#かぐや電波科学による月電離層の観測

Studying the Lunar Ionosphere with the SELENE Radio Science Experiment

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The electron density profiles above the lunar surface are being observed by the radio occultation technique during the SELENE mission using the Vstar sub-satellite. Previous radio occultation observations have indicated the existence of an ionosphere with densities of up to 1000 cm^{-3} above the dayside lunar surface. The measured densities are difficult to explain theoretically when the removal of plasma by the solar wind is considered, and thus the generation mechanism of the lunar ionosphere is a major issue, with even the validity of previous observations still under debate. The SELENE radio science experiment will establish the morphology of the lunar ionosphere and will reveal its relationship with various physical conditions to provide possible clues to the mechanism.

1. Introduction

Lunar ionosphere, which might be produced by the photo-ionization of the tenuous neutral atmosphere (exosphere), is generally thought to have densities on the order of 1 cm^{-3} in the range from the surface to 100 km altitude[1)]. The process that may prevent the accumulation of newly produced ions near the lunar surface is the impingement of the solar wind magnetic field on the lunar surface, which induces an electric field that sweeps away ions[2)].

Radio occultation experiments performed with radio stars, on the other hand, indicated the existence of the lunar ionosphere[3)]. Dual-frequency radio occultation experiments conducted with the Soviet Luna 19 and 22 spacecraft also detected large electron densities near the dayside lunar surface[4,5,6)]. In radio occultation experiments, observed from a tracking station on the Earth, the spacecraft goes behind the lunar plasma layer and then behind the lunar disk, and reemerges in the reverse sequence. The plasma layer causes a time-dependent phase shift in the radio signal, from which the total electron content along the ray path can be retrieved. Vyshlov[5)] obtained peak electron densities of 500-1000 cm^{-3} at heights of 5-10 km, with a gradual decrease at higher altitudes with a scale height of 10-30 km and also a decrease toward the surface. The possible existence of the ionized layer above the lunar surface might be attributed to the effect of the remnant magnetic field[7)], to certain processes that enhance the neutral gas concentration[8)], or to charged dust grains that are lifted up by the near-surface electric field[9)].

The radio science (RS) experiments in the SELENE (KAGUYA) mission using the Vstar sub-satellite, which is illustrated in Fig, 1, will provide opportunities to study this ionized layer to examine its existence and to understand the generation mechanism[10,11)]. The systematic measurements will establish the morphology of the lunar ionosphere and reveal its dependence on the remnant magnetic field, solar incident angle, and solar wind conditions, thereby providing clues to the generation mechanism of the ionosphere.

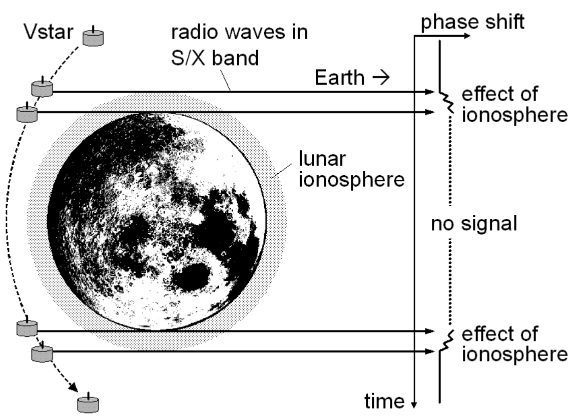

Fig. 1. Schematic of the radio science experiment

2. Method

The subsatellite Vstar is a spinning spacecraft which was put into a polar orbit. Because of the synchronization of the rotation with the revolution of the moon, only the area in the vicinity of the lunar limb as seen from Earth is accessible by radio occultation. The size of the accessible area is determined by the liberation of the moon and will amount to ~10% of the lunar surface in total.

The S-band (2.2GHz) and X-band (8.5GHz) signals transmitted by Vstar is received by the 64-m antenna at the Usuda Deep Space Center in Japan. The received signals will be converted to ~20 kHz by an open-loop heterodyne system stabilized by a hydrogen maser, followed by digitization with a sampling rate of 80 kHz[12]. Signals will be recorded for 20-30 minutes just before each ingress occultation and just after each egress occultation. Given the typical transverse velocity of the ray path of 0.5-1.0 km sec^{-1} in the course of the orbital motion of Vstar, the time needed to probe the whole lunar ionosphere is ~100 seconds.

Although the onboard oscillator is not very stable, linear combination of the phases in the two coherent bands enables us to distinguish the plasma contributions from the fluctuation in the oscillator output frequency. The time-dependent phase shift in the S-band, $\Delta\phi_S(t)$, and that in the X-band, $\Delta\phi_X(t)$, are combined to calculate the differential phase $\delta\phi(t)$ which is related to the electron column density along the ray path, $N_e(t)$:

$$\delta\phi(t) = \Delta\phi_S(t) - \frac{f_S}{f_X}\Delta\phi_X(t) = \frac{\alpha}{c} f_S\left(\frac{1}{f_S^2} - \frac{1}{f_X^2}\right)\cdot N_e(t)$$

where f_S and f_X the nominal frequencies of the S- and X-band, respectively, $\alpha = e^2/8\pi^2\varepsilon_0 m_e \sim 40.3$ m^3 s^{-2} with e, ε_0 and m_e being the elementary charge, dielectric constant in vacuum and electron mass, respectively, and c the speed of light in m s^{-1}. In the region where the contribution of the lunar ionosphere is virtually absent, i.e. at altitudes above several tens of kilometers, a gradual variation caused by the terrestrial ionosphere will be observed. This variation will be extrapolated into the near-moon portion and subtracted from the observed one, thereby eliminating the influence of the terrestrial ionosphere to some extent. The resultant $N_e(t)$ will be converted to a function of the altitude above the surface using orbital information. The vertical profile of electron density will be calculated assuming spherical symmetry of the ionosphere.

Giving the column densities of $\sim 3 \times 10^{14}$ m^{-2} observed by Luna 19 and 22[3], we require a measurement accuracy of 6 10^{13} m^{-2}, which corresponds to the error in differential phase of ~0.021 radian. This value is achievable according to the link budget analysis. The most serious source of error is the density fluctuation in the terrestrial ionosphere. Noguchi et al. [13] studied the root-mean-square (rms) of the total electron content (TEC) fluctuation with periods of 1-10 minutes over the tracking station, as a function of season and local time, using the GPS (Global Positioning System) TEC data. They showed that the hourly-averaged rms is of the order of 10^{14} m^{-2} which is a similar value to the lunar electron content integrated along the ray path.

3. Initial Results

The first occultation measurement has been conducted on November 5, 2007, and 60 occultations have been observed by the end of March 2008. An example of the observed differential phase is shown in Fig. 2. The tangential point of the ray path is near the sunrise terminator in the northern high latitude. The long-term phase variation is attributed to the terrestrial ionosphere and possibly the interplanetary plasma. A portion of the time series is enlarged in Fig. 2, showing a periodic variation due to the spin of the spacecraft with a period of ~5.5 s. The regular pattern indicates a measurement error being smaller than ~0.003 radian.

A slight increase in phase is observed near the lunar surface in Fig. 2, suggesting an increased electron content in this region. The magnitude of this electron content is consistent with the results on the lunar ionosphere from Soviet Luna missions. Studies on the influence of the terrestrial ionosphere and on the conditions for such features to occur are ongoing.

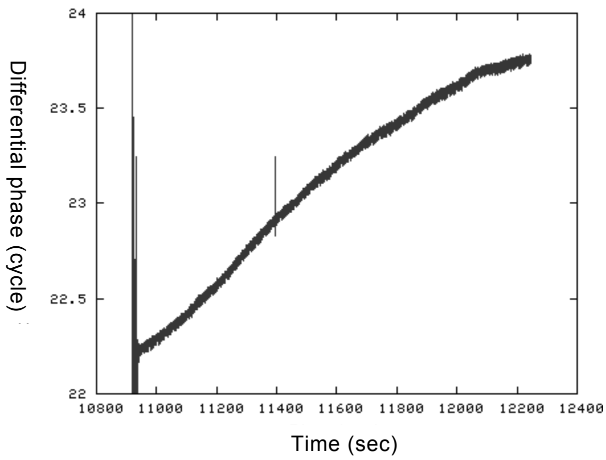

Fig. 2. An example of the time series of the differential phase, taken during an egress occultation on November 8, 2007. The left end of the smooth curve corresponds to the appearance of the spacecraft from behind the moon as seen from the tracking station.

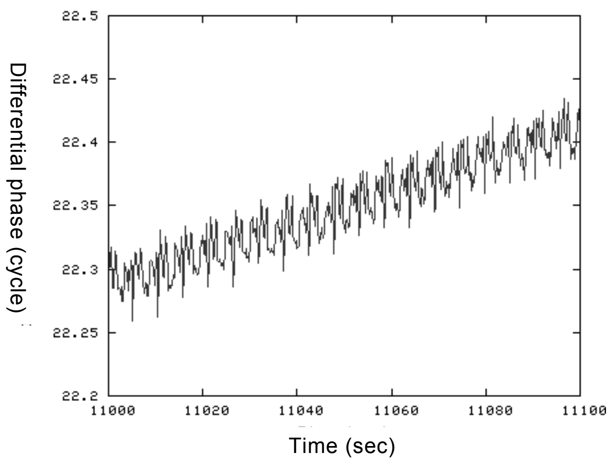

Fig. 3. Enlargement of a portion of the differential phase

curve shown in Fig. 2.

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