INITIAL RESULTS OF GRAVITY EXPERIMENT BY FOUR-WAY DOPPLER MEASUREMENT OF KAGUYA (SELENE) .
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Introduction: The gravity field is a basic and significant data set for the study of the internal structure and the evolution of planetary bodies. Konopliv *et al.* [1] have incorporated tracking data from Lunar Prospector spacecraft into the historical data set, and have developed a model complete to degree and order 150 (LP150Q). These high-resolution gravity models have been used for studies of structure and tectonics of the Moon [e. g., 2, 3].

Current lunar gravity field models, however, include large uncertainties on the far side of the Moon. This is because synchronous rotation of the Moon inhibits a direct link between a ground tracking station and a spacecraft over the far side. Such lack of tracking data has an inevitable influence on the spherical harmonic expansion of the lunar gravity field, as global distribution of observations is required for the harmonic expansion in principle. In order to compensate for the lack of tracking data on the far side, all previous workers [e. g., 1] advocated an a priori constraint [4] in processing tracking data to produce the global lunar gravity field. This problem of the lunar gravity model remains unresolved until global coverage of gravimetry observation is completed.

RSAT experiment. In order to track a spacecraft over the lunar far side, we developed a satellite-to-satellite Doppler tracking sub-system (RSAT) on KAGUYA (SELENE) [5, 6]. Main function of RSAT is to relay Doppler tracking signals between the main orbiter (MAIN) over the far side and ground-based antenna. The tracking sub-system is mostly located on Rstar, with one transponder (RSAT-2) on MAIN to establish the link. When MAIN is orbiting over the far side of the Moon, tracking signal in S band transmitted from Usuda Deep Space Center of JAXA (UDSC) [7] is relayed by RSAT-1 on Rstar to RSAT-2 on MAIN. Then RSAT-2 returns the tracking signal to RSAT-1, and RSAT-1 translates the S band signal into X band to downlink a coherent Doppler signal to UDSC. We call this tracking system four-way Doppler measurement. At the same time, conventional range and range rate measurements are carried out between Rstar and UDSC, which we call two-way Doppler and range measurements. RSAT realizes the first direct observation of the gravity field over the far side of the moon, and enables global gravity anomaly mapping of the Moon up to degree as high as 75 in spherical harmonics without a priori constraint by the end of KAGUYA (SELENE) mission [8, 9].

Gravity Data Acquisition In Initial Check Out: KAGUYA was launched on September 14, 2007. Soon after KAGUYA arrived at the Moon, Rstar was released from MAIN successfully at 0:36 a.m. on October 9 (Universal Time). Rstar was then inserted into an elliptic orbit with altitude ranging from 120 to 2395 km, inclination of 90.1 degree, and a period of 4 hours and 5 minutes with respect to the Moon. Rstar is a spin-stabilized satellite and its spin rate is 11 rpm.

The four-way Doppler measurements started at 19:27 on November 5 (UT) during initial check out phase. After the initial check out, we have collected as much four-way Doppler data as possible by putting the highest priority on the four-way measurement in the operation of Rstar.

Initial Results From Four-Way Doppler Measurements: The very first Doppler data were collected in the initial check out, and processed by Matsumoto *et al.* [10] (Figures 1, 2, and 3). Residuals of observed Doppler data from a prediction based on LP100K lunar gravity model are shown in these figures. Deviation of Doppler data due to spin of Rstar have been removed from raw tracking data by low pass filtering. However, perturbations of ionosphere and low atmosphere still remain. Bias of the data is estimated to be about 20 mm/s. Figures 1, 2, and 3 show Doppler data obtained between 19:27 and 20:20 on November 5, between 23:17 on November 5 and 0:12 on November 6, and between 3:06 and 4:09 on November 6, respectively. The four-way Doppler measurements began while MAIN was visible from UDSC, namely, orbiting over the near-side to prepare for contingency (Figure 4). In the middle of observational periods, MAIN entered in the far side and became invisible from UDSC. In these figures, solid and open symbols indicate the visibility and invisibility of MAIN from UDSC, respectively.

It is evident in the Figures 1, 2, and 3 that, over the near side, variation of the residuals is smaller than 5 mm/s. In contrast, variation over the far side is as large as 30 mm/s. We infer that the latter variation is a true signal of unresolved gravity anomaly on the far side, because these variations of residuals reveal a good correlation when plotted along a ground track of

MAIN (Figure 4). Thus the Figures 1, 2, and 3 suggest an accuracy of current lunar gravity model over the near side as well as our ignorance of the far side gravity field.

Figure 4 further indicates the possibility that the lunar gravity anomaly map on the far side is changed significantly after analysis of the four-way Doppler measurements. Peaks of residuals do not necessarily correspond in space to local maxima and minima of the current gravity anomaly map (Figure 4). A simple estimate shows that a fluctuation of along-track velocity of 25 mm/s corresponds to 6 x 10^{16} kg point mass anomaly on the lunar surface, for instance. This points unmodeled local signature on the far side. Obviously we need to collect more Doppler data to argue gravity field over the far side in a more quantitative manner.

Continuing Observation And Data Reduction: The nominal mission period of KAGUYA and the collection of four-way Doppler measurements continue until October 2008. In the meantime, chances for the four way Doppler measurements are limited, as particular geometry among the two satellites and the ground station must be satisfied. Besides, the small size of Rstar limits electric power supply from solar array panels, and therefore time for four-way measurements. From December 2, 2007 to early January 2008, Rstar is fully lit by the Sun and we are operating Rstar to obtain as much four-way Doppler data as possible.

We plan to release our first lunar gravity model likely in March when sufficient amount of Doppler data are accumulated. Our first lunar gravity model may be limited to degree lower than 60, and adopt tracking data of not only KAGUYA, but also Lunar Prospector, Clementine, Apollo, and so on. After the first release, the lunar gravity model will be updated every three months by incorporating new tracking data.

The four-way Doppler data collected during the first three months will be provided for Lunar Reconnaissance Orbiter (LRO) mission planning under a cooperative agreement between JAXA/SELENE and NASA/LRO. Once nominal mission period ends, our new gravity model will be open to public, too.

After the nominal mission ends, an extended mission is planned for succeeding several months. However, orbital simulation predicts that Rstar will impact at the deep far side early 2009. Until that day, we wish to get most from this unique gravity experiment for the study of the structure and evolution of the Moon, as well as for future lunar missions.

References: [1] Konopliv A. S. et al. (2001) *Icarus*, *150*, 1-18. [2] Wieczorek M. A. and Phillip R. J. (1997) *JGR*, *102*, 10993-10943. [3] Watters T. R. and Konopliv A. S. (2001) *Planet. Space Sci.*, *49*, 743-748. [4] Kaula W. M. (1966) Theory of Satellite Geodesy, pp. 124. [5] Namiki N. et al. (1999) *ASR*, *23*, 1817-1820. [6] Iwata T. et al. (2004) *Int. Assoc. Geodesy Symp.*, 128, 157-162. [7] Hayashi et al. (1994) *Proc. IEEE*, 646-657. [8] Goossens S. and Matsumoto K. (2007) *ASR*, 40, 43-50. [9] Matsumoto K. et al. (2007) *ASR*, *in press* (doi:10.1016/j.asr.2007.03.066). [10] Matsumoto et al. (2008) *this issue*.

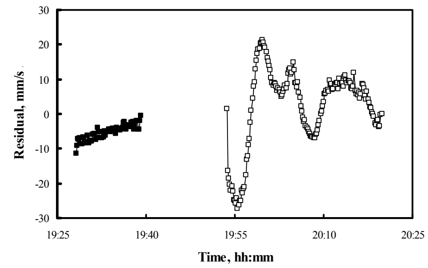

Figure 1. Four-way Doppler residuals in pass from 19:28 to 20:20 on November 5 (UT).

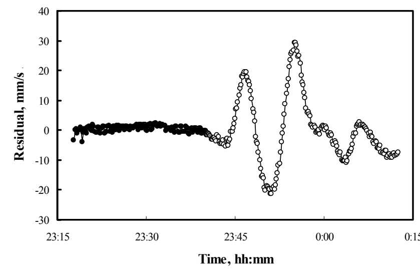

Figure 2. Four-way Doppler residuals in pass from 23:17 on November 5 to 0:12 on November 6 (UT).

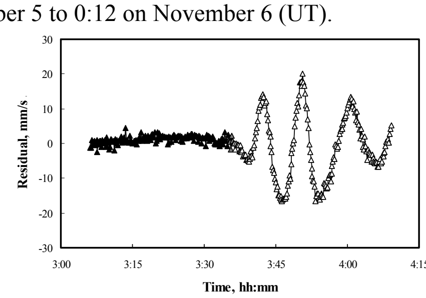

Figure 3. Four-way Doppler residuals in pass from 3:06 to 4:09 on November 6 (UT).

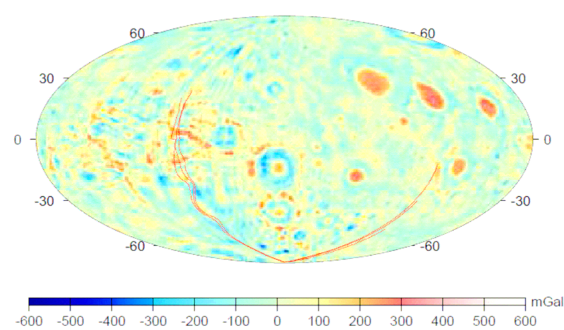

Figure 4. Four-way Doppler residuals plotted along the ground track of MAIN. Near side and far-side are right- and left-hand sides of the map, respectively.