The INPOP planetary ephemerides and applications

A. Fienga[1,2], V. Viswanathan[1,4], P. Deram[1], A. Di Ruscio[1,3], L. Bernus[2], J. Laskar[2], M. Gastineau[2], N. Rambaux[2], O. Minazzoli[5], D. Durante[3], L. Iess[3]

[1]GéoAzur, CNRS, Université Côte d'Azur, Observatoire de la Côte d'Azur, France

[2]IMCCE, CNRS, PSL University, Observatoire de Paris, France

[3]Department of Mechanical and Aerospace Engineering, Sapienza University of Rome, Italy

[4]Goddard Space Flight Center, Greenbelt, USA

[5]Artemis, CNRS, Université Côte d'Azur, Observatoire de la Côte d'Azur, France

INPOP planetary ephemerides

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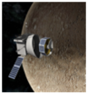
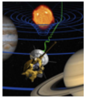
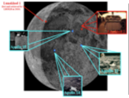
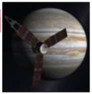
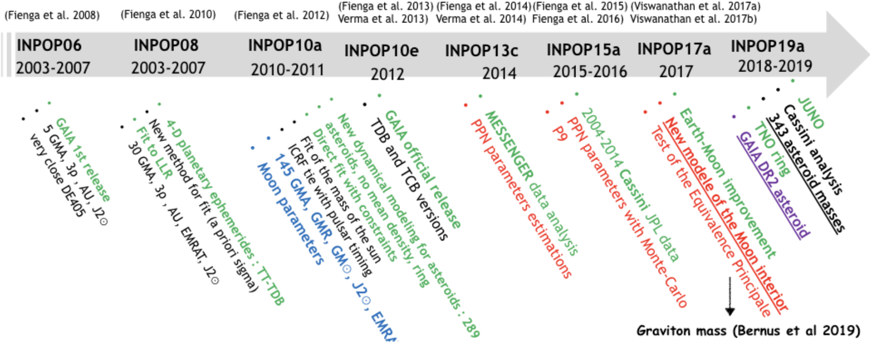
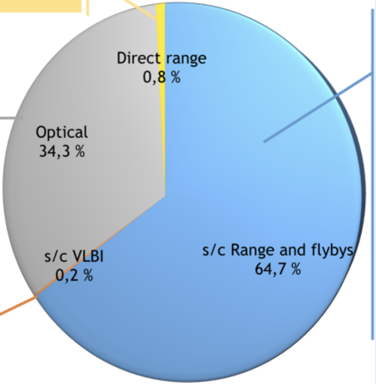







INPOP19a Planets

- 1965-1997
- Mercury,Venus
- *1 km*

- 1924-2014
- Jupiter, Saturn, Uranus, Neptune, Pluto
- planet and satellites
- 300 mas



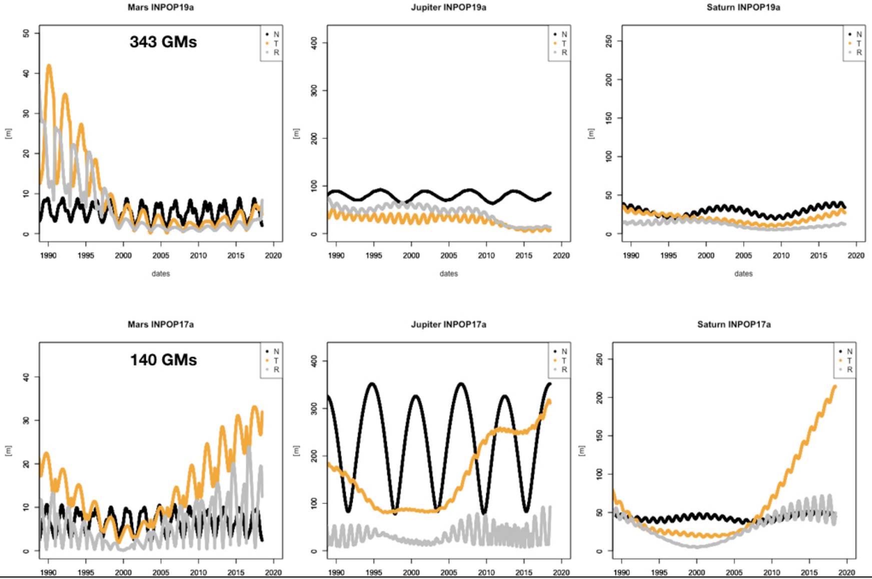
- 1990-2010
- Mars, Venus, Jupiter, Saturn
- 1 mas to 10 mas

- 1976-2018
- MEX, VEX (ESA)
- MRO, MO, Viking, Pathfinder (JPL)
- Mariner, Pioneer, Voyager, Ulysses, Galileo (JPL)
- MESSENGER
  - 2011-2014
  - Verma et al
- Cassini★
- JPL: 2004-2014
- LaS: 2006, 2008-2009, 2011 + 10 gravity flybys (2006-2017)
- Juno:★
  - JPL: 2016.6-2017.6
  - LaS: 2016.6-2018.6

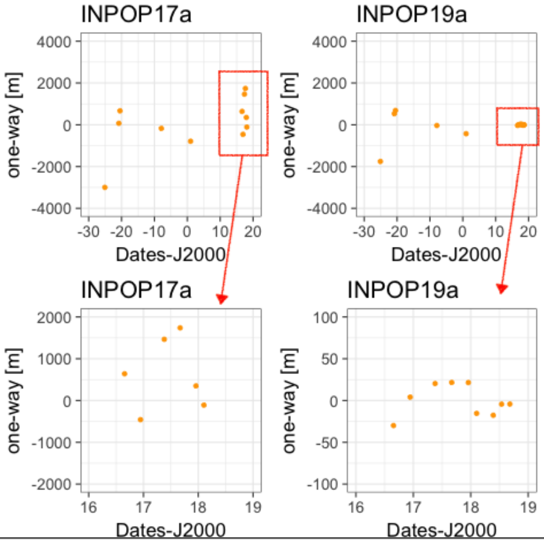
About the new solution INPOP19a

- INPOP19a data sets including Juno from 2016.65 ro 2018.6
- Cassini: 2004-2014 JPL data + Independant analysis (La Sapienza) for 3 years (2006, 2009, 2011) and 10 gravity flybys (including the 2017 Grand Finale)
- 2 specific data analysis for MESSENGER (Verma et al.)
- new IR LLR @ Calern from 2015 to now (Viswanathan et al.)
- Improved solar conjunction correction
- MCLS of 343 asteroid masses, planet initial conditions, GM sun, J2 sun, EMRAT
- 10 most massives TNO + TNO ring

Propagation of uncertainty in RTN



Juno and Jupiter

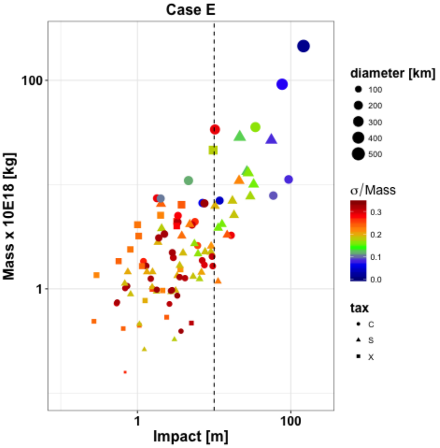


INPOP19a and asteroid masses (Fienga et al. 2019)

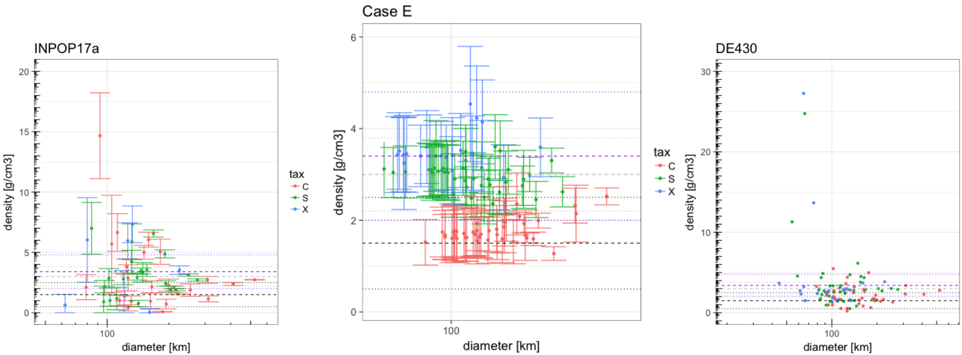
- MGS, MRO/MO, MEX data from 2002 to 2017.3
- New plasma correction

INPOP	MEX one-way [m]	MRO/MO one-way [m]
17a	1.55	1.26
19a	1.48	0.81

- 343 asteroid masses estimated with BVLS+MC
- 103 masses with $S/N > 33\%$ (23 GMs [KF13]))
- Using IR and optical spectra + uncertainties → Prior distribution of constraints
- 3700 MCLS runs for randomly selecting upper and lower bounds
- more than 90 % runs = MRO/MO (O-C) < 1m
- obtained masses = (mean, σ) mass posterior distribution



Asteroid mass: 19a versus 17a and DE430 (Fienga et al. 2019)



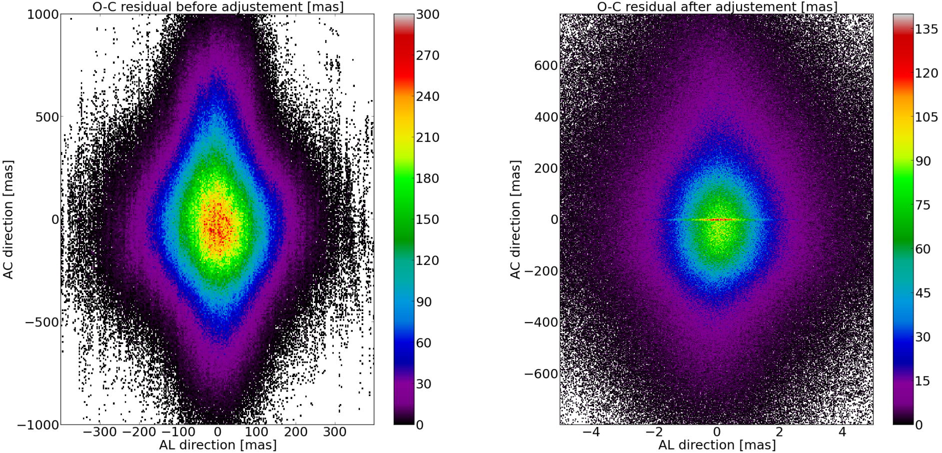
GAIA asteroids in INPOP

GAIA

- GAIA: ESA astrometric mission including SS objects
- GAIA DR2 (22 months of mission): Positions and epoch of observation of 14092 known Solar System objects mainly asteroids based on 1.98 million observations
- asteroid positions in the Gaia Reference frame
- Tie INPOP RF to GAIA RF with asteroid observations at the mas level

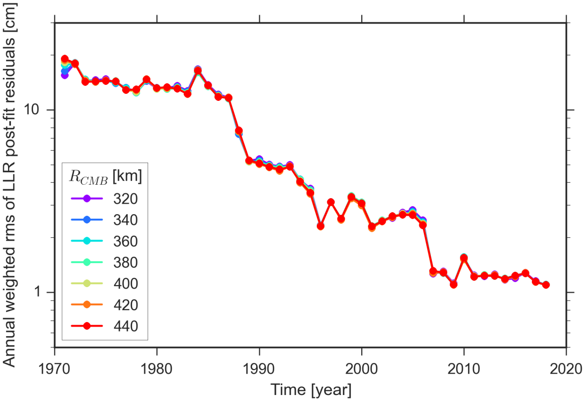
- Integration of GAIA asteroid orbits in INPOP (together with planets)
- Fit to GAIA observations including GAIA correlation matrix
- For INPOP19a delivery: Rotation Matrix between INPOP19(ICRF) versus INPOP19(GRF)
- for DR3: Tools for detecting efficient close encounters for mass determination

GAIA asteroids in INPOP



Results very similar to (Spoto et al.)

INPOP Earth-Moon system: (Viswanathan et al. 2019)



See (Rambaux et al.) Talk next

Testing GR with INPOP: SEP with LLR

Thermal expansion term

Reference	Data time span (Year)	Uncertainty	Estimated Δ_{ESM} ($\times 10^{-14}$)	Corrected $\cos D$ (mm)	Corrected Δ_{ESM} ($\times 10^{-14}$)	Parameter η^c ($\times 10^{-4}$)
Williams et al. (2009)[a]	1969–2004	N/A	3.0 ± 14.2	2.8 ± 4.1	-9.6 ± 14.2	2.24 ± 3.14
Williams et al. (2012)	1969–2011	N/A	0.3 ± 12.8	2.9 ± 3.8	-9.9 ± 12.9	2.25 ± 2.90
Müller et al. (2012)[a, b]	1969–2011	3σ	-14 ± 16	–	–	–
INPOP17A (limited data)	1969–2011	3σ	-3.3 ± 17.7	4.0 ± 5.2	-13.5 ± 17.8	3.03 ± 4.00
Hofmann & Müller (2016)[a]	1969–2016	3σ	–	–	-3.0 ± 6.6	0.67 ± 1.48
INPOP17A (green only)	1969–2017	3σ	5.2 ± 8.7	1.5 ± 2.6	-5.0 ± 8.9	1.12 ± 2.00
INPOP17A (green and IR)	1969–2017	3σ	6.4 ± 6.9	1.1 ± 2.1	-3.8 ± 7.1	0.85 ± 1.59

$$\Delta_{ESM} = (-3.8 \pm 7.1) \times 10^{-14}$$

$$\eta_N = (0.85 \pm 1.59) \times 10^{-4}$$

new interpretation: dilaton theory

V Viswanathan, A Fienga, O Minazzoli, L Bernus, J Laskar, M Gastineau;
The new lunar ephemeris INPOP17a and its application to fundamental physics,
Monthly Notices of the Royal Astronomical Society, Volume 476, Issue 2, 11 May 2018, Pages 1877–1888,
https://doi.org/10.1093/mnras/sty096

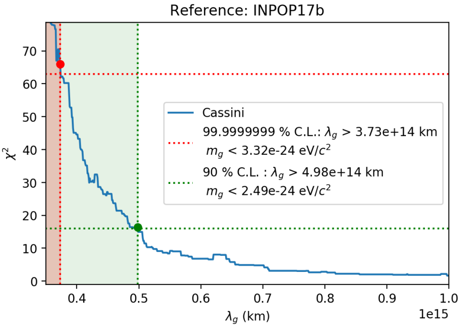
Testing GR with INPOP: Graviton (Bernus et al. 2019)

- Graviton theories (Will 2016) such as:

$$\ddot{x} = \frac{1}{2}\sum_P \frac{GM_P}{\lambda_g^2}\frac{x - x_P}{r} + \Theta(\lambda_g^{-3}),$$

where λ_g is the Compton length. $\lambda_g \approx \hbar/(c \times m_g)$.

- most sensitive data are Cassini for Saturn
- more realistic constraints of the possible mass of the graviton
- consistent with VIRGO/LIRGO in a different regime
- (Bernus et al. 2019, accepted in PRL)
- More is coming with INPOP19a



Perspectives

INPOP19a soon (before 2020) on www.imcce.fr/inpop

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- More Juno data, MRO/MO data analysis in progress, Cassini (GRGS, La Sapienza)

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- Simulation of Bepi-Colombo data analysis for GR (La Sapienza)

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- GAIA DR2: comparisons with radar observations (UCLA)...GAIA DR3

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- GAIA DR2: comparisons with radar observations (UCLA)...GAIA DR3
- Test GR with INPOP19a: PPN, gravity, dilaton (Bernus et al. in prep)

Thank you !