Final report on the results and achievements of NKFIH OTKA K141969 research project

Since the research aims of the proposal were originally separated into two definite groups the presentation of the results and technical achievements is split into two distinguished parts.

1) Results on the analysis of time series of ground tilts induced by geodynamical processes having large variety of time constants

1.1)The general infrastructure of the observations developed in the framework of the project

The idea of the analysis of ground tilt signals recorded continuously by high resolution tilt meters was founded originally on only two observation sites, the Sopronbánfalva Geodynamic Observatory (SOPGO) and the Conrad Observatory (COBS) operated by the Institute of Earth Physics and Space Science (EPSS) and Geosphere Austria, respectively. In the meantime, however, a whole network consisting of 5 stations could be established in the Mur-Mürz tectonic fault zone due to a support provided by ELKH INFRA financing system in 2021. This seismo-tectonically active area separates the Alpine and Pannonian sub-plates near to the state border between Hungary and Austria. It crosses highly inhabited regions of Burgenland and the Vienna basin. SOPGO and COBS are located on its different sides. Since the ELKH INFRA support made the densification of the stations possible 3 more sites have been included during the duration time of the project. The criteria of the site selection are very strict. Only such sites/objects can be candidates which have very stable temperature providing only ~0.01 °C daily variation. The low background/microseismic noise is also preferred so in general underground sites are favoured. SOPGO, COBS and the 3 further stations fulfil the requirements and their locations form nearly a line crossing the fault zone in E-W direction (Fig. 1).

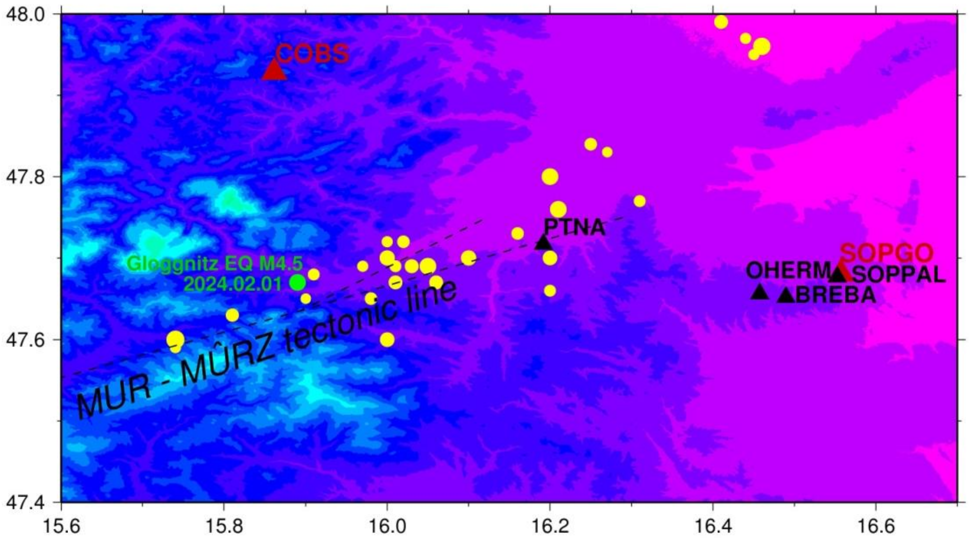

Fig. 1. The locations (red and black triangles) and names of the stations of the Mur-Mürz monitoring network with some unnamed recent earthquake epicentres (yellow circles). Horizontal axis: longitude in degrees. Vertical axis: latitude in degrees. The background shows the SRTM3 topographic model. Please note, that OHERM station is not operational yet

The SOPPAL station is hosted by Eszterháza Nonprofit Kft in the abandoned cellar system belonging to the Carmelita Closter, Sopronbánfalva. The BREBA station is hosted by the Fertő-Hanság National Park in a vault on the ex-mining area of Brennbergbánya. The PTNA station is hosted by Geosphere Austria in a closed iron mine on the area of Pitten, Austria. All the stations are equipped by biaxial Lippmann-type compact high resolution tilt meters (LTS). So by the time of project closing the OTKA team operates a network which provides N-S/E-W tilts, temperature, humidity and air pressure data with 5 Hz sampling rate continuously (Table 1.). One should note that even the program code for the control of data acquisition had to be written by the OTKA team due to the lack of it.

Table 1. Some samples from a daily tilt file recorded at Conrad Observatory by LTS SOP2 sensor

time stamp	X tilt [arcsec]	Y tilt [arcsec]	T [°C]	H [%]	P [mbar]
. . .					
20240414093853.80	-5.6559	8.0448	7.681	97.37	904.37
20240414093854.00	-5.6545	8.0462	7.681	97.37	904.37
20240414093854.20	-5.6533	8.0505	7.681	97.33	904.37
20240414093854.40	-5.6517	8.0527	7.681	97.31	904.37
20240414093854.60	-5.6517	8.0566	7.681	97.34	904.37
20240414093854.80	-5.6530	8.0621	7.681	97.36	904.37
20240414093855.00	-5.6549	8.0631	7.681	97.37	904.37
. . .					

1.2) Development of data flow and pre-processing scheme

The data transfer from the stations is scheduled hourly where the sites have wired internet access. Otherwise one file transfer per day is managed where only GSM internet is available (BREBA station). The data organized in daily files arrive either directly to the HP rx2800 server of EPSS or to a server of the Geosphere Austria, from where those transferred further to HP rx2800 server. Status plots of the actual observations are also drawn periodically and automatically and those are displayed on kepujsag.ggki.hu website managed by EPSS. Eventually all the data are stored and available on the servers of EPSS Sopron. The data are organized in a subfolder structure starting from the root folder named by sensor ID. According to the needs the raw daily files are checked for consistency and pre-processed for analysis using batch processing technique. All the necessary software were developed by the team members, but for the further analysis of data, TSOFT program and ETERNA3.4 package are used on Windows platforms. The ever increasing length of the analysed time series, however, requires the extensive use of the HP rx2800 Unix server, where the memory management is more flexible than in Windows. So, different programs dedicated to visualization, filtering, spectrum estimations, etc… had to be developed by the team members for the HP Unix platform, the improvement of which was financed by the OTKA project. For filtering a batch processing code based on time domain convolution was written providing continuity even if series of daily files are processed. This way the merging of daily files containing 432000 samples (@ 5Hz) is unnecessary which would be a basic condition for spectral filtering. Of course the method is much slower then FFT based filtering but does not need large memory allocation. For instance in case of a year long data set 1.2 GByte RAM memory is needed to store the samples in double precision which cannot be managed by e.g. TSOFT program. Although TSOFT can usually be used also for step detection and correction, the limited memory allocation also needed to implement proper algorithms under HP Unix to handle this problem. The code developed by the OTKA team is based on the statistical investigation of the data processed by a moving differential operator. It can detect locations of data steps (sudden jumps) and based on some pre-set parameters (semi)-automatically can apply corrections to minimize the bias between data segments preceding and following the step.

1.3) Scientific results

The ground tilts $\tau_{N\text{-}S}$ and $\tau_{E\text{-}W}$ have been recorded since 2016 at COBS more or less continuously by an LTS and an experimental version of a short interferometric water tube tilt meter (iWT) developed by the Finnish Geospatial Institute. As a first step of the analysis of tilt data a local tidal model had to be derived from the observations. Due to the limited length of uninterrupted data segments the amplitude and phase parameters of some main diurnal (Q1, O1, K1) and semi-diurnal (N2, M2, S2) wave groups were derived. The preliminary results obtained from the time series of $(\tau_{N\text{-}S}, \tau_{E\text{-}W})_{LTS}$ and $(\tau_{E\text{-}W})_{iWT}$ show good agreement with the gamma factors of the Wahr-Dehant theoretical earth model in E-W direction, especially in case of iWT. Moreover, there is a definite, although small systematic, non-unit scale factor between the two sensors, depending on the period of time of the wave group (Q1 -> S2: 1.0056 -> 1.088). In N-S direction, which is perpendicular to the longitudinal axis of the tunnel, the differences between the observed (which could be derived only from LTS data) and theoretical gamma factors are much larger mainly for the diurnal components due to the so called cavity effect. These results were presented in the IAG symposium G06l of IUGG General Assembly, Montreal. In spite of the limited reliability of the spectral component estimation done by the ETERNA3.4 program package, the tilt effect of tidal excitation could be efficiently removed from the time series. The residual tilt signals, however, showed strange transient signals from time to time with variable amplitude but with a stationary envelope similar to a "shark teeth". Thanks to the excellent infrastructure of COBS the time series of both gravity changes recorded by the GWR SG 025 superconducting gravity meter and meteorological parameters (precipitation, snow height, etc…) could be involved as reference data sets in the analysis of environmental effects.

Based on all the available observations (ground tilts, gravity, meteorological) those environmental effects which are connected to hydro-meteorological processes like air pressure changes, precipitation, the surface distribution of rain water and infiltration/percolation were analysed and modelled. The processes mentioned can cause disturbing signals in the recorded tilt data having significant magnitude (700 – 1000 nrad) which can be e.g. a multiple of the usual tidal tilt effect (50 – 100 nrad). The time span of these transient effects extends from hours to two weeks (relaxation period). For geodynamical analysis the tilt records have to be corrected for these disturbing signals so it implies the need of proper correction models. Based on the analysis of the relations *air pressure – tilt* and *precipitation – tilt* both regression- (admittance) and simple deterministic models were derived. Two main phases of this hydrological process could have been separated.

In the *first phase* of the process the loading of the rain water accumulated on the topographic surface dominates. It causes relatively small (< 10 nrad) but well pronounced signals in the records. It acts immediately so it has no time delay as it was supposed previously. Just like in the case of gravity time series recorded by GWR SG025 superconducting gravity meter. The direct gravitational effect of rain water on tilt records is negligible (< 0.1 nrad) and it is hidden in the background noise of the measurements. Forward gravitational modelling showed that the surface water influences the gravitational tilt effect only up to 200 m and 500 m in east-west and north-south direction respectively in case of the given topography. The gravitational tilt effect of the rain falling on regions located beyond these radii is negligible. The loading effect of the water accumulated on the surface, regarding its mechanism and its admittance, is basically the same as for the *air pressure – surface tilt* coupling. It makes no difference in the tilt observations either the air pressure changes or the weight of the rain water loads the surface at the given observation sensitivity (nrad).

In the *second phase* of the process, when the percolation/infiltration of the rain water into the underlying sediments and rocks (limestone) starts tilt changes having even 10 – 100 times larger than that of experienced in the first phase can be detected, in function of the amount of cumulative precipitation. The source of it, however, is the change of the pore pressure, the signature of which is very consistent. It is, of course, a consequence of the constant geological environment and structure around the observatory. The parallel gravimetric and tilt measurements give a very consistent picture of this phase in two parameter space (gravity change and surface deformation).

Based on a simple time variant model a quantitative analysis was performed. The model consists of a few parameters: saturation at the start and at the end of the process, porosity and the density of the water. Numerical experiments done by this model led to certain parameter combinations, which are, on one hand realistic and on the other, able to simulate the observed gravity changes with a few nm/s^2 of accuracy.

The results described above are all affected by the so called cavity effect (just like in the case of tidal tilt effects) which enlarges the observed tilts in N – S direction (perpendicular to the axis of the tunnel). In the second phase the average tilt ratio $\tau_{E\text{-}W}/\tau_{N\text{-}S}$ is -0.15. It means that tilts in N – S direction are usually 6 times larger than in E – W direction. Its azimuth is (160 – 170) degree. Unfortunately it could not be investigated further if this large difference is purely the result of the cavity effect or it is dominated by anisotropy of the rock structure (karstic structure, fractures, etc...). Probably this latter is the reason because $0.5 \leq \tau_{E\text{-}W}/\tau_{N\text{-}S} \leq 1$ holds for diurnal and semi-diurnal tidal wave groups. The results above were published in a D1 journal Hydrology and Earth System Sciences.

The small systematic deviations between the gamma factors derived from the tidal analysis of the time series recorded by LTS and iWT draw our attention to the calibration problem of high resolution tilt meters. Unfortunately there is no international standard for angle/tilt and the old mechanical devices (level balances) cannot be used to test the characteristics of high resolution tilt sensors at nrad level due to their limited accuracy (±250 nrad). Based on our experience and results obtained in the framework of a previous OTKA project K101603, a metrologically sound and unique method was developed to test these instruments in the range of the tidal tilt effects (10 nrad – 50 nrad). It is based on the Newtonian mass attraction and its feasibility was studied for the specific case of the moving mass gravimeter calibration (MMC) device of Mátyáshegy Geodynamical Observatory (MGO). The theoretical computations showed that a calibration signal having 15 nrad peak to peak amplitude can be generated by the vertical movement of the 3 tons cylindrical ring which is less by 1 order of magnitude than the usual resolution capability of the traditional mechanical devices (e.g. level balances). The uncertainty of the calibration signal was also investigated in terms of the density inhomogeneities of the metal ring. It was proven that such inhomogeneities, which are metallurgically realistic in their measure and were applied in the simulation studies (using either random or systematic density distribution models) cannot influence (degrade) the signal accuracy significantly. The results of the investigations were summarized in a paper published in the D1 journal Journal of Geodesy.

In autumn 2022 we applied the calibration method in practice. Between 2022.09.19 – 2022.09.23 the Hungarian OTKA team members tested 3 LTS sensors (SOP5, SOP6, SOP7) with the MMC device of the MGO. After two days of feasibility tests of different sensor configurations 37 calibration experiments, taking about 25 min one by one, were done altogether (Fig. 2).

The results of the experiments, however, do not fit to the theoretically expected output because the tilt signal derived as the difference between the tilts observed by the so called peripherally and centrally positioned sensors (Fig. 2) is about 10 times larger (150 nrad) than the calculated one (15 nrad). A possible physical reason of this discrepancy can be the large magnetic field variation inside the metal cylindrical ring due to its shielding effect. This is a well know disturbing factor for calibration of metal spring type gravity meters but not yet investigated for tilt sensors. Therefore the methodology of the magnetic measurements had to be also elaborated. Due to the special positioning of the tilt sensors required by the theoretical considerations the magnetic field variations B_x, B_y and B_z had to be simultaneously measured during the up and down movement of the cylindrical ring mass both in peripheral and central positions. Two chip sized magnetometers (HMC5983, HMC5883) were used in 19 experiments (25 min/experiment) done between 2022.10.06 – 2022.10.07 in order to determine the magnetic field variations in function of the time needed for the movement of the cylindrical ring up and down (700 s – 700 s). The results show that the magnitude of changes is similar to that of the total magnetic field of the earth (ΔB_x=+4 μT, ΔB_y=+16 μT, ΔB_z=+46 μT). Due to the common radial orientation of the investigated axes of tilt and magnetic sensors the variation of the magnetic force field in Y and Z may influence the tilt in radial direction.

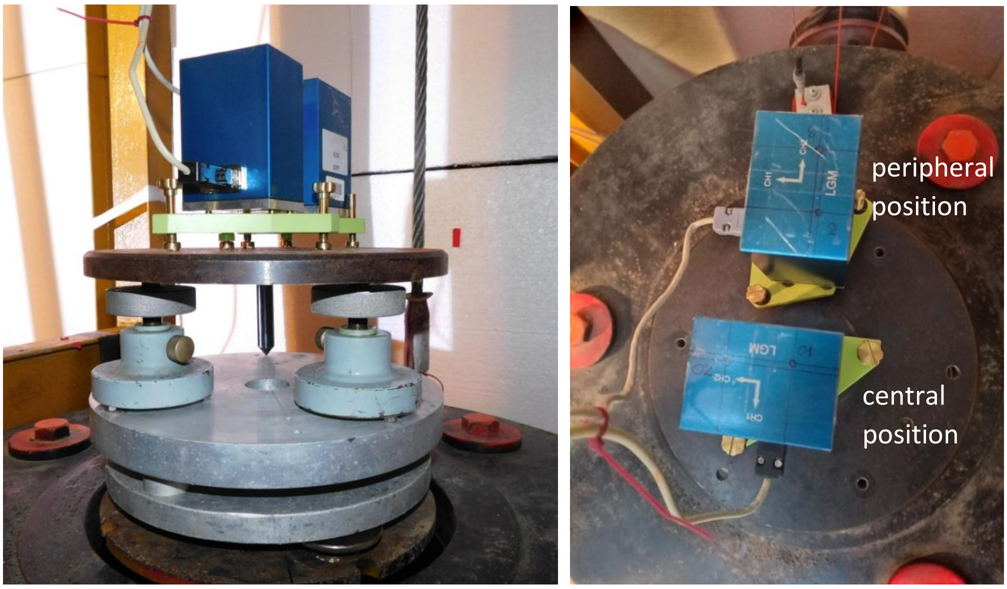

Fig. 2. The experimental configuration of the tilt sensors (blue boxes) prepared for testing them by the moving mass calibration device of Mátyáshegy Geodynamical Observatory, Budapest

The magnetic response of the tilt meters were tested in Merritt- and Helmholtz coil systems simulating the magnetic field variations observed during up and down movements of the MMC device operated in the MGO. Since a 3 m x 3 m x 3 m Merritt coil system, dedicated to magnetic investigations, is available in the tunnel system of COBS therefore the feasibility of it was investigated on 23.11.2023. The mechanical structure of the device, namely the central test table, where the instruments to be investigated have to be installed, however, is not suitable to test the magnetic response of such sensitive mechanical instruments like the Lippmann type tilt sensors. Moreover the coil system cannot be controlled remotely so the presence of the operator disturbs the thermal stability of the vault which influences significantly the mechanical stability of the test table hosting the tilt sensors. But the system was not prepared for the simulation of magnetic field changes by complex wave forms either. Consequently, the tests to indicate the magnetic response of the tilt sensors failed. Therefore it was decided to repeat the experiment in the seismic tunnel of COBS where large and stable concrete piers are available and where the small Helmholtz coil system of EPSS, Sopron could be installed and isolated from external disturbing effects easily. During March 2023 the coil system was tested using the tri-axial HMC5983 chip magnetometer in the geodetic laboratory of EPSS, Sopron to check how accurately the magnetic variations observed at MGO can be simulated by it. After fine tuning of the input functions of the GW Intek current generators by István Lemperger (EPSS Sopron) the results show that the dispersions of the differences between the magnetic fields to be simulated and observed are ±0.3 μT and ±0.5 μT at 3.5% and 1.5% scaling bias along axes H_x (north) and H_y (up), respectively, which is sufficient. The testing of the LTS SOP6 sensor in the Helmholtz coil system using simulated magnetic field variations was done on the 27.04.2023 at COBS. Due to the very low microseismic background noise of ±5 nrad, the one week long relaxation time of the tilt sensor left after its installation and the stable mechanical set up (Fig. 3 left) it was proved that no magnetic effect could be identified in the stationary tilt signals recorded during simulations (Fig. 3 right). The results were presented in IAG G06 poster session of IUGG Gen. Assembly, Berlin, 2023 and will be published in the near future. Up to now, however, we could not give adequate answer for why the tilts observed during the tests of the tilt meters by the MMC device do not fit to the theoretically computed, gravitationally induced tilt signal.

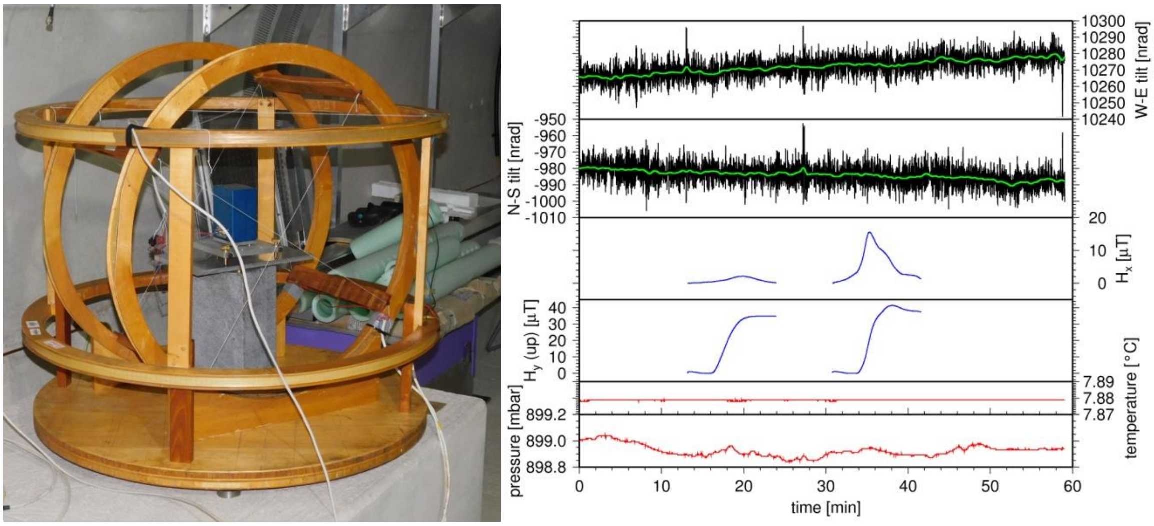

Fig. 3. The set up of the Helmholtz coil system and the LTS SOP6 sensor for magnetic tests at the COBS (left). The observed tilts, the simulated magnetic field variations and the meteorological parameters (right)

Since January 2013 when 5 stations of the Mur-Mürz monitoring network became operational about 9 earthquakes with M>3 have occurred along the fault line. These were clearly detected by the tilt meters of the network and the recorded tilt time series are consistent with the waveforms observed by the seismological stations collocated at COBS, PTNA, SOPGO. Therefore algorithms were developed for the time determination of the first arrival of seismic waves from the tilt waveforms. Its comparison to the first arrival times derived from ground velocities (i.e. seismological records) showed good agreement (~0.1 sec) which is consistent with the 5 Hz data sampling rate ($\Delta t = 0.2$ sec) of the tilt meters. A pre-processing scheme was also elaborated and programmed for the visual analysis of animated time series of 2D tilt vectors recorded during events, for the selection and visualization of tilt vectors generated by compressional P waves and for the directional analysis of the tilt vectors. Moreover, two solutions (a geometric and a numeric one based on L2 norm adjustment) were adapted and programmed for the determination of epicentre location of local earthquakes and the preliminary results of their application are very promising. The deviation between epicentres $\left|\hat{X}_{seis} - \hat{X}_{tilt}\right| \leq 1$ km whereas the RMS of the location coordinates $\mu_{\hat{X}_{tilt}} \leq 1.5$ km in the best cases. The Phyton codes for these computations were written by Enikő Barbély, who de facto joined the OTKA team only in September 2023, in the last semester of her MSc studies in Geodesy (at TU Budapest) and prepared her diploma theses supervised by some OTKA participants (Dr. Meurers, Dr. Benedek and Dr. Papp). Now the OTKA team works on a paper summing up the up to date results on the seismo-tectonic application of the tilt data recorded at the stations of Mur-Mürz monitoring network.

2) Technological developments

2.1) Development of the biaxial differential interferometric hydrostatic tilt meter (iWT^{+})

As it was already mentioned the EPSS procured an experimental configuration of the device (iWT) developed by the Finnish Geospatial Institute in 2014 which was successfully applied in a collocated set up with a Lippmann-type 2D tilt meter in COBS for the monitoring of ground tilt changes until 2018. In the meantime, however, several conceptual and technical deficiencies of the system were discovered so the international team operating the instrument decided to correct the problems and improve the device for a complete, biaxial system, capable to eliminate systematic instrumental effects by differential measuring technique and increase the observation sensitivity providing subnanoradian resolution. The main idea was to construct a "driftless" instrument, based on a Fizeau type interferometer configuration, which can be used as a reference for other compact tilt sensors. Without such a "metrological standard" the instrumental drift cannot be separated from long term steady tilt changes of e.g. tectonic origin. By the end of the project the re-designed and re-manufactured system was installed at the Conrad observatory (Fig. 4 right).

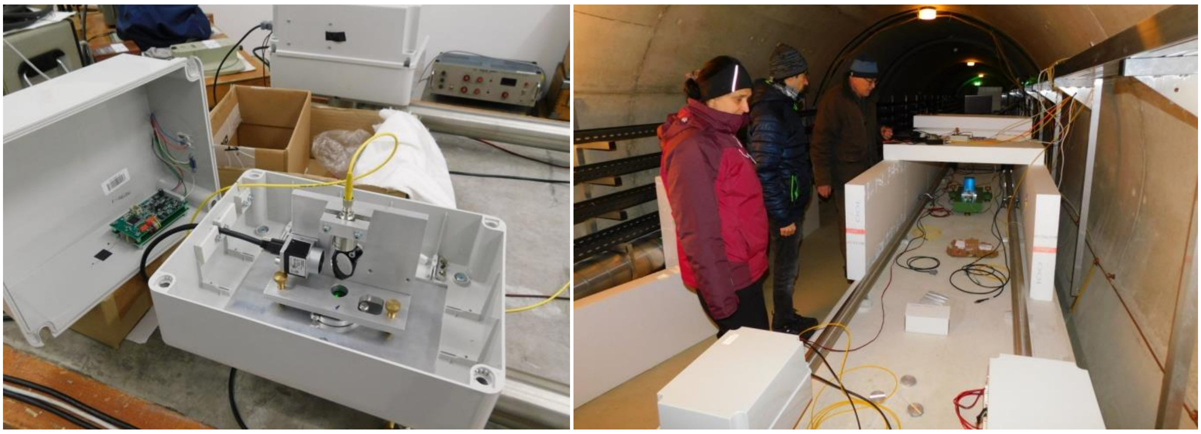

Fig. 4. The re-designed interferometer unit and the built-in electric circuit panels of the array of high resolution meteorological sensor (left). J. Benedek, Cs. Szabó and F. Bánfi in the vault during the installation of iWT⁺

Most of the necessary mechanical works (Fig. 4 left) were done at the mechanical workshop of the EPSS Sopron by F. Bánfi electrical engineer and F. Schlaffer metalworking technician, both retired from EPSS. Only the stainless steel tubes, the joints fitting the tubes and the so called end pots containing the plano-convex lens which reflects the incident laser light back to the water surface inside the end pot for generating the optical interference (Newtonian fringes) had to be purchased from or manufactured by external suppliers. Regarding the optical elements, most of those were acquired from Thorlabs (USA) but some of those were ordered from the Hungarian company OPTILAB. Since the laser light generated by Lasos (Germany) lasers (Fig. 5 left) have to be forwarded from the entrance of the vault of COBS to the interferometer units 100 m long optical cables are applied for this. As Fig. 4 (left) shows all the four interferometer units are equipped by a meteorological sensor array containing 3 thermistors, a barometer and an air humidity sensor for the monitoring of the state of the environment.

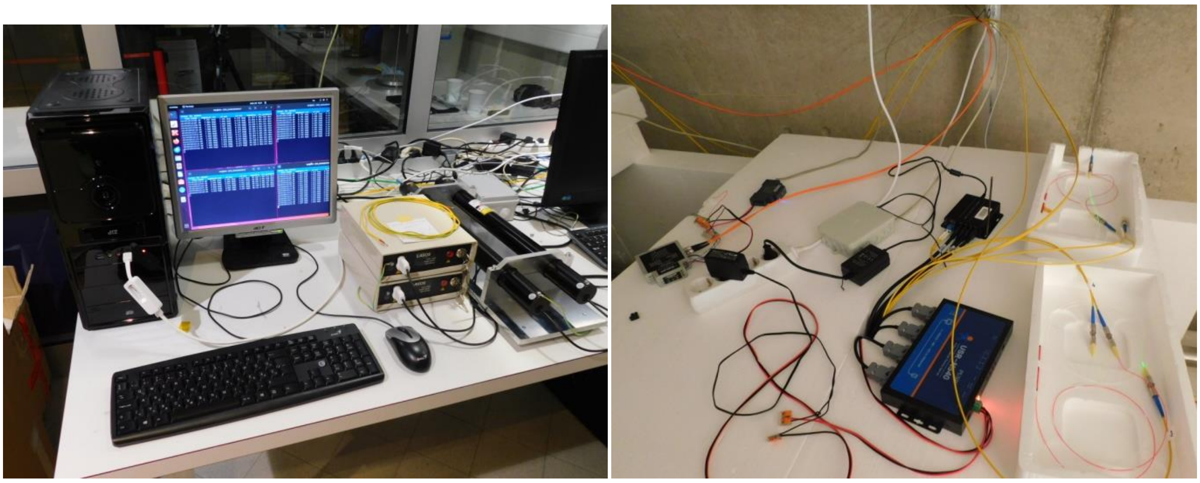

Fig. 5. The control table of iWT⁺ system with the laser tubes (left). Some media converter units and fibre splitters for data and laser light transmission, respectively (right) to bridge the 100 m distance

The re-designed interferometer units make the adjustment of the Newtonian fringes much easier than what was provided by the original experimental construction. By the splitting of the laser beam (λ=543 nm) one laser tube can supply 2 interferometer units at the same time which is a cost effective solution for a longer time span, regarding the price and limited lifetime of the laser tubes. Although the hardware is operational some software issues has not been solved entirely. The original software coded in C++ was optimized for the Basler A602f (firewire) digital camera which has been outdated in the meantime. The new models use usually USB3.0 data transmission protocol and the original data acquisition and image processing program system had to be adapted to it. At the moment the old iWT software has an access to the image stream sent by the Basler aca1920-40um cameras with 40 pictures/sec frame rate but the image processing module is not operational yet. Unfortunately, the Finnish OTKA participant, Hannu Ruotsalainen retired soon after the COVID crisis which delayed the progress of the software adaptation and now it has to be solved by the EPSS members of the OTKA team. Although we tried to involve an industrial partner (Dolphio Technologies Kft) but our problem was regarded as a sales problem not as an R&D cooperation for innovation. In the last minute an MSc student Csaba Németh, studying at TU Budapest, Faculty of Electrical Engineering could be involved and he could solve the adaptation of the new camera type to the old software. But the image processing module has to be improved still.

2.2) Development of a Raspberry-PiZero-based autonomous data logger

As a by-product of the efforts to make the Mur-Mürz monitoring network operational a cost effective autonomous data logger based on the combination of microcomputer technology with GSM and GPS utilities was created (Fig. 6) by the cooperation of T. Molnár and Cs. Szabó OTKA participants who are technical assistants of EPSS. Due to the lack of the electric power supply grid, wired internet access and the low rate GSM coverage at BREBA station an RPiZero-based data logger had to be developed. It controls the data acquisition, stores the daily files locally and transmits “life signals” using scheduled SMS services. An SMS-based program package was created to control the system remotely and a GPS module was integrated to the logger to provide time synchronization with the necessary accuracy. This fully functional Raspbian linux platform is a perfect and cheap solution (200 EUR – 300 EUR) to manage the required high speed data acquisition and if a solar panel is connected to it its operational time can be extended “infinitely”. Otherwise a big car battery can supply it with electric power for 1.5 months.

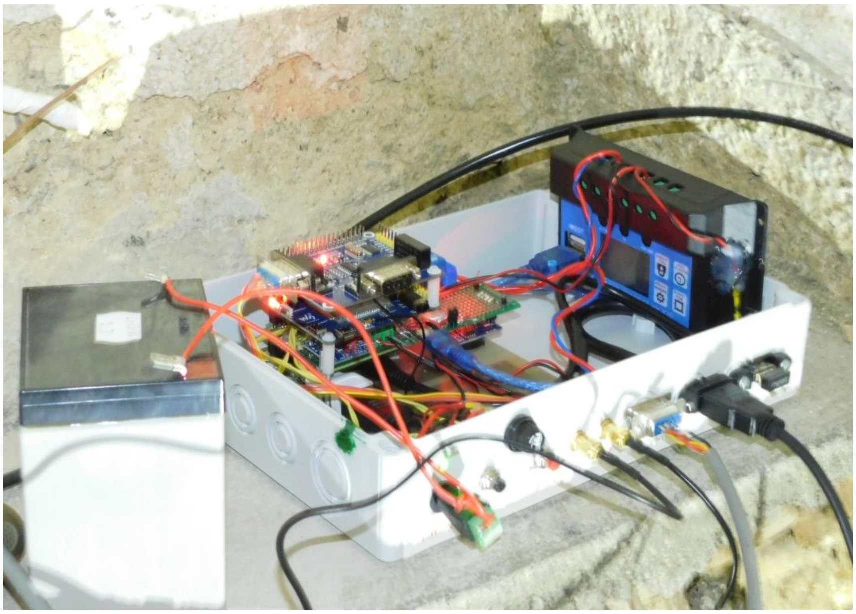

Fig. 6. Prototype of an RPiZero-based autonomous data logger developed by the technical staff of the OTKA project and installed at BREBA station

3) Problems counteracting the planned progress of the project

The main problem was the continuous loss of operable manpower during the lifetime of the project. Until the start of the COVID crisis we could keep the planned timetable even if the order of tasks had to be exchanged already in 2019. During COVID all the in person meetings and workshops had to be cancelled and this way the common interest in progressing the project was decreased in case of the foreign OTKA participants by the end of COVID crisis. After the crisis, i.e. nearly at the originally planned closing time of the project, two foreign partners, B. Meurers and H. Ruotsalainen, retired which made further difficulties. At the same time our efforts to attract and keep young people (undergraduate or graduate students) in the project failed. Although we officially involved and supported Marcell Szántó and Dániel Csáki from the budget of the project and D. Csáki, as an MSc student was a co-author in one of our D1 publications, we lost the cooperation with both of them. Fortunately, Enikő Barbély, when she searched for a topic of her MSc theses, was guided to the EPSS OTKA team and by this step a fruitful cooperation started resulting in an excellent defence of her theses work. Now she prepares for the entrance examinations for studies at the PhD school of TU Budapest and is deeply involved in the research of the OTKA team. Csaba Németh, MSc student of TU Budapest, could also be contracted to solve the adaptation of the new Basler USB camera to the old iWT software.