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Gravity, rotation, and interior of the terrestrial planets from planetary geodesy: example of Mars

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Abstract. Information on planetary interiors can be obtained from planetary geodesy measurements of global parameters such as the gravity field and the rotation variations (including precession). These properties can be derived from radio science experiments in which Doppler shifts of radio signals between the Earth, planetary landers, and orbiters are measured.

A radio link between the Earth and one lander on Mars has been successfully used to constrain the rotation and the precession, and consequently to obtain the moment of inertia of the planet, the global mass repartition, and its seasonal variations. A radio link between the Earth and one orbiter has also been used to determine the gravity field and its time variations. In particular, the tidal Love number \( k_2 \) has been determined, from which the Martian core has been shown to be at least partially liquid. New missions that involve a space geodesy experiment addressing these topics are presented.

A network of landers could probe the interior of the planet through seismic monitoring, magnetic sounding, and measurements of its rotational dynamics by radio science. This would allow the determination of the overall interior structure, including crust, mantle, and core divisions, and the state of the core (liquid/solid, density). Also composition, mineralogy, density, and temperature profiles could be inferred.

Information on the interior of terrestrial planets (and large moons) other than Mars has also been determined by using radio tracking of an orbiter. For example, the tidal Love number \( k_2 \) of Venus was deduced from Magellan’s radio science experiment. Future missions such as Messenger and BepiColombo have dedicated onboard planetary geodesy instruments and will provide improved information on the interior of Mercury from Doppler measurements.

Keywords. Mars tides, Mars rotation, Mars gravity field, planetary interior, radio science, planetary geodesy

1 Introduction

This paper concerns the application of radio science to planetary physics. It is an overview of the present advances in planetary geodesy and it addresses the Earth geodesy community to show that the application of geodesy to other terrestrial planets is an exciting and promising field. We have chosen to concentrate mostly on the planet Mars because it is the planet for which we have the most recent data and because similar approaches for studying rotation and gravity can be used as for the Earth. Space radio science uses radio links between a spacecraft and the Earth, a spacecraft and a lander, and/or a lander and the Earth. From the observed Doppler effects on the signal the relative motions between the two objects can be determined, the trajectory or the orbit of the spacecraft can be reconstructed, and the velocity, the acceleration, and/or the position of the transmitter with respect to the antenna observing the spacecraft or the lander can be derived. It will be shown that such space geodesy experiments allow obtaining geophysical information related to the static gravity field, the time variable gravity field, and the rotation.

2 Static gravity field observation and interpretation

The static gravity field can be deduced from its effects on a spacecraft orbit. From the accumulation of measurements such as those from the US Mars Global Surveyor (MGS) spacecraft performed over a long period of time and covering the whole planet, the gravity field developed in spherical harmonics can be obtained (see Lemoine et al., 2001, Yuan et al., 2001). These data can be compared with the topography as obtained from an altimeter such as MOLA on MGS (Smith et al., 2003). Regions with high correlation between topography and the free-air gravity anomaly as well as areas with very low correlation occur on
Mars (Zuber et al., 2000). A high correlation such as in the Tharsis region means that the topographic load is not fully isostatically compensated. Flexure models can then be used to determine properties of the lithosphere and the crust, such as the crustal thickness, the lithospheric rigidity, and the density of the crust. High gravity anomalies that are not explained completely by the topography are expected to be partially due to internal loading.

Generally speaking, the gravity field follows Kaula’s law: the degree variances of the harmonic development of the field scale as \( \ell/\ell' \), where \( \ell \) is the degree of the gravity coefficients and \( \ell' \) is a scaling that depends on the planet. Kaula’s law is verified for the Earth, Mars and Venus. The scaling coefficient from one planet to the other is based on the hypothesis that the terrestrial planets support the same stresses. The density anomalies are then scaled by \( 1/g \), and as the gravity coefficients are normalized by \( GM/R \), one has a general scaling of \( 1/g (GM/R) \) (where \( g \) is the gravity at the surface, \( R \) is the radius, and \( M \) the mass of the planet). In the literature, one finds scalings of \( 1/g \) (Kaula, 1993, Vincent and Bender, 1990, Wu et al., 1995, 1997) or \( 1/g \) (Milani et al., 2001).

Line-of-sight accelerations of the spacecraft can also be deduced from the radio science Doppler measurements. Examples of line-of-sight acceleration over the Tharsis region on Mars from the ESA Mars Express spacecraft can be found in Beuthe et al. (2005). In the case of Tharsis, the gravity anomalies are very high and can be explained with a rather high density for the crust and/or a rather high rigidity for the lithosphere and/or with an additional internal loading in phase with the topography effect (Belleguic et al., 2005). This is not in contradiction with the recent discovery of the geologically recent volcano activity on Mars as discovered by the camera team of Mars Express (Neukum et al., 2004, 2005).

3 Time variable gravity field observation and its interpretation

Changes in the gravity can be induced by changes in the mass anomalies. Especially fluid motion can lead to mass redistribution on time scales that are within reach for space missions. For Mars for instance, the seasonal changes in the icecaps change the gravity field. The sublimation and condensation of the polar caps can involve up to about one third of the total mass of the atmosphere and induces relative gravity changes on the order of \( 10^{-5} \) – which can be compared with the second-order gravity field coefficient \( J_2 = 0.00195545 \) (Lemoine et al., 2001) – with largest changes for the low-degree zonal gravity coefficients. This signature can be detected in the orbit parameters, and the variations in the lowest-degree zonal gravity coefficients have been determined (Smith et al., 2001, Yoder et al., 2003, Karatekin et al., 2005, see also Balmino et al., present issue). The induced changes in the orbit of a spacecraft are due to a linear combination of the odd coefficients and a linear combination of the even coefficients, called lumped coefficients. With a single orbiter, these lumped coefficients can be derived from radio science experiments. Therefore, the combination of observations from different orbiters with different orbit characteristics is very promising (see Karatekin et al., 2005).

Another source of time-variable gravity is the tides. The solid planet deforms due to the gravitational attraction of the Sun and possibly the other planets and moon(s), and there is an associated mass redistribution inside the planet. This induces in turn a change in the gravitational field exerted on the spacecraft and therefore, changes in the orbital parameters of the spacecraft. Yoder et al. (2003) have used these observed changes to deduce the planet response to the tides, represented by the \( k_t \) Love number. They obtained a value of 0.153 +/- 0.017 for \( k_t \). This number depends on the global structure of the planet and in particular, when the core of a planet is liquid, the Love number is higher than when the core is solid. The value also depends on the dimension of the core. For the Earth, the Love number \( k_t \) is about 0.30, for Mars about 0.1. The presence of a liquid core is visible on these values at more than a few percents. For Mars, one finds in the literature values around 0.07 for a solid core and values ranging between [0.1, 0.2] for a liquid core depending on the dimension of the core; the larger the core, the larger the Love number (see Van Hoolst et al., 2003). The allowed range of models for Mars interior is limited by the total moment of inertia, which is also deduced from observation. It has been determined from an analysis of Mars Global Surveyor tracking and Doppler and range measurements to the Mars Pathfinder and Viking Landers to be 0.3650 +/- 0.0012 (Yoder et al., 2003). From their observed values of \( k_t \), Yoder et al. (2003) inferred a core radius between 1520 and 1840 kilometers. Balmino et al. (2005, this issue) have also determined the value of the Love number from the same geodetic observations, indicating a liquid core. On the other hand, research and development on modeling the interior of Mars have been performed and more realistic models of the Martian mantle mineralogy have been
constructed (Verhoeven et al., 2005). Coupled with an iron core model (containing 14% of the light element sulfur), these models allow computing theoretical Love numbers. For a liquid core and by constraining with the observed moment of inertia, the values are ranging from [0.1, 0.16] for core radius between [1500km, 1850km]. The dimension and state of the core has important implications on the evolution and present constitution and state of Mars (Breuer et al., 1997, Spohn et al., 2001). The evolution of a planet and the possibility to generate a magnetic field are highly dependent on its ability to develop convection in the core and in the mantle. In particular, a core hydrodynamo is related to the presence or absence of a solid inner core, which is in turn related to the percentage of light elements in the iron alloy of the core. Interior structure largely sets the stage for how the mantle may flow and transfer mass and heat. Mantle dynamics is also essential in forming the geological elements of the surface and in sustaining plate tectonics (Spohn et al., 1998). The dimension of the core has also in addition an implication on the possible mantle convection scenarios and in particular on the presence of an olivine phase transition at the bottom of the mantle.

4 Rotation and its interpretation

Periodic rotation variations of planets can most easily be determined from a direct radio link between the Earth and landers on the surface of the planet (see Figure 1). Nevertheless, rotation variations with surface displacements on the order of a few centimeter can also be observed from a combination of a radio link between the Earth and an orbiter and a radio link between the orbiter and landers. Alternatively, an Earth-orbiter radio link can be used together with camera or altimeter observations from the same orbiter of spots on the planet’s surface.

The idea is that, given the very accurate knowledge of the orientation of the Earth in space (at the milliarcsecond level, i.e. 3cm at the surface of the Earth), one computes the orbit from the Earth-orbiter radio link, and Mars’ orientation and rotation in space from the additional radio link between the lander and the orbiter. Simulations for Mars (Yseboodt et al., 2003) have shown that we may expect to get the meter precision on one measurement and even better (a few centimeters) on periodic components (Yseboodt et al., 2003).

Fig. 1. Representation of the radio links between the Earth and the orbiter, the orbiter and landers on the surface of Mars. The Earth’s orientation in space is considered to be almost perfectly known with respect to an inertial frame (at the milliarcsecond level). Radiolinks between the Earth and the orbiter and between the orbiter and the landers provide relative positions of these objects. From these space geodesy measurements, Mars orientation can be deduced with respect to an inertial space.

Rotation variations are represented by several parameters: precession and nutation, libration, polar motion, and length-of-day variations. Together, these motions constitute the orientation of the surface of the planet in space and the rotation speed of the planet.

Precession and nutation are induced by the tidal gravitational torque on an oblate planet; this is the case for Mars and for the Earth for instance. The long-term component, precession, has a period of about 91000 Martian years or 170000 Earth years. Both motions are very interesting for studying the deep interior of Mars, precession because it constraints the moment of inertia of the planet, nutations mainly because they are different for a planet with a liquid core than for a planet with a solid core. Similarly, raw (liquid) and cooked (solid) eggs rotate differently. From the observation of nutation, it can be determined whether Mars has a liquid core or a solid core (see Figure 2).

As for the Earth, the position of Mars’ rotation axis varies with time due to the gravitational attraction exerted by the Sun and the Mars’ natural satellites Phobos and Deimos. Because of the existence of an equatorial bulge (like the Earth, Mars is flattened at the poles), the Sun’s attraction
continuously tends to tilt Mars’ equatorial plane towards the orbital plane. The rotating Mars reacts to this force as a gyroscope, and Mars’ rotation axis describes a broad cone around the perpendicular to the orbital plane. This forced motion is called precession (see Figure 3).

![Fig. 2.](image)

Fig. 2. Nutation of Mars with a solid (left) or a liquid (right) core. The existence of a liquid core enhances the nutation of Mars.

Because the relative positions of the Sun and Mars periodically change with time, precession also shows periodic variations called nutations (see Figure 3) (also Phobos, and Deimos, the two little moons of Mars can be involved). The internal structure of Mars influences the nutations; in particular a resonance effect in the nutations could be seen if Mars has a liquid core. The resonant enhancement of nutation when the core is liquid is due to a normal mode called the free core nutation (Dehant et al., 2000b, Roosbeek, 2000). This mode is related to the existence of a flattened fluid core inside a deformable mantle. It exists only when the core is liquid and when the core is flattened. For Mars it has a period of around 250 days in space, which is very close to the ter-annual nutation (see Dehant et al., 2000a, 2000b, Van Hoolst et al., 2000a, 2000b) (see Figure 4). The prograde semi-annual nutation is not close to the FCN frequency but has a very high amplitude. A very small enhancement (which is the case at that frequency) provides a large effect in terms of the amplitude contribution (see Figure 4).

![Fig. 4.](image)

Fig. 4. Liquid core resonance effect and solid core transfer function (flat curve). The vertical lines indicate the Martian nutation frequencies. The zoom in the prograde band of the nutations shows the enhancement expected for the prograde semi-annual nutation.

![Fig. 5.](image)

Fig. 5. Nutation amplification for three interior structure models of Mars with different core dimensions. The differences reflect the shift in the FCN frequency. The vertical lines indicate the Martian nutation frequencies.

The precision of the observation of the orientation in space must reach the 5cm level as this is the level of the core state contribution. Observing the nutations at a better level provides the answer to the question: has Mars a solid or a liquid core. Additionally, the dimension of the core has an influence on the resonance frequency (see Figure 5) and one will be able to constrain the dimension of the core.

Polar motion is the motion of the rotation axis in a frame tied to the planet. Mars polar motion (see Figure 6) contains the seasonal effects of the atmosphere as well as a resonance to a normal mode of the planet, the Chandler Wobble (CW), related to the fact that an oblate planet that does not rotate around its principle moment of inertia undergoes a wobbling. The period and damping of this mode are very interesting as they are related to the interior structure of the planet. The CW period depends mainly on the dynamical flattening of the...
planet and provides information on the planet’s elasticity (at the level of 11 days), anelastic behaviour (effect of up to 7 days), and the existence of a fluid core (at the level of 1.5 days).

Fig. 6. Computed polar motion of Mars. The large CW component is computed from a random atmospheric excitation and the seasonal components from the periodic changes of mass in the atmosphere.

Length-of-day variations, presented in Figure 7, are deviations from the uniform rotation speed of the planet. They are mostly related to the geophysical fluids entering to the system (core, ocean, atmosphere, hydrosphere… if they exist). For Mars for instance, the seasonal condensation/sublimation of the icecaps induce a large change in the length-of-day at the seasonal periods (Cazenave and Balmino, 1981, Chao and Rubincam, 1990, Defraigne et al., 2000, Van den Acker et al., 2002).

Fig. 7. Length-of-day variations computed from the annual and semi-annual excitation of the atmosphere.

The changes with respect to the uniform rotation induce position changes at the level of 10 meters on the equator. The main part of the signal is due to the moment of inertia changes induced by the mass repartition (see Figures 7 and 8). Length-of-day variations can be computed from general circulation models (GCM) (see e.g. Defraigne et al., 2000, Van den Acker et al., 2002, using the GCM from Forget et al., 1995, 1998) and have been determined from Viking lander data (Yoder and Standish, 1997, Folkner et al., 1997).

Fig. 8. Sublimation/condensation process related to length of day variation.

5 Present and future missions

The interior of the terrestrial planets is presently addressed by several spacecrafts, and a lot of new science will also be done in the future in the frame of space geodesy. The NASA satellites MGS and Mars Odyssey, and the ESA satellite Mars Express (MEX) are continuously tracked from Earth, which has provided unprecedented accuracy on the Martian gravity field. MGS was mostly used for determining the spherical harmonics coefficients of the gravity field development (see Lemoine et al., 2001, Yuan et al., 2001). MEX has recently been used for further improvement. The altitude of Mars Express at pericenter, between 265 and 330 km, is significantly lower than the minimum altitude (370 km) of Mars Global Surveyor (MGS) during its Gravity Calibration Orbit (GCO) and Mapping phases. Short wavelength orbital perturbations due to gravity are thus significantly larger on MEX than on MGS, so that MEX gravity data are useful to improve our knowledge of short wavelength gravity anomalies on the observed targets. The gravity studies performed with the radio science experiment MaRS of MEX use Doppler data along the line-of-sight near pericenter above selected target areas of geophysical interest (Pätzold et al., 2004). The average coherence MEX/Topography is high down to a wavelength corresponding to the altitude of the spacecraft at pericenter. This analysis of the coherence shows that MEX can be used as an independent check of the quality of the existing gravity solutions in the target regions analyzed (Beuthe et al., 2005). The Mars Reconnaissance Orbiter (MRO), which is on its way to Mars, could complementary be used. Recent results on the time variable gravity field and on the $k_2$ Love number are presented and discussed in the present issue (see Balmino et al.). They follow a study published by Yoder et al. (2003), in which it was shown that the $k_2$ Love number from MGS corresponds to a large liquid core. In situ geophysical investigations on Mars with landers would provide a large step forward.
GEP (Geophysical and Environment Package, a Mars long-lived surface package) is a long lived geoscience observatory on Mars, which will consist of a permanent network of fixed stations on the planet, operating for a decade. It will be based on a piggyback approach and will use future Mars missions for its deployment. Space geodesy by means of radio science is foreseen on these stations. The first opportunity for this launch could be in the ExoMars mission within the ESA AURORA program.

Concerning the other planets, the past Magellan mission to Venus has provided us with unprecedented results about Venus’ gravity field (Barriot et al., 1998, Konopliv et al., 1996, 1999). Magellan has answered many questions about Venus geophysics and geological history but it has also raised new questions. A new opportunity to study the gravity field of Venus will be provided by Venus Express (VEX), and in particular the radio science experiment VeRa (Venus Express Radioscience experiment) (Häusl et al., 2005). Given that the VEX pericenter altitude is about 250 km, one can expect an improvement of this wavelength resolution up to about 250 km, similarly as for Mars Express (see above and Beuthe et al., 2005). In turn, the understanding of the lithospheric structure under targeted areas might be improved on the basis of the analysis of the relationship between the topography and the gravity with respect to previous studies as the one of Leftwich et al. (1999).

Rotation variations for a planet with ellipsoidal equatorial shape such as for Mercury, the Galilean satellites, and the Moon, are usually called librations. As an example, Mercury is in a 3:2 spin-orbit resonance and has an oblate equator. Consequently, the Sun exerts a torque on the planet and tends to bring the bulge of the equator into its direction, producing either a slow-down or an acceleration of the rotation. Superposed upon its uniform rotation, the planet is then twisting periodically around its rotation axis. The main forced libration of the planet Mercury has a period of about 88 days and its amplitude reaches a few hundred meters at the equator. A solid core would participate in the libration, but when the core is liquid and the core-mantle boundary is spherical, the core does not participate in the rotation, and the libration amplitude is about twice the libration amplitude for a rigid core (see Peale, 1976, Peale et al., 2002, Wu et al., 1995, 1997, Rambaux and Bois, 2004). The amplitude depends mainly on the moment of inertia of the mantle and on the equatorial flattening. The influence of core-mantle coupling is very small (Peale et al. 2002, Rambaux et al., 2005). By observing repeatedly with a camera spots at the surface of the planet, by tracking the orientation of the camera with respect to the stars, and by determining the spacecraft’s position by radio-tracking, it is possible to obtain the libration of Mercury (Milani et al., 2001). Alternatively, the libration can be determined from the planetary topographic and gravitational shape (Solomon et al, 2001). The future NASA mission MESSENGER is on its way to Mercury and will reach Mercury in 2009. The ESA cornerstone mission BepiColombo will be launched in 2013. These missions will determine a highly accurate gravity field and a precise characterization of the libration of Mercury.

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