Precise phase delay estimation in VRAD mission of Kaguya by same beam and multi frequency VLBI methods


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Abstract
Same beam VLBI (very long baseline interferometry) observations of the two sub-satellites of SELENE (KAGUYA) are demonstrated for purpose of the precise gravimetry of the Moon. The same beam VLBI contributes a great deal to cancel out the tropospheric and ionospheric delays and to determine the absolute value of the cycle ambiguity by using the multi frequency VLBI method. As a result, the differential phase delay of the X-band signal is estimated within an error of below one pico-second. This accuracy is more than one order of magnitude better than former VLBI results, revealing the possibility of precise gravimetry.

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., 2008) 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 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). 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 (Matumoto et al., 2008).

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 1016 el/m2). 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.
Result of correlation
As a result of the software correlation, RFP can be derived successfully both for Rstar and Vstar. Fig. 1 shows DRFP between Rstar and Vstar in the period of the same beam VLBI observation. The RMS of DRFP for three S-band signals is 1.8 degrees and 1.3 degrees for X-band in a 60-second integration interval. This result shows that most of the atmospheric fluctuation common in the propagation paths from Rstar and Vstar to the ground station are canceled out and the RMS error satisfies the condition of the MFV method. The doubly differenced TEC are estimated from the DRFP of the S/X-band signals. As a result, the DDTEC is between -0.07 to -0.02 TECU and the error evaluated from the RMS error of the DRFP is about 0.01 TECU in this observation period. This result satisfies the condition for the TEC error of the MFV method.

![Fig. 1](image1.png)

Fig. 1 The absolute value of the cycle ambiguity estimated by the MFV method. Upper is cycle ambiguity of the S-band signal S1 and lower is that of the X-band signal X1. The green and red points represent the results for 1 and 60 second integration intervals, respectively.

Result of 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/X-band signal are estimated. Once the cycle ambiguity is uniquely determined, the DPD can be derived from the DRFP without any bias. Fig. 2 shows the residual of the DPD for S/X-band signals for three baselines. The average of the RMS error for three baselines is 2.27 ps for S-band and 0.29 ps for X-band in a 60-second integration interval. Closure delay for the combination of three baselines is also shown. If the cycle ambiguity is miss-estimated, the closure delay contains the bias which corresponds to the cycle ambiguity. However, the closure delays converge to near zero and the RMS error is less than 1 ps. This result confirms the successful estimation of the absolute value of the cycle ambiguity.

![Fig. 2](image2.png)

Fig. 2 The residual of the differential phase delay of the S-band signal S1 and X-band signal X1. The baselines are Iriki-Mizusawa, Mizusawa-Ogasawara, and Ogasawara-Iriki. ”closure delay” means the closure delay of the threes baselines.

Conclusion
The DPD estimation is demonstrated by using the MFV and SBV methods. SBV ensures satisfaction of the severe conditions for the MFV method. As a result, the absolute value of the cycle ambiguity is uniquely determined for the first time. The accuracy of the DPD of X-band signal is below one ps. Additionally, the desired accuracy of 3.3 ps for precise gravimetry of SELENE has been achieved for most of the SBV of the S/X-bands until now. The results of overlap analysis confirm the contribution of DVLBI for the orbit determination of R/Vstar, and subsequently this will lead to further improvements of the lower degrees of the lunar gravity field in the future.

References