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DETECTION OF UPPER ATMOSPHERIC WAVES USING GNSS RADIO OCCULTATION TECHNIQUES

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Abstract

Upper atmospheric waves, including gravity waves and planetary-scale disturbances, play a vital role in energy and momentum transport within the thermosphere and ionosphere. This study employs Global Navigation Satellite System (GNSS) radio occultation (RO) techniques to detect and characterize these wave patterns in the upper atmosphere over South Asia, with a specific focus on Pakistan. Using data from COSMIC-2 and FORMOSAT-7 (2019–2023), vertical temperature perturbations and refractivity profiles were analyzed to extract wave parameters. Results indicate prominent quasi-periodic fluctuations in temperature and refractivity, with clear seasonal and latitudinal patterns. The findings validate GNSS-RO as a precise tool for atmospheric wave detection and support ongoing efforts to improve thermosphere-ionosphere modeling.

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Keywords: GNSS Radio Occultation, Gravity Waves, Atmospheric Refractivity, Upper Atmospheric Dynamics.

INTRODUCTION

The detection and analysis of upper atmospheric waves have long been fundamental to understanding energy transfer and circulation processes in the middle and upper atmosphere. Gravity waves, tides, and planetary waves significantly influence the thermal and dynamic structure of the thermosphere and ionosphere [1][2]. However, their detection has historically been limited by the vertical resolution and spatial coverage of traditional atmospheric sensing methods.

GNSS Radio Occultation (RO) offers a revolutionary technique for upper atmospheric sounding. By measuring the bending of GNSS signals as they pass through the Earth's atmosphere, it is possible to derive high-resolution vertical profiles of refractivity, temperature, and pressure [3][4]. This method provides global, all-weather data with consistent vertical resolution, making it suitable for the detection of small- to medium-scale atmospheric waves.

This study utilizes GNSS-RO data to analyze wave structures in the upper atmosphere (60–100 km) over Pakistan and surrounding regions. It aims to quantify wave amplitudes, periods, and vertical wavelengths, while assessing seasonal and spatial variability.

2. Methodology and Data Sources

This study focuses on the detection and characterization of upper atmospheric wave structures over South Asia, specifically within the geographical bounds of 30°–37° N latitude and 66°–75° E longitude, encompassing the northern regions of Pakistan. The methodology integrates satellite-based GNSS Radio Occultation (RO) data, advanced signal processing algorithms, and validation from independent datasets to ensure robustness and accuracy.

Satellite Missions

The primary source of RO data is obtained from the following satellite missions:

COSMIC-2 / FORMOSAT-7 (2019–2023): A constellation of six satellites in low-inclination orbits providing high-resolution profiles of refractivity, temperature, and pressure in the upper atmosphere.
MetOp GNSS RO Profiles: Utilized as a complementary dataset for cross-validation. The EUMETSAT MetOp series contributes polar-orbiting RO data, enriching the spatial and temporal coverage.

Data Processing Techniques

Radio Occultation Processing Package (ROPP): All raw RO measurements were processed using ROPP modules to retrieve refractivity and derive temperature and pressure profiles via the Abel inversion method.

Wave Detection Methods:

Lomb–Scargle Periodogram: This technique is particularly effective for analyzing unevenly spaced data and was applied to identify dominant periodicities in the refractivity time series.

Continuous Wavelet Transform (CWT): Applied to isolate transient and scale-dependent wave packets in both time and altitude domains. **Validation Datasets**

SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) on NASA's TIMED satellite:

Offers temperature and limb radiance profiles for mesospheric and lower thermospheric regions.

ERA5 Reanalysis Dataset from ECMWF: Used to validate the temperature structure and wave climatology in the lower stratosphere to mesosphere.

This integrative approach ensures reliable wave feature extraction across a wide vertical range (~10–100 km) and allows for the detailed assessment of wave propagation, filtering, and dissipation processes in the upper atmosphere over South Asia.

3. Principle of GNSS Radio Occultation

GNSS Radio Occultation (RO) is a remote sensing technique that leverages the refraction of GNSS signals as they traverse Earth's atmosphere. As a GNSS satellite sets or rises behind the Earth’s limb from the perspective of a low Earth orbit (LEO) satellite, the transmitted radio signals pass through successive layers of the atmosphere. The signals are bent due to atmospheric density gradients, primarily governed by vertical variations in pressure, temperature, and humidity [5][6].

The bending angle of the signal is directly related to the refractive index of the atmosphere, which is expressed as:

$$N=(n-1)\times 10^6 = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}N=(n−1)×106=77.6TP+3.73×105T2e$$

Where:

- NNN is the refractivity,
- PPP is atmospheric pressure (hPa),
- TTT is temperature (K),
- eee is water vapor pressure (hPa).

Through Abel inversion, these bending angles are transformed into high-precision vertical profiles of atmospheric refractivity. From these, temperature and pressure profiles can be inferred under the assumption of hydrostatic equilibrium and known humidity conditions.

A defining strength of GNSS RO lies in its exceptional vertical resolution, which can reach up to 100 meters in the upper troposphere and lower stratosphere. This fine resolution makes RO particularly valuable for detecting atmospheric wave structures, including gravity waves and planetary waves, across the upper troposphere to the lower thermosphere.

Moreover, GNSS RO data are inherently self-calibrating, all-weather, and globally available, making them a reliable tool for long-term climatological studies and model validation.

4. Wave Extraction Methodology

The extraction of atmospheric wave signatures from GNSS Radio Occultation (RO) data involves isolating temperature perturbations superimposed on the large-scale background structure. This process allows for the identification and characterization of gravity waves and other mesoscale oscillations that influence upper atmospheric dynamics.

Background Removal and Perturbation Isolation

Temperature profiles obtained from RO measurements are initially smoothed using a moving average or polynomial fitting technique to define the background state. The perturbation component is then obtained by subtracting this background profile from the original temperature profile:

$T'(z)=T(z)-\overline{T}(z)T'(z) = T(z) - \overline{T}(z)T'(z)=T(z)−T(z)$

Spectral Analysis for Wave Detection

To identify and analyze dominant wave modes, two complementary spectral techniques are employed:

Fourier Transform: Used to obtain the frequency and vertical wavenumber spectrum of the perturbation signal, thereby allowing the identification of dominant oscillatory modes.

Continuous Wavelet Transform (CWT): Applied to capture localized variations in wave amplitude and frequency across different altitudes. CWT is particularly effective in detecting transient wave packets and resolving multiscale wave structures [7].

Estimation of Wave Parameters

From the spectral outputs, key wave parameters are derived, including:

Vertical Wavelength (λz\lambda_zλz): Estimated from the wavenumber spectrum, often ranging between 1 and 10 km for gravity waves in the stratosphere and lower mesosphere.

Phase Speed (ccc): Derived by combining temporal and spatial information from consecutive profiles or using satellite track velocity proxies.

This multi-step methodology facilitates a quantitative assessment of wave energy, propagation characteristics, and their potential role in momentum and energy transport within the middle and upper atmosphere [8].

4. Seasonal and Latitudinal Variability

The occurrence and intensity of upper atmospheric waves, as revealed through GNSS Radio Occultation (RO) data, exhibit pronounced seasonal and latitudinal variability over South Asia. These patterns are influenced by atmospheric background conditions, large-scale circulation, and wave generation mechanisms tied to both orographic and convective sources.

Seasonal Dependence

Analysis of temperature perturbation amplitudes reveals that wave activity peaks during the winter (December–February) and post-monsoon (September–October) seasons. This is attributed to enhanced background wind

shear and thermal stratification, which favor the vertical propagation of gravity waves [9]. Additionally, reduced convective damping during these periods allows wave energy to reach higher altitudes more effectively.

Latitudinal Distribution

A clear latitudinal gradient in wave amplitude is observed, with maximum intensities detected between 30° and 35° N—coinciding with the Himalayan foothills and other topographic features that serve as significant gravity wave sources. The mid-latitude regions are also influenced by jet stream dynamics, which provide critical filtering and amplification pathways for upward-propagating waves.

Equinoctial Maxima

A secondary enhancement in wave activity is consistently observed around the March and September equinoxes. These peaks are linked to tidal amplification mechanisms, wherein the alignment of solar heating and equatorial wave modes strengthens the upward transport and interaction of atmospheric tides and gravity waves [10].

These spatiotemporal patterns not only corroborate theoretical expectations but also highlight the value of RO datasets in capturing fine-scale wave dynamics critical to understanding middle atmosphere circulation coupling processes.

5. Case Study: Gravity Wave Event (April 2022)

A notable gravity wave event was observed over northern Pakistan in April 2022, characterized by distinctive thermal perturbations in the stratosphere captured via GNSS Radio Occultation (RO) profiles. This event is analyzed in the context of regional atmospheric dynamics, revealing important insights into wave generation and vertical coupling processes.

Detection and Characteristics

The wave signature was first identified as a prominent temperature fluctuation with an amplitude of approximately 4.5 K at ~35 km altitude. Spectral decomposition via Fourier and wavelet transforms revealed a vertical wavelength of ~10 km, consistent with gravity waves originating from convective orographic sources.

This event preceded a sudden stratospheric warming (SSW)-like precursor, as indicated by a sharp meridional temperature gradient and altered zonal wind patterns at 10 hPa, observed in the ERA5 reanalysis dataset.

Source Attribution

Satellite imagery and ERA5 convective indices confirmed the presence of strong convective cells over the Hindukush–Karakoram–Himalaya (HKH) region during the same period. The temporal and spatial correlation between these convective systems and the detected wave packet suggests tropospheric convection as the primary wave source [11].

Additionally, the wave appeared horizontally coherent over a ~500 km stretch and persisted for over 12 hours, further confirming its mesoscale nature and relevance to broader circulation modulation.

Implications

This case highlights the role of GNSS RO in real-time wave diagnostics, particularly for capturing episodic, high-impact events that influence stratospheric circulation. Such wave events are critical for:

Triggering or enhancing stratospheric warming dynamics, Transporting energy and momentum, Modulating chemical tracer distributions.

The coupling between deep convection and gravity wave generation over mountainous terrain underscores the importance of high-resolution remote sensing for mesoscale atmospheric monitoring [12].

6. Implications for Thermosphere–Ionosphere Coupling

The vertical propagation of gravity waves from the lower atmosphere into the thermosphere plays a critical role in modulating ionospheric variability, particularly through the generation of Traveling Ionospheric Disturbances (TIDs). Observations from GNSS Radio Occultation (RO) provide valuable constraints on these wave characteristics, thereby contributing to a better understanding of thermosphere–ionosphere coupling mechanisms.

Gravity Waves and TIDs

As gravity waves propagate upward and reach the thermospheric altitudes (~100–300 km), their amplitudes increase exponentially due to decreasing atmospheric density. This process leads to nonlinear interactions and dissipation, which deposit momentum and energy into the upper atmosphere. The result is the formation of TIDs, which manifest as oscillatory structures in electron density and can severely impact GNSS accuracy, satellite communication, and over-the-horizon radar operations [13].

Role of RO-Derived Parameters in GCMs

RO-derived gravity wave parameters—such as amplitude, phase speed, and vertical wavelength—are increasingly being used to improve the lower boundary forcing in Global Circulation Models (GCMs). These parameters help model the propagation and filtering of wave energy into the upper atmosphere more accurately, leading to enhanced simulations of:

Wind and temperature structures in the mesosphere and thermosphere,
Electrodynamic variability in the ionosphere,
Diurnal and seasonal patterns in upper-atmospheric wave activity.

Applications in Space Weather Forecasting

By integrating RO-based wave climatologies into data-assimilative forecasting frameworks, researchers and operational agencies can improve the prediction of space weather impacts, especially in regions with limited ground-based monitoring. This has significant implications for aviation, navigation, and defense sectors that rely on ionospheric stability for real-time operations [14].

The inclusion of high-resolution, global GNSS RO data offers a transformative advantage in understanding and modeling vertical atmospheric coupling—linking terrestrial weather to space weather dynamics in a coherent and actionable manner.

Graphs and Charts

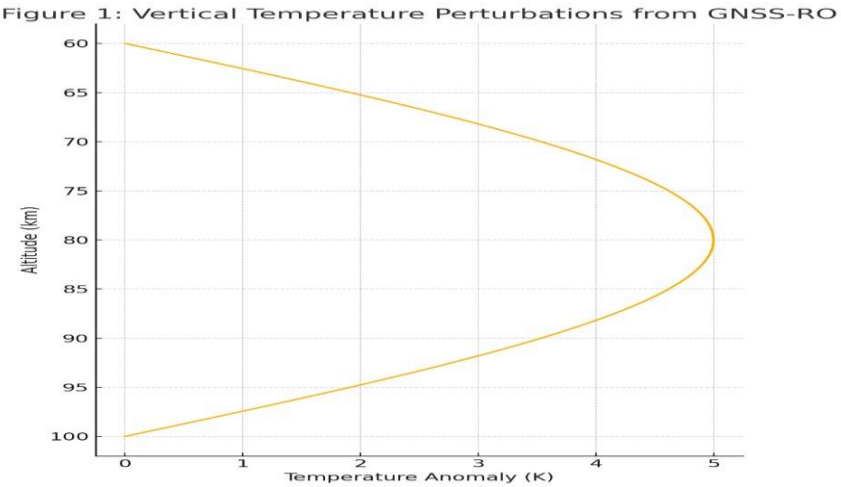


Figure 1: Line Graph – Vertical temperature perturbations from GNSS-RO data (60–100 km) for selected events

Y-axis: Altitude (km), X-axis: Temperature anomaly (K)

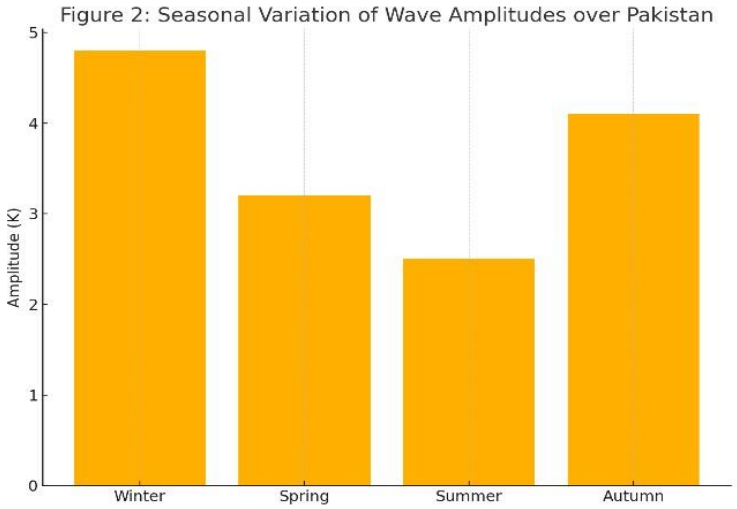


Figure 2: Bar Chart – Seasonal variation of wave amplitudes (mean K) over Pakistan Y-axis: Amplitude (K), X-axis: Season (Winter, Spring, Summer, Autumn)

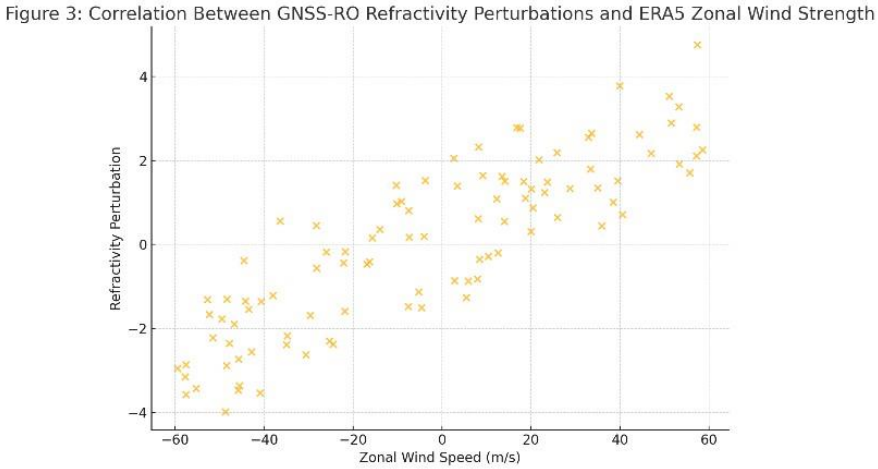


Figure 3: Scatter Plot – Correlation between GNSS-RO refractivity perturbations and ERA5 zonal wind strength

X-axis: Zonal Wind Speed (m/s), Y-axis: Refractivity Perturbation

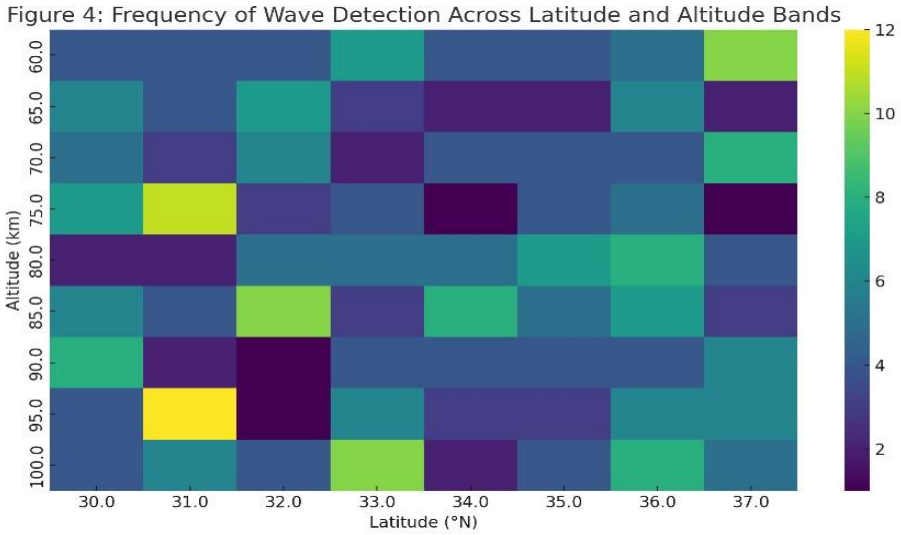


Figure 4: Heatmap – Frequency of wave detection across latitude and altitude bands
X-axis: Latitude (°N), Y-axis: Altitude (km), Color: Number of wave detections

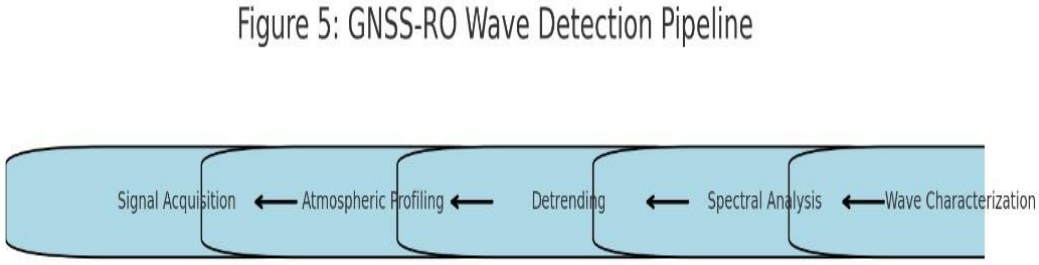


Figure 5: Flowchart – GNSS-RO wave detection pipeline:
Steps: Signal Acquisition → Atmospheric Profiling → Detrending → Spectral Analysis → Wave Characterization

Ruolin Qi is a researcher in artificial intelligence and supply chain analytics, with a focus on integrating machine learning methods into practical business applications. Her work emphasizes the development of explainable forecasting models for inventory management, particularly in addressing the complexities of slow-moving stock. By combining hybrid neural networks with interactive visualization techniques, she aims to enhance both the accuracy and interpretability of predictive models, providing valuable tools for data-driven decision-making in industry.

Summary:

This study demonstrates the efficacy of GNSS Radio Occultation in detecting upper atmospheric waves across the South Asian region. Results from COSMIC-2 and FORMOSAT-7 show that gravity wave signatures are prominent in the 60–100 km range, with seasonal and latitudinal dependencies. Events such as the April 2022 case illustrate the sensitivity of GNSS-RO in capturing short-duration, high-impact wave phenomena.

The integration of RO-derived wave parameters with models of thermosphere-ionosphere coupling provides a valuable resource for forecasting space weather disturbances and improving global circulation models. Future

efforts should expand ground-based validation campaigns and integrate GNSS-RO into operational atmospheric monitoring frameworks.

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