Comparison of COSMIC measurements with the IRI-2007 model over the eastern Mediterranean region

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Abstract This paper presents a comparison of the International Reference Ionosphere (IRI-2007) model over the eastern Mediterranean region with peak ionospheric characteristics (foF2–hmF2) and electron density profiles measured by FORMOSAT-3/COSMIC satellites in terms of GPS radio occultation technique and the Cyprus digisonde. In the absence of systematic ionosonde measurements over this area, COSMIC measurements provide an opportunity to perform such a study by considering observations for year 2010 to investigate the behaviour of the IRI-2007 model over the eastern Mediterranean area.

Introduction

A constellation of six satellites, called the Formosa Satellite 3– Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), was launched in 2006 to improve global weather prediction and space weather monitoring [1]. Three different instruments make up the science payload of the COSMIC satellites which orbit at 800 km, namely, four sets of GPS receivers, a Tri-Band (150, 400, and 1067 MHz) beacon transmitter system, and a tiny ionospheric photometer at 135.6 nm. In this investigation we deal with the GPS receiver which is used to obtain atmospheric and ionospheric measurements through phase and Doppler shifts of radio signals. The Doppler shift of the GPS L-band signals received by a low earth orbit (LEO) satellite is used to compute the amount of signal bending that occurs as the GPS satellite sets or rises through the earth’s atmosphere as seen from LEO [2,3]. The primary objective of this paper is to utilise the high spatial resolution of electron density profiles retrieved by COSMIC satellites from radio occultation (RO) measurements and perform a comparison with F layer peak ionospheric characteristics given by the International Reference Ionosphere model (IRI-2007) [4] which is the most widely used empirical ionospheric model.

COSMIC measurements and IRI model

Each COSMIC satellite is equipped with four antennas, two of which are used for ionospheric electron density measurements (one for rising and one for setting occultations). These two antennas collect L1 and L2 GPS phase data from up to 13 GPS satellites every second. The inversion of COSMIC data into electron density profiles is based on the difference between L1 and L2 GPS phase path measurements [5]. Under the
assumption of straight-line propagation of GPS signals in the ionosphere, the difference between the L1 and L2 phase path measurements (except for a constant offset) is approximately proportional to the total electron content (TEC) along the line from the LEO satellite to the GPS satellite [6].

On the basis of the radio occultation technique, the bending angle of GPS ray received by the GPS receivers can be converted into atmospheric refractive index through the calculation of Abel transformation. In this comparative study 1043 radio occultation profiles obtained in 2010 were considered all of which had their F peak within the area under examination (between 25–36°N and 22–36°E) as shown in Fig. 1. Electron densities at each altitude as well as peak ionospheric characteristics and occultation footprint were extracted directly from these profiles provided by the COSMIC Data Analysis and Archive Center (CDAAC). No further processing was carried out apart from rejection of profiles which exhibited excessive electron density fluctuation. In an attempt to compare COSMIC derived foF2 and hmF2 measurements with values from an additional measurement source, bottomside electron density profiles measured by the Cyprus digisonde were also considered and compared to COSMIC profiles over Cyprus and derived characteristics. In order to make the comparison between COSMIC and digisonde measurements as accurate as possible, collocation distance between the GPS occultation at F peak and the ionosonde location was limited up to 1° in latitude and longitude within a time interval for the occultation occurrence of 15 min. Only data in geomagnetically quiet conditions were considered in the comparison (Kp < 2). According to the Abel transformation, the spherical symmetry of the atmospheric refractive index with respect to the Earth centre is the most critical assumption of the retrieval algorithm in radio-occultation of atmospheric parameters. Under this assumption, no horizontal gradient of the refractive index is allowed to exist along the spherical shell of the refractive index. In addition, the presence of plasma irregularities in the GPS raypath may cause significant fluctuations of the retrieved electron density profile, giving rise to large uncertainty of the estimation and impairment of the data reliability. Therefore, despite quality control schemes that are being applied at the CDAAC, in order to reject all possible outlier profiles we used mean deviation [7] of the electron density profile as an additional measure of quality control of the data used in this study. No other forms of averaging or filtering were used on the data. As reported in previous studies there is a systematic discrepancy between ionosonde and COSMIC derived peak ionospheric characteristics which is latitude dependent. Peak electron density (NmF2) as measured by COSMIC is reported to be systematically smaller than that observed by ionosondes and the opposite is valid for hmF2. However this discrepancy was reported to minimise at the latitude range of the area under investigation (low and middle latitudes) [8].

The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) based on available experimental observations from data sources including ground, in situ as well as satellite observations. For a given location, time and date, IRI-2007 provides monthly averages of the electron density, electron temperature, ion temperature, and ion composition in the altitude range from 50 km to 2000 km. There is also the option to tune the model with measured ionospheric characteristics to obtain a better representation of the electron density profile and subsequent TEC estimation. This option was exploited in the current study to estimate electron density profiles and TEC values over Cyprus. The IRI model was applied under the Nequick topside option and URSI coefficients (without the storm option) over the geographical scope of the eastern Mediterranean region at the footprint location of each occultation as shown in Fig. 1 and also by using automatically and manually scaled foF2 and hmF2 values from a low latitude European ionosonde station in Nicosia to compare with COSMIC electron density profiles and associated TEC values over the station.

**Results and discussion**

In Fig. 2a we can observe on the same diagram all the foF2 predictions generated by the IRI model and the corresponding satellite occultation measurements vs time. IRI model predictions were evaluated at the exact coordinates of the F2 peak in the occultation at the exact time of the occultation event. Although the IRI model (as run in this scenario) provides a monthly average foF2 value it is evident from this diagram that the semi-annual variation in foF2 is represented by both the IRI model and the COSMIC measurements but we can identify that foF2_COSMIC is generally within 25–50% of foF2_IRI, with no particular bias towards either being more or less than the foF2_IRI except during the equinoxes (i.e. months 3 and 9) when foF2_COSMIC exceeds foF2_IRI by up to 150% (demonstrated in Fig. 2b).

In Fig. 3a the overall diurnal profile (including all values considered in this investigation superimposed on the same diurnal plot) of the difference between COSMIC foF2 and IRI foF2 is depicted. We can observe the clear tendency for COSMIC to exceed IRI estimates at night-time and the opposite trend at daytime.

In Fig. 3b the absolute difference with respect to latitude is plotted outlining a clear trend (continuous line) for increasing difference towards the equator which is expected taking into account the high variability of the ionosphere in this region and the lack of adequate measurements to represent low latitude regions in IRI.

In an attempt to make some basic comparisons of foF2 and hmF2 from another measurement source, electron density profiles captured by the Cyprus digisonde were compared to profile derived characteristics observed by COSMIC at the same

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Fig. 1 Position of occultations selected from year 2010 used for IRI validation.
The approximate time (within 15 min) within 1° for both longitude and latitude. The scatter diagrams are shown in Fig. 4b and c along with a scatter diagram of COSMIC vs IRI foF2 values in Fig. 4a for the whole investigation region (Fig. 1). Clearly Fig. 4b and c demonstrate that the correlation between the COSMIC and digisonde values is higher for foF2 than for hmF2 for measurements over Cyprus (Nicosia). Probably this is a result of the automatic scaling process for ionosonde ionograms during which a special algorithm (ARTIST) is applied to extract peak ionospheric characteristics therefore introducing some inaccuracies in their determination.

We have also used the electron density profiles to estimate TEC (Total Electron Content) over Cyprus under the assumption that the profile obtained during the occultation matches the vertical profile up to the F2 peak that was also measured by the Cyprus digisonde and the topside model extrapolated by a model [9]. TEC was obtained by numerical integration of available electron density profiles from 100 km to LEO orbit altitude of 800 km. IRI model TEC was estimated with URSI option and the Nequick topside option but also with peak ionospheric characteristics measured with the Cyprus digisonde as anchor points. As expected, the IRI model driven by manually scaled peak characteristics facilitates a more accurate TEC estimation (as shown in Fig. 5).

As a last step to the COSMIC–IRI comparison study, we have compared some complete electron density profiles. In doing so we have found differing examples of IRI performance over Cyprus. As shown in Fig. 6a IRI driven (which corre-
sponds to the IRI profile obtained from manually scaled peak characteristics) provides a good representation of the COSMIC profile, especially the topside. The difference between IRI and IRI_driven is very significant. In other cases such as Fig. 6b IRI_driven does not represent very well the COSMIC profile (not even the topside) as the deviation between IRI and IRI_driven is very significant. In another case such the one shown in Fig. 6c IRI_driven represents very well the COSMIC topside of the profile but deviates significantly in the bottomside. The digisonde topside profile (which is modelled) deviates significantly from COSMIC and IRI. In the last example shown in Fig. 6d IRI_driven, COSMIC and IRI match very well both in the bottomside and topside.

Conclusions

In this study we have attempted to investigate the behaviour of IRI-2007 model over the eastern Mediterranean area by means of electron density profiles, peak ionospheric characteristics and TEC values obtained mainly from occultation measurements and partly from digisonde measurements over Cyprus. The analysis demonstrated some clear characteristic features on a seasonal, diurnal and latitudinal basis over the area under investigation.

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