A Community Wide Ionospheric Modelling Challenge

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Abstract

This paper describes the results of an open coordinated ionospheric model challenge. This challenge has compared empirical, physics-based and data assimilation models during extremely quiet solar conditions. The models have been compared by their ability to specify electron density profile peak parameters (foF2 and hmF2) as well as the total electron content (TEC). It is shown that the data assimilation models perform the best, but all models struggle during the test scenario.

1. Introduction

There are a wide range of ionospheric models in active use and development around the globe, utilizing a number of modelling techniques. The models can be split into three categories: empirical, data assimilation and physics-based. The ability of these models to provide electron density profiles below the peak of the F2 layer, and the total electron content (TEC) is compared. The developed scenario is a month-long extremely quiet solar period. Previous coordinated test scenarios include Shim et al. [1] and Feltens et al. [2]. However these test scenarios were for relatively short time periods. The advantage of using a longer time period is to provide a more robust statistical analysis.

2. Models

Empirical, data assimilation and physics-based models have been compared. A short description of each model and a reference for more information can be found below:

IRI: The International Reference Ionosphere (IRI) is an empirical monthly median model, widely used due to relative ease, speed and generally acceptable level of validity [3].

IRTAM: The IRI Real-Time Assimilative Mapping (IRTAM) is a data assimilation model which assimilates Digisonde data into IRI in real-time [4].

NeQuick: NeQuick is a quick-run empirical model, able to represent the median conditions of the ionosphere and particularly designed for trans-ionospheric propagation applications [5].

NeQuick Data Ingestion (DI): NeQuick DI is a modified version of NeQuick which assimilates Global Navigation Satellite Systems (GNSS)-derived TEC data and profile peak parameters from ionosondes [6].

EDAM: The Electron Density Assimilative Model (EDAM), which assimilates GNSS TEC and ionosonde information into an IRI-2007 background model [7].

TIE-GCM: The Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM) is a non-linear 3D physics-based thermosphere/ionosphere model which solves the continuity, energy and momentum equations at each time step [8].

GITM: The Global Ionosphere Thermosphere Model (GITM) is a physics-based 3D global thermosphere/ionosphere model that solves the full Navier-Stokes equations for density, velocity and temperature for a number of components at each time step [9].

CTIPe: The Coupled Thermosphere Ionosphere Electrodynamics (CTIPe) model solves the non-linear primitive equations of momentum, energy, and continuity on a 3D spherical polar grid rotating with the Earth [10].

SAMI3: Is a physics-based ionospheric model which relies upon an empirical neutral density model. The model calculates the plasma and chemical evolution of seven ion species [11].

UPC TOMION: The Universitat Politècnica de Catalunya TOmographic Model of the IONosphere (UPC TOMION) is an assimilative TEC model, combining voxel-based ionospheric tomography with Kriging interpolation [12].

USU-GAIM: The Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) Model is a physics-based data assimilation model. The model assimilates bottom-side electron densities from ionosondes, slant TEC, in situ measurements of electron density and line-of-sight UV emissions [13]

3. Test Scenario

3.1 Introduction

An extremely quiet time test scenario has been developed for comparing ionospheric models. The scenario has been presented at international conferences to encourage wide spread community involvement [14].

3.2 Time Period

The analysis interval for this study is from the 8th December 2008 to January 7th 2009. This particular time range was chosen to coincide with very quiet solar conditions. Across the whole month the F10.7 only varies between 68 and 71 flux units and the largest spike in Ap was 22 (Figure 1), which is considerably lower than the storm threshold value of 29 [15]. The average sunspot number for the period was one. Previous work has shown that the recorded F10.7 values for this time period are not representative of the true thermospheric conditions [16].

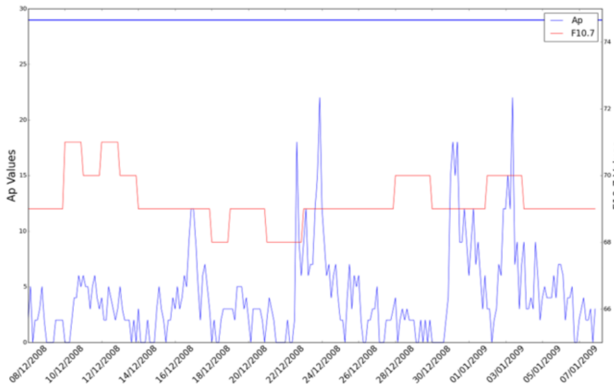

Figure 1. Ap and F10.7 values for test period (Dec 2008 - Jan 2009)

A whole month is used for the test period giving a maximum of 2880 data points when the models are run with a 15-minute time step. A large number of data points reduce the confidence intervals on the error statistics which allows for statistically significant comparisons. Previous coordinated test scenarios include Shim et al. [1] and Feltens et al. [2]. Shim compared a large number of models; however the testing scenarios were only for 1 to 2 days, with a model cadence of 30 minutes. This leads to very few data points (48 – 100) and associated uncertainty in the results. Feltens used month long tests, but only compared four models in terms of differential slant TEC.

3.3. Testing Parameters

The models are compared in terms of the accuracy of their profile shape and their ability at specifying the total electron content (TEC). 3D models, such as EDAM, have both their profiles and TEC output tested; however, 2D models, such as TOMION only have their TEC tested.

To compare the profile shape two parameters are investigated: foF2 and hmF2. These are standard metrics which have been used in other analyses (e.g. [1], [2], [17]–[19]). It is not possible to get absolute TEC values from GNSS measurements for model comparison. This is due to differential code biases (DCBs). Therefore Feltens et al. [2] used differential slant GPS TEC (dSTEC). This is defined as the difference between the slant TEC to points along a phase continuous measurement arc and the slant TEC at the highest elevation of the GPS satellite (Figure 2). Since dSTEC is not an instantaneous measurement it tests both spatial and temporal variations. Differential GPS techniques measure relative TEC to an accuracy of better than 0.1 TECU [2].

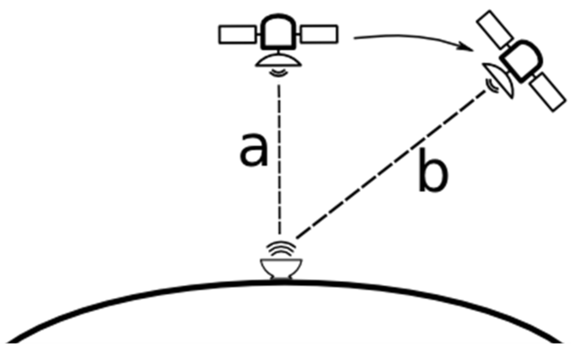

Figure 2. Differential slant TEC (dSTEC) is the difference between the TEC at the satellites highest elevation to a receiver (path ‘a’) compared with each point a long a phase continuous arc (e.g. path ‘b’).

3.4. Data

Data from the ionosonde stations at Chilton, Juliusruh and Pruhonice and a selection of European GNSS stations (Figure 3) can be assimilated into the models (where possible). The models’ profiles parameters are then compared with data from the Dourbes ionosonde in Belgium. The dSTEC is compared to observations from the nearby (~40 km) REDU GNSS station. Data from both the Dourbes ionosonde and the REDU GNSS receiver are not assimilated into the models.

All the ionosonde observations for assimilation were automatically processed (autoscaled) by ARTIST-5 [20]. Although the ionosondes are well maintained and ARTIST-5 is a significant advance on earlier versions of ARTIST, there are still some autoscaling mistakes. To simulate how the models would run operationally this data has been left in the test scenario and the different models may employ different techniques to deal with it.

The Dourbes ionograms, used as truth, were hand scaled to remove autoscaling errors. The dSTEC data was compiled and provided by Manuel Hernández-Pajares at the Polytechnic University of Catalonia (UPC).

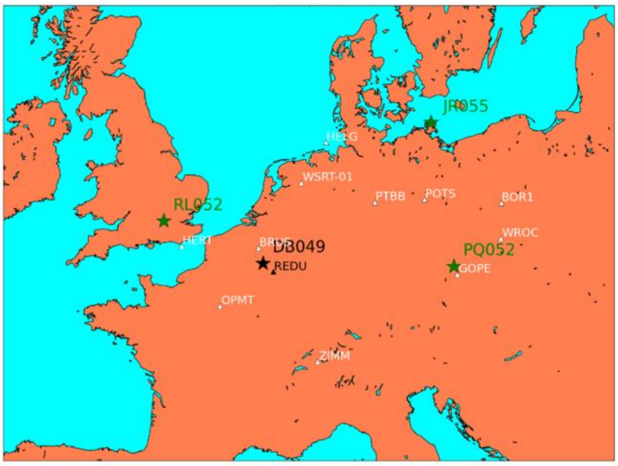

Figure 3. Map of the test scenario. Stations in green are the ionosondes to be assimilated (if possible). Stations in white are GNSS stations to assimilate, and the two stations in black are the stations where the comparisons are made.

4. foF2 Results

foF2 performance across the test scenario is similar to previous analyses (e.g. [21]) (Figure 4). The data assimilation models (EDAM, NeQuick Data Ingestion (DINeQ) and IRTAM) perform the best and similarly (closest to the star which represents a perfect model). These models have a correlation coefficient of approximately 0.95 with the observations and a standard deviation very close to the observations. However, EDAM is positively biased (approximately 0.5 MHz), IRTAM is negatively biased (approximately -0.5 MHz) and DINeQ is only very slightly positively biased (approximately 0.1 MHz). The other data assimilation model, USU-GAIM (GAIM), performs more poorly (0.85 correlation and standard deviation much smaller than the observations) than the other three. This is due to the type of data assimilated: this version of GAIM only assimilates TEC data rather than profile peak parameters so it is not expected to have as good foF2 performance. The empirical models (IRI-2007, IRI-2012 and NeQuick) perform the next best. These have a correlation coefficient of ~0.87. However all the models show a negative bias (>-0.6 MHz) and there is a large spread of the models' standard deviations. IRI-2007 has a standard deviation close to unity, whereas NeQuick has a standard deviation of approximately 1.3 MHz.

The models which perform the worse are the physics-based models: IFM, TIE-GCM and CTIPe. These models have the lowest correlation coefficients of ~0.8. However, the models' standard deviations are close to observation and the biases of the models are relatively small.

It should be noted that compared to other test comparisons the models all perform worse than they usually do [17], [18]. This is due to the particularly difficult conditions (extremely quiet) during this scenario.

Figure 4 also includes results based on the Chilton ionosonde (RL052). This point represents a model which forecasts that the profile above Dourbes is exactly the same as that at Chilton. The Chilton and Dourbes ionosondes are ~400 km apart which is within the expected mid-latitude correlation length of the ionosphere [22]; hence the very good performance of this model.

The test results of the models are artificially improved because of cyclostationary nature of the foF2 driven by the diurnal solar illumination. The correlation coefficients are dominated by the periodic variability and it is necessary to examine the day and night independently to get a realistic measure of the models' performance. Therefore analysis has also been done on separate day (0900 – 1500 LT) and night (2100 – 0300 LT) times. The daytime results show all the models performing much worse. The largest correlation is now 0.7 (DINeQ) and the lowest just 0.1 (TIE-GCM). This is compared to between 0.75 and 0.95 correlation for the 'all times' analysis. All the models also underestimate the standard deviation of the observations.

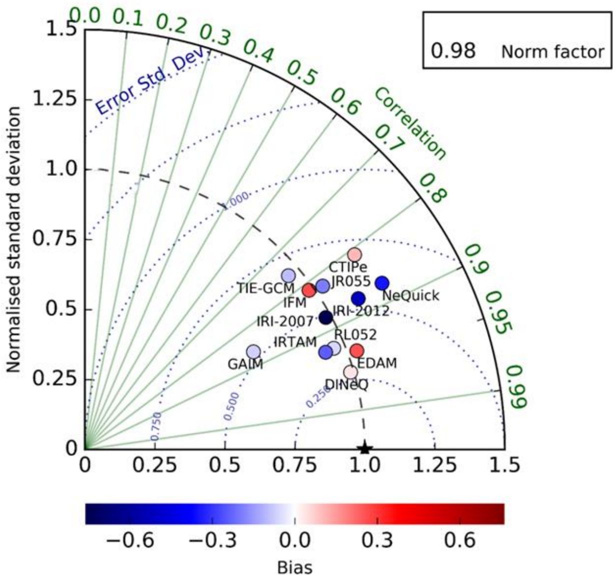

Figure 4. Modified Taylor diagram [18] showing foF2 statistics for IRI-2007, IRI-2012, NeQuick, TIE-GCM, CTIPe, IFM, EDAM, GAIM, NeQuick Data Ingestion (DINeQ), IRTAM and the three nearby ionosondes.

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