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# ANIMo — A New Ionospheric Model. Ionospheric Modeling for Ionospheric Imaging and Forecasting Purposes

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Additional information is available at the end of the chapter

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## 1. Introduction

Ionospheric tomography is a powerful technique for studying and monitoring the upper atmosphere and its dynamics. This is extremely relevant to attempts made to reduce vulnerabilities of Global Navigation Satellite System (GNSS) signal propagation due to the presence of ionospheric charged particles. The concentration of the latter can be measured by considering time and phase delays of GNSS signals. By integrating the measured density values, it is possible to calculate the Total Electron Content (TEC) along a specific signal path. Ionospheric tomography uses GNSS TEC observations in order to compose three dimensional reconstructions of the ionosphere through an operation called inversion. In contrast to other applications (e.g. medical or industrial), ionospheric tomography cannot rely on a designed scanning instrument. Satellites and receivers do not entirely surround the ionosphere, therefore providing an incomplete scan-geometry. Furthermore, GPS ground-receivers are distributed unevenly on the earth's surface which translates to poor data coverage, resulting in a lack of necessary information. MIDAS (Multi-Instrument Data Analysis System) [1, 2] is an ionospheric tomography software package developed at the University of Bath by the INVERT group. In order to overcome the limitations due to poor data coverage, MIDAS is assisted by external information. To date, empirical models are utilized to support the inversion in MIDAS algorithms, especially in relation to the missing vertical information. The idea behind this project is to implement a purely physics-based ionospheric model into MIDAS; ANIMo was built for this intent, which may be applied in different modes. ANIMo can simply be used to substitute erroneous reconstructions or to aid the inversion by adding

sensible vertical information. Besides, ANIMo, together with TEC observations, is expected to be the background model in a DA scheme within MIDAS. The goal is not only to improve ionospheric tomography reconstructions but also to perform short-term forecasting.

Section 2 illustrates ANIMo features and its anatomy. Sections 3 and 4 are dedicated to ANIMo validation and sensitivity tests and their results respectively. Conclusions are presented in Section 5.

## 2. ANIMo

### 2.1. Requirements and assumptions

ANIMo is a physics-based ionospheric model. This characteristic is very important for reaching the aforementioned goals. The advantages of using a first-principle model are various. Firstly, it is preferable to avoid using empirical models in a DA approach, especially when forecasting. Secondly, the usage of a physical model will permit to have more control and awareness on the analysis produced by the DA scheme. This includes, for example, the possibility of simulating specific unsettled conditions and studying their evolution. Further, specific requirements for this model are robustness and stability. These features keep the model reliable also in extreme conditions. In general, the model assumes that the chemical processes of the ion species  $O^+$ ,  $NO^+$  and  $O_2^+$  and the transportation process of the ambipolar diffusion are sufficient to describe the electron density evolution in mid latitude regions. In order to maintain the mentioned requirements and reach a certain level of accuracy, ANIMo was intentionally developed to avoid complexity by taking into account these principal ionospheric processes.

### 2.2. Description

ANIMo is a global model – it solves a three dimensional grid of latitude, longitude and altitude, and is mainly used for mid-latitude regions. It solves the continuity equation only for the ion species  $O^+$  for a given vertical profile:

$$\frac{\partial [O^+]}{\partial t} = Q - L([O^+]) - \frac{\partial ([O^+]_v)}{\partial z} \quad (1)$$

The production rate  $Q$  is calculated by considering the geometry of solar radiation and the relative Extreme Ultraviolet spectra provided by the EUVAC model from Richards, Fennelly and Torr [3, 4]. Together with lists of data from Fennelly and Torr [5], EUVAC supplies absorption and ionization cross section values. The chemical rates used for the calculation of the loss term  $L$  are provided by the work of Torr and Torr [6]. The latter and the EUVAC model are also used to self-consistently calculate the density values of the minor species  $NO^+$  and  $O_2^+$ . The transportation term,  $\partial([O^+]_v)/\partial z$ , considers mainly the vertical ambipolar diffusion. A continuous downward flux of particles is included as the topside boundary condition. The value of this flux can vary, but it is generally around  $1 \times 10^{11} \text{ m}^{-2}\text{s}^{-1}$ . The standard value of the

ion-neutral ( $O^+-O$ ) collision frequency given by Salah [7] is used in the calculation of the vertical diffusion velocity. During day-time the velocity is corrected to provide a day-time maintenance adjustment. The neutral densities are given by the MSIS model [8], in particular, by one of its latest versions NRLMSISE-00 [9]. The ion and electron temperatures are provided by the International Reference Ionosphere (IRI) model [10], whose latest available (IRI 2012) version is also used. The model assumes that the sum of the major ion densities ( $O^+$ ,  $NO^+$  and  $O_2^+$ ) is equal to the electron density. Its outcomes are therefore ion and electron densities profiles included between 80 and 600 km altitude.

The closest existing model to ANIMo is the FLIP (Field Line Interhemispheric Plasma) by Richards et al. [11]. The similarity is to be searched mainly in the modelling of the chemical dynamics.

### 3. Validation

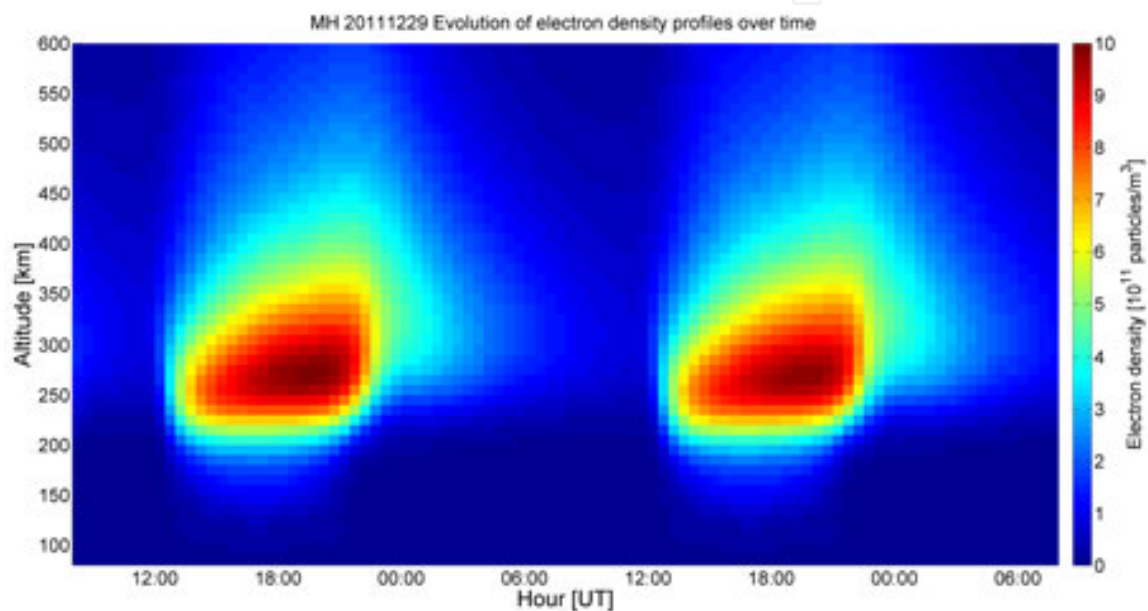
The validity of the model was tested against different instruments and other ionospheric models. In this document four validation tests are presented. For all of them, the simulation was set in order to reproduce the vertical profile above the location of the Millstone Hill Haystack Observatory (Lat.  $42^\circ$  Long.  $288^\circ$ ) from an altitude of 80 to 600 km in 10 km steps. This allowed comparison of the model with measurements from the local Incoherent Scatter Radar (ISR) and ionosonde. Furthermore, the location was chosen in the past for the inter-comparison of physical models by the Ionospheric-Thermospheric community [12]. A geomagnetic unperturbed period with medium-low solar intensity was chosen for all experiments. Table 1 reports details about the selected case studies.

Case study	Validation test parameters (Input parameters)		
	Dates	Ap	F10.7
Winter	29-30/12/2011	9 - 7	142.3 - 136.4
Spring	09-11/03/2010	2 - 9 - 10	76.8 - 79.3 - 83.1
Summer	23-25/06/2011	18 - 11 - 6	99.5 - 99.4 - 96.7
Autumn	07-08/09/2010	10 - 11	77.3 - 75.6

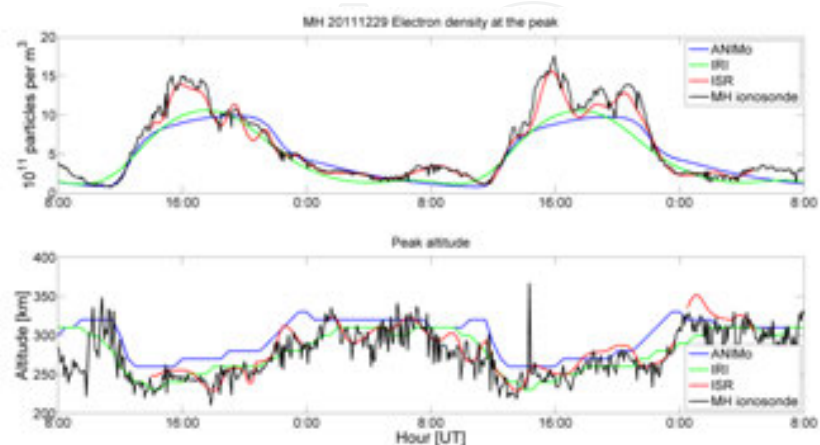
**Table 1.** Details about the presented case studies for the validation test. They correspond, together with the selected location (geographic latitude and longitude), to the used input parameters. ANIMo is able to retrieve Ap and F10.7 parameters automatically.

Figures 1-5 show the evolution of the modelled profiles by ANIMo (blue solid line in Figures 2-5) for a few days, where the outcomes were saved every half-hour. In particular, Figure 1 shows the evolution of the whole electron density profile over the selected time. In Figures 2-5, IRI 2012 (green solid) simulations, Millstone Hill ISR (red solid) and ionosondes (black solid) measurements are also plotted. The latters (Fig. 2-5) show the comparison in terms of

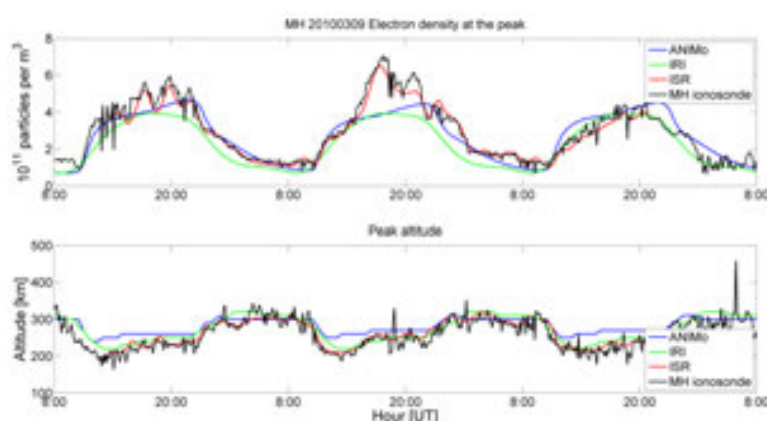
electron density at the peak (NmF2) and peak altitude (hmF2). The choice of the comparison criteria was determined by two factors. First, it is vital that the model performs well for the above terms in order to support ionospheric tomography imaging. Secondly, this is good practice in ionospheric models comparison [12]. ANIMo (solid blue) in general behaves well. It is able to reproduce day-night variations, and as illustrated collectively by the graphs, it also senses seasonal ones. The summer and autumn tests (Fig. 4, 5) show that ANIMo slightly underestimates the electron density at the peak height. Regarding the peak altitude, it tends to overestimate during night-time. Both biases can be corrected by modifying top-side boundary conditions and day-time maintenance adjustments.



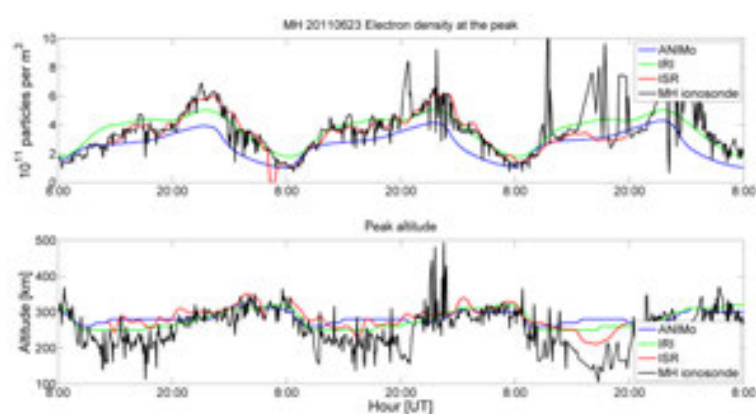
**Figure 1.** The plot shows the evolution of the electron density profile produced by ANIMo for the winter case.



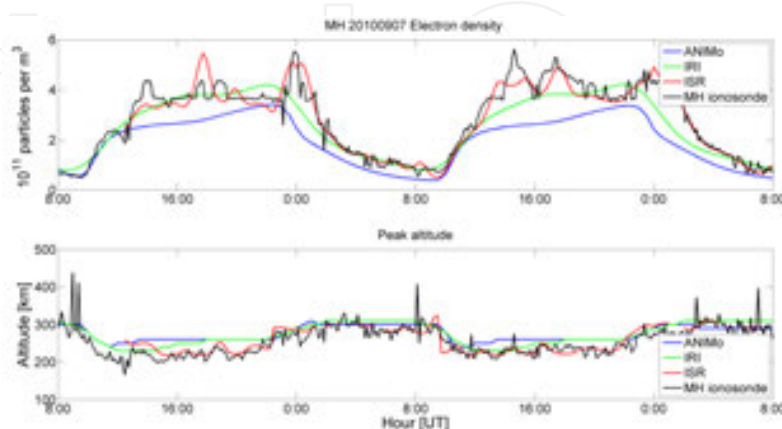
**Figure 2.** Validity test (winter case). The graphs show, respectively, the comparisons of electron densities at the peak and peak heights produced by ANIMo, modelled by IRI 2012 and measured by Millstone Hill ISR and ionosonde.



**Figure 3.** Validity test (spring case). The graphs show, respectively, the comparisons of electron densities at the peak and peak heights produced by ANIMo, modelled by IRI 2012 and measured by Millstone Hill ISR and ionosonde.



**Figure 4.** Validity test (summer case). The graphs show, respectively, the comparisons of electron densities at the peak and peak heights produced by ANIMo, modelled by IRI 2012 and measured by Millstone Hill ISR and ionosonde.

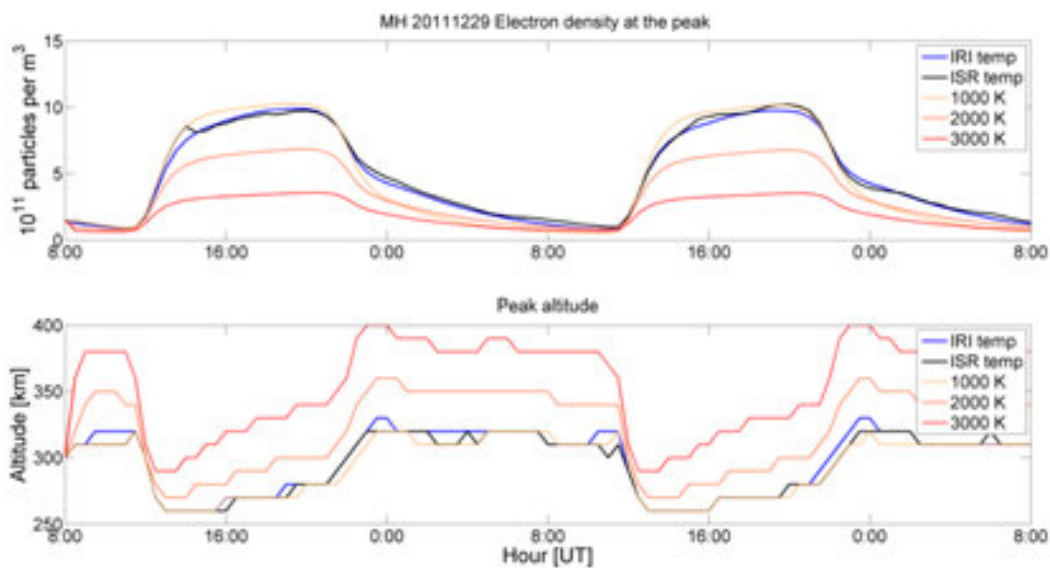


**Figure 5.** Validity test (autumn case). The graphs show, respectively, the comparisons of electron densities at the peak and peak heights produced by ANIMo, modelled by IRI 2012 and measured by Millstone Hill ISR and ionosonde.



### 4. Temperature sensitivity

The aim of this sensitivity test was to check the robustness of ANIMo by modifying input arguments and checking their effects on its outcomes. In particular, this paragraph reports a selection from a series of tests conducted by tuning the temperature input parameter. The chosen case study is that of winter, already presented in the validation test. Figure 6 shows the comparison between outcomes obtained by using different temperature input values. As aforementioned, ANIMo normally uses temperature values produced by IRI 2012, the relative outcome of which is reported in the graph with a solid blue line. The model was also fed with temperature measurements from the Millstone Hill ISR (black solid) and artificial profiles defined by keeping the temperature constant in altitude and time at 1000 K (gold dashed), 2000 K (orange dashed) and 3000 K (red dashed). The test demonstrates the importance of ion and electron temperatures as input in modeling the electron density of the ionosphere. Furthermore, it shows that ANIMo is a robust model in terms of temperature modification, where for robustness is intended the ability of coping with large changes of external forcing parameters. IRI and ISR driven outcomes are very similar. Regarding the remaining simulations, increasing the selected input value translates to a gradual alteration of the model results. As expected, the higher the temperature, the smaller the electron density and bigger the peak altitude. This is due to the fact that the temperature affects the recombination rates and diffusion velocities of the model. In particular, if the recombination rate increases there will not only be a general decrease in electron and ion densities but also a lift of the peak altitude that is not replenished enough by the photoionization. In addition to this, the collision frequency is bigger in a hotter environment. This, plus the diminished charged particle density slows down the diffusion that tends to move ions and electrons to lower positions of the profile.



**Figure 6.** Sensitivity test (winter case). The graphs show, respectively, the comparisons of electron densities at the peak and peak heights produced by modifying ANIMo temperature input parameters.

## 5. Conclusions

The preliminary results of the validation and sensitivity tests presented in this document are very promising. The validation demonstrated that ANIMo is capable of reproducing different features of the ionosphere in a reasonable manner, considering the physics that had been taken into account. This was confirmed by previous comparisons with the Utah State University Time Dependent Ionospheric Model (USU TDIM) [13]. However, further validation tests and minor adjustments are required. Further, the temperature sensitivity test shows that ANIMo is robust and stable. At this phase of its development, ANIMo is exhibiting the characteristics required for supporting ionospheric tomography imaging. The next step will see the implementation of ANIMo in a DA scheme which will develop MIDAS algorithms into a full physics forecasting system.

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