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TEC and f_oF2 variations: preliminary results

Stamatis S. Kouris, Thomas D. Xenos, Konstantinos V. Polimeris and Dimitrios Stergiou
Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Greece

Abstract
Investigation of the relationship between TEC and $(f_oF2)^2$ shows that although they are highly correlated, a «hysteresis» effect exists between them. The slab thickness is greater before than after mid-day for equal cosχ values. Moreover, a comparison of the calculated upper and lower quartiles of variability in TEC, f_oF2 and $N_{\max}$, respectively shows that the variability of TEC lies between those of f_oF2 and $N_{\max}$ depending on the level of solar activity.

Key words *ionospheric variability – radio wave propagation – space and satellite communications*

1. Introduction

Users of satellite navigation and satellite communication systems need to assess and monitor ionospheric effects which may degrade their performance. Empirical ionospheric models predict only monthly mean ionospheric conditions (Bilitza, 1999) and such that have been successful for planning HF terrestrial systems. For Earth-space communication and navigation systems, day-to-day and hour-to-hour variability should be necessarily taken into account. Since ionospheric effects exhibit great temporal and spatial variation meaningful predictions should have statistical character (Rawer, 1993).

Total Electron Content (TEC) is an important ionospheric parameter for satellite navigation and satellite communication systems and a detailed study of its behaviour and especially of its variability from day-to-day, hour-to-hour and within-the-hour is essential. In the present preliminary work first we compare monthly-median values of TEC and $(f_oF2)^2$ and subsequently their hourly daily values are considered, since both monthly-median and daily values are involved in the definition of ionospheric variability (Kouris and Fotiadis, 2002). Indeed, the variability of the referred ionospheric parameters is evaluated from the variation, from day-to-day or hour-to-hour, of the relative deviation of the hourly daily value with respect to the corresponding monthly-median value, *i.e.* from the variation of the relative deviations dX:

$$dX = \frac{X_d - X_m}{X_m} \tag{1.1}$$

where X_d stands for the hourly daily value and X_m for the corresponding monthly-median of each ionospheric parameter. Then, we calculate and compare the upper and lower quartiles of the variability in TEC, in the F-region critical frequency f_oF2 and in $N_{\max}$, the maximum electron density. It is known (Anderson and Fuller-Rowell, 1999) that TEC has a diurnal variation by a factor of 10 and the same is true for $N_{\max}$, proportional to $(f_oF2)^2$. Thus, it is expected that TEC and $N_{\max}$ should vary to some extent in a very similar way from hour-to-hour.

Mailing address: Dr. Stamatis S. Kouris, Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, GR-54 124 Thessaloniki, Greece; e-mail: kouris@vergina.eng.auth.gr

2. Data and analyses

In this work we use TEC data obtained observing the Faraday rotation affecting the signals from geostasionary satellites and measured at Florence (Italy) from 1976 to 1982 and 1989 to 1991, and also TEC data measured at Matera (40°N, 16°E), Italy, from signals transmitted from GPS satellites during the years 1993 to 1999. Moreover, we use corresponding f_oF2 measurements made at Rome (41.8°N, 12.5°E) during the same periods.

First we compare hourly monthly-median TEC with corresponding monthly-median $(f_oF2)^2$ values. Consecutively we examine their hourly daily values from hour-to-hour and at a fixed hour from day-to-day.

Next, we evaluate the relative deviations of TEC, $(f_oF2)^2$ and f_oF2, respectively at each hour of each day/month/year and consider their variations in time. Then, we calculate quartile levels of variability at each hour/month/year and compare corresponding levels.

It is known that TEC is defined as the integral with height, h, of the ionospheric electron density $N(h)$, *i.e.*

$$\mathrm{TEC} = \int_0^h N(h)\, dh \tag{2.2}$$

Besides, the ratio between TEC and the maximum electron density $N_{\max}$

$$\tau = \frac{\mathrm{TEC}}{N_{\max}} \tag{2.3}$$

defines the slab thickness which can be considered as an effective breadth of the ionosphere, depending on the actual shape of the profile (Spalla and Ciraolo, 1994). In terms of f_oF2 eq. (2.3) is written

$$\mathrm{TEC} = 1.24 10^{-6}\, \tau\, (f_oF2)^2 \tag{2.4}$$

where TEC is measured in TEC units (10^{16} electrons m^{-2}), f_oF2 in MHz and τ in meters (Davies, 1990).

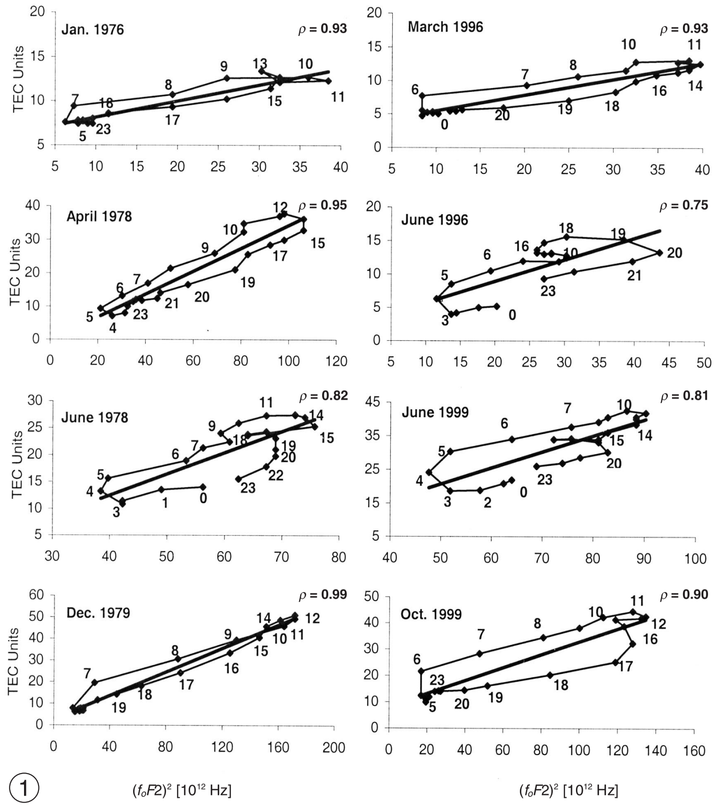
3. Results and discussion

The present study may be divided into two parts: a comparative study between TEC and f_oF2 values and a corresponding study between the variability in TEC and that in f_oF2. Although this investigation aims to the latter item, it is important to start it from the diurnal variation of these two ionospheric characteristics.

3.1. *Comparison of TEC and f_oF2 values*

A linear correlation analysis of the monthly-median TEC and $(f_oF2)^2$ values of each month of a given year shows that the correlation coefficients are very high and usually much higher than 0.80, with the lower values during summer months. This is true whether Faraday rotation TEC data or GPS data are used (fig. 1). A similar population of correlation coefficients is found when hourly daily values measured in a given day/month/year are correlated (fig. 2). On the contrary, when hourly daily TEC and $(f_oF2)^2$ values measured at a given hour in each day of a given month/year are correlated, the correlation coefficients are found to be lower (fig. 3) than in the previous two cases of monthly-median and diurnal values. This result might suggest that the variations from hour-to-hour in TEC and $N_{\max}$ have a greater degree of similarity than those from day-to-day. Thus, from this analysis it can be stated that the correlation between TEC measurements and $(f_oF2)^2$ values is very high, especially when diurnal (monthly median or daily) values are correlated.

The comparison between TEC and $(f_oF2)^2$ values illustrates that there exists a marked hysteresis-like effect. In other words, this investigation shows that there are two different values of TEC (or f_oF2) for a given value of f_oF2 (or TEC). This arises when monthly-median TEC values obtained either from observing the Faraday rotation or from GPS measurements are compared with corresponding $(f_oF2)^2$ values (fig. 1). The same effect is also observed when hourly daily values of these two parameters are examined (fig. 2). From these figures it is evident that for a given value of TEC the afternoon value of f_oF2 is higher than the morning one and viceversa for the TEC values. Although the diurnal anomaly of maximum electron density is well known (Ratcliffe, 1960), the hysteresis-like effect between TEC and $N_{\max}$ produces new evidence of the fact.



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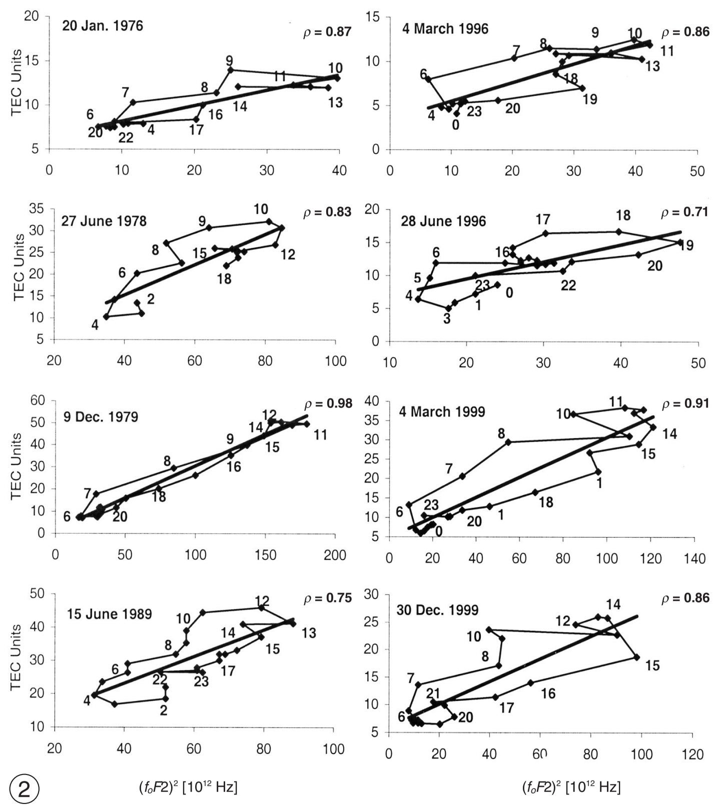

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Fig. 1. Linear correlation between TEC Faraday rotation (*left*), GPS (*right*) and corresponding $(f_oF2)^2$ monthly-median values, at randomly selected months/years. A «hysteresis» effect is evident.

Fig. 2. Linear correlation between TEC Faraday rotation (*left*), GPS (*right*) and corresponding $(f_oF2)^2$ hourly daily values, measured at some selected days in different months/years. A hysteresis-like effect is evident.

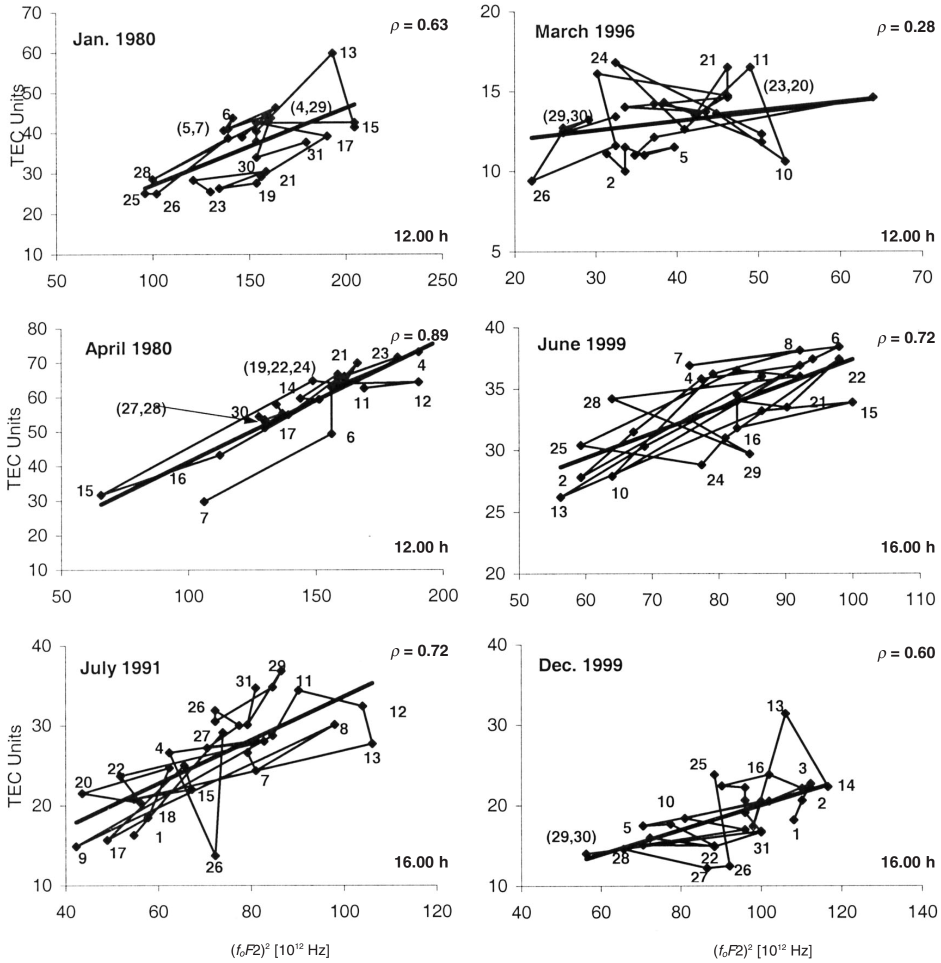

Fig. 3. Linear correlation between TEC Faraday rotation (*left*), GPS (*right*) and $(f_oF2)^2$ hourly daily values at some selected months/years, at given hours (12.00 or 16.00 h).

On the other hand, it is to be noted that this is not verified in the case that hourly daily TEC and $(f_oF2)^2$ values from one day to the next that is, values measured at a given hour in each day of a given month/year are compared. In this case there is no evidence of any «hysteresis» effect, as can be easily seen from the plots of fig. 3 where as an example values of TEC and $(f_oF2)^2$ measured at noon and at 16.00 h are plotted against each other. These results lead to the conclusion that the «hysteresis-like» effect found when TEC and $N_{\max}$ values are compared, is clearly a diurnal phenomenon rightly called diurnal anomaly.

Now, if we consider two nearly equal $\cos\chi$ values (with χ the solar zenith angle) one during morning hours and the other in the afternoon, it is found that the corresponding TEC values are nearly equal, but it is not so for the f_oF2 values. Indeed, the maximum electron densities $N_{\max}$ result to be

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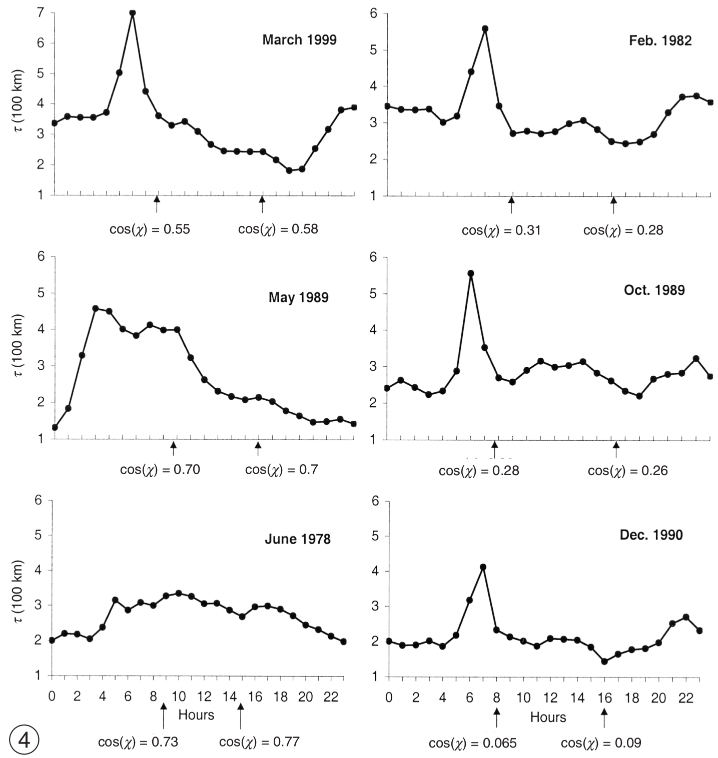

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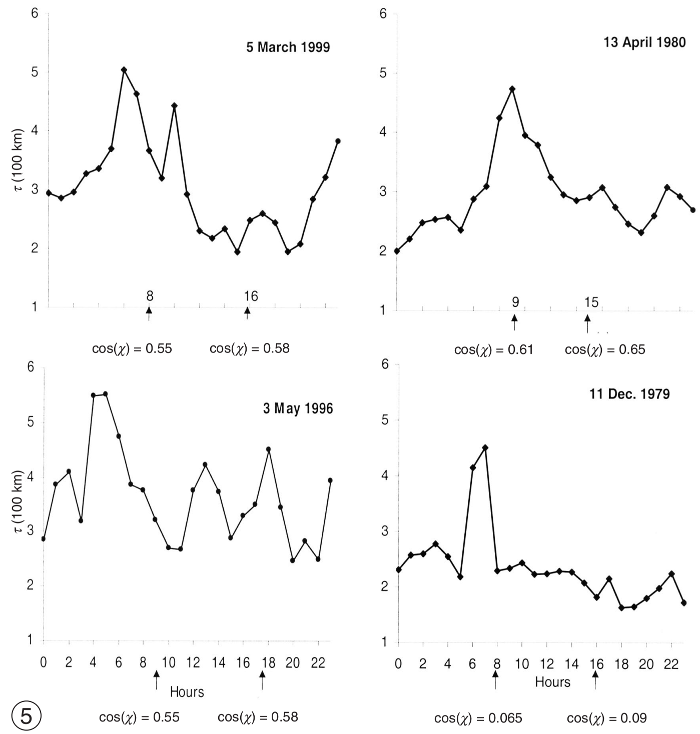
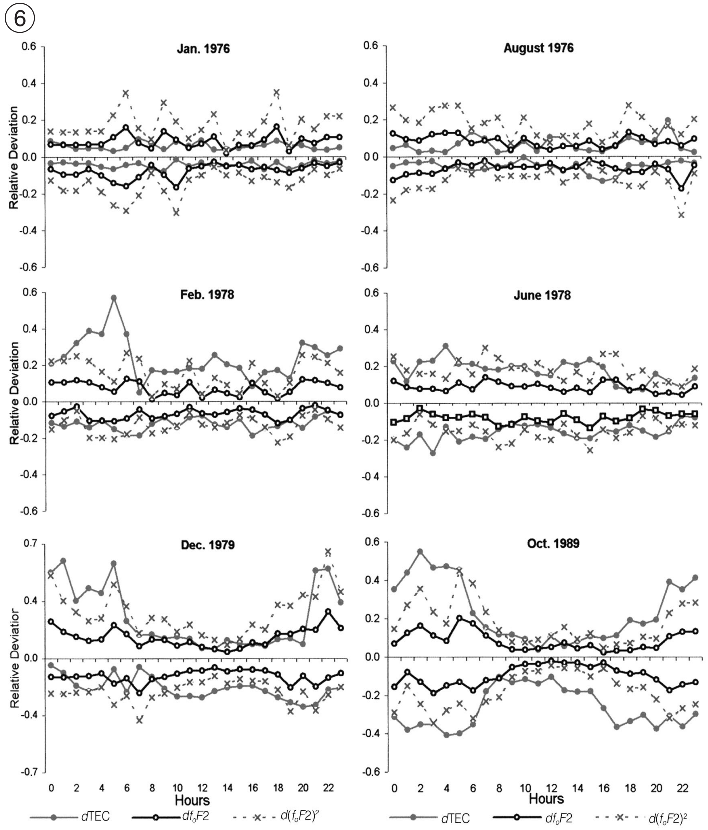


Fig. 4. Diurnal variation of the equivalent slab thickness τ at different months/years (monthly-median values).

Fig. 5. Diurnal variation of the equivalent slab thickness τ at different days/months/years (hourly daily values).



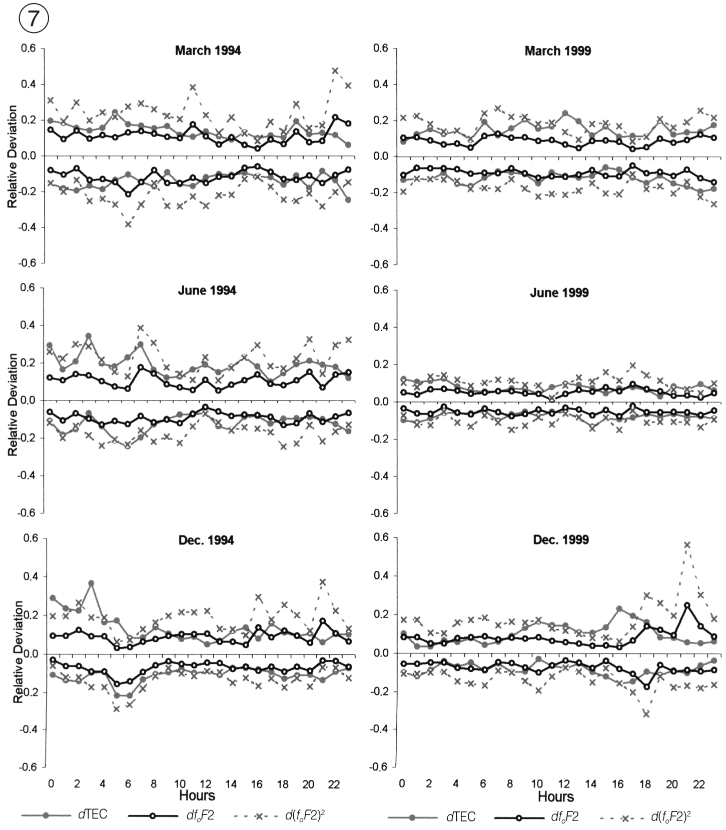


Fig. 6. Variation from hour-to-hour of the day-to-day variability (quarties) of TEC, f_oF2 and $(f_oF2)^2$ at years of different solar activity. Data from Rome and Florence (Italy), respectively.

Fig. 7. Variation from hour-to-hour of the day-to-day variability (quarties) of TEC, f_oF2 and $(f_oF2)^2$ at low (*left*) and medium (*right*) solar activity. Data from Rome and Matera (Italy), respectively.

greater in the afternoon than in the morning hours; on the other hand the slab thickness (eq. (2.3)) is found to be greater before than after mid-day and that it happens whether monthly-median or hourly daily values are considered (figs. 4 and 5, respectively). These findings may be explained as caused by changes during the course of the day in the chemistry and dynamics of the atmosphere at the heights of the ionosphere, and changes in the electron production and recombination, so that the impact on electron density concentration at the height of maximum is different before and after mid-day. We should however note that these findings refer to limited data. Thus, further studies are needed using more data measurements made at different locations in order to make definite statements. In figs. 4 and 5 it is also evident the predawn slab thickness peak. To note that the peak is nearly always present wheter monthly median or hourly daily values are considered.

3.2. *Comparison between the variability in TEC and that in f_oF2*

The purpose of this preliminary investigation is to assess the variability of the available TEC values and compare it with the variability from day-to-day of the corresponding f_oF2 values, as well as with the variability of the maximum electron density values. Thus, for each one of the three parameters, respectively the relative deviation of each hourly daily value from its corresponding monthly-median value is calculated according to eq. (1.1). Then, the upper and lower quartiles are evaluated for each hour in each month/year. It can be seen from the plots of figs. 6 and 7 that the variability in TEC for 75% of the time in each month is between 0.10 and 0.20 (in absolute value) of the monthly-median value, for low or medium solar activity, but at months/years of high solar activity the variability (quartiles) in TEC is greater than 0.20 of the monthly median value with higher values during the nighttime. Moreover, during disturbed months as for instance February 1978 or October 1989 (fig. 6), the variability in TEC could be greater than that in $N_{\max}$. This perhaps means that disturbances affect the topside more than the bottomside of the ionosphere. However, this statement needs to be further investigated.

The comparison of the lower and/or upper quartile of the variability in TEC, f_oF2 and $(f_oF2)^2$ points out that the variability from day-to-day of the TEC values lies between the variability of f_oF2 and that of $(f_oF2)^2$, being close to the levels of f_oF2 variability at months/years of low or medium solar activity (figs. 6 and 7), and close to the levels of $(f_oF2)^2$ variability during months/years of high solar activity (fig. 6). It should be noted that the variability exhibits its greater values mostly during night-time hours, when disturbed conditions usually prevail. However, these studies on variability should be further promoted using values measured at different locations and years to confirm the abovementioned results.

4. Conclusions

The analysis of TEC and $(f_oF2)^2$ values shows that there exists a high correlation between these two ionospheric characteristics, with correlation coefficients usually greater than 0.80. It is also found that a «hysteresis-like» effect exists between TEC and $(f_oF2)^2$, when monthly-median values of a given month or hourly-daily values measured in a given day are compared.

As a result the slab thickness given by eq. (2.3) is found to be greater before than after mid-day. This confirms the already known diurnal anomaly of $N_{\max}$.

The statistically calculated quartiles of variability in each hour/month/ year of the three parameters TEC, f_oF2 and $(f_oF2)^2$ show that the variability of TEC from day-to-day is close to that of f_oF2 during periods of low/medium solar activity whereas at periods of high solar activity the variability of TEC overlaps with that of $(f_oF2)^2$.

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