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Roman Leonhardt & Patrick Arneitz [Hg.]

Conrad Observatory Scientific Contributions 2023–2024

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Conrad Observatory

Preface

Earth Observation remains a cornerstone in advancing our understanding of the Earth system. Through continuous monitoring, it delivers essential insights into environmental, geophysical, and atmospheric processes, supporting informed responses to challenges such as climate variability, seismic activity, and space weather. Long-term observation enables scientists to identify trends, improve models, and enhance early warning capabilities. The Conrad Observatory, operated by GeoSphere Austria, represents a sustained commitment to providing high-quality data and scientific infrastructure in this critical domain.

Beyond its diverse observational facilities, the Conrad Observatory offers a distinctive research environment that combines technical innovation with exceptional underground infrastructure. The laboratory and tunnel systems support a broad range of experimental activities, promoting interdisciplinary research across geodynamics, geomagnetism, and space weather. Notably, the geomagnetic program of the observatory is now in its tenth year of continuous operation, delivering high-resolution magnetic field data that are integral to both fundamental science and applied research in the near-Earth environment.

The Earth system is inherently dynamic, requiring observatories to evolve in tandem with technological and scientific developments. The Conrad Observatory exemplifies this adaptability, maintaining excellence in observation while advancing research through state-of-the-art instrumentation and collaborative projects. Its role as a hub for national and international initiatives reinforces its importance in driving innovation and expanding the frontiers of geophysical knowledge.

In this spirit,

Dr. Andreas Schaffhauser
Director General
GeoSphere Austria

Ing.in Mag.a Sylvia Bauer-Beck
Director General
GeoSphere Austria

Content

SWAP: Space Weather Live Information

Veronika Haberle, Rachel Bailey, Roman Leonhardt

The project "Space Weather: The Austrian Platform", funded by FFG and led by the Conrad Observatory brings together Austria's space weather expertise. The aim is the active exchange between research, industry and stakeholders to define future pathways of this important topic on national level. The platform developed in the framework of this project serves as the national information hub for stakeholders and the general public.

The SWAP (Space Weather: The Austrian Platform) project aims at identifying key topics for the future of space weather in Austria by facilitating active exchanges between representatives from interdisciplinary research and affected industries and stakeholders. One of the main goals of the project is to disseminate relevant information to stakeholders and the general public. For this purpose, the SWAP platform swap.geosphere.at was created and will be officially released at the end of the project. Among general space weather information, the centerpiece is the space weather dashboard displaying the current space weather environmental conditions. Fig. 1 shows the dashboard during a strong space weather event in 2024. The dashboard shows various space weather parameters. On the top and bottom panels, information of expected and ongoing space weather events is displayed. On the very bottom a 3-day forecast is provided. On the very left, the live-image of the Sun from the Solar Dynamic Observatory SDO is shown together with the latest solar wind speed. To its right, the latest solar wind proton density and its magnetic field orientation Bz are visualised. On the very right, information of the auroral oval and geomagnetic activity in Austria is provided. To its left, the global magnetic activity is indicated with Kp and below measured geomagnetically induced currents (GIC) within the Austrian power grid. In the middle, a total of seven gauge panels indicate further important parameters for affected stakeholders and end-users with the levels green, yellow and red according to international definitions. From left to right and from top to bottom:

- Sun icon: Solar Flares
- Radiation icon: Radiation at Flight-altitude
- Satellite dish icon: Radiointerference
- Transmission power icon: GICs
- Warning flag icon: Geomagnetic activity Dst
- Geomagnetic storm classification: G2 in this case
- Satellite icon: Satellite influence

The main aim of the dashboard is to give a comprehensible overview about current space weather conditions while being informative for affected stakeholders. The SWAP platform including the dashboard will be officially released at the ending of the dedicated FFG project in 2025. GeoSphere Austria will continue to operate the platform as official national point of information for space weather.

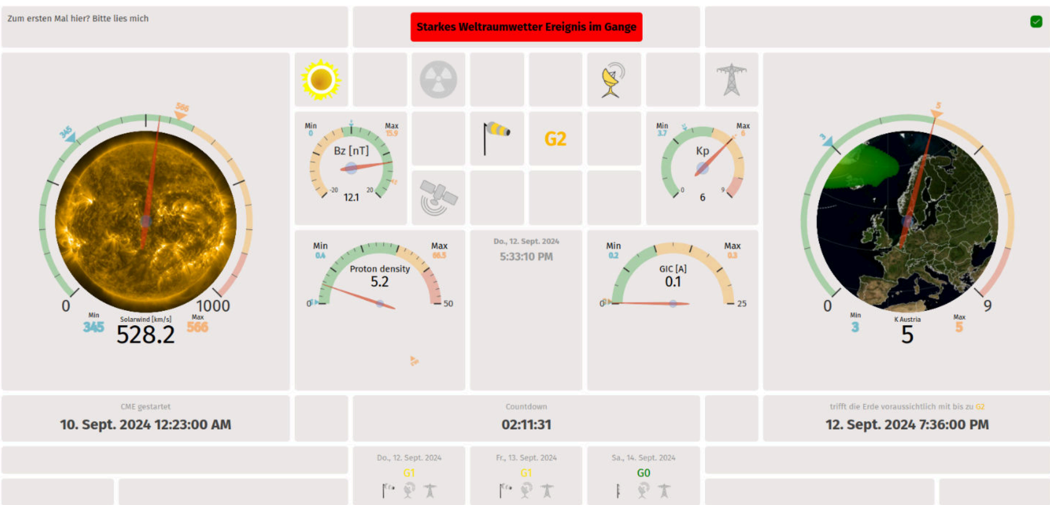

Figure 1: Space Weather Austrian Platform: Live Space Weather Environment Information for stakeholders and the general public.

Authors:
V. Haberle[1], R. Bailey[1], R. Leonhardt[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Dr. Veronika Haberle
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
e-mail: veronika.haberle@geosphere.at

Strongest geomagnetic storm within the past 20 years: The Mother's Day event from May 10-12, 2024

Veronika Haberle, Eva Weiler, Rachel Bailey, Christian Möstl, Roman Leonhardt

Between May 10 and 12 the strongest geomagnetic storm of the past twenty years was measured at the Conrad Observatory. The Austrian Space Weather Office predicted the arrival of the associated solar storms with high accuracy and informed Austrian stakeholders. The event produced beautiful auroras observable all around Austria.

A total of five coronal mass ejections (CMEs) were responsible for the strongest geomagnetic storm on May 10-12 within the past twenty years. Four of these originated from the active region AR 13664 and were associated with major solar flares. NASA's STEREO-A spacecraft provided data 2.5 hours before the arrival of the first shockwave at Earth, showing very high interplanetary magnetic fields. The Austrian Space Weather Office (ASWO) performed model calculations to determine the arrival time of the CMEs and their associated geomagnetic storms in real-time. ASWO predicted the arrival time at Earth with an accuracy of just a few minutes which was the most accurate forecast internationally for the Mother's Day storm. Starting from midday on May 10, timely warnings about the possibility of auroras over Austria were issued to the general public and Austrian stakeholders within the SWAP project. National media outlets (e.g., Ö1) picked up the information that afternoon.

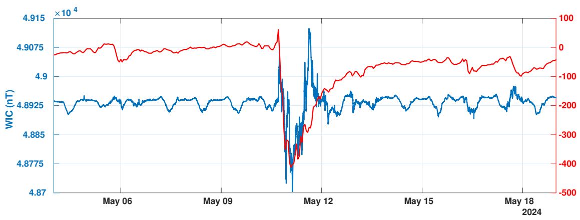

Figure 1: The geomagnetic storm as recorded by magnetometers at the Conrad Observatory in blue. The global magnetic activity index Dst is displayed in red.

At the Conrad Observatory, magnetometers registered the strong geomagnetic disturbance as shown in Fig. 1 in blue. On the days leading to the event, typical day-to-day variations of the quiet geomagnetic field with minor irregularities prevailed. The event starts with a clear increase, also referred to as the storm sudden commencement (SSC), which is followed by a sharp and strong decrease of the magnetic field. After a minimum of 48703.35 nT is reached the magnetic field raises again to a maximum of 49123.81 nT, accounting for a difference of 420.46 nT. The ending of the storm is indicated by receding values towards predisturbance levels after May 12. Quiet day variations set in again from May 14 on, later followed by smaller disturbances.

The Dst index, commonly used to describe global geomagnetic activity, is derived from four magnetic observatories to track the evolution of the ring current, a near-Earth current system that is significantly enhanced during geomagnetic storms. The Mother's Day event, with a Dst minimum of -412 nT, was the strongest since November 2003. In Fig. 1 the Dst index is depicted in red. The SSC and main phase (the following sharp decline) are typical storm signatures and are well timed with observations from the Conrad Observatory. Once the Dst minimum is reached, the Dst index describes a slow and gradual return towards predisturbance levels, referred to as the recovery phase. During this phase the mentioned increase and maximum values observed at the Conrad Observatory occur. Only at the end of the Dst recovery phase, measured values in Austria return to pre-storm levels. This example underlines the differences between global space weather parameters and local variations, highlighting the need for localised magnetic activity indices.

Especially the rate of change of the geomagnetic field dB/dt is an important proxy for geomagnetically induced currents (GICs). During the Mother's Day event, GICs of up to 22.7 A were measured in the Austrian power grid with no unexpected equipment failures while any increased reactive power demands of the transformers were met easily. The positive side effect of the storm was the occurrence of Aurora Borealis observable all across Austria as shown in Fig. 2.

Figure 2: Auroral display over South Burgenland by Christian Möstl on May 10.

Authors:
V. Haberle[1], E. Weiler[1], R. Bailey[1], C. Möstl[1], R. Leonhardt[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Dr. Veronika Haberle
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
e-mail: veronika.haberle@geosphere.at

IMBOT - an automatic data reviewing system

Roman Leonhardt

INTERMAGNET, a network of geomagnetic observatories, publishes so called "definitive" data products, which are subjected to an international peer-review system. Geomagnetic data is submitted by about 100 observatories all over the world. Beside the obligatory 1-min data products, INTERMAGNET requests 1Hz data products since 10 years. In order to check these data products an automatic data checking system, the INTERMAGNET data checking robot, developed at the Conrad Observatory, is used. Since 2023 all data submissions are automatically tested by this routine.

A peer review system is widely considered as essential to ensure the quality and accuracy of scientific research by allowing experts in the field to evaluate and provide feedback on the work before it is published. Such reviews help to identify and correct errors, inconsistencies, or gaps in methodology, analysis, or interpretation, thus improving the overall reliability of the research. Although a peer-review system is widely used for scientific publications, pure data products are typically not reviewed by the science community. INTERMAGNET, a network of geomagnetic observatories, based their data publications since 2005 on an international peer review system. Due to the huge amount of data submissions, data review is partly subjected to a new automatic testing system, the INTERMAGNET data checking robot IMBOT, developed and operational at the Conrad Observatory in Austria.

Geomagnetic data is particular challenging due to its non-stationary character and the highly dynamic, non-periodic signal contributions affecting a wide range of different frequencies and signal origin. Careful control by the data providers and removal or marking of spurious signals is of great interest for the end user. The primary aims of IMBOT are to (1) simplify one-second and one-minute data submissions for data providers, (2) to speed up the evaluation process significantly, (3) to consider current IM archive formats and meta information (e.g. on leap seconds), (4) to simplify and speed up the peer-review process and finally (5) to reduce the workload of human data checkers. Detailed reports are automatically produced and send out along with templates for corrections to the submitting institute.

Notification of data providers and human referees is also performed by IMBOT and any re-evaluation is triggered automatically when updating data or any information in the submission directory. This automated system makes data review faster and more reliable, providing high-quality data for the geomagnetic community. Among the tested quantities are data formats and data structure, data contents, metainformation, consistency, and data quality, providing also helpful comparison tools for different observatories (Fig. 1).

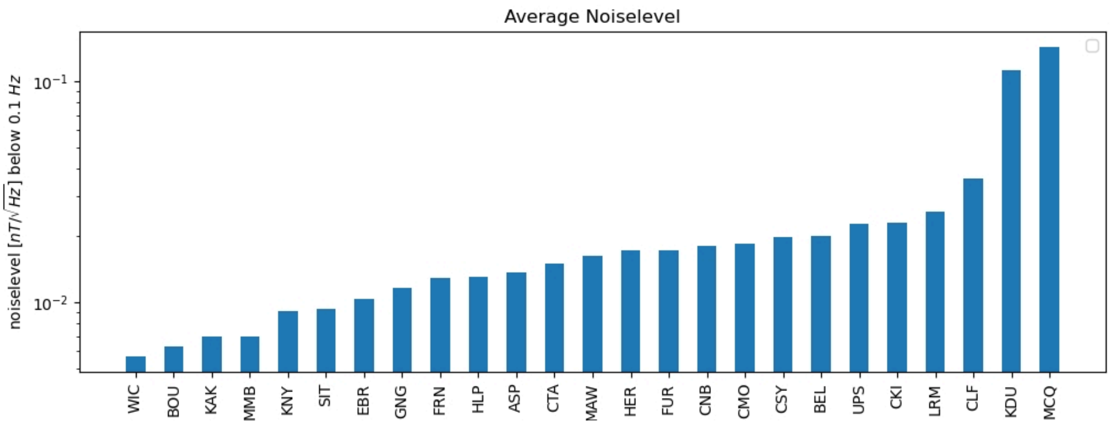

Figure 1: For data quality estimates and testing of INTERMAGNET's quality thresholds, noise levels obtained from the amplitude spectral density (ASD) are evaluated below periods of 10 seconds. Most submitting observatories achieve a noise level below 100pT/sqrt(Hz) in this range (data from 2022), as defined in the IM standard levels.

Authors:
R. Leonhardt[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Dr. Roman Leonhardt
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
Tel +43 (1) 36026 2507
email: roman.leonhardt@geosphere.at

Magnetometer and Data Analysis

Geomagnetic field measurements with a new prototype of an optically pumped potassium sensor

Roman Leonhardt, Niko Kompein, Mike Wilson, Hossam Zoweil, Dough Hrvoic, Shawn Kovacs, Ivan Hrvoic, Peter Melichar

Optically Pumped Magnetometer (OPM) sensors are widely used in geophysical sensing applications but are rarely found in geomagnetic observatories. Here we will present data from OPM sensors using potassium vapor in an observatory environment. The individual OPM sensors, frequently referred to a supergradiometer, has been running since 2015 at different locations within the Conrad Observatory. Data is characterized by extremely small noise level.

Optically Pumped Magnetometer (OPM) sensors are widely used in a variety of Earth-field sensing applications, including mineral exploration, mapping of near-surface hazards, and space missions. Since they rely on quantum measurements, OPM sensors have a number of important benefits when it comes to sensitivity, accuracy, and signal bandwidth. Although these sensors often need to be heated, their total power consumption is low and their disturbing influence on nearby sensors is very limited, making them highly suitable for Earth-field measurements. Their application in observatory environments, however is not very common. Most observatories make use of sensors based on the Overhauser principle, since these sensors are well known for their long term stability. The underground geomagnetic part of the Conrad Observatory near Vienna, Austria, was originally designed by Peter Melichar specifically for the installation of these high-sensitivity sensors operating in the femto-Tesla range. For the test measurements, we focused on two aspects: Long term data from a GEM Systems GP20S3 Potassium gradiometer system is shown, which has been running at the Conrad Observatory continuously since 2015.

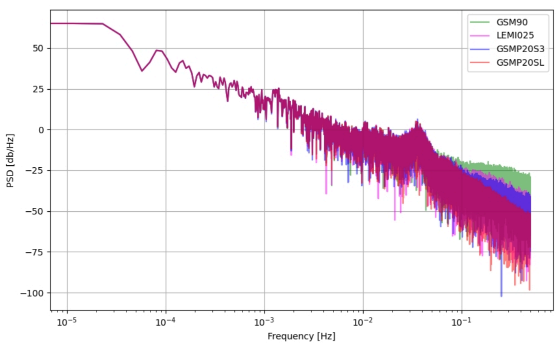

Figure 1: Filtered 1 second data using exactly the same Gaussian filter for all data sets from the same day (21. Sep 2024).

The sensor system is characterized by a very low noise level in the order of 0.1 pT/rt-Hz for the total magnetic field. This is a factor of ~100 lower than the noise of the GSM90 and POS1 Overhauser sensors, which are the current standards (Fig. 1). The data is highly stable and has been used as the primary permanent scalar signal at the Conrad Observatory for eight years now (Fig. 2). The GP20S3 sensor system is specifically designed as a gradiometer and thus can be used to distinguish between nearby and distant anomaly sources. The very high sensitivity of this gradiometer helped to identify numerous electromagnetic noise sources in the observatory and to separate these signals from geomagnetic signatures.

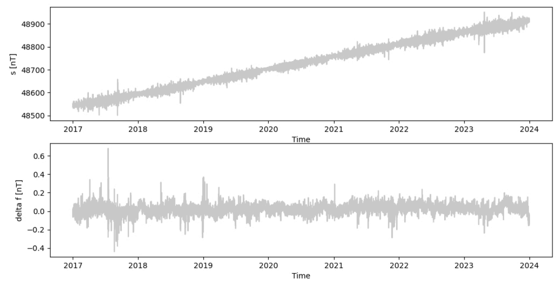

Figure 2: Long term comparison between primary variometer and the OPM N-sensor. The delta value between vector F from the variometer and scalar F from the OPM sensor is extremely stable and close to zero for a period of seven years (the variometer was installed end of 2016).

For most observatory applications, a three-sensor potassium gradiometer is not required. Building on experiences with the long term gradiometer system based at the Conrad Observatory, GEM Systems has now developed a new ultrahigh sensitivity single potassium sensor for long-term measurements. The new sensor is driven by a stabilized laser, in contrast to the previous sensors' plasma lamps. This provides even greater sensitivity, accuracy, reliability, and flexibility in installation. The sensor was tested a the Conrad Observatory in 2024. It has a noise level of less than 0.05pT/rt-Hz, and an absolute accuracy of less than 0.1nT and has an even higher sensitivity at periods below minutes than all other sensors (Fig. 1).

Authors:
R. Leonhardt[1], N. Kompein[1], M. Wilson[2], H. Zoweil[2], D. Hrvoic[2], S. Kovacs[2], I. Hrvoic[2], P. Melichar[1]
1) GeoSphere Austria, Vienna, Austria
2) GEM Systems Inc., Markham, Canada

Corresponding author:
Dr. Roman Leonhardt
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
Tel +43 (1) 36026 2507
email: roman.leonhardt@geosphere.at

Proof-of-concept for delta inclination – delta declination measurements with an all-optical quantum interference magnetometer

Christoph Amtmann, Martin Agú, Alexander Betzler, Gerhard Fremuth, Irmgard Jernej, Sunny Laddha, Andreas Pollinger, Roland Lammegger, Werner Magnes

A novel method for measuring the magnetic field vector with an all-optical measurement principle is presented, which is based on a quantum mechanical interference effect. A proof-of-concept setup demonstrated the angular stability of delta inclination - delta declination measurements during a more than five days long test campaign.

The Coupled Dark State Magnetometer (CDSM) is an optically pumped scalar magnetometer that utilises the quantum mechanical interference effect of coherent population trapping (CPT) in the atomic vapor of rubidium-87. Developed in a cooperation between the Institute of Experimental Physics at Graz University of Technology and the Space Research Institute of the Austrian Academy of Sciences. The CDSM measures the magnetic field strength by detecting the Zeeman frequency shifts within the hyperfine structure energy levels via coupled CPT resonances. The instrument operates omnidirectionally by utilizing two sets of coupled CPT resonances. The sensor angle β, which is the angle between the magnetic field vector and the laser light propagation direction within the vapor cell, affects the resonance amplitudes. By switching between these two sets, the scalar magnetometer can operate without dead zones.

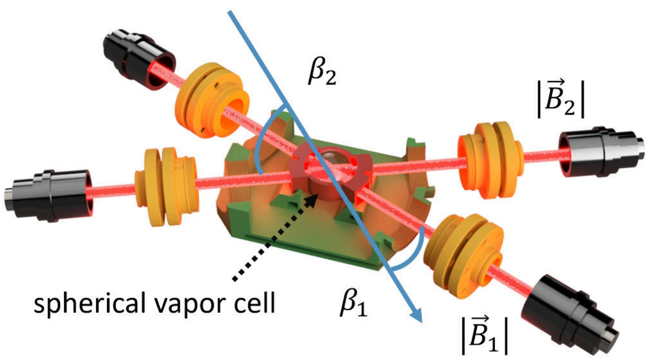

Figure 1: Rendering of the proof-of-concept sensor unit with two (red) light beams at a 45° angle. In addition to the regular scalar values, the measurement method allows detecting the magnetic field angles β_1 and β_2 (in blue) relative to the two light beams within the vapor cell.

In addition to scalar measurements, the resonance amplitudes can be used to determine the sensor angle β. However, these amplitudes are influenced by other operational parameters such as optical power and vapor temperature. To reduce these effects, a calibration curve can be created to associate the ratio of the resonance amplitudes of two different sets with the angle β. To prevent dead zones in angular measurements, a second laser beam is introduced at a 45° angle to the first beam. This configuration allows for the measurement of a second sensor angle β_2, providing complementary information (Fig. 1). Combining measurements from both beams enables the determination of the alignment of the magnetic field for most directions around the sensor unit. This two-beam sensor setup could be of particularly interest for delta inclination and delta declination measurements in geomagnetic observatories, where prior knowledge of the magnetic field is available. A proof-of-concept setup was designed and built to verify this method (Fig. 1). It was tested at the geomagnetic Conrad Observatory which provides optimal conditions for testing novel instrument concepts. The measurement performance was evaluated using the double Merritt coil system, by applying a constant magnetic field opposing Earth's magnetic field to reduce the field strength to about 5300 nT. This low magnetic field strength was required to stay in the linear Zeeman shift regime which simplifies the setup. The setup allowed the sensor unit to detect changes in the field's inclination and declination. For angular measurements, the magnetic field angles β_1 and β_2 were calculated from observatory data and compared with the proof-of-concept setup measurements for a period of more than five days (angle β_1 in Fig. 2). The results showed some drift in the measured angles. However, after correcting for the drift caused by changes in optical power within the vapor cell, the angular residuals were reduced, demonstrating the setup's potential for accurate angular measurements. For the corrected data over the period of more than five days a stability in the order of one to two arcminutes was found.

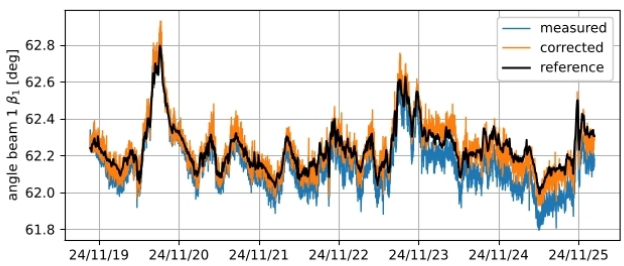

Figure 2: Results for the sensor angle β_1. The measured angle (blue) and the corrected measured angle (orange) is compared with the reference of the observatory (black line).

Authors:
C. Amtmann[1,2], M. Agú[2], A. Betzler[1,2], G. Fremuth[2], I. Jernej[2], S. Laddha[1], A. Pollinger[2], R. Lammegger[1], W. Magnes[2]
1) Institute of Experimental Physics, Graz University of Technology, Austria
2) Space Research Institute, Austrian Academy of Sciences, Graz, Austria

Corresponding author:
Dr. Christoph Amtmann
Institute of Experimental Physics, Graz University of Technology
Petersgasse 16, 8010 Graz, Austria
e-mail: christoph.amtmann@tugraz.at

A new system for measuring DC currents in high-voltage lines

Ramon Egli, Barbara Leichter, Richard Kornfeld, Patrick Arneitz, Roman Leonhardt

DC currents represent a challenge for AC electric power transmission, since they saturate the magnetic core of large transformers. The main source of large DC currents in high-voltage power lines is the underground electric filed associated with rapid changes of the Earth's magnetic field associated with solar storms. An increasing role is also played by DC-AC inverters from HVDC lines and solar power plants. In 2023 we developed a new contactless system for measuring DC currents in high-voltage power lines, using differential magnetometry. After a successful testing phase, a first system of this type became operational in 2024 and is delivering data to the Austrian Grid Operator APG.

DC currents in excess of $\sim$5 A represent a potential threat for high-voltage power transformers which can lead to complete disruption due to overheating. It is therefore important for power grid operators to measure these currents in real time and disconnect the transformers in critical cases. Neutral point measurements are used for this purpose. However, more complete information is provided by measurements along individual power lines. One method for performing these measurements exploits the magnetic anomaly produced by DC currents in the conductors. Traditional systems measure this anomaly with a vector magnetometer buried underneath the power line and compare it with the reference signal of another magnetometer located far from the line in what is known as differential magnetometer method (DMM). Because of their extreme temperature sensitivity, vector magnetometers need to be buried deep in the underground and tend to drift irregularly. Furthermore, a single magnetometer cannot discriminate between DC currents flowing in the conductors from underground currents.

Figure 1: One of four stations under a high-voltage line. The Overhauser magnetometer is placed inside a thick aluminium cylinder (right) which acts as a shield against high-frequency disturbances. The black box (left) contains the electronics.

To overcome these limitations, we developed a new measurement system based on an array of scalar (Overhauser) magnetometers which measures the magnetic anomaly profile perpendicular to the conductors. Overhauser magnetometers are drift-free and insensitive to temperature changes and can be placed above ground (Fig. 1). Comparison with theoretical anomaly profiles derived from the actual conductor geometry enables to determine the DC current flowing in individual three-phase systems (typically two for a single line) and in the underground.

Data are provided in real-time with a one-second sampling rate, which is fully sufficient to capture DC current variations down to $\sim$10 s. Our measurements compare favourably with direct neutral point measurements and with values expected from the electric field induced by Earth magnetic field variations. The example below (Fig. 2) was recorded during a major magnetic storm beginning around 17:35 UTC on April 23, 2023. Maximum geomagnetically induced currents (GIC) of $\sim$12 A are observed just after the storm onset. Periods of time with significant DC contributions not related to GICs, up to $\sim$5 A, have also been observed and successfully compared with neutral point measurements.

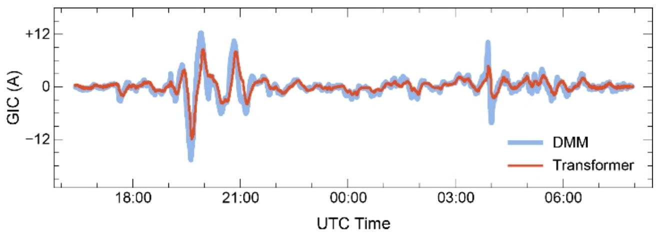

Figure 2: DC-currents reconstructed from differential magnetometry measurements (DMM, blue, thick line) and neutral point measurement at the transformer station (thin red line) during the magnetic storm of April 23, 2023.

Authors:
R. Egli[1], B. Leichter[1], R. Kornfeld[1], P. Arneitz[1], R. Leonhardt[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Dr. Ramon Egli
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
Tel.: +43 (1) 36026 2503
e-mail: ramon.egli@geosphere.at

Setting up a magnetometer station for Paraguay

Niko Kompein, Veronika Haberle, Patrick Arneitz, Roman Leonhardt

Paraguayan colleagues contacted us with the intention of borrowing old equipment stored at the Conrad Observatory. They wanted to use a high frequency variometer on permanent loan in Luque to measure ground induced current (GIC) effects together with geoelectric measurements on site. Based on this idea, we proposed to add an absolute magnetometer to the variometer to fill a gap of missing absolute measurements for global field modelling in South America. We prepared a complete station setup ready for deployment in Paraguay including a preconfigured data acquisition system based on MARTAS/geomagpy©, data collection system MARCOS/geomagpy© for analysis of GIC effects and an uninterruptible power supply.

The setup included the design of the data acquisition (MARTAS on a beaglebone black) and collection (MARCOS on a raspberry pi 5) system, its data transfer system (LANROUTER: milesite), the power supply (EFFEKTA), the power protection and its housing for long-term field measurements, a LEMI025 flux-gate variometer and a POS1 Overhauser absolute field magnetometer (Fig. 1). The acquisition and collection systems are based on the "mqtt" IoT protocol, released in 1999, and are implemented through the "geomagpy©" MARTAS/MARCOS open source project, which is continuously maintained by the staff of the Conrad Observatory and the worldwide magnetic observatories.

Figure 1: Package prepared for cargo.

The sensor setups were tested in the observatory tunnel (Fig. 2) to ensure that everything would work properly at the target site in Luque. A station commissioning manual was written to provide the Paraguayan colleagues with enough additional information for a future autonomous relocation option of the full station setup. Fault recovery routines were reviewed to keep the station as operative as possible in the event of a power failure. We provided the Paraguayan colleagues with details of the necessary offsets between sensors and data digitisers and/or other magnetic materials in the vicinity (e.g. metal fences, etc.). The loan also included permanent access to the measured fields for GeoSphere Austria through the use of geomagpy©MARTAS/MARCOS systems, which allows multiple authorised users to access the acquired data measured on site in real time and/or to back up the recorded data to multiple locations if required. Another feature of geomagpy© is the included data analysis software package "xmagpy", which is able to read numerous observatory standard data format files, filter, analyse and/or export specific features of given data sets from the recorded data. We are now looking forward to handing over the equipment for loading and transport, and plan to be on site to assist with commissioning in September 2025.

Figure 2: POS1 sensor testing.

Authors:
Niko Kompein[1], Veronika Haberle[1], Patrick Arneitz[1], Roman Leonhardt[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Mag. Niko Kompein
GeoSphere Austria
Trafelberg 1-2, 2763 Muggendorf, Austria
Tel.: +43 2632 73276
e-mail: niko.kompein@geosphere.at

Magnetometer and Data Analysis

Studying magnetic effects of electric currents in the grounding system

Richard Mandl, Patrick Arneitz

Like most modern buildings, the Conrad Observatory is equipped with a grounding system to prevent damage by lightning strokes. Even the underground parts are protected by 50mm^2 copper wires which are laid in the gravel bed on both sides of the tunnels. Copper conducts electric currents much better than the surrounding earth and rock, which makes overvoltages divert at times of thunderstorms. But also on quiet days the copper wires attract low currents producing magnetic fields that can be measured with highly sensitive magnetometers.

When the observatory was planned, it was a wise decision to let the copper wires emerge from the gravel in certain places as shown in Fig. 1. This makes it possible to monitor the grounding currents by installing a current transformer or to configure a tree structure by opening the connecting brackets to avoid loops in the grounding system. Once, when we opened such a bracket, we noticed a jump in the signal from a magnetometer. Obviously this action changed the way the currents were passing the sensors.

Figure 1: Copper wires coming out of the gravel connected by a bracket. Electric current is conducted from a lead battery over a small resistor into the grounding system. The other connection is on the other side of the main tunnel.

A good reason for an experimental test: We fed 12 mA current (resulting in 0.16 mW) into the grounding system as seen in Fig. 2 and measured the current at different locations of the tunnel system while opening and closing brackets at several places. This relatively small power caused quite a large spike in the measurements of the supergradiometer system (e.g. blue line in Fig. 3).

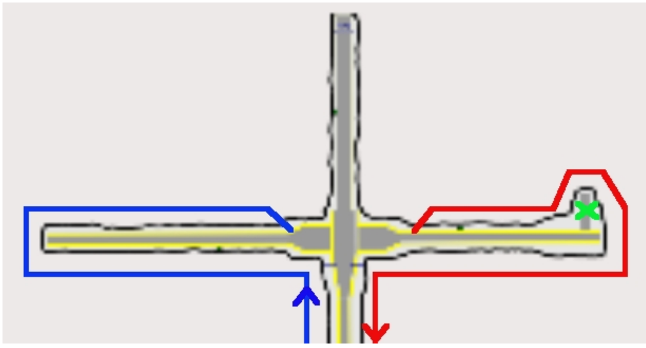

Figure 2: Current from the 12V battery +pole (red line) over a 1kOhm resistor passing by one absolute magnetometer (green cross) to the main building 250m south and back to the battery (blue line).

Small, potentially man-made, disturbances < 10 pT can be observed by the highly sensitive instrumentation (green line in Fig. 3 after 15:40 UTC). It is our aim to find out, if these signal contributions originate from currents in the grounding system and whether they come from outside or arise from devices in the observatory itself. By permanently monitoring these currents, we are able to detect disruptive effects of new installations or experiments in order to guarantee a low noise environment for the geomagnetic measurements.

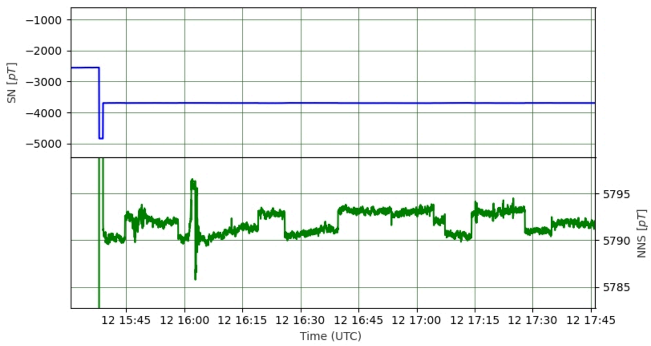

Figure 3: Jumps given by different gradients (top: SN, bottom: NNS) produced by +12 mA and -12 mA currents, that were finally turned off at 15:39 UTC. Note the different scales for the gradients.

Authors:
R. Mandl[1], P. Arneitz[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Richard Mandl
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
Tel.: +43 (1) 36026 2539
e-mail: richard.mandl@geosphere.at

New archeointensity data from Central Europe for the period around 1000 BC

Elisabeth Schnepp, Gaëlle Ségué-Passama, Patrick Arneitz, Robert Scholger

Archeointensity investigations of archeological materials have been performed for eight sets of potsherds with ages between 1200 and 800 BC from sites in Germany and Bosnia. The obtained archeointensities show a strong and rapid variation of the field strength. Further confirmation of this evolution is expected from studying more potsherds provided by Austrian and Serbian archeologists.

Around 1000 BC, at the Bronze to Iron Age transition (BIAT) unusually strong and rapid variations in archeointensity are observed in Iberia, Central Mediterranean and Levante. This so-called “Levantine Iron Age Anomaly"[1] is characterized by exceptionally high intensities around 900 BC. For Central Europe, the data coverage is poor compared with other regions, as only one comprehensive study from Bavaria provides archeointensity data for the period from 1250 to 750 BC.

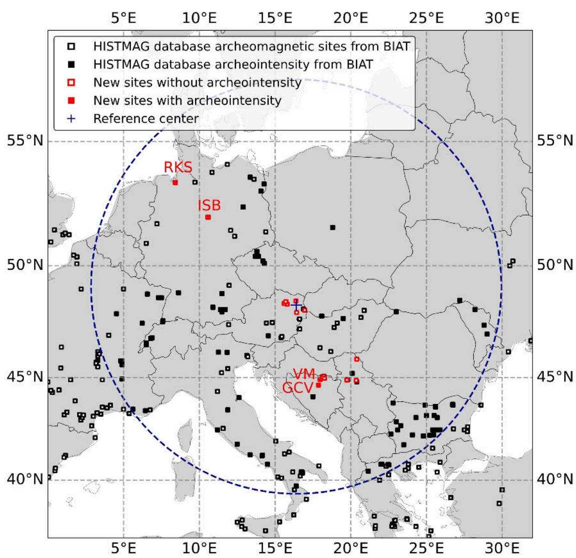

Figure 1: Archeomagnetic sites for the period from 1500 BC to 0 AD. The circle around Vienna (48.25°N, 16.36°E) has a radius of 1000 km.

Potsherds from 16 archeological sites in Austria, Bosnia, Germany, and Serbia (Fig. 1) have been collected for investigation of archeointensity. Ages between 1300 to 750 BC were provided by the archeologists by means of pottery and/or metal typology, stratigraphy and in nine sites by radiocarbon dating.

Archeointensity is determined using the MT4 protocol[2], a Coe variant of the Thellier method. While most of the pottery collections are still being examined, final results are already available for six of them. For three of them the sherds were reheated during their use and provided an archeointensity for their production time as well as for the time of the last reheating. For three potsherd collections sufficient material was available to test also the multiple-specimen domain-state corrected archeointensity method (MSP-DSC[3]) which has the advantage that only five heating steps per specimen are required. However, this method demands also the absence of secondary magnetisation components. Because this condition was not fulfilled for many specimens, only one result was obtained which is in very good agreement with the result obtained from the Thellier method.

As corrections for anisotropy increased the uncertainty of the mean archeointensities they were not used in most cases, but corrections for cooling rate were applied in all cases. The new archeointensities range from 37.5 to 74.9 µT. They are based on 2 to 8 successful Thellier experiments and relative errors of the mean values are below 10% with one exception.

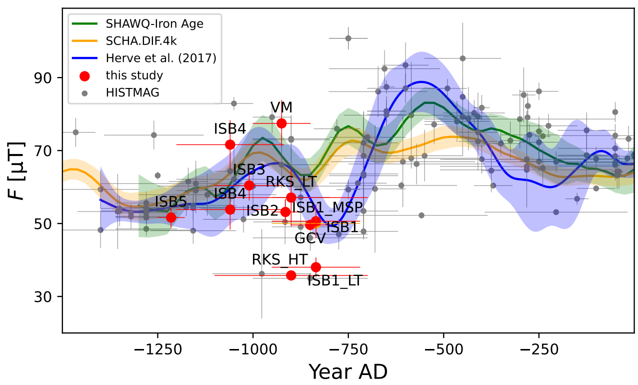

Figure 2: Archeointensity records in Central Europe from HISTMAG database[4] within a radius of 1000 km from the relocation site Vienna (Austria, see Fig. 1) in comparison with our new data (MT4 in red, MSP-DSC in orange) and with model curves[5,6,7].

The new archeointensity data further confirm the strong variation of geomagnetic field strength and a rapid drop by more than 50% around the Bronze to Iron Age transition is observed (Fig. 2).

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Authors:
E. Schnepp[1], G. Ségué-Passama[2], P. Arneitz[2], R. Scholger[1]
1) Montanuniversität Leoben, Leoben, Austria
2) GeoSphere Austria, Vienna, Austria

Corresponding author:
Dr. Elisabeth Schnepp
Palaeomagnetic Laboratory Gams, Chair of Applied Geophysics, MUL
Gams 45, A8130 Frohnleiten, Austria
Tel.: +43 (3842) 402 2643
e-mail: elisabeth.schnepp@unileoben.ac.at

New archeomagnetic data in Central Europe for the Early Medieval Ages

Gaëlle Ségué-Passama, Elisabeth Schnepp, Patrick Arneitz, Roman Leonhardt, Ramon Egli

Archeological material from Central Europe was investigated with sets of samples from eight sites from the early Medieval Ages, covering a time range between 500 and 1200 AD. The archeointensities show lower values, at the beginning of the period, than observed in other parts of Europe, and then an increase around 800 AD. New studies on archeological sites from Austria and Germany are currently in process to verify this trend.

In the Early Medieval Ages (EMA), remarkably strong and rapid geomagnetic field variations have been measured in Western Europe[1], with two peaks at 600 and 800 AD with an intensity value around 80 µT. In Central Europe, these field variations are poorly constrained due to the scarcity of archeological sites.

New archeointensity data is thus needed in order to reconstruct more closely the spatio-temporal evolution of these field features. Archeological materials were collected for studying the archeointensity, from three sites in Germany, two in Poland and three in Austria (Fig. 1).

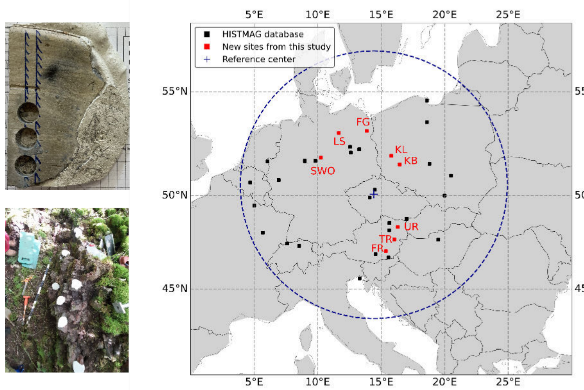

Figure 1: Map of the archeomagnetic sites for the period 300-1300 AD. The circle around Prague (50.07°N, 14.42°E) has a radius of 750 km. Example of archeological materials : potsherds from Ternitz and a rampart from Fergitz (image credit: F. Biermann).

The type of material was mainly potsherds, with four archeological sites, kiln rocks from one site, two oriented remparts and three different types of material for KB: potsherds, daub and roaster fragments. The archeologists provided ages between 500 and 1200 AD estimated with radiocarbon dating for one site, pottery and ceramic typology for four and dendochronology for three sites.

Archeointensities were determined using the MT4 protocol[2] - a Coe variant of the Thellier method - including pTRM, tail checks and additivity checks, as well as corrections for anisotropy and cooling rate. Accepted specimen values have been selected with modified Thellier Tool criteria sets TTA and TTB. For two sites, the multi-specimen domain-state corrected method (MSP-DSC[3]) was used and the results obtained for FG is in very good agreement with the Thellier method.

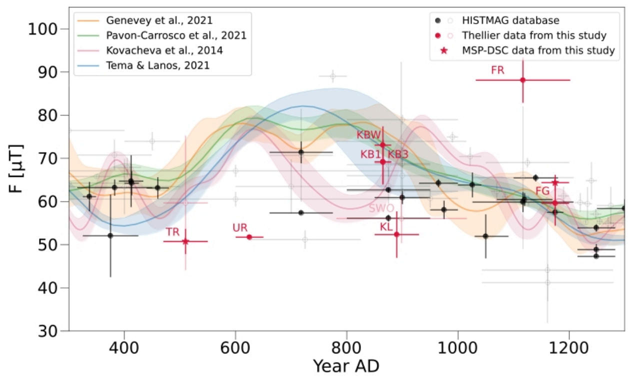

Figure 2: Archeointensity in Central Europe from HISTMAG database[4] in a circle of 750 km around the relocation site Prague (see Fig.1), in comparison with our new data (MT4 with the circle, MSP-DSC with the star) and with model curves[1,5,6,7]. Lighter colors give a lower quality data.

Six of the eight sites gave reliable archeointensities. Two sites yield values 20-30 µT lower than seen in the other intensity curves between 500 and 700 AD (Fig. 2). However, more data are needed to confirm this trend, because such intensity differences at 1000 km distance are not known from historical and paleomagnetic models.

After 700 AD, we can observe an increase of the intensity and then, a decrease after 800 AD. The age of site FR is still under debate with the archeological partners.

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Authors:
G. Ségué-Passama[1], E. Schnepp[2], P. Arneitz[1], R. Leonhardt[1], R. Egli[1]
1) GeoSphere Austria, Vienna, Austria
2) Montanuniversität Leoben, Frohnleiten, Austria

Corresponding author:
Ms. Gaëlle Ségué-Passama
GeoSphere Austria, Department of Geophysics and Conrad Observatorium
Hohe Warte 38, 1190 Vienna, Austria
e-mail: gaelle.segue-passama@geosphere.at

A new superconducting gravimeter at the Conrad Observatory

Ramon Egli, Patrick Arneitz, Roman Leonhardt, Bruno Meurers

The monitoring of temporal gravity variations at the Conrad Observatory resumed in April 2024, after the old superconducting gravimeter ceased to function properly in 2018, after over 23 years of operation. The new superconducting gravimeter iGrav050 (GWR) has been installed to continue the very stable continuous record of gravity variations. Gravity records from the Conrad Observatory and other observatories around the word are used for a precise definition of the shape of the Earth, and for the characterization of geophysical, hydrological and atmospheric processes involving mass relocations.

Continuous gravity measurements have been performed at the Conrad Observatory since 2007, after transferring the superconducting gravimeter GWR C025 from its original location in Vienna. The gravimeter ceased to function in November 2018 after over 23 years of operation. The successor model, iGrav050, was ordered from GWR in 2021. Due to the COVID pandemics, installation by GWR was not possible and we proceeded autonomously (Fig. 1). Measurements were resumed in April 2024. Superconducting gravimeters (SG) record subtle gravity changes by levitating a superconducting sphere. The feedback required to keep the sphere at a fixed height is proportional to the gravitational force. Calibration and correction of a residual slow drift are performed yearly by comparison with absolute gravity measurements. Superconductivity is maintained with liquid helium. The old GWR C025 required a yearly helium refill, while the new SG relies on a helium liquifying system, saving helium costs. As seen in Fig. 1, the iGrav050 has a noticeably smaller dewar and control electronics. The smaller dewar gives the new instrument a reduced autonomy in case of power outage; however, the liquifying system is powered by an USV, granting the continuous operation required to maintain consistent calibration and offset values.

Figure 1: Left: the old GWR C025 (blue, foreground) with electronics (gray, behind). The green structure supports the cold head above the blue dewar. Middle: the new iGrav050 without cold head. The gray beams support the red plate on the top, on which the cold head is mounted. Right: the new iGrav050 in operation.

Gravity variations are driven by mass transport and deformation of the solid Earth and associated fluids. Due to this wide range of sources, separation of the corresponding signals is challenging. Accurate corrections are required to remove spurious signal contributions. Such corrections include tidal gravity variations as well as atmospheric processes, ocean loading and Earth rotation changes.

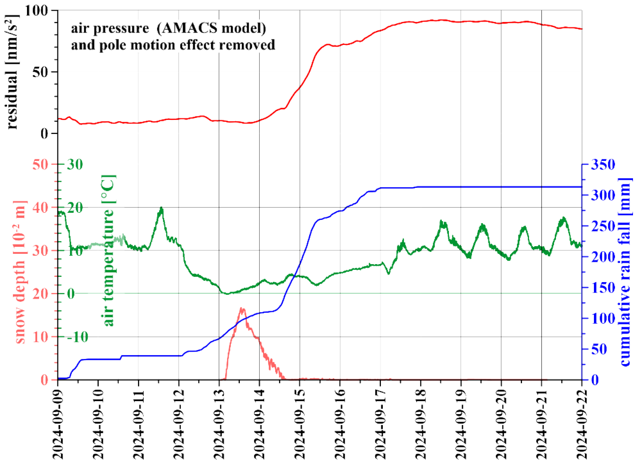

Figure 2: Gravity residual (top) and meteorological records (bottom) in September 2024. Notice the subtle differences between residual and cumulative rainfall, which are driven by the water balance of the underground.

Hydrological processes are a major challenge at the Conrad Observatory, due to the karstic nature of the underground. Complex water transport and storage effects associated with heavy precipitation events cause short and long term disturbances. An exceptional example was the so-called “Vb-cyclone” of September 2024, which produced $>$300 mm of cumulative rainfall in one week. This event induced a gravity residual increase of $\sim$100 nm/s^2 (0.01 ppm), which persisted during the following months (Fig. 2). Excess gravity clearly indicates that water has been accumulated in the underground instead of running off.

Authors:
R. Egli[1], P. Arneitz[1], R. Leonhardt[1], B. Meurers[2]
1) GeoSphere Austria, Vienna, Austria
2) University of Vienny, Vienna, Austria

Corresponding author:
Dr. Ramon Egli
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
Tel.: +43 (1) 36026 2503
e-mail: ramon.egli@geosphere.at

Scale factor determination for iGrav 050 based on Earth tide models

Bruno Meurers

The compact superconducting gravimeter GWR C025 was replaced by the GWR iGRav050, which has been in operation since April 16, 2024. Determining the scale factor is an important issue after the installation of a relative gravimeter. Usually, this is done by simultaneous observations with an absolute gravimeter (AG). Independent calibration experiments are required to obtain a reliable scale factor (SF) at the desired accuracy level of 1 ‰ or even less, as required for various geodynamic problems. AG experiments could not be performed so far. Therefore, the use of a well-defined tidal model is an alternative to obtain the scale factor for iGrav050.

For the Conrad Observatory (CO), accurate local Earth tide (ET) models including ocean loading (OL) are available, based on the eleven years long gravity time series recorded by GWR C025. Of course, this approach poses some problems because various assumptions have to be made that do not necessarily apply. First of all, it is assumed that the tidal parameters at the site are stable over time. This assumption is reasonable in terms of the Earth's response to tidal forces, at least for a few decades. However, changes could also occur at shorter time intervals, especially due to changes of indirect effects (OL). Another problem is that observed gravity contains contributions from meteorological and hydrological processes in a broad frequency range that can only be partially captured by models. This applies in particular to local hydrology, for which no model is available.

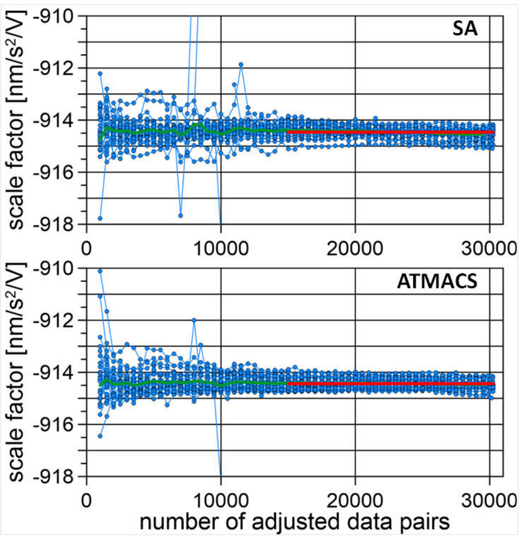

Figure 1: SF adjustment after applying the SA-concept and the ATMACS model respectively for predicting atmospheric effects. Red line: SF average for 15000 < number of adjusted data pairs < 31000. Green line: SF average as function of the number of adjusted data pairs.

The single air pressure admittance (SA) approach is suitable for modeling atmospheric effects (gravity and load), but does not take into account the frequency dependence of the gravity response to atmospheric processes. The latter is better reflected – at least for low frequencies - by physical atmospheric models (AM) such as the 4D-model time series provided by the ATMACS service of BKG (Klügel & Wziontek, 2009, https://doi.org/10.1016/j.jog.2009.09.010) which are combined at high frequencies by an SA-concept to overcome the limited spatial and temporal resolution of the model (e.g. Meurers, 2024, https://doi.org/10.5194/hess-25-217-2021).

To minimize the influence of unmodeled instrumental drift and the long-period contribution (hydrology and other sources) to the observed temporal gravity variations, the iGrav time series was divided into overlapping intervals of about 21 days each, after resampling from 1 second to 1 minute by appropriate numerical filters. Synthetic gravity time series were calculated on the basis of local ET models applicable to CO, and the SA approach or the ATMACS model, respectively. The first ET model results from fitting the gravimetric factors and phases for 58 wave groups together with an SA that applies to daily and semi-daily frequencies. The second model is derived by subtracting the ATMACS air pressure effect before the tidal analysis and fitting only the tidal parameters. The linear regression between observed and synthetic data provides the SF. Fig. 1 shows the results for both approaches as a function of the number of data pairs for all overlapping time intervals. Finally, average SFs were determined using only the results for a high number of data pairs when the SFs converge to an almost constant level. The results, -914.46 (SA) and -914.44 (ATMACS), differ about 0.02 ‰, proving that both approaches work well. However, the scatter in the combination of ET and 4D AM is significantly lower, probably because an AM takes the gravitational effect of air pressure fluctuations at lower frequencies into account better than an SA approach. The results are confirmed by frequency domain tidal analysis, which also provides, in addition, an estimate for the instrumental time lag. The gravimetric factors of the main tidal waves O1 and M2 obtained by tidal analyses of the GWR C025 and iGrav050 gravity time series each differ by 0.02 ‰ only; the time lag of iGrav050 is about 8.61 sec.

Authors:
B. Meurers[1]
1) University of Vienny, Vienna, Austria

Corresponding author:
Dr. Bruno Meurers
Department for Meteorology and Geophysics, University of Vienna
Josef-Holaubek-Platz 2, UZA 2, 1090 Vienna, Austria
e-mail: bruno.meurers@univie.ac.at

Geoelectrics and Electromagnetism

Geoelectrical monitoring at the Conrad Observatory

Birgit Jochum, Anna Ita, Stefan Pfeiler, David Ottowitz, Philipp Högenauer, Stefanie Gruber, Martin Heidovitsch

A geoelectrical monitoring was installed in 2023 at the Conrad Observatory to measure the effect of precipitation events observed in gravimetric data.

In November 2023, a geoelectrical monitoring system was installed at the Conrad Observatory, perpendicular to the tunnel of the Seismological-Gravitational Observatory (SGO). The center of the geoelectric profile was positioned directly above the superconducting gravimeter. The aim of the resistivity measurements was to monitor the precipitation induced water infiltration along the profile, which is also detected by gravimetric data. The profile comprises 93 electrodes with an electrode spacing of 1.5 m (Fig. 1). To protect against external influences, all installed cables were pulled into armored tubes laid in the field.

Figure 1: Fully installed monitoring system (solar panel, Geomon4D measuring boxes on the pole), aluminium boxes with fuel cell and batteries.

To reduce the effect of the electrical noise on the nearby Geomagnetic Observatory (GMO), measurements are scheduled only once a day, and the current input is limited to 200 mA at a maximum voltage of 200 V.

In general, there is a very heterogeneous electrical resistivity distribution in the area of the geoelectrical monitoring profile (Fig. 2), which tends to show relatively high electrical resistivity values (limestone). There is one exception that is the low-resistive anomaly in the central area of the profile, which can be assigned to the tunnel area.

The monitoring system at the Conrad Observatory is designed for medium to long-term operation, yet wild animal damage is a major problem, as the cables are repeatedly nibbled and contact with the electrodes is lost.

In December 2024, the measuring device was replaced with the newer GEOMON4D-IP, also developed by the GeoSphere Austria (Ottowitz et al, 2022, https://doi.org/10.3997/2214-4609.202220041). The major benefits of the new system are a higher measuring speed, which reduces the negative influence on the GMO, and the ability to monitor also the chargeability of the subsurface with the IP-measuring mode.

The first evaluation of the geoelectrical monitoring data shows a very good correlation between the gravimeter data and the inversion data for precipitation events. Differences between long-lasting rain/heavy thunderstorms can also be observed (see Arneitz et. al, 2025, https://doi.org/10.5194/egusphere-egu25-15367).

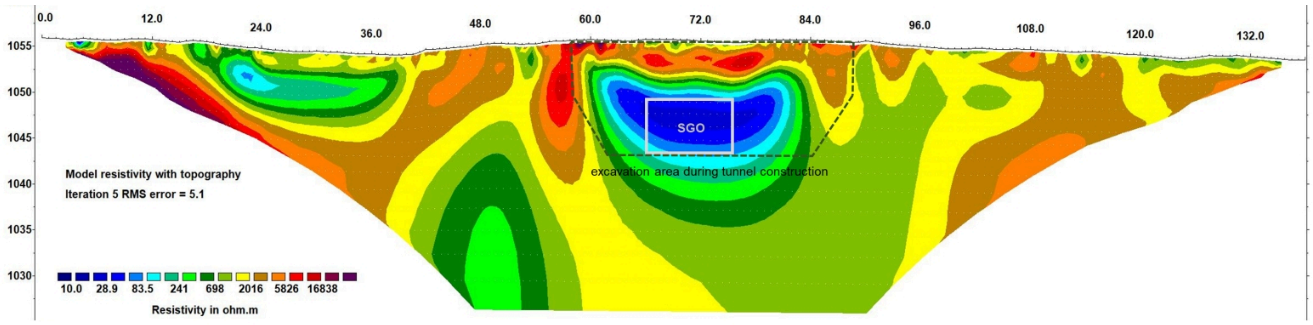

Figure 2: Result of the data inversion shown as a model of the electrical resistivity from the geoelectrical monitoring profile at the Conrad Observatory. The rectangle around "SGO" indicates the position of the tunnel. X- and Z-scales are given in meters.

Authors:
B. Jochum[1], A. Ita[1], S. Pfeiler[1], D. Ottowitz[1], P. Högenauer[1], S. Gruber[1], M. Heidovitsch[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Birgit Jochum
GeoSphere Austria
Neulinggasse 38, 1030 Vienna, Austria
Tel +43 712 5674 6381
email: birgit.jochum@geosphere.at

Processing of magnetotelluric soundings at different sites in Austria

Anna Hettegger, Adrian Flores-Orozco

Comparative magnetotelluric (MT) soundings were conducted at two contrasting sites in Austria: the Neusiedler See-Seewinkel National Park and the Hydrological Open-Air Laboratory (HOAL) in Petzenkirchen. These soundings aim to identify and understand sources of anthropogenic noise and their impact on MT data quality, impedance estimation, and interpretation.

Magnetotellurics (MT) is a passive geophysical method that measures the orthogonal components of the Earth's natural electric and magnetic field variations. The natural sources of such fields include solar winds or global thunderstorms. A typical MT set-up includes induction coils for measuring three orthogonal components of the magnetic field (H_x, H_y and H_z) and two electrode pairs for measuring the electric field (E_x and E_y), with a distance between the sensors is generally less than 100 m. Processing of the time series of the allows to resolve variations in the electrical conductivity, for investigations ranging from a few meters to km. Here, we present exemplary 40-minute MT time series, sampled at 1024 Hz collected at two contrasting sites in Austria: the Neusiedler See-Seewinkel National Park and the Hydrological Open-Air Laboratory (HOAL) in Petzenkirchen. The first one is related to negligible sources of contamination of MT data due to urban activity, while the second one reflects the influence in the MT data due to power lines, railways, oil pipelines, residential areas, and roads. The collected time series were processed using an open-source workflow using the Python package SigMT.

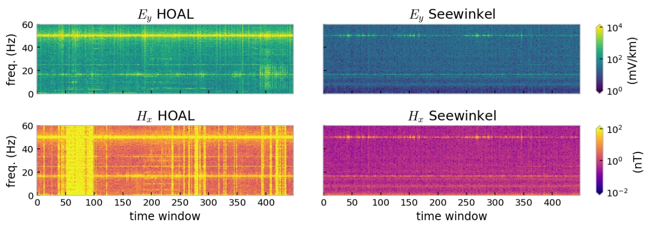

Figure 1: Electric (top) and magnetic (bottom) spectra in the frequency range 0-60 Hz. The HOAL (left) shows a higher noise level than the Seewinkel (right), due to the stronger influence of anthropogenic infrastructures.

Fig. 1 shows displays the power spectra of the electric channel E_y (East-West) and the magnetic channel H_x (North-South) of the HOAL and Seewinkel data. The distortions due to the power line can be identified at 50 Hz, and the railway at 16.7 Hz. The Figure 1 also demonstrate that the closer distance to the source of parasitic electromagnetic (EM) fields, the larger distortions are significantly higher in the HOAL. Additionally, at this site it is possible to observe random noise characterized by high-amplitude anomalies across the entire frequency range, in particularly between time windows 40 to 100. High noise levels due to strong anthropogenic interference at HOAL degrade the quality of impedance tensor estimation. Currently, we are working on the development of robust methodology to permit the collection of good quality MT data in urban areas. As a first approach we focus on data collected at low frequencies (<7 Hz). Fig. 2 presents the apparent resistivity and phase estimates from the Seewinkel dataset for the frequency range between 2.37 and 237 Hz. The apparent resistivity provides a preliminary insight into the resistivity variation with depth, with smooth curves indicating high data quality.

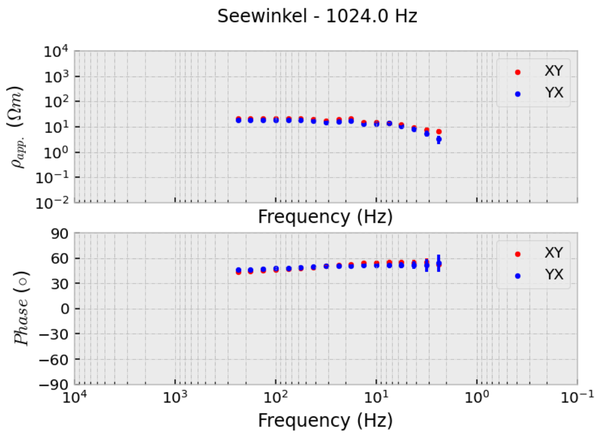

Figure 2: Apparent resistivity and phase estimates of MT soundings at Seewinkel. The red dots represent the North-South (XY) estimates, while the blue dots are the East-West (YX) estimates.

Examining raw MT data in time- and frequency domain helps to identify and understand sources of anthropogenic noise affecting the data quality, impedance estimation and ultimately interpretation.

Authors:
A. Hettegger[1], A. Flores-Orozco[1]
1) Research Unit Geophysics, Department of Geodesy and Geoinformation, TU Wien, Vienna, Austria

Corresponding author:
Prof. Dr. habil. Adrian Flores-Orozco
TU Wien
Wiedner Hauptstr. 8–10, 1040 Vienna, Austria Tel.: +43 1 58801 12834
e-mail: adrian.flores-orozco@geo.tuwien.ac.at

Benefits of the new seismic array at COBS

Maria-Theresia Apoloner, Stefan Weginger

Since 2021, the Conrad Observatory has been recording seismic signals with two additional stations, C21A and C22A, alongside the existing stations CONA and CSNA. This new seismic array allows for advanced processing techniques to extract more detailed information from the seismic waves of local earthquakes, including parameters like slowness and back azimuth.

Depending on distance and magnitude, a single seismic station at Conrad Observatory can detect earthquakes from all around the world. However, it is limited to wave onset time, amplitudes and periods. With a seismic array, wavelengths λ smaller than array aperture can be further processed for back azimuth and slowness (inverse of apparent velocity), which are both important for later seismic phase identification.

In 2021 the stations C21A and C22A were installed at the geomagnetic part of the Conrad Observatory, as is shown in Fig. 1. The extend of the existing tunnel system limited the array aperture to 480 m in E-W direction. Additionally, a borehole sensor was deployed close to station CSNA at 92 m depth in 2024, but not considered here.

In a first step, we calculated the array transfer function. It defines an array's sensitivity and resolution for seismic signals with varying frequencies and slownesses. Fig. 1 illustrates that a value of 1 indicates optimal tuning for a specific wavenumber ($1/\lambda$).

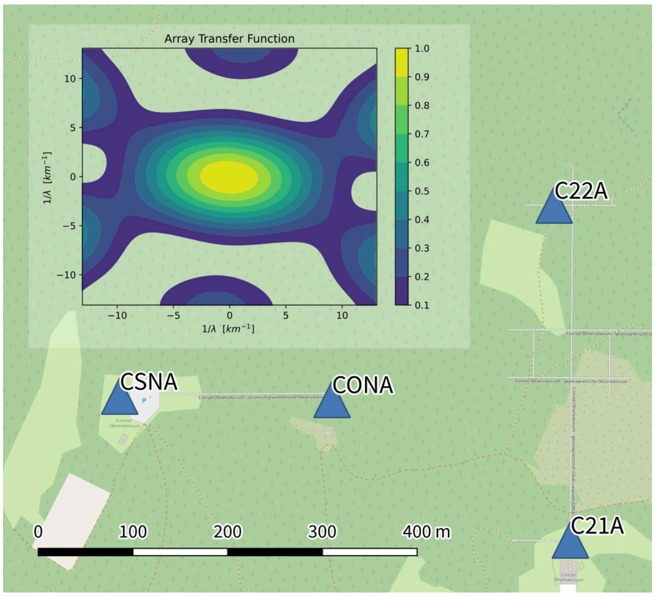

Figure 1: Aperture und Array Transfer Function for COBS seismic array.

Furthermore, we examined signals of three local earthquakes between 14 and 50 km distance with local magnitudes ranging from Ml 0.3 to 2.4. Utilizing the seismic software package ObsPy we stacked the data for various slownesses to enhance the signal.

Fig. 2 presents the results for the smallest earthquake analysed, with a local magnitude of 0.3, located 14 km away at a 220° back azimuth. The dotted black lines represent the estimated back azimuth and slownesses for the earthquake. The calculated values closely align with the observed P-wave arrival shortly before 03:17:01; however, the same is not observed for the S-wave arrival around 03:17:02. Similar results were observed for all three earthquakes.

Therefore, this seismic array proves valuable for enhancing data on even very small local events by providing additional information on the back azimuth and slowness of the first arrivals. With further parameter tuning, it could also enable analysis of later phases, depending on the wavenumber.

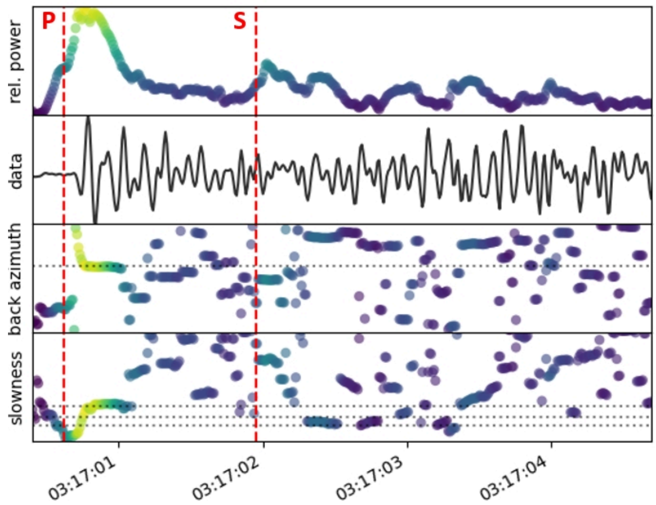

Figure 2: Results of array processing at COBS seismic array for Ml 0.3 earthquake at Schwarzau in 14 km distance and 220° back azimuth for P- and S-arrivals.

Currently, the data is not utilized for routine analysis in the earthquake service, as the improvements primarily apply to local events. In future, the array could enhance event location, phase identification, and interpretation of subsurface structures.

Authors:
M.-T. Apoloner[1], S. Weginger[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Dr. Maria-Theresia Apoloner
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
Tel.: +43 (1) 36026 2550
e-mail: maria-theresia.apoloner@geosphere.at

Listening to the Atmosphere

Ulrike Mitterbauer

The continuous monitoring of potential nuclear tests is performed by the Austrian National Data Center (NDC-AT). The Comprehensive Test-Ban Treaty (CTBT) forwards data from a worldwide network of different sensors to all signatory states for verification purposes. One technology used to monitor atmospheric explosions is infrasound. To study its attributes and to understand the behaviour of infrasound propagation the Infrasound Array ISCO was installed in 2021 in the premises of the observatory. Meanwhile the system was upgraded and continuous data has been recorded in real-time. An overview of the detection capability is presented in the article.

Installed in 2021, the ISCO array became part of the Central Eastern European Infrasound Network (CEEIN) which was established in 2018 by Romania, Czechia, Hungary, Ukraine and Austria (Bondar et al, 2022, https://doi.org/10.1093/gji/ggac066). In 2024 the array was upgraded with a new portable Wind Noise Reduction System, purchased from Enviroearth (https://enviroearth.fr). The installation was supported by an employee of the company.

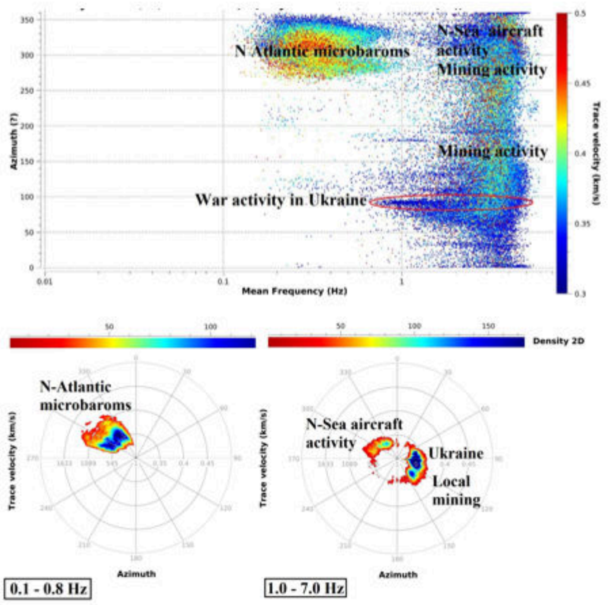

Figure 1: Detection at ISCO as a function of frequency and azimuth, color-coded by trace velocity (top). Detections as function of azimuth and trace velocity, color-coded by density (bottom).

ISCO array detects infrasound signals from different sources, natural (microbaroms, volcanoes, bolides, earthquakes) and anthropogen (local quarry blasts, sonic booms of military aircrafts, military activity in Ukraine). A variety of signals was registered in the years 2023 and 2024. Fig. 1 shows the dominant coherent noise sources at ISCO as a function of mean frequency and azimuth for 2023 and 2024 and the density of detections in relation to frequency range using the dtkDIVA-Software, developed by CEA/DASE (Commissariat à l'Énergie Atomique/Département analyse, surveillance, environment, France). A repeating source of infrasound is generated by local mining industry close to the array (distance up to 50 km). ISCO detects as well constantly signals of shelling, bombardment and missiles along the battle line in Ukraine. Huge explosions in ammunition depots in Pavlovgrad (30.4.2023, distance 1500 km), in Chmelnyzkyj (13.5.2023, distance 800 km), in Schytomyr (28.5.2023, distance 975 km) and in Toropets (18.9.2024, distance 1425 km) were recorded. Other events of interest were two bolides, one of which was sighted in the sky in Lower Austria at around 23:45 UTC on September 18, 2024 and the other on October 24, 2024 at 19:27 UTC in Upper Austria. The Austrian Seismological Service was able to record the shock waves of both events at several seismic stations, as well at ISCO.

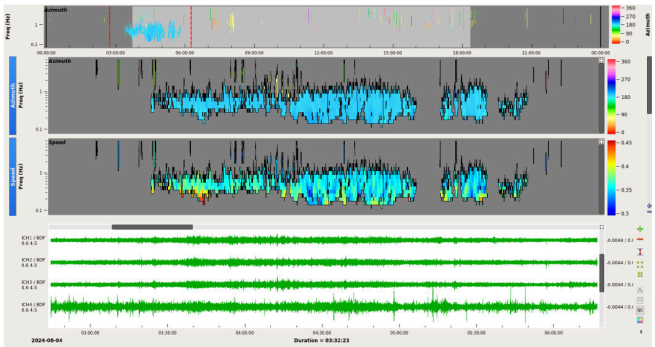

Figure 2: Detection of eruptions of volcano Etna (4.8.2024).

In August 2024 eruptions of volcano Etna (distance from array ISCO 1150 km) were detected. Data was processed and analyzed manually by using the dtkGPMCC- Software, developed by CEA. In the upper part of Fig. 2, the detections are color-coded by azimuth, in the middle panel by trace velocity. In the lower part of Fig. 2 waveforms are displayed, filtered between 0.5-4Hz. These signals lasted for around two hours.

Authors:
U. Mitterbauer[1]
1) GeoSphere Austria, Vienna, Austria

Corresponding author:
Dr. Ulrike Mitterbauer
GeoSphere Austria
Hohe Warte 38, 1190 Vienna, Austria
Tel.: +43 (1) 36026 2527
e-mail: ulrike.mitterbauer@geosphere.at

Continuous Long-term Radon Measurement for Earthquake Research

Harry Friedmann

Many observations have shown a correlation between abnormal radon concentrations in ground water or soil gas and subsequent earthquakes. The catastrophic earthquake in the Friuli area in 1976 has triggered research in this field at the Institut für Radiumforschung und Kernphysik in Vienna where the technique of radon measurements has a long tradition. At that time there was a great optimism that earthquake prediction will be possible within a few years. The main reason were the apparent successful predictions of several strong earthquakes in China. In Austria a continuous measurement station was established at the Freibadquelle in Warmbad Villach with the help of the Fonds zur Förderung der Wissenschaftlichen Forschung in Österreich and the special support of the owner of the spa (Family Lukeschitsch). During the following years several improvements were necessary to keep the station running. Especially the change from paper to digital recording allowed a much better investigation of the data. In 2023 the digital data of the radon concentration in the water of the spring were transferred to the Conrad Observatory and since that time the data are continuously collected there.

The spa of Warmbad Villach with its warm springs is situated along the Periadriatic Fault Zone which is close to the epicentre of the 1976 earthquake of Friuli. The water of the springs is a mixture of surface water and deep water according to tritium measurements. The theories of earthquake preparation predict the opening of cracks with increasing stress before earthquakes (dilatancy-diffusion and dilatancy-instability theory), causing several observable effects, especially an increased radon transport to the surface either by ground water or soil gas as well as a change in the stream of subsurface water. Generally, most of the observable parameters show variations (Fig. 1) in time caused by effects which cannot be related to the subsurface stress changes. Unfortunately, in many publications the occurrences of so called anomalies are rather questionable. Next, a verification of a correlation between a proofed anomaly and a subsequent earthquake is necessary. Usually, a magnitude-distance relation is used to filter out relevant earthquakes. Today, a correlation between observed effects and earthquakes can be revealed only on a statistical basis which means long observation times. For a meaningful earthquake prediction we need: (1) The time of occurrence with a 'small' uncertainty; (2) The location with a 'small' uncertainty; (3) The magnitude with a 'small' uncertainty; (4) The long-term probability for an earthquake within the predicted intervals of an earthquake-forecast must be close to zero. (Explanation: For an area where every week an earthquake occurs, an earthquake prediction for a certain week is not a meaningful prediction.)

We need also the probability for the occurrence of the predicted earthquake within the predicted uncertainties. This probability is a crucial point for the announcement of a prediction, but generally it is not known. It can only be said that it is anti-correlated with the size of the uncertainties of the prediction. The adjective 'small' in (1)–(3) depends on the type of prediction and must be seen in connection with the time span up to the time of the predicted earthquake. Generally predictions are distinguished into (1) long term (many years); (2) mid term (months to one year); (3) short term (days to weeks); (4) immediate (hours to one day).

The final goal of an earthquake prediction is the issue of a warning. On a scientific basis it is necessary to estimate the losses in an assumed earthquake, the reduced losses after a warning and the losses according to a false warning (problem of comparing lives and economic losses). In combination with the uncertainty of a prediction we have to compare the error of the first kind and the error of the second kind (false warning, earthquake but no warning). With the continuous radon measurements in Warmbad Villach which are probably one of the longest continuous data sets worldwide we try to contribute to the global challenge of earthquake prediction. The data are now collected at the Conrad Observatory that will assure continuity for the measurement in the future.

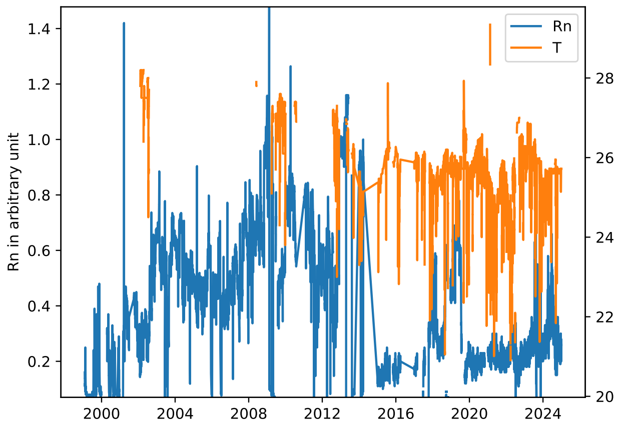

Figure 1: Radon concentration and water temperature in the Freibadquelle Warmbad Villach for the last 25 years.

Authors:
Harry Friedmann[1]
1) Retired from Isotope Research and Nuclear Physics, University of Vienna, Austria

Corresponding author:
Mag. Dr. Harry Friedmann
Esterhazygasse 23/23, 1060 Vienna, Austria
Tel.: +43 664 73928466
e-mail: harry.friedmann@univie.ac.at