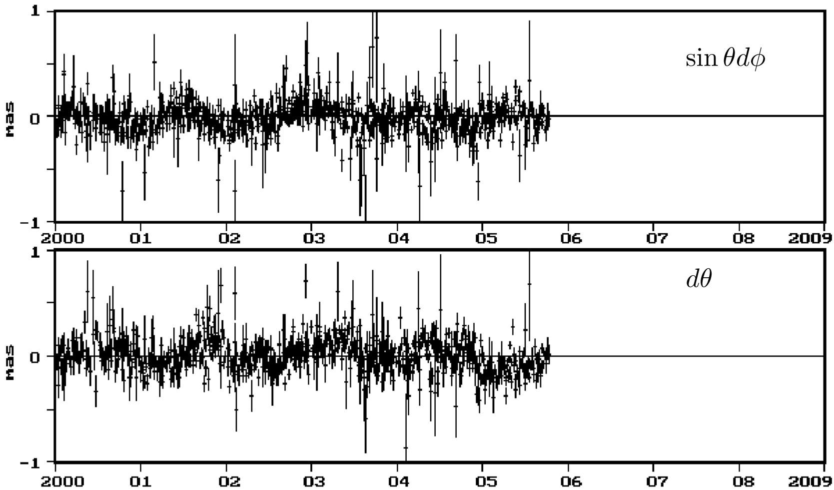

Figure 2. Observed corrections to ERA-2005, GSFC series.

complex ERA (Ephemerides for Research in Astronomy), see (Krasinsky and Vasilyev, 1997). The complicated time-behavior of the free oscillations may be seen in Fig 6 where the differences between the numerical ERA-2005 and the analytical IAU 2000 theories are presented after transforming the latter to the same ecliptical inertial frame J2000. Because in the analytical theory in use there is no model of the free oscillations, we have to attribute the oscillations of the differences to ERA-2005. One can see that these oscillations basically follow the patterns of those for the IAU 2000 residuals given in Figs 3,4 but have somewhat less amplitudes.

Statistics of the residuals are presented in Table 1 of Section 3 where they are given both for the GSFC series and the series of other Analysis Centers as well. We have also included in the analysis also the preliminary dataset IAA1 obtained in IAA with an alternative software package Quasar under supervision of V.Gubanov.

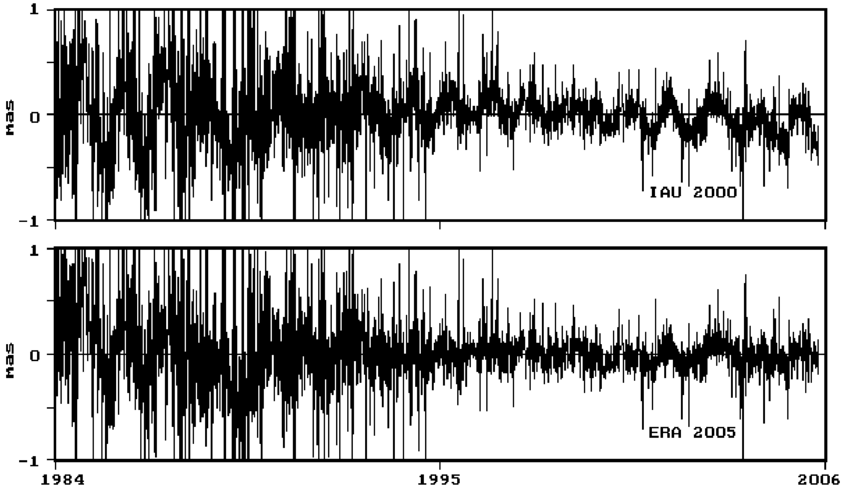

Figure 3. Residuals $\sin\theta d\psi$ for IAU 2000 and ERA-2005, GSFC series.

Mathematical basis for ERA-2005 and physical meaning of its parameters are briefly outlined in the next section. In Section 3 we present results of the analysis of all the available sets of VLBI-based Celestial Pole positions, comparing WRMS errors and parameters of the theory con-

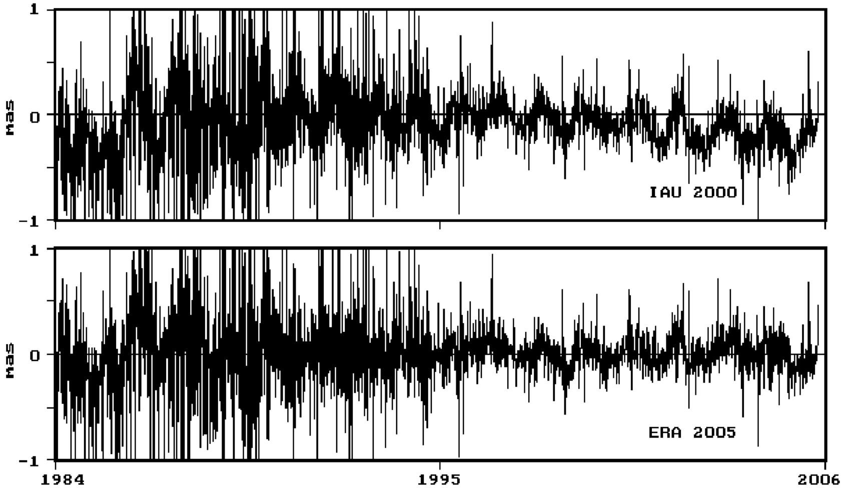

Figure 4. Residuals $d\theta$ for IAU 2000 and ERA-2005, GSFC series.

structed by fitting to the corresponding series (if quality of the data makes it possible.)

2. ERA-2005 model of the Earth rotation

Differential model of the deformable Earth given in paper (Krasinsky, 2005a) was refined by accounting for the mantle-core friction and a number of other effects of less importance. The corresponding differential equations were integrated numerically from the initial epoch 1983, December, 27 (JD=2445695.5) up to the last date 10, October, 2005, of the updated GSFC series GSFC2005a.eops (3588 points) and then the numerical theory was fitted to these data. The obtained numerical theory was considered as a basic version. After that the theory was continued to the epoch of 2015 and presented in the form of Chebyshev's polynomials. In brief, the theory presents the time behavior of the 18 variables which determine the absolute rotation of the Earth as a whole, and the differential rotations of external and inner parts of its fluid cores (effects of the solid inner core being ignored). The first three variables θ, ϕ, ψ are the Euler's angles of nutation, precession, and axial rotation referred to the inertial ecliptical coordinate frame J2000. The conjugate impulse-type variables are $m_1 = \dot{\theta}$, $m_2 = \dot{\psi} \sin\theta$, $m = \dot{\phi} + \dot{\psi}\cos\theta$. The variables n_1, n_2 are the equatorial projections of the vectorial angular velocity of the differential rotation of the fluid core relative to the mantle (in the inertial frame), n is the polar projection. Similarly, the variables q_1, q_2 are the equatorial projections of the angular velocity of the inner part of the fluid core relative to its outer part, q is the polar projection. While integrating we accounted for the perturbations caused by the Moon, Sun and by the major planets from Venus to Saturn, coordinates of these celestial bodies being taken from the DE/LE405 ephemerides. Coordinate-type variables which are conjugate to the differential angular velocities v_1, v_2, v are differences of the corresponding Euler's angle of the mantle and fluid core. The variables that are conjugate to the projections q_1, q_2, q have the analogous meaning. These variables are cyclic (do not enter explicitly the right parts of the differential equations) unless potentials of interactions of the mantle and core or of the external and inner cores at their boundaries are taken into consideration.

Because the coordinate frame of the theory differ from that in which the measured Celestial Pole offsets are published, a special procedure to confront the theory with these offsets was developed and described in (Krasinsky 2005b). Evaluating the residuals for the precessional angle ϕ, we have to add the correction ψ_{GRT} predicted by General Relativity Theory (the so called geodetic precession and nutation). Its numerical value is calculated making use of the analytical expression from the work (Fukushima, 1991)

$$\psi_{GRT} = 1.9194'' \ (t - \mathrm{J2000})/36525.0 + 0.153 \sin l',$$

in which the coefficients are given in mas, and l' is the solar mean anomaly. The sign of the right part is reversed to be in accordance with our definition of ψ. It appeared that omitting this reduction, the WRMS errors significantly increase (about 30%). Estimating the linear trend $\dot{\psi}_{GRT}$ from observations simultaneously with other parameters of the numerical theory, we have obtained

$$\dot{\psi}^{obs}_{GRT} = (2.07 \pm 0.09)''/cy$$

in a good accordance with the GRT prediction.

The geophysical parameters, actually accounted for in this analysis, are the following ones: the ratio α of the main moment of inertia of the core to that of the Earth as a whole, the ellipticities e of the Earth and e_c of the external core, tidal phase delay δ of the Earth and that δ_c of the core, the static Love numbers k_2, the dynamic Love number k_2^u, the Love number k_2^c of the core, the ratio α_{ic}=α_i/α of the main moment of inertia of the inner core α_i to α, the period $\mathrm{T_{FICN}}$ of the free oscillation of the inner core, two parameters $k_2^{(1)}$, $k_2^{(2)}$ of the ocean tide model, the parameter κ_{dis} characterizing the mantle-core friction, and some other parameters of less importance. Because it appears impossible to separate the correction to α from that to the dynamical Love number k_2^u we have fixed k_2^u to its theoretical value, estimating only α. It is practically impossible to separate also corrections to the ellipticity e_c of the core with the Love number k_2^c of the core, so we estimated only e_c. Because the period $\mathrm{T_{FCN}}$ of Free Core Nutation is a function of e_c and k_2^c, in this way this period is implicitly defined. In contrast, we have preferred to estimate in an explicit way the second period $\mathrm{T_{FICN}}$ of the free oscillations (caused by the inner part of the fluid core) but not the ellipticity of the inner core.

Unfortunately, the force interplay in the dynamics of the Earth's rotation is not yet understood good enough and ERA-2005, as well as any other of the published theories, includes some empirical terms to reach satisfactory fitting to the observed Celestial Pole positions. In the present version of the theory, six of the estimated parameters are empirical. Two of them are reconciliation parameters in the expressions for the perturbing torques (they do not affect secular rates of the angles θ, ϕ) and the four parameters are amplitudes of annual harmonics.

As Nutation IAU 2000 is the sum of the purely periodical forced harmonics, the free oscillations in the calculated differences between these theory and ERA-2005 (see Fig 6) are to be attributed to the latter. Because the numerical theory does not use any model of excitation of the free oscillations, it is clear that the well-known diminishing of the FCN amplitudes at 1998 and their increase after this epoch is just the result of beatings between the two close modes of the free oscillations of the external and inner parts of the fluid core.

In this work we do not discuss the derived estimates of the geophysical parameters under study but are concerned with studying the dependence of these parameters on the VLBI series used to construct the numerical theory.

The computer time needed to integrate the differential equations on the 25 year time span is about 12 minutes for an ordinary PC. However, because the partials for the parameters under estimation are obtained by the similar integration, one step of iterations takes several hours to fit the theory to the observations. With the reasonable computer time needed to construct or update the dynamical theory we could construct a version of the theory for each independent series of the VLBI data. That made possible to estimate objectively quality of the each series and compare their systematic errors.

3. Comparison of results for different series

3.1. Statistics of residuals

In Table 1, there are given WRMS errors of the residuals for each of the five VLBI series under study. The statistics for the series GSFC, USNO, BKG, IAA and IAA1 were calculated applying the numerical Earth rotation theory fitted to the corresponding series, while for AUS and MAO we used the GSFC-based theory because these two series appeared to be inferior in accuracy. To reject outlets we have applied a conservative 3.5 σ criterion, because the residuals are not randomly distributed (due to remaining signature of the free oscillations). The table gives also the numbers of the points used and deleted, both for $d\theta$ and $\sin\theta d\phi$. Rejecting the outlets not only have led to diminishing the WRMS errors but also to reducing the errors of the all parameters under estimation. For any of the series less 2 % of the data have been deleted. One can see that the least WRMS errors correspond the GSFC series, though for USNO, BKG IAA and IAA1 they are only marginally larger. Because there are two overlapping MAO series 1984-2003 and 2000-2005 we deleted the overlapping part when calculating the WRMS errors. As the two series are obtained with different packages, such a procedure is not quite correct.

The IAA and AUS series are derived applying the same package OCCAM in which Kalman method efficiently filters out the high frequency fluctuations in the atmosphere and the atomic clocks; however, these two series strongly differ in quality. It implies that some methodical deficiencies take place in either reduction procedures or the strategy of processing the AUS series.

The series of GSFC, USNO and BKG are derived by different teams making use of the same Calc/Solve software, so, it was natural to expect that the results would prove very similar. And indeed, as one can see from Table 1 that is the case.

Table 1. Numerical model: statistics $\sigma_{d\theta}$, and $\sigma_{d\phi}$ (mas), 1983 Dec – 2005 Oct

Series	$\sigma(d\theta)$	N_{obs}	N_{del}	$\sigma(\sin\theta d\phi)$	N_{obs}	N_{del}	Package
GSFC	0.136	3546	42	0.129	3545	43	Calc/Solve
USNO	0.138	3260	29	0.131	3255	34	Calc/Solve
BKG	0.140	2916	56	0.133	2922	50	Calc/Solve
IAA	0.138	3041	55	0.131	3041	55	Occam
IAA1	0.139	3074	79	0.132	3056	97	Quasar
AUS	0.170	1466	2	0.171	1455	13	Occam
MAO	0.179	2852	2	0.198	2849	4	SteelBreeze

In Table 2, the WRMS errors are given for the IAU 2000 model, the same outlets being deleted. Comparing data in Table 1 and Table 2, one can see that for the series of good quality the numerical theory provides much better fitting than IAU 2000.

Table 2. IAU 2000: statistics $\sigma_{d\theta}$, and $\sigma_{d\phi}$ (mas), 1983 Dec – 2005 Oct

Series	$\sigma(d\theta)$	$\sigma(\sin\theta d\phi)$
GSFC	0.172	0.165
USNO	0.179	0.167
BKG	0.180	0.168
IAA	0.173	0.162
IAA1	0.171	0.162
AUS	0.184	0.183
MAO	0.196	0.193

3.2. Empirical annual terms

Corrections to the amplitudes of the annual terms are very sensitive to the frequencies of the two modes of the free nutations, and thus they are strongly influenced by deficiencies of modeling. The empirical corrections to the annual terms are given in Table 3, the solar mean anomaly l' being taken as the argument of the annual terms.

One can see that for the CALC-based series GSFC, USNO and BKG the largest corrections are for the out-phase amplitudes $(d\theta)_{sin}$, $\sin\theta(d\phi)_{cos}$

indicating that the problem of modeling the dissipative effects is far from being solved. On the other hand, corrections to the in-phase amplitudes $(d\theta)_{cos}$, $\sin\theta(d\phi)_{sin}$ are small being within the limits of their statistical errors (especially for the USNO and BKG series). Situation with IAA and IAA1 series is more complicated: while the corrections to the in-phase amplitudes qualitatively agree with those for the other series, the out-phase corrections are significantly larger. It seems strange that the corrections for the two independent software (OCCAM an Quasar) are very close. Probably that indicates that the problems with reductions of raw VLBI data are the same in the both packages. It is surprising that deficiencies in reductions could contribute to the dynamical model in the such rather specific way.

Table 3. Corrections to annual terms, mas

Series	$(d\theta)_{sin}$	$(d\theta)_{cos}$	$\sin\theta(d\phi)_{sin}$	$\sin\theta(d\phi)_{cos}$
GSFC	0.507(27)	-0.064(92)	0.053(94)	0.236(28)
USNO	0.480(23)	0.004(71)	-0.019(74)	0.208(24)
BKG	0.505(25)	0.001(79)	-0.014(82)	0.238(26)
IAA	0.570(26)	-0.345(74)	0.352(78)	0.318(27)
IAA1	0.563(25)	-0.427(69)	0.393(73)	0.299(26)

3.3. Estimates of geophysical parameters

Table 4 illustrates dependence of the basic estimated geophysical parameters on the VLBI series used to construct the numerical theory. One can see that these estimates are in a good accordance. However, because the series GSFC, USNO and BKG are based on the same software, the agreement was beforehand expected. The IAA and IAA1 estimates, obtained with independent software packages, in general also agree with those of the other series except one important parameter: the period T_{FICN} of the free oscillations. That might be anticipated because corrections to the amplitudes of the annual terms for the IAA and IAA1 differ from those for other series. As corrections to T_{FICN} strongly correlate with the in-phase amplitudes of the annual terms, the IAA and IAA1 values of T_{FICN} differ from others. For them, the period T_{FICN} is more close to the FCN period, and as the result the amplitudes of the beatings between the two modes increase. It leads also to slower convergence of the iterative process (five iterations are needed, if the starting values are taken from the GSFC-based theory).

Table 4. Estimates of geophysical parameters

	GSFC	USNO	BKG	IAA	IAA1	Units
e	3.283410	3.283409	3.283408	3.283423	3.283425	10^{-3}
	6	6	7	7	6	
e_c	3.3761	3.3751	3.3742	3.3878	3.3874	10^{-3}
	23	24	26	25	25	
k_2	0.27272	0.27278	0.27283	0.27335	0.27214	
	36	39	42	41	41	
α	0.109412	0.109417	0.109411	0.109455	0.109474	
	16	16	18	18	17	
δ	6.502	6.423	6.367	6.277	6.384	deg
	66	70	76	74	74	
δ_c	3.430	3.417	3.491	3.497	3.434	deg
	47	50	54	53	53	
$k_2^{(1)}$	1.084	1.019	1.028	0.878	1.123	10^{-3}
	43	45	49	49	48	
$k_2^{(2)}$	0.890	0.903	0.910	0.714	0.745	10^{-3}
	46	49	54	55	52	
α_i/α	1.49	1.52	1.46	1.95	2.240	10^{-6}
	12	12	14	12	9	
$\mathrm{T_{FICN}}$	420.31	420.84	419.54	425.36	426.64	days
	94	98	1.12	1.12	1.08	
κ_{dis}	0.0362	0.0320	0.0311	0.0330	0.0279	10^{-7}
	24	24	28	27	27	

3.4. Comparison of the Earth's rotation theories

Fig 5 shows discrepancies between the numerical theories constructed applying different series of VLBI data with the numerical theory based on the GSFC series. The curves A, B and C present the differences IAA-GSFC, BKG-GSFC, and USNO-GSFC, respectively. All the three curves demonstrate the signature of the free core oscillations. The largest amplitudes are in the IAA-GSFC differences which probably is the result of the IAA largest FICN period (428 days) compared with its GSFC value 420 days. As the result, FCN and FICN periods for the IAA theory are the nearest, the period of the beating is longer and the amplitudes of the beatings increase. Noteworthy that all three theories are shifted with respect to that of GSFC, the USNO and BKG series having close values of the shifts, especially in the angle θ (about 0.043 mas). It implies that the catalogues of the quasars used in these centers differ slightly from that in GSFC.

Fig 6 presents differences between the numerical theory ERA-2005 and the adopted model IAU 2000. We believe that it is the time behavior of the IAU 2000 errors that are described by these curves, but not of ERA-2005.

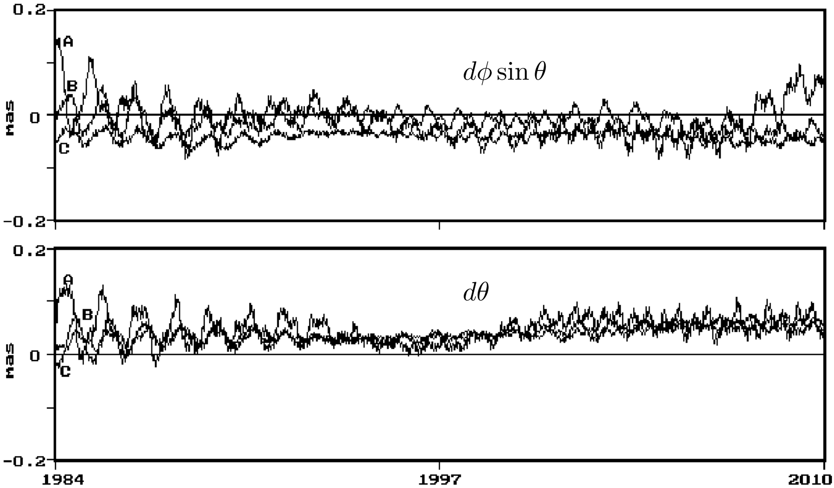

Figure 5. Discrepancies of Euler's angles between the numerical theories based on different VLBI series, (A: IAA-GSFC, B: BKG-GSFC, C: USNO-GSFC).

4. Conclusions

We would like to note the following advantages of the numerical theory ERA-2005.

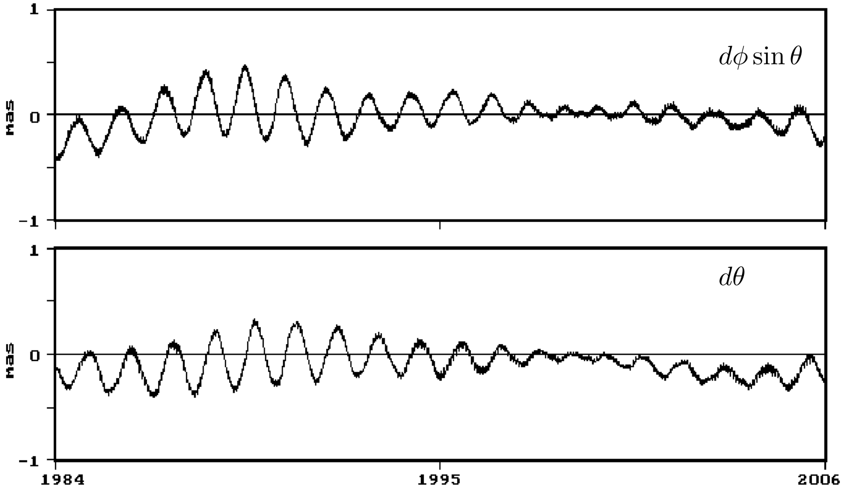

Figure 6. Differences of the Euler's angles (ERA-2005 minus IAU 2000).

1. At present, the theory provides the best fitting of VLBI based Celestial Pole offsets (see Table 1).

2. The theory not only gives nutational periodic oscillations of the Celestial Pole but also its precessional motion consistent with the nutations. The consistency between the nutational and precessional motions has made it possible to confirm the relativistic effect of the geodetic precession for the first time. With this theory, there is no more need in a special procedure of the Lieske's type to calculate the precessional motion.

3. The theory is referred to the well defined reference system J2000, avoiding the moving mean equator and ecliptic. Thus, making use of the theory, no intermediate reference system with a non-rotating origin, like that recommended by the resolution of General Assembly IAU 2000, is to be introduced.

4. The theory may be easily updated expanding the observational base. The software to do that may be acquired at request.

More rigorous usage of the numerical theory requires reprocessing of the raw VLBI time-delays. Indeed, the numerical theory contains small diurnal oscillations (with the amplitudes about 0.01 mas) which are the Chandler's oscillations transformed into the inertial frame. If the time-delays are processed with the help of the IAU 2000 model (in which there are no such oscillations) any really existing diurnal terms are transformed to small nutational harmonics of the derived Terrestrial Pole Positions, but do not enter the derived Celestial Pole offsets. As deleting the diurnal terms in the numerical theory cannot be produced, at present there are small inconsistencies between the numerical theory and the Celestial Pole offsets used.

At last, we would like to add that the next 3-5 years will be crucial for validation of the theories of the Earth rotation. Indeed, Fig 1 shows that the numerical theory predicts further deterioration of the IAU 2000 model of the Earth rotation, the error in the angle of precession exceeding 2 mas at 2009.

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