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The dependence of ionospheric characteristics on the state of the solar-cycle

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Abstract
A review on the solar-cycle dependence of the monthly median critical frequencies of the different ionospheric layers is attempted. Some of the existing questions are emphasized and the differing viewpoints are reported. Moreover, the correlations between daily values of the critical frequencies and solar activity indices are briefly considered and compared to those for monthly median values.

Key words *ionosphere, standard ionospheric characteristics – radio wave propagation – solar activity*

1. Introduction

The name «ionosphere» is used to indicate that part of the Earth's atmosphere lying between about 50 km above sea level and the outer limit of the atmosphere, that is several earth radii. The ionosphere is also defined as «the part of the Earth's upper atmosphere where ions and electrons are present in quantities sufficient to affect the propagation of radio waves» (Institute of Radio Engineers, 1950).

The ionosphere is divided into «regions» within which there can exist distributions called «layers» (Ratcliffe and Weekes, 1960). The part of the ionosphere below 90 km is called the *D*-region, that between 90 and 160 km the *E*-region and that above 160 km the *F*-region. These limits are rather conventional boundaries for it has been observed for example that the ionization of the *F*-region extends below 140 km under certain circumstances.

Our knowledge concerning the state of the ionosphere has been derived primarily from routine ionosonde measurements, although *in situ* measurements from rockets and satellites also play an important role. Routine observations employing the pulse method have been carried out at many stations (Piggott and Rawer, 1978) and many observational data, such as critical frequencies, minimum virtual heights and other useful parameters have been accumulated over more than 50 years at some stations (Hanbaba, 1993, 1994; PRIME, 1995; COST 251-II Annual Report, 1997).

The statistical study of these data provides the most widely spread information about the complex phenomena that take place in the ionosphere. In these studies the experimental results, on the one hand, are usually compared with the predictions of the classical theory of the formation of ionospheric layers first devel-

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oped by Chapman (1931) and on the other hand, are used to develop empirical prediction models and maps (Rawer and Bilitza, 1989; Bilitza, 1990; ITU, 1993; PRIME, 1995).

Although Chapman's theory stands upon several simplifying assumptions, it substantially succeeds in explaining the origin of the ionosphere. According to this theory, the electron densities, and hence the critical frequencies, should be effectively controlled by solar radiation, and thus by the solar zenith angle χ and the state of solar activity. It seems that, to a first approximation, this classical theory explains the more obvious synoptic features of the ionosphere. Features that do not fit Chapman's theory are still often referred to as anomalous. The world morphology of most of these anomalies as well as their origin and the mechanism by which they are produced, are still the subject of detailed studies (*e.g.*, Titheridge, 1997). It is evident that the actual interpretation and estimation of the non-Chapmanlike variations on a world-wide basis will greatly contribute to our knowledge of the ionosphere.

To a first approximation, the E and F_1 layers vary with $\cos\chi$, both diurnally and seasonally, in a fairly regular manner as is expected for a Chapman layer (fig. 1). This is not the case for the F_2-layer; its behaviour is found to be very complicated and is difficult to summarize. Usually the behaviour of the F_2-layer is described by pointing out how it differs from that of a Chapman layer. Systematic deviations mainly in the F_2-layer behaviour and in much smaller scale in the other layers, are due to geomagnetic perturbations and seasonal variations of atmospheric parameters (composition, temperature etc.). Moreover, movements of ionization affect the distribution of electron densities in the E and F regions. This effect is particularly important in the F_2-region where the lifetime of free electrons is measured in hours. Vertical drifts of ionization in the F_2 region which are generated by tidal air motions have been investigated by many workers and although their importance has been established, the detailed nature of their effects is not yet known (Fejer, 1965). Vertical drifts in the E region are not as important as those in the F_2 region (Shimazaki, 1959), because of the quick recombination of charged particles, which have a typical lifetime of a few minutes, and also because of the greater drag of the neutral gas. Besides, it is well assessed that the ionospheric electron density depends very strongly on the state of the solar cycle (Beynon and Brown, 1959; Appleton, 1964; Rawer and Suchy, 1967; Jones and Obitts, 1970). The law of dependence on the state of solar activity of the maximum electron densities of the layers and thus of their critical frequencies, is the basis of any numerical or computerised prediction models of the ionosphere, developed to support HF communications (*e.g.*, Cander and Zolesi, 1991; Zolesi *et al.*, 1993).

According to the current theory, the ionospheric electron density is due to the ionization of the neutral atmosphere by solar radiation, mainly in the ultraviolet and X-ray region. Although both components are involved in the ionization of the ionosphere, the relative importance of each component is not accurately known and may well vary during the solar cycle, because both X-ray and ultraviolet radiation vary during the solar cycle. Since the solar radiation has an eleven-year cycle, similar changes are expected in the important characteristics of the ionosphere, such as the critical frequencies of the various layers, the propagation factor $M(3000)F_2$, the Maximum Usable Frequency MUF etc. The level of solar activity is often expressed in terms of a numerical index. A number of such indices have been considered and are in use (Bradley, 1993, 1998; ITU-R, 1994).

2. Indices of solar activity

Three different classes of indices are in use. The first class of indices is «solar indices» based on solar radiation. The second class is «ionospheric indices» based on the observed trends in ionospheric characteristics measured at a selected number of locations. The third class of indices is «mapping indices» which are mean interpolation factors appropriate to specific maps, needed to match the values these give with the measured ionospheric characteristics values at reference measuring stations (Bradley, 1993). Within these classes the following indices are included (Bradley, 1998):

a) Solar indices: R, R_{12}, Φ and Φ_{12};

b) Ionospheric indices: IF_2, T, MF_2;

c) Mapping indices: IG, IG_{12}, $R_{\text{eff.}}$;

where R is the sunspot number (Bradley, 1993; ITU-R, 1994), Φ the 10.7 cm solar flux (Covington, 1969), IF_2 the F-region ionospheric index (Minnis, 1955, 1964; Minnis and Bazzard, 1959), T the Australian index (Turner, 1968; Caruana, 1990), MF_2 an ionospheric index recently proposed (Mikhailov and Mikhailov, 1995; Mikhailov *et al.*, 1996), IG applies for global maps (Liu *et al.*, 1983) and $R_{\text{eff.}}$ is an effective sunspot number (Secan and Wilkinson, 1997).

Present recommendations of the International Telecommunication Union are that R_{12} should be used for all long-term predictions more than 12 months ahead; moreover, R_{12} or Φ_{12} should be used for long-term prediction of the monthly median F_2-layer critical frequency, f_0F_2 and of the propagation factor $M(3000)F_2$ up to 6 and perhaps to 12 months ahead of the last observed value, whereas Φ_{12} should be used for predicting monthly median values of the E-layer critical frequency, f_0E and of the F_1-layer, f_0F_1 up to 6 and perhaps up to 12 months ahead of the last observed value. However, other indices like the index T or the ionospheric index MF_2 are also used successfully in empirical prediction models. Mean expressions relating the different indices have been published. Thus, a mean relationship between R_{12} and Φ has been given by Joachim (1966). Stewart and Leftin (1972) have examined the relationship between R_{12} and Φ_{12}. Several workers have examined the relationship between R_{12} and IF_2 (Barclay, 1962) and *vice versa* (Joachim, 1966; Muggleton and Kouris, 1968). Similar relationships have been proposed for the indices T and R_{12} (Turner, 1968).

The choice of a «best» index is usually based on a number of potentially relevant factors which may be summarized as follows (Bradley, 1993):

i) Degree of correlation with ionospheric characteristics values.

ii) Predictability of the index.

iii) Linear dependence of ionospheric characteristics values on index.

iv) Availability of the index and adequate dissemination.

It is to be noted that to date no indices fulfil all the above factors for all ionospheric characteristics. For example, the ionospheric index MF_2 seems to provide a slightly higher degree of correlation with f_0F_2 than any other index, but it is not so when it is correlated with $M(3000)F_2$ (Kouris *et al.*, 1997). According to Mikhailov *et al.* (1996), effects as «saturation» at high solar activity and «hysteresis» in the course of a solar cycle are avoided when MF_2 is used, contrary to what happens when R_{12} or Φ_{12} is used; but on the other hand the prediction of the solar index R_{12} is accurate and readily available well in advance (Kouris *et al.*, 1993a).

At this point we must observe that linearity nowadays should not be a factor to consider in determining a «best» index. More important factors are predictability with adequate service of dissemination of the index values. However, the choice of long-term index and the law of solar-cycle variation are very important for mapping generation. The use of only a single index in long-term predictions could be very useful and positive but it seems impossible at present. Short-term forecasting might additionally involve a separate disturbance index, which might also prove necessary to the long-term index (Alberca *et al.*, 1997).

3. The dependence of f_0E on solar activity

The critical frequency of the E-layer, f_0E, varies with the time of day, season and epoch in the solar cycle, as well as with the location on the earth. At one epoch in the solar cycle, f_0E is approximately a unique function of the sun's zenith distance χ, whether χ changes through the day or the season at one location or by displacement over earth at one time. Figure 1 illustrates a typical variation of f_0E during the course of one day.

The values of the critical frequency f_0E measured at different locations over the earth, have been examined by various workers to see how well they fit the expression

$$(f_0 E)^4 = K \cos \chi \tag{3.1}$$

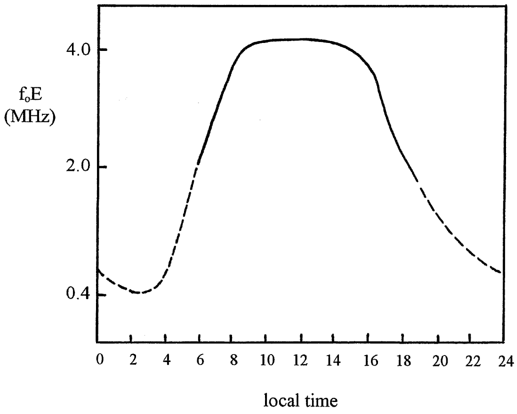

Fig. 1. Sketch of a typical variation of f_0E during the course of one day.

as they would if the E-layer, under equilibrium conditions, behaved like a Chapman-layer. In eq. (3.1) K depends mainly upon the solar ionizing radiation, which may vary according to the state of solar activity and the annual variation of the Sun-Earth distance. It follows therefore from eq. (3.1) that when the seasonal variation with $\cos\chi$ is removed, as well as any other seasonal, annual and latitude influences (Appleton, 1963; Kouris and Muggleton, 1973; Titheridge, 1997), then $(f_0E)^4$ will vary according to the epoch in the solar cycle. Different methods have been adopted to remove the influence of the time of day and of the season, so as to isolate the component which is attributable to changes in solar activity. For example one technique is to apply at each location and for each month of the year the following relationship

$$(f_0E)^n = a_m(1+b_mR) \qquad (3.2)$$

where R is the sunspot number and the subscripts of a_m and b_m refer to separate months of the year. In all these techniques it is assumed that the scale height and the recombination coefficient do not change with solar cycle and season.

All investigators agree that the relationship between $(f_0E)^n$ and any index of solar activity is approximately linear whatever the value of the exponent in eq. (3.2). However, there is considerable inconsistency in their results (see for example, Kouris, 1971, 1981a).

A simplified expression of eq. (3.2) is the following;

$$f_0E = 0.9[(180+1.44R)\cos\chi]^{0.25}\ \text{MHz} \qquad (3.3.)$$

which is valid for any time of day and any season (Davies, 1990). A detailed analysis of monthly median data from 45 stations, over a period of at least one solar cycle, has given much more accurate results (Kouris, 1981b). In this analysis monthly median noon $(f_0E)^4$ values of one or more complete solar cycles, for each month of a given station are correlated with corresponding monthly mean values of each of the three indices of solar activity, R, Φ and IF_2 (Kouris and Muggleton, 1974; Kouris, 1977). The overall correlations were very high, of the order of 0.97. The conclusion is that the best linear relations between f_0E and the three indices are of the form

$$(f_0E)^4 = a_R(1+b_RR) \qquad (3.4)$$

$$(f_0E)^4 = a_\Phi(1+b_\Phi\Phi) \qquad (3.5)$$

$$f_0E = a_{IF_2}(1+b_{IF_2}IF_2) \qquad (3.6)$$

where

$$b_R = 9.1\times10^{-3} \pm 0.2\times10^{-3} \qquad (3.7)$$

$$b_\Phi = 9.4\times10^{-3} \pm 0.2\times10^{-3} \qquad (3.8)$$

$$b_{IF_2} = 1.44\times10^{-3} \pm 0.02\times10^{-3}. \qquad (3.9)$$

It is to be noted that the above relationships (3.4) to (3.9) are valid at any location for the prediction of the monthly median values as well as of daily values with a mean error of about the same magnitude (Kouris, 1981b).

4. The dependence of f_0F_1 on solar activity

The undisturbed F_1-layer is observed only during the day; it is most pronounced in sum-

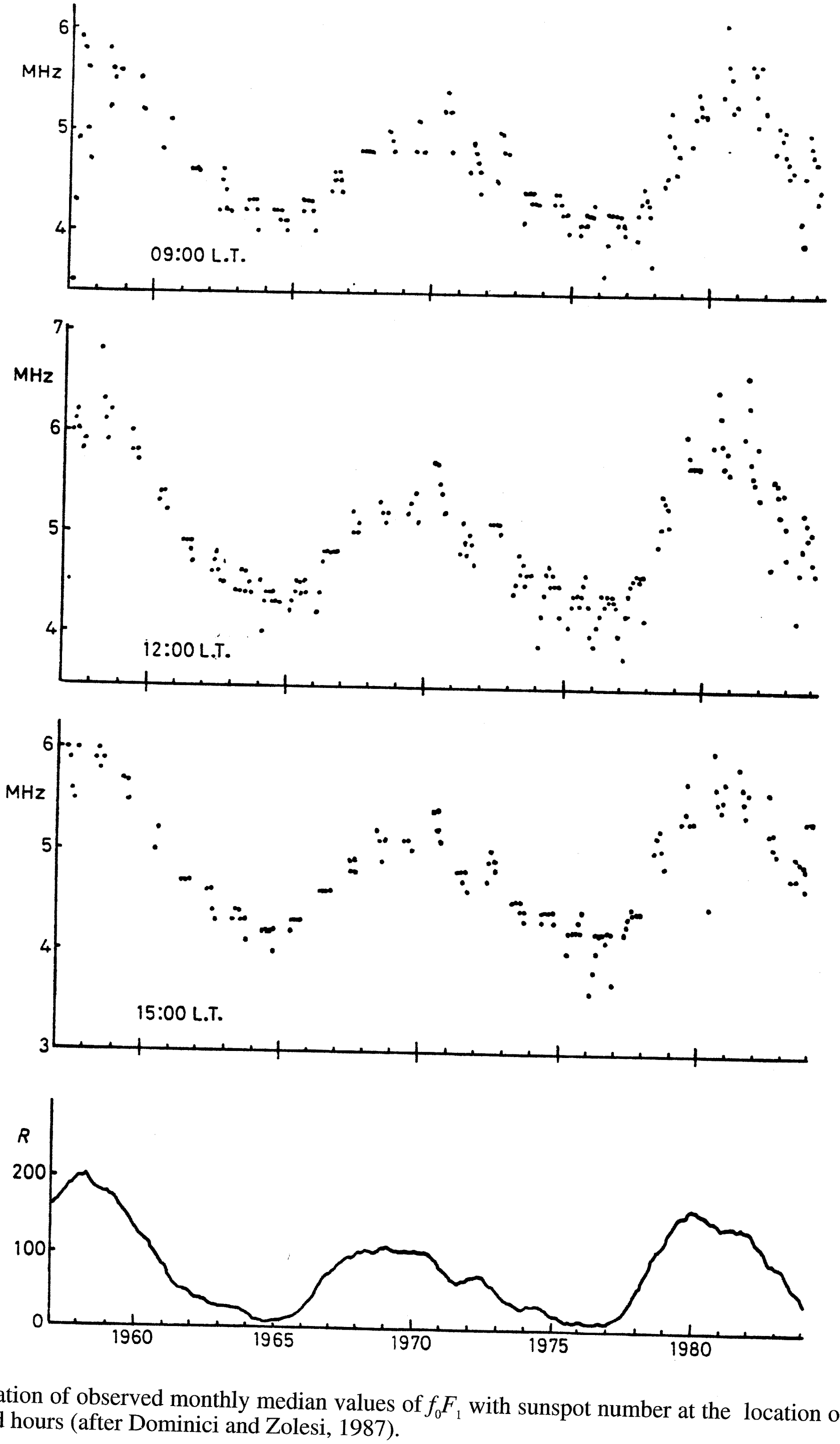

Fig. 2. Variation of observed monthly median values of f_0F_1 with sunspot number at the location of Rome for some selected hours (after Dominici and Zolesi, 1987).

mer and at low solar activity, and during ionospheric storms; in winter at the maximum of solar activity it is never observed.

The ordinary critical frequency of the F_1-layer, f_0F_1, measures the maximum electron density in the F_1-layer, as any critical frequency does for its corresponding layer. It is found that f_0F_1 varies in a remarkably regular way and resembles that of the E-layer critical frequency f_0E, that is it resembles the critical frequency of a Chapman layer. Figure 2 illustrates the variation of f_0F_1 with season and sunspot number at the location of Rome (41.9°N, 12.5°E). It is evident from fig. 2 that the monthly median values of f_0F_1 are positively correlated with the twelve-monthly smoothed sunspot number R_{12} quite well.

Statistical analyses accomplished by different investigators (*e.g.*, Ducharme *et al.*, 1971, 1973; Dominici and Zolesi, 1987), similar to those carried out on f_0E, and based on many observed data have led up to different analytical expressions between f_0F_1 and R_{12}, Φ_{12} or IF_2. An approximate relationship (Davies, 1990), valid for any time of day and any season, is

$$f_0F_1 = (4.3 + 0.01R_{12})\cos^{0.2}\chi. \qquad (4.1)$$

A more comprehensive expression for f_0F_1 has been established by Ducharme *et. al.* (1971, 1973), based on a large amount of ionosonde data. This relationship gives f_0F_1 in terms of R_{12}, χ and magnetic dip latitude ψ (Bilitza, 1990):

$$f_0F_1 = f_s\cos^n\chi \qquad (4.2)$$

$$f_s = f_0(f_{100} - f_0)\frac{R_{12}}{100} \qquad (4.3)$$

$$f_0 = 4.35 + 0.058|\psi| - 0.00012\ \psi^2 \qquad (4.3a)$$

$$f_{100} = 5.348 + 0.011|\psi| - 0.00023\ \psi^2 \qquad (4.3b)$$

$$n = 0.093 + 0.0046|\psi| - 0.000054\ \psi^2 + 0.0003R_{12} \qquad (4.3c)$$

5. The dependence of f_0F_2 on solar activity

The F_2-layer is the most important layer from the point of view of HF radiocommunications. When the F_2-layer is investigated at different locations at different times, its behaviour is found to be very complicated. Unlike the E-layer or F_1-layer the overall behaviour of the F_2-layer can be described as that of a non-Chapmanlike layer. Thus, presentations of the variations of the F_2-layer electron density and hence of its critical frequency f_0F_2 or of any other ionospheric characteristics of this layer cannot be derived from theoretical considerations which only take account of production by photoionization but through the statistical analysis of past measurements. As a consequence, different models have been developed by different investigators (*e.g.*, Rawer and Bilitza, 1989; Bradley, 1990) in order to take into account the peculiarities of the electron density of the F_2-layer and/or the physical processes which appear as irregularities with respect to the standard assumptions (*e.g.*, Kouris *et al.*, 1993b). It is common practice in studying these peculiarities of f_0F_2 to investigate in the first place its actual relationship with solar activity.

Many workers have investigated the solar-cycle variations of the monthly median f_0F_2 values, seeking to establish empirical relationships in terms of indices of solar activity. An example is reported in fig. 3. Several different solar and ionospheric indices have been considered (Bradley,1993); but not all investigators are agreed on which is the best index to use. This is not contrary to expectations because on the whole each index does not differ markedly from the others. On the other hand, the «best» index for f_0F_2 may well differ from that of the other ionospheric characteristics, *e.g.*, f_0E, f_0F_1 etc.. Then, the question arises whether each characteristic should be determined by means of its «best» index or one index should be used for all of them? For example in COST 238-PRIME (Prediction and Retrospective Ionospheric Modelling over Europe) the former practice has been followed.

Further to that, for very high solar activities f_0F_2 measurements indicate a saturation effect;

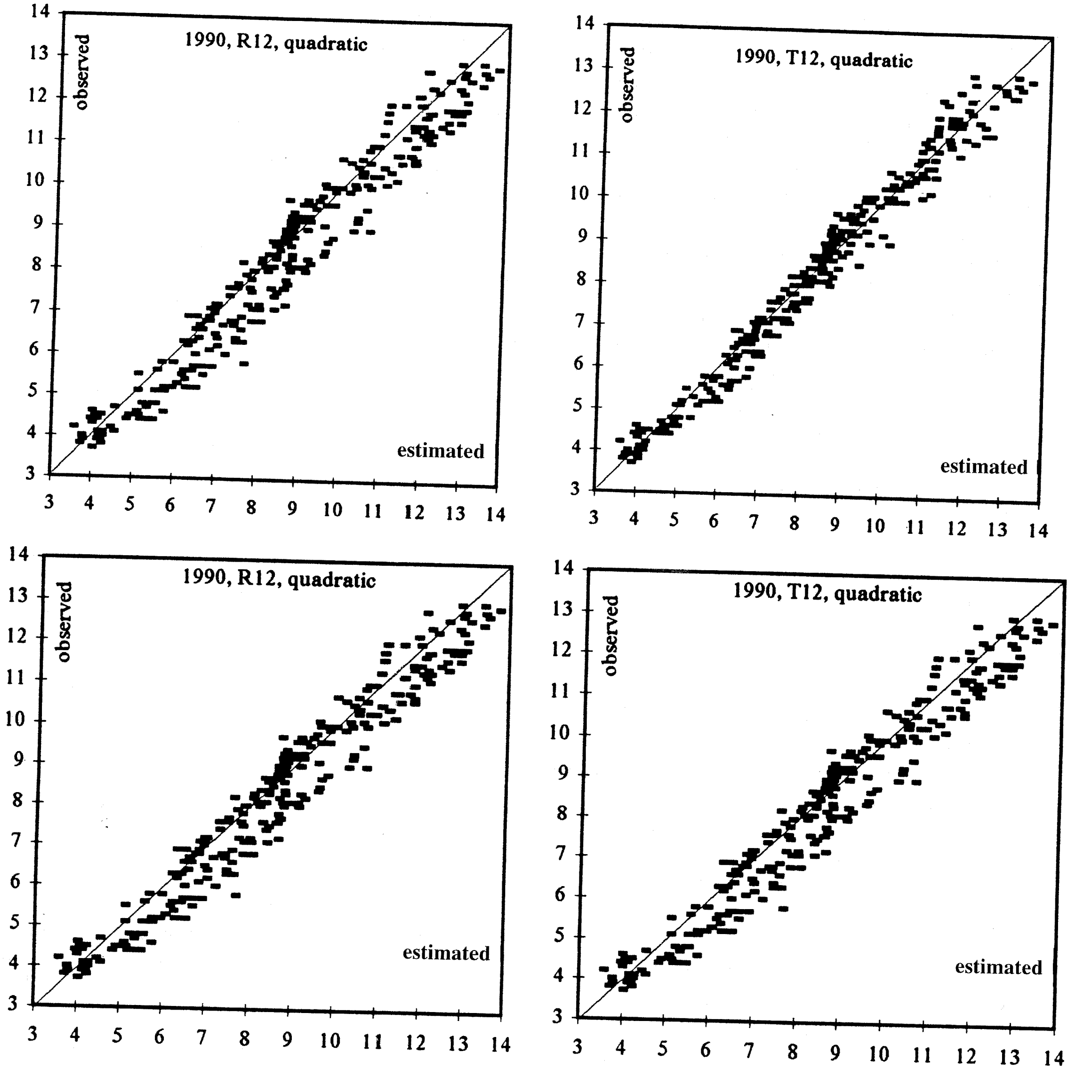

Fig. 3. Comparisons between f_0F_2 values observed (Slough: top panel; Rome: bottom panel) during the year 1990 and estimated using a second-degree relationship and the indices R_{12} and T_{12}, respectively (after Xenos *et al.*, 1996).

when measurements for the rising and falling portions of a solar cycle are separately compared, a hysteresis-like variation of f_0F_2 in the course of a solar cycle is evident (Rao and Rao, 1969). Appleton and Piggott (1955) pointed out that, for the same sunspot number, the degree of magnetic storminess may cause different effects on f_0F_2, indicating thus the strong magnetic control on the F_2-layer characteristics. This view is also shared by Rao and Rao (1969), Apostolov *et al.* (1993) and by Kane (1992). The type of hysteresis in f_0F_2 may be different, sometimes even negligible (Kouris, 1995). To face the hysteresis phenomenon

Kane (1992) proposed using simultaneously a solar index and an index of geomagnetic activity; but a small hysteresis effect still remains. Mikhailov and Mikhailov (1992) suggested that by using an index related to EUV radiation the hysteresis will be eliminated. Furthermore, there is evidence of changes between cycles, but these are irregular and small compared to the scatter and non-repeatable features of the hysteresis. Therefore, taking account of the above complexities the PRIME group for instance, decided that for modelling and prediction purposes the hysteresis effect should be neglected and a single relationship should be used for a given month and hour to describe solar-cycle variations (Bradley, 1994; Kouris, 1995). Since the solar-cycle law is different for different locations it has conveniently been quantified for each station, month and hour by reference values within the low, medium and high epoch bands (Bradley *et al.*, 1995).

It is clear that critical to any mapping are the choice of the index representative of state of the solar cycle and the law of dependence of the critical frequency f_0F_2 on solar activity. The sunspot number is convenient for use because of its long series of reliable observations, although all other indices have also been available regularly for some decades. All indices of solar activity show the 11-year sunspot cycle. The behaviour of f_0F_2 with respect to each one of the most used indices in ITU, URSI or PRIME seems to be virtually identical. The CCIR supposes that f_0F_2 increases linearly with R_{12} for values less than 150 and that for higher R_{12} there is complete saturation. An alternative f_0F_2 global mapping of Jones and Obitts (1970) based on the same measurements data set applies a parabolic dependence. Kouris and Nissopoulos (1994) and Bradley (1994) have examined the correlation of f_0F_2 with each of the following indices: R_{12}, Φ_{12}, IF_{212}, IG_{12} and T_{12}, using data sets measured at six European locations. They have shown that practically there was not any appreciable difference in the degree of correlation for the separate indices. A difference may be found (Kouris *et al.*, 1997) in the correlation between f_0F_2 and the MF_2 index proposed by Mikhailov and Mikhailov (1995).

Kouris and Nissopoulos (1994), Bradley (1994) and Mikhailov (1993) have also examined the law of dependence of the critical frequency f_0F_2 on the different indices and found that hourly monthly median f_0F_2 values give close agreement to a linear variation with each index most of the time but a second-order relationship provides better fit in particular epochs, that is in summer daytime and winter nighttime hours (Kouris and Nissopoulos, 1994). On the other hand, it seems that the index MF_2 holds better a linear relationship. Sizun (1992a,b) and Apostolov *et al.* (1993) have suggested to adopt different second-degree relationships for the rising and falling half solar cycles; and in addition the latter also indicated that the coefficients of these relations should be evaluated using data measurements over a period of three solar cycles.

It is evident that there exist different viewpoints regarding the index of solar activity to be used and the law of dependence of f_0F_2 on solar activity. On the other hand, the statistical analyses show that the standard error of estimate calculated using a linear or quadratic relationship and any solar or ionospheric index is of the same order, *i.e.* ± 0.4 MHz. Besides, we should perhaps take account of the fact that the monthly median values are still affected, to a less extent may be, by the effects of the geomagnetic activity and the ionosphere storminess on the daily f_0F_2 values. Therefore, the specification of these effects on the daily f_0F_2 values and consequently the specification of the quiet ionosphere and its ionospheric electron density might give the desirable solution.

Similar statistical analyses accomplished on daily f_0F_2 values (Kouris *et al.*, 1998; Secan and Wilkinson, 1997) show that the degree of correlation of f_0F_2 with corresponding daily values of solar indices is rather poor. The difference in the degree of correlation when monthly median or daily f_0F_2 values are used, is attributed to the effects of ionospheric day-to-day variability not associated with ionization production (Wilkinson, 1995; Kouris *et al.*, 1998). Therefore, it is concluded that an adjusted solar or ionospherically derived index might give better results.

6. The propagation factor $M(3000)F_2$ and the maximum usable frequency

The propagation factor $M(3000)F_2$ is defined as the ratio between the Maximum Usable Frequency (MUF) and the critical frequency f_0F_2 of the F_2-layer. The MUF is the conventional maximum usable frequency that, refracted in the ionosphere, can be received at a distance of 3000 km (Bilitza, 1990). $M(3000)F_2$ is a fair measure of the height of the maximum electron density on a reciprocal scale (Rawer and Suchy, 1967).

The dependence of the propagation factor $M(3000)F_2$ on solar activity has received relatively limited treatment (*e.g.*, Dominici and Zolesi, 1987; Bradley, 1994; Kouris *et al.*, 1994). It is merely assumed that $M(3000)F_2$ varies with the 11-year solar cycle as does f_0F_2. However, it has been shown that there exist some substantial differences in their respective changes with solar activity (Kouris, 1995). Indeed, the statistical analyses showed that a linear dependence of $M(3000)F_2$ with solar activity may be retained. Moreover, the degree of correlation between the propagation factor and each of the different indices of solar activity is very high and of the same magnitude without any appreciable difference from one to another (Kouris, 1998). Unlike the critical frequency f_0F_2, the $M(3000)F_2$ shows a negative correlation with solar activity.

Similar statistical analyses to establish the law of dependence of MUF on solar activity have shown that the correlation between the maximum usable frequency and the twelve-month running mean sunspot number R_{12} is very high, showing a strong positive solar control. Regarding the law of dependence it is found that monthly median MUF values give close agreement to a linear variation with R_{12} most of the time but a second-degree relationship provides better fit in particular epochs of year and hours of day.

It is worth stating that the MUF presents the same features as f_0F_2 that is, the MUF behaviour during the rising part of the solar cycle is different from the behaviour during the falling part, resulting in a hysteresis effect.

7. General remarks

The critical frequency of the E-layer f_0E, varies with the epoch in the solar cycle as is expected for an equilibrium Chapman layer. Observed measurements of monthly median f_0E values at different locations on the earth and estimated values using eqs. (3.4) to (3.9) show close agreement. The same could be stated for f_0E daily values.

The critical frequency f_0F_1 of the F_1-layer, when it is evaluated using eqs. (4.2) and (4.3), is in very good agreement with the observed measurements data.

When the ionospheric characteristics of the F_2-layer are considered, it is found that their behaviour is not very simple. On the other hand, they are extremely important to the description of the International Reference Ionosphere. All empirical prediction models and maps describe the synoptic ionosphere with different degrees of success, since they rely upon the adopted values of f_0F_2 and $M(3000)F_2$. Efforts to upgrade maps of the ionospheric characteristics f_0F_2 and $M(3000)F_2$ have been made in the past and are still pursued. Indeed, there is a tendency to improve global and regional maps. The question is the choice of the «right» index to use and the law of solar-cycle dependence to adopt.

It is evident from the above-reported findings that there exist different viewpoints. It is to be noted, however, that the differences between the different recognised models are usually small in comparison with the daily variations of the characteristics. Monthly median f_0F_2 and $M(3000)F_2$ values must be influenced by the effects of geomagnetic storms on the daily values; these may lead to an increase or decrease of the monthly value according to the frequency and magnitude of the storms. An approach to minimize daily variability could be the adoption of an adjusted solar or ionospherically derived index of solar activity. Another is to specify the ionospheric day-to-day variability and then to define the quiet or normal ionosphere. It is clear consequently that more studies are needed to improve monthly median models and to evaluate day-to-day ionospheric variability.

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