INPOP13a AND ITS APPLICATIONS FOR TESTING GRAVITY

A. FIENGA[1,2], A.K. VERMA[3,4], J. LASKAR[2], M. GASTINEAU[2], H. MANCHE[2]
[1] Observatoire de la Côte d'Azur, GéoAzur CNRS UMR-7329, Valbonne, France
[2] IMCCE, Paris Observatory, UPMC, univ. Lille1, CNRS, Paris, France
[3] Observatoire de Besançon, UTINAM CNRS UMR CNRS-6213, Besançon, France
[4] Centre National d'Etudes Spatiales, Toulouse, France
e-mail: agnes.fienga@oca.eu

ABSTRACT. The new INPOP13a planetary ephemerides constructed in using Messenger raw data is introduced. Improvements over Mercury and Earth orbits are presented as well as new constraints obtained for the Sun oblateness J_2, the Sun gravitational mass and the deviations to General relativity through the PPN parameters β and γ. Preliminary results for acceptable time variations of the gravitational constant G are also given.

1. INPOP13a

A full description of the analysis of the Messenger spacecraft raw data can be found in Verma et al. (2013) as well as the detailed description of the construction of the INPOP13a planetary ephemerides. We stress particularly in this presentation the results obtained for the PPN parameters β and γ and the Sun oblateness J_2. As Messenger is orbiting Mercury, the closed planet to the sun, its orbit is very sensitive to the gravitational potential of the sun and to possible violations of general relativity. The tracking data of Messenger and the deduced estimation of the Earth-Mercury distances are then very efficient to estimate the oblateness of the sun and acceptable non-unity or non-zero values of PPN parameters. Table 1 gives an overview of the improvements obtained with INPOP13a such as a two order of magnitude improvement in the estimations of the geocentric distances of Mercury, a factor 3 improvement in the estimation of $GM_\odot$ and a reduction of 25% in the uncertainty of $J_2^\odot$.

Table 1: Most significant determinations of parameters done with INPOP13a in comparisons with INPOP10e (Fienga et al. 2013), DE423 (Folkner 2010) and DE430 (Williams et al. 2013). The $GM_\odot$ line gives values of $GM_\odot$ - 132712440000. The line labeled MSG range gives the residuals obtained by comparisons between the Mercury-Earth distances deduced from the raw tracking of Messenger and the one deduced from the corresponding ephemerides. Intervals of $\beta - 1$ and $\gamma - 1$ correspond to values inducing modifications of postfit residuals below 25% in comparison to INPOP13a residuals.

	INPOP13a	INPOP10e	DE423	DE430
	± 1σ	± 1σ	± 1σ	± 1σ
$J_2^\odot \times 10^{-7}$	(2.40 ± 0.20)	(1.80 ± 0.25)	1.80	(2.10 ± 0.70)
$GM_\odot$ [km^3. s^{-2}]	(48.063 ± 0.4)	(50.16 ± 1.3)	40.944	41.94
(EMRAT - 81.3)$\times 10^4$	5.770 ± 0.020	5.700 ± 0.020	5.694 ± 0.015	5.691 ± 0.024
MSG range [m]	-0.4 ± 8.4	6.2± 205	3.8 ± 106	-0.5 ± 41.9
	INPOP13a	INPOP10a	DE423	Cassini (Bertotti et al. 2003)
$(\beta - 1) \times 10^5$	0.2 ± 2.5	-6.2 ± 8.1	4 ± 24	
$(\gamma - 1) \times 10^5$	-0.3 ± 2.5	4.5 ± 7.5	18 ± 26	2.1 ± 2.3

The use of Messenger data allows also to improve drastically the quality of the estimations of acceptable intervals of values for PPN β and γ different from 1. Based on the method presented in [2] we obtained new maps of acceptable violations (cf. Fig 1 and Table 1) showing the reduction of one order of magnitude in the size of acceptable intervals in $\beta - 1$ and $\gamma - 1$ but also the better disentangling of the two determinations compared to the one obtained with INPOP10a. Table 1 gives the obtained acceptable intervals of β and γ for a 25% modification of the postfit residuals.

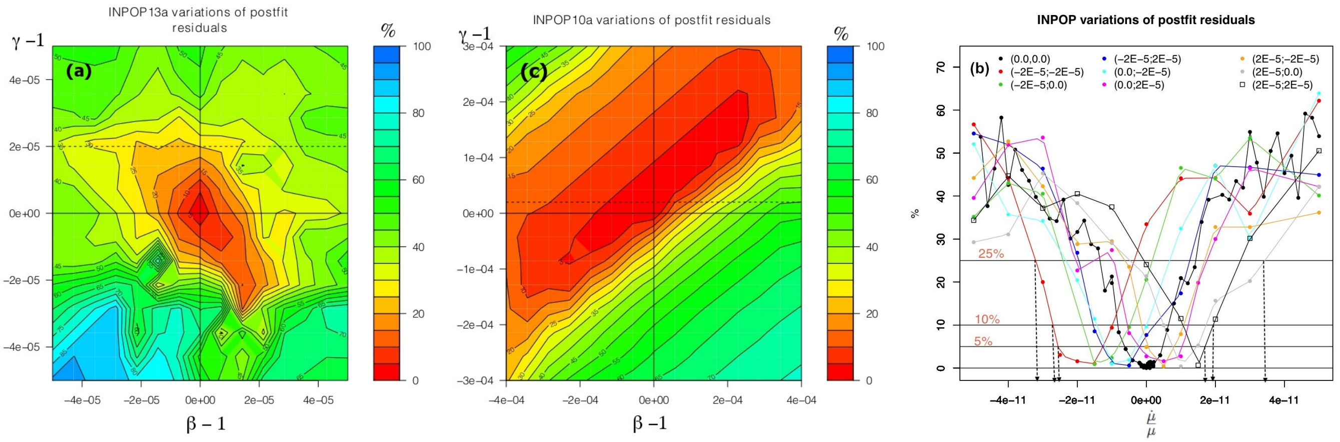

Figure 1: Panels a and c: Variations in postfit residuals obtained for different values of PPN β (x-axis) and γ (y-axis). Panel b: Variations in postfit residuals (% in y-axis) obtained for different values of $\dot{\mu}/\mu$.

Table 2: Comparisons of $\dot{G}$/G values found in the literature and values obtained with INPOP13a considering $\beta = \gamma = 1$ and $\beta \neq \gamma \neq 1$ with $\eta (= 4 \times \beta - \gamma - 3) = (1.05 \pm 12.55) \times 10^{-5}$.

Method	$\dot{G}$/G $\times 10^{13}$ yr^{-1}	Method	$\dot{G}$/G $\times 10^{13}$ yr^{-1}
LLR	(4 ± 9)	EMP (Pitjeva & Pitjev 2013)	$(0.166 \pm 0.724)^*$
Binary pulsar	(40 ± 50)	DE (Konopliv et al. 2011)	$(1.0 \pm 1.6)^{**}$
Helioseismology	(0 ± 16)	INPOP $\beta = \gamma = 1$	$(0.72 \pm 1.71)^*$
Big Bang nucleo.	(0 ± 4)	INPOP $\beta \neq \gamma \neq 1$	$(1.30 \pm 1.46)^*$
Planck +WP+BAO	(-1.42± 2.48)		

$^*\dot{M}_\odot/M_\odot = (-0.67 \pm 0.31) \times 10^{13}$ yr^{-1} $^{**}\dot{M}_\odot/M_\odot = -0.9 \times 10^{13}$ yr^{-1}

2. PRELIMINARY RESULTS FOR $\dot{G}/G$

The equations introducing possible time variations of the gravitational constant G have been introduced in the INPOP integration of the planetary equations of motion in considering :

$$\begin{aligned}
\frac{\dot{\mu}}{\mu} &= \frac{\dot{G}}{G} + \frac{\dot{M}_\odot}{M_\odot} \\
M_\odot(t) &= M_\odot(t_0) + (t - t_0) \times \dot{M}_\odot \\
G(t) &= G(t_0) + (t - t_0) \times \dot{G} \\
\mu(t) &= G(t) \times M_\odot(t).
\end{aligned}$$

Following the idea of the PPN β and γ estimations, several planetary ephemerides have been built and adjusted to observations considering different values for $\dot{G}/G$. A first step was to introduce the non-zero values of G with β and γ equal to unity. This approach is the one used by previous authors such as Pitjeva & Pitjev (2013) and Konopliv et al. (2011). Results and comparisons with the previous estimations can be found in Table 2. A second approach was to modify the values of the 3 parameters β, γ and $\dot{G}/G$ in the same time. For a seek of simplification, the changes of β and γ are given with the PPN parameter $\eta = 4 \times \beta - \gamma - 3$. Considered modifications of β and γ led to variations of η of about $(1.05 \pm 12.55) \times 10^{-5}$. New competitive constraints given in Table 2 were found but also new correlations between these parameters (Figure 1). Since then, deeper investigations based on Monte-Carlo simulations for β, γ, $J_2^\odot$ and $\dot{G}/G$ were investigated and will be intensified in using denser computations.

3. REFERENCES

Bertotti B., Iess L., and Tortora P., 2003, A test of general relativity using radio links with the Cassini spacecraft., Nature, 374–376.

Fienga A., Laskar J., Manche H., Kuchynka P., Desvignes G., Gastineau M, ., and Cognard I., 2011, The planetary ephemerides INPOP10a and its applications in fundamental physics., Celest. Mech. Dyn. Astr. 111, 363.

Fienga A., Manche H., Laskar J., Gastineau M., and Verma A.K., 2013, INPOP new release: INPOP10e. ArXiv e-prints 1301.1510.

Folkner W. M., 2010, Planetary ephemeris DE423 fit to Messenger encounters with Mercury., JPL interoffice memorandum IOM 343R-10-001 .

Konopliv A.S., Asmar S.W., Folkner W.M., Karatekin O.,Nunes D.C., Smrekar S.E., Yoder C.F., and Zuber M.T., 2011, Mars high resolution gravity fields from MRO, Mars seasonal gravity, and other dynamical parameters, Icarus 211, 401–428.

Pitjeva E. V., and Pitjev N. P., 2013, Relativistic effects and dark matter in the Solar system from observations of planets and spacecraft., MNRAS 432, 3431–3437.

Verma A.K., Fienga A., Laskar J., Manche H., and Gastineau M., 2013, Use of MESSENGER radioscience data to improve planetary ephemeris and to test general relativity, A&A 561, A115 (2014)

Williams J., Boggs D., and Folkner W., 2013, DE430 lunar orbit, physical librations, and surface coordinates., JPL JPL interoffice memorandum IOM 335-JW,DB,WF-20130722-016