PASHA: regional long-term predictions of ionospheric parameters by ASHA

Giorgiana De Franceschi and Angelo De Santis
Istituto Nazionale di Geofisica, Roma, Italy

Abstract
In this paper it is shown that the adjusted spherical harmonic analysis (ASHA), previously used for the regional mapping of the monthly medians of the critical frequency of the $F2$ ionospheric layer (f_0F2), can be adapted to obtain a regional long-term prediction model of the ionospheric parameters. By assuming that, at a fixed month, the monthly median value of f_0F2 is a function of the geographic longitude λ and colatitude θ and of the 12-month running mean value R_{12} of the Zürich sunspot number, *i.e.* $f_0F2=f(\lambda, \theta, R_{12})$, PASHA (regional long-term predictions of ionospheric parameters by ASHA) is applied for mapping and modelling of this ionospheric parameter over Europe. Some examples are shown concerning the PASHA model results obtained for different solar activity conditions, seasons and geographic latitudes. The PC version of the FORTRAN 77 program is also available enabling the easy use of the PASHA model to obtain, as a final output, both a grid (2×2 degrees) of the predicted monthly medians of f_0F2 in the European area and the 24 predicted monthly medians of the parameter at a given point in the region of interest.

Key words *ionospheric mapping – spherical harmonics – long-term prediction*

1. Introduction

When *regional* modelling and mapping of a geophysical field is required the spherical harmonic analysis, SHA, widely used in geophysics for global modelling (*e.g.* Melchior, 1983; Albertella *et al.*, 1993), has some limitations. The Fourier longitudinal series are still valid functions in a restricted area, but the associated Legendre colatitudinal functions are not orthogonal over a limited portion of the Earth's sphere. Haines (1985) introduced a new technique for regional 3-dimensional modelling of the geomagnetic field, the spherical cap harmonic analysis, SCHA, based on the use of *fractional* Legendre colatitudinal functions $P^m_{n_k}$ (cos θ), of integer order m but, in general, non integer degree n_k. This technique was successfully adapted in the case of the monthly medians of f_0F2 for 2-dimensional regional mapping of this parameter in the European area (De Santis *et al.*, 1991, 1992).

With the aim of searching for a technique of SCHA using conventional Legendre polynomials, De Santis (1992) proposed the adjusted spherical harmonic analysis, ASHA, for regional modelling of the geomagnetic field. The basic improvement of ASHA consists of the use of conventional SHA after an *artificial* enlargement of the spherical cap, including the region of interest, into a hemisphere. This enlargement of the cap allows the real degree n_k to be replaced by the integer value k, *i.e.* the easier and more practical conventional Legendre colatitudinal functions can be used as new basis orthogonal functions.

Recently agreement has been found between the results obtained when both SCHA and ASHA were used for regional 2-dimensional mapping of f_0F2 over a suitable spherical cap including Europe (De Franceschi *et al.*, 1992, 1994). ASHA procedure and the corresponding computer program and subprograms are fully described by De Santis *et al.* (1994).

In this paper it is shown that ASHA technique, considered as a spatial 2-dimensional fitting algorithm, can be also used for regional long-term ionospheric predictions purposes. It can be done by introducing the solar dependence of the ionospheric parameter into the ASHA expansion coefficients. By assuming the monthly medians values of f_0F2 as a function of the geographic coordinates and of the 12-month running mean value R_{12} of the Zürich sunspot number (*e.g.* Kouris and Agathonikos, 1992), the ionospheric parameter can be expanded in the following way:

$$f_0F2(\lambda, \theta', R_{12}) = \sum_{k=0}^{K} \sum_{m=0}^{k} (g_k^m (R_{12}) \cos m\lambda + h_k^m (R_{12}) \sin m\lambda) \cdot P_k^m (\cos\theta') \tag{1.1}$$

where λ is the geographic longitude, θ' is the *adjusted* colatitude (*i.e.* $\theta' = s \cdot \theta$, where θ are the stations colatitudes referred to a spherical cap with half angle θ_0 and pole at the centre of the region of concern, and $s = 90/\theta_0$ (De Franceschi *et al.*, 1992, 1994)), and where the spherical harmonic coefficients $g_k^m(R_{12})$ and $h_k^m(R_{12})$ are of the form of a power expansion:

$$g_k^m (R_{12}) = \sum_{q=0}^{Q} g_{k,q}^m \cdot R_{12}^q \tag{1.2}$$

and

$$h_k^m (R_{12}) = \sum_{q=0}^{Q} h_{k,q}^m \cdot R_{12}^q \tag{1.3}$$

The set of coefficients $g_{k,q}^m$ and $h_{k,q}^m$ can be determined by a least squares fit with the observational data. K is the maximum value of the index k at which the spherical harmonic expansion is truncated. Q is the maximum value of q, *i.e.* the maximum degree of the polynomial functions (1.2) and (1.3) expressing the dependence of f_0F2 on the solar index R_{12}. K and Q are chosen as high as to preserve the significant spectral content of the phenomenon under study (*e.g.* De Santis *et al.*, 1991).

2. Data and analysis

PASHA model is applied to the monthly medians of f_0F2 as observed at a network of ionospheric stations operating in Europe from January 1967 to December 1976. A spherical cap with half angle $\theta_0 = 20°$ centred at 50°N and 14°E is used to include the European area. On the basis of the number of available stations and considering Kouris and Agathonikos (1992) results, for which a second-order relation between f_0F2 monthly medians and R_{12} should be used as the best correlation model, $K = 2$ in (1.1) and $Q = 2$ into (1.2), (1.3) are used. So that, for a fixed month and for a fixed hour of the day, the number of coefficients $g_{k,q}^m$ and $h_{k,q}^m$ is $N = (K + 1)^2 \cdot (Q + 1)$, *i.e.* $N = 27$.

Expansion (1.1) is applied to every month, so twelve sets of coefficients (one for each month) are calculated. Conversely, by applying (1.1) it is possible to obtain a grid of predicted values or, alternatively, the 24 predicted values at a given point of the investigated region by using the suitable coefficients set and the predicted R_{12} for the corresponding month.

In figs. 1 to 4, maps of the predicted monthly medians of f_0F2 are shown for March and June at 12 universal time, UT, and for different values of R_{12} ($R_{12} = 108$ and $R_{12} = 21$ for March, and $R_{12} = 106$ and $R_{12} = 15$ for June). Higher isolines values can be observed for high solar activity as to be expected.

In fig. 5 PASHA and CCIR (*e.g.* Jones and Gallet, 1965) results are compared for Slough station (51.48 N, 359.43 E) and for March and June under different solar activity. Comparisons with the measured values appear satisfactory, but it seems to give bet-

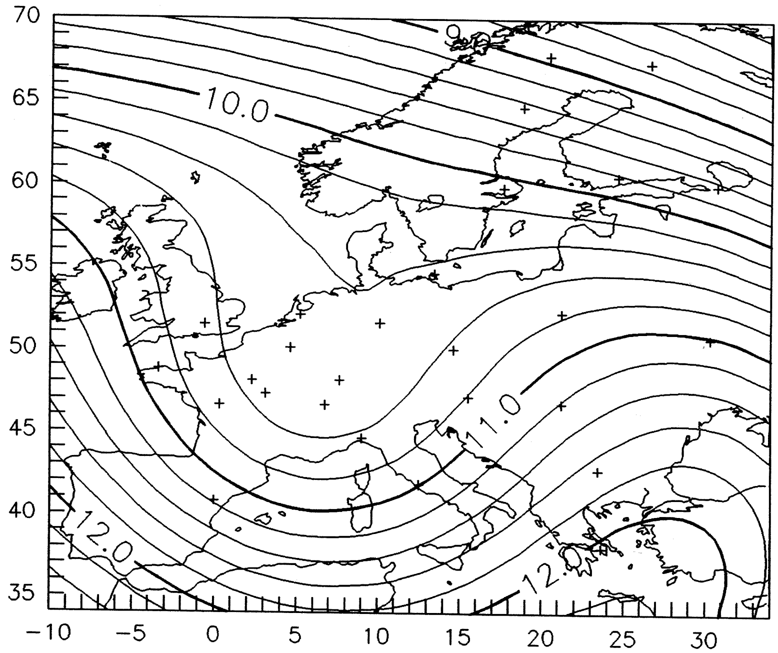

Fig. 1. Map of PASHA predicted monthly medians of f_0F2 at 12UT for March with R_{12} = 108. Units are MHz. Crosses represent the locations of ionospheric stations used in the analysis.

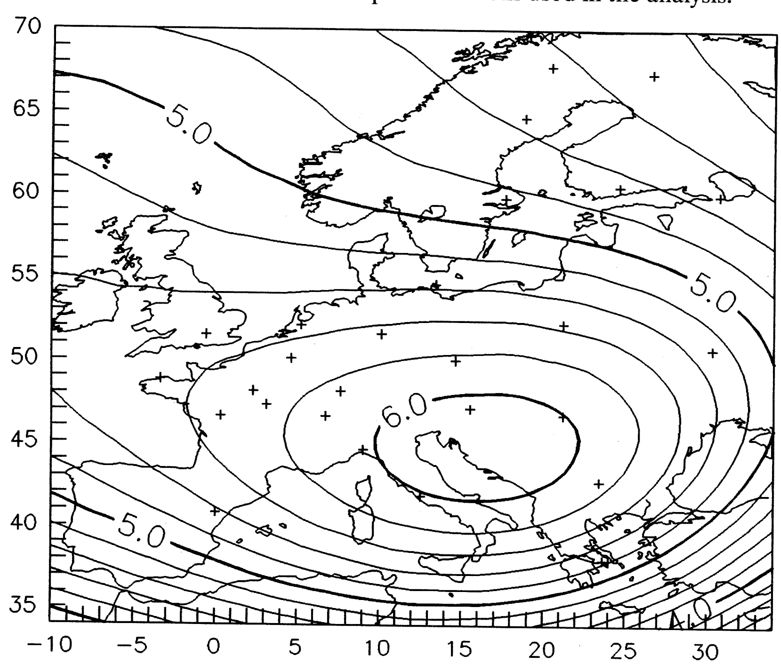

Fig. 2. Maps of PASHA predicted monthly medians of f_0F2 at 12UT for March with R_{12} = 21. Units are MHz. Crosses represent the locations of ionospheric stations used in the analysis.

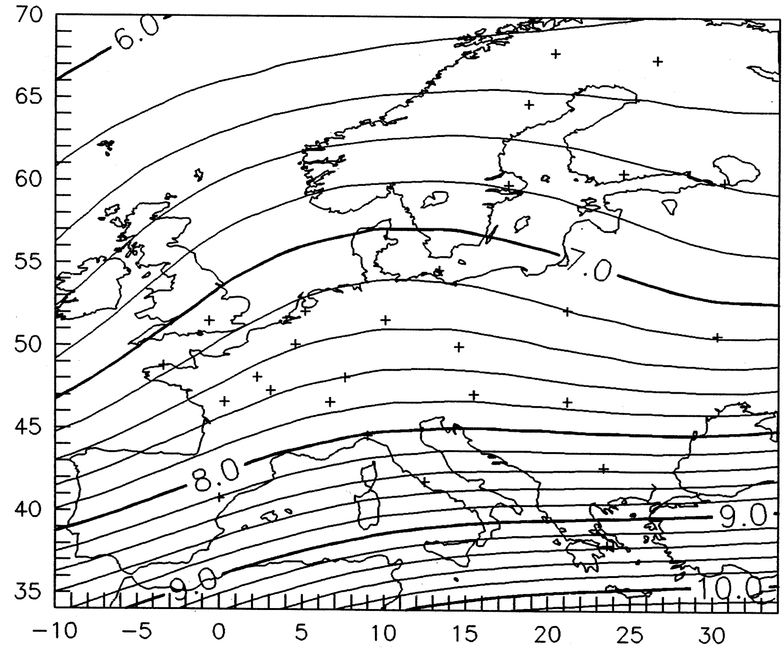

Fig. 3. Maps of PASHA predicted monthly medians of f_0F2 at 12UT for June with R_{12} = 106. Units are MHz. Crosses represent the locations of ionospheric stations used in the analysis.

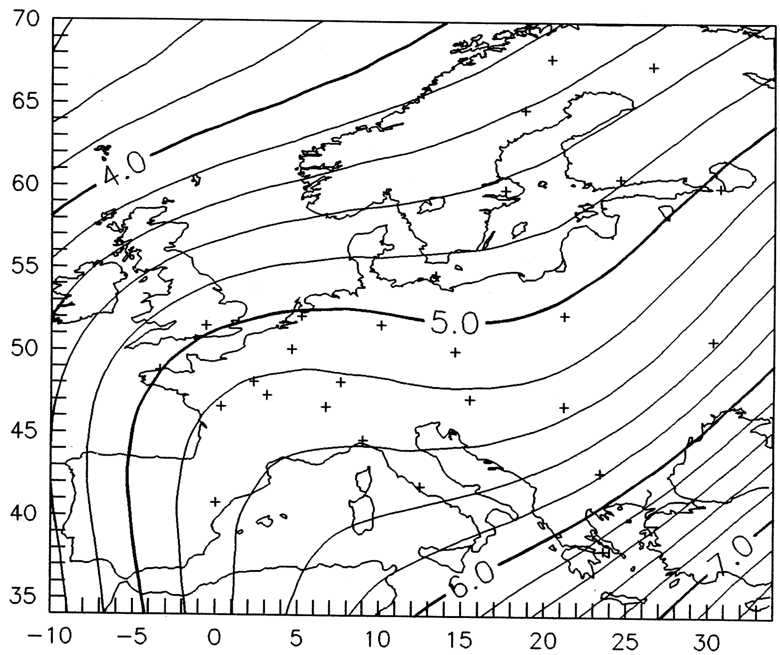

Fig. 4. Maps of PASHA predicted monthly medians of f_0F2 at 12UT for June with R_{12} = 15. Units are MHz. Crosses represent the locations of ionospheric stations used in the analysis.

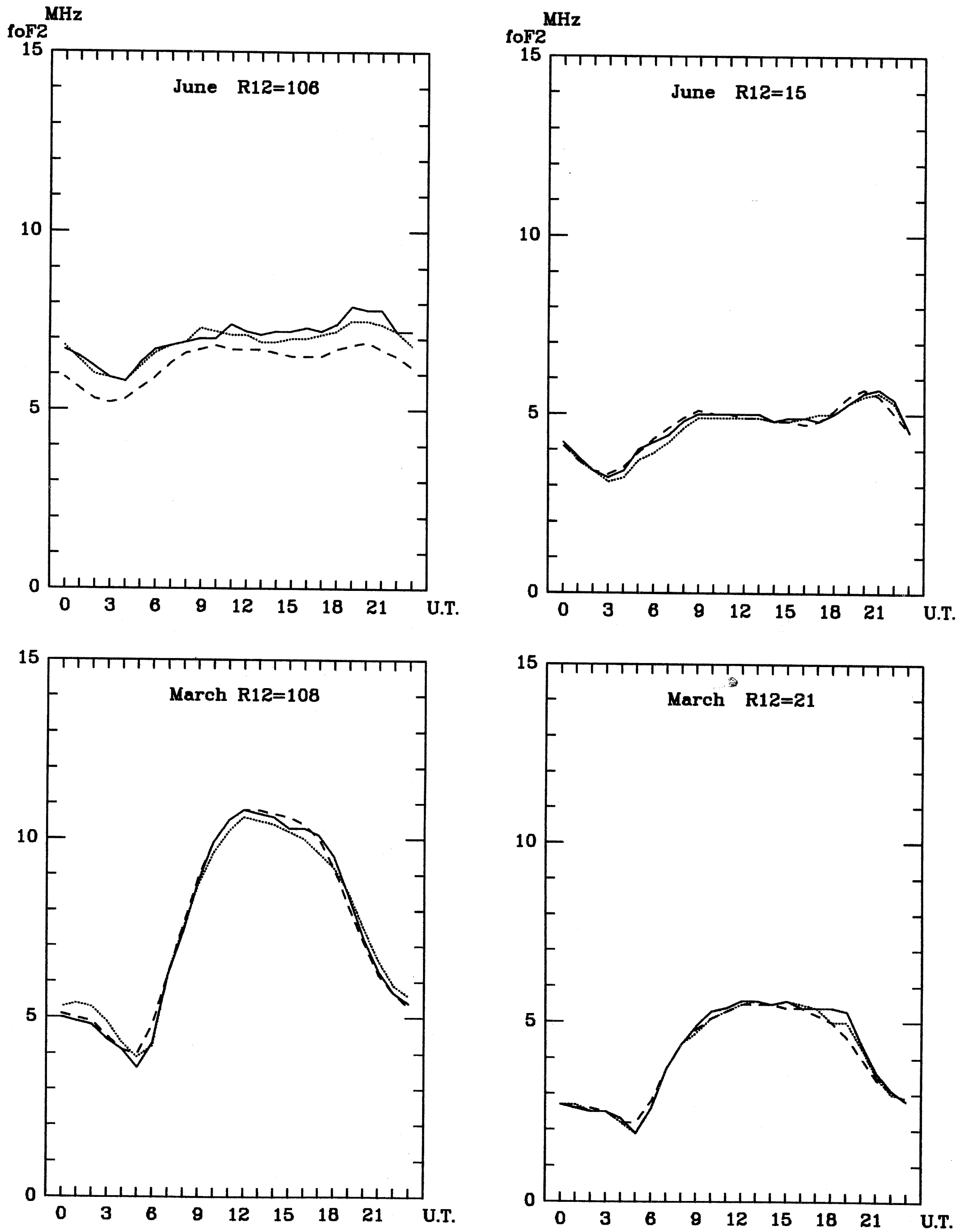

Fig. 5. PASHA (dotted line) and CCIR (dashed line) predicted values and corresponding measured values (continuous line) of the monthly medians of f_0F2 at Slough station for high (left) and low solar activity and for March (below) and June.

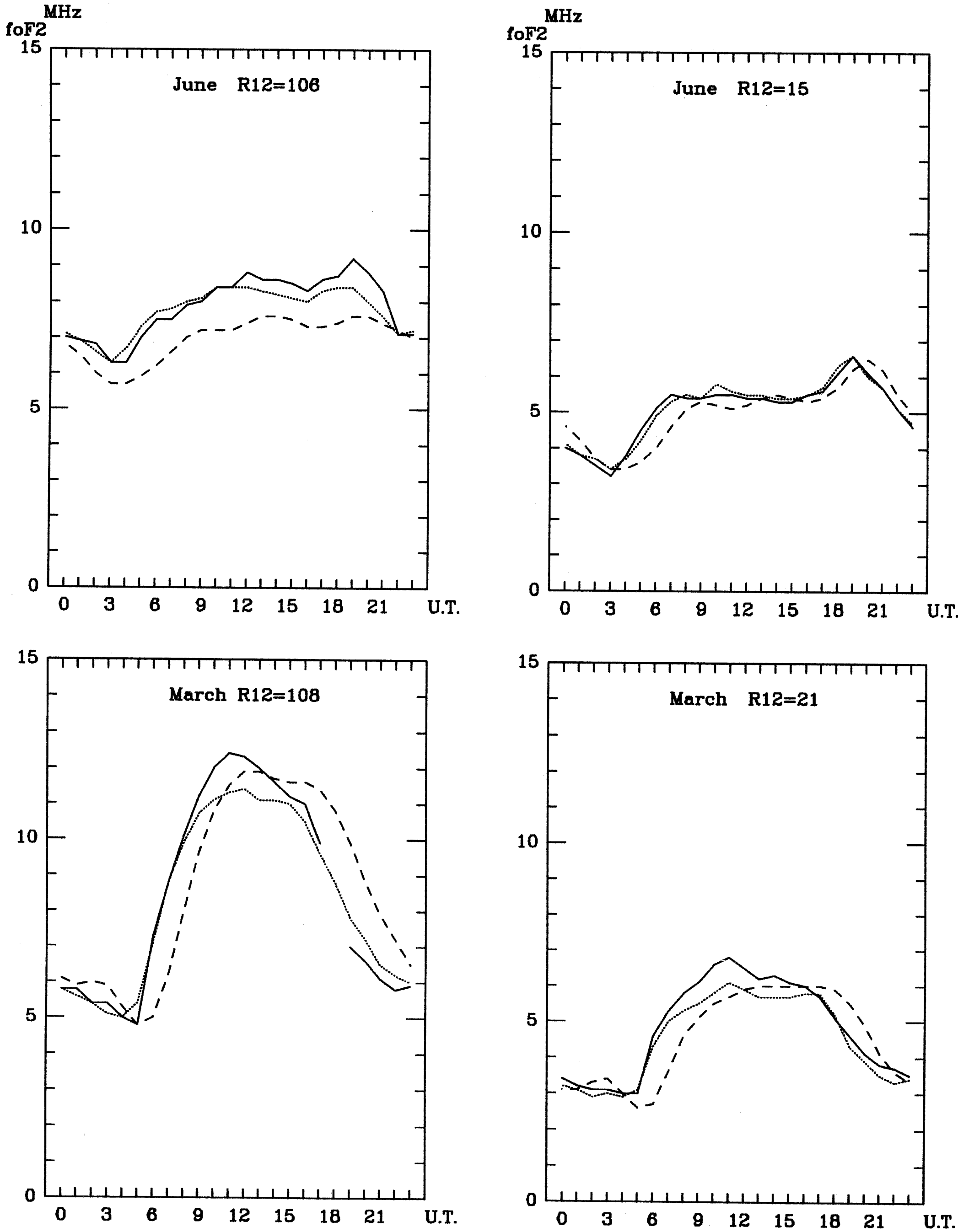

Fig. 6. PASHA (dotted line) and CCIR (dashed line) predicted values and corresponding measured values (continuous line) of the monthly medians of f_0F2 at Rome station for high (left) and low solar activity and for March (below) and June.

ter results when PASHA predicted values are considered for June with $R_{12} = 106$. Similar results are shown in fig. 6 concerning Rome station (41.8 N, 12.5 E). In the particular case of March with $R_{12} = 108$, in spite of the fact that during the daytime the differences between measured and PASHA predicted values reach more than 1 MHz, it seems that (in average over the day) PASHA gives better results than CCIR.

As a preliminary test concerning the reliability of PASHA model, the following analysis is carried out. PASHA predicted values of f_0F2, Pf, are calculated for every month of the years 1969, 1972 and 1975 (*i.e.* for high, medium and low solar activity, respectively), and for every station for which the measured values exist. Then the twelve months are grouped into the four seasons and the stations are grouped in two zones of medium (35°-50°N) and high (50°-70°N) geographic latitude. For every hour of the day, h, for every year, y, for every season, s, and for the two latitudinal zones, lz, the mean value of the differences, MVD, between the measured and predicted monthly medians of f_0F2 is calculated with its standard deviation σ, *i.e.*:

$$MVD(h) = \frac{1}{N} \sum_{st(lz)=1}^{S(lz)} \sum_{\text{month }(y,s)=1}^{3(y,s)} D(h) \quad (2.1)$$

and

$$\sigma(h) =$$

$$= \sqrt{\frac{1}{N(N-1)} \sum_{st(lz)=1}^{S(lz)} \sum_{\text{month }(y,s)=1}^{3(y,s)} (D(h)-MVD(h))^2} \quad (2.2)$$

with

$$D(h) = \quad (2.3)$$

$$= |f_0F2(h)_{st(lz),\text{month}(y,s)} - Pf(h)_{st(lz),\text{month}(y,s)}|$$

$S(lz)$ is the maximum number of stations, enumerated by $st(lz)$, included in one of the two latitudinal zones lz for which the measured value of f_0F2 is available, *month* $(y, s) = 1, 2, 3$ are the months comprised within any season s at a given year y, and $N = S(lz) \times 3$.

In figs. 7 to 10 the MVD histograms, obtained for every season, for the three levels of solar activity (*i.e.* for the years 1969, 1972 and 1975) and for the two latitudinal zones, generally show that MVD reaches its maximum of about $.5 \pm .05$ MHz for high solar activity. In summer nighttime the MV_sD are comparable or just a little greater than the daytime values. Especially in winter, but also in autumn, daytime MV_sD are generally greater than nighttime values. During spring MV_sD are comparable during the entire day except for high solar activity at the mid-latitude zone where the maximum values of MVD occur from 10UT to 19UT.

3. Concluding remarks

An alternative approach for regional long-term ionospheric prediction purposes has been developed and applied to the monthly medians of f_0F2 observed at several stations operating in Europe from January 1967 to December 1976. This model, called PASHA, is based on ASHA technique as a spatial spherical harmonic fitting (1.1) and on a second-order polynomial function in R_{12} of the spherical harmonic expansion coefficients (1.2), (1.3) to take into account the correlation between monthly medians of f_0F2 and solar activity.

In general the results show a good agreement between PASHA predicted values and measured values under different solar activity conditions, for different seasons and for mid and high-latitude areas.

By expressing the f_0F2 dependence on the solar index R_{12} into the expansion coefficients g_k^m (R_{12}) and h_k^m (R_{12}) (1.2), (1.3), a continuous long period (one solar cycle) of ionospheric measured data coming from a given station is not necessary, and gaps in the input data are also allowed. This fact represents an evident advantage with respect to the regional long-term predictions models for which a linear or quadratic re-

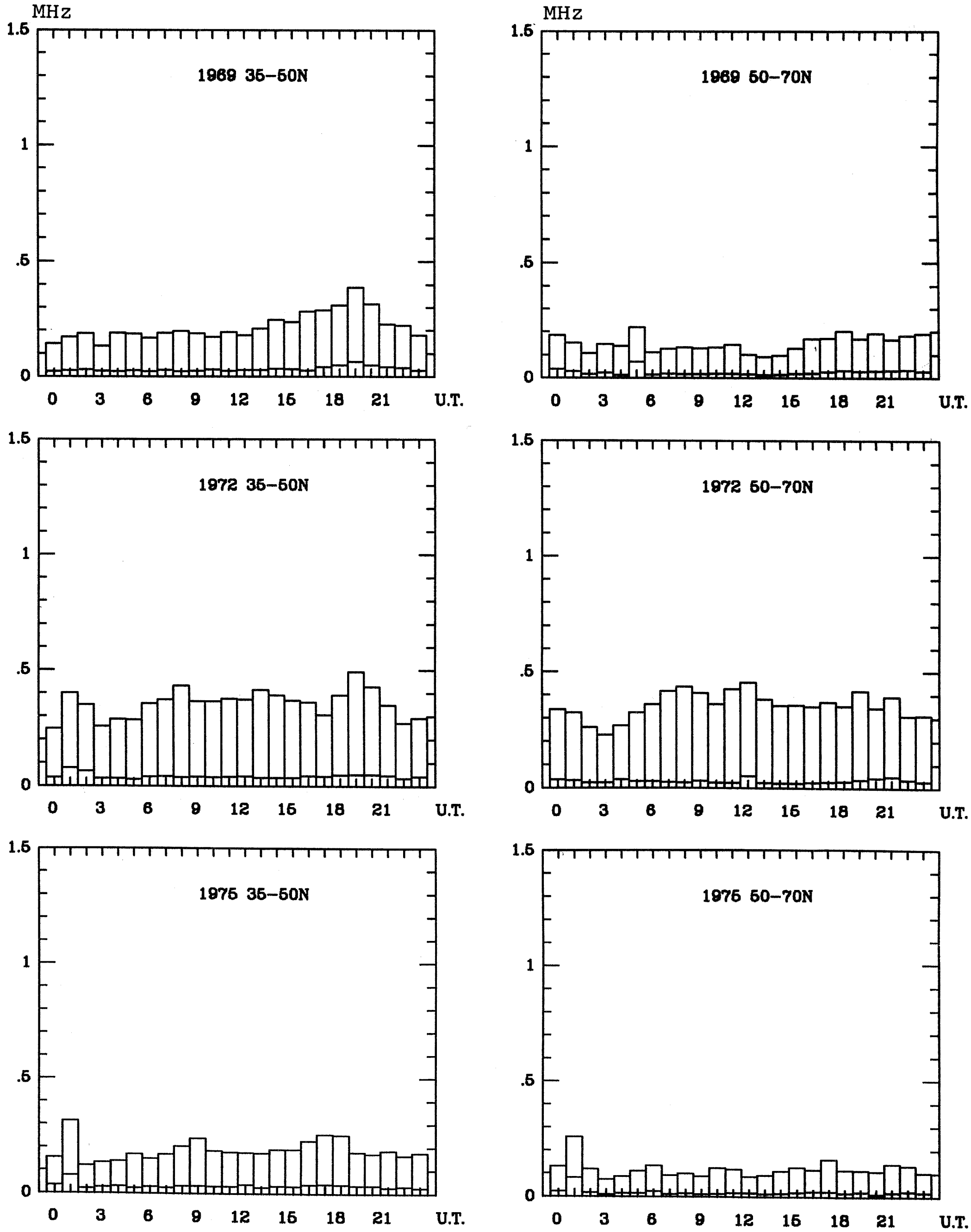

Fig. 7. *MVD* histograms and the corresponding standard deviations σ are plotted vs. UT in summer and for mid-latitude zone (left) and for high latitude zone, from top to bottom according to high, medium and low solar activity, respectively.

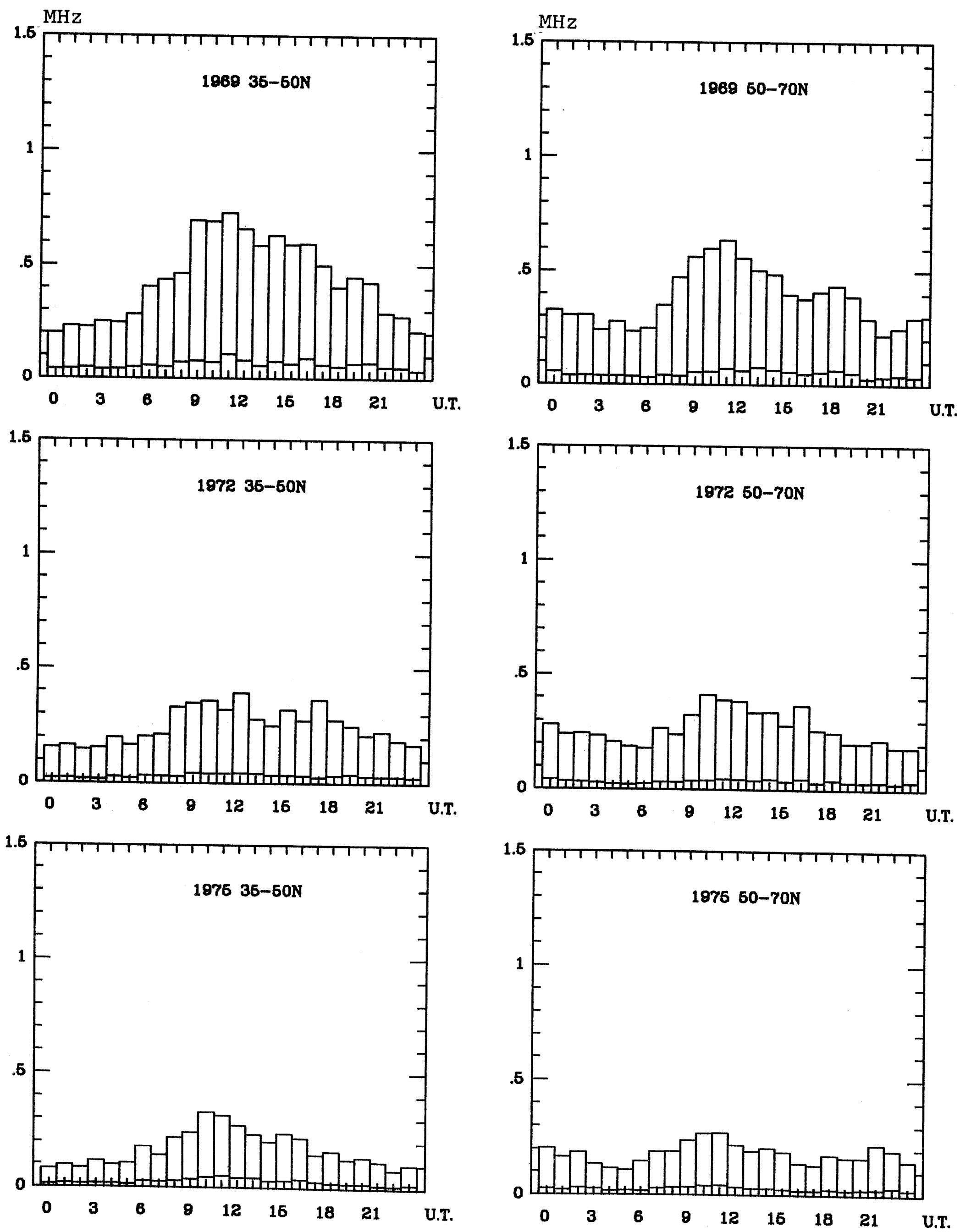

Fig. 8. *MVD* histograms and the corresponding standard deviations σ are plotted vs. UT in winter and for mid-latitude zone (left) and for high-latitude zone, from top to bottom according to high, medium and low solar activity, respectively.

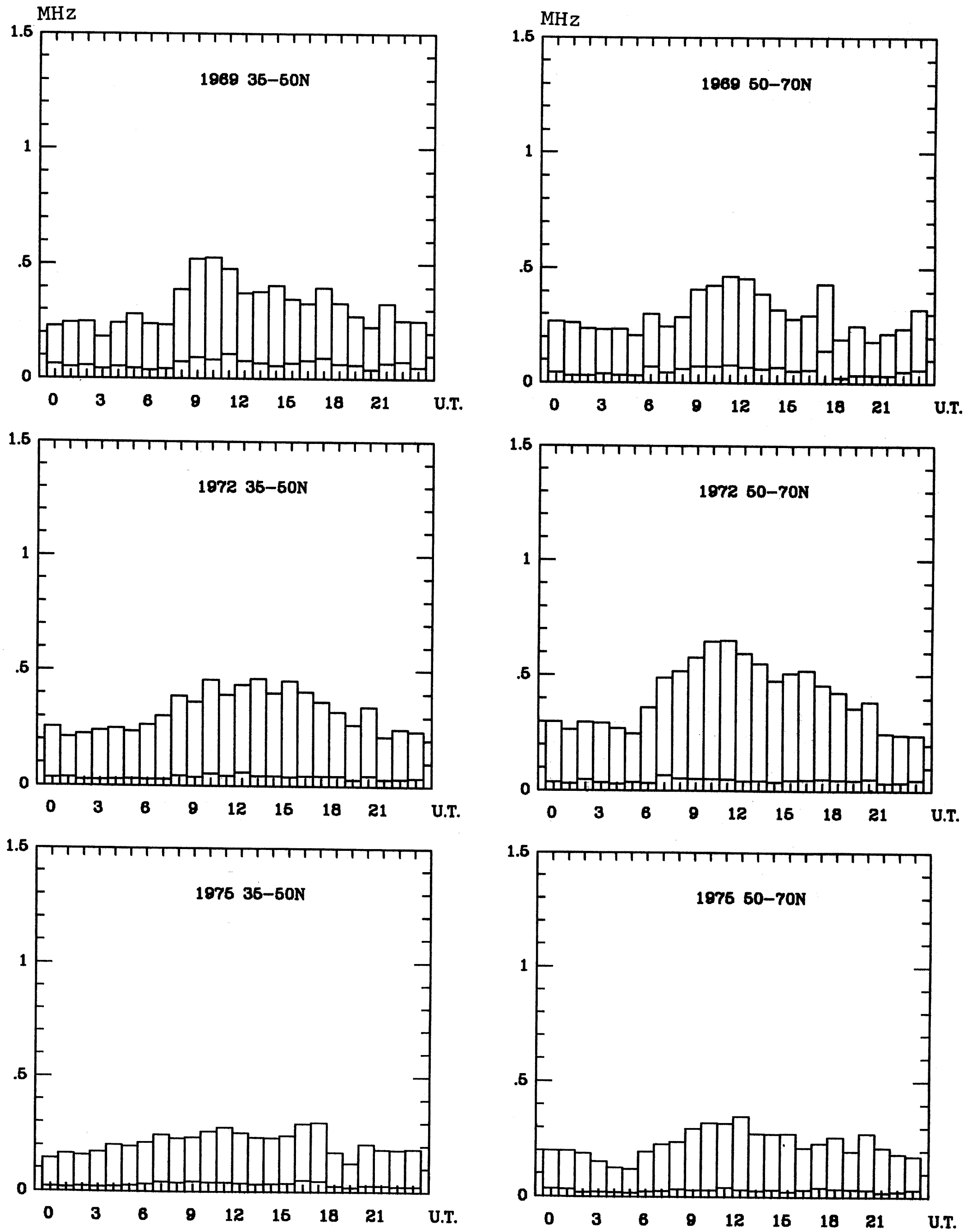

Fig. 9. *MVD* histograms and the corresponding standard deviations σ are plotted vs. UT in autumn and for mid-latitude zone (left) and for high-latitude zone, from top to bottom according to high, medium and low solar activity, respectively.

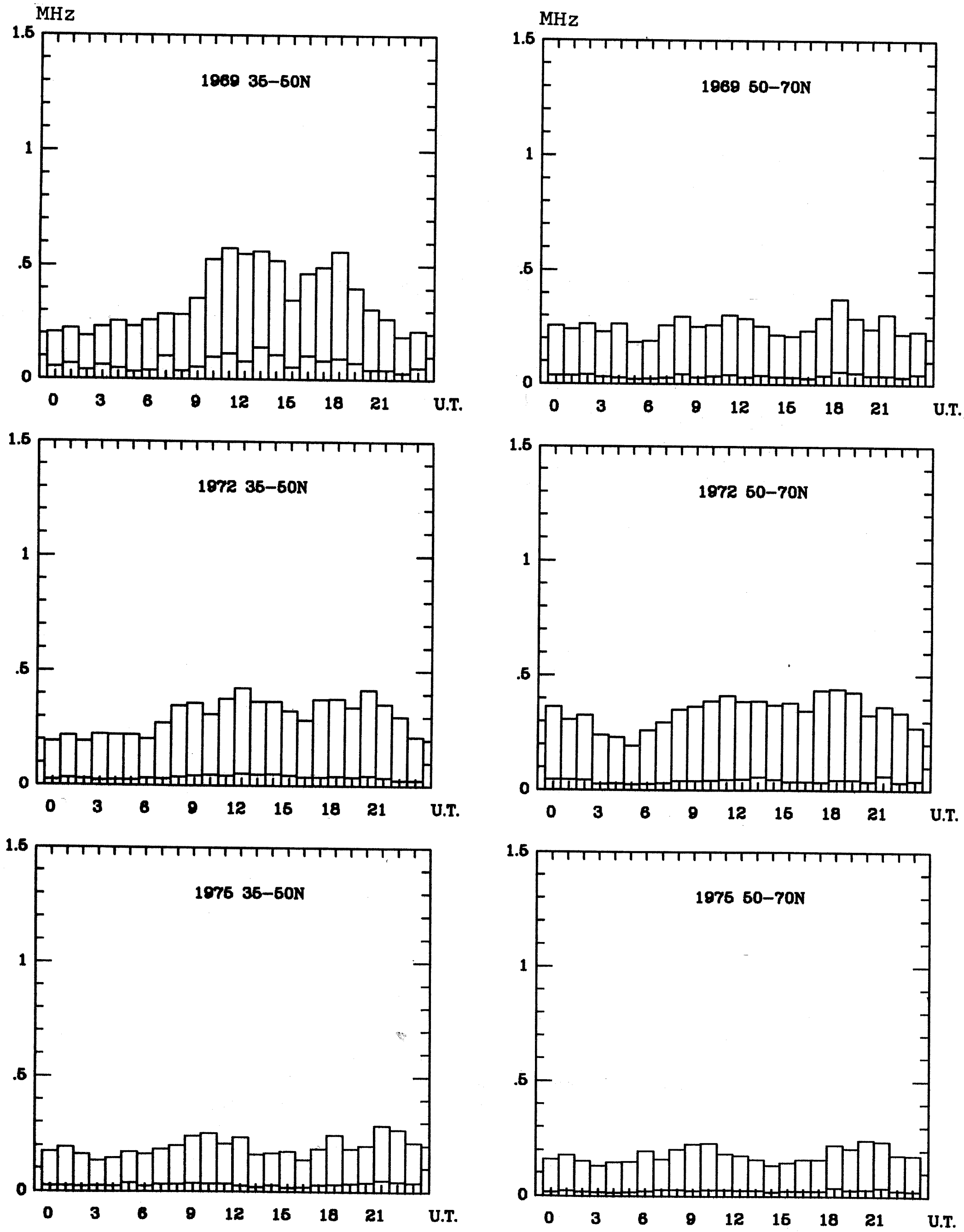

Fig. 10. *MVD* histograms and the corresponding standard deviations σ are plotted vs. UT in spring and for mid-latitude zone (left) and for high-latitude zone, from top to bottom according to high, medium and low solar activity, respectively.

gression between the measured monthly medians of the ionospheric parameters and a given solar activity index is applied at every station (included in the area of interest) before some kind of analysis in time, latitude and longitude is used (*e.g.* Zolesi *et al.*, 1991, 1993). In conclusion, PASHA model can be also considered as an alternative regional mapping and modelling approach to be used when several sparse (in time and space) measurement points are available; it requests a suitable choice of the maximum degree K by which the spherical harmonic expansion (1.1) is truncated, according to a reasonable detailed spatial description of the ionospheric parameter under consideration. The data base of every station can be related to different short periods of observation but the ensemble of the experimental data coming from different stations (operating in different periods) should cover, at least, one solar cycle.

PASHA FORTRAN 77 program is available for a VAX 9000 and for a PC-IBM compatible. The program runs in about 2 min on an 80286 16 MHz PC if the set of coefficients is already available for the analysed month, and in about 7 min if the model needs to be calculated. PASHA program can be easily adapted for other ionospheric parameters and for other limited regions of the Earth.

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