INPOP
planetary ephemeris
2004-2014
and
Constraints on gravitational models

A. Fienga, GéoAzur, OCA

J. Laskar, IMCCE, Obs. Paris

H. Manche, IMCCE, Obs. Paris

M. Gastineau, IMCCE, Obs. Paris

and

P. Kuchynka, A. Verma

Planetary ephemerides in the world

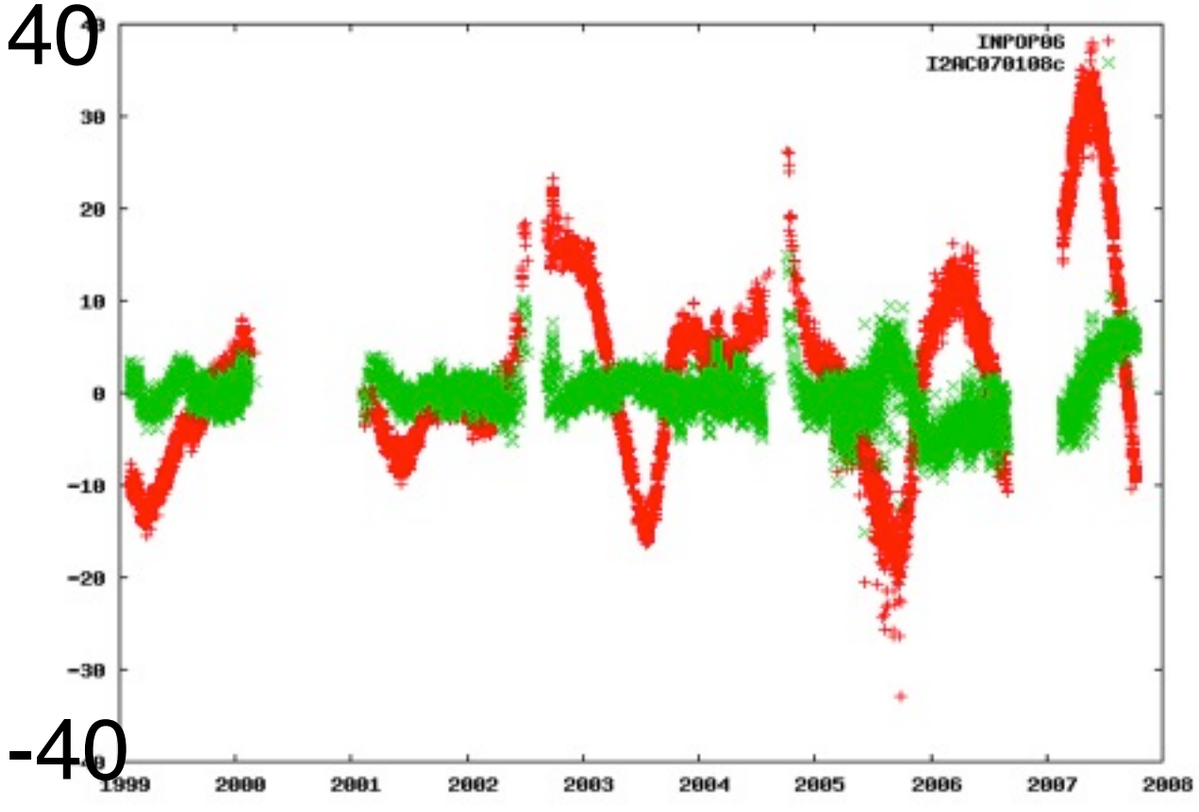
3 teams

DE	JPL	DE405 (Standish et al. 1998) DE421 (Folkner et al. 2008) DE423 (Konopliv et al. 2011)	JPL dedicated No flexibility for specific use
EMP	IAA	EMP20.. (Pitjeva 2009)	Very close from DE Limited Distribution
INPOP	IMCCE/ OCA	INPOP06 (Fienga et al. 2008) INPOP08 (Fienga et al. 2009) INPOP10a (Fienga et al. 2011) INPOP13x (in progress)	Scientific Use ESA ephemeris for GAIA Modification on request Long term (1Myr) IAU TT-TDB, $GM_\odot$

INPOP Evolution

INPOP08	4D planetary ephemerides : TT-TDB	54 Planet IC
(Fienga et al. 2009)	New method for fit (a priori sigma)	30 GM_{ast},3ρ,AU
TT-TDB 1st release	Fitted to planetary data and LLR	$J_2^{\odot}$,EMRAT
INPOP10a	289 asteroids, no mean density, ring	54 Planet IC
(Fienga et al. 2011)	Direct fit with constrains	145 GM_{ast},GM_{ring}
	Improvement of outer planet orbits	$GM_{\odot}$, $J_2^{\odot}$,EMRAT
Long-term La2010	Fixed AU	
INPOP10e	Direct fit with constrains + a priori sigma	54 Planet IC
(Fienga et al. 2013)	Solar corona studies and corrections	152 GM_{ast},GM_{ring}
(Verma et al. 2013a)	Improvement of Mars extrapolation	$GM_{\odot}$, $J_2^{\odot}$,EMRAT
GAIA last release	Use of raw MGS tracking data (GINS)	
INPOP13a	MESSENGER orbit determination	54 Planet IC
(Verma et al 2013b, ArXiv)		62 GM_{ast},GM_{ring}
Tests of GR	β, γ, $(\dot{G}/G)$	$GM_{\odot}$, $J_2^{\odot}$,EMRAT

Status of the INPOP Planetary Part: Mars and Venus



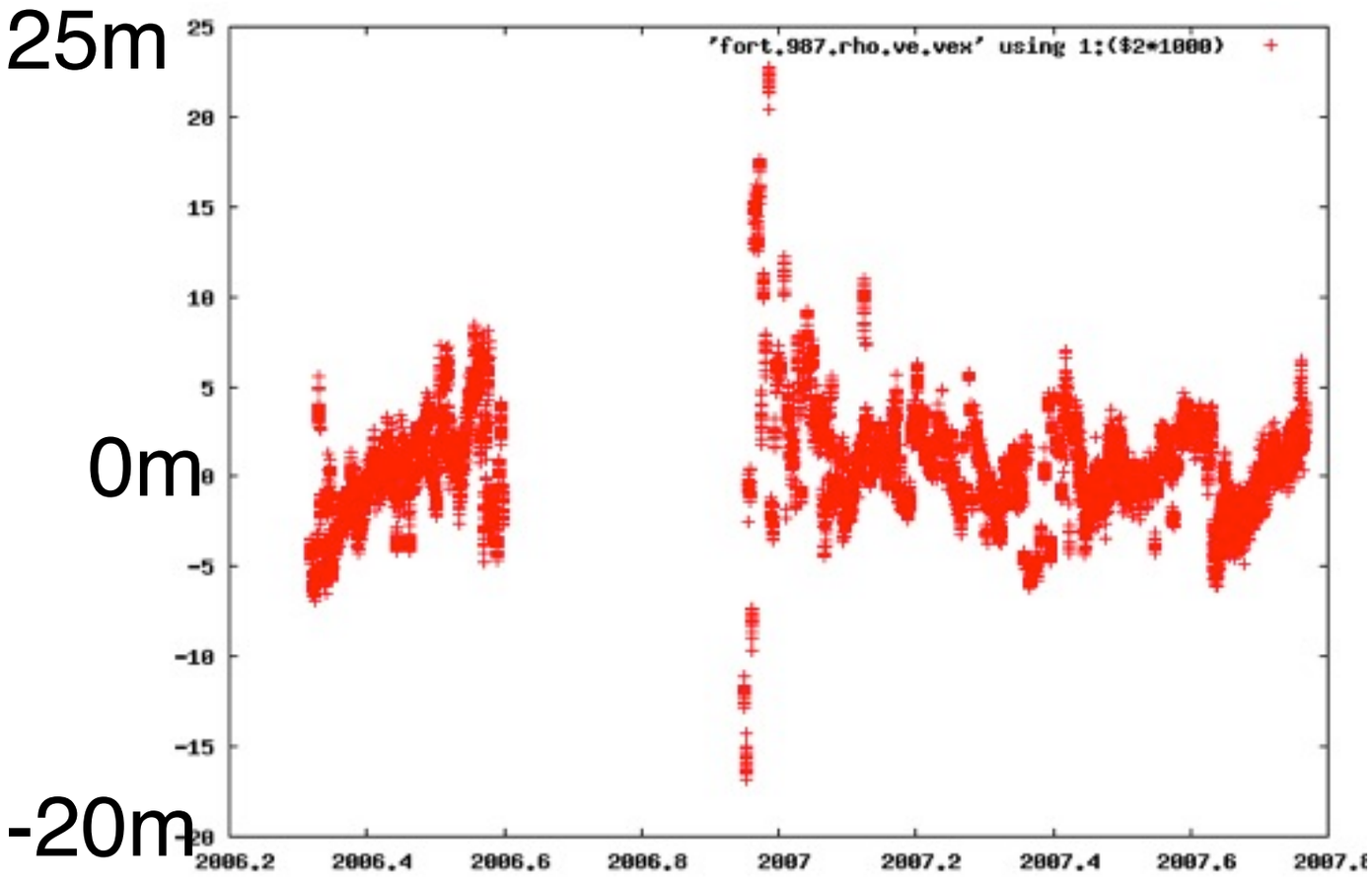
MGS/MEX residuals

INPOP06

INPOP07

VEX residuals

INPOP07



Fienga, Laskar, Morley, Manche, Kuchynka, Le Poncin-Lafitte, Budnik, Gastineau, Somenzi,, A&A, **2009**

Limits of solar system gravity tests with spacecraft tracking

- Accuracy $\approx$ 1 cm over 1 to 5 years
- deflection of light $\rightarrow \gamma$

- navigation unknowns (AMDs, solar panel, accelerations)
- planet unkowns (potential, rotation...)
- solar plasma
- correlation with planet ephemerides ?
- .. or a dedicated mission

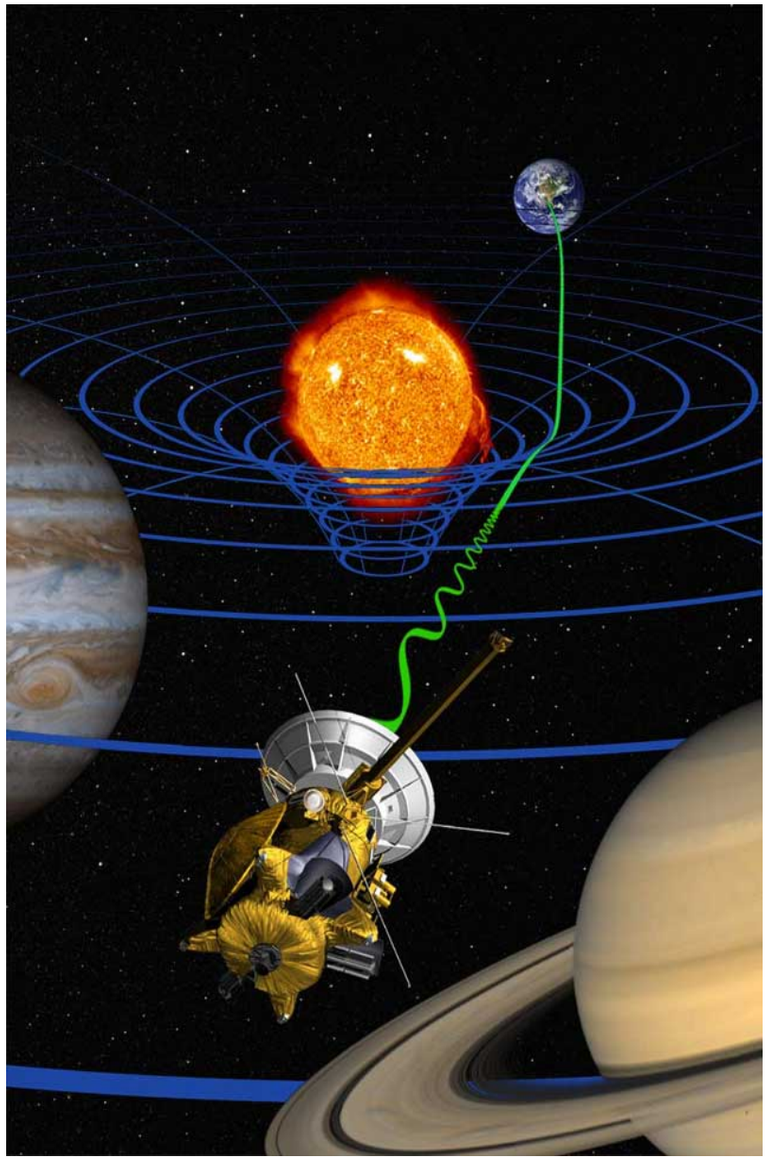
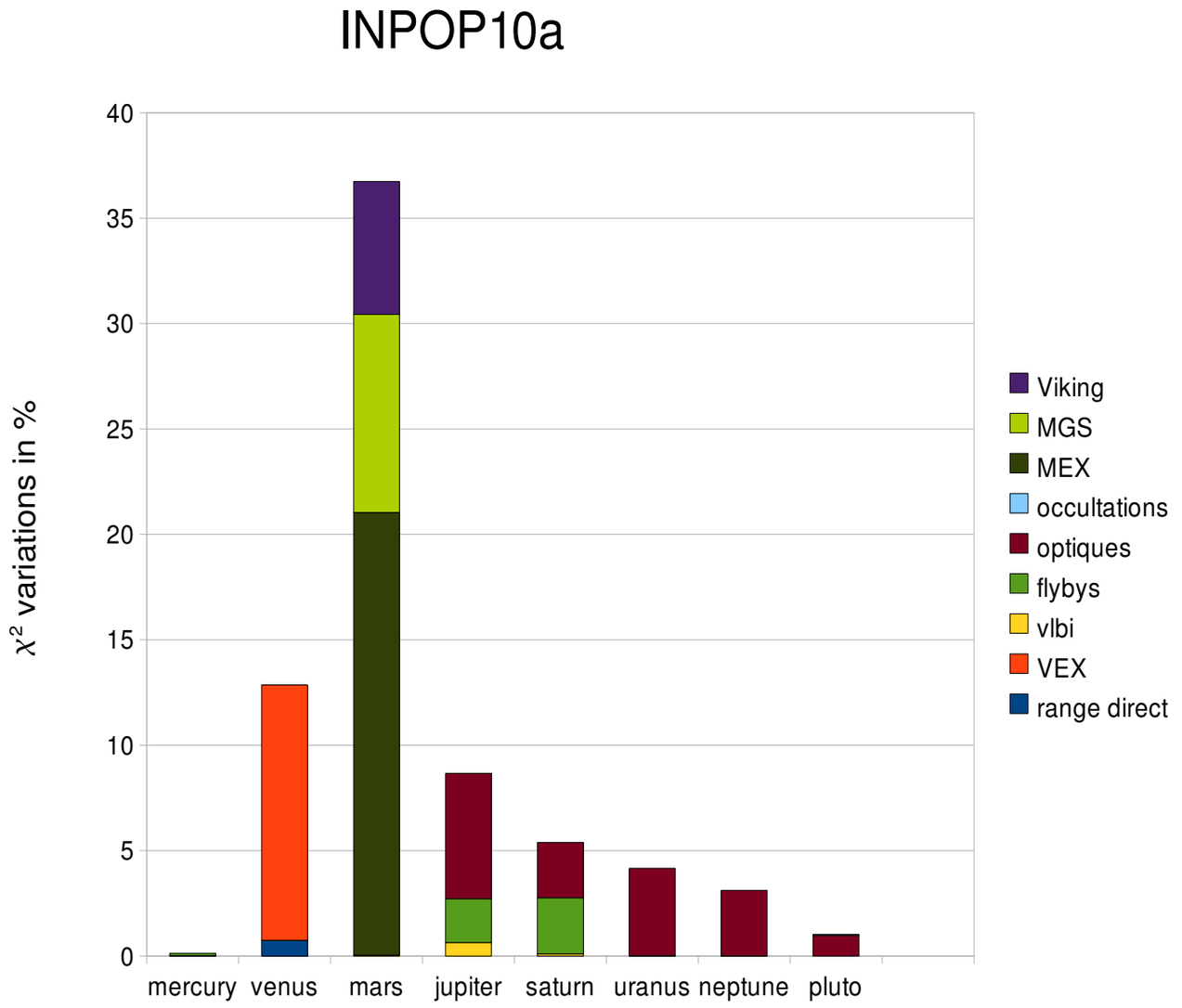


Figure : (Bertotti et al. 2003)
$(\gamma - 1) \times 10^4 = (0.21 \pm 0.23)$

Limits of solar system gravity tests with planetary ephemerides

- accuracy $\approx$ 2 m over 10 years (Earth-Mars)
- β, γ, Sun $J2$, $\dot{\varpi}$, $\dot{\Omega}$, $\dot{AU}$, $\dot{G}/G$

- Mars
- Dependence on spacecraft navigation



Grid of sensitivity for PPN β,γ determinations with INPOP (Fienga et al. 2009)

- method initialized with INPOP08: $\gamma = 1$, $J2$ and β varying
- with INPOP10a: J2 fixed, γ and β varying with (1) + (2)
- postfit residuals /INPOP $\rightarrow (\beta, \gamma)$ interval with Δ residuals $< 5\%$
- Several planets $\rightarrow$ decorrelation J_2 and PPN parameters
- $\Delta\dot{\varpi}$ + Shapiro delay $\rightarrow$ decorrelation β,γ

$$\Delta\dot{\varpi} = \frac{2\pi(2\gamma - \beta + 2)GM_\odot}{a(1-e^2)c^2} + \frac{3\pi J_2 R_\odot^2}{a^2(1-e^2)^2} \quad (1)$$

$$\Delta t = (1+\gamma)GM_\odot ln\frac{l_0 + l_1 + t}{l_0 + l_1 - t} \quad (2)$$

News: INPOP13a

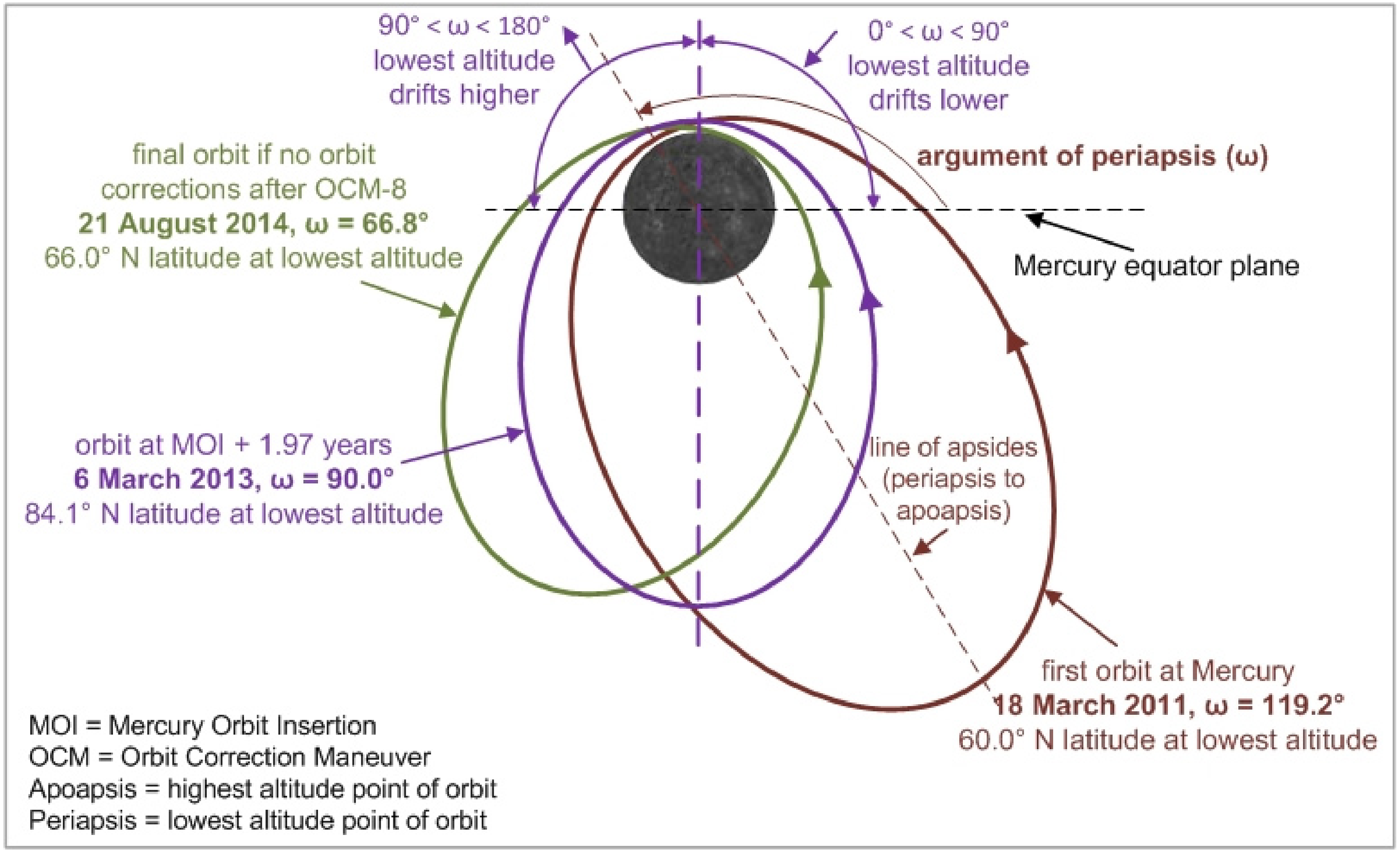
MESSENGER

- 1.5 yr of Doppler + range data (level 2) @ PDS
- Original orbit analysis with GINS software
- with hypothesis on Macro-model, maneuvers

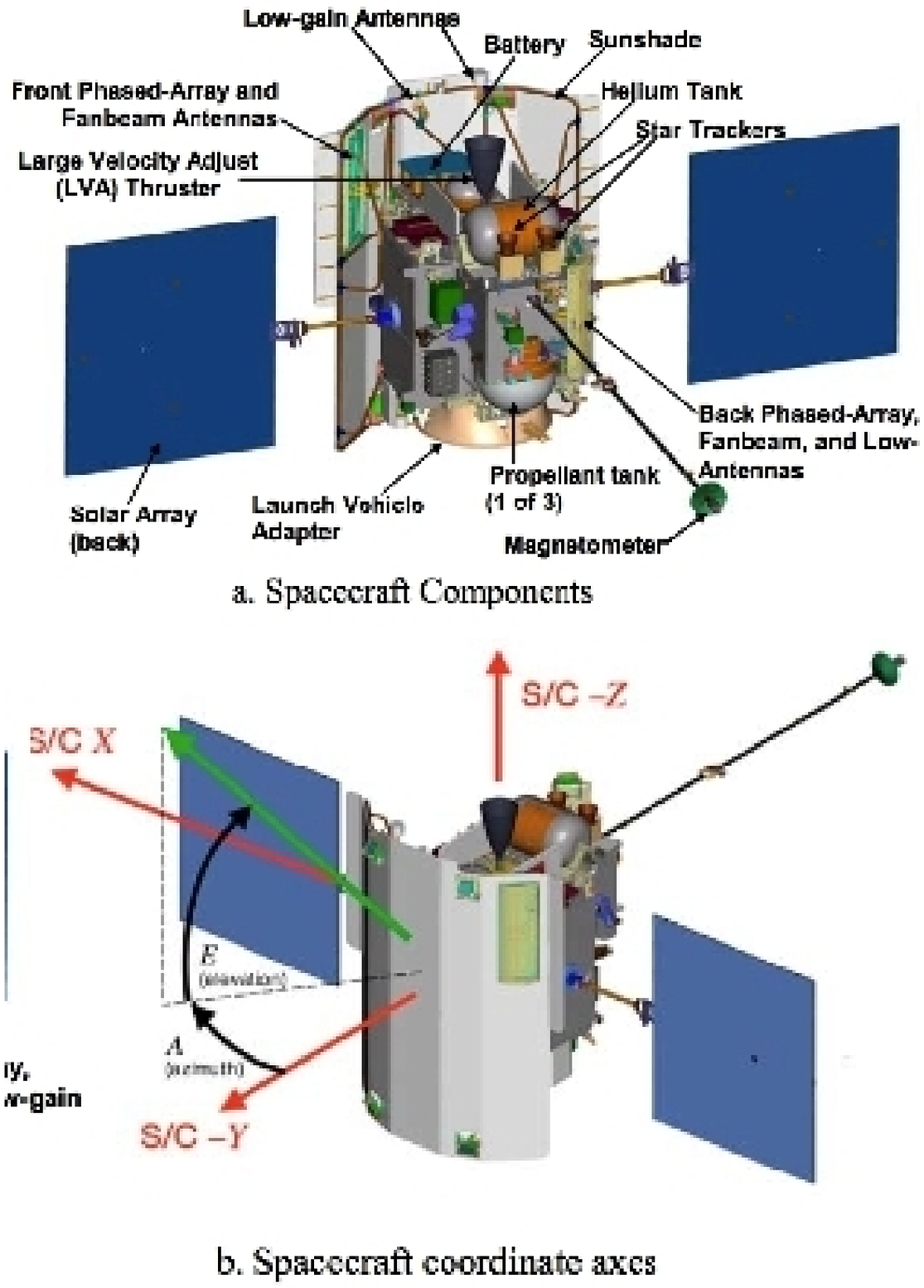
Results

- accurate orbit determination / (Smith et al. 2013)
- Full fit of all planets: INPOP13a
- new constrains over β, γ, $\frac{\dot{G}}{G}$
- A. Verma, A. Fienga, J. Laskar, H. Manche, M. Gastineau 2013, submitted

MESSENGER mission: 2 periods



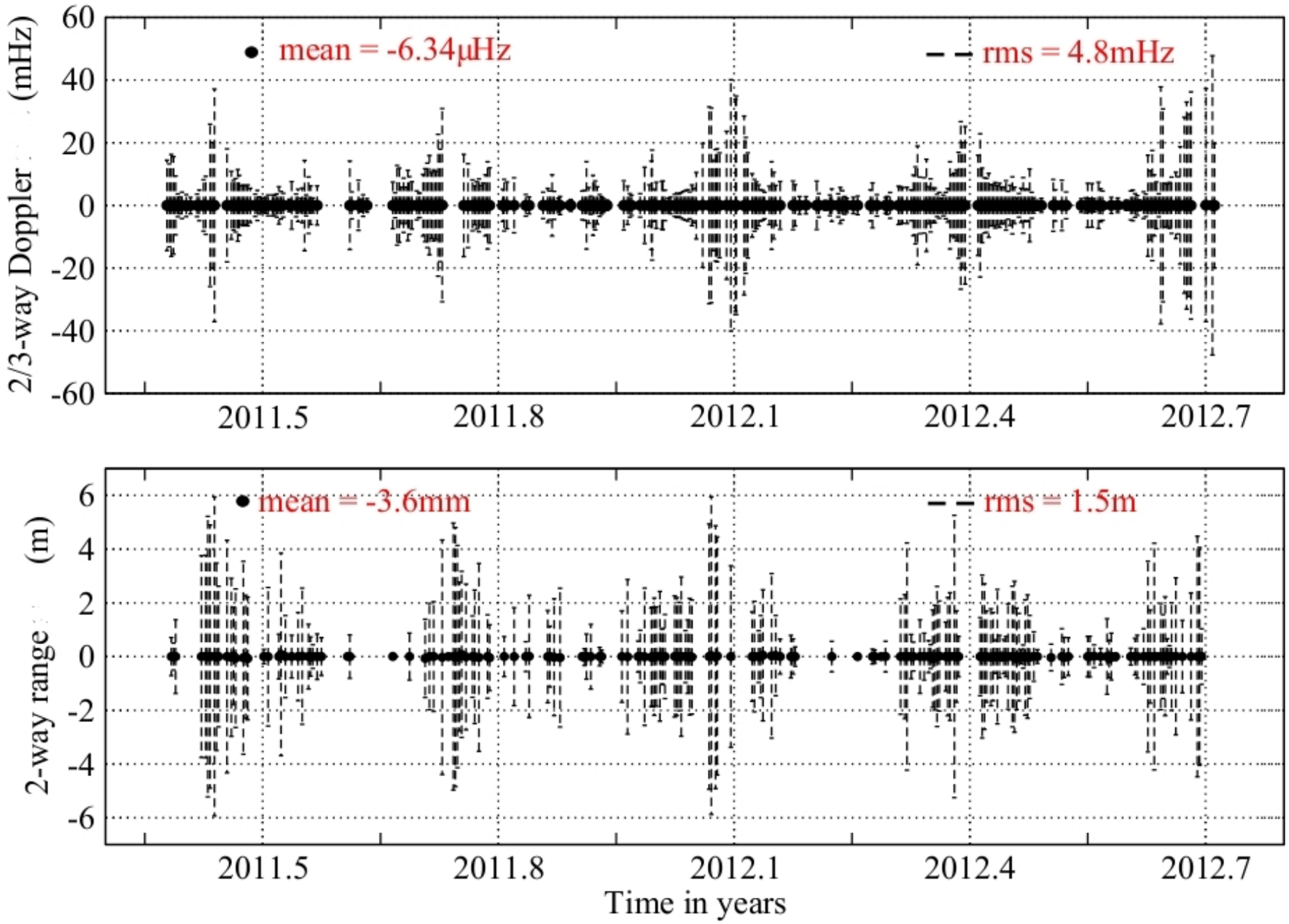
MESSENGER OD with GINS



Main characteristics:

1. GINS original multi-arc analysis
2. Rotation (Margot 2009) + gravity (Smith et al.,2012)
3. Macro-modele: Box-and-wings modele (Vaughan et al. 2006)
4. maneuvers: optimization of the data arc length $<$ period of maneuvers
5. 3+4 $\rightarrow$ 1-day data arc for the fit of each arc of orbit

MESSENGER OD results



Author	Doppler @ 10s	Range
Verma et al. 2013b	-0.00063±4.8 mHz	-0.003±1.5 m
Genova et al. 2013	-0.00088±3.6 mHz	-0.06±1.87 m
Smith et al. 2012	0.4±2.0 mm/s	-

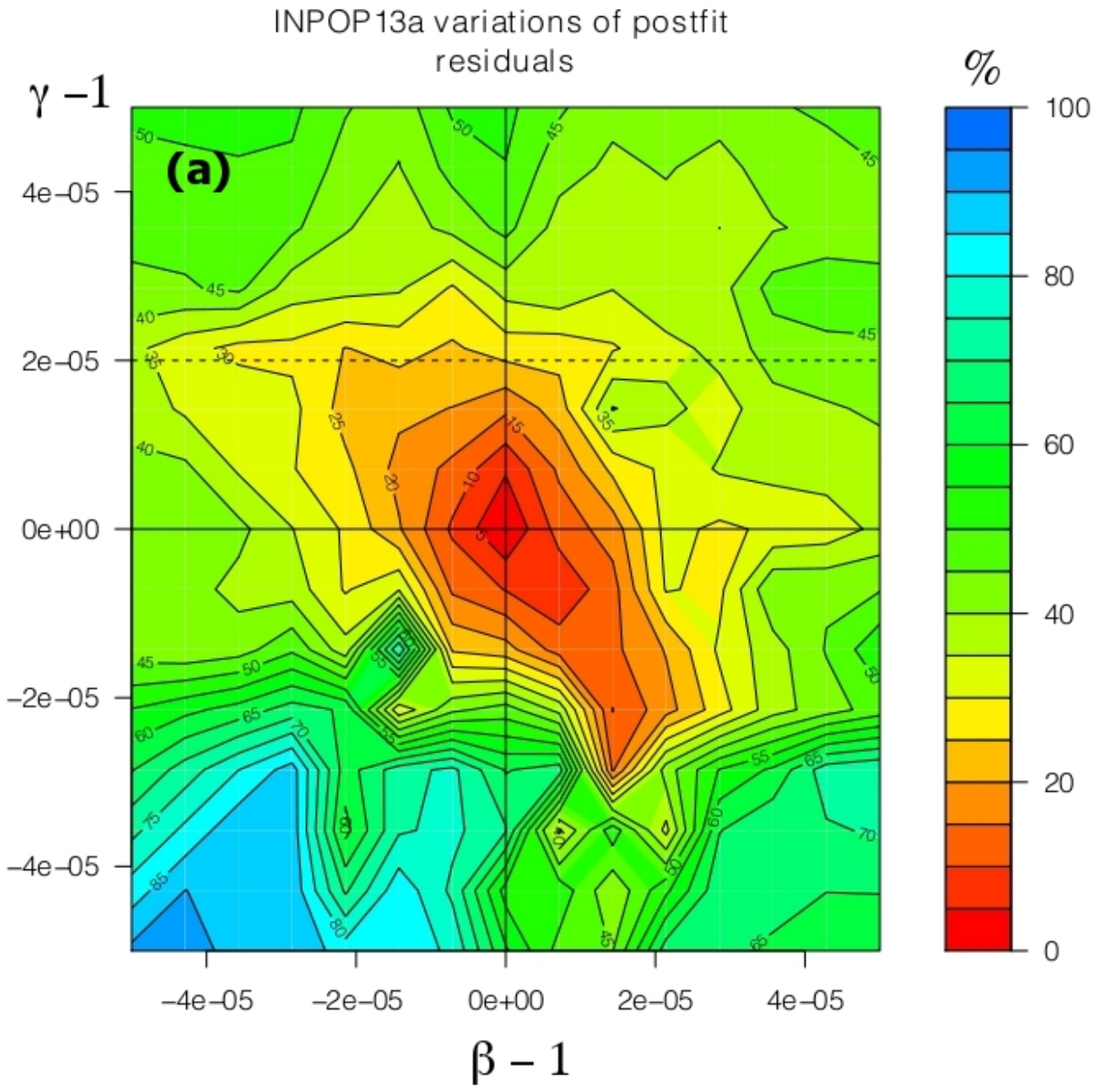
INPOP13a

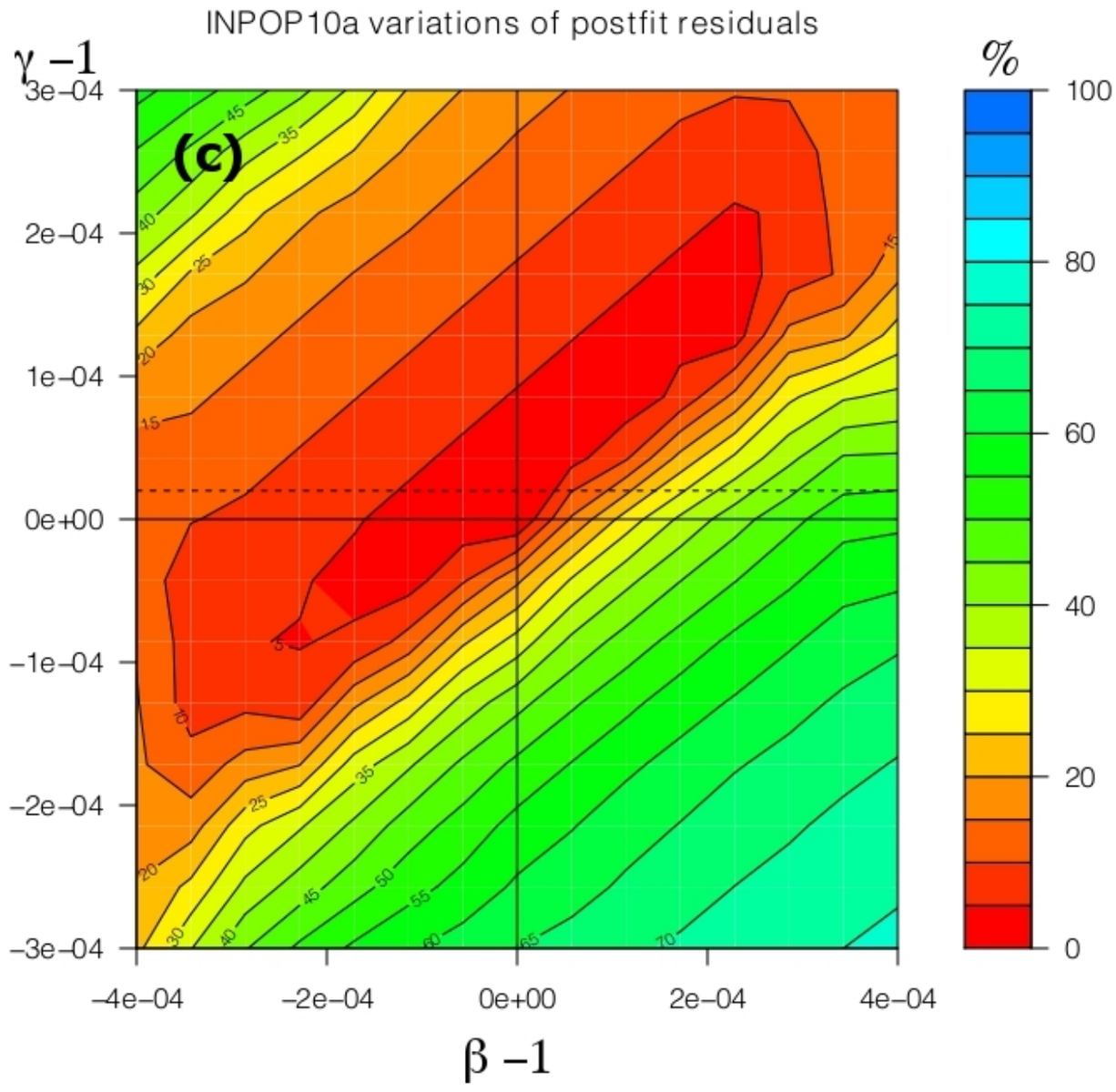
Construction

- same structure as INPOP10e (Fienga et al. 2013)
- Messenger range biais deduced from GINS OD
  $\rightarrow$ 314 data points from 2011.4 to 2012.6
- Refit over full data sets (INPOP10e + MSG)
  $\rightarrow$ 54 IC, $GM_\odot$, 62 GM_{ast}, $J_2{}^\odot$

	INPOP13a $\pm 2\sigma$	INPOP10e $\pm 2\sigma$	DE423 $\pm x\sigma$
$J_2{}^\odot \times 10^{-7}$	(2.40 ± 0.20)	(1.80 ± 0.25)	1.80 (2.0 ± 0.20) [P13] (2.1 ± 0.70) [DE430]
$GM_\odot$ - 132712440000 [$km^3.\ s^{-2}$]	(48.063 ± 0.4)	(50.16 ± 1.3)	40.944
GM(Ceres) [10^{12} x $M_\odot$]	468.430 ± 1.18	467.267 ± 1.85	473.485 ± 1.33
GM(Pallas)	103.843 ± 0.98	102.65 ± 1.60	103.374 ± 6.92
GM(Bamberga)	5.087 ± 0.19	4.769 ± 0.43	5.422 ± 1.00
GM(Metis)	3.637 ± 0.40	4.202 ± 0.67	4.524 ± 0.67

INPOP13a and tests of GR: PPN β and γ





Decorrelation + improvement of a factor 10

Bepi Colombo and Gaia

parameter	acc. @ 25%	Bepi Colombo	Gaia
γ	3×10^{-5}	2.5×10^{-6}	$< 10^{-6}$
β	3×10^{-5}	5×10^{-6}	$< 3 \times 10^{-4}$
Sun J_2	3×10^{-8}	2×10^{-9}	$10^{-7} - 10^{-8}$
$\dot{G}/G$	3×10^{-13}	3×10^{-13}	$\times 10^{-12} - \times 10^{-13}$