ANNALI DI GEOFISICA, VOL. XXXIX, N. 6, December 1996

# Assessment of the solar-cycle dependence of $f_0F_2$

**Thomas D. Xenos** [1], **Stamatis S. Kouris** [1] and **Bruno Zolesi** [2]
[1] *Department of Electrical Engineering, University of Thessaloniki, Greece*
[2] *Istituto Nazionale di Geofisica, Roma, Italy*

**Abstract**
Comparisons between observed hourly monthly-median values of $f_0F_2$ at Slough and Rome, and calculated $f_0F_2$ values using as an index of solar activity $R_{12}$ or $T_{12}$, demonstrate that there is practically no difference in the results when a solar (*e.g.*, $R_{12}$) or ionospheric index (*e.g.*, $T_{12}$) is used. The choice of the index should be based on other criteria. It is also shown that there is a slight degree of favourability for a quadratic law between $f_0F_2$ and each index of solar activity. Therefore, in mapping the $F$-layer characteristics a second-degree relation should be adopted independently of rising or falling solar-cycle. Saturation and hysteresis effects could be then minimised.

**Key words** *ionospheric propagation – ionosphere – indices of solar activity*

## 1. Introduction

It is well established that the ionospheric electron density of the $F_2$-layer and thus the critical frequency $f_0F_2$ depend strongly on solar activity. Traditionally sunspot number is considered as an index of solar activity, although other indices, solar or ionospherically derived, are also used. The sunspot number is convenient for use because of its long series of reliable observations though the other indices have also been regularly available for some decades. All indices show the 11-year sunspot cycle and their behaviour with respect to $f_0F_2$ seems to be virtually identical. Indeed, Kouris and Nissopoulos (1994) using all the available data over at least two solar-cycles irrespective of which solar-cycle they come or for the rising or falling parts of a cycle, have shown that the correlation of $f_0F_2$ with respect to each of the most used indices is practically the same, and their standard errors of estimate are of the same order. That means that the saturation effect and the hysteresis effect are not eliminated by using one rather than another index.

Mikhailov and Mikhailov (1992) state that a one-to-one correspondence could be obtained if an ionospherically derived index is used. On the other hand, Kane (1992) suggests using a multiple regression equation of two variables, one being a solar index and the other the geomagnetic $A_p$ index, but he concludes that even solar flux $\Phi$ and $A_p$ together do not explain the $f_0F_2$ variations. Sizun (1992) has proposed a second-degree polynomial separately for the rising and falling parts of a solar cycle to account for saturation and hysteresis effects,

*Mailing address*: Dr. Stamatis S. Kouris, Aristotle University of Thessaloniki, Faculty of Technology, Department of Electrical Engineering and Computer Engineering, Telecommunications Division, 54006 Thessaloniki, Greece; e-mail: kouris@vergina.eng.auth.gr; tdxenos@vergina.eng.auth.gr

whereas Kouris and Nissopoulos (1994) have demonstrated that a second-degree equation is needed mostly during winter-time and night-time in summer.

In the above papers it has also been shown that the gain in using the quadratic relationship instead of the linear one is very little. In the present communication we show some more facts which confirm the above mentioned deductions and lead to some clear proposals to use for the approach to follow in mapping of $F$-layer characteristics.

## 2. Data

The data used in the present analysis are hourly monthly-median values of $f_0F_2$ measured at some European mid-latitude stations from 1964 to 1986. They are fitted by the method of least squares to the linear relationship

$$f_0F_2 = a_0+a_1X_{12} \tag{2.1}$$

and to the quadratic

$$f_0F_2 = b_0+b_1X_{12}+b_2X_{12}^2 \tag{2.2}$$

respectively, and independently of the solar cycle and of the rising or falling part of it. $X_{12}$ stands for the twelve-month running mean values of the sunspot number $R_{12}$, the 10.7 cm solar radio flux $\Phi_{12}$, the ionospheric index $IF_{2_{12}}$, the $IG_{12}$ index and the Australian $T_{12}$-index. Thus, the coefficients $a_0$ and $a_1$ in the linear eq. (2.1) and $b_0$, $b_1$ and $b_2$ in the quadratic eq. (2.2) are determined for each hour of each month at each station, and for each index of solar activity. It is therefore conceivable using the appropriate values of the coefficients $a_0$, $a_1$, $b_0$, $b_1$ and $b_2$ to evaluate $f_0F_2$ at a given location at any time of the day and month of the year.

In order to evaluate the reliability of eqs. (2.1) and (2.2), it is worth comparing observed and estimated values as given by these models. It is clear that we cannot expect a one-to-one correspondence in either case, but the second-degree law must give a better approximation than the linear one (Kouris and Nissopoulos, 1994). To this end, the values $f_0F_2$ at the location of Slough were estimated for some selected hours: 8.00 h, 12.00 h, 16.00 h and 20.00 h and for each month during years of high solar activity (1969 and 1980), medium solar activity (1983) and low solar activity (1976 and 1986). Two indices of solar activity were chosen with the criterion of one being a solar index and the other an ionospherically derived index; thus $R_{12}$ and $T_{12}$ were chosen.

Further, a comparison between estimated values of $f_0F_2$ and observed at the stations of Rome and Slough during the year 1990 was made in order to test the reliability of the values of the coefficients $a_0$, $a_1$, $b_0$, $b_1$ and $b_2$ as determined for these locations from the analysis using data measured at each station over the period 1964 to 1986.

## 3. Results and discussion

Figures 1 to 3 show plots of the observed versus expected values of $f_0F_2$ at Slough for a year of minimum solar activity (1986), medium solar activity (1983) and high solar activity (1980). The expected $f_0F_2$ values are those referred to 8.00 h and 12.00 h calculated from eqs. (2.1) and (2.2). Two indices of solar activity were used, $R_{12}$ and $T_{12}$, respectively. A glance at these plots shows that the values are near the 45° slope line, indicating a reasonably good match and in any case within the standard error of ± 0.4 MHz (Kouris and Agathonikos, 1992). Moreover, it can easily be seen that the results are practically the same whether the index $R_{12}$ or $T_{12}$ is used. This is valid for any index solar or ionospherically derived and is in agreement with what has been found elsewhere using statistical analysis (Kouris and Agathonikos, 1992). Furthermore, we may note that the gain in using the quadratic relation over the linear is very little (figs. 1, 2 and 3). However, it was demonstrated that a second-degree relationship is needed especially during winter-time and night-time in summer (Kouris and Agathonikos, 1992; Sizun, 1992; Mikhailov, 1993; Kouris and Nissopoulos, 1994).

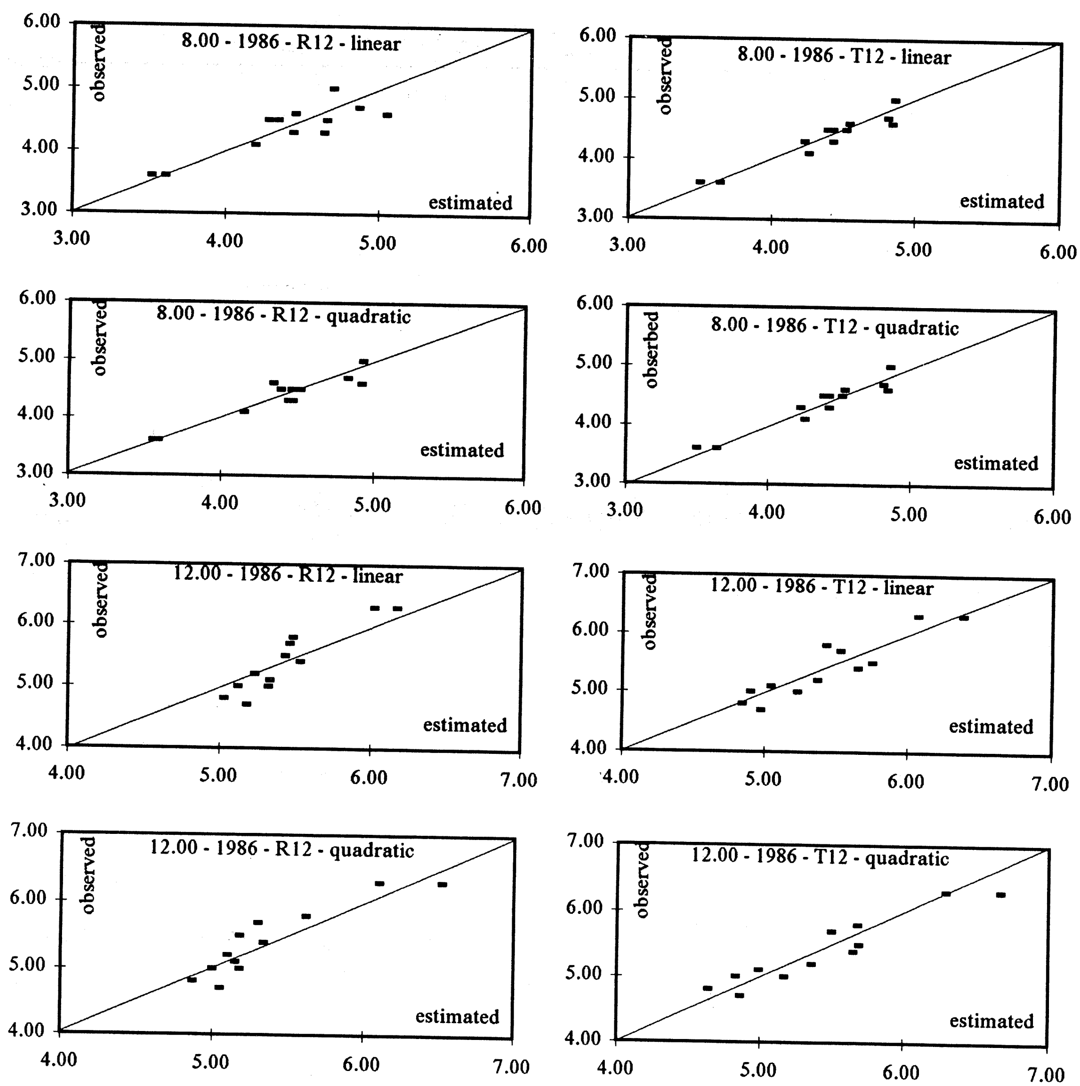


**Fig. 1.** Comparisons between $f_0F_2$ values observed at Slough (1986) and predicted using eq. (2.1) and eq. (2.2), and the indices $R_{12}$ and $T_{12}$ respectively.

Figures 4 and 5 illustrate plots of $f_0F_2$ observed values at Slough in June and December during the period 1964 to 1986 versus estimated values using $R_{12}$ or $T_{12}$, respectively, and the linear and the quadratic models. It is clear from these figures that a hysteresis effect is always present, though the discrepancies between points referring to the rising part of the sunspot cycle 20 or 21 and those referring to the falling part are nearly always less than the estimated mean standard error, even in winter (December) where it seems that the hysteresis effect is more significant (Apostolov *et al.*, 1992). On the other hand, the hysteresis cycle

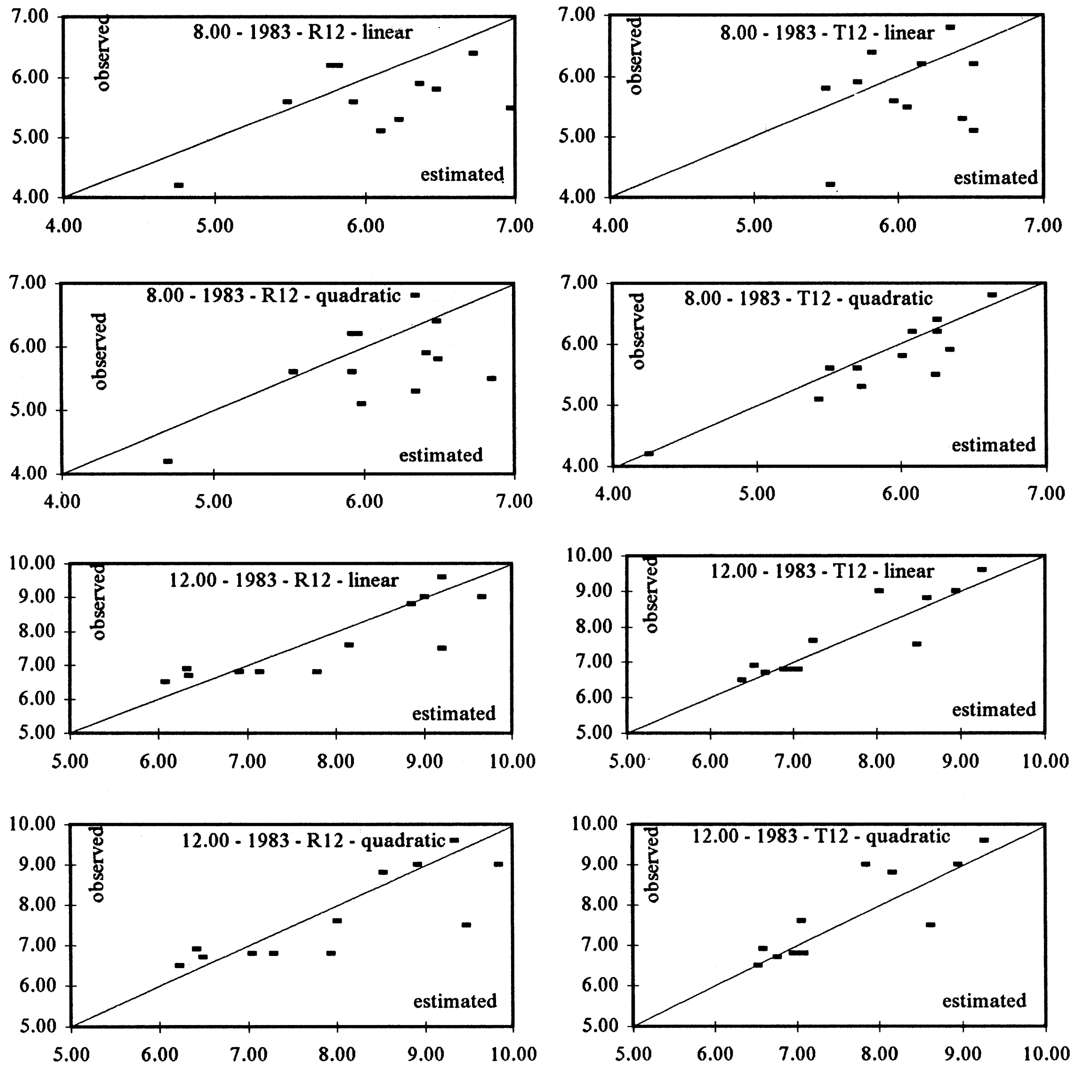


**Fig. 2.** Comparisons between $f_0F_2$ values observed at Slough (1983) and predicted using eq. (2.1) and eq. (2.2), and the indices $R_{12}$ and $T_{12}$ respectively.

seems to be contracted when the second-degree law is adopted as it can easily be seen from figs. 4 and 5.

Furthermore, the results of the present analysis show clearly (figs. 4 and 5) that there is no difference as far as the hysteresis effect is concerned, when a solar index (*e.g.*, $R_{12}$) or an ionospherically derived index of solar activity (*e.g.*, $T_{12}$) is used, contrary to what is claimed by some research workers (*e.g.*, Mikhailov and Mikhailov, 1992). At this stage, we may also observe that the hysteresis effect was still present even when a multiple regression equation of two variables was used, one being an index

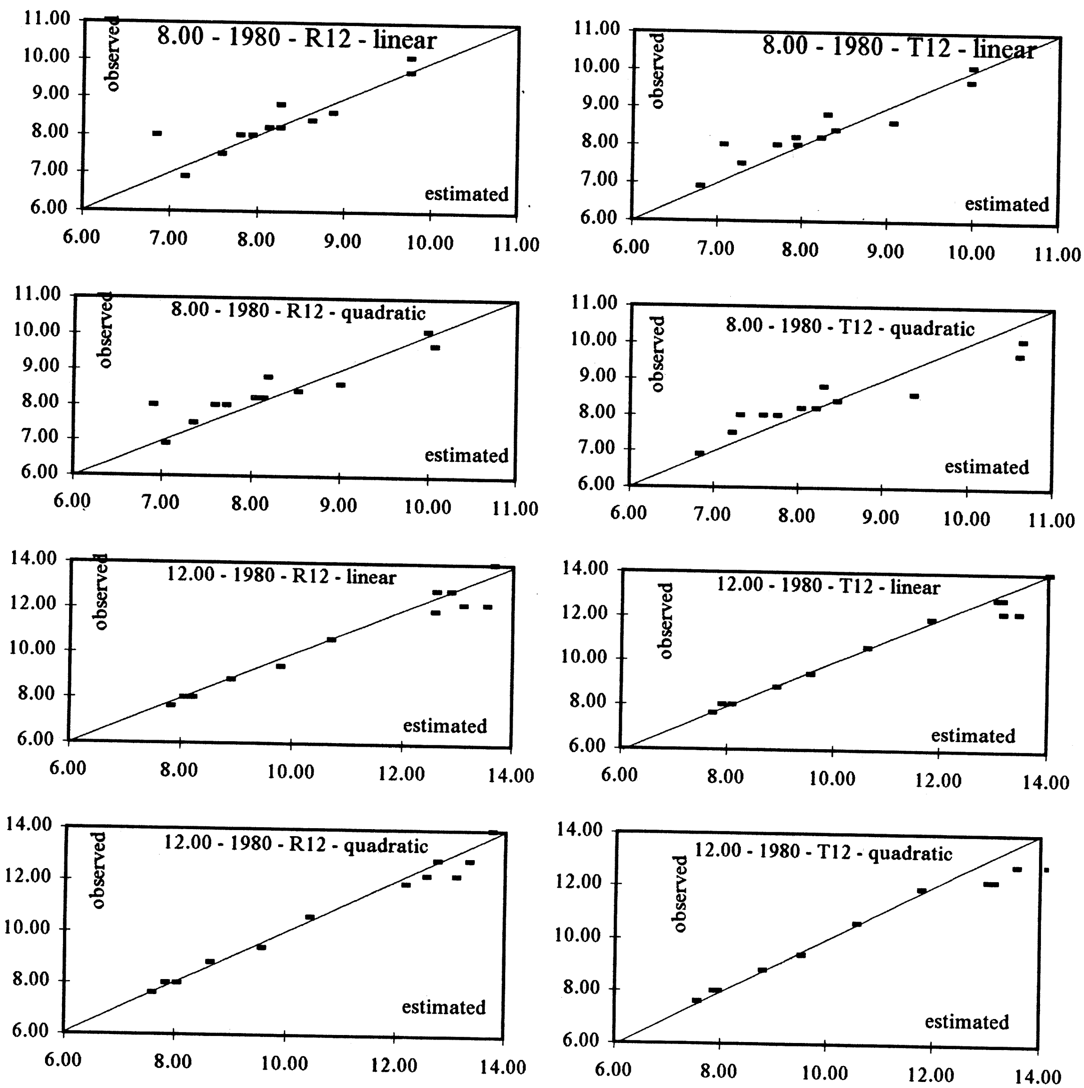


**Fig. 3.** Comparisons between $f_0F_2$ values observed at Slough (1980) and predicted using eq. (2.1) and eq. (2.2), and the indices $R_{12}$ and $T_{12}$ respectively.

of solar activity and the other the geomagnetic $A_p$ index (Kane, 1992). The discrepancies between rising and falling parts in that case are at least of the same order as those shown in the results of the present analysis. Indeed, Kane (1992) had to conclude that even solar flux and $A_p$ together do not explain $f_0F_2$ variations. On the other hand, discrepancies of the same order were still present when a separate quadratic law for the rising and the falling part of a solar-cycle was used (*e.g.*, Sizun, 1992, figs. 5 to 8). These facts indicate that the reasons for the discrepancies between observed and estimated values of $f_0F_2$ due to saturation and hys-

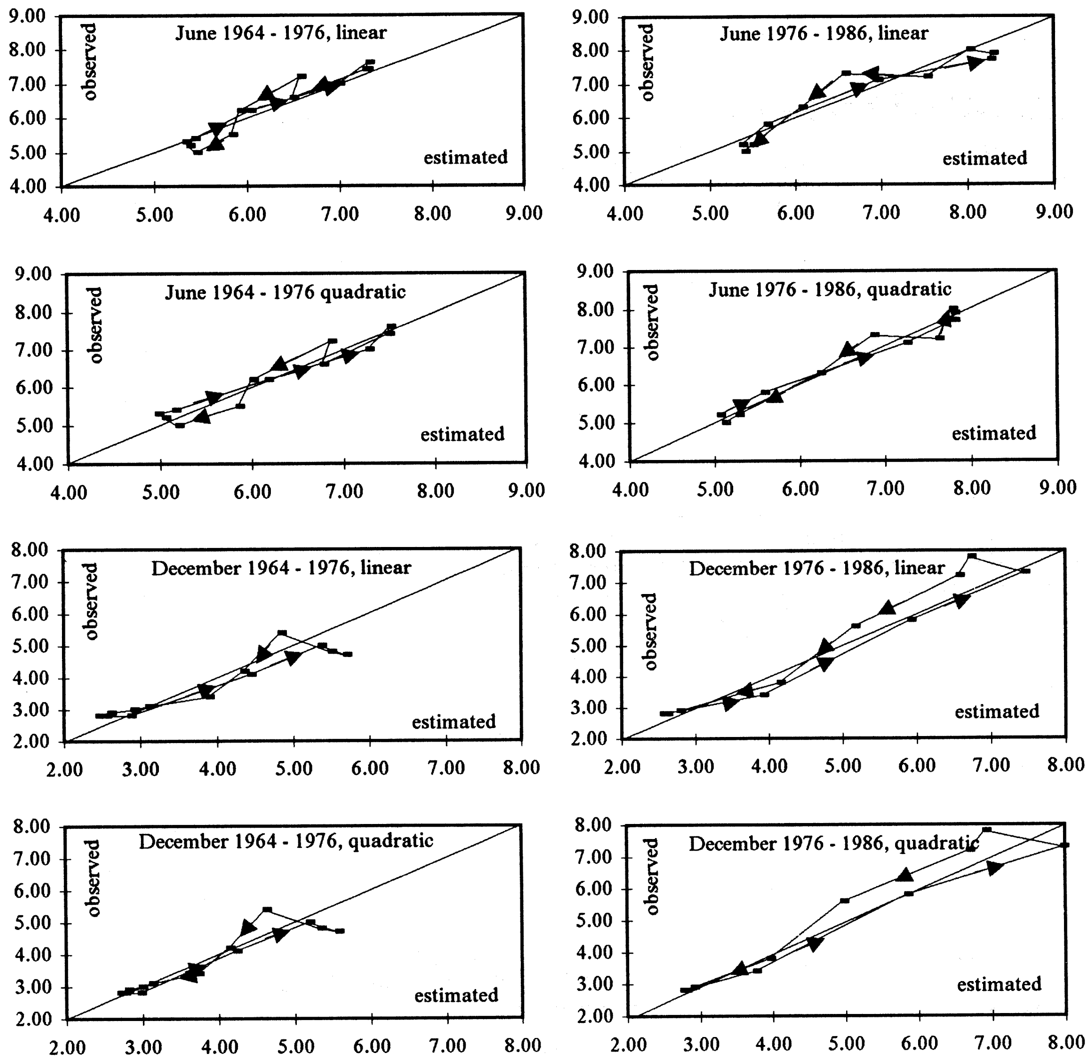


**Fig. 4.** Plots of $f_0F_2$ values observed at Slough for 18.00 h during 20 and 21 solar cycles, when $X_{12} = R_{12}$ in eqs. (2.1) and (2.2).

teresis effects should be sought in other causes and phenomena such as the variable thermospheric neutral composition and the dynamical processes that take place in this part of the ionosphere (Kouris *et al.*, 1993).

It is interesting to see how $f_0F_2$ observed values and those calculated from eqs. (2.1) and (2.2) were distributed against both time and location. For this purpose, $f_0F_2$ experimental data which had not been used in determining the coefficients $a_0$, $a_1$, $b_0$, $b_1$ and $b_2$ in eqs. (2.1) and (2.2) were examined. These are hourly monthly-median values measured during 1990 at the stations of Slough and Rome. They were

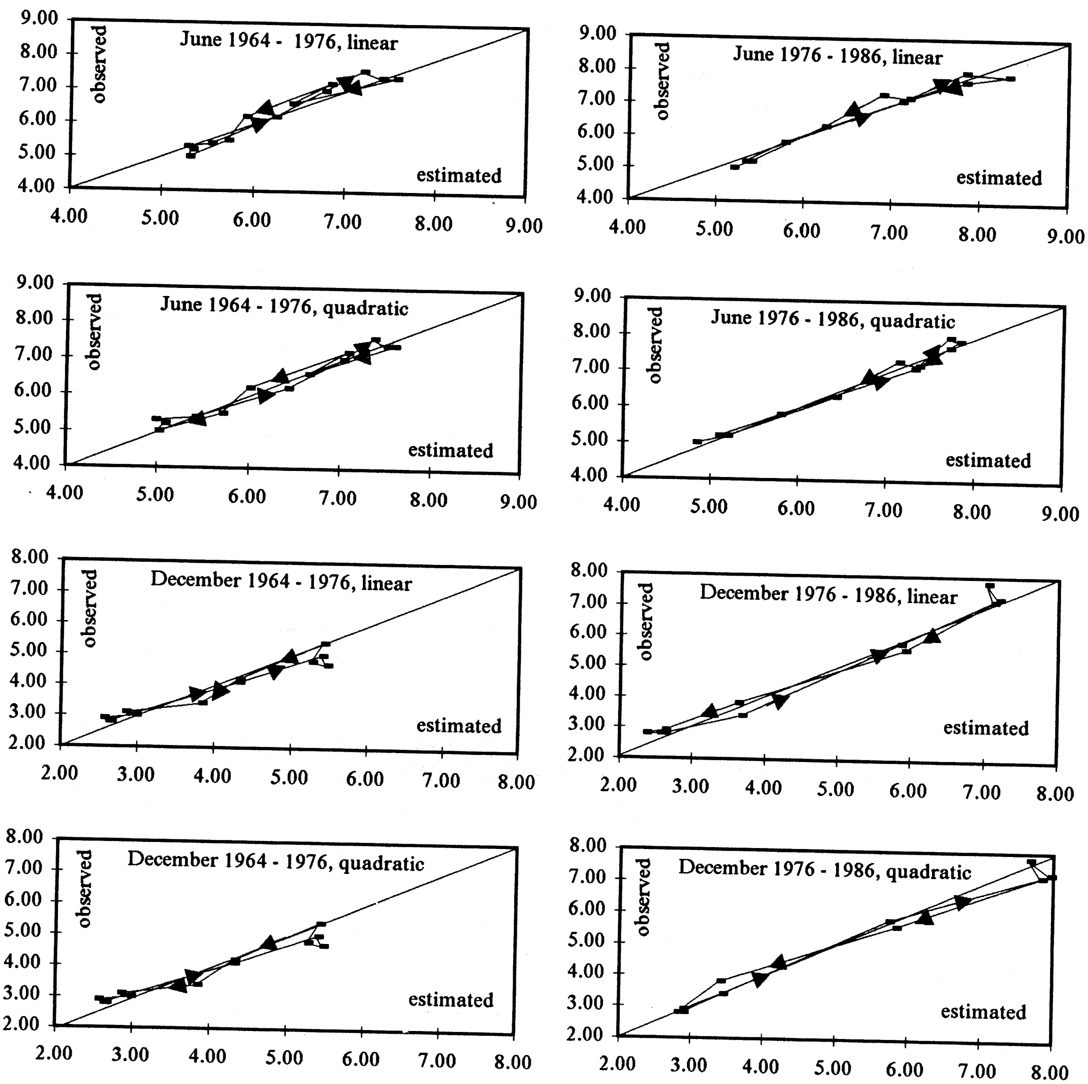


**Fig. 5.** Plots of $f_0F_2$ values observed at Slough for 18.00 h during 20 and 21 solar cycles, when $X_{12} = T_{12}$ in eqs. (2.1) and (2.2).

compared with the corresponding estimated values from eqs. (2.1) and (2.2). The results are reported in figs. 6 and 7, respectively.

It is clear from these figures that there exists very close agreement between observed $f_0F_2$ values and those calculated from eqs. (2.1) and (2.2), and also that this agreement is better when the second-degree equation is used than the linear one. Moreover, it can be seen from these figures that there is virtually no difference in using $R_{12}$ or $T_{12}$. Thus, any index of solar activity may be used. The choice of the index should be based on availability, reliability and predictability.

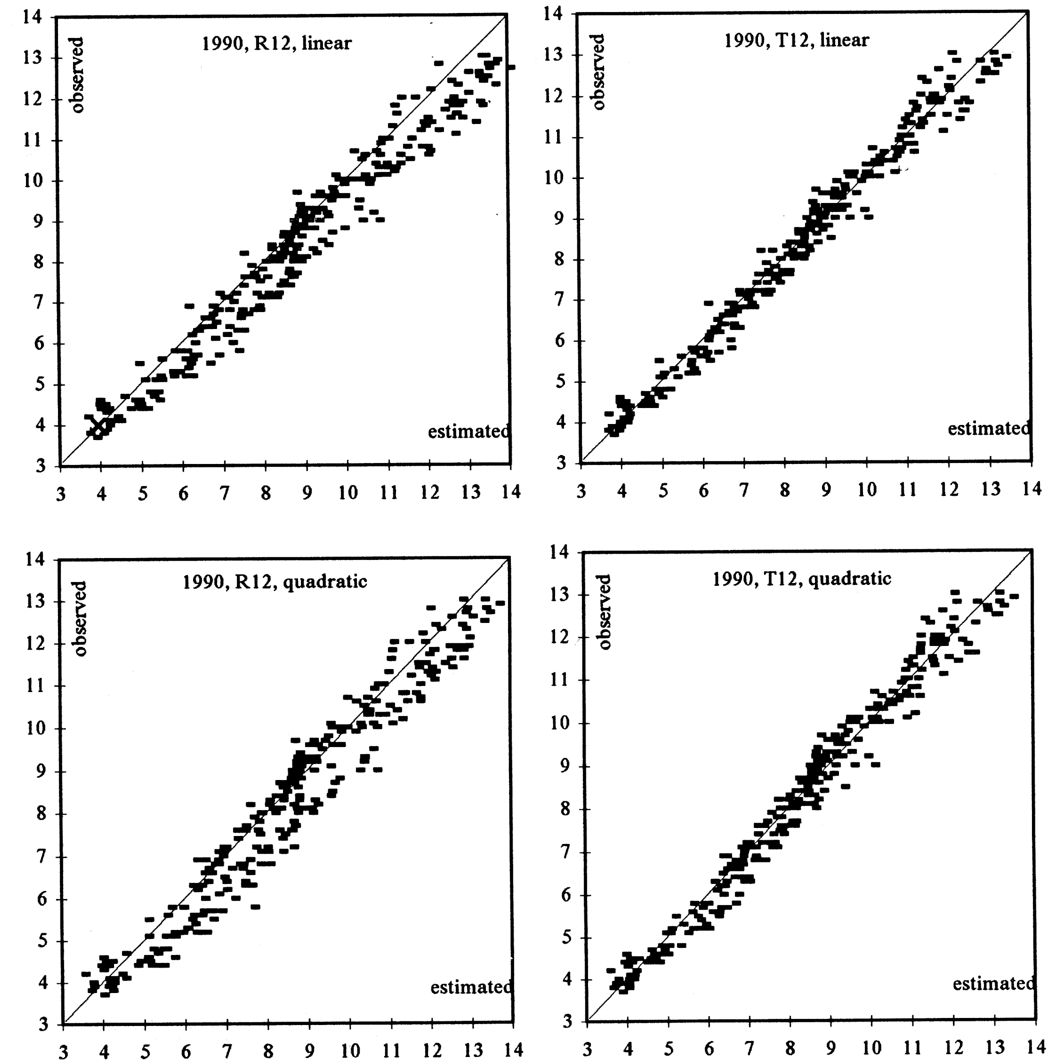


**Fig. 6.** Comparisons between $f_0F_2$ values observed at Slough (1990) and predicted using eq. (2.1) and eq. (2.2), with $R_{12}$ and $T_{12}$ respectively.

From this last point of view we may note that $R_{12}$ has advantages over the other indices. Indeed, we may note that:

1) the prediction of $R_{12}$ is accurate and readily available well in advance;

2) it is the only index that can be used for all retrospective series of $f_0F_2$ data;

3) the discrepancies between observed monthly-median values of $f_0F_2$ and estimated using $R_{12}$ are virtually identical to those when the estimated values are calculated using any other index of solar activity, and they are mostly within the standard error of ± 0.4 MHz;

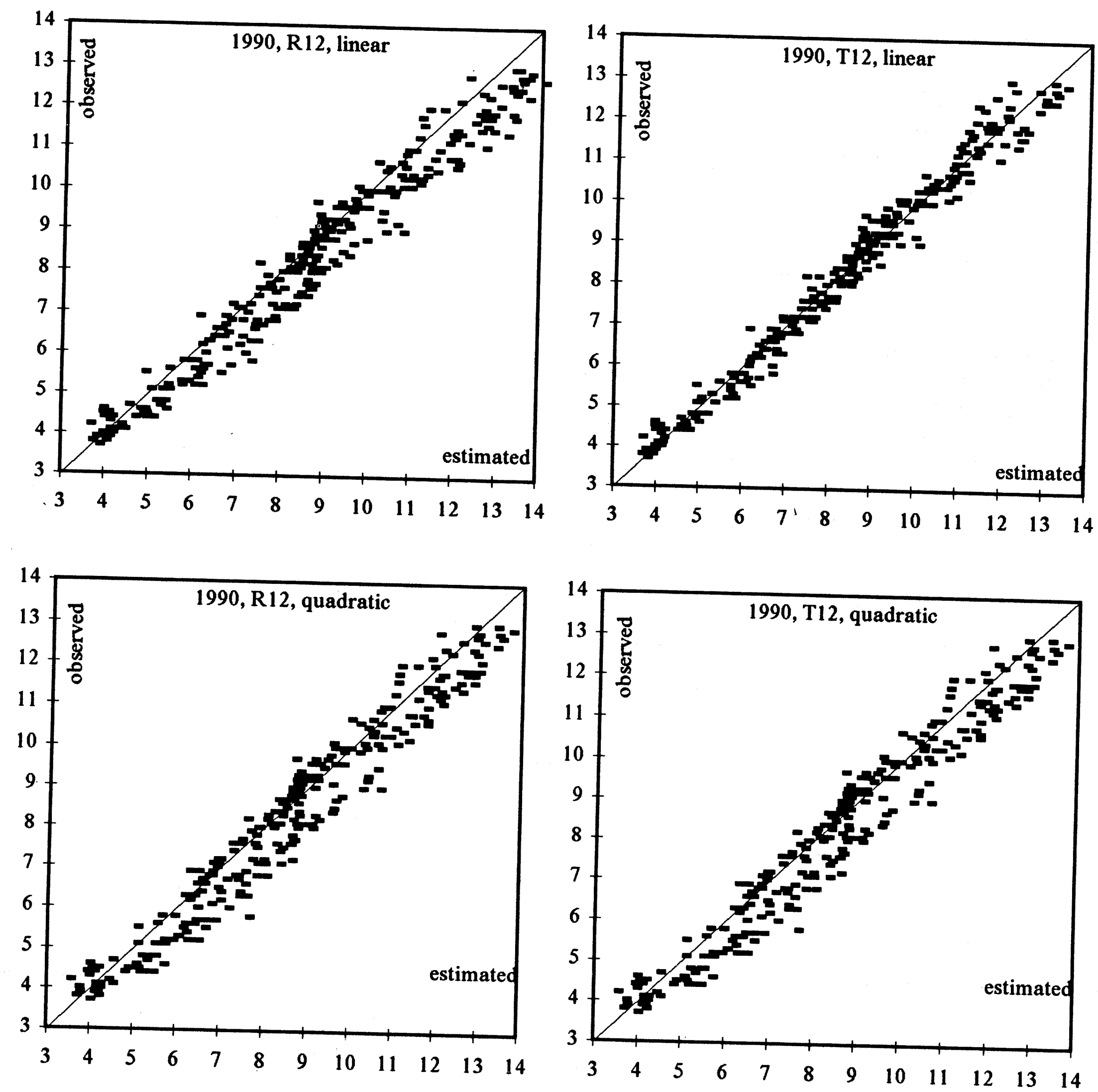


**Fig. 7.** Comparisons between $f_0F_2$ values observed at Rome (1990) and predicted using eq. (2.1) and eq. (2.2), with $R_{12}$ and $T_{12}$ respectively.

4) it offers an easier comparison between new and old mapping models.

As regards the most useful relation to use in mapping the $F$-layer characteristics, we may state that a second-degree relationship is necessary regardless of rising or falling solar-cycle or of the cycle itself, which will account to some extent for saturation and hysteresis effects. However, attention should be paid to the fact that the coefficients of the adopted second-degree eq. (2.2) must be evaluated for each hour of each month at a given location by regression analysis of data measured over at least two solar cycles.

## 4. Conclusions

The results of the present analysis show that there is no difference in the expected monthly-median values of $f_0F_2$ when these are estimated using a solar index (*e.g.*, $R_{12}$) or an ionospheric index of solar activity (*e.g.*, $T_{12}$). Thus, any index of solar activity may be used. The choice of the approach to follow in mapping the $F$-layer characteristics should be based on availability, reliability and predictability of the index, and $R_{12}$ has all these advantages over any other index.

Regarding the law to apply, it can be observed that a second order relation between $f_0F_2$ and $R_{12}$ is necessary in particular epochs of the year. Then, a greater accuracy, of the order of about 0.1 MHz is obtained but a small saturation effect and hysteresis effect remain. Moreover, the analysis has shown that for reliable results the coefficients of eq. (2.2) should be evaluated where possible using a long period of data.

### Acknowledgements

The present work is part of a joint Greek-Italian research program supported by the cultural collaboration (4th protocol) between the two countries to which the authors are thankful.

*REFERENCES*

APOSTOLOV, E.A., L.F. ALBERCA and D. PANCHEVA (1992): Long term prediction of the $f_0F_2$ on the rising and falling parts of the solar cycle, in *Proceedings PRIME/URSI, 1992, Memoria (Publicationes del Observatorio del Ebro)*, **16**, 178-185.

KANE, R.P. (1992): Solar cycle variation of $f_0F_2$, *J. Atm. Terr. Phys.*, **54**, 1201-1205.

KOURIS, S.S. and N.D. AGATHONIKOS (1992): Investigation of the variation of $f_0F_2$ with solar activity $f_0F_2/R_{12}$, $f_0F_2/\Phi_{12}$, $f_0F_2/IF_{12}$, $f_0F_2/IG_{12}$ models, in *Proceedings PRIME/URSI, 1992, Memoria (Publicationes del Observatorio del Ebro)*, **16**, 186-204.

KOURIS, S.S. and J.K. NISSOPOULOS (1994): Variation of $f_0F_2$ with solar activity, *Adv. Space Res.*, **14** (12), 51-54, 163-166.

KOURIS, S.S., P. DOMINICI and B. ZOLESI (1993): Behaviour of $f_0F_2$ over European mid-latitudes, *Adv. Space Res.*, **13** (3), 53-56.

MIKHAILOV, A.V. (1993): On the dependence of monthly median $f_0F_2$ on solar activity indices, *Adv. Space Res.*, **13** (3), 71-74.

MIKHAILOV, A. and V. MIKHAILOV (1992): On the hysteresis type of monthly median $f_0F_2$ vs. $\Phi_{10.7}$ variation in the course of the solar cycle, in *Proceedings PRIME/URSI, 1992, Memoria (Publicationes del Observatorio del Ebro)*, **16**, 218-221.

SIZUN, H. (1992): $F_2$-layer critical frequency modelisation as a function of upward and downward phase of solar activity cycle, in *Proceedings PRIME/URSI, 1992 (Publicationes del Observatorio del Ebro), Memoria*, **16**, 205-217.

(received February 16, 1996;
accepted June 17, 1996)