Total electron content derived from GNSS signals by double thin-shell model and implication in ionospheric dynamics near the magnetic equator

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Short summary. A new technique was developed to estimate the ionospheric total electron content (TEC) from GNSS satellite signals. The vertically distributed electron density was parameterized by two thin-shell layers (double thin-shell model). Total electron content (strictly speaking, partial electron content) associated with each shell was approximated by the functional fitting of spherical surface harmonics. The major achievements were: 1. The double-shell model achieved precise estimation of TEC compared with the conventional single-shell model; 2. The double-shell model captured the equatorial anomaly more correctly 3. Higher and lower shells exhibited a different pattern of local time vs. latitude variation, which presents information on the ionosphere-thermosphere dynamics such as the redistribution of plasma by field-aligned transportation and the vertical drift due to the zonal electric field.

Introduction

The total electron content (TEC) derived from the differential group delay of the beacon signals of GNSS has been a basic parameter in ionospheric studies. In most applications, the thin-layer approximation is used to convert the slant TEC to vertical one at the ionosphere pierce point. Usually the thin-layer height is assumed to be constant regardless of the location and time, which is unrealistic and can be a source of error in TEC estimations. The error is significant at low latitudes where the ionospheric height greatly varies by the action of the vertical EXB drift due to the zonal electric field and the meridional neutral wind. To avoid this inconvenience, we developed a new technique using double-shell approximation of the ionosphere. The technique was applied to a dataset obtained by the local receiver network near the magnetic equator.

Double-shell model

The ionosphere was parameterized by two thin layers (double thin-shell model) at the height of 250 and 1100 km. The variation of vertical partial electron content related to each layer (TEC_{VLo}, TEC_{VHi}) was approximated by the spherical harmonics expansion as the equations below, where the longitude parameter was the sun-fixed longitude or the local time measured in angle.

$$\begin{aligned}
TEC_V(\theta,\phi) &= TEC_{VLo}(\theta,\phi) + TEC_{VHi}(\theta,\phi) \\
TEC_{VLo}(\theta,\phi) &= \sum_{m=0}^{M}\sum_{n=m}^{N}(A_{nm}\cos m\phi + B_{nm}\sin m\phi)P_n^m(\cos\theta) \\
TEC_{VHi}(\theta,\phi) &= \sum_{m=0}^{M}\sum_{n=m}^{N}(\tilde{A}_{nm}\cos m\phi + \tilde{B}_{nm}\sin m\phi)P_n^m(\cos\theta)
\end{aligned}$$

where, θ and ϕ are the colatitude and local time. The coefficients A_{nm}, B_{nm}, $\tilde{A}_{nm}$, and $\tilde{B}_{nm}$ are unknown parameters and determined from the observations obtained for a whole day (ϕ coverage: 0~2π) by the orthogonal function network (equivalent to the least squares fitting).

Results

The results were first compared with those of the conventional single thin-shell model. A significant difference was found in the ratio of TEC at the equatorial anomaly crests to the trough. The single-shell model yielded somewhat flattened equatorial anomaly. The double-shell model might capture the equatorial anomaly more correctly as the functional fitting error of the double-shell model was smaller than the single-shell model.

Another important result of the double-shell model was the different patterns of TEC variations at the two heights as expected. Diurnal and latitudinal variations of TEC and partial TEC in each shell are shown in Fig. 1. The equatorial anomaly crests and the evening TEC bite-out at the magnetic equator were prominent in the lower shell (middle panel). The diurnal TEC peak in the higher shell appeared later than that in the lower shell. Two shells exhibited different features of north-south asymmetry of TEC, depending on the local time. These results present information on the field-aligned plasma transport by the ionosphere-thermosphere coupling and the variation of the evening enhancement of zonal electric field. More discussion below.

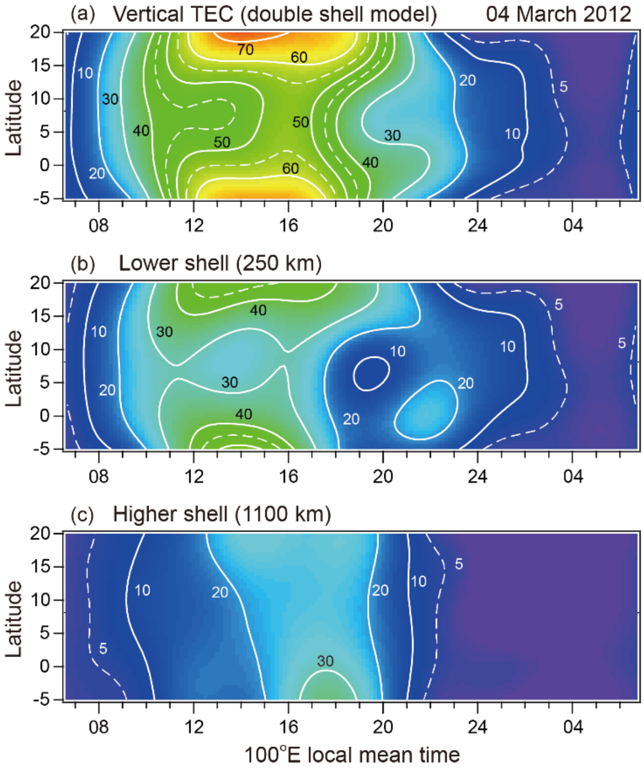

Fig. 1. Diurnal and latitudinal variation of TEC and partial TEC at each shell height

The equatorial anomaly crests were nearly symmetric about the magnetic equator (approx., 8° geographic latitude) from sunrise to 16 LT. North-south asymmetry became prominent from 16 to 24 LT, which was anti-correlated in the lower and higher shells and the feature was ascribed to the transequatorial thermospheric wind as given below. The ionospheric plasma was transported to higher altitudes in the southern hemisphere by the northward wind, which resulted in an increase in partial TEC in the higher layer and depression in the lower layer in the southern hemisphere as observed at around 18 LT. Shortly after that, the evening enhancement of zonal electric field was developed as inferred from the TEC bite out at the magnetic equator. At around 22 LT, the downward field-aligned plasma resulted in an increase in TEC in the lower layer in the southern hemisphere by the reversed wind direction as observed in the middle panel of Fig. 1.