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Possible improvements of the IAU 2006 precession

— The preliminary results

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Motivation

- More than 10 years after the publication of the IAU 2006 precession
- Progresses in
  - New solutions for the EMB motion
  - Theoretical progresses for the precession of the equator
  - Longer time span of VLBI observations
  - Estimations of J_2 variation
- To investigate the possibility of improving the IAU 2006 precession

Outline

- The fundamentals of IAU 2006 precession
- Updated expressions for the precession of the ecliptic
- Recent theoretical improvements and new observations of J_2 by SLR
- Updated expressions for the precession of the equator
- Comparison with IAU 2006 model and check against VLBI

The IAU 2006 (P03) precession model

- Improved polynomial expressions for both the precession of the ecliptic (IAU 1976) and the precession of the equator (IAU 2000)

- The precession of the equator was derived from the dynamical equation expressing the motion of the mean pole about the ecliptic pole

- Precession of the ecliptic: VSOP87 fitted to DE406 over 2000 years

- Precession of the equator is based on
  - The IAU 2000 precession rates in longitude and obliquity,
  - The value $\varepsilon_0 = 84381.406''$ for the mean obliquity of the ecliptic at J2000
  - Contributions to the precession rates r_ψ, r_ε of non-rigid Earth model (Williams 1994; Mathews et al. 2002)
  - “observed” effect resulting from changing ε_0
  - J_2 rate value of $\mathrm{d}J_2/\mathrm{d}t = -3.0\times10^{-9}\ \mathrm{cy}^{-1}$

The polynomial coefficients for all the precession angles are in Hilton et al. (2006).

Improvement of P03 precession in 2005 (P04)

c.f. Capitaine et al. 2005, A&A 432, 355

- Upgrade of the Earth model (non-linear terms) based on Mathews' (2004) work
- Update of the integration constants (the interpretation of spurious effects should be in opposite sign), which gives

$$r_0 = 5038.481270'' \text{ cy}^{-1} \qquad u_0 = -0.024725'' \text{ cy}^{-1}$$

used in this work

- Check against VLBI data (1980-2004) and modify the precession rates
  - However, the time span of VLBI data was not sufficiently long to compare the accuracy of P03 and P04.
- Recommendation to retain P03 as the replacement for IAU 2000 precession
- Parameterized precession expressions depending on integration constants and J_2 rate are developed
- The P03 precession has been adopted as the IAU 2006 precession

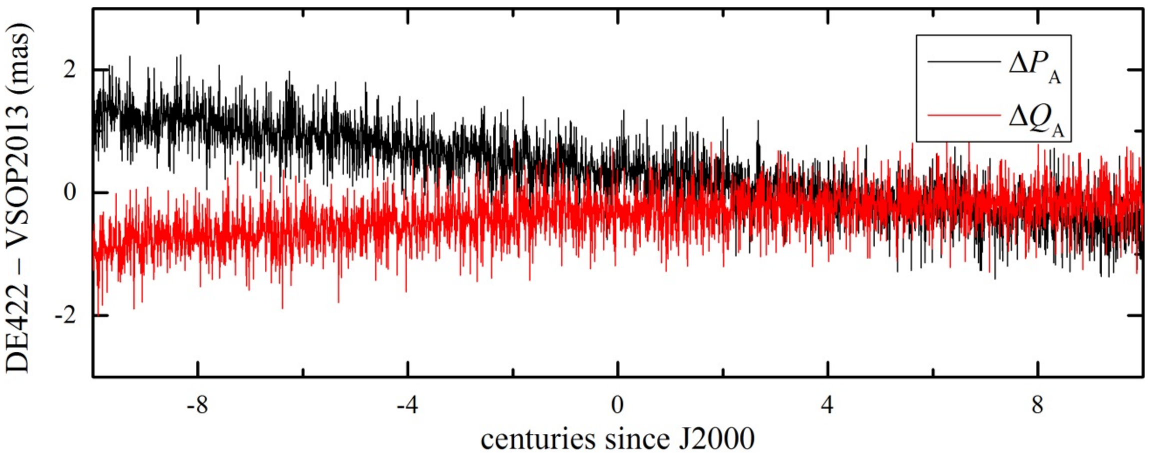
Updating precession of the ecliptic

- New analytical planetary theory VSOP2013 (Simon et al. 2013)
  - Chebyshev ephemerides – compared with DE422 ephemerides
  - Poisson series for elliptic elements – fit to DE422 ephemerides
  - Secular terms of elliptic elements – EMB *p, q* for precession of the ecliptic to be adjusted

$\varepsilon_0 = 84381.41136'', \ \varphi_0 = -0.05188''$

angles used for ecliptic-to-equatorial transformation

- DE422 ephemerides over long time interval
  - observational data
  - used to improve precession of the ecliptic



P_A and Q_A are the primary quantities for the precession of the ecliptic.

The secular term of P_A and Q_A (theoretical) need small adjustments to coincide with observations.

Fit precession of ecliptic using combined data (VSOP2013 + DE422)

- The methods are similar to P03
  - 250-day sampling over J1000 to J3000
  - Best rotation for DE422 from ecliptic coordinates to equatorial coordinates are found
  - Small adjustments are applied to VSOP2013 secular solutions for *p* and *q*

Final updated expressions for the precession of the ecliptic

- The transformation angles:

$$\varepsilon_0 = 84381.411063'', \ \varphi_0 = -0.051033'', \ \psi_0 = 0.112513''$$

- Polynomial expressions for P_A and Q_A

	t^1	t^2	t^3	t^4	t^5
P_A (″)	4.19903	0.19401	−0.00022353	-1.04×10^{-6}	2.16×10^{-9}
This work −P03 (μas)	−65	18	1	−0.1	0.01
Q_A (″)	−46.81099	0.05102	0.00052137	-5.58×10^{-7}	-1.21×10^{-9}
This work −P03 (μas)	28	−11	−3	0.09	0.02

Recent progress in precession theory

- Consideration of relativistic aspect of precession: treat geodetic precession as an additional torque (Gerlach, Klioner, Soffel 2012, arxiv:1202.5870v1)
  - contribute ~ 100 μas cy^{-1} to precession rate in longitude
- Tidal Poisson term contribution to precession rate in obliquity (Folgueira et al. 2007, A&A 469, 1197)
  - contribute 88 μas cy^{-1} to precession rate in obliquity
- Second order torque on tidal redistribution (Lambert, Mathews 2008, A&A 481, 883)
  - 1840 μas cy^{-1} to precession rate in obliquity
- New determination of J_2 variation from SLR observations (*)
- Small effect from Galactic aberration (Liu et al. 2012, A&A 548, A50)

Deceleration of the Earth's J_2
(c.f. Cheng, Tapley, Ries 2013, JGR 118, 740)

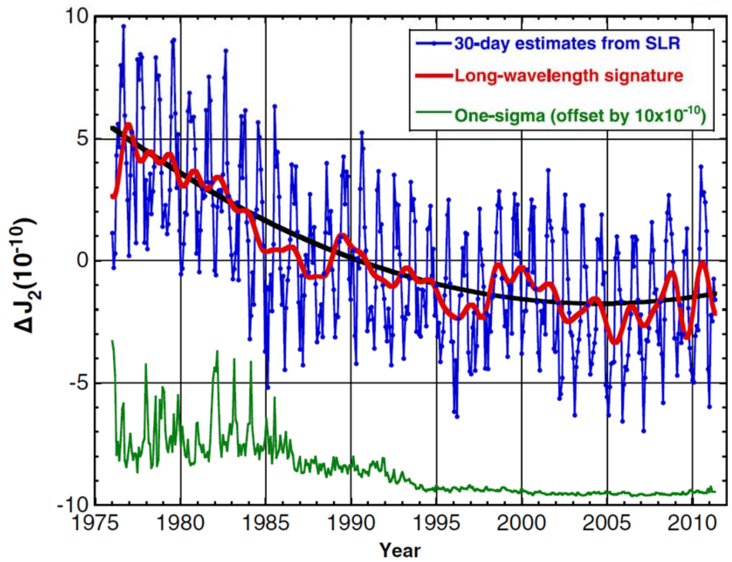
- J_2: gravitational degree-2 harmonic, Earth's dynamical oblateness

- The long-term trend in J_2 has generally been approximated by a negative linear drift due to postglacial rebound of the Earth's mantle

- data: time series of 30-day SLR-based estimates of J_2 over 35 years

- the value of d J_2/dt decreases significantly when the time span is increased and more recent SLR data are included, indicating a significant deceleration in J_2

- J_2 appears to be more quadratic than linear in nature



- P03: $\mathrm{d}\,J_2 \,/\, \mathrm{d}\,t = -3\times10^{-9}\ \mathrm{cy}^{-1}$
- Fit to parabola: $J_2 = A_0 + A_1 t + A_2 t$
- t in Julian centuries

$$A_0 = 0.001082635820642 \pm 1.64693\times10^{-11}$$

$$A_1 = -5.31913\times10^{-10} \pm 1.87982\times10^{-10}\ \mathrm{cy}^{-1}$$

$$A_2 = 1.0894\times10^{-8} \pm 1.90071\times10^{-9}\ \mathrm{cy}^{-2}$$

Contribution to the precession rates in longitude and obliquity

$(r_0)_1 / \cos\varepsilon_0 = 5494.040722'' \text{ cy}^{-1}$

$(u_0)_1 / \cos\varepsilon_0 = -0.0305096'' \text{ cy}^{-1}$

Table 3. Theoretical contributions (from W94, Williams (1995) and MHB) to the precession rates, r_ψ and r_ϵ, of the equator used in the present paper.

Source of the effect	ϵ dependence	Contribution in longitude at J2000			Contribution in obliquity at J2000		
		μas/cy	μas/cy^2	μas/cy^3	μas/cy	μas/cy^2	μas/cy^3
Luni-solar & Planetary torque							
Luni-solar 1st order	$\cos\epsilon$	$(r_0)_1$	−3395	−6	0	0	0
Luni-solar 2d order(a)	$6\cos^2\epsilon - 1$	−33 100	0	0	0	0	0
Luni-solar 2d order(b)	$3\cos^2\epsilon - 1$	−13 680	0	0	0	0	0
Luni-solar J_4	$\cos\epsilon\left(4 - 7\sin^2\epsilon\right)$	+2600	0	0	0	0	0
Planetary 1st order	$\cos\epsilon$	+31 367	0	0	−1400	0	0
J_2 and planetary tilts							
J_2 and planetary tilt(a)	$\cos 2\epsilon / \sin\epsilon$	−269 430	+1074	0	0	0	0
planetary tilt(b)	$\cos\epsilon$	0	0	0	$(u_0)_1$	−44	+3
Tides							
tides(a)	$\cos^2\epsilon$	0	−102	0	0	0	0
tides(b)	$\cos^3\epsilon$	0	−133	0	0	0	0
tides(c)	$\sin\epsilon\cos\epsilon$	0	0	0	+2400	0	0
J_2 rate	$\cos\epsilon$	0	−14 000	0	0	0	0
Non-linear effect	1	−21 050	0	0	0	0	0
Geodesic precession	1	−1 919 883	+3	+1	−1	0	+5
Total		$(r_0)_1$ − 2 223 176	−16 553	−5	$(u_0)_1$ + 999	−44	+8

-960 μas cy^{-1}

J_2 rate contribution: -2482 μas cy^{-2}

J_2 second order contribution: +50629 μas cy^{-3}

+340 μas cy^{-1}

Integration of the dynamical equations

$$\sin\omega_A \frac{d\psi_A}{dt} = (r_\psi \sin\varepsilon_A)\cos\chi_A - r_\varepsilon \sin\chi_A; \quad \frac{d\omega_A}{dt} = r_\varepsilon \cos\chi_A + (r_\psi \sin\varepsilon_A)\sin\chi_A$$

RKF-7(8) integrator
P03: GREGOIRE software

The new precession of the equator is based on:

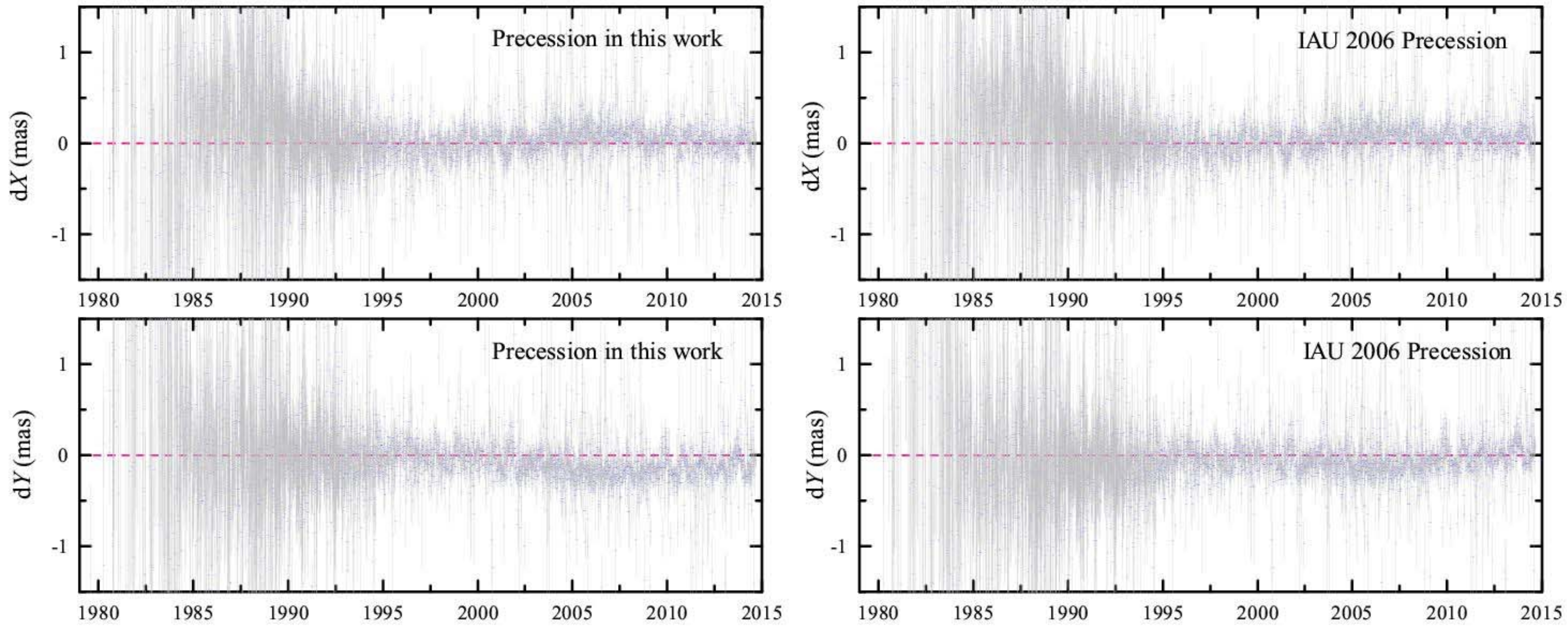
- updated ecliptic precession derived from VSOP2013 and DE422 ephemerides
- P04 integration constants $r_0 = 5038.481270'' \text{ cy}^{-1}$ $u_0 = -0.024725'' \text{ cy}^{-1}$
- updated contributions to precession rates including J_2 secular variation from SLR

	T^1	t^2	t^3	t^4	t^5
ψ_A ('')	5038.481270	-1.0732468	0.01573403	0.000127135	-1.0197×10^{-7}
This work -P03 (μas)	-237	5760	16875	-6	-0.007
ω_A ('')	-0.024725	0.0512626	-0.0077249	-2.67×10^{-7}	2.67×10^{-7}
This work -P03 (μas)	1029	0.3	0.1	0.1	-0.07
p_A ('')	5028.796129	1.1111242	0.0169552	-0.000020031	-1.7×10^{-8}
This work -P03 (μas)	-66	5689	16876	4	0.002
ε_A ('')	-46.835705	-0.0001936	0.00200005	-5.94×10^{-7}	-1.22×10^{-8}
This work -P03 (μas)	1064	-10	-3	-0.02	0.03
χ_A ('')	10.556240	-2.3813876	-0.00121311	0.000160286	-8.60×10^{-8}
This work -P03 (μas)	-163	54	-1	-10	-0.03

Comparison with VLBI

SOFA board are gratefully acknowledged!

- Two series of celestial pole offsets
  1. based on frame bias + precession in this work + IAU 2000A nutation
  2. based on frame bias + IAU 2006 precession + IAU2000A nutation



		Weighted Mean (mas)	WRMS (mas)
This work	dX	0.0304	0.1292
IAU	dX	0.0467	0.1349
This work	dY	-0.1167	0.1794
IAU	dY	-0.0565	0.1442

Discussion and concluding remarks

- Precession of the ecliptic has been updated based on recent new ephemerides
- More recent model for the J_2 variation has been used in the integration
- The P04 integration constants have been used

- Changes in the 2nd and 3rd degree coefficients for the precession in longitude are significant
- Whether a new model is necessary to replace the IAU 2006 precession after 10 years of its publication?

- The IAU 2006 precession is still trustworthy

For the future precession model

- Solve precession and nutation simultaneously

- Precession model in the Gaia reference frame / ICRF3