Ionospheric 3D-Grid Interpolation for the Brazilian Ionosphere Dynamics Forecasting System

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Abstract

The Brazilian operational ionosphere dynamics forecasting system is based on a first principles model to estimate ionospheric parameters aligned with geomagnetic field lines. The spatial distribution of simulated points becomes sparse and non-homogeneous when converted to geographic domain. Then, a 3-dimensional homogeneous grid is constructed, and for every grid location, Inverse Distance Weighting (IDW) is applied using the simulated values in the neighbourhood. We have experienced that different number of neighbours used in grid interpolation leaded to very different TEC maps. Thus, Radio Occultation (RO) data from Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) was compared with several grids interpolated using different number of nearest neighbours for IDW. The solstices and march equinox days of 2012 were evaluated, to verify seasonal variation. For all days tested, when nearest neighbours number in a range from 100 to 200 are used in IDW, the similarity is maximized between RO observations and correspondent interpolated grid values.

Introduction

Ionosphere is an ionized atmosphere layer which plays an important role in atmospheric electrical circuits as well as in the electromagnetic wave propagation. It enables radio communication between antennas, without direct sight, using its reflective properties. Also, satellite communication is directly influenced by ionosphere, where signals can be refracted and can change their velocities when crossing it. Due to its importance in affecting technological systems on Earth, one relevant task in Space Weather area must be to use ionospheric observations, modelling and simulation. In this work, we present a modelling to construct a 3D homogeneous grid of electron density which can be applied to observational data and/or to results of physical models.

The operational ionosphere dynamics forecasting system (Petry, et al., 2013), developed at National Institute for Space Research by the Space Weather team (INPE/EMBRACE), predicts the ionosphere behaviour for 24 hour ahead using a first principles model and a post-processing system. 3-dimensional ionosphere state is evaluated in terms of the concentrations, field-aligned fluxes, and temperatures of the electrons and the O+, H+, N+, He+, N2+, O2+ and NO+ ions. The physical model runs in parallel at several different longitudes, linearly separated. The apex altitude of field lines are 10Km spaced for altitudes up to 1000Km. Above that, larger spacings are used. Physical simulation locations are aligned with geomagnetic field lines, and the conversion to geographic domain results in a set of sparse and non-homogeneously located simulation points. To better understand the ionosphere structures and to enable visualization of results and maps generation, a 3-dimensional homogeneous grid is used, and for every grid location an interpolation procedure is applied using the simulated points in the neighbourhood. The grid altitude ranges from 90km to 1000km with step of 10km, and the grid latitude and longitude covers the hole Globe using step of 1°. Figure 1 shows a 3-dimensional visualization of electron density based on grid data for the year 2012, julian day 356 at 6h UT. Different view angles from the same simulation are shown in (*a*), (*b*) and (*c*). To improve the view, low values of concentration were removed from figure 1, based on the grid's histogram analysis. Considering the total excursion of values, and dividing it in two halfs, only the points whose values belong to the highest half are shown. To highlight inner structures of simulation, that concentrate higher electron densities, it is possible to remove layers from the figures, as shown in figure 2.

Grid Interpolation Method

When the simulated data spatial distribution or resolution over the region of interest is different from that required, we can use interpolation methods to estimate values at different locations, based on data in the neighborhood. Spatial interpolation methods can be represented as a sum of weighted combination of data, as follows:

$$\hat{z}(x_o) = \sum_{i=1}^{n} \lambda_i z(x_i) \quad (1)$$

where $\hat{z}(x_o)$ is the interpolated value at x_o, λ_i are the weights applied to the $z(x_i)$ values in the neighborhood.

One of the most frequently used interpolation method in the literature, and also used to generate the 3-dimensional homogeneous grid mentioned previously, is Inverse Distance Weighting (IDW). It is straightforward to understand and implement, and basically defines the weights λ_i as inversely proportional to the distance (or a power of the distance) between the interpolation location and the value in the neighborhood:

$$\lambda_i = \left(\frac{1}{dist_{x_o,x_i}}\right)^k \quad (2)$$

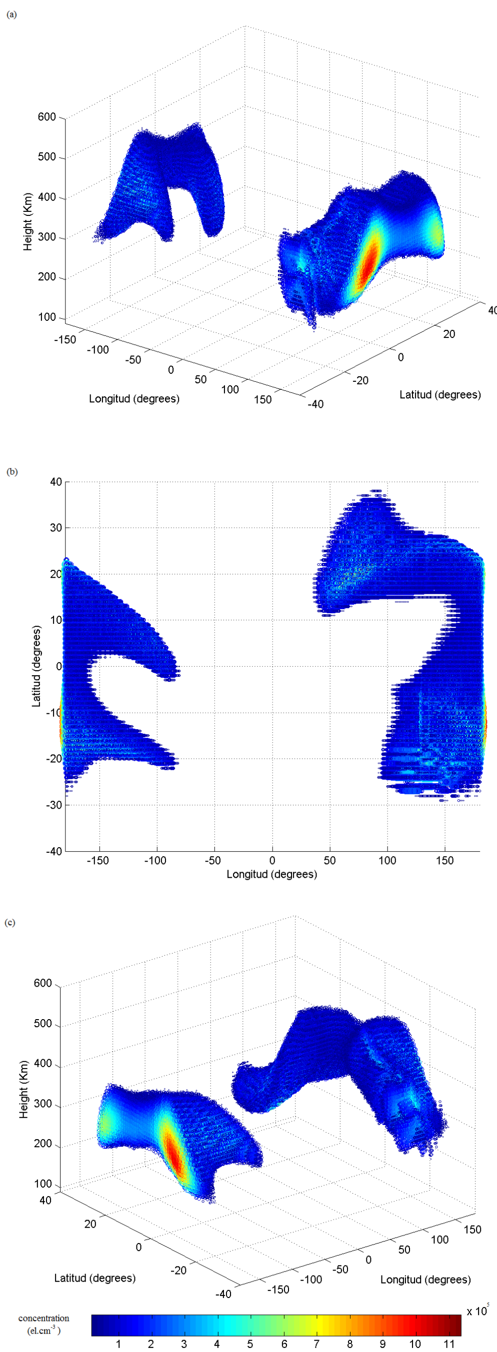

Figure 1: 3-dimensional visualization of electron density for the year 2012, day 356 at 6h UT. Different view angles are shown in (*a*), (*b*) and (*c*).

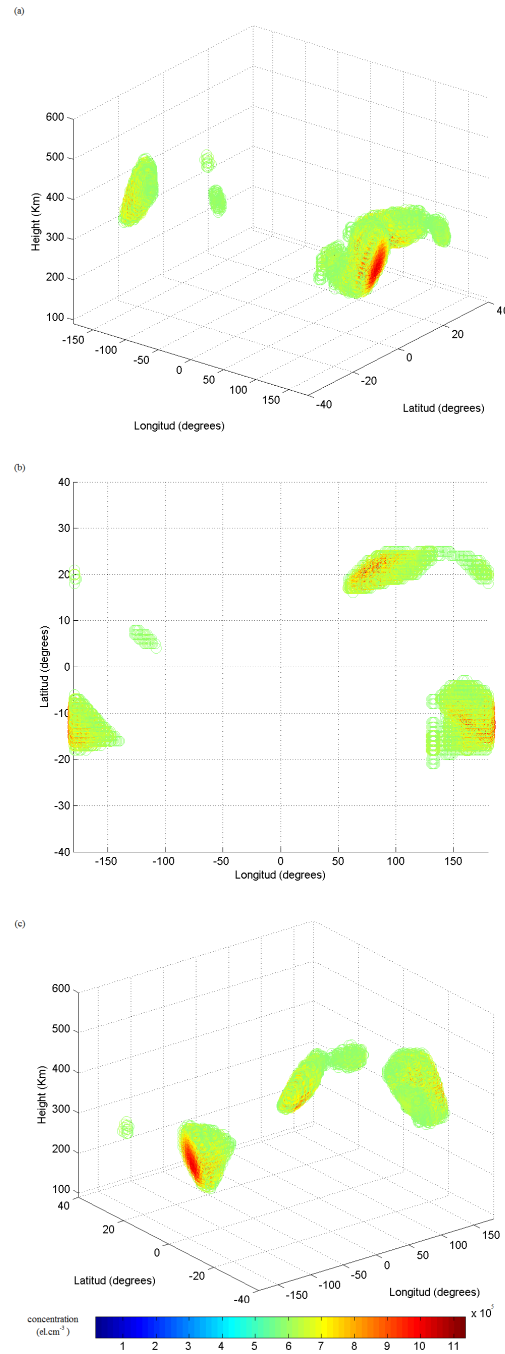

Figure 2: The same as figure 1, but highlighting the inner structures of higher electron densities.

As simulation points are aligned with geomagnetic field lines, a single simulation tends to concentrate its output in a region that covers a wide range of latitudes, but usually a small range of longitudes. Since the physical model runs in parallel at several different longitudes, linearly separated, the resulting set of simulation points are sort of clustered. Being IDW sensitive to clustering in the samples, the output interpolated grid can vary significantly when different number of neighbours are used in the interpolation procedure. Figure 3 illustrates that variation. It shows the interpolated electron density profile using different number of neighbours, for year 2012, julian day 172, 19h UT, at longitude 85° west and latitude 15° north. We can verify that the number of nearest neighbours used during the interpolation procedure can lead to different profiles. When Vertical Total Electronic Content (VTEC) is calculated from these profiles, different values are obtained. To illustrate this variation, figure 3 shows VTEC maps using (*a*) 1 and (*b*) 700 nearest neighbours during interpolation procedure for South America region, for the same day and hour of figure 3.

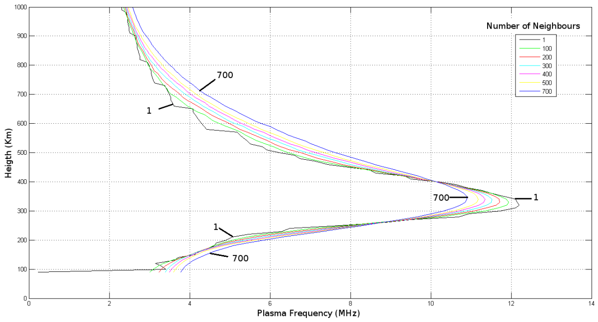

Figure 3: Interpolated electron density profile for year 2012, julian day 172, 19h UT, at longitude 85° west and latitude 15° north, using different number of nearest neighbours.

Observational Data as a Guideline

In this paper we evaluate IDW in terms of number of nearest neighbours to be used by empirically comparing interpolated grid with observational data. Radio Occultation (RO) data from Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) was compared with several grids interpolated using different number of nearest neighbours. To consider seasonal coverage, the experiments were tried for the solstices and march equinox days of 2012. All available observations that matched the simulation universal time, with 5 minutes of tolerance, were used. Figure 5(*a*) shows a 3-D view of observations for julian day 80 of 2012, at 18h UT.

For every RO measurement the closest grid location was identified. Considering the grid spacing used for altitude (10Km), latitude and longitude (1°), the maximum distance between an observation location and the correspondent closest grid location is approximately 78.8Km. Figure 5(*b*) shows a 3-D view for the correspondent grid values of figure 5(*a*), calculated using 100 nearest neighbours. It is clear that simulated values are not far from observations at all. So similarity between RO data and interpolated grid values can be quantified. For that, we used Mean Squared Error (MSE), defined as:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(RO_i - Grid_i)^2 \qquad (3)$$

where n is the number of observations available, RO_i is the i-th Radio Occultation observation and $Grid_i$ the grid value closest to RO_i.

MSE can be calculated considering all available observation data using a grid constructed with a given number of nearest neighbours for interpolation. By doing this, we can identify the appropriate number of nearest neighbours to use during interpolation procedure, that is the one whose grid comparison with RO data minimizes MSE.

Results and Discussion

The tests used the same observational data, that was compared with grids interpolated using different number of neighbours. For every grid, MSE was then calculated

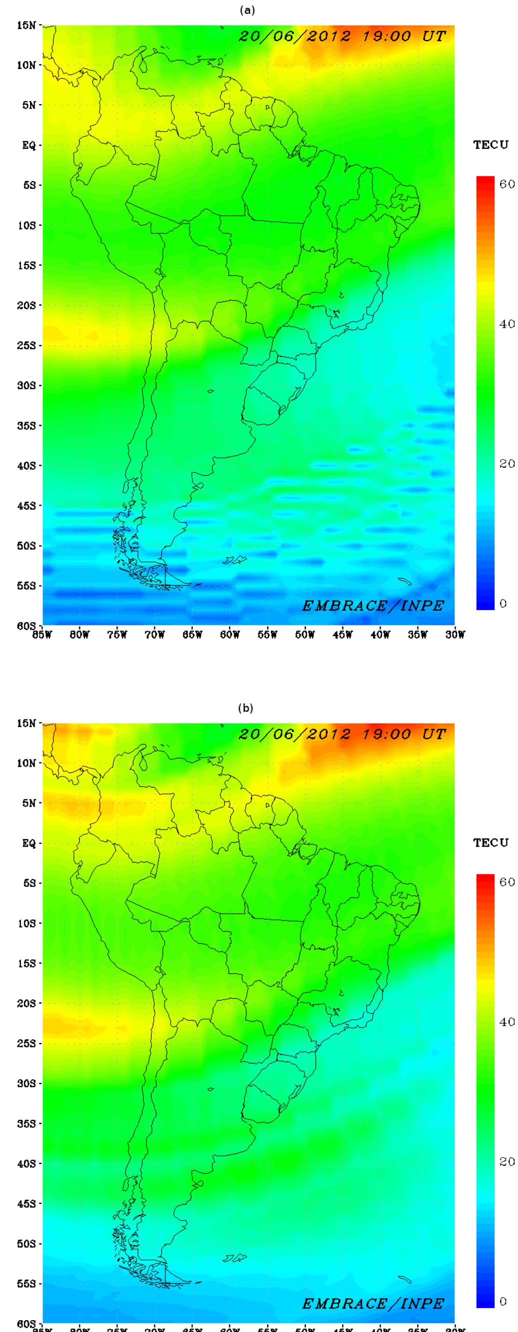

Figure 4: VTEC map for South America region for year 2012, julian day 172, 19h UT, obtained from interpolated grid using (*a*) 1 and (*b*) 700 nearest neighbours.

considering every simulated hour individually, since a different number of observational values was available for every simulated hour, but the weight of a given hour for total error calculation should not vary due to the amount of available observations. So, a total of 24 MSE values per simulated day were calculated for every grid, and these values were averaged to result the final MSE. The number of nearest neighbours tried ranged from 1 to 700, with step 100. Figure 6 summarizes the test results for the

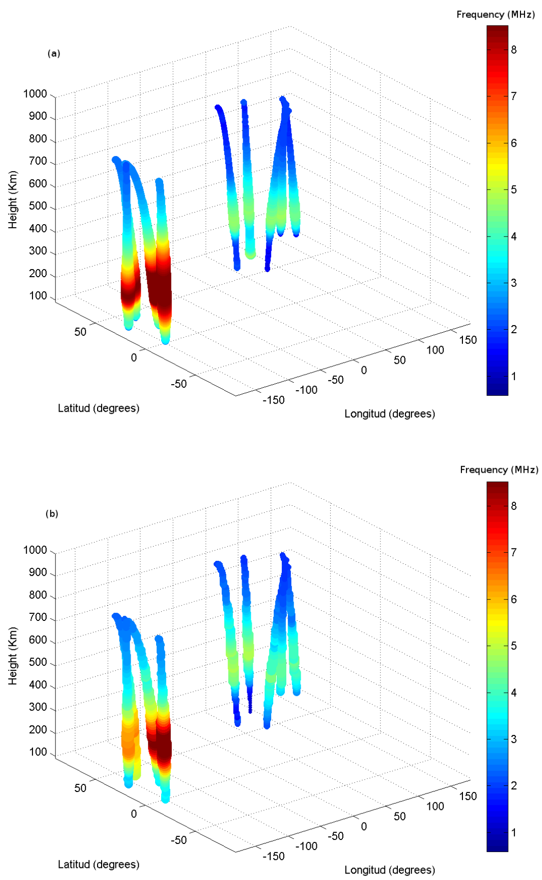

Figure 5: 3-dimensional visualization of (*a*) observed and (*b*) interpolated electron density, using 100 nearest neighbours, for the year 2012, julian day 80 at 18h UT. Besides color, the dots' radius also identify plasma frequency values.

solstices and march equinox days of 2012. Clearly, a too reduced number of nearest neighbours (1) provided grids with high MSE values, when compared with MSE value obtained using 100 or 200 neighbours. On the other hand, if the number of neighbours used is increased, the MSE increases too. So, considering the tried number of nearest neighbours, the best choice to better approximate the interpolated grid to RO data was between 100 and 200 for the days simulated.

Conclusion and Future Work

We have shown an empirical method to define the best value for the number of nearest neighbours used in 3D grid interpolation based on IDW. To verify seasonal variation, solstices and march equinox days of 2012 were simulated, and RO data from those days was used in comparisons. For every day tested, grids were interpolated using several numbers for the nearest neighbours. The tests pointed to a range between 100 and 200 neighbours as the best choice. Future work could verify the influence of the number of available simulation points and grid points. Also, not only the number of neighbours, but the power of the distance used in IDW could be evaluated.

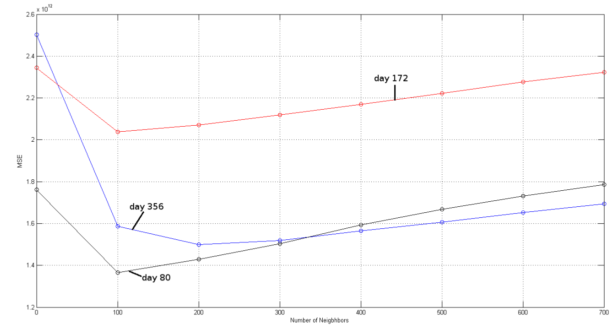

Figure 6: Average MSE for the year 2012, julian days 80, 172 e 356.

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