NEPTool: An Automated Tool for Neutrospheric Variables, GNSS Delay and PWV Modeling

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Abstract

NEPTool (Neutrospheric Evaluation and Processing Tool) is an automated system developed for neutrospheric modeling, with applications in geodesy and atmospheric sciences. It provides neutrospheric variables and allows the estimation of neutrospheric delay, such as ZTD (Zenithal Total Delay), ZHD (Zenithal Hydrostatic Delay) and ZWD (Zenithal Wet Delay), as well as the derivation of PWV (Precipitable Water Vapor). These variables are essential for improving both atmospheric monitoring and the accuracy of GNSS (Global Navigation Satellite Systems) positioning. The high accuracy of GNSS positioning (on the order of a few centimeters) is essential for applications including autonomous navigation, topographic surveying, and geodetic deformation monitoring. By integrating data from multiple sources such as, radiosondes, surface meteorological stations, and GNSS observations. NEPTool automates the processing and retrieval of neutrospheric products. This integration fosters a synergy between geodetic and meteorological approaches, supporting studies related to weather forecasting, climate analysis, and natural hazard assessment. Additionally, based on theoretical references and educational materials, NEPTool serves as a complementary learning resource for students and teachers, offering practical insights through its visualizations from graphs and measurement outputs.

1. Introduction

The Earth's atmosphere consists of a mixture of gases in varying proportions, with its vertical extent defined by an exponentially decreasing mass profile. Approximately 90% of the total atmospheric mass is concentrated within the first 10 to 15 km (the troposphere), and about 99% lies below 50 km, a region commonly referred to as the neutrosphere for signal propagation purposes. The ionosphere extends from approximately 100 km to 1,000 km above the Earth's surface and contains only about one millionth of the atmospheric mass, composed predominantly of ionized particles generated by solar radiation. Together with the neutrosphere, these atmospheric layers represent approximately 5% of the average distance between GNSS (Global Navigation Satellite Systems) satellites and ground receivers (~20,000 km), but they have a significant impact on signal propagation before the onset of the vacuum (Mendes, 1999; Wallace; Hobbs, 2005; Nievinski et al., 2010; Elgered and Wickert, 2017; Gouveia et al., 2020).

In Geodetic Remote Sensing, for the purposes of propagating GNSS signals, the Neutrosphere is a non-dispersive medium. However, gases and water vapor cause a refraction in the signal, which causes a delay in the propagation of radio waves at the frequencies used by GNSS (15 GHz) (Davis et al., 1985; Elgered; Wickert, 2017a). Neutrospheric delay is an error in the distance between the receiving satellite, being in the order of 2.3 m to 2.6 m for satellites at the zenith, and up to ten times greater for satellites close to the horizon (with an elevation angle of 5º) (Davis et al., 1985; Sapucci, 2001; Monico, 2008; Nievinski, 2009; Elgered; Wickert, 2017). An important result from the zenith delay is the measurement of precipitable atmospheric water vapor PWV (Precipitable Water Vapor) (Bevis et al., 1992; Sapucci, 2001, 2014).

Due to the spatial and temporal variability of the atmosphere, direct measurements of neutrospheric variables are often restricted. As a result, various methodologies are applied to characterize their distribution and behavior. When available, direct observations are typically limited to specific atmospheric layers (e.g., surface or up to ~25 km altitude), while indirect estimations are derived from observational datasets and atmospheric models. The same limitation occurs with the estimation of neutrospheric delays - ZTD (Zenith Total Delay), ZHD (Zenith Hydrostatic Delay), and ZWD (Zenith Wet Delay) - which must be minimized in GNSS processing to ensure accurate positioning. This fact directly influences the quality of PWV estimates.

Neutrospheric delay is the error that the GNSS signal suffers when propagating from its transmission at the satellite antenna to its reception at the receiver antenna. From the refraction that the Neutrosphere causes in the GNSS signal, it is possible to calculate PWV values, an additional source of humidity information for Meteorology, which has the emergence of Geodetic Remote Sensing, Synergy of Geodesy and Meteorology.

NEPTool is an automatic tool for evaluation and processing that includes the modeling of different products: neutrospheric variables are the elements that describe the state of the atmosphere at a given time and place, such as pressure, temperature, and humidity, in addition to neutrospheric delay (ZTD, ZHD, and ZWD) and PWV. The design of these products considers different data sources for measurements of neutrospheric variables, such as those obtained by surface meteorological stations (National Institute of Meteorology - INMET); Upper-Air Stations (radiosondes - UAS); numerical weather prediction models (NWP); and the delay estimated from GNSS positioning techniques.

This article is structured into five main sections. Section 2 presents the concepts of neutrospheric modeling and the estimation of GNSS delay and PWV. Section 3 details the

NEPTool methodology, while Section 4 describes the products generated and made available by the tool. And in the last one (session 5) the final considerations are presented.

2. Neutrospheric modelling

The neutrosphere encompasses the troposphere - which spans from the surface to about 15-18 km - and contains the highest concentration of dry gases, such as nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2), as well as water vapor (Chapman, 1950; Vianello & Alves, 2000; Gouveia et al., 2020; GRUAN - GGOS, 2024). The highest concentration of water vapor is found in the initial kilometers of the neutrosphere, from the surface to approximately 10 km. For this reason, to facilitate the modeling of neutrospheric variables, a theoretical division is considered regarding the humid and dry parts of the neutrosphere.

Variations in neutrospheric variables play a crucial role in the development of climatological events. Changes in atmospheric composition, such as fluctuations in gas concentrations, temperature, and water vapor, are directly linked to shifts in precipitation patterns and in the occurrence of extreme weather events.

However, neutrospheric modeling faces two main challenges. The first is the need for measurements with high spatial (i.e., over short distances), vertical (i.e., Earth's surface up to 50 km), and temporal (i.e., within hours or minutes) resolutions, which are crucial for capturing the dynamics of extreme atmospheric events. The second challenge lies in obtaining accurate observations of neutrospheric variables throughout the entire vertical extent of the layer.

These challenges cannot be addressed using a single data source. Therefore, to enable robust neutrospheric modeling, NEPTool integrates multiple data sources and tools, each offering different spatial, vertical, and temporal resolutions.

2.1 Measurements of Neutrospheric Variables

Due to the spatial and temporal variability of the atmosphere, the concentration of neutrospheric constituents is difficult to measure directly. Therefore, different methodologies are applied, with the aim of obtaining an adequate sampling of the characteristics and variations of the atmospheric variables of this atmosphere layer. In general, the values of the concentration of the constituents can be obtained directly (in loco) or indirectly from different sources.

The atmospheric data used in NEPTool are obtained from independent sources, including surface observations from conventional and automatic stations provided by the National Institute of Meteorology (INMET, 2024), which include hourly measurements of temperature (°C), relative humidity (%), and precipitation (mm). Radiosonde (UAS) data are also used, they are obtained from the University of Wyoming (2024), offering vertical atmospheric profiles up to ~28 km altitude, with variables such as temperature (°C), pressure (hPa), relative humidity (%), and Specific Humidity (mixing ratio) (g/kg) recorded during ascent, from one to two daily measurements (00 and 12 UTC).

2.2 Neutropheric delay modeling

The neutrospheric delay results from the refraction that GNSS signals undergo as they propagate through the gas mass (composed of dry gases and water vapor) until reaching the receiver, which is concentrated in the lowest layers of the Earth's atmosphere. This delay is modeled as the sum of two components corresponding to the theoretical layers of the neutrosphere: the dry and the humid components, as stated before (Thayer, 1974; Elgered & Wickert, 2017).

The atmospheric variables used as input in neutrospheric delay models are essential for accurately characterizing the refractive effects on GNSS signals and, consequently, for estimating their total propagation delay through the atmosphere (Sapucci, 2001; Monico, 2008; Elgered & Wickert, 2017b; Gouveia et al., 2020).

The refractivity of air varies according to the density, which is dependent on altitude (h), as well as the mixing ratio of the hydrostatic and humid components (highly variable) (Thayer, 1974; Elgered; Wickert, 2017). The ZTD (d_t^z) is derived from the integration of refractivity across the neutrosphere, extending from the surface (h_0) to 50 km (h_{top}). From equations (1) and (2), one can determine the hydrostatic delay (d_h^Z) (m) and the zenith delay of the non-hydrostatic component (d_{nh}^Z) (m) (Davis et al., 1985; Sapucci, 2001; Nievinski, 2009; Elgered; Wickert, 2017; Gouveia, 2020):

$$d_t^z = 10^{-6} \int_{h_0}^{h_{top}} \underbrace{\left(k_1 \frac{P_d}{T} Z_d^{-1}\right)}_{d_h^z} + \underbrace{\left(k_2' \frac{e}{T} Z_w^{-1} + k_3 \frac{P_w}{T^2} Z_w^{-1}\right)}_{d_{nh}^z} dh \quad (1)$$

where P_d is the pressure at the surface of dry gases (hPa), T is the temperature (Kelvin), P_w is the partial pressure of water vapour (hPa), and k_1, k_2', k_3 are the atmospheric refractivity coefficients empirically determined (Thayer, 1974; Askne & Nordius, 1987; Bevis, 1994; Rueguer, 2002; Albuquerque et al., 2021). Z_d^{-1} and Z_w^{-1} denotes the inverse compressibility constant of hydrostatic and non-hydrostatic gases, respectively.

2.2.1 Estimation of ZTD and PWV from GNSS data

GNSS positioning provides coordinate estimates but also allows the estimation of various errors affecting satellite signals, which can be minimized to improve positional accuracy (Monico, 2008; Elgered & Wickert, 2017). Among the signal propagation errors, the ZTD by GNSS (ZTD-GNSS) stands out, as it results from the composition and variability of neutrospheric constituents, as previously discussed. ZTD-GNSS can be derived using different processing strategies and software packages. Additionally, several regional and global analysis centers, such as IGS TROP (2025), NGL_TROP (2025), and SIRGAS (2025).

The ZTD-GNSS estimation by ZTD-GNSS can be obtained from the ZTD-SIRGAS by subtracting the ZHD from the ZTD, resulting in the ZWD. The ZHD is calculated using the equation (5) proposed by Saastamoinen (1972), later refined by Davis et al. (1985). From the ZTD-GNSS estimate, it is possible to obtain an important measurement of precipitable atmospheric water vapor PWV, in mm.

Initially, ZWD ($d_{nh_{GNSS\_mod}}^z$) is calculated from the difference between the ZTD/GNSS and ZHD modeled ($d_{h_{mod}}^z$), from more robust or simplified models (empirical) (Saastamoinen, 1972; Davis, 1985; Sapucci, 2001; Gouveia et al., 2020; Albuquerque et al., 2022, 2024):

$$d_{nh_{GNSS\_mod}}^z = d_{t_{GNSS}}^z - d_{h_{mod}}^z. \quad (2)$$

PWV-GNSS results from equation (2):

$$PWV = d_{nh}^{z} \cdot \frac{\Psi}{\rho_a} = \frac{10^6}{R_w \left[k_2' + \frac{k_3}{Tm}\right] \cdot \rho_a}, \quad (3)$$

where the constants ρ_a is the density of liquid water (1 g/cm³), Ψ (kg m^3) is the specific constant for moist gases (R_w) (kg/K), and Tm is the mean Temperature (Davis et al., 1985; Bevis et al., 1992; Sapucci, 2005).

3. Neutrospheric Products Tool (NEPTool) Methodology

NEPTool is a robust tool for estimating neutrospheric variables, including pressure (P), temperature (T), relative humidity (RH), specific humidity (SH), and precipitation (Prec), as well as for computing GNSS delay parameters (ZTD, ZHD, and ZWD) and PWV. The synergy between GNSS positioning and meteorology began to be explored in studies by Sapucci (2021). Over the years, Gouveia et al. (2013, 2019, 2020a) contributed to the modeling of the neutral atmosphere using diverse data sources. Furthermore, Gouveia et al. (2020b) and Alves et al. (2015) investigated the correlation between different delay modeling strategies and their effects on GNSS positioning convergence time and accuracy.

These efforts marked the beginning of the Neutrospheric Research Group, responsible for the neutropheric tool. As the research progressed, the software developed within the group was refined and automated through collaborations with other researchers who later joined the initiative (De Lima et al., 2022; Albuquerque et al., 2022; Albuquerque et al., 2024). Currently, NEPTool consists of a suite of integrated tools developed in MATLAB software (Figure 1).

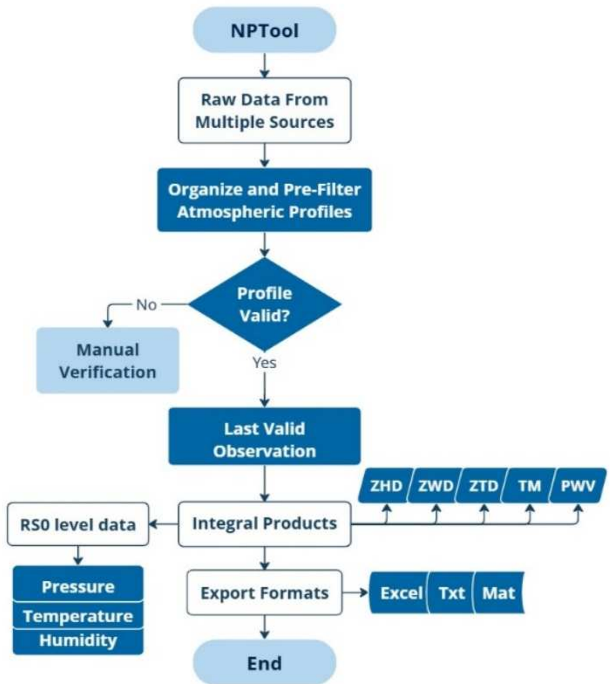

Figure 1. NEPTool Processing Workflow.

NEPTool methodology begins with processing raw data from the multiple sources (INMET, UAS, GNSS) by organizing and pre-filtering atmospheric data. In the next step, it generates preliminary neutrospheric products and performs the integration required for the calculation of GNSS delay parameters, including ZTD, ZHD, and ZWD. The filtering process removes numerical inconsistencies that may result from calibration errors or data transmission failures (Albuquerque et al., 2024). If the profile does not conform to the expected format, the system halts execution and prompts verification, enabling the review and correction of inconsistencies to ensure data integrity. If the profile is validated, the system proceeds to identify reliable observations for each neutrospheric variable.

During the product calculation step, the software applies the formulation of neutrospheric delays (Equations 1 to 3), which results in ZTD, ZHD, ZWD, and PWV considering the different sources Figure 2. The flowchart, Figure 1, brings the operation of NEPTool from the input data to an export in different formats.
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4. NEPTool Products

The results and products generated by NEPTool enable the analysis of neutrospheric variables and signal delay at any location within the spatial coverage of the input data sources, dating back to 2014. Users can obtain specific measurements for a given date and location or generate time series, with outputs provided as text files and graphical visualizations.

NEPTool is structured into two main modules, as shown in Figure 2. Module 1 is responsible for generating atmospheric profile files, providing key variables such as pressure (P, in hPa), temperature (T, in °C), relative humidity (RH, in %), specific humidity (SH, in g/kg), and precipitation (Prec, in mm), based on data from different sources and filtering (Albuquerque et al., 2022; Albuquerque et al., 2024) to their respective spatial, vertical, and temporal resolutions, and can be applied to stations located in regional or global networks. NEPTool has been validated considering Brazilian stations: 43 Radiosonde Stations (UAS), offering vertical profiles from station altitude up to approximately 25–28 km, with two observations at 00 and 12 UTC daily; 560 Surface Meteorological Stations (INMET), with high temporal resolution surface data; and 145 GNSS Stations, providing integrated measurements representing the neutral atmosphere up to 50 km altitude.

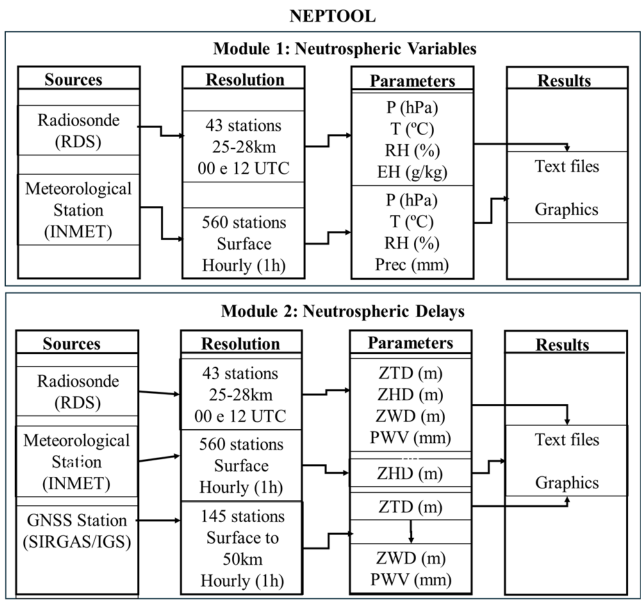

Figure 2. NEPTool flowchart. Data sources: radiosonde (UAS), Meteorological (INMET) and GNSS station (GNSS); Resolutions spatial, vertical and temporal respectively;

Neutrospheric variables (Module 1): Pressure (P-hPa), Temperature (T-ºC), Relative Humidity (RH-%), Specific Humidity (SH-g/kg), Precipitation (Prec-mm); Delays parameters (Module 2): ZTD (m), ZHD (m), ZWD (m) and PWV (mm); and, Results in Test files and Graphics.

Module 2 delivers the computed GNSS delay parameters ZTD (in m), ZHD (in m), and ZWD (in m), along with PWV (in mm). These outputs are generated at the same temporal and spatial resolution as the selected data source, enabling flexible and accurate modeling of the neutrosphere.

The NEPTool website is currently under development and will include comprehensive information about the tool, its theoretical foundations, and key references. It aims to provide users with both introductory and in-depth knowledge to support further research. Additionally, the platform will serve as an educational resource for teachers and students, encouraging the initiation of studies in this field and promoting scientific dissemination beyond academic contexts. The website will also provide access to the products presented in Section 4 and to publications by researchers affiliated with the Neutrospheric Research Group.

4.1 NEPTool Results

NEPTool generates outputs including pressure, temperature, relative and specific humidity, precipitation, ZTD, ZHD, ZWD, and PWV. These results can be provided as vertical profiles or time series, organized by station and observation epoch.

The profiles of neutrospheric variables, such as pressure, temperature, humidity, and precipitation, can be analyzed based on radiosonde (UAS) measurements, which provide data at various altitudes for each sounding, reaching up to approximately 28 km. Figure 3 shows the pressure, temperature, relative humidity, and cumulative preparation profile of a station for the days April 29 to May 1.

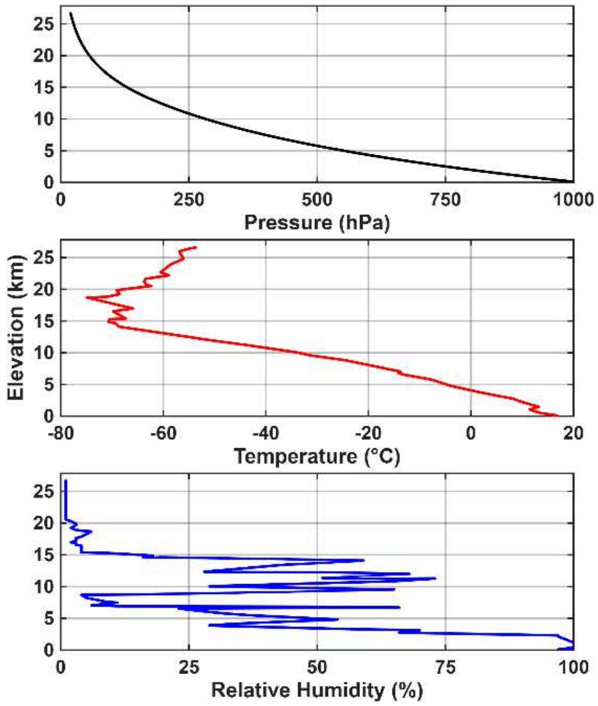

Figure 3. Profile of pressure (hPa), temperature (°C), relative humidity (%), and accumulated precipitation (37.23 mm) on May 3, 2024, at the Brazilian station Santa Maria (SBSM).

Figure 4 presents the time series of ZTD derived from GNSS data and precipitation measurements from INMET over a ten-year period, station in Presidente Prudente, São Paulo, Brazil.

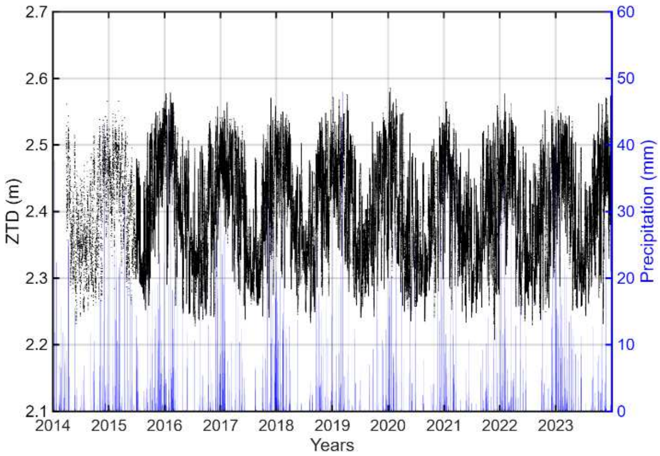

Figure 4. Ten-year time series of ZTD-GNSS and precipitation (INMET), station in Presidente Prudente, São Paulo, Brazil.

5. Conclusion

This study presents NEPTool, a computational tool developed from research focused on the analysis of neutrospheric variations and their impact on GNSS positioning accuracy. By integrating multiple data sources, NEPTool enables a more detailed and reliable representation of atmospheric behavior, particularly relevant in the Brazilian context, where the Amazon rainforest plays a significant role in regional climatology.

NEPTool provides robust neutrospheric modeling, computing key GNSS delay parameters (ZTD, ZHD, and ZWD) and estimating precipitable water vapor (PWV). The outputs include standardized text files containing atmospheric variables by station, time, and parameter, as well as graphical products such as time series and vertical profiles.

These results support detailed spatial and temporal analyses of the neutrosphere, making NEPTool a valuable resource for applications in geodesy, meteorology, and climate studies in the Brazilian region. Future developments will focus on improving delay and PWV modeling and extending NEPTool to additional station networks, spanning regional and global scales.

NEPTool concretely demonstrates how integration fosters synergy between geodetic and meteorological approaches. It supports research in geodesy, GNSS positioning quality, weather forecasting, climate analysis, natural hazard assessment, and others. Moreover, it serves as a complementary educational resource for students and teachers, offering both theoretical foundations and practical insights through graphical visualizations and measurement outputs.

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