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APPLICATION OF GNSS TECHNOLOGY TO SOLVING METEOROLOGY PROBLEMS

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Abstract
The remote monitoring of atmosphere is designed to obtain information about the state of atmosphere. The principle of the remote monitoring of atmosphere is based on registering and processing of GLONASS/GPS radio signals. Modern networks of active reference stations allow us to solve both practical problems of geodesy, navigation, and purely scientific problems that are important in all geosciences. We propose to explore the existing infrastructure of national networks of active reference GNSS stations for remote sensing of the atmosphere in order to determine the water vapour content in the atmosphere as one of the major factors affecting weather.
Key words: GNSS observations, tropospheric delay, water vapour.

Introduction

The Earth's atmosphere is mainly divided into two main shells – the/ ionosphere and troposphere because distributions of satellite signals in these two parts are quite different:

- troposphere (neutral atmosphere) is the lower part of the atmosphere extended from the Earth's surface up to the altitude of about 20 km. Signal propagation depends mainly on temperature, pressure and water vapour content in the atmospheric layers. For the microwave wavelength the neutral atmosphere is not dispersed,
- ionosphere is the upper part of the atmosphere located between about 70 and 1000 km over the Earth. Free charged particles delay mostly the signal propagation. Ionosphere is a dispersive medium for microwave signals. Therefore, it is possible to eliminate the influence of the ionosphere on radio propagation by means of conducting observation on two frequencies.

A signal delay in the troposphere arises due to the presence of tropospheric nitrogen molecules, oxygen, carbon dioxide and water vapour. Under the influence of external radio wave, these molecules are polarized and create additional electrical currents in the troposphere. As a result, total currents are different from currents in vacuum that leads to reducing the phase velocity of radio waves, which depends directly on the concentration of molecules. Consequently, measurements of additional delay of radio signal propagation in the troposphere give information about the integral properties of the atmosphere along the propagation path of a signal. When processing observational data from the spacecrafts one can derive an additional information in the form of files of zenith tropospheric delay (ZTD) of radio signals registered by GNSS receivers. Because of the strong correlation between water vapour in the atmosphere and tropospheric delay of GNSS signals propagation, Integrated Precipitable Water Vapour (IPWV) in the atmosphere can be evaluated from GNSS observations. As it is knows, this parameter is crucial for weather forecasters (meteorologists) because water vapour content in the atmosphere is a key parameter in weather model.
The main purpose of this paper is to analyze the possibilities of using the capacity of network of active reference GNSS stations to solve problems of meteorology.

Methodology of research and materials

Modern GNSS networks provide a significant supplement to other geophysical networks (e.g. seismic, geodynamic, gravimetrical) due to their high precision, sensitivity to the duration of the observation period, ease of deployment, and the ability to perform measurements of deviations in the range from local to global scales.
Currently, research of troposphere by means of GNSS observations is directed towards a deeper understanding weather and climate processes, and ultimately improving weather forecast [1-3, 6-8, 10].
This method was initially used for numerical weather prediction in five countries, namely Germany, Switzerland, Great Britain, Sweden and Denmark. Today, in Central Europe, E-GVAP is an active project aimed to determine near real-time ZTDs from the regional network of GNSS stations. Its major computer center is located at the Royal Observatory of Belgium (ROB). Currently, the network consists of about 1,700 stations, most of them belong to the European Permanent Network (EPN) of EUREF [http://egvap.dmi.dk] and to the International GNSS Service (IGS) [http://igscb.jpl.nasa.gov].

At the EGU General Assembly, held April 7-12, 2013 in Vienna (Austria) was noted that in January of 2013 the E-GVAP-III has been launched which will run until the end of 2017. The main objective of the E-GVAP project is collecting and distributing estimations of atmospheric delays derived from GNSS observations for use in weather forecasting. Operation of E-GVAP is based on close cooperation of geodesy and meteorology.

Severe meteorological events (heavy rains and snowfalls, squalls, river floods, sudden changes of weather, hail, avalanches, mudflows, etc.) cause significant damages for economic sectors and population of Ukraine. Rising economic exploitation of coastal and hazardous flood areas, irrational human economic activity lead to growing number of objects and people being under risk of negative impact of unfavorable meteorological phenomena.

According to experts of the World Meteorological Organization (WMO), in the period from 1991 to 2010 around the globe, over 70% of losses and 90% of events happened when people were affected by natural disasters caused by severe hydrological and meteorological events. Ukraine is a member of the WMO. Obligations on Ukraine's participation in international organizations and treaties are impossible without data of meteorological observations and forecasts, as well as observations of environmental pollution provided by the National Hydrometeorological Service.

A basic activity of the Hydrometeorological Service is operation of integral state system of observation and forecasting. This is a complex multi-level informational system intended to systematic instrumental observations of weather conditions, atmosphere status, and atmospheric pollution by natural and man-made factors.

Unfortunately, the level of technical and technological equipment of Hydrometeorological Service of Ukraine lags behind the needs of the present and is much inferior compared to hydrometeorological services of not only developed countries, but of such neighboring countries as Poland, Romania, Slovakia.

The vast majority of 25,000 measuring instruments used by the Ukrainian meteorological service was developed 30-40 years ago, are obsolete and do not meet modern international standards, including the requirements of WMO and the International Civil Aviation Organization. More than 90% of measuring devices operate with extended service life, and about 50% are in urgent need of replacement (www.mns.gov.ua/laws/regulations/pub.../conception_gidromet.doc).

Such state of technical and technological equipment of Hydrometeorological Service causes particular concern due to increasing repetition and intensity of natural hydrometeorological phenomena in Ukraine, such as catastrophic floods on the rivers of Transcarpathia.

However, modern satellite information technology is not used in the meteorological service. Theoretical and applied aspects of hydrometeorological forecasting based on modern numerical models using computer and information technology require significant development.

The network of active reference stations, which is based on the modern RTK technology and is the most centralized, automated and high-tech infrastructure, helps to solve not only the practical problems of providing coordinate basis but also purely scientific problems being important in all geosciences.

Thus, in order to study atmospheric conditions and to forecast weather, it is necessary to carry out simultaneously and systematically different observation in many points on large areas. In the United States every hour and in Ukraine every three hours, the weather monitoring is carried out. The cloudiness (its density, altitude and type) is characterized; indicators of barometers are observed and supplemented by corrections intended to bring derived values to sea level; direction and wind speed are observed; amount of liquid or solid precipitation, humidity, temperature of air and soil are measured; visibility conditions and other atmospheric phenomena (e.g. storms, fog, etc.) are carefully recorded.

Atmospheric processes develop chaotically. This means that different approaches are required for the prediction of various phenomena in a various space-time scale, particularly for forecasting behavior of large cyclones in temperate latitudes and local heavy rains as well as for long-term forecasts.

Operative forecast is usually based on observations of relative humidity along with pressure and temperature, determined by means of radiosondes and surface meteorological instruments. Radiosondes are launched twice a day and determine the profile changes of atmospheric pressure, air temperature and relative humidity in the atmosphere. One of the main disadvantages of a radiosonde is the relatively low accuracy of its sensors due to contamination during startup.

On the other hand, the amount of water vapour can be determined by radiometers. Radiometers usually provide very accurate data, but the measurements are unreliable during rain, and this

instrument is too expensive. In addition, radiosondes and ground-based or space water vapour radiometers are separated by considerable distances and measurement discreteness is low. Thus, the spatial and temporal distribution of existing measurement methods is of low density and depends on weather conditions.
Thus, there is a need for further development of methods and means of remote sensing of the atmosphere, which on the one hand, would provide high-accuracy measurements of humidity, and on the other hand, would be accessible, reliable, simple and inexpensive in operation.
An advantage of the method of remote sensing of the atmosphere is a possibility of its implementation on the existing GNSS infrastructure (network of active reference stations with single control center), and the fact that these measurements do not depend on rainfall and the presence of clouds. The developed infrastructure of reference stations in Ukraine allows identifying and predicting changes in the dynamics of the water vapour in the atmosphere and thus rainfall in real time to be used at timely forecasting of natural disasters, environmental and climate monitoring.
Use of operative information on the content of water vapour in the atmosphere in numerical weather prediction models will allow to improve data detailization and accuracy of regional short-term weather forecasts, because one can assume that at GPS observations the radio signal passes through Earth's atmosphere immediately. That is the real state of unstable atmosphere is taken into account. Owing to continuous GPS measurements occuring every second, we can expect high measurement accuracy of precipitable water vapour.

Discussions and results

The Transcarpathian Positioning Service ZAKPOS is a local initiative and project of installation of uniform basic infrastructure of differential GNSS (DGNSS) in the Zakarpatska Region with computing center in Mukachevo. Regular GNSS observations at reference stations of ZAKPOS network were started on February 4, 2009 [5].
In geodesic sense, network of active reference stations is a densification networks of permanent stations network. These networks differ in their tasks, accuracy, infrastructure, etc. A network of permanent stations is actually as a basic fundamental network designed to solve scientific and technical problems of the highest accuracy. A network of active reference stations based on RTK technology is able to obtain objective data having object-positioning accuracy of a few centimeters in a single coordinate system and to solve complex issues, primarily of qualitative geodetic providing land-cadastre works.
In mid-2010, ZAKPOS network consisted of 17 stations, by the end of 2010 - 28 stations, and eventually it has became a nationwide network under a new name UA-EUPOS/ZAKPOS [www.zakpos.zakgeo.com.ua]. Today, the network of active reference stations UA-EUPOS/ZAKPOS process data from nearly 90 GNSS stations located on the territory of Ukraine, Poland, Slovakia, Hungary, Romania and Moldova. The use of unknown tropospheric parameters when processing satellite observations allows getting values of tropospheric delay for each reference station of the network. In many countries, similar networks operate, closest of which are SKPOS (Slovakia), CZEPOS (Czech Republic), APOS (Austria), SAPOS (Germany), ASG-EUPOS (Poland) and others networks of active reference stations.
After initial processing of GNSS measurements, distances from observation site to GNSS satellite are determined. A secondary processing of GNSS measurements is to solve navigation problem and provides information on the station location. In order to derive meteorological information it is necessary to develop special methods of secondary data processing, based on the solution of inverse problems.
Only problems of tropospheric delays estimation from permanent GNSS stations have led to creation of a new scientific direction – GNSS meteorology. One of the objectives of GNSS meteorology is the use of ZTDs from regional network of permanent GNSS stations for numerical weather prediction (NWP) [6].
Evaluation of troposphere parameters can be done in two ways [4]:

- by processing of "raw" data of GNSS observation obtained from network of active reference stations;
- by means of ready tropospheric delays obtained from a network software which manages such networks.

The determination of ZTD was traditionally based on the analysis of data in mode of packet network solution using the least squares method and the method of observation that is based on the formation of double differences (DD) [11]. However, in recent years GNSS meteorology exploitates intensively the method of Precise Point Positioning (PPP) [9], the implementation of which requires access to accurate satellite clock corrections together with predicted orbits.

A result of the joint work of Uzhhorod National University (Lead Partner) and its partners – University of Miskolc (Miskolc, Hungary), Vihorlat Observatory (Humenne, Slovakia), Association Center for Research, Innovation and Technology Transfer "NORDTech" (Baia Mare, Romania), and International Association of Regional Development Institution "IARDI" (Uzhhorod, Ukraine) was the project HUSKROUA/1101/252 [www.gnssnet.hu]. The system of remote monitoring of atmosphere on the cross-border area is processing observations from 38 active reference stations networks of neighboring countries. During the construction and operation of the system of remote monitoring of atmosphere is assumed that the satellite data from networks of active reference stations UA-EUPOS/ZAKPOS and meteorological data from weather stations collected on the cross-border area are processed by the Alberding GNSS Status Software. The Alberding GNSS Status Software package uses streams of input data from reference GNSS stations in real time and PPP processing approach for determination of ZTD for each station separately (https://www.alberding.eu/en/GNSSStatus.html). This package is based on the ALBERDING EURONET software module and uses additional external software real-time components of orbit and clock corrections: RTCM3EPH, IGS01, CLK11. From point of view of strategy of GNSS data processing, the PPP method is popular due to that International GNSS Service (IGS) and other organizations create products such as the precise satellite orbit and clock corrections in real-time (RT).

Currently, data from 38 active reference GNSS stations and meteorological data are processed in three analysis centers: one for monitoring the parameters of the troposphere in real time (Uzhhorod National University), one for the analysis of parameters of the atmosphere in near real-time (University of Miskolc), and one in post-processing mode (National University "Lviv Polytechnic").

The analysis center of University of Miskolc uses the Bernese GNSS Software v. 5.2 package. ZTD determination in this software is based on the analysis of data in mode of packet network solution. At its application the following values: station coordinates, phase ambiguities, values of ZTD, ZWD, IPWV and horizontal gradients of the troposphere are unknown. Since coordinates of stations of GNSS networks are closely correlated with the values of ZTD, derived coordinates are corrected later through taking into account ZTD (second step) in near real-time.

The computer center of UA-EUPOS/ZAKPOS network uses network software of the Trimble Inc. (USA), one of the world leaders in the field of GNSS technologies.

Currently, GNSS infrastructure of Trimble Inc. has two new software applications:

- Trimble VRS³Net™ App,
- Trimble Atmosphere App.

Trimble VRS³Net™ App is the latest version of Trimble VRS³Net. The VRS³Net™ App software provides operators of active network of basic GNSS stations with highly integrated set of tools needed to manage the network.

Trimble Atmosphere App is a new infrastructure performing calculation and analysis of integrated precipitable water vapour (IPWV) and total electron content (TEC) in the ionosphere. This module is able to calculate atmospheric conditions basing on GNSS observations and meteorological data from weather stations, radiosondes etc. Trimble Atmosphere App is completely supported by current Trimble infrastructure strategy and is based on VRS³Net technology.

A peculiarity of Trimble Atmosphere App is the module allows one to calculate both IPWV and TEC not from separated GNSS stations but from a network of permanent stations. Here IPWV is calculated using ground-based meteorological data such as temperature and pressure, as well as radiosonde data.

In order to derive independent estimation data, analysis center located at the National University "Lviv Polytechnic" carries out comparison of two different approaches to the study of GNSS observations, namely DD and PPP in their software implementations: Bernese GNSS Software and Alberding GNSS Status Software, respectively, and two additional software products based on the formation of double difference (DD): Atmosphere App software module of Trimble Pivot Platform and GAMIT/GLOBK software package [4].

Mean monthly results of the comparison of these four software products for 10 GNSS stations have showed that the average differences are less than 1 cm, and their mean-square deviations are in the range 0.6-2.3 cm [4].

Consequently, according to the comparison results, the authors have concluded that the use of different strategies of GNSS data processing does not make a significant impact on accuracy of zenith

tropospheric delay. The derived estimations of 1-2 cm meet the requirements of numerical weather prediction (NWP) to evaluate the accuracy of ZTD for the current weather forecast. It is because it is theoretically believed that in GNSS meteorology, the precision of ZTD is in the range from 3 to 10 mm, and NWP requirements to evaluate the accuracy of ZTD for the current weather forecast are ranged from 6 to 30 mm [12].
Currently, there is the possibility of estimation of ZTD and cosequently the tropospheric water vapour content in real time of 1-minute increments in the active network reference stations (see Figs. 1 and 2). After processing these data, the dynamic map of changes of atmospheric delay and precipitable water vapour in the area are obtained in real time (4D measurements of PW (IWV) field).

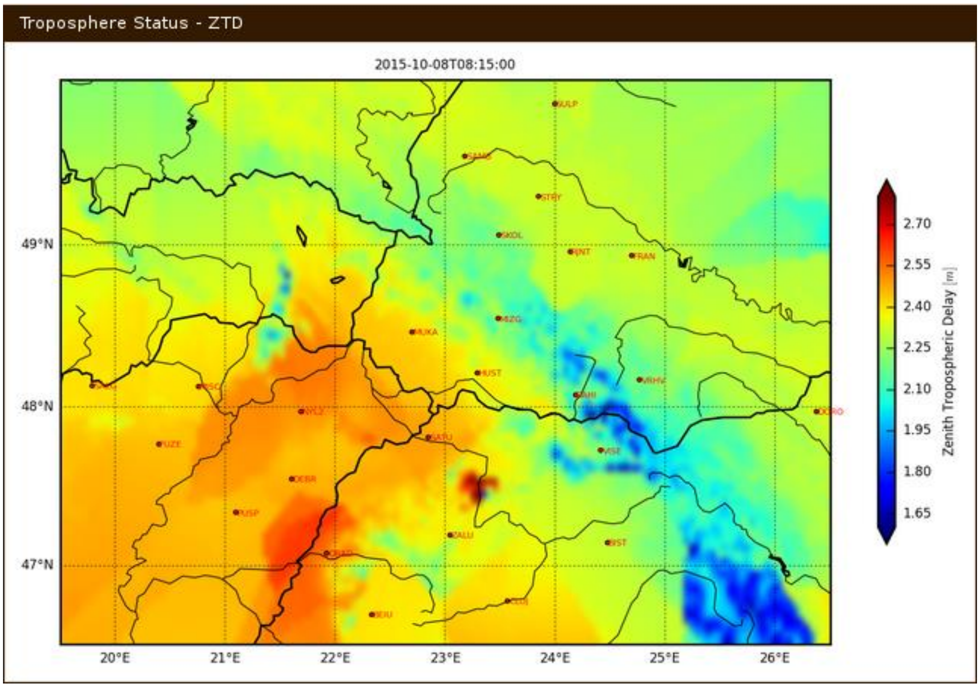

Fig. 1. Spatial (latitude - longitude) distribution of zenith tropospheric delays (ZTD) on 2015-10-08, 15.00 UTC from the Alberding GNSS Status Software

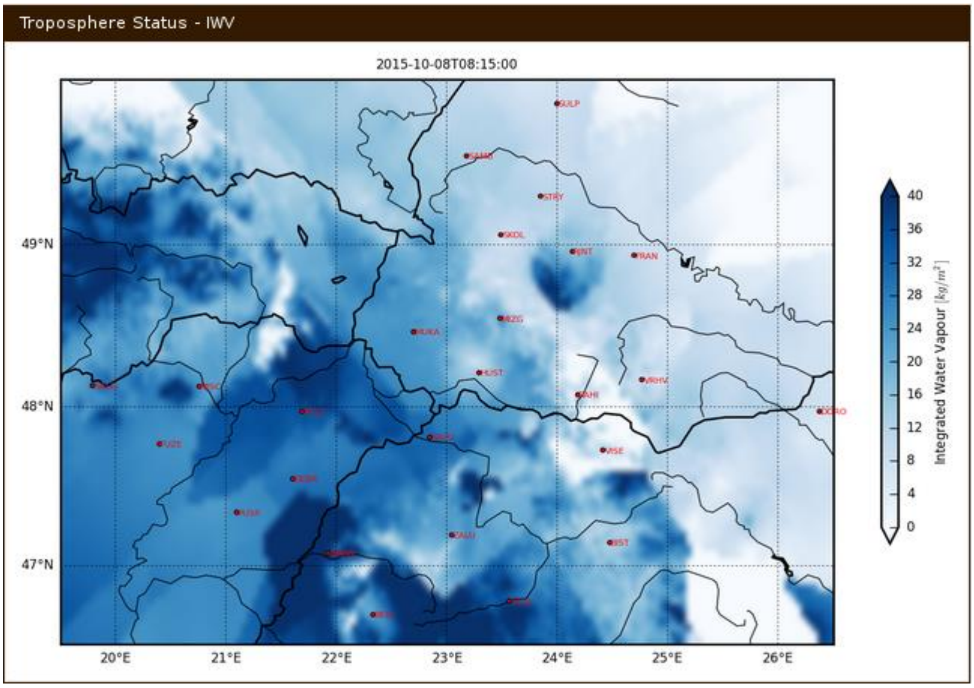

Fig. 2. Spatial (latitude - longitude) distribution of integrated water vapour (IWV) on 2015-10-08, 15.00 UTC from the Alberding GNSS Status Software

The spatial and temporal distributions of ZTD and IWV content in the troposphere obtained from the network of active reference stations in real time can be valuable information in the field of operational numerical weather prediction.

Conclusions and proposals

Operational efficiency of this approach, complete automation and the lack of supplies when carrying out remote sensing open possibilities to wide implementation in practice of continuous and operational monitoring of atmosphere status in order to improve data detalization and enhance accuracy of regional short-term weather forecasts.

GNSS observations in ZAKPOS / UA-EUPOS network and use of cross-border cooperation between European countries allow us to have a precise, dense and frequent sample of IWV values in large areas as well as to identify and predict the dynamics of water vapour change in real time.

The remote monitoring of the atmosphere creates a powerful system and basis for cross-border cooperation in the direction of increasing accuracy of forecast of severe meteorological events in the cross-border territory (heavy rains and snowfalls, hail, icing, heavy squalls, etc.), prediction of dangerous natural phenomena (floods, mudslides, landslides, avalanches in the mountains) and related environmental disasters (ingress of sewage into the river, sources of drinking water, the threat of dangerous infections, pollution, etc.). Therefore, the larger area of study, the forecast will be more accurate.

It should be also noted that the monitoring of water vapour in space and time using GNSS (i.e. GNSS meteorology) could have the following applications:

1. The identification of the current weather and short-term weather forecasting.

Combining GNSS measurements of water vapour (IWV fields derived from GNSS and their time series), upper-air sounding of atmosphere and radar meteorological data can improve the understanding of processes occurring in the atmosphere.

2. Numerical weather prediction (NWP).

Comparing GNSS time series of water vapour and numerical data of weather forecast determined by other methods, one can detect errors in NWP models to be useful for calibration of these models and control of their operation. In addition, GNSS data fill in a gap in observations of humidity due to the presence of some problems in determining the current meteorological data.

3. Climate applications.

GNSS observations are a unique, consistent, reliable and long-term data source being able to improve the monitoring of changes in global climate.

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