VLBI data are the base of orientation of planetary ephemerides with respect to ICRF2 and improvement of other ephemeris parameters

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Historical Introduction

Until the 1960's classical analytical theories of planets (Leverrier, Hill, Newcomb, Clemence) were based entirely on optical observations having accuracy no better than 0.5″ (uncertainty of AU 65000 km, of the Earth-Moon 1 km).

Detection of Venus radioechoes made in 1961 at MIT, JPL (USA), Institute of Radioengineering and Electronics (USSR) and Jodrell Bank (England) opened the era of astrometrical radio observations that led to a revolution in astrometry and ephemeris astronomy.

Two new types of measurements appeared: the time delay (ranging) and the doppler-shift, while the accuracy of observations increased by orders of magnitude.

Then other types of radar observations emerged: differenced ranging, VLBI, tracking measurements of spacecraft.

It was radar measurements of planets and spacecraft (mainly ranging) that made it possible to produce ephemerides of the inner planets and Saturn with high-precision accuracy and to determine a wide range of astronomical constants including relativistic parameters.

However, ranging measurements are relative, usually between the Earth and other celestial object. From these observations, all orbital elements can be detected with the exception of the tree angles of the Earth orientation or angles of rotation of the system to a catalogue.

Orientation

- **classical and earlier ephemerides DE118 and EPM87**

FK4: transits of the inner planets and Sun were obtained with respect to the fundamental star catalog FK4.

- **DE200: dynamical equator and equinox of J2000.0**

A least-squares fit to the motion of node and obliquity of the orbit of the Earth–Moon barycenter about the Sun.

Standish E.M. A&A 1982, 114, 297-302

- **Present (since DE403 and EPM1998)**

ICRF2: ICRF2-based VLBI measurements of spacecraft near planets included into the fitting

Standish E.M. et al. Interoffice Memorandum 1995, 314.10-127, 22p.

a) ΔVLBI at the NASA global Deep Space Network (DSN)

b) Very Large Array – VLA

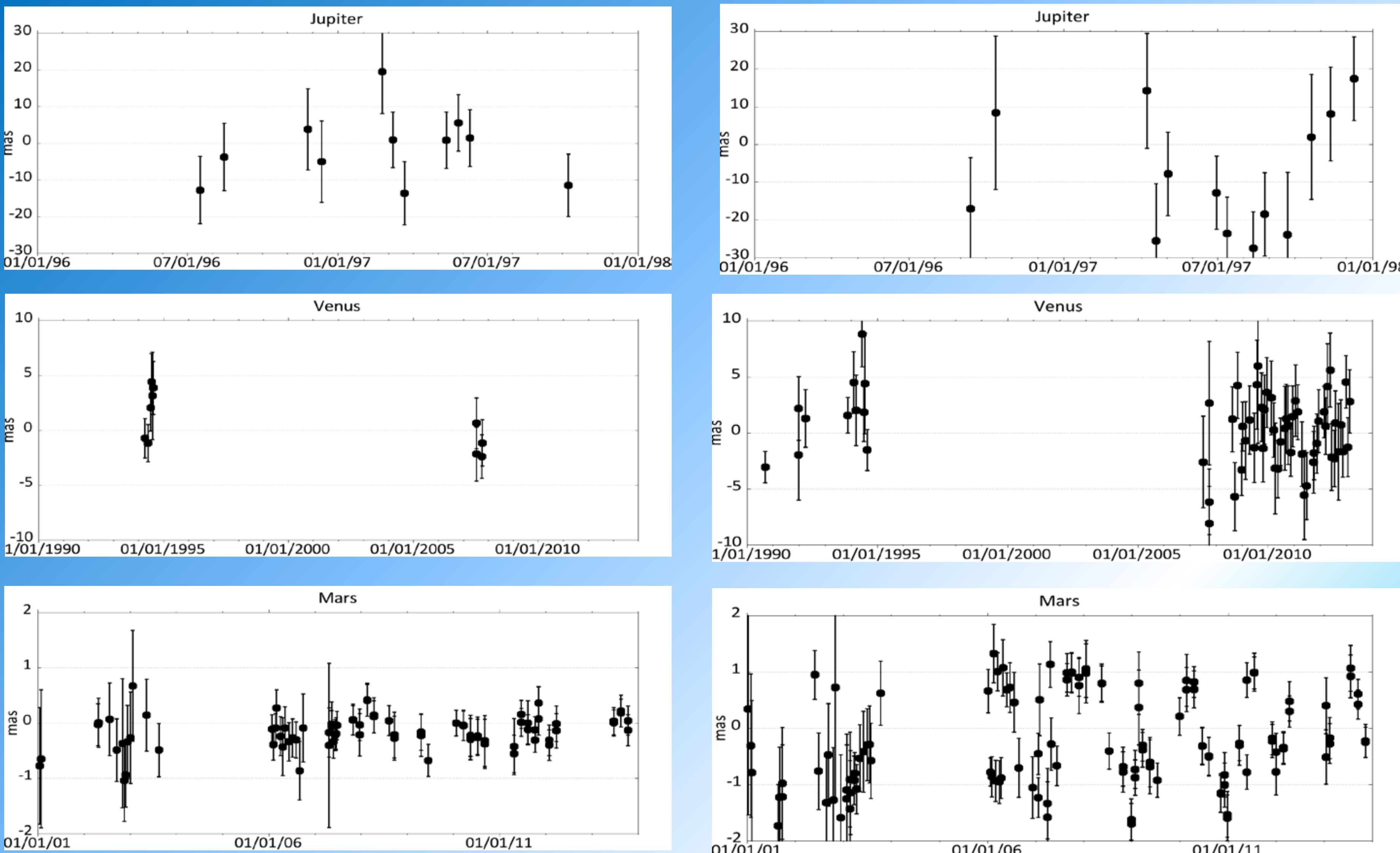
ΔVLBI

ICRF2 ΔVLBI measurements of spacecraft + a planetocentric spacecraft trajectory = the position of a planet with respect to ICRF2. ΔVLBI is one-dimensional angular correction *aldel* to ephemeris as orientation of these observations (the angle *θ*) in the direction connecting the two antennas **(Folkner W.M. 1994, JPL IOM 335.1-94-014)**

$$\Delta\alpha = aldel / \cos\theta \qquad \Delta\delta = aldel / \sin\theta$$

Table. ΔVLBI observations of spacecraft near the planets

Spacecraft	Planet	Time interval	Number of normal points	*A priori* accuracy (mas)
Phobos	Mars	1989	2	3.3–6.2
Magellan	Venus	1990–1994	18	1–4
Gallileo	Jupiter	1996–1997	24	7–15
MGS	Mars	2001–2003	15	0.6–6.1
Odyssey	Mars	2002–2013	111	0.18–1.5
MRO	Mars	2006–2013	76	0.19–0.45
VEX	Venus	2007–2013	54	1.5–5.0

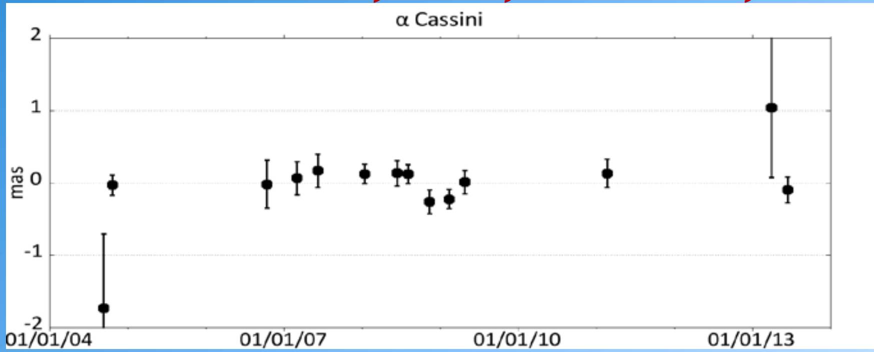


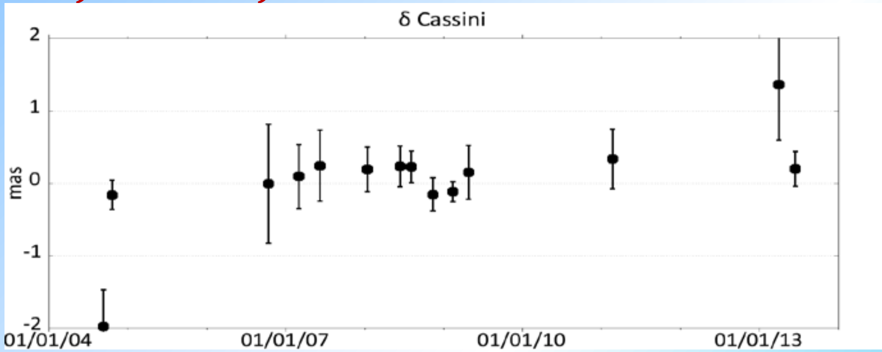
ΔVLBI residuals for spacecraft near Jupiter, Venus and Mars in mas, Goldstone – Canberra baseline (on left), and Goldstone – Madrid or New Norcia – Cebreros baseline (on right).

Cassini VLBA

Very Large Baseline Array techniques with rapidly alternating scans between Cassini and angularly nearby ICRF2 reference sources.
Multi-epoch (**2004-2014**) VLBA observations of Cassini + spacecraft orbit solutions from DSN tracking = the barycenter positions the Saturn with respect ICRF2with an accuracy of 0.2 mas.

Jones D.L. et al., 2011, AJournal, Volume 141, Issue 2, article 29.





The rotation angles for the orientation of EPM2015 onto ICRF2

Interval	Number of observ.	ε_x mas	ε_y mas	ε_z mas
1989-1994	20	2.0±1.5	0.1±1.0	-0.1±0.8
1989-2003	62	0.4±0.2	-0.3±0.3	-0.7±0.2
1989-2007	123	0.294-±0.099	0.083±0.140	0.089±0.073
1989-2010	222	-0.000±0.072	-0.005±0.089	0.004±0.051
1989-2014	296	0.002±0.064	0.001±0.062	0.000±0.036

Jupiter and radar & VLBI observations

The formal standard deviations of planetary orbital elements adjusted in EPM2015 (for Jupiter: O - optic, + radio +VLBI)

Planet	a [m]	*sin* i *cos* Ω [mas]	*sin* i *sin* Ω [mas]	e cos π [mas]	e sin π [mas]	λ [mas]
Mercury	0.0008	0.00121	0.00138	0.00024	0.00011	0.00289
Venus	0.0050	0.00551	0.00383	0.00017	0.00019	0.00350
Earth	0.0028	—	—	0.00004	0.00004	—
Mars	0.0076	0.00103	0.00109	0.00005	0.00007	0.00026
Jupiter-O +23 radio +24 VLBI	2828 747 745	17.099 2.947 2.718	18.366 2.624 2.533	9.491 0.390 0.329	8.396 0.334 0.242	28.176 2.368 2.077
Saturn	10.268	0.1269	0.0897	0.0020	0.0007	0.0236
Uranus	49734	5.531	5.002	4.280	3.514	4.390
Neptune	444853	4.534	7.821	8.724	22.244	19.428
Pluto	1221411	1.155	5.672	27.319	19.279	9.342

EPM (Ephemerides of Planets and the Moon) of IAA RAS began in 1970-s to support Russian deep space exploration

Observations

> 800000 observations were used for improvement of EPM2015

Planets	Radio		Optic	
	Interval of observ.	Number of norm. pts	Interval of observ.	Number of observ.
Mercury*	1964-2014	1918	——	——
Venus	1961-2013	3799	——	——
Mars	1965-2014	47755	——	——
Jupiter+4sat.	1973-1997	51	1914-2013	14866
Saturn+7 sat. *	1979-2014	194	1913-2013	16455
Uranus+4 sat.	1986	3	1914-2013	12550
Neptune+1sat.	1989	3	1913-2013	12404
Pluto	——	——	1914-2013	16674
Total	*1961-2014*	*53723*	*1913-2013*	*72049*

EPM2015 – IAA's Fundamental Ephemeris

The dynamical model of planet part EPM2015 includes the following:

- **mutual perturbations between the 9 planets, the Sun, the Moon;**
- **perturbations from the large 301 asteroids and 30 TNO (included into simultaneous integration) upon the 9 planets, the Sun, and the Moon;**
- **perturbation from the massive two-dimensional asteroid of small asteroids (R_1 = 2.06 au, R_2 = 3.27 au) with constant mass distribution;**
- **perturbation from a massive ring of TNO with the radius of 43 au;**
- **relativistic perturbations;**
- **perturbations due to the solar oblateness.**

New model or lunar orbital and rotational motion (includes liquid core) has been created.

EPM is oriented to the ICRF2 by VLBI measurements of spacecraft near Venus, Mars, and Saturn.

Accuracy ranging: 1-2 m Mars, 20 m Saturn, LLR: several mm,
Uncertainty Earth-Moon distance: 30 cm,
lunar physical libration: 60 mas (50 cm).
orientation of EPM frame to ICRF2: 0.2 mas,
planetary positions (distance): several m (inner), 40 m (Saturn),1.5–500 km(outer)

Use of EPM for scientific research: limitations on dark matter

Any planet at distance r from the Sun can be assumed to undergo an additional acceleration from dark matter:

$$(d^2r/dt^2)_{dm} = -GM(r)_{dm}/r^2$$

At a uniform density ρ_{dm} of the gravitating medium filling the Solar system, the additional acceleration on a body will be proportional to r:

$$(d^2r/dt^2)_{dm} = -kr \quad .$$

The presence of the additional gravitating medium leads to a shorter radial period and a negative drift of the pericenter and apocenter positions (in a direction opposite to the planetary motion):

$$\Delta\theta_0 = -4\pi^2\rho_{dm}/M_{Sun} \bullet a^3(1-e^2)^{1/2}$$

where $\Delta\theta_0$ is the perihelion drift in one complete radial oscillation.

$$\rho_{dm} < 3 \bullet 10^{-19}\ \mathrm{g/cm^3}.$$

Khriplovich I. B., Pitjeva E. V., International Journal of Modern Physics D, 2006, V.15, 4, 615-618.

Limitations on dark matter

Additional perihelion precessions from the observations of planets and spacecraft and estimates of the density ρ_{dm} from the perihelion precessions $\sigma_{\Delta\pi}$ Pitjev, Pitjeva. Astronomy Letters, 2013, v. 39(3), MNRAS, 432,

Planet	π (mas/yr)	$\lvert\sigma_\pi / \pi\rvert$	$\sigma_{\Delta\pi}$ [″/yr]	ρ [g/cm^3]
Mercury	-0.020 ± 0.030	1.5	0.000030	$< 9.3 \cdot 10^{-18}$
Venus	0.026 ± 0.016	0.62	0.000016	$< 1.9 \cdot 10^{-18}$
Earth	0.0019 ± 0.0019	1.0	0.00000190	$< 1.4 \cdot 10^{-19}$
Mars	-0.00020 ± 0.00037	1.9	0.00000037	$\leq 1.40 \cdot 10^{-20}$
Jupiter	0.587 ± 0.283	0.48	0.000283	$\leq 1.7 \cdot 10^{-18}$
Saturn	-0.0032 ± 0.0047	1.5	0.0000047	$\leq 1.1 \cdot 10^{-20}$

For the assumption of a uniform ρ_{dm} distribution in the Solar system, then the most stringent constraint is obtained from the data for Saturn: $\rho_{dm} < 1.1 \cdot 10^{-20}$ g/cm^3.
The mass within the spherical volume with the size of Saturn's orbit is
$M_{dm} < 7.1 \cdot 10^{-11} M_{Sun}$.
The upper limit for the total mass of dark matter was estimated as
$M_{dm} < 7.88 \cdot 10^{-11} M_{sun}$ **into account its possible concentration toin the center.**

Use of EPM for scientific research: change of $GM_\odot$

Taking into account the monotony and smallness of $\dot{\mu}$, it was shown (Jeans, 1924) that the invariant holds μ(t)·a(t) = const, where *a* is the orbital semi-major axis and μ(t)=G(M+m),

then $(G\dot{M}_\odot)/GM_\odot$ = – $\dot{a}/a$

The change of the heliocentic gravitation constant $GM_\odot$ is determined for certain – the accuracy increases as the square of the time interval of observations as:

$(G\dot{M}_\odot)/GM_\odot$ = (-6.3±4.3)•10^{-14} per year (2σ)

that is confirmed by simultaneously determined secular changes of semi-major axes of planets. The positive values for the planets Mercury, Venus, Mars, Jupiter, Saturn provided with the high-accuracy observations confirm the decrease of $GM_\odot$.

Perhaps, loss of the mass of the Sun $M_\odot$ the produces change of $GM_\odot$ due to the solar radiation and the solar wind compensated partially by the matter dropping on the Sun.

Taking into account the obtained limits of the possible change $\dot{M}_\odot/M_\odot$, the value $\dot{G}/G$, is found to be within the interval (with the 95% probability): $-7.0 \cdot 10^{-14} < \dot{G}/G < +7.8 \cdot 10^{-14}$ per year.

Use of EPM for scientific research

PPN parameters β and γ (General Relativity: β= γ =1)

$$\Delta Q_{rel} \sim (1+\gamma)/2$$

$$\Delta \tau_{Shapiro} \sim (1+\gamma)/2$$

$$\Delta \pi_{rel} \sim (2+2\gamma-\beta)/3$$

$$\eta_{Nordtvedt} \sim (4\beta-\gamma-3)$$

The parameters of the PPN formalism

$\gamma-1$	Authors	$\beta-1$	Method
0.00±0.03	Anderson et al.,1975		$\Delta\tau$, Mariner-5,6
0.000±0.002	Reasenberg et al.,1979		$\Delta\tau$, Viking
0.0002±0.0010	Robertson et al.,1991		ΔQ, quasars
-0.0004±0.0017	Lebach et al.,1995		ΔQ, quasars
-0.003±0.003	Froeschle et al.,1997		ΔQ, HIPPARCOS
-0.00006±0.00031	Eubanks et al.,1997	-0.00019±0.00026	$\Delta Q+\Delta\pi+\eta$,quasars
0.002±0.004	Williams et al.,2002	-0.001±0.004	$\eta_{Nordtvedt}$, LLR
-0.0015±0.0021	Anderson et al.,2002	-0.0010±0.0012	$\Delta\tau$, $\Delta\pi$,ranging,spacecraft
0.000021±0.000023	Bertotti et al.,2003		Δf, Cassini
0.00018±0.00026	Konopliv et al.,2011	0.00004±0.00024	$\Delta\tau$, $\Delta\pi$,spacecraft,Cassini
-0.00006±0.00008	Fienga et al.,2011	0.00005±0.00008	$\Delta\tau$, $\Delta\pi$,ranging,spacecraft
-0.13±0.06	Pitjeva,1986	0.24±0.12	$\Delta\tau$, $\Delta\pi$,ranging
0.006±0.037	Pitjeva,1993	0.014±0.070	$\Delta\tau$, $\Delta\pi$,ranging
-0.0001±0.0002	Pitjeva,2005	0.0000±0.0001	$\Delta\tau$, $\Delta\pi$,ranging,spacecraft
$<$ |0.0002 |	Pitjeva,2010	$<$ |0.0002 |	$\Delta\tau$, $\Delta\pi$,ranging,spacecraft

β-1 = –0.00002±0.00003, γ-1 = +0.00004±0.00006 → this leads to correspondence of the planetary motions and the propagation of light to General Relativity and narrows significantly the range of possible values for alternative theories of gravitation

Pitjeva, Proc. IAU Symp. No. 261, 2010, 170-178; Pitjeva, Pitjev, MNRAS, 432, 2013, 3431-3437

Use of EPM for scientific research

•**Masses of about 30 asteroids;**

the total mass of the main belt asteroids represented by the total masses of 301 asteroids and the asteroid ring is:

M_{belt}= (12.25 ±0.19)•10^{-10} $M_{\odot}$ (≈ 3 Ceres mass);

the total mass of all TNO including Pluto, the 30 largest TNO and the TNO ring of other TNO objects with the 43 au radius is:

M_{TNO} = 592•$10^{-10}$$M_{\odot}$, (≈ 125 Ceres mass or 1.6 lunar mass).

=> dynamics of the Solar System and its forming.

Pitjeva, Pitjev, Celest.Mech. & Dyn.Astr., 2014, 119, 237-256.

Pitjeva, Pitjev, Proc. of IAU Symposium 318, S. Chesley, A. Morbidelli, R. Jedicke, D. Farnocchia eds, 2016, V. 318, 212-217.

•**Navigation on the Earth — EPM ephemerides are the basis for the Russian Astronomical Yearbooks and Nautical Astronomical Yearbooks.**

• **Navigation in space — using EPM ephemerides in programs GLONASS.**

Conclusion

✓Fundamental planetary ephemerides have been referenced to ICRF2 by including the ICRF2-based VLBI measurements of spacecraft in the total adjustment using ΔVLBI at the NASA DSN and VLA.

✓The progress in the accuracy of planet ephemerides is ensured by the improvement of dynamical models and improvement of quality and growth of quantity of observational data with the crucial role of spacecraft ranging and VLBI.

✓Expansion of such data on other bodies of the Solar System and on a larger time interval allows to construct more accurate ephemerides and estimate small effects.

IAA RAS

Thank you for your attention !

The dynamical models of planet part EPM take into account:

EPM87:

- **mutual perturbations from the major planets, the Sun, the Moon and 5 most massive asteroids;**
- **the relativistic perturbations.**

EPM98: +

- **perturbations from the other 296 asteroids chosen due to their strong perturbations upon Mars and the Earth.**

EPM2000: +

- **perturbations due to the solar oblateness J_2.**

EPM2004: +

- **perturbation from the massive one dimensional asteroid ring with the constant mass distribution.**

EPM2008: +

- **perturbations from the 21 largest TNO;**

EPM2011: +

- **perturbation from a massive ring of TNO in the ecliptic plane with the R=43 au.**

EPM2013/EPM2015: +

- **perturbation from the massive two-dimensional asteroid ring (R_1= 2.06 au, R_2 = 3.27 au);**
- **perturbations from the 30 largest TNO.**