Koji Matsumoto et al.: Global Lunar Gravity Field Recovery from SELENE, IVS 2002 General Meeting Proceedings, p.381–385
http://ivscc.gsfc.nasa.gov/publications/gm2002/matsumoto

Global Lunar Gravity Field Recovery from SELENE

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Abstract

Results of numerical simulation are presented to examine the global gravity field recovery capability of the Japanese lunar exploration project SELENE (SELenological and ENgineering Explorer) which will be launched in 2005. New characteristics of the SELENE lunar gravimetry include 4-way satellite-to-satellite Doppler tracking of main orbiter and differential VLBI tracking of two small free-flier satellites. It is shown that planned satellites configuration will improve lunar gravity field in wide range of wavelength as well as far-side selenoid.

1. Introduction

Many gravity potential models of the Moon have been developed mainly from 2-way Doppler tracking data of spacecraft orbiting the Moon, in which the lunar gravity potential is usually modelled in terms of spherical harmonics as follows,

$$V(\phi, \lambda, r) = \frac{GM}{r} \sum_{n=0}^{N} \left(\frac{R}{r}\right)^n \sum_{m=0}^{n} \left(\bar{C}_{nm} \cos m\lambda + \bar{S}_{nm} \sin m\lambda\right) \ \bar{P}_{nm}(\sin\phi) \tag{1}$$

where the expansion is given in spherical coordinates with latitude ϕ, longitude λ, radius r; G is the universal constant of gravitation; M is the lunar mass; R is some reference radius; $\bar{C}_{nm}$ and $\bar{S}_{nm}$ are the normalized selenopotential coefficients to be determined, and $\bar{P}_{nm}$ are the normalized associated Legendre functions of degree n and order m. The state of the art lunar gravity models of LP series [1] are completed to degree and order over 100, and have revealed many new masscons. In determining the gravity coefficients in a least-squares sense, however, a kind of constraint taken from Kaula's [2] rule of thumb has been imposed in order to avoid numerical instabilities stemming from spatial data coverage limited to almost near-side. The Kaula-type signal constraint acts as a gravity field smoother and results in good data fit over near-side, but the far-side gravity field is almost meaningless as is clearly shown by Floberghagen [3].

In the Japanese lunar exploration project SELENE (SELenological and ENgineering Explorer) to be launched in 2005, far-side data coverage will be greatly improved by means of high-low 4-way satellite-to-satellite Doppler tracking. The differential VLBI tracking of two sub-satellites [4] is also a new technique applied to the lunar gravimetry. In this article, basing on computer simulation, we discuss the anticipated accuracy of recovered lunar gravity field from SELENE with these new tracking methods.

2. SELENE Gravimetry

SELENE consists of three satellites; the main lunar orbiter (hereinafter referred to as orbiter), the relay sub-satellite (Rstar), and the VLBI sub-satellite (Vstar). The orbiter is a low-altitude

(100 km above the Moon) satellite in a circular orbit with inclination of 90°. The Rstar is a high-altitude (perilune height of 100 km and apolune height of 2400 km) spin-stabilized small satellite in an eccentric orbit with the same inclination as the orbiter. The Rstar is equipped with a communication instrument which relays Doppler signal to/from orbiter, which realizes direct tracking of the orbiter in the far-side (RSAT mission) [5]. The perilune height of the Vstar orbit is 100 km and the apolune height is 800 km. Two radio sources VRAD-1 and VRAD-2 on board the Rstar and the Vstar continuously emit four carrier waves with different frequencies in S and X bands for differential VLBI (VRAD mission) [4].

The orbit of the main orbiter will be perturbed by attitude control maneuver about every 18 hours, while no artificial disturbance will be made to the Rstar and the Vstar orbit. Since gravity acceleration is inversely proportional to r^{n+2}, the orbiter at 100 km altitude is more sensitive to high-degree gravity fields than the Rstar or the Vstar. The Rstar and the Vstar are, on the other hand, more appropriate than the orbiter to determine low-degree gravity fields because of attenuation of high-degree gravity signal on their relatively high mean altitude. Unperturbed long arc-length of the Rstar and the Vstar orbit is also preferable to determine long-wavelength gravity potentials. Consequently, the combination of gravity solutions from the three satellites will result in a fine lunar gravity field model over a wide range of wavelengths.

3. Simulation Setting and Results of Covariance Analysis

GEODYN II [6] and SOLVE [7] programs are used for the simulation and the covariance analysis. GEODYN II has been modified so that it can handle interplanetary 4-way Doppler measurement. The simulation is conducted for the nominal mission period of one year. Table 1 summarizes the tracking data assumed in the simulation in terms of measurement type, accuracy, and data rate. The measurement accuracy depends on the performance of the tracking stations.

Table 1. Tracking data assumed in the simulation

Target satellite	**measurement type**	**accuracy**	**data rate**
Main orbiter	2-way Doppler	2.0 mm/s	10 s
	4-way Doppler	1.0 mm/s	10 s
Rstar	2-way Doppler	0.2 mm/s	10 s
	Differential VLBI with Vstar	1 mm	120 s

The differential VLBI is treated as doubly differenced 1-way range.

Various restrictions to the tracking data acquisition have been taken into account to get realistic simulation results, which are (1) the antenna sharing plan with other space missions, (2) the engineering requirement for the Rstar that the satellite must be in full sunlight during the whole revolution to obtain 4-way Doppler data, (3) the condition that the 2-way and 4-way Doppler data of the orbiter cannot be obtained synchronously, (4) the antenna pattern angle limiting the 4-way link establishment, and (5) the ground station condition restricting the VLBI observation to be 3 days/week and 8 hours/day. Three stations among VERA stations [8] are selected to form over 1000km-long baselines as shown in Figure 1. It is under way to establish an international VLBI network to realize longer baselines [4]. We used LP75G as the true lunar gravity field to simulate observation data as well as a priori gravity field model for the estimation of the gravity potential

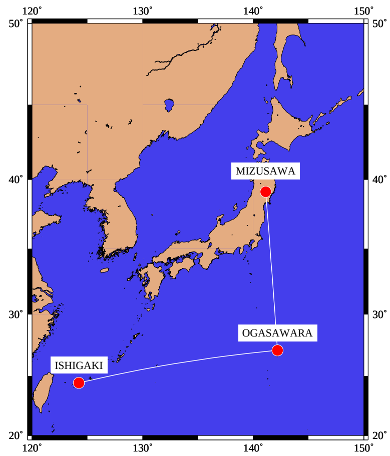

Figure 1. Japanese domestic VLBI stations and baselines used in the simulation.

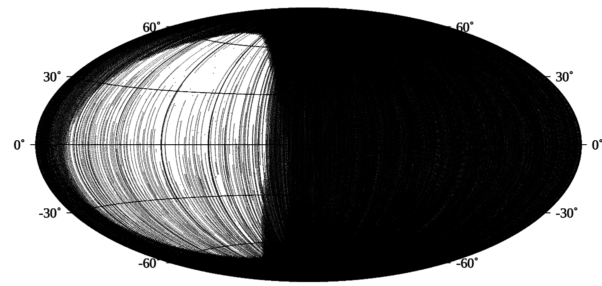

Figure 2. 1-year data coverage of the main orbiter. The map is centered on 270° E longitude, with the far-side of the Moon to the left of the center, and the near-side to the right.

up to degree and order 30. The arc length is set to 1 day for the orbiter and 15 days for the Rstar and the Vstar. Shown in Figure 2 is the date coverage of the orbiter based on the orbit configuration and the analysis conditions described above. A better far-side data coverage in the southern hemisphere is due to the placement of the Rstar apoapsis on the southern hemisphere, which makes the link between the orbiter and the Rstar easier when the orbiter is in the southern hemisphere. Although some data blank areas appear in the northern hemisphere, we can expect generally good far-side coverage from 1 year mission period.

In order to see error spectrum of the recovered gravity field we calculate coefficient sigma degree variance σ_n which is defined as

$$\sigma_n = \left[(2n+1)^{-1} \sum_{m=0}^{n} \left\{ \sigma^2(\bar{C}_{nm}) + \sigma^2(\bar{S}_{nm}) \right\} \right]^{1/2} \tag{2}$$

where $\sigma(\bar{C}_{nm})$ and $\sigma(\bar{S}_{nm})$ are the error of the gravity potential coefficients. Plotted in Figure 3 is the coefficient sigma degree variances for the four cases summarized in Table 2. In case A, the gravity coefficients higher than degree 10 are strongly affected by the constraint. Case B suggests that the 4-way Doppler data on the far-side significantly improves gravity coefficients for all degrees up to degree 30, which is compared with LP100J. This implies the importance of

Table 2. Case setting for covariance analysis

Case name	Measurement type				A priori constraint
	orbiter 2-way	orbiter 4-way	Rstar 2-way	ΔVLBI	
A	Yes	No	No	No	Yes
B	Yes	Yes	No	No	No
C	Yes	Yes	Yes	No	No
D	Yes	Yes	Yes	Yes	No

far-side data coverage on spherical harmonic approach to lunar gravity field recovery. From case C we see that the Rstar contribution is significant for low-degree fields ($n \leq 10$), as expected in section 2. The differential VLBI data further improves low-degree coefficients as seen in the result for case D. Since the accuracy of the lunar moments of inertia is currently dependent on the errors in J_2 and C_{22} [9], the contribution from the Rstar and the Vstar will be of particular importance to constrain the radius or density of the lunar core which can be deduced from the lunar moment of inertia.

Selenoid height errors are calculated by propagating a full error variance-covariance matrix of the gravity coefficients [10]. Figure 4 shows the selenoid height error which is anticipated for case A and Figure 5 is the same but for case D. Large selenoid error exceeding 25 m in Figure 4 indicates that even if a Kaula-type signal constraint is applied to the solution, the lunar far-side gravity filed is poorly determined from conventional near-side 2-way Doppler observation only. However, the selenoid height errors in the far-side are significantly reduced down to below a few meters in case D, much of which is contributed from far-side 4-way Doppler data. Even though relatively larger error is seen in 4-way data blank area, Figure 5 again shows the importance of the far-side data coverage.

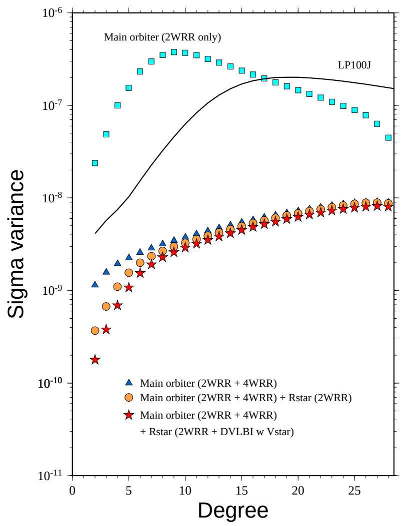

Figure 3. Anticipated coefficient sigma degree variances. The solid line shows LP100J error variances.

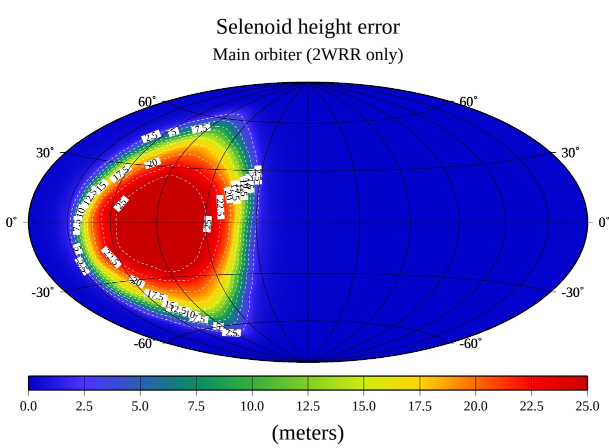

Figure 4. Anticipated selenoid height error for case A. A Kaula-type constraint is applied to the solution in order to avoid numerical instability.

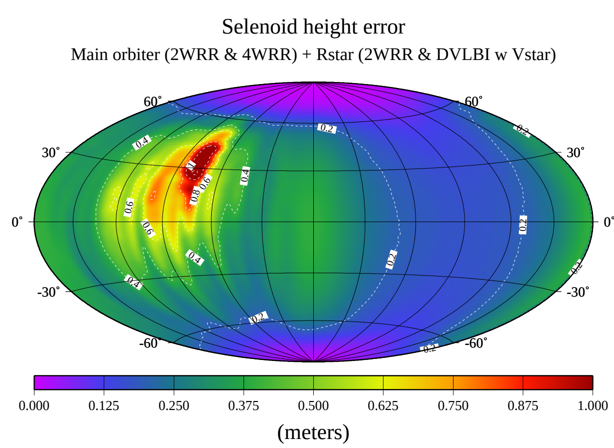

Figure 5. Same as Figure 4, but for case D. No constraint is applied to the solution. Note that the scale is different from that of Figure 4.

4. Summary

We have presented preliminary simulation results with regard to the lunar gravimetry in the coming SELENE project. It is shown that sufficient data coverage over the lunar far-side will be realized by high-low satellite-to-satellite 4-way Doppler measurement with planned satellites configuration. The far-side data result in significant improvement of lunar gravity field over a wide range of wavelengths as well as improvement of the far-side selenoid. The orbiter contribution and the Rstar contribution to the gravity field solution are complementary and the Rstar is expected to contribute to the improvement in low degree gravity coefficients such as J_2 and C_{22}. We can expect further improvement in the low degree coefficients by the differential VLBI measurement between the Rstar and the Vstar. This feature will be enhanced by an international VLBI network with longer baselines.

5. Acknowledgements

GEODYN II/SOLVE programs were introduced to NAO under a joint research contract with NASA/GSFC and we thank Prof. B. Chao and Dr. D.D. Rowlands for their continuous help.

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