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Statistical validation of ionospheric electron density profiles retrievals from GOES geosynchronous satellites

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Abstract—In this paper, we discuss a novel retrieval of ionospheric electron density profiles using the Radio Occultation (RO) technique applied to measurements captured by the Global Positioning System (GPS) receivers onboard two Geostationary Operational Environmental Satellites (GOES). The GOES satellites operate at ~35,800 km altitude and are primarily weather satellites that operationally contribute continuous remote-sensing data for real-time weather forecasting, as well as near-Earth environment monitoring and Sun observations. The GPS receivers onboard GOES-16 and GOES-17 satellites can track GPS signals propagated through the Earth's atmosphere, and although the receivers are primarily designed for navigation and station-keeping maneuvers, these GPS measurements that traverse the Earth's atmosphere can be used to retrieve the ionospheric electron density profiles. This process poses a range of technical challenges. GOES RO links are different from the traditional low Earth orbit (LEO) RO geometry since the receiver is located in an orbit that is higher in altitude than the GPS constellation of transmitters. Additionally, the GPS receivers onboard GOES satellites provide only single-frequency GPS L1 observations and have clocks much less stable than those typically used for RO measurements. The geographical distribution of the retrieved GEO-based RO profiles was found to be uniquely constrained and repeatable based on the relative geostationary fixed positions in the Earth-Centered Earth Fixed reference frame with respect to the GPS constellation orbiting at lower altitude, and significantly different from the coverage patterns of LEO-based RO missions. We demonstrate the successful application of the proposed RO profiling technique with a statistically significant set of GPS observations from GOES-16 and GOES-17 satellites over several years of data collection. This enabled us to retrieve more than 10,000 ionospheric electron density profiles with a maximum altitude of up to 1000–2000 km, much higher than any existing LEO-based RO mission. We demonstrate good performance of GEO-based RO measurements for properly specifying the vertical distribution of ionospheric plasma density by comparing the profiles dataset from the GOES RO experiment with independent reference observations – ground-based ionosondes and LEO-based RO missions, as well as model simulation results provided by the empirical International Reference Ionosphere model. Over multiple years of observations, statistical analysis of discrepancies between the ionospheric F2 layer peak parameters (peak density and height) derived from geosynchronous GOES observations and reference measurements was conducted. This analysis reveals a very good agreement between GOES RO electron density profiles and independent types of measurements in both the F2 peak and the profile shape.

Keywords: Ionospheric density / Electron density profiles / Radio occultation / GPS / Geostationary satellite

1 Introduction

During the last several decades, Radio Occultation (RO) measurement of the Earth's atmosphere and ionosphere using Global Positioning System (GPS) signals from onboard

Low-Earth-Orbiting (LEO) satellites went from a mission-concept to one of the major sources of ionospheric data. The concept of the GPS-based RO technique was tested for the first time in 1995 with the GPS Meteorology (GPS/MET) Experiment that placed a GPS receiver onboard the MicroLab I satellite, which had an orbit of ~740 km altitude and 70° inclination. This GPS receiver was capable of tracking up to eight GPS

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satellites simultaneously at both GPS frequencies. The GPS/MET collected daily ~100–200 globally distributed occultations, and tens of thousands of occultations were recorded during its operation in 1995–1997. The GPS/MET was a pioneer in demonstrating the ability of the GPS-based RO technique to retrieve a vertical distribution of electron density in the Earth's ionosphere and to provide this type of observation globally to complement the limited number of ground-based instrument locations (Haji & Romans, 1998; Schreiner et al., 1999; Tsai et al., 2001). In 2000, the German georesearch satellite mission Challenging Minisatellite Payload (CHAMP) with a dual-frequency GPS receiver onboard was then launched into a near-polar orbit (inclination 87°, altitude ~450 km). This receiver onboard CHAMP provided up to 150 globally distributed vertical electron density profiles (EDPs) per day (Jakowski et al., 2002).

In April 2006, the first RO constellation of six small satellites – Formosa Satellite 3/Constellation Observing System for Meteorology, Ionosphere, and Climate (FormoSat-3/COSMIC, hereafter COSMIC-1) – was successfully launched into an orbit of ~700–800 km altitude and 72° inclination. When fully operational, COSMIC-1 produced 1500–2500 RO soundings of the ionosphere and atmosphere per day, thus providing unprecedentedly dense coverage on a global scale. In total, the mission delivered ~4.6 million ionospheric EDPs during its operational life of 2006–2020. In June 2019, the operational follow-on mission to the COSMIC-1 – the FormoSat-7/COSMIC-2 mission (hereafter COSMIC-2) – was successfully launched (Schreiner et al., 2020). The advanced dual-frequency GNSS receiver onboard COSMIC-2 satellites is capable of tracking GPS and GLONASS signals simultaneously. Six identical satellites placed into a low-inclination (24°) orbit of ~550 km altitude provide an unprecedented dense observational coverage of the entire equatorial region around the globe – up to 5000 EDPs per day for the operational constellation. With technological progress, GPS/GNSS receivers for space-based missions are further miniaturized, and today even nano-satellites can be equipped with a GPS receiver for RO. For example, the commercial operator Spire Global created its own constellation of several dozen 3U CubeSats at various orbits between 400 and 600 km altitudes, capable of providing several thousand ionospheric EDPs per day (Angling et al., 2021). Combining freely available COSMIC-2 data with data purchased from commercial missions could bring the research community more than 10,000 EDPs per day. Currently, RO-based probing of the Earth's ionosphere provides abundant three-dimensional electron density observations on a global scale, which can be used for ionospheric research, as well as for developing, improving, and validating global ionospheric models.

These RO missions have all operated at orbital altitudes of 400–800 km above the Earth's surface – at LEO altitudes. It is important to note that due to the geometry of the RO experiment, the top part of RO-based EDPs is physically limited by the orbit altitude of the specific mission. In this paper, we discuss a novel retrieval of the ionospheric EDPs not from LEO, but from the Geostationary-Earth-Orbit (GEO) – specifically from the Geostationary Operational Environmental Satellites (GOES) mission which operates at ~35,800 km altitude. We believe that RO profiles from GEO hold the untapped potential to generate unique temporal and spatial

atmospheric measurements complementary to those from the LEO space-based receivers, including limb observations of the upper atmosphere at altitudes above traditional LEO RO satellites. The initial proof of concept for estimating EDP from a geostationary platform based on a limited number of examples from the same dataset (Gleason et al., 2022) will be significantly expanded on in this research to demonstrate statistically significant EDP retrieval accuracy estimates using a multi-year set of GOES observations compared to ground-based ionosondes, LEO satellite-based RO profiles and ionospheric models.

2 Data and methodology

The GOES observatories are primarily weather satellites that operationally contribute continuous remote-sensing data for real-time weather forecasting, as well as near-Earth environment monitoring and Sun observations. In this investigation, we analyzed GPS observations from two GOES satellites – GOES-16 (also known as GOES-R) and GOES-17 (GOES-S). The GOES-16 satellite was launched in November 2016. After a yearlong non-operational checkout and validation phase, it drifted to its operational position near the equator at 75.2°W longitude and started to be fully operational in December 2017. The GOES-17 satellite was launched in March 2018, is positioned at 137.2°W longitude, and was declared operational in February 2019.

The GPS navigation receivers onboard these most recent GOES satellites, which were integrated and are maintained by the Lockheed Martin Corporation, can track GPS signals propagated through the Earth's atmosphere and can be potentially used to retrieve ionospheric EDPs. However, it is important to note that GOES GPS receivers were not designed to generate RO profiles – these receivers were designed as navigation receivers only. These navigation receivers are designed to generate position, velocity, and time (PVT) estimates, which are primarily for use in station-keeping maneuvers. The placement of a GPS receiver on a satellite platform in geostationary orbit (above the GPS constellation) is a novel configuration. Figure 1a shows the sketch view of how the GPS receivers onboard the GOES mission observe GPS satellites in the case of a GEO-based RO experiment. The transmissions of the GPS satellites are intentionally directed at the Earth's surface for the benefit of terrestrial users (not away from the Earth, nor towards the geostationary orbit slots). Therefore, the only signals available to the receivers mounted on the GOES satellites are those transmitted by GPS satellites from the relative opposite side of the Earth, or acquired from side or back lobes of the GPS antennas (Fig. 1b). This presents several challenges for estimating a navigation solution with respect to signal acquisition and tracking, as well as being restrained by a rather narrow field of view geometry from geostationary altitude. However, the tracking of GPS signals from the far side of the Earth often fortuitously results in the signals descending through the Earth's atmosphere, where they experience phase perturbations. These signal fluctuations are then tracked by the GPS receivers onboard the GOES satellites and can be processed into traditional radio occultation observations of excess phase and vertical estimates of total electron content along the observation path.

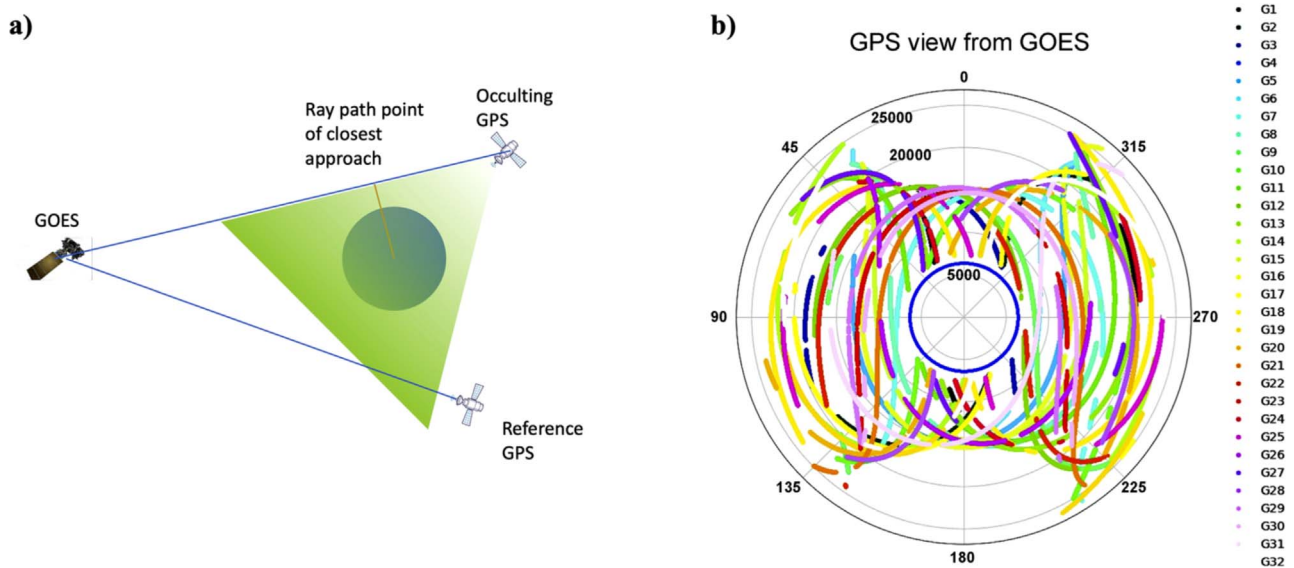


Figure 1. (a) Sketch of the GOES observing GPS satellites; all visible GPS satellites are behind the Earth. (b) GPS satellite tracks from the point of view of the GOES during a single day; 0° on top is the North pole, the blue circle in the center is the Earth, the radial distance is the distance of the point of closest approach of the ray path between GPS and GOES to the Earth's center.

The GPS receivers on the GOES satellites can track GPS signals even as they descend into the ionosphere. However, to estimate a navigation solution, it is desirable to avoid signals that traverse the atmosphere as they both have larger range errors and are contained within a limited line of sight geometry (more or less straight down from the geostationary satellite), which is not optimal in GPS navigation. For these reasons, signals tracked below 1000 km are not used in the navigation solution. Even so, signals are often tracked for as long as possible, down to much lower altitudes. These signals of opportunity, not used by the GOES GPS receivers but still tracked below 1000 km make up the data used to in this research.

The observation paths and associated Earth tangent points are functions of the receiver and transmitter locations. For the two GOES satellites being analyzed (at 75.2°W and 137.2°W, respectively) the resulting coverage forms “ellipses” centered at the equator and the respective longitude of the GOES satellite. This non-conventional coverage pattern has the advantage that the same point on the Earth's surface can potentially be observed at regular intervals (at the cost of more global coverage, which can be achieved from LEO-based RO observations).

A significant requirement in traditional GPS RO processing is the need for precise knowledge of the position and velocity of the GPS receiver platform. This is normally accomplished using a dual-frequency receiver and sophisticated ground processing. The GOES GPS receivers use a simpler single-frequency design concept (suitable to the GOES station-keeping requirements) which results in slightly degraded accuracy with respect to the two-frequency PVT estimates provided by traditional LEO-based RO receivers. This presents some challenges in the RO retrievals using these measurements which have been detailed in (Gleason et al., 2022) and will be elaborated on in the methodology below.

The data generated by the GPS receivers onboard the GOES mission is sufficient to generate TEC profiles for signals tracked into the ionosphere. These data include the standard position,

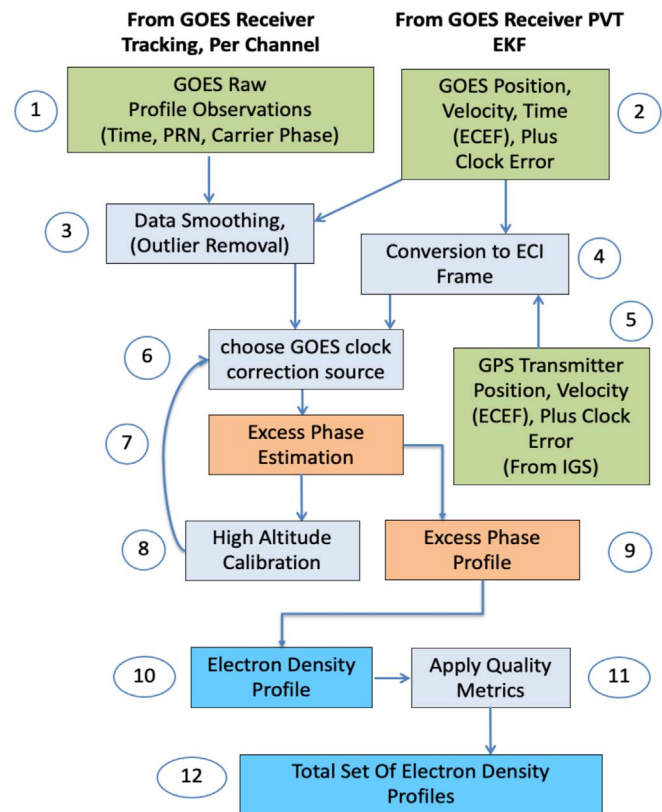


Figure 2. Summary of the processing algorithm for the retrieval of EDPs using measurements from the GOES GPS receivers.

velocity, and clock offset estimates of the GPS receiver, as well as the underlying measurements used: pseudorange and integrated carrier phase (phase) measurements taken on the GPS

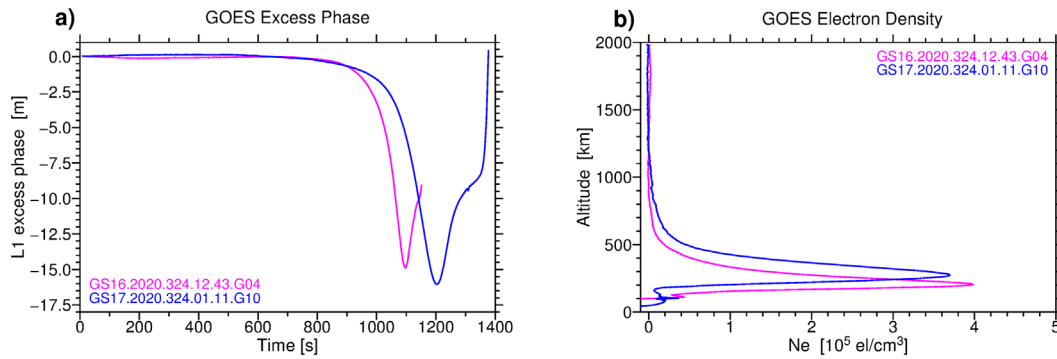


Figure 3. (a) Excess phase profiles and (b) electron density profiles for two examples of GOES occultation events. File names like “GS16.2020.324.12.43.G04” mean GOES-16 mission, year 2020, DOY (day-of-year) 324, time 12:43 UT, “G04” – tracking GPS satellite PRN 04. The first profile for GOES-16 was registered near (50.9°N; 0.4°E) at ~12.7 LT, the second one for GOES-17 was registered near (40.3°S; 59.2°W) at ~21.2 LT.

L1 frequency at 1 Hz. The combination of phase measurements, the GOES and GPS satellite positions, and clock offset estimates allow for the foundational RO profile measurement to be made: The excess phase introduced due to the impact of the atmosphere along the transmission path.

Figure 2 demonstrates the sequence of the processing steps used to generate RO profiles from the GOES GPS receiver measurements. Each numbered step in the processing chain is described in more detail below.

Steps 1 and 2 include the collection and pre-processing of the measurements from the GOES onboard GPS receivers. It comprises both raw measurements (1) and the onboard processed Extended Kalman Filter (EKF) position, velocity, and clock estimates. In step 3, the raw GOES measurements (specifically, the phase and time tags) are filtered to correct spurious and obvious errors over the profile duration. In steps 4 and 5, for each GOES time epoch, the corresponding GPS transmitter information is collected from the International GNSS Service (IGS). This information includes the position and velocity of the GPS satellite and the offset of its clock from GPS time. The positions are then converted to an inertial (ECI) reference frame.

The typical method of computing ionospheric EDPs using GNSS is to compute Total Electron Content (TEC) via differencing of L1 and L2 frequency data. However, as explained in Schreiner et al. (1999), given precise orbits and good clock corrections it is possible to arrive at electron density via inversion of bending angle derived from the ‘excess phase’. The excess phase (phase accumulation due to the ionosphere or neutral atmosphere, with satellite motion and clock effects removed) is computed as follows: $\delta\rho_r' = \phi - \rho_r' - c\delta_r - c\delta_t'$, where ϕ is the full phase from the instrument, ρ_r' is the geometric distance between the transmitter and the receiver, δ_r and δ_t' are the receiver and transmitter clock biases, and c is the speed of light. In this case ϕ , ρ_r' , and δ_t' are known fairly well, but the GOES receiver clock bias δ_r is less well-known. In typical LEO geometry, it is difficult to disentangle the neutral atmospheric from the ionospheric contribution to the excess phase with a single frequency inversion, and thus TEC inversions are more common. For data from the GOES receiver, which is well above the ionosphere, it is simply a matter of stopping the inversion before reaching the neutral atmosphere. Thus, L1-only ionospheric inversions are more practical from GEO than from LEO.

The next issue is how to convert the GOES receiver measurement time stamps to true GPS time. This is a particular problem since the GOES receiver uses a low-quality oscillator and suffers frequent 1 ms clock jumps to stay close to GPS time, as is common in navigation-grade receivers. There are several sources of clock correction information available. One is the GOES receiver navigation solution. Other clock offsets can be obtained by differencing the occulting PRN with other PRNs tracked at the same time, but at high elevation and thus not affected by the ionosphere. Since up to 12 PRNs can be tracked at the same time by the GOES receiver, several such clock solutions are available. Steps 6–8 involve choosing one of the available clock solutions, applying it to the occulting link data, and evaluating how flat the excess phase curve is between 1000 and 2000 km (where little ionospheric phase accumulation is expected). In step 9, the best clock solution is chosen and the resulting excess phase profile is computed. A linear fit between 1000 and 2000 km is then applied to the whole profile to fix the remaining clock error. The altitudes of 1000 and 2000 km were determined empirically based on the typical tracking altitudes of GOES receiver data and the height regime in which the excess phase showed the clearest linear trend. It is hoped with a better-quality receiver that this linear correction will no longer be necessary. In step 10, an EDP is computed from the excess phase using algorithms described by Ao (2009). In Figures 3a and 3b, we show examples of excess phase profiles and resulting EDPs. Step 10 applies a quality control metric to the EDP based on the physical feasibility of the profile, through examining the profile’s proximity to zero level at higher altitudes, where electron density is assumed to be close to zero. This allows us to exclude profiles where some artificial waviness can appear in cases of improper clock correction between the altitudes of 2000 and 1000 km, which can affect the shape of the entire profile. We use the following filtering algorithm: for the section of the profile between 2000 and 1000 km we compute two integrated values of electron content, one for the positive Ne values and one for the negative Ne values. Both absolute values of integrated electron content in this height range must not exceed a threshold of 0.30 TECU (Total Electron Content Unit, 1 TECU = 10¹⁶ el m⁻²). This quality control check is applied in step 11, leading to the final dataset used in this study.

3 Results and discussion

3.1 GOES electron density profiles

We processed the GPS observations provided by the GOES-16 and GOES-17 satellites and analyzed the first ionospheric results derived from GEO RO. The processed dataset covers ~5 years (July 2017–May 2022) for GOES-16 and ~3.5 years (November 2018–May 2022) for the GOES-17 satellite, respectively. Since the onboard GPS receivers were not configured optimally for RO, the number of RO retrievals is quite limited. On average, there are only ~5 recoverable EDPs per day that meet our minimum criteria for retrieval (continuous signal tracked from 2000 km to below 100 km tangent point). From the provided observational dataset that covers several years, we retrieved in total more than 13,000 RO-based ionospheric EDPs within an altitudinal range of 80–2000 km. Since the profiles' upper part of 1000–2000 km altitude is now used in the receiver clock solution, our analysis is focused mainly on the major ionospheric part of the profile between 80 and 1000 km in altitude – this upper limit is still much higher than that of current LEO RO missions.

The ionospheric EDP is one of the most important products for operational space weather monitoring and ionospheric basic research. RO-based EDPs can provide information about plasma density distributions at different layers of the ionosphere, e.g. E, Es, F1, and F2. The ionospheric F2 layer, the highest permanently observable layer with the largest electron density concentration, can be specified by two main parameters of the F2 peak – peak electron density (N_mF2) and peak height (h_mF2). To demonstrate the geographic distribution of the GOES RO profiles, we also utilized the coordinates of the F2 peak tangent point location determined from each profile. The multi-year dataset of the processed GOES occultations was binned into $5^\circ \times 5^\circ$ latitude/longitude bins, the results are shown in Figure 4. One can note that the general pattern of geographic locations of EDPs derived from GOES RO is much different from other LEO-based RO patterns. Due to the geometry of the RO experiment with the GOES satellites in the geostationary orbit, this pattern was found to be highly repeatable and constrained to a circular shape with the GOES satellite equatorial subsatellite location in the center (Fig. 4). From the GOES RO data accumulation within this circular pattern, we found out that observations are distributed non-evenly with large gaps near the equatorial latitudes of $\pm 20^\circ$ and the profiles are concentrated most frequently in the “diagonal” directions. Perhaps, it mostly depends and can be explained by the unusual geometry of the GOES RO experiment. In the classical LEO RO experiment, GPS and LEO satellites form a configuration such that the GPS satellite is considered almost stationary during an occultation session and the LEO satellite is moving quickly, thus forming multiple slices of the ionosphere with GPS–LEO links. In our case, the GEO satellite is stationary and the occulting GPS satellite is moving much faster, so occultations that penetrate closer to the Earth's surface seem to be more frequent in those parts of the GPS orbits (inclined at 55° to the equatorial plane), where a GPS satellite moves from its ascending into descending passes or vice versa (see Fig. 1b). Notably, the RO events to the West in the ellipse in Figure 4 are generally rising GPS satellites (which are often not acquired at low enough altitude to be used) and those toward the East of the

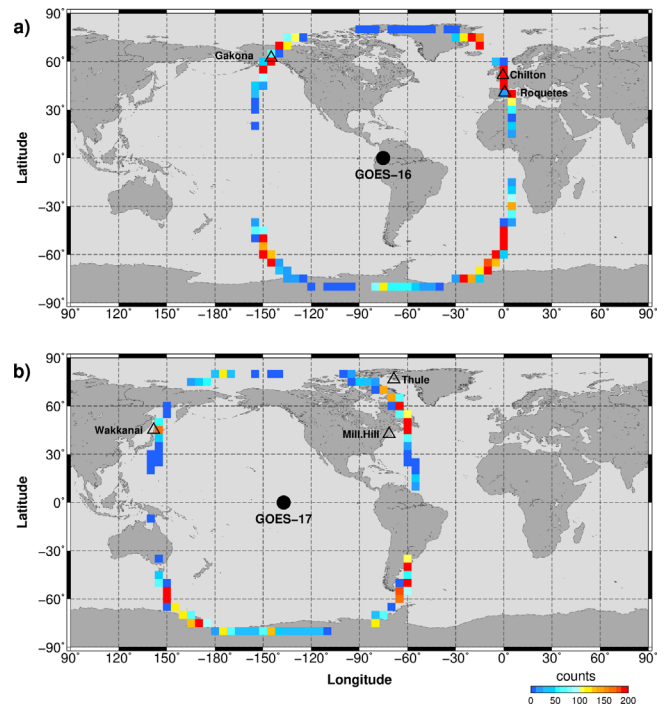


Figure 4. Geographic distribution of RO EDPs at the F2 peak coordinates for (a) GOES-16 in 2018–2021 and (b) GOES-17 satellites in 2019–2021; profiles accumulation per $5^\circ \times 5^\circ$ latitude/longitude bins is shown by color. Black circles show a projection of the GOES satellites and black triangles show locations of several ground-based ionosondes.

ellipse are generally setting occultations which are more amenable to the existing GOES GPS receiver tracking algorithm and hence make up the larger portion of the usable RO profiles.

We note that RO profile distributions from both GOES satellites correspond mainly to the ocean and polar (Arctic/Antarctic) regions that are known to have a very limited number of ground-based observational facilities. Considering the repeatable pattern of the GOES RO experiment, when RO profiles can occur near the same location and near the same time multiple days in a row, it represents an interesting and complimentary source of ionospheric data for these geographic areas. In the following subsections, we compared the obtained GOES RO results with independent ground- and space-based observations and with results derived from ionospheric empirical model simulations.

3.2 Comparison with ground-based ionosondes

Traditionally, for validation and accuracy assessment of RO-based EDPs, the observations from vertical ionospheric sounding stations (ionosondes) are used as a “ground truth” reference. Developed in the 1920s, ionosondes are still considered the “benchmark” data source for unbiased measurements of electron density in the bottom side ionosphere, up to the ionospheric F2 peak height. More than a hundred ground-based ionosondes around the globe measure the Earth's ionosphere routinely with a 5–15 min rate and contribute to the global observational databases.

As mentioned above, the ionospheric profiles derived from GOES RO were found to be located mainly over the oceans and polar regions (Fig. 4), making it a challenge to search for collocation with the ground-based ionosondes. One of the most important parameters in the collocation analysis is the closeness between two measurement points – obviously, the closer these two points are, the higher the chances that two instruments sound in the same area and same structures in the ionospheric plasma. However, the downside of a too tight collocation window (distance between RO-based profile location and ground-based instrument location) is that it might significantly restrict the total number of the collocation events and thus affect the statistical results. In previous validation studies of the RO-based EDPs, the chosen collocation window varied largely from 2° (e.g., Lei et al., 2007) to 4° – 6° (e.g., Sadighi et al., 2009; Habarulema et al., 2014) and up to 10° – 19° (~1000–2000 km) (e.g., Schreiner et al., 1999; Jakowski et al., 2002; Garcia-Fernandez et al., 2005; Kelley et al., 2009; Krankowski et al., 2011). In the recent validation paper of the COSMIC-2 RO EDPs (Cherniak et al., 2021), the collocation window was selected as 5° (~500 km) because of a large amount of RO-based profiles produced in the equatorial region around the globe. To determine the collocation events for GOES RO results, we also started with a window of 5° . For the location of the RO profile, we used the coordinates of the F2 peak. It was found out that for the GOES-16 satellite, the distribution of RO profiles was favorable enough to support collocations with three-spaced ionosondes even with a 5° window. They are two midlatitude ionosondes Roquetes (40.80°N, 0.5°E) and Chilton (51.50°N, 0.6°W) located in Spain and UK, respectively, and a high latitude ionosonde Gakona (62.38°N, 145.0°W) located in Alaska, USA. These locations (shown as black triangles in Fig. 4a) also coincided with places of high accumulation of GOES-16 RO profiles, thus more than 1200 collocations were determined here from a multi-year dataset. For the GOES-17 satellite with even more RO results over the oceans, usage of the 5° window was not very successful, and the collocation window was increased to 10° . With the increased window, we found collocations with the midlatitude ionosondes Millstone Hill (42.60°N, 71.5°W), USA, and Wakkanai (45.16°N, 141.75°E), Japan, and a high-latitude ionosonde Thule (76.54°N, 68.44°W), Greenland (shown as black triangles in Fig. 4b) – however, the total number of the collocation events obtained was only ~600, much smaller than ones for the GOES-16. This is partially due to the shorter period of GOES-17 observations (launched later than GOES-16), as well as the less frequent occurrence of GOES-17 RO-based profiles in the vicinity of these particular ionosondes (Fig. 4b). We should mention that there were also collocations with several other ionosondes, but the number of collocation events for each of them was very small, less than 5–20 events accumulated over several years; we did not include them here.

All considered ionosondes, apart from one in Wakkanai, are modern digital ionosondes (Reinisch et al., 2009) that produce ionograms in the digital format and send them in near real-time into the DIDBase (Digital Ionogram Data Base) repository of Global Ionosphere Radio Observatory (Reinisch & Galkin, 2011). Typically, ionosondes sweep in frequency from about 1–20 MHz and record tracings of reflected high-frequency radio pulses in the form of an ionogram. Directly from ionogram

images, one can identify echoes in the ordinary and extraordinary modes and can scale critical frequencies of major ionospheric layers and their virtual heights. The critical frequency of the F2 layer (foF2), which is the highest o-ray frequency of the F2 layer reflection, is related directly to electron density at the F2 peak (NmF2) as $NmF2 [el/cm^3] = 1.24 \cdot 10^4 \cdot (foF2 [MHz])^2$. The true F2 peak height (hmF2) and true height vertical EDP Ne(h) can be only obtained from the true height inversion analysis using special scaling software. We used the expert ionogram interpretation tool SAO Explorer (Reinisch & Galkin, 2011) to manually scale all selected ionograms provided by digisondes in the “expert level mode”. For the Wakkanai ionosonde, which is VIPIR2 (Vertical Incidence Pulsed Ionospheric Radar, Version 2), we scaled manually only critical frequency foF2 values using the provided tool with the Ionogram Viewer (<https://wdc.nict.go.jp/IONO/HP2009/ISDJ/index-E.html>).

Information about the F2 peak height is not available due to the absence of the proper scaling software. For our purposes, a clear ionosonde ionogram was searched within ± 20 min intervals from the collocation time.

Figure 5 provides several representative examples of collocation events between GOES RO profiles and selected ionosondes, which are located at middle and high latitudes. Additionally, for each case we provided profiles that were derived from the empirically-based International Reference Ionosphere (IRI) model; these comparisons will be discussed in more detail in Section 3.4. It is important to mention that for this cross-comparison, we should use only the bottom-side part of the profiles since ionosondes sense the ionosphere only up to the F2 peak, the topside part of the ionosonde profile (shown as a dashed blue line in plots of Fig. 5) is the result of fitting a model to the measured peak electron density value.

Figure 5a shows two collocation events between GOES-16 and the Roquetes ionosonde in Spain, at midlatitudes. The first case was for daytime conditions, the second for the night-time. One can see that both profiles were derived from an occultation with the same GPS satellite, G30, with separation in time of several months at DOY 040 (9 February) and DOY 171 (20 June). The occultation time changes slightly each day with the orbit precession of GPS satellites, and in several months, it scans different hours in a row. In contrast, the geographical location of the RO trajectory in terms of tangent projections practically does not change with time – one can see that trajectories of these two RO events (red and magenta lines on a left map of Fig. 5a) nearly overlap each other. So typically for the same location, we can expect observation with the same GPS satellite on a day-by-day basis as a specific repeatable pattern of the GEO-based RO experiment. In terms of EDP comparisons for this location, one can note quite a good agreement between GOES RO profiles and ionosonde-based profiles in the bottom-side parts and the ionospheric F2 peak, both height and peak density (Fig. 5a). It is important to note that GOES RO profiles also demonstrate signatures of the sporadic E (Es) layer, which were also detected in the ionosonde observations near 100 km altitude – that confirms the capability of the GOES RO to also sense the sporadic E layer. Figure 5b presents examples of collocation events between GOES-16 RO and the high-latitude station Gakona. Again, both examples were obtained from the occultation events with the same GPS satellites, here G28. The idea was to show examples separated by a shorter

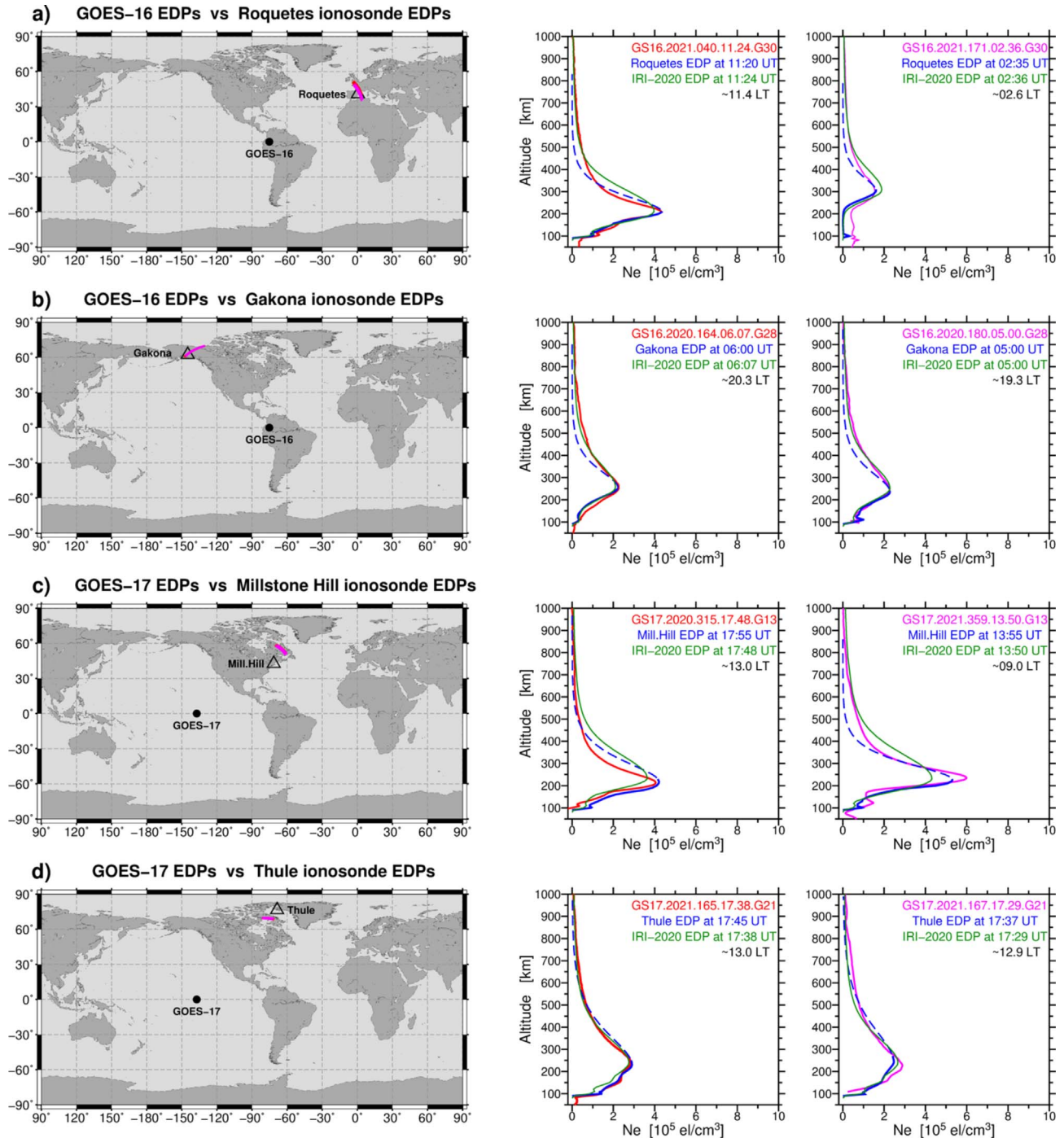


Figure 5. Examples of (a, b) GOES-16 and (c, d) GOES-17 RO EDPs as compared with collocated ground-based ionosonde profiles. Each example also shows EDP (green line) derived from the IRI-2020 model. For ionosonde-based profiles, solid line part shows the measured bottom side part of profile, and dashed part shows the modeled topside part of Ne profile. For each panel, left plot shows a geographical map with the ionosonde location and RO tangent points projections; right plots show RO and ionosonde Ne profiles for two collocation events.

period of time, ~2 weeks. During this period, the time of RO profile registration shifted by ~1 h, from 06:07 UT to 05:00 UT, and we can examine the daily difference in profiles for nearly the same LT (local time). For these collocation events separated by ~2 weeks, EDPs look quite similar with only slight changes in F2 peak density and height and a more pronounced

sporadic E for the second event. In general, a very good agreement was observed between GOES RO and ionosonde profiles, despite locations in the high latitudes.

Figure 5c shows two examples of collocation events between GOES-17 RO and the Millstone Hill ionosonde at middle latitudes. The GOES RO profiles were derived from

observations of the same GPS satellite G13. The two events were separated by ~ 1 year in time, but in space RO projections overlap each other (left map of Fig. 5c). For the first case, the GOES-17 RO profile shows a very good agreement with the ionosonde observation in the shape of the bottom side part of the profile, the registration of the sporadic E, and the F2 peak region. For the second case, one can see a more pronounced difference between RO and ionosonde profiles. This commonly occurs due to the cumulative effect of a larger distance from the ground-based station (difference in space and in local time) and the local morning condition with a rapidly changing ionosphere. Here, even the IRI-based profile (green line) shows a pronounced discrepancy in the F2 peak density from the ionosonde observation, whereas the IRI model tends to have better performance for midlatitude locations. Figure 5d shows two examples of collocation events between GOES-17 RO and high-latitude station Thule. These events were separated by 2 days only to show similarity in day-by-day variability of the ionospheric profiles at the same location. These profiles correspond to the daytime conditions (near 13 LT), and apart from the F2 peak and sporadic E layer, one can see the formation of the well-defined F1 layer in between, in both the GOES RO profiles and ionosonde observations.

For the statistical analysis, we made comparisons in the plasma (critical, foF2) frequency domain because the reference instrument – ionosonde – provides direct measurements of the frequency of radio signal reflected from ionospheric layers. The statistical dataset was formed from the collocation events between GOES RO EDPs and ionosonde-derived EDPs in terms of the ionospheric F2 peak density (converted into foF2) and height (hmF2). Both RO EDPs and ionograms were manually checked and quality controlled before inclusion into this dataset. Figure 6 summarizes the statistical results of comparisons between the RO- and ionosonde-derived values for the ionospheric F2 peak parameters for two separate datasets for the GOES-16 and GOES-17 satellites, respectively. For the GOES-16 RO observations, collocation analysis against the three nearest digisondes provided us with 1240 collocation events during 2018–2022. Figures 6a and 6b show scatter plots for foF2 and hmF2 values derived from these collocations between the GOES-16 RO and ionosondes. The scattering patterns show a rather close, symmetrical distribution of the F2 peak parameters as derived from space- and ground-based measurements simultaneously. The cross-comparisons between two independent types of measurements for the F2 peak parameters reveal a high degree of correlation of 0.942 and 0.965 for foF2 and hmF2, respectively. Though we utilized a much larger collocation window of 10° for the GOES-17 RO observations, the collocation analysis against the three selected ionosondes provided us with only ~ 600 collocation events during 2019–2022. Moreover, the ionograms from Wakkanai ionosonde were scaled for the critical frequency foF2 only; thus, even fewer data points for hmF2 (435 in total) were accumulated in the case of the GOES-17. Figures 6e and 6f show the corresponding scatter plots for foF2 and hmF2 values derived from these collocations between the GOES-17 RO and the three ionosondes. We found a high correlation of 0.962 for the foF2 parameter and a slightly larger scattering for the hmF2 parameter with a correlation of 0.880. This larger scattering and decreased correlation value can be related to a much larger distance from GOES RO to both digisondes at Millstone Hill and Thule (see Figs. 4b and 5c–5d).

We also analyzed residuals for the ionospheric F2 peak parameters derived from collocated GOES RO and ionosonde measurements. Using standard statistical analysis procedures, we calculate the RO–ionosonde measurement residuals and the major characteristics of these residuals: mean, standard deviation (STD), and root mean square error (RMSE). The residuals for the F2 peak critical frequency ($\Delta\text{foF2} = \text{foF2}_{\text{GOES_RO}} - \text{foF2}_{\text{ionosonde}}$) and the F2 peak height ($\Delta\text{hmF2} = \text{hmF2}_{\text{GOES_RO}} - \text{hmF2}_{\text{ionosonde}}$) are expressed in MHz and km, respectively. Figures 6c–6d demonstrate the resulting histograms for residuals between GOES-16 RO and ionosonde profiles. Figure 6c shows a very narrow distribution of the ΔfoF2 residuals with a mean value of -0.05 MHz with an STD of 0.37 MHz. For the F2 peak height, we have obtained also a rather narrow distribution of the ΔhmF2 residuals with the mean value of 0.63 km and STD of 9.98 km (Fig. 6d). For GOES-17 (Figs. 6g and 6h), the distribution of the ΔfoF2 residuals was also quite narrow and Gaussian with a mean value of -0.24 MHz and STD of 0.46 MHz, whereas the distribution of the ΔhmF2 residuals was much wider than that for GOES-16 and it had larger values of the mean (-3.20 km) and STD (14.86 km). This can be attributed to a smaller number of collocation events and larger distances between measurements. Thus, we can conclude that much better results were obtained for the GOES-16 dataset due to more favorable locations of the GOES RO profiles in closer proximity to the midlatitude ground-based stations.

This agreement is consistent with a COSMIC-1 EPDs validation analysis with the European digisondes under low solar activity conditions (Krakowski et al., 2011). In the recent validation study of COSMIC-2 EPDs with globally distributed ionosondes (Cherniak et al., 2021), for the F2 peak parameters distribution at midlatitudes, particularly, it was found the mean value of 0.48 MHz and STD of 0.48 MHz for the ΔfoF2 residuals, and the mean value of 2.22 km and STD of 13.73 km for the ΔhmF2 residuals (Cherniak et al., 2021; Fig. 5). Thus, the obtained statistical results for GOES RO demonstrate very similar behavior as in the previous validation studies for the COSMIC-1/2 missions with ground-based ionosondes. It confirms a very good agreement in the F2 peak parameters between two independent types of measurements – GOES RO and ionosondes.

3.3 Comparison with COSMIC RO

After comparison with the benchmark ground-based ionosonde measurements, we examined collocation events between GEO-based GOES RO and similar types of observations provided by independent LEO RO missions. Here, we decided to use COSMIC-1 and COSMIC-2 missions, whose EDPs products were previously validated with ionosondes and other instruments and demonstrated very good accuracy. The overlapping years to compare GOES RO with COSMIC-1, here 2018–2019, corresponded to the final years of the COSMIC-1 mission, so there was only available a limited amount of RO profiles provided by the last COSMIC-1 satellites C001 and C006. However, the orbit inclination of the COSMIC-1 satellites was quite high (72°) which supported RO observations at middle and high latitudes, where we have some dominant concentration of the GOES RO profiles (see Fig. 4). The overlapping period with the COSMIC-2 mission, which was

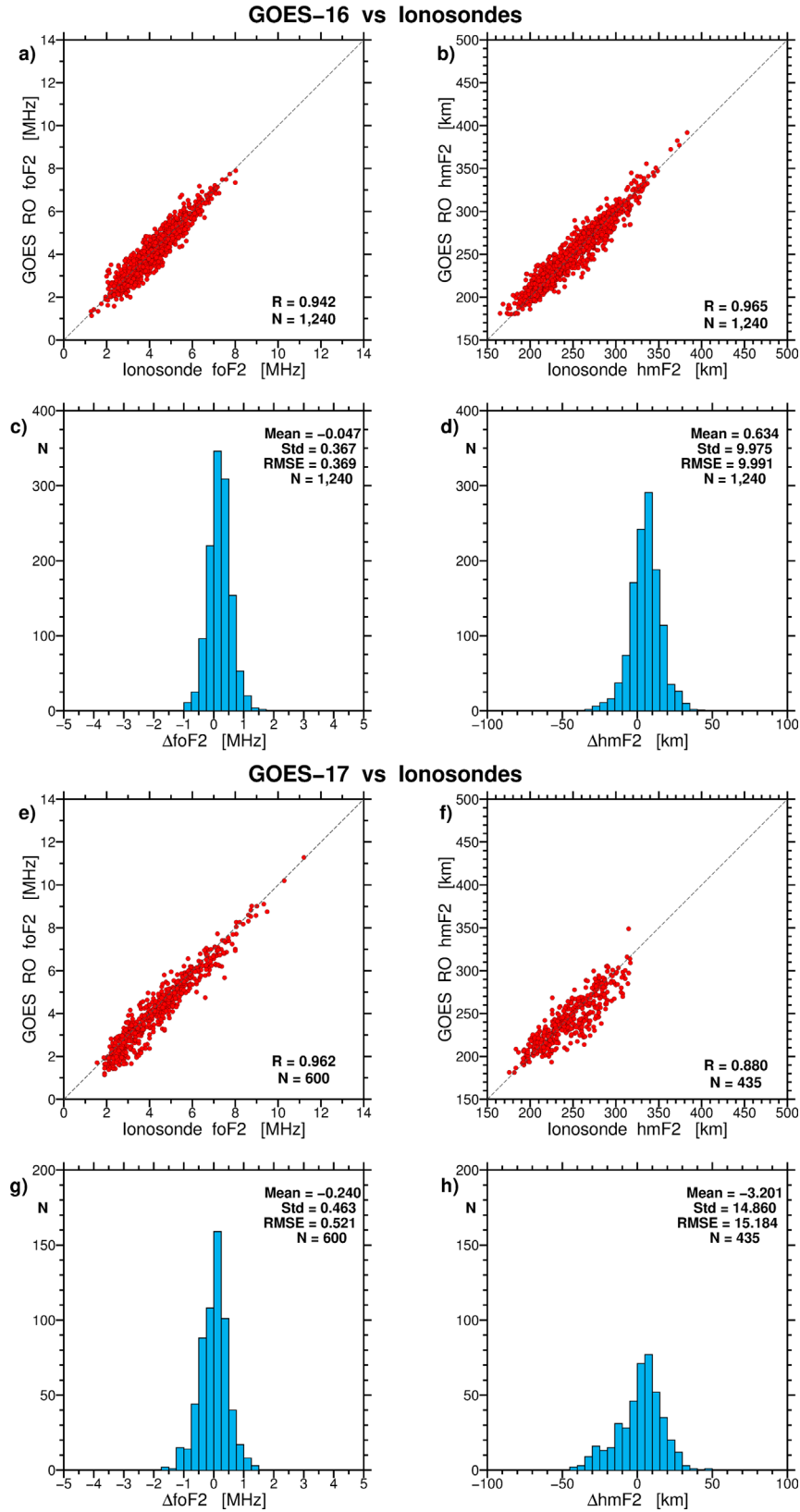


Figure 6. Scatter plots of the GOES RO-based foF2 and hmF2 values against the corresponding ionosonde-derived ones with and histograms of the F2 peak parameters residuals ΔfoF2 ($\Delta\text{foF2} = \text{foF2}_{\text{GOES_RO}} - \text{foF2}_{\text{ionosonde}}$) and ΔhmF2 ($\Delta\text{hmF2} = \text{hmF2}_{\text{GOES_RO}} - \text{hmF2}_{\text{ionosonde}}$) for (a–c) GOES-16 and (e–h) GOES-17 satellites. Each scatter plot contains information about correlation index R and total number of colocations, each histogram plot – information about the mean, standard deviation, and RMS error.

launched in mid-2019, corresponds to the years 2019–2022. This mission has six satellites with advanced GNSS receivers capable of tracking both GPS and GLONASS signals simultaneously, it provides several thousand RO profiles per day. There is the only drawback for our study – due to the orbit inclination of 24° , most of the COSMIC-2 RO profiles concentrate in the equatorial and low-latitude region, where just in opposite we have quite a limited number of GOES RO profiles (see Fig. 4). So, the search for collocation events with both the COSMIC-1 and COSMIC-2 missions revealed specific challenges and limitations that resulted in a small total amount of collocations. As a collocation definition criterion, we selected that both GOES RO and COSMIC RO profiles should have (1) the tangent point of the F2 peak to be within 5° distance from each other, and (2) a time separation of less than 1 h. So, in spatial separation of the F2 peak locations between two RO-based profiles, this criterion was as strict as the tightest one used for collocations between GOES-16 and ionosondes. The time window was relaxed from 20 min to 60 min, since with RO observations we do not have repeatable measurements with a known or schedulable timespan of 5–15 min as in the case of ground-based ionosondes.

Figure 7 shows several representative examples of such collocation events between GOES-16 and GOES-17 RO-based profiles and collocated profiles retrieved either from COSMIC-1 or COSMIC-2 RO observations. Figure 7a shows two examples of collocations between GOES-16 RO and COSMIC-1 RO profiles, which occurred in middle latitudes at $\sim 50^\circ\text{N}$ and $\sim 50^\circ\text{S}$. Case #1 was constructed with the COSMIC-1 satellite C001 during local evening conditions in May 2018. RO retrievals from LEO and GEO show a very similar shape of EDPs with an excellent agreement around the F2 layer peak. Case #2 occurred with the COSMIC-1 satellite C006 near local noon on October 2018. We found a very good agreement between EDPs derived from GEO and LEO RO observations in the shape of profiles, the F2 peak density and height, as well as in registration of the well-formed F1 layer around 150 km altitude, which is quite typical under daytime conditions. We should emphasize the important advantage of the COSMIC-1 mission in providing the RO-based profiles up to very high altitudes of ~ 800 km, even at the end of the mission – that allows us to cross-compare the topside parts of the profiles derived from GOES and COSMIC-1 up to ~ 800 km altitude, which was absolutely impossible in comparison with the ground-based ionosondes. In these two cases with COSMIC-1 C001 and C006 satellites, the GOES-16 RO profiles demonstrated a very good agreement in the shape of the topside parts of the profiles. Similarly, Figure 7b presents two collocation events between ionospheric profiles derived from RO observations provided by GOES-17 and COSMIC-1 C006 satellites in the American longitudinal sector. Here, we had a slightly larger difference in geometry and length of occultation tracks than in Figure 7a, but in general, there is a very good agreement in the ionospheric profile shape from the bottom-side up to ~ 840 km altitude and in the F2 peak parameters.

Figure 7c shows comparisons of RO-derived EDPs for GOES-16 and COSMIC-2 collocation events. In collocations with COSMIC-2, we were mainly limited to cases with RO profiles registered at the farthest distance from the equator, since GOES RO profiles rarely occurred in the equatorial region. Thus, the discrepancy in occultation geometry was the most

evident in comparisons with COSMIC-2 RO observations, though collocation event was selected only if the distance between the F2 peak locations was within 5° . Case #1 occurred near 30°N in the Pacific Ocean in March 2021. Two COSMIC-2 satellites, C2E1 and C2E4, were tracking the same GPS satellite PRN28 and provided two profiles near the same location within a ~ 30 -minute window. One can note how the difference in geometry between two COSMIC-2 RO tracks (blue and green lines in Fig. 7c, left) resulted in the difference between RO profiles, in particular in the bottom-side part of these profiles (blue and green lines in Fig. 7c, middle). In 2021, these COSMIC-2 satellites were already lowered into their operational orbit of ~ 550 km altitude, so the top part of the RO profiles is also limited by ~ 550 km. We found a very good agreement with the topside part of these three RO-based profiles and in the F2 peak density and height. Case #2 occurred near 35°S in the Atlantic Ocean in December 2021. Here, the COSMIC-2 satellite C2E5 tracked simultaneously two GLONASS satellites R02 and R12, and provided two RO events at nearly the same location and time. One can note that even under such “ideal” conditions when several RO profiles are derived from the same LEO satellite with nearly the same geometry, these profiles can have some differences – here, in the F2 peak density and height (blue and green lines in Fig. 7c, right). But in general, a comparison of the GOES-16 RO profile with both COSMIC-2 profiles demonstrated a very good agreement in the shape of profiles between 200 and 550 km and the F2 peak region.

Figure 7d shows two examples of ionospheric profiles corresponding to GOES-17 and COSMIC-2 collocation events in the American longitudinal sector. Occultation geometry for these two cases is rather similar to those in Figure 7b, but here COSMIC-2 tracks had much longer ground projection tracks. For case #1, both GOES-17 and COSMIC-2 profiles demonstrate quite similar distribution of electron density with the presence of a well-defined F1 layer near 150 km altitude, an F2 layer near 250 km altitude, and a good agreement of the profile shape up to ~ 530 km altitude. Case #2 corresponded to the local afternoon conditions in February 2020 (local summer in the Southern Hemisphere). Both GEO and LEO RO profiles demonstrate a well-developed F2 layer with elevated F2 peak density and height. The shape of profiles is quite similar from the sporadic E region at ~ 100 km altitude to ~ 720 km altitude (C2E5 was not lowered yet in February 2020). Some differences in F2 peak and topside shapes can be related to the pronounced differences in occultation geometry.

An assessment of the representative collocation events demonstrates that the RO-based profiles derived from GEO GOES-16/17 and from the reference LEO COSMIC-1/2 observations have a high degree of similarity in the profile shape in its bottom side (including proper reproduction of the Es and F1 layers signatures), the F2 region part, and even the topside part up to 550–800 km altitudes. We found a very good agreement between collocated RO-based EDPs retrieved from the geostationary orbit under different seasons, different levels of solar activity between 2018 and 2022, and different local times for collocation events that mainly occurred near middle latitudes. The examined representative cases with different GOES RO geometry provided the observational evidence that GEO GOES RO-based profiles look quite reasonable and consistent in terms of the ionospheric F2 peak values and the entire

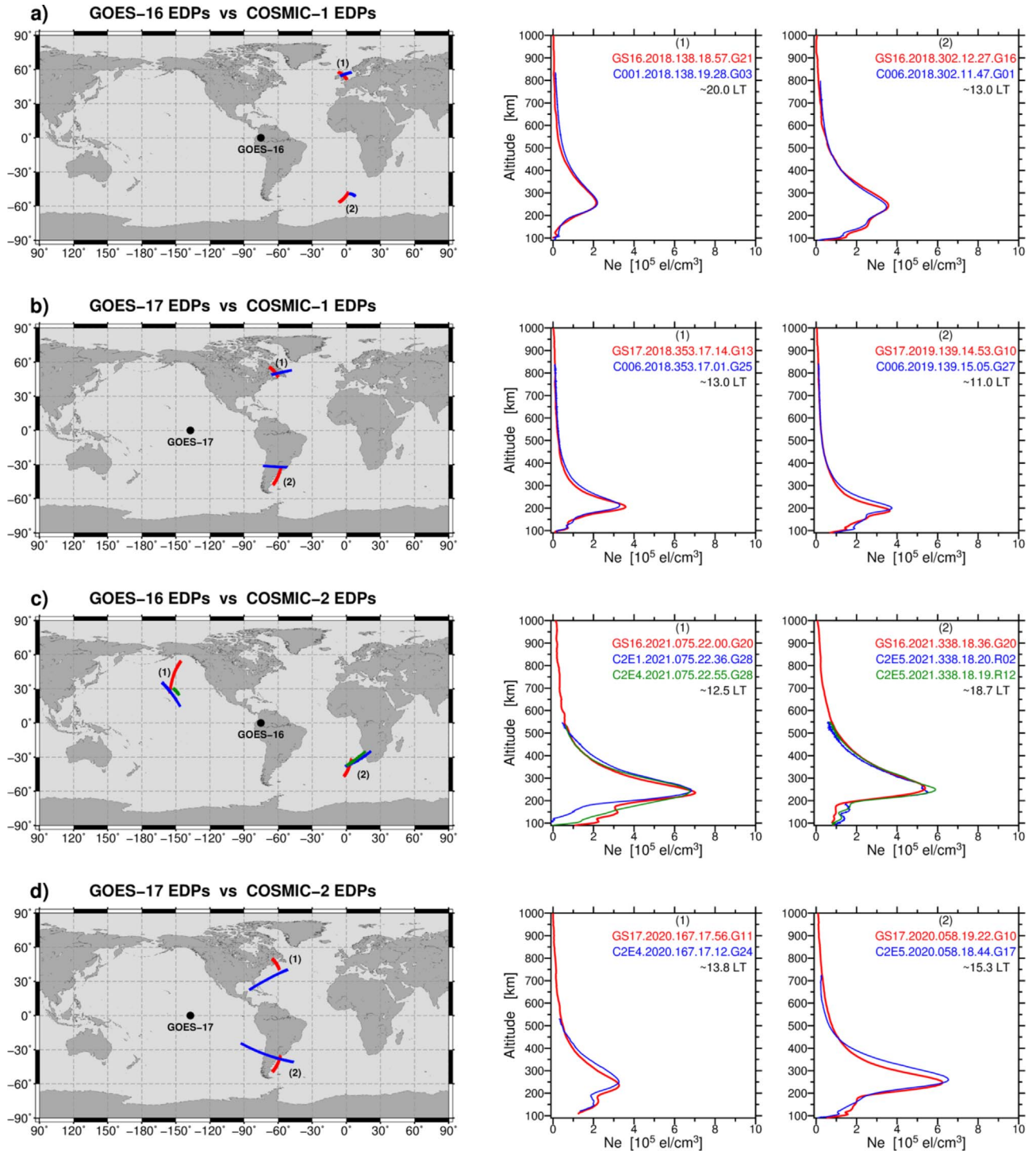


Figure 7. Examples of GOES-16 and GOES-17 RO EDPs as compared with collocated (a, b) COSMIC-1 RO profiles and (c, d) COSMIC-2 RO profiles. For each panel, left plot shows a geographical map with the RO tangent points projections of red color for GOES and blue/green for COSMIC; right plots show RO-derived Ne profiles for two collocation events #1 and #2, respectively.

Ne profile shape in comparison with independent COSMIC-1/2 observations.

Figure 8 demonstrates a summary of the statistical results based on the entire datasets of the collocation events between GOES and COSMIC-1/2 ionospheric profiles. The scatter plots of foF2 and hmF2 values from the comparison of the

GOES-16/17 RO and the COSMIC-1 RO can be seen in Figures 8a and 8b. Here, we had a total of 167 collocation events. We found a very symmetrical pattern in the distribution of the foF2 and hmF2 values and a high correlation of 0.88 and 0.89 for foF2 and hmF2, respectively. The histograms of the discrepancies between the GOES RO and COSMIC-1 RO profiles, in

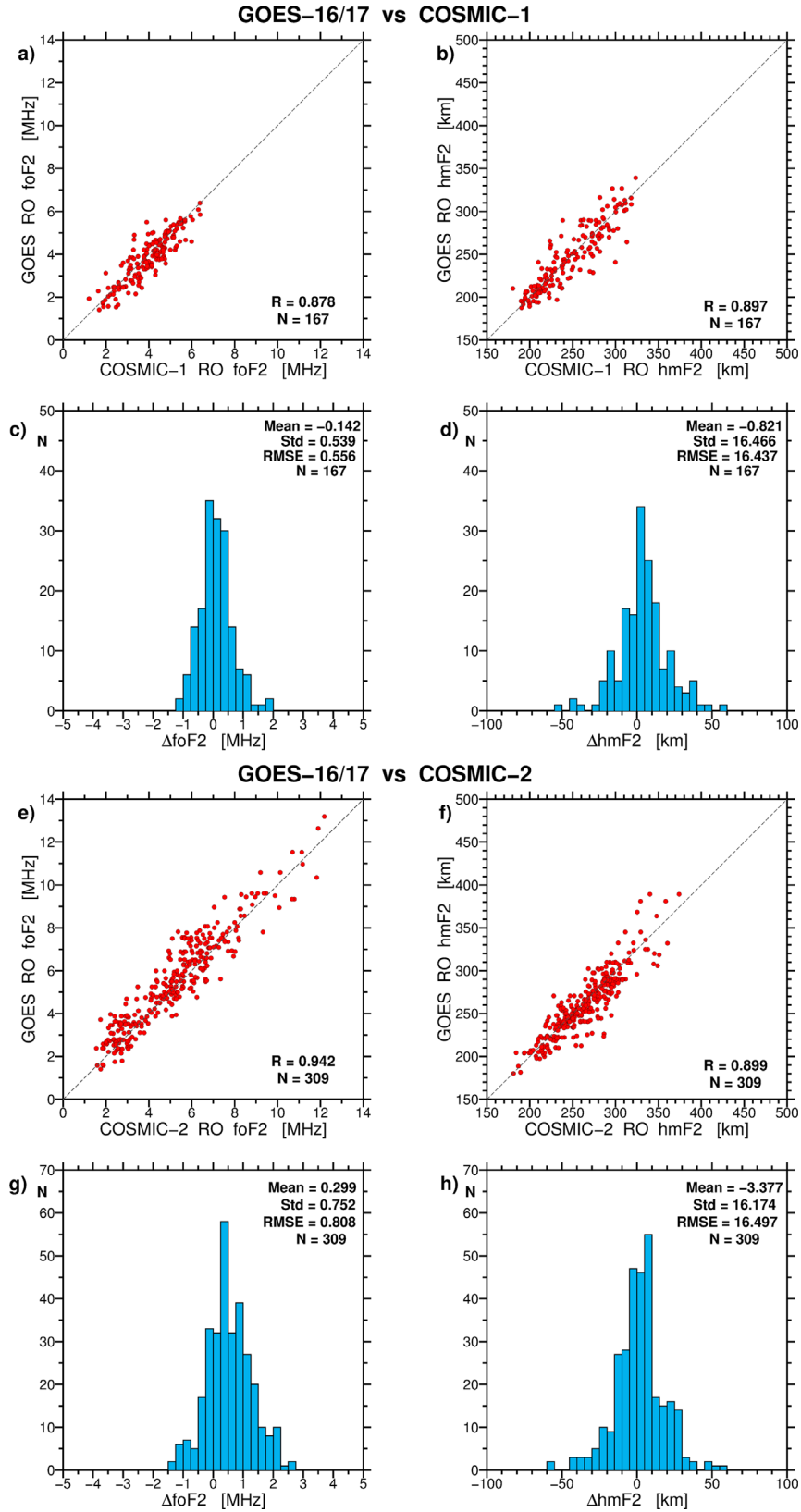


Figure 8. Scatter plots of the foF2 and hmF2 values for collocation events between GOES RO and COSMIC RO profiles and histograms of the F2 peak parameters residuals ΔfoF2 ($\Delta\text{foF2} = \text{foF2}_{\text{GOES_RO}} - \text{foF2}_{\text{COSMIC_RO}}$) and ΔhmF2 ($\Delta\text{hmF2} = \text{hmF2}_{\text{GOES_RO}} - \text{hmF2}_{\text{COSMIC_RO}}$) for (a–c) GOES-16/17 vs. COSMIC-1 and (e–h) GOES-16/17 vs. COSMIC-2.

terms of Δf_oF2 and Δh_mF2 , are displayed in Figures 8c and 8d. For the F2 peak density, we noticed quite a narrow distribution of the Δf_oF2 residuals with a mean of -0.14 MHz and a STD of 0.54 MHz (Fig. 8c). The F2 peak height's Δh_mF2 residuals had a wider range, with a mean of -0.82 km and a STD of 16.47 km (Fig. 8d).

Figures 8e and 8f show scatter plots for f_oF2 and h_mF2 values that were derived from comparing the profile collocations between the GOES-16/17 RO and the COSMIC-2 RO. The number of collocation events here was 309. As previously noted, most of these events occurred at much lower latitudes and during an increased level of solar activity than the COSMIC-1 RO comparison results. These scatter plots clearly depict a rise in maximal observable values for both f_oF2 and h_mF2 due to these reasons. The correlation was even stronger here than in the COSMIC-1 comparison, with values of 0.94 and 0.90 for f_oF2 and h_mF2 , respectively. Figures 8g and 8h feature histograms of the residuals Δf_oF2 and Δh_mF2 between the GOES RO and COSMIC-2 RO profiles. In Figure 8g, the distribution of the F2 peak density residuals Δf_oF2 was found to be more spread out than what was seen in the COSMIC-1 comparison (as seen in Fig. 8c), with a larger mean (0.29 MHz) and an increased STD (0.75 MHz).

Thus, for the F2 peak density, the mean value of the Δf_oF2 residuals between the GOES RO results and those provided by both the ionosondes and COSMIC RO was found to be close to zero. The F2 peak height's Δh_mF2 residuals had also a broader range of residuals distribution, with a mean of -3.37 km and an STD of 16.17 km (Fig. 8h). For the F2 peak height, the comparison of the GOES RO with both ionosondes and COSMIC RO observations demonstrates that the mean of the Δh_mF2 residuals was between -3 and 0 km and the standard deviation was between 10 and 16 km. These values are in good agreement with accuracy results for h_mF2 previously reported for COSMIC-1 and COSMIC-2 RO missions. That confirms the good performance of the GEO-based GOES RO observations for sensing the ionospheric F2 peak parameters.

3.4 Comparison with the IRI model

In the next step, we examined the behavior of GOES RO profiles against the model simulation results provided by the International Reference Ionosphere (IRI) model. IRI is an empirical (data-based) model representing the primary ionospheric parameters based on a long data record that exists from ground and space observations of the ionosphere. The core model describes monthly averages of the electron density, electron temperature, ion temperature, and ion composition globally in the altitude range from 60 to 2000 km (Bilitza et al., 2017, 2022). IRI is the most famous empirical model of the Earth's ionosphere. In 2014, IRI became the International Standardization Organization (ISO) certified standard for the ionosphere (ISO 16457: <https://www.iso.org/standard/61556.html>). Here, we use the most up-to-date version of the IRI model, IRI-2020, which was released in 2022 and is freely available for the research community (<http://irimodel.org/>). The main input parameters of the IRI model are location, time, sunspot number or solar radio flux, and magnetic Ap/Kp index. We used the URSI coefficients to predict the F2 layer peak parameters since the URSI coefficients maps are recommended when the mapping area includes large ocean areas. The f_oF2 STORM model

option was turned off because this study deals with quiet geomagnetic conditions. For the F2 peak height (h_mF2) model, we used the new SHU-2015 option, which is based on the Satellite and Digisonde Model of the F2 layer (SDMF2) model that was recently developed on long-term h_mF2 ionosonde data and COSMIC RO data (Shubin et al., 2013; Shubin, 2015).

It is important to note that IRI is a climatological model. It provides predictions of the monthly average values of electron density and EDPs for a selected location and conditions. These profiles could not reflect the day-by-day variability of the ionosphere. In Figure 5, we showed a few comparisons between the RO-derived and the IRI-derived profiles. In some cases, IRI can show that its profile shape is in excellent agreement with other observations (e.g., Figs. 5b and 5d). For other cases, results of the climatological model may not always perfectly match with the observations, especially with the F2 peak density (e.g., Figs. 5a and 5c), due to various reasons, in particular day-to-day variability of the ionosphere that can be 10 – 50% in electron density even at mid-latitudes (e.g. Zhang & Holt, 2008; Zakharenkova et al., 2014; Cherniak & Zakharenkova, 2019). It is a known feature of the model-data comparative analysis and IRI model performance.

To statistically analyze the performance of the GOES RO profile retrievals against IRI model simulation outcomes, there are no time or location constraints since the IRI Ne profile can be calculated for any user-selected point. We divided the combined GOES-16 and GOES-17 RO profiles into two main regions, the high (60° – 90° magnetic latitude) and middle (30° – 60° magnetic latitude) latitudes, with roughly 4600 and 5200 profiles in each. For each location, determined from the GOES F2 peak coordinates, and time, the relevant IRI Ne profile was computed using the IRI-2020 model. Figure 9 summarizes the statistical results of the GOES–IRI profile comparison. Figures 9a and 9b show scatter plots for f_oF2 and h_mF2 values derived from the GOES-16/17 RO and the IRI model profiles at high latitudes. One can see quite a narrow symmetrical pattern in the f_oF2 values and a more scattered distribution of the h_mF2 values. That can be explained by the fact that at high latitudes the background density is usually much lower compared to the middle and equatorial latitudes, but the height of the F2 peak can vary greatly, especially when plasma density gradients (like polar cap patches) or other plasma dynamic processes are at play. We found that at high latitudes, the correlation between the IRI model and GOES observations for F2 peak parameters was still quite strong at 0.852 and 0.778 for f_oF2 and h_mF2 , respectively. Figures 9e and 9f present scatter plots for f_oF2 and h_mF2 values derived from the GOES-16/17 RO and the IRI-model profiles in the second zone, at middle latitudes. We observe a symmetrical distribution of the model-data values for both f_oF2 and h_mF2 with slightly large absolute values since we moved to lower latitudes. In the middle latitudes, the GOES RO observations were found to have an even higher correlation with the IRI model for F2 peak parameters, with values of 0.890 and 0.862 for f_oF2 and h_mF2 , respectively.

The GOES–IRI residuals for the ionospheric F2 peak parameters at high and middle latitudes are displayed in the histograms of Figure 9. Both the high and middle latitude regions had histograms with the distribution of the Δf_oF2 residuals that were quite narrow and Gaussian (Figs. 9c and 9g). The mean value for the first region was -0.06 MHz with an STD of 0.61 MHz. The second region had a mean value of 0.06 MHz

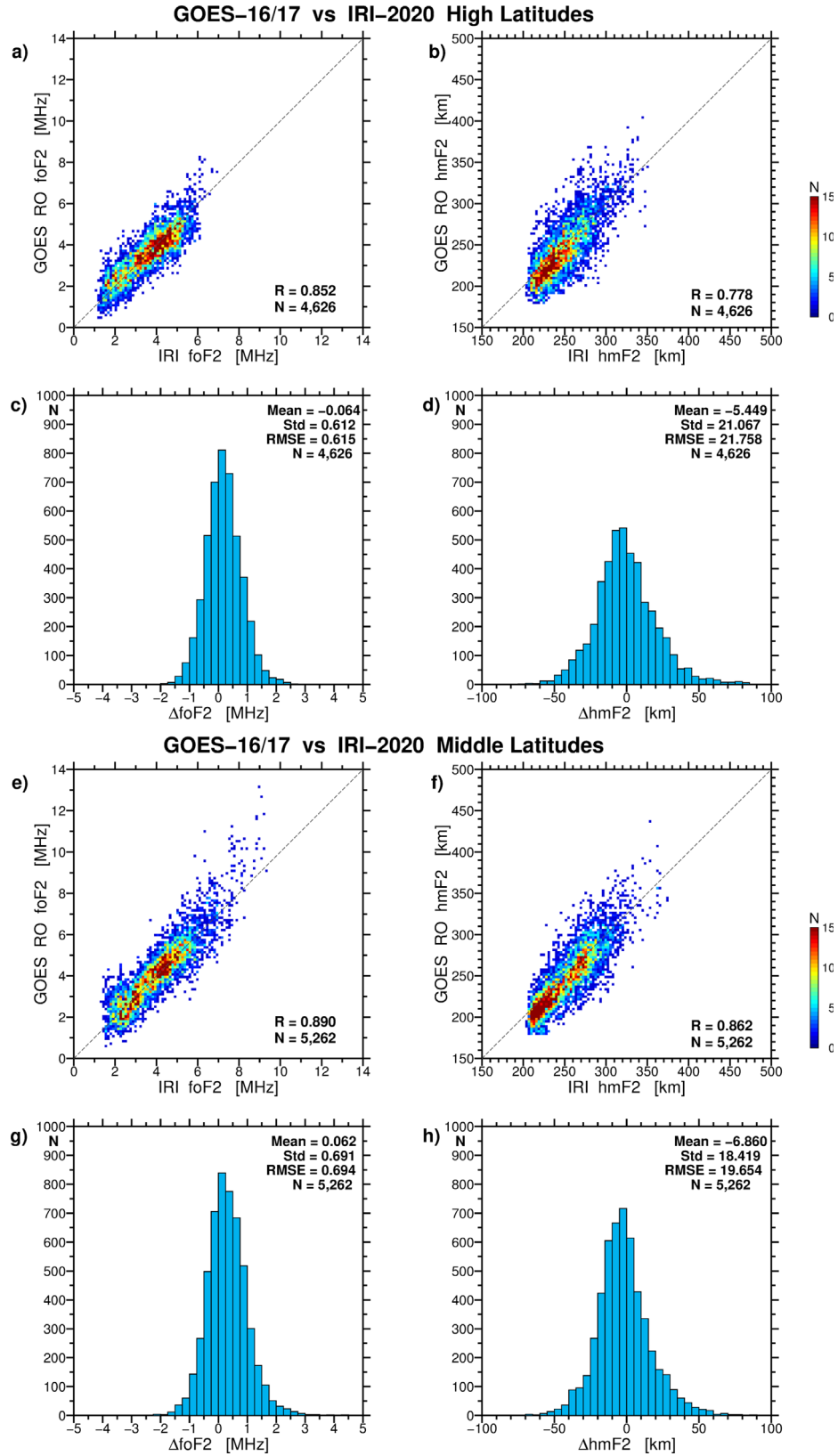


Figure 9. Scatter plots of the foF2 and hmF2 values derived from GOES RO and IRI-2020 model and histograms of the F2 peak parameters residuals ΔfoF2 ($\Delta\text{foF2} = \text{foF2}_{\text{GOES_RO}} - \text{foF2}_{\text{IRI}}$) and ΔhmF2 ($\Delta\text{hmF2} = \text{hmF2}_{\text{GOES_RO}} - \text{hmF2}_{\text{IRI}}$) for (a–c) GOES-16/17 vs. IRI-2020 at high latitudes and (e–h) GOES-16/17 vs. IRI-2020 at middle latitudes.

and an STD of 0.69 MHz. The resulting mean values of the Δf_oF2 residuals that are close to zero are in very good agreement with the near-zero mean results that we obtained in an independent comparison of the GOES profiles with ionosondes and COSMIC RO profiles (Figs. 6 and 8). The STD of the 0.6–0.7 MHz range is greater than the one obtained from the ionosonde comparison (~ 0.4 MHz) but is similar to the values resulting from the COSMIC RO (~ 0.5 – 0.7 MHz).

For the F2 peak height, we noticed also a Gaussian type of distribution of the Δh_mF2 residuals at both high and middle latitudes (Figs. 9d and 9h). The histograms are much wider compared to those of the Δf_oF2 residuals. In the high latitude region, the mean value was -5.45 km, and the STD of 21.07 km. In the middle latitude region, the mean value was -6.86 km, and the STD of 18.42 km. Taking into account the comparison of the GOES RO with both ionosondes and COSMIC RO observations, the mean of the Δh_mF2 residuals was determined to be -3 to 0 km. This suggests that the GOES–IRI mean of the (-7 to -5) km range is likely due to the model overestimating the F2 peak height. The STD of the GOES–IRI Δh_mF2 residuals was 18 – 21 km, much higher than the 10 – 15 km we found in the GOES–ionosonde comparison and the 16 km from the GOES–COSMIC RO comparison.

It is important to remember that the accuracy of the F2 peak height taken from ionosonde measurements relies heavily on the quality of an ionogram and performed trace scaling, as well as the inverting algorithm. In contrast, the F2 peak height derived from RO measurements is considered to be reasonably accurate. This feature of the RO technique was highlighted in early studies that examined the accuracy of RO ionospheric retrieving. According to Jakowski et al. (2009), the “F2 peak height is the most reliable parameter of the retrieved profile,” a statement based on model simulations (Hochegger & Leitinger, 2000) and direct comparisons of the CHAMP RO observations with high latitude EISCAT incoherent scatter radars measurements. A further assessment study of COSMIC-1 RO EDPs accuracy by midlatitude incoherent scatter radar (Cherniak & Zakharenkova, 2014) proved that the absolute discrepancies of F2 peak height against reference ISR measurements were not more than 20 km. Recently the COSMIC-2 EDPs were assessed for accuracy, and it was determined that the ionospheric F2 peak height residuals between COSMIC-2 RO and ground-based ionosonde measurements had a mean of ~ 5 km and ~ 2 km at low and middle latitudes, respectively, and a standard deviation of ~ 23 km and ~ 14 km, respectively (Cherniak et al., 2021). Therefore, GOES RO retrievals of the F2 peak height are found to be in good agreement with independent measurements (ionosondes, COSMIC RO) and with empirical model simulation results, and the observed differences are all within expected ranges.

4 Summary

In this research, we presented a novel approach for obtaining ionospheric EDPs from a GEO mission. This approach was then applied to a statistically significant number of GPS observations from GOES-16 and GOES-17 satellites, which enabled us to retrieve more than $10,000$ ionospheric profiles with a current maximum altitude of up to 1000 – 2000 km, much higher than any existing LEO RO mission. Using this data set, we demonstrated the performance of geostationary RO measurements for

properly specifying the vertical distribution of ionospheric plasma density by comparing GEO-based GOES-16/17 RO profiles with independent reference observations – ground-based ionosondes and LEO-based RO missions. A statistical analysis of the differences between ionospheric F2 layer peak parameters (peak height and density) derived from GEO-based GOES-16/17 observations and from reference measurements indicates that GEO-based RO ionospheric profiles retrievals are reasonably accurate, based on comparisons with reference data sets and model, resulting in the following quantitative accuracy estimates:

1. The F2 peak parameters from GOES RO observations showed a strong correlation when compared with those from ionosondes and LEO RO measurements: 0.87 – 0.95 for f_oF2 and 0.88 – 0.96 for h_mF2 .
2. For the F2 peak density, the mean value of the Δf_oF2 residuals between the GOES RO results and those provided by ionosondes, LEO RO, and by the empirical model IRI-2020 was close to zero, with a symmetrical scattering of data for the F2 peak density. This verifies that no extra calibration of the absolute values of the F2 peak density is required for the current GOES RO profile retrieval.
3. For the F2 peak height, the comparison of the GOES RO with both ionosondes and COSMIC RO observations demonstrates that the mean of the Δh_mF2 residuals was between -3 and 0 km and the standard deviation was between 10 and 16 km. These values are in good agreement with accuracy results for h_mF2 previously reported for COSMIC-1 and COSMIC-2 RO missions. There is confirmation that the GEO-based GOES RO observations are successful when it comes to sensing the ionospheric F2 peak parameters.
4. As for the profile shape, an analysis of the representative collocation events demonstrates that the EDPs derived from GOES RO and from the reference ionosonde and LEO RO observations have a high level of similarity in the profile shape in its bottom side (including proper reproduction of the Es and F1 layers signatures), the F2 region part, and even the topside part up to 550 – 800 km altitudes, if available.
5. We used the empirical ionospheric model IRI-2020 to compare the behavior of the GOES RO profiles at high and middle latitudes to climatological predictions. Examining several thousand profiles, the model-data comparison was found to be in good agreement within the expected range of discrepancies in the F2 peak parameters.

The geometry of GEO–GPS RO links (which do not vary significantly from day to day in comparison to LEO RO) provides the opportunity to use these measurements for long-term monitoring of the ionosphere in certain locations, very similar to permanent ground-based facilities. We ultimately believe that RO profiles from GEO orbit hold the potential to generate unique temporal and spatial ionospheric measurements complementary to those from the ground and LEO space-based receivers, including limb observations of the upper atmosphere at altitudes higher than what traditional LEO RO satellites can reach.

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