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The improvement of the Earth gravity field estimation and its benefits in the atmosphere and fundamental physics

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Abstract

In the present decade, Earth's explorer missions such as CHAMP, GRACE and GOCE are going to dramatically improve the knowledge of the Earth's gravity field. The deep knowledge of the gravity field with unprecedented precision is making feasible new experiments and investigations in the field of geophysics and fundamental physics.

The present work plans to demonstrate that such improvements, together with the huge number of LEO satellites, will make possible model refinements of subtle physical effects acting on the orbital motion of Earth's satellites like general relativistic effects and the smooth modulation of the solar radiation pressure through the Earth's atmosphere (penumbra). The refinement of the gravity field and a better assessment of penumbra effects on the orbits could concur to determine global changes of some atmospheric parameters like the refractivity and extinction. On the other hand, it could make the existing constellation of Earth's satellites suitable for testing Lense–Thirring gravitomagnetic field.

Keywords: Gravitomagnetic effect; Orbital perturbations; Earth's satellites; Gravity field recovery; Penumbra; Climate

1. Introduction

A tremendous improvement of the gravity field estimation is achieving with a completely new generation of low orbiting satellites, namely CHAMP and GRACE, equipped with highly precise inter-satellite and accelerometry-instrumentation.

The CHAMP mission, launched in July 2000, is mainly devoted to the gravity and magnetic field estimation and atmosphere sounding. CHAMP is equipped with a new generation GPS flight receiver for continuous tracking of the low orbiter by the satellites of the GPS constellation for accurately and continuously monitoring of the orbit perturbations and high precision three axes accelerometer for measuring the surface forces accelerations (Reigber, 2000). Such equipment onboard CHAMP is suitable to provide highly precise global long-wavelength features of the static Earth gravity field and its temporal variation. Up to now from CHAMP observations three Earth gravity fields: EIGEN-1S (Reigber et al., 2002), EIGEN-2 (Reigber et al., 2003a) and EIGEN-3p (Reigber et al., 2003b) were delivered. The first EIGEN gravity field was obtained combining the first 88 days of CHAMP data with GRIM-1S normal equations system and the data from Earth laser ranged satellites. The second was derived by CHAMP data out of the period July 2000 through December 2002. Finally, the EIGEN-3p was derived through June 2003 and applying

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a different tuning of the accelerometer calibration parameters and a different normal equation regularization (Reigber et al., 2003b).

GRACE mission, launched in March 2002, can be considered the natural follow-on of CHAMP mission for the recovery of the Earth gravity field. The planned increase in accuracy (five times better than CHAMP at least) is due mainly to the satellite to satellite tracking (SST) adopted for the recovery of the gravity field. GRACE mission consists of two satellites following each other on the same orbital track. The satellites tracks reciprocally by a K-band microwave link to measure the exact distance and its time change to an accuracy of better than 1 μm/s. The position and velocity of the satellites will be measured using onboard GPS receivers. For the present work, the GRACE GGM01S gravity field model has been adopted (Tapley et al., 2004). GGMO1S was estimated with 111 days (spanning April through November of 2002) of GRACE K-band range-rate, attitude, and accelerometric data (GGM01 notes in http://www.csr.utexas.edu/grace/gravity/).

In the past, some experiments were proposed in the field of Fundamental Physics (namely General Relativity tests) by using space geodetic techniques. Noordvedt (1968, 1991) discussed about the possibility of testing relativity by lunar laser ranging. Ashby and Bertotti (1984) analyzed the possibility to measure the perigee precession of LAGEOS, as well as that done by Iorio et al. (2002). A test of the De Sitter geodetic precession at about 15% level (Bertotti et al., 1987) was obtained from the comparisons of the Earth's rotational orientation, measured relative to the distant stars-quasars with VLBI, and locally relative to the Moon with lunar laser ranging.General relativistic effects acting on GPS system were extensively discussed by Ashby (1997).

The most intriguing challenge was, anyway, the measurement of the gravitomagnetic Lense and Thirring (1918) effect by far (hereafter L–T). General relativity predicts the occurrence of subtle effects near a spinning body, caused by its rotation, not only on light and clocks but also on test particles. A particle orbiting around a spinning body has its orbital plane "dragged" around the spinning body in the same sense as the rotation of the body and small gyroscopes that determine the axes of a local, freely falling, inertial frame, where "locally" the gravitational field is "unobservable", rotates with respect to "distant stars" due to the rotation of the body. Thus, an external current of mass, such as the spinning Earth, "drags" and changes the orientation of the gyroscopes. Indeed, a test gyroscope has a precession with respect to "an asymptotic inertial frame" with angular velocity, in weak field

$$\dot{\Omega} = -\frac{1}{2}\mathbf{H} = \frac{[-\mathbf{J} + 3(\mathbf{J}\cdot\hat{\mathbf{x}})\hat{\mathbf{x}}]}{|\,\hat{\mathbf{x}}|^3}, \tag{1}$$

where **J** is the angular momentum of the central object and **H** its gravitomagnetic field generated by **J**. This is the "rotational dragging of inertial frames", or "frame–dragging", as Einstein named it (Pugh, 1959; Schiff, 1960; Ciufolini and Wheeler, 1995). The orbital angular momentum vector of a test particle is itself a kind of gyroscope and is thus dragged by the spin of the central body. Indeed, the node of an orbiting test particle around a central body with angular momentum **J** has a secular rate of change. The change of the longitude of the line of the nodes (intersection between the orbital plane of the test particle and the equatorial plane of the central object) due to L–T is in the weak field approximation

$$\dot{\Omega}^{\text{L–T}} = \frac{2J}{[a^3(1-e^2)^{3/2}]}, \tag{2}$$

where a is the semi-major axis of the test particle and e its orbital eccentricity. The Runge–Lenz vector of an orbiting test particle, for a motion under a central force, is also a kind of gyroscope and is dragged by the spin of the central body. Indeed, the pericenter of an orbiting test particle around a central body with angular momentum **J** has a secular rate of change. The change of the longitude of the pericenter $\dot{\bar{\omega}} = \Omega + \omega$ (defining the Runge–Lenz vector) due to L–T in weak field is

$$\dot{\bar{\omega}} = \frac{2J(\hat{\mathbf{J}} - 3\cos(I)\hat{\mathbf{l}})}{[a^3(1-e^2)^{3/2}]}, \tag{3}$$

where $\bar{\omega}$ is the argument of the pericenter, that is the angle from the equatorial plane to the pericenter, $\hat{\mathbf{l}}$ is the orbital angular momentum unit vector of the test particle and I its orbital inclination (angle between the orbital plane and the equatorial plane of the central object).

Ciufolini (1986) proposed to measure the L–T by measuring the nodal precession of laser ranged Earth satellites by using a twin LAGEOS satellite (Smith and Dunn, 1980) to be injected in supplementary orbit to the first one. Such "butterfly" configuration, indeed, is helpful in canceling out the classical node precession because it depends on cosine of inclination, so enhancing the L–T which it does not as in Eq. (2). The bisector of the angle between the nodal lines of two satellites behaves as a gyroscope affected only by the general relativistic dragging of inertial frames (Bertotti, 1987; Ciufolini, 1989). The twin LAGEOS satellite was never launched even if in the last time a new mission named LARES was conceived by Ciufolini (1998) to be injected in supplementary orbit to LAGEOS, maintaining the same area to mass ratio but lighter of a factor two at least just to minimize the launching costs.