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Atmosphere Monitoring by means of GNSS – Research Activities at TU Wien

    

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Abstract

GNSS signals experience delays as well as bending effects when passing the atmospheric layers. Both effects usually are summarized under the term atmospheric refraction. While the troposphere is a non-dispersive medium for microwaves the ionosphere is dispersive and therefore causes so-called code signal delays as well as phase advances. The multitude of nowadays available GNSS satellites and signals allows to choose among signal linear combinations preferable for atmosphere monitoring as well as an optimized observation geometry. GNSS signals are therefore excellent sensors to describe the state and variability of the ionospheric and tropospheric layers. Modelling the tropospheric and ionospheric refraction by means of GNSS signals constitutes an essential scientific core area at the research division Higher Geodesy of the Department of Geodesy and Geoinformation at TU-Vienna since 20 years. This article outlines some of the related research projects.

Keywords: GNSS Atmosphere Modelling, Tropospheric Refraction, Ionosphere Modelling

Kurzfassung

GNSS-Signale erfahren beim Durchlaufen der atmosphärischen Schichten abhängig vom variablen Refraktionsindex Verzögerungen bzw. Beschleunigungen im Vergleich zu einer Ausbreitung im Vakuum als auch eine veränderliche Krümmung des Strahlenweges. All diese Effekte werden üblicherweise unter dem Begriff atmosphärische Refraktion zusammengefasst. Die Vielzahl der heute verfügbaren GNSS-Satelliten und Satellitensignale erlaubt Optimierungen der Beobachtungsgeometrie und der verwendeten Signal-Linearkombination. GNSS-Signale stellen somit hervorragende Sensoren zur Beschreibung des Zustandes und der Variabilität der ionosphärischen und troposphärischen Schichten dar. Aus diesem Grund ist die Modellierung der troposphärischen und ionosphärischen Refraktion mit Hilfe von GNSS-Signalen seit fast 20 Jahren ein wesentlicher wissenschaftlicher Schwerpunkt am Forschungsbereich Höhere Geodäsie des Departments für Geodäsie und Geoinformation der TU-Wien. Der vorliegende Artikel gibt einen Überblick über eine Auswahl dieser Forschungsarbeiten.

Schlüsselwörter: GNSS-Atmosphärenmodellierung, Troposphärische Refraktion, Ionosphärenmodelle

1. Tropospheric Delay

Based on multi-frequency observations from a GNSS reference station network with adequately dense spatial resolution, both the hydrostatic as well as the wet component of the tropospheric delay can be estimated. In most cases the mostly stable hydrostatic part is covered by a model and therefore just the highly variable wet part is usually subject of the estimation process. The model parameters are so-called zenith wet delays as well as tropospheric gradients which describe the non-asymmetry of the delay with respect to the zenith. The relation between the zenith delays and the delays in line of view is determined by so-called mapping functions. The most precise mapping functions are derived from numerical weather models and can be used also for other space techniques than GNSS.

1.1 Tropospheric Mapping Functions

With the publications of the Vienna Mapping Functions (Böhm and Schuh, 2004, [1]) and the Global Mapping Functions (Böhm et al., 2006, [2]), the Department of Geodesy and Geoinformation at TU Wien has become a prime address in the modeling of troposphere delays for space geodetic techniques. The troposphere delay products had been determined on a daily basis and made available to the public via the server *ggosatm.hg.tuwien.ac.at* for more than 15 years. Thus, research institutes, organizations as well as private companies all over the world could use these products in their analyses and computations.

In April 2019, a new era has begun for the Vienna troposphere delay products. The GGOSATM server was replaced by the new, more comprehensive VMF data server, available at *vmf.geo.tuwien.ac.at*. This step was associated with a set of innovations:

- The latest model for the provision of discrete troposphere delays, the Vienna Mapping Functions 3 (VMF3; Landskron and Böhm, 2018a, [5]), is provided for all GNSS, VLBI and DORIS stations on Earth as well as on a global grid in two different horizontal resolutions. Just like VMF1, it is computed by means of ray-tracing through numerical weather models (NWMs) by the European Centre for Medium-Range Weather Forecasts (ECMWF), based on considerably more sophisticated algorithms though. VMF3 is available for three different NWM representations: the standard product (Operational) is published always one day in retrospect, while the forecast product comes one day in advance. In addition, there is also a VMF3 for re-analysis NWMs starting in 1980.
- A new model for horizontal troposphere gradients referred to as GRAD (Landskron and Böhm, 2018b, [6]), provided for the same NWMs and spatial representations as VMF3, models the variation in troposphere delay with azimuth. This is particularly important for observations at low elevation angles.
- The new empirical troposphere delay model Global Pressure and Temperature 3 (GPT3; Landskron and Böhm, 2018a, [5]) is a refined version of GPT2w and is fully consistent with VMF3. In addition to empirical mapping function coefficients and a number of meteorological parameters, it contains also empirical horizontal gradients on a global grid, available in 5°x5° as well as 1°×1° horizontal resolution.
- Ray-traced delays for every single VLBI observation since the advent of geodetic VLBI in 1980 are provided and regularly updated on the VMF server as well. Being the most rigorous and direct representation of troposphere delays, ray-traced delays may help to further improve output quantities of VLBI analyses such as Earth Orientation Parameters, in particular the irregularity of Earth rotation, dUT1.
- For GNSS and DORIS users, an individual ray-tracing tool constitutes a handy instrument to obtain accurate troposphere delays at arbitrary observation angles and times.
- Our ray-tracing software RADIATE (Hofmeister and Böhm, 2017, [4]), being the basis for the determination of all abovementioned troposphere models, is henceforth freely available via GitHub at *github.com/TUW-VieVS/RADIATE*. Thus, users can extend the range of applications by means of autonomously creating ray-traced delays for any NWM and any point on Earth.
- In the near future, RADIATE will also be capable of computing ray-traced delays for optical wavelengths and thus allowing for optical versions of VMF3, GPT3 and GRAD. This will help further improving the accuracy of tropospheric delay modeling in SLR.

Older troposphere delay models such as VMF1, GMF or GPT are provided on the VMF server further on. In addition to the troposphere delay models, there are also atmospheric pressure loading datasets on a global 1°×1° grid, updated on a daily basis as well. With this abundance of realizations and models, the Department of Geodesy and Geoinformation at TU Wien substantiates its position as a main provider of troposphere delay models for space geodetic techniques.

1.2 GNSS Tropospheric Parameters for NWP

In cooperation with the Austrian Central Institute for Meteorology and Geodynamics (ZAMG), the Department of Geodesy and Geoinformation investigates the benefits of using tropospheric GNSS products in Numercial Weather Predicition (NWP) models. Hourly Zenith Total Delays (ZTDs) and gradients are estimated from double-differenced network solutions using the Bernese software (Dach et. al, 2015, [3]). The station network used in the processing includes 71 stations, operated by different national GNSS reference stations providers or from the International GNSS service (IGS).

The tropospheric estimates are provided to ZAMG in near real-time (approximately 45 minutes delayed) via the department's web server on a regular basis. At ZAMG the data is used for assimilation into the Austrian version the NWP model AROME. After a series of case study model runs and subsequent forecast verifications, the assimilation of ZTD is now ready for operational mode. Several studies and tests have shown the benefits of ZTD assimilation into AROME, especially for precipitation forecasts.

A current cooperation between ZAMG, ETH Zurich and our research division within the ASAP14 project *GNSSnow* investigates the impact of Slant Total Delay (STD) assimilation in NWP. A major goal is to assess the benefits of using STDs instead of ZTDs. Furthermore a closer to real-time (less than the 45 minutes delay) processing and data delivery to ZAMG is strived for. This would improve data availability of short-time forecasts and nowcasting with AROME.

1.3 Troposphere Tomography

GNSS troposphere tomography is a technique that aims to obtain 3D information about humidity in the lower atmosphere based on GNSS signal delays. For tomography the three dimensional domain above the area of interest is usually subdivided in cuboids (voxels) with a horizontal resolution of a few tens of kilometers and a vertical side length of about 1 km. As the slant wet delay (SWD) observations gathered from a network of GNSS reference stations can be interpreted as the integral of the wet refractivity along the ray path, the inversion of the SWDs can lead to the estimation of the wet refractivity distribution.

Nevertheless, GNSS tomography suffers from several problems. What is most striking is that not all voxels of interest are covered by intersecting signal rays. This leads to ill-conditioned normal equation systems to recover the refractivity coefficients. Various algorithms have been established to solve these ill-posed equation systems. Appropriate inversion methods are described in the PhD-thesis of G.Möller [8] and will be further studied at our research division. Currently another PhD-thesis studies the combination of refractivity fields obtained from tomography and radio occultation profiles. These improved fields are assimilated and tested in numerical weather models. The authors assume that GNSS-tomography, potentially supported by Radio-Occultation profiles and radiosonde observations, will very soon become the standard technique to process GNSS observations for troposphere sounding.

2. Ionosphere Modelling

The ionosphere is usually indicated as the atmospheric layer comprising a large number of ions and free electrons. The lower bound of the ionosphere is located about 60 km above the Earth's surface and reaches the largest electron density at about 300 km – 350 km (F2 layer). The ionosphere extends up to 1000 km before it migrates there into the plasmasphere. The ionospheric delay essentially affects the GNSS-range measurement and therefore positioning with GNSS. While the ionospheric delay can be almost eliminated by the dual-frequency ionospheric-free linear combination, single frequency receivers have to apply ionospheric models.

2.1 Regional Ionospheric Model

The Research Division Higher Geodesy conducts also a number of studies in ionosphere modelling. Based on dual-frequency phase observation data of Austrian GNSS reference stations as well as some further international stations, a regional VTEC-model is calculated on an hourly basis for post-processing applications. The model can be employed by any user located within the Austrian territory providing corrections to low elevation angles down to 5 degrees. Comparisons with reference models certify our model an accuracy of about +/-1 TECU. Moreover another global model especially developed for real-time applications is made available. This model referred to as GIOMO (Magnet, 2019, [7]) is based on phase-smoothed pseudo-range observations and performs slightly worse than the previous one. Nevertheless, GIOMO parameters can be easily predicted and the model allows to correct about 70 % of GNSS-range measurements with sub-meter accuracy even down to low observation angles.

2.2 Galileo Reference Center

Since 2018 the Department of Geodesy and Geoinformation is partner in the GRC (Galileo Reference Centre) Member States consortium established by the GSA (European GNSS Agency). The aim of this activity is to study and analyze the performance of the broadcast NeQuick-Gal and Klobuchar ionospheric models in different latitudinal regions. Regular reports are issued to the Galileo Reference Center (GRC) since October 2018. Based on multi-GNSS observations from sites of the IGS, IGS-MGEX and EPOSA networks, maps of VTEC differences with respect to an internal and an external reference model (CODE) are established. For example, bi-hourly VTEC difference graphs of DOY 274, 2018 are visualized in Figure 2.

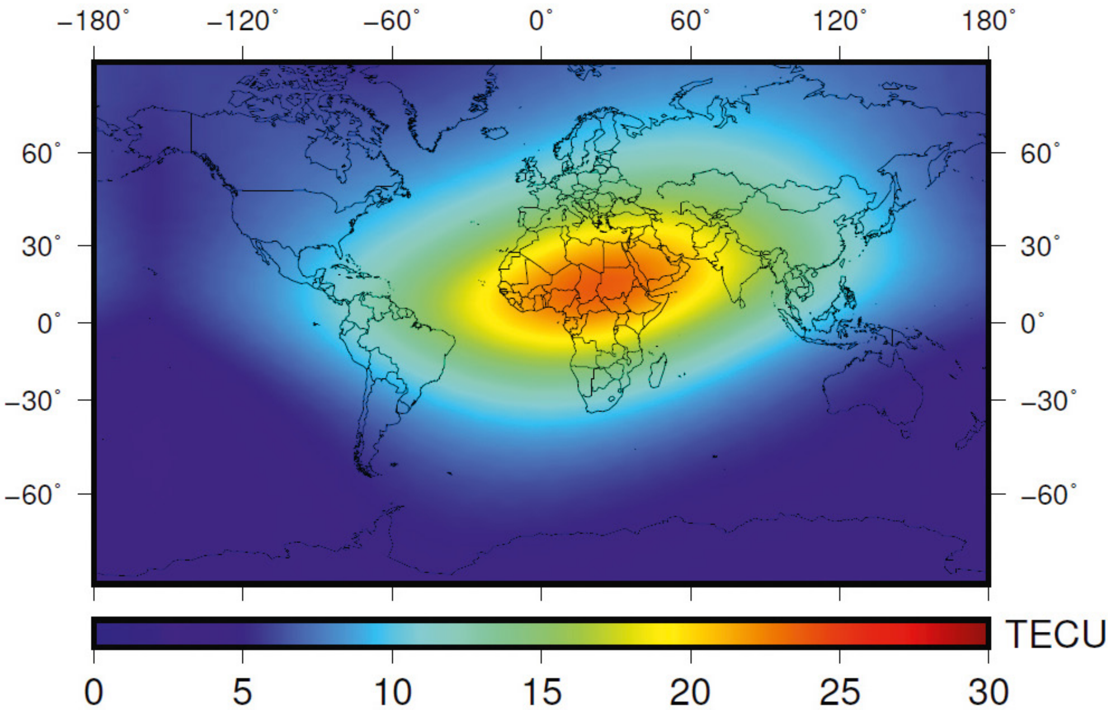

Fig. 1: *VTEC map, May 1st, 2018, 14 UTC modelled by GIOMO*

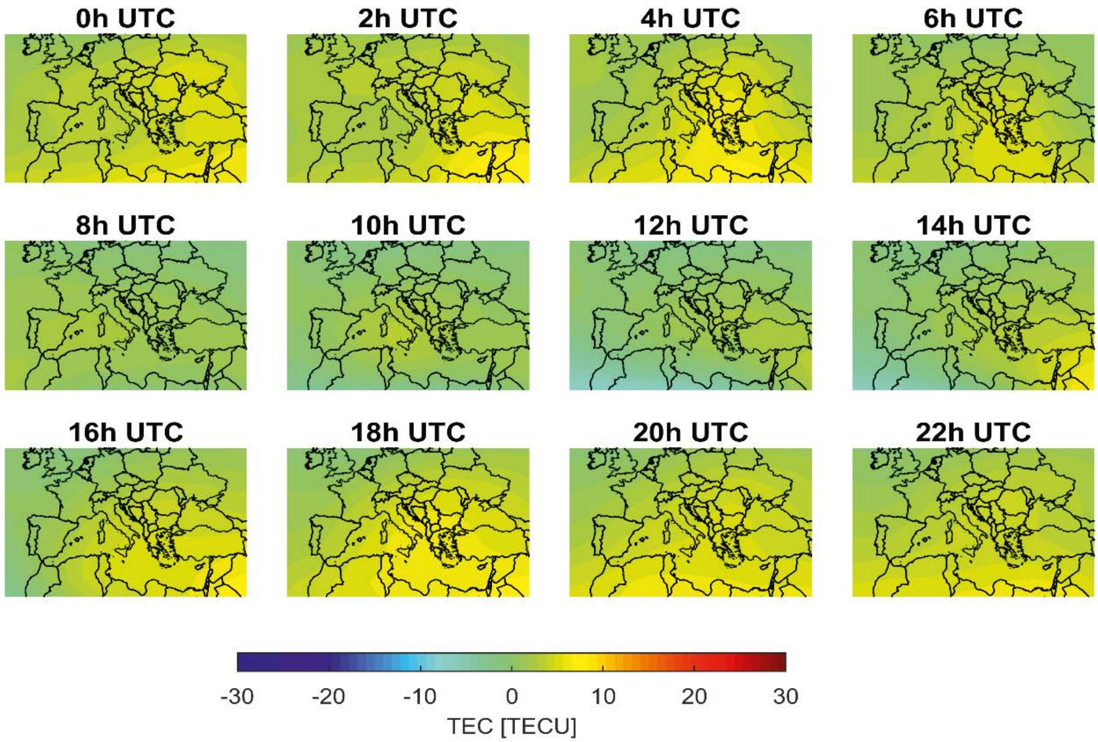

Fig. 2: *Daily VTEC difference maps DOY 274/2018 - CODE minus NeQuick-Gal*

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