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Global model of the F2 layer peak height for low solar activity based on GPS radio-occultation data

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ABSTRACT

We propose a global median model SMF2 (Satellite Model of the *F*2 layer) of the ionospheric *F*2-layer height maximum (h_mF2), based on GPS radio-occultation data for low solar activity periods ($F_{10.7A} < 80$). The model utilizes data provided by GPS receivers onboard satellites CHAMP (~100,000 h_mF2 values), GRACE (~70,000) and COSMIC (~2,000,000). The data were preprocessed to remove cases where the absolute maximum of the electron density lies outside the *F*2 region. Ground-based ionospheric sounding data were used for comparison and validation. Spatial dependence of h_mF2 is modeled by a Legendre-function expansion. Temporal dependence, as a function of Universal Time (UT), is described by a Fourier expansion. Inputs of the model are: geographical coordinates, month and $F_{10.7A}$ solar activity index. The model is designed for quiet geomagnetic conditions ($K_p = 1–2$), typical for low solar activity.

SMF2 agrees well with the International Reference Ionosphere model (IRI) in those regions, where the ground-based ionosonde network is dense. Maximal difference between the models is found in the equatorial belt, over the oceans and the polar caps. Standard deviations of the radio-occultation and Digisonde data from the predicted SMF2 median are 10–16 km for all seasons, against 13–29 km for IRI-2012. Average relative deviations are 3–4 times less than for IRI, 3–4% against 9–12%. Therefore, the proposed h_mF2 model is more accurate than IRI-2012.

1. Introduction

Empirical models of the Earth ionosphere are used to forecast HF radio propagation conditions, to increase positioning precision of satellite navigation systems, to interpret ionospheric radio-sounding results and for other practical applications. Currently, the most widely used and de-facto standard model for ionospheric parameters estimation is the International Reference Ionosphere (Bilitza et al., 1979; Bilitza and Reinisch, 2008). The last version of the model (IRI-2012) is available at the site [http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html]. To calculate the *F*2-layer peak height (h_mF2) IRI uses *M*(3000)*F*2 parameter, which correlates well with h_mF2 (Rawer et al., 1978). The *M*(3000)*F*2 values are usually derived from vertical sounding ionograms. The existing worldwide network of ionospheric sounding stations provided data for the model. To describe the ionospheric parameters, IRI uses a Legendre-function expansion over the modified geomagnetic latitude and geographic longitude and a Fourier expansion over the Universal Time. Coefficients of these expansions (the CCIR coefficients) are stored in files in a tabulated form. The *F*2 peak height value is calculated using the equation (Bilitza et al., 1979), which also includes two other ionospheric parameters – f_oF2 and f_oE.

The IRI model was created back in 1960s and has been continuously improved since then. It proved itself to be extremely successful. However, the network of ionospheric sounding stations is rather sparse and does not cover the entire globe. The stations are numerous enough at the Northern Hemisphere mid-latitudes but there are few of them near the equator and at the Southern Hemisphere, while over the oceans the sounding data are virtually absent. Such unequal distribution of the data hinders the model performance. It may be also noted that, when deriving the peak height from *M*(3000)*F*2, a parabolic form of vertical electron density profiles $N_e(h)$ is assumed, and this assumption is not always correct.

Therefore, recently some attempts have been made to improve the IRI model. A global *F*2 peak height model based on topside sounding onboard the ISIS, Intercosmos-19 and Cosmos-1809 satellites is described in (Gulyaeva et al., 2008). However, insufficient data volume from these satellites (90,000 profiles) allowed the modeling of h_mF2 behavior only at near-midnight, morning, near-noon and evening hours for three seasons (winter, summer and equinoctial periods), without month-by-month partition. This model is hemisphere-symmetrical because in the Southern Hemisphere the data amount was too small. The result could be viewed as a limited h_mF2 model for the Northern Hemisphere only.

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An attempt to improve IRI using the empirical orthogonal functions method is made in (Zhang et al., 2009). However, this model is based on the same approach as IRI – the h_mF2 values were not measured directly but derived from $M(3000)F2$, f_oF2 and f_oE parameters taken from the ground-based ionosonde network. Though the authors claim that the new model is more accurate than IRI, it is clear that the main deficiency of the approach – incomplete coverage of the globe – is still present.

To create a more accurate global model it is necessary to use a much wider data set. An extensive volume of the recent ionospheric measurements makes it possible. In particular, one of the new powerful tools in the ionospheric research is GPS-based radio-occultation technique (e.g., (Gurvich and Krasil'nikova, 1987; Hajj and Romans, 1998)). This method allows to retrieve the $N_e(h)$ profiles in the height range 100–800 km with a resolution better than 10 km (Wu et al., 2009; Yue et al., 2010) and to determine the $F2$-layer peak height, basically, directly.

For the last ten years, an extremely large amount of data was received in the radio-occultation experiments onboard CHAMP, GRACE and COSMIC satellites. These data are freely available through the Internet and could be used to construct a model. However, $N_e(h)$ profile reconstruction from the radio-occultation data is based on many assumptions and is not a trivial task. So the accuracy of the $F2$-layer peak heights obtained from these data was much discussed. Chu et al. (2010a) has shown that h_mF2 obtained from the COSMIC data is higher than h_mF2 from the ionosondes data at all latitudes, especially at the equatorial ones. However, in (Chu et al., 2010b) the opposite was shown – COSMIC-derived hmF2 values are lower than ionosonde-derived ones at all latitudes, and this difference is reduced during the minimum of solar activity. Lei et al. (2007) compared the h_mF2 values from COSMIC experiment with the values provided by Millstone Hill and Jicamarca incoherent scatter radars. It was shown that the deviations are in the range of 10–30 km, the greatest ones are for the equatorial Jicamarca data series. A very careful statistical comparison of the COSMIC-derived h_mF2 values with ground-based European ionosondes (Digisondes) was made in (Krankowski et al., 2011). The Digisonde data were collected by the Pruhonice and Juliusruh stations in January, April, July and October 2008. The average difference between these two data sets appeared to be only 2.8 km. IRI is based on ionosonde data, therefore, we should expect that it reflects the ground-based sounding data better than the satellite measurements. However, Magdaleno et al. (2011) has shown that IRI overestimates the ionosondes data by 30% at high latitudes and vice versa, underestimates them up to 40% at equatorial latitudes. In (Potula et al., 2011) the h_mF2 global distributions for all seasons, obtained from COSMIC data and IRI in 2007, show that the $F2$ layer height according to IRI was clearly higher, especially over the equator. So, the picture is controversial, yet it is clear that IRI needs to be corrected. We think that thoroughly selected radio-occultation data are useful to achieve this goal.

Hoque and Jakowski (2012) present a global median h_mF2 model NPHM (Neustrelitz Peak Height Model). It is based on the CHAMP, GRACE and COSMIC radio-occultation data. This work aimed to provide a simple model for radio-propagation tasks. The core of the model is a non-linear equation system with just 13 numerical coefficients. Such simplicity makes it very useful for high-performance numerical calculations but does not allow describing more subtle ionospheric behavior like longitudinal variations of h_mF2.

The main purpose of this article is to show that radio-occultation data can be used to create an h_mF2 model with greater accuracy than IRI. As a first step we present a median model for low solar activity. As in (Hoque and Jakowski, 2012), we used the ionospheric profiles from the CHAMP, GRACE and COSMIC radio-occultation experiments as a data source. However, we used a larger data set, which has significantly expanded in the last years, and applied a more complicated method for a description of h_mF2 variations. Preliminary estimates show that the data volume is enough to make a full global h_mF2 model for low solar activity, as these data cover all seasons, UT hours and longitudes.

2. The source data

The SMF2 model is based on ionospheric radio-occultation data from GPS receivers onboard CHAMP satellite (January, 2007–September, 2008), GRACE satellites (February, 2007-October, 2010) and COSMIC constellation (January, 2007–December, 2011). Hourly F-layer peak-height data from 60 ionosonde stations were obtained from NOAA/NGDC SPIDR resource (http://spidr.ngdc.noaa.gov/spidr/). These data were used for comparison only. For further processing only the data from low solar activity periods were selected from the dataset, with $F_{10.7A}$ index as a selection criterion. The $F_{10.7A}$ index is daily $F_{10.7}$ index, averaged over three sun rotation periods (81 day). The oblique electron density profile data were obtained from Cosmic Data Analysis and Archive Center (CDAAC), Boulder, Colorado (http://cosmic-io.cosmic.ucar.edu/cdaac/index.html). The $F2$ peak height is included to the file headers ("edmaxalt" field). A preliminary analysis of the data has shown that, unfortunately, not all profiles can be included to the model base set. It turned out that in 10% cases the h_mF2 values are clearly outside the typical range. So the $N_e(h)$-profiles went through a check-up process and those with a dubious quality were omitted from the base dataset. Strongly uneven, inhomogeneous profiles were omitted too.

As an example, Fig. 1 shows one of the vertical plasma frequency $f_p(h)$ profiles obtained from the COSMIC data. The dashed line corresponds to the $F2$-layer peak height included in the data set as a result of an automatic processing. The profile is so noisy that the most distinct outlier is falsely assumed to be the $F2$ maximum. Such profiles have to be excluded from the data to avoid model biases. An algorithm was developed to remove such profiles, at least, as many of them as possible.

Another example of an undesirable COSMIC $f_p(h)$ profile is shown in Fig. 2. It was recorded on the same day 26 January, 2007. It is quite clean, but the corresponding h_mF2 is set to an unlikely low value of 155 km (indicated by the dashed line). Thus, if the h_mF2 parameter ("edmaxalt" field) is less than 180 km (maximal height of $F1$ layer peak), then a special subroutine attempts to find the correct $F2$-layer

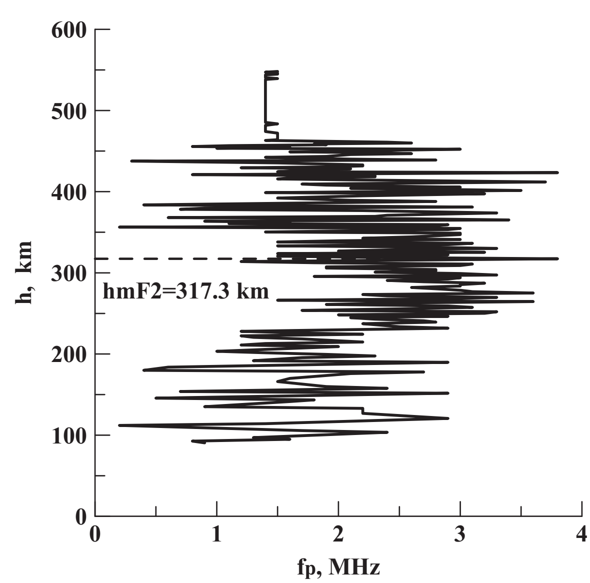

Fig. 1. Ionospheric plasma frequency profile calculated from the COSMIC radio occultation observed on 26 January 2007, 00:31 UT (42.2°N, 14.1°E).