Applicability of Radio Occultation Data for Atmospheric Temperature Estimation over the São Francisco River Basin

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Abstract

Accurate atmospheric profiling is essential for understanding climate dynamics and improving weather forecasting, particularly in data-scarce regions. This study evaluates the performance of the Radio Occultation (RO) technique - using data from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC-2) by comparing vertical temperature profiles with radiosonde (RSO) observations over the São Francisco River Basin (Brazil) during January and July 2020, which represent contrasting seasonal conditions. Statistical analyses, including root mean square error (RMSE), correlation coefficient, relative error, and mean differences, are applied to assess the agreement between the two datasets. Results reveal high consistency, with RMSE values below 1.6 °C, correlation coefficients exceeding 0.84, and average differences generally below 1 °C. The student's T-test confirmed the absence of statistically significant differences at the 5% level, reinforcing the reliability of the RO-derived profiles. Such findings suggest that RO is a promising method for capturing atmospheric temperature structures, making it a valuable complementary tool for climate monitoring in regions with limited in-situ observations.

1. Introduction

Comparative analyses of different atmospheric observation techniques are essential for validating emerging methods and ensuring the quality of data used in meteorology and climatology (QIU et al., 2023). In this context, Radio Occultation (RO) technique, particularly the COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) mission - has emerged as a promising tool for retrieving vertical profiles of temperature, pressure, and water vapor, offering high vertical and horizontal resolution, global coverage, and temporal consistency.

Previous research has validated COSMIC data by comparing it with 38 radiosonde (RSO) stations from the Australian Bureau of Meteorology, emphasizing the importance of temporal alignment and geographical proximity to ensure observational representativeness (Xu et al., 2009). More recent studies have reinforced these methodological considerations by performing intercomparisons between radio occultation data and radiosondes or Numerical Weather Prediction (NWP) models in various regions and atmospheric conditions, highlighting the sensitivity of such comparisons to spatial and temporal collocation criteria (Vergados et al., 2022; El Kenawy et al., 2022).

At the regional level, although radiosonde datasets are affected by several limitations, such as lack of homogeneity, instrumental biases, and data discontinuities (GUO et al., 2020) they remain a widely used and reliable reference for atmospheric measurements, particularly in the upper troposphere and lower stratosphere, due to their capacity to provide direct in situ observations, despite the limited spatial and temporal coverage.

São Francisco River Basin (BRSF) is a region of significant environmental, economic, and social importance in Brazil. Since 2013, the area has experienced adverse hydro- meteorological conditions, with below-average precipitation and streamflow, leading to reduced storage levels in major reservoirs (CBRSF, 2024). However, climate monitoring is challenging because the region is currently covered by only a single RSO station. Such challenges underscore the need for reliable atmospheric monitoring techniques.

The GNSS RO method has been extensively evaluated and shown to yield accurate retrievals of meteorological variables at a global scale. Understanding atmospheric circulation is essential for analysing the interactions among climate phenomena and multiple spatial and temporal scales. Within this context, the present study investigates the reliability of COSMIC-RO data in comparison with RSO profiles, focusing on vertical temperature structures observed during the first week of January and July 2020—months that typify contrasting atmospheric conditions in the Southern Hemisphere (summer and winter, respectively).

The structure of this paper is as follows: Section 2 presents an overview of the atmospheric datasets employed in the analysis, detailing the characteristics of both the GNSS-RO data from the COSMIC-2 mission and the RSO observations obtained from the University of Wyoming repository. Section 3 describes the methodology, including the geographic and climatic characterization of the study area, the selection and preprocessing of atmospheric profiles, and the techniques applied for spatial and temporal filtering, interpolation, and statistical analysis. Section 4 discusses the results, focusing on the comparison of temperature profiles obtained by the two techniques for the first weeks of January and July 2020, as well as the interpretation of atmospheric conditions during these contrasting seasonal periods. Finally, Section 5 summarizes the main conclusions and highlights the potential of RO data as a complementary tool for atmospheric monitoring in regions with limited conventional observations.

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2. Atmospheric data source overview

2.1 Radio Occultation

Atmospheric profiles obtained from RO have played an important role in the investigation of atmospheric conditions, which has justified constant investments aimed at the evolution of the technique in recent years, both in vertical resolution and accuracy (lower uncertainties) and in the sensitivity of atmospheric variations (Banos et al., 2019).

The RO signal can be processed to recover raw data (upstream) and curvature angles, which are then converted into refractivity profiles using Abel's inverse (Chen et al., 2021). Atmospheric refractivity serves as the basis for estimating essential meteorological parameters such as pressure, temperature, and humidity (Kuo et al., 2000).

Thus, the RO technique allows the recovery of detailed vertical profiles of density, pressure, and temperature in the stratosphere and upper troposphere. In addition, through ionospheric refraction, it is possible to derive electronic density profiles, contributing significantly to studies of the ionosphere and its interaction with the Earth's atmosphere (Hoeg, 1996; Jerez et al., 2022; Melbourne, 1994; Schreiner et al., 2020).

This study utilizes observational data from the second constellation of COSMIC satellites (COSMIC-2). According to data provided by the CDAAC platform (http://cdaac-www.cosmic.ucar.edu/cdaac), COSMIC-2 generates approximately 15,000 to 17,000 RO events per month over South America. The mission offers several atmospheric and ionospheric data products, including dry atmospheric temperature profiles (atmPrf), wet atmospheric temperature profiles (wetPrf), and ionospheric profiles (ionPrf). Detailed methodologies for the acquisition and processing of these profiles can be found in Jerez et al. (2022)

In the present analysis, wetPrf product is employed. It is derived from the post-processed one-dimensional variational analysis (1DVAR) of Level 2 COSMIC-2 data, made available by COSMIC (CDAAC; UCAR, 2024). This product provides atmospheric parameters such as temperature, specific humidity, and water vapor pressure, with approximately 4 000 profiles available per day and an average vertical resolution of 0.05 km at low and mid-latitudes. The profiles extend vertically from the Earth's surface up to approximately 60 km altitude. Further information on the wetPrf product is provided by the COSMIC-2 dataset (COSMIC, 2025).

2.2 Radiosonde

The RSO's instrumentation is compactly housed within a small white box attached to a weather balloon filled with hydrogen or helium. The temperature sensor detects thermal variations by measuring changes in electrical resistance as the balloon ascends. Humidity is monitored through a sensor that measures fluctuations in ambient water vapor using humidity-sensitive materials. Atmospheric pressure is tracked by an aneroid barometer, which responds to altitude changes.

An onboard transmitter continuously sends the collected data in real time to a ground-based receiving system, ensuring immediate availability for meteorological analysis and atmospheric modeling. Typically, the balloon can ascend up to approximately 30 km above the surface—around the 10 hPa pressure level in the stratosphere. On average, it rises at about 300 meters per minute and, depending on wind conditions, can drift as far as 200 km from its launch site (MILRAD, 2018).

The RSO data used in this study are obtained from the online repository of the University of Wyoming, a globally recognized institution that systematically and freely provides atmospheric sounding records. These soundings are conducted daily using weather balloons launched from various locations worldwide, typically at 00Z and 12Z, where "Z" denotes Coordinated Universal Time (UTC). The resulting vertical profiles include key atmospheric variables such as temperature, relative humidity, atmospheric pressure, and geopotential height (Milrad, 2018).

3. Statistical Measures

To assess the consistency and reliability of atmospheric profiles derived from Radio Occultation (RO) compared with in situ Radiosonde (RSO) measurements, a set of statistical methods was applied. These methods are widely employed in atmospheric sciences to quantify both the accuracy of estimated variables and the degree of agreement between different observational techniques. Specifically, the Root Mean Square Error (RMSE) was used to measure the magnitude of deviations between RO and RSO values, while the Pearson correlation coefficient quantified the strength of their linear association. The Relative Error (RE) was applied to express systematic discrepancies in percentage terms, providing further insight into potential biases, particularly in the case of water vapor retrievals. Finally, Student's t-test was performed to evaluate whether the differences between mean values from RO and RSO datasets were statistically significant at the 5% confidence level. Together, these methods form a robust framework for validating RO-derived atmospheric profiles against conventional radiosonde observations.

3.1 RMSE

RMSE is a widely used metric for quantifying the difference between estimated values and observed values. In the context of RO and RSO adopted in this study, it measures the accuracy of atmospheric variables derived from RO profiles in relation to direct RSO measurements. Here, RMSE was used to measure the difference between the values obtained from RO and the values obtained with RSO. It was calculated using the formula (Willmoot; Matuura, 2005):

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}\,, \tag{1}$$

where y_i are the observed values of RO (temperature, pressure, water vapor), $\hat{y}_i$ are the values estimated by the RSO technique, n is the total number of observations.

3.2 Cross-correlation

The cross-correlation method is widely used in various fields to analyze relationships between time series (Jiang et al., 2019; Jiang; Zhou, 2011). Pearson's correlation coefficient (R) measures the linear relationship between the values obtained by RO and those obtained by RSO. It indicates the degree of agreement between the two data sets. Values of R close to 1 indicate a high correlation between the methods, suggesting that the RO profiles accurately represent the in-situ measurements of the RSO.

The cross-correlation coefficient R can be defined as (Wilks, 2011):

$$R = \frac{\sum(y_i - \bar{y})(\hat{y}_i - \bar{\hat{y}})}{\sqrt{\sum(y_i - \bar{y})^2 \sum(\hat{y}_i - \bar{\hat{y}})^2}}, \quad (2)$$

where y_i are the values referring to RO,
$\hat{y}_i$ are the values referring to RSO,
$\bar{y}$ is the mean of the observed values of RO
$\bar{\hat{y}}$ is the mean of the values estimated by RSO

3.3 Relative Error

Relative Error (RE) expresses the percentage discrepancy between the values measured by RSO and the values estimated by RO. This metric is useful for assessing the presence of systematic deviations between the two data sets. In the case of water vapor, the relative error is particularly relevant, as the RO signal may be limited due to moisture absorption (Smith; Weintraub, 1953). It is defined as:

$$\boldsymbol{ER} = \frac{|y_i - \hat{y}_i|}{y_i} \times \mathbf{100}, \quad (3)$$

3.4 *t-student*

The student's t-test can be used to verify whether the difference between the mean values of the RO and RSO profiles is statistically significant. It is calculated as:

$$\boldsymbol{t} = \frac{\bar{y} - \bar{\hat{y}}}{\frac{s}{\sqrt{n}}}, \quad (4)$$

Where s is the standard deviation of the differences $(\boldsymbol{y_i} - \boldsymbol{\hat{y}_i})$ and n is the number of observations.
The p-value represents the probability of obtaining a result as extreme as (or more extreme than) the one observed, assuming that the null hypothesis is true. In other words, it quantifies the degree of evidence against the null hypothesis. When the p-value is lower than the adopted significance level (in this case, 0.05), the null hypothesis is rejected, indicating that the observed difference between the RSO and RO profiles is statistically significant.

4. Methodology

This section outlines the procedures adopted for data acquisition, processing, and analysis. First is presented the study area, emphasizing its climatic, geographic, and hydrographic characteristics. Subsequently, the atmospheric data sources are detailed, including RSO e observations and atmospheric profiles retrieved via RO from the COSMIC-2 mission. Then, the criteria for temporal and spatial data selection are described, along with the methods used for vertical interpolation and the construction of weekly average profiles.

4.1 Study Area

The São Francisco River Basin (BRSF) spans the Brazilian states of Minas Gerais, Goiás, Bahia, Pernambuco, Sergipe, Alagoas, and the Federal District, covering the Southeast, Midwest, and Northeast regions of the country (Figure 1). The basin encompasses a total area of 636,099.73 km², comprising 508 municipalities and an estimated population of 20,330,051 (IBGE, 2023). Key surface reservoirs along the São Francisco River—used for flow regulation and hydroelectric generation— include Três Marias in Minas Gerais; Sobradinho, Paulo Afonso, and Itaparica in Bahia; and Xingó, located between Alagoas and Sergipe. Since 2013, the basin has experienced adverse hydro-meteorological conditions, marked by below- average rainfall and streamflows, which have negatively impacted reservoir storage levels (CBRSF, 2024).

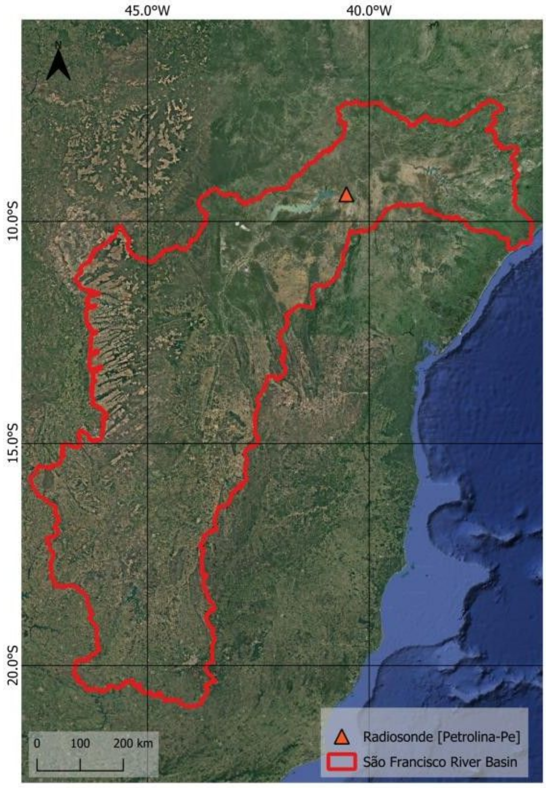

Figure 1. São Francisco River Basin and Radiosonde Station.

Situated within Brazil's tropical zone, the BRSF region experiences annual rainfall exceeding 1,500 mm in its humid and subhumid areas, whereas in the semi-arid and arid zones of the Northeast, precipitation can fall below 350 mm per year, primarily concentrated between January and April. Part of this region includes the *Polígono das Secas* (Drought Polygon), a legally designated area characterized by recurrent critical drought periods, encompassing diverse geographical zones with varying aridity indices (CASTRO; CEREZINI, 2022).

4.2 Radio Occultation and Radiosonde data

Two primary criteria guided the selection of the data time frame: the simultaneous availability of RSO soundings and the presence or absence of precipitation, with particular emphasis on January and July 2020, which correspond respectively to the dry and rainy periods in the region, according to the climatological patterns of the São Francisco

River basin (ANA, 2013; Marengo et al., 2017). To ensure greater compatibility between the datasets, additional filtering is applied to include only those occultations from the COSMIC-2 mission occurring within the time window corresponding to the radiosonde observations. Specifically, only RO profiles recorded between 07:00 and 11:00 UTC are selected, corresponding to the approximate launch and data acquisition times of the RSO soundings conducted in Petrolina, which are launched daily at 09:00 UTC. A 2-hour window is applied to ensure temporal consistency between the datasets.

Spatially, the study area comprises the São Francisco River Basin, extended by a buffer of 2.5 degrees around its boundaries. This spatial filtering is performed using MATLAB tools, and only occultations within this expanded region are considered for the analysis. Figure 2 illustrates the filtering process for one day of occultations, where the red polygon denotes the basin boundaries, the blue area represents the buffer zone, and the red circles mark the selected occultations.

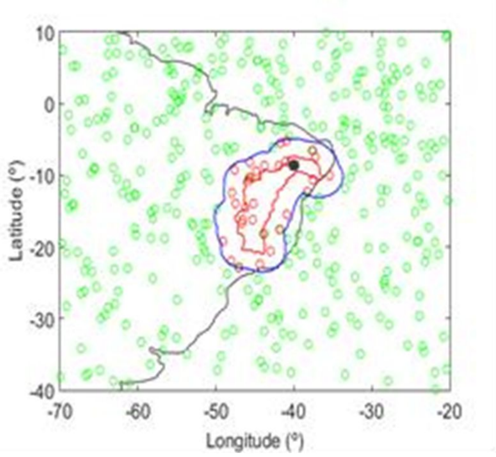

Figure 2. One-day occultations of the wetPrf product from the COSMIC-2 mission (circles) in the São Francisco River Basin region (red outline), along with the 2.5° buffer applied for spatial data selection (blue outline). The location of the radiosonde station in Petrolina is indicated gray.

Average vertical profiles are generated by aggregating multiple individual profiles from the dataset. First, an altitude vector ranging from 0 to 85 km, with increments of 0.05 km, is established. Each individual profile is then interpolated to this common altitude grid using linear interpolation, ensuring consistency in the vertical resolution across the dataset. For each altitude level, the nearest measured or interpolated values within each profile are identified and stored in dedicated matrices corresponding to each analysed variable. Null or missing data are represented as NaN (Not a Number) to avoid biasing subsequent statistical analyses. Weekly averages are then calculated for each altitude level, producing the mean vertical profiles.

To ensure data quality and representativeness, extreme and inconsistent values are subsequently removed. Extreme values are defined as observations that significantly deviate from expected patterns or from the overall data distribution, potentially resulting from measurement errors. Inconsistent values referred to data exhibiting logical or physical contradictions, such as discrepancies between correlated variables or values outside plausible ranges, indicating possible instrument malfunctions or processing errors.

For this study, RSO data collected at 12Z, approximately 9 a.m. Brasília time, are specifically selected. Within the São Francisco River Basin, the only available RSO station is in Petrolina, in the interior of Pernambuco state. This station is used as a reference for comparison with profiles derived from the RO technique. The station's geographical location is shown in Figure 1.

5. Results

Figure 3 presents the comparison between temperature profiles obtained from RO (in blue) and the corresponding RSO measurements (in green). During the first week of analysis (Figures 3a and 3b), there is strong agreement between the two methods, with differences near zero throughout most of the atmospheric columns. However, deviations increase above 25 km altitude, reaching up to 5 °C. In Figures 3c and 3d, corresponding to the first week of July, the largest temperature discrepancies are concentrated between 0 and 5 km altitude.

The temperature profiles derived from RSO exhibit greater vertical variability, likely due to the localized and sensitive nature of direct balloon measurements, which can be affected by local environmental and instrumental factors. In contrast, the RO profiles from the COSMIC-2 wetPrf product result from one-dimensional variational assimilation (1DVAR), which smooths observational data using background information from numerical models. This process typically produces more continuous and consistent profiles, showing less vertical variability, especially at higher altitudes. This methodological distinction likely explains the greater stability observed in the RO data compared to the RSO measurements.

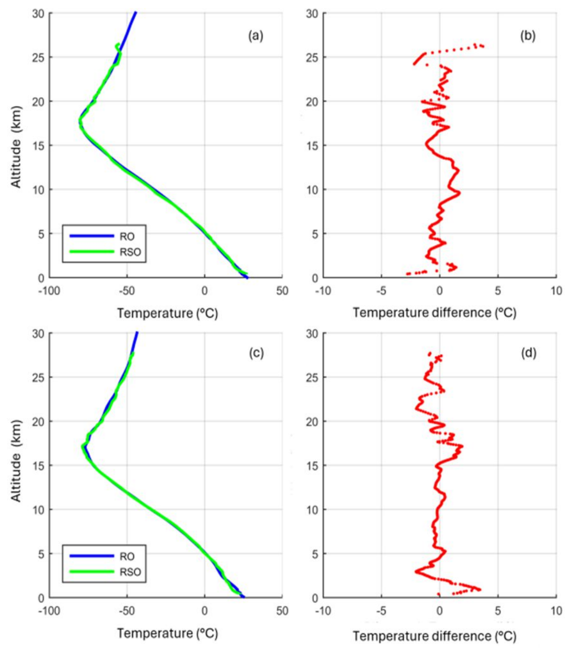

Figure 3. Comparison between RO and RSO data: (a) Temperature profiles for the first week of January; (b) Temperature differences for the first week of January; (c) Temperature profiles for the first week of July; (d) Temperature differences for the first week of July.

Table 1 shows the statistical results obtained by comparing the temperature profiles derived from RO and RSO over the two weeks analysed.

Statistical variables	January	July
RMSE (°C)	1.08	0.94
Correlation	0.86	0.89
Relative Error	3.24%	5.31%
Max. Dif. (°C)	2.96	3.44
Min. Dif. (°C)	0	0
Mean Dif. (°C)	0.74	0.68

Table 1. Error statistics comparing RO and RSO temperature profiles for January and July 2020.

A comparison between January and July reveals subtle variations in the performance of RO relative to conventional sounding. In January, the RMSE is slightly higher (1.08 °C), with a correlation coefficient of 0.86 and a relative error of 3.24%, indicating a smaller percentage discrepancy but a somewhat wider range of differences. In July, the RMSE decreased to 0.94 °C and the correlation increased to 0.89, reflecting greater agreement between the profiles. However, the relative error increases to 5.31%, possibly due to atmospheric variability during the dry season. Average differences remained close, around 0.7 °C, underscoring the overall consistency between the methods despite the more pronounced differences observed in January.

The comparison between the temperature profiles for the first week of January and the first week of July 2020 shows atmospheric differences consistent with the region's seasonal characteristics of the region. In January, a period typically associated with the rainy season in the northeastern semi-arid region, the atmosphere showed greater thermal stability along the vertical column, with more discreet differences between the profiles. The presence of greater humidity and cloudiness currently contributes to a more uniform temperature distribution, limiting sharp variations, especially at the lower levels.

In July, corresponding to the dry season, the greatest deviations between the profiles are concentrated between 0 and 5 km above sea level. This lower layer of the atmosphere is particularly sensitive to the action of radiative processes and the absence of cloud cover, which are common during this period. The combination of strong daytime sunshine, nighttime cooling and low humidity contributes to greater thermal instability at low levels, which may explain the greater variability observed in temperatures during this week.

The student's *t*-test was applied to assess whether the differences between the temperature data obtained from Radio Occultation (RO) and Radiosonde (RSO) measurements were statistically significant at the 5% level ($\alpha = 0.05$). In the first week of January, the test statistic was $t = 0.00$ ($p = 1.00$), confirming that the null hypothesis (H_0) could not be rejected. Similarly, in July, the observed value was $t = 0.02$ ($p = 0.99$), which also falls well below the critical threshold of 1.96. These results demonstrate strong agreement between the two measurement techniques, with no evidence of systematic differences between the datasets.

6. Conclusions

The results of this study demonstrate strong agreement between temperature profiles obtained via the RO technique and those derived from atmospheric RSO, despite differing atmospheric conditions in January and July 2020. Statistical analyses— including RMSE, correlation coefficient, relative error, and mean differences—revealed deviations below 1.6 °C, confirming the reliability of the vertical profiles retrieved by RO.

High correlation coefficients (above 0.89) and low RMSE values (under 0.94 °C), along with average differences generally less than 1 °C, further validate that the RO technique accurately captures the thermal structure of the atmosphere. Additionally, the Student's t-test supported these findings by showing no statistically significant differences between temperature profiles from RO and RSO.

Therefore, such results indicate that RO technique is a promising source of data to be considered in methods for estimating atmospheric temperature profiles, offering a valuable complementary alternative to conventional observations— particularly in regions with sparse monitoring station coverage.

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