PRELIMINARY RESULTS FOR VRAD MISSION OF KAGUYA (SELENE): F. Kikuchi[1], Q. Liu[1], N. Petrova[1], K. Matsumoto[1], Y. Ishihara[1], S. Goossens[1], K. Asari[1], S. Tsuruta[1], T. Ishikawa[1], H. Noda[1], H. Hanada[1], T. Iwata[2], N. Namiki[3], N. Kawano[1], and S. Sasaki[1], [1]NAOJ (2-12 Hoshigaoka, Mizusawa, Oshu, Iwate 023-0861, Japan, fuyuhiko@miz.nao.ac.jp), [2]JAXA (3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan), [3]Kyushu University (6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan).

Introduction: One of the important questions still remaining about the Moon is the existence and state of a lunar core. The size and density of the lunar core estimated from the moment of inertia of the Moon are important constraints for investigating the origin of the Moon. However, the lack of accurate gravity field information especially for the far side and the limb region of the Moon restricts the accuracy of the moment of inertia of the Moon (Hanada et al., 2002). In order to estimate the lunar gravity field more accurate than before (Konopliv et al., 2001), the differential VLBI observation in the VRAD (the differential VLBI RADio sources) mission (Hanada et al., 2002) is carried out, next to the 2-way and 4-way Doppler observations in the RSAT (the Relay SAtellite Transponder) mission (Namiki et al., 1999) of the Japanese lunar explorer KAGUYA (SELENE).

VRAD Mission: In VRAD of KAGUYA, differential VLBI observations between two sub-satellites called Rstar (Okina) and Vstar (Ouna) are carried out. The two sub-satellites have an polar elliptical orbit. Perilune and apolune heights of Vstar are 129 km and 792 km, and those of Rstar are 120 km and 2395 km respectively. The VLBI network consists of four domestic Japanese stations of VERA network: MIZUSAWA, OGASAWARA, ISHIGAKI, and IRIKI, and four foreign stations: SHANGHAI, URUMQI (China), HOBART (Australia), and WETTZELL (Germany). The foreign stations will participate twice in intensive observations each of which consists of one month period.

The VLBI radio sources are loaded on Rstar and Vstar. They transmit four carrier wave signals which consist of three carrier wave signals in S-band (fs1=2212 [MHz], fs2=2218 [MHz], and fs3=2287 [MHz]) and one in X-band (fx1=8456 [MHz]). The frequencies of these signals are allocated to resolve the cycle ambiguity of the differential phase delay (DPD) of the S-band and X-band signals using the multi-frequency VLBI (MFV) method (Kono et al., 2003). It is expected that DPD can be estimated within an error of 3.3 pico-second (ps) (Kono et al., 2003). If the baseline length is assumed to be 2000 km, the relative position of Rstar and Vstar around the Moon can be estimated to an accuracy of 20 cm. Because DPD is highly sensitive to the relative position and velocity of the two sub-satellites in the direction perpendicular to the line-of-sight (LOS), VRAD observations can contribute to estimate the gravity field of the limb region of the Moon.

VRAD System: For the ground receiving system, the radio frequency signals after the video conversion are recorded by the narrow-bandwidth VLBI system, which is newly developed for VRAD. Three S-band and one X-band signals are recorded in four channels of the system. The sampling rate of 200 ksps is an important specification. Because the bandwidth of the carrier wave signal used in VRAD is several tens of Hz, it is possible to reduce the data amount by using the low-rate sampling system, and this introduces the possibility of near-real time data processing. The original correlation software carries out the correlation process. The software is composed of the correlation module which includes the bit shifts, the fringe stopping and the fractional bit correction, and the VLBI delay estimation module which corresponds to the MFV method.

Application of Switching and Same-beam VLBI methods for MFV: In order to derive DPD without cycle ambiguity, three conditions on MFV method must be satisfied (Kono et al. 2003): First, the phase error of the differential residual fringe phase (DRFP) of the signals from two nearby spacecraft must be less than 4.3 degrees in the S-band and 179 degrees in the X-band signals. Second, the total electron content (TEC) of the ionosphere through which the propagation path from the spacecraft travels, must be estimated within an error of 0.23 TECU (1 TECU is 10^{16} el/m^2). Third, the initial geometric delay, which is used in the correlation of the signal from the spacecraft, must be known within an error of 83 nanoseconds (ns).

Two kinds of differential VLBI observation methods are planned to satisfy these conditions. One is a switching VLBI observation method. By alternately observing two nearby spacecraft, some error sources of VLBI such as the tropospheric fluctuation and ionospheric delay can be canceled. The other is the same beam VLBI observation method (Liu et al., 2007 and Kikuchi et al., 2008). When the elongation between two lunar orbiting spacecraft becomes smaller than the beam width of the ground antenna (0.37 and 0.1 degrees for S-band and X-band signals), their signals can be received simultaneously. Most error sources are expected to be canceled out by applying this method.

Initial Check-out Phase: The initial check-out of the on-board system and the ground stations was carried out during November 2007. We have confirmed the function of the on-board VRAD components without problems. All the signals from Rstar and Vstar were also detected in sufficient carrier to noise ratio. Figure 1 shows the spectrum of the received signals for Rstar and Vstar at VERA stations. Both of the signals from Rstar and Vstar were recorded simultaneously because the same beam VLBI observation was carried out in this period. VLBI observations have been carried out for three days per week until now.

Initial Results in Check-out Phase: Preliminary analysis was carried out for the data obtained in the period of the initial check-out phase.

Correlation. As a result of the software correlation, RFP can be derived successfully both for Rstar and Vstar. The SNR (signal-to-noise ratio) of the cross correlation function is almost consistent with the designed value. Figure 2 shows DRFP between Rstar and Vstar in the period of the same beam VLBI observation. In this figure, the long-term trend, which is considered to be caused by the error of the a priori orbit, is removed by an 8^{th} order polynomial fitting function. The RMS of DRFP for three S-band signals is smaller than 2 degrees in a 30-second integration interval. This result shows that most of the atmospheric and the ionospheric fluctuation common in the propagation paths from Rstar and Vstar to the ground station are canceled out. Therefore, it is shown that the severe condition of the phase error in the MFV method can be satisfied by applying the same beam VLBI method.

Differential phase delay estimation. All of the conditions for the MFV method can be satisfied in the period of same beam VLBI observation and DPD of the S-band signal can be derived without cycle ambiguity. Figure 3 shows DPD for three Japanese baselines. The RMS of DPD in a 30-second integration interval are 2 ps, 2 ps, and 1 ps for ISHIGAKI-IRIKI, IRIKI-MIZUSAWA, and MIZUSAWA-ISHIGAKI baselines. The result confirms that the desired accuracy of VRAD, which is 3.3 ps in a 110-second integration interval, can be achieved. Therefore, it can be expected that VLBI data will contribute to improve the lunar gravity field especially for the limb region of the Moon.

Conclusion: As results of the preliminary analysis of VRAD mission, the performance of the on-board and the ground VLBI system is confirmed. Moreover, we can successfully derive DPD without the cycle ambiguity. The same beam VLBI method contributes a great deal to accurate phase delay estimation. Currently, the nominal mission phase has started. With the accumulation of VLBI data in addition to range and Doppler data, orbit determination and lunar gravity field estimation will be started (Matsumoto et al., 2008).

References:[1] Hanada H. et al. (2002), IVS 2002 General Meeting Proceedings, 73-76. [2]Konopliv A. S. et al. (2001), 150, 1-8. [3] Namiki N. et al. (1999) Adv. Space Res. 23, 1817-1820. [4] Kono Y. et al. (2003), Earth Planets Space, 55, 581-589. [5] Liu Q. et al. (2007), Adv. Space Res., 40, Issue 1, 51-57. [6] Kikuchi F. et al. (2008), Earth Planets Space (in press). [7] Matsumoto K. et al. (2008) this issue.

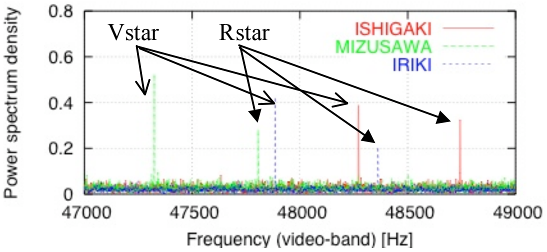

Figure 1. The "video-band" spectra of the received signals (S3=2287MHz) for Rstar and Vstar at three VERA stations.

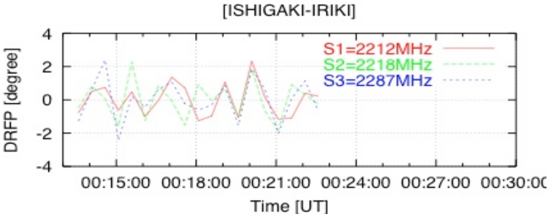

Figure 2. The differential residual fringe phase of the S-band signal between Rstar and Vstar. The baseline is ISHIGAKI-IRIKI. The integration period is 30 seconds.

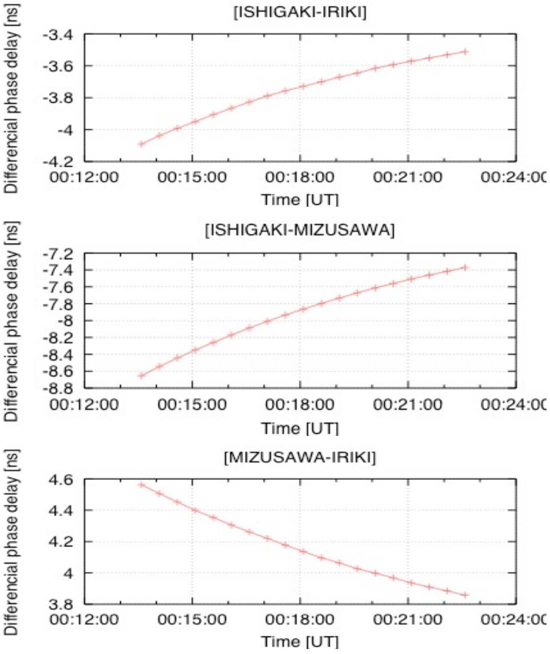

Figure 3. The differential phase delay of the S-band signal for three Japanese baselines.