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Brazilian Ionospheric Scintillation Model (BISM)

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ABSTRACT

The ionospheric irregularities are generated at the magnetic equator after sunset due to the Rayleigh-Taylor instability, and they produce amplitude and phase scintillation in the electromagnetic signal crossing them. These post sunset to midnight irregularities at the Brazilian longitude sector occur from September to April and peak at December solstice and they are most intense and frequent during periods of high solar activity. Additionally they present a large dependence with the location and magnetic activity. The morphology of the ionospheric irregularities over Brazil was presented by some authors [1, 2, 3]. [4]and [5] provided some steps forward the prediction of amplitude scintillation at the Brazilian Southern Equatorial Ionization Anomaly (EIA) crest based on the S4 values at the magnetic equator and using a classification and regression decision tree and [6] using neural network, however they used a limited amount of S4 data. [7] developed an empirical model of the Equatorial Spread F (ESF) for IRI over Brazil using ionosonde data. An empirical ionospheric scintillation model to predict the S4 and its occurrence probability was developed using the amplitude scintillation indices S4 from 1997 up to 2015 for 30 sites over the Brazilian territory and using the Fourier, spline and least square methodologies to fit these data. The one minute average S4 data, measured by 3 networks consisting of different GNSS receivers were classified according to different solar activities, seasons, S4 intensities, Kp levels, local time and geographical positions. This work is the first one to use long term statistics of S4 occurrence [8] with the aim of developing one prediction model. The study of ionospheric scintillations is very important since they affect the positioning and navigation systems oriented by GNSS [9, 10] and also telecommunication systems that make use of satellite signal.

The GNSS signals from 3 networks (SCINTMON/CASCADE, and more recently CIGALA/CALIBRA and LISN) covering the Brazilian territory from 1997 to 2015 at 30 sites were measured at the rate of 50 Hz and the one minute S4 average values were calculated for satellite elevation angles larger than 30^o to avoid multipath and low S/N values. This data collection covers the last solar cycle 23 peak, the extended minimum solar activity and the peak of cycle 24, that was less intense than the previous one, and provided a large spatial and temporal S4 index coverage over Brazil. S4 was measured using 3 different GNSS receivers, that were Novatel (LISN), Gec-Plessey Card/Cornell (SCINTMON/CASCADE) and Septentrio

(CIGALA/CALIBRA), however results from one work under development shows that there is a reasonable agreement between S4 measured by these receivers. The statistics of these S4 data was done considering their dependence on geographical location, local time, season, F 10.7 cm solar flux and Kp, generating data samples representing different conditions. The next step of our analysis was to fit these S4 samples using 3 different methodologies that are Fourier, spline and least square using Bernstein polynomials as base functions, which are described below. Following, one comparative study of these methodologies were done. The last step was to validate the BISM model for different geophysical and spatial conditions.

Finite Fourier series, cubic-B spline and least square methods are used to reproduce separately S_4 index values. The results of these different methods are compared with experimental data to choose the best one to develop our final empirical model. Examples of empirical models developed with these respective methods were published by [11], [7] and [12]. Here, the value of S_4 index, as function of solar flux (F), geomagnetic activity (K_p), season (d), latitude (l) and universal time (t), are obtained by the following equations:

(1) Finite Fourier series:

$$S_4^{(1)}(F,K_p,d,l,t) = A_0(K_p,d,l,t) + \left(\sum_{m=1}^{n-1} A_m\left(K_p,d,l,t\right)\cos(2\pi f m\Delta) + \sum_{m=1}^{n-1} B_m\left(K_p,d,l,t\right)\sin(2\pi f m\Delta)\right),$$

where $A_m(K_p,d,l,t)$ and $B_m(K_p,d,l,t)$ are the coefficients calculated by the successive inverse Fourier transformations applied to K_p index, seasonal, latitudinal and temporal coefficients, respectively; $m=0,1,\ldots,n-1$; n= half number of solar flux nodes; $f=1/2n\Delta$ and Δ is the solar flux step.

(2) Cubic-B spline:

$$S_4^{(2)}(F,K_p,d,l,t) = \sum_{i=1}^{23}\sum_{j=1}^{12}\sum_{k=1}^{8}\sum_{l1=1}^{8}\sum_{l2=1}^{5} a_{i,j,k,l1,l2} N_{i,4}(t) N_{j,2}(d) N_{k,2}(F) N_{l1,2}(K_p) N_{l2,2}(l),$$

where $N_{i,4}(t)$ is a cubic-B spline of order four applied to time, $N_{j,2}(d)$, $N_{k,2}(F)$, $N_{l1,2}(K_p)$, $N_{l2,2}(l)$ are cubic-B spline of order two applied to seasonal, solar flux, K_p index and latitudinal dependences, $a_{i,j,k,l1,l2}$ are the monthly means of the S_4 for each interval of time, solar flux, K_p, and latitude. The number of nodes to cover the time, season, solar flux, geomagnetic activity and latitude distribution, as can be seen in the equation above, are 23, 12, 8, 8 and 5 respectively.

(3) Least squares: $S_4^{(3)}(x) = \sum_{k=0}^{n} b_k B_{k,n}(x)$,

where b_k are the general coefficients of the model and $B_{k,n}(x)$ is the Bernstein polynomial basis of degree n defined as

$$B_{k,n}(x) = \binom{n}{k} x^k (1-x)^{n-k} \quad \text{for } 0 \le x \le 1$$

In this case, the model is developed extracting different coefficient sets for all S_4 dependencies minimizing least squares functions (χ^2).

The BISM model was validated for some spatial and geophysical conditions and presented a good perfomance. It is a valuable tool to predict the ionospheric scintillation and to provide its occurrence probability, what is an important contribution to the users of GNSS for positioning and navigation.

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