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Conrad Observatory

- Geomagnetically Induced Currents
- JUICE Mission
- Magnetic Observatory
- Paleo- and Archeomagnetism
- Seismology and Acoustics
- Gravity and Tilt

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Preface

Earth observation and geoscientific research represent an essential aspect in understanding our living planet. Of particular importance are relationships between humankind and natural environment. Geophysical processes have an undeniable effect on our culture and society, its infrastructure and economy. The Conrad Observatory represents the commitment of the Zentralanstalt für Meteorologie und Geodynamik to facilitate excellent observation and research in this context.

The Conrad Observatory, located in Lower Austria, is an unique infrastructure for geoscientific research, development and observation. Two tunnel systems and laboratory facilities support a wide range of research disciplines, paving the way for trendsetting interdisciplinary science. The infrastructure and its data are used by numerous national and international institutions dealing with all aspects of the Earths' system, from earthquakes to the space environment.

Austria looks back to a long and seminal history of Earth sciences. The foundation of the Zentralanstalt 170 years ago by an "observer", Karl Kreil, was one important factor. The Conrad Observatory represents a state-of-the-art infrastructure continuing the long tradition of earth observation and international collaboration in this field. Thus, we are ready for current and futures challenges.

In this spirit,

Dr. Michael Staudinger
Director of the Zentralanstalt für Meteorologie und Geodynamik

Content

Historical Analysis of Geomagnetic Storm Scales in Austria

Rachel Bailey, Roman Leonhardt, Christian Möstl, Philipp Schachinger, Dennis Albert

Geomagnetically induced currents (GICs) can affect power transmission grids in the form of power operation problems in mild cases and power blackouts in extreme cases. To quantify the risk for Austria, we carried out an analysis of historical geomagnetic field measurements from recent years - since the Conrad Observatory only spans the past five years, this was extended to 25 years by using the data from nearby Fürstenfeldbruck in Germany. Using a model of GICs validated using Conrad Observatory data and GIC measurements, we can estimate the scales of GICs during larger geomagnetic storms.

As a mid-latitude country, Austrian is not expected to suffer greatly during geomagnetic storms as many countries in higher latitudes do. Regardless, geomagnetically induced currents have been found to affect the Austrian power grid and studies are being carried out on the kinds of scales that can be expected during rare and powerful geomagnetic events.

Measurements from the Conrad Observatory over the past years have been used to build and validate a model of geomagnetically induced currents in the Austrian power grid. This model takes geomagnetic variations and computes the geoelectric field induced in the Earth, which is represented by a 1D layered half-space reaching into the ground. The geoelectric field is then fed into a virtual model of the power network, and the currents at each network node (i.e. transformer) are calculated. It has been possible to validate this model by comparing the results to measurements of DC in transformers across Austria.

However, the past years have been relatively quiet with regards to geomagnetic activity and our modelling does not provide estimates of the GICs that would occur during larger and potentially damaging storms. For this, we need a dataset that reaches back further into the past. The data at the Fürstenfeldbruck (FUR) observatory has a high correlation (>0.9 in dB/dt) with that at the Conrad Observatory due to the similar latitudes of the two locations. With minute data reaching back to 1995, it is a useful proxy for the variations we would have expected to see in Austria.

An analysis carried out on FUR geomagnetic data shows that there were dB/dt values of up to 180 nT/min in the East-West direction and 90 nT/min in the North-South direction. As a result, power grid substations susceptible to variations in the East-West direction can be expected to suffer from larger GICs. The largest geomagnetic event of the past 25 years was the 2003 Halloween storm, and with FUR data we were able to model the GICs that likely occurred during that storm, plotted in Fig. 1. At a station near Vienna, the values reach 25 A (middle panel). Generally, DC above 10 A is expected to affect transformer operation. The sum of minute-value GICs over consecutive half-hour periods (lower panel) are around 200 A early on the 29th and late on the 30th of October, showing that there were times of sustained GICs that could lead to eventual overheating problems.

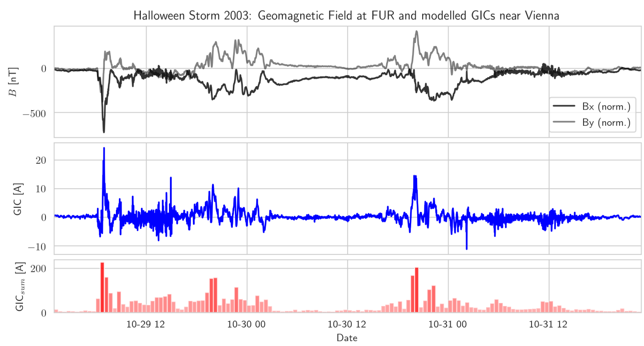

Figure 1: The 2003 Halloween storm (2003-10-29 till 2003-10-31) geomagnetic field variations at Fürsternfeldbruck (top), along with the GIC values computed at one substation transformer in Austria in values over time (middle) and the cumulative GICs over half-hour sections (bottom).

Using the estimates from the past 25 years, we can extrapolate to larger geomagnetic storms such as the Carrington event, where GICs in Austria would be estimated to reach up to a few hundred ampere. What effect currents of this size would have on power operations is a topic that will be investigated in the next years.

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Geomagnetically Induced Current Measurement in the Austrian Transmission Grid

Philipp Schachinger, Dennis Albert, Rachel L. Bailey, Georg Achleitner, Herwig Renner

Low frequency currents (LFC) can lead to serious problems in power transmission grids. The major share of these currents are geomagnetically induced currents (GIC), which are caused by geomagnetic disturbances. Measurements of LFC in transformer neutral points started in 2013 at a single transformer and have since then expanded to six measurement units all over the Austrian transmission grid.

The save and reliable operation of power transmission systems is one of the main responsibilities of transmission system operators. Therefore, risk analysis of the grid and system equipment is an important topic. First investigations in LFC were triggered by unexpected transformer noise in 2013. Measurements in the transformer neutral point, performed by the Institute of Electrical Power Systems (IEAN) from Graz University of Technology, revealed DC currents with a high correlation to fluctuations in the earth's magnetic field. As an outcome of these investigations, a cooperation for further analysis between ZAMG, IEAN, the Austrian Transmission System operator APG and Siemens Transformers was initialized.
The effects of geomagnetic disturbances on power transmission grids and pipelines are a well known problems in countries close to the magnetic poles. Although Austria is a mid-latitude country, the geological structure, with the Alps in the west and the lowlands in the east, can lead to high amplitudes of GICs as well. With magnetic field measurement data, provided by Conrad Observatory, and data from the Austrian Transmission Grid, GICs can be calculated for all transmission lines, transformers and substations in Austria.

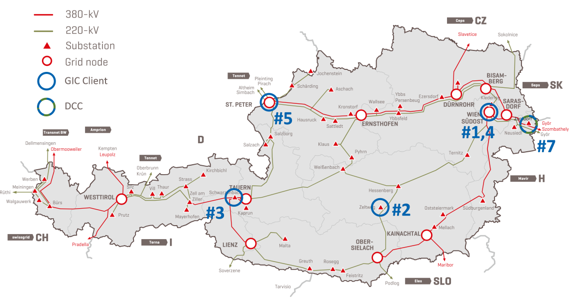

Figure 1: The Austrian transmission grid and equipped transformers with the neutral point current measurement system from IEAN.

The six neutral point measurement systems provide data from transformers in the 380-kV and 220-kV transmission grid, as depicted in Figure 1. The sampled data are sent to the IEAN for further processing and analysis. This measurement data is unique in central Europe and is also used to improve simulation and calculation methods. The combination of measured and calculated currents provides information about impact of GICs in Austria and resulting risks for grid operation. The measured currents are in the range from almost zero to ±13 A during the transition from solar cycle 24 to 25.

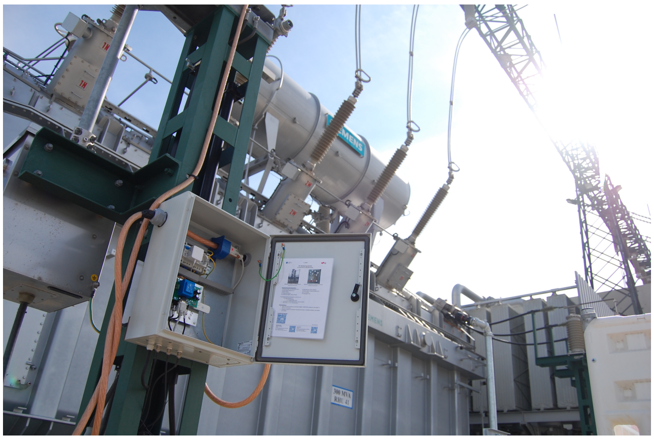

Figure 2: Installed transformer neutral point current measurement system and self-engineered measurement electronic.

Recent research results show that the low frequency transformer neutral point currents are also caused by DC powered public transportation systems, such as the subway system. With this information, mitigation strategies as well as a guideline for operating transmission system during geomagnetic storms can be created. The overall aim to protect the Austrian energy supply is completed with detailed laboratory tests on power transformers.

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Accuracy Investigations on the Scalar Magnetometer of the JUICE mission

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The accuracy of the flight model of the scalar magnetometer for ESA's scientific satellite mission JUICE to Jupiter was investigated with the Merritt coil system.

In 2022, ESA's Jupiter Icy Moons Explorer (JUICE) space mission will launch to investigate the potentially habitable sub-surface oceans of Ganymede, Europa and Callisto. For this mission, a scalar omni-directional magnetometer was developed in a cooperation between the Institute of Experimental Physics (Graz, University of Technology) and the Space Research Institute of the Austrian Academy of Sciences in Graz. This new type of optically pumped magnetometer uses laser light to detect magnetic influences on the atomic states of rubidium vapour. This vapour is contained within a glass cell, which is installed in the magnetometer's sensor unit. Especially prepared laser light is brought from the electronics box by an optical fibre to this glass cell and excites so-called coherent population trapping (CPT) atomic resonances by its interaction with the rubidium atom's energy states. These energy states and their associated CPT resonances are shifted in proportion to the ambient magnetic field. By measuring these shifts, the magnetic field strength is detected by the magnetometer. A CPT resonance leads to a reduction of florescent light, therefore, they are also called dark states. Since multiple of those are coupled simultaneously by this magnetometer, it was named Coupled Dark State Magnetometer (CDSM)[1,2].

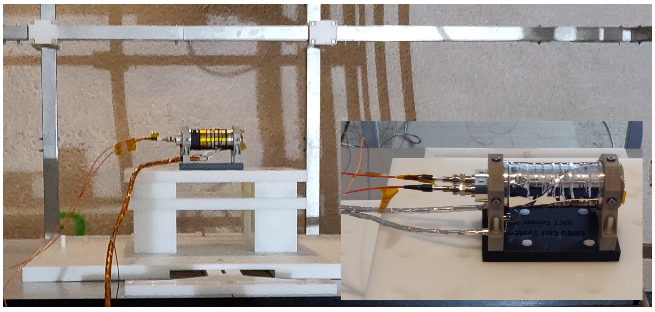

Figure 1: The JUICE QM (main picture) and the FM sensors within the Merritt coil system for performance evaluation.

The JUICE mission requires the scalar magnetometer to measure magnetic field strengths in the range from 200 to 2000 nT with an accuracy of ±0.2 nT. This accuracy has to be confirmed for the entire measurement range and for all angles between the magnetic field direction and the sensor axis (the sensor angle). Due to the CDSM's measuring principle, the instrument's magnetic field reading deviates from the actual field strength as a function of the sensor angle. In order to determine the angular heading characteristics for the entire measurement range, a magnetically very clean, stable and adjustable environment is required. Such an environment is provided by the Merritt coil system at the Conrad Observatory. In addition to the tunnel's temperature stability and the coil's remote-control ability with automation capabilities, this setup is ideal for the efficient development, testing and evaluation of the CDSM. In the course of several measurement campaigns during 2019 and 2020, the qualification model (QM) as well as the flight model (FM) for the JUICE mission were tested with the infrastructure of the observatory. Within the Merritt coils, the CDSM's operational parameters were optimized (Figure 1). During an electronically controlled rotation of the magnetic field relative to the sensor the heading characteristics were measured (see Figure 2). Using this method, the required accuracy of ±0.2 nT was confirmed for the JUICE FM.

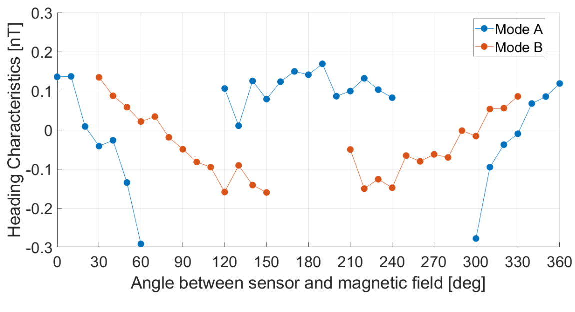

Figure 2: This exemplary heading characteristics of the JUICE FM was measured with the Merritt coil system. By switching between the two instrument modes A and B, the magnetometer's omni-directionality is achieved.

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[2] Pollinger et al., Meas. Sci. Technol., 29, 095103, doi:10.1088/1361-6501/aacde4 (2018)

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Interference Tests with the JUICE J-MAG Qualification Model

A. Pollinger, H.-U. Auster, R. Baughen, C. Hagen, A. Strickland, R. Hudson, P. Brown, W. Magnes, R. Lammegger, M. Dougherty

In August 2020, the J-MAG team carried out interference measurements with the qualification model of a magnetometer developed for ESA's JUICE mission. The follow-up flight instrument will be launched in 2022 and will explore the Jupiter system.

The JUpiter ICy moons Explorer (JUICE) is European Space Agency's (ESA) first mission to the outer solar system. It will carry a total of ten scientific experiments to study the gas giant Jupiter and three of its largest moons, Ganymede, Callisto and Europa. The mission will be launched in September 2022 and its arrival at Jupiter will take place in 2031.

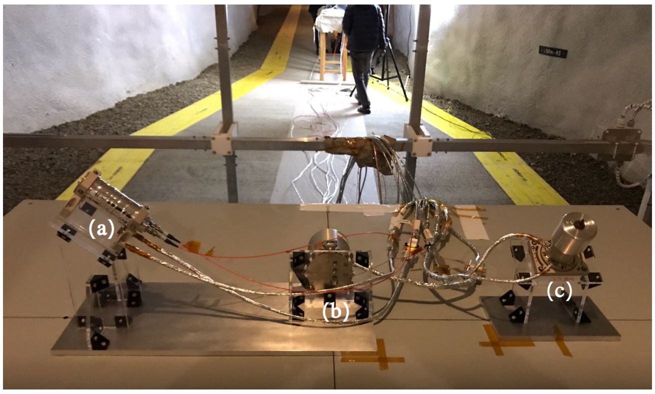

Figure 1: The optical scalar (a) and the two fluxgate vector sensors (b) and (c) were installed in the Merritt coil system in order to simulate the magnetic environment of Jupiter.

The J-MAG instrument is being developed for the JUICE mission by the J-MAG consortium, formed to implement, operate and exploit the magnetic field investigation on JUICE, led by Imperial College London (ICL). The instrument consists of a very specific design with two fluxgate vector sensors and one scalar sensor with low absolute error. One of the fluxgate sensors and associated electronics are provided by ICL, the second fluxgate sensor and associated electronics are developed by Technische Universität Braunschweig (TUBS), and the scalar sensor and associated electronics are provided by the Space Research Institute of the Austrian Academy of Sciences (AAS) in Graz, in close cooperation with the Institute of Experimental Physics of the Graz University of Technology (TUG). The J-MAG magnetometer will measure the magnetic field vector and magnitude (in the bandwidth from DC to 64Hz) in the spacecraft vicinity on a 10.5-meter-long boom.

The test campaign at the Conrad Observatory included timing tests to correlate the measurements of the individual sensors, a simulation of rotating fields with the new Merritt coil system in order to confirm that the on-board calculations needed to operate the scalar instrument are done properly, and several overnight measurements to characterize the stability and frequency response of the sensors. Additionally, the influence of supply voltage variations as well as of the sensors' operational and survival heaters on the magnetic field measurement of the other sensors were investigated.

The Merritt coil system located in the magnetically quiet and thermally stable environment at the Conrad Observatory provides a unique opportunity to evaluate the performance of the entire J-MAG instrument as a whole.

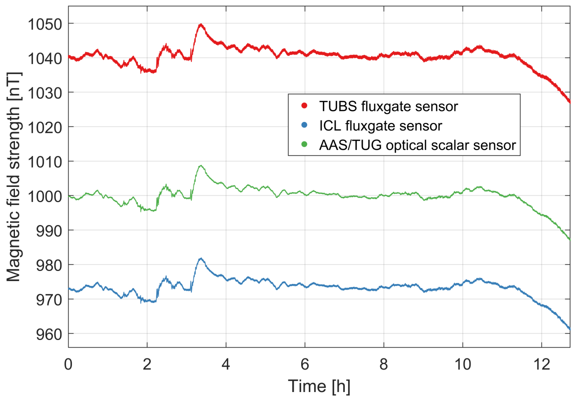

Figure 2: The Merritt coil system compensated the Earth field down to a strength of approximately 1000nT at the beginning of the measurement. The dynamic compensation of additional Earth field variations was paused afterwards and all three sensors followed the Earth field variations overnight. Gains and offsets of the fluxgate sensors are not calibrated in this plot which explains the DC shifts to the optical scalar sensor.

References:

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Magnetometer Calibration Facility

Josef Wilfinger, Roman Leonhardt, Werner Magnes, Aris Valavanoglou, Niko Kompein, Gerhard Berghofer

Only well-calibrated magnetometers produce reliable data and a good calibration requires a magnetically stable environment with precise references. The new three-meter Merritt coil system in the Conrad Observatory provides all these features. Integrated in the magnetic measurement system of the observatory, it can compensate the changing Earth's magnetic field and apply accurate calibration fields to the magnetometer under test. During a magnetically quiet day, the variation of the residual magnetic field in the centre of the coil system is <1 nT.

Accurate magnetometers must be calibrated to produce reliable data. Calibration is typically achieved through compensation of the environmental magnetic field (e.g. the natural Earth's magnetic field) around the magnetometer under test and the generation of a well-known calibration field with a coil system. The Conrad Observatory is an ideal place for this kind of calibration setup. It is far away from artificial disturbers and the available reference magnetometers provide very precise measurements of the Earth's magnetic field with a delay of less than 2 seconds.

Figure 1: Three-meter Merritt coil system for magnetometer calibration in the calibration cavern of the Conrad Observatory.

In 2017, the Space Research Institute of the Austrian Academy of Science (ÖAW) and the Central Institute for Meteorology and Geodynamics (ZAMG), which operates the Conrad Observatory, started a cooperation for the installation of a large and precise calibration facility. The Spanish company Serviciencia S.L.U. was selected to build a three-axes Merritt coil system with a side length of approximately three meters (Figure 1). The coil assembly consists of two separate Merritt coil systems along each axis. The first one compensates the Earth's field using measurements provided by the reference variometer of the observatory. During a magnetically quiet day, the residual field varies with less than 1 nT peak-to-peak in 24 hours (Figure 2). The second coil system applies the calibration field with a dynamic range of ±90,000 nT and a resolution of about 0.2 nT. The used current source electronics equipment for the coils consist of six BE2811 (iTest) and is located in a separate compartment 15 m from the coils. This moves unnecessary disturbances away from the coil system and provides thermally stable conditions that minimize field drifts.

In order to achieve a stable ∼0 nT residual field at the centre of the coil system, it is necessary to synthesize the inverted Earth's magnetic field vector with the three compensation axes. Three steps of matrix and vector operations are involved in this synthesis. These are the rotation of the measured Earth's magnetic field vector to an artificially defined and coil-based orthogonal coordinate system, the compensation of DC effects and the transformation to the real non-orthogonal coil system via non-orthogonality angles, which were determined by scalar measurements [1].

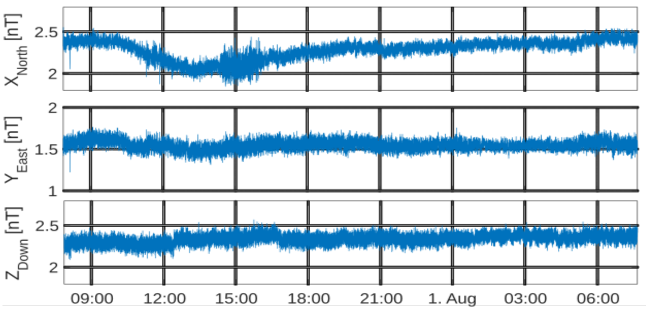

Figure 2: The residual field in the centre of the coil system during 24 hours. A moving average filter reduced the Digital FluxGate [2] data from 128 Hz to 2 Hz.

A graphical user interface and a network socket provide an easy handling of the coil and the possibility to automate and record the calibration process.

References:

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Peculiarities from the frequency analysis of geomagnetic data at COBS

Patrick Arneitz, Niko Kompein, Ramon Egli, Roman Leonhardt

A frequency analysis of geomagnetic time series measured at the Conrad Observatory is performed in order to identify artificial disturbing signal contributions. These disturbances are characterized by periods of 900s and corresponding harmonics, which can be associated with trading intervals of the power grid. Variations of power consumption during the first COVID-19 lockdown and at weekends might cause strong (electro)magnetic signals with a period of 75s.

Frequency analysis tools facilitate the study and isolation of distinct periodic contributions to a recorded signal. The identification of recurring electromagnetic disturbances is crucial in order to guarantee very accurate and precise monitoring of the geomagnetic field. Therefore, time series of geomagnetic field components X (North-component), Y (East-component) and Z (Vertical-component) measured in 2020 at the Conrad Observatory with a LEMI 36 magnetometer (LEMI036_1_0002_0002) have been evaluated using the Fast Fourier Transform technique (Fig. 1).

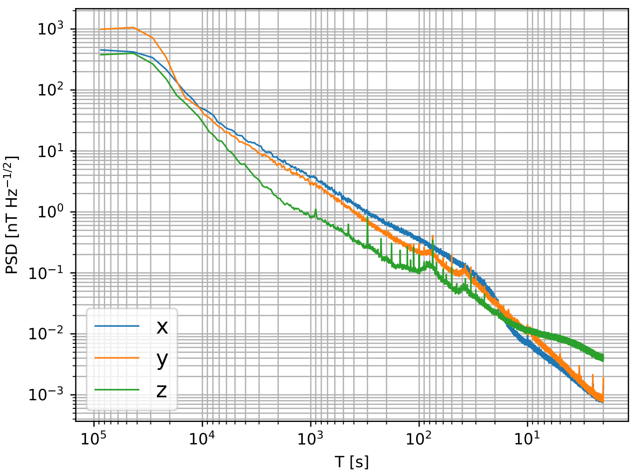

Figure 1: Median of daily power spectral densities for components X, Y and Z.

The medians of power spectral densities (PSD) determined for each day of the year 2020 reveal remarkable features for components Y and Z. Pronounced peaks in the PSD for Z are observed starting from a period T of 900s along with higher harmonics (i.e. multiples of the fundamental frequency f_0=1/900 Hz). The peak at T=75s also strongly stands out in the PSD of Y.

Trading intervals of 15 minutes (=900s) in the European power grid (Schäfer et al., 2018, https://doi.org/10.1038/s41560-017-0058-z) can be conceivable sources of detected (electro)magnetic variations. The exact physical processes – i.e. do disturbances originate directly from the power supply or from stray currents – are subject of ongoing research.

The temporal evolution of PSD Z values at T=75s over the year 2020 reveals further peculiarities (Fig. 2). In spring a steep increase of values is followed by a period of a constant high level, which is then terminated by a sudden decrease. These variations roughly coincide with the phases of the first lockdown due to the COVID-19 pandemic in Austria and might correlate with (public) power consumption. This hypothesis is supported by the fact that other peak values are often observed at weekends. However, the reason for the lack of significant effects during the lockdown phases in November and December remains open.

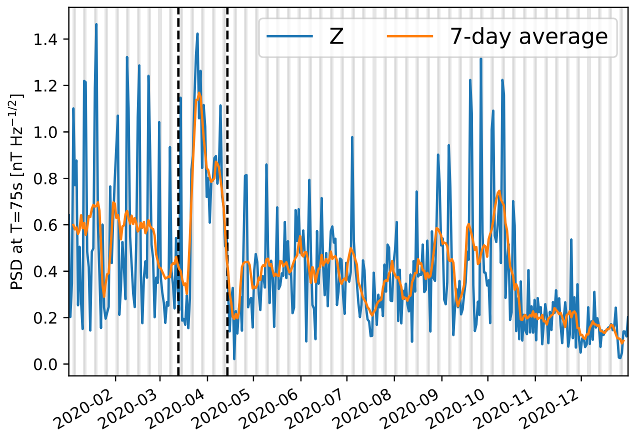

Figure 2: Temporal evolution of PSD values at T=75s over the year 2020. Dashed lines give the period of the first lockdown, while grey areas depict weekends.

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Origin of spectral anomalies in geomagnetic data at the Conrad Observatory

Ramon Egli, Barbara Leichter, Richard Kornfeld, Patrick Arneitz

The sensitivity of modern observatory variometers largely exceeds IAGA requirements and enables the detection of signals in the picotesla (pT) range after adequate data processing. Field variations in this amplitude range have a mixed origin which include ionospheric sources, geomagnetic induced currents, and other electrical currents of anthropogenic origin flowing in the underground. Here we demonstrate the use of mobile variometer stations and multitaper spectral analysis for the localization of underground currents and the detection of sensor artifacts at the Conrad Observatory.

Arneitz et al. ("Peculiarities from the frequency analysis of geomagnetic data at COBS", this journal) demonstrated the existence of periodic magnetic field disturbances in the pT range, which appear to be related to the trading interval $T_0 = 900$ s of the European power grid. In order to better understand the origin of this and other disturbances, a mobile measuring station equipped with a Lemi variometer was placed in the Conrad Observatory near the main entrance. This location is relatively close to the technical room that hosts the electrical distribution and UPS system. The mobile station was powered with a 12 V battery bank in order to exclude possible direct interferences from the power mains. Fig. 1 shows a comparison of the multitaper power spectra of the z-field components B_z recorded by the mobile variometer and by the observatory's reference variometer.

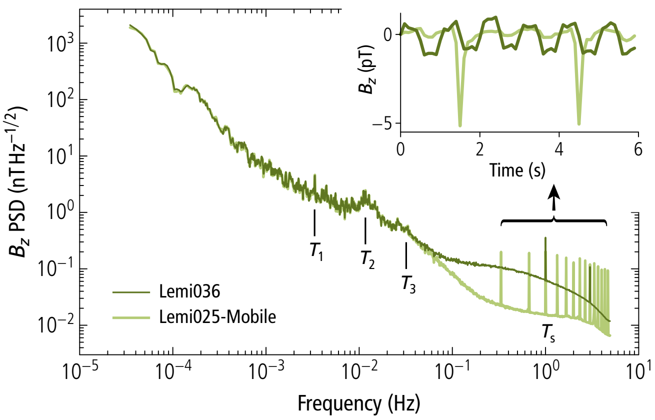

Figure 1: Power spectral densities (PSD) of the z-field components recorded by the reference variometer (Lemi036) and the mobile station (Lemi025) at the Conrad Observatory for two days (9-10.08.2020). A Slepian multitaper with $WT = 6$ was used for PSD estimation. The inset shows a time-domain reconstruction of digital sensor noise, obtained by stacking 28800 consecutive intervals of 6 s duration.

The two spectra are nearly identical, up to a noise floor difference that becomes visible above 0.1 Hz. Notable features superimposed to the $1/f$-characteristic of geomagnetic field variations include (1) a sharp peak with a corresponding period of $T_1 = 300$ s, (2) two broad peaks centred at $T_2 \approx 75$ and $T_2 \approx 30$ s, and (3) a series of sharp peaks representing harmonics and sub-harmonics of $T_s = 1$ s, which arise from a sensor-specific 1 pT rectangular signal. The frequencies of features (1) and (2) appear to be harmonics of T_0.

Further insights are obtained from the PSD of the field difference between the two sensors, which is sensitive to local current systems. The same periodic disturbances of the bulk spectra can be recognized, with sharper peaks at $T_2 = 67.6$ s and $T_3 = 30$ s, as well as an additional peak at $T_4 = 9.4$ s. These peaks affect only B_y and can be explained by N-S flowing electric currents, parallel to the main tunnel, which are stronger near the entrance. Peak broadening is caused by slow frequency variations occurring over a typical time scale of about 6 hours. It thus appears that the broad peaks affecting the bulk spectra originate from the superposition of underground currents flowing at different length scales with slightly different frequencies that vary in time around a constant mean value. All periods are compatible with harmonics of T_0 and thus seem to be related to the interaction of individual utilities with the power grid.

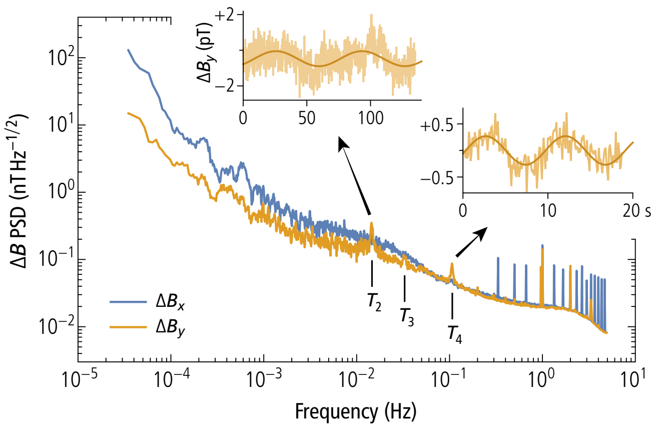

Figure 2: PSD of the horizontal field differences between mobile and reference variometer. The inset shows time-domain reconstructions of two periodic disturbances with center periods $T_{2,4}$ of 67.6 and 9.4 s, respectively, obtained by stacking intervals of duration $2T$ comprised between 06:00 and 12:00 on 09.08.2020.

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Correlations of thunderstorms and magnetic records at COBS

Niko Kompein, Patrick Arneitz, Roman Leonhardt, Ramon Egli, Gerhard Diendorfer

Due to the exposed position of the Conrad Observatory on top of Trafelberg, lightning strikes are frequently observed. Such lightning strikes cause contemporaneous peaks in our geomagnetic records, particularly visible in the live stream of the supergradiometer. These peaks/times were compared with ALDIS LLS (lightning location system) data. After down-sampling of ALDIS data to supergradiometer timestamps a good correlation between the time series was visible. This study focuses on short term effects and determination of amplitudinal calibration factors to check for systematic relations of ALDIS stroke peak currents and magnetic records at COBS.

Detection and measurement of lightnings is a discipline which is very precise in temporal terms and quite robust in spatial and amplitudinal terms. LLS, allows us to distinguish between cloud-ground(CG) and cloud-cloud(CC) lightning dicharges. In Austria ALDIS is one of the main providers of such LLS data which was used in this analysis. The N-S supergradiometer system (GP20S3_NS) at COBS has a comparatively lower sampling rate (1 sample/s) at very good amplitudinal resolution. By down-sampling the ALDIS data with an exponential weighting function in time to the timestamps of GP20S3_NS (Fig. 1) one can see a good temporal correlation.

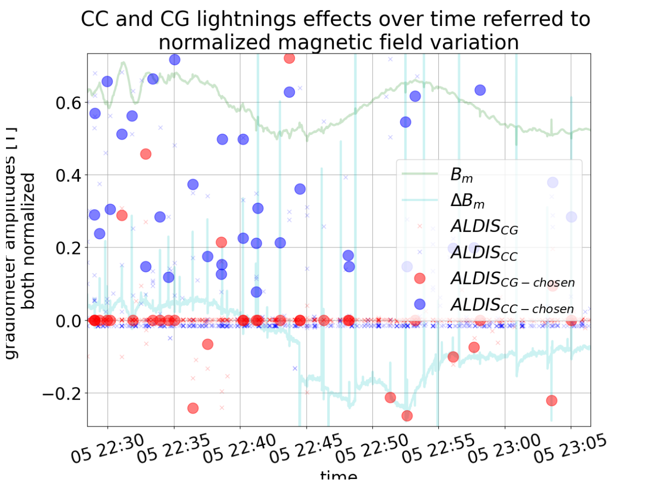

Figure 1: Small outtake of a comparison of the down-sampled ALDIS amplitudes, chosen ALDIS amplitudes and the average absolute and gradient variations of the GP20S3_NS system all normalized by their standard deviations.

The EM-fields of a lightning discharge are interpreted with a formula found in J.L. Bermudez Arboleda (2003, DOI:10.5075/epfl-thesis-2741) evaluated by Uman and Nucci (1975 & 1995) for the three sensors of GP20S3_NS.

Heights were taken as 2km and 10km for CG strokes, depending on ALDIS amplitude sign. 6km was assumed for CC strokes. We were able to derive calibration coefficients for the strongest ALDIS "events" recorded with the GP20S3_NS sensors (Fig. 2) referred to measured field B_m and spatial gradient ΔB_m. The selection of analyzed lightning discharges was done dynamically.

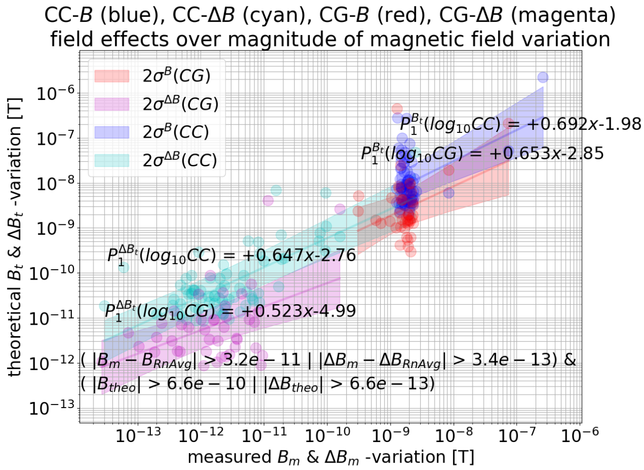

Figure 2: Calibration coefficients of the strongest peaks recorded in the N-S supergradiometer system GP20S3_NS at COBS with ALDIS amplitude effects derived by formula from Uman and Nucci (1995). The conditions met are written in lower left corner.

The polynomial fits and their confidence intervals derived in log-scale are shown in Fig. 2. The results indicate that the supergradiometer system is able to record EM effects of lightning strokes and CC discharges. Yet, ΔB_m and B_m variations are not fully supporting EMPs as solely reason but temporal correlation especially for CC events persists.

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Note on data processing in the Lonjsko Polje Observatory

Igor Mandić

The geomagnetic data from the Conrad Observatory (WIC) are routinely used for the purposes of quality control and preparation of definitive data in the Lonjsko Polje observatory (LON, Croatia). A simple example presented in this report, shows how important WIC data are, not only for science, but also for the operational needs of other European observatories.

The main task of a geomagnetic observatory is to record the Earth's magnetic field and its changes. Nowadays, these recordings should have resolution ≤ 0.1 nT (nanoTesla) and absolute accuracy better than 5 nT. The final 1-minute or 1-second definitive data should be free form spikes, jumps and other degradations in data. All corrupted data must be removed and if possible, data gaps should be complemented with recordings from backup magnetometers.

In the Croatian observatory Lonjsko Polje (LON) the process of the spike/noise detection (and its removal) is based on visual inspection of recordings. Often, very small magnetic contaminations are masked by natural magnetic variations and cannot be recognized even by the eye of experienced data checker. Therefore, at LON we use "difference plots" and dB/dt plots (Worthington et al. 2009) to detect degradations in our data. For this purpose, we routinely use WIC data along with the observatory data from neighbouring countries.

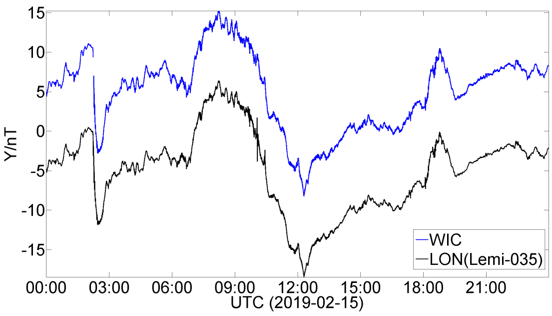

Figure 1: The Y (east) component of geomagnetic field variations recorded at WIC (blue) and LON (black). At LON variations are recorded with backup magnetometer LEMI-035.

As example, Fig. 1 shows LON and WIC recordings (1-second data) on 15th Feb. 2019. For better visibility, recordings are centred to zero and shifted with respect to each other. After careful look at diagrams in Fig. 1 suspicious values can be observed around 10 h UTC on LON diagram (black line). Indeed these are anomalous values of the main spike in the period 09-11 UTC. In this period, the observatory staff worked on maintenance and on several occasions, the location near the Lemi-035 sensor was magnetically contaminated. A much better picture of the extent of magnetic contamination is obtained if we plot differences between LON (Lemi-035) and data from surrounding observatories. Fig. 2 displays differences of the Y variations between LON (Lemi-035) and WIC (blue line), the red line is the difference between LON (Lemi-035) and BDV (Butkov, Czech Republic) observatory. In addition, a third black curve shows the difference between two LON magnetometers, Lemi-035 and DIDD. (For better visibility WIC and BDV difference diagrams are shifted with respect to LON). In contrast to the raw variation diagrams, all three difference-diagrams reveal several dominant spikes during the maintenance period (09-11 UTC). Except spikes, LON-WIC and LON-BDV diagram also show differences between the diurnal variations at three observatories. Due to practically identical magnetic field at locations of the DIDD and Lemi-035 sensor, the difference diagram is practically constant (except in the period of magnetic contaminations in vicinity of the Lemi-035 sensor).

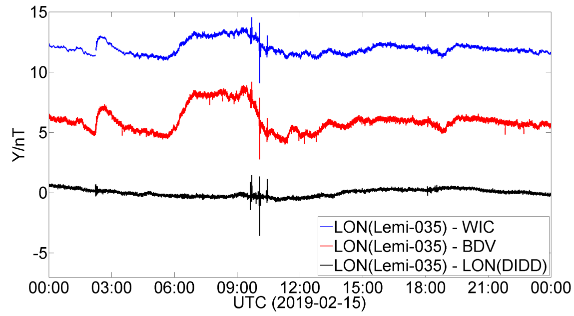

Figure 2: *Blue line*: The difference between LON (Lemi-035) and WIC variations, i.e. the difference between black and blue line on Fig1. *Red line*: The difference between LON (Lemi-035) and BDV variations. Black line: The difference between LON supplement (Lemi-035) and the main (DIDD) magnetometer.

The presented example demonstrates how high quality WIC data are valuable, not only for science, but also for the routine quality control and data processing in other European observatories.

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A Miocene polarity transition recorded on St. Helena, South Atlantic

Elisabeth Schnepp, Patrick Arneitz, Yael A. Engbers, David Pryce, Robert Scholger, Roman Leonhardt, Andrew J. Biggin

Paleomagnetic sampling was undertaken in locations with successions of lava flows on St. Helena in April 2019. Two parallel profiles recorded transitional field directions of a reversal from reversed to normal polarity. The lavas flows are part of the SW Upper Shield and have an age of ∼9.0 Ma. Determinations of paleointensity and ^{39}Ar/^{40}Ar dating are currently under work. The detailed characterization of the polarity transition will allow for Earth's magnetic field modelling and provides a better understanding of the South Atlantic Magnetic Anomaly.

St. Helena is a small remote island in the South Atlantic at 16° S and 5.7° W. Although located in the so-called South Atlantic Anomaly of the Earth's magnetic field, the first paleomagnetic study of secular variation was performed only recently. Engbers et al. (2020) discovered a profile of six lava flows ranging from Prosperous Bay Plain to Fisher's Valley, which recorded a reversed-to-normal polarity transition with three intermediate directions. According to Baker (1967) these lavas were following a massive landslip and filled the associated cuvette rapidly with approximately horizontal lava flows.

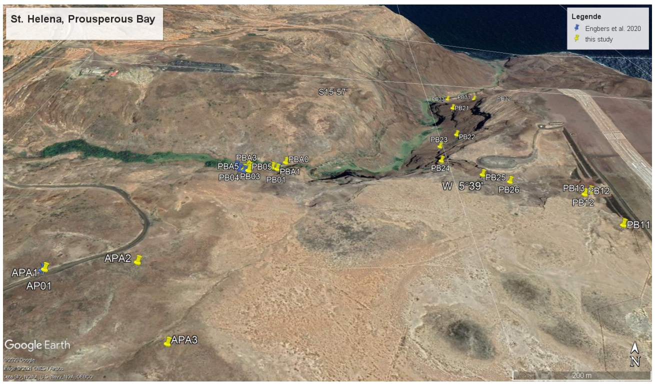

Figure 1: View of the sampling sites in Prosperous Bay and Fisher's valley.

The profile was resampled and extended by three lava flows in our study and another parallel profile following Fisher's Valley to the sea was sampled with 12 lava flows. Five to ten oriented paleomagnetic cores were taken per flow.

The mean characteristic remanent magnetization directions obtained from alternating field or thermal demagnetizations are mostly well defined and reproduce the ChRM directions from Engbers et al. (2020).

Profile 1 (9 flows) starts with three flows with reversed polarity, followed by three transitional directions with virtual geomagnetic poles (VGP) positions close to Brazil and ends with three normally magnetized lavas. The second profile also starts with reverse polarity lava, followed by a normal polarity flow. Above these, six reverse polarity lavas are found, of which one flow shows a low VGP latitude of -48°. Then, two flows with low VGP latitude have again VGP positions close to Brazil and the uppermost flow has normal polarity. The upper eight flows of Profile 1 show very similar directions compared to the five uppermost flows of Profile 2. Accordingly, the transitional nature of the lavas is well supported by two independent sampling campaigns and two parallel profiles.

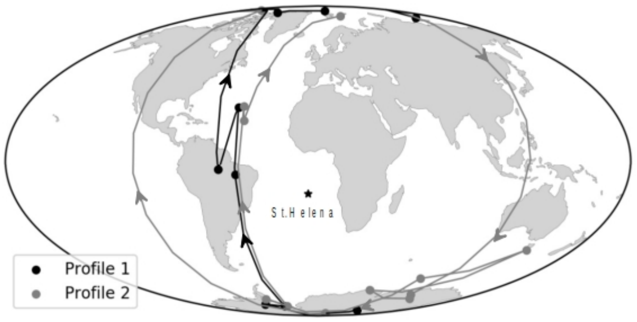

Figure 2: Virtual geomagnetic poles from St. Helena.

Age dating will allow for correlation with the geomagnetic polarity time scale. Along with determinations of paleointensities, the modelling of the polarity transition will contribute to our knowledge on geomagnetic field reversals.

References:

Baker, I., 1967. The Geology of Saint Helena Island, South Atlantic, University of London.

Engbers, Y. A., Biggin, A., and Bono, R. K., 2020. Elevated paleomagnetic dispersion at Saint Helena suggests long-lived anomalous behavior in the South Atlantic Proc. Natl. Acad. Sci. 117, 18258-18263.

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Intermediate Field of Cryptochron C2r.2r-1 Recorded in Styrian Basalts

Elisabeth Schnepp, Patrick Arneitz, Morgan Ganerød, Robert Scholger, Ingomar Fritz, Ramon Egli, Roman Leonhardt

Paleodirections and -intensities were investigated for Pliocene volcanic units from Styria (Austria). Only four virtual geomagnetic poles (VGP) lie close to the geographic pole, while all others are concentrated in a narrow longitude sector offshore South America at low VGP latitudes and relatively low paleointensities were obtained. $^{39}Ar/^{40}Ar$ ages of 2 sites with low latitude VGPs agree at 2.47 ± 0.11 Ma and allow for correlation of the Styrian transitional directions with cryptochron C2r.2r-1 of the geomagnetic polarity time scale.

The Styrian Basin is located at the south-eastern margin of the Alps and its formation started in the Late Oligocene to Miocene at the final collision stage of the Adriatic with the European plate. The major tectonic events were accompanied by volcanism producing volcaniclastics and high-K effusive rocks with Miocene and Pliocene ages. Paleomagnetic sampling was done at 27 sites of 8 Pliocene volcanic units.

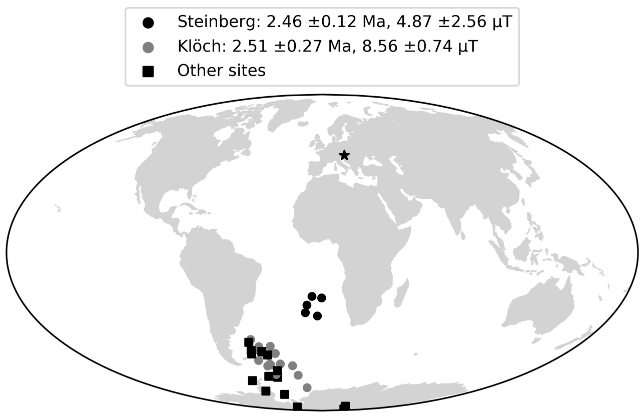

Figure 1: Virtual geomagnetic poles from Styrian volcanic units.

Rock magnetic investigations revealed that the magnetic carriers are Ti-rich or Ti-poor titanomagnetites with mainly pseudo-single-domain grain size. Many samples showed strong alteration of the magnetic particles during heating. This hampered determination of paleointensity. Characteristic remanent magnetization directions were obtained from alternating field as well as from thermal demagnetization. Four localities give reversed directions agreeing with the field direction expected for secular variation. Another four localities of the Klöch-Königsberg volcanic complex (3) and the Neuhaus volcano (1) have reversed directions with shallow inclinations and declinations of about 240°, while the locality Steinberg yields a positive inclination of about 30° at 200° declination. These aberrant directions cannot be explained by local or regional tectonic movements.

Corresponding virtual geomagnetic pole (VGP) positions are located on the southern hemisphere (Fig. 1). Only few VGPs lie close to the geographic pole, while the others are concentrated in a narrow longitude sector offshore South America (310° to 355°) with low VGP latitudes ranging from -15° to -70°.

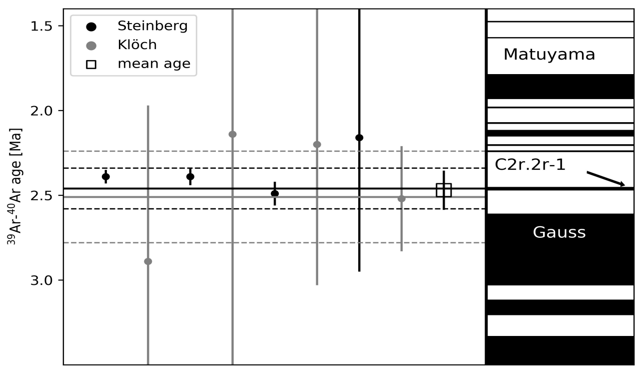

Figure 2: $^{39}Ar/^{40}Ar$-ages with 2 sigma error from individual samples shown together with the weighted mean and error band in comparison with the geomagnetic instability time scale (Singer, 2014, Quaternary Geochronology, 21).

The hypothesis, that the volcanic activity of these five volcanic units had a short duration and that a transitional geomagnetic field configuration was recorded is supported by nine paleointensity results and $^{39}Ar/^{40}Ar$ dating. Virtual geomagnetic dipole moments range from 1.1–2.9·10^{22} Am^2 for sites with low VGP latitudes under 60° and 3.0–9.3·10^{22} Am^2 for sites the higher VGP latitudes. The present value is about 8·10^{22} Am^2. $^{39}Ar/^{40}Ar$ ages obtained for two sites (Klöch, Steinberg) agree. Their mean age (2.47 ± 0.11 Ma) allows for correlation of the Styrian transitional directions with cryptochron C2r.2r-1 of the geomagnetic polarity time scale (Fig. 2).

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A geomagnetic field model covering the past 4000 years

Patrick Arneitz, Ramon, Egli, Roman Leonhardt, Karl Fabian

The systematic monitoring of the geomagnetic field reveals a strong decrease of its global dipole strength along with the expansion of a large-scale low intensity anomaly in the South Atlantic within the last century. In order to thoroughly scrutinize this evolution, the observation period is extended further back into the past by consideration of historical, archeo- and paleomagnetic field records. The resulting models provides field predictions for the last 4000 years and can be used for archeomagnetic dating purposes.

Different record types allow for the reconstruction of the geomagnetic past. Historical man-made measurements date back to 15th century and have mainly been performed using compasses due to orientation and navigation purposes. A further extension into the past is provided by the investigation of the remanent magnetization acquired by rocks and archeological artifacts (archeomagnetic and paleomagnetic data). These different record types have been compiled within the HISTMAG database (https://cobs.zamg.ac.at), which forms the basis of the geomagnetic modelling approach.

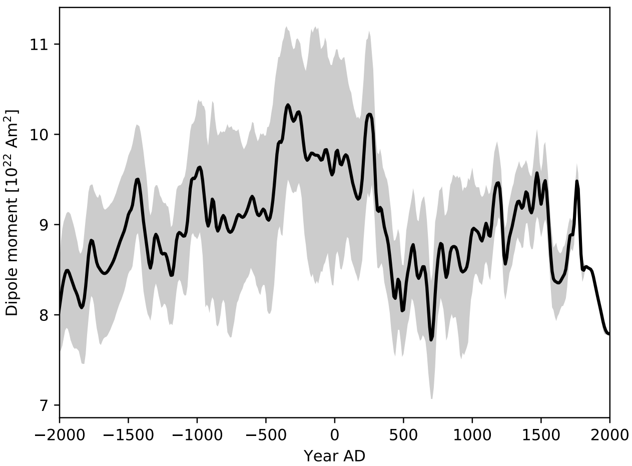

Figure 1: Temporal evolution of the dipole moment over the last 4000 years.

The high variabilty of spatio-temporal data coverage, types and uncertainties represents the major obstacle for geomagnetic field reconstructions. In order to overcome these challenges, a Bayesian modelling approach was developed resulting in the first self-consistent field model based on the combination of historical and archeo- and paleomagnetic records. Resulting model BIGMUDI4k.1 (Arneitz et al., 2019, https://doi.org/10.1016/j.pepi.2019.03.008) provides geomagnetic field predictions everywhere on Earth over the last 4000 years, which can be retrieved online (https://cobs.zamg.ac.at). These predictions can be used as reference curves for archeomagnetic dating approaches.

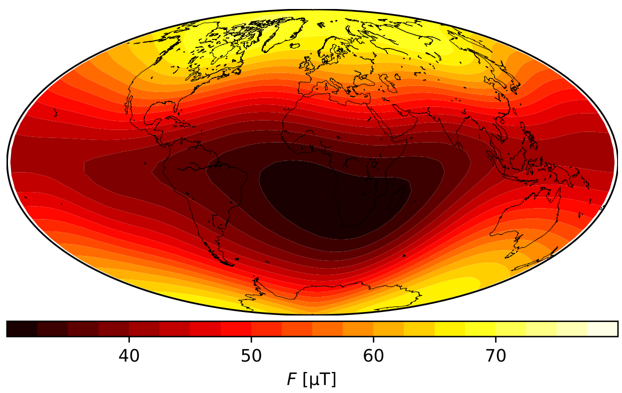

Figure 2: Temporal average of field intensity F over the last 2000 years.

Furthermore, BIGMUDI4k.1 enables a detailed analysis of striking geomagnetic field features. For instance, the currently observed decrease of the dipole moment can be compared to its evolution in the past (Fig. 1). This comparison reveals periods with similar variations for previous millenia. Moreover, the evolution of the South Atlantic Anomaly (SAA) can be outlined (Fig. 2). This study indicates persistent anomalous field behavior around this region over the last 2000 years. An evaluation of SAA in the years BC is limited by the lack of data in the Southern hemisphere.

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Archeomagnetic dating of an Iron Age pottery kiln from Northeast Iraq

Patrick Arneitz, Karen Radner, Roman Leonhardt

An archeomagnetic study on an Iron Age pottery kiln from Gird-i Bazar (Northeast Iraq) was conducted. Reconstructed archeomagnetic field values yield high field intensities, which can be associated with the so-called "Levantine Iron Age Anomaly". The archeomagnetic dating approach is limited by the lack of directional reference data within the Near East.

During the course of archeological investigations in the Peshdar Plain (Northeast Iraq), the wall of a pottery kiln in Gird-i Bazar (Fig. 1) was sampled for the purpose of an archeomagnetic study (for details see Radner et al., 2019, ISBN 978-3-935012-39-3). The site was mainly occupied during the Iron Age, a period, which is associated with remarkably high field intensities in the Near East termed as "Levantine Iron Age Anomaly (LIAA)".

Figure 1: Excavation of the pottery kiln in Gird-i Bazar.

Magnetic measurements have been carried out at the paleomagnetic laboratory of the Conrad Observatory. Magnetic experiments revealed fine-grained (titano)magnetite as primary remanence carriers providing an excellent basis for the reconstruction of the ancient field. Archeomagentic measurements yielded stable characteristic remanence directions (declination D=-8.1°, inclination I=53.0°) and a rather high cooling-rate-corrected intensity value F=58.7 µT, which can be associated with the LIAA (todays field strength is ∼47 µT). The reconstructed field values are compared with reference curves for archeomagnetic dating (Fig. 2). Reference curves were taken from the global field model BIGMUDI4k.1 and constructed based on a regional dataset, respectively. Most probable dated ages are younger than 500 BC for both models using the combined approach considering all three geomagnetic components. This is in contrast to the results of radiocarbon dating and the historical context indicating that the last firing of the kiln was likely carried out during the reign of Shalmaneser III (858-824 BC), when Gird-i Bazar and the wider region was integrated into the Assyrian Empire.

Contradictions of archeomagnetic and radiocarbon as well as historical dating approaches arise from differences of measured inclination, which was based only on one oriented sample, however. In this context, tilting of the kiln wall after the last usage is conceivable. Furthermore, new directional data sets from the Near East are necessary to better constrain reference curves for this region.

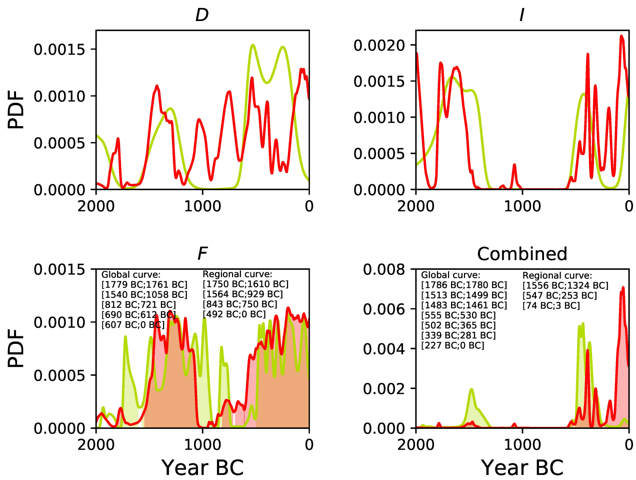

Figure 2: Archeomagnetic dating: probability density functions are given for D, I, F as well as the combined age probability using all three components. Possible age intervals derived from global (red) and regional model curves (yellow) are given for the approach using only F (bottom left) and using all three field components (bottom right).

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Impact of COVID-19 lockdown on seismic noise

Maria-Theresia Apoloner

Seismometers continuously record ground velocity, therefore being the instrument of choice to record earthquakes. Nevertheless, the ground moves even when no earthquakes occur. This interferes with earthquake detection and is referred to as seismic noise. However, recent studies like Lecoq et al. (2020) utilize it to monitor Covid-19 lockdown effects. Seismic noise from traffic, industry and other human sources usually should not affect seismic records on remote sites. However, changes in noise levels due to Covid-19 lockdowns still occur, even at Conrad Observatory Seismometer CONA.

The Conrad Observatory is home to seismic broadband station CONA of the Austrian Seismic Network. The station continuously sends data to Vienna for earthquake analysis. Additionally, for 2020 we used the continuous data of the vertical component HHZ to analyse seismic noise with SeismoRMS by Lecoq et al. (2020). The frequency range from 4-14 Hz was selected, as it is affected strongest by human related noise sources. The RMS of the displacements were calculated for 30 minute-time-blocks for the whole year. Figure 1 shows these noise estimates, including the start of lockdown measures imposed in Austria.

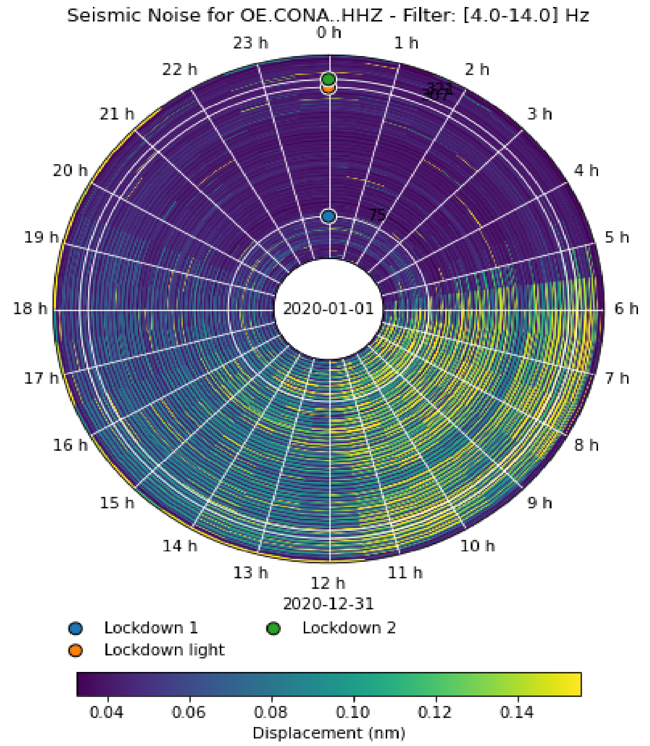

Figure 1: RMS of displacement in 30-minute time blocks for 2020. Circles mark lockdown starts due to Covid-19 (Lockdown 1: 16-03-2020, Lockdown light: 03-11.2020, Lockdown 2: 17-11-2020).

The clock plot clearly shows the diurnal change of noise, with human activity. However, in 2020 there is an additional silent period in the middle of March: It coincides with the first lockdown due to Covid-19 in Austria (blue dot) and lasts approximately 2 weeks. The light and the second lockdown in November 2020 are barely visible (orange and green dots).

Figure 2 shows the long-time impact of the first lockdown for stations CONA and VIE (Hohe Warte, Vienna). Due to high variability of absolute background levels between the stations, the displacement RMS is calculated relative to pre-lockdown average for each station. Although most lockdown measures ceased earlier, noise levels stayed low much longer.

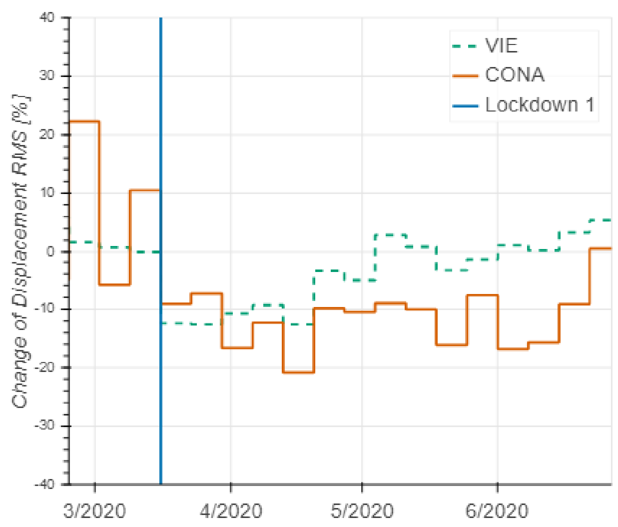

Figure 2: Change of displacement RMS in percent compared to 1 month before first lockdown on 16-03-2020 in Austria for broadband stations CONA and VIE.

References:

Lecocq et al. (2020) Global quieting of high-frequency seismic noise due to COVID-19 pandemic lockdown measures. Science. Vol. 369 Issue 6509

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The Croatian Earthquake on December 29, 2020

Wolfgang Lenhardt, Stefan Weginger, Helmut Hausmann

A strong earthquake hit Croatia in December 2020 near Petrinja, some 50 km south of Zagreb. The magnitude 6.4 earthquake caused severe damage in the epicentre and was noticed widely in Austria. Seismic recordings at the COBS were analysed in terms of frequency content and amplitude.

Earthquakes and seismic activity in the wider Zagreb area are not uncommon. Between 1502 and 1883 as many as 661 earthquakes were noted by Mokrović (1950). The strongest earthquake in recent Zagreb history occurred on November 9, 1880 and has been estimated, according to macroseismic observations, as of magnitude 6.3. This earthquake caused damage to more than 1500 buildings in the city. Another important earthquake in this region occurred on October 8, 1909 in the Kupa valley (Mohorovičić, 1909). This event has many similarities to the December 29 earthquake (Fig. 1), is well known, and occupies a special place in the history of seismology as it occurred soon after the installation of a seismographic station in Zagreb. It was this earthquake which led Andrija Mohorovičić to propose, that the Earth's crust differs in its properties from the Earth's mantle.

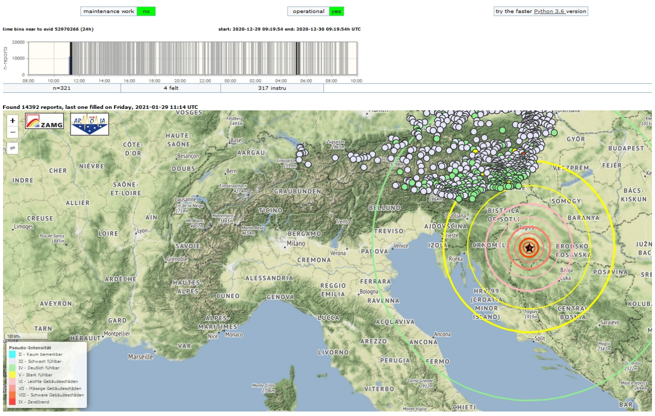

Figure 1: The felt area of potential response is indicated by the green circle. Grey dots refer to places from where observations were reported.

Almost 14.000 questionnaires (13.441 positive reports and 327 negative responses) were collected after the earthquake in Austria. These observations are very valuable as they can be used for verifying ground-motion prediction equations.

At the time of writing (16.2.2021) strong aftershocks are still being observed.

The earthquake was well recorded at the Conrad Observatory. Two seismic stations are compared – one of which (CSNA) is installed in front of the Seismological Observatory in a shaft at a depth of 6 m, while the other station (CONA) is positioned in a 140 m long tunnel on a pier (overburden approximately 50 m). Each station is equipped with a three-component Streckeisen STS-2.0 broadband sensor. The earthquake in Croatia was used to analyse the relative transfer function of both sensors (Fig. 2).

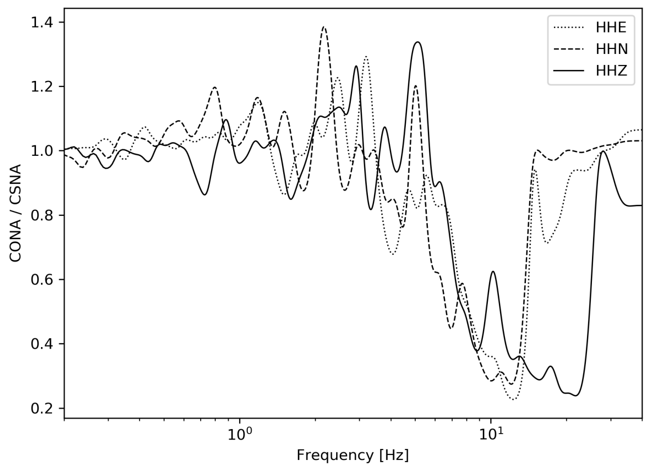

Figure 2: Spectral ratios of stations CONA and CSNA as recorded by STS-2.0 sensors.

The comparison of both sites showed a remarkable similarity, although the sites differ in terms of overburden. However, station CSNA records “high frequent” noise between 5 – 12 Hz, or, in other words, the seismic station CONA is less obscured by these signals. The origin of the noise is now under investigation.

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Acoustic-to-seismic ground coupling: coupling efficiency and inferring near-surface properties

Artemii Novoselov, Florian Fuchs, Götz Bokelmann

A fraction of the acoustic wave energy (from the atmosphere) may couple into the ground, and it can thus be recorded as ground motion using seismometers. We have investigated this coupling, with two questions in mind, a) how strong it is for small explosive sources and offsets up to a few tens of meters, and b) what we can learn about the shallow subsurface from this coupling. 25 firecracker explosions and 5 rocket explosions were analyzed using co-located seismic and infrasound sensors; we find that around 2% of the acoustic energy is admitted into the ground. Recording dynamic air pressure together with ground motion at the same site allows identification of different waves propagating in the shallow underground, notably the seismic expression of the direct airwave, and the later air-coupled Rayleigh wave. We can reliably infer shallow ground properties from the direct airwave, in particular the two Lame constants and the Poisson-ratio.

During most of its history, seismology has regarded elastic and pressure waves, propagating below and above ground, separately, calling the former waves "seismic" and the latter "acoustic". This was in part due to an intellectual boundary, but it was also for convenience: the assumption of a traction-free surface (and of seismic displacements that are discontinuous across it) provided a simple and convenient upper boundary condition for seismic modeling.

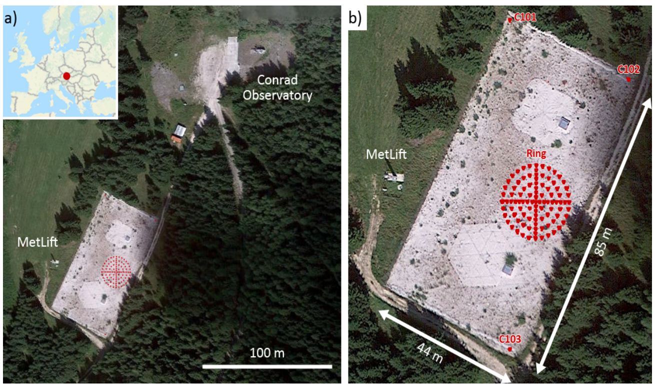

Figure 1: a) Aerial view of the experiment site near the Conrad Observatory, Austria. The location in Europe is highlighted on the inset. b) Close-up view showing the position of the ring array.

The experiment was performed on May 14, 2019, near the Conrad Observatory on the Trafelberg mountain in Austria (see Figure 1). The core of the experiment is a seismic array of 97 geophone nodes (Fairfield ZLand Gen2, 3-components, 5Hz corner period) arranged in a concentric ring layout of 20 m diameter. To study acoustic-to-seismic coupling, we have analyzed 25 firecracker explosions and 5 rocket explosions using the ring array and co-located infrasound sensors.

The spectrograms and waveforms show that the co-located seismic and infrasound sensors have recorded energy in a similar frequency band for the first arrival, which is followed on the seismic trace (and only there) by a prolonged wavetrain with a narrow-band spectrum. For more details please refer to the publication Novoselov et. al 2020 (https://doi.org/10.1093/gji/ggaa304).

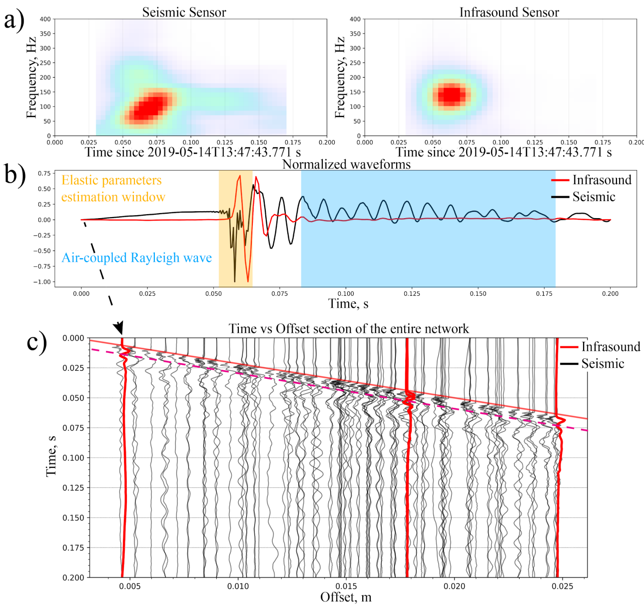

Figure 2: Explosion Experiment: infrasound and seismic measurements of a "large" charge explosion at co-located seismic (R501) and infrasound (HYP01) sensors (data is not filtered). a) Spectrograms for corresponding seismic and infrasound records. b) Normalized and overlaid, on top of each other, seismic and infrasound wave-forms. The background shows the time window of the direct airwave used for determining elastic parameters, and that of the air-coupled Rayleigh wave. c) Section plot (time versus distance). Seismic traces are shown in black (vertical components), infrasound in red. Red solid line indicates picked acoustic velocity. Purple dashed line indicates air-coupled Rayleigh wave. The acoustic wave propagates with a velocity of around 0.3 km/s; coherent phases of the subsequent air-coupled Rayleigh wave suggest a similar phase velocity.

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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. This measure ensures that all member states of the treaty are able to monitor its compliance. One technology used to monitor atmospheric explosions is infrasound. To study its attributes and to understand the behaviour of infrasound propagation in mountainous regions, an infrasound test array was installed at the beginning of 2021 at the Trafelberg in Lower Austria.

Infrasound signals range from 0.01 to 16 Hz. Most known phenomena generating infrasound are atmospheric explosions, volcanic eruptions, thunderstorms, bolides, supersonic flights and launches of space shuttles. Strong earthquakes can also generate infrasound signals. Infrasound propagates through the air across several thousands of kilometers. The position, where the signals originated, is determined using arrays of sensors (minimum 3). Such an array allows to calculate the azimuth (= vector direction) and celerity thus permitting to localize the source.

Figure 1: One element of the newly deployed infrasound array at the COBS.

Each element consists of a recording unit (digitizer, GPS antenna) and a microbarometer. Figure 1 shows a Peli Case box which contains the recording unit. The box is connected with a cable to the microbarometer which is placed inside the bucket. Pressure data are collected via eight porous hoses attached to the sensor.
An infrasound array consisting of four sites was installed at the Trafelberg in early 2021 (Figure 2). The array aperture is approximately 1000 m. All sites are equipped with Hyperion IFS 3000 sensors and sara® dataloggers. Power is supplied by a fuel cell and solar panels. The data is locally saved and stored on USB sticks, as well it is transferred in real-time to the Headquarter of ZAMG in Vienna. The data is recorded in miniseed format and processed and analyzed manually by using the dtkGPMCC- and dtkDIVA-Software, developed by CEA/DASE (Commissariat à l'Énergie Atomique/Département analyse, surveillance, environment, France).

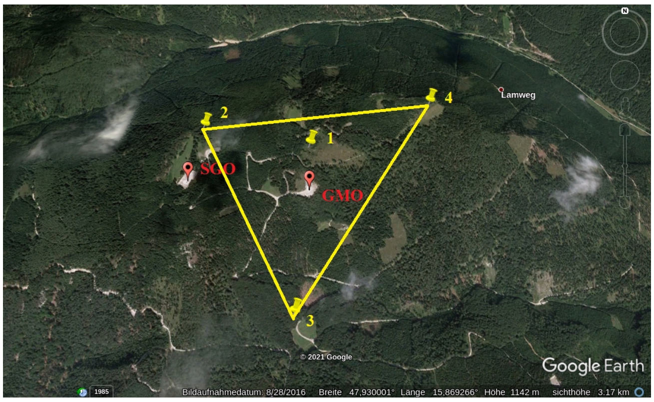

Figure 2: Location of the four elements of the Austrian infrasound array.

The mobile array is part of the Central Eastern European Infrasound Network (CEEIN) which was established in 2018 by Rumania, Czechia, Hungary, Ukraine and Austria. Due to seasonal variations of the stratospheric wind, studies will last for a minimum of one year. After that time it will be possible to evaluate the network quality for analysing infrasound signals from remote areas.

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Co-located tilt and gravity observations at Conrad Observatory

Bruno Meurers, Gábor Papp, Hannu Ruotsalainen, Judit Benedek, Roman Leonhardt

Short-term (a few hours) gravity and tilt residuals at the Conrad Observatory image water accumulation on the terrain surface. Long-term (more than a few days/weeks) gravity and tilt variations are frequently observed after long-lasting rain, heavy rain or rapid snowmelt. The residuals are obviously associated with the same hydrological process but have different physical causes. While gravity is most sensitive to the gravitational effect of water mass transport, tilt residuals indicate deformation caused by surface mass loading. N-S tilts are strongly affected by strain-tilt coupling due to the cavity effect of the observatory tunnel oriented in E-W direction.

Short- and long-term gravity and tilt residual anomalies observed between April 2016 and mid of November 2018 are clearly linked to the same hydrological process: rapid water accumulation at the ground surface due to heavy precipitation (rain/snow) or water infiltration into the ground after rainfall and rapid snowmelt. Short-term (a few hours) residual anomalies can be well explained by the accumulation of precipitation on the terrain surface and in the adjacent topsoil. Gravity residuals reflect the gravitational acceleration of accumulated water/snow, N-S tilt responds to the deformation caused by the load pressure of the water mass onto the terrain surface similarly as in case of air pressure variations (Fig. 1).

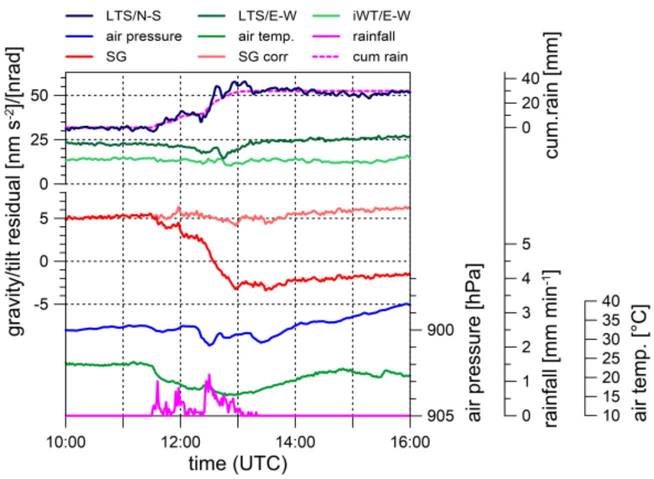

Figure 1: Effect of heavy rain on gravity and tilt at CO on July 11, 2016. Gravity and N-S tilt residuals show patterns clearly related to cumulative rain.

Slow water discharge brings the gravity residuals back to their initial level. However, particularly after long-lasting rain or rapid snowmelt, the residuals exceed the initial level remarkably due to downwards water flow (infiltration) from terrain surface into the ground until water is stored somewhere in the bedrock/soil below the SG sensor. This process probably starts as soon as the subsurface is sufficiently saturated by rain or snowmelt water and therefore needs a certain threshold to be triggered. During all of these events, strong long-term tilt anomalies appear as well with specific trends: N-S tilt shows always a steep residual drop and the E-W tilt residuals increase with much less amplitude. After 1-2 days, N-S and E-W tilts reach their maximum and then slowly decay to the previous level. This process lasts about 14 days or longer and occurs after sufficient water percolation into the subsurface, either after heavy/long-lasting rainfall or after rapid snowmelt (Fig. 2).

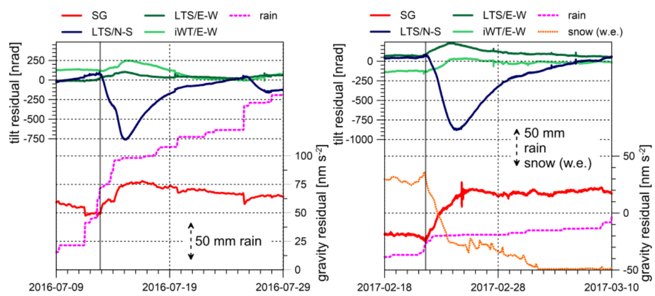

Figure 2: Long-term gravity/tilt residual signals after heavy/long-lasting rain (left) and rapid snowmelt (right).

Strain-induced tilt affects the N-S tilt considerably. Simplistic model calculations of the gravity residuals indicate high initial saturation (95%) or low porosity of the limestone rocks. Downwards water propagation has to be fast enough to store water below the SG sensor. Alternatively, a direct transport downwards along specific flow paths is required. The tilt residual anomalies can be explained by surface or subsurface deformation caused by either surface load (short-term) or water pressure changes in the adjacent fracture system (long-term).

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A decade of international cooperation dedicated to geodynamical research

Gábor Papp, Judit Benedek, Hannu Ruotsalainen, Bruno Meurers, Roman Leonhardt

At the end of 2011 two spring type LCR gravimeters (LCR) from Hungary were installed in the gravimetric laboratory of Conrad Observatory next to the superconducting gravity meter (SG) GWR SG025 in order to check the characteristics of these instruments. It was the beginning of a fruitful cooperation between Austria and Hungary. Later on in 2014 it was extended to a third party and nowadays global and local geodynamical phenomena are investigated by a team of Austrian, Finnish and Hungarian researchers. For this purpose, gravimetric measurements are integrated with high-resolution tilt sensors, exploiting the excellent natural and technical environment provided by the Conrad Observatory.

Almost ten years ago a research group of the Geodetic and Geophysical Research Institute (Hungarian Academy of Sciences, Sopron) and the Eötvös Loránd Geophysical Institute Budapest installed LCR G gravimeters next to the SG for testing the capabilities of LCRs equipped with a conventional CPI readout and with a CCD ocular, respectively. The latter made the LCR G949 capable to produce continuous gravity records. The chance to compare LCR observations with a leading edge instrument was unique. Although the measuring system of G949 was not yet complete, all results of the 6 months parallel observations were promising. They allowed to start a project (NKFIH-OTKA K101603) for mapping and checking tidal gravity effects in the Pannonian basin along a nearly 600 km long line extending from west (CO, Austria) to east (TRPA, Hungary) (Papp et al., 2018).

In 2014 – 2015, a 5.5 m long interferometric hydrostatic (iWT, Finnish Geodetic Institute) and a pendulum type 2D tiltmeter (LTS, LGM Lippmann, Germany) was installed in the seismological tunnel of CO. These instruments are sensitive to tilts of either the solid ground or the potential surface as small as 1 nanoradian, which is equivalent to 1 mm height change over 1000 km. The instruments are operating on the same 6 m long pier in co-located and co-oriented positions, providing consistent tilt data since April, 2016 at 15 Hz (iWT) and 1 Hz (LTS). In addition to the observation and modelling of the global tidal tilt and loading effects at the site, very interesting phenomena related to local hydrological processes have been recorded (Meurers et al., 2021). Based on the positive experience regarding both scientific and technical aspects, a new project was funded in 2018 (NKFIH-OTKA K128527), with the aim to improve the iWT system and to obtain sub-nanoradian resolution. In November 2017, the G949 tidal recording gravimeter completed by an autonomous tilt compensation platform and a remote control unit for the micrometer dial was re-installed next to SG025. Based on the parallel recorded data, an inter-comparison can be repeated and the results can be used to validate the location dependence of the ratio of tidal constituents O1/M2 which is expected to increase slightly ($< 1\%$) going from west (CO) to east (TRPA). Earlier results (Papp et al., 2018) indicated this tendency in spite of the incomplete G949 system in 2011 – 2012.

On request from The Peters Seismological Observatory (TPSO), Australia, operated by the Seismological Association of Australia, the team offered help to organize the acquisition, transfer, preparation and interpretation of tilt data recorded by a Lippmann type 2D sensor in 2018. The team was therefore handling tilt data for two years and made the first tidal analysis presented at IUGG Gen. Assembly, Montreal, 2019 (Papp et al, 2019). Right now the "Australian" sensor is hosted by CO and operates side-by-side with the "Sopron" sensor enabling an inter-comparison.

The aim of project K128527 is to build a complete biaxial and differential iWT system which is intrinsically free of instrumental drift by symmetry principles. Therefore, it may serve the investigation of long-term geodynamic processes in the future.

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