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The representation of time variation of foF2 during geomagnetic storms

G. A. Mansilla(*)

Laboratorio de Ionosfera, Departamento de Física, Universidad Nacional de Tucumán
Av. Independencia 1800, 4000 San Miguel de Tucumán, Argentina
Consejo Nacional de Investigaciones Científicas y Técnicas - Buenos Aires, Argentina

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Summary. — In this paper a technique for describing the variations of the critical frequency of ionospheric F2-layer foF2 at middle latitudes during the 24 hours after geomagnetic storm sudden commencement is proposed, which serves to obtain foF2 values at a location where there are no observations. The reliability of the technique has been verified during both moderate and intense geomagnetic storms.

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1. – Introduction

The study of ionospheric perturbations produced during geomagnetic storms is of practical interest since transionospheric radio communications and also satellite ephemeris predictions are severely degraded during these events [1, 2].

The ionospheric response to the storm most often studied is the perturbation on the peak electron density of the F2 region, which is proportional to the square of the critical frequency of the layer.

The electron density can either increase or decrease during geomagnetic disturbed conditions. These variations are denoted as positive and negative ionospheric storms, respectively. Strong latitudinal and longitudinal asymmetries in the global morphology of the ionospheric response are frequently observed. In addition, the distribution of storm effects varies considerably from one storm to the next (*e.g.*, [3] and references therein).

Intensified electric fields and/or equatorward meridional winds developed during storm periods have been considered as responsible mechanisms for controlling the morphology and phenomenology of the ionosphere during these events (see for example, [3-7] and references therein).

(*) E-mail: gmansilla@herrera.unt.edu.ar

Table I. – *Stations employed in the analysis.*

	Geomagnetic latitude	Geomagnetic longitude
Okinawa	+15.25	195.58
Yamagawa	+20.33	197.81
Kokubunji T.	+25.40	205.46
Akita	+29.47	205.45
Wakkanai	+35.27	206.04
Hobart	−51.57	224.29
Canberra	−43.99	224.29
Mundaring	−43.45	186.08
Brisbane	−35.74	226.87
Norfolk	−34.75	243.22
Townsville	−28.47	218.79
Vanimo	−12.60	211.09

Numerical simulations have been developed in recent years to describe the ionospheric response to geomagnetic storms. The agreement between the simulations and the observations tends to be more qualitative than quantitative [8]. The accuracy of these models is limited either by complex physical assumptions or by inexactly defined boundary conditions. However, the theoretical models are very important since they provide an understanding of the physical mechanisms, which control the structure and dynamics of the ionosphere.

On the contrary, a few empirical models describing the ionospheric behavior during geomagnetic storms have been made (*e.g.*, [9]). This modeling is limited by the lack of available data and by the great variability of the ionosphere during these events. However, the empirical and semiempirical models are used in many practical investigations (*e.g.*, [10, 11] and [12]).

For this reason, in this paper a technique for evaluating the critical frequency of the ionospheric F2-layer, foF2, from geomagnetic storm sudden commencement to subsequent 24 hours at middle latitudes is proposed. The formalism considers that the hourly variation of foF2 during disturbed conditions can be well represented by the cosine portion of a Fourier series with a relatively small number of terms, the corresponding coefficients having latitudinal and longitudinal dependence. This assumption is based on our observations of the comparison between calculated and measured data, in which only 13 coefficients are able to reproduce the temporal variations of foF2 perturbed values.

Although the method was checked at a limited longitudinal and latitudinal region, a satisfactory agreement of the comparison between measured and computed values has been found.

2. – Technique formulation

The first step of the method is to select a series of stations that are to be used to describe the behavior of the ionosphere over the first 24 hours after storm commencement. In this paper database were hourly values of foF2 from ionosondes located in the north and south hemispheres (Japanese and Australian longitudinal sectors, respectively). Geophysical parameters of the stations considered are given in table I.

The foF2 data obtained at each station are then fitted by a Fourier series in which

TABLE II. – *Correlation coefficients obtained from the adjustment of hourly foF2 measured values during some geomagnetic storms.*

	11 November 1977			8 March 1978			26 July 1979		
	$n = 10$	$n = 12$	$n = 13$	$N = 10$	$n = 12$	$n = 13$	$n = 10$	$n = 12$	$n = 13$
Yamagawa	0.960	0.988	0.989	0.917	0.953	0.956	0.887	0.891	0.901
Kokubunki T.	0.953	0.965	0.969	0.943	0.981	0.982	0.962	0.962	0.970
Akita	0.967	0.983	0.986	0.957	0.992	0.997	0.910	0.913	0.933
Hobart	0.917	0.918	0.918	0.939	0.946	0.962	0.977	0.992	0.992
Canberra	0.958	0.963	0.972	0.961	0.973	0.974	0.973	0.987	0.988
Townville	0.964	0.977	0.979	0.958	0.975	0.982	0.955	0.963	0.968

only the cosine portion of the series is used, in the form

$$foF2 = A_0 + \sum_{i=1}^{12} A_i \cos(i\pi t/T)\,, \tag{1}$$

where i is the harmonic number, t is the time after storm onset (in hours) and $T = 24$ hours corresponds to a fundamental period of the diurnal variation of foF2.

A group of 13 coefficients at each station for a particular geomagnetic storm is considered as the best prediction to reproduce the temporal variation of foF2.

Table II presents the squares of the correlation coefficients obtained from the adjustment of foF2 hourly measured values after storm onset (24 values) at several stations considering a different amount of Fourier coefficients ($n = 10$, $n = 12$ and $n = 13$). Such calculations are shown for three geomagnetic storms occurred on 11 November 1977, 8 March 1978 and 26 July 1979. Note the improvement of the fit as the amount of terms increases. A very well adjustment is obtained by considering 13 coefficients. Similar results have been found by analyzing ionospheric responses during other geomagnetic storms not presented in this paper.

In spite of the great variability of foF2 from storm to storm and also from quiet geomagnetic conditions, these results support the assumption that a temporal Fourier series with only 13 terms reproduces the behavior of foF2 at any station during storm conditions.

A larger number of Fourier coefficients to reproduce foF2 values implies more calculations to obtain the latitudinal and longitudinal dependence of the coefficients below described, and no significant improvement in the agreement between measured and computed foF2 values is obtained.

The second step is to combine stations into northern and southern hemisphere sets. Then, the subsets of each of these Fourier coefficients are combined into groups according to the Fourier frequency. Each of these groups of Fourier coefficients is fitted by a function that assumes a linear dependence in latitude and longitude, in the form

$$A_i = a_i + b_i\lambda + c_i\varphi\,, \tag{2}$$

where λ and φ are geomagnetic latitude and longitude, respectively. There are 13 sets of numerical coefficients a, b and c needed for the 13 terms A_0 to A_{12}. It should be

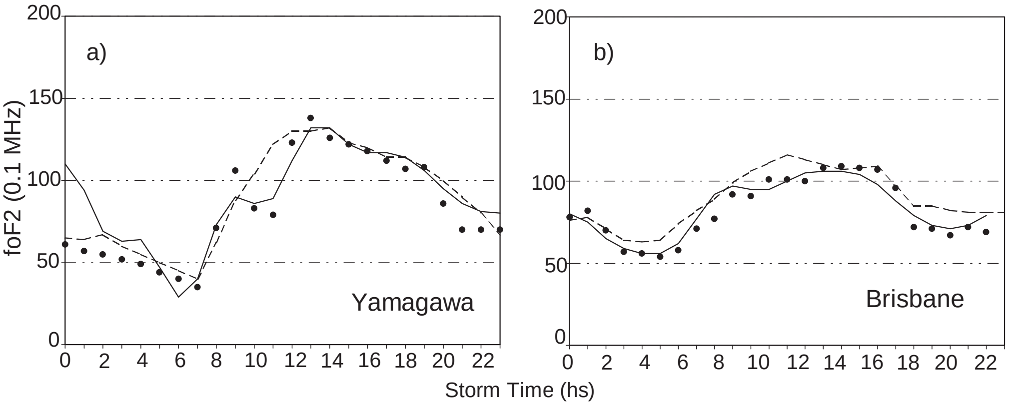

Fig. 1. – a) Hourly behavior from the storm onset of predicted (circles) and measured (solid line) foF2 values at Yamagawa for the geomagnetic storm occurred on 8 March 1978. For comparison, foF2 values of a geomagnetic quiet day of March 1978 are represented (dashed line). b) As in a), but for Brisbane.

noted that at least three stations in each sector are necessary to obtain the coefficients in eq. (2). A multi-linear regression is considered as a better prediction than a simple linear regression analysis of A_i with the latitude because a zonal dependence is included.

It is possible to know a new set of Fourier coefficients for an unknown station located within the range of coordinates of the stations used to obtain the coefficients a, b and c by using numerical coefficients obtained from eq. (2). Then, by applying eq. (1), foF2 values can be obtained at this location during a 24 hours period following storm commencement with 1 hour time resolution.

3. – Results and discussion

A few examples are presented to illustrate the effectiveness of the technique. Computed values are compared with observed foF2 data at stations located at both hemispheres. In the following figures circles indicate the measured values and continuous lines the calculated ones. To show the perturbation degree during the storm, foF2 values corresponding to a geomagnetic quiet day of the month of the storm considered are presented (dashed lines). In the figure abscissas the ionospheric evolution from storm commencement (sc) as storm time (in hours) is represented.

Figures 1a) and b) show the ionospheric storm effects observed during the geomagnetic storm occurred on 8 March 1978 at 1439 UT ($|\mathrm{Dst}|_{\max} = 111$ nT) at Yamagawa and Brisbane (sc: 2339 LT and 0239 LT on 9 March, respectively). Data from Okinawa, Akita, Kokubunji and Wakkanai (north hemisphere), and Hobart, Canberra and Townsville (south hemisphere) were included in database for generating the numerical coefficients. It can seen that measured values are satisfactorily reproduced by computed values at both stations, which corroborate that the assumption for latitudinal and longitudinal variations of the ionospheric characteristics can be well represented by considering a Fourier series with 13 terms.

Figures 2a) and b) illustrate the comparison between measured and modeled values during the geomagnetic storm occurred on 25 November 1977 at 1212 UT ($|\mathrm{Dst}|_{\max} =$

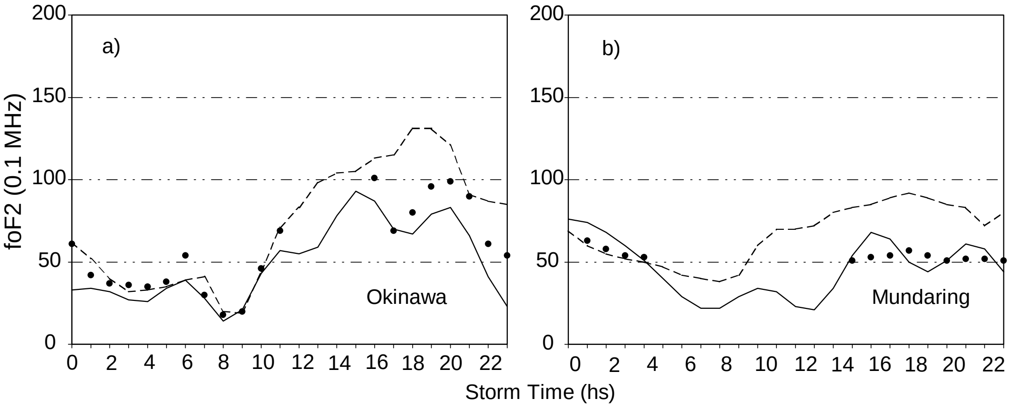

Fig. 2. – a) Hourly behavior from the storm onset of predicted (circles) and measured (solid line) foF2 values at Okinawa for the geomagnetic storm occurred on 25 November 1977. For comparison, foF2 values of a geomagnetic quiet day of March 1978 are represented (dashed line). b) As in a), but for Mundaring.

98 nT) at Okinawa and Mundaring (sc: 2112 LT and 2012 LT, respectively). These stations were used here for testing the reliability of the method and were not included in the database employed for calculating the coefficients (foF2 data from Wakkanai, Akita, Kokubunji and Yamagawa, and Brisbane, Canberra, Townsville, Hobart and Norfolk were used). Again, good agreement between calculated and measured values after storm commencement is observed. Note the missing measured data at Mundaring. One area in which this procedure may be of some value is in the reproduction of the temporal variation of foF2 values at times in which ionosondes were not operative.

Figure 3a) and b) show the ionospheric behavior for the geomagnetic storm occurred on 26 July 1979 at 1833 UT ($|\mathrm{Dst}|_{\max} = 82$ nT) at Brisbane and Vanimo, respectively

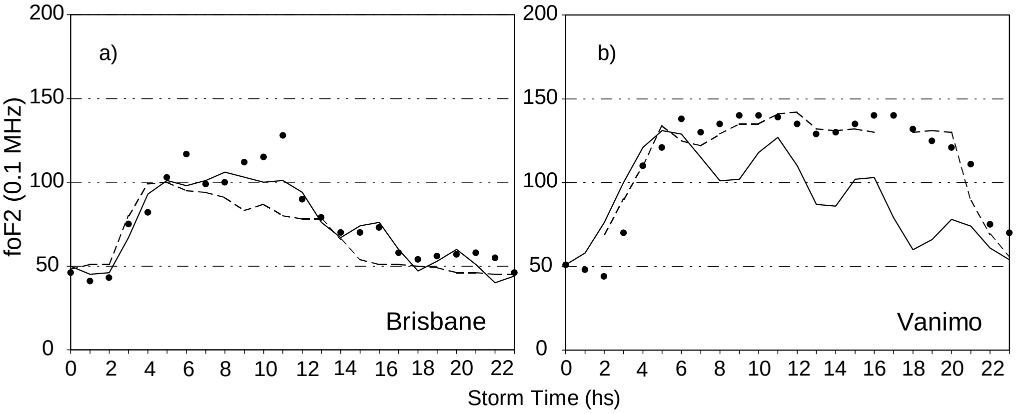

Fig. 3. – a) Hourly behavior from the storm onset of predicted (circles) and measured (solid line) foF2 values at Brisbane for the geomagnetic storm occurred on 26 July 1979. For comparison, foF2 values of a geomagnetic quiet day of March 1978 are represented (dashed line). b) As in a), but for Vanimo.

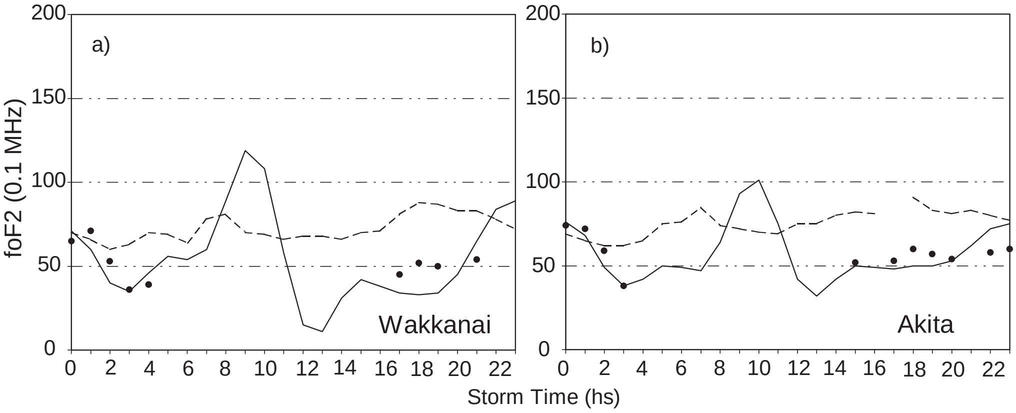

Fig. 4. – a) Hourly behavior from the storm onset of predicted (circles) and measured (solid line) foF2 values at Wakkanai for the geomagnetic storm occurred on 13 July 1982. For comparison, foF2 values of a geomagnetic quiet day of March 1978 are represented (dashed line). b) As in a), but for Akita.

(sc: 0433 LT on 27 July). The remaining south hemisphere stations listed were used for calculating the set of required numerical coefficients. It can be seen that at Brisbane computed values are close to measured values almost during the entire storm period considered ratifying that the technique predicts reasonably well the disturbed behavior of the ionosphere. At low latitudes (fig. 3b) the model's calculations do not match well the real foF2 distribution since predicted values are quite different from experimental values. An extrapolation of the method to lower latitudes using coefficients obtained from mid-latitude station data produces a degradation of results. The foF2 predicted values would be improved by considering a meridional chain of low latitude stations.

In figs. 4a) and b) more examples are presented. Computed and observed foF2 values for the geomagnetic storm of 13 July 1982 at 1617 UT ($|\mathrm{Dst}|_{\max} = 338$ nT) at Wakkanai and Akita (sc: 0112 LT on 14 July) are shown. Although there are a few available experimental data it can be seen again that the model predictions follow the measured values.

The comparisons between predicted and measured data are limited. However, the results show the reliability of the technique to compute the temporal evolution of the foF2 ionospheric critical frequency during the first stages of a geomagnetic storm at middle latitude regions where there are no experimental observations. The simplicity of the technique formulation leads to reduced numerical calculations. As mentioned previously, a great variability in the ionospheric effects associated with geomagnetic storms is observed; therefore, the technique possibly does not explain all features of storm variations (for example, predicted values are closer to quiet values than perturbed ones at Yamagawa during storm on 8 March 1978).

Although the technique was checked in limited regions, their systematic application to other regions would allow make maps for representing the foF2 structure at middle latitudes during disturbed periods. It also has shown their effectiveness during both moderate (peak Dst between -50 nT and -100 nT) and intense (peak Dst of -100 nT or less) geomagnetic storms.

An interesting feature of this procedure is that it can be used during storms started at daytime or at nighttime hours. Therefore, it is capable of predict the positive storm effects (increases of ionization with respect to quiet conditions) observed in the local daytime sector during the initial and main phases of the storms as well as the negative storm effects (decreases of ionization with respect to quiet conditions) often observed in the nighttime sector.

With respect to the longitudinal range of applicability of the technique the results indicate that bands of 30–35 degrees are adequate.

An important limitation of the technique is that it cannot be used for short-term forecasting in real time because it cannot be applied to a specific storm until data from some stations has been collected for a 24 hours period. In addition, it cannot be utilized to predict values beyond the range of the data used to establish the Fourier coefficients (24 hours).

4. – Conclusions

In brief, a technique as a means of interpolating or extrapolating to describe the foF2 behavior during geomagnetic storms at mid latitude location where there are no measurements is presented. It can be applied to any location in mid-latitude regions of the world where there is sparse network of ionosondes.

This technique involves a Fourier series fitting to foF2 data from a set of stations and a multi-linear variation with geomagnetic latitude and longitude of the Fourier coefficients.

From a large number of comparisons, few of which are presented, in general a good agreement between computed and measured foF2 values is observed. On the basis of these results, it is concluded that the trend of a perturbed F2-layer is fairly well reproduced by this representation.

With Fourier coefficients obtained at middle latitudes, a degradation of the agreement between modeled and measured data occurs toward lower latitudes and certainly toward higher latitudes. With an ionosonde data collection from both low- and high-latitude stations a group of coefficients would establish the temporal evolution of the ionospheric disturbances at these regions with better resolution.

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