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# VRAD Mission: Precise Observation of Orbits of Sub-Satellites in SELENE with International VLBI Network

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## Abstract

VRAD (VLBI radio source on the Moon) mission is one of selenodetic missions in SELENE project and we measure angular distance between radio transmitters on board two sub-satellites around the Moon and quasars by differential VLBI. VRAD can contribute to establish a lunar gravity field model and a lunar ephemeris of higher accuracy and higher reliability by measuring components of the orbits perpendicular to line-of-sight direction. The radio transmitters emit three carrier waves in S-band and one wave in X-band and special recording systems as well as conventional ones such as K-4 receive the waves through VLBI antennas and determine phase differences between them within 10 degrees. Combination of Japanese VERA and International VLBI network will observe the radio sources for one year including intensive observation periods of one month. The intensive observation will need more than 200 hour machine time. It is under way to establish an International VLBI network for VRAD mission.

## 1. Introduction

VLBI (Very Long Baseline Interferometer) has a potential to find new phenomena not only on the Earth but also on the Moon and the planets. Some attempts have already been made in order to apply VLBI to selenodesy, for example positioning of landers and spacecrafts on and around the Moon based on positions of quasars [1] [2]. It is, however, not necessarily to be said that ability of VLBI has fully been shown on the observations made until now, partly because they did not obtain a phase delay of carrier waves or they did not solve cycle ambiguities even if they used the phase delay. A multi-frequency VLBI has been proposed for the purpose of precise positioning using the phase delay and the optimum frequency spacing has been obtained [3] [4]. This method uses carrier waves of lower power consumption instead of noise and is appropriate for positioning of a spacecraft. It has been shown by VLBI experiments using carrier waves from Lunar Prospector that measurement error of phase delay of the carrier waves was possible to be less than 10 degrees which was equivalent to positioning error of about 20 cm on the Moon [5].

In SELENE project, which is Japanese lunar exploration using H-2A rocket with the launch in 2005, we plan to apply the multi-frequency VLBI to measurements of angular distances between two radio sources by using an international VLBI network in order to improve the lunar gravity field Model (VRAD mission) [6]. We receive four carrier waves in S and X-bands emitted from the two radio sources in order to resolve the cycle ambiguity. VRAD mission will improve the accuracy of the spherical harmonics of the lunar gravitational field and the lunar ephemeris by one or two orders higher than before in cooperation with 4-way Doppler measurements and two-way Doppler and ranging measurements by using the main orbiter and Rstar (RSAT mission) [7]. This will advance a study of origin and evolution of the Moon since stronger constraint on the bulk composition of the Moon will be imposed.

In this paper we introduce outline of VRAD mission, and show condition of VLBI stations which can participate in the mission and a data policy imposed on co-investigators of VLBI observations of VRAD.

## 2. VRAD Mission

In VRAD mission, two radio sources VRAD-1 and VRAD-2 on board Rstar and Vstar continuously emit four carrier waves with different frequencies in S and X bands for differential VLBI as shown in Table 1. No special X-band carrier wave is produced in Rstar for VLBI observations but down link signal for Doppler measurements is shared, and only noise with 120 kHz bandwidth will be transmitted when Doppler measurements are not carried out. Rstar and Vstar is on the orbits as shown in Table 2 and angular distance between them is in the range from 0 to at most 1 degree. It is possible to discriminate between a signal from Rstar and that from Vstar by frequencies since they vary independently according to respective orbital motions even if they are received by an antenna in the same attitude.

Table 1. Specification of Transmitted Waves from Sub-Satellites

| Wave Name in SELENE | S7 | S8 | S9 | X2 |
|---|---|---|---|---|
| Frequency Band | S | S | S | X |
| Center Frequency | 2212 MHz | 2218 MHz | 2287 MHz | 8456 MHz |
| Band Width | CW | CW | CW | 120 kHz (Rstar)<br>CW (Vstar) |
| EIRP | > 24 mW | > 24 mW | > 24 mW | > 250 mW(Rstar)<br>> 38 mW(Vstar) |

Table 2. Orbits of Two Sub-Satellites, Rstar and Vstar

| | Perilune | Apolune | Inclination | Period |
|---|---|---|---|---|
| Rstar | 100 km | 2,400 km | 90 deg. | 240 min. |
| Vstar | 100 km | 800 km | 90 deg. | 153 min. |

Fringe phases of the $X2$ wave at frequency $f_{x2}$ are the final products for determination of angular distances between Rstar and Vstar. Group delays measured at S-band are used for resolution of cycle ambiguity of $X2$. It is necessary to obtain a group delay with an error smaller than the period of $X2$ in order to resolve the cycle ambiguity. This relation is expressed as

$$\sigma_p/2\pi f_{s7} = \sigma_{g_1} < 1/f_{x2}, \quad (1)$$

where $\sigma_p$ is measurement error (standard deviation) of fringe phase at $S7$ and $\sigma_g$ error of the group delay. Next we need to resolve cycle ambiguity of $S7$ by using the group delay obtained from $S7$

and another wave $S9$. This condition is shown in the relation

$$f_{s9} - f_{s7} > \sigma_p f_{s7}/2\pi. \quad (2)$$

Then we use the third wave $S8$ in order to resolve cycle ambiguity of $S9$ and the relation

$$f_{s8} - f_{s7} > \sigma_p (f_{s9} - f_{s7})/2\pi \quad (3)$$

is necessary. Although cycle ambiguity of $S8$ is not resolved yet, it can be resolved if a group delay with an error smaller than 170 ns is obtained. The group delay will be easily obtained by conventional VLBI between quasars and Rstar/Vstar or delay rate measurements of Rstar/Vstar since the error of 170 ns is corresponds to 9.5km on the lunar surface. The frequencies of $S7$, $S8$, $S9$ and $X2$ shown in Table 1 satisfy the relations (1), (2) and (3).

A VLBI network with 2,000 km baselines and measurements of phases with an accuracy of 0.17 radians (10 degrees) in X-band bring about the accuracy of the angular distance or the distance between Rstar and Vstar of $5.3 \times 10^{-10}$ ($1.1 \times 10^{-4}$arcsec) or 20 cm, since there is the relation

$$\Delta d = c\sigma_\phi l/(2\pi f D), \quad (4)$$

where $\Delta d$ is the positioning error of Rstar and Vstar, $c$ the light velocity, $\sigma_\phi$ the error in the phase delay measurements, $l$ the distance between the Earth and the Moon, $f$ frequency of $X2$ and $D$ baseline length.

## 3. Ground System for VRAD Mission

Carrier waves in S and X bands received by a VLBI antenna are converted to video signals by a video converter in the K-4/Mark-III system and they are recorded either by the K-4/Mark-III system like conventional VLBI experiments or by a narrow band recorder especially developed for VRAD experiments [5]. The narrow band recorder (S-RTP Station, System Design Service Corp.), consisting of four channels for the video signals and one for a reference clock signal, samples and digitizes the video signals at 200 kHz intervals with 6 bit resolution. The digital data are stored in a 8 mm tape with the maximum capacity of 20 Gbytes which corresponds to the data for 7.4 hours. The bandwidth of each channel is restricted to 60 kHz by a low pass filter so that effects of aliasing are not included in the digitized data. We need to adjust frequencies of the video signals by 10 kHz steps by using the video converter in order to put them into the narrow band channel since they change according to Doppler shift which amounts to 40 kHz in S-band and 120 kHz in X-band. Cross-correlation procedures for determination of phase differences between corresponding video signals recorded at two VLBI stations are carried out with a computer, and a special correlator is not necessary.

Seven narrow band recorders will be prepared for VRAD mission and three of them will be distributed to domestic stations belonging to VERA [8] and the others for foreign stations which will participate in VRAD mission. Needless to say, stations which are not equipped with the narrow band recorder can observe the carrier waves from Rstar and Vstar and quasars by the conventional VLBI system. VLBI stations for VRAD mission need to have a performance equivalent to that shown in Table 3 since the power of carrier waves emitted from Rstar/Vstar are not very strong.

The domestic network VERA will take part in VRAD mission for the whole mission period of one year and we make a plan to twice conduct intensive observations each of which consists of one month period under participation of foreign stations. A tentative plan of two kind of observations are shown in Table 4. Anyone who is interested in VRAD mission and is permitted by the principle investigator (PI) of VRAD mission can be a co-investigator. A co-investigator can participate in observations of VRAD mission by using his/her antenna, receiver and VLBI system. Information which is necessary for observations such as observation schedules, orbits and status of the satellites will be provided to the co-investigator by the PI. The Data recorded by the K-4/Mark-III system, however, will not be processed for correlation at an analysis center of VRAD mission due to restriction of facilities but the data recorded by S-RTP Station will be processed there. The co-investigator of VRAD mission can access to the scientific data related to VRAD under any agreed data policy and can read or write papers making use of the data with a permission of the PI of VRAD mission before their official release to the public

We are developing an international network for VRAD mission from the points view of baseline length in north-south and east-west directions, and BKG Wettzell, Shanghai Astronomical Observatory, Urumqi Astronomical Observatory and Hobart Observatory are expected to constitute the international network. It is necessary to make adjustments of machine time and data policy between the international stations including VERA either by direct negotiations or by negotiations with mediation of IVS Coordinating Center.

Table 3. Condition of Typical Ground Stations

| | Gain | Antenna Diameter | Aperture Efficiency | System Temperature |
|---|---|---|---|---|
| S-band | $> 45$ dB | $> 20$ m | $> 0.14$ | $< 150$ K |
| X-band | $> 60$ dB | $> 20$ m | $> 0.35$ | $< 150$ K |

Table 4. Tentative Plan of the VLBI Observations

| | Regular | Intensive |
|---|---|---|
| Network | Domestic (VERA) | International |
| Period | 1 year | 1 month $\times$ 2 |
| Frequency | 3 days a week | $>$3 days a week |
| Observation Time a Day | 8 hours | 8 hours |
| Cumulative Observation Time | About 1300 hours | About 200 hours |

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