ADVANCED GLOBAL NAVIGATION SATELLITE SYSTEMS TROPOSPHERIC PRODUCTS FOR MONITORING SEVERE WEATHER EVENTS AND CLIMATE (GNSS4SWEC)

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ABSTRACT

Global Navigation Satellite Systems (GNSS) have revolutionised positioning, navigation, and timing, becoming a common part of our everyday life. Aside from these well-known civilian and commercial applications, GNSS is now an established atmospheric observing system which can accurately sense water vapour, the most abundant greenhouse gas, accounting for 60-70 % of atmospheric warming. Water vapour is under-sampled in the current meteorological and climate observing systems, obtaining and exploiting more high-quality humidity observations is essential to weather forecasting and climate monitoring. The European COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)" will address new and improved capabilities from concurrent developments in both the GNSS and the meteorological communities. For the first time, the synergy of the three GNSS systems (GPS, GLONASS and Galileo) will be used to develop new, advanced tropospheric products, exploiting the full potential of multi-GNSS water vapour estimates on a wide range of temporal and spatial scales, from real-time monitoring and forecasting of severe weather, to climate research. In addition, the COST Action ES1206 will promote the use of meteorological data in GNSS positioning, navigation, and timing services and it will stimulate knowledge transfer and data sharing throughout Europe.

Key words: Global Navigation Satellite Systems (GNSS), ground-based atmospheric sounding of water vapour, severe weather, climate trends and variability.

1. INTRODUCTION

The use of GNSS technology is continually expanding, with the global market for satellite-based navigation products and services expected to grow to 250 billion by 2030. The European GNSS system, Galileo, alone is forecasted to increase the market value by 14 billion. In addition, GNSS has demonstrated its capacity as an accurate sensor of atmospheric water vapour with the application of GNSS for Numerical Weather Prediction (NWP) as focus of previous European projects (WAVEFRONT, MAGIC, COST-716, TOUGH, E-GVAP). Following the successful COST Action 716, the application of GNSS for NWP is now a well-established technique in Europe. At the present time, EUMETNET supports the operational exploitation of more than 1,800 continuously operating GNSS stations in the framework of the E-GVAP project (http://egvap.dmi.dk). Current state-of-the-art GNSS meteorology is focused on the assimilation of hourly-updated tropospheric Zenith Total Delays (ZTD) into NWP models. Currently, 11 GNSS processing centres deliver their products with a maximum latency (time to the first observation) of 90 minutes. These are used for model validation and assimilation at 10 European national meteorological services and at ECMWF.

Advancements in NWP models with rapid-update cycles require GNSS-based tropospheric products with improved timeliness, and with greater spatial and temporal resolutions, than it is currently available. The potential of GNSS observations to meet these requirements, and also for use in very short range forecasting of severe weather (nowcasting), has improved considerably in the last few years due to: a) improved GNSS raw data timeliness (real-time data streaming), b) improved coverage (the number of ground-based stations of the European GNSS network has trebled in the last 5 years) and c) increased temporal resolution of tropospheric estimates.

The application of GNSS for climate monitoring is an emerging new field of research. Over time, improved GNSS processing algorithms have been developed and the associated processing changes have introduced inconsistencies in (continuously produced) long-term time series, making climate trend analysis challenging. Ongoing re-processing efforts using state-of-the-art models will provide consistent time series of tropospheric data, taking benefit of more than 15 years of GNSS observations from over 600 stations worldwide. This unique dataset will 1) enable validation and quantification of systematic biases from a range of instrumentation, 2) improve the knowledge of climatic trends of atmospheric water vapour, which currently have a large scatter and 3) benefit both global and regional NWP reanalysis and climate model simulations (e.g. IPCC AR5).

Additionally, the synergy between GNSS and NWP is mutually beneficial: GNSS tropospheric estimates are assimilated into NWP models, whilst it can be beneficial to use NWP model data as an input to state-of-the-art GNSS processing schemes. This should improve atmospheric signal propagation modelling, which could in turn significantly improve real-time positioning accuracy.

The COST Action ES1206 (http://gnss4swec.knmi.nl) consists of 3 Working Groups (WGs) that will develop next-generation GNSS tropospheric products and applications that will enhance the quality of weather forecasts and monitoring of climate change, contributing to important societal and political needs.

2. WG1: ADVANCED GNSS PROCESSING TECHNIQUES (AGNSS)

The potential of GNSS observations for troposphere monitoring has been first described in Bevis et al. (1992) concerning post-processing solutions. The development of Near Real-Time (NRT) GNSS data processing suitable for NWP models was not possible until 1999 mainly due to the lack of a hourly data flow from the permanent GNSS stations and the limited quality of predicted precise orbits. First NRT tropospheric solutions for Europe were demonstrated in 2000 (Gendt et al. (2001), Dousa (2001)). During the COST Action 716 (1998-2004; Elgered (2001)) a NRT demonstration campaign was initiated in 2001 (van der Marel et al. (2004)). The campaign continued during the TOUGH EU project (2003-2006; http://web.dmi.dk/pub/tough) and the E-GVAP projects (2005-2017). In particular, E-GVAP aimed for establishing an operational ZTD estimation with three main objectives: 1) to deliver ZTDs within 90 minutes, 2) to develop an active quality control of these ZTDs and 3) to support their assimilation in NWP models. The number of routinely processed GNSS stations has grown up to 1800 in Europe and the number of contributing analysis centres has reached 11, plus 4 additional centres being still in a test phase. The state-of-the-art in GNSS data processing for meteorology provides hourly updated NRT ZTD parameters, currently estimated from only GPS observations. The majority of the analysis centres utilize the network solution eliminating GNSS receiver and satellite clock errors in double difference observations. Two GNSS analysis centres provide an alternative approach based on the Precise Point Positioning (PPP) technique (Zumberge et al. (1997)) which exploits original data without differencing. However, the network approach was preferred to PPP by many analysis centres due to a lack of ultra-fast precise satellite clock products necessary for the PPP technique.

The emerging new satellite systems and new signals can be used for strengthening the ZTD solutions and for improving the estimates of the atmospheric asymmetry in the vicinity of the GNSS receiver. Although the GLONASS system is still not officially operational, data are already collected and used. Since 2008 the IGS has provided ultra-rapid precise orbits for GLONASS satellites with contributions of at least 4 analysis centres. The product is sufficiently robust for generating operational multi-GNSS (GPS+GLONASS) NRT solutions (Dousa (2010)). The initial inconsistency between stand-alone GPS and GLONASS ZTD solutions disappeared when the IGS08 antenna phase centre models were adopted (Dach et al. (2011b)). In the upcoming years, Galileo and BeiDou will be available for troposphere monitoring too.

With increasing demands on accuracy of positioning and navigation, and with increasing quality and resolution of NWP models, the use of meteorological data might become more beneficial in space geodetic techniques. Direct use of meteorological data during the processing of ground-based GNSS networks has been adopted in the Vienna Mapping Function concept, providing a support for mapping function derived from NWP model by applying the ray-tracing technique (Boehm & Schuh (2004)). The impact of atmospheric loading effect based on actual meteorological data has also been evaluated in various GNSS analysis centres (Dach et al. (2011a)). Services supporting GNSS with meteorological data will further improve the temporal and spatial data resolution and will include modelling of atmospheric asymmetry (e.g. Boehm & Schuh (2007)). Other emerging fields for exploiting actual meteorological data are real-time precise positioning, navigation and timing applications.

The WG1 of COST Action ES1206 will focus on the development of: 1) ultra-fast and real-time GNSS tropospheric products for exploitation in nowcasting, 2) multi-GNSS tropospheric products and 3) exploitation of meteorological data in the GNSS processing.

3. WG2: GNSS FOR SEVERE WEATHER EVENTS MONITORING (GNSS4SWE)

The term severe weather event includes very diverse phenomenon among which are convective clouds with intense precipitation and thunderstorms, which can lead to flash floods and large economic losses. A number of recent publications discuss the application of GNSS meteorology for monitoring intense precipitations associated to convective clouds. Among them, Graham et al. (2012) investigate orographic convection in the Bernese Alps in Switzerland, using a range of independent observations, including GNSS meteorology. They presented two case studies with isolated orographic convection over the Alps in the afternoon and evening, producing thunderstorms. The results showed that large transfer of water vapour occur from the Swiss plain to the mountains. Up to 50 % increase in IWV values are reported at individual Alpine stations, coincident with strong airflow convergence. Baelen et al. (2011) studied the relationship between water vapour dynamics and the life cycle of precipitation systems during the intense observation campaign in the region of the Black Forest Mountain in summer 2007. They show that 1) frontal systems seem to develop preferentially where the largest amount of water vapour is available and 2) water vapour has predominant role as a precursor for initiation of local convection. Accumulation of water vapour on the crest of the orography leads to rich convection and its passing over the orography triggers lee-side convection. de Haan (2008) first demonstrates the benefits of using 2D GNSS water vapour maps for nowcasting two thunderstorms. In the first case, the convergence of the 2D moisture field increased the activity of the thunderstorm. In the second case, the intense lightning of the thunderstorm occurred to the east of the water vapour maximum. With its development the thunderstorm overtakes the water vapour maximum and then weakens. Seco et al. (2012) made an experimental analysis establishing the relation between the variations of the GNSS IWV, surface pressure, and precipitation intensity in a long-term study for the period 2002-2010 in the northern Spain.

Recently, operational NWP models begin to be used as nowcasting tools. In these models, the lack of upper air humidity information is (partially) filled by the assimilation of GNSS tropospheric delays (ZTD). Smith et al. (2007) showed that the assimilation every three hours of IWV derived from GPS-based ZTDs had a positive impact and lead to more accurate short-range moisture forecasts. Also, de Haan (2013) showed that adding humidity information in an hourly update cycle is essential for producing realistic rainfall forecasts in the first few hours of the model run. Note that nowcasting models require the availability of the GNSS tropospheric delay products with a very low latency, i.e. within (at least) 10 minutes from original observations.

The WG2 of COST Action ES1206 will primarily focus on: 1) severe weather forecasting: testing new GNSS tropospheric delay products that provide more information on the spatial heterogeneity and rapid temporal variability of humidity in the troposphere, 2) nowcasting: providing rapid updates in the analysis of the atmospheric state, which will requires a transition from a NRT GNSS network processing (as implemented today in E-GVAP) to a ultra-fast or real-time GNSS processing and 3) real-time positioning: providing NWP model data for use an input to state-of-the-art GNSS processing schemes to improve atmospheric signal propagation modelling.

4. WG3: GNSS FOR CLIMATE MONITORING (GNSS4C)

Atmospheric water vapour is the most abundant greenhouse gas involved in the climate feedback loop. As the temperature of the Earth's surface and atmosphere increases, so does the moisture-holding capacity of the atmosphere and atmospheric water vapour is expected to increase in a warmer climate. Both climate models and observations indicate that the column Integrated atmospheric Water Vapour (IWV) increases by about 7 % per 1 °C increase of temperature (Wentz & Schabel (2000), Allen & Ingram (2002), Trenberth et al. (2005), Held & Soden (2006)). Connected to such changes in the water vapour content are changes in the hydrological cycle, i.e. evaporation and precipitation Bengtsson (2010). The gradient in evaporation-precipitation increases proportionally to the lower tropospheric water vapour leading to larger differences between dry and wet areas. As a consequence, a good knowledge about the regional distribution of the water vapour content of the atmosphere is crucial as it ultimately determines the rate of precipitation.

Traditionally radiosondes and satellite observations have been used to observe the IWV. Gaffen et al. (1992), Ross & Elliott (1996) and Ross & Elliott (2001) found an upward trend in the IWV from radiosonde measurements from 1973 to 1995 over North America except for north-eastern part of Canada. For Eurasia they found increases over China and the Pacific Islands. Over the rest of Eurasia a mixture of positive and negative trends were found, with a tendency for negative trends over eastern Europe and western Russia. Trenberth et al. (2005) found that ocean satellite observations have a positive IWV trend of 0.40 kg/m^2 per decade from 1988 to 2003. However, despite a large radiosonde network the temporal resolution is low and differences in calibrations can give systematic errors in humidity (Wang & Zhang (2008), Wang et al. (2013)). Some remote sensing methods, observing in the infrared and the optical frequency bands, are limited to clear sky conditions. Other methods, using microwave remote sensing techniques, can be used also during cloudy conditions. On the other hand they only provide high accuracy over oceans (Trenberth et al. (2005)). GNSS and DORIS can provide IWV observations with high accuracy that complement radiosonde and satellite measurements (Bock et al. (2007), Wang et al. (2007), Bock et al. (2010)). As the time series of GNSS data grow longer they can also be used for the detection of trends and other systematic effects.

The capability of using GPS data to monitor climate changes (e.g. as a linear trends in IWV) has been investigated in a few studies only. The early attempts were made by Gradinarsky et al. (2002) who used data from 1993 to 2002 in Sweden and found very small linear trends. In their study, the largest trend was seen at Onsala (0.2 $kg/m^2/yr$), on the Swedish west coast, where nearby microwave radiometer data and radiosonde data confirmed the GPS estimates. Their study was completed by Nilsson & Elgered (2008), Jarlemark et al. (2010) and by Ning & Elgered (2012). These authors found IWV trends in the range from -0.5 to +1.0 kg/m^2 per decade for the same area, but different periods. They also studied several sources of uncertainty in the IWV trends due to natural variability of the IWV and errors in the GPS data (antenna phase centre variations, cut-off angle, multipath). Other studies provided IWV trend estimates and comparisons with independent data over specific regions (Morland et al. (2009), Sohn & Cho (2010)) or over the globe (Jin et al. (2009), Heise et al. (2009), Vey et al. (2010)). Most notably, Vey et al. (2010) found good agreement between GPS estimates of seasonal and inter-annual variations in IWV and NCEP (National Center for Environmental Prediction) estimates, except in the tropics and in Antarctica where the NCEP model underestimated IWV by 40 % and 25 %, respectively. Vey et al. (2009) also investigated the homogeneity of the long term GPS IWV series and showed that offsets up to $\pm$ 1 mm can arise due to changes in antennas and radomes and to sudden changes in the number of observations usually associated with failures in the equipment.

In addition, Yuan et al. (1993) and Stauning et al. (2003) demonstrated, using data from climate models, that ZTD is as sensitive to climate change as conventional properties like IWV. Using GNSS estimates for climate monitoring thus circumvents the use of auxiliary data to convert from ZTD to IWV.

The WG3 of COST Action ES1206 will focus on: 1) development of climate data record of GNSS tropospheric products suitable for analysing climate trends and variability and 2) evaluate the accuracy of NWP reanalysis products and climate models.

5. CONCLUSION

The new E.U. COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)" will foster the development of new GNSS processing techniques taking benefits of multi-observations from all satellite constellations currently available (i.e. GPS, GLONASS, Galileo) leading to new and advanced tropospheric delay products with improved latency, accuracy and reliability and providing more information on the atmospheric water vapour distribution. These new and advanced multi-GNSS tropospheric products will improve the understanding of atmospheric processes resulting in more accurate forecasting and nowcasting of severe weather. This will lead to improved hazard management, lowering the risk of loss of life and the risk to national infrastructure. The Action will also promote the use of long-term homogeneously re-processed GNSS-based tropospheric delay datasets for climate research, with a focus on climate-sensitive regions. Correct representation of water vapour in climate models is essential for improvement of global warming and precipitation projections on which the development of socio-economic response strategies are based. Finally, the Action will promote the use of meteorological data in GNSS positioning, navigation, and timing services and it will stimulate knowledge transfer and data sharing throughout Europe.

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