LONG TERM TRENDS IN THE IONOSPHERIC *fo*F2 IN THE INDIAN ZONE LOW LATITUDE IONOSPHERE

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ABSTRACT

In different fields of study involving geophysical databases, removal of data gaps is of utmost importance to understand the underlying patterns or trends in the geophysical data. Different interpolation techniques are used for this purpose, like regression analysis, neural network based methods, etc. Singular value decomposition or principal component analysis or empirical orthogonal function analysis technique has been a very powerful tool which is being used in ionospheric tomography and in the development of empirical models to describe the behavior of observed geophysical data. In this paper, we discuss the use of the singular value decomposition technique to remove data gaps in time series of ionospheric foF2 data recorded at three ionosonde stations in India. Also, the long term trend in the Ionospheric foF2 over the Indian zone ionosphere has been studied using a dataset of foF2 values over a period of twenty six years. The solar F10.7 cm flux has been used as a solar activity index in studying the trend of foF2. A decreasing trend in the ionospheric foF2 values has been observed during the study period.

Keywords: Ionosphere, Fof2, Low Latitude Ionosphere, Singular Value Decomposition, Long Term Trend.

I. INTRODUCTION

The critical frequency of F2 layer, foF2 is the most important factor for HF radio communication as it determines the maximum usable frequency. It has been observed that the ionospheric foF2 has a decreasing long term trend which may be the effect of (i) a cooling of the atmosphere by an increasing greenhouse effect [1], [2], (ii) long term changes of the earth's magnetic field [3], (iii) changes in the geomagnetic activity [4] and (iv) the influence of non-migrating tides [5]. In the analyses of the long term trends of the ionospheric parameter foF2, the monthly median values of the hourly values are used to discern the underlying trend. However, most of the times, the monthly median values are not available because of the failure of the instrument to record the hourly data for a good number of days of the month. In such a situation, monthly median values may be reconstructed using an interpolation technique based on the singular value decomposition technique. In this paper, we describe the technique of interpolation and use it to reconstruct monthly median values of foF2 at six inosonde stations in India and then the interpolated data for Kodaikanal has been used to study the long term trend of foF2 over the station.

II. DATABASE

The ionospheric foF2 data used in this analysis cover the stations (i) Trivandrum (8.5°N, 77°E), (ii) Kodaikanal (10.2°N, 77.3°E), (iii) Tiruchirapalli (10.8°N, 78.7°E), (iv) Bombay(19°N, 72.5°E), (v) Ahmedabad (23°N, 72.6°E), (vi) and Delhi (28.6°N, 77.2°E) for the period of 1958-1980. However, for the study of the long term trends in foF2, we have used the data for Ahmedabad, Delhi and Kodaikanal only.

III. DESCRIPTION OF THE INTERPOLATION TECHNIQUE

The method of Singular value decomposition (SVD) can be applied to the monthly median hourly values of critical frequency of F2 layer, foF2 to get Empirical Orthogonal Functions, eigen values and Expansion Coefficients/principal components directly from the data matrix

$$Z\ (m\times n) = U\ (m\times m)*L(m\times n)*V^T\ (n\times n) \quad (1)$$

Where Z=foF2 with the elements (m, n) is the monthly median hourly values of the observed data represented as a r×s array with rows corresponding to months (m=1,2,……,r, r being the total number of month in the data set) and column corresponding to the local time (n=1,2,………s). The U and V are the orthogonal matrices. The column of U(m×m) are the eigen vectors of ZZ^T and C= U*L are the expansion coefficients/EOF coefficients which reflects the longer term variation of foF2 and the column of V(n×n) are the normalized PC's that are associated uniquely with each EOF. L(m×n) is the diagonal matrix where the diagonal values of L are the eigen values representing the amplitudes of the EOFs. We used a 232×24 array data set. Generally, we need all the 24 order PC's and associated EOF coefficients to reconstruct all the variation of the whole foF2 data set. However, it is desirable to find a basis set that explains as much as possible of the variance of the data set with the few possible EOF coefficients. This reduces the number of component used for the model construction. In our case, the first three EOF components can explain 99.7% of the variances of the whole data set. Therefore, we can use only the first three components to reconstruct the foF2. The correlation between the observed foF2 and the reconstructed foF2 with the first three EOF components is high as 0.901.

Figure.1 shows the time variation in first three principal components/EOF coefficients C_1, C_2, and C_3 which is obtained by decomposing the original observational data matrix (where C_K = U*L) for Kodaikanal. The top panel of the figure shows the variation of the monthly mean solar F10.7 cm flux. From the figure it is seen that the first EOF components as well as the second EOF components have a good negative correlation with solar F10.7 cm flux whereas the third EOF components has no good correlation with solar F10.7 cm flux. It is also seen that the magnitude of first EOF components has a much larger value than the other two EOF components. The correlation between the first EOF component and the solar F10.7 cm flux is r = -0.853 and the value of r^2 = 0.728. Obviously the first component contains an annual and solar cycle variation component. The correlation between the second EOF component and the solar F10.7 cm flux is r = -0.746 and the value of r^2 = 0.557 whereas for the third EOF component it is -0.351, 0.123 respectively. The second EOF component also contains an annual variation component but it has a smaller magnitude than the first one. The variation of C3 is shown in fig 1d. Apparently the variation in C_3 is hard to explain as well as its physical interpretation.

Since the first three EOFs are able to explain the 0.99% of the total variance of the original foF2 data set, we can use these three EOFs to reconstruct the whole picture of the original data set. Therefore (1) reduces to

$$Z(m,n) = C_1\times V_1^T + C_2\times V_2^T + C_3\times V_3^T \quad (2)$$

Now we can model these three EOF coefficients C_k (k=1, 2,3) using the linear regression analysis with solar F10.7 cm flux.

$$C_K\ (m) = S_K + D_K\ F_{10.7}\ (m) \quad (3)$$

The coefficients in (3), S_K and D_K (k=1, 2, 3) are first determined and then these are used to calculate the C_K (m) by (3). These new value of C_K thus determined are referred as modeled C_K (m).By using (2) the value of foF2 is thus calculated which is referred as model foF2.

IV. VALIDATION OF THE PROPOSED TECHNIQUE

To test the suitability of the interpolation technique we have chosen the observational data for a low solar activity year (1965) and a high solar activity year (1980) for the Kodaikanal. We followed the data reconstruction procedure as described above. Here we have excluded the data of the whole year chosen for testing when trying to implement the method and the corresponding foF2 values are reconstructed for that particular year. The same procedure is also followed for the high solar activity year 1980. Figure 2 shows the comparison among the observed foF2 and modeled foF2 during the interval 1958-1980 at Kodaikanal. The upper panel shows the observed foF2 and the lower panel shows the corresponding model foF2 in the reconstruction of which only the first three EOFs have been used. It is seen that model predicted values match very well with the observed data. The performance of the model can be calculated by evaluating the mean difference ($\overline{\Delta Z}$) and the root mean squared error (RMSE) as well as their relative percentage values ($\overline{\Delta Z}_r$, RMSEr) between the model predicted values and the observational ones by the following formulae:

$$\overline{\Delta Z} = \frac{1}{N}\sum_{i=1}^{N}\left(Z_{pred}-Z_{obs}\right) \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Z_{pred}-Z_{obs}\right)^2} \quad (5)$$

$$\overline{\Delta Z}_r = \frac{1}{N}\sum_{I=i}^{N}\left(\frac{Z_{pred}-Z_{obs}}{Z_{obs}}\right)\times 100\% \quad (6)$$

$$RMSEr = \sqrt{\frac{1}{N}\sum_{I=1}^{N}\left(\frac{Z_{pred}-Z_{obs}}{Z_{obs}}\right)^2} \times 100\% \quad (7)$$

Where N is the total number of data points.

The calculated values of ($\overline{\Delta Z}$) and RMSE, relative percentage values $\overline{\Delta Z}_r$ and RMSEr for the low solar activity year, 1965 for all stations are shown in the table below.

Figure 3 represents a comparison between the observed and the interpolated data for the year 1965 for ionosonde station Kodaikanal. Similar results have also been obtained for all the other five stations for which a quantitative measure of the errors in reconstruction has been presented in table 1.

Table1: Quantitative Measure of Errors in Reconstruction

Station Name	$\overline{\Delta Z}$	RMSE	$\overline{\Delta Z}_r$	RMSEr
Trivandrum	0.11	0.694	2.87	13.21
Kodaikanal	-0.446	0.964	-7.06	17.03
Tiruchirapalli	-0.220	0.662	-4.18	11.56
Bombay	-0.137	1.06	0.049	15.6
Ahmedabad	-0.036	1.103	0.364	17.06
Delhi	-0.130	1.19	-1.91	21.38

V. LONG TERM TREND IN foF2

To discern the long term trend of ionospheric foF2, the elimination of the solar and geomagnetic activity induced effects are absolutely necessary. Different groups have used different methods to eliminate such effects, e.g., regression analyses, a statistical inversion method, etc. Sunspot number R, solar F10.7 cm flux, E10.7 index, etc. have been used as the proxy for solar EUV radiation in the ionospheric trend analyses. We have used the F10.7 cm flux as the proxy for EUV radiation.

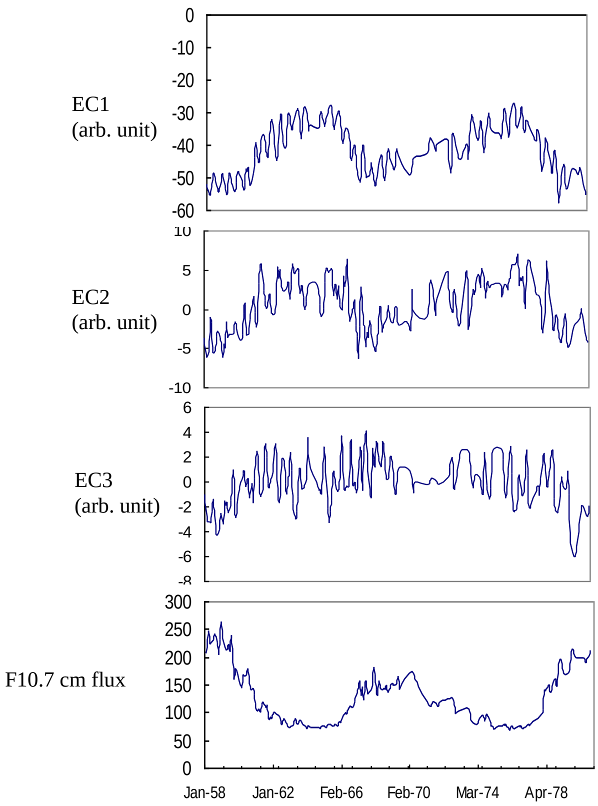

Figure 1 Variation of monthly median solar F10.7 cm flux and the first three EOF components during the interval 1958-1980

4.1 Method of Trend Analyses

We have adopted the bilinear regression method to eliminate the solar and geomagnetic activity induced effects from the foF2 data. The regression equation is

$$X_{th}=A+B.SA+C.Ap$$

Here X is the ionospheric parameter foF2, SA is the solar activity parameter F10.7 cm flux, and Ap is the global geomagnetic activity index. Then the differences between the observed ionospheric parameter X_{exp} and the corresponding model value X_{th} are calculated according to

$$\Delta X=X_{exp}-X_{th}$$

Then, yearly ΔX mean values are used to derive linear trends according to

$$\Delta X=D+E.year$$

Here E is the trend parameter in MHz per year for foF2 values.

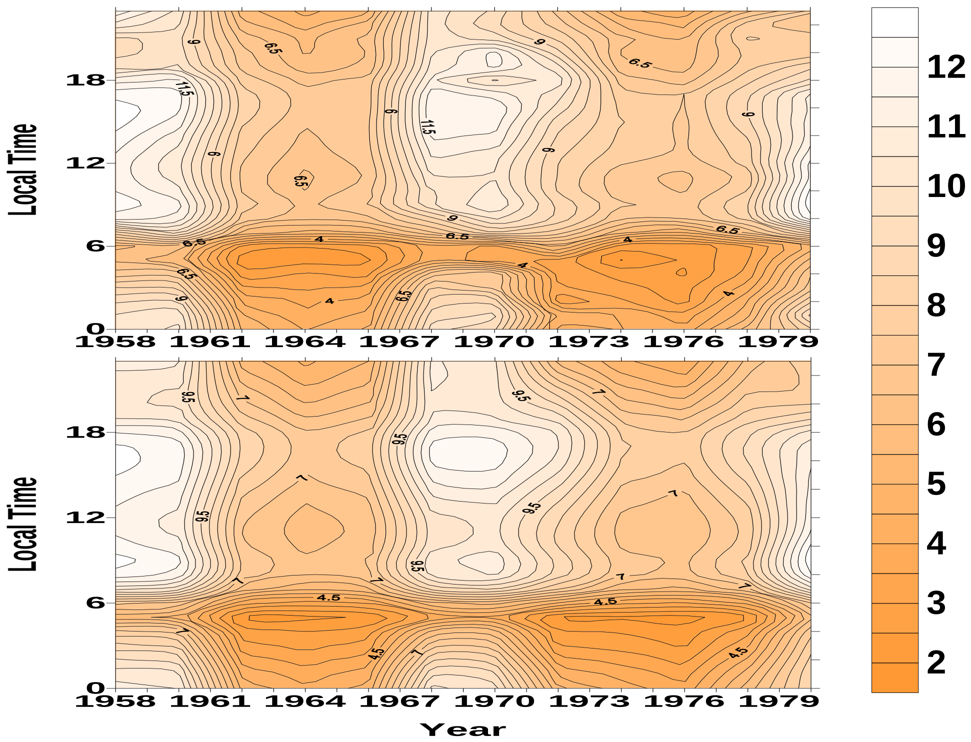

Figure 2: Comparison among the observed foF2 (MHz) and modeled foF2 (MHz) during the interval 1958-1980 at Kodaikanal. The upper panel shows the observed foF2 and the lower panel shows the corresponding model foF2 in the reconstruction of which only first three EOFs have been used

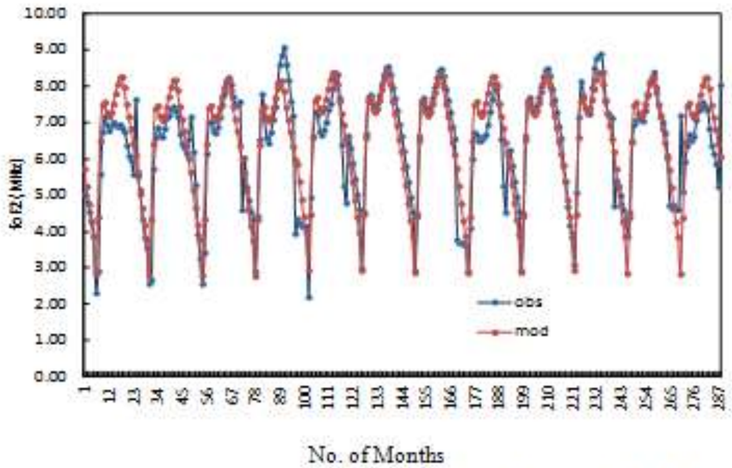

Figure 3: Comparison between the actually observed (OBS) foF2 (monthly median hourly values) and the interpolated (mod) values at the station Kodaikanal

4.2 Results and Discussion

Figure 4 represents the long term trend in ionospheric foF2 as observed for Ahmeadbad, Delhi and Kodaikanal stations in India respectively.

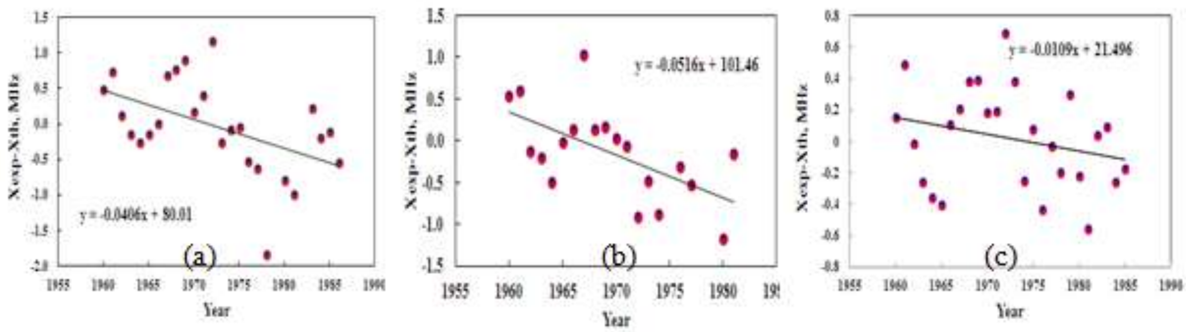

Figure 4: Long term trend of foF2 at (a) Ahmedabad, (b) Delhi and (c) Kodaikanal

It has been observed that the trend parameters for Ahmedabad, Delhi and Kodaikanal are -0.0406MHz per year, -0.0516 MHz per year and -0.0109 MHz per year respectively. It may be noted that the decreasing trend is more prominent in the stations Ahmedabad and Delhi which are closer to the peak of the equatorial ionization anomaly. The foF2 has decreasing trends over the Indian stations which are quite high as compared to the global trend of -0.0038 MHz per year as estimated by Mielich and Bremer, 2013 [6]. As shown by Mielich and Bremer, 2013 [6], the global mean foF2 trends derived for the interval between 1948 and 2006 are in surprisingly good agreement with model calculations of an increasing atmospheric greenhouse effect [1].

V. CONCLUSION

(i) We have discussed an interpolation technique to reconstruct missing data from foF2 values. The interpolated data has shown a good agreement with the observed data using only a few order EOF coefficients.
(ii) Using the dataset with the reconstructed dataset, the long term trend in ionospheric foF2 at Ahmedabad, Delhi and Kodaikanal has been studied. The trend parameter has been observed to be ~ -0.0343 $MHzyr^{-1}$ for the three locations. The estimated value of the trend parameter has been observed to be one order higher than the global trend of ~ -0.0038 $MHzyr^{-1}$ [6].

VI. ACKNOWLEDGEMENT

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