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CORRECTED SOLAR FLUX INDEX FOR IONOSPHERIC APPLICATIONS

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Abstract. A new solar flux index is proposed for ionospheric applications. The index is based on the time series of measured 10.7-cm solar radio flux ($F_{10.7}$) and is corrected to describe the variation of ionospheric-effective solar EUV flux through a statistical analysis and artificial neural network training.

1 INTRODUCTION

The major driver of ionospheric variations is the solar EUV radiation. For numerical modeling and experimental analyses of the ionosphere, 10.7-cm solar radio flux ($F_{10.7}$) has long been used as a proxy of solar EUV inputs to the Earths upper atmosphere because of its long-year availability since 1940 and the reliability being free of instrumental degradation. The $F_{10.7}$ index is reported to have a good correlation with the other measurements at various wavelengths of UV/EUV. However, there also are several disagreements between the $F_{10.7}$ index and EUV flux, which are originated from the fact that the radiation mechanism of the 10.7-cm solar radio noise differs from that of the EUV radiation and that the source region of the 10.7-cm solar radio noise in the solar atmosphere differs from that of the EUV radiation. A significant effect is the difference between the amplitudes of the long-term variation over an 11-year solar cycle and the short-term variation induced by the solar rotation with a period of approximately 27 days, which comes from the different contrast of plague, active network, and quiet sun for the radio noise and EUV radiation. As a result, in the use of the $F_{10.7}$ index as a proxy of solar irradiance for ionospheric studies, the long-term variation of $F_{10.7}$ cannot simply be scaled to the short-term variation.

If we find a statistical relationship between the time series of $F_{10.7}$ and the EUV irradiance, $F_{10.7}$ might be corrected to describe EUV variations. One of such efforts was found in the EUVAC model in which an index P defined as $(F_{10.7} + {F_{10.7}}^{81-daymean})/2$ is used as a parameter to describe the solar EUV activity[1]. Introduction of this index is equivalent to that the solar rotational component is halved. Two parameters, $F_{10.7}$ and its 81-day mean, are used in the series of empirical thermospheric model MSIS and the thermospheric neutral wind model HWM to specify solar inputs. In an artificial neural network (ANN) model for total electron content (TEC), mean values of $F_{10.7}$ for various periods, in addition to the daily value of $F_{10.7}$, describe the TEC variation better than the single use of the daily $F_{10.7}$ index[2]. Concurrent use of daily, 7-, and 81-day backward means of $F_{10.7}$ in the input space of the ANN-TEC model yields even a better result when compared with the case in which daily magnesium UV index (Mg II core-to-wing ratio) alone is used[2]. Unfortunately, the explicit functional form of the combination of the input parameters such as daily, 7-, and 81-day means of $F_{10.7}$ is unknown in ANN applications. In this paper, we empirically determined a functional representation of various parameters generated from the time series of $F_{10.7}$ for better description of ionospheric effective EUV (IE-EUV) variation. The new index is applicable in ionospheric studies over a long period since 1940 for which satellite direct measurements of UV/EUV solar flux are not available.

2 CORRECTED INDEX

In the previous study[2], the index based on the SOHO_SEM measurements at wavelengths of 26-34 nm was found to be the best parameter to describe TEC variations when the daily index alone was used. Also found is that the ratio of amplitudes between the long-term to short-term variations for the SOHO_SEM$_{26-34}$ index is close to that of IE-EUV variations. Therefore, first, the SOHO_SEM$_{26-34}$ and $F_{10.7}$ indices were compared for the period from April 1997 to March 2008, during which both the indices and GPS-TEC database for validation is available. For the convenience of this comparison, the normalized SOHO_SEM$_{26-34}$ to the long-term variation of the $F_{10.7}$ index reported as $S_{10.7}$ was used[3]. Figure 1 shows the relationship of 27-day amplitudes between $F_{10.7}$ and $S_{10.7}$. Amplitudes were calculated daily using the data for the period 13 days before and after that day. The horizontal axis is the amplitude for $F_{10.7}$ and the vertical axis is the amplitude ratio of $S_{10.7}$ to $F_{10.7}(r_A)$. Small dots are the daily values and large dots are the median values in bins for 27- day amplitude of $F_{10.7}$: the bin width varied depending on the number of data points inside it. To approximate this relationship we divided the amplitude range for $F_{10.7}$ into three and lines were fitted as shown by the solid lines in the figure. By using this relationship, the 27-day variation component was reduced from the time series of $F_{10.7}$ such as,

$$\delta = F_{10.7} - F_{base} \tag{1}$$

$$C = F_{base} - \delta \cdot r_A \tag{2}$$

Where $F_{10.7}$ is the daily value and Fbase is the gradually varying component being free of the 27-day rotation modulation.

The gradually varying components for $F_{10.7}$ appearing in the above expression and for $S_{10.7}$ (or more correctly IE-EUV) also differ. The large-amplitude 27-day modulation of $F_{10.7}$ is caused by the localized active region and the reduction of the 27-day modulation in the above expression should be done not about the mean level but about the rotation-free background level. Also gradually varying component originated from active networks may differ between $F_{10.7}$ and IE-EUV. We considered two parameters, the 27-day amplitude calculated from the time series of $F_{10.7}$ with an 81-day length (${A_{81}}^{27}$) and the 81-day amplitude calculated from the same dataset (${A_{81}}^{81}$). Practically, we do not know by what proportion of those parameters should be incorporated for the correction of the $F_{10.7}$ time series to represent the background gradual variation of IE-EUV. The following coefficients, k and a, were empirically determined by the assist of an ANN modeling.

$$A = k[a \cdot {A_{81}}^{81} + (1 - a) \cdot {A_{81}}^{27}] \tag{3}$$

$$F_{base} = {F_{10.7}}^{81-daymean} - A \tag{4}$$

The calculated solar flux index C was used as an input parameter for training of the ANN. The trained ANN was evaluated for various values of k and a by comparing the root mean square error (RMSE) between the ANN outputs and measured TECs. Empirically determined values were $k = a = 0.6$ or $A = 0.36{A_{81}}^{81} + 0.24{A_{81}}^{27}$.

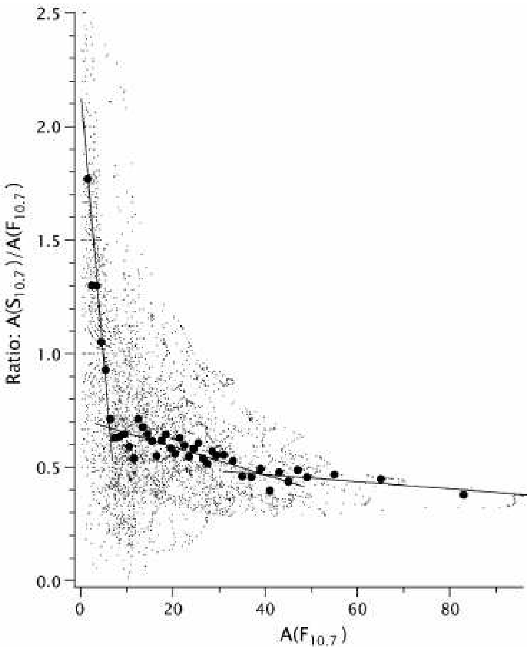

Figure 1: Amplitude ratio of $S_{10.7}$ to $F_{10.7}$.

Another important point that we have to consider is the different behavior of the activity region evolution measured by the 10.7-cm radio flux and the UV/EUV radiations.

Solar irradiance variations are parameterized by a localized plage area and a longitudinally dispersed active network. A plage decays into an active network in one to three solar rotations and the active network remains for several solar rotations. The contrasts for plage and active network components are different between the 10.7-cm radio flux and UV/EUV emissions: the contribution of the active network component to the 10.7-cm radio flux is much smaller than the plage contribution. As a result, there observed episodes of activity in which the 10.7- cm flux peak occurred earlier than the UV/EUV flux[4]. Also the cross correlation analysis shows that the 205-nm UV flux during a peak in a series of 27-day peaks is partially related to the values of $F_{10.7}$ that occurred on the previous rotation[5].

For the evaluation of F_{base} and r_A in Equations (1)-(4), we chose 81- and 27-day periods centered on the day concerned, respectively. To incorporate the above mentioned different evolution characteristics as measured by the 10.7-cm flux and EUV emissions, the periods for 81- and 27-day $F_{10.7}$ time series were shifted by τ_1 and τ_2, respectively:

$$\delta' = F_{10.7} - F_{base}(\tau_1) \tag{5}$$

$$CI_{10.7} = F_{base}(\tau_1) + \delta' \cdot r_A(\tau_2) \tag{6}$$

$$A' = k[a \cdot {A_{81}}^{81}(\tau_1) + (1-a) \cdot {A_{81}}^{27}(\tau_1)] \tag{7}$$

$$F_{base}(\tau_1) = {F_{10.7}}^{81-daymean}(\tau_1) - A' \tag{8}$$

Where the parameters τ_1 and τ_2 were empirically determined through the ANN training and the comparison of RMSEs. The best training result or smallest RMSE was obtained for τ_1 = -21 days and τ_{12} = -6 days. We call thus introduced index $CI_{10.7}$ and Table 1 compares RMSEs for various indices when they are used in the ANN-TEC modeling. In the table, R_i is the international sunspot number and SOHO means SOHO_SEM$_{26-34}$.

index	R_i	$F_{10.7}$	Mg II	P	C	$CI_{10.7}$	SOHO
RMSE	5.37	4.18	3.77	3.53	3.45	3.41	3.31

Table 1: Comparison of solar indices for the application of ionospheric TEC modeling

3 CONCLUSIONS

- A new solar flux index for ionospheric applications was generated from the time series of 10.7-cm solar radio flux.
- The new index describes well the long- and short-term variations of ionospheric effective solar EUV flux.
- The new index is applicable in ionospheric studies over a long period since 1940 for which satellite direct measurements of UV/EUV solar flux are not available.

REFERENCES

[1] P. G. Richards, J. A. Fennelly, and D. G. Torr, EUVAC: A solar EUV flux model for aeronomic calculations, J. Geophys. Res., 99(A5), 89818992 (1994).

[2] T. Maruyama, Solar proxies pertaining to empirical ionospheric total electron content model, J. Geophys. Res., 115, A04306, doi:10.1029/2009JA014890 (2010).

[3] W. K. Tobiska, S. D. Bouwer, and B. R. Bowman, The development of new solar indices for use in thermospheric density modeling, J. Atmos. Solar-Terr. Phys., 70, 803819 (2008).

[4] R. F. Donnelly, D. F. Heath, J. L. Lean, and G. J. Rottman, Differences in the temporal variations of solar UV flux, 10.7-cm solar radio flux, sunspot number, and Ca-K plage data caused by solar rotation and active region evolution, J. Geophys. Res., 88(A12), 98839888 (1983).

[5] R. F. Donnelly, J. W. Harvey, D. F. Heath, and T. P. Repoff, Temporal characteristics of the solar UV flux and He I line at 1083 nm, J. Geophys. Res., 90(A7), 62676273 (1985).