INPOP06: the new European Planetary, Moon and Earth rotation Ephemeris

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INPOP Planetary ephemeris

INPOP06
(Fienga et al. 2006)

- Intégrateur Numérique Planétaire de l'Observatoire de Paris
- began in 2003 with J.Laskar et al.

- Numerical integration with extended precision 80b
- Planets, Asteroids , Moon, Earth Rotation
- Einstein-Infeld-Hoffman equation of motion
- INPOP(TCB) and INPOP(TDB)

- Fit to ~ 50 000 space and Earth-based data
- Asteroid masses and densities
- J2 estimated (β,γ tested)
- INPOP realisation of TCB

- ESA ephemeris (GAIA)
- ESA tracking data (MEX)

INPOP General Aspect – I: Planets and Asteroids

$$
\begin{aligned}
\ddot{\mathbf r}_i = \sum_{j\neq i}\frac{\mu_j(\mathbf r_j-\mathbf r_i)}{r_{ij}^3}\Bigg\{ & 1-\frac{2(\beta+\gamma)}{c^2}\sum_{l\neq i}\frac{\mu_l}{r_{il}}-\frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} \\
& +\gamma\left(\frac{\dot s_i}{c}\right)^2+(1+\gamma)\left(\frac{\dot s_j}{c}\right)^2-\frac{2(1+\gamma)}{c^2}\dot{\mathbf r}_i\cdot\dot{\mathbf r}_j \\
& -\frac{3}{2c^2}\left[\frac{(\mathbf r_i-\mathbf r_j)\cdot\dot{\mathbf r}_j}{r_{ij}}\right]^2+\frac{1}{2c^2}(\mathbf r_j-\mathbf r_i)\cdot\ddot{\mathbf r}_j\Bigg\} \\
& +\frac{1}{c^2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}^3}\left\{[\mathbf r_i-\mathbf r_j]\cdot[(2+2\gamma)\dot{\mathbf r}_i-(1+2\gamma)\dot{\mathbf r}_j]\right\}(\dot{\mathbf r}_i-\dot{\mathbf r}_j) \\
& +\frac{3+4\gamma}{2c^2}\sum_{j\neq i}\frac{\mu_j\ddot{\mathbf r}_j}{r_{ij}}
\end{aligned}
$$

PPN RG (β=γ=1)

(Newhall, 1983)

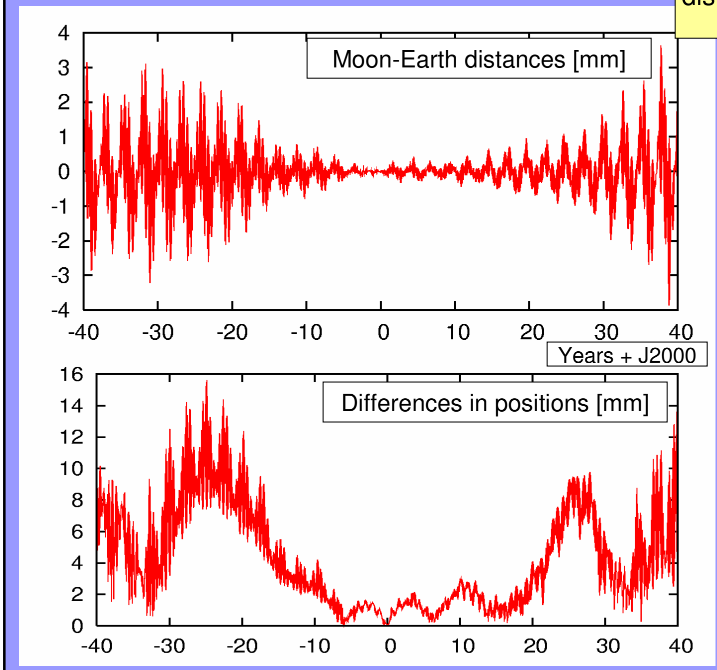
- Einstein-Infeld-Hoffman equation of motion
- BCRF (IAU 2001)
- β,γ, J2
- Asteroids integrated like planets
- Asteroid Ring perturbations included
- SSB

INPOP General Aspect – II: The Moon and Moon Libration

- EIF pertubations of planets, Sun and 300 asteroïds (integrated)
- **Non-spherical bodies ⇔ point mass bodies**
  - Sun (J2) ⇔ Planets
  - Earh (J2) ⇔ (Moon, Sun, Venus, Jupiter)
  - Moon (J2,C21,C22,S21,S22) ⇔ (Earth, Sun, Venus, Jupiter)
- **Deformation of extended bodies (tides) ⇔ point mass bodies**
  - Earth (Sun, Moon) ⇔ (Moon, Sun, Venus, Jupiter)
  - Moon (Spin, Earth, Sun) ⇔ (Earth, Sun, Venus, Jupiter)
- Earth Shape ⇔ Moon shape (torque exerted by the Moon)
- DE/LE405 : fitted to LLR / INPOP06: Not yet fit to LLR data (in progress)

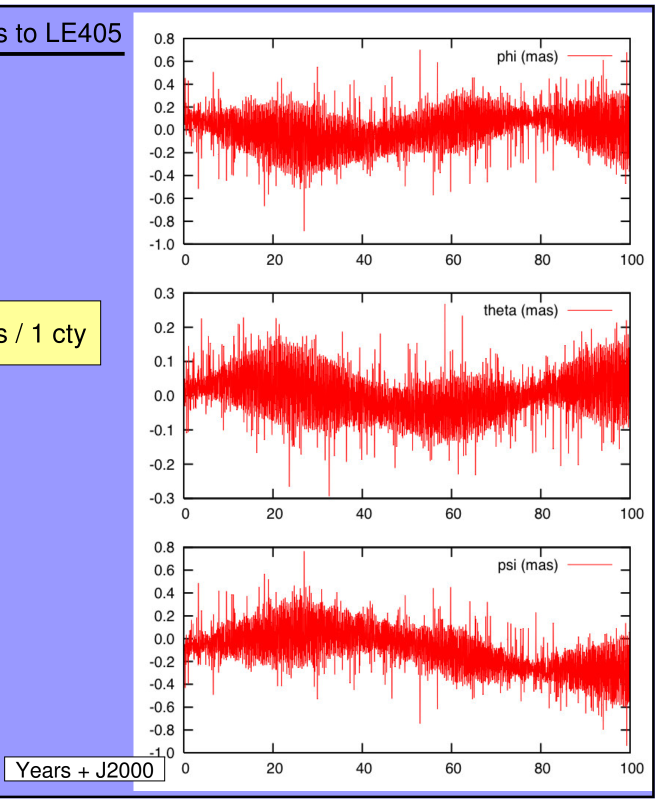
The Moon Positions: Comparisons to LE405

Few mm for Moon geocentric distances on LLR data interval



The Moon Libration: Comparisons to LE405

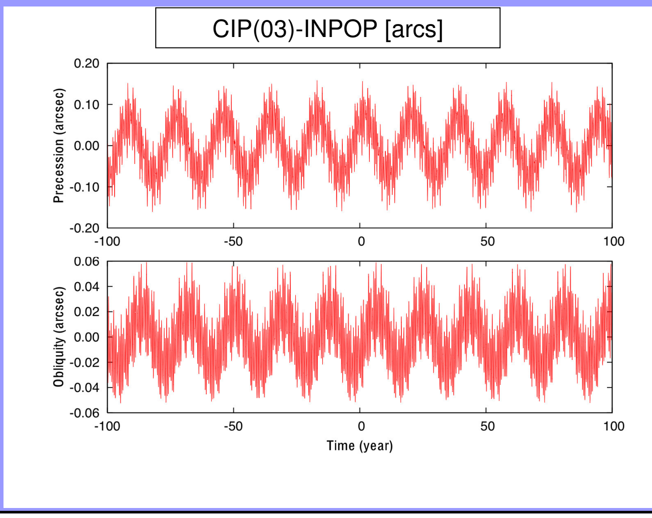
< 1 mas for the 3 Euler angles / 1 cty



INPOP General Aspect – III: Earth rotation

See Jacques Laskar Presentation …

- INPOP Earth Rotation solution = Integration of the angular momentum
- Takes into account the Earth tidal deformation
- does not depend of the Inner Earth modelling



General Relativity and INPOP

For ESA missions (GAIA),

- Einstein-Infeld-Hoffman equation of motion
- Barycentric Celestial reference frame : IAU 2001 BCRS if T_{eph} = TCB
- Each planetary ephemeris realises its own TCB (Klioner 05)

⇒ (TCB_{inpop} – TCG) estimated via an iterative process and INPOP fit to observations

(Fienga, Le Poncin-Lafitte et al., 2006)

- In INPOP, RG SSB definition is

$$\Sigma_i \mu^*_i r_i = 0 \text{ and } \Sigma_i \mu^*_i dr_i/dt + \mathbf{d\mu^*_i\, dt\, r_i} = 0$$

Work in progress…

INPOP06 Data Set

- [1898-2006] data set
- JPL space data
- US/Russian direct radar
- Transit data
- Original CCD data
- **ESA MEX/VEX**

JPL/Observatoire de Paris Astrometric Planetary Data Base

Planets	Types of Observations	Time Interval	SOURCES	<σ>	
Mercury	Radar	1972-1997	Goldstone,Arecibo,Evpatoria	1 km	443
Venus	Radar	1970-1990	Goldstone,Arecibo,Evpatoria	1 km	511
	Spacecraft VLBI	1991-1994	Magellan	1 mas	18
	Spacecraft radar	*Sept 2006*	***ESA VEX in sept 06***		
Mars	Spacecraft radar	1978-2005	JPL Vkg,Pathf,MGS,MO	5/10 m	10474
	Spacecraft radar	2005-2006	**ESA MEX**	2 m	19000
	Spacecraft VLBI	2001-2003	JPL MGS,MO	1 mas	44
	Spacecraft Doppler	1980, 1999	JPL Vkg, Pathf	1 km	3020
Jupiter	Spacecraft VLBI	1996-1997	JPL Galileo	1/10 mm/s	24
	CCD or transit (α,δ)	1970-2004	USNO,Nikolaev,CAMC,Bdx, MPC	500 mas	3191
Saturne	CCD or transit (α,δ)	1970-2004	USNO,Nikolaev,CAMC,Bdx, MPC	500 mas	3863
Uranus	CCD or transit (α,δ)	1900-2004	USNO,Nikolaev,CAMC,Bdx, MPC	500 mas	3849
Neptune	CCD or transit (α,δ)	1900-2004	USNO,Nikolaev,CAMC,Bdx, MPC	500 mas	3898
Pluto	CCD or transit (α,δ)	1988-2004	USNO,Nikolaev,CAMC,Bdx, MPC	500 mas	1124

INPOP06 adjusted physical parameters

Planet Initial Conditions +

	Unit	DE405 (Standish, 98)	DE411 (Standish, 04)	EMP04 (Pitjeva 05)	DE414 (Standish, 05)	INPOP06 (Fienga, et al 06)
Mass of Ceres	10^{-10} $M_\oplus$	4.64	4.554	4.753±0.007	4.699	4.746±0.006
Mass of Vesta	10^{-10} $M_\oplus$	1.34	1.280	1.344±0.001	1.358	1.338±0.002
Mass of Pallas	10^{-10} $M_\oplus$	1.05	1.059	1.027±0.003	1.026	0.995±0.003
Mass of Iris	10^{-10} $M_\oplus$			0.063±0.001	0.060	0.089±0.002
Mass of Bamberga	10^{-10} $M_\oplus$			0.055±0.001	0.047	0.060±0.002
Density of C class		1.8	1.8	1.4	1.6 ±0.22	1.93±0.12
Density of S class		2.4	2.4	3.5	2.07	2.13±0.11
Density of M class		5.0	5.0	4.5	4.3±0.43	4.47±0.012
Mass of Asteroid ring	10^{-10} $M_\oplus$			3.55±0.35	0.329	0.34±0.15
Distance of ring	UA			3.13±0.05	2.8	2.8
Sun J2	X 10^{-7}	2	2	1.9±0.3	2.3±2.5	1.95±0.55

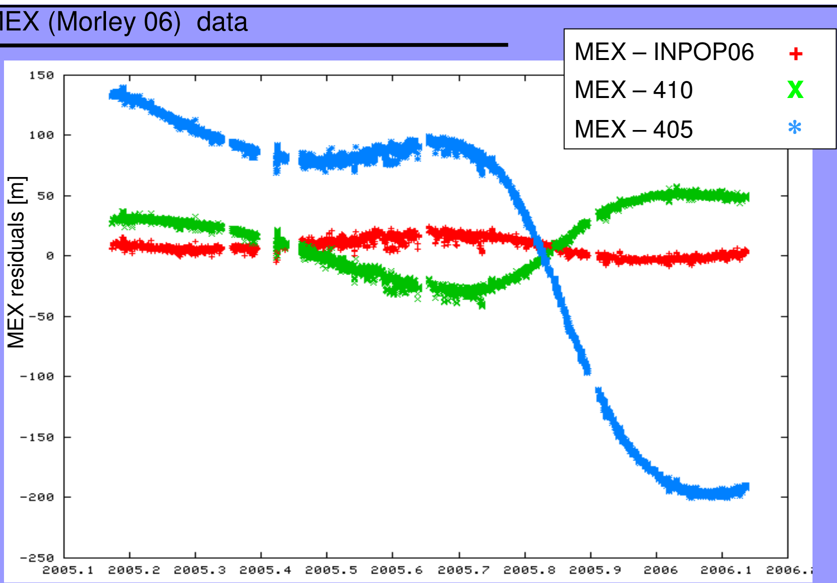
INPOP06b: $1 \leq \beta \leq 1.0001$, $1 \leq \gamma \leq 1.00002$

INPOP06 / DE414

- INPOP06: Original dynamical modele
  Asteroids / **all planets**
  5 Bigs + 297 in 3 classes+ Asteroid ring
  General Ephemeris over [1899:2005.43]
- DE414 : **64 Asteroids GM fitted + Asteroid ring**
  236 in 3 classes
  Mars & Saturn Space missions dedicated
  [2000:2005.3]

Planets	Types of Observations		DE414	INPOP06
Mercury	**Radar [m]**	**444**	**-596 ± 956**	**-108 ± 871**
Venus	**Radar [m]**	**511**	**-3578.0 ± 4671**	**-1126.0 ± 4527**
	Spacecraft VLBI [mas]	18	1.7 ± 2	0.6 ± 2
Mars	**Vkg radar [m]**	**1256**	**-5.7 ± 18**	**0.2 ± 20**
	MGS Radar [m]	**10474**	**7.4 ± 4.1**	**2.5 ± 7.5**
	MEX Radar [m]	***19000***	***11.2 ± 12.1***	***8.3 ± 6.7***
	Spacecraft Doppler Vkg [mm/s]	1501	-0.26 ± 4.5	-0.25 ± 4.4
	Spacecraft Doppl MGS [mm/s]	1519	0.35 ± 1.0	-0.32 ± 1.2
	Spacecraft VLBI [mas]	**44**	**0.04 ± 0.5**	**0.1 ± 0.5**
Jupiter	**Spacecraft VLBI [mas]**	**24**	**-1 ± 12**	**3 ± 12**
	CCD or transit (α,δ) [mas]		(47 ± 222, 36 ± 198)	(23 ± 214, -26 ± 190)
Saturne	CCD or transit (α,δ) [mas]	444	(29 ± 280, -1 ± 196)	(-28 ± 270, -2 ± 196)
Uranus	CCD or transit (α,δ) [mas]	511	(11 ± 440, 13 ± 370)	(0.5 ± 351, 4 ± 361)
Neptune	CCD or transit (α,δ) [mas]	18	(12 ± 404, 11 ± 438)	(-0.4 ± 360, 0.5 ± 350)
Pluto	CCD or transit (α,δ) [mas]	1256	(13 ± 264, 8 ± 252)	(0.9 ± 250, -47 ± 190)

MEX (Morley 06) data



	Time interval	INPOP	DE410	DE405
MEX [m]	2005.18-2006.2	8.3 ± 6.7	14.3 ± 25.2	27.8 ± 112.3

Project

- **Lunar Laser Ranging and INPOP Lunar fit**

  with Observatoire de Paris (S.Bouquillon, J.Chapront)

- **Adjustement with the new VEX and MEX Data**

  with ESOC (T.Morlay)

- **Pulsar Timing for EMB orbit fit**

  - with Observatoire de Besançon and Nançay (F.Vernotte, I.Cognard)
  - Contact with ATNF (R. Edwards)

- **RG β, γ influences and VEX determinations**

  with Dresden Lohrmann Observatory (C.Le Poncin-Lafitte)

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