Second Summer School

Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate – GNSS4SWEC

Students Abstracts

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Effects of meteorological data on tropospheric products from VLBI

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We assess the impact of meteorological data on geodetic very long baseline interferometry (VLBI). Pressure and temperature values are used to mitigate the effects of neutral atmospheric propagation delay and thermal deformation of antennas respectively. VLBI observations are analyzed from all non-intensive sessions spanning the period from 1994 to 2015 using VieVS@GFZ. The explicit purpose of this contribution is to produce the VLBI reference solution for the "EU COST Action" and to make all VLBI-derived tropospheric products available via the latest Tropo-SINEX format. For this, we test different approaches to obtain the meteorological data and to homogenize the in situ meteorological records. Since an erroneous degree-zero term in either the pressure or the temperature observations employed in the geodetic analysis could bias the heights and hence the scale of the resulting terrestrial reference frame, the estimation of these values is particularly explored. We study the effects of different meteorological data sets on the estimated geodetic parameters such as the station coordinates and the Earth orientation parameters. We also estimate long-term trends in the atmospheric water vapor content from VLBI and we compare them with those obtained from GNSS zenith wet delay time series.

Evaluation of the atmospheric water vapor in the Regional Climate Model ALARO coupled to the land surface scheme SURFEX using GNSS measurements

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Over the past few decades, the ALADIN model consortium has been developing a Limited Area Model (LAM) covering Europe, the Mediterranean region and some North African countries. This model has been further improved with physical parameterizations, hence ALARO. The first version ALARO-0 run at the Royal Meteorological Institute of Belgium (RMI) has already proven its ability for regional climate modelling. Furthermore, it is now contributing to the Coordinated Regional Climate Downscaling Experiment (CORDEX) project. The setup of ALARO-0 is originally with the Interaction Soil-Biosphere-Atmosphere Interaction (ISBA) land surface scheme. Meanwhile the more recent land surface scheme of Météo-France SURFace EXternalisée (SURFEX) has been implemented in this ALARO-0 RMI version. With respect to Numerical Weather Prediction (NWP) modelling, the introduction has shown neutral to positive effects on both temperature and precipitation compared to the previous used ISBA scheme. Consequently, the evaluation of SURFEX within ALARO-0 for climate simulations is pressing, and even more so because SURFEX will be implemented in the next version of ALARO for NWP and climate.

The European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis is dynamically downscaled to the RCM ALARO-0. The model runs at 20km horizontal resolution, and the analysis period covers 10 years from 1991 to 2000. Both temperature and precipitation were already validated against an observational gridded dataset for Europe. The original ALARO-0 setup with ISBA produced a cold and wet bias. However, the use of SURFEX within ALARO-0 improved the mean state of both temperature and precipitation, but this improvement is not uniform along the year and regions. Importantly, the observational dataset includes non-homogeneously distributed stations with areas of low station coverage, resulting in smoothed precipitation. Therefore, it is of interest to use GNSS water vapor measurements that are distributed along Europe for the further validation of ALARO-0 coupled to SURFEX. The integrated water vapor (IWV) from ALARO-0 will be compared with the IWV from the IGS

repro 1 dataset. This study focuses on the mean state of the IWV for the 10- year analysis period 1991-2000. Besides, we will compare the diurnal cycle in the model with the GNSS observations, to see whether the model is able to capture the peak and amplitude correctly.

Detecting the occurrence of ionospheric scintillation by VTEC gradient and the TEC rate index

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Ionospheric scintillation is defined as a relatively rapid fluctuation of the amplitude phase of the radio signal and is mostly caused by irregularities in the ionosphere electron density along the path that the signal propagated. To get scintillation, we need scintillation receivers, which operate on high-rate frequencies (50Hz or 10Hz) and are able to provide direct measurements of the scintillation indices. But when there is no receiver that provides high frequency measurements, an alternative way to detect ionospheric scintillation is to use Vertical Total Electron Content (VTEC) gradient or the rate of TEC (ROT) and the standard deviation of ROT (ROTI). ROTI can be calculated directly from the RINEX file with interval 30 seconds data over a time span of 5 minutes and can be used to predict the presence of ionospheric scintillation also. This study shows that ROTI appears to correlate to a certain extent with phase scintillation. Using the ionosphere software tool in this project, one can detect the presence of ionospheric scintillation and evaluate the strength of scintillation in the GNSS raw data.

Comparison of PWV solutions using Bernese and GAMIT/GLOBK softwares

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GNSS meteorology, the estimation of precipitable water vapor from Global Navigation Satellite Systems, has been a new research subject for meteorologists and geodesists. In order to monitor long term PWV derived from GNSS, the conversion parameters between ZWD and PWV (the weighted mean temperature Tm and the conversion factor Q) are crucial. Therefore, the conversion parameters applicable to Turkey have been developed using one year of radiosonde data from 8 radiosonde national stations (Istanbul, Ankara, Erzurum, Izmir, Diyarbakir, Samsun, Isparta, Adana). For the verification of the PWV models (Tm=48.55+0.80Ts±2.57K and Qhybrid models), ZTD and PWV are estimated from the GNSS stations established in Istanbul and Ankara using Bernese and GAMIT/GLOBK software (PWVGNSS), and compared with those from the collocated radiosonde stations (PWVRS). The results show that PWV estimates from GAMIT/GLOBK software and PWVRS (approximately 86% for Ankara, 90% for Istanbul) are in closer agreement than PWV estimates from Bernese software and PWVRS.

Long term evaluation of tropospheric horizontal gradients in Europe

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Several studies have shown that modeling tropospheric delay gradients in GNSS data processing improves positioning and that the estimated parameters represent real atmospheric features and not artifacts due to other mismodelling. However, even though horizontal tropospheric gradients are routinely estimated when processing global and regional GNSS networks they are still not yet used for operational meteorology.
The availability of 18 years of GNSS data belonging to the European Permanent Network (EPN, http://www.epncb.oma.be) and homogeneously reprocessed, in the framework of the ENP Repro2 campaign, provides an excellent opportunity for studying and analyzing, along with the ZTD, the gradient components on a long term basis.
In this study, we will focus on a subset of European GNSS stations and will use the EPN Repro2 solutions provided by the 5 EPN Analysis Centres. The investigation will include an intra and inter technique evaluation. As regard as the inter technique evaluation, ERA-INTERIM data, provided by the European Centre for Medium-Range Weather Forecasts, (ECMWF) will be considered.

Providing Near Real-Time Precipitable Water Vapour from continuous GPS over Ethiopia

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The Global Positioning System (GPS) offers the advantage of operating a real time continuous observations under all weather conditions, with high temporal resolution, and high accuracy. The precipitable water vapor (PWV) can be estimated from GPS derived parameters, Zenith Total Delay (ZTD) in Near-Real Time (NRT). First, the ZTD are estimated from the carrier phase range observations based on the accurate coordinates of the GPS stations and then the wet delay is computed by subtracting the a priori hydrostatic delay from ZTD. The objective of this proposal is for the development and demonstrations of NRT processing system of GPS PWV from continuous GPS (cGPS) network stations over Ethiopia using techniques and concepts of GPS meteorology. All the cGPS sites will also equipped with the state-of-the art meteorological sensors. In general, this thesis project will mainly benefits ground based GPS PWV measurements in their use by Numerical Weather Prediction (NWP) systems and now-casting for meteorological events, and the need to know the total atmospheric water budget to increase the capabilities of the Ethiopian National Meteorology Agency (NMA).

Analysis of GNSS-derived ZTD estimates during a heavy rainfall – a case study within the COST ES1206 benchmark campaign

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In this research, zenith total delays (ZTD) of the troposphere derived from GPS data are analyzed during heavy rainfall period. GPS observational data provided by COST ES1206 Benchmark campaign were used. The ZTD was estimated for permanent stations localized in the western Czech Republic (Poustka, Rakovnik) and also for adjacent stations in Germany (Bad Koetzting, Hof). Test period covered a passing of a strong weather front over these stations. The ZTD was estimated in different variants based on IGS final and ultra-rapid products using G-Nut/Tefnut software in PPP mode. Then the ZTD estimates were compared to reference values from the Benchmark campaign dataset and also to EUREF solution. The study showed that various processing strategies may result in differences from reference the data even up to 5 cm.

Effect of Mapping Functions on PWV Estimations for Turkey

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GNSS receivers are an attractive means for total zenith delay (ZTD) and precipitable water vapor (PWV) data for weather prediction since they are portable, economic and provide measurements that are not affected by weather conditions. They cannot provide a humidity profile as radiosondes can, however they have the advantage of producing automated continuous data as opposed to operational radiosondes usually providing two measurements in a day. Therefore, tropospheric delay modeling methods for estimating precipitable water vapor using GNSS signals are being developed frequently in the world. As with all tropospheric models, mapping functions also need atmospheric parameters such as Global Mapping Function (GMF) and Vienna Mapping Function (VMF1). Today the tropospheric model with the highest accuracy can be computed with these two models. Apart from GMF and VMF1, Niell Mapping Function is also being often used in academic studies. In this study, PWV values are obtained from radiosonde profiles and from continuously operating GNSS observations processed with BERNESE v5.0 using Niell Mapping Function and Vienna Mapping Function in order to see the effect of mapping functions on PWV estimations.

Radio occultation data retrieval from ROWUELS algorithm

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Since 2015, Wroclaw University of Environmental and Life Sciences (WUELS) routinely collects and processes GPS radio occultation level1b data of FORMOsa SATellite mission 3 / Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC) using products provided by COSMIC Data Analysis and Archive Center (CDAAC). From over 1,500 daily occultations available worldwide, we find those occurred over Polish territory to derive atmospheric profiles of bending angle and refractivity. L1/L2 excess phases serve as inputs to the phase-locked loop (PLL) retrievals which are enhanced in the troposphere by open-loop (OL) tracking. The multipath effect is resolved in radio-holographic Phase Matching (PM) method. For data inversion we use the Abel transform to calculate refractive index profile as well as to derive bending angle by forward operator from external meteorological sources. Ray-tracing algorithm is developed to provide independent retrievals for space-based applications so that bending angles can be calculated in the domain of numerical weather prediction model based on Eikonal equation. In addition to reference values from atmPrf product of CDAAC, the quality assessment of output data is carried out by comparing radio occultation profiles in the immediate vicinity of three Polish radiosonde stations with reports available two times daily: at 00 and 12 UTC.
Key words: bending angle, COSMIC, GPS RO, radio occultation, refractivity

Sparsity-driven tomographic reconstruction of atmospheric water vapor using GNSS and InSAR observations

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An accurate knowledge of the 3D distribution of water vapor in the atmosphere is a key element for weather forecasting and climate research. On the other hand, as water vapor causes a delay in the microwave signal propagation within the atmosphere, a precise determination of water vapor is required for accurate positioning and deformation monitoring using Global Navigation Satellite Systems (GNSS) and Interferometric Synthetic Aperture Radar (InSAR). However, due to its high variability in time and space, the atmospheric water vapor distribution is difficult to model. Since GNSS meteorology was introduced about twenty years ago, it has increasingly been used as a geodetic technique to generate maps of 2D Precipitable Water Vapor (PWV). Moreover, several approaches for 3D tomographic water vapor reconstruction from GNSS-based estimates using the simple least squares adjustment were presented.
In this presentation, we present an innovative and sophisticated Compressive Sensing (CS) concept for sparsity-driven tomographic reconstruction of 3D atmospheric wet refractivity fields using data from GNSS and InSAR.
The 2D zenith wet delay (ZWD) estimates are obtained by a combination of point-wise estimates of the wet delay using GNSS observations and partial InSAR wet delay maps. These ZWD estimates are aggregated to derive realistic wet delay input data of 100 points as if corresponding to 100 GNSS sites within an area of 100 km × 100 km in the test region of the Upper Rhine Graben. The made-up ZWD values can be mapped into different elevation and azimuth angles.
Using the Cosine transform, a sparse representation of the wet refractivity field is obtained. In contrast to existing tomographic approaches, we exploit sparsity as a prior for the regularization of the underdetermined inverse system. The new aspects of this work include both the combination of GNSS and InSAR data for water vapor tomography and the sophisticated CS estimation. The accuracy of the estimated 3D water vapor field is determined by comparing slant integrated wet delays computed from the estimated wet refractivities with real GNSS wet delay estimates. This comparison is performed along different elevation and azimuth angles.

GNSS for Snow Depth Estimation at Mt. Etna

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Omni-directional GNSS antennas, while tracking satellites, receive a contribution of energy also from ground reflections. Thus, receivers actually track the interference of the direct and reflected electromagnetic waves. The frequency of this interference feature changes as changing of satellite elevations and varying the reflective geometry. Thus, it also depends on the height H above the antenna above the reflecting surface. This interference pattern can be measured in the GPS Signal to Noise Ratio (SNR) data. In SNR data, the unwanted effect of the direct signal can be removed by a simple polynomial fit. The residue is caused by the reflected signal. Assuming a horizontal planar reflector, the frequency is a constant as a function of the sine of the satellite elevation angle. As snow levels increase, the frequency of the SNR data decreases. These frequency changes can be easily observed in the periodogram retrievals, and directly relate to snow depth. Here, the technique was applied at Mt. Etna (Italy) for the last 2 years of data. Unfortunately no continuous data are available for a comparison, but the times, lengths and strengths are in good agreement with the periodic local snow official reports. In this regard, the GNSS based approach could be the first public service for routinely measuring the level of snow on Mt. Etna.

Detection of ionospheric disturbances from GPS radio occultation measurements

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Radio waves are sensitive to electron density anomalies in the ionosphere. This fact leads to degradation in global communication and navigation signals. The GPS signals are also weakened and disturbed when passing ionospheric irregularities. Our investigation is based on GPS radio occultation (RO) data measured by the U.S./Taiwanese COSMIC satellite constellation. During an occultation the Earth's atmosphere is scanned between the satellite's orbit altitude and Earth's surface. Due to the refraction of the electromagnetic waves, induced by electron density gradients in ionospheric altitudes, the GPS signals contain information on current ionospheric conditions. Strong electron density gradients cause large fluctuations in the GPS signal amplitudes and Signal-to-Noise (SNR) profiles. In this study, we use the SNR profiles of the GPS L1 signal to approach disturbances in Earth's ionosphere on a global scale. We will present the global distribution of the occurrence of strong SNR scintillations in dependence on time and space.

Owen Lewis

Zenith Total Delay (ZTD) observations from Global Navigation Satellite Systems (GNSS) are assimilated into the Met Office's global and UK Numerical Weather Prediction (NWP) models. Atmospheric observations can contain systematic biases that need to be removed before being assimilated into NWP. Currently, the Met Office uses a static bias correction scheme which uses a 28 day average of the background departures for each station and analysis centre combination. With a recent move to using variational bias correction (VarBC) for the operational assimilation of satellite radiance data, the ground based GNSS bias has been investigated for potential suitability for use in the VarBC scheme.
The temporal variation in background departures was investigated across both the network as a whole and on an individual station basis, with particular focus over the UK. The individual stations biases were found to vary on timescales of 3-7 days and if using the current static scheme would produce a significantly different value for the bias correction every 28 days. A longer term average is suggested for use with a static scheme. The network bias was found to be largely uniform across the UK on a daily basis.
Predictors for a VarBC scheme were also investigated. The predictors considered were surface

temperature, surface humidity, pressure at mean sea level, thickness 1000-300 hPa, 1000-50 hPa and 1000-850 hPa. The correlation between the background departures and these variables was weak. Future work will look to identify predictors that could be used to enable Ground based GNSS to take up a VarBC scheme in the Met Office's NWP models.

Improving BeiDou real-time precise point positioning with numerical weather models

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Precise positioning with the current Chinese BeiDou Navigation Satellite System is proven to be of comparable accuracy to the Global Positioning System (GPS), which is at centimeter level for the horizontal components and sub-decimeter level for the vertical component. But the BeiDou precise point positioning (PPP) shows its limitation in requiring a relatively long convergence time. In this study, we develop a numerical weather model (NWM) augmented PPP processing algorithm to improve BeiDou precise positioning. Tropospheric delay parameters, i.e., zenith delays, mapping functions, and horizontal delay gradients, which are derived from short-range forecasts from the Global Forecast System (GFS) of the National Centers for Environmental Prediction (NCEP), are applied into BeiDou real-time PPP. Observational data from stations, which are capable of tracking the BeiDou constellation from the International GNSS Service (IGS) Multi-GNSS Experiments (MGEX) network are processed, with both the standard PPP and the introduced NWM augmented PPP processing. The high accuracy and quality of tropospheric delay parameters derived from NCEP are demonstrated by comparison with those from the European Centre for Medium-Range Weather Forecasts (ECMWF) and with the IGS final tropospheric delay products. The positioning results show that an improvement of convergence time up to 75.0% and 75.0% for the east and vertical components, respectively, can be achieved with the NWM augmented PPP compared to the standard PPP. The positioning series with the NWM augmented PPP solution performs better than with the standard one for each coordinate component especially before the solution convergence, exhibiting less jumps and fluctuations. With the NWM augmented PPP, an average positioning accuracy improvement of 43.7% for the north component is observed. The accuracy for the east component is improved by 52.2% and by 45.6% for the vertical component.

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Water vapour content of the atmosphere low layers (up to about 15 km), known as troposphere or neutral atmosphere, affects the Global Navigation Satellite System (GNSS) signals by lowering their propagation velocities with respect to vacuum. A reduced speed, results in a time delay in the signal propagation along the satellite-receiver path, that multiplied by the vacuum speed of light adds an extra-distance to the satellite-receiver geometrical one.
It is worth reminding here that the tropospheric delay due to the water vapour, is just one out of many other systematic errors affecting GNSS observations, which are to be accounted for, in order to achieve sub-centimetre accuracy positions. If from the positioning point of view this delay is just a systematic error to be removed, it puts forward GNSS as a tool for the remote sensing of the troposphere water vapour content. Currently GNSS water vapour retrieval is performed routinely from existing permanent networks of geodetic receivers, deployed for other purposes, such as reference frame definition, real-time and post-processing positioning services or ground deformation monitoring. These receivers are typically dual-frequency (L1/L2), Global positioning System (GPS)-only or GPS+GLONASS, and their cost is in the order of 10.000-15.000 €. On the other hand, the presently available on the market low-cost (in the order of 300 Euros) single frequency GNSS receivers, which have opened the way to a lot of innovative applications of the GNSS systems, have not been used yet for troposphere sensing. Considering the state-of-the-art and the new technological availabilities, the reasonable goal of this research project is the quality assessment of the water vapour retrieval from a GNSS permanent network using L1 phase observations only, with the aim to establish a low-cost pilot GNSS permanent network for monitoring extreme weather events.

Terrestrial water storage anomaly during the 2007 heat wave in Bulgaria

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Heat waves have large adverse social, economic and environmental effects including increased mortality, transport restrictions and a decreased agricultural production. The estimated economic losses of the 2007 heat wave in Southeast Europe exceed 2 billion EUR with 19 000 hospitalisation in Romania only. The aim of this study is to investigate the anomalies of temperature, precipitation, integrated water vapour (IWV) and terrestrial water storage (TWS) in 2007 compared to 2003-2013, that could have led to the heat wave.
The heat wave month (July 2007) was 2 °C hotter than the 2003-2013 mean in Sofia, Bulgaria. The 2007 annual precipitation was on 10 % higher than the 2003-2013 mean, but in spring the negative precipitation anomaly in April was followed by a large positive anomaly in May. A large negative precipitation anomaly is recorded in July 2007. In alignment with the precipitation, IWV computed from a GNSS station in Sofia shows a large positive anomaly in May 2007, while a negative anomaly in July. The terrestrial water storage anomaly, derived from the GRACE mission, has one month of delay and with a negative anomaly recorded in August 2007. It is possible that is due to the slower soil response to the atmospheric drying and the heat.
Intercomparison is performed for the period 2003-2008 with ALADIN-Climate regional climate model. The following can be concluded for 2007 anomalies in the model and observations: 1) a strong correlation for temperature and IWV anomalies data sets, and 2) a weak relation between the precipitation and TWS anomalies data set.

Preliminary results of GPS water vapour and its comparison with radiosondes and Era interim reanalysis in Algeria

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Remote sensing of atmospheric water vapour using Global Positioning System (GPS) has become an efficient tool in meteorology and climate research. This paper presents the estimation of precipitable water from GPS receivers and meteorological data in Algeria, over three stations located at Algiers, Bechar and Tamanrasset. The objective of this study is to analyse the sensitivity of the GPS Precipitable Water (PW) estimates for the 3 sites mentioned above to the weighted mean temperature (Tm), either obtained from the Bevis et al. 1992 T_m-T_s regression, the Boutiouta & Lahcene (2013) T_m-T_s regression developed for Algeria, and calculated directly from ERA interim reanalysis. The results indicate that the differences in T_m are of the order of 18 K, but this produces differences of 1.8 mm in the final evaluation of PW. A good agreement is found between GPS-PW and PW calculated from radiosondes, with a small mean difference with Vaisala radiosondes (RS 92). A comparison with GPS and Era interim show a large difference of (4 mm) in the region of highlands. This difference is possibly due to the Earth's topography. These first results are encouraging, in particular for meteorological application in this region, with good hope to extend our dataset analysis to a more complete, global coverage over Algeria.
Key words: GPS; atmospheric water vapour; radiosondes; Era interim.

Investigation of pre-earthquake ionospheric anomalies in Romania and Greece using GNSS global and national networks

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During the last two decades a significant effort has been invested in order to understand and interpret the link between seismic activity and ionospheric perturbations. Since not any individual seismo-ionospheric precursor can be used as an accurate stand alone for earthquake prediction it is required to integrate different kinds of precursors and analysis techniques. In this context, the aim of this study is to investigate pre-earthquake ionospheric anomalies that occurred prior to large (M>6) earthquakes in Eastern European (Romania and Greece) area following a multi-technique approach, using Total Electron Content (TEC) observations from GNSS global and national networks. To identify possible ionospheric anomalies before the earthquakes we applied statistical and spectral analysis on diurnal TEC variations several days prior to the seismic events. It was found that pre-earthquake abnormal ionospheric TEC variations appear within 5 days prior to all seismic events. Intensified wave-like TEC oscillations with periods around 20 min were also revealed up to 5 days prior to the earthquake shocks in all cases that could be interpreted as possible ionospheric precursors of the impending earthquakes.
Keywords: Ionospheric earthquake precursors, Total Electron Content (TEC), GNSS network

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UNB3m-NN: Using real meteorological data to improve the prediction of the UNB3m tropospheric propagation delay model through assimilation in a neural network

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In GNSS processing, tropospheric delay handling still remains one of the major accuracy limiting factors, when aiming for geodetic precision. The troposphere refractive medium causes GNSS signal to delay from about 2.3 m to 2.6 m at sea level and can reach up to 28 m at 5 degrees and 50 m at 3 degrees elevation angle. This delay although it has a minimal effect on horizontal position introduces a height error that can reach up to several meters for low elevation angles. Thus, several approaches have been attempted from scientists over the past few years to represent the state of the troposphere as realistically as possible, including the use of polynomial scale factors, stochastic estimation and numerical weather models.

However, the vast majority of current GPS processing software suites, parametrize the tropospheric effect employing a number of available models (such as Saastamoinen, MOPS, GPT2 and UNB3m) associated with their estimation technique to model the excess path delay in the GPS observation. These models can be classified based on their input data as those employing standard atmosphere parameters and those employing surface - measured meteorological data.

Although the standard atmospheric models provide a fair approximation of the expected tropospheric conditions, they are deficient in the spatial domain, in predicting local weather phenomena, and in the temporal domain, accounting for short-term variations of the meteorological parameters (pressure, temperature, water vapor content, specific humidity, lapse rate and so on) and for deviations of the latter from the expected climatology.

Surface meteorological models on the other hand are able to represent the current state of the troposphere for a particular site and their ability to predict the tropospheric delay is apparent especially in modelling the hydrostatic part of the delay, which is in direct correlation with the surface total barometric pressure.

UNB3m, the improved version of UNB3, employs a look-up table to determine values of surface meteorological parameters, which was derived from the U.S. Standard Atmosphere Supplements, 1966

(COESA, 1966) . UNB3m has been shown to have a mean error of -0.5 m and a standard deviation of 4.9 cm globally (Leandro R.F., M.C.
Santos, and R.B. Langley (2006). UNB Neutral Atmosphere Models: Development and Performance. Proceedings of ION NTM 2006, the 2006 National Technical Meeting of The Institute of Navigation, Monterey, California, 18-20 January 2006; pp. 564-573). Although these values are small, the absolute errors can be higher.
In this study we modified the UNB3m model by replacing the look-up table with actual measured meteorological parameter values (hereafter, we refer to this modification as UNB3m-met). The computed zenith total delays were compared against the IGS final tropospheric zenith path delay product with a claimed accuracy of 4 mm.
Subsequently, we computed the residuals between the UNB3m-met and the UNB3m models and we assimilated them in a neural network. The input layer of the neural network consists of the meteorological parameters (pressure, temperature and relative humidity), the latitude and the height of the particular site and the computed UNB3m values of the total tropospheric delay for the days of the time spam. The output layer consists of the residuals between the two models for the same time. After training, the neural network is able to predict residuals for a future epoch without the need of meteorological data.
The result of the neural network (residual) is added to the predicted UNB3m delay to produce the final tropospheric delay value. The latter, named UNB3m-NN is a hybrid of the UNB3m model with a neural network incorporation. It combines the advantages of assimilating real meteorological data with the use of the widely recognized and validated UNB3m model. Moreover, the fact that it depends solely on the site's location and time (similarly to UNB3m) renders it convenient to use in GNSS processing regardless of the user location or the availability of meteorological data.
To assess the new tropospheric model, UNB3m-NN, experiments were conducted for 5 GNSS stations distributed in the North and South hemisphere and for 3 periods of time: 3 months, 6 months and 1 year. The different time spans were used to assess the prediction ability of the neural network. The performance of the new model is assessed by evaluating site coordinates repeatability. To achieve this, UNB3m-NN was incorporated into UNB's GNSS Precise Point Positioning software and implemented as the tropospheric model to account for the excess path delay in the observation. The output site coordinates were tested internally for their consistency and externally against the IGS weekly solution for the respective time spans.
Moreover, the hydrostatic and wet (non-hydrostatic) components of the total tropospheric delay have been analyzed for each different realization of the UNB3 model: UNB3m, UNB3m-met and UNB3m-NN (assimilated and predicted values) and a complete statistical comparison is presented.

Tropical cyclone intensification, water vapor distribution and GNSS measurements

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Tropical cyclones represent the most important weather system involving La Reunion Island and an accurate prediction of their track and intensity is crucial to reduce the damages caused by their strong precipitation and winds. Cyclone Bejisa is a tropical cyclone that affected Reunion Island and Mauritius in the late December 2013 and early January 2014 with strong consequences both on the population and on energy supplies. Atmospheric water vapor is the main driver in the development of the cyclones and GPS continues observations of precipitable water (PW) constitute extremely important tools in studying its temporal and spatial distribution. Because of the high temporal resolution of their observations, they allow the resolution of high-frequency (e.g. diurnal) variations and they can be used to study, monitor and predict weather extreme events such as the tropical cyclones. In this work we apply the GPS sensing technique to estimate the PW from the zenith wet delay (ZWD) due to the passage of the cyclone Bejisa, and we estimate the cloud top altitude using the Radio Occultation profile and find the relationship between cloud top altitude, storm intensity and IPWV variation.

Validation of climate model simulations using GPS data

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A high quality, global, long-term GPS precipitable water (PRW) dataset was used to assess IPSL's LMDZ climate model simulations. Four different configurations of the climate model were considered: new and old physics, as both free runs and nudged simulations with 3-hourly ERA-Interim wind fields. The models simulations fields were extracted at the GPS sites. Time-series and trends (computed using a linear trend model) were compared.
Results show an improvement with the nudged simulations, for both model physics, with an increase in the correlation coefficient between GPS and model PRW time series and anomalies. In addition, for the nudged versions of the model, both absolute and relative trends are closer to the estimated GPS PRW trends. These results obtained for the nudged configurations are consistent with the comparison between GPS and ERA-Interim PRW data, which yielded similar outcomes for the trends and correlation coefficients.
The ERA-Interim reanalyses were also compared with each model configuration, in terms of spatial variability. The differences between trends and variability are slightly lower for the nudged versions, especially over the ocean. However, the differences in the mean PRW are of the same order of magnitude for all 4 configurations. Finally, the model configurations were also spatially inter-compared. In general, the new physics appears to be more sensitive to the nudging, while the differences between nudged versions are smaller in trend and variability. The results also suggest some feedbacks between model dynamics and physics.

Monitoring soil moisture at station Marquardt, Germany

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Soils are one of the main water storages on the Earth. Unlike rivers, lakes and oceans, the amount of water, stored in soils is very hard to measure. The most common methods of measuring soil moisture content are Time Domain Reflectometry (TDR) and Gravimetry. These methods have both spatial (for TDR) and temporal (for Gravimetry) limitations. Soil moisture can be measured with much better spatial and temporal resolutions using GNSS Reflectometry methods. In this study we will focus on monitoring soil moisture and GNSS derived atmospheric water vapour from GNSS. This preliminary study will be the base for further research on the synergy between GNSS techniques for analysis of sinks and sources of water in the atmosphere.

Development of severe weather tool with GNSS tropospheric products in Bulgaria

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Operational forecasting of formation and development of vigorous thunderstorms producing heavy rain and hail is currently done using radar images, surface and satellite observations in combination with Numerical Weather Prediction model. However, the challenge remains to resolve the high temporal and spatial variability of severe weather events and additional information like water vapour derived from

GNSS tropospheric products has a potential to be a valuable operational tool. The goal of this study is to use the synergy between the NWP WRF, radar data and GNSS severe weather products (2D water vapour maps and time series) to develop prototype tool for now-casting in Bulgaria.

Validation of new GNSS baseline processing strategy for ZTD estimation in regional networks

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The poster shows new results of studies on the improvement of the processing strategy designed to reprocess GNSS ground data for climate monitoring applications, in particular for analysis of trends and variability of Zenith Total Delay (ZTD) and Integrated Water Vapor (IWV).
The processed network is composed of 136 stations, including 104 stations of Polish ASG-EUPOS network and 32 EPN stations (remote and in Poland). The processing was carried out for GNSS data collected during year 2014 using Bernese GNSS Software v.5.2. Three variants of processing were carried out and analyzed: 1) using network design strategy which works quite well for coordinates; 2) the standard “obs-max” strategy recommended for Bernese software; 3) a newly developed baselines design strategy optimized for ZTD estimation.
The studies show that the network design has a strong impact on the quality and continuity of ZTD estimates. It is also shown that in case of sub-daily gaps in the measurements at reference stations, small clusters of stations can be disconnected from the main network. As a result, offsets of a few centimeters in ZTD estimates and spikes in their formal errors can appear. These offsets and spikes cannot always be detected. This phenomenon is quite frequent in large networks such as the one considered in this study. It is also responsible for significant discontinuities in the estimated ZTD series which are detrimental to climate monitoring applications. This problem might be observed also for “obs-max” solution.
The new network design strategy proposed here allows to circumvent these events and assure that all the stations remain connected to the main reference network. Using this new strategy, the ZTD time series are much more continuous and homogeneous in comparison to the standard strategy. However, even when an optimal processing procedure is used, some outliers in the ZTD series still remain (e.g. due to short data gaps). Therefore, a post-processing screening procedure consisting of the removal of the first and the last ZTD estimates around observations gaps, range and outlier check of ZTD and formal errors is applied to remove these bad values. The results are also further validated with respect to ERA-Interim reanalysis.
In addition, a long term Precise Point Positioning (PPP) – based ZTD solution are also produced and compared to the network processing results. This is because PPP method does not contain artifacts related to the network design. Hence, PPP solution might be an interesting alternative to DD processing.
Keywords: GNSS, processing, screening, ZTD, climate

Typfication and climatology of the foehn in Sofia 1975-2014

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Foehn is a warm and dry wind that blows on the leeward side of the mountain. It is the well-known example of local atmospheric circulation, and also an extreme weather event. Forecasting extreme weather events is an important task for the short-range weather forecasts. The foehn in Bulgaria is observed on the northern slopes of the mountains, as a result of advection of warm air from the south (S) and southwest (SW). Its occurrence is highest north Vitosha and north of the Balkan Mountains. The aim of the study is to make synoptic classification, of the meteorological conditions led to foehn in the central meteorological station in Sofia for the period 1975-2014. Prepared is foehn climatology and evaluation of the foehn as an extreme weather event by wind speed. For the period 1975 - 2014, there were 280 days with foehn in Sofia, which are realized in 201 synoptic situations. The average annual number of days with foehn is 7. Depending on atmospheric circulation the foehn is classified into four

main types. Of them 103 (51 %) are of type I, 48 (24 %) are of type II, 44 (22 %) are of type III, and 6 (3 %) are of type IV. Tendency for reduction of the number of days with foehn after 1990 is found. The annual mean number of days with foehn to 1990 is 8.5 days, and after 1990 is less than 5.9 days. In 54 % of the days the foehn wind speed is 14-19 m/s, in 22.5 % is 20-29 m/s, and in 1.5 % is over 30 m/s. In 4 cases the wind speed is over 30 m/s.

Relationship between the variation in sea surface temperature and GNSS-derived precipitable water vapor

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Water vapor (WV) is a principal atmospheric variable and a central component in Earth energy budget and global water cycle. Investigation into long-term variation in WV in both spatial and temporal domains is significant for studying the dynamics of the Earth's climate system and climate change. Quantifying the variation and distribution of WV at a high accuracy and high resolution is often a challenge if only traditional meteorological sensors are used due to their low temporal and spatial resolutions. Nowadays, using Global Navigation Satellite Systems (GNSS) to remotely sense the precipitable water vapor (PWV) contents in the atmosphere has heralded a new era for climate research due to their 24-hour availability, global coverage, high accuracy, high resolution and low cost. In this study, the long-term trend and seasonal oscillations in PWV time series for the period 1994−2013 across the GNSS stations located in the tropical regions were investigated. The PWV time series were obtained from GNSS-derived zenith wet delay and ECMWF-derived water-vapour-weighted mean temperature. An enhanced time series analysis method, named singular spectrum analysis (SSA), was investigated to study the trend and seasonal oscillations in the PWV time series. An investigation into the relationship between the variation in monthly PWV and monthly sea surface temperature was also conducted. Results indicate a strong correlation existing between these two variables. Moreover, comparisons between the PWV time series and the occurrence of the El Nino and La Nina events were also performed for an investigation of correlation between them. The result shows that the variation in the PWV is strongly affected by the El Nino and La Nina events.

Integrated model of troposphere for GNSS precise positioning

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Finding an accurate a priori model of troposphere is still a challenge, especially for Precise Point Positioning. A common approach is to use the standard atmosphere parameters or global models, such as GPT (global pressure/temperature) model or UNB3 (University of New Brunswick, version 3) model, but they may not be sufficient for positioning in severe weather conditions.
In this study, we present o model of troposphere from GNSS data and numerical weather prediction (NWP) model WRF (Weather Research and Forecasting). Data provided by different sources are highly inhomogeneous, both in time and in space. We present a method to interpolate tropospheric parameters (total refractivity and zenith total delay) at any point, with known accuracy. We reconstruct the troposphere conditions using the least-squares collocation software COMEDIE (Collocation of Meteorological Data for Interpretation and Estimation of Tropospheric Pathdelays) developed at ETH Zurich.
We implement a regional troposphere model into the PPP (Precise Point Positioning) software GNSS-WARP (Wroclaw Algorithms for Real-time Positioning) developed at Wroclaw University of Environmental and Life Sciences to constrain the troposphere estimates. Application of the troposphere model based on integrated data results in shortening the convergence time and reducing the positioning error, especially for the Up component. For further improvement, the customized mapping functions based on the WRF model will be proposed.

Spectral and Trend analysis of ZTD and IWV Time Series

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Seasonal components in the ZTD (Zenith Tropospheric Delay) and IWV (Integrated Water Vapour) time series are important and provide information about weather conditions in a given region. The main purpose of this research is to analyze linear trends and seasonal components of ZTD's and IWS's in GPS reprocessing campaign at selected stations in Europe (IGS repro1 dataset-URL1). The seasonal components and linear trends were estimated using the LSE (Least Square Estimation) approach. The frequencies in the ZTD and IWV time series were found and periodograms were prepared. The frequency spectrum was estimated by using combined sine and cosine functions to the time series. Since the estimation of trends and seasonal components in time series is very sensitive to inhomogeneties in time series caused due to possible instrumental changes, quality degradation, and observation biases, methods to detect inhomogeneties were performed.

Solar Impact on Earth's Ionosphere Along the Equatorial Region

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The Ionosphere is a dispersive medium with respect to microwave signals. The main parameters driving the ionosphere are solar radiation and geomagnetic activity. The ionosphere around the geomagnetic equator located between -20° and +20° is distinctively different from other latitudinal regions due to magnetic field at this area; this region is usually called equatorial ionospheric anomaly (EIA). In this work, we studied the monthly and seasonal variation/behavior of EIA based on vertical Total Electron Content (VTEC) values obtained from ground based GNSS measurements at different selected latitudes across the African continent in the year 2013 at solar max conditions. The work employs data from solar and indices like sun spot numbers (SSN) and solar flux (f10.7) to study the temporal variation of VTEC. The vertical total electron content values obtained within the northern and southern hemisphere of EIA anomaly zone in African region are compared with VTEC values obtained beyond the EIA zone. The result shows a monthly and seasonal variation of VTEC and also the impact of the solar activity on VTEC values along the equatorial zone.

Numerical study on the effect of charge separation at low cloudtemperature and effective water content on thunderstorm electrification

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In the present study the effect of the charging at low effective water content as well at low cloud temperatures on simulated clouds charge structure and lightning activity is evaluated. Two idealised cloud cases were simulated with MesoNH using different configurations of the main known parameterizations for non-inductive charging. Simulations in regions with very low effective cloud water content were performed with the parameterization proposed in Mitzeva et al. (2006) based on the "Relative Growth Rate" hypothesis, while for simulations in regions with low cloud temperature, Avila et al. (2011) charge values were used. Results showed that the inclusion of the charge separation at very

low effective water content influences more the simulated clouds charge structure than the inclusion of the charge separated at low temperatures. Also, the effect of the charge separated at very low effective water content is more significant when the original parameterization for non-inductive charging is based on the effective water content rather than on the rime accretion rate.