



Image Generation and Visualization System for Ionosphere Dynamics

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Abstract

This work shows the development of a data interpolation and visualization system for Earth's ionosphere, based on the results of an ionosphere dynamics model – the Sheffield University Plasmasphere-Ionosphere Model (SUPIM). During the system construction, several ionospheric simulation runs are performed at different geographic longitudes. These "profiles" are mapped from magnetic coordinates to geographic coordinates. Then, a data interpolation technique is proposed to obtain the ion concentration values for neighborhood of simulated points, in homogeneous grid. The resulting interpolated data is recorded in a file format that can be used on a software tool for visualization of Earth science data. Although 2-dimensional images of ionosphere Vertical Total Electron Content (VTEC) forecast can be well shown using a sequence of static images, Keyhole Markup Language (KML) codec was created, allowing more interactive data visualization also on other platforms like Google Earth.

Introduction

Data interpolation and visualization systems are designed and used in a variety of different fields, with particular needs [1]. Atmospheric data from simulation of geophysical models are used in forecast systems and represent an important area where data manipulation and visualization techniques are necessary.

Ionosphere is an important part of atmosphere that is composed by ionized atoms and molecules, basically due to solar radiation, chemical and physical interactions. Its behavior directly affects important technological systems, like global positioning systems (GPS), satellite transmissions and telecommunication. Physical models of ionosphere have been proposed, and can provide solid estimative for its dynamics. This information could be used, for example, to improve the accuracy of systems whose functioning depends on ionosphere state.

In this work, first the ionosphere model used is detailed, focusing on its main characteristics, data output and geographic mapping. These information are necessary to better understand the interpolation technique proposed here, named "exploded profiles". Its development was to

meet physical boundary conditions of data interpolation as well as to guarantee system execution in reasonable time. After, the software tools used for visualization of Earth data are shown. At last, the work is summarized and conclusion is addressed.

The ionosphere model

The Sheffield University Plasmasphere-Ionosphere Model (SUPIM) is a physics-based model implemented computationally using Fortran 77 programming language that simulates the distribution of ionization within the Earth mid to equatorial latitude ionosphere and plasmasphere. It has been developed for over 20 years by Professor John Graham Bailey from University of Sheffield, UK, and colleagues [2]. This model solves coupled time-dependent equations of continuity, momentum and energy balance along magnetic field lines for six different ions (O⁺, H⁺, He⁺, N₂⁺, O₂⁺ and NO⁺) and the electrons. Several physical and chemical processes are considered in the model like ion production due to solar radiation, production and ion losses due to chemical reactions between ions and neutral gases, ambipolar and thermal diffusion, collisions among ions and between ions and neutral elements, thermospheric winds, vertical electrodynamic drift, thermal conduction, photoelectric heating and heating due to friction [2]. Its input includes the date of simulation, the solar flux, the neutral atmosphere model, and the model of meridional and zonal wind velocities. Depending upon the inputs, the model can describe different solar cycle, seasonal, daily, and magnetic activity variations. It can also provide description of the diurnal, altitude, latitude, and longitudinal variation [3].

SUPIM outputs are basically the ion and electron densities, temperatures, and field-aligned fluxes. These outputs are given discretely in a 2-dimensional plane aligned with Earth magnetic field lines, with fixed magnetic longitude coordinate. The field lines covered are defined by the ground station geographical coordinates and the pre-defined range of altitude. Although the ground station coordinates are geographic, throughout the simulation all calculus are done in magnetic coordinates, taking in account the irregular organization of Earth's magnetic field. As a result, the simulated points are not geographically aligned, and form a twisted plane, here referred to as a "profile" of ionosphere state. Figure 1 illustrates the latitude and longitude values covered by an output of one SUPIM run. Altitude is present in the simulation, but is not represented in the figure for easy viewing. Note that the geographic location of simulated points is not aligned with geographic coordinates, but with magnetic coordinates.

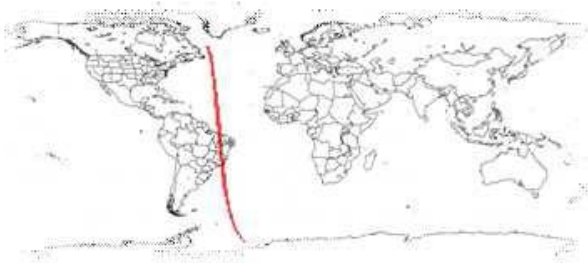


Figure 1. Latitude and longitude covered by one simulation run

Proposed data interpolation technique

The appropriate interpolation technique should consider several particularities to be successful applied to the output provided by SUPIM. Since one simulation run generates one “profile” of ionosphere state, with data aligned to the magnetic field lines that cross a specific ground station at different heights, several runs on different ground station longitudes result in various “profiles”, whose simulation points are neither geographically aligned nor homogeneously spaced. Also, the influence of simulation points is physically restricted to its neighborhood, and should not influence interpolating points far away. It is also important that the final result could be presented in a grid, with interpolated points equally spaced, using reasonable processing time. Those requirements led to the proposition of an interpolation technique, named “Exploded Profiles”, which can work with unaligned simulation points and provide variable region coverage in reasonable time.

Basically, the “Exploded Profile” technique starts by evaluating the geographic coordinate of every simulated point, and matching it to the closest point in a homogeneously spaced grid of points, as illustrates Figure 2 (a), for simulation points dark (A), grey (B) and white (C) placed over a 2-dimensional grid. Note that at this time, the number of grid points associated with at least one simulation point is less than or equal to the number of simulation points. After that, the first “explosion” can take place, where every grid point associated with at least one simulation point is spread on its neighborhood, as shown on Figure 2 (b). For the real 3-dimensional system, every “exploded” point would be transformed into a cube composed by 27 points carrying the same information about the associated simulation point. Now, there will be much more overlaps on the grid points, so one grid point would more probably carry information about more than one simulation point. The same “explosion” process can be repeated as many times as desired, always from the first grid point (the closest to the simulated point) towards its neighborhood farther and farther. Figure 3 (a) shows a second order “explosion”, resulting in 24 grid points associated with no simulation point, 29 grid points associated with only one simulation point, 16 grid points associated with two simulation points and 3 grid points that will consider all three simulation points (A, B and C). When the desired “explosion” order is achieved, a simple Inverse Distance Weighting (IDW) [5] technique can be used on every grid point, considering

the influence of only the associated simulation points, as shown Figure 3 (b), and not all simulated points.

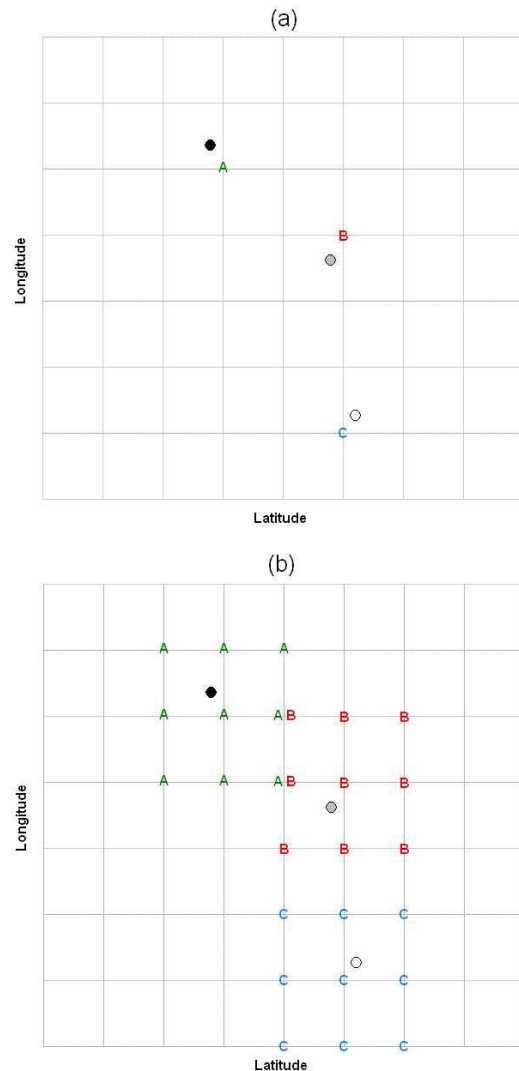


Figure 2. Grid point closer to every simulation point (a), and correspondent first order “profile explosion” (b)

The whole process results in regions of grid points interpolated, closer to the simulated points (“profiles”), but with no guarantee that all grid points will be covered. On the other hand, the higher the “profile explosion” order, the larger the area that is covered, eventually merged from separated areas resulting in a continuous area. Other interesting characteristic of this technique is that the processing load is highly reduced when compared to other similar techniques, especially when the number of points to be evaluated is much larger than the number of grid points.

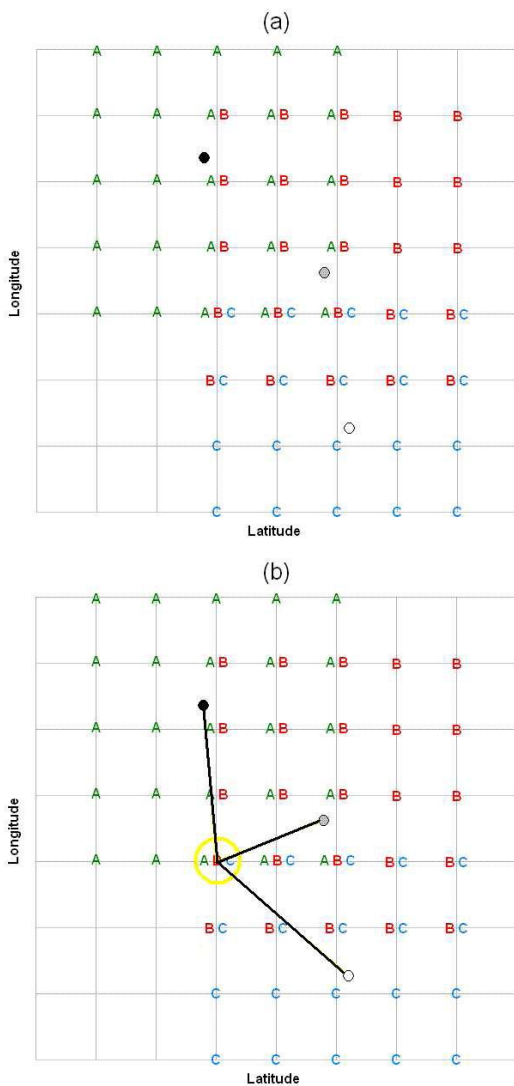


Figure 3. Second order “profile explosion” (a), and illustration of IDW using associated simulation points (b)

Figure 4 was generated using 12 different profiles, obtained from SUPIM runs on ground stations 5 degrees apart in longitude from each other, latitude 0 degrees, over South America. First order “profile explosion” was applied to the 3-dimensional grid with 1 degree resolution in latitude and longitude, and 10 Km resolution in altitude. Vertical Total Electron Content (VTEC) [6] was estimated and visualized over a geographic map using Grid Analysis and Display System (GrADS) Gridded Data Sets [7] – Figure 4 (a). Since VTEC is estimated considering the electronic sum on height, a 2-dimensional map was obtained. The same method was used for second order and third order “profile explosion”, respectively resulting in Figure 4 (b) and (c). Third order explosion shown in Figure 4 (c) provided an almost fully completed image and, due to IDW applied to merged “exploded profiles”, with smoother variation in VTEC values, when compared to Figure 4 (b).

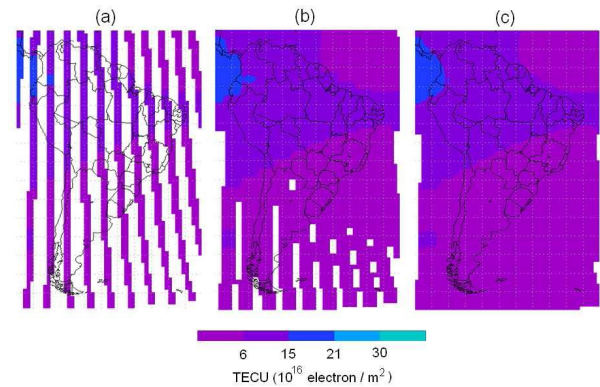


Figure 4. VTEC estimation using first order (a), second order (b) and third order (c) “profile explosions”

Processing load

The reduction of processing load of “exploded profiles” technique is significant when compared with the regular method for Inverse Distance Weighting (IDW) [5] applied on all grid points. Consider homogeneous grid covering the whole globe, composed by n grid points. Suppose that several simulation runs are performed at different locations, providing a total of m simulation points, and “exploded profiles” technique of order x is to be used. For that case, IDW complexity is $O(n.m)$, while “exploded profiles” is $O(\max(n,m.(2.x+1)^3))$. For most cases, $O(m.(2.x+1)^3)$ will overcome $O(n)$, even using small value of x . For those cases, the software complexity is linearly dependent of the number of simulation points.

Processing time was measured in a concrete case, using processor Intel Core 2 Duo P7450 @ 2.13 GHz, where a grid with 248,492 points was used, obtained with 37 latitude, 73 longitude and 92 altitude values. 23 simulation runs are performed at different locations, providing a total of 2,239,625 simulation points. Table 1 summarizes the results.

Table 1. Processing time for different interpolation methods

Interpolation Method	Processing Time
IDW alone	66360.4 s
“Exploded Profiles” order 1	8.5 s
“Exploded Profiles” order 2	31.2 s

Map visualization

When the result of a proper interpolation is obtained, it is possible to write data in specific formats in order to make use of existent software tools to better show Earth data. On this work, we used Gridded Data Sets format for data file writing, and GrADS software [7] for file loading and map generation. After that, using Keyhole Markup Language (KML) [8] the images generated by GrADS could be displayed also on Google Earth platform.

KML [8] is a file format used to display geographic data in an Earth visualization tool such as Google Earth, Google Maps, or Google Maps for mobile. KML uses a tag-based structure with nested elements and attributes and is

based on the Extensible Markup Language (XML) standard. Using KML it is possible, for example, to overlap images on Google Earth globe using tag <GroundOverlay> for interactive visualization. The image on Figure 5 illustrates a simple superposition on Google globe using an image generated similarly to Figure 4, but using 24 different profiles, obtained from SUPIM runs on ground stations 15 degrees apart in longitude from each other, latitude 0 degrees, over the whole globe. First order "profile explosion" was applied to the 3-dimensional grid with 5 degrees resolution in latitude and longitude, and 10 Km resolution in altitude. VTEC [6] was then estimated, data was recorded on a Gridded Binary Data file and a correspondent Data Descriptor file was also generated. GrADS generated the image files, that were used on a KML code.

Using KML it is also possible to create animations for a time interval, where multiple images are shown associated with time or date ranges. It is done using tag <TimeSpan> that determines the beginning and ending time that the images will be superimposed.

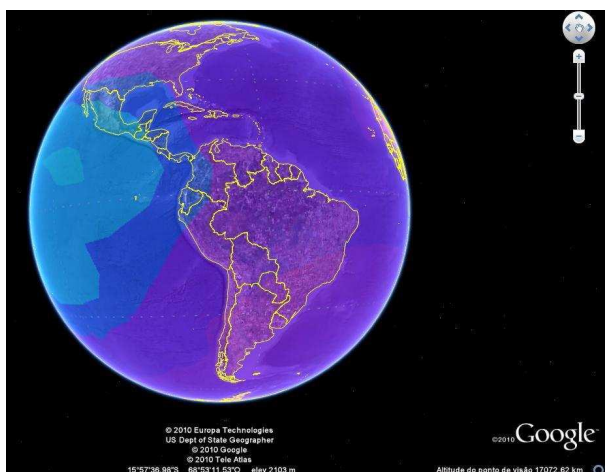


Figure 5. Image superimposed on Google Earth software

Conclusions

This work presented the development of an image generation and visualization system for ionosphere dynamics that uses data provided by SUPIM code. An interpolation technique was proposed that matches specific characteristics of SUPIM output runs, and is capable of generating a complete image of ionosphere content by merging several "profiles", at reasonable time. Different formats for Earth data codification and visualization were used: GrADS Gridded Data Sets and KML formats, which enabled the results to be visualized using Google Earth software. Further work can be addressed to compare the results obtained with our approach with similar ionosphere modeling systems.

Acknowledgments

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