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XXV.

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1 Introduction

This paper summarizes the contribution of Hungarian research groups to the work of the Commission 4 (Positioning and Applications) of the International Association of Geodesy in the period of 2019-2023. Extensive research was carried out in the field of atmospheric remote sensing using GNSS, tropospheric delay modelling, the integrity of satellite positioning services for safety-of-life applications. A novel and increasingly important area is the navigation and localization of not only ground, but also aerial autonomous vehicles (UAVs) using GNSS, IMUs and Lidar data. New methods have been developed for the fusion of various positioning sensors, such as IMUs and multiple GNSS receivers. This article also introduces the recent results in the application of interferometric synthetic aperture radar observations in the quantification of recent crustal displacements, too. Finally, a structural displacement monitoring system using low-cost dual frequency GNSS receivers that was applied during the construction of a railway bridge in Budapest is also introduced.

The period of 2019-2023 brought many new results in the research of positioning techniques and the application of geodesy for engineering. Significant advances could be reported in the field of environmental remote sensing using satellite signals and observations. Atmospheric remote sensing using GNSS has been further improved to incorporate multi-GNSS signals in the past years and a new near real-time tomographic reconstruction algorithm has been developed to retrieve the spatial distribution of atmospheric water vapour and the assimilation of these result has also been started by the meteorologist community. Moreover, GNSS reflectometry studies has been initiated for the monitoring the level of rivers. The surface deformation induced by natural processes and man-made activities is continuously monitored by radar interferometry.

Since PNT services are being used for safety-of-life applications not only in the aviation but also in ground transportation, the reliability of these services must be monitored and improved. In the past years a national integrity monitoring network was established at the major airports in Hungary to monitor the EGNOS system performance as well as to study GNSS interference issues. Moreo-

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ver, methodology developments were done to better estimate the residual error of the tropospheric delay models for the calculation of protection levels to assess the integrity of the positioning service.

The availability of low-cost dual frequency multi-GNSS receivers opened up new research areas in the application of GNSS positioning in structural monitoring and gave a new momentum to our research activities in the development of localization and navigation solutions for moving platforms including autonomous vehicles.

These research activities were carried out by the following research institutes: the Department of Geodesy and Surveying of the Budapest University of Technology and Economics, the Institute for Computer Science and Control and the Institute of Earth Physics and Space Science of the Eötvös Loránd Research Network (formerly 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 Infrastructure

Following the strategy of the European Union, satellite based instrument landing approaches have been introduced at a great number of aerodromes all around Europe. Hungarian procedures for seven civilian and three military airports were designed and published within the framework of the PBN4HU (Implementation of PBN procedures in Hungary) project granted by INEA (Innovation and Networks Executive Agency) program. Besides the procedure, the Hungarian E-GNSS (European GNSS) monitoring network was also deployed within the framework of the project (Takács et al. 2020). The most important aim of the network is to monitor the performance of the EGNOS augmented positioning and gain the experience necessary for the applications of GNSS for the safety of life applications. The network consists of 11 stations equipped with the most modern triple frequency, Galileo capable receivers. Raw measurements are recorded and post processed in a fully automatic way on a daily basis in accordance with ICAO (International Civil Aviation Organisation) standards and requirements. Spectrum analyzers are also installed at the stations and monitor all the three carrier frequencies.

During the reporting period an automotive proving ground for conventional and autonomous cars was opened in West-Hungary, in Zalaegerszeg. A new EUREF EPN station was established in the premises of the ZalaZONE Proving Ground. Moreover, a backup station of the BUTE EPN station was also established as an EPN station (BME1). These permanent GNSS stations are equipped with the latest multi-GNSS technology and form the backbone of scientific research in developing the localization technology of autonomous vehicles (Rózsa et al. 2022).

3 Remote sensing the atmospheric water vapour using GNSS

Remote sensing the atmospheric water vapour is still one of the most important topics in the Hungarian contributions to the activities of IAG Commission 4. Recently, a new near real-time GNSS observations processing facility was established with international collaboration in the framework of the GeoSES Interreg+ project (HUSKROUA/1702/8.1/0065). GNSS observations are collected on a regular basis (Fig.1.) from IGS, EUREF EPN stations as well as from Hungarian and Ukrainian GBAS (ground based augmentation service) providers and the stations operated by the Budapest University of Technology and Economics (BME). The majority of the stations are equipped with multi-GNSS receivers that opened up the possibility of including GLONASS and Galileo observations in the estimation of zenith wet delays and tropospheric gradient parameters. Radiosonde comparisons of the estimated zenith wet delays showed that the inclusion of multi-GNSS signals improved the uncertainty by more than 50% with respect to the GPS only solution (Rózsa et al. 2021). The estimated tropospheric delays are available at (http://gpsmet.agt.bme.hu, 2023-06-19) in various formats, including the Little-R format to be used as input in the Weather Research and Forecasting (WRF) numerical models.

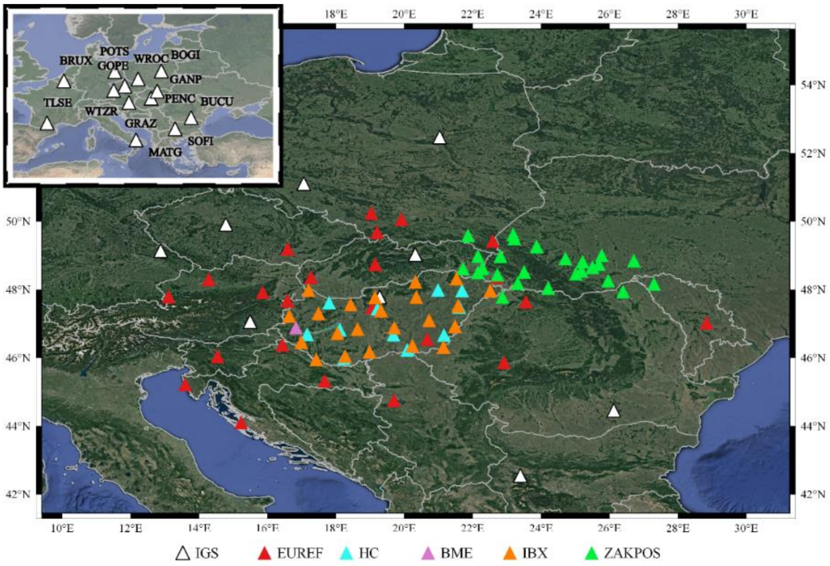

Fig. 1. The GNSS network used for the near-realtime estimation of atmospheric water vapour in Hungary

Since the zenith wet delays and the tropospheric gradient parameters are regularly estimated using GNSS observations in Hungary, they can be used as inputs for a tomographic reconstruction of atmospheric water vapour in the area. Turák et al. (2023) developed a tomographic algorithm to restore the slant wet delays from the estimated zenith wet delays and the tropospheric gradients and used the multiplicative algebraic reconstruction technique to compute the wet refractivities in a 3D voxel model in Central Europe. The algorithm is suitable for near real-time processing, thus refractivity profiles are regularly estimated over Hungary and the results are published on the project website in various formats including Little-R for the WRF model (http://gpsmet.agt.bme.hu, 2023-06-19).

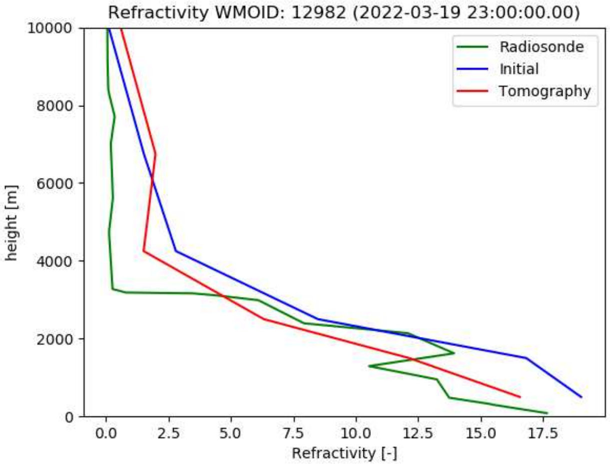

Fig. 2. Wet refractivity profile at WMO station 12982 (Szeged) on March 19, 2022 at 23:00:00 UTC

Fig. 2. shows a comparison of the estimated refractivity profile and the one calculated from radiosonde observations, while Fig. 3. shows the residual error of the wet refractivities using one month of radiosonde observations as reference.

The results showed that uncertainty of the estimated wet refractivity values is better than 5 ppm below the altitude of 3 km, and it decreases to 0.3 ppm at the altitude of 10 km.

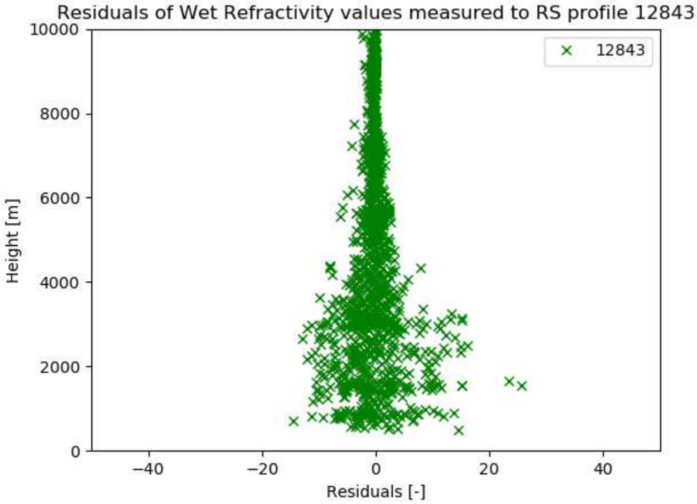

Fig. 3. Residuals of wet refractivities with respect to the elevation at WMO station 12843 (Budapest) in March, 2022

4 Methodology developments

4.1 A Numeric-Symbolic Solution of GNSS Phase Ambiguity

Solution of the Global Navigation Satellite Systems (GNSS) phase ambiguity is considered as a global quadratic mixed integer programming task, which can be transformed into a pure integer problem with a given digit of accuracy. For the solution of the problem Paláncz and Völgyesi (2020) suggest three alternative algorithms. Two of them are based on local and global linearization via McCormic Envelopes, respectively. These algorithms can be effective in case of simple configuration and relatively modest number of satellites. The third method is a locally nonlinear, iterative algorithm handling the problem as {-1, 0, 1} programming and also lets compute the next best integer solution easily. However, it should be kept in mind that the algorithm is a heuristic one, which does not guarantee to find the global integer optimum always exactly. The procedure is very powerful utilizing the ability of the numeric-symbolic abilities of a computer algebraic system, like Mathematica and it is properly fast for minimum 4 satellites with normal configuration, which means the Geometric Dilution of Precision (GDOP) should be between 1 and 8. Wolfram Alpha and Wolfram Clouds Apps give possibility to run the suggested code even via cell phones. All of these algorithms are illustrated with numerical examples. The result of the third one was successfully compared with the LAMBDA method, in case of ten satellites sending signals on two carrier frequencies (L1 and L2) with weighting matrix used to weight the GNSS observation and computed as the inverse of the corresponding covariance matrix.

The algorithms based on local as well as global linearization were proved to be efficient in cases of one carrier frequency. The third one, a locally nonlinear, iterative algorithm, can be employed successfully when L1 and L2 carrier frequencies are used with weighting matrix having elements of very different magnitudes. For multi-GNSS cases, when more satellite should be tracked simultaneously, one may employ the same strategy however at this time the memory management of CAS does not allow to handle large system of equations.

4.2 Multi-Sensor Systems

Low-cost sensor based high accuracy localization algorithms are the keys of autonomous navigation. This topic is constantly evolving with the variation of integratable sensors. However, the Global Navigation Satellite System (GNSS) based navigation remains one of the fundamental localisation methods. As low-cost GNSS receivers continue to evolve, real-time, multi-frequency, multi-constellation, Real-Time Kinematic (RTK) and Precise Point Positioning (PPP, PPP-RTK) localisation techniques are becoming more widespread in UAVs and in the automotive industry. However, the GNSS technology remains sensitive to the measurement environment such as urban canyons or tunnels. The tightly coupled integration of the measurements of low-cost inertial (INS), magnetic (MAG), barometric (BARO) sensors and multiple GNSS receivers and baselines aims to improve the reliability and the accuracy of the position and attitude estimation of the moving platform. However, low-cost sensors suffer from major errors (INS, MAG, BARO: sensor bias, sensor drifts, scale factor error; GNSS: clock asynchronicity, clock jump) that need to be compensated to achieve the high accuracy. Tightly coupled integration allows to estimate all the localization information and the error terms in a single nonlinear Extended Kalman Filter (EKF) algorithm.

The developed estimation algorithm also uses the moving baseline carrier-phase data to estimate the attitude angles of the measurement platform. The algorithm uses the quaternion constrained LAMBDA method to resolve the integer ambiguities on the moving baselines (Farkas et al., 2019). The estimation algorithm and the integer ambiguity resolution method were tested and validated on low-cost multi-baseline, multi-constellation, GNSS and inertial measurements using a small UAV platform.

Our sensor integration method is also suitable for detecting and improving sensor-related phenomena. The GNSS carrier-phase measurement related undetected cycle slip can cause position and attitude degradation in challenging measurement environment such as urban canyons. The developed prediction based cycle slip method (Vanek et al. 2023) uses the EKF algorithm states and triple differenced carrier-phase measurements to detect and reinitialise integer ambiguity states in case of cycle slip. The proposed method produced more accurate post-processed localization results than traditional linear combination-based methods in the deep urban canyon environment.

4.3 Integrity and quality control

The upper part of the Earth's atmosphere, the ionosphere impacts the accuracy and reliability of satellite based positioning. Major part of the effect can be taken into account by applying corrections of SBAS (Satellite Based Augmentation Systems), the EGNOS (European Geostationary Navigation Overlay Service) in Europe. One of the major concerns is the deviances at the edge of the EGNOS coverage area which was investigated in detail (Lupsic and Takács, 2019). In addition to classical ionosphere models, a novel approach based upon Gauss Process Regression (GPR) was introduced and developed (Lupsic and Takács, 2019). GPR is a nonparametric, Bayesian approach to regression. GPR has several benefits for ionosphere monitoring since it is quite robust and efficient to derive a grid model from data available in irregular set of ionospheric pierce points. The GPR model is capable to accurately estimate regional Total Electron Content (TEC) maps from snapshot measurements of a relatively sparse monitoring station with the required accuracy.

Multi-frequency civilian GNSS signals enable to users to mitigate the ionospheric effects in positioning. However, the neutral part of the atmosphere still affects the signal propagation and severe weather can degrade the positioning accuracy and reliability. Rózsa et al. (2020) has developed an advanced residual tropospheric delay error model with the extreme value analysis (EVA) technique using more than a decade of global numerical weather data. The developed model takes into consideration the effect of climate and the seasonal variability of the performance of the tropospheric delay models. The residual error model parameters including the bias and the amplitudes of annual and semi-annual signals were derived for various latitude bands. By taking into account the climatic effects, a substantial reduction of the estimated residual error could be achieved globally leading to higher availability of GNSS positioning for safety-of-life applications.

5 Low-cost GNSS Sensor Development for Structural Monitoring

At the department of Geodesy and Surveying of the Budapest University of Technology and Economics a low-cost monitoring system was designed and realized. The system consists of field modules and server side components (Égető et al. 2021). The field module contains a low-cost U-blox F9 GNSS RTK receiver, a Raspberry Pi 4 computer, a GSM WiFi modem and battery. The open source RTKLib Demo5 program is used to send the NTRIP correction to the GNSS receiver and the positions to the server components. On the server side the positions and related information are collected in a PostgreSQL database (Fig 4). Data are published using thin web clients in the browser.

The developed monitoring system (Fig. 4.) was used in the construction of the new triple railway bridge above the Danube at Budapest between 2020 and 2022. The individual bridges consist of six 80-90 meters long parts which were lifted from two crows. Six field modules were installed, four on the lifted element and two on the connecting one. Our monitoring system is responsible to track the elevation changes of the bridge elements caused by the water level change during the installation.

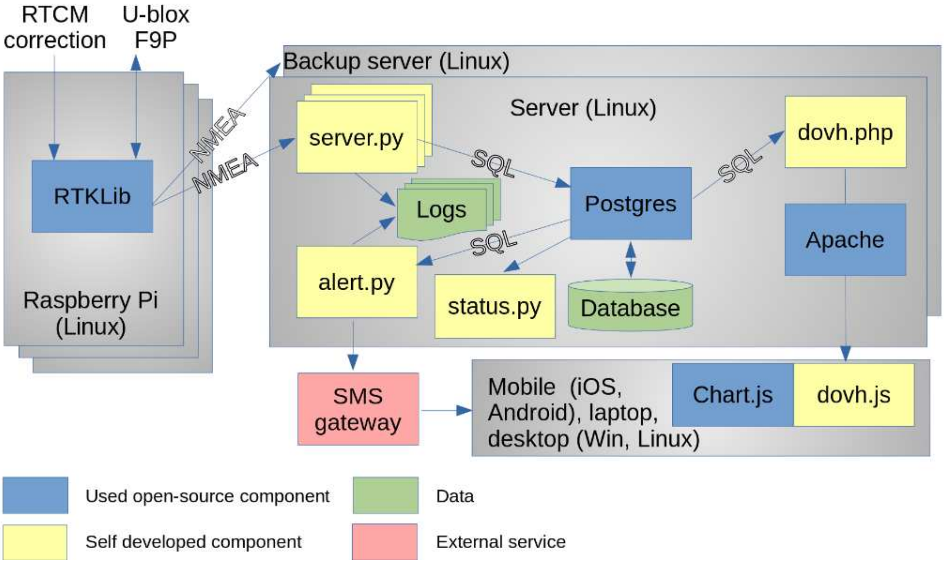

Fig. 4. The structure of the low-cost GNSS monitoring system

It has been shown that low-cost GNSS receivers and dual frequency GNSS patch antennae can be used to achieve cm accurate coordinates in real time. Thus, these instruments can be used for several structural health or deformation/displacement monitoring tasks in civil engineering or in Earth sciences.

6 Calibration of levelling staves

The geodetic research group of the Institute of Earth Physics and Space Science, Sopron (formerly Geodetic and Geophysical Research Institute, Sopron) published a final report on the improvement steps of an automatic interferometric calibration system for levelling staffs equipped with code bar scale (Orbán et al. 2020). The aim of the development was to support the quality management of high precision first order levelling network of Hungary. The system provides an accuracy of ±3μm in terms of the determination of the position of a specific bar code i.e. rod division. The calibration results of some staffs were compared and validated to those provided by the system operated by the Technical University of Munich. An example can be seen in Fig. 5.

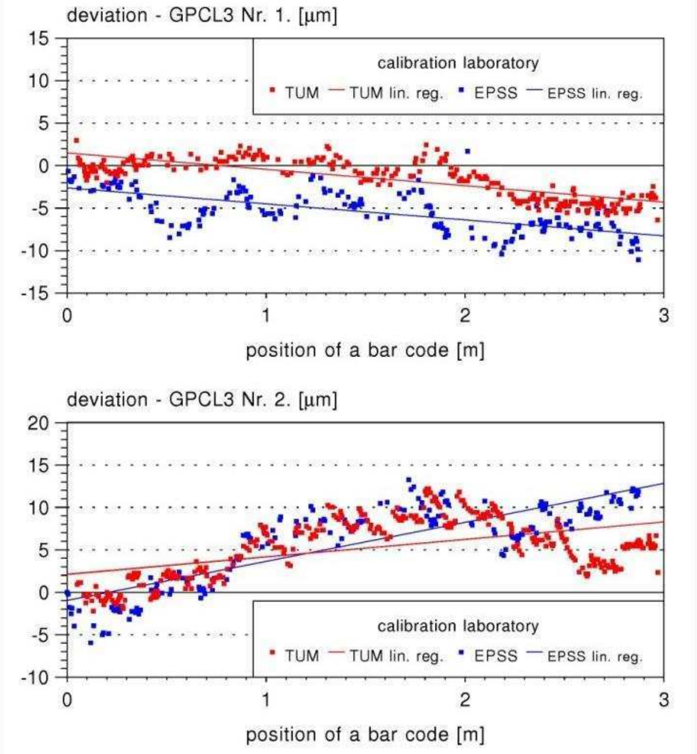

Fig. 5. Comparison of the calibration results of a pair of levelling staffs used by the surveying team of Satellite Geodetic Observatory, Lechner Knowledge Centre. The staves were calibrated at TUM (Technical University of Munich, Germany) and at EPSS (Institute of Earth Physics and Space Science, Sopron, Hungary) in 2005 and 2015, respectively. Deviation is the difference between the measured and theoretical positions of a specific bar code

7 Applications of Synthetic Aperture Radar Interferometry

Satellite based Synthetic Aperture Radar (SAR) interferometry (InSAR) plays an increasingly important role in mapping displacements. The open availability of high-quality SAR images with high temporal frequency ensured by the Sentinel-1 A and B satellites, operating in C-band (5.4 GHz) enabled the application InSAR processing methods to monitor the stability of infrastructure with high-accuracy and to carry-out regional or even continental scale surface motion studies.

In order to confidently estimate surface displacements, C-band based InSAR requires coherent scattering objects to be present in the area of interest in a high enough number. In areas where this is not the case artificial corner reflectors can be installed to serve as scattering objects. Such reflectors were developed as part of the “Integrated Sentinel-PSI and GNSS technical facilities and procedures for the determination of 3D surface deformations caused by environmental processes” ESA project (project ID: 4000114846/15/NL/Nde). So-called integrated benchmarks (IB) were deployed in three areas in Hungary, affected by landslide activity. Integrated benchmarks contain a reflector pairs, oriented in ascending and descending directions, and a GNSS adapter. The design, mechanical parameters and reflecting characteristics of the developed reflectors were measured and analyzed. Reflecting characteristics, such as signal-to-clutter ratio (SCR) and radar cross section were determined by numerical simulation and analogue measurements using scaled back models of reflectors. The SCR for the reflectors of two IB networks were also estimated from Sentinel-1 images (Bányai et al. 2019).

As part of the ESA project GNSS measurements were carried out at the three IB networks in Hungary, between 2017 and 2018. The methodology for combining InSAR and GNSS measurements, also developed as part of the project, was tested using data from the IB network sites. The methodology is capable of identifying the reflectors in the SAR image, correct unwrapping errors and estimate 3D displacements from InSAR and GNSS datasets (Bozsó et al. 2020).

A fourth IG network was also installed in the city of Sopron in Hungary. Together with measurements from the Széchenyi István Geophysical Observatory gives a unique opportunity to study the effects of the neutral atmosphere and ionosphere on the interferometric phase of SAR interferograms. Since large surface movements are not expected in the area, it is also possible to link the interferometric phase to atmospheric inhomogeneities and transient atmospheric phenomena (Szárnya et al. 2022).

Surface movements caused by sinkholes, originating from past salt mining activities were investigated in Solotvyno, Ukraine with the application of multi-baseline InSAR using Sentinel-1 ascending and descending images covering 4 years (Szűcs et al. 2021). Observed satellite line-of-sight (LOS) displacements were decomposed into vertical and east-west components and source modeling of the surface deformation pattern was carried out. Surface displacements are mainly composed of vertical subsidence with the magnitude of 2-3 cm/yr, concentrated around the already developed sinkhole. Although source modeling results fit the observed deformations well, some larger discrepancies are still present owing to the insufficient InSAR datapoint density in certain parts of the studied area.

A PS-InSAR analysis utilizing archive descending ENVISAT ASAR images between 2002 and 2006 was carried out for the Szentes geothermal field, SE Hungary (Békési et al. 2022). Results indicate a positive LOS motion, associated with the uplift of the studied area. Inverse geomechanical modeling calibrated with the InSAR LOS displacements was performed to link surface motions to subsurface volume/pressure changes within the reservoir. The resulting model was capable of reproducing the major anomalies in the observed displacement pattern, indicating that pore pressure recovery within the reservoir could explain the observed surface uplift.

Within the ENI CBC supported GeoSES Project (HUSKROUA/1702/8.1/0065), the InSAR related activities were conducted by the Budapest University of Technology and Economics and the Satellite Geodetic Observatory at Penc. Supporting this, InSAR analysis was carried out on the common border sections of Hungary-Slovakia-Romania-Ukraine, as well as on some focused area of interests (AOI). The scope of the focused analyses were related to Aknaszlatina (Solotvyno, Ukraine) and Nagyida (Nizhna Hutka, Slovakia), using 1 year of Sentinel-1 data with single-reference PSI approach in LOS level. In the Aknaszlatina AOI, residential and industrial blocks were to be found endangered by the abandoned salt mines; while in the Nagyida AOI the identified deformation pattern is mostly related to mass-related deformations in the tailings piles related South to Kosice Steel Works (Magyar et al. 2021). Furthermore, as one of the outputs of the GeoSES Project, an interactive deformation map (available at: https://geoses.sgo-penc.hu/) were also presented for the Transcarpathian and surrounding regions covering the 2014-2021 period using descending Sentinel1 data with multi-reference PSI approach. Several representative deformation affected areas and infrastructure were identified during the regional scale InSAR analysis, ranging from the groundwater withdrawal affected village of Csincse near Bükkábrány (Hungary), through the ancient Transylvanian mining town of Nagybánya (Romania) to the examples above as well (Magyar and Horváth, 2022).

Moreover, the coseismic deformation field of the 2020 Petrinja Eartquake Sequence (Croatia) were determined in the Satellite Geodetic Observatory, via 2.5 DInSAR technique using ascending and descending Sentinel-1 data. The derived East-West components can be characterized by +40 and –40 cm maximum local displacements, while the vertical components indicated 15 cm local subsidence and 19 cm local uplift patterns in the Eartquake Sequence affected area (Magyar, 2022).

In the Satellite Geodetic Observatory, analysis of radar cross section (RCS), signal-to-clutter ration (SCR) and estimation of the phase center of the corner reflector (CR) and active corner reflector (E-CR/CAT) have been also implemented in sub-pixel level, aiming the testing and integration of E-CR technology to GNSS and InSAR data combinations (Horváth et al. 2022).

8 Conclusion 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.

Apart from GNSS related studies, satellite interferometry has become another important tool to study the crustal displacements in Central Europe. Several research groups became active in this field and their research activities helped to better understand geohazards especially in the Hungarian-Slovakian-Romanian-Ukrainian cross-border region.

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 four years. Due to the increase of solar activities real-time satellite positioning faces new challenges in the next years. Moreover, the increased demand for cm accurate positioning requires the development of PPP technology leading a continuous need to improve the accuracy of our systematic error correction models as well as to extend the validity of these models using efficient prediction techniques such as the application of machine learning algorithms and artificial intelligence.

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 requires 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 and software tools 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 2019-2023 in the research of positioning in Hungary will provide a good basis for an even more prosperous future.

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