Optimizing the NeQuick Topside Scale Height Parameters Through COSMIC/FORMOSAT-3 Radio Occultation Data

Alessio Pignalberi, Michael Pezzopane, and Bruno Nava

***Abstract*— In this study, the NeQuick topside scale height empirical parameters H_0, g, and r are globally retrieved, for the first time, exploiting a selected dataset of about 1.8M COSMIC/FORMOSAT-3 radio occultation topside electron density profiles. Corresponding spatial, diurnal, seasonal, as well as solar and magnetic activity median trends are studied and discussed. The results of this study could be considered as a baseline for the implementation of an improved NeQuick topside formulation. Indeed, applications relying on single-frequency Global Navigation Satellite System (GNSS) signals would benefit from an ameliorated characterization of the topside ionosphere because empirical ionospheric models, like NeQuick, are used to mitigate the detrimental effect that the ionosphere–plasmasphere system has on GNSS signals.**

***Index Terms*— COSMIC/FORMOSAT-3 radio occultation (RO) data, NeQuick model, topside ionosphere modeling, topside scale height.**

I. Introduction

THE accuracy of positioning based on Global Navigation Satellite System (GNSS) applications is deeply influenced by the refraction of signals due to the presence of free electrons in the ionosphere–plasmasphere system [1]. GNSS signals experience an ionospheric range delay which is proportional to the total electron content (TEC) along the signal path between the receiver and the GNSS satellite [2]. To mitigate such effect, an accurate knowledge of the electron density distribution in the ionosphere–plasmasphere system is therefore essential. For example, for single-frequency observations, the ionospheric delay is usually mitigated using empirical ionospheric models. These models, embedded in the receivers, are driven by coefficients broadcast within navigation messages. This is the approach adopted by the Global Positioning System (GPS) with the Klobuchar model [3] and by Galileo with the NeQuick-G model [4], a specific version of the NeQuick model [5], implemented by the European Space Agency.

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NeQuick is a global empirical model describing the median climatological behavior of the electron density in the ionosphere–plasmasphere system [5], which allows a fast calculation of TEC values up to GNSS heights. The topside ionosphere is the region extending from the F2-layer peak height (*hm*F2), corresponding to the ionospheric electron density maximum (*Nm*F2), to the plasmasphere [6]. As a consequence, a reliable modeling of the topside is very important since it strongly affects the TEC estimation.

In this work, we focus on the calibration of the topside NeQuick scale height parameters, H_0, g, and r, by exploiting the entire dataset of COSMIC/FORMOSAT-3 radio occultation (RO) observations. Recent works [7]–[9] suggested that a revision and a more refined description of these three parameters are needed to allow for a better description of the topside ionosphere. This is why, considering the topside electron density profiles collected by the COSMIC/FORMOSAT-3 satellite constellation, in this work we retrieve H_{Epstein} values by applying the procedure proposed by Pignalberi *et al.* [7] and fit them with the NeQuick topside scale height formulation [5] to obtain the best estimates for H_0, g, and r. Corresponding trends are then studied to highlight their spatial, diurnal, seasonal, solar, and magnetic activity variabilities.

II. Improving the NeQuick Topside Model Through COSMIC/FORMOSAT-3 Data

A. NeQuick Topside Model

The NeQuick topside section of the electron density profile N_e is described by a semi-Epstein layer starting from the *Nm*F2 value at the *hm*F2 height, with a tailored scale height H which allows a smooth transition from the altitudes near the electron density peak to the plasmaspheric ones [5], [7]

$$N_e(h) = 4NmF2\frac{\exp\left(\frac{h-hmF2}{H}\right)}{\left[1+\exp\left(\frac{h-hmF2}{H}\right)\right]^2} \tag{1}$$

with

$$H(h) = H_0\left[1+\frac{rg(h-hmF2)}{rH_0+g(h-hmF2)}\right]. \tag{2}$$

The NeQuick topside scale height H is a function of three empirical parameters H_0, g, and r. H_0 is the value assumed to be the scale height at the F2-layer peak height (*hm*F2); $g = 0.125$ is the gradient of H near the F2-layer peak; and $r = 100$ controls the asymptotic behavior of H at infinity. The meaning and altitude variation of each of these three parameters were carefully described and discussed by Pignalberi *et al.* [7]. Since H_0 is modeled as a function of the bottomside thickness parameter [5], NeQuick exhibits a strong coupling between the bottomside and the topside part of the profile. However, due to the very different physical phenomena affecting the bottomside and the higher ionosphere, in some cases, this constraint can result in inaccurate and unreliable results [8], [9].

B. COSMIC/FORMOSAT-3 RO Dataset

COSMIC/FORMOSAT-3 is a satellite mission specifically designed for the study of the atmosphere and ionosphere through the RO technique [10]. It is a constellation of six microsatellites launched in 2006 into a circular orbit (72° of inclination), with a separation angle of 30° in longitude between neighboring satellites, at about 800 km of altitude. The satellites are all equipped with GPS RO receivers which can be used for the determination of the ionospheric electron density profile by measuring the phase delay of radio waves from GPS satellites as they are occulted by the earth's atmosphere. COSMIC RO data are stored in the COSMIC Data Analysis and Archive Center (CDAAC, http://cdaac-www.cosmic.ucar.edu/cdaac/products.html).

In this work, the most reliable COSMIC profiles recorded from April 22, 2006, to December 31, 2018, were selected following the procedure described by Pignalberi *et al.* [11]. This COSMIC dataset consists of 1 791 993 electron density profiles.

C. Calibration of the NeQuick Topside Scale Height Parameters H_0, g, and r

Pignalberi *et al.* [7] described a method to obtain the effective topside scale height $H_{\mathrm{Epstein}}(h)$ by analytically inverting (1).

Equation (3), as shown at the bottom of the page, allows to obtain $H_{\mathrm{Epstein}}(h)$ values for the entire topside section probed by the COSMIC satellite, using corresponding $N_{\mathrm{e}}(h)$, NmF2, and hmF2 measurements. This approach was first applied by Pignalberi *et al.* [7] to a small selected COSMIC dataset (some hundreds of profiles) to derive a simple linear description of the topside scale height, which was further confirmed by Pignalberi *et al.* [11] considering the whole COSMIC dataset.

In this work, the NeQuick topside scale height $H(h)$ is fitted to $H_{\mathrm{Epstein}}(h)$ values retrieved from the topside part of each COSMIC measured electron density profile by optimizing the three NeQuick topside parameters (H_0, g, and r) through the trust region reflective algorithm [12]. As a consequence, for each COSMIC profile, calibrated values of H_0, g, and r are obtained. An example of the fitting procedure is shown in Fig. 1. Blue points in the top panel of Fig. 1 are $H_{\mathrm{Epstein}}(h)$ values calculated by applying (3) to COSMIC measured $N_{\mathrm{e}}(h)$ values represented as blue points in the bottom panel. The red curve in the top panel is the NeQuick topside scale height $H(h)$ fitted to the $H_{\mathrm{Epstein}}(h)$ values and is identified as $H_{\mathrm{NeQuick\ calibrated}}(h)$. H_0, g, and r values optimizing the fit are those reported in the upper left box of the top panel. The modeled $N_{\mathrm{e}}(h)$ values are calculated by inserting

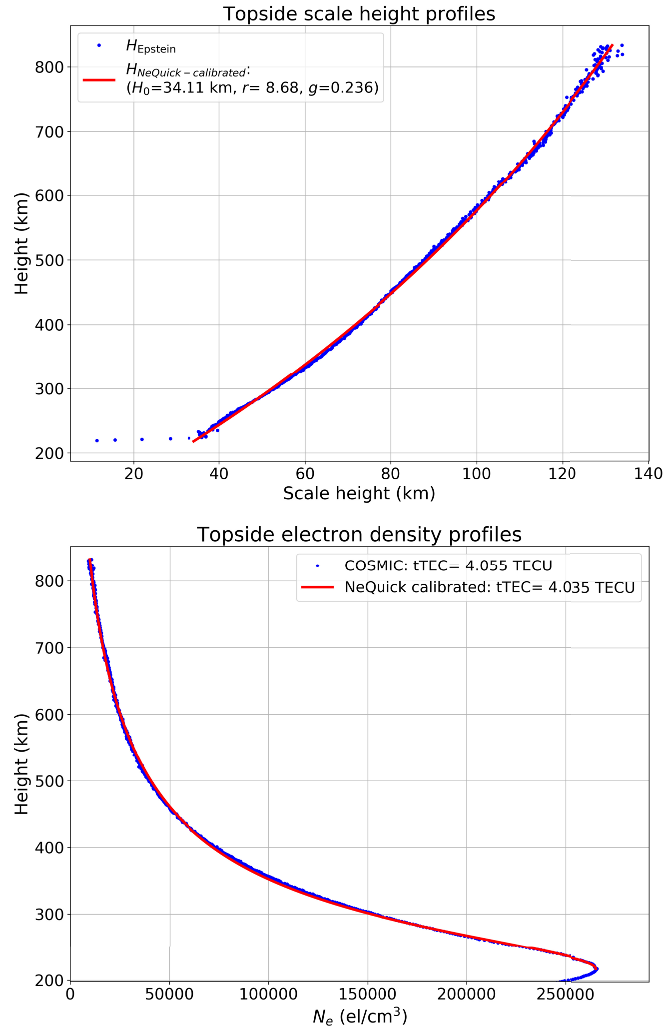

Fig. 1. Example of NeQuick topside scale height fitting on a COSMIC profile measured on July 25, 2007, at 16:11:52 Universal Time at a latitude of 56.44 °N and a longitude of 12.38 °E. See the text for more description.

$H_{\mathrm{NeQuick\ calibrated}}(h)$ in (1) in place of $H(h)$ and are represented by the red curve in the bottom panel.

Through this fitting procedure, three datasets of calibrated H_0, g, and r parameters, each one constituted by 1 791 993 values, were collected.

III. Climatological Behavior of the Calibrated NeQuick Topside Scale Height Parameters for Different Geophysical Conditions

Since the COSMIC dataset used in this study spans over several years (2006–2018), by probing different local times, seasons, as well as solar and magnetic activity conditions, for different geographic locations, a climatological investigation of the calibrated NeQuick topside parameters is possible. Therefore, calibrated values of H_0, g, and r are binned as a function of different variables, and the median value in

$$H_{\mathrm{Epstein}}(h) = \frac{h - hm\mathrm{F2}}{\ln\left\{\frac{1}{N_{\mathrm{e}}(h)}\left[(2Nm\mathrm{F2} - N_{\mathrm{e}}(h)) + 2\sqrt{Nm\mathrm{F2}^2 - N_{\mathrm{e}}(h)\cdot Nm\mathrm{F2}}\right]\right\}} \tag{3}$$

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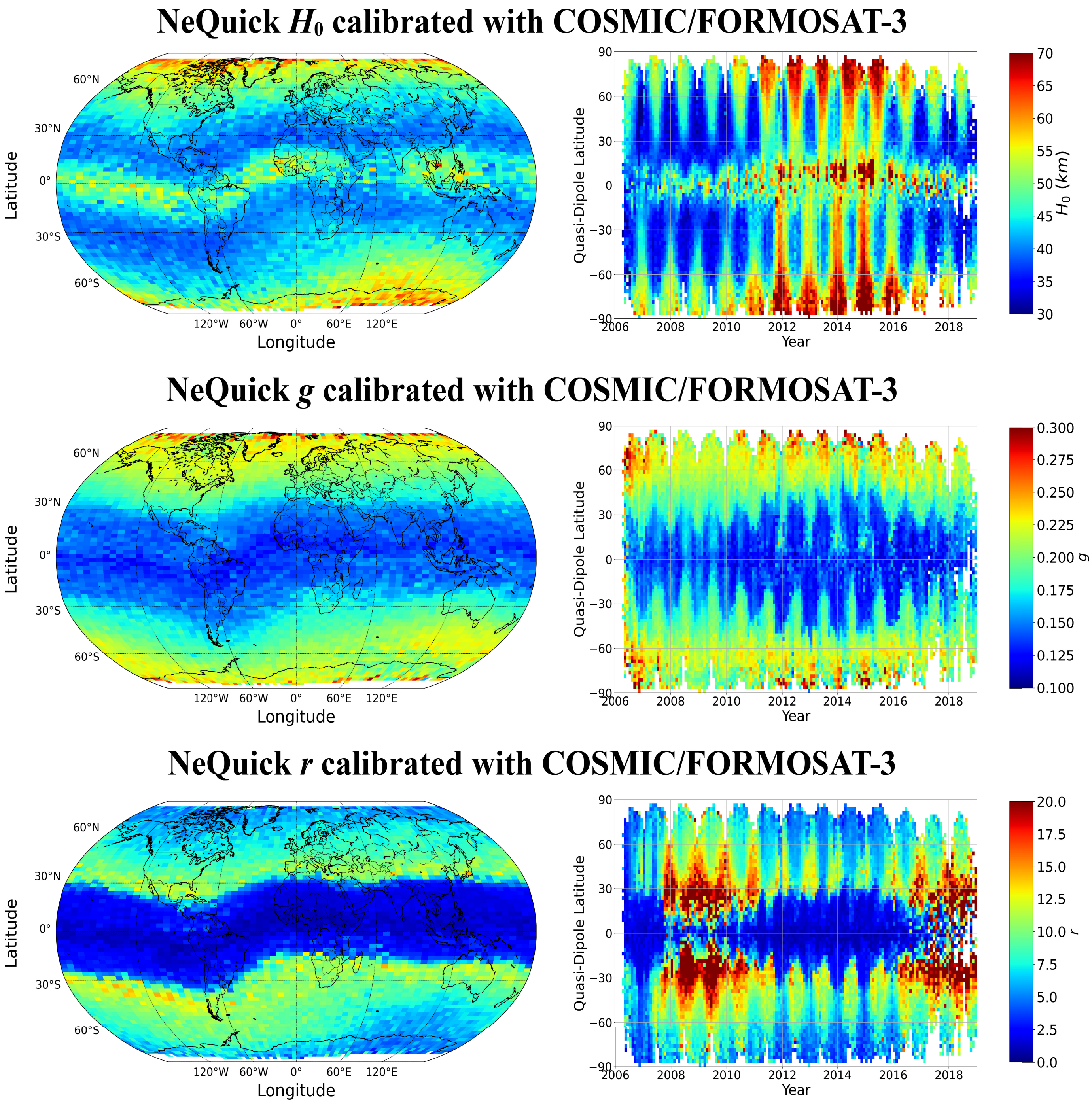

Fig. 2. NeQuick topside parameters calibrated through COSMIC/FORMOSAT-3 RO profiles. (Top row) H_0, (middle row) g, and (bottom row) r. Panels represent binned median values in (left) geographic coordinates and (right) QD latitude versus time.

the bin is considered as a representative of the corresponding climatological behavior.

Fig. 2 highlights the spatial and temporal distribution of H_0, g, and r. Left panels show median values of H_0 (top row), g (middle row), and r (bottom row), in geographic coordinates; right panels show median values as a function of the quasi-dipole (QD) latitude [13] and time. Left panels in Fig. 2 highlight that each of the three NeQuick topside parameters exhibits a spatial pattern linked to the earth's magnetic field.

This is particularly clear at low latitudes where right over the magnetic equator H_0 shows a relative maximum, while g and r show the minimum values. For this reason, in the following, data will be binned as a function of the QD latitude. In general, H_0 is characterized by lower values at mid-latitudes and higher values at low and high latitudes. Differently, g shows a steady decrease from high to low latitudes with minimum values right over the magnetic equator. The spatial behavior of r is the most difficult one to be understood because the increasing trend from high to low latitudes is abruptly stopped at about $\pm 30°$ of magnetic latitude by reaching values near to zero.

We carefully investigated this peculiar behavior by checking COSMIC topside profiles at low latitudes. It turned out that the magnitude decrease of r values at low latitudes is a

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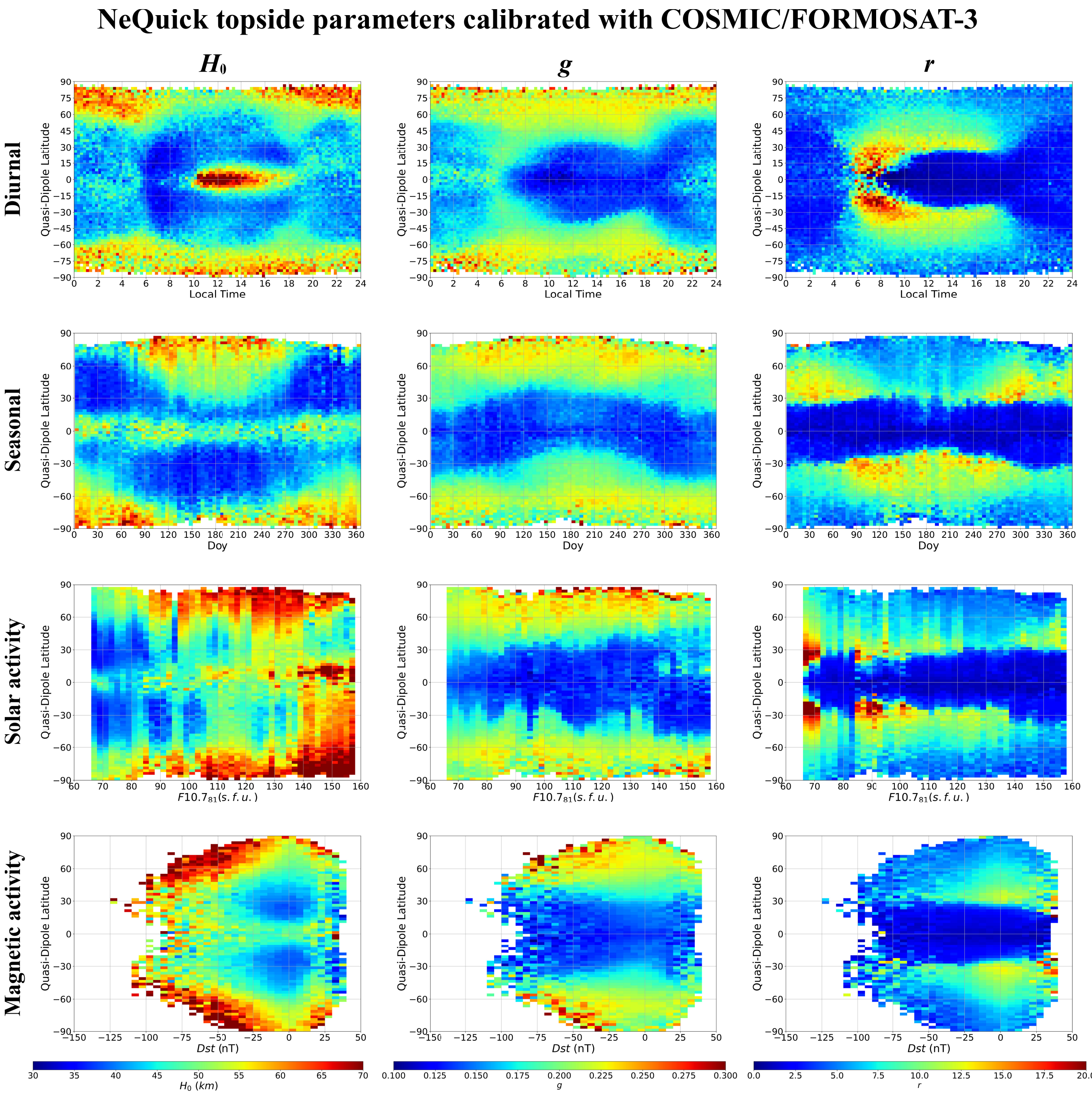

Fig. 3. NeQuick topside parameters calibrated through COSMIC/FORMOSAT-3 RO profiles. (Left column) H_0, (middle column) g, and (right column) r. Binned median values are represented in (top) QD latitude versus local time (diurnal trend), (second row from the top) QD latitude versus Doy (seasonal trend), (third row from the top) QD latitude versus $F10.7_{81}$ (solar activity trend), and (bottom) QD latitude versus Dst (magnetic activity trend).

consequence of the limited COSMIC satellites orbit altitude (about 800 km). In fact, low-latitude profiles are characterized by the *hm*F2 values much higher than those at other latitudes. As a consequence, the altitudinal extension of the COSMIC topside profiles is significantly reduced in these cases. Since the r parameter drives the scale height variation at heights much higher than *hm*F2, it is not possible to properly estimate its value for topside profiles with a limited altitudinal range. This means that the r behavior between $\pm 30°$ of magnetic latitude might be an artifact and cannot be considered as real; further studies based on different satellite missions or different remote-sensing techniques are needed to overcome this issue. However, the corresponding results for mid- and high-latitudes are trustworthy and will be considered in the following.

Right panels in Fig. 2 give a first insight on the seasonal and solar activity variability characterizing H_0, g, and r. H_0 manifests a definite positive correlation with the solar activity showing the highest values in years 2012–2016 encompassing the last solar cycle maximum. However, g does not show any definite solar activity dependence, while for r a negative correlation is observed.

We have also studied the diurnal, seasonal, as well as solar and magnetic activity dependence of H_0, g, and r. Corresponding results are shown in Fig. 3. Binned median values as a function of the QD latitude versus local time, the day of the year (Doy), the 81-day running mean of the $F10.7$ solar index ($F10.7_{81}$), and the Dst magnetic index are, respectively, shown. H_0 exhibits a peculiar diurnal trend characterized by a daytime maximum at low latitudes preceded by a post-sunrise minimum. Differently, northern high latitudes exhibit the highest H_0 values at night, while no marked diurnal trend characterizes the southern high latitudes. Except for the low-latitude daytime maximum, g exhibits a similar diurnal pattern as H_0 does but with the lowest values found just before noon and for a latitudinal range less extended than that of H_0. The diurnal trend of r confirms the fact that it cannot be correctly computed at low latitudes because of the limited altitudinal extension of COSMIC topside profiles. In fact, r is correctly estimated at low latitudes only around sunrise when the ionosphere is compressed and characterized by low values of *hm*F2. Anyhow, the r values are characterized by a well-defined pattern with the highest values during daytime and the lowest ones at night. Fig. 3, like Fig. 2, also highlights a marked seasonal dependence for each of the three parameters. At mid- and high-latitudes, H_0 exhibits the highest values from the spring equinox to the autumn one. On the contrary, low latitudes do not show any clear seasonal dependence. g shows a less marked seasonal dependence, although the band of the lowest values at low latitudes follows a seasonal trend by affecting different latitudes. By excluding the low latitudes, r has a seasonal trend opposite to that of H_0. The solar activity trends confirm the results of Fig. 2. In spite of the latitude, H_0 exhibits a clear positive correlation with the solar activity, while no clear dependence is found for g. Differently, r shows a negative correlation with the solar activity particularly at low- and mid-latitudes. Finally, a magnetic activity dependence is also visible. Except for the very low latitudes, H_0 shows a distinct increase for disturbed conditions (i.e., for very low Dst values), particularly at mid- and high-latitudes. Concerning g, only a slight magnetic activity dependence is visible for mid- and high-latitudes. Contrary to H_0, only at mid-latitudes, r manifests slightly decreased values for disturbed conditions.

IV. Conclusion

We exploited a dataset of about 1.8M COSMIC/FORMOSAT-3 RO profiles to obtain, for the first time, all over the globe calibrated values of the NeQuick topside scale height parameters H_0, g, and r.

In the original NeQuick model, g and r are empirical parameters that are kept constant, respectively, at 0.125 and 100, independent of the geophysical conditions. The results of this study have instead shown how these parameters are characterized by very large spatial, diurnal, and seasonal variations and also by a clear dependence on both solar and magnetic activities. This is a really important result since it tells us that, for a better characterization of the topside electron density profile shape, there is a need to model these topside parameters, also taking into account that recent studies [8], [9], [14] demonstrated that the current modeling of H_0 needs to be significantly revised. From this point of view, the dataset and the methodology employed in this study present a novelty and are very valuable, especially for the modeling of H_0 and g. Conversely, more data are needed to constrain the r behavior in the range $\pm 30^\circ$ of magnetic latitude. This study is of utmost importance for a better estimation of TEC and, consequently, for the space weather effects mitigation. In fact, it aims at attenuating the detrimental effect that the ionosphere–plasmasphere system has on the propagation of GNSS electromagnetic signals.

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