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ORIGINAL ARTICLE

Lunar gravity field determination using SELENE same-beam differential VLBI tracking data

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Abstract A lunar gravity field model up to degree and order 100 in spherical harmonics, named SGM100i, has been determined from SELENE and historical tracking data, with an emphasis on using same-beam S-band differential VLBI data obtained in the SELENE mission between January 2008 and February 2009. Orbit consistency throughout the entire mission period of SELENE as determined from orbit overlaps for the two sub-satellites of SELENE involved in the VLBI tracking improved consistently from several hundreds of metres to several tens of metres by including differential VLBI data. Through orbits that are better determined, the gravity field model is also improved by including these data. Orbit determination performance for the new model shows improvements over earlier 100th degree and order models, especially for edge-on orbits over the deep far side. Lunar Prospector orbit determination shows an improvement of orbit consistency from 1-day predictions for 2-day arcs of 6 m in a total sense, with most improvement in the along and cross-track directions. Data fit for the types and satellites involved is also improved. Formal errors for the lower degrees are smaller, and the new model also shows increased correlations with topography over the far side. The estimated value for the lunar GM for this model equals 4902.80080 ± 0.0009 km^3/s^2 (10 sigma). The lunar degree 2 potential Love number k_2 was also estimated, and has a value of 0.0255 ± 0.0016 (10 sigma as well).

Keywords Lunar gravity · Differential VLBI · Orbit determination · Gravity field determination

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1 Introduction

Until recently, lunar gravity field models were determined from either 2-way tracking (where the up- and downlink stations are the same) or 3-way tracking (where they are different) between stations on Earth and a satellite orbiting the Moon. Due to the 1:1 spin-orbit resonance of the Earth–Moon system, this leads to a gap in the tracking data when the satellite flies over the far side of the Moon. This gap in coverage severely hampers the determination of the global lunar gravity field, and the standard way of dealing with this is to impose additional constraints on the solution in the form of regularisation to smooth the solution and make the inverse problem stable [see Lemoine et al. (1997) and Konopliv et al. (2001) for examples of gravity field solutions, and Floberghagen (2002) for a thorough discussion of the lunar gravimetric inverse problem].

The Japanese SELENE mission (Kato et al. 2008) has filled in the tracking data gap by employing a tracking

technique called 4-way Doppler (Namiki et al. 1999). SELENE consisted of three satellites: a main orbiter in a polar, circular orbit at an average altitude of 100 km above lunar surface, and two sub-satellites in polar, elliptical orbits, called Rstar and Vstar. One of these sub-satellites, Rstar, carried communication instruments to forward a radio signal to the main orbiter, and to receive the return signal. By establishing this link while the main orbiter was over the far side of the Moon, the first tracking data over the far side were collected. This has resulted in new lunar gravity field models. Namiki et al. (2009) reported the first results, a 90th degree and order spherical harmonics expansion of the lunar gravitational potential based on data collected in the first 5 months of the SELENE mission. This model named SGM90d clearly resolves ring-shaped structures associated with basins on the far side. Matsumoto et al. (2010) reported an updated model, named SGM100h, a 100th degree and order spherical harmonics expansion based on all 4-way tracking data that were obtained. Owing to the tracking data over the far side, this model can estimate the coefficients up to degree and order 70 without application of an a priori constraint.

In addition to the 4-way tracking data, SELENE collected one more tracking data type not used extensively before in planetary gravity mapping: same-beam differential VLBI (Very Long Baseline Interferometry) tracking between the two sub-satellites, and two stations on Earth. VLBI tracking is based on the delay between the arrival times of a radio source at two different stations constituting a baseline, and as such, it carries information on the angular position of the source (e.g. Thornton and Border 2000). Since 2-way (Doppler or range) tracking has only sensitivity in the line-of-sight direction from the station to the satellite, including VLBI data improves the three-dimensional positioning of the satellite. The accuracy of VLBI tracking is limited by, amongst others, delay measurement accuracy, media effects and clock offset errors. These errors can be largely removed in differential measurements, where delay differences from two sources close to each other in the sky are measured. As a result of the differencing, clock errors and instrumental errors are cancelled, and if the propagation paths of both sources are nearly identical, most media effects are removed as well (Thornton and Border 2000). The benefits of using differential VLBI were recognised early on (Counselman III et al. 1972, 1973; Counselman III 1973), followed by a wide range of successful applications. To list a few, differential VLBI has been used to determine the relative position of the Apollo 16 and 17 lunar rovers (Salzberg 1973), to determine the lunar librations (King et al. 1976), to derive winds on Venus from the Pioneer probes (Counselman III et al. 1979) and from the VEGA balloons (Sagdeev et al. 1986; Preston et al. 1986) and to observe the descent of the Huygens probe on Titan (Witasse et al. 2006). Differential VLBI has furthermore been used in orbit determination of planetary satellites (Border et al. 1992; Folkner et al. 1993), and VLBI tracking of spacecraft contributes systematically to planetary ephemeris solutions (e.g. Folkner et al. 2009).

The same-beam differential VLBI measurements on SELENE have the goal to improve the orbit estimates of the sub-satellites and to improve the estimate of especially the lower degrees of the spherical harmonic expansion of the lunar gravitational potential (Heki et al. 1999; Matsumoto et al. 2008). S and X-band signals broadcast from artificial radio sources on board both satellites are captured simultaneously at a station on Earth (hence they are called same-beam observations), by tracking the mid-point of the satellites in the sky seen from the Earth. The differences of delay between arrival times of the signal at different stations, further differenced between the two satellites, constitute a doubly differenced 1-way range, where most of the media effects and clock errors on the data are cancelled through the differencing. The system used in SELENE is further described in Hanada et al. (2008) and in Hanada et al. (2010). Analysis of the actual VLBI data collected from SELENE has shown that a picosecond accuracy (equivalent to a 0.3 mm differential VLBI residual) is possible with these data (Kikuchi et al. 2009), and that media delays were indeed kept to a minimum (Liu et al. 2010a).

The orbit determination software used to process the tracking data into satellite orbits is GEODYN II (Pavlis et al. 2006). The same-beam differential VLBI data are modelled in this software as follows, with $S_i \rightarrow T_i$ denoting a link from satellite i to station i ($i = 1, 2$ in both cases):

$$[(S_1 \rightarrow T_1) - (S_2 \rightarrow T_1)] - [(S_1 \rightarrow T_2) - (S_2 \rightarrow T_2)] \tag{1}$$

It should be stressed that the differences in this equation are different from those used in GPS double-difference modelling (e.g., Seeber 2003). Light times are computed so that ranges from the same satellite to different stations have the same transmit epoch, instead of using the same receiving epoch at different stations. These differences are further denoted in this paper by singly-differenced VLBI measurements.

The research presented here is the result of the analysis of data of an extensive VLBI tracking campaign, lasting 14 months. All same-beam differential VLBI have been correlated and used for the purpose of orbit and gravity field determination. The results presented here show how these tracking data help to improve the orbit estimates of the sub-satellites, and consequentially, how the data help to improve the estimate of the lunar gravity field model.

This paper is structured as follows: Section 2 describes the VLBI data. In Sect. 3, results for orbit determination using these data are presented. Based on these results the lunar