3 Studies of Ionospheric Variations for Radio Propagation

3-1 Requirements of Ionospheric Studies for Society

3-1-1 Effects of the Ionosphere on Telecommunications, Satellite Positioning, and Electric Navigations

ISHII Mamoru

The origin of NICT is in the routine monitoring and studies of the ionosphere for keeping long distance telecommunications with shortwaves. This role has been decreasing with the development and wide uses of satellite communication, however, it is still fundamental infrastructure. In addition, the study of behavior of ionosphere become important in the utilities of satellite navigation. The global navigation satellite system(GNSS) is expected as an important and fundamental technique to build the secure and safety society. One is the example of the utility is electric navigation with GNSS. Because it is difficult for electric navigations to use any additional information from the ground station, the improvement of positioning precision become important. It is necessary to provide the ionospheric information precisely and on real time for contributing the next-generation utilities with GNSS.

Keywords
Ionosphere, Satellite navigation, Electric navigation, Plasma bubble, Telecommunications

1 Introduction

The NICT has its roots in the start of a study on radiotelegraphy at the Electro-technical Laboratory of the Ministry of Communication back in 1896[1]. The Laboratory's major task was to observe the ionosphere. This task was important as a national operation stemming from the needs to maintain and monitor shortwave lines—the only means available at the time for long-distance overseas communications by utilizing multi-reflection between the ionosphere and the ground. The importance of satellite positioning has increased in recent years in an environment where the use of shortwave communications has been declining due to developed communications networks such as those involving submarine cables and satellite communications systems. Radiowaves of 1.2 to 1.5 GHz used for satellite positioning systems such as GPS are subject to ionospheric delay that causes positioning errors when the amount of delay deviates from that given by a model due to disturbances in the ionosphere. Studies on the effects of the ionosphere will become essential

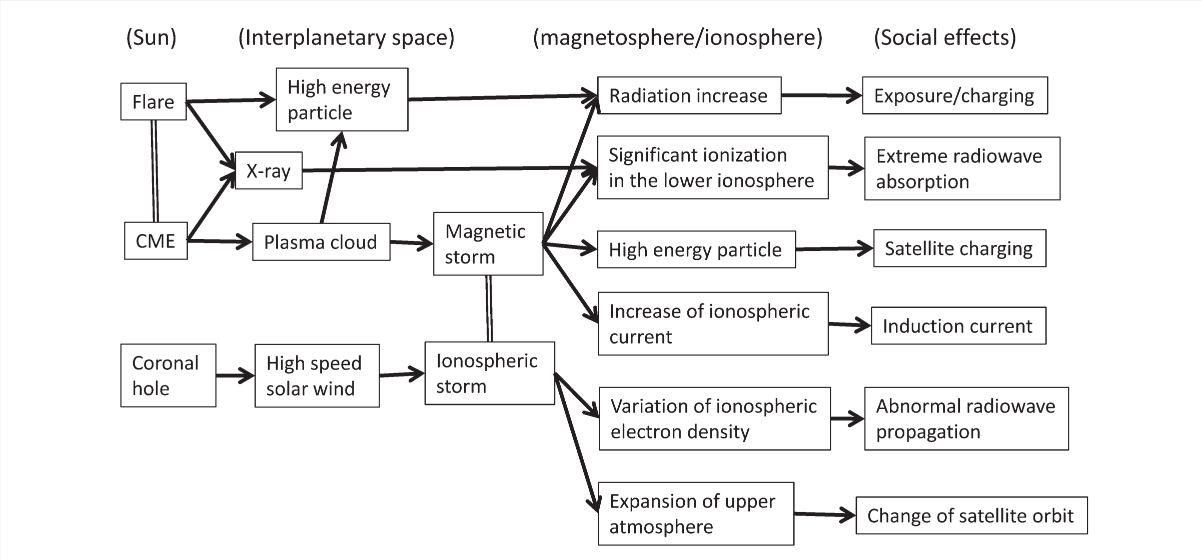

Fig. 1 Phenomenal chain from solar phenomena to space environmental disturbances (excerpt from Reference [2])

due to more widespread use of satellite positioning systems in the future.

Most energy flowing to the earth originates from the sun. Moreover, electromagnetic waves directly irradiated from the sun and the hot, charged gas known as solar wind trigger electromagnetic phenomena in the space surrounding the earth [2]. However, there are complex mechanisms involved between these actual phenomena and their causes that go through many stages of processes as illustrated in Fig. 1, and some of those mechanisms have yet to be fully understood. Since conditions of the ionosphere differ significantly as demonstrated by numerous examples, even when solar conditions are nearly identical, the accurate, long-term forecasting of ionospheric disturbances is not possible by precisely measuring only phenomena related to the sun.

Two types of approaches are commonly adopted in conducting studies on ionospheric disturbances: arranging phenomena provided by ionospheric observations for as long as possible (at least 11 years as being equivalent to the solar activity cycle) including quiet and disturbed periods, and seeking causes by reproducing phenomena through simulations.

2 Ionospheric fluctuations influencing the utilization of radiowaves

2.1 Ionospheric storms

Ionospheric storms are defined as a phenomenon that significantly deviates from the normal transitional behavior of electron density. Solar radiation and solar wind are the main sources of energy involved in producing the ionosphere. Solar radiation is a source of regular variations of the ionosphere, while solar wind causes complicated interactions with the geomagnetosphere and creates disturbances.

Figure 2 illustrates variations of the critical frequency (foF_2) in the ionosphere F2 layer as observed by ionosondes in Wakkanai and Okinawa on April 9 to 11, 1980. The solid line represents normal daily variations in a month (monthly mean time). It is understood that the critical frequency in Wakkanai was reduced below normal daily fluctuations over 24 hours starting at 02:00 on April 10, while the critical frequency in Okinawa increased above normal fluctuations from 18:00 on April 9 until 02:00 on April 10. Such variations of foF_2 are typical phenomena in mid-latitude regions including Japan; foF_2 reduced below normal and that increased above normal are referred to as neg-

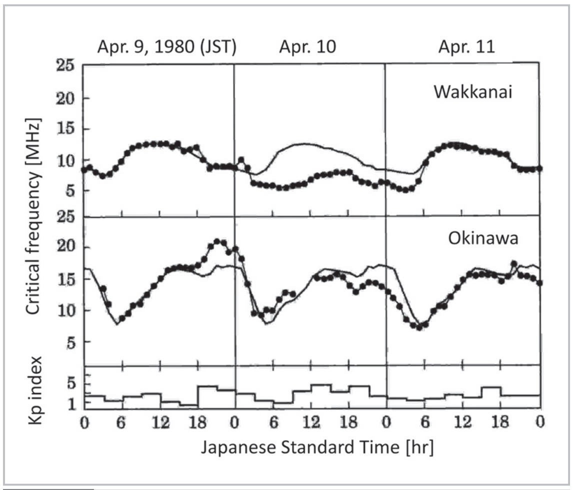

Fig.2 *Example of ionospheric storm (excerpt from Reference [2])*

ative phase (negative storm) and positive phase (positive storm), respectively.

(a) Positive storm

The occurrence of a positive storm can be explained by the displacement of plasma at high altitudes. There are two possible causes of such plasma movement. One is the effect of being pushed up in the direction of magnetic field lines due to the collisions of neutral and ions caused by thermospheric horizontal wind blowing from the polar regions toward the equator. Such thermospheric horizontal wind is known to be generated by a drastic energy input into the polar regions due to magnetic storms. The other cause is the effect of ascending plasma due to the **E**×**B** drift attributed to the electric field originating in the magnetosphere. Due to these effects, the recombination coefficient becomes smaller and the plasma density increases at higher altitudes, while plasma is supplied through ionization during the daytime at lower altitudes and electron density increases as a whole.

(b) Negative storm

The cause of a negative storm is related to ion chemical reaction. The atomic oxygen (O) density determines the production of electrons in the F region of the ionosphere, while the molecule nitrogen (N_2) density mainly determines the extinction of such electrons. Energy flowing into the polar regions heats up the thermospheric neutral in auroral activity. Thermal expansion of the atmosphere during this process causes changes in the altitude distribution of neutral particles as well as global atmospheric movement (general atmospheric circulation). At ionospheric altitudes, N_2 increases more than O, the recombination coefficient increases, and the electron density decreases. These phenomena dominantly appear particularly at higher latitudes, but may develop even at lower latitudes in a summer hemisphere and usually remain at higher latitudes in a winter hemisphere.

2.2 Dellinger phenomenon

The D region of the ionosphere at an altitude of about 80 km has the effect of absorbing electric waves in shortwave bands due to its high atmospheric density and the frequent collisions between electrons and neutrons there. Thus, Dellinger phenomenon occurs when ionization develops in the D region by X-rays irradiated in chromospheric eruptions (solar flares), thereby interrupting shortwave communications. This phenomenon occurs about 10 minutes after the generation of a solar flare, and the absorption of short waves continues for about 30 minutes. In addition, the effect is limited to during the daytime when subject areas face the sun upon the generation of a solar flare.

2.3 Sporadic E layer

The sporadic E layer, a region with a high electron density, is formed during the period from daytime to evening in summer at an altitude of about 100 km. A quantitative evaluation of the sporadic E layer has yet to be completed and forecasting it has proved difficult although its formation is considered caused by neutral wind shear. Interference, such as disturbed TV screens due to the intrusion of radiowaves into receivers from remote locations (such as neighboring countries like mainland China) are known to occur when the sporadic E layer forms. Similar phenomena occur in FM broadcasts, resulting in audible broadcasts from remote stations that are normally inaudible.

2.4 Development and diurnal variations in the equatorial anomaly

A preparation of the spherical distribution of TEC clarifies the existence of high TEC bands at latitude of around 10 to 15° on each side of the magnetic equator (based on coordinates with reference to the earth's main magnetic field) in both the northern and southern hemispheres. This band referred to as the equator anomaly can be explained by the **E**×**B** drift due to an electric field in the east-west direction and diffusion along magnetic field lines. In the F region of the ionosphere near the equator, the electric field forms eastward during the daytime and westward during the nighttime. Due to the northward horizontal magnetic field existing in equatorial regions, the daytime eastward electric field causes a vertical, upward **E**×**B** drift. The high-altitude plasma descends along the magnetic field lines, thereby structuring the equatorial anomaly. Note that the term "anomaly" is used to describe a phenomenon that deviates from a simple model, and the equatorial anomaly is not an unusual phenomenon.

Both the region where the equatorial anomaly occurs and the value of its electron density are known to vary according to the solar activity cycle over the long term, and vary dramatically day to day over the short term. This diurnal variance is known to have little relevance to magnetic storms, but is considered as having significant relevance regarding other factors such as neutral wind.

Japan and its surrounding area are located in a region influenced by diurnal variations in the equatorial anomaly. Figure 3 shows an example of diurnal variations in the equatorial anomaly under magnetically quiet conditions (at 20:45 JST on January 23 and 24, 2002). The amount of delay and latitudinal gradient of GPS L1 electric waves due to the ionosphere were 19.7 m at 30° latitude and 3.2 m/deg, respectively. This gradient is nearly one order of magnitude larger than the value forecast by the IRI model.

2.5 SED (Storm Enhanced Density)

SED is defined as a phenomenon involving plasma of the equatorial anomaly at lower latitudes flowing into the daytime side by a

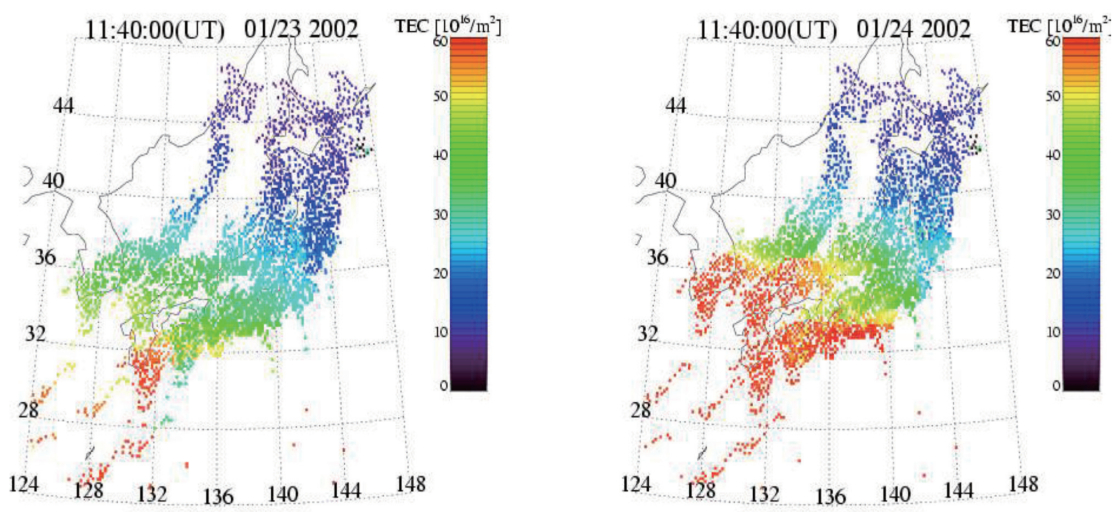

Fig.3 *Observational example of diurnal variations in the equatorial anomaly (excerpt from Reference[2])*

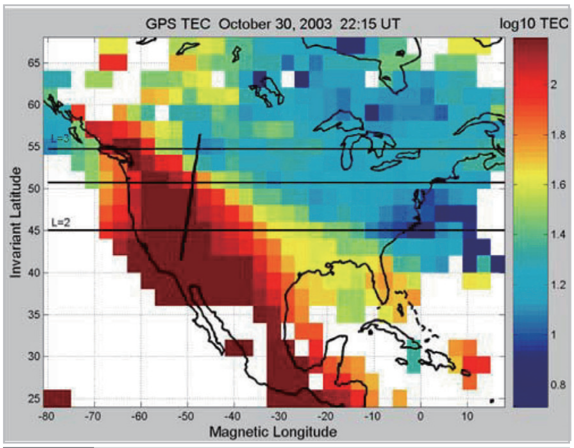

Fig.4 *Observational example of SED (excerpt from Reference[5])*

convective electric field caused by magnetic storms. Figure 4 shows an observational example of SED that occurred in the U.S. on October 30, 2003. SED is known to readily occur in conjunction with high solar activity. It is said that about 10 such events were observed in the U.S. and a few in Japan during the last active period, meaning that SED occurs very infrequently. The typical duration is about several hours. The mechanism of SED occurrence has yet to clarified, but a possible longitudinal dependence has been suggested.

2.6 Plasma bubbles

Plasma bubbles (as known as equatorial plasma bubbles or EPBs hereinafter) are "bubbles" that form in the ionosphere near the magnetic equator and are a phenomenon that the regions having a lower electron density in the lower layer of the ionosphere moves upward[3]. The formation of EPBs exhibits a seasonal dependence known to be longitudinally variant[4]. EPBs form more often in spring and autumn at longitudes where Japan is located and quickly spread to reach a size of several thousand to 10,000 km in the north-south direction along the magnetic field lines, and about 100 km in the east-west direction. After forming, EPBs propagate eastward at a speed of about 100 km per hour due to the ionospheric electric field. The forming of EPBs is due to the Rayleigh-Taylor instability and the fundamental mechanism of its creation is understood. However, what triggers this creation process has yet to be sufficiently clarified and forecasting it remains difficult even now.

3 Importance of ionospheric effect on utilizations

As described above, ionospheric disturbances based on solar activity are significantly influenced by such factors as interaction with the geomagnetosphere and thermospheric winds, although forecasting such disturbances remains in a situation of great difficulty. One practical measure that has been proposed is focusing on and continuously monitoring phenomena that could most seriously affect the subject bodies of usage, and constructing an "early warning system" to alert against approaching ionospheric disturbances based on propagation direction and speed.

3.1 Communications and broadcasting

Ionospheric disturbances (e.g., ionospheric storms, EPBs) significantly affect communications using shortwave bands due to the use of multi-reflection between the ionosphere and the ground. Regarding EPBs, ionospheric delay poses no problems for such applications as satellite positioning; however, scattering due to the variance of electron densities near regional borders and abnormal propagation along with EPBs are known to occur.

Due to the relatively short propagation distance of 100 km and high frequency, TV broadcasting is less influenced by the ionosphere, but crosstalk caused by development of the sporadic E layer poses a problem.

3.2 Satellite positioning

The use of satellite positioning is divided into two types: precision positioning as typified by electronic positioning, and the real-time use of information as typified by electronic navigation. Since 1.2 GHz and 1.5 GHz are used as the frequency bands for satellite positioning, propagation delay occurring in the ionosphere directly affects positioning accuracy[5].

For precision positioning, ionospheric delay is complemented by multiple measurements in different periods. The costs for positioning may be reduced when ionospheric influences can be forecast and the results reflected in actual operation. On the other hand, systemizing the real-time use of information has improved the accuracy of positioning by utilizing complementary information obtained, for example, by a differential GPS using pseudolight or a trip meter for an automobile navigation system as a typical example of ground use. However, since this technique cannot be used for air traffic control where the subject flies over the sea, how to avoid the influence of the ionosphere has been a serious issue. The next section addresses this issue.

3.3 Air traffic control

In considering the use of ionospheric information for electronic navigation systems, negative storms as one of the phenomena described above have little effect on positioning errors. In addition, SED is a very serious phenomenon that only occurs a few times during the maximal period of solar activity. It is considered important to construct an early warning system by focusing on daily variations of the equatorial anomaly and positive storms, while studying their mechanisms of occurrence in order to make an ionospheric disturbance forecasting system available in the future.

4 Conclusion

Propagation delay is the most significant factor regarding errors in the positioning accuracy of artificial satellites. Monitoring ionospheric disturbances and improving forecasting technologies are important issues regarding the more widespread use of positioning information in the future. A frequent exchange of information between developers and users is therefore essential, and more cooperative relationships need to be enhanced for developing useful systems relative to what information is required or what information can be provided.

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ISHII Mamoru, *Dr. Sci.*

Director, Project Promotion Office, Applied Electromagnetic Research Center

Upper Atmospheric Physics