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Advances in Space Research xxx (2014) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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First results of operational ionospheric dynamics prediction for the Brazilian Space Weather program

Adriano Petry [a,*], Jonas Rodrigues de Souza [b,1], Haroldo Fraga de Campos Velho [c,2], André Grahl Pereira [d,3], Graham John Bailey [e]

[a] Southern Regional Space Research Center, National Institute for Space Research, Santa Maria, RS, Brazil
[b] Aeronomy Division, National Institute for Space Research, São José dos Campos, SP, Brazil
[c] Associated Laboratory for Computing and Applied Mathematics, National Institute for Space Research, São José dos Campos, Brazil
[d] Informatics Institute, Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[e] Department of Applied Mathematics, University of Sheffield, Sheffield S3 7RH, UK

Received 28 August 2013; received in revised form 19 February 2014; accepted 14 March 2014

Abstract

It is shown the development and preliminary results of operational ionosphere dynamics prediction system for the Brazilian Space Weather program. The system is based on the Sheffield University Plasmasphere–Ionosphere Model (SUPIM), a physics-based model computer code describing the distribution of ionization within the Earth mid to equatorial latitude ionosphere and plasmasphere, during geomagnetically quiet periods. The model outputs are given in a 2-dimensional plane aligned with Earth magnetic field lines, with fixed magnetic longitude coordinate. The code was adapted to provide the output in geographical coordinates. It was made referring to the Earth's magnetic field as an eccentric dipole, using the approximation based on International Geomagnetic Reference Field (IGRF-11). During the system operation, several simulation runs are performed at different longitudes. The original code would not be able to run all simulations serially in reasonable time. So, a parallel version for the code was developed for enhancing the performance. After preliminary tests, it was frequently observed code instability, when negative ion temperatures or concentrations prevented the code from continuing its processing. After a detailed analysis, it was verified that most of these problems occurred due to concentration estimation of simulation points located at high altitudes, typically over 4000 km of altitude. In order to force convergence, an artificial exponential decay for ion–neutral collisional frequency was used above mentioned altitudes. This approach shown no significant difference from original code output, but improved substantially the code stability. In order to make operational system even more stable, the initial altitude and initial ion concentration values used on exponential decay equation are changed when convergence is not achieved, within predefined values. When all code runs end, the longitude of every point is then compared with its original reference station longitude, and differences are compensated by changing the simulation point time slot, in a temporal adjustment optimization. Then, an approximate neighbor searching technique was developed to obtain the ion concentration values in a regularly spaced grid, using inverse distance weighting (IDW) interpolation. A 3D grid containing ion and electron concentrations is generated for every hour of simulated day. Its spatial resolution is 1° of latitude per 1° of longitude per 10 km of altitude. The vertical total electron content (VTEC) is calculated from the grid, and plotted in a geographic map. An important feature that was implemented in the system is the capacity of combining observational data and simulation outputs to obtain more appropriate initial conditions to the ionosphere prediction. Newtonian

* Corresponding author. Address: Av Roraima, s/n, campus UFSM, prédio do INPE, sala 2014, Caixa postal n. 5021, CEP 97105-970, Santa Maria, RS, Brazil. Tel.: +55 55 33012011.

E-mail addresses: adriano.petry@crs.inpe.br (A. Petry), jonas@dae.inpe.br (J.R. de Souza), haroldo@lac.inpe.br (H.F. de Campos Velho), andre.grahl.ai@gmail.com (A.G. Pereira), g.bailey@sheffield.ac.uk (G.J. Bailey).

[1] Tel.: +55 12 3945 7162.
[2] Tel.: +55 12 3945 6547.
[3] Tel.: +55 51 3308 6168.

http://dx.doi.org/10.1016/j.asr.2014.03.017
0273-1177/

relaxation method was used for this data assimilation process, where ionosonde data from four different locations in South America was used to improve the system accuracy. The whole process runs every day and predicts the VTEC values for South America region with almost 24 h ahead.

Keywords: Ionosphere; Space weather; Total electron content; Operational system

1. Introduction

Considering the coupled system Earth–Sun, solar events have impact on the Earth's environment. With propagation to the heliosphere, they can change the plasma concentration, magnetic fields, and radiation. The study, monitoring, and description of such changes for the Earth–Sun system are nowadays called *Space Weather*. There are two main interests in this activity: scientific research and applications.

An important space weather activity concerns ionosphere monitoring and forecasting. The ionosphere state can vary significantly within one hour period, what may impact several human technological systems, including high-frequency communication, and systems based on Global Positioning System (GPS) satellites. Substantial effort has been made to estimate the ionosphere electronic content from empirical and physics-based models as well as observed data. In this context, International Reference Ionosphere (IRI) model has been used in several works like (McNamara, 1984; Ezquer et al., 1997; Sethi et al., 2011), which compared estimated total electron content (TEC) against other models or observations. However, it seems that scientific community has found that the most reliable way to estimate and forecast dynamic systems like ionosphere is based on data assimilation techniques combined with a physics-based model. Different data assimilation techniques and models were tried (Angling and Cannon, 2004; Bust et al., 2004; Angling and Khattatov, 2006), but we can highlight the initiatives to develop and operate two different systems with similar names and the same acronym (GAIM): the Global Assimilation of Ionospheric Measurements (Schunk et al., 2004, 2005; Scherliess et al., 2006, 2009) and the Global Assimilative Ionospheric Model (Wang et al., 2004; Hajj et al., 2004; Mandrake et al., 2005; Liu et al., 2005; Komjathy, 2010). They were developed by different teams, but both are based on a physics-based model, use large amount of observational data – basically from ground-based GPS measurements, ionosondes and COSMIC satellites through radio occultation, and have implemented the state-of-the-art in data assimilation techniques.

The Brazilian Space Weather program was officially started in 2007, and one important activity is the development of an operational system to predict the ionosphere dynamics. Sheffield University Plasmasphere–Ionosphere Model (SUPIM) was used as a starting point. Several enhancements have been implemented in the code, and pre and post-processing procedures were developed and tested. A data assimilation technique was also implemented and tested using ionosonde data. This paper details this effort that resulted in an operational system for daily forecast of ionospheric parameters.

2. Physical model

SUPIM is a first-principles model of the Earth's Ionosphere and Plasmasphere that has been developed over the last three decades (Bailey and Sellek, 1990; Bailey et al., 1993; Bailey and Balan, 1996; Souza et al., 2000, 2010, 2013). In the model, coupled time-dependent equations of continuity, momentum, and energy balance are solved along closed magnetic field lines to calculate values for the concentrations, field-aligned fluxes, and temperatures of the electrons and of the O^+, H^+, N^+, He^+, N_2^+, O_2^+ and NO^+ ions. SUPIM includes numerous physical and chemical processes, and simulates the ionosphere and plasmasphere behavior for geomagnetically quiet periods. The main processes used in the model are: ion production due to solar EUV radiation, ion production and loss due to chemical reactions between the constituent ions and neutral gases, ambipolar and thermal diffusion, ion–ion and ion–neutral collisions, thermospheric meridional and zonal winds, electromagnetic drift ($E \times B$ drift), thermal conduction, photoelectron heating, frictional heating, and a host of local heating and cooling mechanisms (Bailey and Balan, 1996). In the present work, the geomagnetic field is represented by a tilted centered dipole with the angle of tilt and magnetic declination angle given by International Geomagnetic Reference Field (IGRF) 2011 model (Finlay et al., 2010). For SUPIM model, a series of input parameters are provided to enable the running process and simulation at a given day. These inputs are basically: date/time desired for simulation, magnetic field, neutral atmosphere, termospheric neutral wind, vertical drift and information about solar fluxes at different frequency bands (EUV, F10.7 and F10.7A). For simulation at future days we used Solar2000 empirical solar irradiance model and forecast tool (Tobiska et al., 2000) to give us a good estimative for solar fluxes (EUV, F10.7 and F10.7A) at future days. All these input parameters, except the magnetic field, depend on the F10.7 and F10.7A values.

2.1. Code stability

We have frequently noticed numerical instability in the SUPIM code, mainly for period of low solar activity, when negative ion temperatures or concentrations have been