Studying the Lunar Ionosphere with 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 mission using the Vstar and Rstar sub-satellites. In addition to a traditional technique which uses one orbiter, we are conducting another method which uses two orbiters with the second one being used to measure the terrestrial ionosphere contribution. Previous radio occultation measurements have indicated the existence of an ionosphere with densities of up to 1000 cm^{-3} above the dayside lunar surface. These 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 conditions to provide possible clues to the mechanism.

Key Words: Moon, Ionosphere, radio occultation

Nomenclature

t	:time
$\Delta\phi$	:phase shift
$\delta\phi$	:differential phase
N_e	:electron content along the ray path
f	:frequency
e	:elementary charge
ε_0	:dielectric constant in vaccuum
m_e	:electron mass
c	:speed of light

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 sub-satellites, 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.

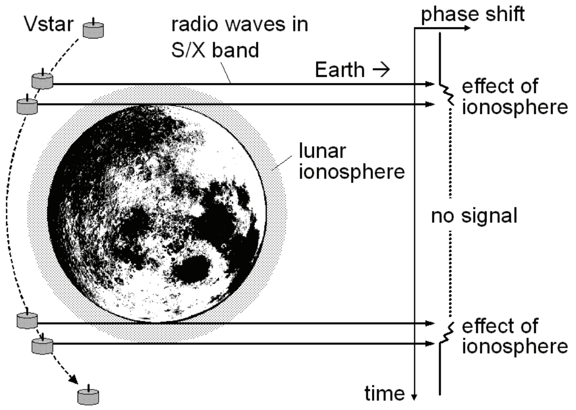

Fig. 1. Schematic of the radio science experiment

2. Method

2.1 Single-spacecraft method

The sub-satellite 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 are received by the 64-m antenna at the Usuda Deep Space Center in Japan. The received signals are converted to video frequencies by an open-loop heterodyne system stabilized by a hydrogen maser, followed by digitization[12)]. Signals are recorded for 10-30 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 ~1 minutes.

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 is 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 $N_e(t)$ is converted to a function of the altitude above the surface using orbital information. The vertical profile of electron density can also be calculated assuming spherical symmetry of the ionosphere.

Giving the column densities of ~3 × 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.

2.1 Dual-spacecraft method

In addition to the above-mentioned method, we also use the Rstar sub-satellite, which transmits coherent two signals at two S-band frequencies, to measure the terrestrial ionosphere during the lunar occultation of Vstar; the subtraction of the Rstar's measurement from the Vstar's measurement gives the lunar ionosphere. However, te use of two S-bands which are separated only by 70 MHz instead of S- and X-bands greatly reduces the sensitivity of the differential phase to the electron column density, and thus the signal-to-noise ratio of the measurement is reduced. Another disadvantage of this method is that observation opportunities are rather limited because the two spacecraft must be located within a rather narrow beam width of the ground antenna.

3. Examples of Initial Results

Fig. 2 shows an example of the time series of the integrated electron density in unit of TECU (10^{16} m^{-2}), taken for the solar zenith angle (SZA) of 45°, during an ingress occultation of Vstar on May 27, 2008. Short timescale fluctuations are attributed to the spin of the spacecraft, and the overall long-term trend is attributed to the temporal fluctuation of the terrestrial ionosphere. The slight increase just before the occultation (from the surface to ~25 km altitude) might be a signature of the lunar ionosphere, although the possibility that this part is caused by the terrestrial ionosphere cannot be excluded.

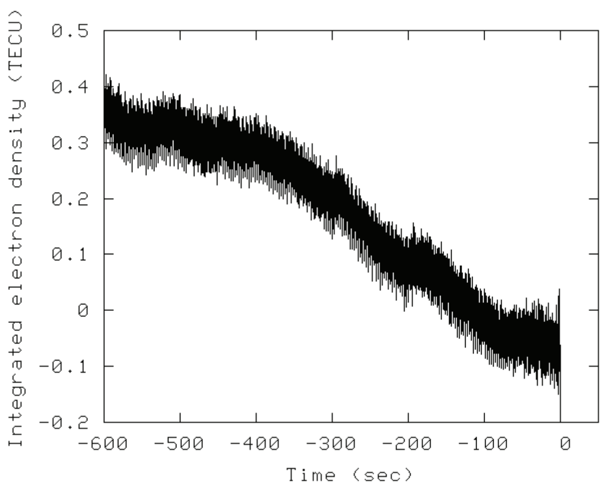

Fig. 2. An example of the time series of the integrated electron density in unit of TECU (10^{16} m^{-2}), taken during an ingress occultation of Vstar on May 27, 2008. The offset for the electron density has been chosen arbitrarily. The origin of the time is the moment at which the spacecraft is occulted by the moon as seen from the tracking station. The rate of change in the tangential altitude above the lunar surface was 0.31 km s^{-1}.

More than 300 measurements have been conducted with the single-spacecraft method. Although the influence of the terrestrial ionosphere is significant and the method of data analysis is still under development, there seems to be a tendency that the integrated electron density increases on the dayside lunar surface for the distance to the lunar surface of less than ~30 km. Based on this observation we assumed that the lunar ionosphere exists below 30 km and that the terrestrial ionosphere varies smoothly. Then, a linear function was fitted to the 50-sec interval above 30 km for each observation, and subtracted from the whole time series. Fig. 3 shows 19 profiles obtained with this procedure for SZA < 60°. Measurements which took >100 sec to cross the 30-km thick layer have been excluded since such measurements tend to be seriously affected by the fluctuation of the terrestrial ionosphere. In this result the tendency of positive deviation in the electron content near the lunar surface is evident, although the occurrence of negative values suggests that the scatter of data due to the fluctuation of the terrestrial ionosphere is still significant. No systematic tendency was observed for other SZAs (not shown here). The validity of these statistical tendencies is being examined.

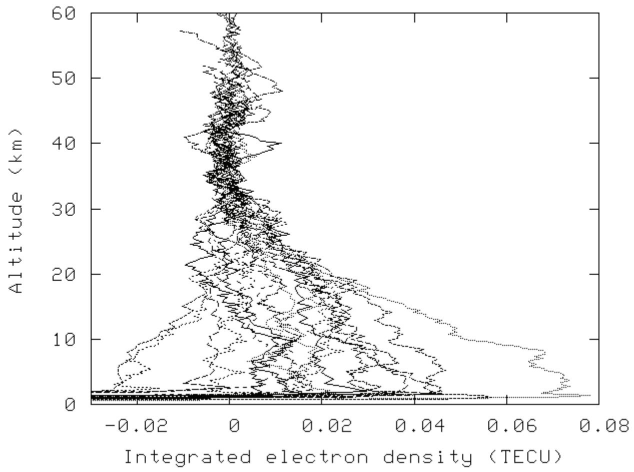

Fig. 3　Electron densities integrated along the ray path as functions of the altitude on the moon　(distance between the lunar surface and the ray path)　for the solar zenith angles of < 60°. 19 profiles are plotted. Each profile has been obtained by subtracting the terrestrial ionosphere component, which is assumed to be a linear function fitted to the 50-second interval of the time series above 30 km altitude.

Fig. 4 shows an example of the measurement with the dual-spacecraft method conducted for SZA of 74° during an egress occultation on August 8, 2008. In the simultaneous measurement by the single-spacecraft method, which is also plotted for comparison, the signature of the lunar ionosphere can not be observed due to the superposed fluctuation of the terrestrial ionosphere. The subtraction of the Rstar's measurement from the Vstar's measurement shows an increase in the electron content just after the egress, which might be due to the lunar ionosphere, although the uncertainty due to the measurement noise has a similar magnitude. Detailed analysis is being made for the 30 results obtained with this method.

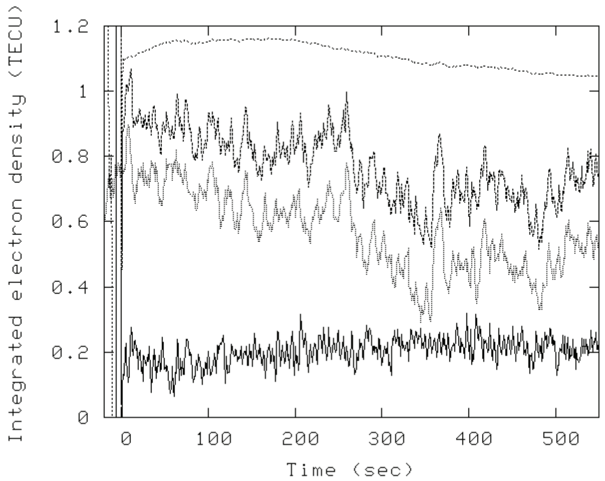

Fig. 4　An example of the time series of the integrated electron densities along the ray paths of Vstar S/X-bands　(top curve), Vstar S-bands　(second curve), Rstar S-bands　(third curve), and the subtraction of the Rstar S-bands result from the Vstar S-bands one　(bottom curve), taken during an egress occultation on August 8, 2008. The offset for the electron density has been chosen arbitrarily. The origin of the time is the moment at which Vstar is occulted by the moon as seen from the tracking station: only Rstar provides measurement before 0 second. The rate of change in the tangential altitude above the lunar surface was 0.71 km s^{-1}.

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