# HUNGARIAN CONTRIBUTION TO THE RESEARCH ON POSITIONING AND APPLICATIONS (2015 - 2018) - IAG COMMISSION 4

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## 1 Introduction

The period of 2015-2019 brought many new results in the research of positioning techniques and the application of geodesy for engineering. The hottest topics are the application of continuously operating GNSS receivers for atmospheric remote sensing as well as the modelling of tropospheric delays in satellite navigation; the assessment of the integrity of satellite positioning services for safety-of-life applications such as airborne navigation; the localization of autonomous vehicles using GNSS/IMU/Lidar and sensor fusion techniques; the application of InSAR data for the estimation of cristal displacement. These research activities were carried out by the following research institutes: the Department of Geodesy and Surveying and the Department of Photogrammetry and Geoinformatics of the Budapest University of Technology and Economics, the Institute for Computer Science and Control and the Geodetic and Geophysical Institute of the Research Center of Astronomy and Earth Sciences of the Hungarian Academy of Sciences and the Satellite Geodetic Observatory at Penc.

The next sections introduce the most important results achieved in each topic. Due to the limitations of a review paper, further details can be found in the cited publications.

## 2 Remote sensing the atmospheric water vapour using GNSS

Continuously operating GNSS stations can provide valuable information on the spatial and temporal distribution of atmospheric water vapour. In 2013 a near-realtime GNSS processing facility was set up by the collaboration of the Satellite Geodetic Observatory Penc (SGO) and the Budapest University of Technology and Economics (BME). The applied computational strategy can be found in Rózsa et al. (2014). The processing center (SGOB later renamed to SGO1) joined to the EUMETNET's E-GVAP programme in 2013. Since then the ZTD estimates at the stations of the Hungarian GNSS Network are available for meteorological applications.

Hungary, with its representing institutions BME, SGO and the Hungarian Meteorological Service participated in the COST Action ES-1206 (GNSS for Severe Weather and Climate - GNSS4SWEC) studying the application of ground based GNSS observations for climatic studies and the modelling and forecasting of severe weather.

In the recent years Juni and Rózsa (2018) developed a new global model for the conversion of GNSS derived zenith wet delays (ZWD) to integrated water vapour (IWV) using a global archive numerical weather model dataset. The aim of this study was to provide an optimal solution for the conversion of ZWDs to IWVs, that takes into consideration the geographical variations of empirical conversion factors, since many recent studies still use the empirical models derived from North-American radiosonde observations. The studies showed that the coefficients of the empirical functions show a strong geographical variation. The conversion algorithm and data set is available at http://gpsmet.agt.bme.hu/zwd2iwv.

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In Meteorology, the various atmospheric parameters are assimilated in numerical models. The first results of the application of GNSS derived ZTDs in numerical weather models in Hungary and the Carpathian Basin was reported in Mile et al. (2019). The results showed that the assimilation of GNSS ZTDs have a positive impact on the prediction of relative humidity as well as on the temperature. A significant improvement was observed in the short-term predictions (up to 5 hours) with a rather neutral on the longer predictions.

## 3 Studying the integrity of GNSS positioning

In safety-of-life navigation applications of GNSS the major concern of the user is not only the accuracy but the integrity of the positioning service. To assess the integrity, the protection level is calculated by overestimating the positioning error even at very rare probability levels. Recent studies show that - by the emerging multiple frequency civilian signals - the tropospheric delay becomes the most significant error source especially at low elevation angles. The RTCA MOPS (minimum operational performance standard) for GNSS systems in aeronautics specifies a global constant of ±0.12m for the maximum tropospheric residual error in the zenith direction in terms of standard deviation. Recent studies suggest that this value is too conservative in many regions of the globe leading to lower availability and continuity of the positioning service (Rózsa et al. 2017). To overcome this limitation, a new residual tropospheric error model was formulated in the frame of a ESA funded project by the colleagues of the Department of Geodesy and Surveying of the Budapest University of Technology and Economics together with the Hungarian Meteorological Service and Integricom.NL, that considers both the geographical and the seasonal variations of the tropospheric delay model performances. The advanced residual tropospheric delay error model (ARTE) was developed using the methodology of extreme value analysis of existing tropospheric delay models using 16 years of worldwide numerical weather model analysis (Rózsa 2018). The studied tropospheric delay models were the RTCA troposphere model, the ESA GALTROPO model and the GPT2W model.

The developed ARTE model was validated globally using IGS ZTD estimates, radiosonde observations and numerical weather models. Moreover they were tested in a case study under real extreme weather conditions in Central-Europe (Juni and Rózsa 2018). The results showed that the performance of the studied tropospheric delay models show strong seasonal variations (Figure 1-3). Thus various integrity models were formulated for the positioning applications. The most complex one considers both the seasonal and the geographical variations, while a simplified model was also developed that considers the geographical variations only. Finally a global constant model was also formulated that complies fully with the existing RTCA recommendations. The validation proved that the proposed model maintained the conservatism of the original model, nevertheless it provided a significantly lower residual error estimate in many regions of the globe (Figure 4). Among the studied three tropospheric delay models, GPT2W and ESA GALTROPO models provided significantly lower protection levels compared to the RTCA recommendations, that also means that the application of the developed models could improve both the availability and the continuity of satellite navigation services in safety-of-life applications.

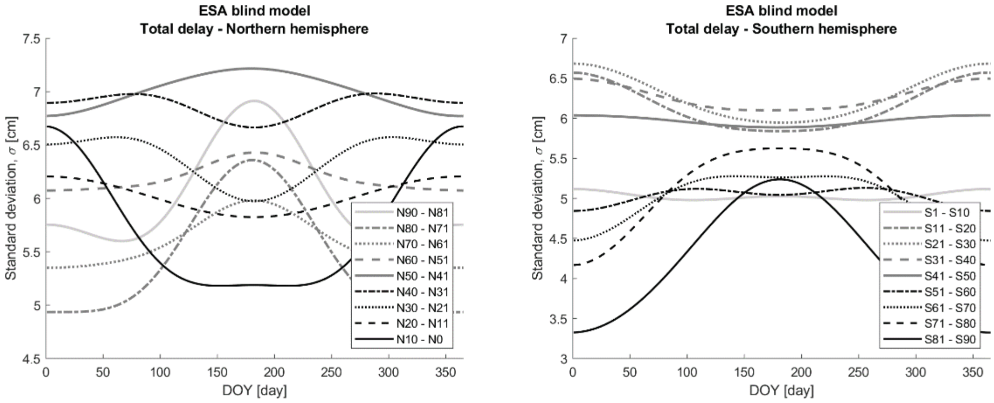


**Figure 1**. The seasonal variation of the sigma value of the ESA blind model in the different latitude bands

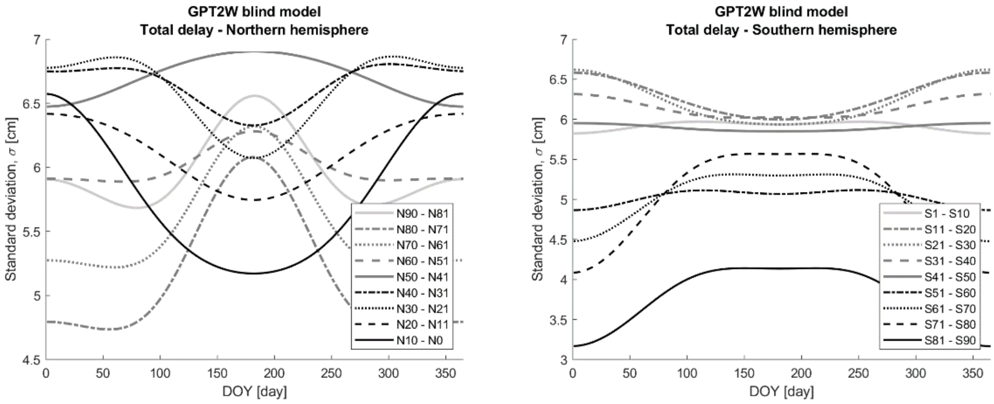


**Figure 2**. The seasonal variation of the sigma value of the GPT2w blind model in the different latitude bands

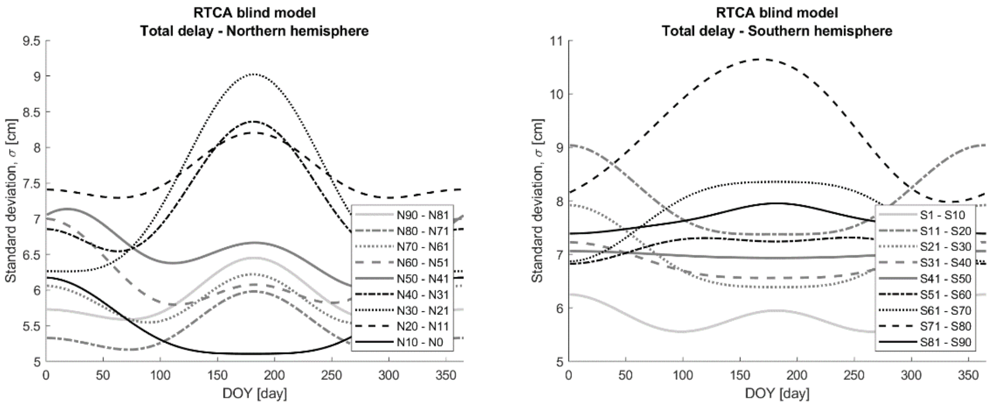


**Figure 3.** The seasonal variation of the sigma value of the RTCA blind model in the different latitude bands

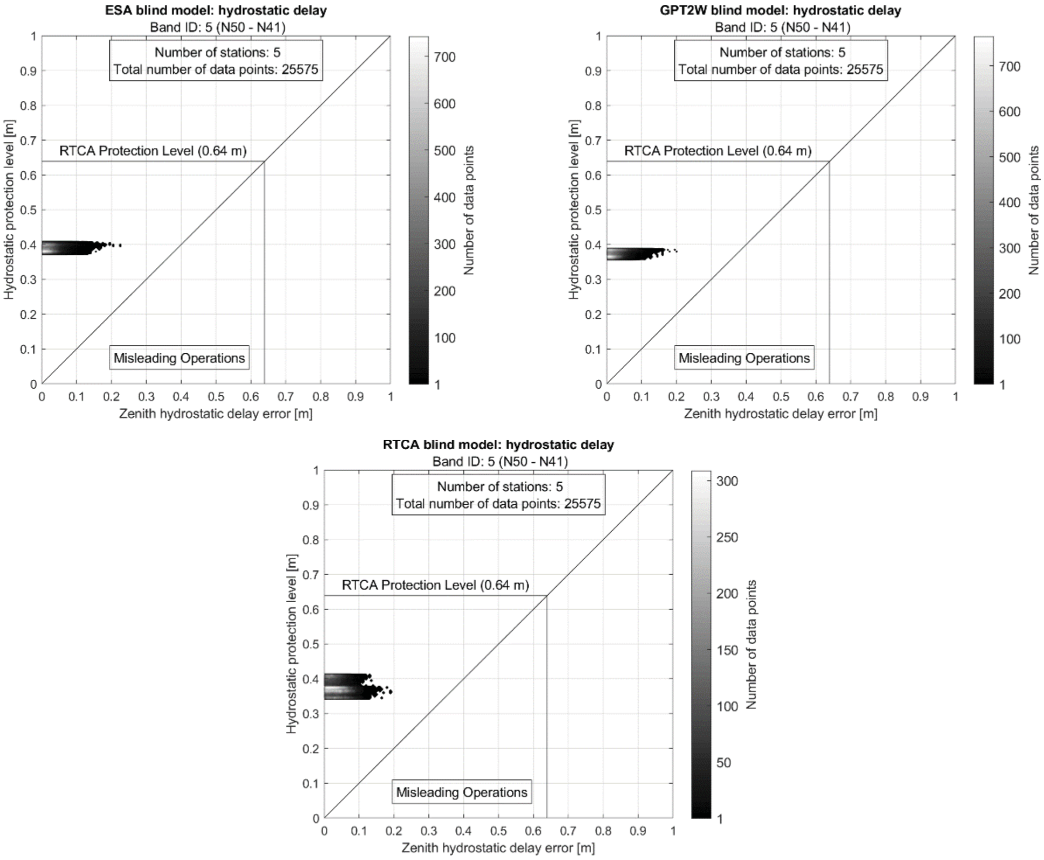


**Figure 4.** Validation of the residual tropospheric delay model using IGS ZTD products for the latitude band of N41°-N50°

The evaluation and monitoring of the integrity of GNSS positioning is inevitable for air traffic service providers and is an important research area (Markovits-Somogyi et al. 2017), too. In order to provide these professionals with open source software solutions, the well-known RTKLIB package (Takasu 2009) was extended with the calculation of protection levels based on the RTCA recommendations (Takács et al. 2017). The developed algorithm was tested with the commercial Pegasus and magicGemini softwares.

## 4 Position and orientation determination of autonomous platforms

The sensor fusion methods are getting more indispensable in the navigation. This information is the key of the high accuracy control of the moving platform used for mapping tasks. Although the low-cost inertial (INS) and Global Navigation Satellite Systems (GNSS) sensors are widespread, these equipment suffer from various significant error sources, which influence usability. The inertial sensors have bias, bias instability error, the single frequency GNSS receivers have clock error, multipath, inter-channel biases and the unknown integer ambiguity values of the carrier-phase measurements. Usually the higher sampling rate (50-2000Hz) of the inertial sensors complement the lower sampling rate (1-20Hz) of GNSS observations. The aim of a sensor fusion system is to provide high rate and high accuracy navigational data of the moving platform.

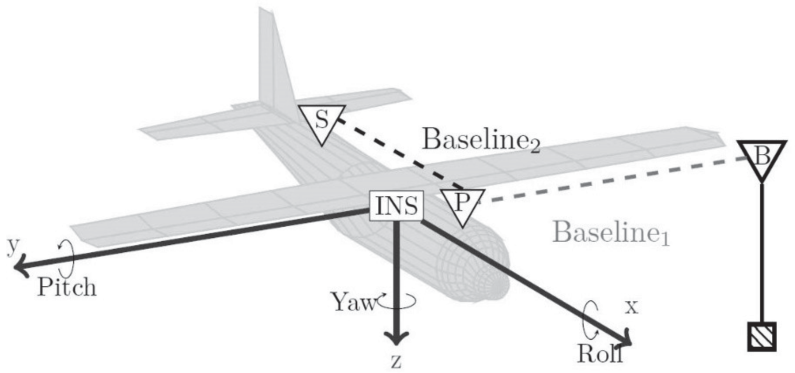


**Figure 5.** The onboard sensors (P, S: primary and secondary GNSS receivers; INS: inertial navigation sensor) of the UAV and the ground reference receiver (B)

Farkas et al. 2018 investigates a multi baseline GNSS positioning and attitude determination method, using low-cost differential GNSS, accelerometer and gyroscope data. The attitude angles are represented in quaternion form. The tightly coupled sensor fusion is accomplished by an EKF algorithm. The moving baseline's integer ambiguities are resolved by a quaternion constrained LAMBDA method. That sensor fusion method was based on inertial sensor data and non-differential GNSS code and Doppler measurements.

The key of the high accuracy GNSS positioning is to resolve the integer ambiguities of the carrier-phase measurements. The developed uses the least-squares ambiguity decorrelation adjustment method. The integer ambiguity resolution is applied only for the GPS measurements on both baselines.

The integer ambiguity resolution is different at the moving baseline. Giorgi and Teunissen (2010) use baseline length constrain, and a rotating matrix constrain based on Euler angles. Since our approach uses quaternion representation, the original ambiguity resolution method had to be modified with the constrain that the norm square of the quaternions is equal to one. The optimum is the integer ambiguity conditional quaternion vector, which has the smallest distance in the metric of the conditional covariance matrix with the norm square of one.

The method was tested with real flight data. The duration of the flight was nearly 3000 seconds. The base, the primary and the secondary receivers were u-blox NEO-M8T single frequency low-cost GNSS receivers with Tallysman 33-2405-05-0150 antennas (Figure 5).

These receivers were collecting GPS and GLONASS data. Integer ambiguities were resolved for GPS satellites, while float ambiguities were used for the GLONASS constellation. The maximal length of the first baseline was 11 kilometres and the second baseline was 0.29 meters long. The UAV was equipped with a PIXHAWK flight control computer with INS sensors, and a Sony ILCE-6000 camera for photogrammetric service. The onboard flight controller system uses a loosely coupled sensor fusion algorithm based on a single GNSS receiver and the INS sensor. The camera took 1200 pictures during the flight. The collected GNSS data was post processed with using the PPK technique for the position. Attitude angles were also estimated from the photogrammetric processing (PGP) of aerial images with known ground control points (GCPs) using the Pix4D software.

The developed EKF algorithm was used to process the raw INS and GNSS from observations. The position solution is compared to the PPK solution, and the attitude angle solution is compared to the PGP solution in the common epochs. Figure 6 depicts the comparison of the PPK and the EKF coordinate solutions. The mean value of the horizontal differences during the whole measurement is 0.007 meters in north and 0.002 meters in east with the root mean square (rms) value 0.01 and 0.003 meters. The mean vertical difference is -0.053 meters with 0.055 meters rms error. The ambiguity success rate is 99.12% for the first baseline.

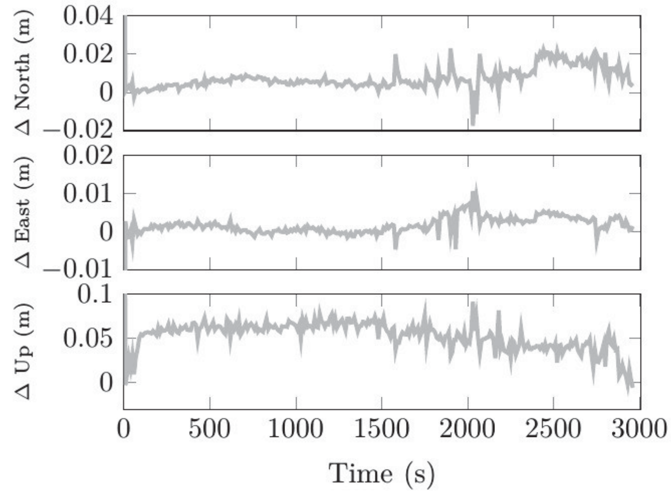


**Figure 6.** The comparison of the post-processed kinematic and the EKF sensor fusion coordinate solutions

Figure 7 depicts the comparison of the attitude solutions provided by the PIXHAWK onboard flight controller system and the developed EKF algorithm using the PGP orientation angles as references. The roll angle is estimated only by the angular velocities because there is no $y$ axis lever arm component between the antennas of the moving baseline in the body coordinate frame. The two solutions have similar error magnitudes compared to the PGP results. However, the GNSS attitude estimation reduced the bias in the pitch angle compared to the PIXHAWK solution significantly. Moreover, the improvement in the yaw angle is significant, too. Moreover, the trend between 1500-2500 epochs is completely removed from the residuals. The mean value of the differences from the PGP solution is 0.27° with 0.62° rms compared to the PIXHAWK's mean value -3.06° with 3.52° rms. This result can be explained with the applied measurement configuration. Since GNSS observations provide lower accuracy in the vertical direction, its effect on the pitch angle is expected to be significantly lower than on the yaw angle. The ambiguity resolution success ratio for the moving baseline is 97.35%.

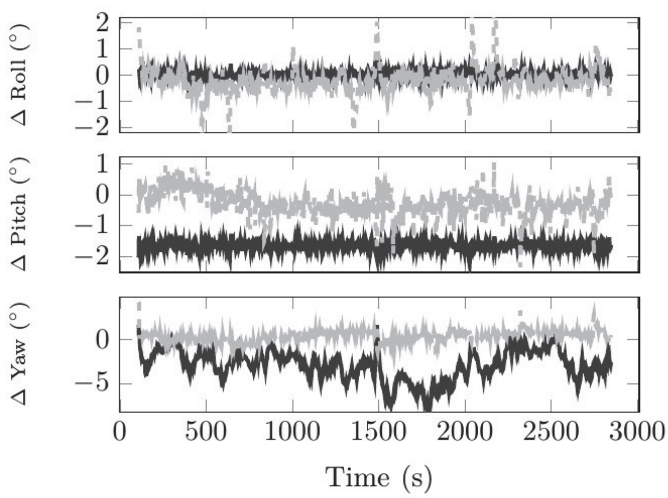


**Figure 7.** The comparison of the attitude solutions of the onboard flight controller and the developed sensor fusion algorithm wrt the photogrammetric processing (red: onboard sensor, green: developed EKF sensor fusion algorithm)

## 5 Supporting autonomous navigation by 3D maps

Intensive research has been conducted in the field of automated driving. The development of self-driving vehicles is a very hot topic in vehicular research currently. Such vehicles require effective and reliable decision mechanism to control the movement, which is expected by the development of artificial intelligence (AI). Beyond the AI-controlled driving, these vehicles have to collect very detailed information about their neighbourhood, that is realized by cutting-edge sensors, like vehicular Lidars, cameras and radars. Further data capture mechanisms are also welcome to increase the redundancy and reliability. Vehicles are nowadays already equipped with satellite based positioning systems, sometimes even with inertial measurement units, but there are still circumstances, when this technology has troubles in accuracy or even totally fail (urban canyons, tunnels etc.). In such situations alternative solutions are required, where prior captured 3D map data can help.

To establish highly detailed accurate 3D map database, several surveying technologies are involved. Among them terrestrial laser scanning and mobile mapping are the two flagship tools (Potó et al. 2017b, Potó and Barsi 2017a). Data acquisition by these modern technologies results huge amount of field data, which is the base not only for traditional mapping but also to derive products being able to support automated driving. The 3D map data is mainly point clouds (mostly colored, but at least with signal intensity values) and CAD models (created by the evaluation of the field surveys). New data sources are urban models, pavement descriptions or lane models. All these products can be extracted from the map data base (Potó et al. 2017a, Barsi et al. 2017, Potó and Barsi 2017b).

Scientific results of the last decades can be summarized in the data processing chain and development of non-existing neighbourhood model descriptions. Lane models, navigation aids or static occupancy maps are the most relevant new findings. The research group has focused on the collaboration with car maker industry, where simulator software packages can be fed by data taken from the reality. Strong efforts were made therefore in producing standard simulator inputs. The most important results were achieved with the OpenCRG models, where CRG stands for Curved Regular Grid. It is an efficient and highly potential model to bring information about the pavement surface.

## 6 Recent Application of Synthetic Aperture Radar Interferometry

The interferometric SAR observations play an important role in the monitoring and the analysis of recent crustal displacements in the Central-Europe, too. The Carpathian bend is amongst the tectonically most active areas in Europe where intraplate subduction triggers sub-crustal earthquakes releasing significant amount of seismic energy in a well-defined seismic zone. To constrain the deep processes by exploiting their linkage to the surface processes knowledge of surface deformations is required. Detection of small-magnitude tectonic processes with high reliability is challenging in which the recent space geodetic techniques may bright a breakthrough. A retrospective analysis of archive Envisat data set of the European Space Agency acquired in the frame of ESA CAT-1 project was used to investigate the feasibility limit of detecting crustal deformations in the region of the south Carpathian bend (Bozsó et al. 2017, Bozsó et al. 2018a, Szűcs et al. 2018), where past geodetic observations failed to unravel the tectonic processes with high details. Despite the inherent limitations of radar interferometry the results show that coherent velocity field can be estimated with a magnitude of few mm/yr. The vertical displacement suggest subsidence in the Brasov basin which is in agreement with former studies, however radar interferometry can provide more detailed picture.

In the framework of Integrated Sentinel-PSI and GNSS technical facilities and procedures for the determination of 3D surface deformations caused by environmental processes (4000114846/15/NL/NDe) ESA project the use of space geodetic methods and developments in the observation of tectonic processes was studied. So-called integrated benchmarks, equipped with GNSS adapter and corner reflectors for descending an ascending satellite passes, have been developed (Bányai et al. 2018), that provide a long-term stable reflection for Sentinel-1 twin satellites. Using exclusively the satellite observations of Sentinel-1, the surface deformation field in 3D can only be determined with bias. Therefore a process based on Kalman filtering has been developed, that combines the absolute positioning provided by global navigation systems with relative surface changes based on interferometric processing of Sentinel-1 images (Bányai et al. 2017a, Bányai et al. 2017b). With this, it is possible to produce high-precision, 3D, absolute deformation data time series from the integrated points. Radar reflector networks can be utilized in areas where the traditional radar interferometry cannot be applied successfully. The developed procedure and benchmarks were tested (Bozsó et al. 2018b) in areas subjected to landslide of different intensity and characteristics (spatial distribution and time dependence) and proved its effectiveness.

## 7 Geodetic monitoring and early warning systems

At the Department of Geodesy and Surveying of the Budapest University of Technology and Economics a software system called Ulyxes has been developed for geodetic monitoring and early warning systems. Ulyxes is an open source project to drive robotic total stations as well as other sensors, collect their measurements in database and finally publish the results for authorized users on the web. On special requests the results are also presented with web based maps in the background (Siki 2015).

This project is like an instant coffee: three in one (coffee, sugar and milk). The coffee and the strongest part is the research and coding. The sugar is the application of the program in industrial environment and the milk on the top is the educational usage. The software development started in 2008 connected to a monitoring task in the Hungarian Nuclear Power Plant. Since then the development has been extended from total stations to different positioning capable sensors.

In 2012 the development of a new Python based object oriented framework started. The code is based on the results of some other open source projects, Python, PySerial, GNUGama, SQLite, OpenCV, etc. After connecting to the international Geo4All network in 2014, Ulyxes became a project of our Geo4All Lab. The project has its own home page (http://www.agt.bme.hu/ulyxes) and the source code is available on the GitHub portal (https://github.com/zsiki/ulyxes). The code is maintained by the colleagues at the Department of Geodesy and Surveying at the Budapest University of Technology, volunteers from all over the World are welcome. BSc and MSc students are also involved in the development and testing. More theses were connected to this project in the recent five years.

In the curriculum of an MSc subject called Surveying Automation, Ulyxes is used to demonstrate automatized tasks in engineering surveying. The system has been applied for several projects during the last 10+ years. Typical applications are the load tests of bridges and other engineering structures and on the other hand Ulyxes can be used to monitor the movements of buildings in the nearby of constructional works, like metro stations, underground garage and other buildings as well.

The source code is divided into three parts. The first one is the Ulyxes API which is the core of the system. The second one, Ulyxes Apps is a collection of applications based upon the API. The third part is the server side scripts to publish observation results through the Internet. The software has been extensively used in various monintoring and early warning systems (Kovács et al. 2016, Siki et al. 2018).

## 8 Geo-spatial mapping for engineering geology

Research has been conducted to support engineering geological studies with advanced geospatial mapping technologies (Terrestiral Laser Scanning – TLS and Remotely Piloted Aircraft System – RPAS). These techniques were used to obtain data on terrain morphology and to provide highly detailed geometry.

The investigations began with the survey of Sirok Castle and the cliff faces in its surroundings in 2016 (Török et al. 2016). The purpose of the study was to map the geologically dangerous areas, which led the strengthening of these areas. The investigation included both geology (field and laboratory) and remote sensing measurements, which were jointly processed in FEM analyses. The point clouds obtained by spatial data acquisition were processed both separately and combined to test their applicability and to minimize the obscured surfaces. The spatial models proved to be suitable for providing information (e.g. through spatial sections) on steep, hardly accessible, extremely complex areas.

Later in 2017, measurements have been carried out in the Sárbogárd mine, which aimed to determine the dominant slips and layers and assess the potential of utilizing the intensity values obtained from laser scanning (Török et al. 2017). Also in an open pit mine in Bükkösd in 2018 the planning of the extraction of the coming years were supported by TLS and RPAS measurements (Török et al. 2018).

## 9 Conclusions and outlook

This paper introduced the most important achievements in the field of positioning and the application of geodesy in engineering in the past 4 years. Based on the reviewed results, one can see that the area of positioning is still in the forefront of actual research activities. The emerging techniques such as the introduction of autonomous driving inevitable relies on localization techniques and positioning services. Thus more and more accurate and reliable models are needed to take into consideration the systematic effects contaminating the position solution. Moreover, an optimal localization technique needs to be available under all circumstances. Not only under the clear sky, but also in urban canyons, underground, etc. Therefore the development of localization techniques of autonomous vehicles must rely on various, complementing positioning sensors and apply a proper sensor fusion algorithm to achieve the best results.

In the next years the introduced research topics will have a growing importance. Autonomous driving needs not only accurate, but also reliable positioning solution. Although the integrity assessment techniques exist for aerial navigation, these techniques need to be tailored to ground based applications. That is certainly one of the key challenges of the next four years.

Moreover, the understanding of Earth processes will remain in the forefront of geodetic research. The monitoring of the changing climate, the prediction of more and more frequent severe weather event require the combined assessment of all available observations of atmospheric parameters. A relatively new research field in this area is the study of the properties of the reflected GNSS signals to estimate further geophysical and hydrological parameters such as soil moisture, snow coverage, water levels, etc.

The availability of free InSAR imagery will further improve the understanding of surface processes, such as the recent crustal deformations, too.

Thus we are absolutely convinced that the successful period of 2015-2019 in the research of positioning in Hungary will provide a good basis for an even more prosperous future.

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