remote sensing

Editorial

Editorial for the Special Issue: "Radio Occultations for Numerical Weather Prediction, Ionosphere, and Space Weather"

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1. Ionospheric Research

Sounding of the Earth's ionosphere is an important application of the RO technique. In particular, sporadic E layers, or E_s, may significantly affect communication. This indicates the need for an E_s climatology as well as for robust methods to estimate E_s occurrence rates (ORs). Ref. [1] compared estimates of ORs with an fbEs of $\geq$3 MHz and those without an fbEs limit, using five GPS-RO techniques and ionosonde measurements over an eight year period between 2010 and 2017. The GPS-RO methods were as follows: (1) the Arras method, (2) the Niu method, (3) the Chu method, (4) the Yu method, and (5) the Gooch method. These methods analyze the L1 amplitude or different combinations of L1 and L2 excess phases. It was demonstrated that these techniques exhibits significant variations in ORs. Nevertheless, the Yu technique gave the best agreement with ionosonde rates without a lower limit on the fbEs, and the Chu technique provided a good agreement for fbEs of $\geq$3 MHz.

Another ionospheric region of importance is the F layer. Its peak density (NmF2), height (hmF2), and critical frequency were estimated from RO observations. Ionospheric irregularities in the F layer are one of the causes of radio signal scintillation. In [2], a dataset containing low-latitude RO events observed by the GNSS Receiver for Atmospheric Sounding (GRAS) on board Meteorological Operational (MetOp) satellites was created to train an automatic detection model of F layer scintillations. To this end, the following ionospheric characteristics were employed: (1) the S4 index, defined as the fourth moment of the signal amplitude; (2) the standard deviation of the detrended phase excess, σ_ϕ; and (3) the spectral densities of the amplitude and the detrended phase excess. In order to develop a supervised detection model for F layer scintillation, a dataset of labelled observations was generated, accounting for different geographical regions, the local time, the season, and solar and geomagnetic activities. The dataset was used to train a Support Vector Machine (SVM) algorithm to automatically classify events with ionospheric scintillation (label 1) and other disturbances (label 0). It was demonstrated that S4 and σ_ϕ are poor predictors. Nevertheless, the developed SVM model described sets a standard for the use of machine learning algorithms in the detection of F layer scintillation in RO measurements. The classifier has the potential to collect a large number of occultations with specified characteristics and to analyze their ability as predictors of different atmospheric conditions.

At middle and low latitudes, the electron density of the F2 layer exceeds that of the E layer. At high latitudes, energetic particles from the magnetosphere can enhance the electron density of the E layer up to values exceeding that of the F2 layer. Such events are referred to as E layer dominated ionosphere (ELDI) events. The duration of ELDI events can reach up to 5 h. The authors of [3] developed an empirical climatological model of ELDI events (the Neustrelitz ELDI Event Model, or NEEM). The model consists of four submodels: (1) NEEM-N: a model for E layer peak ionization; (2) NEEM-H: a model for the E layer peak height; (3) NEEM-W: a model for the E layer vertical profile width;

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and (4) NEEM-P: a model for the ELDI occurrence probability (%ELDI). The model was validated using a test dataset.

2. Severe Events

Another application of RO data is in the analysis of severe events. Ref. [4] utilized temperature, pressure, and humidity data retrieved from COSMIC2 observations by means of a one-dimensional variational assimilation (1D-Var) in order study monsoon moisture and predict severe weather based on a humidity indicator (the total precipitable water). It was demonstrated that the moisture indicator accurately provides a nowcast of daily moisture variations in the South China Sea and the Bay of Bengal. Assimilation of RO data had a positive effect on the forecasting of typhoon Hagupit (2020), enhancing the simulations of the typhoon structure and intensity, as indicated by a statistical analysis. These results provide a benchmark for advanced assimilation schemes or observation operators.

Ref. [5] used RO-determined temperatures, densities, and bending angles to monitor tropical atmospheric anomalies during the sudden stratospheric warming (SSW) in January–February 2009 using COSMIC, GRACE, and MetOp-A observations. The study analyzed the anomalies of the above variables, defined as the deviation from the collocated climatological profiles. It was demonstrated that polar stratospheric warming correlated with tropical stratospheric cooling. The altitude of the layer with the largest temperature anomalies was 5 km higher in the tropics than it was in the polar region. The largest tropopause anomalies revealed the largest variations at 20°N–30°N. The study proved the capability of GNSS RO data to monitor atmospheric conditions on a daily basis in tropical regions during SSW.

3. LEO-LEO Sounding

Low Earth orbit intersatellite link (LEO-LEO) microwave occultation (LMO) using frequencies around the 22 GHz and 183 GHz water absorption lines has been considered for a long time as the key to determining humidity and temperature without supplementary information. Nowadays, microsatellites are proposed to implement this technique. Ref. [6] conducted a LEO-LEO occultation orbit analysis and a constellation assessment as a first step for future LEO-LEO mission designs. It was demonstrated that the inclination, right ascension of the ascending node, and the orbital height are the main parameters impacting the number of occultation events and the coverage. The number of LEO-LEO occultation events increased rapidly with the increase in the number of satellites. An ideal two-satellite LEO-LEO constellation includes co-planar and counter-rotating transmitters and receivers. Polar and near-polar orbit constellations are optimal for achieving global coverage of RO events. It is important to demonstrate the capabilities of the LMO technique, and the existing or planned constellations can be used for this purpose.

4. Neutral Atmospheric Retrieval

Studies of the Planetary Boundary Layer (PBL) have used RO observations for a long time. Ref. [7] examined the lowest RO-observed altitude and its relation with the refractivity gradient and PBL height on the basis of COSMIC2 observations. An analysis of a typical case suggested that the penetration depth is limited by levels with a strong refractivity gradient. A statistical analysis confirmed this correlation. Another important factor affecting the propagation of RO signals is the horizontal gradient of refractivity. It was demonstrated that this also limits the minimum height of RO retrievals.

Different RO missions utilize the same GNSS signals, but they have different antennas and receivers, which results in different noise levels and, accordingly, different signal-to-noise ratios (SNRs). Ref. [8] investigated the SNRs for different missions, including COSMIC, COSMIC2, METOP-A, METOP-B, and METOP-C. The actual SNR was defined as the ratio of the average signal amplitude in the height range of 60–80 km to the noise floor (NF) determined in the shadow zone. The most likely value of the NF was the lowest for the 3U nanosatellite mission Spire, where the NF was about 10 v/v for all GNSS constellations. COSMIC and METOP have slightly higher values of the NF, at about 11–12 v/v. COSMIC-

2 exhibits the highest NF, which noticeably differs from GPS (18.4 v/v) to GLONASS (14.6 v/v). The use of a SNR normalized to the actual NF allowed for a comparison of the RO inversion characteristics as function of the SNR.

Time-frequency analyses have important applications in the analysis of RO observations in multipath zones. Time and frequency are the coordinates of the phase space associated with an oscillating signal. By now, a series of different types of distributions in the phase space have been employed: (1) spectrograms, (2) the Wigner distribution function (WDF), and (3) the Kirkwood distribution function (KDF). Ref. [9] introduced a new type of such distributions by averaging the KDF over phase space rotations, which was implemented by means of the fractional Fourier transform (FrFT). This results in a WDF combined with a smoothing kernel. The smoothed WDF (SWDF) was validated for simple test signals and then applied in an analysis of real RO observations. It was demonstrated that the SWDF allows a clearer visualization of the ray manifold compared to the WDF due to the suppression of oscillating structures.

5. Variational Assimilation

Variational data assimilation (VDA) is currently the most advanced method of separating dry and wet terms in RO-determined atmospheric refractivity. The kernel of the VDA algorithm is the Forward Model (FM), which represents a physical model of the observed variables. Ref. [10] numerically evaluated the FM in bending angle (BA) calculations in the 1D-Var framework. The FM is based on the Abel integral. Three algorithms were studied: (1) the "direct" algorithm, based on the hyperbolic transformation of the Abel integral, (2) the "exp" algorithm, based on the exponential interpolation of refractivity, and (3) the "exp_T" algorithm, involving more temperature interpolation operators. It was demonstrated that the "exp" algorithm with log-cubic interpolation was the most accurate; however, it may amplify the input errors. A second finding was that the "exp" algorithm with log-linear interpolation, which is less computationally intensive, is feasible in many cases. Finally, the authors noted that the enhancement provided by the "exp_T" algorithm is limited compared to the "exp" algorithm.

Ref. [11] provides a detailed description of 1D-Var implementation at the University Corporation for Atmospheric Research (UCAR). The UCAR 1D-Var system utilizes the FM to determine the BA based on the discrete Abel integral. In order to reduce the effect of errors in the impact parameter, the Abel inversion was replaced by the variational inversion, and the optimal refractivity thus acquired was used as the observable. The a priori temperature, pressure, and humidity were extracted from an NWP model at the observed time along the trajectory of the rays' tangent points. The observation errors for the BA and the refractivity were estimated from innovation statistics, under the assumption that background errors are correlated in space, whereas observation errors are not correlated with themselves or the background errors. The error covariance of the background was estimated from the difference between short- and long-term forecasts. Tests with synthetic data showed that the 1D-Var can enhance the background. This conclusion holds for real-world datasets. The 1D-Var shows close agreement with analyses of the European Center for Medium-Range Weather Forecasts (ECMWF).

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Abbreviations

The following abbreviations are used in this manuscript:

1D-Var	One-Dimensional Variational Assimilation
BA	Bending Angle
ELDI	E Layer Dominated Ionosphere
ECMWF	European Center for Medium-Range Weather Forecasts
FM	Forward Model

FrFT	Fractional Fourier Transform
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAS	GNSS Receiver for Atmospheric Sounding
KDF	Kirkwood Distribution Function
LEO	Low-Earth Orbiter
LMO	LEO-LEO Microwave Occultation
MetOp	Meteorological Operational Satellite
NEEM	Neustrelitz ELDI Event Model
NF	Noise Floor
NWP	Numerical Weather Prediction
OR	Occurrence Rate
PBL	Planetary Boundary Layer
RAAN	Right Ascension of the Ascending node
RO	Radio Occultation
UCAR	University Corporation for Atmospheric Research
SNR	Signal-to-Noise Ratio
SSW	Sudden Stratospheric Warming
SVM	Support Vector Machine
SWDF	Smoothed Wigner Distribution Function
VDA	Variational Data Assimilation
WDF	Wigner Distribution Function

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