A Geodynamic Network for the Monitoring of Seismo–Tectonic Activity Along the Mur–Mürz Fault Line (Austria)

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Abstract

The Mur-Mürz fault line is an active boundary between the geological units of the Eastern Alps and the Pannonian basin. Some moderate earthquakes shake this densely inhabited border area between Austria and Hungary every year, consequently special attention is paid for the research of its seismo-tectonic activity. Beyond the seismological monitoring the continuous observation of long periodic crustal deformations may efficiently help the understanding and interpretation of the mechanism of tectonic processes connected to the seismological events. Therefore, in the national networks of seismometers operated in and around the area (Vienna basin), three seismic stations were completed by high resolution tilt meters and two more independent tilt stations were installed on a 51 km by 25 km area in east-west and north-south directions, respectively, on both sides of the fault until 2023. This report shortly introduces the observations sites, their instrumentation and technical infrastructure as well as the processing methodology of the time series of recorded ground tilts. It also refers to the achieved results briefly.

Keywords: high resolution tiltmeter, Mur-Mürz fault line, monitoring network, data corrections.

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Introduction

Due to the recent tectonics of the Mur-Mürz fault line separating the Eastern Alps and the Pannonian basin near to the state border between Austria and Hungary some earthquakes of small and moderate magnitude may occur from year to year. There were 9 such events ($2.5 \leq M \leq 5$) along the fault between January, 2023 and April, 2024. Since the area which includes the Vienna basin is densely inhabited the monitoring of the seismo-tectonic activities using different kinds of devices and technologies is a justified public need. Although the national seismological networks of Austria, Slovakia and Hungary watch and record continuously the 3D ground speeds at their nearby stations the instrumentation of some were gradually completed by high resolution tiltmeters. This improvement was financed by the Eötvös Loránd Research Network, Hungary in the framework of an application call for infrastructure development (ELKH IF-1/2021)[†]. So nowadays at 3 sites co-located seismometers and tilt meters are operated by GeoSphere Austria and HUN-REN Institute of Earth Physics and Space Science (EPSS) in cooperation. The other two sites run only tiltmeters, but all the sites are installed in underground facilities (abandoned mine vaults, tunnels, cellars) providing high temperature stability (typically below 0.01° C/day) required for the undisturbed observations. The search for the location of one more suitable station is currently under discussion. The sites are situated nearly along a line between the Conrad Observatory (COBS), Austria and the Sopronbánfalva Geodynamical Observatory, Hungary (SOPGO) crossing the fault in south-east and north-west direction. Both observatories have been equipped also by recording gravity meters (COBS: GWR Superconducting Gravimeter, SOPGO LCR G949 spring type gravimeter) applied to measure and record the time variation of the gravity field. SOPGO is equipped also by a 20 m long extensometer. The distance between COBS and SOPGO is about 60 km. The network and its surrounding can be seen in Fig. 1.

Network Stations and Their Instrumentation

Stations

All the stations and the instrumentation installed and operated there are listed in Table I. The depth of the observation sites measured from the ground surface varies between 5 m (SOPPAL) and 30 m (COBS).

- Conrad Obsevatory (COBS), Geosphere, Austria The Conrad Observatory is located 60 km SW of Vienna (Austria) in a carbonate region belonging to the Eastern Alps, close to the top of the Trafelberg Mountain at an elevation of 1050 m. The Trafelberg Mountain itself is part of the Northern Calcareous Alps consisting of Main Dolomite and Wetterstein/Gutenstein

[†]The project budget was 14 million HUF (∼35.000 EUR).

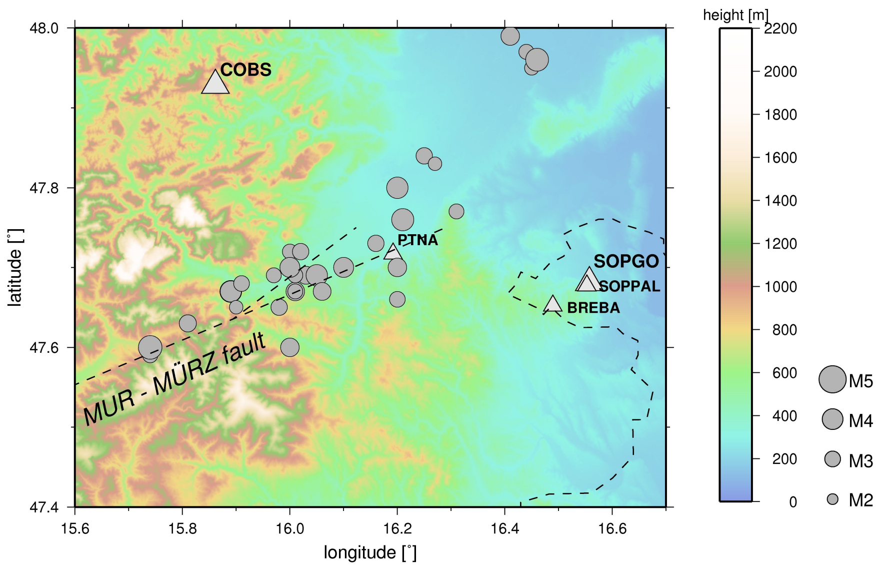

Fig. 1. The locations of the observation sites (triangles) and the epicentres of earthquakes (circles) occurred recently (30.01.2008 01.02.2024) on the research area. The color coded background picture shows the SRTM3 topography of the area (Jarvis et al., 2008). The dashed line shows the state border between Hungary and Austria.

limestone (Blaumoser, 2011; Bryda and Posch-Trözmüller, 2016). The observatory consists of a 144 m long and 3 m wide tunnel drilled in an EW direction (https://cobs.zamg.ac.at/gsa/index.php/en/observatory/virtual-3d-tour-sgo).

The facility has an outstanding infrastructure and provides a very stable environment for geodynamical investigations (e.g. seismological monitoring, observations of earth tides and loading effects). Table II shows the results of statistical and spectral analysis of more than 4 years of temperature data of the tunnel at the pier where the LTS SOP2 and the iWT tiltmeters are installed.

Between August 2014 and February 2020 the Geodetic and Geophysical Institute (GGI, Sopron, Hungary, predecessor of EPSS) operated a 5.5 m long Michelson–Gale-type interferometric water level tiltmeter (iWT), in order to monitor E–W ground tilts. It was designed and built by the Finnish Geodetic Institute (FGI; Ruotsalainen et al., 2016a,b; Ruotsalainen, 2018) and installed on a 6 m long pier in the middle of the tunnel.

In July 2015, a high-resolution Lippmann tilt sensor (LTS SOP2) was installed by GGI close to the iWT on the same pier (Papp et al., 2019). The LTS provides both NS and EW tilt time series. Local thermal insulation, made from 10 cm thick polystyrene plates, was applied for both tilt instruments. The sampling rate of the SOP2 tiltmeter was 1 Hz until February 2022 and since then the LTS has been recording with 5 Hz. The collocated measurements of the two type of tiltmeters (iWT and LTS SOP2) allow for a comparison of the response of tiltmeters with long (several metres) and short (a few decimetres) base lengths.

The Central Institute for Meteorology and Geodynamics (ZAMG, Austria, predecessor of Geosphere Austria) had operated the superconducting gravimeter (SG) GWR–C025 at COBS over 11 years (2007–2018).

- Sopronbánfalva Geodynamical Observatory (SOPGO), EPSS, Hungary The Observatory, established in 1965 and located close to Sopron, is in the Sopron Mountains. The area belongs to the extensions of the Eastern Alps, which is formed by metamorphic rocks of Palaeozoic age, such as gneisses and various mica schist–granites (Haas, 2001). The observatory is a 60 m long artificial gallery (Mentes, 2010). On the 18th of January, 2023 the LTS SOP3 tiltmeter was installed in the deepest part of the tunnel system, in a chamber which was originally made to host so called horizontal pendulums. The selection of this final position of the tiltmeter was preceded by a series of test measurements at three other locations which proved to be inadequate because of the noise level and frequent disturbances (sudden steps) observed in the tilt time series. Nowadays the urban surrounding of SOPGO is not really ideal due to the city and the railway traffic. The railway line connecting Wien and Sopron runs approximately 900 m away from the station. It, however, provides very stable thermal conditions (Table II). The application of an insulation hut certainly contributes to this excellent thermal stability (Fig. 2).

An STS2 seismometer (seismological station code: SOP) and a 20 m long extensometer are operated in an 8–10 m distance to SOP2 sensor.

- Cellar of Pauline/Carmelites Cloister Sopronbánfalva (SOPPAL), Eszterháza Cultural-, Research- and Festival Center, Non-profit, Public Benefit Ltd, Hungary The LTS SOP4 sensor is installed in a small side chamber of the southern part of the cellar system on a concrete pillar. Although the cellar system is fully abandoned and permanently closed from the public, the usual local thermal insulation hut is applied. 0.1 °C/year temperature increase was detected. The results of spectral analysis of temperature data are shown in Table II.

- Brennbergbánya Szálasi bunker (BREBA), Fertő–Hanság National Park, Hungary The LTS SOP5 sensor is installed in the southern part of the vault system on a concrete pillar with thermal insulation (Fig. 2). The distance between the opening of the vault and the pillar is only 25 m. The amplitude of the annual thermal variation is 0.2 °C (Table II) due to the passive air ventilation system. This is an order of magnitude larger than that of other stations.

Table I. The stations, their instrumentation and some auxiliary data. Abbreviations: LTS – Lippmann type high resolution tiltmeter, SOP2, ..., SOP7 – sensor names, GWR SG – GWR superconducting gravity meter, LCR G949 – LaCoste and Romberg G type gravity meter, STS – Streckeisen seismometer, iWT – FGI type interferometric water tube (hydrostatic) tiltmeter. For further explanations see the sections from - *Conrad Obsevatory (COBS), Geosphere, Austria* to - *Seismological Station at Georgistollen, Pitten (PTNA), Geosphere, Austria.*

Stations	WGS84 (λ, φ, h)	Instruments and their owner	Operation period	Sampling rate
COBS	15.8613° 47.9282° 1045 m	LTS SOP2 (Hungary)	2015.07–	1 Hz, 5 Hz
		GWR SG-C025 (Austria)	2007–2018.11.17	1 Hz
		LCR G949 (Hungary)	2017.11.23–2021.01.25	1 Hz
		iWT (Hungary)	2014.08.14–2020.02.09	15 Hz
		STS2.5 (Austria)	2002	100 Hz
SOPGO	16.5526° 47.6771° 298 m	LTS SOP3 (Hungary)	2022.01.26–	5 Hz
		LCR G949 (Hungary)	2021.06.16–	1 Hz
		extensometer (Hungary)	1990–	1 min
		STS2 (Hungary)	–1994 2011–	analog 100 Hz
SOPPAL	16.5526° 47.6771° 263 m	LTS SOP4 (Hungary)	2022.04.28–	5 Hz
BREBA	16.4893° 47.6518° 415 m	LTS SOP5 (Hungary)	2023.06.15–	5 Hz
PTNA	16.1920° 47.7171° 370 m	LTS SOP7 (Hungary)	2023.01.13–	5 Hz
		STS2.5 (Austria)	2023.01.13–	100 Hz

- Seismological Station at Georgistollen, Pitten (PTNA), Geosphere, Austria PTNA station is located in a vault of an 18$^{\text{th}}$ century iron mine where GEOSphere operates a seismological station too. The LTS SOP7 sensor is installed in a distance of about 300 m from the entrance of the vault on a concrete pillar, in co-located position with the STS2.5 seismometer. The usual local thermal insulation hut is applied (Fig. 2). The results of spectral analysis of temperature data are shown in Table II.

Table II. The results of main statistics and spectral analysis of temperature data registered by LTS sensors.
∗: cannot be estimated due to the short data length

Stations	Analyzed time interval	**Mean** temperature [°C]	Coefficient of **linear trend** [°C/year]	Amplitude of **annual** variation [°C]	Amplitude of **diurnal** variation [°C]	Amplitude of **semidiurnal** variation [°C]
COBS	2016.04.19–2020.04.03	8.468	-0.014	$4\ 10^{-3}$	$4.4\ 10^{-5}$	$1\ 10^{-4}$
SOPGO	2023.01.18–2024.11.06	12.368	0.022	$3\ 10^{-3}$	$1.6\ 10^{-4}$	$2\ 10^{-4}$
SOPPAL	2022.04.30–2024.09.17	10.842	0.110	$7\ 10^{-2}$	$2.5\ 10^{-4}$	$2\ 10^{-4}$
BREBA	2023.06.18–2024.08.04	10.738	∗	$2\ 10^{-1}$	$5.8\ 10^{-4}$	$1\ 10^{-4}$
PTNA	2023.03.07–2024.07.30	12.358	∗	$3\ 10^{-3}$	$1.6\ 10^{-4}$	$3\ 10^{-4}$

Fig. 2. A typical insulation hut of the tiltmeters applied at most sites.

Comparison of the Noise Characteristics of the Stations

Selecting a bit longer than 1 month continuous and overlapping time segments from the time series of N–S ground tilt data recorded at all the stations in 2023, their power spectra were determined and plotted for demonstration in Fig. 3. It clearly indicates that COBS station has the lowest noise level above 1 Hz (up to 2.5 Hz) which is basically dominated by anthropogenic noise. Here the peak amplitude varies between 0.01 mas (PTNA) and 0.03 mas (SOPGO) and generally it is higher by almost two orders of magnitude than what characterizes the observed noise level at COBS in the same frequency range.

There are only slight differences between the powers in the range of microseismic noise (0.06 Hz–0.2 Hz) generated by the interactions of atmospheric and hydrological processes in the North Atlantic region (e.g. Papp et al., 2012).

The large differences at lower frequencies, dominantly below 0.01 Hz, are mainly caused by the abrupt changes of the tilt which indicates the dynamics of local deformations of the sites. Whereas steps (sudden tilt changes) are small and rarely contaminate the data observed at COBS, SOPGO and SOPPAL, the time series recorded at the other two sites BREBA and PTNA are disturbed by steps and transient signals frequently. The reason of it could be either local (e.g. type and structure of the surrounding rocks) or regional, connected to the seismo–tectonic activity of the Mur–Mürz fault. PTNA is located just in the fault zone but both stations are operated on areas of abandoned mining activity. Thermal and hydrological impacts (Meurers et al., 2021) can also induce disturbing transient signals lasting for several days or even weeks in the time series.

The two sharp spectral peaks show the diurnal and semidiurnal wave group components of the tidal tilt spectrum.

Instrumentation

- LTS The Lippmann-tiltmeter is a very compact instrument (Fig. 4), equipped with two pendulums which provide tilt angles measured in two perpendicular directions (X/Ch#1 and Y/Ch#2) with nrad resolution (1 nrad = 10^{-9} m/m = 0.2 milliarcsec). Except COBS the orientations of the X and Y pendulums are N–S and E–W, respectively. The sign of tilt is positive in N and E directions. At COBS positive X and Y tilts mean tilt to E and tilt to S, respectively. An integrated meteorological station measuring the air temperature, -humidity, and -pressure is also build in inside the cover box of the instrument. At present the data provided by the tiltmeters are recorded with 5 Hz sampling rate at all stations.

- LCR G949 A LaCoste–Romberg G type gravity meter (LCR G949) purchased in 2000 has been used for more than two decades at the Geodetic and Geophysical Research Institute and its successors for different purposes. The instrument, originally manufactured for field surveys, was improved gradually to a

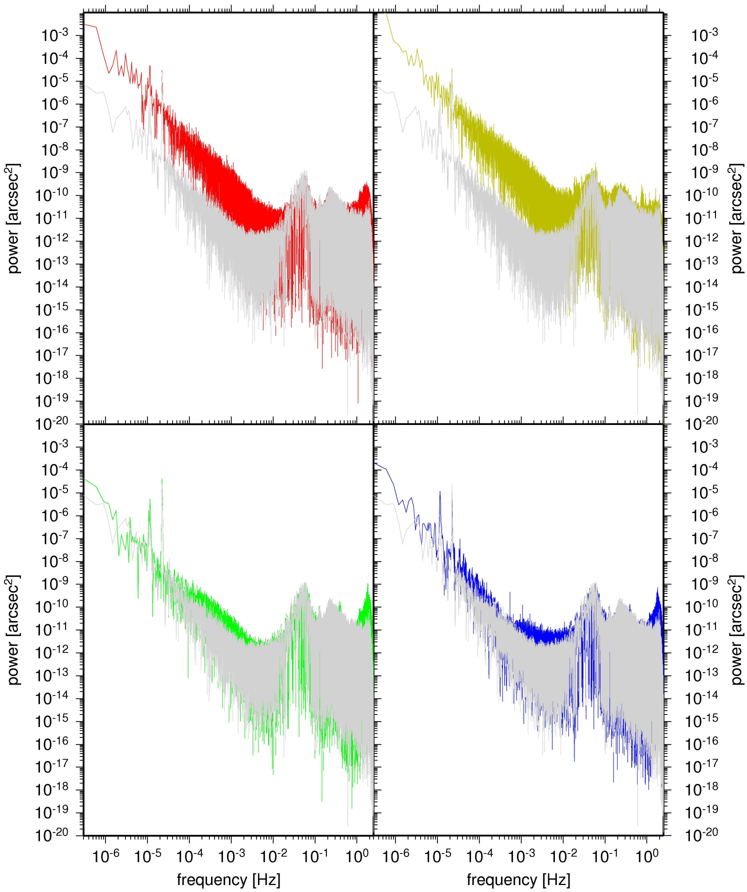

Fig. 3. Comparison of PSDs of N–S ground tilt time series observed at the monitoring stations of the Mur–Mürz fault line. The PSD of data recorded at COBS is the reference (grey), the other curves show PSDs of SOPGO (green), SOPPAL (blue), BREBA (red) and PTNA (yellow) stations.

complete and continuously operable gravity tide recording system in 2010–2014 by the scientific and technical staff of EPSS (Fig. 5a). Most of the hardware and software components necessary for that were designed, developed and made at the Institute. The complex reading system of the instrument controlled by a PC provides several types of data, which are recorded with 1 Hz sampling rate. For further details see the paper by Papp et al. (2018).

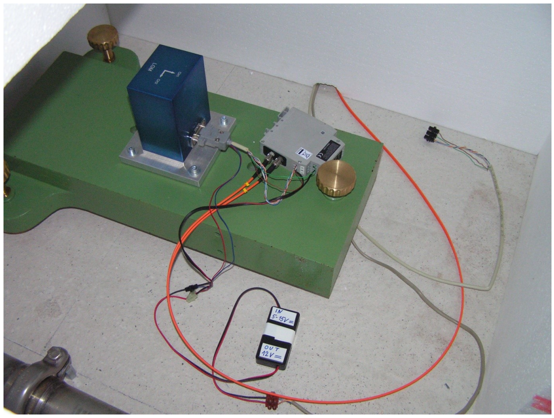

Fig. 4. The LTS SOP2 tiltmeter (blue cube) installed at COBS. Its heavy iron instrument platform (green) was made in the mechanical workshop of EPSS.

The tidal recording system has been operational at SOPGO since June, 2021. Before that it was used at several places in the Pannonian basin between 2012 and 2021 (Papp et al., 2018). Until now the longest time series provided by it was recorded at the Conrad Observatory (Barbély, 2023) between autumn of 2017 and June 2021 where it operated side by side with the GWR SG C025 superconducting gravity meter (Fig. 5b).

a b

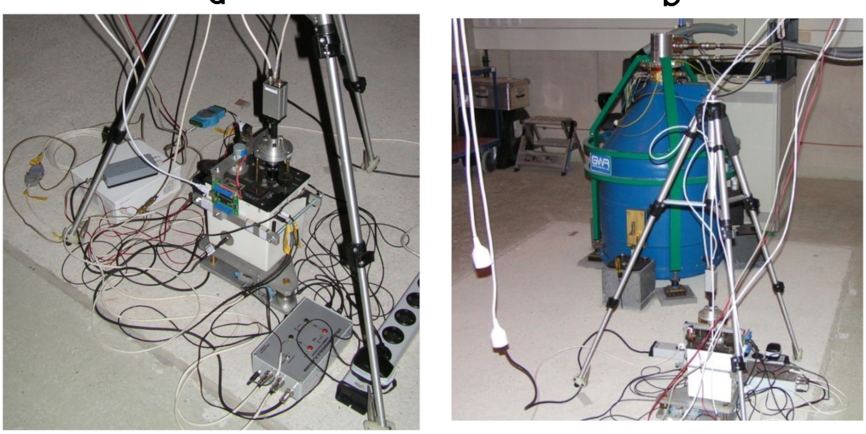

Fig. 5. (a) The complete gravity tide recording system. **(b)** The co-located setup of the GWR SG C025 superconducting- and the LCR G949 gravity meters at COBS.

Data Acquisition and Processing

Tiltmeter Data

At all the five stations (SOPGO, SOPPAL, BREBA, COBS and PTNA) the data is collected continuously on 5 channels with 5 Hz sampling rate. The channels consist of the tilt measurements along the x and y coordinate axes and the meteorological parameters (air temperature, -humidity and -pressure), measured inside the tiltmeter box, are recorded as well (Table III).

Table III. Example of some records of raw tiltmeter data recorded at station SOPPAL.

Timestamp	**X tilt [arcsec]**	**Y tilt [arcsec]**	**Temperature [°C]**	**Humidity [%]**	**Air pressure [mBar]**
20240919000000.00	-3.3406	7.4230	11.101	47.63	991.31
20240919000000.20	-3.3442	7.4232	11.101	47.60	991.31
20240919000000.40	-3.3422	7.4215	11.101	47.61	991.31
20240919000000.60	-3.3387	7.4231	11.101	47.62	991.31
20240919000000.80	-3.3361	7.4218	11.101	47.63	991.31
20240919000001.00	-3.3387	7.4220	11.101	47.64	991.31
20240919000001.20	-3.3403	7.4224	11.101	47.64	991.31
...	...	...	...	...	...

Data collection of tiltmeters is controlled by different Raspberry Pi platforms (RPiZero, RPi4). Remote access to the data collection systems is possible at each station. In case of internet access (COBS, SOPGO, SOPPAL, PTNA) a scheduled FTP process manages the data transfer of the daily data files. The measurements are updated hourly and are forwarded to the public web page (https://kepujsag.ggki.hu) maintained by EPSS Sopron. In case of lack of internet access (BREBA), the low bandwidth of the GMS internet service allows only one data file transfer per day. If an NTP server is unavailable (BREBA), then a GPS module card can be added to the system to provide time synchronization. In case of lack of mains electricity (BREBA), a fully autonomous data logger system characterized with very low current consumption (∼100 mA) has been developed. This system (sensor and data logger) can be powered by an 110 Ah battery providing 1.5 months of continuous operation. By the installation of a charging system connected to a solar panel the operation time could be arbitrarily increased without changing the battery.

For every day a sequential ASCII file is created the name of which is constructed from the station- and sensor names, a character string indicating the orientation and the directions of positive tilts of the sensors X and Y axes and the datum string followed by the file extension named tlt (e.g. soppal_sop4_+XN_+YE_20240919.tlt). The data acquisition method, coded in FreeBasic language, is fitted to both the internal sampling process of the sensor and its requested served reading method (i.e. software triggering) provided by the firmware of the tiltmeters. So a time stamp of a digital reading managed through RS232 serial interface represents the nominal mean time of two internal sampling segments of 0.1 s length, preceding and following the specific time stamp. It practically means the averaging of 32 samples taken at 160 Hz internal sampling rate. The recorded and compressed daily files are transferred to the HP RX2800 unix server of the EPSS together with some status plots of the running observations made on the fly at regular time intervals and displayed on https://kepujsag.ggki.hu website managed by EPSS. Then the daily files can be downloaded for further processing.

The original size of a daily file containing 432000 samples at 5 Hz sampling is about 26.8 MByte. Its compressed version takes about 3.6 MByte disk space.

Table IV summarizes some statistics of the stability of data recording. The averages of the number of missing samples due to instantaneous failure of data transmission and recording (average length of automatically filled gaps per day, column 7, Table IV) varies between 11 and 238 samples, depending on the stations and their examined time periods. The histograms of the missing data records of each station are presented in Fig. 6, where the dashed vertical lines indicate the average values (column 7, Table IV) in sample unit. The higher number of missing samples (column 6, Table IV) causing gaps longer than what can be automatically filled, is usually resulted in by technical breakdowns (e.g. power failure) of the local recording systems.

LCR G949 Data

The data are arranged in daily files (e.g. 20181125.dat), which contain the temporal change of gravity (Δg), and the image shift, both measured in pixels due to the special electro–optical reading unit developed for the continuous and automated recording (Papp et al., 2018). In addition, the (so called cross level) X and (so called long level) Y tilt measurements, indicating the momentary levelled position of the instrument, are also recorded through an A/D converter in mV unit (Table V).

Meteorological data provided by a Procontrol meteorological sensor (THP-05-LD) is recorded every minute in a separate file (meteo.dat). It contains the temperature in degrees Celsius, the humidity in percentage, and the air pressure in mBar units (Table VI).

The Structure of Data Storage

The systematically named daily files (see e.g., Section *Tiltmeter Data*) are organized and stored in a hierarchical folder system (Fig. 7). It starts at the level

Table IV. Some statistics of the missing data per stations. The maximum number of the recorded samples is 432000 per day at 5 Hz sampling rate. The statistics in columns 5, 6 and 7 refer to the time period under consideration (column 2), excluding the missing full days (their number is listed in column 4).

Station	**examined time period**	**length of examined time period [days]**	**number of missing days**	**missing data [%]**	**average daily missing data records**	**average length of filled gaps [sec/day]**
SOPGO	2021-03-13 – 2024-11-05	1333	15	0.54	2320	2.18
SOPPAL	2022-04-30 – 2024-09-18	872	13	1.03	4453	5.08
BREBA	2023-06-16 – 2024-10-12	484	0	0.37	1607	33.33
COBS	2022-07-29 – 2024-07-01	703	20	0.81	3484	47.54
PTNA	2023-01-14 – 2024-07-29	562	46	1.05	4538	37.76

Table V. Some example data recorded by the LCR G949 gravimeter.

Timestamp	**Delta g** [pixel]	**Image shift** [pixel]	**X tilt** [mV]	**Y tilt** [mV]
20181115000000	-138.5	13.0	-000.61	-000.23
20181115000001	-139.0	13.0	-000.59	-000.23
20181115000002	-139.5	13.0	-000.61	-000.23
20181115000003	-139.0	13.0	-000.61	-000.25
20181115000004	-138.5	13.0	-000.63	-000.25
20181115000005	-139.0	13.0	-000.61	-000.25
20181115000006	-140.0	13.0	-000.59	-000.25
...	...	...	...	...

of data type (e.g., LTS_data). The next sub-level is identified by the sensor name (e.g., sensor_sop2). Below that level there are sub-folders indicating the format of the daily files (e.g., TSF). Then the sub-folders, identified by station

Table VI. Meteorological data.

Timestamp	**Temperature** [°C]	**Humidity** [%]	**Air pressure** [mBar]
2018.11.25. 0:00	018,5	46	0583,2
2018.11.25. 0:01	018,5	46	0583,2
2018.11.25. 0:02	018,5	46	0583,1
2018.11.25. 0:03	018,4	46	0583,2
2018.11.25. 0:04	018,4	46	0583,1
2018.11.25. 0:05	018,5	46	0583,1
2018.11.25. 0:06	018,4	46	0583,1
...	...	...	...

names, where the sensor has ever been installed and operated, follow. In the station name folder, the sub-folders are identified by different sampling rates (5Hz, 1sec, 1min, 1h). This indicates that the time series stored on this level contain not only the original recorded samples, but also filtered and decimated data. Finally, in the last sub-folder level the measurement years are defined.

In addition, a possibility of quick statistical characterization of the daily tsf files (complete, incomplete, missing) for a given year is also provided by running an interactive graphical file listing utility developed for this purpose under HP Unix (Fig. 8). The required statistics are saved in a log file too.

Software Used for Data Processing

For the on-site visualization, compression and transfer of the recorded data a scheduled process is used parallel to the data acquisition software at each sites. It hourly starts:

1. the drawing of the status plots creating the corresponding BMP files directly from codes written in FreeBasic,
2. to convert the BMP files to PNG format to reduce size of about 600 Kbytes to about 5 Kbytes,
3. the compression (gzip utility) of the daily files before the data transfer starts,
4. the FTP process of the compressed daily- and status plot files.

For further visualisation, data processing and manipulation Tsoft is used. It is an open-source software package developed for the analysis of time series (e.g.,

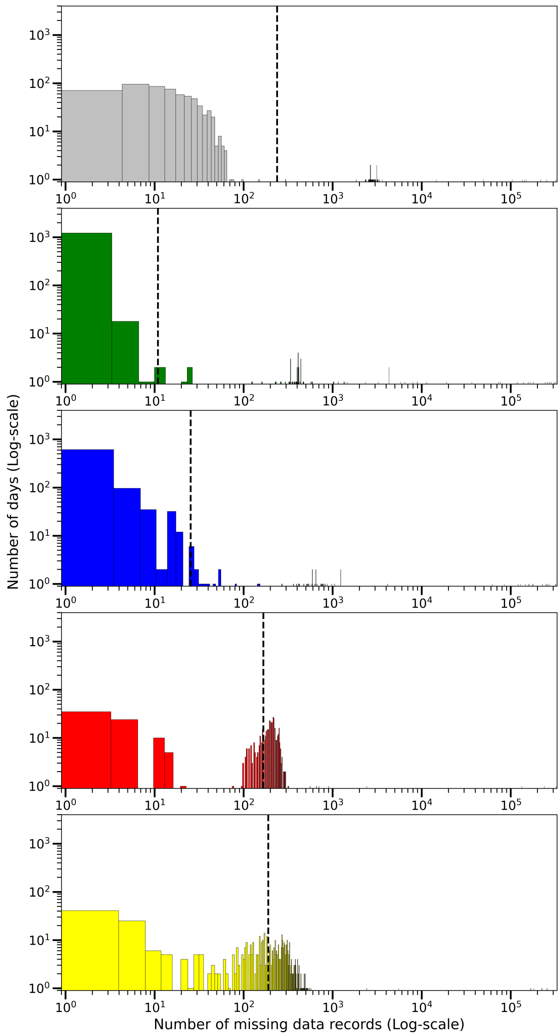

Fig. 6. Distributions of the number of missing data records per stations. The grey, green, blue, red and yellow colors from top to bottom indicate station COBS, SOPGO, SOPPAL, BREBA and PTNA, respectively. The dashed vertical lines represent the average value of missing records due to the failure of data transmission and recording (column 7, Table IV).

Earth tides) by the Royal Observatory of Belgium (Van Camp and Vauterin, 2005).

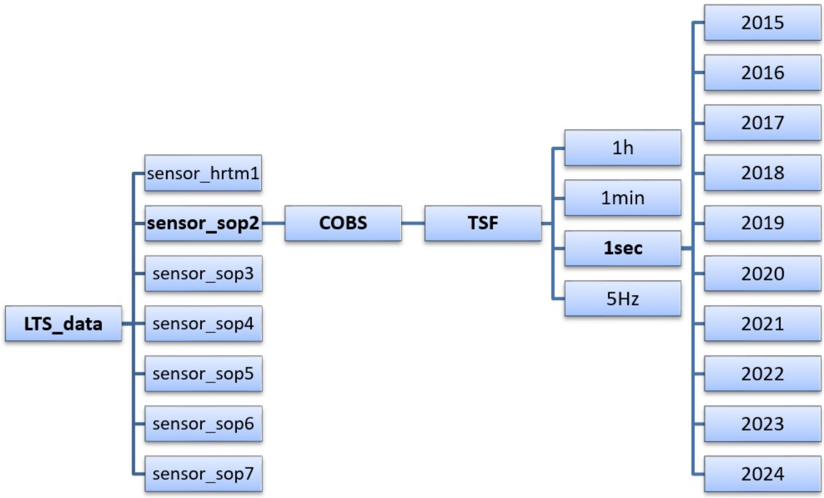

Fig. 7. Hierarchical folder structure to store daily TSF files measured by SOP2 sensor at the Conrad Observatory on QNAP disk unit mounted to rx2800 HP Unix server.

The input file format required by Tsoft is, however, different of that of the raw recorded data so a conversion utility applying a daily file based batch processing scheme is necessary. It was also developed at EPSS and its function is multiple. Beyond the format conversion it checks the consistency of data regarding formal record structure and the continuity of the time series. Short, few second long gaps can be filled on the fly by repeating the last valid recorded value of the respective channel. It calculates some statistics (data maximum and minimum, number of records, number of missing samples, etc...) and if the data structure is corrupted e.g., due to truncated records caused by accidental breakdown of the communication between the sensor and the data logger, it warns the user and records the situation in a log file. Using the log information the user can eliminate the irregular structure manually and can run the conversion program again in an iterative manner. The latest version of it can also be used to detect high noise sections in the time series being converted which makes the automatic determination of the first arrival of a transient tilt signal connected e.g., to seismological events (Benedek et al., 2024) possible.

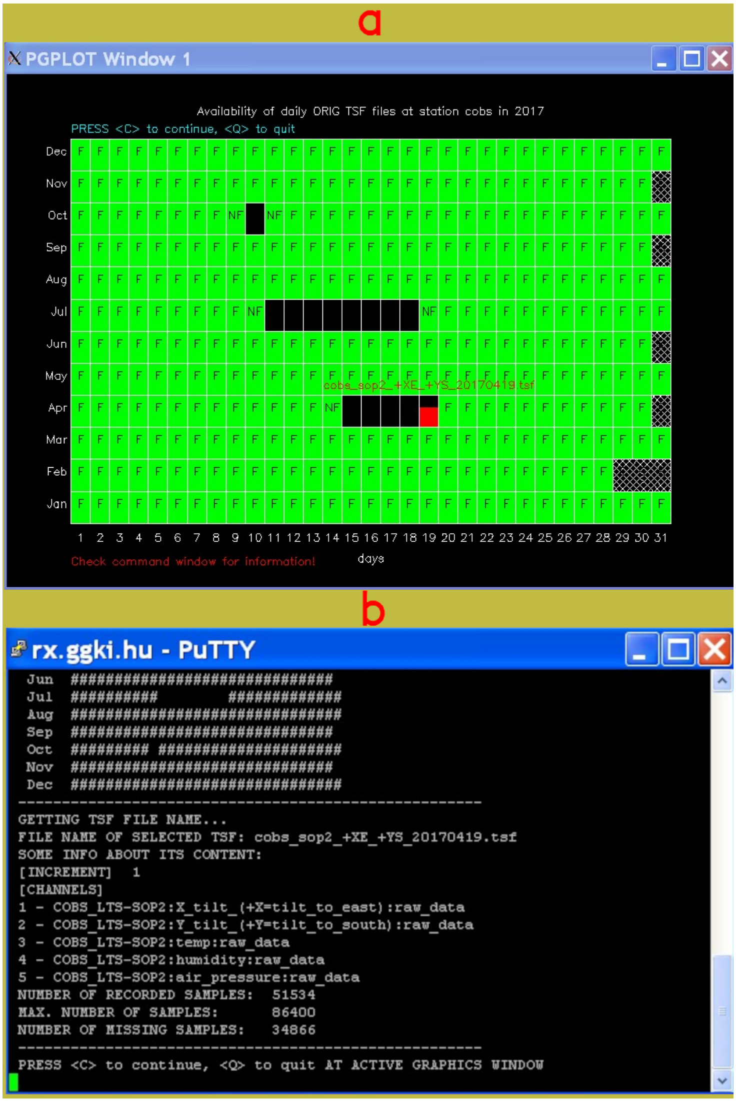

Fig. 8. **(a)** A calendar like presentation of the availability of the daily TSF files recorded by the SOP2 sensor at COBS in 2017. F: full, NF: not full. The height of the red column on the 19$^{\text{th}}$ of April is proportional to the number of available data. **(b)** Some details about the selected TSF file (cobs_sop2_+XE_+YS_20170419.tsf) and the data stored in it.

The time series defined in the file format of the software (TSF) are arranged into channels. In addition to efficient multi-channel visualization, both whole channels and single data can be manipulated, corrected, or deleted as it is required. Although Tsoft is perfectly suitable for quick visual checking and calculations, it can process only segmented data in case of longer time series. However, as the amount of data increases, the use of the software becomes more and more difficult, slower, or after a certain amount of data, simply impossible. To overcome this problem an EPSS program was developed under HP Unix to visualize very long time series in X11 environment, where the RAM is user manageable up to its physical limit. This way two data vectors (time stamps and the data to be visualized) of 450 million samples in double precision can be handled easily. A one year long data set sampled at 5 Hz contains almost 157 millions of samples in a channel.

Table VII shows the structure of a TSF file containing data recorded by the LCR G949 gravity meter at Conrad Observatory. The header of the file basically defines the sampling rate, the format of the time stamp, the channels, their measurement units, and the number of the records. So, in the example given in Table VII there are seven channels with their names and measurement units. The data section of a TSF file contains the timestamps (year, month, day, hour, minute, second and alternatively millisecond columns) followed by the corresponding channel data. The meteorological data is only recorded at every full minute in this example. Where the data is missing and it cannot be filled automatically because of its length, the gap is indicated by the number 9999.9. This is the default value for NaNs (=not a number) in TSOFT but the user can arbitrarily define it in the TSF header section.

During the years of tidal analysis and data processing in EPSS, Sopron, many programs have been written to manage large data sets (data preprocessing, manipulation, filtering and spectral analysis), tending to automate some of the corrections and to make the data visualization interactive. These include, for example, the compilation and conversion of data files, and the batch processing tool of the continuous time domain convolution of daily TSF files applying various types of filters. According to processing needs the data is filtered and decimated and then stored in different time resolutions, for example in 5 Hz, 1 second, 1 minute and 1 hour time resolution (Fig. 7). These data are available in separate daily files so to obtain a continuous time series they must be interlaced for further analysis.

There are different types of corrections that need to be done during processing of data recorded by both the LCR G949 gravimeter and the Lippmann tiltmeters. These include the step and spike corrections and the diminishing of the unfavourable effects of earthquake signals and background microseism (Papp et al., 2012).

Step- and Spike Corrections

A step can be defined as a sudden shift (i.e. jump) between the values measured at two consecutive observation data and the data series continues with

Table VII. The structure of daily TSF files containing data recorded by both the LCR G949 gravimeter and a Procontrol meteorological station.

```
[TSF-file] v01.0


[UNDETVAL]  9999.9

[TIMEFORMAT] DATETIME

[INCREMENT]  1

[CHANNELS]
CO_g949: -delta_g
CO_g949: image_shift
CO_g949: X_tilt
CO_g949: Y_tilt
CO_g949: temp
CO_g949: humidity
CO_g949: air_pressure

[UNITS]
pixel
pixel
mV
mV
deg_C
percent
mbar

[COMMENT]

[COUNTINFO]  86400

[DATA]
2018 11 25 00 00 00  129.40   16.10   -0.76   -0.36   18.5   46.0  583.2
2018 11 25 00 00 01  127.90   16.10   -0.72   -0.38 9999.9 9999.9 9999.9
2018 11 25 00 00 02  128.90   16.10   -0.74   -0.36 9999.9 9999.9 9999.9
…
```

either bigger or smaller point values meanwhile the difference, represented by the jump, remains constant for a sufficiently long time interval. In other words: before and after a step/jump the mean values of the data segments are significantly different (see e.g., Students t-test). Such features frequently occur in ground tilt time series indicating that the tilt of the rocks underlying the instrument may be changed by sudden deformations caused by e.g., thermally or tectonically induced stress variations. One, however, can find artificial jumps also in gravity time series as well (Fig. 9), due to e.g., range compensating the effect of instrumental drift. It is possible to remove it manually and with a built in step correction tool in Tsoft. There is also an EPSS program that is used for step detection and its semi-automatic correction (Fig. 10).

Spikes (single outliers) are generally identified as sharp data peaks caused by abrupt positive or negative change decaying very quickly in the dataset. Unlike steps the data segment after the spike continues on the same average signal level as beforehand, only the spike (i.e. outlier data point) needs to be corrected. The removal of such a feature is also possible by Tsoft manually or with the autodetect spike function, which can be very efficient with an experimentally well-defined parameter set.

The importance of the step- and spike correction is obvious if spectral methods are applied in the processing of data. The whole spectrum of the processed signal is influenced by these anomalies, consequently the estimation of the characteristics of specific spectral components can be highly biased if proper corrections of the anomalies are not applied.

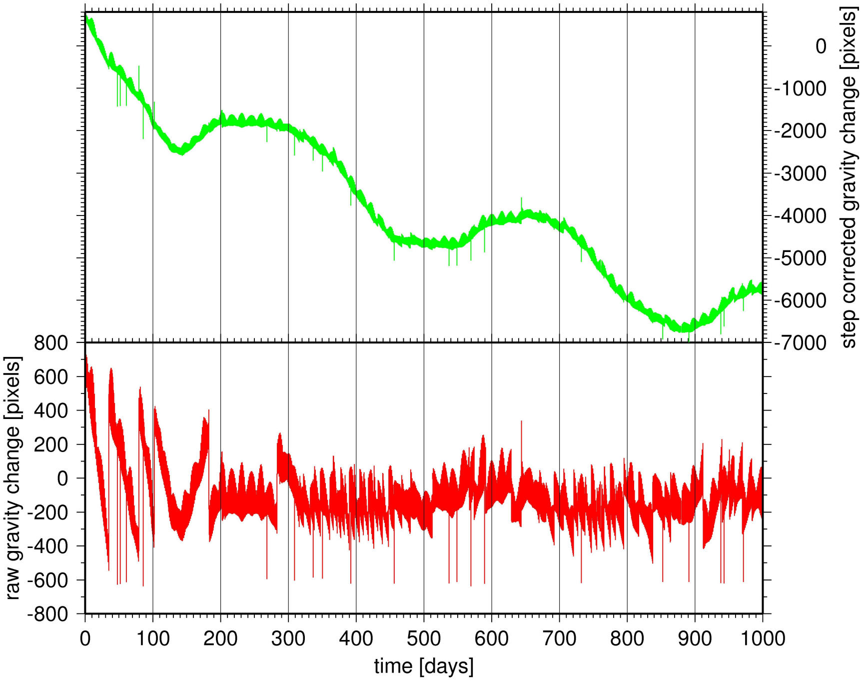

Fig. 9. A thousand days long time series of gravity variations recorded at COBS between 2017–2020 before (bottom panel) and after (top panel) step corrections. The waving shapes on the diagrams are the indications of the harmonic tidal signal.

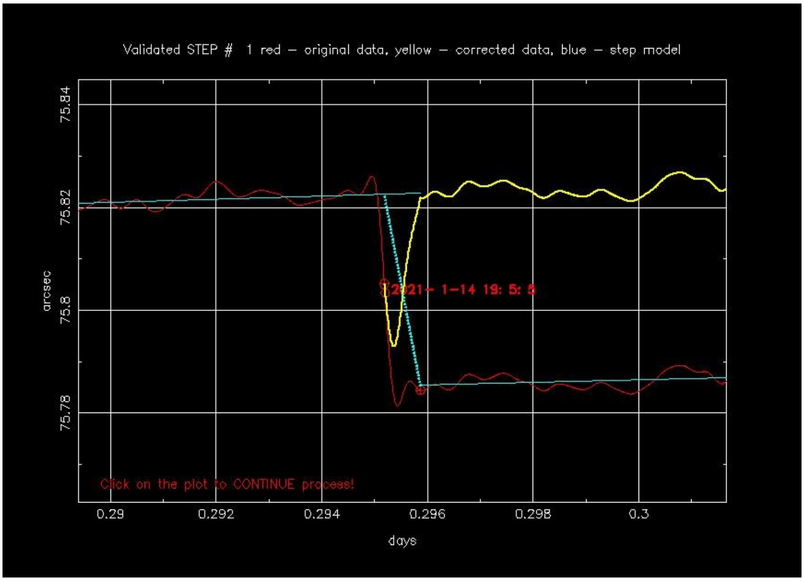

Fig. 10. An example of how the program developed at EPSS detects, models and corrects a step in a tilt time series interactively.

Gap Correction

Data gaps are continuous segments of missing data in the time series with varying length. The EPSS conversion program mentioned above (Section *Software Used for Data Processing*) can already handle the short, few second long gaps, however, in case of longer gaps another approach is necessary. The main goal of gap correction is to eliminate discontinuities in the data series by taking into consideration the trends of data segments located directly before and after the missing data. Gaps, however can also be created artificially if, for example, a data segment distorted by a transient signal of instrumental origin needs to be replaced for some reason. The method used to correct a gap or time segment of biased data lasting for a few hours at most, was developed by the Geodesy Research Group.

First the time series has to be low-pass filtered e.g., with the Chebyshev filter G1S1M (Fig. 11) (Hábel and Meurers, 2014), then the starting and ending point of the segment to be replaced or filled have to be identified (see interval A in Fig. 12). In the next step, the time derivative function of the filtered data is calculated numerically. Then, the derivatives have to be interpolated on interval A (Fig. 12) by e.g., linear or bicubic interpolation depending on its length. Finally, the derivative function has to be numerically integrated in order to get back the approximate signal on interval A. In all other sections of the time series the original signal is preserved, naturally.

This method can efficiently be used to correct an unfavourable effect of earthquake signals recorded by the LCR G949 gravimeter (Fig. 12). In general, such a situation occurs when high-magnitude earthquakes are observed. This may cause a gap-like effect in the first, max. 30 minutes long segment of the earthquake signal (see interval B) because the arriving long periodic surface waves of large amplitudes may stick the index beam (which is a mechanical part of the sensor) to one of the two beam limiters (Instruction Manual, 1991). After the beam gets released a relaxation signal (see interval C) which may last for hours distorts the time series. This data segment can also be corrected by the method described above (Fig. 12). The correction is done manually with Tsoft.

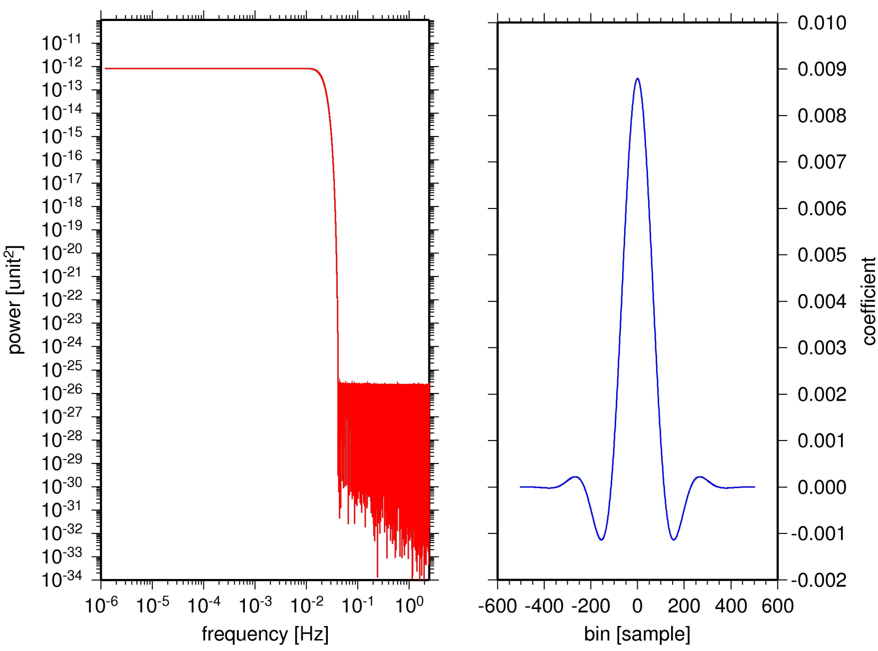

Fig. 11. The frequency (left panel) and time (right panel) representations of the low-pass GGP filter (g1s1md) used to eliminate high frequency noise from the tilt observations recorded at 5 Hz sampling rate.

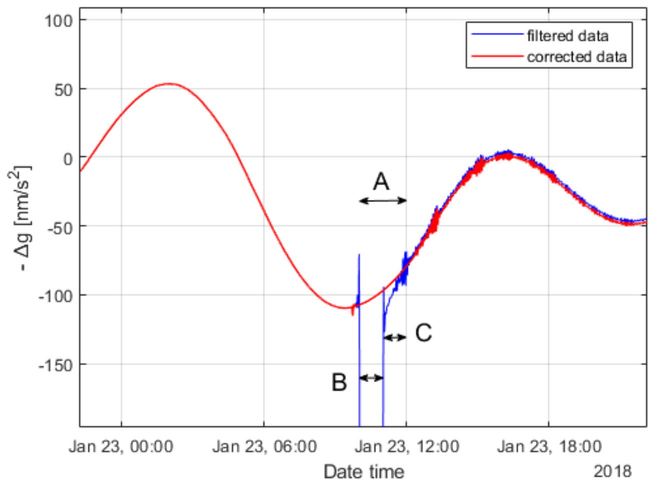

Fig. 12. Gap due to sticking of the index beam to one side of the measuring range caused by a large magnitude earthquake and its correction in the gravimeter measurements. Interval A: Filled/interpolated gap, Interval B: Data gap due to temporal index beam sticking. Interval C: Relaxation period after the index beam freely moves again.

Conclusions and Results

The network described in this paper provides simultaneous ground tilt and auxiliary meteorological data from its five stations since 15^{th} of June, 2023. Based on the recorded data a successful attempt to locate epicentres for local earthquakes linked to the tectonic activity of the MurMürz fault line was made. The best inversion method developed for the processing of the tilt time series gives epicentre coordinates sufficiently close to the epicentres (4.5 km on average) determined from the observations of the nearby seismological stations. The first results are under publication (Benedek et al., 2024).

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