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Eight proxy indices of solar activity for the International Reference Ionosphere and Plasmasphere model

T.L. Gulyaeva [a,*], F. Arikan [b], U. Sezen [b], L.V. Poustovalova [a]

[a] IZMIRAN, Troitsk, Moscow, 108840, Russia
[b] Department of EEE, Hacettepe University, Beytepe, Ankara, 06800, Turkey

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ABSTRACT

In view of the recent recalibration of the sunspot number time series SSN2, a need has arisen to re-evaluate solar and ionospheric indices in the International Reference Ionosphere, IRI, and its extension to the Plasmasphere, IRI-Plas models, which are developed using the predecessor SSN1 index. To improve efficiency of the model, eight solar proxy indices are introduced in IRI-Plas system: the daily measured solar emissions, the Ottawa 10.7-cm radio flux ***F10.7*** and the H ***Lyman-α*** line at 121.6 nm; the core–to–wing ratio of the magnesium ion h and k lines at 279.56 and 280.27 nm, ***MgII*** index; sunspot number ***SSN1*** observed before 05.2015 and modelled afterwards; re-calibrated ***SSN2*** sunspots time series; the ionosonde foF2-based global ***IG***-index and the Global Electron Content, ***GEC***, index, the new ionospheric ***TEC***-noon index based on GPS-derived Total Electron Content measurements at 288 IGS stations for 1994–2018. The regression relations are deduced between the different solar and ionospheric proxy indices smoothed by 12-month sliding window. The IG, TEC and GEC saturation or amplification effect is observed towards the solar maximum. The SSN1 and F10.7 data serve as a default IRI-Plas input while the rest indices are scaled to SSN1 units envisaged by the F2 layer peak maps. Relevant subroutines are incorporated in IRI-Plas system for automatic conversion of user's predefined index to other related indices which are applied by the different model procedures.

1. Introduction

The most significant component in formation of the Earth's thermosphere and ionosphere is the introduction of energy from EUV and soft X-ray wavelengths in the solar electromagnetic spectrum. This spectral range is created in the solar chromosphere, chromosphere-corona transition region, and corona. These solar emissions, consisting of wavelengths shorter than 102.7 nm down to the X-rays, are absorbed in the upper atmosphere by the major neutral constituents of O, N2, and O2. These emissions are also responsible for the ionization of the E and F regions and their variation in time is one of the fundamental variables in thermospheric and ionospheric physics (Tobiska and Barth, 1990).

The International Reference Ionosphere (IRI) (Bilitza et al., 2017) and its extension to the plasmasphere (IRI-Plas) (Gulyaeva et al., 2013) are recognized as the international standard models (Gulyaeva and Bilitza, 2012). IRI represents monthly averages of electron and ion densities and temperatures in the altitude range of 50 km–2000 km. IRI-Plas – International Reference Ionosphere and Plasmasphere model includes data assimilation of Global Ionospheric Maps of Total Electron Content, GIM-TEC; the F2 layer foF2 critical frequency, proportional to NmF2 peak electron density; and the F2 layer peak height hmF2. IRI-Plas system presents modular design so that more data types can be added in the future. The system is computationally efficient capable to forecast the ionosphere state up to 24 h ahead of the assimilated data using the Spherical Harmonic Analysis based on 96 preceding hours data. The advantage of including the plasmasphere model up to 20,200 km (GPS orbit) allows an analytical conversion of the GPS-derived Total Electron Content (TEC) to foF2 and hmF2 at each grid point of the Global Ionospheric Map, GIM-TEC. In this conversion the grid points are processed in parallel. As a result, the products of IRI-Plas system include GIM_foF2, GIM_hmF2, and GIM_W-index maps of the ionosphere variability. The aims of IRI-Plas system are to produce the good nowcasts background model dependent; accurate and actionable forecasts up to 24 h ahead; and the long-term prediction of median ionosphere conditions.

The model output depends on what solar and ionospheric control parameters we set in the model. The 3D representation of electron density profile (vs latitude, longitude and height) is critically dependent on global ITU-R (former CCIR) model for the F2 peak plasma frequency,

* Corresponding author.
E-mail address: gulyaeva@izmiran.ru (T.L. Gulyaeva).

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foF2, and M(3000)F2 factor applied for product of the peak height hmF2 values computed with IRI or IRI-Plas. The (CCIR, 1983) mapping of foF2 and M(3000)F2 is based on using a special set of geographic functions in combination with harmonics in UT (Jones and Gallet, 1962). These functions are built for four levels of solar activity (12-monthly smoothed sunspot number $SSN1_{12} = 0$, 50, 100, and 150 index units) introducing interpolation in between for any other level of solar activity. Another set of URSI coefficients (Rush et al., 1989) are designed in a similar manner but improved over the less inhabited sea-surface areas.

IRI imports global effective ionospheric IG_{12} index based on ionosonde measurements of the critical frequency foF2 as a proxy of solar activity with foF2 CCIR or URSI map (Brown et al., 2017). Similarly, the global electron content, GEC, smoothed by the sliding 12-months window, GEC_{12}, is used as a solar proxy in the ionospheric and plasmaspheric model IRI-Plas. GEC has been calculated from global ionospheric maps of total electron content, GIM-TEC, since 1994 up to date whereas its productions for the preceding years and predictions for the future are made with the empirical model of GEC dependence on solar activity (Gulyaeva and Veselovsky, 2014).

The recent revision of the long-term sunspot number time series SSN2 over the period from 1818 to the present day (Clette et al., 2014) arises a need to re-evaluate solar and ionospheric control parameters of the ionospheric models (Gulyaeva, 2016). The modified sunspot number time series SSN2 significantly differ from the original long-term series SSN1. Values of SSN2 near the solar maximum are generally higher than those of the proxy solar index of 10.7 cm microwave radio flux, F10.7, which, in turn, are on average by 60 units higher than values of SSN1.

Since June 2015, the production of the International sunspot number time series SSN1 has ceased. This reform stimulated investigations on a potential new proxy solar activity to be ingested into the ionospheric models (Hocke, 2008; Maruyama, 2010; Chen et al., 2012; Gulyaeva, 2016; Perna and Pezzopane, 2016). In the present study eight solar and ionospheric proxy indices of solar activity are introduced into IRI-Plas model. The relation between the different solar proxies is described in Section 2. The regression relations between the different proxy indices smoothed by the 12-month sliding window are deduced to be applied automatically by the IRI-Plas system which allows adapt system to new reality of the modernization of the original set of the sunspot number time series for scientific engineering and telecommunication issues.

2. Relations between the different solar proxies

The long-term relation between the 12-monthly smoothed $SSN1_{12}$ and $SSN2_{12}$ sunspot numbers is established in (Gulyaeva, 2016) as

$$SSN1_{12} = 0.7 \times SSN2_{12} \quad (1)$$

The $SSN2_{12}$ activity predictions up to 2020 are based on (McNish and Lincoln, 1949) time-series analysis starting 6 months back from the current time. The option of input of $SSN2_{12}$ by IRI (from January 2014) and IRI-Plas system (from January 1948) onwards includes its conversion to $SSN1_{12}$ with Eqn. (1).

We can also derive the model relation between the solar radio flux $F10.7_{12}$ and $SSN1_{12}$ for the period of their observation (1947–2014) in terms of their variation with the phase of solar cycle, Φ (Gulyaeva and Stanislawska, 2008). Fig. 1a and b presents $F10.7_{12}$ and $SSN1_{12}$ versus the phase Φ of the solar cycle from 1947 to 2015:

$$\Phi = (T - m) / (M - m) \quad (2)$$

Here T is the month for a parameter under consideration (fractional year monthly number, e.g. 2013.9 for November 2013), m is the month of the solar minimum, M is the month of solar maximum (the pair of m and M embracing the parameter). Also, $\Phi = 0$ for solar minimum, $\Phi = 1$ for solar maximum.

The best fit in the least squares sense to the family of curves in Fig. 1a and b is expressed by the 5th order polynomial:

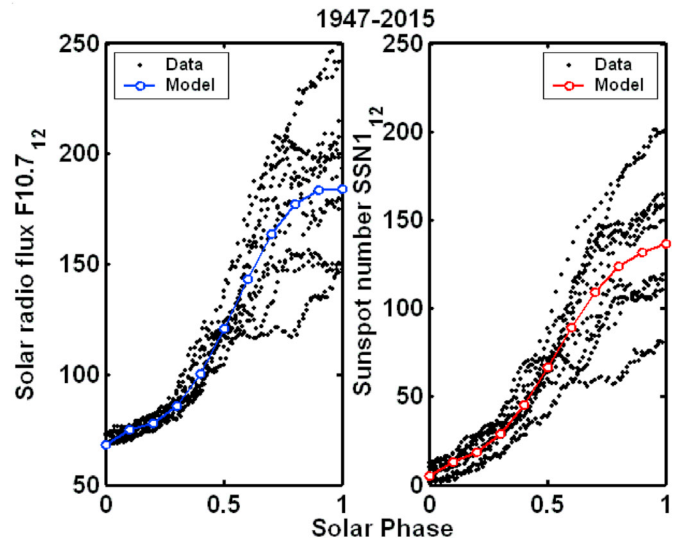

Fig. 1. Solar phase projection of (a) solar radio flux $F10.7_{12}$ in unit of 10^{-22} $Wm^{-2}Hz^{-1}$ and (b) sunspot number base series $SSN1_{12}$ in index unites, i.u. Solid lines indicate the model outputs.

$$F10.7_{12}(\Phi) = 1285.33\Phi^5 - 3559.77\Phi^4 + 3156.59\Phi^3 - 894.06\Phi^2 + 127.43\Phi + 68.34 \quad (3a)$$

$$SSN1_{12}(\Phi) = 1195.45\Phi^5 - 3197.77\Phi^4 + 2729.00\Phi^3 - 721.49\Phi^2 + 126.61\Phi + 5.01 \quad (3b)$$

The linear regression between the fitting polynomials (3a) and (3b) is plotted in Fig. 2 and expressed by Eqn. (4):

$$SSN1_{12} = 0.9802\ F10.7_{12} - 60.04 \quad (4)$$

Thus we observe that two independent solar proxies ($SSN2_{12}$ with Eqn. (1) and $F10.7_{12}$ with Eqn. (4)) are capable to produce $SSN1_{12}$ missing from 2015 onwards. Interchangeability of Eqns. (1) and (4) serves as a guarantee to overcome a risk of absence of either one of the source indices.

The two indices $SSN1_{12}$ and $F10.7_{12}$ are used by the different submodels in IRI and IRI-Plas systems. It is worth to note that the regression relationship between SSN1 and F10.7 employed by IRI and IRI-Plas models held until 2000, but after 2001 it is changed (Lukianova and Mursula, 2011). To avoid calculation of $F10.7_{12}$ from $SSN1_{12}$ designated

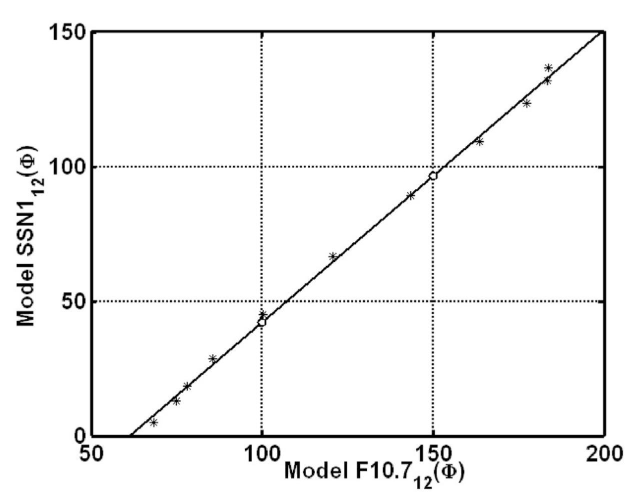

Fig. 2. Relation of solar proxy model of $SSN1_{12}(\Phi)$ with solar radio flux $F10.7_{12}(\Phi)$.