THE GEODESIC PRECESSION IN THE INPOP EPHEMERIDES

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ABSTRACT. The INPOP ephemerides include the eight planets, Pluto and the Moon, and are fitted to planetary observations (and to Lunar Laser Ranging data for the version currently in development). They also integrate the Earth orientation. Compared to INPOP06 (Fienga et al., 2008), the next version takes into account the geodesic precession for the Earth and for the Moon. We present here some comparisons with analytical theories of the Earth rotation and the consequences on LLR computations.

Warning: All the INPOP solutions presented here, except INPOP06, are working versions. The numbering from INPOP08_b1 to INPOP08_b5 is valid only inside this paper, to facilitate comparisons. In particular, the following INPOP08_bx solutions are not exactly the one that is described in this volume by Fienga et al. in "Evolution of INPOP planetary ephemerides".

1. THE GEODESIC PRECESSION FOR THE EARTH

Together with the equations of motion of the bodies of the Solar System, INPOP integrates a model of Earth orientation for the computations of interactions between the Earth and other bodies due to its non spherical potential (figure effects). It should be noted that for the reduction of the observations, the more precise IAU2000 model is used. By integrating a spin model for the Earth, the precession-nutation evolution is consistent with the planetary and lunar motions, and integrations are not limited by the polynomial development of the precession.

The orientation of the Earth in the dynamical part of INPOP08_b1 (solution close to INPOP06) is modellized by its angular momentum $\vec{G}$. Its time derivative is equal to the sum of all external torques exerted upon the Earth, and then is solution of the differential equation:

$$\dot{\overrightarrow{G}} = \sum_{bodies} \left(\overrightarrow{M}_2 + \overrightarrow{M}_3 + \overrightarrow{M}_4 + \overrightarrow{M}_{tides}\right) \tag{1}$$

In this expression, $\overrightarrow{M}_i$ are the torques due to the zonal coefficients J_i of the Earth potential ($\overrightarrow{M}_3$ and $\overrightarrow{M}_4$ were neglected in INPOP06) and $\overrightarrow{M}_{tides}$ is the torque due to the deformation of the Earth raised by the Moon and the Sun (solid tides).

Initial conditions and the C/MR^2 ratio are fitted to the CIP-P03 coordinates over a period of 200 years around J2000. The CIP-P03 is the unit vector computed with the precession of Capitaine et al. (2003) and the nutations of Mathews et al. (2002).

The left side of Fig.1 (black curves) shows the differences between the orientation of the Earth integrated in INPOP08_b1 (X and Y coordinates of the unit vector $\overrightarrow{G}/\|\overrightarrow{G}\|$) and the CIP-P03.

The discrepancies between INPOP08_b1 and CIP-P03 are mainly due to the transformation function of Mathews from solid to non-rigid Earth and to the different nature of the pole compared: the CIP-P03 is related to the figure-axis of the Earth, whereas $\overrightarrow{G}$ is the angular momentum. Instead of comparing $\overrightarrow{G}$ to the CIP-P03, one defines REN2000-P03 as the pole computed with the precession of Capitaine et al. (2003) and with the angular momentum nutations of REN2000 (Souchay et al., 1999), converted to the

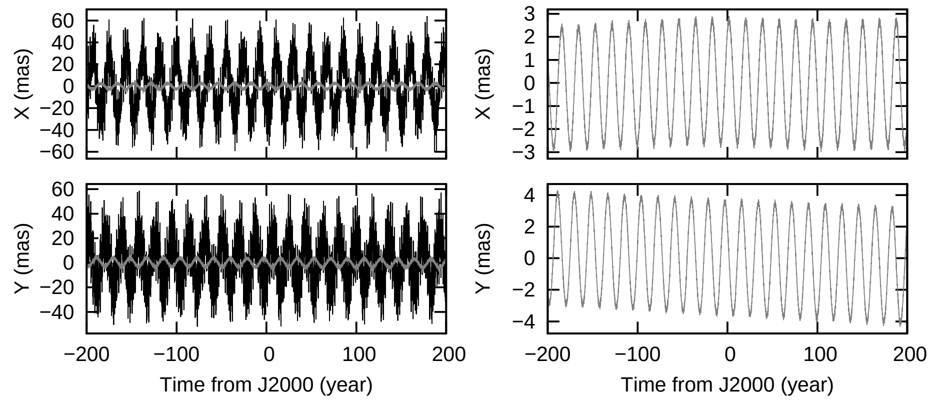

Figure 1: These curves show the discrepancies between INPOP08_b1 (or INPOP06) and analytical solutions for the Earth rotation (CIP-P03 in black, REN2000-P03 in grey). On the right side, the discrepancies between INPOP08_b1 and REN2000-P03 are plotted with a more convenient scale than on the left side. X and Y are the GCRS coordinates of the Earth's pole, expressed in milliarcsecond over a period of 200 years around J2000.

same dynamical ellipticity as IAU2000/P03. REN2000 is the rigid Earth theory on which the IAU 2000 nutation is based.

On Fig.1 (grey curves), one can see that the pole computed in INPOP08_b1 is much closer to REN2000-P03 than to CIP-P03. But there is still a small periodic signal, whose period is 18.6 years.

To reduce this signal, we introduced the geodesic precession, which was omitted in INPOP08_b1. If the Earth is considered as a point mass gyroscope, the geodesic precession can be modelized as an additional torque in the angular momentum equation (see Misner et al., 1973):

$$\dot{\overrightarrow{G}} = \sum_{bodies} \left(\overrightarrow{M}_2 + \overrightarrow{M}_3 + \overrightarrow{M}_4 + \overrightarrow{M}_{tides} \right) + \frac{1+\gamma}{2} \sum_{bodies} \frac{\mu}{c^2 r^3} \left(\vec{v}_E \wedge \vec{r} \right) \wedge \overrightarrow{G} \tag{2}$$

In this expression, μ is the product of the gravitational constant G by the mass of the body, c is the light velocity, $\vec{r}$ is the Earth-Body position vector and $\vec{v}_E$ is the barycentric velocity vector of the Earth. In fact, only the Solar contribution is taken into account, the next one (Lunar), which is 1000 times lower, has been neglected. Without any change of parameter (same initial conditions and C/MR^2 value), the solution INPOP08_b2 is built from INPOP08_b1 by adding the geodesic precession.

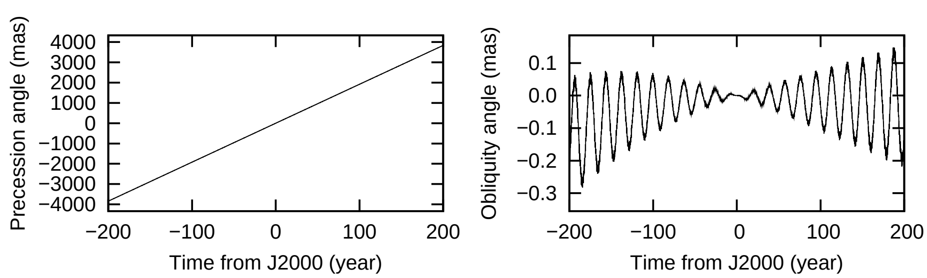

Figure 2: Comparison between the INPOP solutions for Earth rotation with and without the geodesic precession (respectively INPOP08_b2 and INPOP08_b1). The precession angle and the obliquity angle are expressed in milliarcsecond over a period of 200 years around J2000.

The main effect is observed on the precession angle, where the geodesic precession induces a linear drift (see Fig. 2). The slope is measured to 1.9193 arcsecond per century, and is close to the value from Brumberg et al. (1992). Because of this drift, initial conditions, and mainly the C/MR^2 ratio need to be changed. After a new fit on REN2000-P03 coordinates, one obtains INPOP08_b3, and the curves Fig.3 show the improvement.

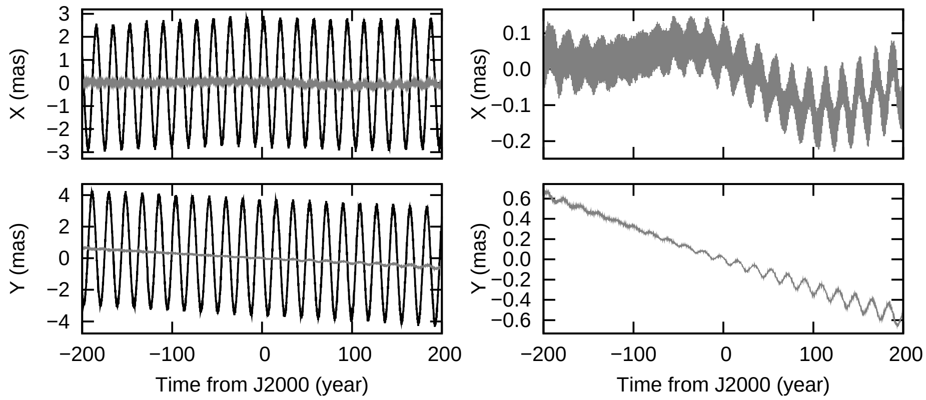

Figure 3: These curves show the discrepancies between REN2000-P03 and INPOP08_b1 (in black), and between REN2000-P03 and INPOP08_b3 (in grey, both on left and right sides). X and Y are the GCRS coordinates of the Earth's pole, expressed in milliarcsecond over a period of 200 years around J2000.

2. THE GEODESIC PRECESSION FOR THE MOON

Once the geodesic precession has been taken into account for the Earth, similar torques can be added to the angular momentum equation of the Moon:

$$\dot{\vec{G}} = \sum_{bodies} \left(\vec{M}_{C_{nm}} + \vec{M}_{S_{nm}} + \vec{M}_{tides} \right) + \frac{1+\gamma}{2} \sum_{bodies} \frac{\mu}{c^2 r^3} \left(\vec{v}_M \wedge \vec{r} \right) \wedge \vec{G} \tag{3}$$

In this expression, $\vec{M}_{C_{nm}}$ and $\vec{M}_{S_{nm}}$ are the torques exerted by bodies upon the Moon due to the potential coefficients C_{nm} and S_{nm} (the Moon is not considered to have a revolution symmetry), $\vec{M}_{tides}$ is the torque due to the deformation of the Moon raised by the Earth and the Sun (solid tides), and the last term is similar to the one seen earlier for the Earth. The contributions of both the Sun and the Earth (only 100 times lower) are here taken into account. INPOP08_b4 is built from INPOP08_b3, with the geodesic precession for the Moon, without any change of parameter.

The effect on LLR residuals depends on the location of the reflector, as it is shown on Fig.4. For Apollo XI (and for Apollo XIV, which is not shown in the figure), one can see that the effect of the geodesic precession (upper center plot) is not significant compared to the residuals (upper left corner). But for Lunakhod2 (the results are similar for Apollo XV), the geodesic precession induces a signal (see bottom center plot) that is not negligible when compared to LLR residuals (bottom left corner). Therefore, a new fit of parameters on LLR data is needed, leading to INPOP08_b5. After fit, the differences between INPOP08_b1 and INPOP08_b5 (right side of Fig.4) are small when compared to LLR residuals (left side of Fig.4).

Finally, Fig.5 shows the INPOP08_b1 LLR residuals for the Grasse and MLRS2 ground stations (black dots). The discrepancies between INPOP08_b1 and INPOP08_b5 (both fitted to LLR data) do not exceed 2 millimeters (gray dots), and the two solutions have the same standard deviation (4.75 cm for Grasse, 4.07 cm for MLRS2 before J2000 and 6.60 cm for MLRS2 after J2000).

3. CONCLUSION

In conclusion, taking into account the geodesic precession for the Earth is necessary as it is shown by comparing with analytical solutions like REN2000-P03. The same correction applied to the Moon librations does not improve the LLR residuals: the effect is not negligible, but can be fitted with a change of parameters.

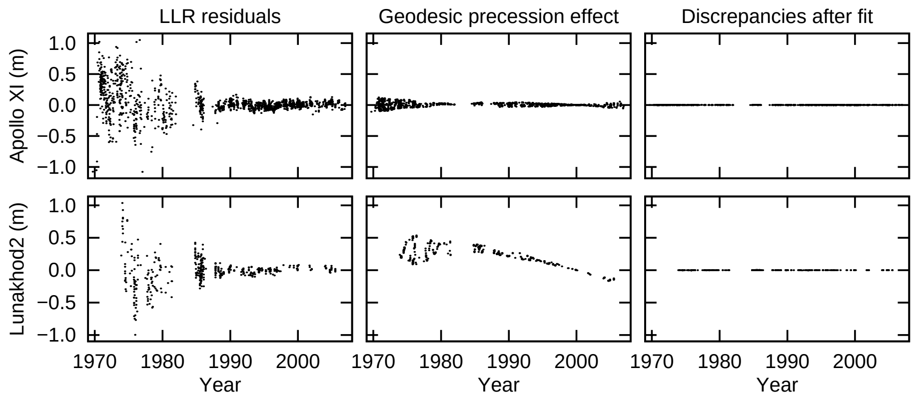

Figure 4: On the left side are shown the LLR residuals (in meter) for Apollo XI and Lunakhod2 reflectors computed with INPOP08_b1 (same as for INPOP08_b3). On the center column is shown, at the same scale and for the same dates of observations, the effect of the geodesic precession for the Moon (difference between INPOP08_b3 and INPOP08_b4). The right column show the differences between the two solutions fitted to LLR observations INPOP08_b1 and INPOP08_b5, respectively without and with the geodesic precession for the Moon.

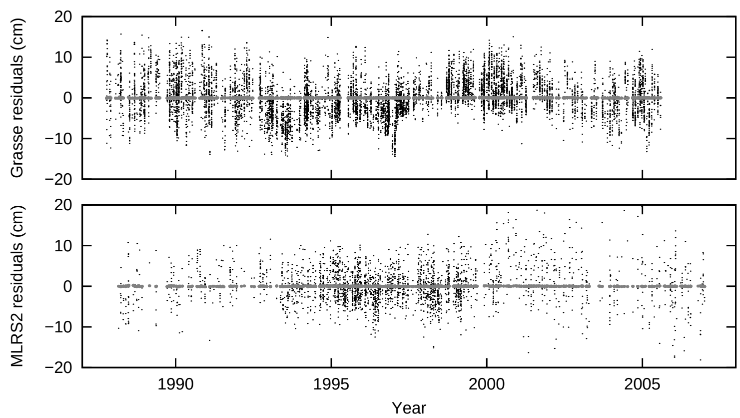

Figure 5: LLR residuals (in centimeters) for Grasse and MLRS stations, computed with INPOP08_b1 (in black). The discrepancies between INPOP08_b1 and INPOP08_b5 are shown in gray.

4. REFERENCES

Brumberg, V. A., Bretagnon, P., Francou, G., 1992, Proceedings of the Journées 1991 "Systèmes de référence spatio-temporels", N. Capitaine ed., Observatoire de Paris, pp. 141-148

Capitaine, N., Wallace, P. T., Chapront, J., 2003, "Expressions for IAU2000 precession quantities", A&A 412, pp. 567-586

Fienga, A., Manche, H., Laskar, J., Gastineau, M., 2008, "INPOP06: a new numerical planetary ephemeris", A&A 477, pp. 315-327

Fienga, A., Laskar, J., Kuchynka, P., Manche, H., Gastineau, M., Somenzi, L., 2009, "Evolution of INPOP planetary ephemerides", this volume

Mathews, P. M., Herring, T. A., Buffett, B. A., 2002, "Modeling of nutation-precession: New nutation series for non-rigid Earth, and insights into the Earth's interior", J. Geophys. Res. , 107 (B4), doi: 10.1029/2001JB000390

Misner, C. W., Thorne, K. S., Wheeler, J. A., 1973, "Gravitation", San Francisco: W.H. Freeman and Co, pp. 1118-1119

Souchay, J., Loysel, B., Kinoshita, H., Folgueira, M., 1999, "Corrections and new developments in rigid Earth nutation theory", A&AS 135, pp. 111-131