

VOLUME  
*Évfolyam*

**XXV**

2022

HUNGARIAN NATIONAL REPORT

HUNGARIAN NATIONAL REPORT  
ON THE CONTEMPORARY SITUATION OF THE  
GEODESY AND GEOPHYSICS

9-2022

201

Geomatics  
Dublicatio  
Geomatikai Közlemények

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HU ISSN 1419-6492



GEODÉZIAI ÉS GEOFIZIKAI INTÉZET  
SOPRON

**Hungarian National Report**

**on International Union of  
Geodesy and Geophysics**

**2019-2022**

**GEOMATIKA ÉS LEVELEZÉSI TUDOMÁNYOK**

*Geomatikai Közlemények*

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készült  
**LÓVÉR PRINT Kft.**  
9400 Sopron, A  
tel.: +36 99 529 911

meielent 50 példányban

Sopron, 2022.

HU ISSN 1419-6492

**HUNGARIAN NATIONAL REPORT  
ON INTERNATIONAL UNION OF  
GEODESY AND GEOPHYSICS  
2019-2022**

**PUBLICATIONS IN GEOMATICS**

*Geomatikai Közlemények*

**XXV.**

"Minden nemzet a maga  
nyelvén lett tudós,  
de idegenen sohasem."

(Bessenyei György)



## GENERAL INFORMATION

Publications in Geomatics is a periodical journal since 1998 issuing generally one number a year. The purpose of the journal is to provide the home researchers and experts a forum to publish, mainly in Hungarian language, their new scientific results in the field of geosciences (geodesy, photogrammetry, geoinformatics, physical geodesy, geophysics, Earth magnetism, geodynamics, research of the inner structure of the Earth and the physics of its troposphere and solar-terrestrial environment) obtained from the analysis of spatial-temporal data using the methods of geomatics. The submitted papers are subject to an editorial procedure which is in compliance with the present-day standards, namely two independent referees form opinion about the manuscript. By default the names of the referees are known only to the editorial board, but their identity can be disclosed according to their wish. On the basis of reviews the editorial board decides whether it meets the requirements of the form, and content of the Publications in Geomatics and whether the eventual errors and shortcomings can be corrected and complemented by revision. The expert work of the editorial board is supported by an advisory board.

Editors, accomplishing the Journal's editing as a voluntary work, place emphases on rapid and high quality work. Therefore both the authors and the referees are expected to make efforts which are appreciated by the Editorial Board in advance. For this to do, it is suggested to peruse the instructions for authors and reviewers

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These files provide basic information for the use of the editorial system and for maintaining the high professional standards.

Publications in Geomatics is published by Institute of Earth Physics and Space Science (EPSS). Publishing costs are covered from grant money, the sponsorship of scientific organizations (e.g. Soproni Tudós Társaság) and from subsidy of the Seminar Series on Geomatics organized by the EPSS every two years.

**The technical editing and the printing costs of the recent volume of Publications in Geomatics were financed by the EPSS and the Soproni Tudós Társaság, respectively.**

The association-, division- and commission reports were reviewed by Zsuzsanna Soósné Dezső, Anna Kis, Judit Benedek, Márta Kis, János Lichtenberger, Lajos Völgyesi, Bálint Magyar, Sándor Tóth, Gabriella Szépszó, Rita Pongrácz, Tamás Weidinger, Mónika Lakatos, Péter Ván, László Haszpra, László Szarka, Eszter Békési, István Lempenger, Ernő Prácsner, Attila Novák, Veronika Barta, Csenge Czani, Gyula Mentés, Gabriella Sántó, Katalin Gribovszki, Árpád Kis, Ambrus Kenyeres, György Busics, Katalin Bene, András Herceg, László Bozó, Péter Kovács, László Fodor and Gábor Újvári.

The editors in charge of the reports were Lajos Völgyesi, László Bányai, Judit Benedek, Katalin Gribovszki, Ambrus Kenyeres, Árpád Kis, Gábor Papp, Szilárd Szabó, Gábor Újvári and János Gejger.

## PREFACE

The Hungarian National Committee of the International Union of Geodesy and Geophysics is pleased to present the 2019-2022 quadrennial Hungarian report to the IUGG community.

The Report covers the research and development performed by Hungarian universities, research institutes, and government agencies, subdivided by subjects in agreement with the following International Associations of IUGG: a) IACS (International Association of Cryospheric Sciences), b) IAG (International Association of Geodesy), c) IAGA (International Association of Geomagnetism and Aeronomy), d) IAHS (International Association of Hydrological Sciences), e) IAMAS (International Association of Meteorological and Atmospheric Sciences), f) IAPSO (International Association for the Physical Sciences of the Oceans), g) IASPEI (International Association of Seismology and Physics of the Earth's Interior). Unfortunately the Hungarian IAVCEI report is missing, because the manuscript was not submitted before the extended deadline. After the Association chapters, we provide a summary report of IUGG-related events, held on the occasion of the 100th anniversary of the death of the physicist, geodesist and geophysicist Baron Roland Eötvös (1848- 1919), that is the Eötvös 100 Commemorative Year in 2019.

Finally, in the end of our Report, you find the necrology about József ÁDÁM†, President of Hungarian National Committee for IUGG and National IAG Correspondent. He passed away on December 29, 2022.

After his death, in the present transitional state the Hungarian National Committee for IUGG is led by its Secretary, László BOZÓ (IAMAS National Correspondent). Further National Correspondents are as follows: Péter BAKONYI (IAHS), István BONDÁR/Erzsébet GYŐRI (IASPEI), Judit BARTHOLY (IACS), Gábor DOBOSI (IAVCEI), Balázs HEILIG (IAGA), László HORVÁTH (IAPSO) Zoltán GRIBOVSKI (IAHS), Lajos VÖLGYESI (IAG), Further NC members: Antal ÁDÁM, László BÁNYAI, Attila GALSA, Szabolcs HARANGI, Péter MÁRTON, Gábor PAPP, László SZARKA, József SZILÁGYI, Tamás WEIDINGER and Viktor WESZTERGOM.

In the past period the Hungarian National Committee for IUGG could not hold every business, due to various reasons, first of all because of the COVID-19 pandemy.

This quadrennial Report is published by the Geomatikai Közlemények (Publications in Geomatics), a Journal issued by the Institute of Earth Physics and Space Science, (that is the former Geodetic and Geophysical Institute of the Research Centre for Astronomy and Earth Sciences of the Hungarian Academy of Sciences), in the Volume XXV, 2022. The chapters of the Report are prepared by different Sections of the Hungarian National Committee for IUGG, and written and compiled by different authors.

This Report would not be possible without the unselfish service of authors and editors. We hope that this Report can provide to our foreign Colleagues a fairly clear picture of the development and what has been done in the past four years in the wide spectra covered by IUGG in Hungary.

On behalf of the Hungarian National Committee for IUGG:

László Bozó  
Secretary

Budapest, February 28, 2023

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# HUNGARIAN NATIONAL REPORT ON IACS (2019-2022)

*Judit Bartholy\*, Rita Pongrácz\**

## 1 Introduction

The current reporting paper serves as a summary of the research activity related to the cryosphere and carried out with the participation of Hungarian scientists (both senior and junior) during 2019-2022.

## 2 The cryosphere-related research in Hungary

The first group of cryospheric research focuses on the past. For such purpose, ice cores are used quite often. A thorough review study is published by Kern and Persoiu (2022), on the basis of 20 cave ice deposits mainly from Central European caves. This paper summarises the achievements of ice core drilling in caves. The collected experiences and challenges led to a proposition of the special approach named Cave Ice Sedimentary Architecture and Deposition (CISAD) to facilitate the selection of future drilling sites, which will result in high quality paleoenvironmental data. The data from the Greenland ice core is analysed by Hatvani et al. (2022) using a Bayesian changepoint detection method. The main aims of this research were to find the atmospheric forcing of these changepoints, and whether they are related to the North Atlantic Oscillation (NAO). The past glaciation and deglaciation processes in the Jablanica Mountain (located in the central Balkan Peninsula) and in the Retezat Mountains (located in the Southern Carpathians, Romania) are analysed by Ruszkiczay-Rüdiger et al. (2020; 2021) using  $^{10}\text{Be}$ -based geochronology.

The more recent decades are studied by the second group of cryosphere-related research involving Hungarian scientists. Baxter et al. (2019) evaluated the contribution of the recent cooling of the sea surface temperature of the tropical Pacific Ocean to the acceleration of sea ice melt in the Arctic region on the basis of the Pacific-Arctic teleconnection (i.e. cold Pacific, warm Arctic). The Baffin Bay's sea ice cover is analysed by Ballinger et al. (2022) for the 21st century and found an abrupt autumn warming resulting in a 2-week delay of the autumn sea ice formation since 2001. Moreover, climate model simulations from CMIP5 (Coupled Model Intercomparison Project Phase 5) are used by Topál et al. (2020) to explore the potential atmospheric drivers of the Arctic Sea ice melting during summer. Also, the Greenland ice sheet is analysed by Topál et al. (2021) for the last two millennia on the basis of the Ensemble Kalman Fitting Paleo-Reanalysis (EKF400, for 1602-2003) and the Last Millennium Reanalysis (LMR, for 0-2000) with monthly and yearly resolution, respectively. The difference between climate model simulations and observation-based reanalysis, with respect to the Greenland ice sheet melting, is evaluated by Topál et al. (2022).

Other regions were also studied by Hungarian scientist. For instance, the current cold conditions in the South American continent are analysed by Nagy et al. (2020), Aszalós et al. (2020), and Kereszturi et al. (2022). The high elevation region, namely, the Mt. Ojos del Salado (6893 m above sea level) of the Andes is a relatively long-term measuring site initiated by the Institute of Geography and Earth Science of the ELTE Eötvös Loránd University. Aszalós et al. (2020) focuses on a permafrost thaw pond at 5900 m above sea level with a special ecological point of view. The interactions between wind and snow is analysed by Kereszturi et al. (2022), collected temperature data from local measurements below the surface (Nagy et al., 2020) imply that ice melting is rare, so the surface processes are dominated by the desiccation of the cryosphere and the local wind.

Long time series of snowfall, starting at the early 20th century (110 years altogether), are studied by Kis and Pongrácz (2021) for several European regions including the Carpathian Basin and the Carpathian Mountains. The statistical analysis of ERA-20C reanalysis data showed that in spite of the anthropogenic warming signal the snowfall was the smallest not only at the beginning of the 21st century, but also in the first decades of the 20th century. Furthermore, the relationship between the snowfall and the NAO is also evaluated in eight regions with different climatic conditions. The results show that the connection is stronger in the northern and western regions compared to the continental

central European regions because of the geographic locations relative to the northern action centre of the NAO, i.e. the Icelandic low pressure centre.

A shorter but more specific relationship is studied by Füzi and Ladányi (2020), namely, how the frost risk appears in the Sopron wine region during 1961–2016. The research clearly showed that due to the regional warming the frost-free period of the region tended to increase resulting in a higher success of pests' survival during the winter period.

The last group of publications includes the BSc and MSc thesis work of students specialised in meteorology (BSc), weather forecaster or climate researcher (MSc) at the ELTE Eötvös Loránd University. The focus of the students' work is on the Arctic area in Topál (2019), Szekeres (2020), and Bokros (2022). Szekeres (2020) summarises the meteorological conditions specifically present in the polar zone of the Arctic, including the Arctic oscillation, in addition, the polar amplification is presented with respect to global warming. The Arctic oscillation is also analysed by Topál (2019), and how it is possibly related to the decreasing extension of the Arctic Sea ice. Statistical analysis is used to connect the trends in the Arctic Sea ice with the frequency changes of midlatitude blocking situations and bomb cyclones. The possible teleconnection between the Arctic and the Carpathian region is evaluated by Major (2020). The ice cover is analysed as a global climate change signal in Baki (2020) where not only the Arctic but the Antarctic polar zone is considered. The regional snow conditions are also analysed in the relation with country-scale regional warming. For example, the frequency of snowfall occurrences is evaluated by Simon (2019) for the days around Christmas. The analysis also appeared in a more concise form as a journal paper (Simon et al., 2020). The effects of changing snow conditions on ski tourism are analysed for the Carpathian region by Felföldi (2019) and Szabián (2019). Other regions of the cryosphere are also studied, e.g. Berényi (2019) carried out a sensitivity analysis of a mesoscale climate model (WRF – Weather Research and Forecasting model) to describe the extreme cold conditions with snow surfaces of the Andes. Furthermore, a detailed literature review is provided by Szalkai (2019) on a special snow-related phenomenon, the so-called lake-effect snow in the North American Great Lakes region. The avalanches cause severe impacts, their classification, development and forecasting possibilities are summarised by Bencsik (2020). A very specific air traffic hazard, namely the icing is analysed by Bencsik (2022). The possible forecasting methods are validated and compared using case studies.

### 3 Conclusions

The present report includes 27 publications from Hungarian researchers and students. A large group of research focuses on the analysis of ice cores either from ice caves or the Greenland ice sheet. Another cryosphere-related research activity involving Hungarian researchers aimed to analyse the sea ice melt over the Arctic and its teleconnections. Furthermore, the analysis of sub-surface measurements in the high Andes mountains connects wind and snow, and study their relationship in modifying the geomorphological formation of the surface. Also, century-long time series of snowfall are analysed over different European regions with different climatic conditions, where NAO effects are also considered. The last group of publications includes the BSc and MSc thesis work of students graduated at the Department of Meteorology, at the ELTE Eötvös Loránd University.

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# HUNGARIAN CONTRIBUTION TO THE RESEARCH ON NUMERICAL THEORIES AND SOLUTIONS IN MATHEMATICAL GEODESY (2019-2022) – IAG INTER- COMMISSION COMMITTEE

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## 1 Introduction

The current reporting paper serves as a summary of the research activity related to the Numerical Theories and Solutions in Mathematical Geodesy carried out in Hungary during 2019-2022.

## 2 Vertex search and biquadratic interpolation in a triangle-based (TIN) digital surface model

Triangle-based surface model allows surface interpolation fitting to a given, irregularly distributed set of points. If only the elevation of base points are taken into account, then the interpolation surface can be generated by continuous triangular element interpolation exclusively. Consequently the local extrema for the surface generated by triangular faces can be found only at the vertices of triangular faces. In order to improve the procedure of the local extrema searching, in the study of Kalmár and Benedek (2021) a smooth surface was generated with a surface-fitting technique, using biquadratic interpolation. The smooth fitting of biquadratic local surfaces along the sides of joining triangles is provided using an adequate estimation for the partial derivatives at the base points. Prescribing the matching of the directional derivatives along the triangle edges in addition to the height matching conditions, construction of a TIN-based biquadratic finite-element surface interpolation, where the adjacent surface elements fit together smoothly can be realized. Furthermore, the condition of existence of local extrema and its position inside of triangular face was determined.

In Kalmár et al. (2020) the smooth fitting of biquadratic local surfaces along the edges is realized. An adequate estimation for the partial derivatives at the base points is provided so that in addition to the height fit conditions the identity of the directional derivatives along the triangle edges is assumed. The directional derivative was generated from the partial derivatives estimated in the base points as a weighted average of the normal vectors of the plane fitted to the certain triangles. A continuously differentiable quadratic spline interpolation is defined given the starting value for the derivative only in one point, the polynomial coefficients for each section can be determined independently of each other.

## 3 Analytical formulation of sampling error of periodic signals

Data acquisition for geoinformatics cannot be done continuously, but by discrete sampling of the object or phenomenon. The sampling involves errors on the knowledge of the continuous signal due to the loss of information in the sampling procedure. An analytical formulation of the L1-norm and L2-norm sampling error of a periodic signal is provided, which embodies the amplitude, phase, bias, and periodicity of the sampling error. According to the tests, the formulation was found to be stable for instability of the sampling rate up to  $\pm 10\%$  (Földváry 2021a).

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#### 4 Remote sensing aspects of numerical theories and solutions in mathematical geodesy

Relevant contribution to the Hungarian Geoinformatic Society was provided by establishing a Doctoral School in the field of Geoinformatics in Uzbekistan within the DSinGIS project (Balázsik et al. 2020) and an innovative open-source e-learning platform in the field of remote sensing applications was developed within the IRSEL project (Bauer et al. 2021, Veróné Wojtaszek et al. 2020a).

Several papers were presented in the field of urban and forest ecology with Hungarian contribution by developing new classification and mathematical methods used in processing of remote sensing data sources (Qi et al. 2022, Meng et al. 2022, Shi et al. 2022, Wang et al. 2022, Meng et al. 2020).

#### 5 Error sources of a rotary laser level instrument

The required calibration measurements were carried out in the measuring hall of Antal Tárczy-Hornoch, at the Institute of Geodesy and Geophysics of the Astronomy and Earth Science Research Center (at present Institute of Earth Physics and Space Science). In Kalmár et al. (2021) the researchers deal with the sources of error in the calibration of the rotary laser levelling instrument.

During the measurement, the laser beam of the rotary laser level equipment has to rotate in a horizontal plane. The maximum allowed deviation between the actual plane defined by the rotating laser beam and the horizontal plane (the tail-swing) is  $\pm 0.2\text{mm/m}$ . Levelling error of the rotary laser level equipment can be caused by horizon-skewness and cone error. Previous studies could not separate the effect of the mentioned angle errors, but our geometric modelling made the separation possible. The angle errors can be separately determined from the readings, detected on specially located levelling poles. The readings provide height errors at these specially located levelling poles positions.

The geometrical modelling was able to show that with specially positioned measuring bar positions, the horizontal skewness and cone error of the rotary laser levelling instrument can be determined separately based on the height errors measured at the bars. The approximation of the solutions of the two-unknown quadratic system of equations written on the direction vector of the stationary axis is given in figures, and the angular errors can be calculated. It was possible to validate the theoretical results (formulas) both in the experimental numerical models and based on real measurements.

#### 6 Gravity field of the Earth described with the Laplace equation

The gravity field of the Earth can be represented using the Laplace equation. The potential of the gravity field is a scalar function, which can be given by a series expansion. It is the sum of the product of coefficients and kernel functions, where the kernel functions are all elementary solutions of the Laplace equation. The spherical coordinates chosen for the spatial coordinates are those that best fit the boundary condition (i.e. the shape of the Earth), so that the solution is the product of the negative powers of the distance from the origin, the harmonic functions of longitude and the associated Legendre functions of the polar distance angle. Both the variables in the volume integral of the coefficients and the variables of the kernel functions are converted into Cartesian coordinates. The transformation was automated using the MATLAB symbolic language toolbox. The kernel functions and coefficients written in rectangular coordinates can be directly compared with the Taylor series form of the  $1/r$  function written in Cartesian coordinates. It is striking that certain kernel functions are identical for both the cylindrical and Cartesian solution and the spherical solution consist of fewer members for each degree (if  $n$  greater than 1) (Gilányi and Molnár 2022).

## 7 Hybrid symbolic-numeric methods

Hybrid symbolic-numeric computation is a large and growing area at the boundary of mathematics and computer science, devoted to the study and implementation of methods that mix symbolic with numeric computation.

Three major areas of computation are written about Hybrid Symbolic-Numeric Methods in our new book the *Mathematical Geosciences* (Awange et al. 2022), which is the second revised and extended edition of our previous one (Awange et al. 2018). The first part discusses methods for computing all solutions to a system of polynomials. Purely symbolic methods e.g. via Gröbner bases tend to suffer from algorithmic inefficiencies, and purely numeric methods such as Newton iterations have trouble finding all solutions to such systems. One class of hybrid methods blends numerics into the purely algebraic approach e.g., computing numeric Gröbner bases or Dixon resultants (the latter being extremely efficient e.g., for elimination of variables). Another mixes symbolic methods into more numerical approaches, e.g., finding initializations for numeric homotopy tracking to obtain all solutions.

The second part goes into the realm of "soft" optimization methods, including genetic methods, simulated annealing, and particle swarm optimization, among others. These are all popular and heavily used, especially in the context of global optimization. While often considered as "numeric" methods, they benefit from symbolic computation in several ways. One is that implementation is typically straightforward when one has access to a language that supports symbolic computation. Updates of state, e.g., to handle mutations and gene crossover, are easily coded. (Indeed, this sort of thing can be so deceptively simple, baked into the language so to speak, that one hardly realizes symbolic computation is happening.) Among many applications in this part there is, again, that of solving systems of equations. Also covered is mixed-integer programming (wherein some variables are discrete-valued and others continuous). This is a natural area for HSNC since it combines aspects of exact and numeric methods in the handling of both discrete and continuous variables.

The third part delves into data modelling. This begins with use of radial basis functions and proceeds to machine learning, e.g., via Support Vector machine (SVM) methods. Symbolic Regression, a methodology that combines numerics with evolutionary programming, is also introduced for the purpose of modelling data. Another area seeing recent interest is that of robust optimization and regression, wherein one seeks results that remain relatively stable with respect to perturbations in input or random parameters used in the optimization. Several hybrid methods are presented to address problems in this realm. Stochastic modelling is also discussed. This is yet another area in which hybrid methods are quite useful.

The second edition of *Mathematical Geosciences* book adds five new topics: Solution equations with uncertainty, which proposes two novel methods for solving nonlinear geodetic equations as stochastic variables when the parameters of these equations have uncertainty characterized by probability distribution. The first method, an algebraic technique, partly employs symbolic computations and is applicable to polynomial systems having different uncertainty distributions of the parameters. The second method, a numerical technique, uses stochastic differential equation; Nature Inspired Global Optimization where Meta-heuristic algorithms are based on natural *Itô's* form phenomenon such as Particle Swarm Optimization. This approach simulates, e.g., schools of fish or flocks of birds, and is extended through discussion of geodetic applications. Black Hole Algorithm, which is based on the black hole phenomena is added and a new variant of the algorithm code is introduced and illustrated based on examples; The application of the Gröbner Basis to integer programming based on numeric symbolic computation is introduced and illustrated by solving some standard problems; An extension of the applications of integer programming solving phase ambiguity in Global Navigation Satellite Systems (GNSSs) 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. Three alternative algorithms are suggested, two of which are based on local and global linearization via McCormic Envelopes; and Machine learning techniques (MLT) that offer effective tools for stochastic process modelling. The

Stochastic Modelling section is extended by the stochastic modelling via MLT, and their effectiveness is compared with that of the modelling via stochastic differential equations (SDE). Mixing MLT with SDE also known as frequently Neural Differential Equations is also introduced and illustrated by an image classification via a regression problem.

## 8 Particle Swarm Optimization

The idea of the Particle Swarm Optimization (PSO) was inspired by the social behaviour of big groups of animals, like flocking and schooling patterns of birds and fish and suggested in 1995 by Russell Eberhart and James Kennedy, see in (Yang 2010).

In the searching space we define discrete points as individuals (particles) which are characterized by their position vector determining their data (fitness) values to be maximized (similar to fitness function) and their velocity vectors indicating how much the data value can change and a personal best value indicating the closest the particle's data has ever come to the optimal value (target value).

The velocity value is calculated according to how far an individual's data is from the target. The further it is, the larger is the velocity value.

Everyone's personal best value only indicates the closest the particle's data has ever come to the target since the algorithm started.

The best bird value only changes when any particle's personal best value comes closer to the target than best bird value. Through each iteration of the algorithm, best bird value gradually moves closer and closer to the target until one of the particles reaches the target.

The study of Awange et al (2021) investigated the particle swarm method, its variants, and their applications in geosciences, i.e., optimization of GNSS network, approximation of local geoid surface, inversion of residual gravity anomalies, determination of optimal well locations, inversion of refraction seismic data, and solution of geophysical inverse as well as modelling direct current resistivity.

## 9 Forecasting of Time Series via Neural Networks

It is a frequent problem to continue a time series on bases of the earlier values. In this research neural networks are employed to carry out this forecasting task. Two types of networks are considered, namely

- a) Shallow networks with different models for ARX activation functions. ARX is also known as Autoregressive with Exogenous Variables. In addition, for representing the stochastic feature of the forecasting process, assembly learning has been used,
- b) Deep recurrent network employing LSTM (Long Short-Term Memory) layer. In order to simulate stochastic process, drop-out technique was carried out.

The forecasting of the wind speeds at John F. Kennedy Airport during summertime was considered as verification and a practical application of these networks. The computations were carried out with Wolfram Mathematica. The further details can be found in these notebooks (Paláncz 2022a,b).

## 10 Geodetic datum transformation by Procrustes method

In this paper, the Procrustes method is presented to provide solution to the 7-parameter and 9-parameter transformation problems.

The Procrustes „matching bed” method is a very effective method for determining the Helmert's datum transformation parameters since it requires neither initial starting values nor iteration. Due to this attractive attribute the Procrustes algorithm has been extended it to solve the 3D affine transformation problem where scale factors are different in the three principal direction X, Y, Z. After computing the centre of mass coordinates of two given systems, scale, translation and rotation parameters are opti-

mised using Frobenius (in other term: Euclidean) norm. The transformation consists of three translation parameters, three rotation elements and one or three scale factors. The solution is demonstrated by practical applications using GPS and LiDAR measurement data (Papp 2021).

## **11 About the energy and age of the plate tectonics**

Recently, several research findings have come to light about the age of plate tectonics and energies are needed to operate it. The aim of study (Varga and Fodor 2021) was to investigate whether the energy of plate tectonics process was different during the Phanerozoic (Pz) and in earlier eons, and if there is such a discrepancy, whether it can be justified by changes in the processes that able to move the plates. The research tracked temporal changes in important components of plate tectonics such as length of mid-ocean ridges, subduction zones and relative oceanic crust coverage during Phanerozoic. Next, it was examined how the knowledge gained in this way can be reconciled with the results of studies of previous eons. It was found that the temporal variation of kinetic energy of axial rotation due to changes in length of day (LOD) can be assumed as a determining energy which acts on the tectonic plates as in the Phanerozoic as earlier in Archean (Arch) and Proterozoic (Ptz).

## **12 Influence of tidal forces**

Reviewing the results of the calculations it was concluded in Varga and Grafarend 2019 that the magnitude of triggering effect of earth tides is different in case of zonal, tesseral, and sectorial tides and also significantly depends on the latitude. The results of calculations carried out using theoretical models show that only the horizontal shear stresses produced by earth tides are able to influence the outbreak of earthquake. The load caused by oceanic tides due to their local influence on solid Earth has only a limited role in earthquake triggering by tides.

## **13 Relation of different type Love-Shida numbers**

There are different equations to describe relations between different classes of Love-Shida numbers. In the study Varga, Grafarend and Engels 2019 with the use of the time-varying gravitational potential an integral relation was obtained which connects tidal Love-Shida numbers, load numbers, potential free Love-Shida numbers generated by normal and horizontal stresses. The equations obtained was the only one which holds for every type of Love-Shida numbers, describes a relationship not between different, but the same type of Love-Shida numbers, and it does not follow from the sixth-order differential equation system of motion usually applied to calculate the Love-Shida numbers.

## **14 Geospatial analyses applied for medical sciences**

The application possibilities of the results achieved in the field of numerical theories and solutions in the field of mathematical geodesy have been manifested in several articles and studies.

By spring of 2020, the COVID-19 disease has spread all around the world, and the COVID-19 outbreak has been declared to be a pandemic by the World Health Organization (WHO) on 11 March 2020. A MATLAB tool has been developed for monitoring and analysing the spread of the COVID-19 virus. With the use of the tool geostatistical analysis of the continuously developing time series of contagion can be performed, which may be a useful tool for decision makers on planning future actions. The major features are geographical display of the status of the virus spread, time series of confirmed / fatal / recovered / active cases of the disease on cumulative and on daily basis, centre and radius of the spread, best fitting bell curve of the active cases, and general statistics (CRF, modified CFR, attack rate, mortality rate). Each feature can be used globally or country-wise (Földváry 2021b).

At the end of the 20th century and at the beginning of the 21st century, because of a sharp reduction in the water flow from the Amudarya and Syrdarya rivers into the Aral Sea, the actual disappearance of the Aral Sea, the ecological balance was disturbed in the Aral Sea region, the external environment was degraded, an extreme condition for people's habitation arose. An analysis of the leading sanitary-ecological factors of the environment affecting the incidence rates among the population of the Karakalpakstan in 2009-2018 found that between the indicators of the primary incidence of malignant neoplasms and water samples of open reservoirs that are not standard in chemical composition, strong direct correlations in the Northern zone, average direct correlations in the Western and Central zones were established. The solution to the problem lies in providing for the population of the detected districts with centralized drinking water that meets the state standard (Turdimambetov et al. 2021).

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# HUNGARIAN NATIONAL REPORT ON REFERENCE FRAMES (2019-2022) – IAG COMMISSION 1

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## 1 Institutional background

The national report summarizes the Hungarian activities over the period of 2019-2022 related to GNSS service provision, GNSS data analysis on national and international level, geokinematic research from infrastructure maintenance to data interpretation.

In Hungary the Institute of Geodesy, Cartography and Remote Sensing (Hungarian abbreviation: FÖMI) was historically the responsible institution for geodetic reference networks, positioning services and the related research activities. Since January 2017 FÖMI has been moved under the Government Office of Capital City Budapest (Hungarian abbreviation: BFKH) as a department, but the professional work continued without significant disruption. After two years in early 2019 several branches, including the units responsible for the positioning, coordinate systems and reference frames are moved into the Lechner Knowledge Center Ltd. The acting groups and responsibilities remained the same.

## 2 Active GNSS network (GNSSnet.hu) and related services

The Hungarian active GNSS reference station infrastructure and services have been established and being maintained by the GNSS Service Centre (GSC) acting as part of the LTK Satellite Geodetic Observatory (SGO). The GNSSnet.hu network consists of 35 Hungarian and 19 permanent stations from the neighbouring countries. The GNSS data is collected and processed in real time to provide nationwide homogeneous coverage with cm-accuracy services. The average inter-station distance is less than 60 km, enabling accurate modelling of distance-dependent errors like ionosphere, troposphere and orbits. All of the Hungarian stations and most of the integrated external sites are equipped with GPS+GLONASS sensors and individually calibrated antennae. Fifteen receiver/antenna units are already Galileo capable, where the update is planned to be finished in 2023.

The GNSS Service Centre uses the GNSMART network RTK software package, developed by Geo++ GmbH to provide reference data for both real-time and post-processing applications. GNSMART had been upgraded to GNSMART2 in mid-2022 and since then we are providing multi-GNSS RTK corrections as well. Real-time correction data is distributed using the Ntrip protocol in all proprietary formats. Besides the network RTK we also distribute single baseline multi-GNSS RTK streams via our in-house developed caster solution. RINEX and virtual RINEX data is provided for post-processing via the GSC website ([www.gnssnet.hu](http://www.gnssnet.hu), 2023-06-21) in RINEX version 2.11 and 3.03 formats.

As of December 2022 more than 2200 organisations registered for the GNSS services and the number of registered user account exceeded 4000. The majority of land surveying tasks in Hungary are carried out using real-time GNSS technique.

GNSSnet.hu reference station coordinates are determined in ETRF2000 reference frame. Transformation to the Hungarian local grid (EOV) is supported in both real-time and post-processing mode. An online transformation service (EHT) is provided at the GSC website and a real-time transformation solution (VITEL2014) is available for most receiver brands as an extension of the RTK rover receivers' controller software.

The GSC concentrates its efforts on service quality improvements. Besides the automatic quality control of the GNSMART2 software the GSC developed a number of real-time and post-processing quality monitoring tools for both internal use and information dissemination to the clients. The actual status of the service can be monitored online via the GSC website: <https://www.gnssnet.hu>. A



## 4 International collaboration

SGO supports the operation of EUREF and EPN. The Head of the SGO (Dr Ambrus Kenyeres) was the EPN Reference Frame Coordinator over the period of 2009-2017. From 2015 to 2018 he served as the chair of the EUREF Governing Board.

SGO as initiator of the EPN Densification (EPND) WG has started the integration of all European active GNSS network products – in terms of daily/weekly SINEX files - to provide a high quality, homogeneous and dense position and velocity product in close cooperation with all national data providers. All details on EPND can be found on a dedicated webportal (<https://epnd.sgo-penc.hu>). The EPND products are annually updated, the last solution (D2200) includes data up to March 2022. The position and velocity results are expressed in ITRF2014. In the frame of the European Ground Motion Service (EGMS) project the EPND product, extended with the Nevada Geodetic Laboratory (NGL) data had been used to generate the reference velocity model for the InSAR derived ground motion product. EPND is the input data for the generation of the European GNSS Velocity model created Lantmateriet (Steffen et al, 2021).

SGO is a service provider of EPOS (European Plate Observing System) and contributes to the long term EPOS service with GNSS product integration, time series generation and velocity results delivery.

## 5 GPS geokinematics

SGO continued the investigations in the framework of the GPS crustal deformation monitoring program - commenced in 1991. The latest campaign had been organized in 2019. The more than two decade long campaign style MGGA (Hungarian GPS Geokinematic Reference Network) measurement series had been merged with the long term analysis results of the GNSSnet.hu permanent data in the frame of EPN Densification. This allow us to extend our view and analysis over a larger area and interpret the displacement field as a complex tectonic environment. This new data enabled us to better constrain the 3D crustal deformation map of the Pannonian basin and estimate horizontal crustal motions and vertical tectonic signals to detect the main crustal blocks and faults and their present-day kinematics.

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# HUNGARIAN CONTRIBUTION TO THE RESEARCH IN GRAVIMETRY, GRAVITY FIELD MODELLING AND GEOID DETERMINATION (2019-2022) – IAG COMMISSION 2

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## 1 Introduction

This paper is made for the 28th International Union of Geodesy and Geophysics (IUGG) General Assembly 2023, Berlin, Germany as a quadrennial report of the Hungarian Contribution to the research in gravimetry, gravity field modeling and geoid determination (IAG Commission 2). In the past four years, we have conducted extensive and successful researches in the field of gravimetry, which are summarized below.

## 2 Hungarian Gravimetric Network

The Hungarian Gravimetric Network (MGH, Fig. 1) is presently maintained by the Supervisory Authority of Regulatory Affairs (which has been the successor of Eötvös Loránd Geophysical Institute since 2022). According to the state in 2022, the MGH contains 25 absolute stations and 435 1st or 2nd order base points. The maintenance work includes the checking the status of base points as well as the substitution or installation of destroyed or new base points. Between 2019 and 2022, two previously problematic (long-unused) absolute 0-th order base points were recovered and occupied again for absolute measurements (86H Szerencs and 88H Nagyvázsony), three base points were reinstalled. These stations were linked to the 3 nearest MGH base points by relative gravimetric measurements.

In order to improve the reliability and accuracy of the network, the gravity acceleration was re-determined on 12 absolute stations between 2019 and 2022 (Kis 2022). The measurements were carried out by using AXIS FG-5 No. 215 and 251 (the latter was upgraded by HS5-system developed by VÚGTK) absolute gravity meters, operated by the staff of Východní ústav geodetický, topografický a kartografický, v.v.i. (VÚGTK, Czech Republic). Before the absolute measurements, vertical gravity gradient (VG) was determined on every station by at least two LCR-G gravimeters, using a 3-level arrangement and at least 6 series of measurements.

Between 2019 and 2022 two reinstalled INGA (Integrated Geodesic Point Network) base points were connected to the MGH network by comparative relative gravimetric measurements, the INGA stations were linked to the 3 nearest MGH base points.

Due to results of scene investigations of base points, ab. 10% of checked points (mainly 2nd order ones and in some cases 1st order ones) proved to be problematic, harmed or destroyed every year, because of highly growing number of church-, school- or self-governmental building reconstructions and low public awareness at the affected stations.

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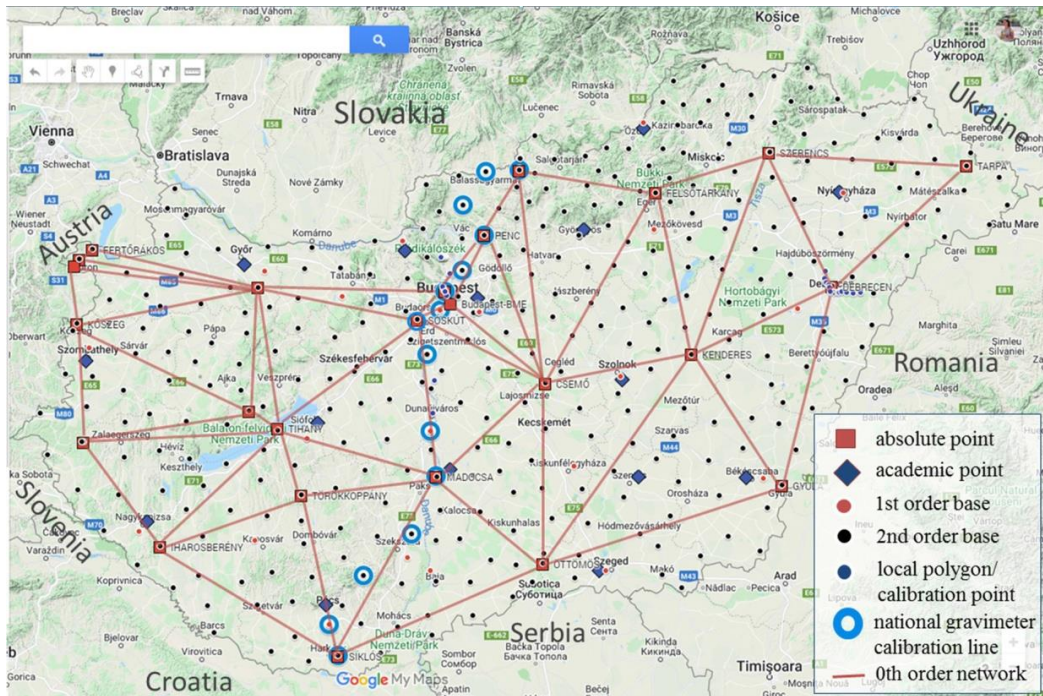


Fig. 1. Hungarian Gravimetric Network in 2022

In favor of the protection of MGH base points, up to our possibilities, started to inspect the recordings of base points into the Hungarian land and property registration system by counties, and in few cases, to supply recordings according to the relevant rules of law. An overall registration campaign is planned to ensure the legal protection which could help preventing point destructions and protecting the integrity of points and network.

Besides destroyed base points, another main difficulty of the network maintenance is the highly decreased human capacity (1 person for the operation between 2019 and 2022).

### 3 Scale factor determination of spring type gravimeters

The idea of moving mass calibration (MMC) of relative gravity meters dates back to the seventies of the last century. The MMC apparatus built in the underground Budapest-Mátyáshegy Gravity and Geodynamicals Observatory has been used extensively and several spring type instruments (LaCoste – Romberg and Scintrex) have been investigated and calibrated by it. The paper Koppán et al (2019) investigates the characteristics and the metrological limits of the calibration of spring type gravimeters by using a cylindrical test mass moved vertically around the gravimeter by a lifting device operated in the Budapest-Mátyáshegy Observatory. The movement of the 3100 kg iron mass generates a sinusoid-like calibrating signal having a peak-to-peak amplitude of  $1102 \text{ nm s}^{-2}$ . The careful determination of the geometrical and physical parameters of the test mass combined with the analytical modeling of its gravitational effect and the related uncertainties provides an accuracy of  $3 \text{ nm s}^{-2}$  in absolute sense. The overall accuracy, however, is influenced by several other instrumental and environmental factors which are investigated in detail except the cylindrical mass inhomogeneities. Possible material inhomogeneities of the ring mass and their gravitational effects are investigated by forward simulations and inversion is investigated in Papp et al (2022). The conclusions formulated by Koppán et al (2020) are based on more than 400 experiments with 5 LCR G instruments. As a unique case a Scintrex CG-5 instrument was also involved in the tests what is probably the very first moving mass calibration of this type of gravimeters. Two processing methods, *Max-*



*Min* and *Full-Fit*, based on L2 norm adjustment of the observations were developed and applied to obtain instrumental scale factor and other related parameters. The results show that the observations corrected for the disturbing effects still contain a systematic constituent with amplitude of (10–20)  $\text{nm s}^{-2}$  regardless which LCR instrument was calibrated. It resembles the second time derivative of the calibrating signal that may indicate the non-uniform elastic response of the spring sensors to the rate of gravity change. Due to the problems mentioned above the overall dispersion of the resultant random and non-random residuals of the calibration observations provided by *Full-Fit* method are typically  $10 \text{ nm s}^{-2}$ . The a posteriori standard deviations of the individual scale factors provide, however, measurement accuracy of  $2 \text{ nm s}^{-2}$ . The overall accuracy of the reference signal provided by the facility operated in the Mátyáshegy Gravity and Geodynamic Observatory Budapest is sufficient for many kinds of instrument tests. Consequently the MMC method gives an accurate solution for the calibration of both LCR and Scintrex CG-5 gravimeters used in tidal research. Moreover it can be applied for the investigation of sensor characteristics of the instruments equipped with different reading utilities either or not supported by feed-back system.

The main advantage of the MMC against any other method is methodological. On one hand it provides the simplest metrological standard and on the other it satisfies the conditions of constrained centricity and synchrony derived from an extended interpretation (generalization) of Abbe principle of alignment. But these positive features can probably be exploited only for microgravimetry, where the range of the signals to be measured does not exceed significantly the range of the signal generated by the movement of the mass, for example in tidal research or in experiments relying on highly precise determination of spatial gravity differences like in watt balance experiments. It cannot replace the traditional calibration lines although it may help the investigation of the instruments used to establish such lines below microgal level.

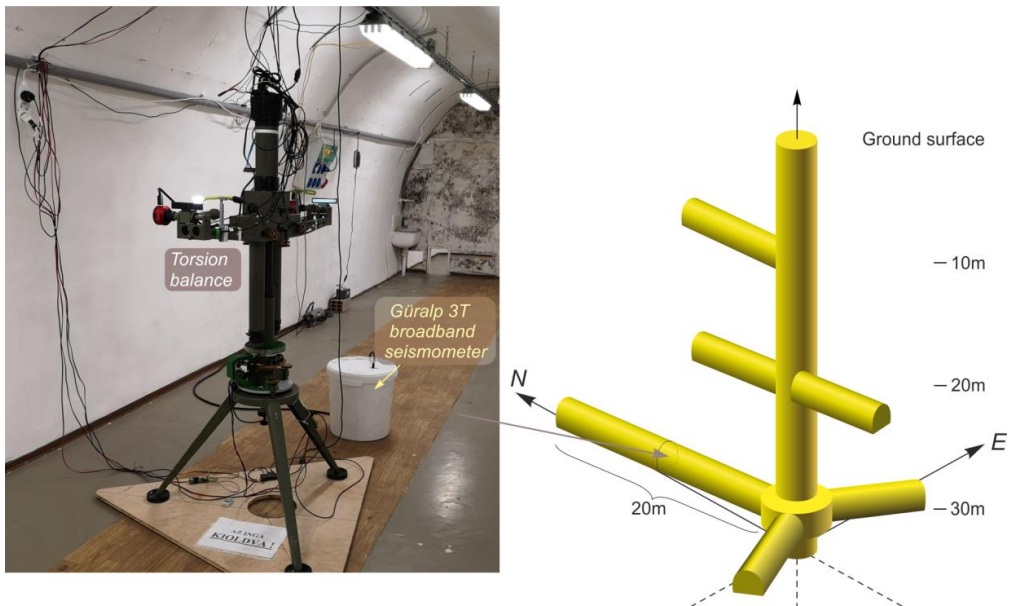
The same principle and technology can be applied to test compact tilt sensors having nanoradian resolution capability, as it is presented by Papp et al (2022). Up to now rigorous testing methods below microradian range were not available in practice. The analysis of the so-called off-axis variation of the gravitational vector generated by the vertical movement of the cylindrical ring mass of the Mátyáshegy MMC device, however, showed that a sufficiently accurate reference signal having  $(15 \pm 0.02) \text{ nrad}$  peak-to-peak amplitude can be provided for calibration. It is just in the range of tilt induced by earth tide effect, which is a “standard” signal component in the time series recorded in observatory environment. In the first part of the paper by Papp et al (2022), a discussion of the proposed methodology of tilt meter calibration is given. Then the analysis of the effect of volumetric discretization of the cylindrical ring on the accuracy of calibration is provided. The discretization of the ring mass is unavoidable due to the rigorous calculations required to determine the effect of off-axis position of the gravity sensor during the calibration experiments. The exact position of the effective point of the sensor of an LCR gravity meter, however, is not known because of the complexity of its sensor mechanics. Therefore, one should give a worst-case estimation to quantify the limit on the largest possible effect of sensor eccentricity related to the axis of symmetry of the cylindrical test mass. Analytical expression for off-axis computation of its gravitational attraction is, however, not available, so the decomposition of the mass to simple volume elements having closed gravitational formula is also unavoidable. Rectangular prisms and polyhedrons possessing triangular base were applied to fill (i.e. discretize/approximate) the volume of the cylindrical ring and a kind of convergence analysis was performed to see the effect of the increasing spatial resolution of the respective models. High accuracy ( $1 \text{ nm/s}^2$ ) is already provided by a very low resolution polyhedron model containing only 180 volume elements. In order to obtain the same accuracy a prism model should contain more elements by 2 orders of magnitude. Furthermore Papp et al (2022) showed that realistic density inhomogeneities ( $\pm 20 \text{ kg/m}^3$ ) proved by metallurgic investigations cannot modify the calibrating signal significantly. Its contribution is less than  $0.05 \text{ nm/s}^2$  and  $1 \text{ nm/s}^2$  in terms of gravity acceleration, 20 prad and 100 prad in terms of tilt in case of random like and systematic distributions of density inhomogeneities, respectively. In order to explain the residual gravity signal provided by the least squares adjustment of the gravity variation recorded during MMC experiment, as it is described by Koppán et al. (2020), both direct and inverse gravitational computations were performed. This signal has a  $20 \text{ nm/s}^2$  peak-to-peak amplitude showing systematic characteristics.

In the direct computations, fictive density contrasts were applied in the form of segmented cylindrical ring. Based on the characteristics of the residual signal a model consisting of 3 joining segments supplied with high and different density contrast was selected. Indeed, such a model can generate a gravitational signal having amplitude similar to that of the residual signal indicated by Koppán et al. (2020). The size of these density inhomogeneities are, however, unrealistic based on both the error estimate of the total mass of the cylindrical ring and the data obtained from metallurgic investigations. The L2 norm inversion of the residual signal solved for 6 joining cylindrical rings results in also very high (i.e. unrealistic) density variations along the vertical providing excellent fit ( $\pm(2.5 - 3.5) \text{ nm/s}^2$ ) between the observables and the gravitational effect of the 6 cylinder model. Consequently, the residual signal cannot be interpreted as the gravitational effect of the mass inhomogeneities of the cylindrical ring.

#### 4 Torsion balance measurements

Nowadays, the use of torsion balance has come to the fore again. At present, it is of great importance in determining the fine structure of a geoid and in clarifying the question of the principle of equivalence and the fifth force in physics, and interesting observations have been made in behavior of some torsion balances before certain earthquakes. The torsion balance is one of the most accurate instruments in physics to date, and with the current technical possibilities, we have the opportunity to further increase the previous reading accuracy by up to two orders of magnitude. With a Pekár balance, which we have renovated and improved, we are currently carrying out measurements at a depth of 30 m in the Jánossy Underground Laboratory of the Wigner Research Center for Physics. The renovation and further developments of three more Auterbal balances is now being completed and new test measurements are starting (Völgyesi et al. 2021).

Between 1906 and 1908 Roland (Loránd) Eötvös and his colleagues Dezső Pekár and Jenő Fekete made measurements with revolutionary precision (the EPF measurement) for validating the equivalence of gravitational and inertial mass. Almost 80 years later, in 1986, E. Fischbach and his colleagues reanalyzed the results of the EPF measurement and discovered a correlation between the small violations and the specific baryon charge. Several repeated experiments were unable to reproduce this correlation, but there is still no valid explanation of these differences in the EPF results.



**Fig. 2.** The location of Eötvös-Pekár torsion balance and the Güralp 3T seismometer at the Jánossy Underground Research Laboratory (JURLab) (Völgyesi et al. 2019)



Our analysis of the EPF experiment pointed to a possible bias that justifies repeating the tests under better conditions and using modern new technology. Planning and preliminary measurements started at July of 2017. Participants are from Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Department of Geodesy and Surveying of Budapest University of Technology and Economics (BME), Society for the Unity of Science and Technology (SUST), and the Department of Control Engineering and Information Technology of BME in cooperation with other organizations, departments and experts. After more than one year of thoughtful preparation, in December 2018 preliminary tests have been started in a controlled and undisturbed environment of the Jánosy Underground Physics Laboratory at KFKI, 30 meters below ground level (Fig. 2). The papers (Tóth et al. 2019, Völgyesi et al. 2019) give an overview of the basic physics, history, preparations and present status of the new experiments.

## 5 Satellite gravity gradiometry

InSAR images enable determination of surface deformation over large region even with some cm amplitude over short and long time scales as well. In the frame of EU's Copernicus Programme, by the launch of Sentinel-1B in 2016, an additional satellite has become available for InSAR determination of surface deformation apart from Sentinel-1A. The two missions are essentially identical, which enables the reduction of the repeat time of imaging. SAR images acquired along descending and ascending orbits has a view of a surface deformation from a different angle. Accordingly, the surface deformation they show are affected by foreshortening and related projection errors. By combination of two deformation models, 3D deformation can efficiently be modelled. As a case study, reconstruction of the surface motions due to the 2018 Oaxaca earthquake was performed, with the joint use of a Sentinel-1A deformation model taken on a descending orbit and a Sentinel-1B deformation model taken along an ascending orbit (László and Földvály 2019).

In association with UNESCO, the world's scientific community has commemorated year 2019 to be Loránd Eötvös Commemorative Year to mark the 100th anniversary of the death of Loránd Eötvös (1848-1919). In this apropos, from the Eötvös torsion balance until the present-day achievements of satellite gravimetry (Földvály et al. 2019a) and the up-to-date status and results of geodesy and geophysics unfolding the work of Eötvös (Földvály et al. 2019b) has been overviewed.

By the end of the GRACE satellite mission in 2017, the demand on continuation was resolved by the launch of GRACE-FO satellite pair in 2018. However, the gap between the two missions resulted in need of interpolation of the missing data. Before the GRACE-FO data became accessible, time series analysis methods have been tested for forecasting of GRACE-FO monthly gravity field solutions. The estimation was done by ARIMA modelling, a method extensively used for prediction of stochastic processes. The results show that although the prediction can be done, the approximately 1-year gap is too large for such an estimation, resulting in too large standard deviation of the predicted time series (Földvály 2019). After the GRACE-FO data has been published, relevant tests on the consistency of the GRACE and GRACE-FO monthly solutions was delivered (Földvály and Nyilas 2020), and combined GRACE and GRACE-FO monthly solutions have been used for determination of the desiccation processes of the Aral Sea (Földvály et al. 2020). As a conclusion, GRACE models for the period March–June 2017 are suggested to be neglected from time series analysis studies.

Deformation monitoring is an unavoidable task of construction works for major industrial investments. As an example, vertical deformation monitoring of the construction of the Family Park shopping centre facility in Samarkand, Uzbekistan was performed, making use of a monitoring network in 8 epochs, and future subsidence has been provided by extrapolating of best-fitting exponential curve. It was found that in all test points the relevant subsidence has been ceased. Additionally, the tilting of the building has been estimated, which was also found to be unidirectional, so no deformation of the structure was expected due to it (Aminjanova et al. 2021).

## 6 Determinations of the vertical deflections

QDaedalus is an automated, computer-controlled astrogeodetic measuring system (Fig. 3) capable of measuring the astronomical deflections of the vertical (DOV). The basic element of the system is a modified Leica TCA1800 total station. The modification concerns the optics of the instrument, the eyepiece has been replaced by a high-resolution and highly sensitive CCD sensor.

When the eyepiece of the telescope of a geodetic instrument is replaced by a CCD sensor, the first important task is calibration (Völgyesi and Tóth 2020).

The purpose of calibration is to establish a connection between the readings on the horizontal and vertical circles of the instrument, and the readings in the frame attached to the CCD sensor. During calibration, the servomotor moves the instrument's telescope in small steps around a target point selected for calibration, records horizontal and zenith angles, while the CCD sensor registers target's coordinates. Calibration (transformation) parameters can be computed from these measurements.

After discussing the principle of calibration, practical solutions of calibration were considered, and we have presented a new, simple and accurate technical solution by using a collimator (Völgyesi and Tóth 2020).

During our measurements and tests, the optimum number of calibrations, the optimal calibration matrix size and the effect of temperature change were considered.

An important issue is the optimum number of the calibrations. Our test with the QDaedalus system showed, that at least 10 calibrations should be performed but more than 15 do not significantly improve the results, so a number of calibrations between 10 and 15 appear to be the best compromise in terms of accuracy and the required measurement time.

The calibrated area of the CCD sensor can be varied depending on the size and grid spacing of the calibration matrix. We found that increasing the size of the calibration matrix despite a significant increase in calibration time does not significantly increase the accuracy of the principal point. Therefore  $2 \times 2$  or  $3 \times 3$  matrix sizes are appropriate, but  $4 \times 4$  size is quite an unnecessary waste of time. The optimal solution found is to increase the number of measurements using small matrix size (Völgyesi and Tóth 2020).

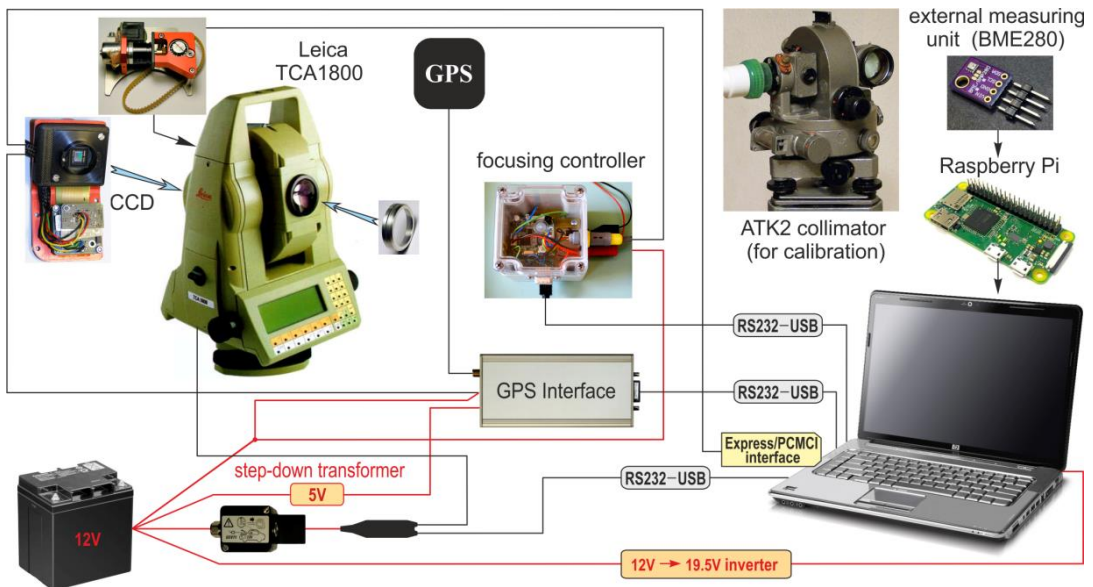


Fig. 3. Schematic construction of the QDaedalus system (Völgyesi et al. 2019)

We also tested errors caused by temperature change. It was found that temperature change during the time between the start of the calibration and the end of the astrogeodetic measurement cannot exceed 1-2°C. In case of significant temperature decrease mainly at dusk it is advisable to calibrate before and after the astrogeodetic measurement and calculate the mean principal point and mean transformation parameters. We confirmed with our tests that before the start of field measurements when the instrument is transported from a heated room to the outdoor, one should wait for complete temperature stabilization of the whole instrument, including the inner optical structure (Völgyesi and Tóth 2020).

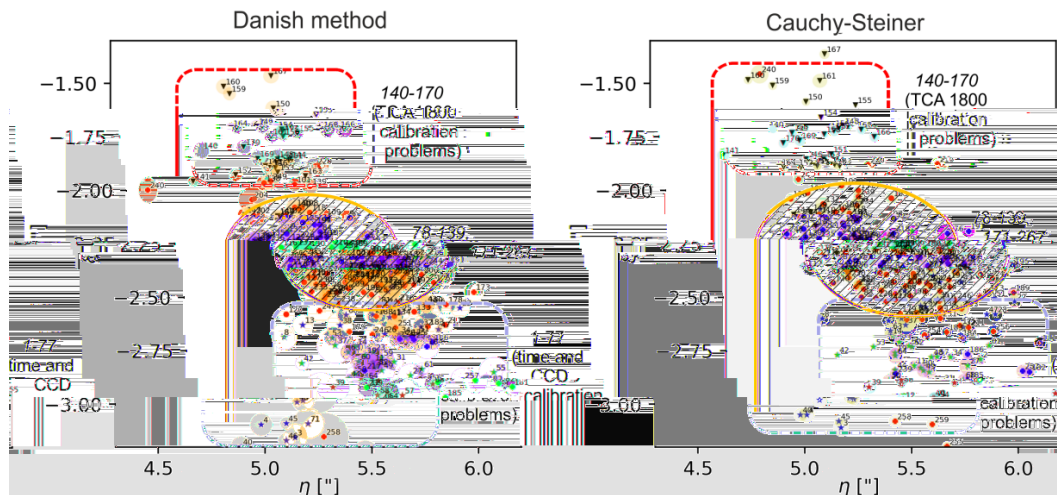
Finally we recommend that our new calibration method, which uses a collimator, should be adopted if possible by other groups. The expected costs are moderate, since any old theodolite can serve as a collimator with minor modifications and a LED lamp attached to its eyepiece. On the other hand our method has several important benefits: the target can be placed quickly within just a few meters distance, reducing the time of field operations. Additionally, we found that it has a beneficial effect on the accuracy of the calibration (Völgyesi and Tóth 2020).

Over the last 7 years we made 267 night measurements of DOV values by QDaedalus system at the Pistahegy point in the southern part of Budapest. These measurements made in different seasons, in the most diverse meteorological, temperature and refraction conditions.

On Fig. 4 the results of all 267 Qdaedalus measurements of DOV at the Pistahegy station can be seen, both the results of the Danish adjustment method and the Cauchy-Steiner weights (Tóth and Völgyesi 2017) are presented. The results of problem-free measurement series 78 to 139 and 171 to 267 are located in hatched area in the middle part of the Fig. 4, these points marked by red dots and the serial number of measurements are given next to the dots. The DOV values marked by blue stars computed from the first 77 measurements are separated in the lower part of the figure, and the values marked by black reverse triangles computed from the series of 140-170 Qdaedalus measurements can be found in the left upper part of the figure.

Astronomical deflections of the vertical measured by the QDaedalus system are significantly influenced by atmospheric refraction, which depends primarily on the environmental parameters (air pressure, temperature, humidity) and the spectrum of the stars.

In previous measurements, meteorological parameters were determined only at the beginning and end of the measurements, but more recently we have switched to high-precision recording of barometric pressure, temperature, and humidity every 10 seconds (Völgyesi and Tóth 2021). This made it possible to continuously determine the refraction and take its effect into account during the entire measurement time.



**Fig. 4.** DOV inversion results of 267 QDaedalus measurement series by the Danish method vs. Cauchy-Steiner weights at Pistahegy Station. Numbers of series are given on the plots. Ellipses indicate estimated inversion errors. Median of  $\zeta$  is  $-2.39'' / -2.37''$ , median of  $\eta$  is  $5.15'' / 5.17''$  for Danish/Cauchy-Steiner methods, respectively (Völgyesi and Tóth 2021)

During the 30 min measurements time session temperature fluctuated by 1°C and pressure changed by 0.3 hPa. All the measured zenith angles were in the range of 30°±2°.

Compared to the value calculated for the average temperature and air pressure, the refraction changed by ± 0.06″.

We want to emphasize, that although we applied two standard inversion procedures with Danish and Cauchy-Steiner weights, the latter gave consistently better results in terms of both accuracy of the inversion parameters and correlation norm. This is probably due to the higher statistical efficiency of M-inversion in cases of non-Gaussian distribution of residuals compared with the robust E-estimation with Danish method commonly used in geodetic data processing.

Refraction also depends on the wavelength of the observed light. Measured stars have different spectral characteristics, and the value of refraction should vary with the spectral type depending on how the spectrum is distributed across the instrument's passband. We calculated refraction using environmental data with and without taking into account the spectra of measured stars. Utilizing our algorithm for QDaedalus measurements we calculated refraction differences for stars measured near zenith distance 30° that resulted from using spectral information in the computation. The differences were in the range  $-0.125'' \div 0.070''$ . It is obvious that variation of refraction due to the different colors of stars (spectra) should be included in refraction modeling. The average biases in estimated N-S and E-W vertical deflection components for 34 measurements were  $-0.009''$  and  $-0.003''$ , respectively, if we neglect stellar spectra. The standard deviations of differences are 0.013″ and 0.018″ for the N-S and E-W components (Völgyesi and Tóth 2021).

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# HUNGARIAN CONTRIBUTION TO THE RESEARCH OF PHENOMENA RELATED TO EARTH ORIENTATION TIDES AND TECTONICS (2019-2022) - IAG COMMISSION 3

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## 1 Problems related to the Earth's rotation

### 1.1 Effect of tides and tidal friction on earthquake activity

The increase of lunisolar radial and shear stress components ( $\sigma_{rr}$ ,  $\sigma_{\varphi\varphi}$ ,  $\sigma_{\lambda\lambda}$ ,  $\sigma_{r\varphi}$ ,  $\sigma_{r\lambda}$  and  $\sigma_{\varphi\lambda}$ ) until the 1000 - 2000 km depth zone is monotonous (some stress types reach their maximum value in this depth range while others continue to grow monotonously) and are not substantially depending on the inner structure of the Earth. The biggest observed Earth model dependence did not exceed 20 percent. The depth distribution of tidal stresses has lesser subordinate importance for studying possible tidal triggering since 95% of the earthquake energy is released within the depth interval (0-50) km. The role of the lunisolar effect to some extent can be significant in horizontal shear stresses  $\sigma_{\varphi\varphi}$  and  $\sigma_{\lambda\lambda}$ . The likelihood of triggering effect in case of shallow seismicity in all probability can increase the fact, that the majority of the forces generating earthquakes are horizontal (or nearly horizontal) (e.g. normal, reverse or strike slips). However, it should be taken into account that the geographical distribution of  $\sigma_{\varphi\varphi}$  and  $\sigma_{\lambda\lambda}$  is diversified. In the equatorial area, there is no triggering by tesseral (diurnal) tides, but the sectorial (semi-diurnal) and zonal (long periodic) tides are big. At mid-latitudes, the zonal tide-generated stresses are missing, while in polar regions only the zonal stress tensor component is significant (Varga and Grafarend 2019). This effect is apparent in the global distribution of seismic energy with respect to latitude (Fodor and Varga 2022).

The viscous low velocity zone (LVZ) can result in a decoupling effect between the lithosphere and the mantle due to the fact, that the annual rotational energy change is on the same order of magnitude, as the force, that is required to move the lithosphere over the stationary elastic mantle. This differential rotation is most likely generated by tidal friction (Varga and Fodor 2021; Varga and Fodor 2022).

### 1.2 Variations in Virtual Dipole Moment and Length of Day over time

The data of the International Bank of Digital Information on the time distribution of the virtual dipole moment (VDM), supplemented by the data of more recent studies (a total of 5645 values) were used as the basis of the virtual dipole moment values distribution analysis for the Earth history within the concept of the Earth's magnetic dipole field. The results revealed the positive linear trend from  $4.2 \cdot 10^{22} \text{ Am}^2$  4.2 billion years ago up to  $\text{Am}^2$  to  $5.15 \cdot 10^{22} \text{ Am}^2$  in recent times. The straight lines in Figure 1 show the regression  $VDM = a \cdot t + b$  with numerical values for the slope  $a = (-0.00019 \pm 0.00028) \text{ Am}^2/\text{Ma}$  for the Pz (Phanerozoic) and  $a = (0.00019 \pm 0.00008) \text{ Am}^2/\text{Ma}$  for the Arch+Ptz (Archean+Proterozoic).

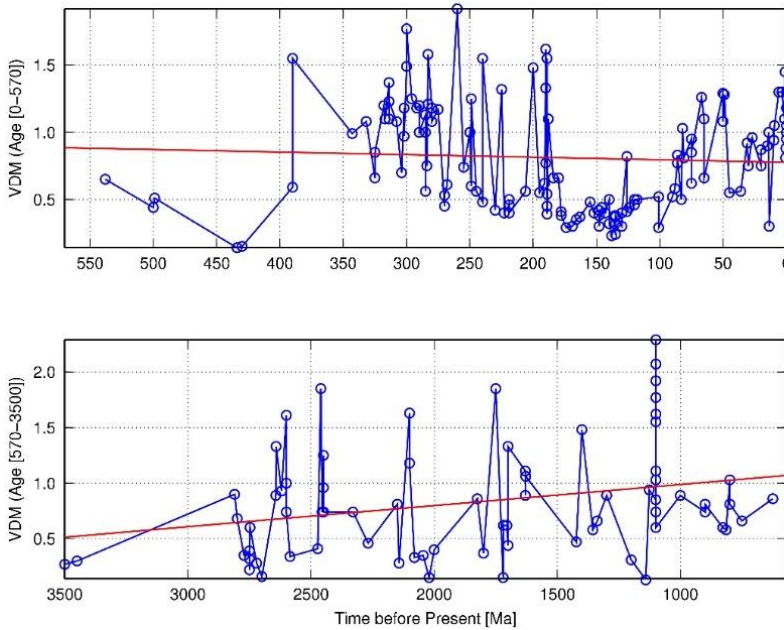
The question whether the slope estimates reflect a significant trend in the change of VDM in the time-interval from 3.500 Ga to 0.570 Ga (Arcean+Proterozoic) and from 0.570 Ga to Present Epoch (Phanerozoic) has been verified using an F statistical hypothesis test using a confidence level of 5%. It was found that it is significant for the Arch+Ptz and not significant for the Pz. If this process of successfully increasing VDM during the time interval from 3.500 Ga to 0.570 Ga is related to the evolution of the core it leans toward the conclusion that the absolute and relative sizes of the

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inner and outer cores continue to form (Schreider 2019 a,b). The growth of the Earth cores may have stopped during the Pz.



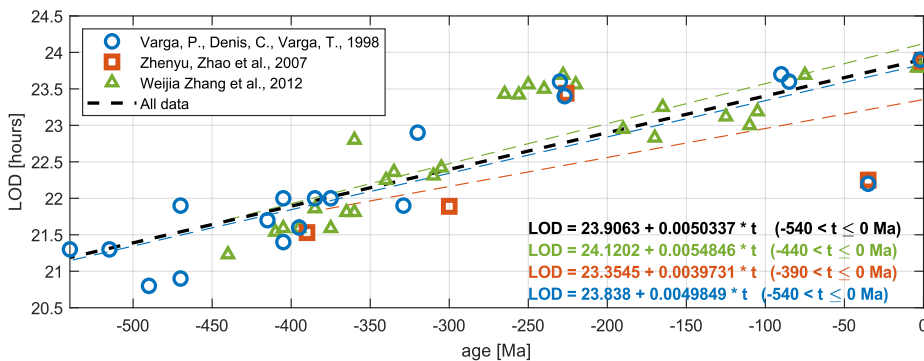
**Figure 1.** Dipolar geomagnetic moment values during the time intervals from 0.570 Ga to present (above) and from 3.500 Ga to 0.570 Ga (below). The straight lines show the regression  $VDM = a \cdot t + b$  with numerical values for the slope  $a = (-0.00019 \pm 0.00028) \text{ Am}^2/\text{Ma}$  and  $a = (0.00019 \pm 0.00008) \text{ Am}^2/\text{Ma}$  for the Pz (Phanerozoic) and Arch+Ptz (Archean+Proterozoic) respectively (Schreider et al. 2019a,b)

The despinning caused by the tidal friction results in an extension of the length of the day (LOD). The LOD database for Proterozoic (Ptz, 2500 Ma BP-540 Ma BP) and Phanerozoic (Pz, 540 Ma BP-Present) (Varga and Fodor 2021; Fodor and Varga 2022) gives the slope  $a$  ( $LOD = a \cdot t + b$ )

$$(0.00503 \pm 0.00072) \text{ h/Ma for Ptz} \tag{1}$$

$$(0.00059 \pm 0.00060) \text{ h/Ma for Pz.} \tag{2}$$

The significance of the trend estimate of LOD assuming normally distributed data has been verified using F statistical hypothesis test using a confidence level of 5% and it was found that the slope is statistically significant in both cases.



**Figure 2.** Length of the day during Phanerozoic (Fodor and Varga 2022)



With the use of results of statistical analysis of LOD data, it has been found that during the Pz the LOD increased on average at a rate of 5.0 h/Ga (1.80 ms/century) (Eq. 1 and Figure 2) while during the Ptz, the average rate was only 0.5h/Ga (0.18 ms/century) (Eq. 2 and Figure 3), i.e. 10 times smaller (Varga et al. 1998, Varga 2006, Zhenyu et al. 2007, Zhang 2012).

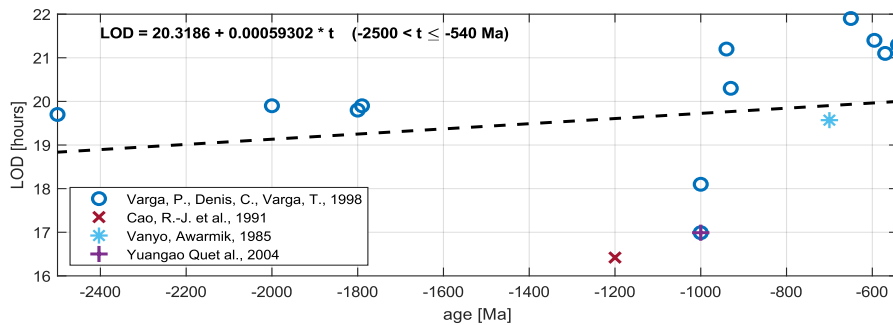


Figure 3. Length of the day during Proterozoic (Fodor and Varga 2022)

Based on the aforementioned LOD variations in Fodor and Varga (2022) it was concluded that during the last 3 Ga the Earth-Moon distance increased by about 12%, and the day became six hours longer. Earth lost 33% of its rotational energy and the rotational energy loss rate was 4.1 times higher during the Pz than earlier in the Arch and Ptz, which means that near the boundary of Ptz and Pz there took place a significant alteration in the despinning of the Earth's axial rotation.

The results on changes in LOD over time suggest that

- the analysis of the mutual relationship between earthquake activity and Earth's rotation concluded that the correlation between changes in the speed of Earth's rotation (that is, changes in the LOD) may affect earthquake activity (Fodor et al. 2020),
- the slowing down of Earth is reflected in the latitudinal distribution of earthquake energy, which is symmetric concerning the equator and there are clear maxima at mid-latitudes (Fodor 2021).

The low-velocity zone (LVZ) results in a decoupling effect between the lithosphere and the Earth below the LVZ. It can be shown that if the viscosity of the LVZ is between  $10^{13}$  Pa·s and  $10^{15}$  Pa·s, tidal friction can contribute to the movement of tectonic plates (Varga and Fodor 2021).

## 2 Research of tectonic movements, Earth's tides and related phenomena by extensometers and tilt sensors

### 2.1 Test of ocean tide loading models on the of extensometric measurements

Tidal strain observations carried out in the SOPGO were used to test thirteen different ocean tide loading models (SPOTL, supplemented by the local model osu.mediterranean.2011, EOT11a, HAMTIDE11a, OSU.TPXO72atlas, OSU.TPXO72, TPX070, DTU10, CSR4.0, FES2004, FES95.2.1, SCHW1 and three other models were chosen from the Free Ocean Tide Loading Provider created by Scherneck and Bos (<http://holt.oso.chalmers.se/loading/>): FES2012, FES2014b, GOT00.2). for diurnal and semi-diurnal tidal harmonic constituents O1, K1, P1 and M2. Strain data with one-minute sampling rate were corrected for temperature and barometric pressure and decimated to one hour sampling rate. Strain data, corrected in this way, were subjected to correction for ocean tide load. In the case of the diurnal tidal constituents O1 and K1 the measured amplitude factors of nearly 0.5 became close to the theoretical as a result of the correction, while in the case of the M2 semi diurnal wave the measured amplitude factor of almost one hardly changed due to correction. It was only found a negligible difference between the individual global ocean tide loading models mainly due to using different Earth models and Green functions. The effect of the diurnal

(O1 and K1) and the semidiurnal (M2) ocean tide loading components is in the same order of magnitude at the SOPGO. The large residual vectors after the correction suggest that local effects need further investigation (Mentes 2021).

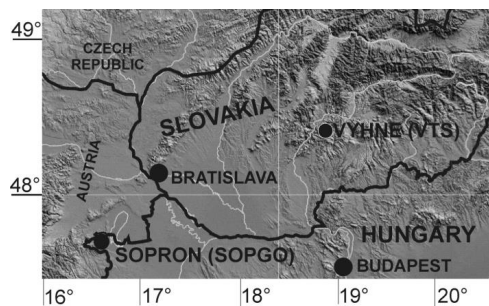
The same ocean tide loading models were used for correction of strain data measured at the VTS in Slovakia. The ocean loading corrections were carried out on yearly strain data measured between 2015 and 2019 in both observatories. Comparison of the obtained uncorrected and corrected average amplitude factors obtained at the SOPGO and VTS are shown in Table 1 (Brimich et al. 2021).

**Table 1.** Comparison of the effectiveness of ocean tide loading correction at the VTS and SOPGO in the case of O1, P1, K1 and M2 tidal waves on the basis of extensometric measurements between 2015-2019. (S.D. denotes standard deviation)

Observatory	Tidal waves	Average amplitude factors			
		Uncorrected	$\pm$ S.D.	Corrected	$\pm$ S.D.
VTS	O1	1.01482	0.10443	1.10817	0.02831
	P1	1.21691	0.08242	1.35717	0.07076
	K1	0.83173	0.01769	0.92809	0.06272
	M2	1.09392	0.08773	1.28812	0.01787
SGO	O1	0.58767	0.07697	0.98893	0.05520
	P1	0.38967	0.11192	1.89117	0.02841
	K1	0.41548	0.11112	1.00430	0.03712
	M2	1.00564	0.00297	1.04962	0.01941

## 2.2 Monitoring of local tectonic movements by extensometers and tilt sensors

In the Pannonian Basin quartz tube extensometers of the same construction are used for measurement of local tectonic deformations, Earth's tides and related phenomena. The locations of the extensometric stations are shown in Figure 4. Extensometric data obtained in two Hungarian observatories: Sopronbánfalva Geodynamic Observatory (SOPGO), Mátyáshegy (Budapest) Gravity and Geodynamic Observatory (MGGO) and in Slovakia the Vyhne Tidal Station (VTS) were regularly pre-processed to eliminate short and long periodic seasonal disturbing effects (temperature, air pressure) and local effects depending on the properties of the measurement site (geology, cavity, etc.). To ensure the best data quality the instruments were yearly calibrated by the same calibration instrument, in addition to the daily calibration by the built-in calibrator. This method provides data of the same quality, allowing comparisons of data measured in each observatory, especially for the interpretation of tectonic movements.

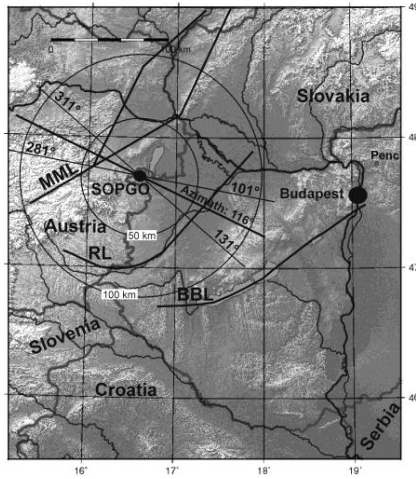


**Figure 4.** Location of extensometric stations

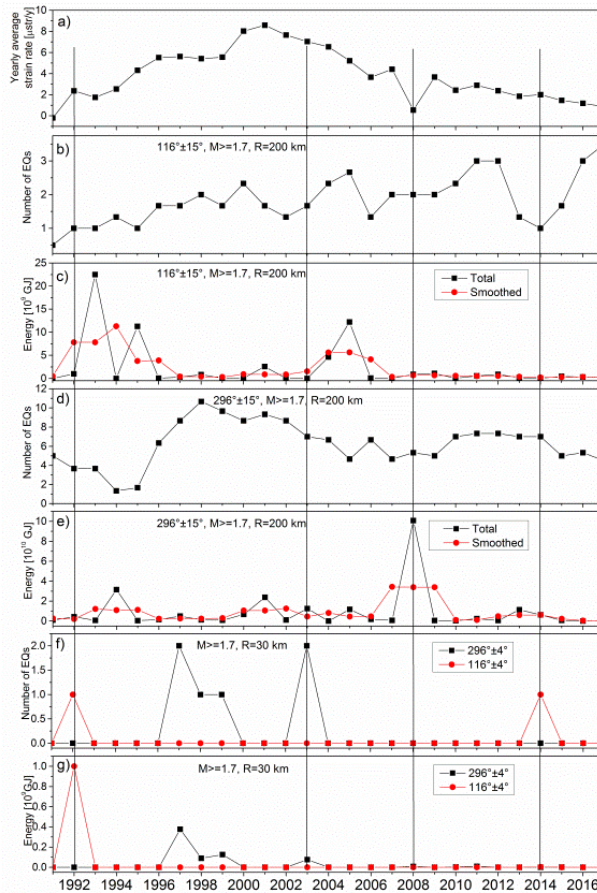
## 2.3 Investigation of local tectonic movements and deformations

In this period the local strain rate variations measured in the SOPGO were compared with the temporal and spatial distribution as well as with the magnitudes of earthquakes occurred within 200 km from the observatory in two sectors around the azimuth of the extensometer ( $116^\circ$ ):  $116^\circ \pm 15^\circ$  and  $296^\circ \pm 15^\circ$  (Figure 5). The detailed results are shown in Figure 6. Our investigations show that earthquakes can influence the strain rate. Earthquakes to the west of SOPGO generally increase the com-

pressive strain rate, while earthquakes in the Pannonian Basin, with some exceptions, have no significant effect on the local strain rate variations (Mentes and Kiszely 2019).



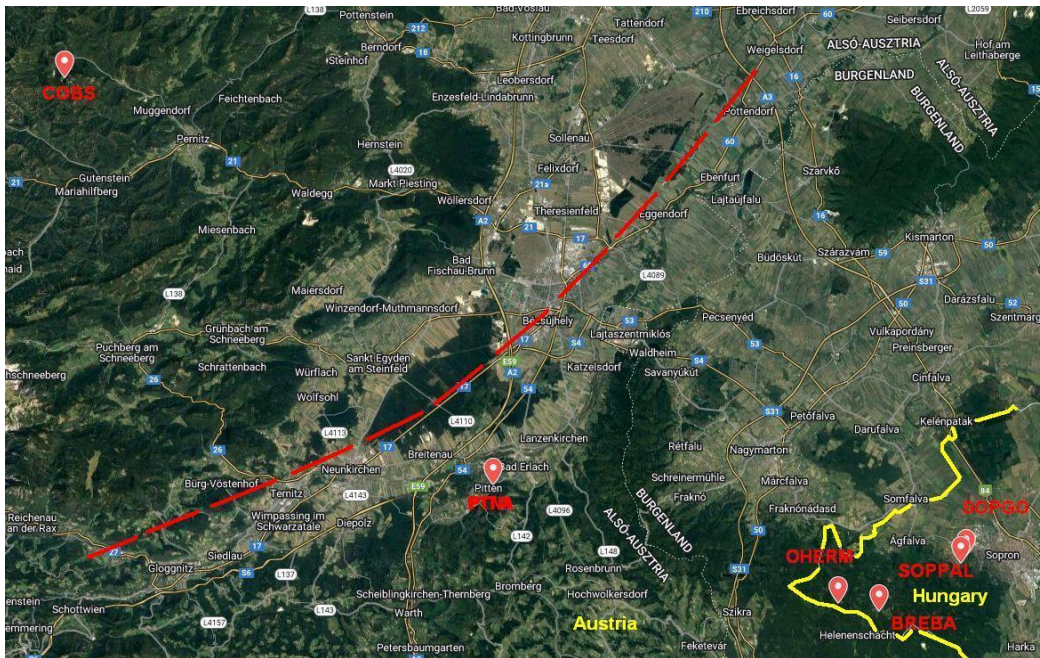
**Figure 5.** Location of the SOPGO with the sectors in which the impact of earthquakes was investigated and the main faults in its region. MML, RL, BBL are the Mur-Mürz, Rába, and the Balaton-Bodrog lines, respectively



**Figure 6.** Yearly strain rates (a), smoothed number (b) and energy of earthquakes (c) within 200 km from the SGO in the sector  $116^{\circ}\pm 15^{\circ}$ , smoothed number (d) and energy of earthquakes (e) within 200 km from the SGO in the sector  $296^{\circ}\pm 15^{\circ}$ , number (f) and energy (g) of earthquakes within 30 km from the SGO in the sectors  $116^{\circ}\pm 4^{\circ}$  and  $296^{\circ}\pm 4^{\circ}$

## 2.4 Monitoring of the Mur-Mürz tectonic fault system by high resolution tilt meters

The Austro-Fenno-Hungarian trilateral cooperation established to use tilt meters for geodynamical investigations has been extended to the continuous monitoring of the seismo-tectonic deformations of the active Mur-Mürz tectonic fault system. A network between the Conrad Observatory (COBS, Austria) and the Sopronbánfalva Geodynamic Observatory (SOPGO, Hungary) crossing it nearly in E-W direction and hosting six Lippmann type tilt meters was established in 2022 (Figure 7). All the stations are underground providing stable thermal conditions, four of them (COBS, PTNA, SOPGO, SOPPAL) are operational and three of them (COBS, PTNA, SOPGO) are equipped also by STS 2/2.5 seismometers.



**Figure 7.** The locations of the tilt meter stations with their code names nearby the Mur – Mürz tectonic fault zone (red dashed line)

## 2.5 Earth tides and environmental effects

The cooperation between Hungarian, Austrian and Finnish researchers on the fields of earth tide investigations and related environmental effects have been continued in the recent reporting period by the support of a Hungarian National Research Fund in the framework of project K141969. The cooperation started in 2012 and has resulted in a number of shorter and longer time series (max. 6.5 years at present) of gravity changes and ground tilts, measured by partly the GWR SG025 and partly the LCR G949 gravity meters and a Lippmann-type high resolution tilt meter (SOP2), respectively. The data were recorded at the Conrad Observatory (COBS), Austria providing outstanding research infrastructure (Meurers et al. 2020a, Papp et al. 2020). The main achievements from the careful correlation analysis of these data sets and the corresponding time series of different environmental parameters, like air pressure and temperature, led to admittance models (Meurers et al. 2021). These models helped to separate and identify signal components of the recorded data and short term transient events connected to long lasting or heavy rain or rapid snowmelt, respectively. The investigation of the co-located and detided tilt and gravity observations (residuals) focusing on these transient signals, as well as the analysis of in situ precipitation data revealed a complex and systematic hydrological process in the close geological (karstic) surrounding of COBS and provided a time



dependent model of it. It clearly proves that both the gravity and tilt residuals are associated with the same hydrological process but have different physical causes. While gravity is most sensitive to the gravitational effect of water transport, tilt residuals indicate deformation caused by surface mass loading and the change of pore (water) pressure during charge and discharge processes in the adjacent fracture system. N-S tilts are strongly affected by strain-tilt coupling due to the cavity effect of the observatory tunnel oriented in E-W direction. The gravitational and loading signals correlated with the different phases of hydrological processes are typically in the range of  $\pm 30 \text{ nm/s}^2$  and  $\pm 1000 \text{ nrad}$ , respectively, depending on the intensity and the cumulative amount of precipitation (Meurers et al. 2021).

The tidal processing of the 2.5 years long tilt data series recorded parallel by a bi-axial pendulum (Lippmann type, LTS) and an uni-axial (oriented in E-W direction) interferometric hydrostatic water tube (iWT, FGI type) tilt meters provided sets of the main components of diurnal and semidiurnal solid earth tidal constituents (Meurers et al. 2021) both in N-S and E-W directions. The analysis of the gamma factors of the diurnal (O1, K1) constituents revealed a clear presence of cavity effect in N-S direction which nearly doubles the theoretical gamma factors obtained from Wahr-Dehant (WD) model. The comparison of the gamma factors of the same E-W wave groups (O1, K1, N2, M2, K2, S2) processed from the LTS and the iWT time series indicated some systematic deviations between the instruments. The average scale factor defined by the ratios  $\gamma_{LTS}/\gamma_{iWT}$  of each corresponding wave groups is 1.0786 whereas  $\gamma_{iWT}$  factors are closer to the theoretical values of  $\gamma_{WD}$  than  $\gamma_{LTS}$  factors. The results above were presented also in the IUGG General Assembly, Session G06I, Montreal, 2019.

### 3 Development of a possible early warning system for observation of river bank stability

Many river banks throughout the world are prone to landslides; therefore, serious efforts are made to develop landslide early warning systems. This study presents a method by which the stability changes of the river banks can be continuously monitored; necessary measures can be taken in time to reduce the damage. The method was tested in Dunaszekcső (Hungary), where the high loess bank of the River Danube has been intensively moving since 2007. The tilts of the high bank were measured by two borehole tiltmeters, one on the stable and one on the unstable part of the high bank. The connection between tilt values and the river- and groundwater-level variations was investigated by multivariable and moving window regression analyses on the basis of a 6-year-long observation from 2011 to 2016. Continuous moving window regression analysis between the online measured tilt and water-level data allows the remote sensing of the up-to-date stability of the high bank without the need for expensive geodetic or geophysical measurements on the high bank. The results show that increasing regression coefficients mean decreasing stability of the high river bank, so the developed method can be used for continuous supervision of the high bank stability and for studying the causes of motion processes. The method can be adapted to any active river bank to observe slope stability variations and to take the necessary measures for mitigation of damages in case of a possible landslide due to stability loss; thus, it can be used as a landslide early warning system (Mentes 2019).

### 4 On the history of tidal knowledge

The tidal phenomenon is much more general than it is usually assumed, since it occurs in all gravitational interactions between non-point-like bodies. It was presented by Varga (2022) how our knowledge of this phenomenon has evolved from ancient to modern times, describes the role of tidal research in understanding the interior of our planet and gives a description of the instruments for tidal observations. Finally, a few examples illustrate the role of ocean tides in human history.

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# HUNGARIAN CONTRIBUTION TO THE RESEARCH ON POSITIONING AND APPLICATIONS (2019-2022) – IAG COMMISSION 4

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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.



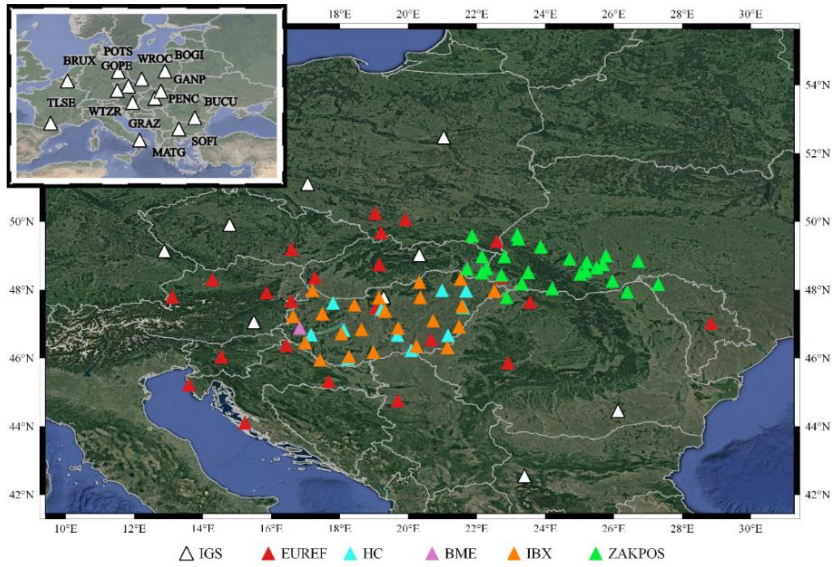


Fig. 1. The GNSS network used for the near-realtime estimation of atmospheric water vapour in Hungary

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).

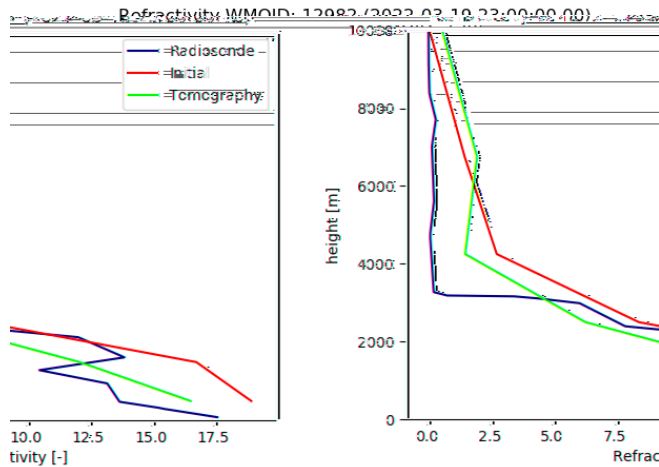
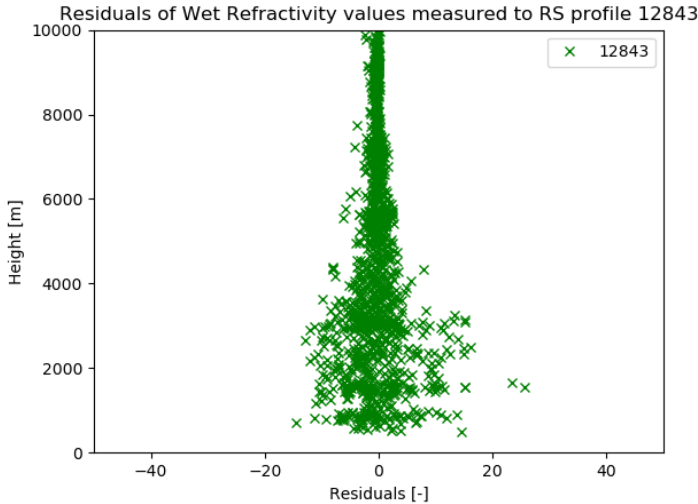


Fig. 2. Wet refractivity profile at WMO station 12982 (Szeged) on March 19, 2022 at 23:00:00 UTC

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.

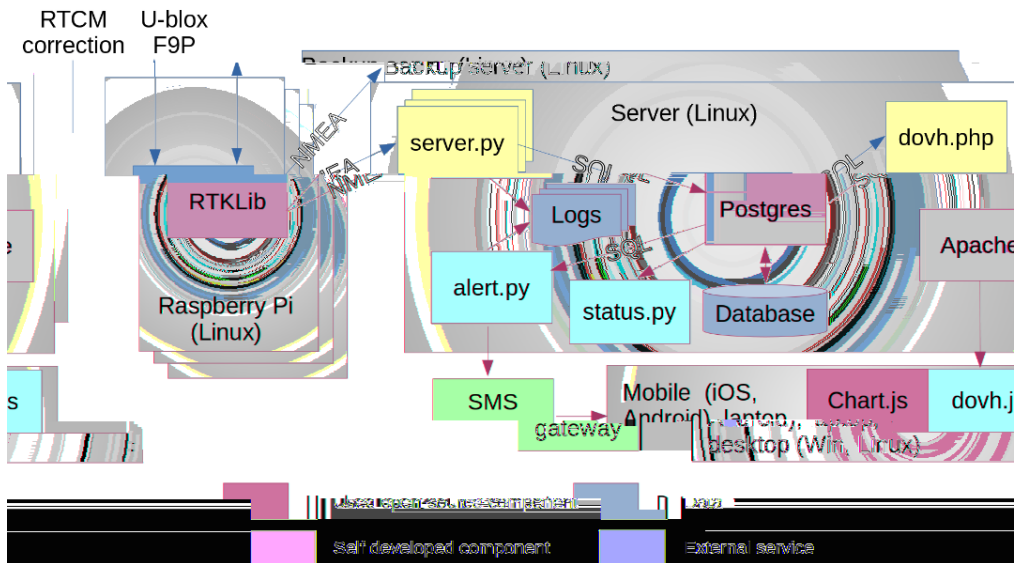
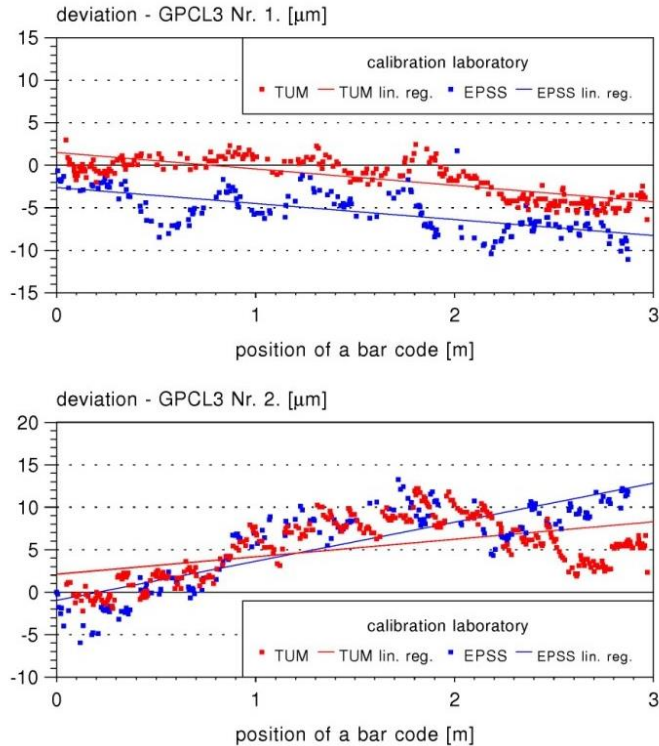


Fig. 4. The structure of the low-cost GNSS monitoring system

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  $\pm 3\mu\text{m}$  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 Earthquake 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 Earthquake Sequence affected area (Magyar, 2022).

In the Satellite Geodetic Observatory, analysis of radar cross section (RCS), signal-to-clutter ratio (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 inevitably 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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# HUNGARIAN CONTRIBUTION TO PALAEOMAGNETISM AND MAGNETIC ANISOTROPY (2019-2022) – IAGA DIVISION I – PART I

*Emő Márton\**

## 1 Introduction

The focus of the above subject has been paleomagnetic research, in the wider sense carried out mainly in co-operation with scientists from abroad, and the results are summarized below. It is worth noting, however, that the laboratory measurements were mostly made in the Paleomagnetic Laboratory of the SARA in Budapest. This laboratory, apart from the below-summarized publications, contributed with magnetic/paleomagnetic results to papers published about the Miocene ignimbrite volcanism in NE Hungary (Biró et al. 2020, Hencz et al. 2021, Karátson et al. 2022) and to Quaternary stratigraphy of the Pannonian Basin (Püspöki et al. 2020, 2021).

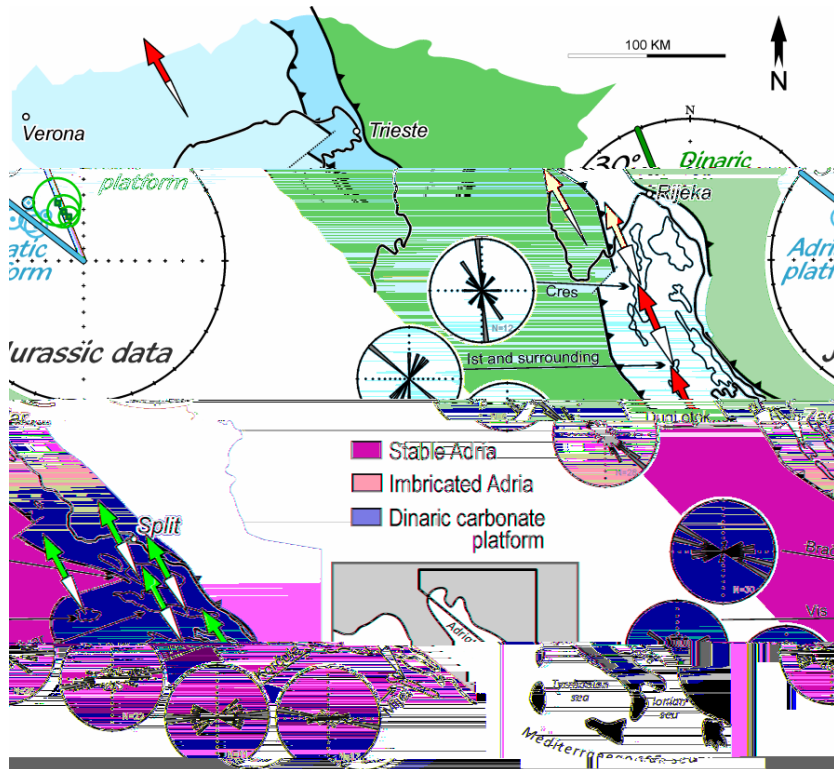
## 2 Tectonic application of paleomagnetism in the Carpatho-Pannonian region, the Vardar zone, and the External Dinarides

The target areas during the last few years had been the Outer and Inner West Carpathians on one hand and the three segments of the Vardar zone, on the other hand.

For the West Carpathian units, the paleomagnetic constraints for the last phase of the large-scale rotations were reviewed (Márton 2020) with the conclusion that it must have taken place after 18Ma and terminated around 11Ma. This vertical axis counterclockwise (CCW) rotation of about 50° involved the Central West Carpathians and the Outer Carpathian Magura, Dukla and Silesian nappe units. As a previous review (Márton et al. 2016) pointed out, the paleomagnetic data for the pre-Cenozoic formations of the Inner West Carpathians were quite often not satisfying the modern quality criteria. The obvious need for updated or new paleomagnetic results induced a systematic research (Márton et al. 2019), which so far lead to constraints concerning the Hronicum, the uppermost nappe pile of the Central West Carpathians. The conclusion of the study (Márton et al. 2020) was that the Hronic unit must have rotated in the clockwise (CW) sense about 34° between the Permian and 80–90Ma, and about 36° afterwards in the same sense, probably before the Cenozoic.

From the Vardar Zone, which is the suture between Eurasian and Adriatic (African) margins, the first paleomagnetic results (Lesić et al. 2019, Márton et al. 2022a) provided evidence for 30° post-Oligocene CW rotation for all three segments, the Western, Central (Sava) and Eastern Vardar Zones (Toljić et al. 2019), triggered by the interaction of subduction processes both below the Carpathian and Dinaric orogens. Pre-Oligocene paleomagnetic directions were only preserved in the Central Vardar zone. They are interpreted as indications for a general moderate CCW rotation connected to compression and thrusting of the northern segment of the Vardar zone over CCW rotating Adriatic elements (Márton et al. 2022a). Indications for CCW rotation were also observed for the Drina-Ivanjica unit, west of the Vardar zone (Márton et al. 2018).

From the External Dinarides, the new paleomagnetic results are from the roughly W-E-oriented Central and Southern Adriatic islands. The orientations of the tectonic structures of these islands significantly differ from those of the Northern Adriatic islands, yet the post-Aptian paleomagnetic directions are consistent throughout the chain of the islands (Fig. 1). The conclusion is that not the relative rotations, but the dominance of the differently oriented Late Cretaceous, Late Eocene and Neotectonic strain fields, respectively, are responsible for the arcuate shape of the island arc (Márton et al. 2022b).



**Fig 1.** The general tectonic subdivision of the NE part of the Adriatic region after Tari (2002) with Turonian-Santonian paleomagnetic declinations (arrows with statistical errors) illustrate the lack of relative movements between the islands and with respect to stable Adria, which is proved by all paleomagnetic data after the Late Aptian-Early Albian tectonic event. The arcuate shape of imbricated Adria is explained by the dominance of one of the three main compressional regime of different orientations, getting younger from NW to SE (Marinčić 1997). The rose diagrams based on our strike measurements in the field are presented to show that the tectonic strikes reflect in Cres island the dominance of the latest Cretaceous Laramian (N-S), in Ist and Dugi Otok islands the mid-Eocene–Oligocene (NW-SE) and in the Central and Southern Adriatic the neotectonic phase (WNW-ESE) tectonic structures. The stereoplot documents the difference in the magnitude of the CCW rotation between the Adriatic and Dinaric platforms

### 3 Relation of magnetic fabrics to deformation and sedimentary transport

The relationship between magnetic fabrics and deformation was studied in the Pohorje Mts, situated at the Eastern Alps-Pannonian basin transition (Fodor et al. 2020). Here a main intrusive body (pluton, 18.6Ma), associated subvolcanic dykes, and surrounding Miocene sediments were investigated. A good correlation was found between anisotropy of magnetic susceptibility (AMS) and mesoscopic lineation/foliation directions, which were interpreted as imprinted in the pluton in the presence of a regional strain field (NE-SW to E-W extension), which decreased progressively during the emplacement of the dykes. The AMS of the structurally highest dykes reflect only magmatic flow. The Miocene sediments were deformed in a stress field of similar orientation as the magmatic and metamorphic rocks of the Pohorje Mts.

All these events occurred during the main syn-rift extension of the Pannonian Basin and the fastest exhumation of the Tauern and Rechnitz windows, before 15Ma.

The role of the sedimentary transport and incipient tectonic deformation was investigated in the Oligocene turbidites of the Central Carpathian Paleogene Basin (Madzin et al. 2021). Magnetic fabrics (AMS and anisotropy of anhysteretic remanent magnetization, AARM) were compared with the sedimentary structures of the Bouma sequence and tectonic brittle mesostructures. It was concluded

that the AMS fabric is of synsedimentary origin, while the AARM fabric reflects the combined effect of inherited sedimentary petrofabric and the strain associated with basin inversion and uplift during the Early to Middle Miocene.

#### 4 Complex approach to enhancing the reliability of the magnetostratigraphy of azimuthally nonoriented drill cores

A study was published on the problem of how to improve the reliability of magnetic age assignment of azimuthally non-oriented drill cores (Márton et al. 2022c). The object was a 100m long drill core penetrating the Miocene lake sediments of the intramontane Turiec Basin of the Inner West Carpathians, where the magnetic mineral was dominantly greigite. The early diagenetic origin of the natural remanent magnetization (NRM) residing in this mineral was documented in the following steps: (1) consistency of the NRM signal within a core segment; (2) reorientation of the core segments using the silt intercalations and or AMS foliation planes which resulted in a remarkable consistency of the NRM direction throughout the core, except the uppermost part of the core; (3) the latter was proved to be redeposited sedimentary material (the uppermost 14 m of the core) by the inconsistency of the NRM and AMS directions as well as by micro CT, which was regarded as a kind of “conglomerate” test; (4) the core was azimuthally fully restored by the tilt direction close to the drill site and entered into a tilt test together with coeval outcrop results from the basin, which proved the pre-tilting age of the NRM.

**Acknowledgment** – This work was supported by the National Development and Innovation Office of Hungary, project K 128625. We are grateful for reviews by László Fodor and Péter Kovács and their suggestions for improving the paper.

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# HUNGARIAN CONTRIBUTION TO THE RESEARCH OF EARTH'S INTERNAL MAGNETIC FIELD (2019 - 2022) - IAGA DIVISION I - PART II

*Lukács Benedek Kuslits* \*

With respect to research aimed specifically at the internal field itself, recent studies show a wide range of activity from developing and interpreting ground observatory and satellite measurements to modelling the main field and understanding the geodynamo.

Examples of observatory-related research include the work of Lemperger et al. (2021), which provides an overview of the recently upgraded observation system at the Széchenyi István Geophysical Observatory and Csontos et al. (2019) who used a method for tracking the time variation of the curvature of geomagnetic field lines based on inclination measurements in ground observatories.

Concerning the investigation large-scale variations of the internal field, two studies were published. Partick T. Taylor (Taylor et al. 2019) cooperated with Hungarian researchers to determine and interpret magnetic anomalies above Central Europe using measurements of the Swarm A satellite and International Geomagnetic Reference Field data. Kuslits et al. (2020) gave a review of the difficulties currently faced by research inferencing the main geomagnetic field and the geodynamo and describes an alternative concept relying on deep learning. The paper demonstrates some promising results on reconstructing synthetic data coming from a simplified phenomenological model using equivalent current loops as sources placed in an Earth-like geometric arrangement.

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# HUNGARIAN CONTRIBUTION TO THE RESEARCH OF DYNAMIC PROCESSES COUPLED WITH THE UPPER ATMOSPHERE/IONOSPHERE SYSTEM (2019-2022) – IAGA DIVISION II: AERONOMIC PHENOMENA

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*Tamás Bozóki* \*, *Attila Buzás* \*\*, *Kitti A. Berényi* \*\*\*, \*\*\*\*, \*,  
*Dávid Koronczay* \*\*\*, *Árpád Kis* \*, *István Lemperger* \*, *Attila Novák* \*,  
*Karolina Szabóné André* \*

## 1 Schumann resonance research

A new inversion algorithm has been introduced which estimates the location and intensity of global lightning activity in an absolute unit ( $C^2km^2/s$ ) from the Schumann resonance (SR) field components measured at distant observation sites on the globe (Prácser et al. 2019). The applicability of the inversion algorithm was tested via synthetic data. The forward model of the inversion model has been made openly available as part of a newly established python package named “schupy” (Bozóki et al. 2019). The code enables the simulation of SRs generated by given lightning sources within the uniform Earth-ionosphere cavity and returns the theoretical electric and magnetic fields at an arbitrary geographical location. In the same paper, three short studies have been presented, which demonstrates the usefulness of “schupy” in investigating SR-related scientific questions.

Subsequently, two new algorithms have been developed to model lightning-generated electromagnetic fields in the lowest part of the ELF band ( $<100$  Hz) that takes into consideration the day-night asymmetry of the Earth-ionosphere cavity (Prácser et al. 2021). The models are based on the analytical and numerical solutions of the two-dimensional telegraph equation (TDTE). Numerical tests showed conspicuous conformity between the output of the two models (the relative difference between them was less than 0.4%) which can be regarded as the validation of the two independent methods.

In 2022, a new description of the inversion algorithm aimed at reconstructing the global lightning activity based on SR measurements was published with a strong emphasis on describing quality indicators of the singular value decomposition-based inversion technique (Prácser and Bozóki 2022). The inversion was again tested on synthetic data and the reliability of the obtained results was examined based on the described quality indicators.

Based on multi-station observations of SR it has been shown that SR intensity records document a common behaviour in the evolution of continental-scale lightning activity in the transition from cold to warm phase preceding two super El Niño events, occurring in 1997/98 and 2015/16 (Williams et al. 2021). SR-based results were strengthened by comparison to independent lightning observations from the Optical Transient Detector (OTD) and the World Wide Lightning Location Network (WWLLN), which also exhibit increased lightning activity in the transition months. It has been suggested that SR intensity variations might be applied in the future to predict the occurrence of these extreme climate events.

Links between the variations of atmospheric electricity parameters, including SR peak parameters, and continental scale atmospheric circulation types (CT) in Europe have been studied in order to examine the sensitivity of the biosphere to variations of the electrical state of the atmosphere. It was shown that different CT unquestionably affect the near-ground electric state of the atmosphere but in different ways, especially when dust/particle transport is involved in the air circulation.

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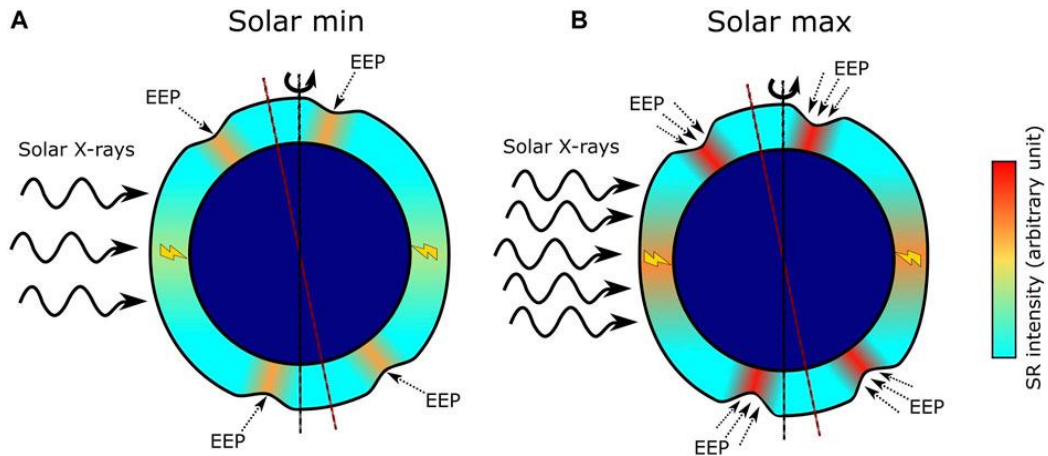
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**Figure 1.** Illustration of the deformation of the Earth-ionosphere cavity at solar minimum (A) and solar maximum (B). At solar maximum X-rays and EEP reduce the cavity height more significantly (dominantly over low- and high latitudes, respectively) which results in enhanced SR intensity values beneath the deformed regions. Reprinted from Bozóki et al. (2021)

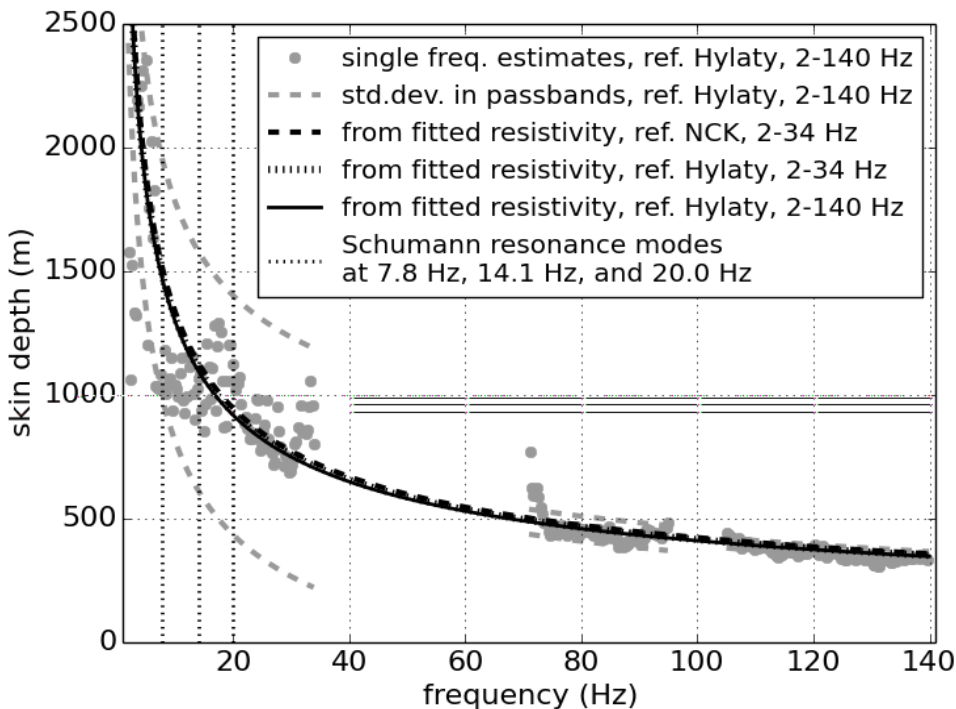
It was concluded that the atmospheric electric environment deserves to be included in CT-related bioclimatic studies (Kourtidis et al. 2021).

By analysing long-term SR intensity time series from remote stations around the world, as well as data from independent ground-based (SuperDARN) and satellite-based (DEMETER, POES, GOES) observations, it has been shown how the Earth-ionosphere cavity is deformed on the solar cycle time-scale by precipitating charged particles (dominantly over higher latitudes) and the X-ray radiation from the Sun (dominantly over lower latitudes) (Bozóki et al. 2021; Fig. 1). Four distinct factors have been identified which can play important role in shaping long-term SR intensity records: 1) X-ray related deformation of the cavity, 2) X-ray related changes in the Q-factor of the cavity, 3) EEP (energetic electron precipitation)-related deformation of the cavity and 4) EEP-related changes in the Q-factor of the cavity.

## 2 Schumann resonance transients

Integrated conductivity of the crust in the Mátra hills, Hungary ( $70 \Omega\text{m}$ ) was determined by quantifying the frequency-dependent attenuation of the ELF transients under the ground using a new method, i.e., using lightning-induced ELF transient signals (Q-bursts) which were detected in the Mátra Hills at the surface and at depth of 140 m in a mine shaft. Data from reference ELF stations (NCK, Hungary and Hylaty, Poland) were incorporated in the study to overcome the difficulty that the surface and sub-surface measurements in the Mátra Hills were made in non-overlapping time periods (Bór et al. 2022). Local skin depth of electromagnetic waves in the Earth's crust was also determined. The local skin depths at the peak frequency of the lowest three Schumann resonance modes (7.8 Hz, 14.1 Hz, and 20.0 Hz) were found to be 1470 m, 1100 m, and 920 m, respectively (Fig. 2).





**Figure 2.** Skin depths in the Mátra mountain, Hungary as calculated from both the bulk resistivity of the Earth's crust obtained from measured local signal amplitude loss ratios (lines) and from amplitude loss ratios found at discrete frequencies (dots). Corrected standard deviations of discrete points with respect to the curve of the fitted resistivity using Hylaty data in the 2–140 Hz range are 482 m, 51 m, and 20 m for the passbands 2–34 Hz, 71–95 Hz, and 105–140 Hz, respectively. Reprinted from Bór et al. (2022)

### 3 Transient luminous events

Studying the climatology of transient luminous events (TLEs) in Europe and over the Mediterranean Sea showed that nighttime lightning recorded by the WWLLN lightning detection network can be used to infer occurrences of TLEs. The global average occurrence rate of TLEs estimated upon this finding was 2.6 TLE per minute. The study, based on optical TLE observations in Europe between 2009 and 2013 (including observations from Hungary), pointed out characteristic differences between the distributions of WWLLN-detected lightning strokes and the distributions of TLE observations within the studied area. This suggests that the geographical distribution of extreme lightning responsible for TLE production may differ from the geographical distribution of general lightning. The database of optical observations has been published together with the results (Arnone et al. 2020).

Maximum emission altitude (84.3 km) and the altitude of the brightest emissions (69 km) in red sprites were determined for events detected in South Africa. According to the results, moderate positive correlation can be found between the charge moment change of the sprite-parent lightning stroke (CMC) and the top altitude of the produced emissions, and there is a weak positive correlation between the CMC and the height of the brightest emissions (Mashao et al. 2021).

Remotely controlled observations of electro-optical upper atmospheric phenomena made from Baja, Hungary were described and primarily evaluated. More than 1600 optical admission was observed between 2014 and 2020 (Fig. 3). Most red sprites were observed in June, while the highest number of sprite halos was registered in September within the examined time period (Bór et al. 2021). Aiming to improve and ease observing, the conception of a computer monitoring, and function-specific remote controlling application framework were described and explained in detail. This solution is for general use, it is secure, allows remote controlling of the desired functionalities only, and it is ready for implementation (Bór and Szabó, 2021).



**Figure 3.** Red sprite observed from Sopron on the night of 27 June, 2020

#### 4 Quasi-static electric field-related research

The vertical, quasi-DC atmospheric electric field is most commonly described by the inverse of it, the atmospheric electric potential gradient (PG) which is an important measure of the Global Electric Circuit (GEC) and has been measured at the Széchenyi István Geophysical Observatory near Nagycenk (NCK) since 1962.

Results from the GloCAEM (GLObal Coordination of Atmospheric Electricity Measurements) project demonstrated that the database of atmospheric electric potential gradient data recorded at separated measurement sites can be effectively used to study the near-Earth environment. The database contains PG data from 17 stations on four continents including measurements also from NCK, Hungary. The stations were classified by the suitability of their data for studying specific environmental questions. Averaging data measured at different stations in fair weather conditions yielded globally representative diurnal variation which justifies the usability of the data for studying day-to-day variations of the global electrical circuit with unprecedented reliability (Nicoll et al. 2019).

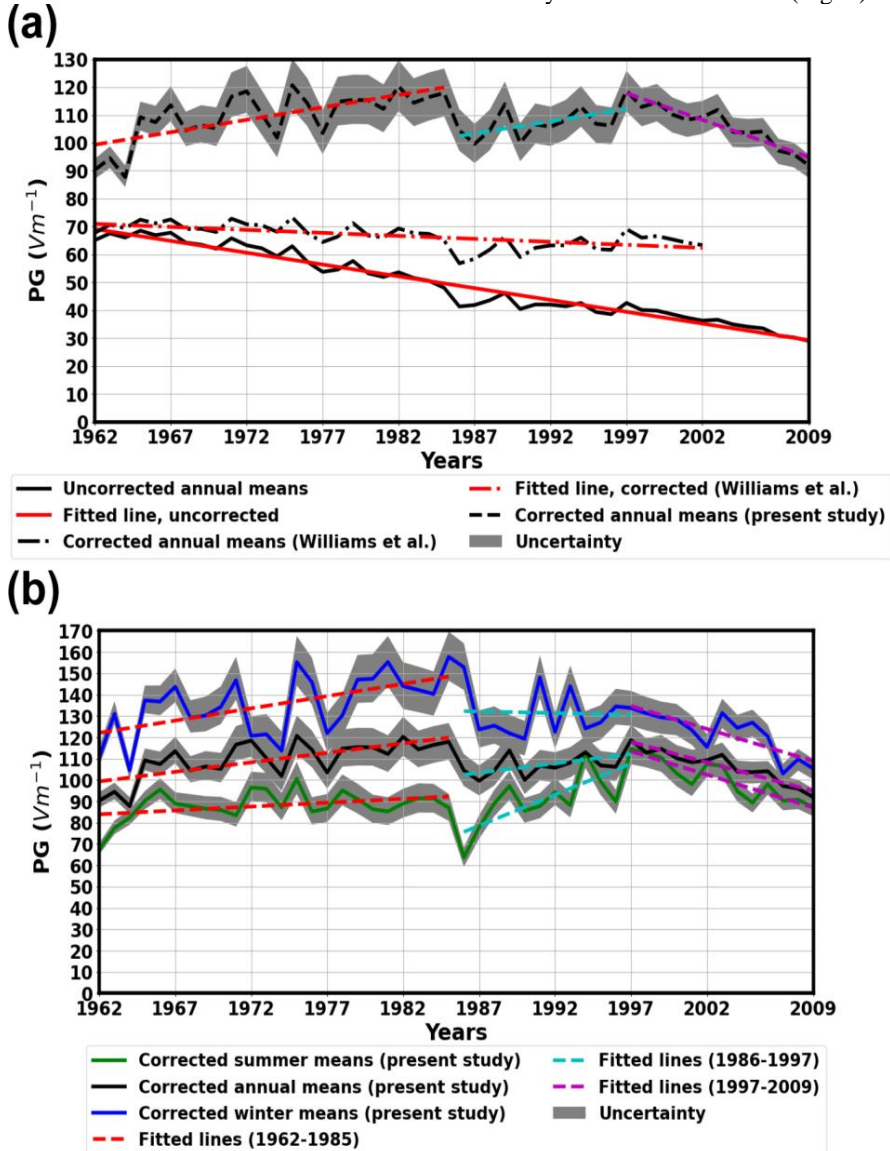
The history of atmospheric electricity measurements in the Széchenyi István Geophysical Observatory, Hungary has been documented and published. With this work, we took part in an international effort for creating records that commemorate the hard work done to establish the infrastructure upon which present day atmospheric electricity research has been built (Bór et al. 2020).

Joint analysis of atmospheric electricity (AE) measurements has been carried out in connection with effects of catastrophic nuclear accidents (Chernobyl and Fukushima). The results demonstrate that atmospheric conductivity is the most sensitive parameter for surveying the properties and the spreading of radioactive contamination in the atmosphere. On the other hand, the atmospheric electric

potential gradient well mirrors both short and long-time scale variation of the local composition and deposition of the airborne radioactive material (Dragovic et al. 2020).

A glossary of the most frequent scientific terms used in the fields of atmospheric electricity and biology has been produced and published with a contribution of Hungarian researchers, too, to support interdisciplinary research in the fields of atmospheric electricity and life sciences (Fdez-Arroyabe et al. 2021).

In 2021, an article about the effect of the long-term shielding effect of nearby trees on the PG measurements at NCK was published (Buzás et al. 2021). In this study it was concluded that the long-term (1962–2009) decrease in the PG data was caused by the time-dependent electrostatic shielding effect of trees growing in the vicinity of the PG measurement site at NCK. By applying numerical modelling, the shielding effect was removed from the dataset and the actual long-term trends were established: an increase between 1962 and 1997 followed by a decrease after 1997 (Fig. 4).



**Figure 4.** Long-term variation of PG recorded at NCK. (a) Annual means of PG data uncorrected and corrected for the shielding effect. (b) Annual, summertime, and wintertime averages of the corrected PG data (Fig. 5 in Buzás et al. 2021)

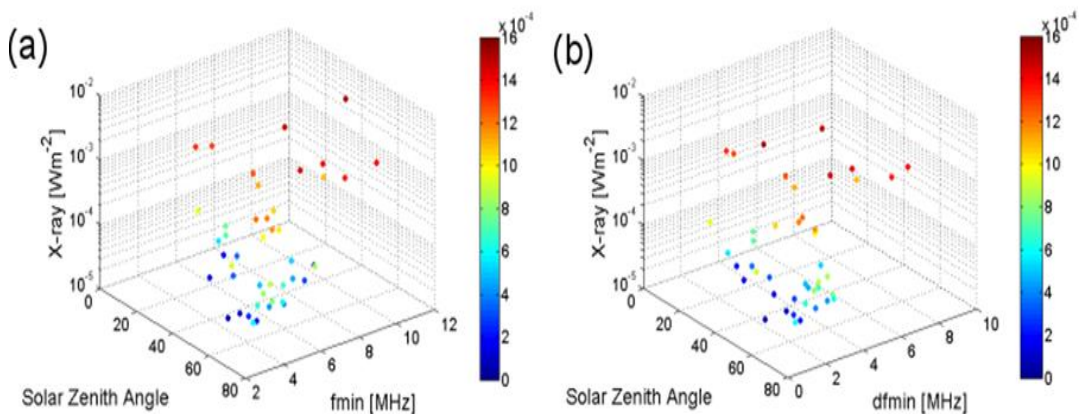
The group of trees near the measurement site was cut down in 2020. In order to assess the impact of this event on the PG measurements, the PG data recorded in the preceding and succeeding time periods in 2020 were analysed and a numerical electrostatic model was built. It was found that the PG increased by up to 32% compared to its former value after the removal of the trees (Buzás and Bór, 2021).

The long-term (1962–2009) PG hourly averages recorded at NCK together with measured (2000–2009) and reanalysed (1962–2009) meteorological data were published in 2022 in an international data repository (Buzás et al. 2022). Subsequently, an image processing algorithm was developed to digitise the archive PG data which were recorded on photo papers and scanned in digital raster format. The data digitised by this algorithm in a better temporal resolution (up to 42s) were published as well (Magos et al. 2022).

## 5 Ionospheric research

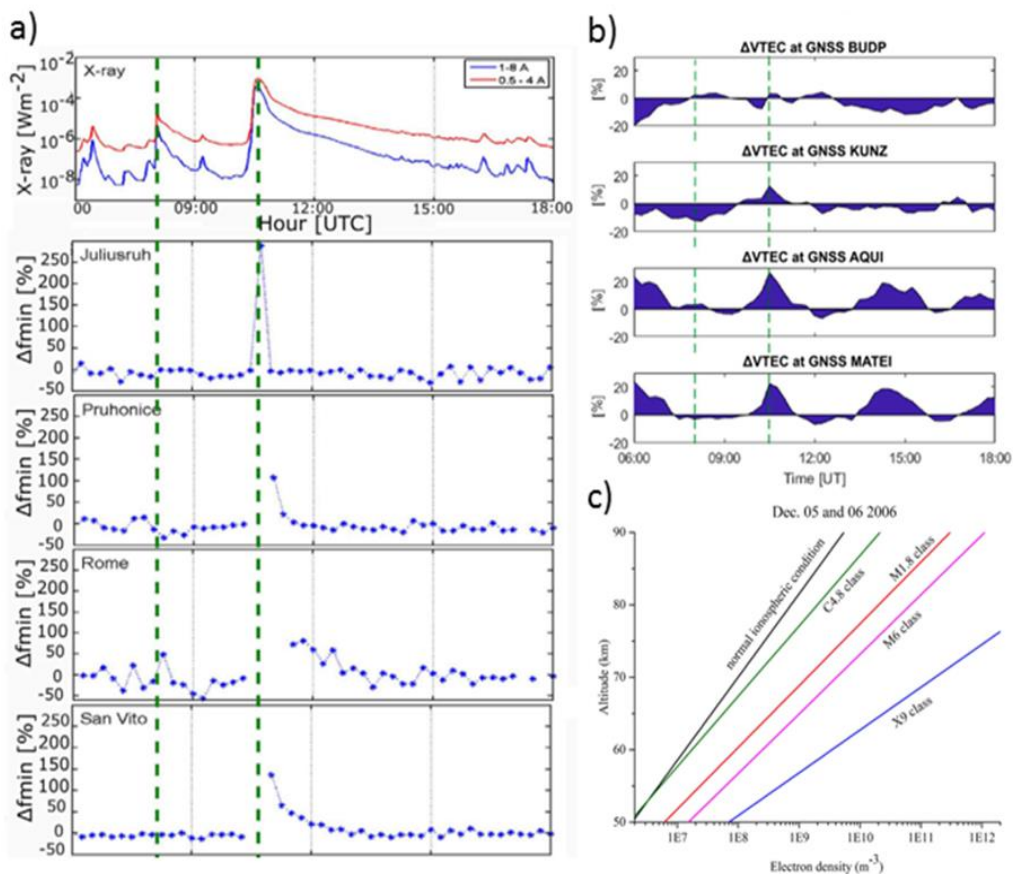
A digital ionospheric radar system (DPS4D digisonde) has been installed at the MTA Széchenyi István Geophysical Observatory, Nagycenk in the framework of GINOP-2.3.2-15-2016-00003 project “Cosmic hazards and effects” (translated from the Hungarian title “Kozmikus hatások és kockázatok”) and it is operating since June, 2018 (<http://iono.nck.ggki.hu/>, 2023-06-21). Our station joined the international network of the digisondes, GIRO (Global Ionospheric Radio Observatory, <http://giro.uml.edu/>, 2023-06-21), which provides quasi real-time data about the state of the ionosphere.

Solar flare effects on ionospheric absorption were investigated with the systematic analysis of ionograms measured at midlatitude and low-latitude ionosonde stations under different solar zenith angles (Barta et al. 2019). The lowest recorded ionosonde echo, the minimum frequency ( $f_{min}$ , a qualitative proxy for the “nondeviative” radio wave absorption occurring in the D-layer), and the  $df_{min}$  parameter (difference between the value of the  $f_{min}$  and the mean  $f_{min}$  for reference days) have been considered. Data were provided by meridionally distributed ionosonde stations in Europe and South Africa during eight X- and M-class solar flares in solar cycle 23. Total and partial radio fade-out was experienced at every ionospheric station during intense solar flares ( $> M6$ ). The duration of the total radio fade-out varied between 15 and 150 min, and it was highly dependent on the solar zenith angle of the ionospheric stations. Furthermore, a solar-zenith-angle-dependent enhancement of the  $f_{min}$  (2–9 MHz) and  $df_{min}$  (1–8 MHz) parameters was observed at almost every station (Fig. 5). The  $f_{min}$  and  $df_{min}$  parameters show an increasing trend with the enhancement of the X-ray flux.



**Figure 5.** The solar zenith angle of the ionosonde stations at the time of the peak, the X-ray radiation at the peak, and the value of the  $f_{min}$  (a) and  $df_{min}$  (b) parameters at the peak of the flare events or after the fade-out. In order to represent the X-ray radiation dependence a color bar has been connected to the different measurements during the flares with different intensities. The color bar shows the X-ray radiation in watts per square meter ( $W m^{-2}$ ) (Barta et al. 2019)

Barta et al. (2022) investigated the solar flare impact on the ionosphere above Europe on 05 and 06 December 2006 using ground based (ionosonde and VLF) and satellite-based data (Vertical Total Electron Content (VTEC) derived from GNSS observations). Based on the Kp and Dst indices, 5 December 2006 was a quiet day, while there was a geomagnetic storm on 6 December 2006. The total fade-out of the EM waves emitted by the ionosondes was experienced at almost all investigated stations during an X9 class flare on 5 December 2006. A latitude-dependent enhancement of  $f_{min}$  (2–9 MHz) and  $\Delta f_{min}$  (relative change of about 150%– 300%) was observed at every station at the time of the X9 (on 5 December, Fig. *iono\_2\_a*) and M6 (on 6 December) flares. Furthermore, they analysed VTEC changes during and after the flare events with respect to the mean VTEC values of reference quiet days. During the X9 solar flare, VTEC increased depending on the latitude (2–3 TECU and 5%– 20%, Fig. *iono\_2\_b*). On 6 December 2006, the geomagnetic storm increased the ionization (5–10 TECU) representing a “positive” ionospheric storm. However, an additional peak in VTEC related to the M6 flare could not be detected. Moreover, the amplitude and phase of ground-based, subionospherically propagating VLF signals were measured simultaneously during the investigated flares to analyse ionosphere reaction and to evaluate the electron density profile versus altitude. The electron density around 65–75 km height increased by 100% after the C4.8 class and with one order of magnitude after the M class flares while the rate of change even reached the three orders of magnitude after the X9 class flare (Fig. 6).



**Figure 6.** The variation of X-ray flux (upper plots) and the  $\Delta f_{min}$  parameters detected at different European stations (from higher to lower latitudes) between 06:00 and 18:00 on 5 December (a). The  $\Delta VTEC$  on 5 December (b). The green dashed lines indicate the time of the investigated flares, i.e. 08:03 UTC (M1.8) and 10:35 UTC (X9.0). Altitude profile of electron density in the D-region height (50 – 90 km) at normal ionospheric condition (black line) and for the four solar flare events occurred on 5 and 6 December 2006 (c) (Barta et al. 2022)



The 15 January 2022 eruption of the Hunga Tonga-Hunga Ha’apai volcano provided a unique opportunity to study the reaction of the ionosphere to large explosive events. Verhulst et al. (2022) investigated the global propagation of travelling ionospheric disturbances (TIDs) related to this event using various instruments. They focused on detecting the ionospheric disturbances caused by this eruption over Europe, where dense networks of both ionosondes and GNSS receivers are available. This event took place on the day of a geomagnetic storm. They showed how data from different instruments and observatories can be combined to distinguish the TIDs produced by the eruption from those caused by concurrent geomagnetic activity. The Lamb wavefront was detected as the strongest disturbance in the ionosphere, travelling between 300 and 340 m/s, consistent with the disturbances in the lower atmosphere. By comparing observations obtained from multiple types of instruments, they also showed that TIDs produced by various mechanisms are present simultaneously, with different types of waves affecting different physical quantities. This illustrates the importance of analysing data from multiple independent instruments in order to obtain a full picture of an event like this one, as relying on only a single data source might result in some effects going unobserved.

The spatial extent of energetic electron precipitation into the upper atmosphere was investigated during substorms for three selected events using different ground-based geophysical measurements (Bland et al. 2022). It has been shown that the area affected by electron precipitation may be much more extended than currently accepted statistical models predict. The Hungarian contribution covered the analysis of narrowband VLF measurements in connection with one of the substorms.

**Acknowledgements** – The authors are grateful to Csaba Molnár, Tibor Molnár, Dániel Piri, and Csongor Szabó for the technical and IT help in carrying out the presented research. The authors acknowledge networking support by the COST Action CA15211 - Atmospheric Electricity Network: coupling with the Earth System, climate and biological systems (ELECTRONET). This work was supported by the National Research, Development and Innovation Office (NKFIH), Hungary, under Projects NKFIH-K115836, NKFIH-K138824 and NKFIH-PD141967. The contribution of Veronika Barta was supported by Bolyai Fellowship (GD, no. BO/00461/21). The installation of the DPS4D digisonde in the MTA Széchenyi István Geophysical Observatory was supported by the GINOP-2.3.2-15-2016-00003 project.

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# HUNGARIAN CONTRIBUTION TO THE RESEARCH OF MAGNETOSPHERIC PHENOMENA (2019-2022) – IAGA DIVISION III: MAGNETOSPHERIC PHENOMENA

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## 1 Introduction

This concise quadrennial report serves as a summary of the research activity related to the main objectives of IAGA Division III carried out in Hungary during 2019-2022. Major institutional changes took place during this period. The Eötvös Loránd Research Network was established in 2019 with the aim to manage and operate the publicly funded independent research network in Hungary. Former research institutes of the Hungarian Academy of Sciences including the Wigner Research Centre for Physics, Space Physics and Space Technology, as well as the Institute of Earth Physics and Space Science (EPSS, established in 2021 transforming the former Geodetic and Geophysical Research Institute) are now belong to this new research network. Due to institutional changes, magnetospheric research ended in the Mining and Geological Survey of Hungary (MBFSZ) by the end of 2021, and the Tihany Geophysical Observatory maintained earlier by MBFSZ was taken over by EPSS. The Space Research Group of the Eötvös Loránd University continued its activity in the field.

## 2 The near-Earth solar wind

The ULEIS detector aboard the ACE spacecraft offers a continuous data set of suprathermal (0.04 to 2 MeV)  $^3\text{He}$ ,  $^4\text{He}$ , C, O, and Fe ion fluxes in the interplanetary space at 1 AU from the Sun. The positive correlation of the quiet sun ion fluxes detected in the 23rd and 24th solar cycle (SC) with the parameters of solar activity and the inclination of the heliospheric current sheet suggests that they predominantly originate from active processes on the Sun. Whereas the ion fluxes were lower in SC24 than in the previous one both in perturbed and quiescent periods, the temporal variations of  $^3\text{He}/^4\text{He}$ , C/O and Fe/O ratios are different and depend on the first ionization potential of the atoms. The maximum of the distribution of Fe/O was higher in SC23, the  $^3\text{He}/^4\text{He}$  and C/O distributions are practically the same in the two cycles (Zeldovich et al.2019).

The relative abundances of thermal and suprathermal C, O, and Fe ions were analyzed and compared in solar wind streams from near-equatorial coronal holes during quiet periods of nearly two solar cycle minima (Zeldovich et al. 2021). Ion fluxes with energies of  $\sim 0.04\text{--}2$  MeV/nucleon were studied using data from the ULEIS instrument aboard the ACE spacecraft together with thermal ions in the fast and slow (Maxwellian) solar wind using data from the SWICS instrument aboard ACE.

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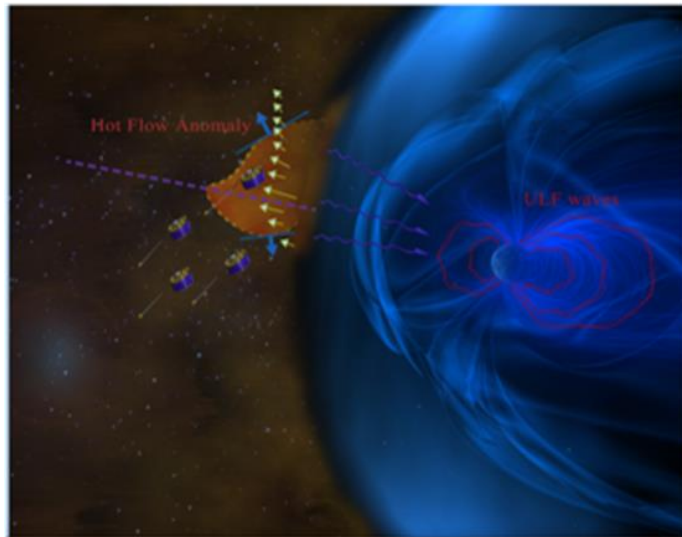
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The analysis was carried out for quiescent periods in 2006–2012 and 2015–17 when solar wind flows from near-equatorial coronal holes (CHs) were detected at 1 AU. Near the minimum of SC23, although they displayed large variability, the C/O and Fe/O ratios of suprathermal ions were, on average, near the corresponding relative abundances of the solar wind. During the decreasing solar activity phase of SC24 suprathermal Fe/O ratios matched those of solar wind ions from CHs. In both cycles the thermal and suprathermal Fe/O ratios exhibited a similar character of dependence on maximum solar wind speed. Our results suggest that the sources of suprathermal ions from CHs in low solar activity periods are accelerated solar wind thermal ions. The thermal and suprathermal Fe/O ratios were found higher in 2015–17 than those measured in 2006–2010.

### 3 Interactions of the solar wind with planetary magnetospheres

#### 3.1 Dayside transient phenomena and their impact on the magnetosphere and ionosphere

Using numerical simulations and spacecraft observations, the members of an international research team reviewed the transient events of the dayside magnetosphere (Fig. 1), created by the interaction of the terrestrial magnetosphere and solar wind discontinuities. Their global influence in the magnetosphere, the ionosphere, and the polar regions was clarified. The study produced a 150-page long review paper (Zhang et al. 2022).



**Figure 1.** The hot flow anomalies are created by the interaction of the terrestrial bow shock and a tangential discontinuity in the solar wind. These phenomena trigger ultra-low frequency waves in the Earth's magnetosphere (Zhang et al.2022 credit: Peking University)

#### 3.2 Study of turbulent dynamics in the terrestrial magnetosheath and magnetospheric plasmas

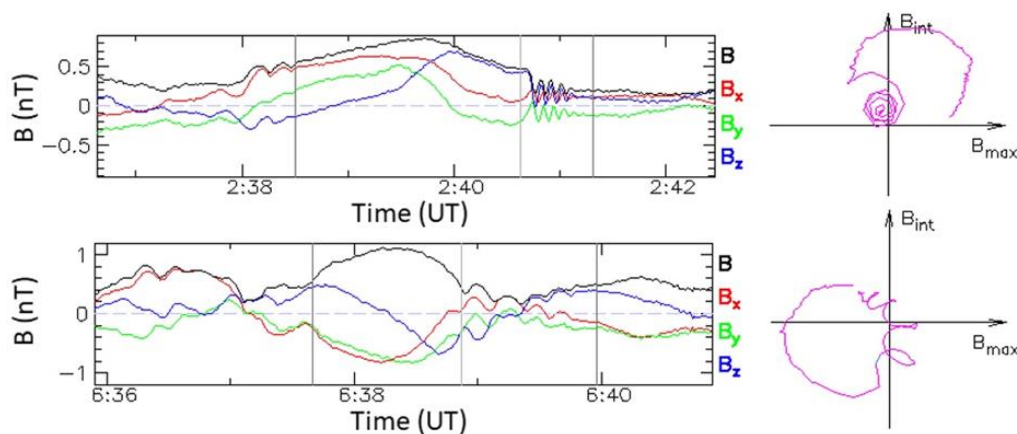
A comprehensive statistical analysis of the spectra of 337, high-resolution magnetic field time series recorded by the Cluster mission in the terrestrial magnetosheath was carried out. The power-law spectral ranges and the spectral exponents were derived by an automatic procedure developed by us. The wave origin of the turbulent fluctuations was tested by computing the propagation angles and compressibilities of the magnetic field fluctuations in terms of frequency and spatial scales (supposing that the Taylor hypothesis was valid). On average, the spectra exhibited a clear spectral break at the frequency of 10 fci (fci being the ion gyrofrequency). It was conjectured that beyond the break, the

perpendicularly propagating Alfvén waves could partly explain the statistical analysis of the spectra (Dwivedi et al. 2019).

During the reporting period, we published a review paper in the Geophysical Monograph Series on the theme of turbulence and complexity in magnetospheric plasmas (Echim et al. 2019).

### 3.3 Short Large Amplitude Magnetic Structures at Saturn

We analyzed the physical properties and evolutionary characteristics of Short Large Amplitude Magnetic Structures (SLAMS) upstream of the quasi-parallel bow shock of Saturn, using the measurements of the Cassini Plasma Spectrometer (CAPS) and the Magnetometer (MAG) instruments onboard of the Cassini spacecraft. Locally the SLAMS act as a fast mode shock wave, with several features (ion beam reflection, multiple beams, deceleration and plasma heating) that are in agreement with the near-Earth observations. We also detected whistler precursor waves (Fig.2) associated with the SLAMS events multiple times. The frequency of the upstream ULF waves (from which the SLAM structures arise) detected at Saturn is lower than it is at Earth, which has an effect on the spatial extension of the observed magnetic structures (Bebesi et al. 2019).



**Figure 2.** Two cases of SLAMS whistler precursor waves were detected on December 10th, 2004 (top) and October 8th, 2005 (bottom) with the corresponding hodograms shown in the inserts on the right (Bebesi et al. 2019)

### 3.4 Inner Southern magnetosphere of Mercury

Mercury's southern inner magnetosphere is an unexplored region as it was not observed by earlier space missions. In October 2021, BepiColombo mission passed through this region during its first Mercury flyby. The BepiColombo SERENA team investigated the ion content of this region. The dayside magnetopause and bow-shock crossing were much closer to the planet than expected, a signature of a highly eroded magnetosphere. Different ion populations have been observed inside the magnetosphere, indicating various magnetospheric structures (Orsini et al. 2022).

## 4 Monitoring cold plasma dynamics

### 4.1 Magnetospheric plasma mass density monitoring by means of field line resonances

The cold electron density inside and outside of the plasmasphere is a key parameter for radiation belt dynamics, that can affect satellites negatively, its precise measurement can be fruitful in many applications. In the past two decades a lot of effort was put into a development of a fully automated system monitoring magnetospheric cold plasma mass density (Del Corpo et al. 2019). The monitoring system is based on the European quasi-Meridional Magnetometer Array ranging from Finland to Italy is run

by a consortium of several European institutes. The monitoring system is being developed in collaboration with Italian teams (University of L'Aquila, and more lately INGV) since the launch of a joint EU project (PLASMON) in 2011. Using EMMA observations, Del Corpo et al. (2020) developed a local time-dependent empirical model of the equatorial plasma mass density. Models of the plasmasphere, plasmatrough, and plasmopause are derived separately and then combined. The whole model is limited to the local time sector 06:00-18:00 and the range of equatorial distances  $2.3 < L < 8$ . The model is dependent on the geomagnetic activity but only in determining the plasmopause position. Combined with in-situ electron density measurements of the Van Allen Probes, also the plasmaspheric/trough average ion mass values have been derived (Del Corpo et al. 2022).

EMMA plasma mass density data have been successfully applied in cases studies of the response of the Geospace plasma to the dynamic evolution of magnetospheric storms (Pezzopane et al. 2019, Vellante et al. 2021, Regi et al. 2022).

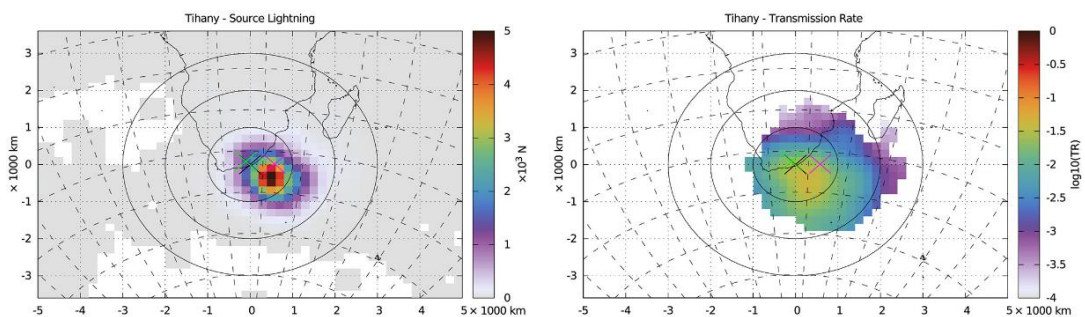
## 4.2 Improved whistler detection

Whistlers have been measured and collected for decades, however, due to the noisy nature of the detection data, the precise, automated estimation of the physical parameters through whistler traces, a pre-requisite of accurate cold plasma monitoring of the near-Earth space, has been a challenging task. Pataki et al. (2022) presented a fully automated way to perform such an image segmentation by leveraging the power of convolutional neural networks, a state-of-the-art method for computer vision tasks. Testing the proposed method against a manually, and semi-manually segmented whistler data set achieved  $<10\%$  relative electron density prediction error for 80% of the segmented whistler traces, while for the L-value, the relative error was  $<5\%$  for 90% of the cases. By segmenting more than 1 million additional real whistler traces from Rothera station Antarctica, logged over 9 years, seasonal changes in the average electron density were found. The variations match previously published findings and confirm the capabilities of the image segmentation technique.

## 5 Magnetospheric wave phenomena

### 5.1 Source regions of whistlers

Koronczay et al. (2019) presented a new method for identifying the source regions of lightning-generated whistlers observed at a fixed location. In addition to the spatial distribution of causative lightning discharges, the ratio of lightning discharges transmitted into ground-detectable whistlers was calculated as a function of location. The method was applied to whistlers recorded at 15 ground-based stations in the Automatic Whistler Detector and Analyzer Network (AWDANet) between 2007 and 2018 and to locate lightning strokes from the World Wide Lightning Location Network (WWLLN) database. The results showed that the source region of whistlers corresponding to each ground station is around the magnetic conjugate point of the respective station (e.g., Fig. 3).



**Figure 3.** Regional distribution of source lightning (near the Southern tip of Africa) and transmission rate of whistlers detected at Tihany (Koronczay et al. 2019)

The size of the source region is typically less than 2,000 km in radius with a small fraction of sources extending to up to 3,500 km. The transmission ratio is maximal at the conjugate point and decreases with increasing distance from it. This conforms to the theory that whistlers detected on the ground propagated in a ducted mode through the plasmasphere, and thus, the lightning strokes of their causative spherics must cluster around the footprint of the ducts in the other hemisphere. The new method resolved the whistler excitation region mystery that had resulted from correlation-based analysis methods, concerning the source region of whistlers detected in Dunedin, New Zealand.

## 5.2 Chorus wave inversion

A new inversion method providing thermal plasma population parameters from characteristics of chorus emissions only was developed by Juhász et al. (2019). The method builds on previous works on the nonlinear wave growth theory. The ultimate goal is to apply it to ground-based data in the future in order to derive the lower-energy boundary condition for radiation belt models. The new chorus inversion method was tested on in situ data of the Van Allen Probes in the generation region. The density and thermal velocity of energetic electrons (a few kiloelectron volts to 100 keV) were derived from the frequency sweep rate and the starting frequencies of chorus emissions. The results of the inversion are compared with the density and thermal velocities (parallel and perpendicular) of energetic electrons derived from the unidirectional flux data of the Helium, Oxygen, Proton, and Electron instrument onboard the Van Allen Probes, showing a good agreement: The normalized root-mean-square deviation between the measured and predicted values were less than ~15%. The theoretical amplitudes were also found consistent with the measured ones. The relation between linear and nonlinear wave growth agreed with the basic assumption; namely, linear growth is a preceding process of nonlinear wave growth.

## 5.3 ULF waves

Takahashi and Heilig (2019) developed a new data analysis technique to study the spatiotemporal structure of ground magnetic pulsations on the dayside by displaying magnetic field perturbations detected by the European quasi-Meridional Magnetometer Array (EMMA) as 2-D images in the magnetic L value versus time-space, called EMMAGrams. In addition to signatures of field line resonance driven by a cavity mode oscillation, the method was suitable for discriminating poleward propagating structures with L-independent periods in the Pc2 band. The Pc2 structures are attributed to periodic magnetohydrodynamic pulses (upstream waves) originating from the ion foreshock and propagating in the magnetosphere along the path proposed by Tamao. The ringing of local field lines at L-dependent periods (transient pulsations) is also clearly detected as dispersive poleward propagating structures. Successive excitation of transient pulsations by variations of the solar wind dynamic pressure appears to contribute significantly to the formation of cross-phase peaks that are widely used in magnetoseismic studies.

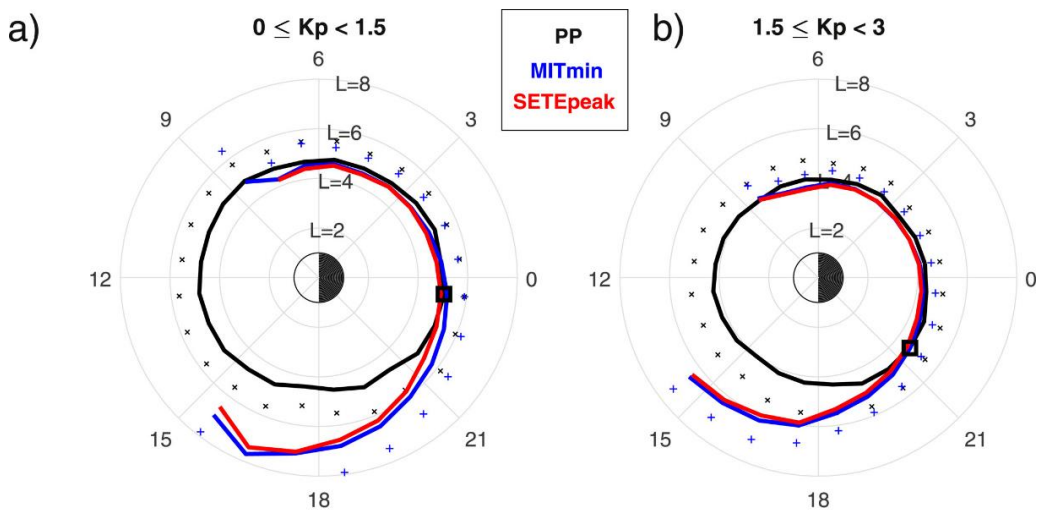
## 5.4 Stray magnetic field effects on linear colliders

Wave activity on the ground may affect technical devices. For these devices, the otherwise meaningful geophysical signals appear as magnetic stray fields. One example of these is extreme-energy (>TeV) linear colliders. While planning the future of the Large Hadron Collider at CERN, one of the two options considered was the so-called Compact Linear Collider (CLIC) which was designed to collide multi-TeV electrons and positrons. As spatially and temporally varying magnetic fields affect the particle beams, degrading their luminosity, it was critical to assess the possible impact of frequently occurring natural phenomena on the system and to find ways to mitigate these risks. This work was done in collaboration with the Mining and Geological Survey of Hungary (Gohil et al. 2020, 2021).

## 6 Phenomena of the topside ionosphere

### 6.1 Magnetosphere-ionosphere coupling in the subauroral region

The relation between the plasmopause (PP) and various ionospheric phenomena, such as the midlatitude ionospheric trough (MIT) has been studied for decades. More recently, it was found that the equatorward boundary of small-scale field-aligned currents (SSB) and the PP are also closely coupled. In spite of prolonged efforts many details of these relationships, as well as the mechanisms responsible for them remain poorly understood. ESA's Swarm mission in conjunction with magnetospheric missions (RBSP, Arase, and THEMIS) provided an unprecedented opportunity to study these relationships on a global scale and over an extended period. Swarm delivers observations of MIT, the associated sub-auroral electron temperature enhancement (SETE), as well as SSB, while PP crossings can be inferred from in-situ magnetospheric electron density measurements. In a study, Heilig et al. (2022) used 7 years of Swarm observations and PP positions from 2014 to 2017 to address some of the open questions. They confirmed that MIT/SETE and PP are directly coupled, however only in the nighttime (Fig. 4). Their correlation remains high after post-dawn, however, with an increasing, MLT-dependent time lag. Afternoon MIT observations were found conjugated with a plasmaspheric plume. The correlation between SSB and PP is also high, and they intersect each other near MLT midnight. The results confirm the scenario that the PP is formed on the night side and propagates to the dayside by co-rotating with the Earth and suggest that the plasma is transported from the depleted ionospheric/dense plasmaspheric stagnation region also westward/sunward forming the afternoon MIT/narrow plumes, respectively (supported by ESA through EPHEMERS and PRISM projects).



**Figure 4.** The location of the equatorial plasmopause (PP), the main ionospheric trough (MIT) minima, and the associated electron temperature enhancement (SETE) mapped onto the equatorial plane along magnetic field lines at two levels of geomagnetic activity (Heilig et al. 2022)

### 6.2 Magnetic field irregularities in the ionosphere

We investigated the space weather contexts of the solar and solar wind dynamics. Making use of the high-frequency three-component magnetic records of ESA's low-Earth orbit (LEO) Swarm mission the typical occurrences of irregular magnetic field fluctuations were explored in the high-latitude and equatorial geomagnetic regions. Relying on the turbulent nature of the irregularities, we developed an intermittency index (IMI) for the quantitative monitoring of the irregular magnetic fluctuations



along the orbits of the Swarm spacecraft. It turned out, that in the equatorial region, the most intermittent fluctuations appeared symmetrically about the dip equator, at  $\pm 10^\circ$  magnetic latitudes, in post-sunset magnetic local times. Clearly, this finding was explained by the appearances of equatorial spread F (ESF) and plasma bubble phenomena.

The occurrence rate of equatorial irregularities exhibited a clear solar cycle dependence, being greater in solar maximum than in minimum. The space weather context of the equatorial irregularities was shown by the subtle correlation of these events with GNSS loss of lock (LOL) occurrences onboard Swarm spacecraft as well as with scintillation effects recorded in ground GNSS stations. In the polar region, IMIs were modelled by Adjusted Spherical Cap Harmonic analysis, for three levels of geomagnetic activity. The models exhibited intermittent fluctuations in two oval regions about the geomagnetic poles. It was suggested that the poleward region was coincident with the auroral oval, while the equatorward region was indicative of the ionosphere footprint of the plasmopause. The research was supported by ESA, within the framework of the EPHEMERIS project.

## **7 Investigations of the plasma environment of Comet 67P/Churyumov-Gerasimenko**

### **7.1 Solar wind pressure at Comet 67P**

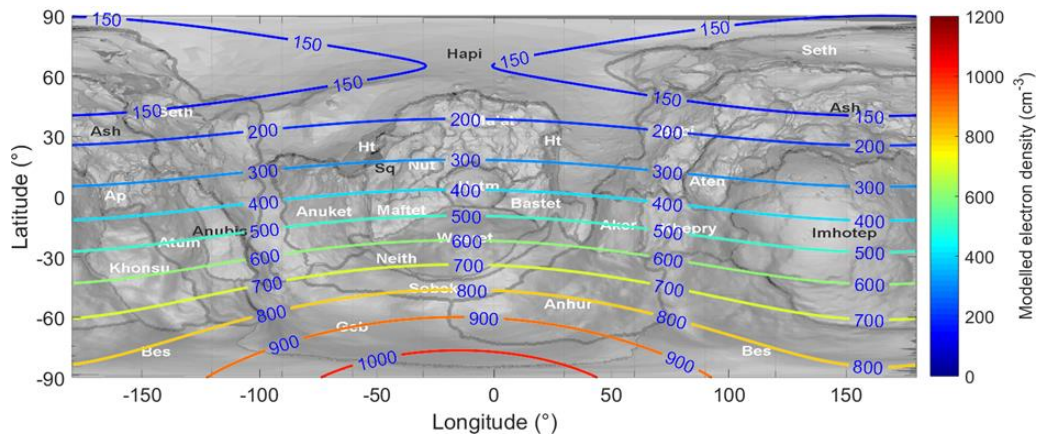
We determined a proxy for the solar wind pressure around Comet 67P/Churyumov-Gerasimenko for the time interval between late April 2015 and January 2016. The pressure proxy is based on magnetic field data. Since the spacecraft was deep inside the induced magnetosphere of the comet in that time period, direct measurement of the solar wind pressure was impossible. We compared our pressure proxy to solar wind pressure extrapolated to Comet 67P from near-Earth measurements. After exclusion of disturbances caused by transient events, we found a strong correlation between the two data sets (Timar et al. 2019).

### **7.2 The dynamics of the magnetic field-free cavity around comets**

The diamagnetic cavity is the innermost region of the magnetosphere of an active comet from which the magnetic field is expelled by the outflowing matter. This phenomenon, first detected around the Comet 1P/Halley, was extensively studied recently by the Rosetta comet chaser mission. Rosetta observed a surprisingly large diamagnetic cavity around comet 67P/Churyumov-Gerasimenko and revealed an unforeseen structure, rich and highly dynamic. We presented a simple (1+1)-dimensional analytic MHD model of the diamagnetic cavity, which for the first time explained the unexpected size and variability of the cavity (Nemeth 2020). In this model inward and outward-moving time-dependent solutions emerge, featuring distinct differences, in accordance with observations. The plasma density is increased in the entire magnetized region. The density enhancement is more pronounced for weak comets, resulting in a stronger interaction and hence the larger than the expected cavity. Space weather effects determine the asymptotic plasma speed, thus driving the variations of the plasma properties observed near the cavity.

### **7.3 Plasma distribution around Comet 67P in the last month of the Rosetta mission.**

After accompanying Comet 67P/Churyumov-Gerasimenko on its journey around the Sun and observing the evolution of its induced magnetosphere throughout the comet's life cycle, the Rosetta operations concluded at the end of September 2016 with a controlled impact on the cometary nucleus. At that time, the comet was located more than 3.8 AU from the Sun, but the data still show clear indications of a small but well-developed plasma environment around the nucleus. These observations, performed along multiple recurring elliptical orbits, allowed us to investigate the properties and spatial structure of the fading cometary magnetosphere. We examined the measured electron and neutral densities along these consecutive orbits, from which we were able to determine the structure of the plasma distribution (Fig. 5) using a simple latitude and longitude-dependent model (Nemeth et al. 2020).



**Figure 5.** Plasma distribution contours of the fading magnetosphere of comet 67P, projected to the surface of the nucleus (Nemeth et al. 2020)

## 8 Participating in the planning and development of new space missions

Researchers of various Hungarian institutions are participating in two recently launched space missions: the Solar Orbiter mission to explore the inner Heliosphere (Horbury et al. 2020) and the two-spacecraft BepiColombo mission investigating planet Mercury and its space environment (Milillo et al. 2020). Hungarian researchers also contributed to studies proposing a new mission to Jupiter's moon Europa to characterize its habitability and search for extant life (Blanc et al. 2020), and LEO missions (Trabant, NanoMagSat) to study dynamic processes taking place in the topside ionosphere.

The ESA-JAXA BepiColombo mission to Mercury will provide simultaneous measurements from two spacecraft, offering an unprecedented opportunity to investigate magnetospheric and exospheric dynamics at Mercury as well as their interactions with SW, radiation, and interplanetary dust. After the launch on October 20, 2018, initial operations began. The Space Research Group of Wigner Research Centre for Physics is involved in the particle instrument, while ELTE Space Research Group contributes to the plasma wave experiment.

### 8.1 SERENA: Particle Instrument Suite

The particle instrument suite SERENA (Search for Exospheric Refilling and Emitted Natural Abundances) is flying in space onboard the BepiColombo Mercury Planetary Orbiter (MPO) (Orsini et al. 2021). The only particle instrument aboard the BepiColombo Mercury Planetary Orbiter (MPO) is SERENA (Search for Exospheric Refilling and Emitted Neutral Abundances), which comprises four independent sensors: ELENA for neutral particle flow detection, Strofio for neutral gas detection, PICAM for planetary ions observation, and MIPA, mostly for SW ion measurements. SERENA is managed by a System Control Unit located inside the ELENA box. Our researchers participated in the paper, in which the scientific goals of this suite are described, and then the four units are detailed, as well as their major features and calibration results. Finally, the SERENA operational activities are shown during the orbital path around Mercury, with also some reference to the activities planned during the long cruise phase.

### 8.2 PWI: The Plasma Wave Investigation

The Plasma Wave Investigation (PWI) aboard the BepiColombo Mio (Mercury Magnetospheric Orbiter, MMO) will enable the first observations of electric fields, plasma waves, and radio waves in and around the Hermean magnetosphere and exosphere (Kasaba et al. 2020). The PWI has two sets of receivers (EWO with AM2P, SORBET) connected to two electric field sensors (MEFISTO and



WPT) and two magnetic field sensors (SCM: LF-SC and DB-SC). Those receivers and sensors will provide (1) in-situ measurements of electron density and temperature that can be used to determine the structure and dynamics of the Hermean plasma environment; (2) in-situ measurements of the electron and ion scale waves that characterize the energetic processes governed by wave–particle interactions and non-MHD interactions; (3) information on radio waves, which can be used to remotely probe solar activity in the heliocentric sector facing Mercury, to study electromagnetic-energy transport to and from Mercury, and to obtain crustal information from reflected electromagnetic waves; and (4) information concerning dust impacts on the spacecraft body detected via potential disturbances.

### 8.3 Coordinated observations in the inner Heliosphere

During its cruise phase, the BepiColombo spacecraft will cover a wide range of heliocentric distances (0.28 AU–0.5 AU), which provides a great opportunity for coordinated observations, especially with the Solar Orbiter and Parker Solar Probe. Despite some payload constraints, many instruments onboard the spacecraft are operating before its orbit insertion around Mercury in December 2025. A detailed catalog of events was compiled specifying the various spacecraft configurations and detailing the combined in-situ and remote sensing measurements available from the different spacecraft. The identified science topics, the operational instruments, and the method used to identify the windows of opportunity were summarized and the plans for joint observations in the future were discussed (Hadid et al. 2021).

### 8.4 Scientific observations during the BepiColombo cruise phase

BepiColombo cruise trajectory is a long journey into the inner heliosphere, and it includes one flyby of the Earth (in April 2020), two of Venus (in October 2020 and August 2021), and six of Mercury (starting from 2021), before orbit insertion in December 2025. A big part of the mission instruments is fully operational during the mission cruise phase, allowing unprecedented investigation of the different environments that will encounter during the 7-years long cruise. A review of all the planetary flybys and some interesting cruise configurations was presented (Mangano et al. 2021) with additional scientific research that will emerge in the coming years, including the instruments that can contribute.

### 8.5 Jovian electrons at the Earth orbit

The influence of the structure of the inner heliospheric magnetic field was studied on the propagation of Jovian electrons from Jupiter to the Earth orbit (Logachev et al. 2021). Beginning in 1974, 13-month variations of relativistic Jovian electron fluxes were recorded by spacecraft near the Earth. 22 synodic cycles were analyzed. The best connection in each cycle was found within a narrow longitudinal interval with an angular divergence of the planets  $230 \pm 20^\circ$ , when the Parker field line connecting the two planets is formed at solar wind speed  $450 \pm 50$  km/s. Such invariability for more than 45 yr is improbable to be accidental. The observed phenomenon was attributed to the long-term presence of recurrent stationary structures in the solar wind generated near the Sun. This assumption is confirmed by comparing the time profiles of the solar wind speed measured over all solar rotations in the solar activity minima in 1975 and 2007–2008.

## 9 Development of data products to monitor the Geospace

Three products were developed to monitor ionospheric phenomena directly linked to the dynamic plasma boundary layer based on plasma density, total electron content (TEC), and field-aligned current observations and data products of ESA's LEO mission, Swarm (Heilig et al. 2022). Two products characterize the main ionospheric trough (MIT) based on Langmuir probe measurement of electron density and GNSS-based TEC observations, respectively, as well as the MIT-associated enhancement of the electron temperature. The third product characterizes the equatorward boundary of the particle

precipitation-related small-scale field-aligned currents. All these phenomena are described as spatial structures with a series of parameters. All these products are available via ESA's Swarm Data Dissemination Server (<https://swarm-diss.eo.esa.int/>). The products are used to derive proxies for the location of the plasmopause that has been applied successfully for monitoring the response of Geospace to geomagnetic storm-related plasma erosion and the subsequent recovery (Vellante et al. 2021). In 2022, EPSS became a member of the Swarm DISC consortium resulting in deeper and more direct involvement in the mission.

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# RECENT RESULTS ON SOLAR WIND AND INTERPLANETARY MAGNETIC FIELD PHENOMENA (2019-2022) – IAGA DIVISION IV

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## 1. Heliosphere, solar wind and suprathermal ions

Zeldovich et al. (2021) analyze the dependence of ion abundance on solar wind speed by using suprathermal ion observations from coronal holes at 1 AU; here they focus on observations during solar cycles 23 and 24. The fluxes of suprathermal ions is also the topic of the article by Zeldovich et al. (2019) where they analyze the time variations in the fluxes of suprathermal ions at 1 AU over the period of 1998-2017. Timar et al. (2019) in their article make an estimation of the solar wind pressure at comet 67P from Rosetta magnetic field measurements.

Logachev et al. (2021) study Jovian electrons and stationary structures in the solar wind at the Earth's orbit. Roberts et al. (2022) in their article present a multi-scale study with Cluster data of the scale-dependent kurtosis of magnetic field fluctuations in the solar wind.

The complex study by Zhang et al. (2022) investigates the dayside transient phenomena and their impact on the magnetosphere and ionosphere of the Earth by using multiple observation data, simulation results and theoretical approach.

Voeroes et al. (2021) present a case of magnetic reconnection within the boundary layer of a magnetic cloud in the solar wind.

## 2. Waves and turbulence

Pitna et al. (2021) analyzed and compared the turbulence upstream and downstream of interplanetary shocks. Yordanova et al. (2021) studied a possible link between turbulence and plasma heating, while Roberts et al. (2020c) studied the possible coexistence of kinetic Alfvén and ion Bernstein modes in sub-ion scale compressive turbulence in the solar wind.

Another work related to sub-ion scale compressive turbulence in the solar wind is the study by Roberts et al. (2020a) where they used MMS spacecraft potential observations. The solar wind turbulence was also the topic of the article by Roberts et al. (2020b) where they studied the higher-order statistics in compressive solar wind plasma turbulence by using data provided by MMS. In the article by Narita et al. (2020) they study the transport ratios of the kinetic Alfvén mode in space plasmas.

## 3. Involvement in BepiColombo and Solar Orbiter missions

Hadid et al. (2021) explores the BepiColombo's cruise phase as a unique opportunity for synergistic observations. The article by Mangano et al. (2021) also investigates the scientific opportunities of BepiColombo cruise and flybys at the Earth, Venus and Mercury. The article by Horbury et al. (2020) provides an in-depth description about the magnetometer on-board Solar Orbiter.

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# HUNGARIAN CONTRIBUTION TO THE RESEARCH ON OBSERVATORY, INSTRUMENTS, SURVEYS AND ANALYSIS (2019-2022) - IAGA DIVISION V

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## 1. Introduction

In line with the aims of the quadrennial IUGG national committee reports, the present paper gives a short review of the Hungarian contribution to the main objectives of IAGA Division V, achieved between 2019 and 2022. Our contribution is primarily relied on two Hungarian geomagnetic observatories located in Tihany and Nagycenk, and on our geomagnetic country survey and repeat-station survey networks. The following main sections of the paper are devoted to the presentation of the current infrastructural status, and the main developments and tasks carried out in relation to our geomagnetic infrastructures during the last IUGG report period. We also present our main scientific achievements obtained with the processing and analyses of our geomagnetic observations as well as of public geomagnetic data sources.

## 2. Tihany Geophysical Observatory

The Tihany Geophysical Observatory (IAGA code: THY) is maintained by the Mining and Geological Survey of Hungary (2019-2021) and the Supervisory Authority of Regulated Activities (2022). The observatory is situated in a national park on the Tihany peninsula of Lake Balaton. Since 1955 the observatory has continuously recorded geomagnetic data. Tihany is a founding member of the INTERMAGNET. The geomagnetic data gathered here are published yearly on the INTERMAGNET CD-ROMs and on the DVDs.

### 2.1 Instrumentation and data acquisition

During the last IAGA period, three fluxgate variometers and two Overhauser effect-based magnetometers were operating for continuous recording at the observatory: a LEMI-035 tree-axial fluxgate magnetometer with XYZ oriented suspended sensor, a suspended DTU FGE triaxial fluxgate magnetometer with XYZ orientation, a Narod triaxial ring-core fluxgate magnetometer installed in HDZ orientation, a GSM-19 Overhauser magnetometer (GEM-Systems) for recording the total field and a dIdD (delta inclination delta declination vector Overhauser magnetometer) system. The LEMI-035 and the Narod fluxgate magnetometers are installed in the variation pavilion of the observatory. The temperature in this hut is being controlled within  $\pm 0.2^\circ\text{C}$ . Nevertheless, the temperature of the sensor and the electronics is monitored by the built-in temperature sensors of the LEMI-035 magnetometer. The GSM-19 Overhauser magnetometer is installed in the absolute house of the observatory. The distance between the absolute pillar and the sensor of the magnetometer is about five meters.

The dIdD system and the DTU FGE magnetometer are installed in the old variation house. This building is a cellar that is why the yearly temperature variation is attenuated there.

The LEMI-035 magnetometer is equipped with an OBSDAQ type, 24-bit A/D converter. Its output signal is transmitted to the recorder through a 120 m long optical cable. Optical cable is applied for protection against lightning hazards. Accuracy of time synchronizing to GPS time is  $\pm 2$  msec. The applied sampling rate is 128Hz. After digital filtering 1-second resolution data are also recorded in addition to the 1-minute mean values required by INTERMAGNET. LEMI-035 magnetometer is the main recording system of the observatory since 2020.

The high-resolution NAROD fluxgate magnetometer belongs to the EMMA geomagnetic pulsation recording array. The DTU FGE magnetometer is recorded by the DGRAB-24 24-bit A/D converter with MAGOR data acquisition system (DAQ).

The dIdD system records inclination and declination, as well as total field data in every five seconds. When these data are used as input to a task-oriented DAQ, they produce real-time XYZF 1-minute means. Of course, all the original readings are stored, as well. Thus, the dIdD instrument can serve as back-up systems for our base main magnetic recording system.

The observatory has two absolute instruments: a Zeiss 20A theodolite and a Zeiss 10A theodolite equipped with a DMI D&I sensor. The absolute measurements are taken weekly according to the null reading method. A set of absolute observations consists of two independent measurements of D and I. The total field is continuously recorded by a GSM-19 and even by the dIdD. All the baselines are derived from standard absolute observations.

In order to apply some convenient networking technologies (i.e. remote control, file transfer, secured connections, etc.) a Linux-based data logger was developed. The DAQ in THY is able to acquire magnetic data and housekeeping data from one or more different instruments, including fluxgate, Overhauser, dIdD magnetometers or temperature sensors, etc. (through A/D converters or RS-232 protocol). GPS PPS is used for sample triggering and time labeling of magnetic data.

All of our data acquisition units are linked into a local network, while communication between the observation site and the office is realized by a microwave (2.4 GHz) transmitter. For data security reasons, the recorded data are stored parallel on three different computers located in different buildings.

## 2.2 Observatory data and database

Since 2013 data from the main observatory system have been quasi-real time transmitted to Edinburg GIN server instead the previously used e-mail transmission. The data are also available to partner researchers through a real-time ftp server. The observatory developed a website where the recordings of all instruments are plotted near real-time. Since 2005 the second sampled XYZ variation data have been real time transmitted to the National Institute of Information and Communication Technology (Japan) Space Environment Information Service. In 2015 the observatory joined to the quasi-absolute minute mean data transmission to the INTERMAGNET website in order to support the work of satellite missions. Since 2009, the metadata base of the definitive data sets of the observatory is available on the GEOMIND ([www.geomind.eu](http://www.geomind.eu)) and KINGA ([kinga.elgi.hu](http://kinga.elgi.hu)) Internet information services.

## 2.3 Additional measurements and activities in Tihany Geophysical Observatory

- Coordinator and PI of EMMA (European quasi-Meridional Magnetometer Array ranging from Finland to Italy) for space weather studies (by monitoring global ULF wave activity and plasmaspheric density)
- Since 1968 onwards whistlers have been detected in the observatory as a joint project with the Space Research Group of Eötvös Loránd University (ELTE), Budapest. Presently this activity is a member of the AWDAnet (Automatic Whistler Detector and Analyzer Network).
- Seismological recording is performed using a Güralp CMG-3T seismometer. The instrument belongs to the network of permanent seismograph stations in Hungary. The station is operated by Kövesligethy Radó Seismological Observatory, Institute of Earth Physics and Space Science of Eötvös Loránd Research Network.
- Temperature gradient observation for geothermal studies has been started in 2010.
- Non-magnetic temperature test hut was built in the observatory to study the most important source of temperature effect on magnetometers by using high amplitude thermal change.
- Since 2018 onwards soil-water content and precipitation data as well as humidity and air pressure have been recorded in the observatory.



- A new site for the measurement of absolute gravity was established in 2013. Recording of the Earth-tide was performed on this site in the period of 2017-2022.
- Member of the WWLLN global lightning detector network (University of Washington, Seattle)

#### **2.4 Electricification of the railway near Tihany Observatory**

The railway north of the observatory was electrified in 2021. Up to now, the level of electromagnetic noises in the DC to ELF frequency band has been among the lowest in Europe. With the appearance of EM noises and transients generated by the electric locomotives, most of the experiments are exposed to high risk. The observatory had to face a similar challenge in the 1980's, when the railway at a similar distance south of the observatory was electrified. In that case the AC railway was carefully designed applying 2X25 kV solution at that time to protect the nearby underground communication lines.

From the AC technologies, that had risen up as potential options of innovation, we only found the 2X25 kV (50Hz) technology acceptable. Our technical reports for the decision-makers, which made them accept our point of view. The tests and the common train service started in the year of 2021. The trains approach the observatory in seven kilometers. We have no detectable artificial noise caused by the trains now.

#### **2.5 Geological and geophysical investigations on the site of Tihany Observatory**

Since the beginning of geomagnetic recording at Tihany Geophysical Observatory, baseline instability has been observed, especially in the case of the old variation house. The regularly observed annual baseline change is independent from the type of magnetometer used. Common environmental effects on the instruments (for example temperature effects) are not suitable to characterize this variation. A possible reason of this instability is an unconventional geomagnetic effect on the magnetic properties of the sediment. The water saturation of lake mud shows correspondence with the variation of the base values (Csontos et al. 2019a).

The appearance of the above mentioned systematic baseline instability with large spatial differences motivates us to perform a detailed geophysical survey on the site of Tihany observatory including electric resistivity tomography (ERT), geomagnetic measurements and susceptibility measurements. Soil samples were also collected based on the measurement results, on them an X-ray powder diffraction (XRD) measurement was completed to identify the minerals of the sediments. After these investigations deposits with different magnetic properties could be linked to structures created by the mud of lakes (i.e. Lake Pannon and hydrothermal deposits) so the impoundment of magnetic anomalies of the crust were performed. As a consequence of our study we verified, that the absolute control of the geomagnetic observatory is not influenced by strong crust anomalies (Csontos A and Tildy P 2019).

A deeper understanding of the geomagnetic processes of the nearby deposited sediments make it possible to distinguish different instabilities of magnetic gradient. The record of some geomagnetic observatories presents significant instabilities of geomagnetic gradient. In order to identify the effects a sensitive indicator is the magnetic curvature which is regularly measured by absolute measurements. A comprehensive study was presented to verify the existence of the phenomena (Csontos 2019).

### **3. Repeat-station survey in Hungary**

In Hungary, the first geomagnetic network survey was carried out between 1847 and 1857. During this campaign, 52 stations were occupied in the former territory of Hungary under the leadership of Karl Kreil (Szabó, 1983). Later, eight further country surveys (CS) have been carried out. Between 1950 and 1995, the surveys were completed in regular periods of 15 years. In 1965, a so-called repeat-station (RS) network comprising 15 non-anomalous stations (Aczél, Stomfai, 1969) was also established aiming to monitor the spatial distribution of the secular change of the magnetic field in 2-3

years of intervals, and through this, to enable the regular update of the field obtained from CS. In 2003, we were among the founding members of the European scientific association, MagNetE, that was called into life in order to unify the practice of RS activities throughout Europe. The 7th workshop of MagNetE was held in Hungary by us.

The country and RS networks were established by the Eötvös Loránd Geophysical Institute (ELGI). During the report period (2019-2022), however, the networks were already maintained by two of the successor institutions of ELGI, the Mining and Geological Survey of Hungary (2019-2021) and the Supervisory Authority of Regulated Activities (2022).

### 3.1 Activities between 2019 and 2022

Since 2019, one repeat station campaign has been carried out, in 2020. Following the practice of previous campaigns, the magnetic declination, inclination and the total field were measured in 13 repeat stations. The measurements were performed in the geomagnetically most quiet morning and afternoon periods of the occupation days. The definitive magnetic elements of the campaign were reduced to the epoch of 2020,5 with the use of the magnetic records of the Tihany Geophysical Observatory. Additionally, for the cases of four stations located in East Hungary (i.e. far from Tihany), the temporal reductions were also carried with the use of the record of a temporary on-site three-axial fluxgate variometer installed in the Baradla cave. Our previous studies proved that the use of the on-site variometer can improve the accuracy of the temporal data reduction by about 2-3 nT in each Cartesian geomagnetic element (Kovács et al, 2012). The definitive results of the campaign were submitted to the World Data Centre node in Edinburgh, according to the recommendation MagNetE.

The RS campaigns allow to compile the geomagnetic normal field as well as the geomagnetic secular variation (SV) models of Hungary, for each Cartesian geomagnetic element as well as for declination, inclination and total field. Traditionally, the models are expressed by first-order polynomials of the geographic coordinates, separately for each component. The last geomagnetic normal field models were referenced to the epoch of 2020,5 while the SV model was computed for the period lasting between the reference epochs of the last two campaigns, 2018,5 and 2020,5. The independent expansions for the different magnetic elements cannot consider the conservative nature of the magnetic field in the absence of electric currents. To avoid this shortcoming, in the modeling procedure we have also implemented and applied the adjusted spherical harmonic analysis (ASHA) published by De Santis (1992) for the compilation of the normal fields of the last epochs (Vujić et al. 2016).

Finally, it is to be noted that our RS campaign results form the basis of various mapping and navigation purposes claimed by national and commercial entities. For instance, the declination isogon map of Hungary updated regularly with the use of our SV models is submitted to the Zrínyi nonprofit Ltd. of the Hungarian Ministry of Defence, on a yearly basis. Besides, in 2020 we carried out the order of Hungarocontrol cPLC by providing them the model declination and declination SV values for 9 DVOR navigation stations in Hungary.

## 4. Nagyecenk Geophysical Observatory

Besides regular geomagnetic observations and continuous data services for IGRF and main field modeling, the main objectives of the ground-based electric and magnetic observations are monitoring the solar-terrestrial environment and development of models to specify and predict the state of the Sun-Earth system (space weather and climate). Measurements include the monitoring of geomagnetic field variation, ionospheric parameters, solar emissions and determination of solar wind and radiation environment parameters. Model developments are required for the propagation of coronal mass ejection and energetic particle radiation, interaction between the interplanetary medium and the Earth's magnetosphere, the filling and depleting of the radiation belts, ionospheric composition, density, diffusion, convection and induced electric fields.

## 4.1 Geomagnetic observations

Continuous observation of geomagnetic elements with control of the absolute observations started in 1961. The observatory is equipped with 3 sets of triaxial fluxgate magnetometers. The temperature variations of the triaxial fluxgates are maintained within 0.5 °C between the weekly absolute observations. The fluxgate variometer sensors are aligned in X, Y, Z directions. For better time resolution one of them is run with 1 second sampling rate. Simultaneous low-altitude satellite and meridional magnetometer array (1.56<L<1.88) measurements were used to interpret the controversial relation between space and ground ULF signal, evaluate the effect of the ionosphere on the transmission and study the field line resonance phenomenon and study the expected ULF precursors of seismic activity. In the frame of the INTERMAGNET data service 10 second samples are used to provide minute values centered on the minute, by means of a 7-point cosine filter. Geomagnetic indices and transient events are also scaled from these data.

Protonmagnetometer (Overhauser- effect magnetometer) in dIdD configuration consists of two orthogonal sets of coils (proton head is mounted at the center). Coils are orientated so that one provides bias fields approximately perpendicular to F vector in the magnetic meridian and the other provides bias fields approximately perpendicular to F in the horizontal plane.  $\Delta D$  and  $\Delta I$  relative to the initial values ( $D_0$ ,  $I_0$ ) are calculated. dIdD proton magnetometer samples at 1Hz from which F (total force) and quasi-absolute values of D and I are obtained. To ensure continuous recording a high stability torsion photoelectric magnetometer (type PSM-8711) is run as a backup system. Data along with telluric data are logged by a DR-02 type digital recording system. The PSM magnetometer records the H, D and Z components with exceptionally high parameter stability. The baseline variation never exceeds 1.5 nT/year. Maximum resolution is 3 pT, sampling rate applied is 10°s, frequency response: 0.3 Hz to DC, sensitivity to tilting: less than 10 nT'.

Baselines of the variometer systems are derived from absolute observations of F, D and I. The standard instrument for absolute measurements is the proton magnetometer (type: GSM 19 of GEM Systems) and the new fluxgate theodolite. To determine the momentary angle of declination four observations (four null positions in the horizontal plane) are taken and it is repeated at least twice. The inclination angle is determined in the plain of the momentary magnetic meridian in the same way as D. Total intensity is measured simultaneously with I-measurements on the next (F) pillar with an Overhauser magnetometer. Absolute values of all geomagnetic elements are referred to the same pillar of the absolute hut. Observations are made weekly, occasionally more often. Baseline determination was improved by new Overhauser effect protonmagnetometer, a Theo 020A based fluxgate theodolite, also called DI-flux.

## 4.2 Description of the new complementary measurement system

The relative house's instrumentation has been expanded with an additional variometer set to enable real-time data transmission of second sampled geomagnetic data to the Edinburg GIN server of INTERMAGNET.

The core of the new system is a triaxial fluxgate magnetometer model FGE by DTU Space which has a proven track-record at many observatories worldwide. It is easy to set up and operate and has demonstrated baseline stability over decades. The FGE has analog outputs enabling the user to adapt the instrument to their own data logging systems. The analogue/digital conversion of the magnetometer analogue output is performed by a SYMRES USB8CH 24 bit real-time continuous data acquisition system with an individual A/D per channel architecture. Suitable for sampling from DC to 10kHz, an on-board 4 MB FIFO guards against any data loss even on heavily interrupted and multitasking computers. Sitting outside the PC for improved noise performance, the system communicates its acquired data to the computer via a standard USB port. All analog inputs are fully differential with amplitude ranges of +/- 4 Volts. The data is processed and stored on a BeagleBone Black microcomputer by the platform independent software environment provided by SYMRES. Full featured acquisition programs like DVM and Scope are included with the system software easily controlling acquisition rates and continuously saving acquired data to disk. The pipelined architecture allows simple

customization of the provided programs. For developing custom utilities, low-level pipeline functions are supplied.

The microcomputers are equipped with industrial quality 16GB SD cards to secure the reliable data acquisition for long turn. The original flexible pipeline has been supplemented by some extra scripts for automatic quasi real-time data service to Edinburg INTERMAGNET GIN and direct real-time data forwarding to a separated high performance data server by local network. The last element of the data acquisition system is the server which stores the second sampled geomagnetic data in an SQL database with separated tables for each day and one table for the last 24 hours of data. Archived data includes the GPS time stamp, 3 geomagnetic components ( $X$ ,  $Y$ ,  $Z$ ), the sensor temperature ( $T_s$ ) and the temperature of the electronics ( $T_e$ ) leaving open the possibility of a subsequent temperature correction.

The power of the whole system is supplied from a 12V 74Ah battery continuously fed by the central solar power system of the Observatory. The clone system is archived on a backup memory card in case of emergency to secure permanent data acquisition.

### 4.3 Telluric current recording

Continuous measurement of the geomagnetically induced currents (telluric currents) started in 1957. The value of the telluric data of the observatory lies in the exceptional length of data series. The long-term stability of the observations had been ensured by the reconstruction of the electrode system. This nearly sixty years long telluric recording forms a unique data set for statistical analysis of the long-term variation of the geomagnetic activity and its induction effect. The occurrence of high geomagnetically induced electric fields and their coincidence with the phases of solar activity is less clear than that of maximum magnetic activity. As the weights of variations with different periods are rather different in geomagnetic and earth-current indices, there are also differences between the two kinds of activities.

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# HUNGARIAN CONTRIBUTION IN EM METHODS (2019-2022) - IAGA DIVISION VI: ELECTROMAGNETIC INDUCTION IN THE EARTH AND PLANETARY BODIES

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## 1 Introduction

In geophysical research related to „electromagnetic induction in the earth”, decades ago, there were several active groups in Hungary: the “Sopron” (Antal Ádám et al.), the “Oil Exploration” (led by Zoltán Nagy), the “ELGI”, and the “Miskolc” (founded by Ernő Takács). In the past decades, especially in the past several years, serious re-organizations took place. The EM geophysical activity in the Hungarian hydrocarbon industry was ceased long ago. The Geodetic and Geophysical Research Institute in Sopron operated from 2012 to 2021 as a part of the Research Centre for Astronomy and Earth Sciences, when, in 2020, the entire institute network went from the Hungarian Academy of Sciences (MTA) to the umbrella of the newly formed Eötvös Loránd Research Network (ELKH). Since 2021, the institute has been again “independent”. Its new name: “Institute of Earth Physics and Space Science” (EPSS), where the magnetotellurics (MT) group is an integral part of Lithosphere Physics Research Unit of the institute. The former ELGI (Eötvös Loránd Geophysical Institute) in Budapest underwent several merges. After various periods, from 2017-2021 it was a section of the Hungarian Mining and Geological Survey. From beginning of 2022 the whole Survey went under the umbrella of the Supervisory Authority of Regulatory Affairs (SZTFH). The hosting institute of the Miskolc EM group (Geophysical Department, Miskolc University) recently operates as a part of larger university units (Institute of Geophysics and Geoinformatics at the Faculty of Earth and Environmental Sciences and Engineering).

Several Hungarian scientists known in the EM induction communities have passed away: András Madarasi (2017), Zoltán Nagy (2019), Ernő Takács (2012), Géza Varga (2022) or retired (Antal Ádám, Mihály Dobróka, Dezső Drahos, Ákos Gyulai, László Nemesi, Gábor Pethő, László Szarka, Endre Turai). In the last four years in Hungary, in the field of magnetotellurics, only one PhD (Nádasi, 2022) and one MSc thesis (Rubóczki 2020) were successfully defended. In wider EM geophysics, a Doctor of Science thesis (Szalai 2021) was also defended.

In Section 2, a publication-based summary of the Hungarian activity in the field of IAGA Division VI - Electromagnetic Induction in the Earth and Planetary Bodies is provided. The papers are listed at the affiliation of the main author.

## 2 Hungarian IAGA Division VI Results, 2019-2022

### 2.1 The Sopron Institute

This report should start with a paper, missing from the previous Hungarian National Report: Ádám et al. (2017) summarized the main crustal and mantle conductivity anomalies observed in the Pannonian Basin (PB).

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In the beginning of the actual report period, Ván et al. (2019) carried out complex (seismic, infrasound noise, electromagnetic attenuation and cosmic muon radiation) measurements in the underground Mátra Gravitational and Geophysical Laboratory near Gyöngyösoroszi, Hungary.

MT was applied to find proper ELF field test sites in Hungary, which are suitable for monitoring Schumann resonances (Bozóki et al., 2020a). Bozóki et al. (2020b) published a report on a detailed EM noise test carried out in the Széchenyi István Geophysical Observatory (NCK) on July 9, 2020.

Patkó et al. (2021) published a summary article on the Nógrád-Gömör volcanic area, providing magnetotelluric information on the root zone of an intraplate volcanic field, where magmatism may be more extensive and persistent even after recent active eruptions than previously thought based only on the spatial extent and volume of eruptions.

Bör et al (2022) compared Q-bursts detected in the magnetic field near the surface and at a depth of 140 m to characterize signal attenuation in the Earth's crust.

Among others, MT results were also applied in the Hungarian seismotectonic project of the Institute „Creating and analysing the seismotectonic model of Hungary” (Project ID: 2018-1.2.1-NKP-2018-00007).

In frames of the Pannon Lithoscope Lendület Project (Kovács et al. 2019), the installation and data collection of the MT stations undertaken under the project has been completed. In total, data from 38 MT stations were provided to estimate the depth of the lithosphere-asthenosphere boundary (LAB). Updating of the new LAB depth map at a uniform scale, supplemented with data from archival MT stations, has started. Errors in the high-frequency and long-period signals of the raw data were corrected by noise and decomposition filtering, thus removing noise due to artificial noise, galvanic distortion and static shift phenomena. A test processing was developed to refine the results of 1D inversion processing using magnetotelluric 3D synthetic modelling based on geochemical layer models. The results of the developed routine gave a good approximation between the modelled and measured MT results. It is planned to use this processing routine to ensure the refinement of the LAB depth map for the Pannonian Basin and to generate a unified geodynamic model, complemented with geochemical and seismological results. The processing and interpretation of Lendület MT data started in the Ambrózfalva area in the Southern Great Plain, Hungary. In addition to the general MT processing steps, an important component of the work is the ability to compare the inversion models derived from MT with electrical resistivity rock column models calculated from geochemistry, based on the knowledge of rock composition, volatile content, pressure and temperature. This provides an estimate of the rock composition and fluid content in the depth range below the Conrad surface, which greatly aids deep structural interpretation.

In connection with the TopoTransylvania NKFIH NN141956 Project (see for details of the project description Matenco 2018), six broadband MT stations were measured along an east-west transect in the Carpathian Gorge to determine the depth of the lithosphere-asthenosphere boundary (LAB). The measured stations were complemented by two archival magnetotelluric stations (Gyula and Csomád/Ciomadul) with an average station spacing of about 70-80 km. The stations recorded the changes of the electric and magnetic field components at the surface for a period of two weeks, reaching a period of 10,000 sec. The data consist of high-frequency (“shallow depth”) and long-period (“large depth”) data, which were processed to filter out near-surface disturbances by decomposition. The processed 1D results of the large-scale MT measurements along the Transylvanian Basin provide a good indication of the variation of the asthenospheric depth. At the western end of the section, the decrease in resistivity at shallow depths (60 km) associated with the upwelling of the asthenosphere in the Pannonian basin is well validated. Moving eastwards along the section, the LAB depth deepens, averaging 70-80 km around the Transylvanian Basin, then the LAB depth increases below the Eastern Carpathians, and a shallower depth is again obtained in the return arc (Csomád/Ciomadul volcanic mountains). Based on the geomagnetic induction data, it can be said that in the depth range of the crust, the induction arrows point towards the interior of the basin, indicating possible high-conductivity anomalies, which at greater depths are oriented eastwards towards the Eastern Carpathians arc. The results will facilitate understanding of the kinematics of the lithosphere-asthenosphere system in the geologically active segment of the Alpine orogen, and estimates of fluid (H<sub>2</sub>O, CO<sub>2</sub>, etc.) migration can predict the effective viscosity of the lithosphere and asthenosphere. Additional MT station

locations have been finalized near the Perşani Mountains (Persányi-hegység, Munții Perşani) in order to investigate the distribution of subsurface conductivity in relation to post volcanic activity and the presumed fluid injection of upper mantle xenoliths.

It should be mentioned that EM induction studies led, among others, to original results in geoelectric methods, namely to those in the so-called quasi-null arrays. The technique was summarized by Szalai et al. (2020). Some aspects of this method was highlighted by Zubair et al. (2020), Szűcs et al. (2021) and Metwaly et al. (2021).

## 2.2 The former Eötvös Loránd Geophysical Institute

By this team between 2018 and 2022, among others, interesting methodological studies were carried out. They are published only in Hungarian, therefore we provide here a longer description on them.

The starting point of the paper by Kiss et al. (2020) is that the classical magnetotelluric formulas accurately describe the effects only for the case of a homogeneous medium. But in case of various interfaces, some of the electromagnetic field components are continuous, while the others change abruptly. Such changes, described by the interface conditions (or regularities) are discussed in theory of electromagnetic methods using artificial fields, presumably have not yet been studied in the case of magnetotellurics, neither in Hungary nor in the world. Dielectric permittivity, magnetic permeability, and electrical conductivity all together determine the normal and tangential electromagnetic field components, which are usually measured. In order to clarify the geological interpretations, the authors describe these regularities, through some practical examples. They look at whether the theoretical correlations appear during the evaluation of the field measured data. Magnetotelluric measurements along profiles CEL07 and CEL08 are used as case histories.

Kiss and Prácsr (2021) focuses on a common magnetotelluric problem. Namely, from E and H polarization inversion, very different results are obtained, with very different specific resistivity sections. Whether the difference between the two directions is an error or it contains a geological information. The question is theoretical, since there are obvious geological reasons for the phenomenon, which has perhaps not addressed enough deeply so far. The authors call the divergence directional anisotropy (caused by two- and three-dimensional effects), which they have so far only associated with directional changes in the conductivity of the geological medium. However, based on the study of boundary transition phenomena (Kiss et al. 2020), they have found something else, a directional anisotropy that depends not only on conductivity but also on the magnetic properties and/or dielectric permittivity of the medium. Since the electromagnetic (electric and magnetic) field components are measured, this is actually not surprising. But this should make interpretative geophysicists and geological users cautious. In a previous study, investigating the role of magnetic permeability over the Curie temperature range, they also performed a wide range of modelling using in-house developed programs. By re-examining the results of these runs, the boundary transition laws that were discovered explained many phenomena that had been incomprehensible. Kiss and Prácsr (2021) present results by “dusting down” the data and extending the paper of 2009. Along the CEL08 profile at Kab Hill (Kabhegy) a clear connection between the basaltic cap and the maximum anisotropy can be assumed (see Kiss et al. 2020). The location of the anisotropy maximum in the section is much deeper and much larger than what had been known about the possible position and size of the basalts based on the geological knowledge. Whether it is possible to assume that this phenomenon also has geological origin — more precisely, that it would be due to the propagation of the electromagnetic field? Could it be that everything in nature happens according to the laws of physics, but that we have not yet recognised these laws? Kiss and Prácsr (2021) investigate this question too; using two-dimensional direct modelling and then examining field sounding curves.

Some further, papers by this team, mainly gravity and magnetic ones, where MT plays less or no role (Kiss et al. 2019, Bodoky and Kiss 2020, Kiss 2020, 2021, 2022) should also be mentioned.

### 2.3 The Miskolc Team

As mentioned in the Introduction, the Department of Geophysics is deeply integrated in large-scaled projects and units. Their recent EM results are as follows.

Nuamah and Dobróka (2019) described a comprehensive robust inversion-based Fourier transformation algorithm, based on the advantages of Hermite functions for processing even in random-walk data, known as the iteratively reweighted least squares Fourier transformation (IRLS-FT) method. Nuamah et al. (2021) presented a new inversion based Fourier transformation technique named as Legendre-Polynomials Least-Squares Fourier Transformation (L-LSQ-FT) and Legendre-Polynomials Iteratively Reweighted Least-Squares Fourier Transformation (L-IRLS-FT).

Fancsik et al. (2021) proposed a new inversion method to process laboratory-measured induced polarization (IP) data. In the new procedure, the concept of the series expansion-based inversion is combined with a more general definition of the objective function.

In their paper Turai et al. (2021) presented recent results of Monte Carlo inversion of IP data. The time constant spectrum is determined by inversion and applied for characterizing environmental contaminations and ore deposits.

Nádasi et al. (2022) developed a regularized method of 3D inversion of magnetotelluric (MT) data using the Gauss–Newton algorithm in the data space. The method was applied to a large-scale 3D inversion of MT data collected over the Western Superior region of the Canadian shield in the frameworks of Lithoprobe and EarthScope projects.

A mineral exploration MT paper by Nádasi et al. (2015) is also should be mentioned, for two reasons: (1) it was missing from the Hungarian IUGG Report (2015–2018), (2) it was one of the last co-authored papers by the magnetotellurician András Madarasi (1951–2017) from ELGI.

In 2022, a lecture session was dedicated in Miskolc to Professor Ernő Takács, a key person of the heroic era of Hungarian magnetotellurics, on the occasion of 10<sup>th</sup> anniversary of his death (MFK 2022).

### 3 Closing remarks

For further relevant and complementary results see this volume. For example, related observatory and field studies have been published by Lemperger et al. (2023). Magnetotelluric results have been used, among others, by Hungarian volcanologists (e. g., Kiss et al. 2019). For us, EM geophysicists, it is evident that magnetotellurics and other EM geophysical methods have become reliable tools in understanding the physical reality beneath our feet. There are promising indications that the generational change taking place in Hungarian geology involves a change in attitude that relies much more heavily on the quantitative results of magnetotellurics and other EM methods than before.

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# HUNGARIAN NATIONAL REPORT ON IAHS (2019-2022)

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## 1 Introduction

The Hungarian National Committee of IUGG prepares a national report detailing the International Association for Hydrological Sciences activities every four years. This paper summarises the most important hydrology-related projects and research performed by universities, scientific institutions, and government agencies in Hungary from 2019 to 2022. The National Representative of IAHS reviewed the relevant water-related activities and their publication background.

Traditionally, the Environmental Protection and Water Resources Research Institute (Hungarian acronym VITUKI) managed hydrological research, but VITUKI dissolved in 2013 due to reorganisation. Other organisations have since taken over their main research tasks and projects. These organisations include the General Directorate of Water Management (Hungarian acronym OVF) and universities such as the Budapest University of Technology, the National University of Public Service, the Hungarian University of Agriculture and Life Sciences, the Széchenyi István University, the University of Miskolc, the University of Pécs and the University of Sopron, among others.

## 2 Selected research and development activities in Hungary

### 2.1 Budapest University of Technology

Department of Hydraulic and Water Resources Engineering conducted the following research activities.

In the past four years, research further developed the complementary relationship (CR) of evaporation, reaching its apex in laying the theory fully on thermodynamical settings (Szilagyí 2021). In the meantime, the CR was tested with great success in China, the USA, and the globe. The CR was finally generalised, resulting in a very effective evaporation estimation method that can be easily applied at any point of the world as it can account for horizontal advection of moisture (Ma and Szilagyí 2019, Ma et al. 2019, Ma et al. 2020, Ma et al. 2021). Previously the method overestimated terrestrial evaporation rates in desert areas adjacent to oceans or seas due to such unaccounted advection of moisture from the open water surface. The generalised method can be calibrated locally (it has only two parameters), or it can be applied without any calibration since one of its parameters can be related to air temperature (and the other one can be set manually before application of the method with gridded data of the input variables) (Szilagyí et al. 2020, Szilagyí et al. 2022).

The study of catchment response time at small catchments was continued. The number of studied catchments and events was extended to 61 and 2152, respectively.

First, a novel numerical response time estimation procedure (E-DMCA method) was developed to collect rainfall-runoff events from measured rainfall and runoff time series and estimate the catchment response time for these events in an automated manner (Nagy et al. 2022). This method yields response time values significantly faster than existing approaches. Response time values were also calculated using eight different graphical definitions. As a result, it was proved that the characteristic value of the lag time and the time of concentration could be estimated from the catchment response time values of the E-DMCA method. The lag time results from the median, while the concentration time is from the maximum of those values. The other part of the study focused on analysing dimension reduction and catchment clustering (Nagy et al. 2021). Sixty catchment descriptors were examined, including size/relief, river network, shape, land use/soil, and hydro-meteorologic metrics. All regressions analysis proved to be the most efficient in selecting the best descriptors, while the conclusions

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derived from the cluster analysis were manifold. Eventually, a new empirical estimation method was proposed based on the study's outcomes.

In groundwater analysis, a laboratory scale (or sandbox) model was developed to research seepage flow and well hydraulics. In the model, pumping tests were simulated, and measurements were taken with different discharge rates, along with the pressure- and velocity values near the pumped well. Based on the results, numerical models were successfully set up to validate the results of laboratory measurements. Results from the laboratory scale were extended to real-size field tests (Farkas et al. 2019). Furthermore, the laboratory investigations of the groundwater flow near the pumped well resulted in essential parameters of well losses and efficiency.

In river research, an easy-to-implement field measurement and data processing framework for quantifying the near-shore effects of ship waves has been developed (Fleit et al. 2019). The measurement methodology has been complemented by an acoustic measurement of suspended sediment concentration, which allows the quantification and interpretation of the impact of wave components on near-shore sediment transport (Fleit and Baranya 2021). The field methodology also allows high-resolution numerical modelling of ship-generated waves based on measurements, allowing the spatial extension of the measurement results (Fleit et al. 2019). A case study has demonstrated that by combining detailed hydrodynamic results with numerical ecological data (swimming speed of juvenile fish), it is also possible to quantify the hydraulic effects of wave action on habitats – in this case, by generating drift risk maps (Fleit et al. 2021). The validated model also allows the investigation of unmeasured or unmeasurable (e.g., future, planned) conditions. For example, the wave attenuation effects of environmentally friendly measures to protect littoral habitats can be investigated from hydrodynamic and eco-hydraulic perspectives (Preuss et al. 2023).

The so-called large-scale particle image velocimetry (LSPIV) method, which has a broad literature background, has been further developed and improved to analyse river flows and sediment transport processes. The LSPIV method provides the horizontal distribution of near-surface flow velocities of free surface flows based on video images. A novel adaptive implementation of the method significantly reduces computational demands, bringing LSPIV closer to real-time applications (Fleit and Baranya 2019). Combining the LSPIV method with additional image processing techniques, a tool for video-based measurement of bedload yields has been developed (Ermilov et al. 2022). Advances have been made in river dune movement studies based on acoustic bed surveys (Baranya et al., 2023). A new assessment method to analyse the grain size characteristics of the riverbed's uppermost, active sediment layer was also developed using an image-based approach (Ermilov et al. 2019). New results have been achieved in large-scale river morphodynamics introducing a new relationship between riparian vegetation and river morphology (Török and Parker 2022). A thorough comparative analysis of riverine suspended sediment measurement methods has been performed, resulting in the assessment of the techniques (Pomázi and Baranya 2020); moreover, the 3D nature of suspended sediment transport has been revealed in the Danube River in the vicinity of a tributary inflow (Pomázi and Baranya 2022).

Research at the Sanitary and Environmental Engineering Department covers various environmental topics: hydrology and water quality in natural catchments and urban areas, public works and sanitation, and water and wastewater technologies.

The department participated in the Danube Hazard m3C DTP Interreg project. This research focused on tackling hazardous substance pollution in the Danube River Basin. Our main contribution was the implementation of continuous water quality monitoring at two Hungarian catchments with an autonomous flow-proportional sampling method (Budai et al. 2020) and other online sensors.

A significant statistical relationship has been identified between county-scale groundwater trends and maize crop yields in Hungary (Pinke et al. 2020). As a follow-up of this analysis, department members participated in the FK-134547 OTKA project, where the relations of climatic variables, soil moisture, and European crop yields were analysed statistically (Pinke et al. 2022). Further research is being carried out in this project in the field of wetland reclamation and the estimation of provisioning ecosystem services (Hidy et al. 2022).

The department investigated the connections between hydrological conditions and various Hungarian water bodies' ecological/water quality status (Decsi et al. 2020a, Hatvani et al. 2020, Kardos

and Clement 2020, Szomolányi and Clement 2022). Practical contributions to major national environmental programmes accompanied these descriptive studies:

- Improvement of emission load estimates for the implementation of the Water Framework Directive (Jolánkai et al. 2020),
- Identification of the two main types of natural flood regulation mechanisms for the Mapping and Assessment of Ecosystem Services in Hungary (Vári et al. 2022)
- Recommendations for appropriate hydrological ecosystem services selection for mapping tool (Decsi et al. 2022).

A hot spot analysis was conducted to mitigate the water-related consequences of timely environmental challenges in a small hilly catchment (Decsi et al. 2020b). A coupled algorithm of an integrated hydrological model and an ecosystem services assessment toolset was tested at a pilot area heavily affected by excess inland water (Kozma et al. 2022). Finally, ambitious planning is in progress to rethink the water resource management strategy of the Hungarian Tisza River Valley, with the central goal to mitigate the region's most crucial water balance issues (drought, flood, and inland excess water) at the same time. This process focuses on adaptation, water retention, and land use change, emphasising the controlled inundation of deep floodplain areas and natural terrain depressions of the alluvial plains (Murányi and Koncsos 2022).

## 2.2 National University of Public Service

The Faculty of Water Science at the National University of Public Service had the following projects and research activities.

Based on the contract with the Hungarian General Directorate of Water Management, a comparative analysis of discharge measurement and calculation methodologies was conducted on Hungary's watercourses. A series of measurements in 31 cross-sections on 18 different watercourses in Hungary were taken to prepare to implement EN ISO 748:2008 standard (Keve et al. 2022).

The Faculty of Water Sciences traditionally research rivers' water regimes and sediment (and ice) regimes. These have also occurred over the past four years (Tadic et al. 2022).

Within the framework of the IPA project titled Sustainable wetland management of the trans-boundary Palić-Ludas catchment area, the Faculty of Water Sciences conducted research between 2017 and 2019 in the Hungarian-Serbian cross-border catchment area of the Palić-Ludas water system.

Between 2019 and 2022, the Faculty of Water Sciences participated in the field research projects underpinning the project entitled HOMER (Sampler suitable for online monitoring of the mobile sediment phase of surface water bodies and development of the related material analysis and biological System) project within the framework of an assignment.

On-site wastewater treatment systems (OWTS) treating the wastewater of a single or a few households provide alternative solutions to centralised systems and are becoming increasingly popular. OWTS-related research focuses on treatment efficiency, post-treatment alternatives and the study of organic micropollutant degradation. Physical and 3D numerical modelling and fluid flow simulations of the investigated OWTS are also performed, assuming varying discharge conditions.

Research on large eddy simulation in computational fluid dynamics has shown that machine learning techniques can effectively compute the sub-grid scale. Data-driven approaches were outlined, and a member of the Faculty proposed a novel modelling guideline. Direct numerical simulation was applied as an a priori test, and the computation cost was minimised (Karches 2022a).

Process control philosophy is a key determinant of the energy efficiency of wastewater treatment plants. Cascaded aeration control can reflect the real-time load of the plant, providing the air required with cost benefits. Research has focused on functional designs for the activated sludge process that can benefit small capacity and less robust plants (Karches 2022b).

### 2.3 Hungarian University of Agriculture and Life Sciences

Finishing a set of short-term variations from the former Pannon University, the Georgikon Faculty has merged into Gödöllő, forming a vital part of the Hungarian University of Agriculture and Life Sciences (MATE). The Georgikon Campus of MATE remained at Keszthely with unbroken research activity.

Extended soybean and cereals water supply-related investigations sponsored by the GINOP-2.3.2-15-2016-00029 project were finished in 2022. This project focused on evapotranspiration measurements under field and controlled environments (Anda et al. 2020a, b, Farkas et al. 2020, Anda et al. 2021a, b, c).

The second source of our experimental results was the EFOP-3.6.3-VEKOP-16-2017-00008 project sponsoring local studies connected to crop-water interaction and functioning of the Kis-Balaton wetland system (Anda et al. 2021d, Simon-Gáspár et al. 2022) including litter decomposition in waters (Simon et al. 2021).

### 2.4 Széchenyi István University

At Széchenyi István University, a Water Resources Research Group was formed; the research here will focus on responding to short to medium-term water resource issues and preparing effective water management decisions.

Our first research area is flood risk analysis, the development of integrated flood protection and ecological planning methods, and the possibilities of reducing flood exposure in small watercourses and unexplored river basins, as well as modelling the behaviour of flood protection works/ structures under flood loads and the development of analytical methods. (Alsibile and Bene 2022).

The second research direction of the Water Resources Research Group is in integrated water management, with the potential to develop a region-wide integrated water management model. The research aims to take into account, in addition to the quantitative assessment of surface and groundwater resources, the specific aspects of the social actors in the area and to allow the establishment of a basis for water-related developments in the study area and the resolution of conflicts in water resource management.

Thirdly, in water management in residential areas, Water Resources Research Group focuses on micro- and macro-scale applications of blue and green infrastructure development and methodological studies on developing innovative water utility systems and networks. The final goal of these projects is the following:

- In flood risk analyses, the research will analyse the flood risk of small watercourses and flood protection works' structural and hydraulic load capacity and develop proposals for near-natural improvements.
- The research will focus on developing a regional integrated water management model in integrated water management.
- In residential water management, research will aim to develop proposals and models for applying blue-green infrastructures.

As a consortium partner, Széchenyi István University participated in the KEHOP-1.1.0-15-2021-00013 research program titled “Insula Magna–Complex Water Management and Sustainable Development Program”. The overall goal of the Insula Magna project was to find project ideas that have the potential to promote the sustainable development of the Szigetköz region, focusing on water-related issues.

The National Laboratory (RRF-2.3.1-21-2022-00008) started in 2022. The primary goal of the National Laboratory is to substantially broaden the knowledge base on fluvial and lacustrine systems (e.g., River Danube, Lake Balaton, and Lake Neusiedl). The inherent complexity and interactions in their hydrology, hydrodynamics, morphology, water quality and ecology are examined for a more innovative and secure subsurface, agricultural, rural, and urban water management. Széchenyi István University is a consortium partner.

## 2.5 University of Miskolc

The Faculty of Earth Science and Engineering at the University of Miskolc had several national and international projects dedicated to sustainable groundwater resource management and geothermal energy utilisation activities. The following research activities were realised during 2019-2022 to handle hydrogeology-related challenges.

WaterWiseWays – Innovative solutions for sustainable groundwater resource management project (GINOP-2.3.2-15-2016-00031) was carried out under the framework of the Széchenyi 2020 Plan, funded by the European Union, co-financed by the European Structural and Investment Funds. The project goal was to support and work out new and innovative methods in the following areas of groundwater resources management:

- Long hydrological data sets were investigated with unique mathematical methods to understand the effects of extreme weather conditions on the global water circle (Ilyés et al. 2022),
- An innovative method was elaborated to utilise abandoned hydrocarbon wells in the vicinity of the Bükk Mountains (Szűcs et al. 2022),
- The hydraulic behaviour of radial collector wells screened in riverbank aquifers was simulated with the help of the Multi-Node-Well package (Székely et al. 2021).

The karst hydrogeological activity of the research group was mainly focused on developing a methodology for the quantitative classification of carbonate and fissured hydrogeological systems (Miklós et al. 2020). Based on analytical solutions, the developed methodology determines the hydrogeological System's hydraulic and geometrical parameters with the help of source and well hydrograms. Sophisticated hydrogeophysical methods were also elaborated to characterise different aquifers and groundwater bodies (Szűcs et al. 2021). It was also demonstrated that the radiocarbon methods could be used successfully in the calibration processes of subsurface transport models (Székely et al. 2020). The regional hydrogeology description of the Tokaj Mountains world heritage site was prepared after many field measurements by the experts at the University of Miskolc (Fejes et al. 2021).

## 2.6 University of Pécs

Over the past four years, the University of Pécs had four project scopes directly related to water and hydrologic processes.

A Horizon 2020 project aimed at increasing crop diversification and water retention capacity by using diverse cropping methods, like intercropping with various intercrops grown on soils of different textural properties. Project title: "DiverFarming Crop Diversification and Low-Input Farming across Europe" WP-5 (Dezső et al. 2019, Lóczy et al. 2020).

Sustainable land use management in the hilly regions of SW-Hungary and Eastern Slovenia was analysed within the framework of the Hungarian-Slovenian collaborative project "Possible ecological control of flood hazard in the hill regions of Hungary and Slovenia" (NKFIH contract no SNN 125727) and within the framework of the programme Excellence in Higher Education, Theme II. 3. ("Innovation for sustainable life and environment") (Nagy et al. 2020, Czigány et al. 2020, Czigány et al. 2023).

Various projects related to the hydrologic consequences of weather extremities, with a special focus on flash floods, were conducted: (a) Mapping of flash flood vulnerability for the hilly and low-mountain regions of Hungary, (b) Morphometric characterisation of headwater catchments in the Mecsek Hills, (c) Adaptation measures to water management and hydrologic monitoring strategies in both lowland floodplains and headwater catchments (Farics et al. 2021, Schmeller et al. 2022, Sarkadi et al. 2022, Víg et al. 2022)

Project related to hydromorphologic processes in medium and large rivers was focused on the following topics: (a) Bedload entrainment, channel sediment texture, and bathymetric mapping of the River Drava between the confluence of the River Mura and the state boundary at river km 73. (b) physical modelling of channel evolution with a computer-controlled flume, (c) modelling ice cover

and water temperature on the Danube (Halmai et al. 2020, Liptay et al. 2021, Pirkhoffer et al. 2021, Słowik et al. 2021).

## 2.7 University of Sopron

Institute of Geomatics and Civil Engineering at the University of Sopron, the following research activities were implemented from 2019 to 2022.

Urbanised catchment ecological state analysed related to the project TÁMOP 4.2.1/B-09/KONV-2010-0006. Szita et al. (2019) evaluated stream contamination levels in a mid-sized Hungarian city (Székesfehérvár) using hydro-morphological, chemical, and hydrobiological (BMWP and MMCP protocols) measurements by comparing the results of two separate years (2011, 2018). As a conclusion of the complex analysis, Székesfehérvár has better than expected water quality, which can be attributed to the good ecological status of the hydromorphology and the streamside zone.

Hydrological conditions in Hungary were analysed in the context of Climate Change in the frame of Agrárklíma.2 (VKSZ\_12-1-2013-0034), EFOP 3.6.2 and TKP2021-NKTA-43 projects especially focusing on forests.

The water-holding capacity of the forest litter (an essential parameter for hydrological modelling) was determined for spruce, beech, and a sessile oak forest in Hungary (Zagyvai-Kiss et al. 2019). Litter data were collected from about 450–500 samples over two years (2003–2005). The litter oven-dry weights of the forest stands were different. However, interestingly the specific water-holding capacities of the litter were near-identical for needle-leaf and broad-leaf forest ecosystems.

The hydrological impact of climate change was analysed by developing a Thornthwaite-type monthly step water balance model to evaluate the plants' adaptation strategies (Herceg et al. 2019). A key parameter of the simple model was the water storage capacity of the soil (SOILMAX), represented in terms of a maximum rooting depth. An extended rooting depth for the effects of climate change was also simulated. The simulations suggest that the vegetation of the chosen agricultural field may successfully adapt to the water scarcity by growing its roots to the maximum possible.

In the same own developed Thornthwaite-type monthly step water balance model, three different surface land cover types were compared: (i) a natural forested area; (ii) a parcel with mixed surface cover; (iii) an agricultural area (Herceg et al. 2021). The 21 st century climate model projected that less water stress is predicted to occur at the forested area compared to the other two surface covers showing shallow rooting depth.

The hydrological role of forests in changing climate was analysed, focusing on the importance of crown and litter interception, forest-groundwater relations, and the impact of forests on runoff during extreme weather conditions in Hungary (Gribovski et al. 2019).

The relationship between the groundwater decline, soil moisture regime, and groundwater recharge under aged forests has remained unclear. A black locust, a black pine, and a grassland control site hydrological parameters were compared. The observed differences in the soil moisture dynamics were connected to the water uptake of the vegetation form, even if forests can locally contribute to the groundwater decline at the monitored hilltop site that other regional factors may more strongly drive (Szabó et al. 2022).

Budyko-type spatially distributed long-term climate-runoff model was used to analyse the water balance of three nested sub-catchments of the Zala River Basin (Hungary), an essential runoff contributing region to Lake Balaton (the largest shallow lake in Central Europe). The mean annual evapotranspiration rate is expected to increase slightly during the 21 st century. A substantial decrease can be anticipated for runoff, which may exceed 40% by 2071–2100 relative to the reference period (1981–2010). Based on the projected reduction in runoff from the Zala Basin, the increased evaporation rate of Lake Balaton will probably transform this water body into a closed lake without outflow (Csáki et al. 2020).

Hydrologic scientific networks in the eastern middle European region have suffered due to significant societal and economic changes in the last decades. Previously, flourishing experimental research became underfinanced, and internationally supported education almost disappeared. Against this background, the Department of Land and Water Resources Management of the Slovak University of



Technology in Bratislava, the Institute of Hydraulic Engineering and Water Resources Management of the TU Vienna, and the Institute of Geomatics and Civil Engineering of the University of Sopron started a HydroCarpath Conference series to allow young scientist in the region to present their results and re-network on the emerging topics of scientific hydrology connected to the hydrology of the Carpathians interactions of climatic drivers and hydrological processes on local and regional scales (Szolgay et al. 2020).

## 2.8 OVf (General Directorate of Water Management)

General Directorate of Water Management had the following involvements in cooperation and projects.

**Water Science and Water Security National Laboratory:** The Water Science and Water Security National Laboratory was established and is operational in 2022, considered a significant milestone in restarting joint research works in water management sciences. Therefore, the National Laboratory's primary goal is to substantially broaden the knowledge base on fluvial and lacustrine systems (e.g. River Danube or Lake Balaton), considering inherent complexity and interactions in their hydrology hydrodynamics, morphology, water quality, and ecology. The Laboratory gives an excellent opportunity and platform for the cooperation of the most acknowledged Hungarian research institutions in water management, covering all relevant fields and ensuring interdisciplinarity. As a member organization, the General Directorate of Water Management – in close cooperation with the territorial water directorates and other participating universities – is involved, among other things, in subprojects pursuing the following objectives:

- developing floodplain restoration methods for maximising ecological potential,
- working out operational methods of reservoirs,
- development of guidelines for professionals regarding the use of statistical methods in hydrology,
- examination of changes in groundwater resources for the sake of sustainable water management,
- developing guidelines for the connection of inland water and urban water drainage systems,
- defining the framework of operational water management for surface water resources etc.

**Flood Risk Management Plan:** In 2021, within the framework of the compulsory revision (Floods Directive 2007/60/EK) of the previously prepared flood risk maps and management plans, the re-evaluation of action plans was completed (KEHOP-1.1.0-15-2016-00006). Regarding flood prevention issues, elaborating the strategic and scientific background of differentiated flood protection was also a deciding objective and task for sustainable and long-term effective flood protection and damage prevention. The preparation of the results legislative introduction is currently in progress.

**River basin management planning:** The Water Framework Directive (WFD) requires the Member States to review their River Basin Management Plans (RBMPs) every six years. Accordingly, the next second revision of the RBMP was carried out in the European Union-funded project with identification number KEHOP-1.1.0-15-2016-00008. The water resource management methodology and models were developed for our surface and groundwater as part of the review. Water balance and water resource management models were created for sub-catchments of the country. In the framework of the project, the National Integrated Water Resources Management Plan (NIWRMP) was prepared, and a GIS database and display system was created.

**DEEPWATER-CE project:** During the project, an integrated framework for developing targeted groundwater recharge (Managed Aquifer Recharge - MAR) systems was developed, contributing to the long-term protection of Central European water resources threatened by climate change and water use conflicts. With the support of MAR (Managed Aquifer Recharge) systems, surplus surface, and rainwater from periods of abundant water can be collected and stored in underground water for drier periods by sending it deep.

**PROLINE-CE project:** The goal of the PROLINE-CE project, started in 2016, is to develop an international guide based on the experiences gathered from the partner countries, which facilitates the

effective protection of the drinking water supply, as well as protection against extremely fluctuating water conditions, water levels (droughts and floods) resulting from climate change. The material, which presents both practical advice and good practice, primarily focuses on "drinking water-friendly" and sustainable land use, reducing floods and droughts caused by climate change and developing measures to protect against them.

Geotechnical research of levees in Cooperative Doctoral Programme: The Geotechnical Group of the Budapest University of Technology and Economics and the General Directorate of Water Management cooperate (KDP-2020-1022641) in researching the effect of climate change on dikes constructed from high-plasticity clays.

In recent years, the first-order flood protection lines crack assessment has been completed (Illés and Nagy 2022). Furthermore, a monitoring system was installed at a cross-section of a Tisza dike. It measures the embankment's moisture content and negative pore water pressure at several points.

**Acknowledgements** – The 143972SNN project and the TKP2021-NKTA-43 project supported the preparation of this paper. TKP2021-NKTA-43 has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary (successor: Ministry of Culture and Innovation of Hungary) from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

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# HUNGARIAN NATIONAL REPORT ON IAMAS (2019-2022)

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## 1 Introduction

Global warming and finding the right responses gave the leading institution in weather and climate, the Hungarian Meteorological Service (HMS) serious tasks. New challenges added to the classic areas of responsibility: to help preparation for extreme weather conditions by expanding the measuring and observation system with new instruments, improving weather forecasts and warnings, strengthening the climate research activity and developing the air quality protection services. However, the results of all these professional tasks can only be used properly when combined with close cooperation with the end-users. The areas where comprehensive developments were carried out during the past four years are briefly summarized below.

## 2 Surface observations

The surface monitoring network is currently made up of 139 own, 142 jointly operated by General Directorate of Water Management and 12 other automatic weather stations and there are about 460 conventional rainfall stations. The automatic meteorological stations basically measure the weather parameters (air temperature and humidity, air pressure, wind, precipitation), but gamma-dose rate measurements are also performed at 28 sites for early detection of radioactive hazard. At three places aerosols with alpha, beta and gamma activity are monitored and at some dozen stations soil temperature and soil moisture at several layers are also measured, which are important for agriculture. HMS makes its best to meet the needs of reliable meteorological data by installing mobile measuring stations where flexibly adjusts the measuring program, communication and power supply to user requirements. For continuous operation the network inspectors of HMS regularly check the technical parameters of the stations and perform the necessary maintenance.

New generation data collectors have been installed at laboratories involved in the operation of National Air Pollution Monitoring Network of the Governmental Offices. The computer program developed by HMS performs real-time visualization of the measured data.

For the observation of weather, the cooperation with amateur observers is going on. Through the MET-ÉSZ project HMS keeps in touch with volunteer observers and they are provided with regular training sessions. It is important to note that the number of observers and the number of observations they carry out are continuously growing.

## 3 Weather forecasts

The development and running of models covering the entire Earth still require very serious resources, so this is only possible in the most developed countries and through international cooperation. Covering smaller areas and providing finer spatial resolution, however, national meteorological services are also capable of running regional models.

Detailed, high spatial resolution forecasts serve as the basis for alerts and warnings regarding rapidly developing, dangerous weather phenomena. These forecasts are made by running regional models, which refine the results of global (e.g. ECMWF) models in space and time, within a small European area.

For short-term regional weather forecasting, HMS runs the ALADIN/AROME model family, which is developed as a part of the ALADIN international cooperation (Kolláthné et al.2021). Short-term regional forecasts have been prepared regularly since 1998 on the HMS's high-performance supercomputer.

The ALADIN model runs four times a day to almost all of Europe at a spatial resolution of 8 km, and the AROME model to the Carpathian basin eight times a day at a spatial resolution of 2.5 km. An 11-member ensemble system is also based on the ALADIN model, with the help of which we can make probabilistic forecasts (Bán et al. 2021).

It is very important to constantly check the quality, i.e. the accuracy, of our forecasts by comparing the values predicted by numerical forecast models (e.g. ALADIN, AROME, ECMWF) (wind, temperature, humidity, etc.) with the actual measured values. The results provide important feedback on which models can be used well in which weather situations, and on the extent to which a specific development improves model forecasts.

On the public website of the HMS ([www.met.hu](http://www.met.hu)), one can get a comprehensive picture of the models used. Based on the forecast of the ECMWF model, an automatic graphic forecast is prepared for more than 3,000 settlements in Hungary, as well as for many cities in the world. Probability forecasts are available in the form of specific flare diagrams. The expected development of the most important meteorological elements, such as temperature, precipitation and wind, can also be monitored in mapped form. In addition to providing public forecasts and hazard warning activities, many special user needs are fulfilled with our regional model forecasts.

#### **4 Climatology and climate modelling**

Global warming and its consequences are challenging issues to deal with in recent times. Hence, a special responsibility is placed on HMS to evaluate the past and present climate of the country, to monitor changes and to prepare projections for the future climate.

The HMS is committed to provide users with services that can meet various needs. With methodological developments in statistical climatology, with climate modelling activities, as well as with climate assessments, the HMS contributes to the preparation of national climate adaptation strategy.

The most important homogenized data sets were compiled for basic meteorological variables (e.g. maximum, minimum and average temperature, global radiation, wind, relative humidity, air pressure, cloudiness) and other derived parameters, indices (e.g. precipitation and temperature threshold days, drought indices, tourism climate indices). The data base is regularly updated, partially new stations that can be used during data recording taking into account, partially extended to new variables, and extended to the past years (Izsák et al. 2022; Lakatos et al. 2020; Lakatos et al. 2021).

The climate modelling activity is based on the adaptation of two regional climate models (ALADIN-Climate and REMO). HMS has joined the European research network, as a partner, and participated in several international research projects aiming at the investigation of effects of climate change. Several simulations are available for the 21st century to characterize expected changes in Hungary (Zsebeházi and Mahó 2021).

#### **5 Application of satellite data**

Meteorological satellites measure radiation data in several wavelength ranges, with which we aim to monitor the atmosphere, the earth's surface and clouds. This helps to diagnose the current weather, monitor the climate and better understand atmospheric processes. Satellite data also supports (partially) computerized weather forecasting.

Many atmospheric and surface parameters can be calculated from the measured radiation data (e.g. cloud top or surface temperature, vegetation cover) in addition to being displayed as an image. Modern meteorological satellite images are no longer simple "photographs", but the display of images is still important in meteorology today. Forecasters can study series of satellite images dense in time (up to every 5 minutes). On these, the development of atmospheric processes can be clearly traced: the movement of cloud formations, the formation and development of thunderstorms, the dissolution of fog patches, etc.

Satellite data also helps forecasters in short- and medium-term forecasts. More and more satellite data and parameters derived from them are used in numerical weather forecasting models.



Satellite observations are especially important where there are few traditional (on-site, point-based) measurements: such are, for example, altitude parameters (wind, temperature and water vapor concentration at several altitude levels) or the characteristics of the Earth's surface condition (the degree of vegetation cover).

The chemical composition of the atmosphere can also be observed from a satellite. It is particularly important to observe and monitor the spread of substances that affect our health, air pollutants or gases that affect the climate (e.g. carbon dioxide, water vapor). During a volcanic eruption, the examination of the ash cloud that enters the atmosphere is not only important from a climate point of view, but also from an aviation safety point of view. Forest fires and their smoke can also be observed with the help of satellites, which also affects the climate and the amount of pollutants.

With the same instrument, we can get information from the satellites from a large area, even from the entire Earth, so these measurements also provide a great help for observing the climate. Satellites provide information on a number of climatically significant environmental elements and phenomena: among other things, radiation arriving and leaving the Earth, changes in temperature, rainfall and wind conditions, the vegetation covering the surface, and the temperature of the sea surface, its height, sea currents, polar ice caps (Major 2022).

## **6 Atmospheric science applied to industrial purposes**

Accurate knowledge of the current state of the atmosphere, i.e. a constantly updated database based on observations made with authentic measuring instruments, is essential for forecasting potentially usable wind and solar energy in a given area, and, in a given time interval. In addition to traditional meteorological elements, the database includes information provided by weather satellites, meteorological radars, vertical wind profilers and cloud base meters, as well as cloud cameras.

The most important part of our developments is the harmonization of the measured atmospheric data with other background information: the creation of an objective analysis (Cséplő et al. 2019). The concept of objective analysis has existed since the beginning of numerical modeling. This concept originally meant the production of information from an irregular monitoring network on a regular grid, using an objective method. Later, with the appearance of the background field and other types of information, the concept of objective analysis was also expanded, but the emphasis is definitely on the production of the analysis field on the regular grid automatically, without direct human intervention. The creation of these types of methods became essential with the appearance and development of numerical forecasting, since computers can only be entrusted with operations that can be performed automatically. The objective analysis forms the basis of the linear forecast, which is prepared for the next 1-2 hours. It is called meteorological nowcasting: according to our expectations, significant methodological development results will be achieved in the field of objective analysis and nowcasting.

Our developments may later pave the way for making forecasts with dynamic models for several hours or days more accurate (Horváth and Simon 2022). Due to the non-linear development of the atmosphere, this is currently the only possibility to predict the future state of the atmosphere, thus the availability of renewable energies. In addition to conventional models, the WRF (Weather Research and Forecasting) model, which is also used for research and development tasks, can play a role in our research and development.

## **7 Air quality modelling**

The vast majority of articles investigating the impact of meteorological conditions on air quality have concluded that, in addition to changes in anthropogenic emissions, changes in meteorological conditions also play an important role in the long-term evolution of pollutant concentrations. As a result of our earlier research, it was determined to what extent trans-border sources contribute to the development of air quality in Hungary and Budapest. Since the proportion of long-range transport is very significant in the case of Hungary, this effect is not negligible for measures aimed at improving air quality, and therefore significantly influences the effectiveness of the measures. At the same time,

during our further research, it was also shown that the evolution of the concentration values determined by the chemical transport model is significantly influenced by the meteorological conditions in our country (Ferenczi et al. 2020, Ferenczi et al. 2021). In addition to the direction and speed of the wind, the spatial distribution and amount of precipitation, as well as the quality of the forecast of the height of the planetary boundary layer significantly influence the accuracy of the prediction of the concentration fields. Accurate knowledge of the temporal and spatial variability of the emission grid point data is also a factor that significantly affects the accuracy of the forecast.

The aim of the research topic is to contribute to a more reliable assessment of the state of air quality by using emission inventories, measurement information and model calculations. This can have important socio-economic benefits by enabling both individuals and society to prevent/minimize exposure to poor air quality and reduce pollutant emissions and associated negative health effects. Exploring the connections between air pollution and sustainable development goals is also important from the point of view of society. In addition, research into the factors that reduce pollution and the factors that cause pollution and the evaluation of these effects are also important from the point of view of a more efficient climate/air quality policy. Exploring the spatio-temporal behavior of air quality is also an important research area from the point of view of sustainable development.

## 8 Education

Eötvös Loránd University, Budapest (ELTE) provides BSc, MSc and PhD trainings in meteorology. Besides the education, the research activity of the Department of Meteorology is rather broad. Their main focuses are:

- Past and future tendencies in the Carpathian Basin;
- Hungarian tall tower and aircraft measurements at Hegyhátsál;
- Vegetation analysis based on satellite measurements;
- Satellite based urban climatology research;
- Biogeochemical modelling;
- Air pollution meteorology research;
- Land surface - atmosphere analysis with WRF modelling.

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# HUNGARIAN NATIONAL REPORT ON IAPSO (2019-2022)

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## 1. Introduction

This paper summarizes the activities of Hungarian scientists in preparing scientific studies in the field of oceanography between the period of 2019 and 2022. In this compilation, a summary is given based on the abstracts that appeared in journal articles. In the reported period some research papers were published partly or fully dealing with aspects of oceanography by Hungarian authors or, in co-authorship by Hungarians. We disregarded the papers dealing only with climate aspects unless the relation with oceans is mentioned.

## 2. Scientific research in connection with oceanography

Ballinger et al. (2022) found that the delay in autumn sea ice formation is an important consequence of Arctic Amplification. Baffin Bay is one such region impacted by delayed ice formation, though spatiotemporal analyses to date have not detailed the evolution and drivers of such autumn ice changes. In this study, they document abrupt Baffin Bay Sea ice cover changes in the key transition month of October from 1950 to 2021. The ice cover mean, and variance dramatically changed from 2001 onward with a transition to largely ice-free conditions in the northeast and thinner ice in the northwest. Ocean model experiments attribute these changes to the warming of the Atlantic-origin water (AOW) flowing into north-eastern Baffin Bay from the south. Transport and upwelling of this above-freezing AOW has stunted ice formation in this area, while the basin's cyclonic surface current has contributed to reduced cooling and ice formation in the north-western portion of Baffin Bay.

Bozóki et al. (2019) reported a laboratory study on the large-scale ocean circulation in connection with Drake Passage. They reported a laboratory model of the large-scale flow phenomena in the Southern Ocean with a closed Drake Passage, imitating the situation before the Eocene-Oligocene transition (EOT) ca. 34 million years ago. In a differentially heated rotating annular wave tank, an insulating 'meridional' barrier is installed to block zonal circulation. The obtained temperature fields and time series are compared to the ones from control runs with partially blocked and fully opened 'passages'. In the 'closed' case a persistent azimuthal temperature gradient emerges whose magnitude scales linearly with the 'meridional' temperature contrast. The anomalous temperature distribution is accompanied by perturbations of the background flow yielding significantly larger low-frequency variability than in the 'opened' configuration. The experimental findings have implications for the EOT but at present, the validation of results is hindered by the lack of deep-sea drilling data from the Southeast Pacific and adjacent parts of the Southern Ocean. The model may inspire further paleoceanographic research in this largely unexplored region.

In the study of Haszpra et al. (2020a), they investigated the changes in the El Niño–Southern Oscillation (ENSO) phenomenon and the alterations of its precipitation-related teleconnections from 1950–2100 in the CESM-LE climate simulations. The changes in the ENSO phenomenon and its precipitation-related teleconnections over the globe under climate change are investigated in the Community Earth System Model Large Ensemble from 1950 to 2100. For the investigation, a recently developed ensemble-based method, the snapshot empirical orthogonal function (SEOF) analysis, is used. The instantaneous ENSO pattern is defined as the leading mode of the SEOF analysis carried out at a given time instant over the ensemble. The corresponding principal components (PCs) characterize the ENSO phases. By considering sea surface temperature (SST) regression maps, we find that the largest changes in the typical amplitude of SST fluctuations occur in June–July–August–September (JJAS) season, in Niño3–Niño3.4 (5° N–5° S, 170–90° W; NOAA Climate Prediction Center)

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region, and the western part of the Pacific Ocean; however, the increase is also considerable along the Equator in December–January–February (DJF). The Niño3 amplitude also shows an increase of about 20% and 10% in JJAS and DJF, respectively. The strength of the precipitation-related teleconnections of the ENSO is found to be nonstationary, as well. For example, the anticorrelation with precipitation in Australia in JJAS and the positive correlation in central and northern Africa in DJF are predicted to be more pronounced by the end of the 21st century. Half-year-lagged correlations, aiming to predict precipitation conditions from ENSO phases, are also studied. The Australian and Indonesian precipitation and that of the eastern part of Africa in both JJAS and DJF seem to be well predictable based on the ENSO phase, while the southern Indian precipitation relates to the half-year previous ENSO phase only in DJF. The strength of these connections increases, especially from the African region to the Arabian Peninsula.

In the paper of Haszpra et al. (2020b), they analysed the properties and surface temperature-related linkages of the Arctic Oscillation (AO) in the ensemble-based SEOF approach, by using the ensemble simulations of the Max Planck Institute for Meteorology (MPI-M) Grand Ensemble (MPI-GE) and the Community Earth System Model Large Ensemble (CESM-LE) subject to forcings RCP2.6, 4.5, and 8.5, respectively, with historical forcing before 2006. The Arctic Oscillation (AO) and its related wintertime phenomena are investigated under climate change by 2099 in an ensemble approach using the CESM1 Large Ensemble and the MPI-ESM Grand Ensemble with different RCP (Representative Concentration Pathway) scenarios. The loading pattern of the AO is defined as the leading mode of the empirical orthogonal function (EOF) analysis of sea level pressure from 20° to 90° N. It is shown that the traditional AO index (AOI) calculation method, using a base period in a single climate realization, brings subjectivity to the investigation of the AO-related phenomena. Therefore, if an ensemble is available, the changes in the AO and its related phenomena should rather be studied by a reconsidered EOF analysis (snapshot EOF) introduced herein. Their novel method is based only on the instantaneous fields of the ensemble, and hence it is capable of monitoring the time evolution of the AO's pattern and amplitude. Furthermore, the instantaneous correlation coefficient  $r$  can objectively be calculated between the AOI and, for example, the surface temperature, and thus the time dependence of the strength of these connections can also be revealed. Results emphasize that both the AO and the related surface temperature pattern are non-stationary, and their time evolution depends on the forcing. The AO's amplitude increases and the Pacific center strengthens considerably in each scenario. Additionally, there exist such regions (e.g., northern Europe or western North America) where  $r$  shows remarkable change (0.2–0.4) by 2099. The study emphasizes the importance of the snapshot framework when studying changes in the climate system.

In another paper by the same authors (Haszpra et al. 2020c) they applied the mathematically well-established “snapshot view” based on dynamical systems theory to the analysis of SMILEs (Single Model Initial-condition Large Ensemble) and reconsidered traditional methodologies to study possible future changes in internal variability. A future direction of the research could be comparing SEOF (Snapshot Empirical Orthogonal Function) results to observations. One might try a comparison using carefully chosen (but still subjective) multiple time windows centered to the instantaneous SEOF year to construct the relevant traditional EOF pattern using a single time series. However, this comparison is expected to yield similar results only if the external forcing does not change much within the chosen time window and, therefore, ergodicity approximately holds. Equally, the ongoing climate change is not ergodic. Consequently, the above-mentioned comparison can serve as a measure of ergodicity as well. A crucial message of the snapshot view is that all the traditional, time series-based methods can be reformulated for ensembles, which will be of use to the broader climate community. In this way, utilizing ensemble-based (snapshot) analyses of the available SMILEs, ambiguous results arising from subjective choices of traditional methods (e.g., length and centre of time windows) can be avoided, the possible climate states at each time instant can be properly characterized, and forced changes in any ensemble-based quantity can be determined.

According to a research by Jánosi et al. (2019), an empirical flow field data evaluation in a well-studied ocean region along the US west coast revealed a surprisingly strong relationship between the surface integrals of kinetic energy and enstrophy (squared vorticity). This relationship defines a single isolated Gaussian super-vortex, whose fitted size parameter is related to the mean eddy size, and the

square of the fitted height parameter is proportional to the sum of the square of all individual eddy amplitudes obtained by standard vortex census. This finding allows very effective coarse-grained eddy statistics with minimal computational efforts. As an illustrative example, the westward drift velocity of eddies is determined from a simple cross-correlation analysis of kinetic energy integrals.

Jánosi et al. (2021) studied the distinct freezing–melting dynamics between the Arctic and the Antarctic. The classical methods of identifying significant slow components (modes) in a strongly fluctuating signal usually require strict stationarity. A notable exception is the procedure called empirical mode decomposition (EMD), which is designed to work well for nonstationary and nonlinear (quasiperiodic) time series. However, EMD has some well-known limitations such as the end divergence effect, mode mixing, and the general problem of interpreting the modes. Methods to overcome these limitations, such as ensemble EMD or complete ensemble EMD with adaptive noise, promise an exact reconstruction of the original signal and a better spectral separation of the intrinsic mode functions (IMFs). All these variants share the feature that the decomposition runs from the top to the bottom: The first few IMFs represent the noise contribution and the last is a long-term trend. In the study, they proposed a decomposition from the bottom to the top, by the introduction of smoothness-controlled cubic spline fits. The key tool is a systematic scan by cubic spline fits with an input parameter controlling the smoothness, essentially the number of knots. Regression qualities are evaluated by the usual coefficient of determination  $R^2$ , which grows monotonically when the number of knots increases. In contrast, the growth rate of  $R^2$  is not monotonic: When an essential slow mode is approached, the growth rate exhibits a local minimum. They also demonstrated that this behaviour provides an optimal tool to identify strongly quasiperiodic slow modes in nonstationary signals. They illustrated the capability of the method by reconstruction of a synthetic signal composed of a chirp, a strong nonlinear background, and a large-amplitude additive noise, where all EMD-based algorithms fail spectacularly. As a practical application, they identified essential slow modes in daily ice extent anomalies in both the Arctic and the Antarctic. The analysis demonstrates the distinct freezing–melting dynamics on the two poles, where apparently different factors are determining the time evolution of ice sheets. Thus, it is believed that the methodology offers a competitive tool to identify modes in strongly fluctuating data and advances significantly the state of the art regarding the decomposition of nonlinear time series.

Jánosi et al. (2022) performed mesoscale eddy statistics based on integrated kinetic energy and enstrophy correlations. They recently introduced the concept of a “vortex proxy” based on an observation of strong correlations between integrated kinetic energy and integrated enstrophy over a large enough surface area. When mesoscale vortices are assumed to exhibit a Gaussian shape, the two spatial integrals have particularly simple functional forms, and a ratio of them defines an effective radius of a “proxy vortex”. In the original work, the idea was tested over a restricted area in the Californian Current System. In the study, they extended the analysis to a global scale using 25 years of AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic) altimetry data covering the (ice-free) global ocean. The results are compared with a global vortex database containing over 64 million mesoscale eddies. They demonstrated that the proxy vortex representation of surface flow fields also works globally and provides a quick and reliable way to obtain coarse-grained vortex statistics. Estimated mean eddy sizes (effective radii) are extracted in very good agreement with the data from the vortex census. Recorded eddy amplitudes are directly used to infer the kinetic energy transported by the mesoscale vortices. The ratio of total and eddy kinetic energies is somewhat higher than found in previous studies. The characteristic westward drift velocities are evaluated by a time-lagged cross-correlation analysis of the kinetic energy fields. While zonal mean drift speeds are in good agreement with vortex trajectory evaluation in the latitude bands 30–5° S and 5–30° N, discrepancies are exhibited mostly at higher latitudes on both hemispheres. A plausible reason for somewhat different drift velocities obtained by eddy tracking and cross-correlation analysis is the fact that the drift of mesoscale eddies is only one component of the surface flow fields. Rossby wave activities, coherent currents, and other propagating features on the ocean surface apparently contribute to the zonal transport of kinetic energy.

Károlyi et al. (2021) developed a conceptual coupled atmosphere–phytoplankton model by combining the Lorenz'84 general circulation model and the logistic population growth model under the

condition of a climate change due to a linear time dependence of the strength of anthropogenic atmospheric forcing. The following types of couplings are considered: (a) the temperature modifies the total biomass of phytoplankton via the carrying capacity; (b) the extraction of carbon dioxide by phytoplankton slows down the speed of climate change; (c) the strength of mixing/turbulence in the oceanic mixing layer is in correlation with phytoplankton productivity. They carried out an ensemble approach (in the spirit of the theory of snapshot attractors) and concentrated on the trends of the average phytoplankton concentration and average temperature contrast between the pole and the Equator, forcing the atmospheric dynamics. The effect of turbulence is found to have the strongest influence on these trends. Their results show that when mixing has sufficiently strong coupling to production, mixing can force the typical phytoplankton concentration to always decay globally in time and the temperature contrast to decreasing faster than what follows from direct anthropogenic influences. Simple relations found for the trends without this coupling do, however, remain valid; just the coefficients become dependent on the strength of coupling with oceanic mixing. In particular, the phytoplankton concentration and its coupling to climate are found to modify the trend of global warming and can make it stronger than it would be without biomass.

Medjdoub et al. (2019, 2020) published articles on their laboratory investigations on the resonant feature of the ‘dead water’ phenomenon. They summarized interfacial internal wave excitation in the wake of towed ships studied experimentally in a quasi-two-layer fluid. At a critical ‘resonant’ towing velocity, whose know value following the ship reaches a maximum, in unison with the development of a drag force acting on the vessel, depends on the structure of the vertical density profile, the amplitude of the internal wave train following maritime literature as ‘dead water’. The amplitudes and wavelengths of the emerging internal waves are evaluated for various ship speeds, ship lengths, and stratification profiles. The results are compared to linear two- and three-layer theories of freely propagating waves and lee waves. They found that even though the observed internal waves can have considerable amplitudes, linear theories can still provide a surprisingly adequate description of subcritical-to-supercritical transition and the associated amplification of internal waves. They argue that the latter can be interpreted as a coalescence of frequencies of two fundamental stable wave motions, namely lee waves and propagating interfacial wave modes.

In another laboratory experiment by the same authors Medjdoub et al. (2021), they studied the damping of water surface standing waves (seiche modes) and the associated excitation of baroclinic internal waves in a quasi-two-layer laboratory setting with a topographic obstacle at the bottom representing a seabed sill. They find that topography-induced baroclinic wave drag contributes markedly to seiche damping in such systems. Two major pathways of barotropic–baroclinic energy conversions were observed: the stronger one – involving short-wavelength internal modes of large amplitudes – may occur when the node of the surface seiche is situated above the close vicinity of the sill. The weaker, less significant other pathway is the excitation of long waves or internal seiches along the pycnocline that may resonate with the low-frequency components of the decaying surface forcing.

According to Topál et al. (2020) an internal atmospheric process will determine summertime arctic sea ice melting in the next three decades. Arctic sea ice melting processes in summer due to internal atmospheric variability have recently received considerable attention. A regional barotropic atmospheric process over Greenland and the Arctic Ocean in summer (June–July–August), featuring either a year-to-year change or a low-frequency trend toward geopotential height rise, has been identified as an essential contributor to September sea ice loss, in both observations and the CESM1 Large Ensemble (CESM-LE) of simulations. This local melting is further found to be sensitive to remote sea surface temperature (SST) variability in the East Central Pacific. In the paper, they utilized five available single-model large ensembles and 31 CMIP5 models’ pre-industrial control simulations to show that the same atmospheric process, resembling the observed one and the one found in the CESM-LE, also dominates internal sea ice variability on interannual to interdecadal time scales in pre-industrial, historical and future scenarios, regardless of the modelling environment. However, all models exhibit limitations in replicating the correct magnitude of the observed local atmosphere-sea ice coupling and its sensitivity to remote tropical SST variability. These biases cast a shadow over models’ credibility in simulating interactions of sea ice variability with the Arctic and global climate systems. Further efforts toward identifying possible causes of these model limitations may provide profound

implications for alleviating the biases and improving interannual and decadal time scale sea ice prediction and future sea ice projection.

Topál et al. (2022) found discrepancies between observations and climate models of large-scale wind-driven Greenland melt influence sea-level rise projections. While climate models project that Greenland ice sheet (GrIS) melt will continue to accelerate with climate change, models exhibit limitations in capturing observed connections between GrIS melt and changes in high-latitude atmospheric circulation. Here they impose observed Arctic winds in a fully coupled climate model with fixed anthropogenic forcing to quantify the influence of the rotational component of large-scale atmospheric circulation variability over the Arctic on the temperature field and the surface mass/energy balances through adiabatic processes. They showed that recent changes involving mid-to-upper-tropospheric anticyclonic wind anomalies – linked with tropical forcing – explain half of the observed Greenland surface warming and ice loss acceleration since 1990, suggesting a pathway for large-scale winds to potentially enhance sea-level rise by  $\sim 0.2$  mm/year per decade. They further reveal fingerprints of this observed teleconnection in paleo-reanalyses spanning the past 400 years, which heightens concern about model limitations to capture wind-driven adiabatic processes associated with GrIS melt.

### 3. Studies on palaeoceanography

Demény et al. (2021) pointed out the role of North Atlantic Ocean circulation on moisture transport. Their analysis of Middle and Late Holocene speleothem-based hydroclimate reconstructions and paleoclimate model simulations has revealed sub-millennial fluctuations in the spatiotemporal variability of precipitation in the European and Mediterranean regions, that complements previous dendrochronological and pollen-based reconstructions with an improved temporal resolution. Although insolation forcing is the primary driver of Holocene hydroclimate changes in Europe on a multimillennial scale, the evaluation of the principal component analysis of speleothem records and correlations with sea surface temperature data indicates that North Atlantic ocean circulation played a significant role in the sub-millennial variation of continental moisture transport, with increasing importance during the Late Holocene. The combined evaluation of speleothem-based data, climate simulations, and sea surface temperature records therefore advances our understanding of the governing processes of Holocene hydroclimate changes in the European and Mediterranean regions.

Hatvani et al. (2022) found that structural changes, or changepoints, coinciding in multiple ice core records over the Greenland Ice Sheet (GrIS) may reflect a widespread response of the GrIS to atmospheric forcing. Thus, to better understand how atmospheric circulation may regulate sudden changes in  $\delta^{18}\text{O}$  of Greenland precipitation, we seek synchronous changepoints occurring in ice core-derived  $\delta^{18}\text{O}$  time series across the GrIS and in the North Atlantic Oscillation (NAO) over the past millennium. By utilizing a Bayesian changepoint detection method, four changepoint horizons were revealed: at the beginning of the 20th century, in the late-15th century, and around the turn of the 11th and 10th centuries. Although the changepoints in ice core  $\delta^{18}\text{O}$  records exhibited distinctive spatial arrangements in each horizon, all corresponded to changepoints in the NAO, indicative of a consistent atmospheric influence on GrIS surface changes over the past millennium.

Nyerges et al. (2021) studied the changes in calcareous nannoplankton assemblages around the Eocene-Oligocene climate transition in the Hungarian Palaeogene Basin (Central Paratethys). The Eocene-Oligocene climate transition (EOT) is the last major greenhouse-icehouse climate state shift in Earth's history, ending the warm, ice-free early Palaeogene world and ushering in the Antarctic glaciation. Their study is focused on the Hungarian Palaeogene Basin within the Central Paratethys, aiming to characterise the effect of the global cooling event in the calcareous nannoplankton assemblages and to reconstruct the palaeoenvironmental evolution of the region. Calcareous nannoplankton biostratigraphy is focused on documenting the NP21 Zone. Hierarchical cluster analysis allowed us to distinguish five successive assemblages. Thereby defined phases are compared with recently published trends in  $\delta^{18}\text{O}$  values and foraminiferal changes. Taxa with a preference for oligotrophic and warm surface waters dominate the lowest assemblage. The next assemblage contains taxa that indicate oligotrophic conditions but temperate surface water at the onset of the EOT. Nannoplankton

abundance drops to a minimum in the third phase, when taxa adapted to cool surface waters gradually became dominant. A gradual rebound of nanoplankton abundance is observed in the fourth phase, possibly reflecting regional climate change related to the uplifting Alpine chain. After the end of the EOT, the youngest assemblage includes mostly eurytopic taxa which could tolerate an increased rate of freshwater and terrestrial influx.

Vincze et al. (2021) investigated the impact of the opening of the Drake Passage on the role of global cooling around the Eocene-Oligocene transition. Pronounced global cooling around the Eocene–Oligocene transition (EOT) was a pivotal event in Earth’s climate history, controversially associated with the opening of the Drake Passage. Using a physical laboratory model, they revisited the fluid dynamics of this marked reorganization of ocean circulation. They showed seemingly contradicting paleoclimate records, that in the experiments opening the pathway yields higher values of mean water surface temperature than the “closed” configuration. This mismatch points to the importance of the role ice albedo feedback plays in the investigated EOT-like transition, a component that is not captured in the laboratory model. Their conclusion is supported by numerical simulations performed in a global climate model (GCM) of intermediate complexity, where both “closed” and “open” configurations were explored, with and without active sea ice dynamics. The GCM results indicate that sea surface temperatures would change in the opposite direction following an opening event in the two sea ice dynamics settings, and the results are therefore consistent both with the laboratory experiment (slight warming after opening) and the paleoclimatic data (pronounced cooling after opening). It follows that in the hypothetical case of an initially ice-free Antarctica, the continent could have become even warmer after the opening, a scenario not indicated by paleotemperature reconstructions.

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# HUNGARIAN NATIONAL REPORT ON IASPEI (2019–2022)

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## 1 Introduction

Significant organizational changes have taken place in the past four years in the life of institutions belonging to the IASPEI community.

On 1st August, 2019, the Parliament established the Eötvös Loránd Research Network (ELKH). Since the second half of that year, research centres, research institutes and the supported research groups have been operating and managing by the ELKH instead of the Hungarian Academy of Sciences.

The Geodetic and Geophysical Institute (GGI), which included the Kövesligethy Radó Seismological Observatory (KRSO) was part of the Research Centre for Astronomy and Earth Sciences (RCAES) until 1st of April, 2021. Since then, it continues its work as an independent institute under the name of Institute of Earth Physics and Space Science (EPSS). In the following, for events before 2021, we use the name GGI, then EPSS.

The general and universal legal successor of the Mining and Geological Survey of Hungary (MBFSZ) became the Supervisory Authority for Regulatory Affairs (SZTFH) from 1st of January, 2022. Research activities are also carried out within the framework of the Authority. We will mention the name of the geological survey as SZTFH from 2022.

## 2 Observational seismology

The EPSS Kövesligethy Radó Seismological Observatory (EPSS KRSO) is a member of the International Federation of Digital Seismograph Networks (FDSN, <http://www.fdsn.org>), the Observatories & Research Facilities for European Seismology (ORFEUS, [www.orfeus-eu.org](http://www.orfeus-eu.org)), the International Seismological Centre (ISC, [www.isc.ac.uk](http://www.isc.ac.uk)), the European-Mediterranean Seismological Centre (EMSC, [www.emsc-csem.org](http://www.emsc-csem.org)), and the Central and Eastern European Earthquake Research Network (CE3RN, <http://www.ce3rn.eu>) organizations (Lenhard et al. 2021).

### 2.1 The Hungarian National Seismological Network

The EPSS KRSO operates the Hungarian Seismological Network (doi: 10.14470/UH028726). The instrumentation and geometry of the 15 permanent station have not changed significantly since 2018.

EPSS KRSO also operates numerous temporary seismological stations in the framework of international projects. From 2016 to 2019, in the western part of Hungary, 14 temporary stations were operated as the part of the AlpArray Seismological Network (AASN) (doi: 10.12686/alpararray/z3\_2015).

Although the AASN officially finished in 2019, the stations continued to operate. A cooperation is established between the GGI and the German Seismological Broadband Array (DSEBRA) consortium. While GGI moved its 8 temporary stations to the eastern part of the country, the former AlpArray sites were equipped by DSEBRA. DSEBRA provided the equipment for 15 stations in Hungary including 12 former AlpArray stations in the western and four new stations in the eastern part of Hungary (Schlömer et al. 2022). In 2019, GGI together with other 9 institutes from 6 countries (Austria, Czech, Germany, Poland Slovakia, and Switzerland) established an AlpArray complementary experiment, called Pannonian-Carpathian-Alpine Seismic Experiment (PACASE). This network (doi:

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10.7914/SN/ZJ\_2019) included all the 26 temporary stations in Hungary and covered the Pannonian Basin, the Eastern Alps, the Western Carpathians and parts of the Bohemian Massive. Summarising the changes in the station distribution in 2019: instrumentation changed in the case of 11 AlpArray temporary stations and 12 new stations were deployed east of the Danube. DSEBRA stations are all equipped with Nanometrics Trillium Horizon 120 seismometers and Nanometrics Centaur data loggers, while the other temporary stations have Güralp CMG-3T seismometers and Güralp DM24SEAM digitizers. Süle et al. (2020) provides a short description of noise characteristics and detection capability of the network.

In 2022, a new international project, AdriaArray has started. Four new broadband stations were installed in the eastern part of Hungary in this framework. One of them are equipped with Güralp CMG-3T seismometer and Güralp DM24SEAM digitizer, the others with Nanometrics Trillium Horizon 120 seismometers and Nanometrics Centaur data loggers. EPSS contributes to AdriaArray seismological network with all of its permanent and temporary stations. The 15 stations cooperated by DSEBRA and EPSS KRSO also continue to operate in the framework of AdriaArray. In this way a total of 45 broadband seismological stations are working in Hungary. Considering the whole territory of the country, the Pannonian Basin has never been covered by such a dense seismic network.

In the 2019-2022 time period, two earthquakes  $M > 4$  occurred in Hungary. In both cases two additional temporary station were deployed for monitoring the aftershocks (Süle et al. 2021a, Wéber et al. 2020). From 2020 May to the end of 2021 a local network is operated in the Mór Graben, one of the seismically most active region of Hungary (Bondár et al. 2022).

Data acquisition, automatic and manual phase picking and hypocentre location are done by SeisComp3 ([www.seiscomp3.org](http://www.seiscomp3.org)) and SeisComp (10.5880/GFZ.2.4.2020.003) software. Automatic and manually revised bulletins are published on the observatory's website ([www.seismology.hu](http://www.seismology.hu)). The final hypocentre parameters of the detected seismic events are determined by iLoc (Bondár and Storchak, 2011) and published (together with the macroseismic observations) annually in the Hungarian National Seismological Bulletin (Süle et al. 2021a, 2021b, 2022).

In their publication, Gyóri et al. (2021a) delineated the seismotectonic settings and seismicity of two different seismicity country, Hungary and Kazakhstan, furthermore described the operating seismological networks and the related scientific research areas with emphasis on civil protection. They have concluded that in addition to the similarities, there are also significant differences between the aims and problems of their seismological networks.

## 2.2 The Hungarian National Infrasond Network

The Hungarian National Infrasond Network (HNIN, doi:10.14470/UA114590) was established by the CSFK GGI KRSO with the deployment of the PSZI (Piszkés-tető) infrasond array in 2017 and the array is operated by EPSS from 2021. It consists of four elements and has an aperture of approximately 300 m. Each element of the array is equipped with a SeismoWave MB3d microbarometer with a built-in digitizer. The central element of the infrasond array is co-located with a permanent broadband seismological station, PSZ, jointly managed by the KRSO and the GFZ German Research Centre for Geosciences.

Waveforms are collected in real time at the GEOFON EIDA node (<https://geofon.gfz-potsdam.de/doi/network/HN>). For data acquisition SeisComp3 ([www.seiscomp3.org](http://www.seiscomp3.org)) and for infrasond data processing DTK-PMCC (Cansi, 1995) are used. The seismo-acoustic and infrasond-only events are located with iLoc (Bondár et al. 2018).

The Hungarian Seismo-Acoustic Bulletins have been published every year since 2018 (Bondár et al. 2019, 2020, 2021, 2022a).

The Central and Eastern European Infrasond Network (CEEIN) has been established in 2018 with the collaboration of four research institutes, the Zentralanstalt für Meteorologie und Geodynamik, Vienna, Austria; the Institute of Atmospheric Physics of the Czech Academy of Sciences, Prague, Czech Republic; the Research Centre for Astronomy and Earth Sciences belonging formerly to the Hungarian Academy of Science, Budapest, Hungary; and the National Institute for Earth Physics, Magurele, Romania. The Main Centre of Special Monitoring National Centre for Control and

Testing of Space Facilities, State Agency of Ukraine joined CEEIN in 2019. The CEEIN infrasound arrays improve the detection capability of the European infrasound network. Bondár et al. (2022b) presented the first CEEIN bulletin (2017–2020) of infrasound-only and seismo-acoustic events and using ground truth events, they demonstrated how adding infrasound observations to seismic data in the location algorithm improves location accuracy.

### 3 Seismicity studies

#### 3.1 Historical seismicity

Research on past earthquakes plays an important role in understanding the seismicity of the region. Going backwards in time, we have less and less information about the earthquakes that occurred. Kázmér and Gyóri (2020) has found that the available earthquake catalogue can only be considered complete for earthquakes with magnitude greater than 5 causing major damage to buildings from the 19th century onwards. In AD 455, a strong  $M > 6.0$  earthquake occurred in or near the ancient town of Savaria (today's Szombathely). Varga (2019) found that the recurrence time of  $M6$  and  $M6.5$  earthquakes in the Szombathely region is 1000 and 3000 years, which is significantly lower than in the Pannonian Basin in general.

By conducting systematic archaeoseismological research, Kázmér et al. (2022) identified 6 additional, previously unknown events that damaged six Roman cities: Brigetio and Salla (Hungary), Celeia (Slovenia), Siscia (Croatia), Virunum (Austria) and Napoca (Romania). These events occurred in the Roman period, in the 1st–5th centuries AD, and concentrated between 200 and 400 AD. At the same time, no earthquake-related building damage could be identified from the second half of the first millennium. Assuming a nearly uniform distribution of earthquakes, the reason for this was assumed to be that the Romans were able to build high quality buildings that survived earthquakes. Where damage was caused by earthquakes, it was repaired during periods of economic prosperity, but political, military and economic decline halted restoration and reconstruction. Thus, archaeoseismology can reveal many more devastating earthquakes in antiquity than in the early Middle Ages, since the high Roman civilisation left behind so many masonry buildings suitable for recording past seismic events.

Kázmér et al. (2021) presented historical and archaeological evidence for an intensity IX earthquake, which destroyed buildings of the royal town of Visegrád. Evidence includes vertical fissures cutting through the 30-m-high, thirteenth-century donjon Salamon Tower, built on hard rock. Some parts of the adjacent fifteenth-century Franciscan friary, built on the alluvial plain, collapsed because of liquefaction of the subsoil. The date of a potentially responsible earthquake was also determined. Photographs and drawings of the donjon made three centuries later faithfully reflect the status of sixteenth-century seismic damage, corroborated by modern archaeological excavations in the ecclesiastic complex.

The 1763 Komárom earthquake was probably the biggest historical and recorded seismic event in the Pannonian basin in the last millennium. Varga (2021) presented contemporary documents including building damage reports from the towns of Komárom, Győr, and other locations, aftershock reports, liquefaction reports, and local surveys of taxpayers' loss in villages to build all available datasets to evaluate the effects of the quake. Damage in towns was recorded in detail only at the aforementioned two locations. However, the spatial distribution of shaking intensity could be inferred over a larger area from information obtained from other sources. Based on the analysis of the most reliable description of damages, Varga (2021) assumed that the most probable magnitude of this earthquake could be around  $M=6.3-6.4$ . Distributions of secondary environmental effects, aftershocks, and village damage showed interesting spatial correlation and indicated that the epicentre may have been WNW of Komárom, north of the Danube River (Varga et al. 2021).

### 3.2 Recent seismicity

The Hungarian National Seismological Bulletin (HNSB) contains more than 2800 events in the period between 2000 and 2016. Czece and Bondár (2019) have applied a single-linkage hierarchical cluster analysis, the Dynamic Tree Cut algorithm (Langfelder et al. 2008) on the entire seismicity of the Pannonian Basin to identify event clusters in the basin. This method created more than 80 event clusters.

Czece selected different types of event clusters (anthropogenic and naturally occurring earthquake clusters with poor and outstanding station geometry) to represent the feasibility of their methodology to relocate earthquake clusters and potentially discriminate between earthquakes and anthropogenic seismic events.

The first step of the data preprocessing was re-picking the phases for the test clusters in the Hungarian National Seismological Bulletin to provide a better-quality dataset. The multiple event location algorithms require good initial locations. These locations were created with the state-of-the-art single-event location algorithm, iLoc (Bondár and Storchak 2011), using the global 3D RSTT velocity model (Myers et al. 2010). To collect differential times, and correlation matrices at each station, they performed waveform cross-correlation. The double-difference relocations (Waldhauser and Ellsworth 2000) tighten the initial iLoc locations into concentrated clusters and provide improved hypocentres for events determined even with poor station geometry. The combination of the re-picked travel times and the differential times from waveform cross-correlation significantly provides more accurate final solutions.

Even though the double-difference analysis did not bring dramatic change in one of the mixed event clusters (explosions and earthquakes together), the secondary hierarchical clustering using the correlation matrices as distance metrics successfully associated events with active mines and correctly reidentify them as explosions. Czece and Bondár created a methodology that opens the way for a systematic analysis of seismic earthquake clusters in the Hungarian National Seismic Bulletin and helps in the event discrimination between naturally occurring events and anthropogenic explosions.

Visnovitz et al. (2021) researched the neotectonics of Lake Balaton and the surroundings to the East. They have integrated new seismic-reflection data with lake and land seismic profiles, regional geological, geophysical data, seismicity data, and geomorphological observations. Czece created Bayesloc (Myers et al. 2007, 2009) hypocentre locations for this research. Bayesloc is a statistical model of the multiple event location problem that may provide more accurate hypocentre locations than standard linearized location methods such as Geiger's method. Ground truth events (Bondár et al. 2004; Bondár and McLaughlin 2009a) were used in this bayesian analysis to anchor down the seismicity pattern relative to GT locations representing tighter prior distributions (Bondár and McLaughlin 2009b). The relocation of the earthquake hypocentres combined with other type of geophysical and geological data allowed to represent the Quaternary structural pattern.

### 3.3 Cluster analyses of Vrancea earthquakes

In their paper, Czirok et al. (2022) described the cluster analyses of the focal mechanism solutions estimated from local, teleseismic measurements and stress inversions to support the recent and previously published studies in the Vrancea seismic zone. The authors applied different established clustering methods — e.g. hierarchical density-based clustering for applications with noise (HDBSCAN) and agglomerative Hierarchical analysis — to the geographical coordinates, focal depths and parameters of the focal mechanism solutions of the gathered seismic events. They attempted to develop a fully automated algorithm for the classification of earthquakes (CluStress) and to support the further investigation of stress inversions. This algorithm does not call for the setting of hyper-parameters by the users, thus the contribution from any bias of the user can be reduced significantly and the time required to carry out the clustering can also be decreased.

Considering the geodynamic implications of the results, Czirok et al. (2022) were able to verify that compression tectonic style has predominant role in the Vrancea Zone. This is probably due to the still ongoing subduction processes, with additional traces of extension, which could also be inferred

in the eastern and north-eastern part of the area. Czirok et al. (2022) noted that the resulting stress tensors produced by each type of the applied clustering have for the most part were able to reproduce the results of previous studies. Nevertheless, the authors could also declare that they had a more detailed mapping of the stress field variations due to the depth based division of the study area and the subsequent declustering for the stress inversions. A large scattering of the estimated stress field orientations characterizes the studied region, which mirrors the complex tectonic situation, the variable reliability of the used data and the sensitivity of stress inversion. In terms of validating CluStress, this work has also an important methodological aspect. It was able to verify that the applied clustering algorithm (CluStress) is more robust with respect to the type of clustering problem presented here than the demonstrated, pre-existing methods (HDBSCAN and agglomerative Hierarchical clustering). The stress tensors for the subareas produced by CluStress algorithm, give a more comprehensive understanding of the stress field in the study area.

It can be concluded that it has the ability to ensure a sufficiently reliable pre-processing of the input data for mapping stress relations. All of these statements was achieved by a logical scheme producing limited, compact subsets of earthquake where a relatively large concentration of similar earthquakes occurs. A potential usefulness in implementing one such or similarly built classification logic results in the avoidance of the time consuming tuning of hyper-parameters.

### 3.4 Discrimination of earthquakes and quarry blasts

Because of the increasing sensitivity of the seismic network, nowadays a new challenge is to develop the capability to discriminate between chemical explosions, quarry blasts and small earthquakes at local distances in Hungary. Contamination of earthquake catalogues with anthropogenic events largely complicates seismotectonic interpretation. It is especially true for relatively low seismicity areas, such as Hungary where more than 70 % of the recorded seismicity is attributed to anthropogenic events. However, relatively little attention has focused on discriminatory methods for very local distances (< 20 km), the range at which the smallest events are recorded and may not be seen at more distant stations.

Kiszely et al. (2021) focused on discrimination techniques that can be applied at the closest range from the source. They analysed the characteristics of the waveforms of earthquakes and quarry blasts that occurred within extreme local-distance of Csókakő (CSKK) station in the Vértes Hills, Hungary. Their motivation was to determine the linear discrimination line between the populations of earthquakes and explosions. CSKK is located in the Mór Graben, a seismically relatively active region, and also characterized by significant mining activity. They tested the effectiveness of the maximum P/S amplitude ratios in various frequency bands. Because most of the quarry blasts are carried out by ripple-fire technology, they also computed spectrograms and examined the spectral ratio between low and high frequencies and the steepness of spectra. They found that earthquakes and quarry blasts are best separated by the linear discrimination that combines the amplitude ratios and the different spectral ratios.

The infrasound array that has been operating on the Piskés-tető, Hungary since 2017 provides also a significant help in separating earthquakes and quarry blasts and makes it possible to determine their location more precisely. Czanik et al. (2021) introduced an automatic search method to associate infrasound detections with a preliminary list of explosions detected by the seismic network. Once infrasound detections are associated with seismic events, they relocated the events using both the seismic arrival time and infrasound azimuth observations. They validated their methodology on ground truth events, i.e., explosions confirmed by the mine operators. They demonstrated that seismo-acoustic locations are able to identify the source of explosions even for closely spaced quarries. The discriminative power of the infrasound azimuth is strongest at near-field distances, where local and regional seismic discrimination methods have the most difficulties.

## 4 Earthquake hazard studies

### 4.1 Microzonation

Local soil conditions can significantly amplify damages caused by earthquakes. Knowledge of shear wave velocities is essential when this amplification is computed or soil classes are determined during application of earthquake safety standards. Györi et al. (2021b) showed some examples of seismic site characterization that were performed during seismic microzonation of Budapest. To determine shear wave velocities, both active (Multichannel Analysis of Surface Waves - MASW) and passive (ESAC, Refraction Microtremor - ReMi) surface wave measurements were carried out in different parts of the city. In order to reveal the possible subsoil resonance HVSR ratios (Horizontal-to-Vertical Spectral Ratio) were computed based on microseismic noise measurements. To increase the reliability of the results, joint inversion of different types of dataset and/or full velocity spectra inversion were performed.

Usually the MASW and ESAC measurements provided good results, velocity spectra computed from them were clear and well usable. In case of ReMi measurements, distribution of noise sources strongly influenced the appearance of velocity spectra. The colour scale of the spectrum also influenced the designation of apparent dispersion curve so its interpretation was much more subjective. Reliability of velocities increased by joint inversion of different type of dataset but one exclusively preferable methodology that would be the best in every circumstances could not be found. In case of mode jumps, often the Full Velocity Spectra (FVS) inversion gave the most realistic results but in other cases picking of dispersion curve gave better results. One of the experiences was that the value of  $V_{S30}$  was quite stable even if the different processing methods resulted in different  $V_S$  profiles.

Györi et al. (2021b) studied the local applicability of ambient noise cross correlation method and have concluded that the quality of the results strongly depends on the location of the measurements.

They have got miscellaneous results; the quality of CCFs (Cross Correlation Functions) was better in more quiet environments, far from strong seismic noise sources. If they considered all of the measurements (regardless of the location within the territory of Budapest), 60 % of the transversal CCFs could be considered of good quality. In the case of vertical and radial CCFs this ratio was much lower, it was around 30 %. Making a distinction between the densely and sparsely built/populated areas they found a significant difference between ratios of good quality CCFs. This phenomenon unfortunately limits the applicability of the method in urban environments.

### 4.2 Seismic hazard assessment of the planned Paks II NPP site

The new nuclear power plant blocks planned at the Paks site, Hungary, made it necessary to review the seismicity and to update the earthquake hazard analysis that was prepared twenty to twenty-five years ago.

Tóth et al. (2021) determined the characteristics of the design basis earthquake and the risk of other earthquake-induced hazards, such as soil liquefaction for the Paks site. Based on historical and instrumental sources, a comprehensive, homogeneous earthquake catalogue was compiled and the statistical properties of seismicity were investigated. It was found that the obtained earthquake frequencies correlate well with the results obtained with paleoseismological and modern space geodetic methods. Using seismic source models constructed based on complex neotectonic studies, the earthquake hazard was determined by probabilistic method. The calculation method also included the determination of uncertainties. For frequencies of  $10^{-4}$  and  $10^{-5}$  years, the expected value of the peak acceleration (PGA) on the bedrock was calculated as 0.24g and 0.49g, respectively. Site response calculations were performed by nonlinear effective stress method and 0.34g mean surface PGA were determined for the safety earthquake. Soil liquefaction hazard was analysed using the effective stress method and it was found that local occurrence of soil liquefaction cannot be ruled out at the site. The effects of soil liquefaction can be avoided using proven geotechnical methods, such as soil stabilization and appropriate foundations.



Permanent ground displacements/deformations caused by earthquakes can seriously challenge the safety of the nuclear power plants. The state-of-the-art hazard analysis methods provide a fault displacement hazard curve, i.e., the annual probability of given measure of displacement will be exceeded. The evaluation of ground displacement hazard requires great effort, empirical evidence, and sufficient data for the characterization of the fault activity and capability to cause permanent surface displacement. There are practical cases when the fault at the site area revealed to be active, and, despite this, there are no sufficient data for the evaluation of permanent ground displacements hazard and for judging on the safety significance of permanent ground displacement. Katona et al. (2021) developed and applied a methodology, which is based on the seismotectonic modelling and results of the probabilistic seismic hazard analysis. It provides conservative assessment of the annual probability of fault displacement that allows the decision whether permanent displacement hazard is relevant to nuclear power plant safety. The feasibility and applicability of the method is demonstrated for the Paks site, Hungary.

### 4.3 Liquefaction hazard assessments

The seismicity of Hungary can be considered moderate, nevertheless contemporary reports from the past approx. 350 years documented surface manifestations of liquefaction occurrences.

The last such earthquake was the 1956 Dunaharaszti ground motion, for which the location of two liquefied sites could be identified approx. 60 years after the event. This provided an excellent opportunity to analyse possibly the only accessible liquefied sites in Hungary. Bán et al. (2020) analysed two sites using field and laboratory tests and estimated the maximum horizontal ground acceleration that occurred during the earthquake. This parameter was previously unknown, because the closest seismometer saturated during the event. The performed back-analysis using the principles of paleoliquefaction studies was the first of such analyses in the country. In areas with low to moderate seismicity, geotechnical engineers often neglect and overlook liquefaction hazard, however, when it is addressed, the hazard is often overestimated due to improper characterization of the seismic loading and site characterization. To explore this observation more deeply, probabilistic seismic and liquefaction hazard assessment were carried out at the two liquefied sites and it was found that this conclusion is also valid for Hungary, but the degree of conservatism of the pseudo-probabilistic procedures decreases with increasing earthquake return period (lower annual probability of occurrence).

Katona et al. (2019) also studied the differences between safety factors obtained by the performance based liquefaction hazard assessment method and the models used in conventional earthquake engineering practice. For the new nuclear power plants, the hazard of liquefaction due to earthquakes should be excluded by appropriate site selection or eliminated by engineering measures. An important question is how to define a quantitative criterion for negligibility of the liquefaction hazard. In the case of operating plants, liquefaction can be revealed as a beyond-design-basis event. It is important to learn whether the liquefaction hazard has a safety relevance and whether there is a sufficient margin to the onset of liquefaction. The use of pseudo probabilistic method would be practicable for the definition of probability of liquefaction, but it could result in overconservative results. In their paper, the applicability of the pseudo probabilistic procedure was demonstrated for the sites in diffuse seismicity environment and for low hazard levels that are typical for nuclear safety considerations. Use of the procedure was demonstrated in a case study with realistic site-plant parameters.

Cyclic stress-based empirical liquefaction potential assessment is generally based on the results of CPT (Cone Penetration Test), SPT (Standard Penetration Test) or shear wave velocity ( $V_S$ ) measurements. In more complex or high-risk projects, CPT and  $V_S$  measurement are often performed at the same location commonly in the form of seismic CPT. However, combined use of both in-situ indices in one single empirical method has been limited. After the compilation of a case history database, Bán et al. (2019) have developed a combined probabilistic method where the results of CPT and  $V_S$  measurement can be used in parallel. The fact that peak ground acceleration, used commonly for empirical liquefaction assessment, is not capable of characterizing the entire ground motion impelled the development of energy-related intensity measures to characterize seismic demand. To adopt this

approach, the developed equation was also derived with Arias intensity as the intensity measure characterizing the ground motion. The main goal of their paper was to evaluate the prediction capability of the developed equations on an independent dataset of the 2010-2011 Canterbury Earthquake Sequence and compare it with commonly used empirical procedures. Although, our cyclic stress-based equation had worse overall performance than the most commonly used empirical methods, the result was still promising as it yielded the lowest number of mispredicted cases. On the other hand, the performance of the Arias intensity-based equation reflected a major drawback in the procedure.

#### 4.4 Speleoseismology

In certain cases, stalagmites are useful for giving upper bounds of maximum credible earthquakes in the present and the past. The examination of an intact, vulnerable, candlestick shape stalagmite in the Katerloch Cave (Austria) allows estimating an upper limit for horizontal peak ground acceleration generated by paleoearthquakes.

Gribovszki et al. (2020) determined the geometrical dimensions and the eigenfrequencies of the intact stalagmite by in situ observations. The value of horizontal ground acceleration resulting in failure and the eigenfrequencies were assessed by simple theoretical calculations. In these calculations the results of mechanical laboratory measurements of broken stalagmite specimens collected in Baradla Cave were used (tensile failure stress, density and elastic properties, Szeidovitz et al. 2008). U/Th ICP-MS measurements for age determination of the stalagmites standing in Katerloch Cave (Boch 2008, Boch et al. 2006, 2010) were used for assessing the average growth rate of the stalagmite.

The acceleration level ( $0.439 \text{ m/s}^2$ ) determined by Gribovszki et al. (2020) for the territory of Katerloch Cave is much lower than the PGA value interval ( $0.075 \text{ g}$  and  $0.1 \text{ g}$  in case of arithmetic mean and 85% percentiles, respectively; bedrock) determined by probabilistic seismic hazard calculation (SHARE Model) for a 475-year recurrence time (in 50 years with 10% probability of exceedance). The approach used in their study is a conservative one and yields significant new constraints on seismic hazard, as the intactness of the stalagmites suggests that tectonic structures close to Katerloch Cave, i.e. the Mur-Mürz fault, did not generate strong paleoearthquakes in the last few thousand years. Study of Gribovszki et al. (2020) is particularly important for understanding the seismic hazard associated with the town of Graz.

### 5 Earthquake source studies

#### 5.1 The Somogyszob earthquake sequence

Between February 16 and April 5, 2019, a series of earthquakes took place around the village of Somogyszob, Somogy County, Hungary. The mainshock occurred on March 7 with a local magnitude  $M_L = 4.0$  and epicentral intensity of 5 on the EMS scale. The main event was preceded by four foreshocks and followed by four aftershocks. The largest foreshock ( $M_L = 2.6$ ) was also felt with maximum intensity of 4 EMS. This earthquake sequence is the first remarkable one in the region that was recorded by a significant number of high-quality broadband digital seismographs. The hypocentres of the 9 earthquakes have been estimated using the hypoDD multiple-event location algorithm (Wéber et al. 2020). The events occurred in a tight region around the mainshock at around 13–14 km depth. The analysis of displacement P- and S-wave spectra has revealed that, for the main event, the average moment magnitude is  $M_w = 3.75$ , the source radii are  $r_P = 509 \text{ m}$  and  $r_S = 400 \text{ m}$ , and the static stress drops are  $\Delta\sigma_P = 1.19 \times 10^6 \text{ Pa}$  and  $\Delta\sigma_S = 4.00 \times 10^6 \text{ Pa}$ . The resulting spectral source parameters for the investigated events agree well with the results of earlier research. The focal mechanism of the mainshock, a foreshock and an aftershock has also been successfully estimated (Wéber et al. 2020). Each earthquake was a thrust faulting event with a sub-horizontal P-axis pointing towards N-NE, coinciding with the general trend of the compressional stress field in the epicentral region.

## 6 Lithospheric studies

### 6.1 Deep geological investigation of a volcanic field in North-Eastern Hungary

Until the end of December 2021, the deep geological investigation of the volcanic field in North-Eastern Hungary took place in the framework of the Mining and Geological Survey of Hungary (MBFSZ), and in the framework of the Supervisory Authority for Regulatory Affairs (SZTFH) from 1st January, 2022.

János Kiss, László Vértesy, Ernő Prácer, Ágnes Cserkész-Nagy, Ernő Takács, Katalin Lőrincz, László Zilahi-Sebess, Károly Rádi, Ágnes Gulyás, and Márton Bauer participated in the research presented below (Kiss et al. 2019, Kiss and Vértesy 2020, Kiss 2021a, 2021b, 2022).

#### *Collecting geophysical data from the area*

The geological exploration of the area is incomplete and less known due to the surface (Tokaj Mountains) and buried volcanic rocks (Nyírség). Based on existing geological-geophysical data, complex data processing was required in the area. Drilling data, borehole geophysics, surface mapping geophysical measurements and seismic and magnetotelluric measurements along sections were used, supplemented by modern processing techniques.

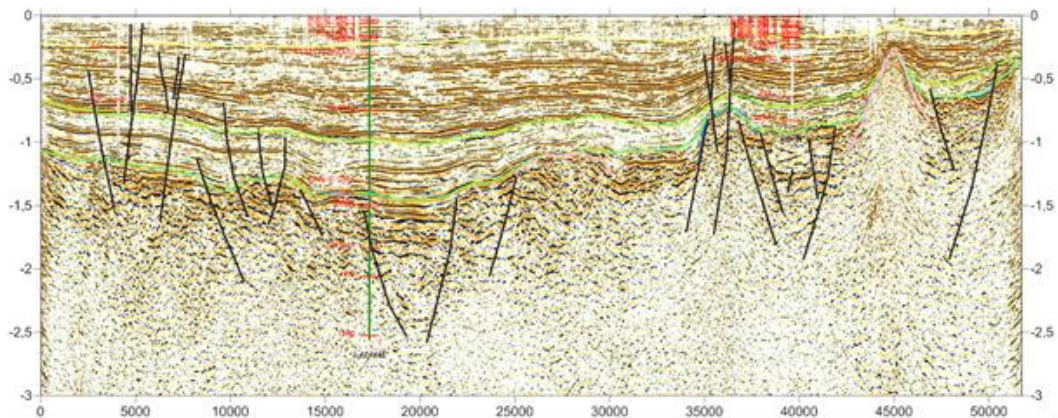
The results of high-resolution seismic reflection measurements (depth, shape, form, amplitude) and depth-sliced maps from spectral filtering of airborne magnetic and field gravity measurements were used, but also lithosphere research deep seismic tomography and magnetotellurics were processed.

#### *Borehole geophysics*

They examined deep drilling geophysical data from the relatively small number of existing boreholes. As these are mainly CH exploration wells, the typical rock physics parameters of the sediments overlying the volcanic assemblages and the velocity and density data that increase with depth due to diagenesis were mainly analysed. Thanks to these investigations, they were able to determine the depth trend in the area, which was of great help for the depth transformation of the seismic time sections. The seismic time sections had to be converted into depth sections for comparison with other data.

#### *Seismic reflection measurements (~40 sections)*

A reprocessing of the mainly hydrocarbon prospecting seismic reflection section in the area was carried out. They were primarily looking for structural and volcanic morphological features (Fig. 1). They searched for constructive (constructive activity - positive forms: intrusive volcanoes, stratovolcanoes, subvolcanoes) and destructive (destructive activity - negative forms: explosive eruption centres, calderas) volcanic morphologies and checked the suspected structures with magnetic, gravity and electromagnetic measurements.



**Figure 1.** Seismic reflection section with subvolcanic bodies

### Seismic velocity tomography sections (CEL04, CEL06)

In the context of deep geological research, they investigated the velocity data of our CELEBRATION-2000 lithosphere survey sections in the buried Nyírség Volcanic Field (NYFV) area, searching for volcanic tectonic structures and volcanic morphological features. To do this, they extracted the overall deep velocity-depth trend from the original velocity sections, which can be determined from tomographic velocity data. The resulting "velocity anomaly" highlighted the anomalously high and anomalously low velocity values caused by the varied intrusive and effusive volcanic activity (Fig. 2).

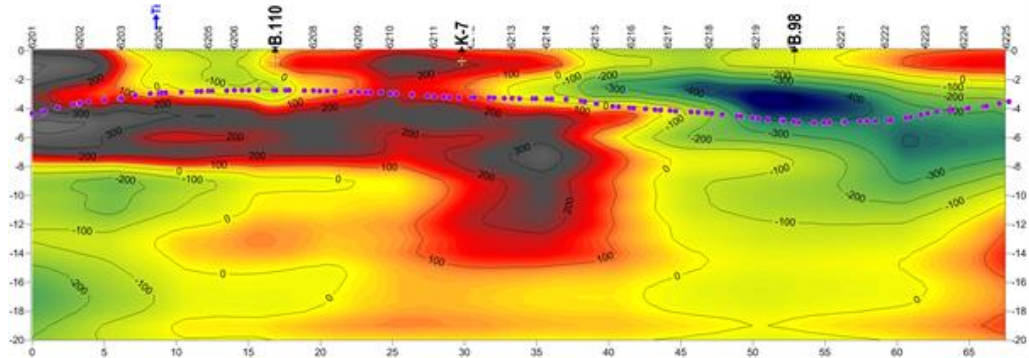


Figure 2. Seismic tomographic "velocity anomaly" section

### Potential field, geophysical data

Based on the gravity and magnetic data, spectral analysis was used to determine the characteristic depths and the corresponding filtered anomaly maps. Relative density and magnetization depth sections and a spatial grid were constructed to identify buried three-dimensional structures that are indicative of volcanic morphology (Fig. 3). Some of the spatial structures can be verified and identified along the geophysical sections, while others are too deep to give additional data.

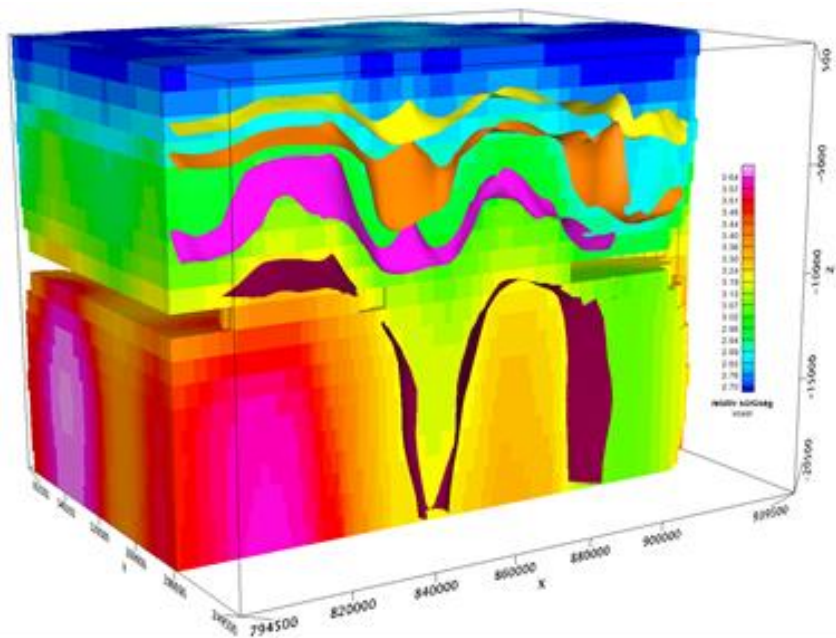


Figure 3. Relative density 3D distribution with different density surfaces



## 6.2 Base magnetotelluric sections of Hungary (MTOA— as Hungarian description)

Until the end of December 2021, base magnetotelluric soundings were carried out in the framework of the MBFSZ, and in the framework of the SZTFH from 1st January, 2022.

János Kiss, Károly Rádi, László Vértesy, Ágnes Gulyás, Ernő Prácer and László Zilahi-Sebess participated in the research presented below (Kiss 2005, 2009, Kiss et al. 2010, 2011, 2020, Kiss and Prácer 2016, 2021).

They have gone back to archival geophysical measurements, which go from country border to country border and can therefore be considered as magnetotelluric base sections (Fig. 4).

They are:

- The MTOA-01 base section corresponds to its entirety to the MT measurements taken on the CEL07 lithospheric seismic section.
- The MTOA-02 base section will collectively report the KA-3 sections of the Little Plain, the 101 sections of Somogy area, the MT grid measurement points of Nagyatád and the Sb-1 section of South-Transdanubia. A missing 20 km section will be filled by field measurements.
- The base section MTOA-03 is composed of the DKH-1 in the Little Plain area and the measurements on line CEL08, SB-5 and MV-2 sections. There is also a missing section of about 30 km, which has to be filled in with field measurements.

Thus, magnetotelluric soundings were also available along the seismic sections CEL07 and CEL08, measured in the Transdanubia region in the framework of the CELEBRATION-2000 programme. Previously, gravity and magnetic data processing along the lines were also performed (Kiss 2005, 2009, Kiss and Prácer 2016).

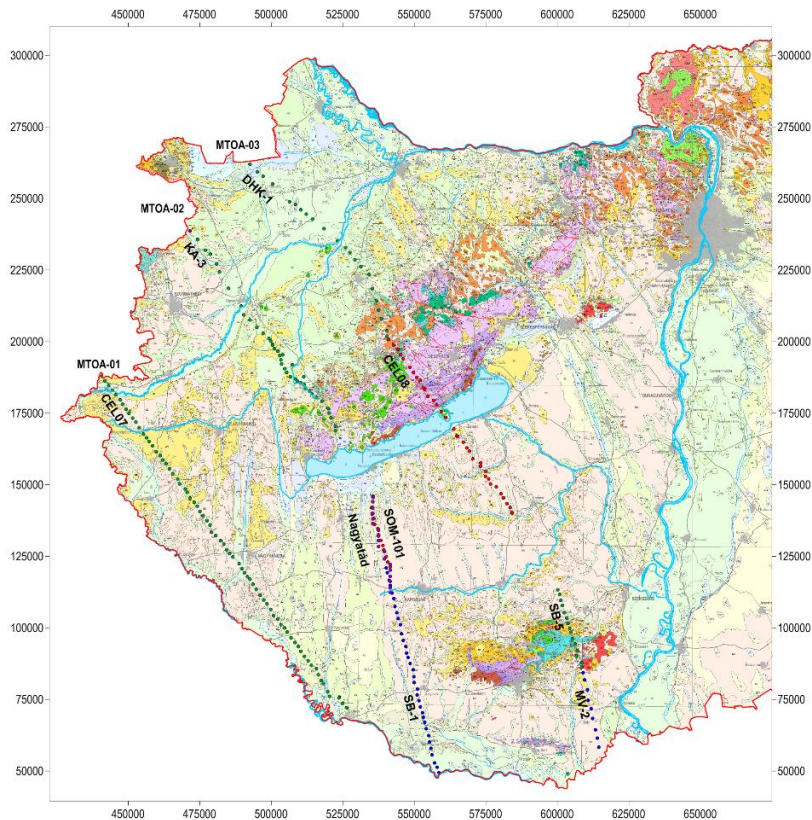


Figure 4. Base magnetotelluric sections of Transdanubia

The tectonic, main structural zone of Central Hungary and the volcanism (with mantle xenoliths) of the Balaton highlands make these sections interesting. In addition to seismic tomography, magnetotelluric measurements at the depth of penetration allow crustal depth studies and analyses. They have been involved in this research using the electromagnetic method, taking into account the research aspects mentioned above and the AlpArray measurement program that are currently underway in the field.

The processing was preceded by a methodological study to investigate the discrepancy between the E and H polarisation measurements of the magnetotellurics, i.e. the anisotropy in the physical properties. “AniMax” (the sum of  $\rho_{xy}/\rho_{yx}$  and  $\rho_{yx}/\rho_{xy}$  ratios), which is sensitive to structural anisotropy and distortions appearing in the presence of magnetic bodies, appeared to be the most appropriate value for this purpose (Kiss et al. 2020). The anisotropy appearing in the presence of magnetic fields was also verified by modelling (Kiss and Prácser 2021). It does not matter whether the apparent resistivity or the inverted resistivity are used for this purpose. Their experience shows that the apparent resistivity source data are the most favourable.

### 6.3 Receiver function analysis

The receiver function research was carried out by Dániel Kalmár and his colleagues, below you can read about their results. Dániel Kalmár has obtained his PhD degree in 2021 (Kalmár 2021).

They collected altogether 454089 three-component broadband waveforms from 3098 teleseismic events that were recorded at 221 stations in the East Alpine-Carpathian-Pannonian-Dinaric system for the P receiver function (RF) analysis. In order to process such a large amount of data, they developed an automatic preprocessing method and three independent quality control procedures (Kalmár et al. 2019, 2021).

The most important step after the quality controls was the deconvolution of the ZRT components (result of the ZNE rotation). The radial and tangential RFs were calculated by the iterative time domain deconvolution (Ligorria and Ammon 1999). They used three RF data processing techniques (Kalmár et al. 2021) and applied the station-wise H-K grid search algorithm (Zhu and Kanamori 2000), as well as the Common Conversion Point migration (Zhu 2000) procedure to image the topography of the Moho. However, these methods contain approximations and are highly dependent on the background model (Kalmár et al. 2019).

Therefore, they focused on the S-wave velocity structure of the area, which was determined by the Neighbourhood Algorithm inversion method (Sambridge 1999) at each station, where data were subdivided into backazimuthal bundles based on similar Ps delay times. The 1D non-linear inversions provided the depth of the discontinuities, shear-wave velocities and Vp/Vs ratios of each layer per bundle (Kalmár et al. 2021).

They developed a 3D imaging method called Natural Neighbour Cone Interpolation to obtain the 3D crustal structure from the local inversion results. This interpolation method can handle data gaps in backazimuth coverage as well as dipping discontinuities (Kalmár et al. 2021).

They mapped the thickness of major intracrustal layers and determined their S-wave velocity conditions and Vp/Vs ratios. The Conrad depth (Fig. 5a), upper crust, and lower crust thickness maps are the first for the Pannonian Basin region. They propose that the Conrad discontinuity is a change in velocity gradient between upper and lower crust, rather than a large velocity jump at the lower-upper crust boundary (Kalmár et al. 2021). The obtained sedimentary layer thickness and Moho depth (Fig. 5b) maps show good correlation with previous ones, and this is richer in details.

The dense seismic network with large amounts of quality-controlled data processed here allowed them to infer a 3D crust structural and shear-wave velocity model of the research area, which is valuable new information for any region.

Furthermore, they are performing S RF analysis for the Alpine-Carpathian-Pannonian region. The unprecedented station density owing to the temporary networks allowed them to value the lithospheric discontinuities in great detail. The 3-year project started at the end of 2022, detailed results are expected in the near future.

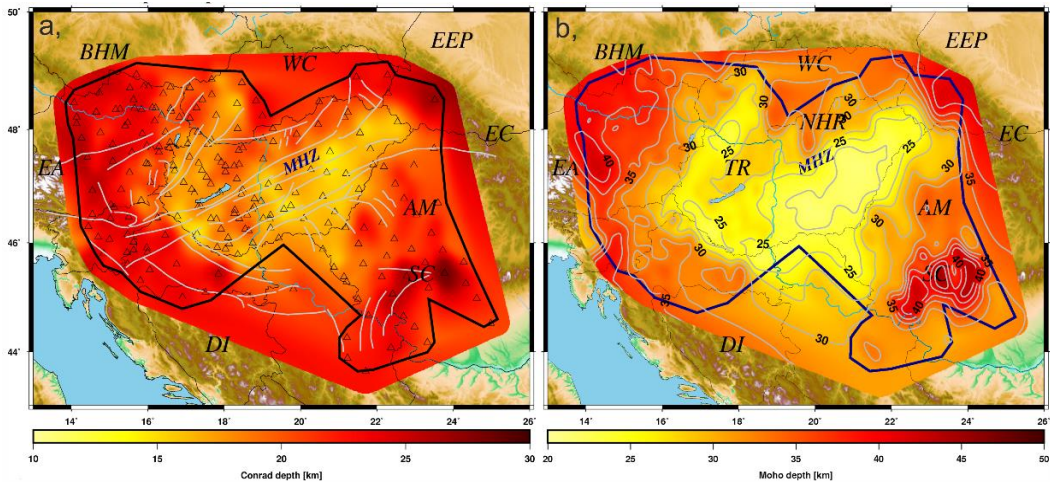


Figure 5. Interpolated Conrad (a) and Moho (b) depth map of the Pannonian Basin region

#### 6.4 Travel time tomography

The Pannonian region is a back-arc basin located within the arcuate Alpine–Carpathian mountain chain in central Europe. Beneath the basin, both the crust and the lithosphere have smaller thickness than the continental average. During the last few decades, several studies have been born to explain the formation of the Pannonian Basin but several key questions remain unanswered.

Timkó et al. (2019) have constructed a new high-resolution 3D P-wave velocity model of the crust and uppermost mantle in the Pannonian Basin, which may help us to better understand the structure and evolution of the region. For the 3D P-wave velocity structure estimation, over 32 thousand travel time picks have been derived from the ISC bulletin and the local Hungarian National Seismological Bulletin, and more than 3200 seismic events (local, near-regional and regional) and more than 150 seismic stations were used from the time period between 2004 and 2014. For the 3D velocity field inversion, the FMTOMO software package was applied, which uses the so-called Fast Marching Method for calculating the travel time estimations, and the subspace inversion method to recover the model parameters. Several checkerboard tests were performed both to select the appropriate regularization parameters and to help the interpretation of the resulting P-wave velocity model. The obtained seismic velocity anomalies well resolve the effects of the deep sedimentary basins and also the Moho topography and the associated updomings of the asthenosphere below the Pannonian Basin (Timkó et al. 2019). Different major tectonic units and fault zones separating them seem to show characteristic velocity anomalies. Subrecent volcanic activity or associated melt and fluid percolation, heat transfer in the upper mantle and crust may also have an impact on the propagation of seismic waves.

#### 6.5 Ambient noise tomography

Ambient seismic noise tomography has, over the last two decades, developed into a well-established tool for imaging seismic properties of the Earth's crust. Fundamental mode Rayleigh and Love wave phase velocity dispersion curves can be measured from ambient noise cross-correlation functions (CCF) either using a high-frequency approximation theory, or by fitting the spectrum of the CCF to a Bessel function. Wiesenberg et al. (2022) advanced the latter approach and presented an automated algorithm that fits the phase of the Hankel function to the phase of the causal symmetric part of the CCF in order to determine phase velocity curves as continuous functions of frequency. Synthetic tests verified the reliability of the proposed method in the presence of low signal-to-noise ratio (SNR). Moreover, usage of the phase allowed for robust phase velocity measurements at longer periods than when using the zero crossings of the Bessel function only and is, therefore, particularly useful at short

inter-station distances. In the frequency domain, acceptable bandwidths of smooth phase velocity curves were obtained in an automated procedure using a set of fine-tuned quality criteria. They applied the method to 2.5 yr. of continuous waveform data recorded by 58 temporary and permanent broadband seismic stations in northern Oman. They obtained 1072 and 670 phase velocity curves for Rayleigh and Love waves, respectively, in the period range of 2–40 s. The data were inverted for isotropic and azimuthally anisotropic period-dependent phase velocity maps. Synthetic reconstruction tests showed that the phase velocity maps had a lateral resolution of ~30 km. Their results suggested distinctly different middle to lower crustal architecture between the northern and eastern Oman Mountains. Azimuthal anisotropy showed contrasting fast propagation orientations in the shallow and deep crust, which were attributed to stress-induced and structural anisotropy in the upper crust and to lattice-preferred orientation in the lower crust.

Szanyi et al. (2021) studied the transition zone between the Eastern Alps and the Pannonian Basin by ambient noise tomography. The results implied the presence of low seismic velocities in deep sedimentary basins and high velocities along the orogenic rim in the shallower crust. In the deeper crust higher velocities may indicate mantle updoming which is responsible for the higher seismic velocities. The authors identified an extremely deep low velocity anomaly beneath the Vienna Basin of which origin is uncertain and can be interpreted by low velocity sediments transported to the lower crust, ductile deformation or the occurrence of deep fluids.

## **6.6 Joint interpretation with xenolith based geophysical parameters from the Carpathian-Pannonian region and geodynamic inferences**

Kovács et al. (2018) and Lange et al. (2019) demonstrated how upper mantle xenoliths from the Persány Mts. can be used to infer the electric conductivity, seismic velocity and effective viscosity of upper mantle and lower crustal rocks based on experimentally determined physical parameters and chemical and mineralogical composition of xenoliths. Patkó et al. (2019) presented that pyroxenes in upper mantle xenoliths usually show extremely low structural hydroxyl contents, anomalous infrared spectra and distribution in the Nógrád-Gömör Volcanic field. This was particularly obvious with respect to those experimental and natural samples, which experienced higher water activity environment. Later Liptai et al. (2021) confirmed further that upper mantle xenoliths from the central part of the basin, which was more affected by extension and subsequent heating, lose a considerable proportion of their structural hydroxyl content. With the use of water contents, physical properties such as effective viscosity and electrical resistivity are calculated for the different tectonic environments of the region. The results reveal that due to the difference in water contents, the marginal and central areas of the Carpathian-Pannonian region – and likely, other young extensional basin systems as well – are physically different: the marginal, supra-subductional and well-hydrated mantle lithosphere is less viscous and more conductive than its drier central counterpart. This is one of the pioneer studies, which aim to combine geological and geophysical aspects in mantle research.

In Patkó et al. (2021) we aimed to combine geophysical results (long period magnetotellurics (MT)) and upper mantle xenolith characteristics in a single volcanic locality situated in the northern part of the Carpathian-Pannonian region. The MT measurements revealed a low resistivity anomaly (<10  $\Omega\text{m}$ ) at 30–60 km depth beneath the central part of the Nógrád-Gömör area, indicating the presence of a conductive body beneath the Moho. This is the same area where wehrlitic (clinopyroxene-rich) xenoliths were collected from six quarries. These wehrlite xenoliths were formed as a result of mantle metasomatism. The spatial coincidence of the geophysical anomaly and the metasomatized upper mantle suggests their probable relationship. To test this assumption, we estimated the electrical resistivity of the wehrlites with variable melt contents. The models revealed that even ~0.5 vol. % of interconnected melt is appropriate to lower the electrical resistivity below 10  $\Omega\text{m}$  in the wehrlites. This conclusion suggests that melt likely exists in the mantle of the study area, which is in agreement with the conclusion drawn by another study.

In Kovács et al. (2020) megacrysts in basaltic rocks from the Bakony-Balaton Highland (central Pannonian Basin) were analysed, which were formed during the earliest stage of crystallization. The analyses involved measuring the water content of these crystals with a specific infrared method, which



has an accuracy of detecting even as low as 1 ppm (parts per million in mass) water. Based on the results, it was found that the mantle under the Pannonian Basin can be considered quite 'wet', containing 400-520 ppm water bound in the structure of mantle minerals. This is similar to values characteristic for the mantle under ocean islands (e.g., Hawaii) or island arcs above subducting oceanic slabs (e.g., New Zealand). What makes these results interesting is that currently there are no heat columns or subducting oceanic slabs known under the Pannonian Basin, which would facilitate the transport of volatiles, most importantly water. Therefore, the authors came to the conclusion that the 'wetness' of the mantle can be attributed to previous oceanic subductions, which were going on for tens of millions of years in the region. These oceanic slabs have long since disappeared due to continental collisions, but may still be producing water fluxes from their subduction 'graveyard' ~400-600 km deep. One major consequence of this finding is that with this high water content in this depth, upper mantle rocks are likely to be partially molten, which means they are capable of producing melt. But how and when can these melts rise to the surface? The new study offers to give an answer to this question as well. Basaltic melts have reached the surface in the last few million years only when the tectonic regime changed to compressional due to the convergence of the Adriatic and European continental plates. This compression forced the less dense melts out of the solid rock framework of the asthenosphere and towards the surface. The upward melt movement was further aided by the vertical foliation of the asthenosphere, and the folding and cracking of the cold, rigid lithosphere, both of which were also the results of the compressional regime. Overall, the results suggest that there may be a small amount of basaltic melt present in the asthenosphere under the Pannonian Basin even today, and there is likely a sea's worth of water still bound in the structure of mantle minerals.

In a follow-up study Koptev et al. (2021) utilised 1D thermo-kinematic modelling to explore the behaviour of the lithosphere during extension and the subsequent tectonic inversion stage. The study revealed that the extension is more favourable for the formation of calc-alkaline magmas since different layers in the lithosphere more likely to be tectonically decoupled. This leads to the formation of various magma chambers at different levels of the lithosphere leading to considerable fractionation and contamination. In contrast, during the subsequent inversion stage, the lithosphere is thermally more relaxed and coupled which provides direct pathways for the melts in the asthenosphere to reach the surface without fractionation and differentiation. Furthermore, the compression in the lithosphere and asthenosphere facilitates the quick transport of the melt from the asthenosphere to the surface. The applied thermo-kinetic model uses realistic geodynamic parameters from the Western Pannonian Basin.

Liptai et al. (2022) investigated the nature of seismic anisotropy of the upper mantle in the western Carpathian-Pannonian region by the combined application of geophysical and petrological methods. Shear wave splitting analyses were compared with seismic properties obtained from lattice preferred orientation of olivine in mantle xenoliths to characterize the depth, thickness, and regional differences of the anisotropic layer in the mantle. Regional differences occur between the northern and the central/southern part of the studied area. Beneath the Western Carpathians, the lack of azimuthal dependence of the fast split S-wave indicates a single anisotropic layer, which agrees with xenolith data from the Nógrád-Gömör volcanic field. In the central Pannonian Basin, multiple anisotropic layers are suggested by data from several seismological stations, which may be explained by two xenolith subgroups described in the Bakony-Balaton Highland, representing two, petrographically and structurally different depth layers. The shallower layer is suggested to have a 'fossilized' lithospheric structure, which could account for the occasionally detected E-W fast S-orientations, whereas the deeper one reflects structures responsible for the regional NW-SE orientations attributed to the present-day convergent tectonics. Spatial coherency analysis of the splitting parameters put the centre of the anisotropic layer at ~140-150 km depth under the Western Carpathians, which implies a total thickness of ~220-240 km. Thicknesses calculated from seismic properties of the xenoliths resulted in lower values on average, which may be explained either by heterogeneous sampling by the xenoliths, or different orientation of the mineral deformation structures (foliation and lineation) within the mantle.

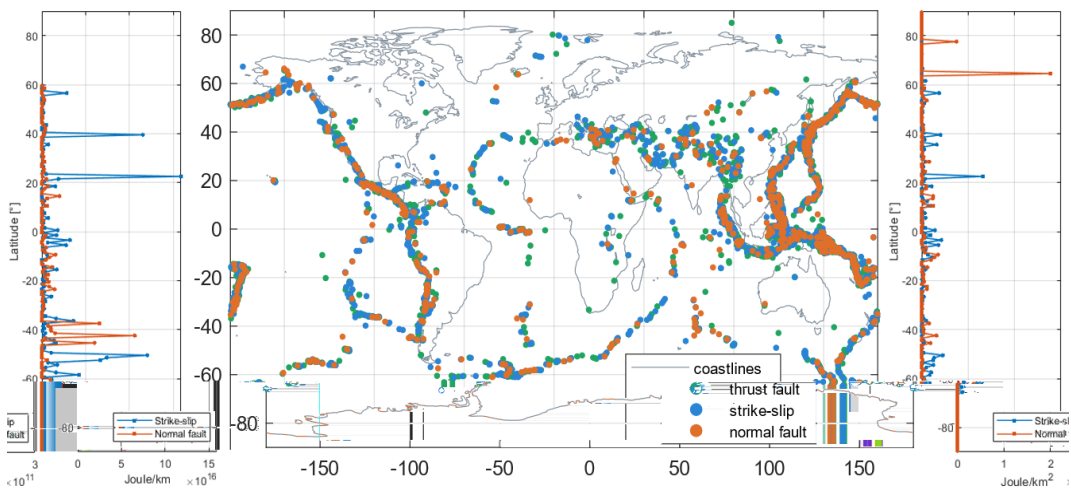
In Patkó et al. (2022) ten single-lithology harzburgite and three composite upper mantle xenoliths were studied from Mindszentkállya, central Pannonian Basin. The composite xenoliths consist of various combinations of dunite, olivine-orthopyroxenite, harzburgite, orthopyroxenite, websterite and

amphibole-phlogopite domains. The evolution of these variable lithologies was linked to two major magmatic events. The first event resulted in orthopyroxene enrichment, forming harzburgitic mantle volumes. This change in the lithology was likely linked to interactions between silica-rich melt and peridotitic wall rock in a suprasubduction zone. Some of these rocks were also affected by enrichment in U, Pb and Sr. Since these elements are fluid mobile, their enrichment in certain xenoliths indicate reaction with a subduction-related fluid, subsequent to the harzburgite formation. During the second event, the formation of orthopyroxenite and websterite domains and amphibole-phlogopite veins of the composite xenoliths took place. These lithologies are related to variably evolved mafic silicate melts. The orthopyroxenites must have been formed via melt-rock reactions, whereas the websterite and amphibole-phlogopite veins are crystallized products of mafic melts. The first event is possibly linked to the subduction of either the Budva-Pindos or the Vardar Ocean during the Mesozoic–Paleogene, far from the current position of the Mindszentkállya locality, where the metasomatized lithosphere was transferred by extrusion. The lithologies of the second event represent a younger, Neogene basaltic magmatic event, possibly the same that produced the basalts transporting the xenoliths to the surface.

## 7 Geodynamic studies

### 7.1 Effect of secular Earth rotation change on global seismicity

Earth experiences a constant loss of rotational speed because of tidal friction. Due to this, the secular despinning of the Earth amounts to  $\Delta\omega = -(5.4 \pm 0.5) \cdot 10^{-22} s^{-2}$ , resulting in a change of the length of day  $\Delta LOD = (2.3 \pm 0.1) ms/century$  (Stacey 1992). Changes in the rotational speed result in flattening variations. Denis and Varga (1990) have shown how changes in geometrical flattening cause variations in the stress tensor components. They found that at the so-called critical latitude ( $\varphi = \pm 48.2^\circ$ ) the stress derivatives have their maxima, thus generating the greatest stress along the latitude. This critical latitude separates two provinces, the strike-slip province towards the equator and the normal fault province towards the poles. Based on earthquake catalogues, it was found that the global seismic activity aligns to this pattern (Fig. 6). It shows bimodal distribution with respect to latitude, as well as the dominating fault types, the strike-slip and the normal fault province (Fodor 2021, Fodor et al. 2019).



**Figure 6.** The global distribution of earthquakes with different fault types. At low latitudes ( $\sim 0\text{--}45^\circ$ ), the seismic energy is mainly originating from strike-slip events, whereas at high latitudes ( $\sim 45\text{--}90^\circ$ ) the majority of seismic energy comes from normal fault events (Fodor and Varga 2022)

## 7.2 Research in Earth Physics

Varga et al. (2019) described mathematically the relations between different classes of Love-Shida numbers, which describe the deformations of the elastic Earth.

The distribution of lunisolar stress tensor in terms of their components at the spherical surface of the Earth as well as inside the Earth (up to the core-mantle boundary) were calculated by Varga and Grafarend (2019). Based on this, it was shown that tidal triggering effect differently depends on the type of the acting tide (zonal, tesseral, and sectorial) and also significantly depends on the latitude.

Varga and Fodor (2021) showed by a model calculation that length of day (LOD) variation due to tidal friction is able to move tectonic plates. The LOD variation during Archean and Proterozoic was significantly smaller than during Phanerozoic. Consequently, plate tectonics process (and probably the earthquake activity) was different during the Phanerozoic (Pz) and in earlier eons (Archean (Arch), Proterozoic (Ptz)).

The analysis of the mutual relationship between earthquake activity and Earth rotation concluded that the relationship between changes in the speed of Earth's rotation (that is, changes in the Length-of-Day (LOD)) may affect earthquake activity (Fodor et al. 2019; Fodor and Varga 2021).

It has been revealed by Schreider et al. (2019a, 2019b) that the magnitude of magnetic field increases toward present day. The virtual dipole moment (VDM) characterized by a positive linear trend from  $4.2 \cdot 10^9$  years ago to  $5.2 \cdot 10^9$  years today.

## 7.3 The pargasosphere hypothesis

In Kovács et al. (2021) a hypothesis was introduced that describes how a small amount of volatiles (mainly water) and the stability of volatile-bearing minerals (mainly pargasite) – depending on the age and temperature of continental lithospheres – can explain the lithosphere-asthenosphere boundary in young and hot plates, and the weakness zones observed at 100 km depth in old and cool lithospheres. Another important result of our theory is that the origin of CO<sub>2</sub>-emanations with ‘magmatic’ origin observed on the surface can be explained even in areas distant from active volcanism. The hypothesis states that the source of the CO<sub>2</sub> is the cooling asthenosphere itself, where the crystallisation of small amount of silicate melts leads to the enrichment of CO<sub>2</sub> in the residual fluid, which is extremely mobile towards the surface. CO<sub>2</sub>-emanations of mantle origin were so far barely taken into account in the global CO<sub>2</sub>-cycle, although they likely have an important role in the quantitative modelling of climate change processes.

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# IUGG ASPECTS OF THE EÖTVÖS 100 COMMEMORATIVE YEAR

*László Szarka\**

## 1 Introduction

2019 was 100th anniversary year of the death of Baron Roland Eötvös (in Hungarian Bárá Eötvös Loránd, (Buda, July 27, 1848 – Budapest, April 8, 1919), a pioneer of high precision gravitational physics, founding father of applied geophysics (Rankine 1948) and innovator of higher education (Figure 1). This centenary was commemorated in association with UNESCO (Eötvös 100 2019a).



**Figure 1.** The Eötvös 100 logo and image. Design: Juhász Márton (Juhász 2019), István Orosz, UNESCO NC for Hungary

Results by Roland Eötvös are still with us, both in capillarity (before 1880) and in various fields of gravity. The Eötvös rule, Eötvös constant, Eötvös number (all related to surface tension of liquids), as well as several gravity terms: the Eötvös torsion balance, Eötvös experiment, Eötvös parameter, Eötvös tensor, Eötvös effect, and the Eötvös (E) physical unit. Roland Eötvös was President of the Hungarian Academy of Sciences (1889-1905), Rector of the leading Hungarian university (now: Eötvös Loránd University), Minister of Religion and Public Education. He was not only a great scientist (explorer of true and deep relations), he was also a great man: supporter of young talents, sports organizer, sportsman, and stereoscopic photographer.

Although the Union of Geodesy and Geophysics (IUGG) was established only in the year of his death, the name of Roland Eötvös, via a pre-IUGG association, Internationale Erdmessung, became an integral part of IUGG. In the Eötvös 100 Commemorative Year, the IUGG National Committee for Hungary played an active role. Throughout 2019 four IUGG-related Eötvös 100 events were organized. In the following a brief summary is given about these four project events, as well as about some further events, which might be interesting for the IUGG community.

## 2 IUGG-related Eötvös 100 events

### 2.1 Opening event of the Eötvös 100 Commemorative Year

At the Opening event of the Eötvös 100 Commemorative event (Eötvös 100 2019b), on 14, January, 2019, József Ádám (1950-2022, see Figure A1), President of IUGG NC for Hungary read the letter of the President of IUGG (Sideris 2019), addressing the Eötvös 100 Commemorative Year with the following words:

„As you know, the International Union of Geodesy and Geophysics (IUGG) was established in Brussels on 28 July 1919 at the general assembly of the International Research Council (now the International Science Council), to coordinate international research in the geosciences as an international, non-governmental, non-profit organization, in place of several pre-existing independent scientific organizations.

The Hungarian scientist Loránd Eötvös, who was very active in pre-IUGG international organizations, died 111 days earlier, on 8 April 1919. 2019 marks not only the 100th anniversary of IUGG, but also, as it is recently accepted by UNESCO, the 100th anniversary of the great Hungarian "physicist, geophysicist, and innovator of higher education".

I am very pleased that Roland Eötvös and his contributions will be commemorated throughout the year in Hungary and abroad. At our centennial IUGG General Assembly in Montreal this year, we will also celebrate the accomplishments of the previous century in Earth and space science research, and will look forward to the next century of scientific advancement. The oeuvre of Roland Eötvös belongs to the turn of the 19th and 20th centuries - Roland Eötvös presented his results at the General Conferences of the "Internationale Erdmessung" (one of the predecessors of IUGG) in Budapest (1906), in London and in Cambridge. These results are still with us in terms as the Eötvös effect, the Eötvös experiment, the Eötvös number, the Eötvös parameter, the Eötvös rule, the Eötvös tensor, the Eötvös torsion balance, and the Eötvös unit. Looking forward to our centennial IUGG General Assembly, I hope that you will be able to present the rich, multidimensional character of Roland Eötvös to the young Earth scientists of from all over the World.

I am really sorry that I cannot personally attend the Opening celebrations, but I wish you a very successful event and Eötvös centennial year. Sincerely, Prof. Michael G. Sideris, President of IUGG”.

### 2.2 Eötvös 100 Commemorative Ceremony

On April 8, 2019, at the central event of the Eötvös 100 Commemorative Year in the Ceremony Hall of the Hungarian Academy of Sciences (Eötvös 100 2019c, Figure 2), IUGG was represented by its Vice President, Kathryn Whaler (Whaler 2019, Figure 3). She addressed the audience with the following words. „Greetings on behalf of the International Union of Geodesy and Geophysics, or IUGG, on this auspicious occasion! I am the current Vice-President of IUGG, and I wish to thank you most sincerely for the invitation to participate in this wonderful event in these magnificent surroundings. It celebrates the life, science and activities of Baron Loránd Eötvös, in association with UNESCO, exactly 100 years after his death, but the year 2019 also marks the centenary of the birth of the IUGG. With its establishment at a General Assembly of the International Research Council (now the International Science Council), IUGG brought together international societies with interests in geodesy, geomagnetism and electricity, meteorology, physical oceanography, seismology, and volcanology. Those subject areas now constitute six of IUGG’s eight International Associations, with the other two covering hydrological sciences, and the most recent addition, cryospheric sciences.

We will hear about many of Baron Eötvös’ interests and achievements in the course of the day and I do not wish to pre-empt those contributions. However, I would like to mention that Baron Eötvös was very active in fostering and furthering international cooperation and collaboration, essential ingredients of IUGG. One of his scientific interests was geodesy – loosely, characterising the Earth’s shape and the variation in gravitational acceleration on its surface – and he presented his results in Budapest (1906), London and Cambridge at General Conferences of the ‘Internationale Erdmessung’, which was one of the international societies that was brought together to form the IUGG. We know

him and his science now through terms such as the Eötvös parameter, Eötvös effect, Eötvös rule, Eötvös tensor, Eötvös experiment and Eötvös number, some of which refer to his geodetic work, as well as features named after him on Earth and the moon, and planetoid 12301 Eotvos in the asteroid belt.

Baron Eötvös developed a high precision torsion balance, still one of the most accurate ways of measuring Earth's gravitational acceleration. This would go on to provide proof of part of Einstein's general theory of relativity. I first heard his name in relation to the Eötvös effect, which describes how gravitational acceleration changes when measured from a moving (eastward or westward) platform. Originally, the Eötvös effect corrected measurements of gravity made from ships, but now data are collected from helicopters, fixed wing aircraft and even satellites. We see the results of plate tectonics, such as mid-ocean ridges and subduction zones, reflected in marine gravity data, and they enable us to infer the strength of the tectonic plates. Gravity data are also used to explore for Earth resources, such as hydrocarbons and minerals, so the torsion balance and Eötvös effect have important economic implications, too. It is perhaps fitting that the geological mineral named after him, Lorándite, occurs in economically viable ore bodies containing gold, thallium, arsenic and antimony (amongst others). I'm sure he would be fascinated to know that Lorándite is now being used to determine the flux of neutrinos from the Sun, enabling scientists to understand its nuclear fusion reactions.

So, although I am here representing IUGG and have hence concentrated on Baron Eötvös' geodetic work, it eclipsed IUGG and had much wider-reaching implications, and he had interests that would have associated him with many other International Unions that are around to-day. These include the International Astronomical Union, also celebrating its centenary this year, the International Union of Geological Sciences, formed more recently but also with predecessors dating back to Baron Eötvös' time, and the International Union of Pure and Applied Chemistry that collates surface tension data, another of his interests. He truly was one of our great polymaths.

I know you have plans to showcase some of Baron Eötvös' work, equipment and three-dimensional images at the IUGG centenary General Assembly in Montreal, Canada in July. This will enable a new generation of scientists from all over the world to appreciate his contributions and understand better the history of our subject and how it has developed from Baron Eötvös' time, over the century of IUGG, to the next century of advancement.

Thank you!"



Figure 2. Opening concert by the Choir of the Piarist High School, Budapest





**Figure 3.** The audience (Kathryn Whaler is in turquoise seats in the first line on the fourth chair from left)

### 2.3 Eötvös 100 exhibition in Montreal



**Figure 4.** Exhibitors (István Bozsó, Csenge Czani, Veronika Barta) and James R. Fleming, in front of Roland Eötvös pop-up wall

The Eötvös 100 exhibition (201 Booth #4 IUGG Centennial Year, Eötvös 100 2019d, see Figure 4) was carried out by MTA CSFK GGI (since 2021: Institute of Earth Science and Space Physics). As it was written in the conference book: „... on the 100th anniversary of death of Roland Eötvös (1848-), physicist, geophysicist, commemorated in association with UNESCO. Eötvös was Academy President, Rector, Minister, alpinist, and he was very active in pre-IUGG international collaborations.” The Eötvös 100 booth attracted many visitors. Some of them were already familiar with the scientific works of Eötvös, others knew only his name, since they regularly use e.g. the correction named after him. Even those who had never heard of him were eager to hear a summary of his complex work and were impressed by his versatility. A professor of science history (see Figure 4) called our booth “the best thing at this year’s IUGG exhibition”, but it also made us proud to hear an Indian colleague’s memories from back in the ‘90s when she learned a lot about Eötvös at the university, or seeing a Chinese visitor proudly showing us a commemorative stamp of Eötvös as a precious part of his collection.

#### 2.4 Eötvös 100 Session at the World Science Forum

On November 20, between 11:00 and 12:30 a Special Session of the World Science Forum (WSF) took place in the Ceremony Hall of the Hungarian Academy of Sciences, co-moderated by Kathryn Whaler, President of the International Union of Geodesy and Geophysics, and Alik Ismail-Zadeh, Secretary of the International Science Council, former Secretary-General of IUGG (Eötvös 100 2019e, UNESCO 2019, WSF 2019, IUGG 2019, IUGG 2020, Figure 5). Presentations were about stereographic photos taken by Roland Eötvös, and a recent re-measurement of the celebrated Eötvös experiment (demonstrating the Weak Equivalence Principle with a high precision). The event ended with a book launch: Eötvös’ most famous work (had been available until the event in German) was published in a historical context both in English and in Hungarian (Kilényi 2019).



**Figure 5.** Kathryn Whaler, President of IUGG opens the Eötvös 100 session at the WSF in Budapest, Sitting in the middle: Alik Ismail-Zadeh, to his right: Sierd Cloetingh and Zsolt Regály, to his left: Lajos Völgyesi and László Szarka

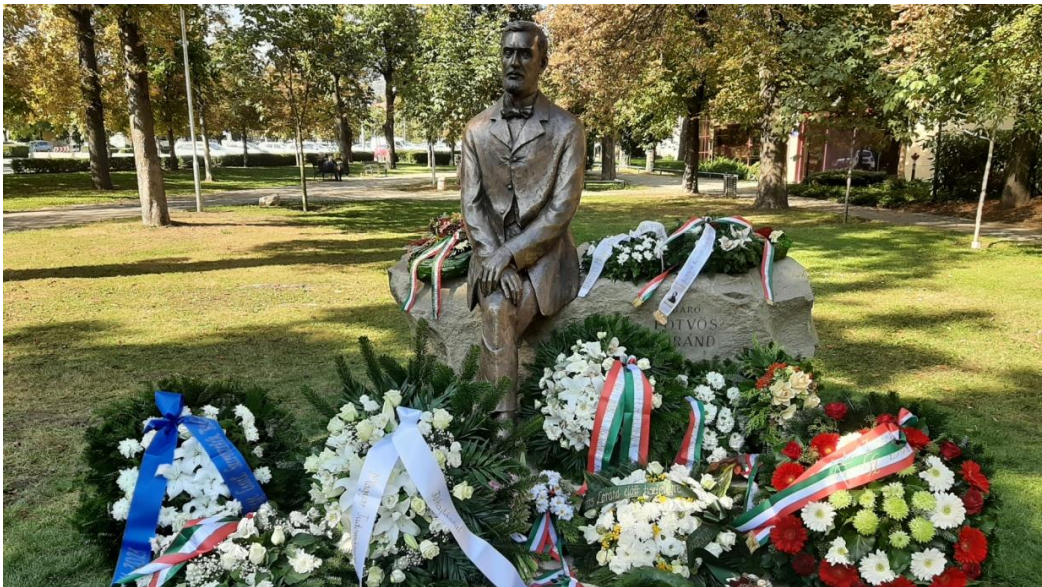


## 2.5 On non-IUGG events

Starting from the Eötvös Commemorative Day (April 8, 2019) an original Eötvös balance was exhibited in Vienna, at the annual assembly of the European Geoscience Union.

Concomitant with the Budapest World Science Forum (November 20–23, 2019), in Budapest several further Eötvös 100 events were organized. On November 22, a temporary Eötvös 100 exhibition was opened at ELTE University Library, with interactive exhibits and commentary in Hungarian and English. On November 23, the Finals of the “Roland Eötvös Commemorative Competition” for high schools took place at the Hungarian Academy of Sciences. On November 26, The Roland Eötvös Memorial Album was launched both in Hungarian and in English (Dobszay et al. 2019, reviewed in German by Kautzleben 2020). On November 28, in the series „High School Students at the Academy”, “Eötvös 100” presentations were held.

The Roland Eötvös Commemorative Year officially ended in 2019. A tribute and a new memory by Henks Kubbinga (2020a, 2020b) were published already in 2020. In autumn of 2020, a collection of poems and literary translations made by the child Roland Eötvös was published (Kis 2020). Finally, the statue of the famous scientist (physicist, Earth scientist) and cultural politician Loránd (Roland) Eötvös (1848–1919), was inaugurated on October 5, 2021, Tuesday in Budapest-Hegyvidék (District XII, see Figure 6 and Hegyvidek 2021).



**Figure 6.** Statue of Baron Roland Eötvös in Budapest Sculptor: Tibor Rieger

## 3 Summary

An eye-opening conclusion of the Commemorative Year: the name “Roland Eötvös” is an even greater brand in international science than it had been thought before 2019. Roland Eötvös was an exceptionally visionary researcher. His experimental results (both in capillarity and gravitational physics) survive any theory. In gravitational physics, the famous Eötvös experiment has become a focal and reference point again. For Earth scientists living and working in the Carpathian Basin, his name represents a cohesive force. Roland Eötvös can be a veritable role model for young people. This is our message for 2023. This year is again a commemorative year: 175th anniversary of his birth. At the Berlin IUGG General Assembly, at the booth of the Institute of Earth Physics and Space Science (EPSS, Sopron; a member of the Eötvös Loránd Research Network) stereoscopic photographs on his research and mountaineering activities will be displayed, as well as an original Eötvös torsion balance.

**Acknowledgements** – The centennial project was carried out by the Library and Information Centre of the Hungarian Academy of Sciences (MTA KIK) represented the core of the whole Eötvös 100 Commemorative Year. Project no. ED\_18-1-2018-0011 was implemented with support from the National Research, Development and Innovation Fund of Hungary, financed under the ED\_18 funding scheme. The direct partners of MTA KIK in the project were: BEAC, Eötvös Loránd University, Eötvös Loránd Physical Society, Eötvös Loránd Geophysical Foundation, Hungarian Mining and Geological Survey (MBFSZ), Association of Hungarian Geophysicists, Hungarian Geological Society, Hungarian Academy of Sciences / CSFK, SZTAKI, Wigner FK; Hungarian Tourist Association, MOM Memorial Foundation, and the Hungarian National Commission for UNESCO (UNESCO MNB). Special thanks to the Patrons, Sponsors, and the Eötvös 100 Honorary Board Members (<https://eotvos100.hu/hu/page/partners>).

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## Appendix

József Ádám (1950-2022), the President of the Hungarian National Committee for IUGG and the national correspondent for IAG was a very enthusiastic partner in organization of IUGG-related Eötvös 100 events. He passed away on December 29, 2022. His message: Love never ends (1 Corinthians 13:8).



**Figure A1.** The letter by Michael Sideris, President of IUGG sent to the opening event of the Eötvös 100 Commemorative Year was read by József Ádám (1950-2022)



## IN MEMORIAM JÓZSEF ÁDÁM

*Szabolcs Rózsa\**



(1950-2022)

We are deeply saddened to inform the international scientific community that Prof. József Ádám, member of the Hungarian Academy of Sciences, president of the IAG National Committee and IAG National Representative, the former President of the COB/Member of the EC passed away on the 29th of December, 2022. Both the Hungarian and the international geodetic communities have lost a remarkable scientist, an outstanding professor, and a good friend.

József Ádám was born in 1950 in Kocsér, a small village in Central Hungary. He was enchanted as a child by the work and the instruments of land surveyors, who were taking observations on the 3rd order geodetic control point in his home village. In the 1960s his teenage years coincided with the evolution of the space era. He read lots of articles about the artificial satellites, that determined his future activities. He studied land surveying at the Technical University of Budapest (now Budapest University of Technology and Economics, BME) and earned his PhD in 1977 with the thesis „Determination of station coordinates using satellite laser ranging”.

He started his professional career in 1974 at the Satellite Geodetic Observatory of the Institute of Geodesy, Cartography and Remote Sensing in Hungary working on the application of the emerging satellite geodetic observation techniques in the development and refinement of geodetic networks. The datum transformation parameters between the Hungarian Datum 1972 and WGS-72 as well as WGS 84 were determined by him using doppler and GPS observations, respectively. Later he joined to the research group studying VLBI and space VLBI techniques. In 1985 he was awarded an Alexander von Humboldt Fellowship in Stuttgart and received a research associate position in the late 1980s at the Ohio State University, where he studied the geodetic applications of space VLBI observations and published his well-known work „Estimability of geodetic parameters from space VLBI observables”. In 1995 he held a research associate position at The Observatoire de Paris.

He was continuously active in teaching even during this period. He was the lecturer of Geodetic Control Networks and Satellite Geodesy at BME. In 1992 he earned his DSc in Geodesy at the Hungarian Academy of Sciences and was appointed as professor to the Department of Geodesy at BME. He taught several generations of land surveyors and geodesists during the subsequent more than 30 years.

His research activities focused on the application of satellite geodetic techniques in the establishment and maintenance of geodetic control networks, on geoid determination, as well as on the development of continental and international reference frames. The Hungarian Academy of Sciences (HAS) elected him as a corresponding member in 1998 and as a full member in 2004. He was a very enthusiastic member of the HAS, acted as vice president and later president of the Section of Earth Sciences for 6-6 years. As a member of the HAS his interest turned to the history of earth sciences and technology as well as the conservation and further development of the Hungarian technical and scientific language.

He was also deeply involved in the activities of the international geodetic community. He has been the Hungarian National Representative of the International Association of Geodesy since 1991, the chairman of the IAG Special Study Group 2.109 (Application of Space VLBI in the Field of Astrometry and Geodynamics) and the president of its Communication and Outreach Branch between 2003-2019. He was a member of the IUGG Working Group of History (2014-2019) and the Member of the IUGG Permanent Council (2015-2019). He organized several IAG conferences in Budapest, such as the 3rd EUREF Symposium in 1993; the 2nd Continental Workshop on the Geoid in Europe in 1998; the IAG Scientific Assembly in 2001 and the IAG International Geoid School in 2005. He was the convenor and/or co-convenor of IUGG union and Inter-Association Symposia in 2011, 2015 as well as in 2019 as well as the Fellow of the IAG since 1995. He has been serving as the President of the IUGG Hungarian National Committee since 2011.

Due to his long-term commitment to advancing regional and global geodetic research as well as to the promotion of international geodetic cooperation, the German Geodetic Commission of the Bayerische Akademie der Wissenschaften elected him as the corresponding member in 2001, while he became the member of the Leibniz Society of Sciences in Berlin in 2021.

He was devoted to the science of geodesy and to serving the geodetic community both on the international and national level. He was an appreciated member of the geodetic community due to his knowledge, his deliberate and patient personality and positive, supporting attitude. May he rest in peace!