Advancements in GNSS Radio Occultation Techniques: Opportunities and Challenges in CubeSat Platforms

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***Abstract*—The GNSS radio occultation (RO) technique has become a crucial method for precise atmospheric probing, utilizing signals from global navigation satellite systems (GNSS) to derive key atmospheric parameters. Traditionally, RO measurements have been conducted using larger satellites. CubeSats, also known as nanosatellites, offer cost-effective platforms for space missions, including RO instruments. However, the use of Cubesats for RO presents some drawbacks that can jeopardize the mission, due the restricted volume, such as limited power constraints, antennas with smaller design, limitation for orbit determination and attitude control payloads, reduced orbital lifetime, challenges to get high quality constellation management, data downlink, data quality, calibration and validation. In addition, the Cubesat platform requires reduced weigth and power from instruments which in turn restricts the techniques that can be employed. This paper presents a literature review about key technical, operational, data quality issues as long as existing RO methodologies and integration of RO techniques for CubeSat platforms, highlighting their potential benefits and challenges.**

***Index Terms*—GNSS Radio Occultation, CubeSats, Atmospheric Probing, Nanosatellite Platforms, Earth's Atmosphere**

I. INTRODUCTION

Satellite observations play a critical role in disaster response and mitigation, especially in the context of increasing natural disasters such as floods and hurricanes [1]. Remote sensing has been effective in monitoring various natural hazards, including earthquakes, volcanic activity, and wildfires [2]. A key technology in atmospheric monitoring is radio occultation (RO), which uses the refraction of GNSS signals through the Earth's atmosphere to gather data on temperature, pressure, humidity, and refractivity—essential for weather forecasting and climate research.

CubeSats, small and cost-effective satellites, have emerged as a promising platform for RO. Despite their affordability, CubeSats face limitations such as reduced power and instrument capacity, which present challenges for complex tasks like RO.

RO using CubeSats involves receiving GNSS signals and analyzing changes caused by atmospheric conditions, as illustrated in Fig. 1. This method offers global coverage and high measurement accuracy by leveraging signals across various frequency bands [3]. Although still in early stages in Brazil, advancements in RO technology hold significant potential for improving local meteorological research and agricultural planning.

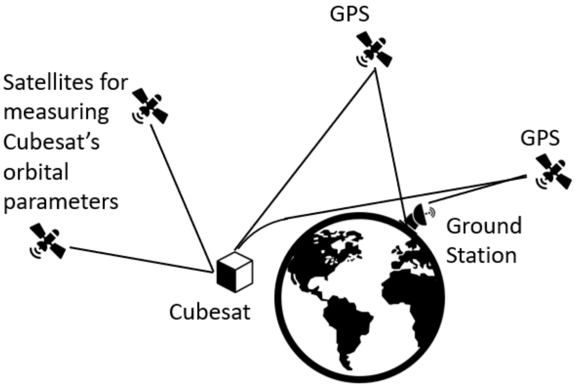

Figure 1: *Measurement extracted from a CubeSat and a GNSS based on [3].*

A. Objectives

This article explores the integration of RO techniques on CubeSat platforms, providing an analysis on the benefits and challenges. We compare established RO methodologies with emerging approaches in CubeSat projects, highlighting technological advancements that make CubeSat RO missions feasible. The study focuses on improving signal processing techniques and overcoming limitations such as power constraints and instrument accuracy.

The primary goal is to establish a solid foundation for the practical development of GNSS signal acquisition and processing techniques in nanosatellites. This will contribute significantly to the ROCUS-1 mission, the first RO mission developed at SpaceLab UFSC,

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advancing our understanding and monitoring of Earth's atmosphere.

B. Organization

This article is structured as follows. Section **Context and Problematics** describes the RO technique and its challenges. Section **Advanced Techniques for Radio Occultation** explores methods to enhance RO measurements. Section **Comparative Analysis** provides a comparative review of advanced techniques. Section **Methodology** shows the guidelines of the underlying work. Section **Results** synthesizes the findings, and Section **Conclusion** summarizes the work and offers perspectives on the future of CubeSat-based RO missions.

II. CONTEXT AND PROBLEMATICS

This section delves into the fundamental principles of Radio Occultation (RO), its historical development, and the general techniques involved in both tropospheric and ionospheric measurements.

A. The Radio Occultation Principles

Radio Occultation (RO) is a crucial atmospheric sounding technique that utilizes the refraction of radio signals as they pass through the atmosphere. By measuring the bending of the signal, which is influenced by the atmospheric refractive index, atmospheric parameters such as temperature, pressure, humidity, and composition can be deduced [4].

Prior to the 1990s, RO was predominantly used to study planetary atmospheres, such as those of Jupiter through missions like Pioneer 10 and 11. These early applications highlighted the technique's capability to penetrate deep into planetary atmospheres, providing high-resolution data on atmospheric structure via signal refraction and attenuation [5].

The advent of Global Positioning System (GPS) technology revolutionized RO applications on Earth. Originally designed for geolocation by the US Air Force, GPS began to be utilized for atmospheric profiling. GPS satellites, operating in the L-band frequencies (1.57542 GHz and 1.2276 GHz), provide stable signal sources. When these signals are received by satellites in low Earth orbit (LEO), scientists can derive detailed atmospheric profiles. Missions such as CHAMP, GRACE, METOP, and COSMIC have set high standards for acquiring precise atmospheric data, demonstrating the effectiveness of GPS-based RO in Earth sciences [6], [7].

GNSS RO employs signals from multiple satellite constellations, including GPS, GLONASS, Galileo, and BeiDou. increasing the number of occultations. Knowing that a single LEO satellite can observe over 500 events daily, the multiplication of receivers can allow the improve the global coverage and the high vertical resolution provided by GNSS signals [8], [9].

The emergence of low-cost CubeSats has introduced new possibilities for RO missions. Despite limitations in power and payload capacity, CubeSats equipped with RO instruments offer a cost-effective means of collecting high-resolution atmospheric data. These nanosatellites can perform RO measurements at a fraction of the cost of traditional satellites, making them an attractive option for expanding atmospheric research [10], [11].

Although CubeSats offer exciting opportunities for atmospheric research, the fundamental physical principles of RO remain constant. Therefore, we will outline the general aspects inherent to each RO mission, categorized into general techniques, tropospheric measurements, and ionospheric measurements.

1) Overview of General RO Technique:

a) Bending Angle: The primary parameter measured during an RO mission is the bending angle (α), which reflects how the atmosphere influences the signal (Fig. 2). Due to atmospheric refraction, the signal path deviates from the straight line $\vec{r}_{Rx-Tx}$, following a curved trajectory (blue line). This curvature occurs as the GNSS signal passes through the atmosphere and reaches the LEO receiver. The bending angle α represents the deviation between the straight-line segments of the trajectory before and after atmospheric refraction. The method for measuring this angle, particularly using the Doppler effect, will be detailed later.

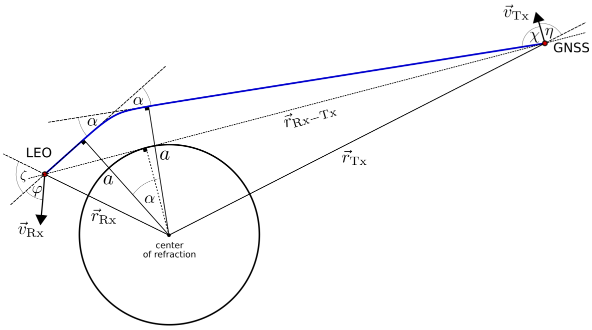

Figure 2: *Illustration of the RO geometry showing the α angle of the bent GNSS signal (blue line) received by the LEO satellite (note the straight line $\vec{r}_{Rx-Tx}$). [12]*

b) Extracting Refractive Index from Bending Angle: The bending caused by the atmosphere is a result of the gradient in the refractive index. Using Snell's law, the refractive index can be derived from the bending angle [13]. Figure 3 illustrates this relationship. In a spherically symmetric atmosphere, the product of the refractive index n, the distance to the center of the sphere r, and the angle of incidence θ remains constant (Eq. (1)). This constant, generally referred to as a, is known as the impact parameter.

$$rn\sin\theta = \text{constant} = a \tag{1}$$

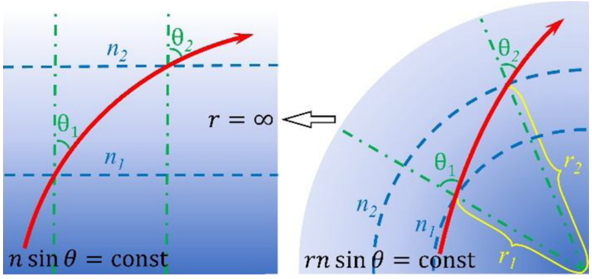

Figure 3: *Illustration of Bouguer's rule (right), an extension of Snell's law (left), applied to a spherically symmetric medium [14].*

The Abel transform inversion formula (Eq. (2)) is used to derive the refractive index $n(a)$ from the bending angle $\alpha(\xi)$ in a spherically symmetric medium.

$$n(a) = \exp\left[\frac{1}{\pi}\int_a^\infty \frac{\alpha(\xi)}{\sqrt{\xi^2 - a^2}}\,d\xi\right] \tag{2}$$

However, deriving $n(a)$ from $\alpha(\xi)$ using the Abel transform inversion assumes spherical symmetry. The Earth's ellipsoidal shape and horizontal atmospheric gradients cause deviations from this idealized symmetry in the refractive index field. Additionally, ray paths during an occultation do not scan the atmosphere radially or tangentially, which means that measurements of $\alpha(a)$ are influenced by tangential refractivity gradients and occultation geometry, potentially introducing systematic errors. Errors from the Abel transform inversion are generally related to how well the spherical symmetry approximation holds. First-order errors due to the Earth's ellipsoidal shape can be minimized by selecting an appropriate center and radius of curvature based on the latitude and orientation of the occultation measurement [6].

c) Doppler Effect on the Signals: The Doppler effect is employed to calculate the bending angle. This calculation is based on analyzing frequency shifts in GPS signals caused by the signals passing through different atmospheric layers, allowing for the reconstruction of refractivity profiles when combined with geometric analysis.

The Doppler effect can be implemented using the following equation:

$$f_D = \frac{f_T}{c}\left(\mathbf{V_T}\cdot\mathbf{k_T} + \mathbf{V_R}\cdot\mathbf{k_R}\right)$$

However, it is practically used under the vector projection:

$$f_D = -\tfrac{f_T}{c}\left(V_T^r\cos\phi_T + V_T^\theta\sin\phi_T + V_R^r\cos\phi_R + V_R^\theta\sin\phi_R\right) \tag{3}$$

Combining the Doppler effect with Bouguer's rule (Eq. (1)), and considering n close to unity, we get:

$$a = r_T\sin\phi_T = r_R\sin\phi_R \tag{4}$$

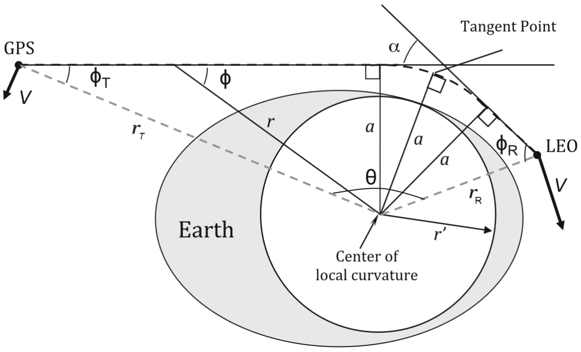

Figure 4: *Image derived from [15] showing other geometric aspects compared to Fig. 2 and illustrating the contribution of the Doppler effect to the recovery of α.*

The problem geometry allows us to use this relationship between angles:

$$\alpha = \phi_T + \phi_R + \theta - \pi \tag{5}$$

The following variables are used in calculating the Doppler shift and the total bending angle $\boldsymbol{\alpha}$:

- f_D: The additional Doppler shift, measurable.
- f_T: The known frequency of the GNSS signal.
- c: The speed of light in a vacuum.
- V_T^r and V_R^r: Radial components of the velocity vectors of the transmitting and receiving satellites, respectively (measurable using a GNSS receiver).
- V_T^θ and V_R^θ: Tangential components of the velocity vectors of the transmitting and receiving satellites, respectively (measurable using a GNSS receiver).
- ϕ_T and ϕ_R: Angles between the ray paths and the position vectors of the transmitting and receiving satellites, respectively (initially unknown).
- θ: Angle between position of transmitting and recieving satellite, taken from center of local curvature.

The Doppler effect provides detailed insights into the bending angle, assisting in the measurement of the refractive index profile and thus contributing to atmospheric research and weather prediction [16], [17].

III. ADVANCED TECHNIQUES FOR RADIO OCCULTATION

Beyond the general techniques specific to radio occultation (RO), advanced techniques are substantial for overcoming challenges in measurements. RO depends on accurate interpretation of GNSS signals, which can be distorted by atmospheric phenomena like ionospheric scintillation, multipath interference, or diffraction. Techniques such as dynamic error estimation, machine learning, and bending angle optimization enhance data precision by addressing these distortions in real-time.

Machine learning algorithms can correct signal distortions adaptively, while bending angle optimization and Radio Holographic & Back Propagation methods refine signal processing to reduce errors. Multi-GNSS processing uses multiple satellite constellations to improve Doppler shift reliability and mitigate ionospheric disturbances. These approaches collectively improve RO data quality.

The main feature of future missions remains enhancing RO data accuracy is essential for better weather forecasting, climate monitoring, and space weather prediction.

The following section outlines twelve categories of advanced techniques designed to address and mitigate the majority of challenges encountered in RO engineering.

A. Comparison Criteria and Advanced Techniques

1) Abel Inversion: The Abel inversion technique is used to transform bending angle measurements into refractivity profiles. It is crucial for the accurate extraction of atmospheric profiles such as density, temperature, and pressure. Although simple and effective, this method can be limited by assumptions of spherical symmetry and noise sensitivity, particularly in the presence of ionospheric scintillation. *Problems Addressed*: **Accuracy of Atmospheric Profiles** [18], [19]. This technique falls under the category: **Improvement of Measurement Accuracy**.

2) Doppler Shift Analysis: Doppler shift analysis allows for the precise determination of satellite velocity and trajectory, which is essential for compensating errors due to rapid orbital movements. This technique is also effective in detecting and correcting multipath effects caused by radio wave reflections. *Problems Addressed*: **Doppler Shift**, **Multipath Interference** [20], [21]. This technique falls under the categories: **Improvement of Measurement Accuracy** and **Multipath Management**.

3) Advanced Wave Optics Processing: Advanced wave optics processing techniques are used to model and correct complex diffraction effects in the atmosphere, thus improving measurement accuracy in challenging atmospheric conditions. They are particularly effective in handling multipath interference and signal distortions. *Problems Addressed*: **Multipath Interference** [22], [23]. This technique falls under the categories: **Improvement of Measurement Accuracy**, **Multipath Management**, and **Processing of Complex Signals and Diffraction**.

4) Dynamic Error Estimation and Weighting: This technique dynamically estimates and weights errors in radio occultation measurements to improve the robustness of results. It is particularly useful in reducing the impact of ionospheric scintillation and managing real-time errors in varying atmospheric conditions. *Problems Addressed*: **Ionospheric Scintillation**, **Accuracy of Atmospheric Profiles** [24], [25], [26]. This technique falls under the categories: **Correction of Ionospheric Scintillation Effects**, **Dynamic Error Optimization and Correction**, and **Improvement of Measurement Accuracy**.

5) Variational Inversion: Variational inversion integrates radio occultation data into numerical models to improve the accuracy of weather forecasts. It better manages observation errors and precisely incorporates data into models, which is essential for large-scale meteorological applications. *Problems Addressed*: **Accuracy of Atmospheric Profiles**, **Data Integration in Atmospheric Models** [27], [28]. This technique falls under the categories: **Data Integration in Atmospheric Models** and **Improvement of Measurement Accuracy**.

6) Bending Angle Optimization: Bending angle optimization aims to correct signal distortions by optimizing derived bending angles, improving the quality of atmospheric profiles, particularly in environments where multipath effects are pronounced. *Problems Addressed*: **Multipath Interference** [29], [23]. This technique falls under the categories: **Multipath Management** and **Improvement of Measurement Accuracy**.

7) Machine Learning Approaches: Machine learning approaches are used to detect and correct anomalies in radio occultation data, such as ionospheric scintillation and multipath effects. They improve real-time measurement accuracy by adapting models to observed conditions. *Problems Addressed*: **Ionospheric Scintillation**, **Accuracy of Atmospheric Profiles** [30], [31], [**?**]. This technique falls under the categories: **Correction of Ionospheric Scintillation Effects**, **Improvement of Spatial and Temporal Resolution**, and **Improvement of Measurement Accuracy**.

8) Radio Holographic & Back Propagation Methods: Radio holographic and back propagation methods are used to analyze signals and filter out noise and multipath effects. They are particularly effective in enhancing vertical resolution and the accuracy of atmospheric profiles in complex propagation conditions. *Problems Addressed*: **Multipath Interference**, **Accuracy of Atmospheric Profiles** [32], [33]. This technique falls under the categories: **Multipath Management**, **Processing of Complex Signals and Diffraction**, and **Improvement of Measurement Accuracy**.

9) Multi-GNSS Processing: Multi-GNSS processing uses multiple satellite constellations to improve the coverage and accuracy of radio occultation measurements. This technique is particularly effective in reducing the effects of ionospheric scintillation and multipath by combining signals from different GNSS frequencies. *Problems Addressed*: **Ionospheric Scintillation** [34], [35], [36]. This technique falls under the categories: **Correction of Ionospheric Scintillation Effects**, **Multipath Management**, **Improvement of Spatial and Temporal Resolution**, and **Improvement of Measurement Accuracy**.

10) Phase Matching: Phase matching aligns the phases of signals from different frequencies to correct variations caused by multipath and improve measurement accuracy, particularly in the lower troposphere. *Problems Addressed*: **Multipath Interference**, **Ionospheric Scintillation** [37], [38]. This technique falls under the categories: **Multipath Management** and **Correction of Ionospheric Scintillation Effects**.

11) Ionospheric Scintillation: Techniques specific to ionospheric scintillation are used to detect and correct rapid fluctuations in radio signals caused by the ionosphere, improving data quality by reducing errors associated with these scintillations. *Problems Addressed*: **Ionospheric Scintillation** [39], [40], [41]. This technique falls under the category: **Correction of Ionospheric Scintillation Effects**.

12) Precise Orbit Determination (POD): Precise orbit determination is essential for accurately knowing the satellite position, which is crucial for correcting errors related to orbital movements and satellite geometry. This technique minimizes errors in radio occultation measurements. *Problems Addressed*: **Accuracy of Atmospheric Profiles** [42], [43]. This technique falls under the categories: **Dynamic Error Optimization and Correction** and **Improvement of Measurement Accuracy**.

In summary, each technique has distinct advantages and challenges. Effective CubeSat-based RO requires balancing computational constraints, data quality, and integrating techniques to optimize atmospheric observations.

IV. COMPARATIVE TABLE OF ADVANCED TECHNIQUES

Evaluating advanced techniques for CubeSat-based radio occultation (RO) is key to ensure the success of a future mission. This analysis helps identify the most effective advanced techniques, highlighting their strengths and limitations for a future CubeSat mission.

In this study, we conducted a comparative analysis of advanced GNSS (Global Navigation Satellite System) radio occultation techniques, focusing on three specific criteria: **sufficient power supply**, **measurement accuracy**, and **measurement band management**. These criteria were selected because of the importance attributed to them in previous work [10].

Sufficient power supply refers to the amount of energy required to implement a specific technique on a platform like a CubeSat. To estimate this criterion, we considered the **algorithmic complexity** and the **computational load** of the techniques, as more complex or resource-intensive algorithms generally demand more power to run, especially on resource-limited platforms.

Measurement accuracy is a key criterion that assesses the technique's ability to provide reliable and accurate data. This criterion was directly evaluated based on the results presented in the articles, which often detailed the improvements in the accuracy of atmospheric refractivity profiles or bending angles achieved by the technique in question.

Measurement band management involves the complexity of using and managing the different GNSS frequency bands required to capture occulted radio signals. To estimate this criterion, we looked at the **use of multiple frequencies** and the **signal processing techniques** mentioned in the articles. A more complex band management is often required when multiple frequencies are used simultaneously or when advanced signal processing techniques are employed to enhance data quality.

As a more dynamic visualization, Table I summarizes the results of this analysis, categorizing the techniques based on their relative performance concerning each criterion. Following this, two comparative analyses will be presented: one comparing the techniques based on their differences, and the other analyzing the techniques according to the established criteria.

V. RESULTS

The advancement of CubeSat-based Radio Occultation (RO) techniques presents a promising frontier in atmospheric science and satellite technology. As CubeSats become increasingly utilized for RO missions, addressing the technical challenges of these small, constrained platforms is critical for achieving high-quality atmospheric data. This chapter discusses the findings from the literature review, highlights the performance of different techniques, and assesses their applicability to CubeSat-based RO missions. It also presents the results of our comprehensive evaluation of advanced RO techniques, focusing on their performance, advantages, and limitations in the context of CubeSat missions. By analyzing various techniques, we aim to identify the most effective approaches to enhance RO data accuracy and reliability within the constraints of CubeSat platforms.

A. Overview of Key Findings

Our investigation revealed that each advanced RO technique has distinct strengths and limitations when applied to CubeSat missions. The comparative analysis considered several factors, including accuracy, computational requirements, and adaptability to CubeSat constraints such as size and power limitations. The techniques evaluated include Abel Inversion, Advanced Advanced Wave Optics Processing, Dynamic Error Estimation and Weighting, Variational Inversion, Bending Angle Optimization, Machine Learning Approaches, Radio Holographic & Back Propagation Methods, Multi-GNSS Processing, Phase Matching, and Ionospheric Correction.

Our evaluation of advanced RO techniques highlights the following key findings.

Advanced Techniques	Embedding Requirements	Computational Complexity	Measurement Accuracy	Minimum Bandwidth	Minimum Space Requirements	References
Abel Inversion	No	Moderate	Moderate	Weak	FPGA only + eventual external memory for managing error estimates.	[18], [19]
Doppler Shift Analysis	Yes (Critical real-time)	High	High	Moderate	FPGA + Dedicated processor for real-time Doppler shift derivation.	[20], [21]
Advanced Wave Optics Processing	No	High	High	Moderate	FPGA + external memory for handling spectral calculations.	[22], [23]
Dynamic Error Estimation and Weighting	Yes (Critical real-time)	High	Moderate	Moderate	Always FPGA + external memory for real-time error management.	[24], [25], [26]
Variational Inversion	No	High	High	Moderate	Always FPGA + external memory for managing complex models.	[27], [28]
Bending Angle Optimization	No	Moderate	Moderate	Moderate	FPGA only + eventual external memory for covariance matrix handling.	[29], [23], [25]
Machine Learning Approaches	Implicit mention of fast processing	High	High	Moderate	Always FPGA + external memory for model and data storage.	[30], [31], [41]
RH & BP Methods	No	High	Moderate	High	Always FPGA + external memory for hologram processing.	[32], [33]
Multi-GNSS Processing	Implicit mention of fast processing	Moderate	Moderate	Moderate	Always FPGA + external memory for real-time multi-signal processing.	[34], [35], [36]
Phase Matching	Yes (Critical real-time)	High	Moderate	High	FPGA only + eventual external memory for managing reflection data.	[37], [38]
Ionospheric Scintillation	Implicit mention of fast processing	Moderate	Moderate	Moderate	FPGA only + eventual external memory for scintillation model storage.	[39], [40], [41]
Precise Orbit Determination (POD)	Yes (Critical real-time)	High	High	High	Always FPGA + external memory for precise orbit data processing.	[42], [43]

Table I: *Summary of Criteria for Advanced GNSS Radio Occultation Techniques*

1) Abel Inversion: Abel Inversion remains a foundational technique due to its simplicity and computational efficiency. It allows for direct retrieval of atmospheric profiles from bending angle data without requiring extensive a priori information. However, its reliance on spherical symmetry and sensitivity to noise limits its accuracy, particularly in the lower troposphere. For CubeSat missions, integrating Abel Inversion with other techniques to enhance error handling and profile accuracy is essential.

2) Advanced Wave Optics Processing: Advanced Wave Optics Processing offers significant improvements in handling diffraction effects and enhancing vertical resolution, especially in the lower troposphere. This technique's computational complexity and sensitivity to observation errors are notable challenges. For CubeSat missions, balancing computational demands with data quality and potentially combining this technique with simpler methods could enhance performance.

3) Dynamic Error Estimation and Weighting: Dynamic Error Estimation and Weighting enhances measurement accuracy through adaptive processing and better error quantification. It optimizes data usage and improves vertical resolution. Despite its potential, this technique's high computational burden and dependency on accurate error models pose challenges. Adapting it to CubeSat constraints requires careful consideration of computational resources and error management.

4) Variational Inversion: Variational inversion excels in integrating multiple data sources and handling non-linear problems, leading to more accurate atmospheric profiles. However, its high computational demands and dependence on a priori information can lead to over-constraining. For CubeSat-based RO, improving data quality and leveraging constellation missions are critical.

5) Bending Angle Optimization: This technique optimizes bending angles to correct distortions, improving data quality and reducing sensitivity to ionospheric effects. Despite its advantages, bending angle optimization is computationally intensive and relies on statistical methods, which can lead to the loss of smallscale structures. Noise reduction and extending the altitude range are important considerations for CubeSat adaptation.

6) Machine Learning Approaches: Machine learning techniques offer significant potential for handling complex data relationships, improving accuracy, and reducing noise post-training. However, these methods require substantial data and are prone to overfitting. Their 'black box' nature and sensitivity to data quality add complexity. Addressing data limitations and onboard processing potential is vital for CubeSat integration.

7) Radio Holographic & Back Propagation Methods: This approach provides higher vertical resolution and improved accuracy by resolving multipath effects and analyzing full wave fields. The method's ability to detect super-refraction is advantageous, but it is computationally intensive and sensitive to noise. Enhancing vertical resolution while managing computational limitations is crucial for CubeSat applications.

8) Multi-GNSS Processing: Utilizing multiple GNSS constellations increases data volume and accuracy while reducing system-specific issues. However, the increased complexity and computational requirements pose challenges. Addressing hardware constraints and leveraging constellation synergy are necessary to unlock the full potential of multi-GNSS processing in CubeSat missions.

9) Phase Matching: Phase matching improves accuracy and vertical resolution by correcting phase variations and handling multipath effects. While it ensures consistent processing across altitudes, it faces challenges such as computational complexity and dependence on accurate orbit information. Improving lower troposphere retrievals and enhancing vertical resolution are key considerations for CubeSats.

10) Ionospheric Correction: This technique enhances accuracy in neutral atmosphere retrievals and extends the altitude range. It offers dual-use potential and mitigates systematic errors, but it relies on dual-frequency measurements and faces residual errors and computational complexity. Addressing hardware constraints and data quality improvements are critical for effective use in CubeSat-based RO.

B. Performance Analysis of Techniques

The performance analysis reveals that:

- **Accuracy and Reliability:** Techniques such as Variational Inversion, Bending Angle Optimization, and Machine Learning Approaches stand out for their potential to improve accuracy and reliability. Variational Inversion and Bending Angle Optimization excel in handling errors and improving data quality, while Machine Learning Approaches offer adaptability and advanced error correction capabilities.
- **Computational Constraints:** Techniques like Advanced Wave Optics Processing, Radio Holographic & Back Propagation Methods, and Multi-GNSS Processing present significant computational challenges. These methods require substantial processing power and may need optimization or simplification to fit within CubeSat constraints.
- **Adaptation to CubeSat Constraints:** Abel Inversion, Phase Matching, and Ionospheric Correction show potential for adaptation due to their relatively lower computational demands and compatibility with CubeSat missions. However, their effectiveness depends on careful integration with other techniques and robust error handling.

C. Comparative Evaluation

Using criteria detailed on chapter IV Comparative Analysis and the identified challenges of CubeSat missions, we are able to classify the techniques as follows:

The performance analysis reveals that:

- **High Potential:** Variational Inversion, Bending Angle Optimization, and Machine Learning Approaches are classified as high potential due to their ability to address accuracy and reliability challenges effectively. These techniques offer substantial improvements in data quality and have potential for adaptation to CubeSat missions with appropriate modifications.
- **Moderate Potential:** Dynamic Error Estimation and Weighting, Phase Matching, and Ionospheric Correction have moderate potential. They offer benefits but also face challenges related to computational constraints and data quality. With careful adaptation and integration, these techniques could enhance CubeSat-based RO performance.
- **Lower Potential:** Advanced Wave Optics Processing, Radio Holographic & Back Propagation Methods, and Multi-GNSS Processing are categorized as having lower potential due to their high computational requirements and complexity. These techniques may be more suitable for larger platforms or require significant optimization for effective CubeSat implementation.

D. Initial Reflections and Future Work

The comparative analysis highlights that integrating advanced techniques, adapting them to CubeSat constraints, and combining their strengths can enhance RO data accuracy and reliability. Future work should focus on:

- **Optimizing Computational Efficiency:** Developing strategies to balance computational demands with the benefits of advanced techniques, ensuring effective use within CubeSat constraints.

- **Enhancing Data Integration:** Combining techniques such as Variational Inversion with Machine Learning Approaches to leverage their strengths and address specific challenges.
- **Exploring New Techniques** Investigating emerging techniques and technologies that could further improve RO data quality and address CubeSat-specific challenges.

These topics reflect the challenges and opportunities identified in the results and offer a pathway for future research in CubeSat-based RO technology.

E. Foundation for the ROCUS-1 Project

The insights and findings from this study lay a solid foundation for the ROCUS-1 project, which represents a significant step forward in integrating advanced GNSS Radio Occultation (RO) techniques with CubeSat platforms. The primary objective of the ROCUS-1 project is to develop and deploy a CubeSat-based RO system that enhances the accuracy and reliability of atmospheric measurements while addressing the unique challenges posed by CubeSat missions.

1) Structural and System Design:: Based on the theoretical framework established in this study, the ROCUS-1 project will involve the construction of a comprehensive CubeSat framework, often referred to as the "skeleton" of the satellite. This framework will encompass the design and integration of key components including the payload, communication systems, power supply, and structural elements. The design process will ensure that the CubeSat is optimized for the specific requirements of RO measurements, including size, power, and thermal management.

2) Development of a System State Machine:: A crucial aspect of the ROCUS-1 project will be the development of a system state machine, which will manage the CubeSat's operations, including data collection, processing, and transmission. The state machine will coordinate the various subsystems and ensure that the satellite operates efficiently and reliably throughout its mission. This involves designing algorithms for automated error correction, data handling, and system diagnostics.

3) Integration of Advanced Techniques:: The project will integrate several advanced GNSS RO techniques reviewed in this study, including Abel Inversion, Advanced Wave Optics Processing, Dynamic Error Estimation and Weighting, and Machine Learning Approaches. The integration of these techniques will be tailored to address the specific challenges of CubeSat missions, such as limited size and power, and will focus on improving the accuracy of atmospheric profiles.

4) Exploration of Doppler Effect:: Future work in the ROCUS-1 project will also delve deeper into the Doppler effect, which has been identified as a significant factor in signal processing and data accuracy. This involves developing and implementing advanced algorithms to correct Doppler shift distortions and enhance the precision of RO measurements. Understanding and mitigating the Doppler effect will be crucial for improving the overall performance of the CubeSat-based RO system.

5) Preliminary Testing and Validation:: To ensure the effectiveness of the design and integration, the ROCUS-1 project will include rigorous testing and validation phases. This will involve simulations, ground tests, and, where feasible, preliminary flight tests to assess the CubeSat's performance and the accuracy of the RO data. The results from these tests will guide further refinements and optimizations.

In conclusion, the ROCUS-1 project builds on the theoretical base established through this study, providing a pathway to realizing a state-of-the-art CubeSat-based RO system. The project's success will depend on effectively addressing the identified challenges, integrating advanced techniques, and advancing our understanding of critical factors such as the Doppler effect. The outcomes of the ROCUS-1 project will contribute significantly to the field of atmospheric science, enhancing our ability to obtain accurate and reliable atmospheric data from CubeSat platforms.

VI. METHODOLOGY

The methodology for analyzing GNSS RO techniques for CubeSat platforms involves:

- Reviewing approximately 50 articles and 4 books for a comprehensive overview of radio occultation.
- Developing an action plan to address CubeSat RO mission solutions.
- Analyzing key challenges, techniques, and problems in CubeSat missions.
- Conducting comparative and historical analysis through further literature review.
- Identifying initial reflections to guide future work.

VII. CONCLUSION

In this study, we explored the integration of advanced GNSS Radio Occultation (RO) techniques with CubeSat platforms to enhance the accuracy and reliability of RO data, while addressing the unique challenges posed by CubeSat missions. We conducted a thorough review of both the fundamental challenges and the state-of-the-art techniques available for improving RO measurements.

We identified several major challenges associated with CubeSat-based RO missions, including limitations in size and power, the need for efficient collision avoidance, and the complexities of data downlink and regulatory compliance. These challenges are compounded by the inherent constraints of CubeSat platforms, which necessitate innovative solutions for successful deployment and operation.

In response to these challenges, we reviewed advanced GNSS RO techniques such as Abel Inversion, Advanced Wave Optics Processing, Dynamic Error Estimation and Weighting, Variational Inversion, and Machine Learning Approaches. Each technique was evaluated for its ability to address specific issues such as signal distortion, multipath interference, and ionospheric scintillation. Our analysis highlighted the strengths and limitations of each approach, providing a comprehensive overview of their potential applications in CubeSat missions.

The insights gained from this study form the theoretical foundation for the ROCUS-1 project, which aims to implement these advanced techniques in the development of a CubeSat-based RO system. The findings provide a crucial basis for designing and optimizing the CubeSat's structural framework, including its hardware and software components. This includes the construction of the CubeSat's "skeleton" or structural framework and the development of a system state machine to manage the CubeSat's operations effectively.

Looking forward, the ROCUS-1 project will build on these insights to address the practical implementation of advanced RO techniques, with a particular focus on overcoming the challenges identified in this study. Future work will involve constructing and testing the CubeSat's complete framework, integrating the advanced techniques reviewed, and exploring further developments in Doppler effect correction and other related areas.

By laying a solid theoretical groundwork and identifying key areas for future research, this study paves the way for the successful realization of the ROCUS-1 project. The integration of these advanced techniques into CubeSat missions will enhance our ability to obtain accurate and reliable atmospheric profiles, ultimately contributing to improved weather forecasting, climate monitoring, and space weather prediction.

In summary, this research underscores the importance of combining advanced GNSS RO techniques with CubeSat technology to overcome existing limitations and achieve significant advancements in atmospheric observation. The conclusions drawn from this study will guide future research and development efforts, ensuring that the ROCUS-1 project and subsequent missions are well-positioned to address the challenges of CubeSat-based RO and deliver valuable scientific data.

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