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[EN-107] Impact of the low latitude ionosphere disturbances on GNSS studied with a three-dimensional ionosphere model

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Abstract The ionosphere is one of the most serious error source in GNSS. Among other error sources, the ionosphere induced error is the most difficult one to correct it, because of its dynamic variability. Since the behavior of the ionosphere is different for regions, especially for magnetic latitudes, ionospheric threat model suitable for each region is needed for advanced use of GNSS in aviation. This paper introduces a three-dimensional ionosphere delay model for low latitude ionosphere developed in ENRI. Studies with this model on the ionospheric impacts on aviation use of GNSS are presented.

Keywords GNSS, Ionosphere, CNS

1 INTRODUCTION

Spatial gradient of the ionospheric plasma density is one of the most important error source of differential GPS (DGPS) systems, such as a ground-based augmentation system (GBAS) or a space-based augmentation systems (SBAS). In the low magnetic latitude regions, effects of low latitude ionospheric phenomena, especially the plasma bubble and the equatorial anomaly must be taken into account carefully.

The important parameter for GNSS is the ionospheric delays that is proportional to the total number of electrons, or total electron contents (TECs), between a satellite and a receiver. The ionospheric delay I is given by

$$I = \frac{40.3}{f^2} TEC \qquad (1)$$

where f is the frequency of the satellite signal in Herz and TEC is the number of electrons integrated over the satellite-receiver path and expressed in the unit of electrons per square-meter given as

$$TEC = \int_{rec}^{sat} n_e ds \qquad (2)$$

where n_e is the number density of electrons per cubic meters.

In the past studies, observed TECs are used to develop ionosphere models. However, since the ionospheric structures are constraint by the Earth's magnetic field, they have characteristic three-dimensional anisotropic features. To evaluate the impacts of the ionosphere appropriately to have more optimized ionosphere threat model, the ionosphere should be treated three-dimensionally.

Since the integrity requirement is extremely high, quite rare events that may not have ever been observed must be cared. To evaluate such events, modeling studies based on the knowledge obtained in the long history of the ionosphere studies are effective. At the Electronic Navigation Research Institute (ENRI), a three-dimensional ionosphere model that takes into account the equatorial anomaly and the plasma bubble has been developed to study the impact of the low latitude ionosphere on GNSS[1, 2].

2 LOW LATITUDE IONOSHERE

There are two major low latitude ionospheric phenomena that accompany significant spatial inhomogenuity of the ionospheric delay. One is the equatorial anomaly, and the other is the plasma bubble.

2.1 EQUATORIAL ANOMALY

Equatorial anomaly is a pair of belts where ionospheric plasma density is high and having peaks around $\pm 15°$ in magnetic latitude. Ionospheric delay also has the maxima at the equatorial anomaly crests. Fig. 1 shows an example of global ionospheric vertical delay distribution reproduced by an empirical model. Equatorial anomaly always exists, but the location and intensity significantly change in time to time. At the equatorward and poleward edges of the equatorial anomaly, there are large-scale ionospheric delay gradient.

For GBAS, the large-scale gradient increases the background ionosphere variability and would act to increase the protection level. For SBAS, the large-scale gradient could have more significant impact because it assumes smooth variation of the ionosphere in space.

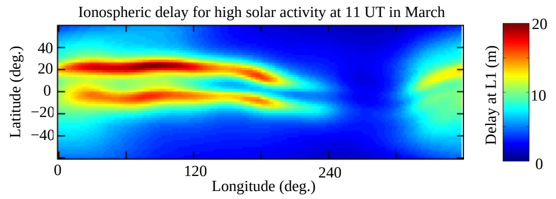

Figure 1 Global distribution of ionospheric vertical delay reproduced by an empirical model for the L1 frequency for high solar activity at 11 UT in March.

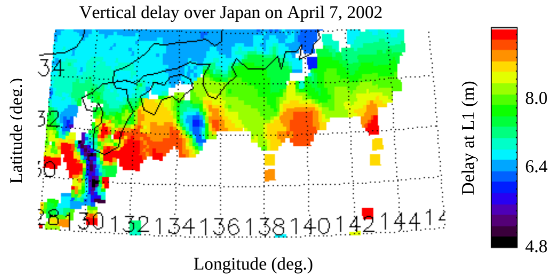

Figure 2 Vertical delay over Japan at 21:28 JST on April 7, 2002.

2.2 PLASMA BUBBLE

The plasma bubble is a low-latitude and equatorial ionospheric phenomenon where the low density plasma in the bottom-side ionosphere explosively rises to the topside.

Inside the plasma bubble, plasma density is extremely lower than that of outside. The boundary is very sharp, and the local plasma density changes 100 % to less than 10 % within a few tens kilometer. Therefore, the ionospheric delay gradient at the edges of the plasma bubble can be extremely steep.

Fig. 2 shows the observed depletions in ionospheric delay associated with plasma bubbles. Two depletions elongated in the North-South direction around 130 and 135°E are caused by plasma bubbles.

The plasma bubble has a very characteristic three-dimensional structure. The shape of the plasma bubble is aligned with the earth's magnetic field lines. It is a cleft of the ionosphere with a fan-like shape extended in north-south and very thin in east-west (Fig. 3). Therefore, it is tallest over the magnetic equator, and the latitudinal extent is determined by the top altitude at the magnetic equator. To account for the characteristic shape of the plasma bubble appropriately, a three-dimensional ionosphere model is developed and used in this study.

3 3-D IONOSPHERE DELAY MODEL

The model consists of two major components. One is the background ionospheric density distribution taken from the empirical model. NeQuick model [3, 4] is adopted as the background ionosphere model. Using the NeQuick model, TEC along an arbitrary path can be calculated. The equatorial anomaly is described in this model.

Another component is the depletion due to the plasma bubble. It is expressed as relative depletion to the background and defined in the vertical plane over the magnetic equator. Multiplying the relative depletion to the background delay, the total electron density at the particular point is calculated. Integrating the electron density along the ray path, the TEC, and hence the ionospheric delay between the satellite and the receiver is derived.

Example of modeled depletion in ionospheric delays due to a plasma bubble is shown in Figure 4. Figure 4a shows the zonal-altitudinal cross section of the ionospheric electron density over the magnetic equator. The vertical ionospheric delay distribution with the plasma bubble at 133.7°E at the magnetic equator is shown in Figure 4b.

4 STUDIES WITH THE MODEL

4.1 GBAS

The effects of the plasma bubbles on GBAS was studied by Saito et al. (2010) [2] to show the potential threat that undetected error may exceed the limit prescribed by ICAO [5]. It has been shown that the range error due to the plasma bubble is largest when the ray path between a satellite and a receiver passes along the plasma bubble edges in the equatorial anomaly at low elevation angles. Dependence of the threat on the approach direction is also studied.

Fig. 5a shows an example of simulated GBAS user error without monitors. In this simulation, one plasma bubble is assumed. An airplane is assumed to approach eastward to a GBAS reference station.Parameters used in the simulation are summarized in Table 1. In this simulation, two satellites are impacted by the plasma bubble (Fig. 5c). The results shows that the expected vertical error is larger than 10 m all the time.

This study is further extended to validate the requirements for anomalous ionosphere mitigation defined in the baseline SARPs of GAST-D, which is the single-frequency CAT-III GBAS [6]. Exhaustive investigation on this issue are being done [7].

4.2 SBAS

For SBAS which aims at wide-area augmentation, both the plasma bubble and the equatorial anomaly can be a serious problem. To expand SBAS service areas to low latitude regions, both the issues must be cleared. Ionosphere characterization is a key point to assure integrity of the system. However, it requires huge amount of data, and it takes long time to collect them. Studies based on realistic models are suitable

Table 1 Parameters of simulation.

Background ionosphere	
Solar radio flux index (F10.7)	193 (high solar activity)
Season	March equinox
Local time	20 LT (11 UT)
Plasma bubble	
Initial longitude	134°E
Zonal width	100 km
Depletion level	100 %
Equatorial height	1500 km
Scale length of boundary	20 km
Eastward velocity	100 m s^{-1}
Reference station	
Location	25°N, 135°E
Carrier-smoothing	100 sec
Airplane	
Initial location	25°N, 134.6°E
Velocity	80 m sec^{-1}
Satellites	
Constellation	RTCA standard 24 satellites
Elevation mask	5°

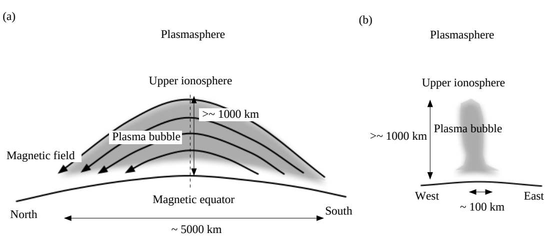

Figure 3 Illustration of the plasma bubble shape in (a) meridonal and (b)zonal planes.

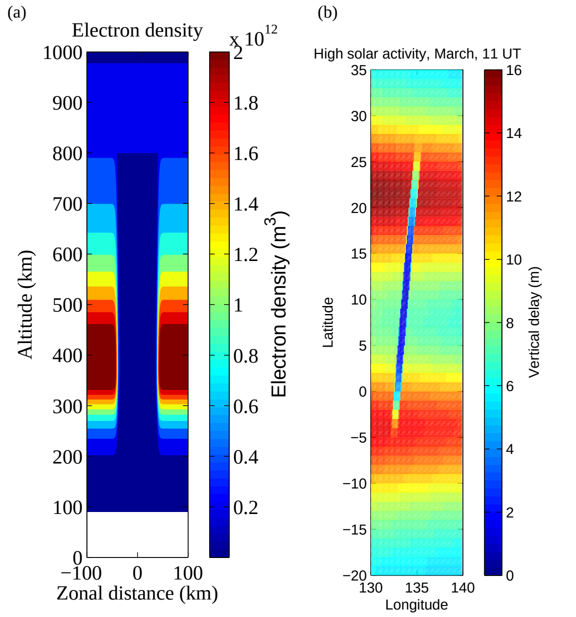

Figure 4 (a) Zonal-altitudinal cross section of the modeled electron density over the equator associated with a plasma bubble. (b) Vertical ionospheric delay at the L1 frequency with the plasma bubble at 133.7°E at the magnetic equator.

for this purpose, because various conditions can be created and tested.

At ENRI, constructing an ionosphere threat model for MTSAT Satellite-based Augmentation System (MSAS) has been tried by using the three-dimensional ionosphere delay model. It has been shown that the equatorial anomaly has a great impact on the threat model to increase the uncertainty associated with the ionospheric inhomogeneity. It is because the change in the ionospheric delay associated with the equatorial anomaly cannot be well described by the fitting algorithm that takes into account first order variation in space to estimate ionospheric delays at the ionosphere grid points. For plasma bubbles, it is found to be difficult to be detected by the ground monitoring stations. This means that the plasma bubble can threaten users. Further studies are now being conducted.

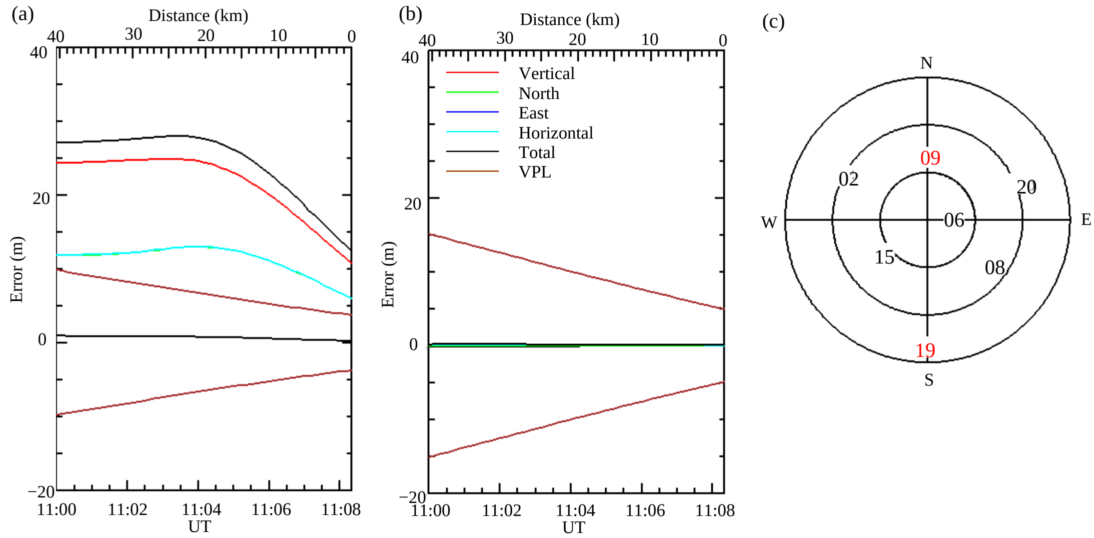

Figure 5 (a) Simulation results without monitors. Parameters used in the simulation are summarized in Table 1. Red, green, blue, cyan, and black lines show the positioning errors in the east, north, and vertical (upward) directions and the total error, respectively. Brown line shows the vertical protection level. (b) Same as (b), but with a backscatter radar monitor. Parameters used in the simulation are summarized in Table 2. (c) Skyview plot of the satellite positions. Concentric circles show the elevation angles of 0, 30, and 60°. Satellites with its number in red color are impacted by the plasma bubble.

4.3 PLASMA BUBBLE DETECTION BY A VHF RADAR

The plasma bubble is known to accompany plasma irregularities of various scale sizes from kilometers down to meters. Using a VHF radar that transmits VHF radio waves (usually at 30–50 MHz), intense backscatter echoes from the irregularities can be detected, when the radar beam is pointed in the direction perpendicular to the wavefronts of the irregularities that are parallel to the magnetic field line, because plasma irregularities develop along them. By swinging radar beams, the ionosphere in a wide area can be scanned to monitor whether any plasma bubbles exist in the radar coverage.

To investigate how useful such backscatter radars are for GBAS, a simulation study has been conducted [8]. In the simulation, any satellites of which ray paths to the ground reference station passes any portions of a plasma bubble that can be detected by a radar are removed from GBAS correction (Fig. 6). Fig. 5b show the result of a simulation with a backscatter radar monitor with the same parameters as Fig. 5a. It can be seen that positioning error of a GBAS user is drastically reduced from more than 10 m without any ionosphere monitors to almost zero with a radar.

Further simulations can be conducted to investigate how much extent such a backscatter radar can be utilize to monitor plasma bubbles, not only for GBAS but also for SBAS. Optimal location of a radar can also be investigated.

Table 2 Parameters of radar monitor.

Location	20°N, 135°E
Number of beams	8
Beam width	5°
Beam directions	-50, -35, -20, -5 10, 25, 40, 55°
Observation range	300–1500 km

5 SUMMARY

In this paper, the three-dimensional ionosphere delay model that takes the plasma bubble into account and suitable for low latitude regions. Several studies with the model to evaluate the ionospheric impact on GNSS for aviation are presented. For GBAS, the model is utilized to establish the international standards for CAT-III GBAS as well as to study the newly proposed external ionosphere monitoring system. For SBAS, impacts of the equatorial anomaly and the plasma bubble on the ionosphere characterization are estimated. The model is shown to be very much useful to develop systems based on GNSS.

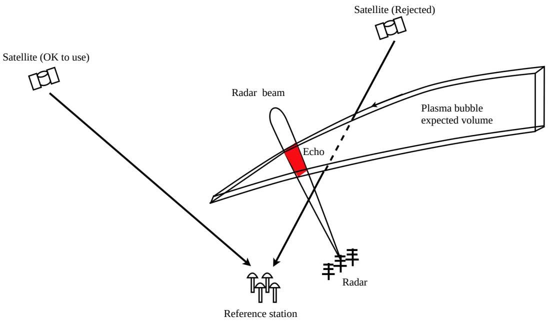

Figure 6 Principle of radar monitoring of plasma bubble.

6 ACKNOWLEDGMENTS

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Copyright Statement

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