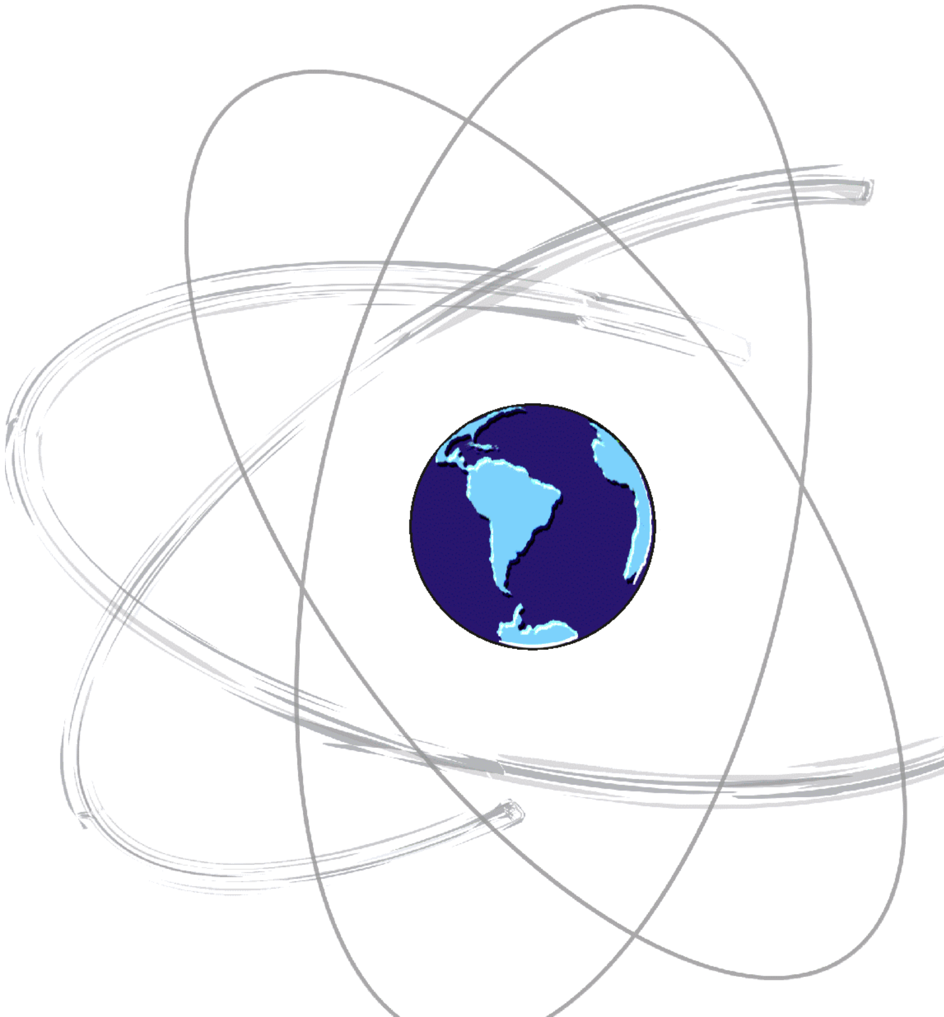
RESSALVA

Atendendo solicitação do(a) autor(a), o texto completo desta dissertação será disponibilizado somente a partir de 16/06/2025.

UNESP – UNIVERSIDADE ESTADUAL PAULISTA
CAMPUS DE PRESIDENTE PRUDENTE
FACULDADE DE CIÊNCIAS E TECNOLOGIA
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS CARTOGRÁFICAS

ANA LUCIA CHRISTOVAM DE SOUZA

GNSS SINGLE FREQUENCY IONOSPHERIC MODEL FOR EQUATORIAL PLASMA BUBBLES DETECTION IN THE BRAZILIAN REGION



PRESIDENTE PRUDENTE
2023

ANA LUCIA CHRISTOVAM DE SOUZA

GNSS SINGLE FREQUENCY IONOSPHERIC MODEL FOR EQUATORIAL PLASMA BUBBLES DETECTION IN THE BRAZILIAN REGION

Thesis presented to "Programa de Pós-Graduação em Ciências Cartográficas" at São Paulo State University – UNESP School of Technology and Sciences.

Supervisor: Dr. Paulo de Oliveira Camargo
Co-Supervisor: Dr. Fabricio dos Santos Prol
Co-Supervisor: Dr. Manuel Hernández-Pajares

PRESIDENTE PRUDENTE

2023

S729g

Souza, Ana Lucia Christovam de
GNSS Single Frequency model for equatorial plasma bubbles detection in the Brazilian region / Ana Lucia Christovam de Souza. -- Presidente Prudente, 2023
94 f.

Tese (doutorado) - Universidade Estadual Paulista (Unesp), Faculdade de Ciências e Tecnologia, Presidente Prudente
Orientador: Paulo de Oliveira Camargo
Coorientador: Fabricio dos Santos Prol

1. GNSS. 2. Ionospheric Modeling. 3. Ionospheric plasma bubbles. 4. TEC single frequency. I. Título.

Sistema de geração automática de fichas catalográficas da Unesp. Biblioteca da Faculdade de Ciências e Tecnologia, Presidente Prudente. Dados fornecidos pelo autor(a).

UNIVERSIDADE ESTADUAL PAULISTA

Câmpus de Presidente Prudente

CERTIFICADO DE APROVAÇÃO

TÍTULO DA TESE: GNSS SINGLE FREQUENCY IONOSPHERIC MODEL FOR EQUATORIAL PLASMA BUBBLES DETECTION IN THE BRAZILIAN REGION

AUTORA: ANA LUCIA CHRISTOVAM DE SOUZA
ORIENTADOR: PAULO DE OLIVEIRA CAMARGO
COORIENTADOR: MANUEL HERNANDEZ PAJARES
COORIENTADOR: FABRICIO DOS SANTOS PROL

Aprovada como parte das exigências para obtenção do Título de Doutora em Ciências Cartográficas, área: Aquisição, Análise e Representação de Informações Espaciais pela Comissão Examinadora:

Prof. Dr. PAULO DE OLIVEIRA CAMARGO (Participaçao Presencial)
Departamento de Cartografia / Faculdade de Ciencias e Tecnologia de Presidente Prudente

Prof. Dr. JOÃO FRANCISCO GALERA MONICO (Participaçao Presencial)
Departamento de Cartografia / Faculdade de Ciencias e Tecnologia de Presidente Prudente

Dr. ALISON DE OLIVEIRA MORAES (Participaçao Virtual)
Centro Técnico Aeroespacial / Instituto de Aeronáutica e Espaço

Prof. Dr. MARCIO TADEU DE ASSIS HONORATO MUELLA (Participaçao Virtual)
Instituto de Pesquisa e Desenvolvimento / Universidade do Vale do Paraíba

Dr. JONAS RODRIGUES DE SOUZA (Participaçao Virtual)
Coordenação Geral de Ciências Espaciais e Atmosféricas / Instituto Nacional de Pesquisas Espaciais

Presidente Prudente, 16 de junho de 2023

ACKNOWLEDGMENTS

I would like to thank my supervisor, Prof. Paulo O. Camargo, who was the main motivator of this research. I would also like to thank Fabricio S. Prol from Finnish Geospatial Research Institute (FGI) for their support and contributions as co-supervisors. I am also grateful to Prof. Manuel Hernández-Pajares from Universitat Politècnica de Catalunya (UPC) for kindly sharing his knowledge about ionospheric modeling and geodetic positioning during the internship supervision.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. Ph.D. scholarship from 03/2019 to 02/2023 (Grant: 88882.433958/2019-01) and from 03/2023 to 05/2023 (Grant: 88887.817768/2023-00). Internship abroad at Universitat Politècnica de Catalunya Capes-PrInt (PrInt - *Programa Institucional De Internacionalização*) from 11/2022 to 01/2023 (Grant: 88887.569761/2020-00).

This works was also supported by:

GNSS in Support of Air Navigation (INCT GNSS-NavAer), funded by CNPq (Grant: 465648/2014-2), FAPESP (Grant: 2017/50115-0) and CAPES (Grant: 88887.137186/2017-00).

Postgraduate program in Cartographic Sciences, São Paulo State University (UNESP) – School of Technology and Sciences.

Department of Mathematics at the Universitat Politècnica de Catalunya, Barcelona, Spain.

ABSTRACT

The ionospheric layer can be considered difficult to model due to the high variation in electron density presents in the upper atmosphere. In regions of low latitude, such as Brazilian region, the ionosphere presents a peculiar dynamic, considerably affecting communication systems and global navigation satellite systems (GNSS). Total Electron Content (TEC) is the main parameter capable of describing the ionospheric layer. Therefore, ionospheric models based on TEC values become critical for monitoring space weather and the ionospheric layer. However, in low latitude regions, the performance of these models degrades due to the high sensitivity of the global positioning system (GPS) L2 frequency to ionospheric scintillation. In an effort to overcome this problem, this thesis investigates the potential of utilizing only GPS L1 frequency for imaging the ionospheric bubbles during ionospheric scintillation. Two methods for estimating TEC using single frequency are presented. The first one is based on the calibration method, i.e., information retrieved by external ionospheric models are used to correct the TEC using single frequency measurements. The second one is based on independent regional ionospheric model to calibrate GPS using single frequency measurements. Both methods successfully detected plasma bubbles by mapping TEC using single frequency. In addition, single frequency model presented similar accuracy to the dual frequency models and, at the same time, provided less observations affected by ionospheric scintillations. These results demonstrate the feasibility of using single frequency GNSS data to develop ionospheric models and to improve GNSS positioning in low latitudes.

Keywords: Ionosphere; spherical harmonics; TEC; single frequency; plasma bubbles; airglow images.

RESUMO

A camada ionosférica pode ser considerada de difícil modelagem devido à alta variação na densidade de elétrons presente na atmosfera superior. Em regiões de baixa latitude, como a região brasileira, a ionosfera apresenta uma dinâmica peculiar, afetando consideravelmente os sistemas de comunicação e os sistemas GNSS (Global Navigation Satellite System). O Conteúdo Total de Elétrons (TEC) é o principal parâmetro capaz de descrever a camada ionosférica. Portanto, os modelos ionosféricos baseados em valores de TEC tornam-se essenciais para o monitoramento do clima espacial e da camada ionosférica. No entanto, em regiões de baixa latitude, o desempenho desses modelos é prejudicado devido à alta sensibilidade da frequência L2 do GPS (Global Positioning System) à cintilação ionosférica. Em um esforço para superar esse problema, esta tese investiga o potencial de utilizar apenas a frequência L1 do GPS para obter imagens das bolhas ionosféricas durante a cintilação ionosférica. São apresentados dois métodos para estimar o TEC utilizando simples frequência. O primeiro método é baseado na calibração do TEC, ou seja, as informações obtidas por modelos ionosféricos externos são usadas para corrigir o TEC usando medições de simples frequência. O segundo método, baseia-se em um modelo ionosférico regional independente para calibrar o GPS usando medições de simples frequência. Ambos os métodos detectaram com sucesso bolhas de plasma mapeando o TEC usando frequência única. Além disso, o modelo de simples frequência apresentou precisão semelhante à dos modelos de dupla frequência e, ao mesmo tempo, forneceu menos observações afetadas pelas cintilações ionosféricas. Esses resultados demonstram a viabilidade do uso de dados GNSS de simples frequência para desenvolver modelos ionosféricos e melhorar o posicionamento GNSS em baixas latitudes.

CONTENTS

CHAPTER 1
INTRODUCTION

CHAPTER 2
ASSESSMENT OF GPS POSITIONING PERFORMANCE USING DIFFERENT SIGNALS IN THE CONTEXT OF IONOSPHERIC SCINTILLATION

CHAPTER 3
SINGLE FREQUENCY TEC CALIBRATION TO DETECT EQUATORIAL PLASMA BUBBLES

CHAPTER 4
PPP AT LOW LATITUDES WITH IONOSPHERIC MODEL EXCLUSIVELY BASED ON SINGLE FREQUENCY GNSS MEASUREMENTS

CHAPTER 5
PPP AT LOW LATITUDES WITH IONOSPHERIC MODEL EXCLUSIVELY BASED ON SINGLE FREQUENCY GNSS MEASUREMENTS

CHAPTER 6
FINAL REMARKS

CHAPTER 1
INTRODUCTION

1 OVERVIEW AND MOTIVATION

The ionosphere is a layer of the Earth's atmosphere, located at approximately 50 to 1000 km altitude, characterized by a high concentration of ionized particles. The propagation of radio signals through the ionosphere with irregularities in the electron density distribution may produce phase and amplitude scintillations in radio frequency (RF) signals (Aarons, 1982; Yeh and Liu, 1982). These scintillations degrade the accuracy of navigation and positioning applications based on Global Navigation Satellite Systems (GNSS). Several authors point out (Skone et al., 2001; Sreeja et al. 2012; Vani et al. 2019; Guo et al 2019; 2020) that rapid phase variations lead to a higher probability of cycle slip. Depending on its severity, scintillation is capable of leading to the loss of satellite signal tracking. These extreme phenomena are more usual near the equatorial and low-latitude regions. In such regions, several electrodynamics processes may lead to large-scale plasma depletions in the F region of the ionosphere, called as Equatorial Plasma Bubbles (EPBs). The EPBs are large-scale ionospheric structures characterized by depleted electron density in comparison to the surrounding ionosphere, developed after the local sunset at the magnetic equator (Li et al., 2021; Bhattacharyya, 2022). The pre-reversal enhancement in the evening zonal electric field causes an increase in the eastward electric field that causes initial plasma depletions to rise to higher altitudes. This uplift contributes to an increase in the vertical growth of the magnetic aligned plasma-depleted structures formed by the Rayleigh–Taylor instability mechanism. (de Paula et al. 2007; Kelley, 2009; Hasse et al. 2010; Abdu 2016; Muella et al. 2017; Moraes et al., 2018b; Barros et al. 2018; Bhattacharyya, 2022). During the development of the EPBs, they tend to extend to latitudes of larger background plasma density in the Equatorial Ionization Anomaly (EIA), located at around 15°- 20° north and south of the magnetic equator (Muella et al., 2017; Li et al., 2021).

Several researches describing the dynamics of the ionosphere and the ionospheric scintillation-producing irregularities are supported by GNSS data(for example see Mannucci et al. 1993; de Paula et al., 2007; Haase et al. 2010; Spogli et al., 2013; Guo et al., 2019; Macho et al., 2022). The GNSS simultaneous information in multiple frequencies can be used as a tool for ionospheric sounding, due to the dispersive medium of the ionosphere. From GNSS data, it is possible to perform ionospheric modeling using the total electron content (TEC) parameter capable to describe the properties of the ionosphere. TEC is the integral of electron density along the signal path counted passing through the ionosphere. The TEC is calculated in a column along a signal path between a satellite based GNSS transmitter and a receiver, typically ground-based (Seeber, 2003; Leick, 2004). Therefore, if the signal path from transmitter to receiver is known, the differential delay by two signals can be used to derive the TEC along the signal path. As the ionospheric delay is in very good approximation (better than 99.9%) proportional to TEC (see for instance Hernández-Pajares et al. 2014), combinations of signal frequencies and GNSS observables can be performed to obtain a relationship with ionospheric delay. Considering dual frequency measurements, TEC can be obtained using a linear combination, since the non-frequency dependent terms are cancelled out. The eliminated terms in the geometric-free combination are the geometric distance between the receiver and the satellite, the satellite and receiver clocks, and the tropospheric delay. If only single frequency is available, TEC can be eliminated or estimated using combinations between GNSS observables, for instance, the GRoup and Phase Ionosphere Correction (GRAPHIC), proposed by Yunck (1992), and the Code-Minus-Carrier (CMC) proposed by Xia (1992). Both combination exploits the opposite sign of the ionospheric error in the pseudorange and carrier-phase. The GRAPHIC combination is computed by the arithmetic mean of the code and carrier phases, removing the TEC term; while the CMC is given by differencing the pseudorange and carrier-phase measurements, all geometry-dependent components are cancelled. However, the main problem about these combinations are the multipath and noise of the pseudorange. It is worthwhile to highlight that the dual frequency ionosphere-free combinations for pseudorange and carrier-phase are only constructed from observations of the same type. In contrast to the GRAPHIC and CMC combinations, the dual frequency combinations are constructed from different observables, they maintain their basic characteristic properties and can be processed similarly to the original uncombined observations except for the increased noise (Teunissen; Montenbruck, 2017; Hernández-Pajares et al, 2018).

Techniques and algorithms are being continuously developed and evaluated to improve the accuracy and resolution of TEC estimates. Accurately determining TEC values continues to be a challenging, particularly in low latitude regions and especially during ionospheric scintillation events. Prol et al. (2018a), for instance, evaluated the performance of TEC calibration procedures by analyzing the improvement in single frequency PPP (Precise Point Positioning) considering several latitudes. The authors have found a worse PPP performance in low latitudes, mainly due to the ionospheric variability associated with the EIA and ionospheric scintillation. According to Moraes et al. (2018b) the distribution of plasma bubble irregularities in relation to the geomagnetic field configuration can amplify the effects of scintillation. In low latitude regions, such as the Brazilian region, the geomagnetic field configuration, characterized by a large magnetic declination angle, provides a particular and favorable condition for the occurrence of such effects. The authors showed a correlation between the intensified scintillation occurrence and Global Positioning System (GPS) signals that propagated through plasma bubbles aligned to the magnetic field's direction. In addition, the authors showed large PPP errors due to these events in such regions. Several authors (Delay et al. 2015, Spogli et al. 2016; Xiong et al.2016; Moraes et al. 2017; Souza et al. 2022) showed a close relationship between the occurrences of EPBs and severe ionospheric scintillations at different radio bands at low latitudes. In such regions, the lack of TEC data especially obtained using dual frequency measurements, can be associated with disruptions in the received signal caused by ionospheric plasma bubbles under ionospheric scintillation, which are zones with high electron density variability (Li et al. 2021). During ionospheric scintillation, the GPS L2 signal presents greater ionospheric interference when compared to the GPS L1 signal. Therefore, during the presence of ionospheric scintillation, it is expected that a single frequency can provide better alternative for ionospheric plasma bubbles imaging. Since the single GPS L1 frequency is supposed to minimize the loss of synchronism, ionospheric models based on GPS L1 frequency should improve the imaging of ionospheric bubbles.

To enhance the imaging of ionospheric bubbles during ionospheric scintillation in low latitude regions, this work aims to develop and analyze a regional single frequency ionospheric model for TEC estimation.

1.1 Objectives

The main goal of this research is to develop a methodology capable to detect equatorial plasma bubbles using only GPS single frequency measurements. In this regard, the Ph.D. research has the following specific objectives:

(1) investigate which GPS signal frequency is the best one to detect equatorial plasma bubble;

(2) develop an ionospheric regional model exclusively based on single-frequency GPS measurements;

(3) understand if plasma bubbles can be detected using single frequency GPS measurements;

(4) verify if the single frequency precise point positioning (PPP) based on single frequency ionospheric regional model can provide a comparable level to those ionospheric models obtained by dual frequency GPS measurements.

1.2 Content and Contributions

The thesis can be summarized in two purposes: First, we evaluate and understand which GPS signal has the best capability of ionospheric bubble imaging and whether it is possible to detect the ionospheric plasma bubbles using only a single frequency GNSS measurements. Second, we present an ionospheric model for the Brazilian region using a single frequency and evaluate its quality.

Chapter 2 shows the study developed by Souza et al. (2022). The authors presented an assessment of GPS positioning performance using different signals in the context of ionospheric scintillation. Chapters 3 and 4 are devoted to investigating the feasibility of detecting ionospheric plasma bubbles using GNSS single frequency measurements, i.e., it answers if it is possible to detect ionospheric plasma bubbles using single frequency TEC maps. In Chapter 3, we present a technique for TEC single frequency calibration, and we use a previously estimated TEC to generate ionospheric maps. As a result, ionospheric plasma bubbles are successfully detected using single frequency data. However, the calibration method uses external ionospheric models based on dual frequency data. Therefore, in order to use only single frequency data in all steps, Section 4, also summarized in Christovam et al. (2023a), shows a methodology based on a regional model to calibrate GNSS single frequency measurements and derive ionospheric maps with no external information. In Chapter 5, Christovam et al. (2023b) present an evaluation of a new regional model by means of single frequency precise point positioning (PPP), comparing the positioning results against the correction using dual-frequency GPS signals, as well as compared to the corrections provided by global ionospheric models produced by the international GNSS service (IGS).

CHAPTER 6
FINAL REMARKS

In this work, a methodology capable to detect equatorial plasma bubbles using only GPS single frequency measurements was proposed. For this purpose, it was investigated which GPS signal frequency is best suited to detect equatorial plasma bubbles. Two TEC single frequency estimation procedures were presented. Finally, the quality of TEC obtained by the proposed method was evaluated based on PPP.

Chapter 2 presented the results of a quantitative analysis of the scintillation amplitude of GPS signals at L1, L2 and L5 frequencies, aiming to evaluate the impact of the ionospheric scintillations on the GPS frequencies. During ionospheric scintillations, a smaller magnitude was observed for the GPS L1 frequency. Therefore, it can be concluded that L1 frequency is the most suitable signal for ionospheric plasma bubble imaging, since it is the least affected by the ionosphere.

Chapters 3 and 4 answer if it is possible to detect plasma bubbles using single frequency measurements of GNSS. In Chapter 3, TEC single frequency calibration procedure was proposed. TEC single frequency was calibrated using TEC values retrieved by global ionospheric models. As expected, TEC values obtained with single frequency are noisier than the dual frequency values, due to the combination between the observables CMC. However, it is important to highlight that code noise and multipath issues from the combination were not able to impair the plasma bubble imaging. Therefore, it can be confirmed that it is possible to detect ionospheric plasma bubbles by single frequency TEC data. The calibration procedure is an alternative to estimate TEC with less computational effort. This approach can provide new opportunities, particularly for ionospheric sounding. In addition, an increasing interest in the precise positioning with low-cost receivers is recognized. The number of low-cost GNSS receivers has been continuously increasing, especially with the growing number of cell phones that make single frequency GPS receivers with performance available for positioning (Gikas and Perakis 2016, Hernandez-Pajares et al. 2018). In future, it would be relevant to evaluate the capabilities of the proposed calibration method with low-cost cell phone data.

Although the calibration method requires less computational effort, it also requires external information, which was estimated using dual frequencies. Therefore, in order to estimate the TEC using exclusively single frequency data, a regional model to calibrate the single frequency GNSS measurements and derive TEC values was proposed in

Chapter 4. The regional model also confirmed the possibility to detect ionospheric plasma bubbles by single frequency TEC data in regions with high number of GNSS stations. The developed method was capable of diagnosing the spatial and temporal progress of ionospheric plasma bubbles in VTEC maps and keograms. The results were confirmed by comparing the estimated TEC depletions with accurate airglow images. In addition, it can be seen a good agreement between the STEC data obtained with dual and single frequency.

Finally, Chapter 5 presents an evaluation of the performance of the regional model based on single frequency measurements. The assessment is made by means of single frequency PPP, comparing the positioning results against the correction using dual-frequency GPS signals, as well as compared to the corrections provided by GIMs produced by IGS. As a result, the positioning performance using single frequency model presented similar accuracy to the dual frequency models and, at the same time, provided less observations affected by ionospheric scintillations. These results demonstrate the feasibility of using single frequency GNSS data to develop ionospheric models and to improve the positioning over low latitudes. In the future, the following investigations are recommended: (1) to perform an assessment of single frequency ionospheric models using other evaluation techniques, like using ionosonde data (Jerez et al. 2020) and dSTEC values (Hernadez-Pajares et al, 2017; Zhao et al. 2021) and (2) to perform the estimation of TEC single frequency uncertainties since they can provide an additional improvement in the single frequency PPP (Jerez et al. 2022), in particular for low latitude regions.

With the GNSS modernization program, the new frequencies present more complex signal structure with specific functionalities. Therefore, it would be interesting investigate the performance of the ionospheric model proposed for different channels/codes at L1 modernized signal (e.g., L1C(D), L1C(P), L1C(D+P), L1(Y), L1(M)).

The regional ionospheric model proposed was based on VTEC estimation, where the conversion between VTEC and STEC was performed through a mapping function related to satellite elevation and thin layer ionospheric height. In this conversion, the ionosphere is assumed to be an infinitely thin fixed-height layer, i.e., the ionospheric variation is not considered. As a future recommendation, it would be interesting to explore methods that consider the spatial variability of the ionosphere, both horizontally and vertically. In addition, it would be interesting to carry out future work to verify the possibility of adapting the developed method for real-time applications. Real-time approaches are highly relevant for GNSS positioning applications and space climate monitoring.

REFERENCES

AA E.; ZOU S.; EASTES R.; KARAN D. K.; ZHANG S. R.; ERICKSON P. J.; COSTER A. J. Coordinated ground-based and space-based observations of equatorial plasma bubbles. Journal of *Geophysical Research: Space Physics*, v. 125, n. 1, p. e2019JA027569, 2020. doi.org/10.1029/2019ja027569.

AARONS, J. Global morphology of ionospheric scintillations. *Proceedings of the IEEE*, v. 70, n. 4, p. 360-378, 1982. doi.org/10.1109/PROC.1982.12314

ABDU, M. A.; BATISTA, I. S.; TAKAHASHI, H.; MACDOUGALL, J.; SOBRAL, J. H.; MEDEIROS, A. F.; TRIVEDI, N. B. Magnetospheric disturbance induced equatorial plasma bubble development and dynamics: A case study in Brazilian sector. *Journal of Geophysical Research: Space Physics*, v. 108, n. A12, 2003. doi.org/10.1029/2002JA009721

ABDU, M. A.; ALAM KHERANI, E.; BATISTA, I. S.; DE PAULA, E. R.; FRITTS, D. C.; SOBRAL, J. H. A. Gravity wave initiation of equatorial spread F/plasma bubble irregularities based on observational data from the SpreadFEx campaign. In: *Annales Geophysicae*. Göttingen, Germany: Copernicus Publications, 2009. p. 2607-2622. doi.org/10.5194/angeo-27-2607-2009

ABDU, M. A.; BATISTA, I. S.; REINISCH, B. W.; MACDOUGALL, J. W.; KHERANI, E. A.; SOBRAL, J. H. A. Equatorial range spread F echoes from coherent backscatter, and irregularity growth processes, from conjugate point digital ionograms. *Radio Science*, v. 47, n. 06, p. 1-8, 2012 doi.org/10.1029/2012RS005002

ABDU, M. A. Electrodynamics of ionospheric weather over low latitudes. *Geoscience Letters*, v. 3, p. 1-13, 2016. doi.org/10.1186/s4056 2-016-0043-6

ANDRADE, L.S.; ALVES, D. B. M. Novas observáveis GPS e a melhoria na acurácia do posicionamento. *Revista Brasileira de Cartografia*, 68 (5), pp.991– 1004, 2016

AGYEI-YEBOAH E.; PAULINO, I.; MEDEIROS, A. F.; BURITI, R. A.; PAULINO, A. R.; LOMOTEY, S.O.; TAKAHASHI, H.; WRASSE, C. M. Seasonal variation of plasma bubbles during solar cycle 23–24 over the Brazilian equatorial region. *Advances in Space Research*, v. 64, n. 7, p. 1365-1374, 2019. doi.org/10.1016/j.asr.2019.06.041

ARAGON-ANGEL A.; ROVIRA-GARCIA, A.; ARCEDIANO-GARRIDO, E.; IBÁÑEZ-SEGURA, D. Galileo Ionospheric correction algorithm integration into the open-source GNSS Laboratory Tool Suite (gLAB). *Remote Sensing*, v. 13, n. 2, p. 191, 2021. doi.org/10.3390/rs13020191

ARIKAN, F. E. Z. A.; NAYIR, H.; SEZEN, U. M. U. T.; ARIKAN, O. Estimation of single station inter frequency receiver bias using GPS-TEC. *Radio Science*, v. 43, n. 04, p. 1-13, 2008. doi:10.1029/2007rs003785

Barros D, Takahashi H, Wrasse CM, Figueiredo CAO. (2018). Characteristics of equatorial plasma bubbles observed by TEC map based on ground-based GNSS receivers over South America. In *Annales geophysicae* (Vol. 36, No. 1, pp. 91-100). Göttingen, Germany: Copernicus Publications. doi.org/10.5194/angeo-36-91-2018

BARROS, D.; TAKAHASHI, H.; WRASSE, C. M.; FIGUEIREDO, C. A. O. Characteristics of equatorial plasma bubbles observed by TEC map based on ground-based GNSS receivers over South America. In: *Annales geophysicae*. Göttingen, Germany: Copernicus Publications, v. 36, n. 01, pp. 91-100, 2018. doi.org/10.5194/angeo-36-91-2018

BHATTACHARYYA, A. Equatorial plasma bubbles: a review. *Atmosphere*, v. 13, n. 10, p. 1637, 2022. doi.org/10.3390/atmos13101637

BRUNINI, C.; MEZA, A.; AZPILICUETA, F.; VAN ZELE, M.A.; GENDE, M.; DÍAZ, A. A new ionosphere monitoring technology based on GPS. *Astrophysics and space science*, v. 290, p. 415-429, 2004.

BURKE, W. J.; HUANG, C. Y.; Gentile, L. C.; Bauer, L. Seasonal-longitudinal variability of equatorial plasma bubbles. In: *Annales geophysicae*. Göttingen, Germany: Copernicus Publications, 2004. p. 3089-3098. doi:10.5194/angeo-22-3089-2004

CAMARGO, P.O.; MONICO, J. F. G.; FERREIRA, L. D. D. Application of ionospheric corrections in the equatorial region for L1 GPS users. *Earth, Planets and Space*, v. 52, p. 1083-1089, 2000.

CHRISTOVAM A. L.; PROL, F. S.; HERNANDEZ-PAJARES, M.; CAMARGO, P. O. Plasma bubble imaging by single-frequency GNSS measurements. *GPS Solutions*, v. 27, n. 3, p. 124, 2023. doi:10.1007/s10291-023-01463-z

CHRISTOVAM, A. L.; PROL, F. S.; JEREZ, G. O.; HERNANDEZ-PAJARES, M.; CAMARGO, P. O. PPP at low latitudes with ionospheric model exclusively based on single frequency GNSS measurements, 2023 (*Submitted to Space Weather*)

CIRAOLO, L.; AZPILICUETA, F.; BRUNINI, C.; MEZA, A.; RADICELLA, S. M. Calibration errors on experimental slant total electron content (TEC) determined with GPS. *Journal of Geodesy*, v. 81, p. 111–120, 2007. DOI 10.1007/s00190-006-0093-1

CONKER, R. S.; EL-ARINI; M. B.; HEGARTY, C. J.; HSIAO, T. Modeling the effects of ionospheric scintillation on GPS/satellite-based augmentation system availability. *Radio Science*, v. 38, n. 1, p. 1-1-1-23, 2003. doi.org/10.1029/2000RS002604.

COOPER, C.; MITCHELL, C. N.; WRIGHT, C. J.; JACKSON, D. R.; Witvliet, B. A. Measurement of ionospheric total electron content using single-frequency geostationary satellite observations. *Radio Science*, v. 54, n. 1, p. 10-19, 2019. doi.org/10.1029/2018RS006575

DELAY, S. H.; CARRANO, C. S.; GROVES, K. M.; DOHERTY, P. H. Statistical Analysis of GPS L1, L2, and L5 Tracking Performance During Ionospheric Scintillation. In: *Proceedings of the ION 2015 Pacific PNT Meeting*. 2015. p. 1-9.

DE PAULA E. R.; KHERANI, E. A.; ABDU, M.A.; BATISTA, I. S.; SOBRAL, J. H. A.; KANTOR, I. J.; TAKAHASHI, H.; REZENDE, L. F. C.; MUELLA, M. T. A. H.; RODRIGUES, F. S.; KINTNER, P. M.; LEDVINA, B. M.; MITCHELL, C.; GROVES, K. M. Characteristics of the ionospheric irregularities over Brazilian longitudinal sector, *Indian Journal of Radio Space*, 36:268–277, 2007.

EASTES, R.W.; SOLOMON, S. C.; DANIELL, R. E.; ANDERSON, D.N.; BURNS, A. G.; ENGLAND, S. L.; MARTINIS, C. R.; MCCLINTOCK, W. E. Global-scale observations of the equatorial ionization anomaly. *Geophysical Research Letters*, v. 46, n. 16, p. 9318-9326, 2019. doi.org/10.1029/2019GL084199

ENGEL, U. A theoretical performance analysis of the modernized GPS signals. *In: 2008 IEEE/ION Position, Location and Navigation Symposium*. IEEE, 2008. p. 1067-1078. doi.org/10.1109/PLANS.2008.4570114

ESTEY, L. H.; MEERTENS, C. M. TEQC: the multi-purpose toolkit for GPS/GLONASS data. *GPS solutions*, v. 3, n. 1, p. 42-49, 1999. doi.org/10.1007/PL00012778

FAGUNDES P.R.; PILLAT, V. G.; BOLZAN, M. J. A.; BECKER-GUEDES, F.; ABALDE, J. R.; ARANHA S. L. Observations of F layer electron density profiles modulated by planetary wave type oscillations in the equatorial ionospheric anomaly region. Journal of Geophysical Research: *Space Physics*, v. 110, n. A12, 2005. doi:10.1029/2005JA011115

FELTENS, J. Chapman profile approach for 3-D global TEC representation, IGS presentation. In: *Proceedings of the 1998 IGS analysis centers workshop*, ESOC, Darmstadt, Germany, 9–11 Feb 1998, pp 285–297. 1998

GEORGIADIOU, Y. Modelling the ionosphere for an active control network of GPS stations. In: LGR series 7. Delft: Delft Geodetic Computing Centre, 1994.

GIKAS, V.; PERAKIS, H. Rigorous performance evaluation of smartphone GNSS/IMU sensors for ITS applications. *Sensors*, v. 16, n. 8, p. 1240, 2016. doi.org/10.3390/s1608 1240

GOSS, A.; SCHMIDT, M.; ERDOGAN, E.; GÖRRES, B.; SEITZ, F. High-resolution vertical total electron content maps based on multi-scale b-spline representations. *Annales Geophysicae*, *37*(4), p. 699–717, 2019. https://doi.org/10.5194/angeo-37-699-2019

GOSS, A.; HERNÁNDEZ-PAJARES, M.; SCHMIDT, M.; ROMA-DOLLASE, D.; ERDOGAN, E.; SEITZ, F. High-resolution ionosphere corrections for single-frequency positioning. *Remote Sensing*, v. 13, n. 1, p. 12, 2020. https://doi.org/10.3390/rs13010012

GUO, K.; AQUINO, M.; VADAKKE VEETTIL, S. Ionospheric scintillation intensity fading characteristics and GPS receiver tracking performance at low latitudes. *GPS Solutions*, v. 23, p. 1-12, 2019. https://doi.org/10.1007/s10291-019-0835-1

GUO, K.; AQUINO, M.; VADAKKE VEETTIL, S. Effects of GNSS receiver tuning on the PLL tracking jitter estimation in the presence of ionospheric scintillation. *Space Weather*, v. 18, n. 7, 2020. doi.org/10.1029/2019SW002362

HAASE, J.S.; DAUTERMANN, T.; TAYLOR, M. J.; CHAPAGAIN, N.; CALAIS, E.; PAUTET, D. Propagation of plasma bubbles observed in Brazil from GPS and airglow data. *Advances in Space Research*, v. 47, n. 10, p. 1758-1776, 2010. doi:10.1016/j.asr.2010.09.025

HEIN, W.Z.; GOTO, Y.; KASAHARA, Y. Estimation method of ionospheric TEC distribution using single frequency measurements of GPS signals. *International Journal of Advanced Computer Science and Applications*, v. 7, n. 12, 2016. doi:10.14569/ijacsa.2016.071201

HEGARTY, C.; EL-ARINI, M.B.; KIM, T.; ERICSON, S. Scintillation modeling for GPS-wide area augmentation system receivers. *Radio Science,* v. 36, n. 5, p. 1221-1231, 2001. doi.org/10.1029/1999RS002425.

HERNÁNDEZ-PAJARES, M.; JUAN, J. M.; SANZ, J. New approaches in global ionospheric determination using ground GPS data. *Journal of Atmospheric and Solar-Terrestrial Physics,* v. 61, n. 16, p. 1237-1247, 1999. doi.org/10.1016/S1364-6826(99)00054-1

HERNÁNDEZ-PAJARES, M.; JUAN, J.M.; SANZ, J.; ORUS, R.; GARCIA-RIGO, A.; FELTENS, J. The IGS VTEC maps: a reliable source of ionospheric information since 1998. *Journal of Geodesy*, v. 83, p. 263-275, 2009. doi.org 10.1007/s00190-008-0266-1

HERNÁNDEZ-PAJARES, M.; ARAGÓN-ÁNGEL À.; DEFRAIGNE P.; BERGEOT N., PRIETO-CERDEIRA R., GARCÉA-RIGO A. Distribution and mitigation of higher-order ionospheric effects on precise GNSS processing. *Journal of Geophysical Research: Solid Earth*, v. 119, n. 4, p. 3823-3837, 2014. doi:10.1002/2013JB010568.

HERNÁNDEZ-PAJARES, M.; ROMA-DOLLASE, D.; KRANKOWSKI, A.; GARCÍA-RIGO, A.; ORÚS-PÉREZ, R. Methodology and consistency of slant and vertical assessments for ionospheric electron content models. *Journal of Geodesy*, v. 91, n. 12, p. 1405-1414, 2017. doi.org/10.1007/s00190-017-1032-z

HERNÁNDEZ-PAJARES, M.; ROMA-DOLLASE, D.; GARCIA-FERNÀNDEZ, M.; ORUS-PEREZ, R.; GARCÍA-RIGO, A. Precise ionospheric electron content monitoring from single-frequency GPS receivers. *GPS solutions,* v. 22, n. 4, p. 102, 2018. doi.org/10.1007/s10291-018-0767-1

JEREZ G. O.; HERNÁNDEZ-PAJARES, M.; GOSS, A.; DA SILVA, C. M.; ALVES, D. B.; MONICO, J. F. G. Impact and synergies of GIM error estimates on the VTEC interpolation and single-frequency PPP at low latitude region. *GPS Solutions*, v. 26, n. 2, p. 40, 2022. doi.org/10.1007/s10291-022-01228-0

JEREZ, G. O.; HERNÁNDEZ-PAJARES, M.; PROL, F. S.; ALVES, D. B.; MONICO J. F. G. Assessment of global ionospheric maps performance by means of ionosonde data. *Remote sensing*, v. 12, n. 20, p. 3452, 2020. https://doi.org/10.3390/rs12203452

JEREZ, G. O.; HERNÁNDEZ-PAJARES, M.; GOSS, A.; PROL, F. S.; ALVES, D. B. M.; MONICO J. F. G.; SCHMIDT, M. Two-way assessment of ionospheric maps performance over the Brazilian region: Global versus regional products. *Space Weather*, v. 21, n. 2, 2023. doi.org/10.1029/2022SW003252

KARAN, D. K.; DANIELL, R. E.; ENGLAND, S. L.; MARTINIS, C. R.; EASTES, R. W.; BURNS, A. G.; MCCLINTOCK, W. E. First zonal drift velocity measurement of Equatorial Plasma Bubbles (EPBs) from a geostationary orbit using GOLD data. *Journal of Geophysical Research: Space Physics*, v. 125, n. 9, 2020. https://doi.org/10.1029/2020JA02817.

KELLEY, M. C. The Earth's Ionosphere*: Plasma Physics & Electrodynamics*. 2. ed. Ithaca: Academic Press, 2009. 556 p.

LEE C. C.; SU, S. Y.; REINISCH, B. W. Concurrent study of bottomside spread F and plasma bubble events in the equatorial ionosphere during solar maximum using digisonde and ROCSAT-1. *In Annales Geophysicae*. Göttingen, Germany: Copernicus Publications, p. 3473-3480, 2005. https://doi.org/10.5194/angeo-23-3473-2005

LEICK, A. *GPS Satellite Surveying*, 3rd ed., John Wiley & Sons, Inc, p. 464, ISBN 0-471-05930-7, 2004.

LI, Z.; YUAN, Y.; WANG, N.; HERNANDEZ-PAJARES, M.; HUO, X. SHPTS: towards a new method for generating precise global ionospheric TEC map based on spherical harmonic and generalized trigonometric series functions. *Journal of Geodesy*, v. 89, p. 331-345, 2015. doi:10.1007/s00190-014-0778-9

LI, G.; NING, B.; OTSUKA, Y.; ABDU, M. A.; ABADI, P.; LIU, Z.; WAN, W. Challenges to equatorial plasma bubble and ionospheric scintillation short-term forecasting and future aspects in east and southeast Asia. *Surveys in Geophysics*, v. 42, p. 201-238, 2021. doi.org/10.1007/s10712-020-09613-5

LIU, K.; LI, G.; NING, B.; HU, L.; LI, H. Statistical characteristics of low-latitude ionospheric scintillation over China, *Advances in Space Research*, v. 55, n. 5, p. 1356-1365, 2015. https://doi.org/10.1016/j.asr.2014.12.001

MACHO, E. P.; CORREIA, E.; SPOGLI, L.; MUELLA, M. T. D. A. H. Climatology of ionospheric amplitude scintillation on GNSS signals at south American sector during solar cycle 24. *Journal of Atmospheric and Solar-Terrestrial Physics*, v. 231, p. 105872, 2022. doi.org/10.1016/j.jastp.2022.105872

MAKELA, J. J.; LEDVINA, B. M.; KELLEY, M. C.; KINTNER, P. M. Analysis of the seasonal variations of equatorial plasma bubble occurrence observed from Haleakala, Hawaii. In: *Annales Geophysicae*. p. 3109-3121, 2004. https://doi.org/10.5194/angeo-22-3109-2004, 2004

MANNUCCI, A. J.; WILSON, B. D.; EDWARDS, C. D. A. New Method for Monitoring the Earth's Ionospheric Total Electron Content Using the GPS Global Network, *Proceedings of the 6th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1993)*, Salt Lake City, UT, pp. 1323-1332, 1993.

MANNUCCI, A. J.; WILSON, B. D.; YUAN, D. N.; HO, C. H.; LINDQWISTER, U. J.; RUNGE, T. F. A global mapping technique for GPS-derived ionospheric total electron content measurements. *Radio science*, v. 33, n. 3, p. 565-582, 1998. doi.org/10.1029/97RS02707

MONTENBRUCK, O; HAUSCHILD, A.; STEIGENBERGER, P. Differential code bias estimation using multi-GNSS observations and global ionosphere maps. *Navigation: Journal of the Institute of Navigation,* v. 61, n. 3, p. 191-201, 2014. doi.org/10.1002/navi.64

MORAES, A. O.; COSTA, E.; ABDU, M. A.; RODRIGUES, F. S.; DE PAULA, E. R.; OLIVEIRA, K., PERRELLA, W. J. The variability of low-latitude ionospheric amplitude and phase scintillation detected by a triple-frequency GPS receiver. *Radio Science*, v. 52, n. 4, p. 439-460, 2017. doi:10.1002/2016RS006165

MORAES, A. O.; VANI, B. C.; COSTA, E.; ABDU, M. A.; DE PAULA, E. R.; SOUSASANTOS, J.; SHIMABUKURO, M. H. GPS availability and positioning issues when the signal paths are aligned with ionospheric plasma bubbles. *GPS Solutions,* v. 22, p. 1-12, 2018. doi.org/10.1007/s10291-018-0760-8.

MUELLA, M. T. A. H.; DUARTE-SILVA, M. H.; MORAES, A. O.; DE PAULA, E. R.; DE REZENDE, L. F. C.; ALFONSI, L.; AFFONSO, B. J. Climatology and modeling of ionospheric scintillations and irregularity zonal drifts at the equatorial anomaly crest region. In: *Annales Geophysicae*, p. 1201-1218, 2017. doi.org/10.5194/angeo -35-1201-2017

NIE, W.; XU, T.; ROVIRA-GARCIA, A.; JUAN ZORNOZA, J. M.; SANZ SUBIRANA, J.; GONZÁLEZ-CASADO, G.; XU, G. Revisit the calibration errors on experimental slant total electron content (TEC) determined with GPS. *GPS solutions*, v. 22, n. 3, p. 85, 2018. doi.org/10.1007/s10291-018-0753-7

NISHIOKA, M.; SAITO, A.; TSUGAWA, T. Occurrence characteristics of plasma bubble derived from global ground-based GPS receiver networks. *Journal of Geophysical* Research: Space Physics, v. 113, n. A5, 2008. doi:10.1029/2007ja012605

OLIVEIRA, C. B. A. D.; ESPEJO, T. M. S.; MORAES A. O.; COSTA, E.; SOUSASANTOS, J.; LOURENCO, L. F. D.; ABDU, M. A. Analysis of plasma bubble signatures in total electron content maps of the low-latitude ionosphere: A simplified methodology. *Surveys in geophysics,* v. 41, n. 4, p. 897-931, 2020. https://doi:10.1007/s10712-020-09584-7.

PENG, S.; MORTON, Y.; PELGRUM, W.; VAN GRAAS, F. High latitude ionosphere scintillations at GPS L5 band. In: *Proceedings of the 24th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2011). p. 597-607, 2011*.

PROL, F. S.; CAMARGO, P. O. Estimativa da tendência diferencial do código nos receptores GNSS. *Boletim de Ciências Geodésicas*, v. 20, p. 735-749, 2014. doi.org/10.1590/S1982-21702014000400042

PROL F. S.; CAMARGO, P. O.; MONICO J. F. G.; MUELLA, M. T. D. A. H. Assessment of a TEC calibration procedure by single-frequency PPP. *GPS Solutions*, v. 22, p. 1-11, 2018a. doi.org/10.1007/s10291-018-0701-6

PROL, F.S.; HERNANDÉZ-PAJARES, M.; MUELLA, M. T. A. H.; CAMARGO, P. O. Tomographic imaging of ionospheric plasma bubbles based on GNSS and radio occultation measurements. *Remote Sensing*, v. 10, n. 10, p. 1529, 2018b. https://doi:10.3390/rs10101529.

ROMA-DOLLASE, D.; HERNÁNDEZ-PAJARES, M.; KRANKOWSKI, A; KOTULAK, K.; GHODDOUSI-FARD, R.; YUAN, Y.; GÓMEZ-CAMA, J. M. Consistency of seven different GNSS global ionospheric mapping techniques during one solar cycle. *Journal of Geodesy*, v. 92, p. 691-706, 2018. https://doi.org/10.1007/s00190-017-1088-9

ROVIRA-GARCIA, A.; IBÁÑEZ-SEGURA, D.; ORÚS-PEREZ, R.; JUAN, J. M.; SANZ, J.; GONZÁLEZ-CASADO, G. Assessing the quality of ionospheric models through GNSS positioning error: methodology and results. *GPS solutions*, v. 24, n. 1, p. 4, 2020. doi.org/10.1007/s10291-019-0918-z

SAHAI, Y.; FAGUNDES, P. R.; BITTENCOURT, J. A. F-region ionospheric plasma bubbles: solar cycle effects. *Journal of Atmospheric and Solar-Terrestrial Physics*, v. 62, n. 15, p. 1377-1383, 2000.

SCHAER, S.; BEUTLER, G.; ROTHACHER, M.; SPRINGER, T. A. Daily global ionosphere maps based on GPS carrier phase data routinely produced by the CODE Analysis Center, In: *Proceedings of the IGS AC Workshop, Silver Spring, MD, USA*. p. 181-192. 1996.

SCHAER, S.; GURTNER, W.; FELTENS, J. IONEX: The ionosphere map exchange format version 1. In: *Proceedings of the IGS AC workshop, Darmstadt, Germany*. 1998.

SCHAER, S. *Mapping and predicting the Earth's ionosphere using the Global Positioning System*. 205 p. Tese (Doutorado) — University of Berne, Berne, 1999.

SCHÜLER, T.; OLADIPO, O. A. Single-frequency GNSS retrieval of vertical total electron content (VTEC) with GPS L1 and Galileo E5 measurements. *Journal of Space Weather and Space Climate*, v. 3, p. A11, 2013. doi.org/10.1051/swsc/2013033

SEEBER, G. Satellite Geodesy: foundations, methods and applications. 2. ed. Berlin: Walter de Gruyter, 2003. 589 p.

SKONE, S.; KNUDSEN, K.; DE JONG, M. Limitations in GPS receiver tracking performance under ionospheric scintillation conditions. *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, v. 26, n. 6-8, p. 613-621, 2001. doi.org/10.1016/S1464-1895(01)00110-7

SOBRAL, J. H. A.; ABDU, M. A.; SAHAI, Y. Equatorial plasma bubble eastward velocity characteristics from scanning airglow photometer measurements over Cachoeira Paulista. *Journal of atmospheric and terrestrial physics*, v. 47, n. 8-10, p. 895-900, 1985.

SPOGLI, L.; ALFONSI, L.; ROMANO, V.; DE FRANCESCHI, G.; MONICO, J. F. G.; SHIMABUKURO, M. H.; AQUINO, M. Assessing the GNSS scintillation climate over Brazil under increasing solar activity. *Journal of Atmospheric and Solar-Terrestrial Physics*, v. 105, p. 199-206, 2013. doi.org/10.1016/j.jastp.2013.10.003

SPOGLI, L.; CESARONI, C.; DI MAURO, D.; PEZZOPANE, M.; ALFONSI, L.; MUSICÒ, E.; FLOURY, N. Formation of ionospheric irregularities over Southeast Asia during the 2015 St. Patrick's Day storm. *Journal of Geophysical Research: Space Physics*, v. 121, n. 12, p. 12,211-12,233, 2016. doi.org/10.1002/2016ja023222

SOUSASANTOS, J.; MORAES, A. O.; SOBRAL, J. H. A.; MUELLA, M. T. A. H.; DE PAULA, E. R.; PAOLINI, R. S. Climatology of the scintillation onset over southern Brazil. I In: *Annales Geophysicae. Göttingen*. p. 565-576, 2018. doi.org/10.5194/angeo-36-565-2018

SOUZA, A. L. C.; CAMARGO, P. O.; MUELLA, M. T. A. H.; TARDELLI-COELHO, F. Drift velocity estimation of ionospheric bubbles using GNSS observations. *Radio Science*, v. 56, n. 8, p. 1-18, 2021. doi.org/10.1029/2020RS007220

SOUZA, A. L. C.; JEREZ, G. O.; CAMARGO, P. D. O.; ALVES, D. B. M. Assessment of GPS positioning performance using different signals in the context of ionospheric scintillation: a month-long case study on São José dos Campos, Brazil. *Boletim de Ciências Geodésicas*, v. 28, 2022. doi.org/10.1590/s1982-2170202200040001

SREEJA, V.; AQUINO, M.; ELMAS, Z. G.; FORTE, B. Correlation analysis between ionospheric scintillation levels and receiver tracking performance. *Space Weather*, v. 10, n. 6, 2012. doi.org/10.1029/2012SW000769

TAKAHASHI, H.; WRASSE, C. M.; OTSUKA, Y.; IVO, A.; GOMES, V.; PAULINO, I.; SHIOKAWA, K. Plasma bubble monitoring by TEC map and 630 nm airglow image. *Journal of Atmospheric and Solar-Terrestrial Physics*, v. 130, p. 151-158, 2015. doi:10.1016/j.jastp.2015.06.003.

TAKAHASHI, H.; WRASSE, C. M.; DENARDINI, C. M.; PÁDUA, M. B.; DE PAULA, E. R.; COSTA, S. M. A.; SANT'ANNA, N. Ionospheric TEC weather map over South America. *Space Weather*, v. 14, n. 11, p. 937-949, 2016. doi.org/10.1002/2016SW001474

TAKASU, T.; YASUDA, A. Development of the low-cost RTK-GPS receiver with an open source program package RTKLIB. In: *International symposium on GPS/GNSS*, p. 1-6, 2009.

TERRA, P. M.; SOBRAL, J. H. A.; ABDU, M. A.; SOUZA, J. R.; TAKAHASHI, H. Plasma bubble zonal velocity variations with solar activity in the Brazilian region. In: *Annales Geophysicae*., p. 3123-3128, 2004. doi.org/10.5194/angeo-22-3123-2004, 2004.

TEUNISSEN P.; MONTENBRUCK O. *Handbook of Global Navigation Satellite Systems*, Springer, Switzerland, 2017. 1335 p. doi.org/10.1007/978-3-319-42928-1

TSUNODA, R. T. Time evolution and dynamics of equatorial backscatter plumes 1. Growth phase. *Journal of Geophysical Research: Space Physics*, v. 86, n. A1, p. 139-149, 1981.

TONGKASEM, N.; MYINT, L. M. M.; SUPNITHI, P. Estimation and Validation of Ionospheric Delay using Standalone Single-Frequency observations. *IEEE Access*, v. 10, p. 103485-103495, 2022. https://doi: 10.1109/ACCESS.2022.3208102

VADAKKE VEETTIL, S.; AQUINO, M.; MARQUES, H. A.; MORAES, A. O. Mitigation of ionospheric scintillation effects on GNSS precise point positioning (PPP) at low latitudes. *Journal of Geodesy,* v. 94, n. 2, p. 15, 2020. doi.org/10.1007/s00190-020-01345-z

VANI, B.C.; SHIMABUKURO, M. H.; MONICO, J. F. G. Visual exploration and analysis of ionospheric scintillation monitoring data: The ISMR Query Tool. *Computers & Geosciences*, v. 104, p. 125-134, 2017. https://doi.org/10.1016/j.cageo.2016.08.022.

VANI, B. C.; FORTE, B.; MONICO, J. F. G.; SKONE, S.; SHIMABUKURO, M. H.; MORAES, A. O.; MARQUES, H. A. A novel approach to improve GNSS Precise Point Positioning during strong ionospheric scintillation: Theory and demonstration. IEEE Transactions on *Vehicular Technology,* v. 68, n. 5, p. 4391-4403, 2019. doi: 10.1109/TVT.2019.2903988.

XIA, R. Determination of absolute ionospheric error using a single frequency GPS receiver, In: *Proceedings of the 5th international technical meeting of the satellite division of the institute of navigation* (ION GPS 1992). 1992. p. 483-490.

XIONG, C.; STOLLE, C.; LÜHR, H. The Swarm satellite loss of GPS signal and its relation to ionospheric plasma irregularities. *Space Weather*, v. 14, n. 8, p. 563-577, 2016. doi.org/10.1002/2016SW001439

ZHAO, J.; HERNÁNDEZ-PAJARES, M.; LI, Z.; WANG, N.; YUAN, H. Integrity investigation of global ionospheric TEC maps for high-precision positioning. *Journal of Geodesy*, v. 95, p. 1-15, 2021. doi.org/10.1007/s00190-021-01487-8

YEH, K. C.; LIU, C. H. Radio wave scintillations in the ionosphere. *Proceedings of the IEEE*, v. 70, n. 4, p. 324-360, 1982. doi.org/10.1109/PROC.1982.12313

YUNCK, T. P. Coping with the atmosphere and ionosphere in precise satellite and ground positioning. In: *Environmental Effects on Spacecraft Positioning and Trajectories*, ed. by A.V. Jones (AGU, Washington) pp. 1–16, 1992.

WALTER, T. Effect of ionospheric scintillations on GNSS—a white paper. SBAS Ionospheric Working Group, 2010.

WILD, U. Ionosphere and satellite systems: permanent GPS tracking data for modelling and monitoring. *Geod-Geophys*. Arb. Schweiz, v. 48, 1994.

ZOLESI, B.; CANDER, L. R. *Ionospheric Prediction and Forecasting*. Berlin, Heidelberg: Springer Berlin Heidelberg. 2014. https://doi.org/10.1007/978-3-642-38430-1.