The Role of Non-tidal Atmospheric Loading in the Task of Gravity Field Estimation by Inter-Satellite Measurements

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Abstract

The paper reviews models of tidal and non-tidal variations of the Earth's gravitational field. Proposing an algorithm for the estimation of the Stokes coefficients based on inter-satellite measurements of low-orbit spacecrafts. By processing measurements of the GRACE mission, we obtained experimental estimates of gravity field monthly variations. The analysis of these values was carried out by calculating the change in the equivalent water height for a given area.

Keywords

GRACE · Gravity field · Atmospheric tides

1 Introduction

In 2002 satellites of the GRACE mission (Greicius 2013) were launched into near-earth orbit, allowing the mapping of the Earth's gravitational field at monthly intervals. The spatial resolution of derived models is several hundred kilometers, determining the height of a quasigeoid with an accuracy of a few centimeters.

The basis for calculating the monthly models of the gravity field is the joint processing of inter-satellite measurements and data on the position of spacecraft obtained from measurements of the navigation receiver (Beutler et al. 2010). The procedure consists of three stages:

- for each spacecraft (SC) the trajectory of its motion obtained from measurements of the onboard receiver is aligned by a model;
- a system of equations is formed, linearized in the vicinity of the obtained orbits using inter-satellite velocities and orbits of both spacecrafts as measurements;
- a joint system of linear equations is formed on the monthly interval and is solved by the least squares method.

As a result of the estimation, independent monthly models of geopotential are obtained.

As is known, in addition to the tidal and relativistic effects corresponding to the IERS 2010 convention (Petit and Luzum 2010), the processing of spacecraft in low orbits takes into account the influence of non-tidal atmospheric loading calculated according to the NWP (Numerical Weather Prediction model) of the European Center for Medium-Term weather forecasts (ECMWF – European Center for Medium-Range Weather Forecasts) at the German Research Center for Geoscience (GFZ German Research Center for Geoscience) (Dobslaw et al. 2016).

In current work we compare the first results of in-house estimation of monthly gravity field models based on satellite-to-satellite measurements with other solutions, and also study the contribution of non-tidal atmospheric loading using a specially developed experimental programming and mathematical software KAGOR (Kartography Geodesy and Orbit determination). KAGOR allows simulating orbits, kinematic trajectories and corresponding inter-satellite measurements with any given parameters, as well as to process real satellite-to-satellite measurements to estimate gravity field models.

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2 Non-tidal Atmospheric Loading

Based on the analysis and forecasting of the data from the operational high-resolution global model of the numerical weather forecast of the European Center for Medium-Range Weather Forecasts and bottom pressure data obtained by simulation without imposing additional restrictions on the global general circulation model MPIOM and ECMWF data, a product of non-tidal gravitational variations in the atmosphere and oceans is formed (Atmosphere and Ocean De-Aliasing Level-1B, AOD1B) which provides a priori information on temporal variations in the gravity field due to global mass redistribution in the atmosphere and the ocean (Dobslaw et al. 2017).

AOD1B was determined by the fully normalized Stokes coefficients of the anomalous external gravitational field of the Earth caused by the redistribution of masses predicted by the numerical models described above.

AOD1B consists of four sets of coefficients:

- *ATM* – the effect of the atmosphere, which includes contribution of the atmospheric surface pressure over the continents, the static contribution of the atmospheric pressure above the surface of the oceans to bottom pressure and the much weaker contribution of density anomalies of the upper atmosphere over continents and oceans;
- *OCN* – contribution of the movement of ocean masses to bottom pressure;
- *GLO* – the sum of *ATM* and *OCN* coefficients;
- *OBA* – model bottom pressure data that include contribution of water and air over the entire surface of the Earth.

This product is set with a resolution of 3 h. Since January 1, 1976, atmospheric anomalies and bottom pressure anomalies have been arranged in a series of spherical functions up to the 100 d/o to ensure the processing of space geodetic missions equipped with laser retroreflectors, in particular, LAGEOS. Since January 1, 2000 AOD1B is set by decomposition to a degree and order of 180 and, in addition to atmospheric anomalies and anomalies in bottom pressure, takes into account density anomalies of the upper atmosphere, which allows to meet the high requirements of modern space geodetic missions aimed at the study of gravity field (CHAMP, GRACE, GOCE).

The influence of the atmosphere consists of two parts: non-tidal and tidal. Depending on the direct gravitational attraction of atmospheric masses by bodies generating tidal potential and, more significantly, on the periodic motion of the lower boundary of the atmosphere caused by the tide in the Earth's solid body and oceans and on the absorption of solar radiation by the atmosphere, which causes a signal with a period close to 24 h. The tidal part includes 12 waves (P1, S1, K1, N2, M2, L2, T2, S2, R2, T3, S3, R3) and is calculated by updating the coefficients of the corresponding waves of the tidal potential in the observation interval 2007–

2014. A non-tidal atmospheric load is formed by subtracting the obtained waves from the measurements, the study of the influence of which this work is devoted to.

An example of non-tidal atmospheric load for the 1st January, 2003, 00:00 in the form of an equivalent water height (EWH) Using a Gaussian filter (300 km) (Wahr 2007) is shown in Fig. 1.

3 Estimation of Monthly Gravity Filed Models

As previously noted, the gravity field monthly model estimation procedure consists of three stages:

- for each spacecraft from a pair, its trajectory obtained from the measurements of the onboard receiver using the kinematic method of high-precision determination (Precise Point Positioning – PPP) is independently aligned by a model at a 3-h interval;
- at the same time interval a system of equations is generated, linearized in the vicinity of the obtained orbits using inter-satellite velocities and orbits of both spacecraft as measurements;
- joint system of linear equations on a monthly interval being formed and solved by the method of least squares.

Independent monthly models of geopotential are the result of an estimation.

Any processing is based on a measurement model. In general, it has the following form:

$$y(t) = f(t, r_0, v_0, C_{nm}, S_{nm}, p, \dots) + \epsilon, \quad (1)$$

where $y(t)$ measurements, t time, r_0, v_0 initial conditions in inertial reference frame, C_{nm}, S_{nm} Stokes coefficients of degree and order less or equal then n and m , p instrumental parameters, ϵ measurement error

At the first stage, the kinematic trajectory of the spacecraft (the position of the spacecraft for all navigation receiver measurements epochs on the processing interval calculated with PPP technique) was used as measurements. In the second, besides the trajectories of both spacecraft, the relative velocity was added.

At the first stage, we estimated the initial conditions of the spacecraft and the parameters of the accelerometer, while the Stokes coefficients was not estimated. For the calculation of the spacecraft coordinate system, star camera data was used. The orbit parametrization is generally similar to that used in the work devoted to the analysis of high-precision methods of ballistic-navigational support of space geodetic complexes using the Geo-IK2 spacecraft as an example (Zaliznyuk et al. 2019). At the second stage, Stokes coefficients up to the 80th degree and order and model empirical parameters of the measurement errors of the inter-satellite line were added

Fig. 1 Non-tidal atmospheric load in the form of equivalent water level for the 1st January, 2003 00:00

to the refined parameters. At both stages, the relationship between the dependent variables and the independent ones is nonlinear, so linearization is performed in the vicinity of the a priori orbit. The a priori orbit was calculated by numerical integration of the system of equations of motion with the initial conditions, taking into account a number of perturbations in accordance with the IERS 2010 convention. Table 1 shows the perturbations taken into account. At both stages, the derivatives of the measurements with respect to the orbital parameters were calculated by numerical integration of the variations equations.

Table 1 The perturbations taken into account when integrating the system of equations of motion

Perturbation	Model
Static Earth gravity field	EGM2008
The direct attraction of the Sun, the Moon and planets	DE430
Solid Earth tides	IERS Conventions 2010
Ocean Loading	FES2004
Pole tide	IERS Conventions 2010
Deformation due to polar motion	IERS Conventions 2010
Relativistic effects	IERS Conventions 2010
Non-tidal atmospheric loading	AOD1B RL06
Non-gravitational perturbations	Accelerometer data

The contribution of various gravitational effects and a typical change in gravity filed over a monthly interval are shown in Fig. 2 in the values of the root of the degree variance in the logarithmic scales. Obviously, the static gravitational field has the greatest influence on the motion of spacecraft in the entire gravity spectrum. Then comes the ocean tide, whose contribution to the low-wave part of the spectrum is smaller than the changes in the gravity at monthly intervals. The atmospheric non-tidal load, for its part, has a greater effect on the gravity filed than its monthly variability up to 10–15 harmonics and less on higher harmonics.

Also, notice that when integrating the equations of motion, in addition to the conventional perturbations, measurements of non-conservative forces made by accelerometers installed on board both GRACE spacecraft were taken into account. Because of that, we need to add to the vector of the estimated parameters a systematic error for each of the three axes of the accelerometer and scaling factors in all of them as well.

At the third stage, from the matrices of conditional equations formed at the second stage corresponding to 3-h intervals, the matrix of normal equations was formed on a monthly interval. The vector of specified parameters of the monthly interval is a superposition of 3-h vectors in terms of orbital and instrumental parameters, and includes one set of

Fig. 2 The contribution of various gravitational effects

Stokes coefficients for the entire interval. On average, one monthly solution includes about 3,600,000 measurements, 10,000 estimated parameters, takes about 200 GB on the hard drive and lasts 3 days on PC.

4 Results

To assess the contribution of non-tidal atmospheric load to the estimation of monthly gravity field models, two series of solutions were carried out: with and without AOD1B. In Fig. 3 is a diagram of the solutions made to estimate the monthly gravity models. The missing of 2 months of both sets of solutions is due to the lack of accelerometer data at these intervals. This interval was chosen because of the relatively more successful functioning of the mission as a whole (a relatively small number of hardware failures). Considering the informativeness of the results of comparing the obtained time series of monthly gravity models and

the high cost of computational resources for calculations, solutions without the use of non-tidal atmospheric loading for 2005 were not implemented.

To evaluate the characteristics of both obtained time series of the gravity models, the equivalent water height was calculated using a Gaussian filter (300 km) in the Greenland region, since for this region a pronounced annual signal of changes in the gravity field and a long-period trend are observed. A rectangle was used (60..85 deg. of latitude; -70..-20 deg. of longitude). For the entire 3-year interval, the average value of gravitational potential was found, the pairwise difference of all monthly models with the obtained average was constructed, then for each point in the region with an increment of 1° the equivalent water level of the difference of the monthly model with the average was considered and the average value for the entire region was considered. The values obtained for both series of gravity models and similar values calculated from models of other official GRACE measurement processing

Fig. 3 Diagram of monthly gravity field solutions

Fig. 4 The equivalent water level in Greenland (60..85 deg. of latitude; -70..-20 deg. of longitude), calculated and averaged over the grid with a step of 1 degree using a Gaussian filter (300 km) over a 3-

year interval according to monthly models of gravity filed by different analysis centers CSR, GFZ, JPL and IAC

centers (CSR, GFZ, JPL) are shown in Fig. 4. Considering that in the C_{20} series obtained from GRACE measurements, an unknown 161-day period is observed, the values of the C_{20} coefficient were taken from the results of processing five satellites (LAGEOS-1/2, Stella, Starlette, AJISAI) laser location data (Satellite Laser Ranging, SLR) (Loomis et al. 2019).

The results of the three official GRACE data centers are in good agreement with each other, due to the similarity of the models and processing algorithms used. The solutions we obtained taking into account the non-tidal atmospheric loading agree much better than the solutions obtained without taking into account AOD1B. It can be seen that ignoring the non-tidal loading in processing introduces a distortion in the estimation of the gravity field models the same size as the signal of its change. This is the first result for the KAGOR software and this software has potential capability to increase the accuracy of the solutions obtained, in particular, in outlier search algorithms and reducing the influence of anomalous measurements. Nevertheless, this SW already provides an account of all the necessary effects and allows to obtain an adequate estimate of the gravity field signals.

5 Conclusions

1. The KAGOR (cartography, geodesic research and orbit determination) experimental software has been developed, which allows to model orbits, kinematic trajectories

and to take corresponding satellite-to-satellite measurements with any given parameters, as well as to process real satellite-to-satellite measurements to estimate gravity field models.

2. A general form of a measurement model was presented, the perturbations taken into account, the instrumental corrections taken into account, and the monthly solution generation algorithm.
3. The contribution of non-tidal atmospheric loads to the monthly gravity filed models were analyzed.
4. The monthly gravity field models were calculated taking into account and w/o taking into account non-tidal atmospheric loads.
5. The results obtained show that the signal of non-tidal loads exceeds the signal of monthly variations of the gravity field.

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