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Application of the GPS network to estimate the effect of the terrestrial ionosphere on the radio occultation measurements of planetary ionospheres

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Abstract. A feasibility study to observe the low-density Martian nightside ionosphere and the cislunar electron layer by radio occultation technique is presented. Since the total electron contents (TECs) along the ray paths of radio occultation in the ionospheres of Mars and the Moon are comparable to the fluctuation of the TEC of the terrestrial ionosphere, the distortions of radio occultation data by the terrestrial ionosphere should be taken into account. Local time and seasonal dependences of the terrestrial TEC fluctuations are investigated using the GPS receiver network, showing that the terrestrial ionosphere is calm at night in winter and that this period is suitable for the radio occultation measurements of the planetary ionospheres. A method is also developed to estimate the terrestrial TEC fluctuation along the ray path of radio occultation from GPS TEC data.

1. Introduction

Radio occultation measurements will be carried out using the Mars spacecraft, Nozomi, expected to arrive at Mars in the year 2004, and the lunar spacecraft, Selenological and Engineering Explorer (SELENE), planned to be launched in 2004. In the Nozomi mission the ionized and neutral atmosphere of Mars will be observed by radio occultation with emphasis on the nightside ionosphere for the reasons discussed below. In the SELENE mission, attempts will be made to detect the photoelectron layer or ionosphere near the lunar surface.

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Radio occultation measurement is usually carried out using a spacecraft which transmits unmodulated radio waves toward the Earth [*Fjeldbo and Eshleman*, 1968]. The phase of the radio wave is perturbed when the ray passes through a planetary atmosphere. The density profiles of the ionized and neutral atmosphere are then derived from the phase perturbations of the received signals assuming that the atmosphere is spherically symmetric.

The electron density profiles of the Martian nightside ionosphere have been obtained in the Mars 4 and 5 [*Savich et al.*, 1976] and the Viking [*Lindal et al.*, 1979] missions using radio occultation. However, only a very few observations of the Martian nightside ionosphere have been reported because the electron density is too low to be detected [*Zhang et al.*, 1990]. The cislunar electron layer was obtained in the Luna 22 mission using radio occultation [*Vyshlov*, 1976]. Their observations have shown the peak electron concentrations of $0.5-1 \times 10^9$ m^{-3} at altitudes from 5 to 10 km above the sunlit lunar surface. However, it is difficult to draw a general picture of the cislunar electron layer from the limited number of reported electron density profiles [*Bauer*, 1996].

The detection of the Martian nightside ionosphere and the cislunar electron layer is difficult because the total electron contents (TECs) along the ray paths of radio occultation in these ionospheres are comparable to the fluctuation of TEC in the terrestrial ionosphere. In order to examine the feasibility of observing these ionospheres we investigate the local time and seasonal dependences of terrestrial TEC fluctuations over Japan using the Global Positioning System (GPS) receiving network established by the Geographical Survey Institute, that is, the GPS Earth Observation Network (GEONET) [*Saito et al.*, 1998]. Furthermore, we propose a method to estimate the terrestrial TEC fluctuation along the ray path between a spacecraft and an Earth-based receiving station using GEONET.

2. Method of Plasma Measurement by Radio Occultation

The phase shift of a signal in radio occultation, $\delta\phi$, is expressed as

$$\delta\phi = \delta\phi^P_{\rm Planet} + \delta\phi^N_{\rm Planet} + \delta\phi^P_{\rm Earth} + \delta\phi^N_{\rm Earth} + \delta\phi^P_{\rm IP} + \delta\phi_{\rm TR}, \quad (1)$$

where $\delta\phi^P_{\rm Planet}$, $\delta\phi^N_{\rm Planet}$, $\delta\phi^P_{\rm Earth}$, $\delta\phi^N_{\rm Earth}$, and $\delta\phi^P_{\rm IP}$ are the effect of the planetary ionospheric plasma, planetary neutral atmosphere, terrestrial ionospheric plasma, terrestrial neutral atmosphere, and interplanetary plasma, respectively, and $\delta\phi_{\rm TR}$ is the phase noise of the transmitter. As described below, $\delta\phi^N_{\rm Planet}$, $\delta\phi^N_{\rm Earth}$, $\delta\phi^P_{\rm IP}$, and $\delta\phi_{\rm TR}$ can be removed or neglected while $\delta\phi^P_{\rm Earth}$ should be accounted for to obtain $\delta\phi^P_{\rm Planet}$.

In the SELENE mission, S-band (2.3 GHz) and X-band (8.4 GHz) signals are used to remove $\delta\phi_{\rm TR}$, $\delta\phi^N_{\rm Planet}$, and $\delta\phi^N_{\rm Earth}$ from $\delta\phi$. The phase shift $\delta\phi\ (f)$ of a radio wave of frequency f is given by

$$\delta\phi(f) = \frac{f}{c}\int[\mu(f) - 1]dx + \delta\phi_{\rm TR}(f), \quad (2)$$

where c is the light velocity in the free space, $\mu\ (f)$ is the refractive index of the medium including neutral gases and plasma, and dx is an length element along a ray path. The first term on the right-hand side of (2) represents all the terms on the right-hand side of (1) except $\delta\phi_{\rm TR}$. Refractive index $\mu(f)$ is expressed as

$$\mu(f) \simeq 1 + vN_n - \frac{e^2}{8\pi^2 m_e \varepsilon_0}\frac{N_e}{f^2} \simeq 1 + vN_n - 40.3\frac{N_e}{f^2}, \quad (3)$$

where v is a proportionality constant known as the refractive volume, N_n is the number density of neutral gases, e is elementary charge, m_e is electron mass, ε_0 is permittivity of vacuum, N_e is electron density in $\rm m^{-3}$, and f is the frequency in hertz. The phase noises of the S- and X-band transmitters have a coherency relationship given by

$$\delta\phi_{\rm TR}(f_S) = \frac{f_S}{f_X}\delta\phi_{\rm TR}(f_X), \quad (4)$$

where f_S and f_X are the S- and X-band transmitter frequencies, respectively. To eliminate $\delta\phi_{\rm TR}$, $\delta\phi^N_{\rm Planet}$ and $\delta\phi^N_{\rm Earth}$, we calculate the residual phase shift $\delta\phi_{\rm res}$ due to plasma by using (2), (3), and (4):

$$\delta\phi_{\rm res} \equiv \delta\phi(f_S) - \delta\phi(f_X)\frac{f_S}{f_X} = -\frac{40.3}{c}\frac{f_X^2 - f_S^2}{f_S f_X^2}I, \quad (5)$$

where $I = \int N_e dx$ is the TEC along the ray path of radio occultation through the planetary ionosphere, interplanetary plasma, and terrestrial ionosphere. The phase shift due to interplanetary plasma $\delta\phi^P_{\rm IP}$ is small compared to $\delta\phi^P_{\rm Planet}$ in the timescale of radio occultation (less than a few minutes) if the ray path is far from the Sun [*Woo and Armstrong*, 1979]. In this case, $\delta\phi_{\rm res}$ is composed of $\delta\phi^P_{\rm Planet}$ and $\delta\phi^P_{\rm Earth}$. For the measurement of $\delta\phi^P_{\rm Planet}$, $\delta\phi^P_{\rm Earth}$ should be evaluated by another method.

In the Nozomi mission the onboard S-band transmitter stopped operation, and therefore the ultrastable oscillator, which is connected to the transmitter, is also unavailable. Therefore, in order to get stable frequency, we need to carry out measurements in two-way mode; that is, an onboard S-band receiver is locked to an S-band uplink generated by a stable hydrogen maser at the ground tracking station, and an X-band downlink signal is locked to the S-band receiver. Since the Allan variance of the hydrogen maser is small (less than 3×10^{-15} in 10^3 s), $\delta\phi_{\rm TR}$ is negligible. Although $\delta\phi^N_{\rm Planet}$ and $\delta\phi^N_{\rm Earth}$ cannot be removed explicitly, $\delta\phi^N_{\rm Planet}$ can be distinguished from $\delta\phi^P_{\rm Planet}$ because they occur at different altitudes, and $\delta\phi^N_{\rm Earth}$ is small enough in the timescale of radio occultation. Also in this mission, $\delta\phi^P_{\rm Earth}$ must be known for the measurement of $\delta\phi^P_{\rm Planet}$.

3. Probability of Detection of Planetary Ionospheres

The probabilities to detect the thin Martian nightside ionosphere and the cislunar electron layer are estimated

Table 1. Maximum TECs Along the Ray Paths of Radio Occultation in the Ionospheres of Mars and the Moon and the Time for the Ray Paths of Radio Occultation to Scan Vertically the Planetary Ionospheres

Planet	$I_{\rm Planet}$ ($\times 10^{16}$ $\rm m^{-2}$)	Scan Time
Mars (nightside)	0.26	1 min (perigee) 10 min (apogee)
Moon	0.05	40 s

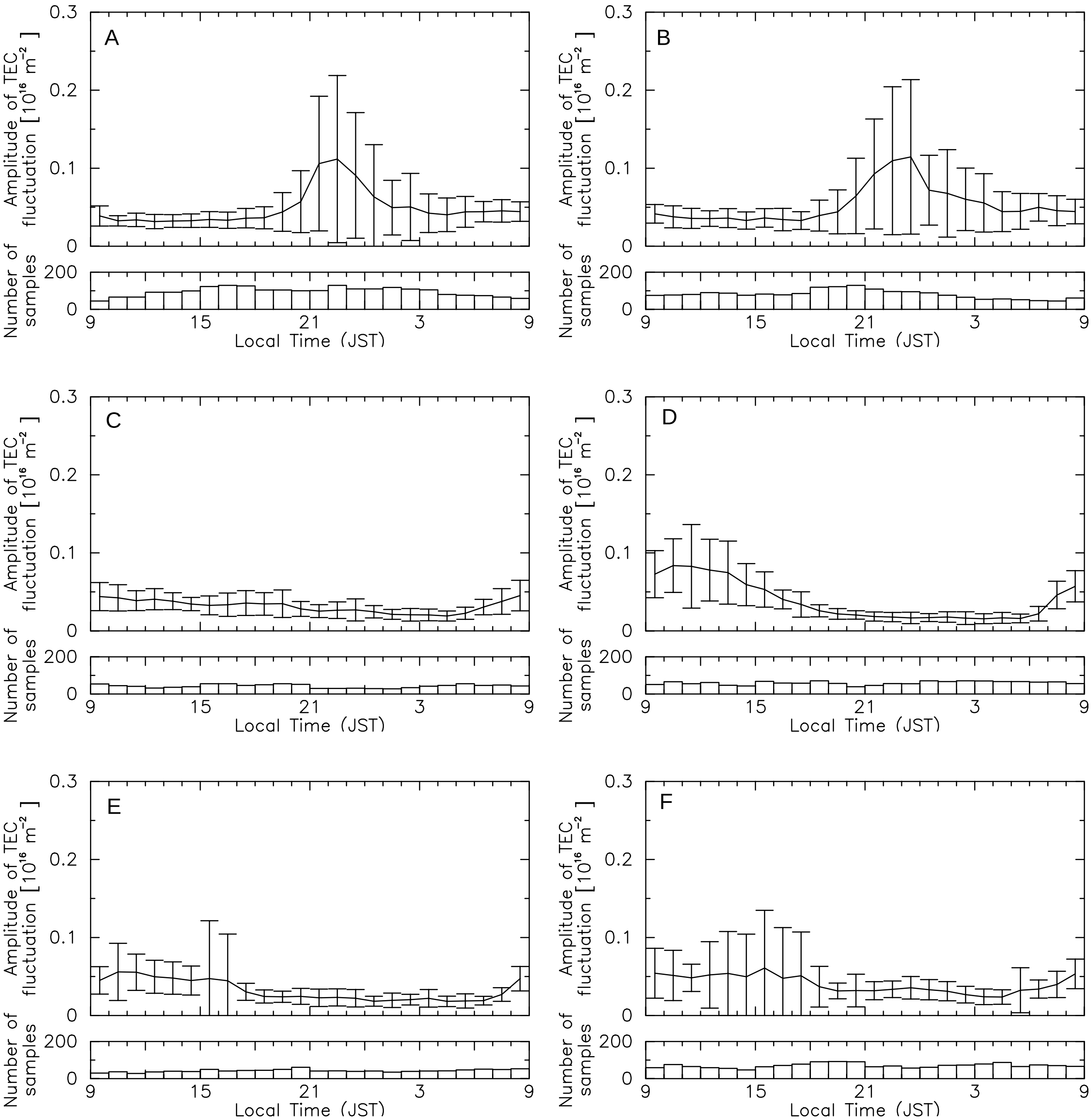

Figure 1. Mean of the amplitude variations of the terrestrial TEC fluctuations (period $\leq$ 10 min) against local time in (a) May and June 1999, (b) July and August 1999, (c) September and October 1999, (d) November and December 1999, (e) January and February 2000, and (f) March and April 2000. The error bars show ±1 σ and indicate day-to-day variability. JST indicates Japan standard time.

with respect to local time and season using the terrestrial TEC data taken by the GPS network. When the TEC fluctuation in the terrestrial ionosphere is regarded as a noise, the signal-to-noise ratio R is defined as

$$R = \frac{I_{\mathrm{Planet}}}{I_{\mathrm{Earth}}}, \qquad (6)$$

where I_{Planet} is the maximum TEC along the ray path of radio occultation in the planetary ionosphere and I_{Earth} is the amplitude of the TEC fluctuation in the terrestrial ionosphere. The probability of detection P at a given local time in percentage is defined as

$$P = \frac{N_{\mathrm{detectable}}}{N_{\mathrm{all}}} \times 100, \tag{7}$$

where $N_{\mathrm{detectable}}$ is the number of detectable samples which have R values greater than 10 for the Martian nightside ionosphere and greater than 2 for the cislunar electron layer and N_{all} is the total number of samples in the given period. A rather stringent criterion is adopted for the Martian nightside ionosphere because we seek to obtain a detailed morphology of the ionosphere rather than a simple detection.

The values of I_{Planet} in (6) and the time for radio ray paths to scan vertically the planetary ionospheres are summarized in Table 1. To evaluate I_{Planet} in (6), the electron density profiles observed by the Viking mission [*Lindal et al.*, 1979] and the Luna 22 mission [*Vyshlov*, 1976] are adopted for the Martian nightside ionosphere and the cislunar electron layer, respectively. The thickness of the ionosphere is 70 km for Mars and 50 km for the Moon as estimated from these profiles. The spacecraft velocity is $\sim$3.3 km s^{-1} around perigee and $\sim$0.24 km s^{-1} around apogee for Nozomi and $\sim$4.4 km s^{-1} for SELENE, which is planned to be placed into a circular orbit.

To evaluate I_{Earth} in (6), the measured slant TEC along the ray path between a GPS satellite and a ground receiver is converted to the equivalent vertical TEC by multiplying with a geometrical factor, which is the ratio of the thickness of the ionosphere and the length of the ray path within the ionosphere. It is also assumed that ionospheric plasma is distributed between 250 and 450 km altitudes [*Saito et al.*, 1998]. Since we are interested in the short-term component of the TEC fluctuation in the terrestrial ionosphere, long-term components are removed by subtracting a 10 min running average from the raw TEC value. A bias factor, which depends on individual GPS satellite-ground receiver pairs and is also contained in the raw TEC value, can be removed in this manipulation. The typical amplitude of fluctuation, I_{Earth}, is evaluated every hour by calculating the standard deviation of TEC fluctuation after removing the running average.

The GPS receiver to evaluate I_{Earth} is located at 36.03°N, 138.22°E, which is near the antenna of the Usuda Deep Space Center (UDSC, 35.95°N, 138.36°E) for the radio occultation measurements. We examine the data only when the geomagnetic activity index Kp is less than 2- because the number of samples with higher Kp index is not enough. The sampling interval at individual GPS receivers is 30 s. The random error of raw TEC value is less than 10^{14} m^{-2} [*Hernández-Pajares et al.*, 1998].

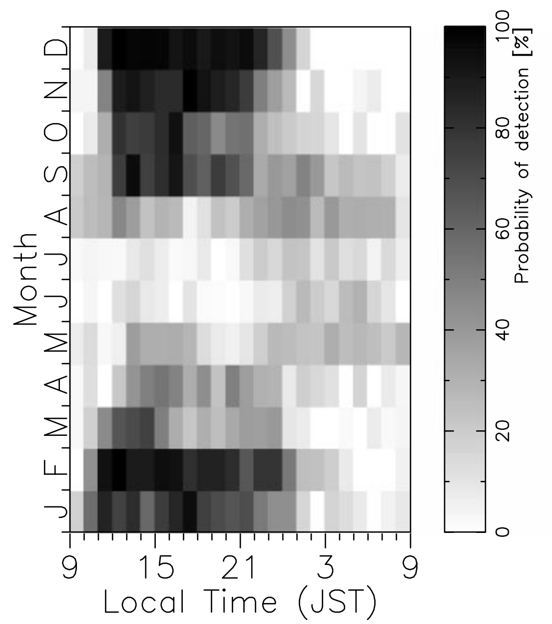

Figure 2. Probability of detection of the Martian nightside ionosphere versus local time and month. The primary noise source is assumed to be the TEC fluctuation in the terrestrial ionosphere.

Figure 1 shows the mean of I_{Earth} from May 1, 1999, to April 30, 2000. The samples are almost uniformly distributed in local time. The local time of maximum fluctuation changes with season. During May–August the maximum amplitude occurs between 2100 LT and 2400 LT, during November–December the maximum amplitude occurs between 1000 LT and 1300 LT, and during January–April and during September–October the activity is relatively high in the daytime, although any clear peak is missing.

Figure 2 shows the probability of detection P for the Martian nightside ionosphere. As shown, P is as high as 80–100% at night during November–February, which is most suitable for observing the Martian nightside ionosphere. Similar probability also exists during September–October though the local time window is slightly reduced. Although the nighttime during March–April and daytime during May–August might be also promising, P is no more than 50%. The results for the cislunar electron layer are found to be similar to those for the Martian nightside ionosphere.

4. Estimation of Terrestrial TEC Fluctuations Along Radio Ray Paths

4.1. Method

It has been shown in section 3 that the period suitable for the observation of planetary ionospheres is restricted

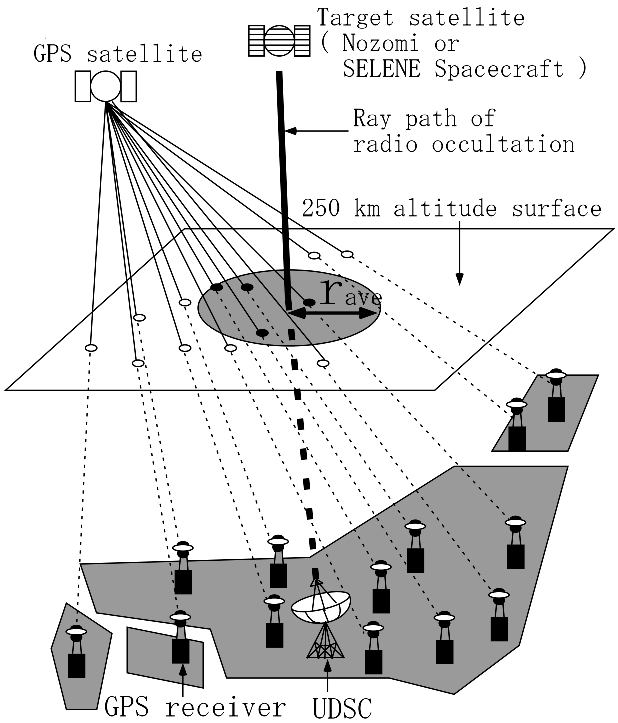

Figure 3. Schematic of the method to estimate the terrestrial TEC fluctuation along the ray path of radio occultation using the GPS network. The TEC samples inside the circle (solid symbols) are used for the estimation.

to the nighttime in winter if the distortion by the TEC fluctuation in the terrestrial ionosphere cannot be removed.

In this section, we propose a method to estimate the terrestrial TEC fluctuation along the ray path of radio occultation using the GPS receiver network. We rarely find a GPS satellite-ground receiver pair whose ray path is close to the ray path of radio occultation. Therefore, instead of finding such a pair, we use a number of TEC samples obtained from many GPS satellite-ground receiver pairs whose ray paths are not necessarily close to the ray path of radio occultation.

In this method, the TEC fluctuations in the terrestrial ionosphere are assumed to be localized on a thin layer. The altitude where TEC fluctuations occur will be termed "ionospheric fluctuation height" throughout this paper. The results of estimation are not sensitive to the choice of the ionospheric fluctuation height provided that it is in the range of 250–300 km. The ionospheric fluctuation height seems to be much below the effective ionospheric height, which is known to be 350–420 km [e.g., *Titheridge*, 1972; *Poletti-Liuzzi et al.*, 1977]. *Saito et al.* [1998, 2001] considered the ionospheric fluctuation height to be 300 km, and their study concluded that the TEC fluctuations occur in the bottomside ionosphere because the TEC distributions derived from different GPS satellites on the assumption that fluctuations occur at 300 km are consistent with each other. In our case, a slightly lower altitude of 250 km gives a better result.

Therefore the TEC fluctuations observed by individual GPS satellite-receiver pairs are converted to the fluctuations of the vertical TECs at the intersections where the ray paths cross the 250 km altitude surface. The TEC fluctuation at the intersection where the ray path of radio occultation crosses the surface is estimated by averaging the values of the TEC fluctuations inside a circle with the center at the intersection and the radius of r_{ave} (Figure 3). The averaged value is reconverted to the fluctuation of the slant TEC along the ray path of radio occultation by multiplying with a geometrical factor.

4.2. Feasibility Check

The feasibility of the above method is tested by considering one GPS satellite as the virtual Nozomi or SELENE spacecraft. The TEC samples belonging to this "target satellite" are not used in the above estimation procedure. The adopted radii of the circles, r_{ave}, are 20, 30, and 40 km. Since we obtained similar results for these radii, only the results for r_{ave} = 30 km are presented. The width of the running average to remove long-term components is 10 min.

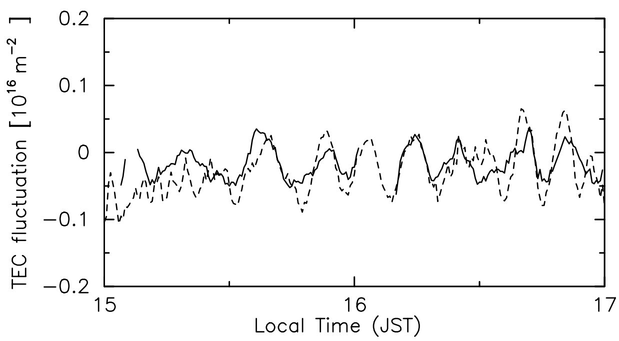

Figure 4. A feasibility test to estimate the terrestrial TEC fluctuation along the ray path of radio occultation using the TEC samples obtained by the GPS network. The dashed curve is the "true TEC fluctuation" observed by the target GPS satellite PRN16 and one ground receiver while the solid curve is the "estimated TEC fluctuation," which is the average of the values at surrounding points obtained by the GPS satellite PRN14 and 1–20 ground receivers (Figure 3). The number of the ground receivers depends on the geometry of the GPS satellites and the ground receivers.

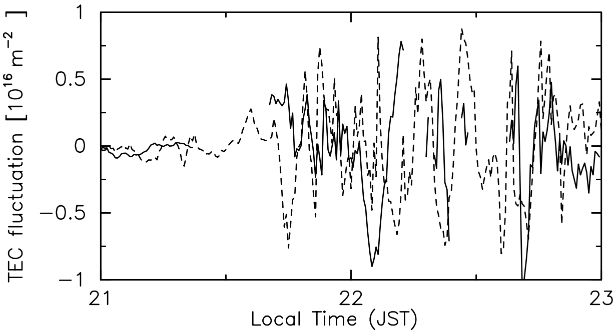

Figure 5. Similar to Figure 4, although for a large-TEC-fluctuation case.

An example of the feasibility check is shown in Figure 4. In this case, the combination of the target GPS satellite "PRN16" and one ground receiver near UDSC gives the true TEC fluctuation, while the TEC samples obtained by the GPS satellite "PRN14" and several ground receivers are used to estimate the TEC fluctuation along the ray path belonging to the satellite PRN16. The direction of the satellite PRN14 is different from that of the satellite PRN16 by ~70°.

The wavelike fluctuation observed by the target satellite PRN16 is well reproduced by the estimation from the TEC samples obtained by the satellite PRN14. The estimation error is less than 5×10^{14} m^{-2}. The wavelike fluctuation in Figure 4 is caused by the movement of the ray path of the satellites across the traveling ionospheric disturbances (TIDs), which are thought to be due to atmospheric gravity waves. The estimation would be improved if the three-dimensional structures of TIDs are taken into account with the aid of theoretical models [*Hooke*, 1968; *Beach et al.*, 1997] and horizontal structures revealed by GEONET [*Saito et al.*, 1998].

An example of an unacceptable estimation is shown in Figure 5. The estimation becomes unacceptable when the spatial structures of the TEC fluctuations are smaller than r_{ave}. However, even in such cases, the present method enables us to estimate the magnitude of the distortion of radio occultation caused by the terrestrial ionosphere. Those small-scale TEC fluctuations are considered to be associated with F region field-aligned irregularities (FAIs), since *Saito et al.* [2001] showed that 3-m-scale FAIs were detected when the TID activity is high or moderate. An $E \times B$ instability mechanism proposed by *Maruyama* [1990] may account for these irregularities. However, further studies are needed to reveal the physical mechanism.

5. Concluding Remarks

The present study has focused on the TEC fluctuation in the terrestrial ionosphere, which is a serious error source in the radio occultation measurements of thin planetary ionospheres. A study using the GPS network has shown that the nighttime in winter is most suitable for the measurements of planetary ionospheres. A method to estimate the TEC fluctuation in the terrestrial ionosphere along the ray path of radio occultation using the GPS network has also been presented. The method is found to be useful when the spatial structure of the TEC fluctuation is large enough ($\geq$100 km) to be observed with the GPS network.

It has been shown that the maximum activity of the terrestrial TEC fluctuation appears at night in summer and during daytime in winter. *Jacobson et al.* [1995] obtained a similar seasonal dependence of the TID activity at Los Alamos, New Mexico (35.87°N, 106.33°W), which is ~120° east of Japan, with a very long baseline interferometer array illuminated by VHF radio beacons from the GOES 2 satellite. The basic features of the TEC fluctuation, therefore, seem to be common in the broad areas.

As described in section 4.2, TIDs and 3-m-scale FAIs were observed simultaneously [*Saito et al.*, 2001]; therefore ionospheric scintillations, which have been studied by many researchers for several decades and are thought to be caused by ionospheric irregularities, would also be related to TIDs. At midlatitude, however, the occurrence of ionospheric scintillations peaks at night all the year round [*Aarons*, 1982; *Hajkowicz*, 1994], in contrast to our result where the activity of TEC fluctuations peaks at night in summer and during daytime in winter. Further studies are needed to clarify the relationship between TEC fluctuations and ionospheric scintillations.

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