THE **NE**TLANDER **I**ONOSPHERE AND **G**EODESY **E**XPERIMENT (NEIGE).
COMPARISON BETWEEN THE NUTATIONS OF THE EARTH AND OF THE PLANET MARS.

V. DEHANT(1), J.P. BARRIOT(2), T. VAN HOOLST(1), P. DEFRAIGNE(1), M. YSEBOODT(1), and F. ROOSBEEK(1)
(1) Royal Observatory of Belgium
3 avenue Circulaire, B-1180 Brussels, Belgium
e-mail: dehant@oma.be
(2) Observatoire Midi-Pyrénées
14 avenue E. Belin, F-31400 Toulouse, France

ABSTRACT. The NEtlander Ionosphere and Geodesy Experiment (NEIGE) will be launched to the planet Mars in 2007. One of the objectives of this experiment is to get the nutations of Mars. The planets Earth and Mars are very similar. They both have precession and nutations. This paper compares the results and discusses the implications of their different interior structures. In particular, it is shown that the existence or absence of a liquid core, not yet proved for Mars, will be seen in the future observations performed by the NEIGE experiment.

1. DESCRIPTION OF NEIGE

In 2007, four similar landers will be sent to the planet Mars, in the frame of the NetLander mission set up by an European and American consortium (Harri et al., 1999). The small stations will operate on the surface of Mars for about one Martian year (687 days). Among the experiments on-board these four NetLanders, there will be a geodesy experiment called NEIGE (NEtlander Ionosphere and Geodesy Experiment) (Barriot et al., 2001). The NEIGE experiment will use the Doppler shifts of UHF and X-band radio links between the Netlander microstations on the Mars surface and an orbiter and between this orbiter and the Earth (at X-band). The NEIGE Experiment has two series of scientific objectives: (1) to determine Mars orientation parameters in order to obtain information about the interior of Mars and about the seasonal mass exchange between atmosphere and ice caps; and (2) to determine the total electron content (TEC) and the scintillation of radio signals in order to study the large- and small-scale structure of the ionosphere of Mars. These two sets of information will be derived from measurements of Doppler shifts.

From the observation of the variations in Mars' orientation in space, we will be able to determine the precession rate (long-term motion of the rotation axis around an axis perpendicular to the ecliptic; this determination would need also the use of Viking and Pathfinder data), the amplitudes of the main nutations (periodic motions of the rotation axis in space), the amplitudes of the seasonal components and the Chandler Wobble in the polar motion (motion of the rotation axis in a frame tied to the planet), and the rotation speed variations (length-of-day variations). From precession and nutations, we will be able to give information about the core dimension, density and state, provided that the gravitational forcing is correctly known.

2. DESCRIPTION OF THE PRECESSION/NUTATIONS

Precession and nutations are due to the gravitational attraction of the Sun and the moon(s) acting on the whole planet. The other planets have a minor importance, but are taken into account when precise modeling is wanted. Due to the asymmetry of the planets (mainly flattening), there is a resulting torque that tends to re-orient the equator of the planet toward their orbital plane. Because the Earth and Mars are rotating, they react to this torque like a gyroscope, and their rotation axes describe a large motion in space around the perpendicular to the their orbital plane, called precession.

Due to the fact that the Earth, Mars, the Sun, the Moon, Phobos and Deimos, and the other planets are not fixed with respect to each others, periodic motions in space are generated in addition to the large precessional motion, with periods related to the orbital periods of the perturbing and perturbed bodies (such as annual and semi-annual periods from the main perturbing body, the Sun). These periodic motions in space are called nutations.

A first step in the evaluation is to compute these nutations considering that the planets are rigid. See Section 3 for the Earth and 4 for Mars.

In a second step, the non-rigid response of the planets to the forcing is computed. This response must account for the deformability of the planet and also, the potential presence of a liquid core (to be proved for Mars). See Section 5 for the Earth and 6 for Mars. We have computed the nutations of the planets Earth and Mars using particular rheology profiles and allowing a liquid as well as a solid core for Mars.

For the Earth, the nutations are modeled very precisely (< 100 μas (microarcsecond)) because the profiles of the rheological properties and the radii of the different layers are well known, and because we have high precision observations from which parameters can be fitted.

For Mars, we don't know yet the details of the interior of the planet, e.g. we do not know the exact dimension of the core, and we do not have any nutation data yet.

3. RIGID EARTH NUTATIONS

The nutations of the Earth as a rigid body have been computed very accurately by Souchay and Kinoshita (1997), Roosbeek and Dehant (1998), and Bretagnon et al. (1998). The first team has been working using the Hamiltonian approach, and the two others, using the torque approach. In these computations, different second order effects are taken into account. Direct and indirect effects of the planets, nutation on the nutation effect, and the J_2-tilt effect are presently taken into account in the computation of the nutations of a rigid Earth. For details about these contributions, see Dehant et al. (1999).

4. RIGID MARS NUTATIONS

The nutations of Mars, considered as a rigid body, have been computed with a very high precision (Bouquillon and Souchay, 1999, Roosbeek, 1999). The method used is the direct computation of the torque acting on Mars from the gravitational interactions with the other bodies of the planetary system, mainly with the Sun. The main inaccuracy in the amplitudes of nutations for a rigid Mars is related to the uncertainty in the dynamical flattening of the planet. This last parameter has been computed from precession observation and degree-two gravity field (J_2) observation (Folkner et al., 1997), obtained from Viking and Pathfinder data. The most important nutation is the prograde semi-annual nutation (343 days). This nutation has almost the same amplitude as the corresponding prograde semi-annual nutation of the Earth (182 days). The reason why they have the same amplitude relies in the fact that the mean distance between Mars and the Sun is about twice the mean distance between Earth and the Sun, and the flattening of Mars is about twice the flattening of the Earth. The nutations coming from the gravitational attractions form Phobos and Deimos are very small.

5. NON-RIGID EARTH TRANSFER FUNCTION FOR NUTATIONS

The contribution of the planet non-rigidity to nutations are accounted for by means of transfer functions. The present-day transfer functions for the non-rigid Earth nutation account for the fact that the Earth is an ellipsoid, that it is rotating, that there exist an inner core, a liquid outer core, and a solid inelastic mantle. In the model, the Earth is not considered to be in hydrostatic equilibrium. Because the Earth has a liquid core, there exists a normal mode called the Free Core Nutation (FCN), which is related to the fact that the Core-Mantle Boundary (CMB) is ellipsoidal and deformable. Due to the FCN, there is a resonance in the nutation amplitude. This resonance mainly affects the annual retrograde nutation. Additionally, large amplitude nutations far away from the resonance can also feel the influence of the resonance. This is the case for the prograde and retrograde 18.6 year nutations and the prograde semi-annual nutation.

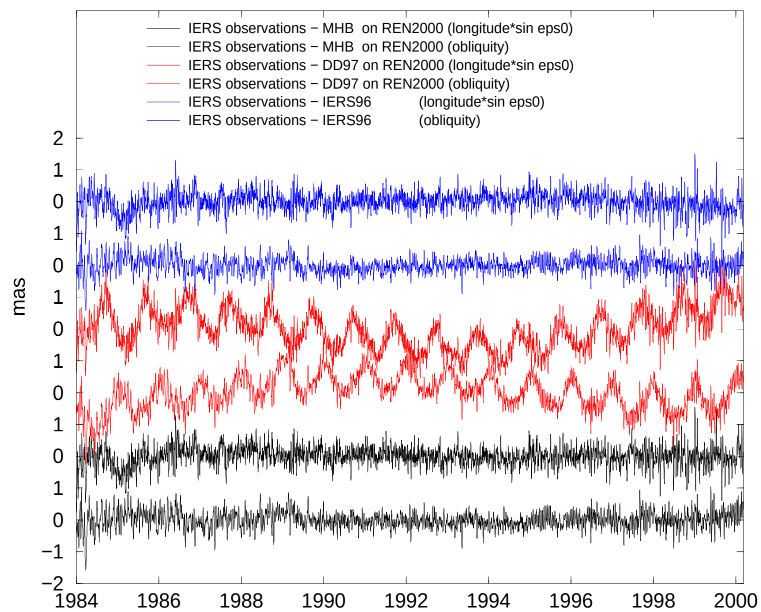

Figure 1: Residuals between the VLBI observed nutation and nutation models for the Earth. The first two curves are residuals for the IERS 1996 model (see McCarthy, 1996), the two middle curves are residuals for the numerical integration model of Dehant and Defraigne (1997), and the two last curves are residuals for MHB2000 model of Mathews et al. (2001).

Empirical models (such as the two first curves in Figure 1, Herring, 1996, see McCarthy, 1996), and geophysical model (such as the MHB2000 shown in the two last curves in Figure 1, Mathews et al., 2001) are in good agreement with the VLBI observations (the residuals are shown in the figure). These models incorporate a FCN resonance which accounts for dissipation at the CMB. Numerical integration models, while incorporating non-hydrostatic CMB topography, do not incorporate any dissipation at the core-mantle boundary and need still improvement (such as the DD97 shown in the two middle curves in Figure 1).

The model MHB2000 has been adopted by the IAU in 2000. It incorporates mantle inelasticity, CMB non-hydrostatic topography, dynamical flattening in agreement with the precession constant, and an electromagnetic torque at the CMB, as well as at the ICB (Inner Core Boundary). Resonances to the Chandler Wobble, the FCN and the Free Inner Core Nutation (FICN, this mode is due to the fact that the Earth has a solid inner core within the liquid outer core, and that the Inner Core Boundary (ICB) is ellipsoidal and deformable) are considered. Constant atmospheric and tidal ocean effects on nutations are considered. Residuals with respect to VLBI data are of the order of a few 10 μas in the frequency domain. The physical parameters such as the electromagnetic coupling at the CMB and ICB are adjusted using VLBI observations. This provides the scientific community with important constraints on the magnetic field amplitude at these boundaries (see Dehant and Mathews, 2002).

6. NON-RIGID MARS TRANSFER FUNCTION FOR NUTATIONS

In order to be able to compute Mars' transfer function for nutations, it is necessary to know some of the properties of the interior of the planet. Figure 2 shows a comparison of the interior of Mars and of Earth.

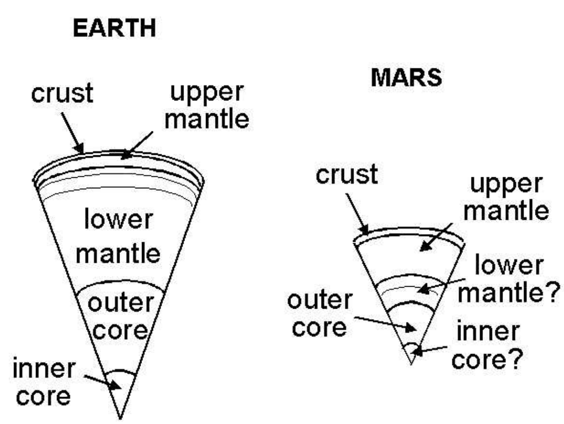

Figure 2: Comparison between the interiors of the Earth and of Mars.

Mars has a radius of about the half of the Earth mean radius. The dimension of the core of Mars is about the dimension of the Earth's inner core. We know its dimension approximately from the observed moment of inertia (1500km +/- 200km) as derived from Viking and Pathfinder data (Folkner et al., 1997). The composition of the core has been deduced from modeling using the SNC meteorites composition. The state of the core is not known with certainty; most models predict a completely liquid core. A completely solid core is also a possibility. The existence of a solid inner core is possible, too. The FCN exists only if Mars has a liquid core. The FICN exists only if Mars has a solid inner core within a liquid outer core. Consequently, different possibilities must be considered when computing non-rigid Mars nutations: with and without resonance at the FCN, with and without resonance at the FICN. The presence of a potential inner core and thus of a resonance at the FICN is treated in detail in separated papers of this volume (Dehant et al., 2002, and Rivoldini et al., 2002). The different possibilities for the core are detailed in Dehant et al. (2000). If there is a liquid core in Mars, there would be a resonance at a period of about -256 days corresponding to the FCN. This is particularly important for the

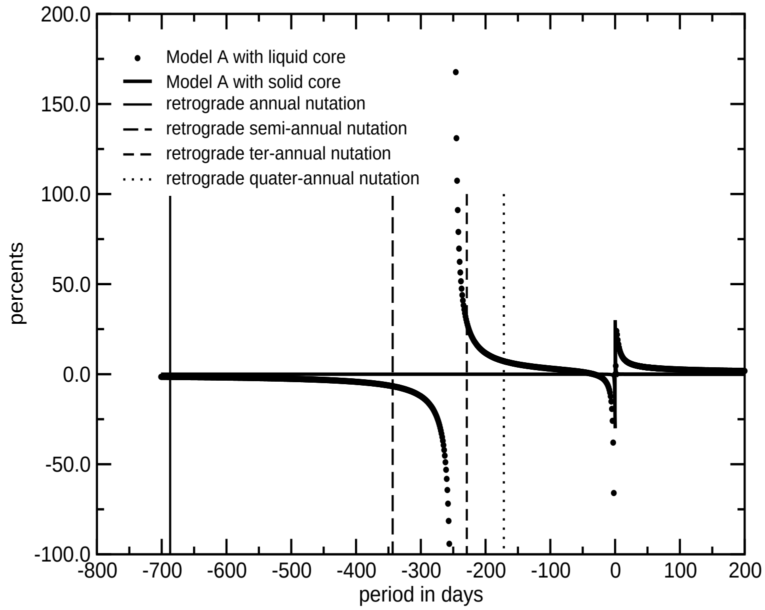

Figure 3: Transfer function of the planet Mars when a liquid core is considered and when a solid core is considered.

retrograde semi-annual (-343 days) and ter-annual (-229 days) nutations. We present in Figure 3 the relative non-rigid contribution to the nutation amplitudes, as a function of the period.

If the core is liquid, the FCN resonance is visible, even in the prograde part of the spectrum. In particular, there is an important effect on the largest nutation, the prograde semi-annual nutation at 343 days; the difference between the non-rigid Mars transfer function with and without liquid core is at the level of 1% at that frequency, which corresponds to about 5 mas (milliarcsecond) on the amplitude of that nutation. The resonance period is highly dependent on the core dimension, and on the non-hydrostatic contribution which could be important as seen from the existence of Tharsis and the associated geoid anomalies. These results are discussed in Dehant et al. (2000).

The expected precision of the NEIGE experiment is below 5 mas, which will, for example, allow us to answer the question about the state of the Martian core. For that purpose, we will deduce the annual, semi-annual, ter-annual, quater-annual nutation amplitudes from the Doppler shift measurements.

7. CONCLUSIONS

Both Earth and Mars have nutations from which the observations can provide information on the interior of the planets. The most important nutation of Mars is the prograde semi-annual nutation; its amplitude is about the same as the corresponding one for the Earth. The moons of Mars, Phobos and Deimos, do not contribute with a high level to the nutational motions, while for the Earth, the 18.6 year nutations (period of the node of the Moon), are the largest nutations.

Present-day VLBI data obtained on Earth are unprecedented high precision data which has allowed to constrain very well the Earth's interior properties e.g. the outer core and inner core flattenings, the coupling at the CMB and ICB. A very precise nutation model, MHB2000, has been adopted by the IAU in 2000. In the future, the NEIGE experiment will allow us to obtain precise nutation of the planet Mars, and so, e.g. to better constrain the core dimension, and to determine the state of the core and the eventual existence of an inner core.

REFERENCES

Barriot J.-P., Dehant V., Folkner W., Cerisier J.-C., Ribes A., Benoist J., Preston R., Van Hoolst T. et Warnant R., 2001, The NetLander Ionosphere and Geodesy experiment, in: Proc. Journées Systèmes de Référence 2000, Paris, France, ed. N. Capitaine, pp 196-198.

Bretagnon, P., Francou, G., Rocher, P., and Simon, J.-L., 1998, SMART97: a new solution for the rotation of the rigid Earth, *Astron. Astrophys.*, 329, pp 329-338.

Bouquillon, S., and Souchay, J., Precise modeling of the precession-nutation of Mars, Astron. Astrophys., 345, 282-297, 1999.

Dehant V. and Defraigne P., 1997, New transfer functions for nutations of a non-rigid Earth, *J. Geophys. Res.*, 102, pp 27,659-27,688.

Dehant V., Arias F., Bizouard Ch., Bretagnon P., Brzezinski A., Buffett B., Capitaine N., Defraigne P., de Viron O., Feissel M., Fliegel H., Forte A., Gambis D., Getino J., Gross R., Herring T., Kinoshita H., Klioner S., Mathews P.M., McCarthy D., Moisson X., Petrov S., Ponte R.M., Roosbeek F., Salstein D., Schuh H., Seidelmann K., Soffel M., Souchay J., Vondrak J., Wahr J.M., Weber R., Williams J., Yatskiv Y., Zharov V. et Zhu S.Y., 1999, Considerations concerning the non-rigid Earth nutation theory, *Celest. Mech. Dyn. Astr.*, 72, 4, pp 245-310.

Dehant V., Defraigne P. et Van Hoolst T., 2000, Computation of Mars' transfer function for nutation tides and surface loading, *Phys. Earth planet. Inter.*, 117, pp 385-395.

Dehant V., M. Greff-Lefftz, H. Legros, T. Van Hoolst, P. Defraigne, and O. de Viron,2002, Free and forced response of a non-rigid Mars with an inner-core. I. Analytical approach, in: *Proc. 'Journées des Systèmes de Référence Spatio-temporels 2001'*, Observatoire Royal de Belgique, sept. 2001, ed. Capitaine N., this issue.

Dehant and Mathews, 2002, Information about the core from Earth nutations, in: 'Core dynamics, structure and rotation', *AGU Monograph*, accepted.

Folkner, W.M., Yoder, C.F., Yuan, D.N., Standish, E.M., Preston, R.A. 1997, Interior structure and seasonal mass redistribution of Mars from radio tracking of Mars Pathfinder, *Science*, 278, 1749-1752.

Harri, A.-M., Marsal, O., Leppelmeier, G.W., Lognonn, P. Glassmeier, K.-H., Angrilli, F., Banerdt, B., Barriot, J.P., Bertaux, J.-L., Berthelier, J.J., Calcutt, S., Cerisier, J.C., Crisp, D., Dehant, V., Di Pippo, S., Giardini, D., Guerrier, D., Jaumann, R., Kumpulainen, K., Langevin, Y., Larsen, S., Menvielle, M., Musmann, G., Polkko, J., Pommereau, J.P., Runavot, J., Schumacher, W., Siili, T., Simola, J., and Tillman, J.E., Network Science Landers for Mars, Advances in Space Research, 23(11), 1915-1924, 1999.

Herring T.A., Gwinn C.R. and Shapiro I.I., 1986, Geodesy by Radio Interferometry: Studies of the Forced Nutations of the Earth. 1. Data Analysis, *J. Geophys. Res.*, 91, B5, pp 4745-4754.

Mathews P.M., Buffett B.A., and Herring T.A., 2001, Modeling of nutation-precession: new nutation series for nonrigid Earth, and insights into the Earth's interior, *J. Geophys. Res.*, in press.

McCarthy D.D., 1996, IERS Conventions. *IERS Technical Notes*

Rivoldini A., P. Defraigne, V. Dehant, et T. Van Hoolst, 2002, Free and forced response of a non-rigid Mars with an inner-core. II. Numerical approach, in: *Proc. 'Journées des Systèmes de Référence Spatio-temporels 2001'*, Observatoire Royal de Belgique, sept. 2001, ed. Capitaine N., this issue.

Roosbeek F. and Dehant V., 1998, RDAN97: an analytical development of rigid Earth nutation series using the torque approach, *Celest. Mech. Dyn. Astr.*, 70, pp 215-253.

Roosbeek, F., 1999, Analytical developments of rigid Mars nutation and tide generating potential series, *Celest . Mech. Dyn. Astr.*,75, 287-300.

Souchay J. and Kinoshita H., 1997, Corrections and new developments in rigid Earth nutation theory: II. Influence of second-order geopotential and direct planetary effect, *Astron. Astrophys.*, 318, pp 639-652.