A Comparison of GPS-derived TEC and foF2 over Japan

G. Ma [(1)] **and T. Maruyama** [(2)]
[(1)] ***Communications Research Laboratory, Tokyo, Japan***
E-mail: ma@crl.go.jp
[(2)] ***As (1) above, but E-mail: tmaru@crl.go.jp***

ABSTRACT

We have analyzed morphology of total electron content (TEC) and ionospheric critical frequency (foF2) for geomagnetically disturbed periods, Apr. 19-28, and Nov. 1-10, 2001, which include a negative and a positive ionospheric storm, respectively. It is found that the daily variation pattern of $TEC/(foF_2)^2$ in April is different from that in November. The ratio of $TEC/(foF_2)^2$ doubles for the negative ionospheric storm, indicating the storm effects is mainly in the F2 layer. Concerning the positive storm, it only reflects on TEC which doubles. foF2 keeps the same as that of quiet days.

INTRODUCTION

The total electron content (TEC) is one of the important parameters in the study of the ionospheric properties. As a dispersive medium to Global Positioning System (GPS), the ionosphere causes group delay to the radio wave propagation from GPS satellites to ground-based receivers [1]. Since the satellites are in an orbit at an altitude of about 20,200 km, the long ray path through the tenuous hydrogen-based plasma of the plasmasphere also contributes to the group delay. The GPS-derived TEC involves electron in the plasmasphere [2]. foF2, from ionosonde observations, is the measured critical frequency of the ionospheric F2 layer. It is equivalent to the maximum electron density of the F2 layer. Comparison of GPS-derived TEC and foF2 has both theoretical and practical meanings. It will help us to understand the coupling process between the ionosphere and the plasmasphere. It will enable us to gain an insight into characteristics of the plasmaphere during ionospheric disturbed conditions. In practical, it will help to develop a better model for single-frequency GPS receiver in navigation uses, and hence higher accuracy of the positional estimate.

This study tries to look for the characteristic pattern of the TEC and foF2, especially for geomagnetically disturbed times. It is also tried to understand the coupling process between the ionosphere and the plasmasphere with comparison of GPS-derived TEC and foF2. The GPS data were downloaded from GPS Earth Observation Network (GEONET) of Geographical Survey Institute, Japan [3]. About 200 stations are used in the study, which have precise code (P code) pseudoranges (P1 and P2) at both frequencies. The differenced pseudoranges, P2-P1, and the differenced phases, L1-L2, are used to obtain slant path TECsl between the GPS satellite and receiver. In order to estimate absolute vertical TEC from TECsl, the ionosphere over Japan is assumed to be a thin screen at a height of 400 km and partitioned into 32 meshes that are 2º in longitude by 2º in latitude. For those slant path TECsl that go through the same mesh, their vertical TECs are assumed to be identical. Then with 28 satellites and about 200 receivers, using observations with 15 minutes interval, the absolute TECs at different meshes for one day are derived by solving a set of equations with about 2,600 unknowns by about 35,000 equations with least squares fitting technique, and the biases intrinsic to satellites and receivers are estimated at the same time.

GPS-derived TEC and foF2

With the procedure described above, 15 min time series of TEC are obtained over Japan for both ionospheric quiet and disturbed days. Then TEC comparisons are made with foF2 observations at several ionosonde stations distributed from Okinawa (27º N) to Wakkanai (45º N).

(1) Apr. 19-28, 2001

Fig. 1 shows 15 min time series of TEC, foF2 and the ratio of $TEC/(foF_2)^2$ (referred to as R) from Apr. 19 to 28, 2001 over Japan. The observation sites and their geographical position are shown in the corresponding panels. The behavior of TEC and foF2 at Kokubunji (35.0°N, 139.0°E) is strikingly similar to each other. The behavior of TEC and foF2 at Wakkanai (45.0°N, 141.0°E) and Okinawa (27.0°N, 127.0°E) is also similar to each other, although it is not shown in the paper. The variations in TEC and foF2 show a high degree of conformity. In addition to diurnal features, a depression of both TEC and foF2 is conspicuous on Apr. 23. It shows a negative ionospheric storm, which is often preceded by a magnetic storm. As shown in the bottom panel, the geomagnetic index Kp indicates a geomagnetic storm occurred on Apr. 22. Since the negative ionospheric storm occurred during night, it is hard to distinguish the onset of the ionospheric storm. And it can be noticed that the daytime levels of TEC and foF2 after the storm did not recover compared with that on the three days before the ionospheric storm.

For ionospheric quiet times, it is found that the ratio R at Kokubunji (35.0°N, 139.0°E) increases by 20% for about 2 hours around the sunset, and decreases by 20% for about 2 hours around the sunrise. The ratio is constant for other times. This implies that after the sunset, the ionization ceases in the ionosphere, the hydrogen plasma in the plasmasphere return to lower altitudes, where charge exchange forms an oxygen plasma that maintain the nighttime F region. It takes about 2 hours to reach the equilibrium state. On the other hand, after sunrise, the solar-produced oxygen plasma in the ionosphere begins to refill the plasmasphere by moving upward along the magnetic field lines. Charge exchange of the oxygen ions with neutral hydrogen gives a hydrogen-dominated plasma above 1000 km [4]. It also takes about 2 hours for the refilling process reaching the equilibrium state.

The increase and decrease of R at Wakkanai are less apparent than those at Kokubunji. It cannot be seen clearly in Okinawa because of data gap.

As to the storm time, the ratio R at Kokubunji (35.0°N, 139.0°E) starts to increase at 14:00 UT (23:00 LT) on Apr. 22, reaches its maximum at about 0:00 UT (9:00 LT) on Apr. 23 and recovers around 16:00 UT (1:00 LT) on Apr. 23 (Apr. 24). So, the depression of the total electron content is not so severe as the decrease of the electron density in the F2 region. This means that the plasmasphere responds to the geomagnetic storm differently than the ionosphere. The time at which the ratio starts to increase is probably the onset of the ionospheric negative storm. The increase of R at Wakanai and Okinawa seems to start and reach its peak at the same times as that of Kokubunji. It should be pointed out that around midnight Apr. 23, the ratio R of Wakkanai has a valley, implying the delayed recover of TEC compared with foF2, and the ratio R of Okinawa seems to have a peak. These can be related to the different lengths of geomagnetic field lines at different geographical locations.

(2) Nov. 1-10, 2001

Fig. 2 is the same as Fig. 1, but for a period of Nov. 1-10, 2001. As that in April, the behavior of TEC and foF2 is similar to each other, except on Nov. 6 when an enhancement of TEC is conspicuous. The geomagnetic index Kp in the bottom panel shows a magnetic storm occurred late on Nov. 5. The nighttime level of TEC on Nov. 6 was higher than normal days'. Although recovered, TEC peak was a little higher for two days after the storm. foF2 did not reflect the ionospheric storm on Nov. 6. It just remained the same as those on other days. Nozaki et al. pointed out that the F2 layer in middle Japan on Nov. 6 was lifted up by a force of $\vec{E} \times \vec{B}$, where the electric field is eastward and induced by the magnetic storm [5]. The enhancement of TEC can be explained by increase of electron density above F2 layer.

Different from that in April, the ratio R shows a diurnal variation like a triangular wave. It starts to increase about one hour after the sunrise, then remains constant for a few hours around noon, and from then on keeps increasing smoothly during the day and night, and it abruptly reaches its maximum (a further higher level) before dawn. Then it decreases sharply soon after the sunrise to its minimum. This seems like that soon after sunrise, the solar-produced oxygen plasma in the ionosphere causes the ratio of R decreases sharply. Then the plasma in the ionosphere begins to refill the plasmasphere by moving upward along the magnetic field lines. Charge exchange of the oxygen ions with neutral hydrogen gives a hydrogen-dominated plasma above 1000 km. Similar to that in April, the refilling process takes about 2 hours for the refilling process reaching the equilibrium state. However, it is different from April in the afternoon. While foF2 decreasing, the ratio R keeps increasing, showing that there are probably more plasmas in the topside ionosphere and plasmasphere in November than in April. After sunset, the production ceases in the ionosphere, the hydrogen plasma in the plasmasphere return to lower altitudes, where charge exchange forms an oxygen plasma that maintain the nighttime F region. This makes the ratio R increase more sharply than daytime.

The behavior of the ratio R in the positive ionospheric storm times is different from that in the negative ionospheric storm. First it increases with the increasing TEC. When the magnetic storm effects disappear, TEC keeps decreasing. foF2 also decreases because it is the time of afternoon. The ratio R remains in a certain level with fluctuation, indicating that there are more electrons kept in the F2 layer during the storm than quiet days. This can be confirmed from the foF2 plot in fig. 2.

Summary

The main results obtained in the study can be drawn as follows:

(1) The variations in TEC and foF2 show a high degree of conformity at both geomagnetically quiet and disturbed times.

(2) Except diurnal variation, the ratio $TEC/(foF_2)^2$ displays different features at sunrise and sunset.

(3) At the time of the negative ionospheric storm, the ratio $TEC/(foF_2)^2$ experienced a process of increase, peak, and decrease. The peak level was about twice that of the quiet days.

(4) At the time of the positive ionospheric or TEC storm, TEC doubled, although the foF2 did not show much difference from that of the quiet days.

(5) The ratio $TEC/(foF_2)^2$ increased first and then remained as a constant with small fluctuation.

Acknowledgement. The GPS data of GEONET used in this study were supplied by the Geographical Survey Institute of Japan. K_p index are downloaded from the website of NSSDC database. The authors are grateful to them for their Support.

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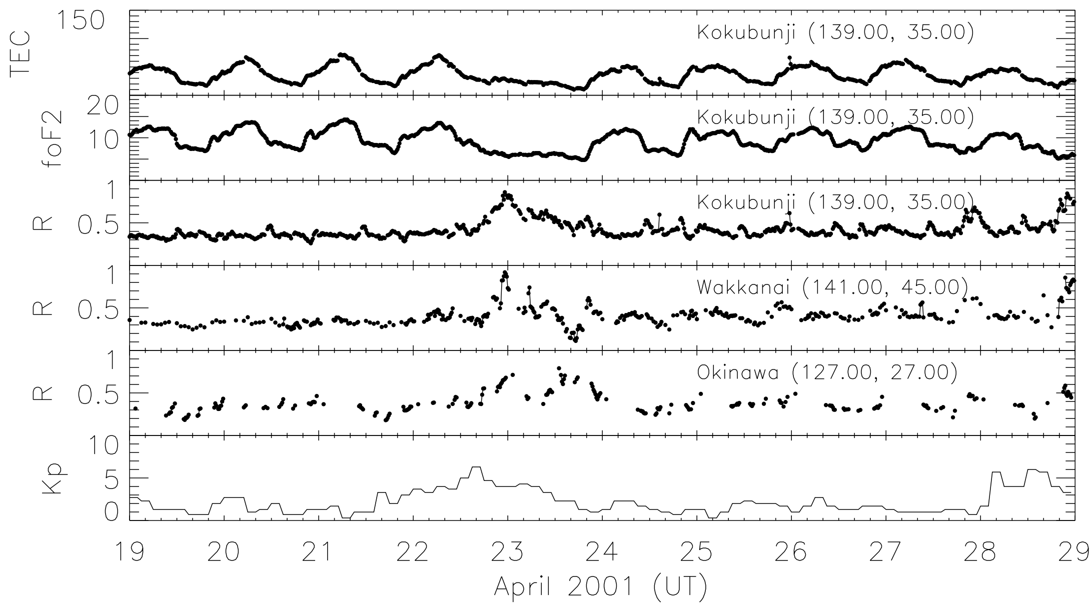

Fig. 1 15–min time series of TEC, foF2, and the ratio of TEC/(foF2)^2 from Apr. 19 to 28, 2001 in Japan. Also shown is Kp index.

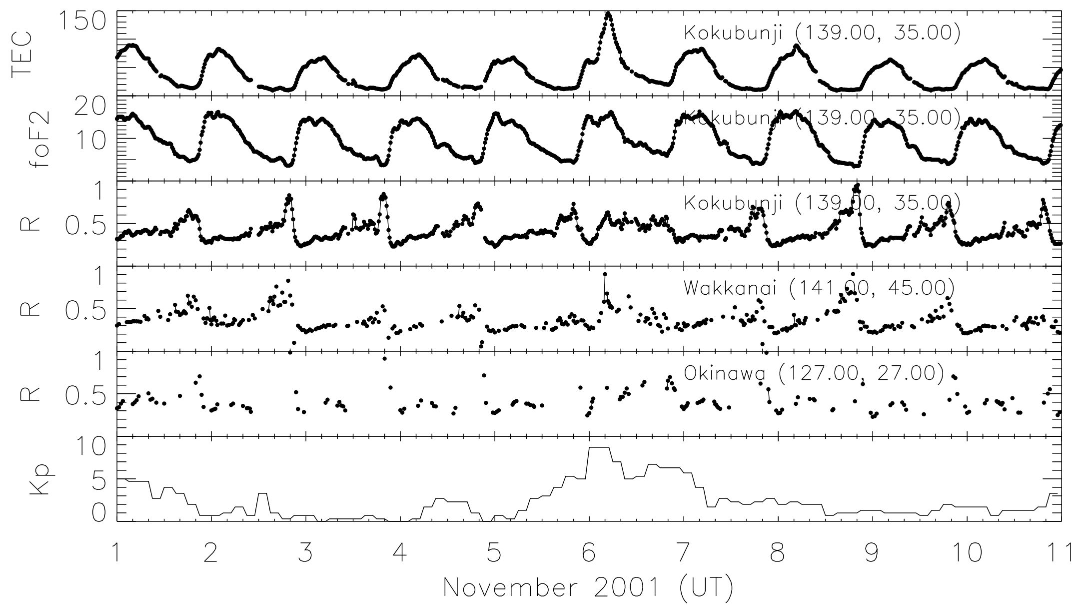

Fig. 2 Same as Fig. 1, but for a period of Nov. 1–10, 2001.