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50 years of synergy between Space Geodesy and Meteorology: from a GNSS positioning error to precipitation nowcasting applications

50 anos de sinergia entre Geodésia Espacial e Meteorologia: do erro no posicionamento GNSS a aplicações de previsão de precipitação de curtíssimo prazo

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Abstract: The neutral atmosphere (or troposphere) causes refraction in radio frequency signals, which results in errors in Global Navigation Satellite Systems (GNSS) measurements. In meteorology, this effect can represent important measurements of the concentration of atmospheric constituents, especially in regions where conventional high-altitude atmospheric sounding (radiosondes) cannot be performed. There are two GNSS techniques used for this. In the first one, GNSS receivers are located on terrestrial stations that provide estimates of the vertically integrated moisture content (Precipitable Water Vapor - PWV). In the second case, receivers are in space platforms, which obtains profiles of atmospheric pressure, temperature and humidity, known as GNSS radio occultation. These measurements have significant potential for nowcasting applications (30 minutes in advance) of extreme precipitation events (>35 mm). This paper presents a review of the state of the art in the synergy between Geodesy and Meteorology for modeling the neutral atmosphere (neutrosphere), its effect on GNSS positioning and in the estimation of atmospheric constituents, and their applications. Furthermore, it offers the improvements and new challenges developed in modeling the delay for high accuracy positioning.
Keywords: Neutral atmosphere. GNSS and Meteorology. Neutral atmosphere delay. PWV-GNSS.

Resumo: A atmosfera neutra (ou troposfera) causa refração nos sinais de radiofrequência, que resulta em erros nas medidas do *Global Navigation Satellite Systems* (GNSS) empregadas no posicionamento geodésico. Já para a Meteorologia esse efeito pode representar medidas importantes da concentração dos constituintes atmosféricos, principalmente em regiões onde não se pode realizar sondagem atmosférica convencional, por meio de radiossondas acopladas a balões. Duas técnicas GNSS podem ser empregadas para isso. A primeira utiliza receptores em estações terrestres que fornecem estimativas do conteúdo integrado verticalmente de umidade na atmosfera neutra (*Precipitable Water Vapor* - PWV). A segunda, com receptores localizados em plataformas espaciais, com os quais obtém perfis atmosféricos de pressão, temperatura e umidade, na técnica conhecida como Rádio-ocultação GNSS. Essas medidas têm um potencial significativo para aplicações em previsões de curtíssimo prazo (30 minutos) de eventos extremos de precipitação (>35 mm). O objetivo principal deste artigo é realizar uma revisão do estado da arte da sinergia entre a Geodésia e a Meteorologia na modelagem da atmosfera neutra (neutrosfera), seu efeito no posicionamento GNSS e na estimativa dos constituintes atmosféricos e suas aplicações. Além disso, apresenta os aprimoramentos e novos desafios desenvolvidos na modelagem do atraso para o posicionamento de alta acurácia.
Palavras-chave: Atmosfera Neutra. GNSS e Meteorologia. Atraso da atmosfera neutra. PWV-GNSS.

1 INTRODUCTION

In different everyday situations, knowing the location you are in or that you want to reach is of fundamental importance for various applications, ranging from the simplest to the most complex, such as transport, itinerary planning, precision agriculture (planting and/or harvesting), civil infrastructure construction (bridges, roads, dams), aircraft landing and takeoff, oil platforms, autonomous vehicles, etc. In this process, Geodesy plays a fundamental role through the use of satellites, especially Global Navigation Satellite Systems (GNSS), a technology that revolutionized positioning and navigation. Different sources of error affect GNSS measurements, from their transmission (at the satellite) to their reception (at the antenna), for which much research is still necessary. Details of the error sources can be found in Monico (2008) and Teunissen and Montenbruck (2017).

One of these error sources is associated with the electrically neutral portion of the atmosphere, called the neutral atmosphere (or neutrosphere), which extends from the Earth's surface up to approximately 50 km. The constituents of this layer, such as water vapor and other gases, vary and cause refraction of radio waves at the frequencies used by GNSS. This results in a signal propagation delay, with respect to the vacuum, of the order of 2.3 m to 2.6 m for satellites at zenith, up to ten times more for satellites close to the horizon (with elevation of 5º) (DAVIS et al., 1985; SAPUCCI, 2001; MONICO, 2008; NIEVINSKI, 2009; TEUNISSEN; MONTENBRUCK, 2017).

In Geodesy, the neutral atmosphere represents an error source for positioning, which can be treated in two ways. The first one is based on the modeling or calculation of the delay considering the values of the constituent gases of the neutral atmosphere (pressure, temperature and water vapor) from meteorological sources (SAPUCCI, 2001; SEEBER, 2003). The second way is dependent on GNSS measurements, where the residual delay is estimated as an unknown parameter in the processing of these measurements (MONICO, 2008; TEUNISSEN; MONTENBRUCK, 2017).

From the measurements of the atmospheric constituents, it is possible to calculate the refractive index and the refractivity of the air and thus the propagation delay. Empirical delay models can be applied based on climatology. There are also other methodologies that consider the refractive integral that is influenced by all levels of the atmosphere (HOPFIELD, 1971; SAASTAMOINEN, 1972; ASKNE; NORDIUS, 1987; DAVIS et al., 1985). The integral of the zenith delay is simpler since the signal path is restricted to the vertical direction.

The determination of the delay in the slant direction, according to a specific elevation angle and azimuth, is carried out through ray tracing (HOBIGER et al., 2008a; HOBIGER et al., 2008b; NIEVINSKI, 2009; NIEVINSKI; SANTOS, 2010). In practice, mapping functions are a convenient way to make the ratio between the slant delay and the zenith delay available to the end user (MARINI, 1972; NIELL, 1996; BOEHM et al., 2004; BOEHM et al., 2006a; BOEHM et al., 2006b e 2007; URQUHART, 2010; LANDSKRON et al., 2018).

The quality of atmospheric data and models has a direct impact on the accuracy of the calculated propagation delay. Therefore, modeling the neutral atmosphere delay is a research area that seeks to investigate the best technique and data source for atmospheric constituents. Better delay modeling, as well as better spatio-temporal precision and resolution, have been investigated and have shown promising results.

In recent decades, GNSS has presented itself for Meteorology as an accurate atmospheric observation system and an additional source of information on the atmosphere. The effects of atmospheric refraction on GNSS signals, which represent errors in positioning applications, are sources of information that can be converted into useful measurements in Meteorology (GUTMAN et al., 2003; SAPUCCI et al., 2010). When GNSS receivers are on terrestrial stations, such as continuously monitoring networks, integrated water vapor (Precipitable Water Vapor - PWV) is obtained with good quality and high temporal resolution (SAPUCCI et al.,2007a; SAPUCCI et al.,2007b). In the technique called GNSS Radio Occultation (GNSS-RO), receivers are installed on orbital platforms, with which one can obtain profiles of atmospheric constituents with high vertical resolution (SAPUCCI et al., 2014b; BONAFONI et al., 2020). GNSS-RO profiles have had a strong impact on the quality of Numerical Weather Prediction (NWP) products within the process of data assimilation, being the second most important observation system (BANOS et al, 2019). As the approach to obtaining measurements from land-based receivers is quite different from that of space-based receivers, only the first one will be detailed in this article, while a second work will be referenced for simplicity.

The synergy between Geodesy and Meteorology culminates in the research area called GNSS-Meteorology (SAPUCCI et al., 2007a; SAPUCCI et al., 2007b; SMITH et al., 2007; YAN et al., 2009; SAPUCCI et al., 2010; GUEROVA et al., 2016). Meteorology provides a prediction of the concentration of atmospheric constituents to calculate the delay for accurate and real-time positioning. Geodesy, in turn, using GNSS technology, provides measurements of the concentration of atmospheric constituents as an additional source of observation. In the process of data assimilation, this synergy is realized since GNSS observations in terrestrial stations (PWV) and in space-borne platforms (atmospheric profiles of GNSS-RO) are incorporated in NWP, which generates products that are used in modeling the delay in geodetic applications. This represents a feedback cycle in which the importance of the evolution of research in both areas of knowledge is evident.

Worldwide for more than 50 years, the effects of the neutral atmosphere in geodetic applications and the complementary use of data assimilation for NWP have been investigated. The state of the art in the modeling of atmospheric delay is often not adequate for Brazil. Its continental dimensions and very different climatic characteristics for the same day in different regions, with the strong influence of the Amazon rainforest and the oceans on atmospheric circulation, is a challenging research scenario. Therefore, for almost two decades, the impact of the neutral atmosphere on GNSS positioning has been investigated considering the particularities of the Brazilian territory. National NWP models have shown promising results in GNSS positioning in relation to global models, due to the spatio-temporal resolutions employed in them. Therefore, having a description of the neutral atmosphere, such as that provided by the Center for Weather Forecast and Climate Studies (CPTEC) of the National Institute for Space Research (INPE), results in better accuracy in GNSS positioning (ALVES et al., 2015). Many researchers from several national institutions associated with the Spatial Geodesy Study Group (GEGE - *Grupo de Estudos em Geodésia Espacial*) at São Paulo State University (UNESP) have been working on the research axis of modeling the GNSS propagation delay due to the neutral atmosphere and its applications in very short-term forecasts (nowcasting) of extreme atmospheric precipitation events. A recent study proposes the use of GNSS receivers for nowcasting (30 minutes in advance) extreme precipitation events (> 35 mm) (SAPUCCI et al.,2019). There are also projects to explore data from COSMIC-2 (constellation of equatorial satellites dedicated to GNSS-RO) to predict extreme precipitation events (BANOS et al., 2018). A parallel development has been the tomography of water vapor (BRENOT et al., 2020), with the potential to better detail the temporal and spatial distribution of this variable (MOELLER et al., 2020). Weather forecasting of extreme (severe) atmospheric conditions is challenging and is at the frontier of human knowledge, in which synergy in different areas of knowledge is fundamental for achieving success. In view of the above, this article aims to conduct a theoretical and historical review of the synergy between Geodesy and Meteorology in the modeling of the neutral atmosphere, its effect on GNSS positioning and in the estimation of the concentration of atmospheric constituents and their applications.

The scientific community usually calls “tropospheric” the effects experienced when a radio wave propagates in this layer (MONICO, 2008; TEUNISSEN; MONTENBRUCK, 2017). However, is the simplification of the neutral atmosphere in the troposphere totally adequate? Approximately 25% of the propagation delays are above the troposphere (15 to 18 km). Therefore, the term “neutral atmosphere” is found more suitable for expressing the real dimension and characteristics of this region of the atmosphere for radio propagation purposes (MENDES, 1999; TEUNISSEN; MONTENBRUCK, 2017). In section 2, this layer is characterized in its conceptual and terminology aspects. To achieve the proposed objectives, this article presents a compendium of the different data sources and models in section 3 (section 3.3), their distinct spatial and temporal resolutions, and their limitations, advantages and disadvantages. The methods for measuring the atmosphere will be presented, as well as for calculating the delay (section 3.4). Improvements and new challenges developed by modeling the delay for high accuracy positioning (section 3.5) will be discussed, as well as the results and products available (section 3.6).

2 NEUTRAL ATMOSPHERE: CONCEPTS AND NOMENCLATURES

The signals transmitted by the GNSS satellites are radio waves that propagate through the Earth's atmosphere. This medium is dynamic, composed of layers of different characteristics and with varying states.

Such signals undergo variations in their propagation velocity (direction and magnitude or speed), polarization and power.

The Earth's atmosphere is composed of a mixture of gases with different proportions. Its vertical extension is defined due to its total mass, which decays exponentially, with 90% being in the first 20 km and 99% up to 50 km; above 100 km, there is only approximately one millionth of the total atmospheric mass. Its vertical structure is due to its composition (physical and chemical properties). These variations in the atmosphere characterize it as a set of layers, approximately spherical and concentric to the Earth, inhomogeneous, with their own characteristics (VIANELLO; ALVES, 2000).

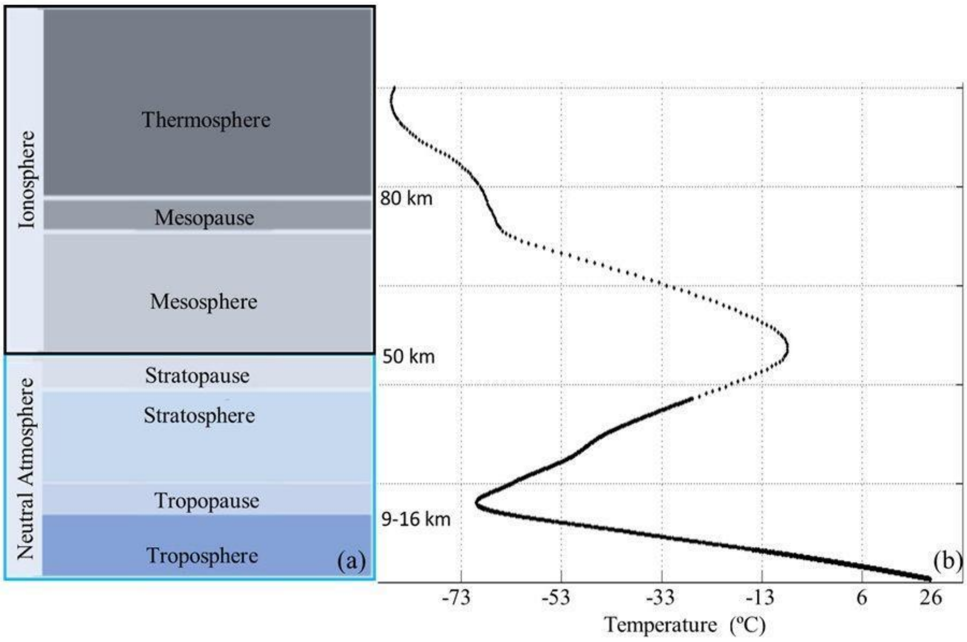
The number of layers, their divisions and their names depend on the subject area of investigation. From the point of view of gas concentration, a division occurs according to the temperature gradient, composed of four layers: thermosphere, mesosphere, stratosphere and troposphere; there are three intermediate boundary surfaces: tropopause, stratopause and mesopause (WALLACE; HOBBS, 2005). In contrast, for the purpose of propagating radio frequency waves (geodetic applications), the atmosphere is essentially divided into two layers, the electrically neutral part and the ionized part, each with very different characteristics. The ionized layer, made up of the thermosphere to the mesosphere, is called the ionosphere and is 50 km to 1000 km thick. The electrically neutral layer, which is from the Earth's surface, is composed of the troposphere, tropopause and stratosphere, with a thickness of 50 km (where the ionosphere begins), or even up to 100 km (the beginning of vacuum) (MENDES, 1999; NIEVINSKI, 2009). The electromagnetic waves transmitted by the GNSS satellites pass through the ionosphere first before entering the neutral atmosphere. In both media, electromagnetic signals are delayed and refracted (TEUNISSEN; MONTENBRUCK, 2017).

Figure 1 shows the layers of the atmosphere. In Figure 1a, the layers are due to the presence or absence of ions, overlapping the layers divided according to the temperature variation. Figure 1b, on the other hand, shows the temperature variation in relation to altitude, where in the inflections, the interfaces in the gas concentrations, are defined. It must be emphasized that the correspondence between the two forms of stratification is not exact, as the ionosphere does not include the entire mesosphere and the neutral atmosphere can advance beyond stratopause.

The ionosphere is composed of rarefied gases that, combined with high temperatures, characterize the state of matter called plasma, where there is a large concentration of energy. Due to the action of solar radiation in this layer, there is a considerable number of ionized atoms and molecules, as well as free electrons (VIANELLO; ALVES, 2000). Such composition causes different effects on GNSS signals, such as refraction and scintillation. When passing through this layer, radio frequency waves are affected in a manner dependent on the electromagnetic frequency (the refractive index is a function of the frequency). The magnitude of this error is proportional to the density of free electrons in the ionosphere, which has temporal and spatial variations. The ionospheric effects of greater magnitude can be eliminated by double frequency processing, forming the ionosphere-free combination (ion-free) (CAMARGO, 1999). Higher order effects, although they represent smaller magnitude, also need to be minimized for high precision applications (IERS, 2010; MARQUES et al., 2011; MARQUES et al., 2014).

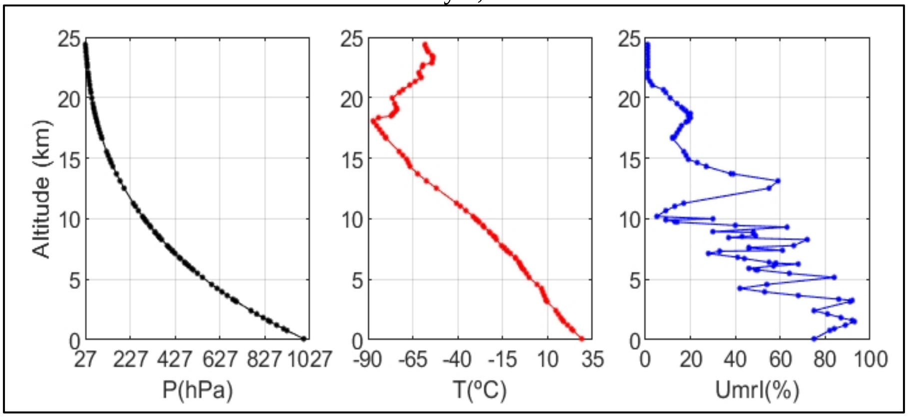
After the ionosphere, the electrically neutral atmosphere causes the largest errors in GNSS positioning. For the purpose of radio frequency propagation, the neutral layer is also called the troposphere. The troposphere's strong influence is due to its composition and mass. The troposphere is the layer in contact with the Earth's surface and reaches an altitude of approximately 15 km to 18 km. It is composed of dry gases (N2, O2, CO2) and water vapor. Dry gases are quite homogeneous and constant, except for CO2, which varies between day and night close to the surface and varies according to pressure and temperature. Despite the low concentration of water vapor, only approximately 0.25%, compared to the other elements (N2 with 78% and O2 with 20%), it presents the greatest variation, both spatial and temporal. Its concentration is not uniform and occurs in the lower portions of the atmosphere (below 10 km, with the highest concentration in the initial 4 km). It is especially dense in hot and humid tropical regions due to the water evaporation process, depending on the variation in altitude (WALLACE; HOBBS, 2005; VIANELLO; ALVES, 2000; TEUNISSEN; MONTENBRUCK, 2017). The variations in temperature, humidity and pressure in relation to altitude (VIANELLO; ALVES, 2000) are exemplified in Figure 2. It can be noted that there is a significant decrease in humidity with increasing altitude. Thus, the wet part of the neutral atmosphere is characterized in the first 10 km, and dry gases predominate from 10 to 15 km, up to 50-60 km (HOFMANN-WELLENHOF, 2008).

Figure 1 – Layers of the Earth's atmosphere in relation to (a) the propagation of radiofrequency waves and (b) the concentration of gases as a function of temperature variation in relation to altitude.



Source: The authors (2020).

Figure 2 – Variation in pressure (P), temperature (T) and humidity (Umrl) in relation to altitude for the Manaus station on January 1, 2017.



Source: The authors (2020).

The neutral atmosphere is not just the troposphere, although this name is used due to its preponderance in the total composition (MENDES, 1999). The simplification of the neutral atmosphere in the troposphere is not adequate as approximately 25% of the propagation delay would be disregarded. This implies disregarding gases that are located above the troposphere, in particular gases in the stratosphere (TEUNISSEN; MONTENBRUCK, 2017).

In contrast to the ionosphere, the iono-free or electrically neutral layer would be more appropriately called the neutrosphere, as proposed by Chapman (1950). However, this nomenclature, although more appropriate, is not used by most authors in Geodesy/GNSS or by more specific works, such as Boehm and Schuh (2013) or Elgered and Wickert (2017). This nomenclature is extended in this article to the refraction and the delay (and its components): the neutral atmosphere (or neutrospheric) refraction and delay.

In this sense, the following issues need to be discussed: How can information be obtained on the constituents of the neutral atmosphere? How to calculate the delay? What accuracy and spatio-temporal resolution are needed? Considering the Brazilian climatological scenario, what are the best models of the delay? The next sections discuss and present the investigations and possible answers.

3 MODELING THE NEUTRAL ATMOSPHERE DELAY: CONTRIBUTION OF METEOROLOGY TO GEODESY

The propagation delay of electromagnetic waves due to the neutral atmosphere cannot be measured directly. For this reason, it is necessary to apply modeling, which is a simplified structure of reality. In this modeling, the laws of refraction, electromagnetic waves and variation of the refractive index are considered, as well as the shape of the Earth with near spherical representation, in addition to hypotheses based on the laws of gas behavior (SILVA et al., 1999).

Thus, the value of the delay is obtained by means of mathematical equations that describe the physical reality of refraction (section 3.1) and of the delay (section 3.2), whose input values are the atmospheric parameters (section 3.3). Both equations and parameters, when applied to specific models (section 3.4), generate values of the delay depending on the location (latitude, longitude and altitude) and time (date and time). A parameter derived from the delay is the integrated water vapor - IWV (section 3.2.1), which is essential in regard to the contribution of Geodesy in the GNSS Meteorology area. Research and improvements in delay modeling directly contribute to IWV modeling.

In this section, in addition to the characteristics and steps for modeling the delay, the delay determination from GNSS positioning (section 3.5) will also be presented. Some references and pointers of publicly available products (section 3.6) will be indicated that can be applied by the user for the time and place he needs.

3.1 Refraction of GNSS signal due to neutral atmosphere

Refraction is a physical phenomenon in which an electromagnetic wave (visible light or other radiofrequency wave) changes velocity (direction and magnitude or speed) from one medium to another (SMART, 1977). The wave can also be modeled using an optical ray or electromagnetic ray. This phenomenon of ray bending can be determined by Snell's law (HECHT, 2002). Refraction due to the neutral atmosphere occurs because it propagates between air parcels with different conditions of pressure, temperature and humidity.

Neutral atmospheric effects that affect signal propagation include attenuation, scintillation and delay. The attenuation is linked to the decrease in the power of the electromagnetic wave, exerted by the components of the neutral atmosphere. Scintillation, on the other hand, is an abrupt oscillation in the amplitude and/or phase of the electromagnetic wave caused by irregularities and sudden variations in the refractivity index (SPILKER Jr., 1996). According to Monico (2008), in the frequency used by the GNSS, these effects are in general relatively small in the neutral atmosphere and can be neglected, except for very low elevation angles (less than 5º). The delay, on the other hand, is the effect of greater magnitude for GNSS signals.

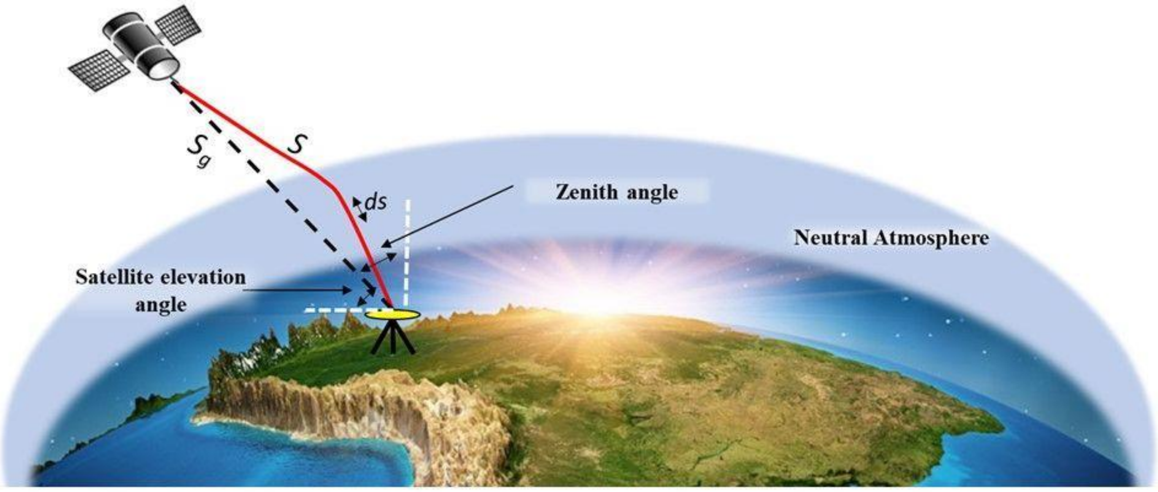
The neutral atmosphere delay is the variation in the propagation time of the GNSS signal and is usually expressed in units of distance measurement (meters instead of seconds) when it is implicitly multiplied by the speed of light. The refractive index, $n = c/v$ (in terms of speed m vacuum c and speed in air), or the refractivity, $N = 10^{+6}\,(n-1)$, causes a change in the magnitude of the speed (speed - scalar) of the wave; on the other hand, the refractivity gradient changes the direction of the wave speed. Then, the delay is defined by the difference between the geometric distance hypothetically traveled by the signal in vacuum and the ray trajectory under the physical effects of the Earth's atmosphere. Therefore, the delay is dependent only on the thermodynamic characteristics of the atmosphere (SAPUCCI, 2001).

The refractivity that impacts the GNSS signal is the sum of two components: the dry component N_d and the wet component N_w. The value of refractivity is then determined by considering the elements that make up each part of the neutral atmosphere (THAYER, 1974; ESSEN; FROOME, 1951 apud TEUNISSEN; MONTENBRUCK, 2017). It is also possible to obtain N in terms of hydrostatic and non-hydrostatic components (MENDES, 1999; NIEVINSKI, 2009). According to Mendes (1999), the term referring to the hydrostatic component can be treated in a way that depends only on the total density of the atmosphere and not on the mixing ratio of the hydrostatic and non-hydrostatic components. On the other hand, the non-hydrostatic component is related to the temperature and pressure of the water vapor. The name “hydrostatic” comes from the assumption of hydrostatic balance made during zenith integration, as described below.

3.2 Electromagnetic wave propagation delay

The trajectory of the GNSS signal between two points will be covered in the shortest time interval (Fermat's principle) (HECHT, 2002). Therefore, considering the atmosphere with multiple infinitesimal layers, the path taken by the satellite signal is curved and unique, defined by the total refractive index (Figure 3). Having determined the position of a point along the ray path, it is possible to calculate n and the ray path length (NIEVINSKI and SANTOS, 2010; NAFISI et al., 2012).

Figure 3 – GNSS signal when propagating in the atmosphere, from satellite to receiver, and the effect of the propagation delay of the GNSS signal carrier wave. Earth image provided by: http://www.casa.org.br/wp-content/uploads/2015/12/america-do-sul.png.



Source: The authors (2020).

GNSS signals are received in multiple directions characterized by elevation and azimuth angles. When a GNSS satellite signal reaches the neutral atmosphere at a different angle of incidence than the normal (or zenith) angle, the ray path becomes curved due to refraction (section 3.1). The smaller the satellite's elevation angle, the greater is the impact of refraction on signals and consequently on GNSS measurements (section 4). Thus, the delay in any direction is obtained as a function of time (t); receiver position (φ, λ, h - latitude, longitude and altitude); and the satellite direction (ε, α – and the direction of the satellite); that is $d \equiv f(t, \varphi, \lambda, h, \varepsilon, \alpha)$. The delay in the zenith (vertical) direction (d^z) is a special case of the slant delay, whose elevation angle equals zenith, $\varepsilon = 90°$ (SAPUCCI, 2001; NIEVINSKI; SANTOS, 2010).

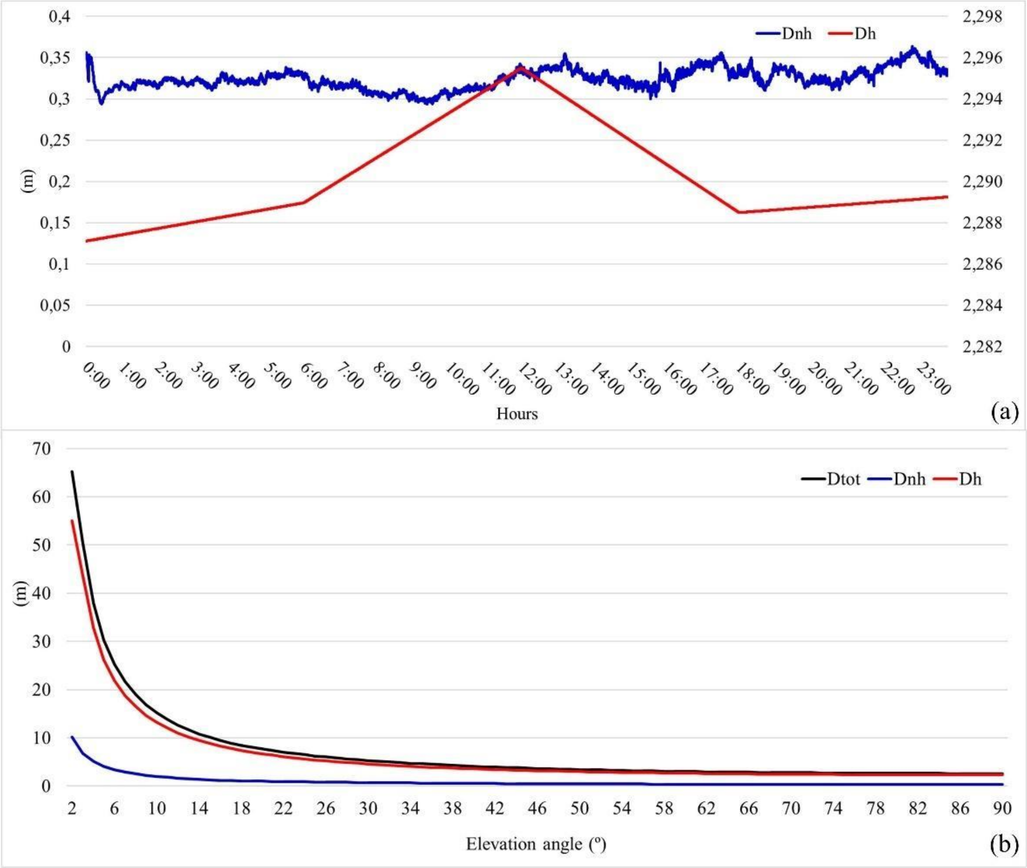
Most of the signals from the GNSS satellites tracked at a receiver do not reach the zenith direction, occurring in slant directions (line of sight between satellite and receiver). The determination of the slant delay is carried out by means of ray tracing, which allows determining the trajectory that the electromagnetic wave has traveled and modeling the atmospheric refraction suffered (NIELL, 1996; BOEHM et al., 2006a; BOEHM et al., 2006b; HOBIGER et al., 2008a; NIEVINSKI, 2009; NIEVINSKI; SANTOS, 2010; SANTOS et al., 2012; LANDSKRON et al., 2018). The ratio between the slant delay and the zenith delay results in the slant factors, d/d^z. From such factors, so-called mapping functions (m) arise, which are models adjusted to the results of ray tracing.

The mapping functions (MARINI, 1972; NIELL, 1996) are more applied in practical works due to their greater practicality in relation to the ray tracing technique itself. Therefore, the model that describes the delay of the neutral atmosphere at any elevation angle is expressed by $d = m_h \cdot d_h^z + m_{nh} \cdot d_{nh}^z$ (DAVIS et al., 1985; TEUNISSEN; MONTENBRUCK, 2017).

The magnitude of the delay is determined according to the thickness of the neutral layer through which the signal passes until it reaches the receiver's antenna, which depends on the elevation angle between the satellite and receiver. For angles close to zenith (90º), the propagation delay of the electromagnetic wave is on the order of 2.3 m to 2.6 m, being up to ten times or more for rising or setting satellites (when the elevation is about 5º, for example, the delay is 25 m). Note in Figure 4 (a) that for elevation angles less than 3º, the slant delay can reach values close to 60 m. This delay causes errors in the final coordinates of the GNSS positioning if it is not modeled properly (DAVIS et al., 1985; SAPUCCI, 2001; MONICO, 2008; NIEVINSKI; SANTOS, 2010; TEUNISSEN; MONTENBRUCK, 2017).

The hydrostatic delay has an order of magnitude of 2.3 m at the zenith, and close to the horizon (below 5º), it can exceed 45 m; it varies according to temperature, altitude, latitude and atmospheric pressure. This component represents 90% of the total delay, and its temporal variation is small (Figure 4 (b), secondary axis), on the order of 1% over several hours. The non-hydrostatic component represents 10% of the total delay, reaching approximately 35 cm at the zenith and is more than 9 m closer to the horizon (elevation below 3º); however, its temporal and spatial variation is much greater (Figure 4 (b)), reaching approximately 20% in a few hours (SEEBER, 2003), as a result of the variation in air humidity.

Figure 4 – Variation in the delay of the neutral atmosphere, according to the elevation angle (a) and time (b), in relation to the three components: total (d: Dtot), non-hydrostatic (d_{nh}: Dnh) and hydrostatic (d_h:Dh) at station NAUS (Manaus-AM).



Source: The authors (2020).

According to Teunissen and Montenbruck (2017), the neutral atmosphere is a non-dispersive medium in GNSS. For both the pseudodistance and the phase, the frequency influence on its effect is less than 0.2 mm for all elevation angles. The non-dispersive characteristic simplifies the modeling of the propagation effect under a neutral atmosphere as these effects are identical for the pseudodistance and carrier phase. However, these effects cannot be reduced by multifrequency measurements, as in the case of the ionosphere, requiring adequate modeling.

Thus, the delay due to the neutral atmosphere varies according to the concentration of the atmospheric constituents that originate it: pressure, temperature and water vapor, a parameter that is more difficult to measure due to its high variability and distribution in the atmosphere. The variations in these constituents occur in relation to seasonality (seasons) and spatial variation. For this reason, the delay and mainly its component composed of water vapor, are considered one of the main sources of error in Space Geodesy.

3.3 Atmospheric Parameters: different sources and modeling

The concentration values of atmospheric constituents can be obtained directly or indirectly from different sources. These sources provide input data to model refractivity and consequently the delay of signal propagation due to a neutral atmosphere (SAPUCCI, 2001; MONICO, 2008; TEUNISSEN; MONTENBRUCK, 2017).

Direct measurements of the concentration of atmospheric constituents over the entire atmosphere are difficult to obtain. Therefore, Meteorology has become a strong ally, providing this information through different data sources of independent measurements, such as: conventional and automatic surface stations, high-altitude stations such as atmospheric sounding by means of radiosondes, ocean buoys, ships, and aircraft data, plus data from weather satellites (such as the Geostationary Operational Environmental Satellite - GOES). Radiosondes stand out because in addition to the quality of their direct measurements of the concentration of atmospheric constituents, they also do so at different levels of the atmosphere, which is important for calculating the delay over the entire trajectory of the GNSS signal.

The observed data can be obtained in different international centers, with global coverage, such as the National Oceanic and Atmospheric Administration (NOAA) (Weather|NOAA, 2020) and the European Centre for Medium-Range Weather Forecasts (ECMWF) (CDS, 2020). Radiosonde data are available from the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) (GRUAN, 2020) and the University of Wyoming (Atmospheric Soundings, 2020). In Brazil, two main centers that provide these data are CPTEC/INPE (CPTEC, 2020) and the National Institute of Meteorology (INMET) (INMET, 2020).

Among the automatic surface weather stations, we can highlight those installed near GNSS stations. Such stations are composed of several sensors that measure temperature, atmospheric pressure, relative humidity, wind speed and direction, among other variables. The measured information is recorded automatically, at the same intervals as GNSS data (MONICO, 2006; SAPUCCI, et al., 2010). For GNSS meteorology (section 4), as well as GNSS positioning applications (section 5), a network of such automatic meteorological stations was installed in stations of the Brazilian Network for Continuous Monitoring of GNSS Systems (RBMC) in the state of São Paulo via thematic project with the FAPESP (Process 2006/04008-2) (GNSS-SP).

The parameters resulting from NWP models are another source of atmospheric data. NWP models are based on the physics of the atmosphere, mathematical models, and the initial state of the atmosphere to then generate its future state. This initial state of the atmosphere is provided by the assimilation of data, which is a technique that consists of adjusting the initial state of the atmosphere considering the observed data.

The observed data are combined with the short-term forecasts of the model itself (“first guess”), thus generating initial conditions (called analysis) for new integrations. When the model reaches an instant when an observation is available, the state predicted by the model (background) is corrected by that observation (filtering of the data). Thus, the integration of the model is restarted after this fix, and the process is repeated for all available observations, generating a new analysis from the NWP model. The data assimilation process in an NWP model is a cyclical or iterative procedure (TALAGRAND, 1997 apud GONÇALVES, 1999; SAPUCCI, et al., 2005; SAPUCCI, et al., 2007a; VENDRASCO et al., 2016).

The following forecast data for atmospheric parameters from global models can be highlighted: European - ECMWF (ECMWF, 2020); Canadian Meteorological Centre (CMC) (CANADA, 2020) and regional models of CPTEC/INPE (CPTEC/PNT, 2020). This requires a large quantity and quality of data, among which radiosondes and other sensors stand out in terrestrial bases and data from remote sensors in satellites.

Climatological models or empirical models are another alternative in modeling the delay. They consider the average configuration of atmospheric behavior over many years of data, that is, the normal behavior of atmospheric phenomena (VIANELLO; ALVES, 2000). Such models can have regional or global coverage; that is, the information used is compatible with the spatial extent of the model. Among the most current global models available for any region and time it can be mentioned: the Global Pressure and Temperature models (GPT – Global Pressure and Temperature) (BOEHM et al., 2007); GPT2 (LAGLER et al., 2013); GPT2w (GPT *wet*) (BOEHM et al., 2014); GPT3 (LANDSKRON et al., 2018); all are available at: VMF Codes (2020).

Brazil has a territorial extension with continental dimensions, which has a distinct climate, varying according to the different regions and times of the year. This implies very different climatic conditions on the same day, hours of the day and according to the region. The Brazilian climate has a strong influence on the Amazon rainforest and the oceans in atmospheric circulation, since gases and water vapor are emitted from the forest and vary throughout the year, which causes a variation in the density of gases, and water vapor makes up the neutral atmosphere. The quality of the data and atmospheric models have a direct impact on the accuracy of the calculated propagation delay, and the advantages and disadvantages of each source and the impact on the quality of the delay are presented in the next section.

3.4 Delay modeling

When dealing with delay modeling, it needs to be clear that there are two main aspects, data and mathematical models (composed of simplifications of refractivity and equations). Given the mathematical equations (section 3.2) and atmospheric parameters (section 3.3), some techniques can be applied to obtain the delay, giving rise to different models, both in the zenith and slant directions. These techniques have been improved over the years.

The delay is determined by different strategies, from the most commonly used ones due to their ease of application but with worse precision to the most sophisticated and accurate ones (MONICO et al., 2009). These strategies can be basically divided into four categories: empirical models of the delay in the zenith direction combined with a mapping function; delay mapping functions, which relate the zenith delay to the satellite's elevation angle; the delay obtained directly from ray tracing; and the estimated delay in GNSS positioning. The most rigorous approach is ray tracing, but it also has high computational and time cost (HOBIGER et al., 2008a; HOBIGER et al., 2008b; NIEVINSKI, 2009; NIEVINSKI AND SANTOS, 2010).

Given the concentration values of atmospheric constituents, it is possible to calculate the delay, whether applied to empirical models, which consider surface measurements, or by different methodologies that consider the integration of refractivity at all levels of the neutral atmosphere (vertical or slant). The simplest delay models for the user are the empirical models, that is, the zenith model and mapping function and empirical data source, such as GPT (BOEHM et al., 2007; LAGLER et al., 2013; BOEHM et al., 2014; LANDSKRON et al., 2018).

These models provide approximate values for delay at low resolution. Although they represent an approximation, their defects are minimized when adjustment methods are used to compensate for the residuals resulting from this modeling (SAPUCCI, 2001; TEUNISSEN; MONTENBRUCK, 2017). However, the most widely used models are the models of Hopfield (SEEBER, 2003) and Saastamoinen (SAASTAMOINEM, 1972), which present satisfactory results in short time intervals.

The modeling of the delay based on surface measurements of atmospheric parameters, such as those from meteorological stations, presents more accurate results than empirical ones. The methodology is applied by applying these data to empirical models of delay such as Saastamoinen, called hybrids. The UNB3m model from the University of New Brunswick (LEANDRO et al., 2006) and the one developed at the Faculty of Sciences and Technology (FCT)-UNESP (FCT-UNESP) can be cited as examples (LIMA et al., 2019).

The application of atmospheric constituents obtained by high altitude meteorological stations, measured by radiosonde, in the zenithal delay equations by means of the integration of refractivity provides results with high accuracy. However, the low distribution of stations in some regions of the globe, such as Brazil, and the time interval of measurements (twice a day), present limitations for the practical use of this methodology. This source is mostly used for scientific investigation and evaluation of the quality of the delay obtained by other strategies.

In this scenario, the methodology that considers the atmospheric parameters resulting from NWP models applied to the refraction equations presents itself as a promising alternative for calculating the delay. The aforementioned models provide the values (pressure, temperature and humidity) for the calculation of the delay for a given location (contained in a specific spatial resolution grid for each model) and moment (temporal resolution of the model), both in the past and in the future (weather prediction). One of its main advantages is the spatio-temporal resolution: the higher the resolution, the greater precision this methodology presents. Thus, the ray tracing technique combined with the input data obtained from the NWP can represent an even more rigorous modeling for the delay (NIEVINSKI, 2009; NIEVINSKI; SANTOS, 2010).

Once the delay in the zenith direction is treated, mapping functions are applied to obtain the delay in the satellite's target direction (satellite-receiver direction). Initially, a simple cosecant model was applied, $\frac{1}{sin(e)}$. But for elevation angles up to 20º, this is inadequate, as it presents significant discrepancies (1% error, approximately 45 cm in the slant delay). In search of precise functions for elevation angles closer to the horizon, other functions have been developed: Marini (1972), Chao (1974) apud Davis (1985), Davis (1985), Herring (1992), Niell (1996) e Niell (2000).

As in the case of zenith delay models, empirical functions, or climatological recovery, are not suitable for all applications, especially when better accuracy is required. Therefore, NWP models started to be applied to the ray tracing technique. Furthermore, for the ratio between the slant delay and the zenith, both coming from the NWP, more promising mapping functions originated. Over the years, these functions have been improved with better quality in determining the delay, such as: Isobaric Mapping Function (IMF) (NIELL, 2001b); Vienna Mapping Function (VMF) (BOEHM et al., 2004); Global Mapping Function (GMF) (BOEHM et al., 2006a); VMF1 (BOEHM et al., 2006b e 2007); UNB-VMF1 (URQUHART, 2010; URQUHART et al., 2010); VMF3 (LANDSKRON et al., 2018); Brazilian Mapping Function (BMF) (GOUVEIA, 2019). GMF is a hybrid function resulting from atmospheric recovery from the ECMWF reanalysis of the global Atmosphere and surface conditions for 45 years (ERA40).

The quality of atmospheric data and models has a direct impact on the accuracy of the calculated propagation delay. Each data source has advantages and disadvantages, either due to its spatial resolution, temporal resolution or quality.

4 ATMOSPHERIC PRODUCTS: THE BENEFIT OF SPACE GEODESY FOR METEOROLOGY (GNSS-METEOROLOGY)

Initially, in the 1950s, the calculation of atmospheric water vapor was determined from radiosondes. Although radiosondes offer measurements at different levels of the atmosphere (from the surface to the top of the neutral atmosphere), they have low spatio-temporal resolution (GUEROVA et al., 2016). Especially considering the sudden variations in water vapor, which occur in specific places and with a very short time (30 minutes), this technique is not adequate. Tralli and Lichten (1990) applied the GNSS technique to perform atmospheric sounding, initially called GPS-Meteorology. Over the years and the expansion of satellite navigation systems, the technique became known as GNSS-Meteorology. Many studies have been developed in this area, such as: Sapucci (2005), Sapucci et al. (2007a), Sapucci et al. (2007b), Smith et al. (2007), Yan et al. (2009), Sapucci et al. (2010) e Guerova et al. (2016). In this scenario, the Global Geodetic Observing System (GGOS) contributes to the state of the art of GNSS Meteorology, in line with the International GNSS Service (IGS), providing products of the neutral atmosphere delay.

4.1 Estimates of Integrated Water Vapor (Precipitable Water Vapor - PWV) using GNSS data

The amount of atmospheric water vapor over a given point on the Earth's surface is defined as a mass of water vapor integrated in the vertical direction, per unit area, called IWV, expressed in kilograms per square meter (kg/m^2). Another way of expressing the amount of integrated water vapor is through the height of an equivalent column of liquid water or precipitable water (PW), in millimeters. With the studies of the relationship between the IWV GNSS and precipitation (also measured in millimeters of water column), it was agreed to use the term PWV (Precipitable Water Vapor). Thus, the relationship between IWV and PWV (or

PW) is obtained considering the density of liquid water (ρ_a):$PWV = \frac{IWV}{\rho_a}$ (BEVIS et al., 1992; SAPUCCI, 2001).

PWV measurements over a given location are obtained by integrating the water vapor density or absolute humidity (ρ_w) from the surface (h_0) up to the altitude (h) at which the water vapor concentration is negligible in an air column of unit cross section, $PWV = \int_{h_0}^{h} \rho_w \, dh$ (VIANELLO; ALVES, 1991; SAPUCCI, 2001; SAPUCCI, 2005).

The determination of this integral requires the use of sophisticated equipment. However, once d_{nh}^{z} is known, it is possible to obtain PWV, from the relationship given by Ψ (kg/m^3), that is, $PWV = d_{nh}^{z} \cdot \Psi$,where $\Psi = \frac{10^6}{R_w\left[k'_2 + \frac{k_3}{T_m}\right]}$. This relationship considers the molar mass of the water molecule (R_w) and the average temperature of the humid atmosphere (T_m, K) (DAVIS et al., 1985; BEVIS et al., 1992; SAPUCCI, 2001; SAPUCCI, 2014a). Sapucci (2014a) presented a specific time-dependent model to be used in obtaining PWV of GNSS data in Brazil. It is important for the application of this technique to use dual frequency GNSS receivers and surface pressure data of good precision (better than 0.5 hPa) measured with a sensor installed next to the GNSS antenna. More details on the methodology used can be found with a wealth of information in Sapucci (2001).

Sapucci et al. (2019) reported an innovative application of PWV data from GNSS receivers, which is the prediction of extreme precipitation events in nowcasting, with the main purpose of issuing alerts about the imminent occurrence of a storm. The focus is on the population vulnerable to the risks of loss of life and material damage, inducing effective and early actions to prevent and reduce damage in the occurrence of such phenomena. Among natural disasters, those generated by severe storms, such as floods and hillside landslides, deserve great attention, as they are the ones that most occur in Brazil. Such impacts on society are significant, generating great economic losses and irreparable losses to families, which highlights the importance of improving this technique.

4.2 GNSS Tomography of water vapor

Tomography is a method applied to obtain constituent quantities from measurements in the slant direction, making it possible to estimate a 2D or 3D structure. This method is applied in different areas, as well as to reconstruct the 3D structure of non-hydrostatic and total refractivity. The delay generated by the influence of atmospheric water vapor in the slant direction (d_{nh}^{S}) is defined as being the integral of the atmospheric refractivity of the non-hydrostatic component in the signal path between the antenna of a GNSS satellite and the receiving antenna. Therefore, the GNSS tomography technique requires that the slant delay be measured by several GNSS stations, preferably nearby (a few kilometers away). Therefore, it allows determining the distribution of the delay of the neutral atmosphere and, consequently, of the water vapor, such as in IWV and PWV (BOHM; SCHUH, 2013).

The atmospheric water vapor integrated in the slant direction is defined as being the integral of the absolute humidity (ρ_w) along the trajectory between the satellite-receiver. Similar to the case of the zenith delay (d_{nh}^{Z}), it is possible to convert values of the tropospheric delay in the slant direction into the values of the slant IWV, the SIWV (Slant IWV) (SAPUCCI, 2001).

In the GNSS estimate of the d_{nh}^{S}, the atmosphere above the GNSS stations needs to be parameterized, which consists of using voxels. Parameterization by voxel implies dividing the atmosphere into boxes, regions where refractivity is considered constant. Therefore, the d_{nh}^{S} from GNSS tomography will be obtained through a linear combination of the refractivity of all voxels in the satellite-receiver direction (BOHM; SCHUH, 2013).

The delay generated by the influence of atmospheric water vapor in the slant direction (d_{nh}^{S}) is more difficult to estimate than the delay in the zenith direction (d_{nh}^{Z}). In the latter case, all (slant) observations are mapped to the zenith direction via an appropriate mapping function. Only one value is estimated in a given time interval. The estimate in this time interval is approximately an average of the delay mapped in all directions, providing high redundancy. In the slant direction, a value is estimated for each line of sight in a given period. This causes a decrease in redundancy and, as a consequence, increases the influence of some errors, such as noise from the instability of oscillators in receivers and GNSS satellites, errors in the ephemeris and the occurrence of multipath errors, among others. However, values of d_{nh}^{S} are capable of generating three-dimensional fields of water vapor distribution (MACDONALD & XIE, 2000), introducing valuable information on the vertical distribution of this variable for assimilation in NWP models (KUO et al., 1996).

Although promising, the GNSS tomography technique has limitations, which allow a field of further investigation and research. One of the limitations is the geometry of "weak" satellites, since GNSS tomography requires a large volume of rays in all directions. Another point to be considered is regarding the system of poorly conditioned equations, which can be solved by applying a priori refractive measurements from NWP models or radiosondes, for example. Another limitation occurs with few rays or the absence of rays in a voxel due to the change in the geometry of the satellites over the course of a day. In these cases, strategies need to be applied, such as restricting the refraction of a voxel considering the neighborhood or a more robust method when applying the Kalman filter (BOHM; SCHUH, 2013).

Properly addressing limitations, GNSS tomography is a promising tool for detecting high spatiotemporal variability in water vapor. Different current works present improvements regarding the technique: Bender et al. (2011), Brenot et al. (2020), Zhang et al. (2020) e Moeller et al. (2020). In Brazil, such studies have not yet been developed.

4.3 Atmospheric sounding from GNSS Radio Occultation

The radio occultation (RO) technique started to be used in the sixties in planetary exploration missions (FJELDBO et al., 1969). However, with the development of GNSS and low orbit satellites (LEO, Low Earth Orbit), RO started to be used for the exploration and investigation of the Earth's atmosphere (KURSINSKI, 1997). Simply put, occultation is the phenomenon in which a celestial body becomes no longer visible due to the obstruction of another body. However, due to the action of the atmosphere, the signal or light emitted behind the hidden object is able to reach the receiver, also carrying information on the atmospheric composition.

The refraction suffered by signal propagation in the atmosphere (ionosphere and neutral atmosphere) allows the calculation of atmospheric refractive indices. From such indices, it is possible to extract atmospheric profiles such as humidity, pressure, temperature and density of electrons (KURSINSKI et al., 2000; HAJJ et al., 2002; JEREZ, 2020; MORAES, 2020), denominated GNSS-RO.

Several RO missions have been developed, including the Constellation Observing System for Meteorology, Ionosphere and Climate mission (COSMIC, 2020) and, more recently, COSMIC-2 (COSMIC, 2020), launched in 2019. With the data from these missions, atmospheric profiles can be obtained for the entire terrestrial globe, including in remote regions where other techniques could not be used. Several studies have been carried out in the most diverse areas using RO data, such as climatological models, ionospheric models, and the detection of natural disasters.

Considering the assimilation of data, the atmospheric profiles arising from GNSS-RO have played an important role, which has justified constant investments aiming at the evolution of the technique in recent years, both in terms of vertical resolution and precision (lesser uncertainties) and in the sensitivity of atmospheric variations (BANOS et al., 2018). These improvements are available in the satellite constellation dedicated to GNSS-RO COSMIC-2 is a partnership of NASA with several space agencies, including INPE. Six satellites were launched to contribute to better observation of the equatorial region, in which the most extreme precipitation events are observed and the models have deficiencies in adequately predicting them. The major limitation for research aimed at studying the contribution of GNSS-RO profiles in improving the prediction of intense precipitation events was the small amount of GNSS-RO data during storms, as the base was scarce in the tropical region where they are concentrated in the strongest storms. With COSMIC-2 in operation, this problem should be minimized, making this type of study feasible. However, it is necessary to adequately process the data to obtain the GNSS-RO profiles since the signature of the occurrence of storms in the atmospheric profiles can be confused with noise and eliminated in conventional processing. A new approach for the processing of these data is an important demand from Meteorology for Geodesy. This improved sensitivity of GNSS-RO, associated with its greater availability over the tropical region, configures a new tool for detection of atmospheric event extremes. It requires a new approach in the processing and use of these products, which is an important challenge to be faced, as it is at the forefront of work on this topic.

5 AVAILABLE DELAY PRODUCTS AND RELATED RESEARCH

In the search to minimize the neutral atmosphere delay in GNSS positioning or to increase the space-time resolution in the quantification of atmospheric water vapor, many works have been developed. These include both scientific investigations and user-friendly products available to the end user (Table 1).

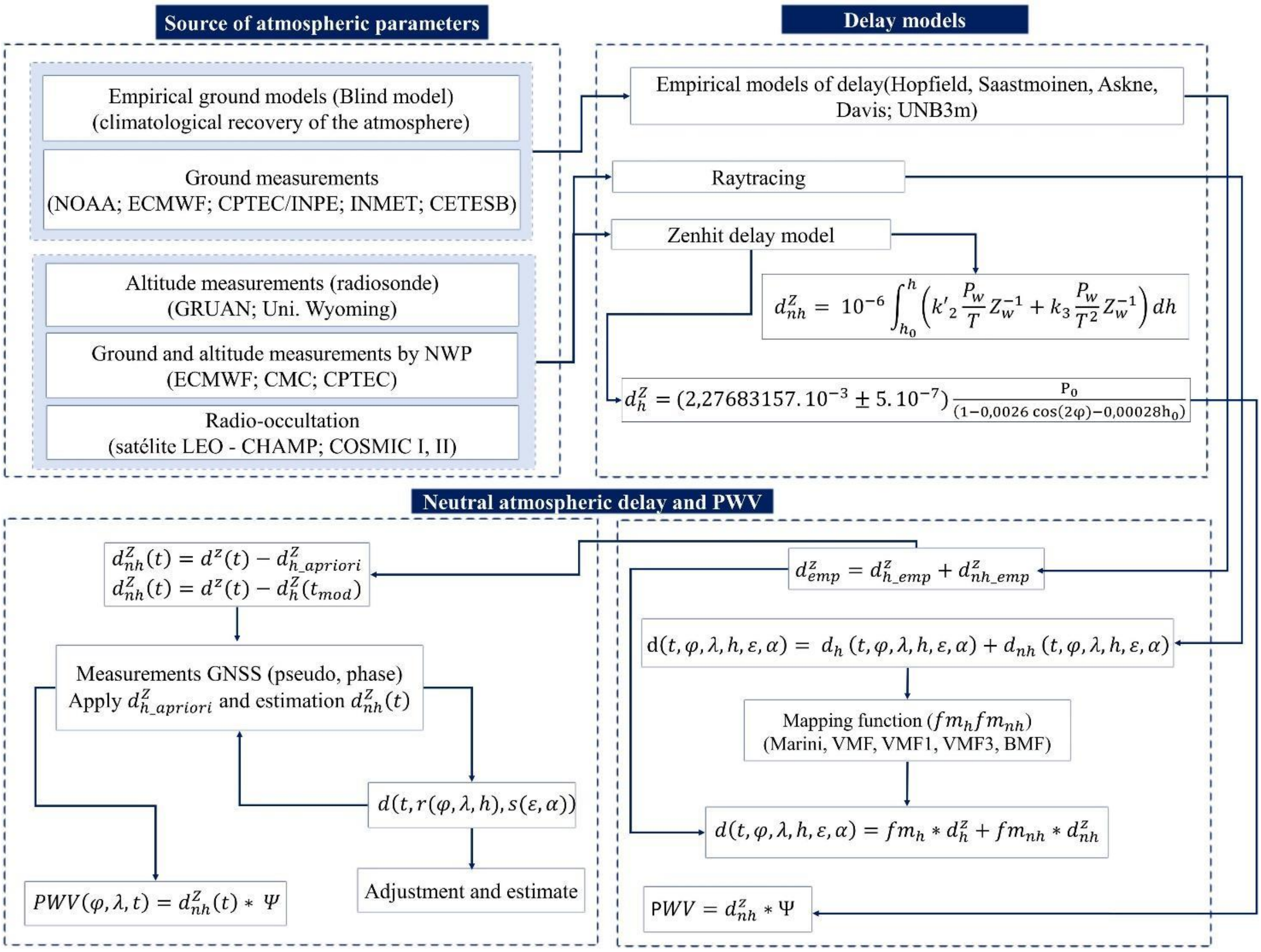
Empirical models are made available through their equations and standard atmospheric data. The user can use such models and improve them by applying other data sources that can present improvements in delay modeling (LIMA, 2019). For real-time applications, empirical, hybrid and NWP models can be applied. This information can be made available even before processing begins. This is the case of air navigation, precision agriculture, autonomous vehicles, etc.

For high accuracy applications (a few centimeters or even decimeters), the empirical or hybrid models may not be appropriate, as they are not able to model the variations in the delay (high variation in pressure, temperature and water vapor) (SAPUCCI, 2006). Unfortunately, the meteorological observations used for the development of these global models were mostly carried out in the Northern Hemisphere. Such values may differ greatly from the others found for these variables in the Southern Hemisphere, when empirical values have been adopted for the entire globe.

The modeling strategies, through the different ways of calculating the delay (zenithal and slant) and the PWV, is presented in Figure 5, considering the different data sources and models of the delay (including the mapping functions).

Studies carried out in Brazil with different types of positioning, regions and times exemplify the low quality of such models (ALVES et al., 2006a, 2006b, 2007a, 2007b, 2015; DALBELO et al., 2006; OLIVEIRA, 2013; OLIVEIRA et al., 2014a e 2014b; ABREU et al., 2014; GOUVEIA, 2013; GOUVEIA, et al., 2014; 2019; 2020; SETTI JR et al., 2016; LIMA, 2019) and highlight the accuracy of meteorological data and regional NWP models. A predominant factor is the tropical climate of this region, which presents sudden variations in temperature, pressure and mainly humidity throughout the seasons. Therefore, Brazil has become a favorable region for such investigations. This is due to the strong influence of the Amazon rainforest, which causes different values of water vapor, temperature and pressure to be found in the same period of the year, according to the location. Theoretical models are generally employed in a restricted way to make a priori corrections in the delay estimate from data processing of GNSS observations (SAPUCCI, 2001; MARQUES, 2012).

Figure 5– Neutral atmosphere delay modeling methodology, considering the different data sources (empirical, ground, altitude, NWP and radio occultation) and different models of the zenith and slant delay, as well as the radius tracing technique to obtain the slant delay or mapping functions.



Source: The authors (2020).

In the scope of the IWV, its quality depends on the modeling of the zenith non-hydrostatic component of the delay and the average temperature. All the improvements and developments in the delay determination corroborate the improvement of the IWV, which is the product made available to meteorology for data assimilation and application in NWP models (SAPUCCI et al., 2007b; YAN et al., 2009; ROHM et al., 2014). In this scenario, the GNSS-RO profiles, as already highlighted, have a great and important contribution. Works that aim to improve both applied techniques and data have been developed (SAPUCCI et al., 2014b). An area of great importance for the application of the IWV is investigations regarding climate change and extreme events (CAMPOS, 2018; SAPUCCI, 2019) (a doctoral thesis in development at FCT-UNESP).

GEGE/UNESP (https://www.fct.unesp.br/#!/pesquisa/grupos-de-estudo-e-pesquisa/gege//home/), on the research axis of GNSS propagation delay modeling due to the neutral atmosphere, presents itself as a Brazilian center of excellence in this theme. Increasingly improved methodologies have been developed, with promising results with respect to the calculation of the propagation delay and its minimization in the different GNSS positioning methods, in estimating the IWV applied to the investigation of climate change and extreme events, and in obtaining atmospheric profiles by GNSS-RO measurements of water vapor (HOLZSCHUH et al., 2010). The main products of the delay in the neutral atmosphere and the IWV made available, both internationally and nationally, are shown in Table 1. The centers that provide them are highlighted, along with some characteristics and their respective electronic addresses.

Table 1 - Delay and IWV products made available, main characteristics and their electronic addresses.

	Product	Features	Address
International	IGS/ZTD GNSS	d^Z, GMF (elevation 7º) Time resolution and extent: 5min (24h/day) Spatial resolution and extent: network IGS	ftp://cddis.gsfc.nasa.gov/gnss/products/troposphere/
	GGOS/ZTD GNSS	d^Z, d^Z_{nh}, VMF (elevation 7º) Time resolution and extent: 5min (24h/day) Spatial resolution and extent: network IGS	http://ggos.org/en/map/
	VMF Raytracer+NWP/ECMWF	d^Z_h, d^Z_{nh}, mf_h, mf_{nh} Time resolution and extent: 06 h (24h/day) Spatial resolution and extent: network global IGS	https://vmf.geo.tuwien.ac.at/
	UNB_VMF1 Raytracer+NWP/NCEP	d^Z_h, d^Z_{nh}, mf_h, mf_{nh} Time resolution and extent: 06 h (24h/day) Spatial resolution and extent: network global IGS	http://unb-vmf1.gge.unb.ca/Products.html
South Amer. Brazil	SIRGAS/ZTD GNSS	VMFs (elevation 3º) Time resolution and extent: 60 min (24h/day) Spatial resolution and extent: network SIRGAS	ftp://ftp.sirgas.org/pub/gps/SIRGAS-ZPD/
	EMBRACE/ZTD/IWV GNSS	VMF (elevation 7º) Time resolution and extent: 5min (24h/day) Spatial resolution and extent: network RBMC	http://www2.inpe.br/climaespacial/portal/iwv/
	Zenith delay CPTEC NWP/CPTEC	d^Z, d^Z_h, d^Z_{nh} Time resolution and extent: 1h (24h/day) Spatial resolution and extent: grid South America	http://satelite.cptec.inpe.br/zenital/
	BMF Raytracer+NWP/CPTEC	d^Z_h, d^Z_{nh}, mf_h, mf_{nh} Time resolution and extent: 1h (24h/day) Spatial resolution and extent: grid South America	In development
	Zenith delay automatic INMET/Un. Wyoming	d^Z, d^Z_h, d^Z_{nh} Resolution and time extension: 6h or 12h (24h/day) Spatial resolution and extent: Brazil	In development

Source: The authors (2020).

6 FINAL CONSIDERATIONS AND FUTURE CHALLENGES

This article discusses in general terms the synergy between Meteorology and Geodesy, with an emphasis on activities in Brazil. On the one hand, it describes the contribution of Meteorology in Geodesy, through the proper characterization of the atmosphere, aiming at minimizing the effects of the neutral layer in the propagation of radio frequency signals. On the other hand, it describes the contribution of Geodesy in Meteorology, in estimating the concentration of atmospheric constituents as an additional source of information. This text contains a compendium of the main developments carried out in this line of research in both ways, which is not intended to exhaust the subject but to provide a basic guide to the research carried out in the last 50 years and an indication of future directions. Another point presented was the discussions regarding nomenclatures: neutrosphere as a synonym for the neutral atmosphere (as presented by CHAPMAN (1950)); as well as the components of refractivity and delay, called hydrostatic and non-hydrostatic (instead of hydrostatic and humid), as they are the most used terms, although not always correct.

With regard to delay modeling, in past decades, efforts have been directed towards accurate GNSS positioning. Therefore, models and data sources have been continuously improved. In addition to the zenith delay, in recent years, the modeling and quality of slant delay and mapping functions in Brazilian territory have also been investigated (GOUVEIA, 2019) due to their climatological complexity. Global empirical models (which use climatological models) are useful for low-accuracy positioning, which may allow metric errors. These models are not capable of expressing the real variability of the delay over a day or hours, but they can be applied in the absence of other models.

The other sources, in isolation, such as surface stations and high altitude stations, provide measurements of atmospheric constituents, which, when applied to mathematical models (section 3.2), provide accurate measurements of the delay. However, these measurements have low temporal resolution, especially in the Brazilian territory. Conventional atmospheric sounding, using radiosondes attached to balloons, measurements often taken as a reference for delay, are costly techniques that restrict the number of daily launches to only four per day (every 6 h) (BEVIS et al., 1992). The estimated delay in GNSS positioning measurements is accurate (ROFATTO et al, 2012; ROFATTO, 2013; MARQUES, 2012), available 24 hours and across the globe. Its spatial distribution will depend on the locations of the GNSS stations. The global IGS network (IGS, 2020) is composed of more than 400 stations distributed around the world, 12 of which are located in Brazil. RBMC has approximately 150 operational stations (RBMC, 2020), 9 of which also belong to the IGS. That is, in the national territory, the delay can be determined at 153 stations, a number that is much greater than in previous decades. In view of this, NWP models are a good alternative to the limitations of other strategies in obtaining the delay (SAPUCCI, 2001; CHEN et al., 2011), mainly in Brazil. A disadvantage is that the best representations of the atmosphere, the analysis (resulting from the assimilation of data), have a low temporal resolution, and the other measurements are obtained by the prediction. The efficiency of propagation delay modeling will depend on the quality of the NWP model forecasts. Regional NWP models, such as those of CPTEC/INPE (CPTEC/INPE, 2020), have high horizontal, vertical and temporal resolutions and can be considered the best options for Brazil and South America since, from these, it is possible to obtain delay modeling with values closer to the reality of that region.

The monitoring of atmospheric water vapor, which fuels the most catastrophic atmospheric natural events, is still an open question, given the lack of techniques for observing the humidity present in the atmosphere. The most important tool for weather forecasting is numerical modeling, but for nowcasting applications, much remains to be improved to obtain reliable and operationally useful results in the characterization of humidity areas. In this context, GNSS products for meteorology can present a good alternative and deserve attention. The results reported by Sapucci et al. (2019) show the existence of a pattern of behavior in the variations of the PWV GNSS at high temporal resolution that precedes a severe storm, which can be improved aiming at nowcasting applications not yet operationally explored with the involvement of continuous monitoring GNSS networks.

Therefore, the data source that best represents the sudden variations caused by extreme events and models that better provide the calculation of the delay needs to be considered for both zenithal and slant directions. Furthermore, the determination of the mapping functions (by means of ray tracing), is a major challenge for the contribution of Meteorology to Geodesy. In the contribution of Geodesy to Meteorology, there may be a strong alliance, seeking to provide increasingly accurate measurements of PWV and with greater spatial resolution, from an even greater number of terrestrial GNSS stations. There may also be a greater number of GNSS-RO profiles, which are of paramount importance in the assimilation technique and consequently for NWP models. Water vapor tomography using dense networks of GNSS receivers is another source of information for nowcasting applications, but it has not yet been explored in Brazil. In the face of the peculiar Brazilian climatology, these challenges are even more pronounced. Thus, the synergy between Geodesy and Meteorology represents a fruitful line of research in the past and it remains promising for the future.

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Author Contributions

The author TAFG was responsible for the idealization and conception of the manuscript. The authors TAFG, LFS and FGN carried out the conceptualization, wrote the first draft of the manuscript and revision. DBMA and JFGM helped to conceptualize, review and supervise the development of the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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