

## Algorithm Description and Accuracy Analysis of ROPP Retrieval Software (Postprint)

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### Abstract

The algorithm and accuracy analysis of radio occultation inversion in the ROPP inversion software are presented. Using full-day excess phase data from the COSMIC satellite on January 1, 2008, parameters including refractive index, temperature, pressure, and humidity were retrieved and compared with corresponding results from CDAAC. Experimental results indicate that below 30 km altitude, the relative errors for refractive index, pressure, and humidity are within 2%, while the temperature error does not exceed 2 K.

### Full Text

### Preamble

#### The Inversion Algorithms and Precision Analysis of ROPP

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### Abstract

Radio occultation offers unique advantages including global coverage, high precision, high vertical resolution, long-term stability, and all-weather observation capabilities, which can provide substantial data for numerical weather prediction systems and thereby improve their accuracy [1]. However, before data assimilation, the signals received by GNSS receivers must be preprocessed to invert the observed excess phase information into atmospheric parameters such as bending angle and refractivity, followed by variational assimilation to retrieve atmospheric parameters including temperature, pressure, and humidity. This paper primarily introduces the algorithmic description and precision analysis

of radio occultation inversion within the ROPP software. Using full-day excess phase data from the COSMIC satellite on January 1, 2008, we retrieved refractivity, temperature, pressure, and humidity profiles and compared them with corresponding products from CDAAC. The experiments demonstrate that below 30 km altitude, the errors in refractivity, pressure, and humidity remain within 2%, while temperature error stays within 2 K. Additionally, we compared our inversion results with ECMWF' s ERA-interim reanalysis data, obtaining similar results.

**Keywords:** Radio occultation inversion, Refractivity, Atmospheric parameters, ROPP

## 0. Introduction

JPL first proposed applying radio occultation technology to actively probe Earth' s atmosphere in the 1960s [2], though this initiative was temporarily shelved due to technological and economic constraints at the time. Following the deployment of the Global Positioning System (GPS) by the United States and GLONASS by the Soviet Union, using occultation technology to detect atmospheric profiles became feasible. In 1993, UCAR, the University of Arizona, and JPL jointly formulated the GPS/MET program. The first experimental satellite of this program, MicroLab1, was successfully launched in 1995. Through two years of operation, it demonstrated that radio occultation technology could play a significant role in atmospheric 探测 and research [3, 4]. Due to the success of GPS/MET, NASA agreed to fund two international missions in 1995: Denmark' s Ørsted satellite and South Africa' s Sunsat satellite [5]. Subsequently, notable radio occultation satellites included SAC-C, CHAMP, GRACE, the Metop series, and COSMIC. Notably, China successfully launched the FengYun-3 satellite in 2013, which can also be applied to radio occultation 探测.

Radio occultation offers advantages of global coverage, high precision, high vertical resolution, long-term stability, and all-weather observation, with each LEO satellite acquiring approximately 500 profiles daily, providing substantial data sources for climate research and numerical weather prediction. A current research focus is how to effectively apply occultation observations to existing numerical weather prediction systems, where the key requirement is that radio occultation inversion precision must meet the accuracy demands of these systems. Currently, influential international GNSS meteorology research institutions include GFZ' s ISDC data system center, JPL' s GENESIS data system center, and UCAR' s CDAAC data system center. The COSMIC mission, jointly launched by UCAR and Taiwan, is widely recognized as having achieved significant breakthroughs in radio occultation 探测.

ROPP was developed by GRAS, a research institution under EUMETSAT, initially intended for processing Metop satellite data. However, in practice, it can be adapted to process other GPS-LEO occultation data by adjusting soft-

ware configurations. During occultation data processing, ROPP can perform preprocessing and quality control of radio occultation data, as well as assimilate occultation data into NWP or other climate models. ROPP is open-source code based on FORTRAN90 that runs under LINUX systems [6]. Reference [7] introduced the relationships between ROPP modules and the algorithmic principles of major modules, using ROPP to process a set of COSMIC data and analyzing the precision of results. Building upon this work, we transplanted the ROPP processing software to Windows and compiled it with MATLAB. These modifications enable batch processing of radio occultation data under Windows, allowing statistical precision analysis of inversion results over a day, a week, or even longer periods, as well as analyzing inversion results across different latitudes, longitudes, and local times.

This article aims to briefly introduce the algorithmic description of the ROPP radio occultation data processing software and, more importantly, to conduct precision analysis of radio occultation data processing results. To achieve these objectives, the paper is structured as follows: Chapter 1 introduces the radio occultation data processing flow and algorithms for major steps, Chapter 2 describes precision analysis of one-day COSMIC data inversion results, Chapter 3 presents conclusions and outlook, and Chapter 4 contains acknowledgments.

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## 1. Radio Occultation Data Processing Flow

Signals transmitted from GNSS satellites, after passing through the ionosphere and atmosphere, are received by LEO receivers. Due to absorption and diffraction effects in the ionosphere and atmosphere, GNSS signals experience phase delays. Above 25 km altitude, traditional geometric optics inversion algorithms can derive signal bending angles from observed phase delays and the relative positions and velocities of GNSS and LEO satellites under the assumption of local spherical symmetry of refractivity, as illustrated schematically. However, below 25 km altitude, due to high water vapor content causing multipath effects and super-refraction, geometric optics inversion becomes inapplicable, requiring wave optics inversion to obtain bending angle profiles below 25 km. Due to ionospheric effects, ionospheric correction must be performed when retrieving atmospheric parameters. After interpolating L1 and L2 bending angles to the same impact parameter level, linear combination and statistical optimization are performed to obtain the optimal bending angle—essentially atmospheric bending angle with ionospheric effects eliminated. Using Abel inversion, refractivity profiles can be obtained. Since refractivity is affected by temperature and pressure, in the absence of water vapor (above 15 km), refractivity is only influenced by dry temperature and dry pressure. Combining this with the hydrostatic equilib-

rium equation allows retrieval of dry temperature and dry pressure above 15 km. However, below 15 km, water vapor effects cannot be ignored, and with only two equations, it is impossible to determine three parameters: temperature, dry pressure, and wet pressure. Therefore, background data from atmospheric models must be used to perform variational assimilation on occultation inversion results. Through integration operators, any observable quantity expressed as a function of analysis variables can be assimilated. ROPP can assimilate both bending angles and refractivity; here we choose to assimilate atmospheric refractivity because assimilating refractivity requires only point coordinate values as additional data, and the observation operator is relatively simple and easy to implement.

### 1.1 Data Processing Flowchart

[Figure 1: see original paper] The flow chart of RO data processing

This illustrates the inversion from excess phase data received by LEO receivers to bending angle and refractivity profiles, followed by retrieval of dry temperature and dry pressure without water vapor components. After obtaining refractivity profiles, one-dimensional variational assimilation is performed on the refractivity profiles to derive temperature, pressure, and humidity information containing water vapor components.

#### 1.2.1 Radio Holographic Filtering

Before geometric optics inversion, radio occultation data must be processed to reduce noise and remove poor data samples. ROPP employs a radio holographic filtering algorithm based on canonical transform (CT2) and radio holographic focusing synthetic aperture methods. First, the received signal is processed through CT2, then divided by a reference signal in the transformed space, convolved with a Fourier filter window, and multiplied by the reference signal to reconstruct the original signal. This algorithm is easy to implement and has been validated through numerical simulations [8].

#### 1.2.2 Geometric Optics

Above altitudes with low water vapor content where multipath effects are absent, bending angle is a single-valued function of impact parameter. Under the assumption of local spherical symmetry of refractivity and using the relative positions and velocities of GNSS and LEO satellites, bending angle and impact parameter can be derived according to Snell's law [9]. Traditional geometric optics inversion achieves high precision in altitude ranges with low water vapor content, and the algorithm is practical.

### 1.2.3 Wave Optics

When water vapor content increases, multipath effects and super-refraction occur. At this point, the single-signal assumption and the correspondence between instantaneous frequency and observations no longer hold, meaning observed bending angles and impact parameters are not in one-to-one correspondence. Wave optics inversion methods based on wave equations are designed to overcome these multipath effects. The main wave optics inversion algorithms include: (a) diffraction method [10], (b) back-propagation inversion, (c) sliding spectral method, (d) full-spectrum inversion, and (e) canonical transform [9]. Among these five algorithms, full-spectrum inversion and canonical transform produce the best results, with full-spectrum inversion being slightly more computationally efficient than canonical transform. ROPP selects the second type of canonical transform algorithm.

### 1.2.4 Ionospheric Correction and Statistical Optimization

Ionospheric correction residual errors and receiver noise are major noise sources in radio occultation, affecting inversion precision in the 35-40 km altitude range. The ionospheric correction and noise reduction algorithm used in ROPP includes the following details: (a) fitting to climate models, (b) dynamically estimating signal and noise covariance matrices using radio occultation signals above 50 km, and (c) performing statistical optimization of neutral atmospheric and ionospheric bending angles based on background bending angles and signal and noise covariance matrices.

## 2. Radio Occultation Inversion Example

This experiment selected all occultation events from COSMIC on January 1, 2008, totaling 2,354 atmospheric occultation events. From the level1b atmPhs files containing excess phase information, we retrieved dry temperature and dry pressure, stored in nssc\_atmPrf. Using ECMWF TOGA model data as background data, one-dimensional variational assimilation was performed to obtain wet temperature, wet pressure, and humidity information, stored in nssc\_wetPrf. After processing by CDAAC, wet temperature, wet pressure, and humidity information are stored in wetPrf files. Comparing our inversion results with the temperature, pressure, and humidity in wetPrf files yielded the mean bias and standard deviation of our inversion results, as shown below.

[Figure 2: see original paper] Comparison of Dry Atmosphere Inversion

In the figure above, the blue curve represents the mean bias between our inversion results (NSSC) and CDAAC, while the green curves on either side represent the mean bias minus standard deviation and mean bias plus standard deviation, respectively. The results show that refractivity inversion performs well from 0 to approximately 45 km altitude, with the mean bias of refractivity relative error remaining within 2%. Dry temperature error mean bias stays within 1 K in the 0-35 km altitude range, while dry pressure remains within 1%.

Subsequently, we used ECMWF TOGA model data as background data to perform one-dimensional variational assimilation on refractivity, thereby obtaining temperature, pressure, and humidity containing humidity information.

[Figure 3: see original paper] Comparison of Wet Atmosphere Inversion

Figure 3 shows that wet atmosphere inversion results are slightly worse than dry atmosphere inversion results. However, within 35 km altitude, temperature error can be controlled within 2 K, while relative errors in pressure and humidity are both less than 2%. In this experiment, we also compared inversion results with ECMWF's ERA-interim reanalysis model data, obtaining similar results.

### 3. Conclusions and Outlook

Through statistical analysis of inversion results, we find that refractivity profiles and dry atmospheric temperature and pressure retrievals achieve high precision within 0-35 km, with relative errors in refractivity and pressure within 2% and dry temperature error around 1 K. Precision decreases above 35 km. Wet atmosphere inversion results show that below 10 km, temperature error ranges between 0.5 K and 1.5 K; between 10-25 km, it remains within 1 K; and above 25 km, error increases. Below 35 km, relative pressure error stays within 2%, and specific humidity error remains within 2%.

Comprehensive analysis indicates that above 30 km, the main error sources are incomplete ionospheric correction and receiver tracking errors, while below 10 km, errors primarily stem from indeterminacy of atmospheric water vapor ambiguity. Errors in atmospheric parameters (temperature, pressure, and specific humidity) are larger than refractivity errors, mainly because background data used in the assimilation process introduces background data errors. Background data errors have smaller impact on specific humidity but larger impact on temperature and pressure. Specific humidity is nearly zero above 10 km, while below 10 km, large water vapor gradients cause dramatic error fluctuations. Major error sources include ionospheric correction effects, receiver noise, water vapor ambiguity, and data assimilation methods.

After systematic transplantation and partial modification of ROPP inversion software, we can also perform statistical analysis based on the latitude, longitude, and time of occultation events. This enables quantitative description and comparison of errors in inversion results across equatorial, temperate, and polar regions, as well as quantifying errors at different local times in the same region. The error characteristics of radio occultation inversion results must be considered when assimilating into numerical weather prediction systems or climate models.

Next, we plan to analyze inversion results across different latitude bands using approximately one month of data. After obtaining error distributions across different latitudes and longitudes, different quality control algorithms can be

applied to reduce errors in the radio occultation inversion process, which represents a future direction for our work.

#### 4. Acknowledgments

We sincerely thank GRAS, the research institution under EUMETSAT, for developing the ROPP software, which has greatly facilitated our work. Its systematic data processing flow and excellent algorithms allow us to adjust configuration options or modify certain functions in specific modules according to actual requirements to obtain needed results.

*Note: Figure translations are in progress. See original paper for figures.*

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