Karlsruhe Institute of Technology

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NEWSLETTER OF THE GEOPHYSICAL INSTITUTE

DEAR GPI ALUMNI

In the last 12 months life at GPI slowly came back and it was so pleasant to see our students back in the lectures and practical classes. Research wise a lot of new field experiments have started ranging from Ecuador to Albania and much closer to home in Rheinstetten. New analysis techniques are being developed by combining different techniques like in Rheinstetten or exploiting new AI techniques to obtain nearly complete seismic catalogues as we are currently doing in Albania.

I also would like to highlight our constant effort to strengthen the link between GPI and BFO and as an example you will find some novel tidal analysis techniques that was developed over the last years.

After now nearly three years of constant change and struggle due to the pandemic it really feels that we are looking into a brighter future. We wish all our Alumni a healthy, successful, and happy 2023 and will go back to our regular newsletter sequence with the next one coming out in the summer of 2023.

Andreas Rietbrock

ANTICS: AlbaniaN TectonIcs of Continental Subduction

By Sofia-Katerina Kufner

In November 2019 a strong earthquake (Mw 6.4) hit Albania's east cost near the port town of Durres. Due to 51 earthquake-related fatalities and severe infrastructural destruction, this event was later listed as the deadliest earthquake of 2019 (Papadopoulos, et al. 2020). At the same time, the earthquake formed the starting point for a joined research initiative between Albanian and German institutes: Directly after the earthquake, a 30-station aftershock network was deployed for nine months by researchers from the Karlsruhe Institute of Technology (KIT, Germany), the German Research Centre for Geosciences (GFZ, Germany) and the Institute of GeoSciences, Energy, Water and Environment of the Polytechnic University Tirana (PUT, Albania). Analysis of this data showed a complex network of seismically active subsurface structures, potentially corresponding to unmapped faults (Van der Heiden et al., 2022; Woollam et al., 2022), calling for a general reevaluation of existing seismotectonic maps of Albania.

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This finding led to the ANTICS (AlbaniaN TectonIcs of Continental Subduction) project, conducted as a joined effort of KIT, PUT and GFZ. ANTICS aims to study the ongoing continental subduction process beneath Albania using a dense (6 km inter-station distance) seismic network consisting of 390 seismic stations, covering a major part of Albania's territory (Fig. 1).

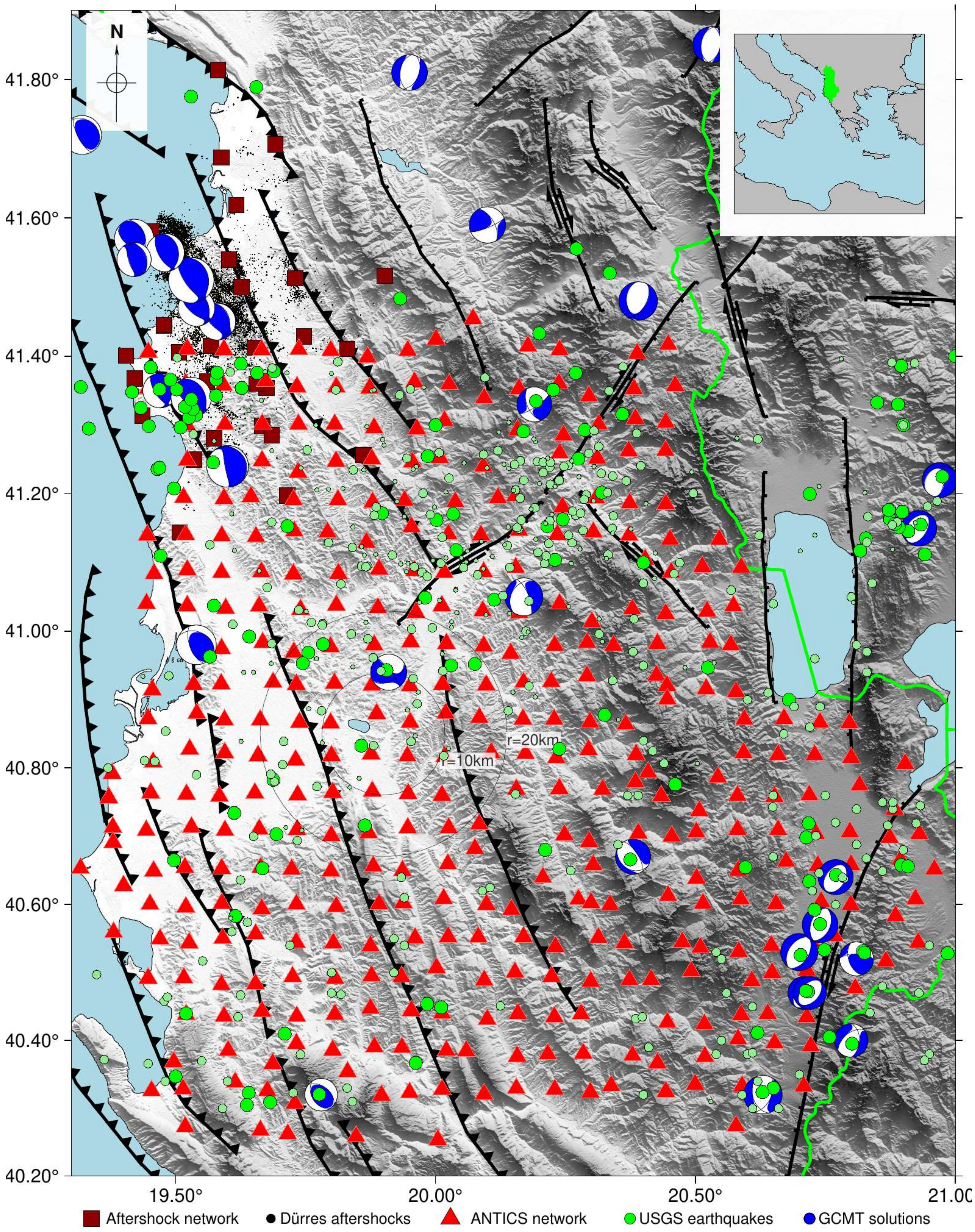

Figure 1: Geographic and tectonic setting of the ANTICS and Durres aftershock networks. Main composite fault lines from Styron et al. (2020) are highlighted in black; the political boundary of Albania in green. Furthermore, earthquakes from UAGS within the last 20 years (green) and aftershock activity recorded by the Durres aftershock network (black; van der Heiden, 2022) are included. Moment tensors are from GCMT (Dziewonski, et al. 1981; Ekström, et al. 2012) since 1976. The topography is in grayscale from 0 to 2 km.

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Seismicity in Albania is driven by the convergence between the Adriatic microplate and Eurasia at 2 to 4 mm/year (Aliaj, 2006). Deformation manifests itself through frontal thrusting near the Adriatic cost but is dominated by extensional tectonics in the hinterland (Fig. 1). The origin and driving mechanisms for extension, which seems to be omnipresent in the Mediterranean, are poorly understood (e.g., Jolivet & Faccenna, 2000). Yet, both regimes have proven to produce large earthquakes in the historic past (e.g. Hoffmann et al., 2010; Papadopoulos, et.al. 2020). The ANTICS network is situated in a ~150x150 km^2 area across these distinct deformation regimes. Joined field teams from KIT and PUT deployed the seismic stations during four weeks in September and October 2022. Stations are either equipped with 4.5-Hz natural frequency 3-component geophones (340 stations) or 3-component broadband instruments (50 stations). In combination with Cube-data loggers this instrumentation has very low power consumption, which allowed for an installation based on batteries only and without solar panels. This resulted in an extremely quick deployment time per station. Whenever possible, the instruments were installed within private properties for security reasons while aiming to deploy the station within a 1 km radius, relative to the ideal grid-location of the site. Fulfilling these restrictions was mostly possible due to the friendly and helpful Albanian property owners and due to the persistency of our field teams. In sum, 336 stations are installed within private properties, the remaining 46 are left hidden on public ground aiming to keep the distance limit, which was possible in most cases. The instruments will be left at the sites for approximately one year to register seismicity and background seismic noise. After this, the network will be rearranged into two lines, most suitable for receiver function analysis (e.g. Mroczek et al., 2021), and left recording for additional nine months.

The ANTICS network is unique due to the number and density of seismic stations deployed. Due to this setup, the recording will allow for novel ways of seismological analysis. We plan to implement earthquake locations through AI applications, the derivation of moment tensors from geophone recordings only, and variable types of subsurface imaging, including full waveform inversion at high frequencies. Our objectives are to understand the mode of convergence between Adria and Europe and the ongoing process of continental subduction, which ultimately drives large earthquakes in Albania.

Figure 2: Example for a typical geophone installation**.** The geophone is buried shallowly, while the battery and the Cube data recorder are protected beneath a plastic bucket. Photo: Sofia-Katerina Kufner

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Consistent imaging of near-surface targets using indirect joint petrophysical inversion of shallow-seismic and multi-offset ground-penetrating radar field data

By Tan Qin, Thomas Bohlen, Niklas Allroggen, and Yudi Pan

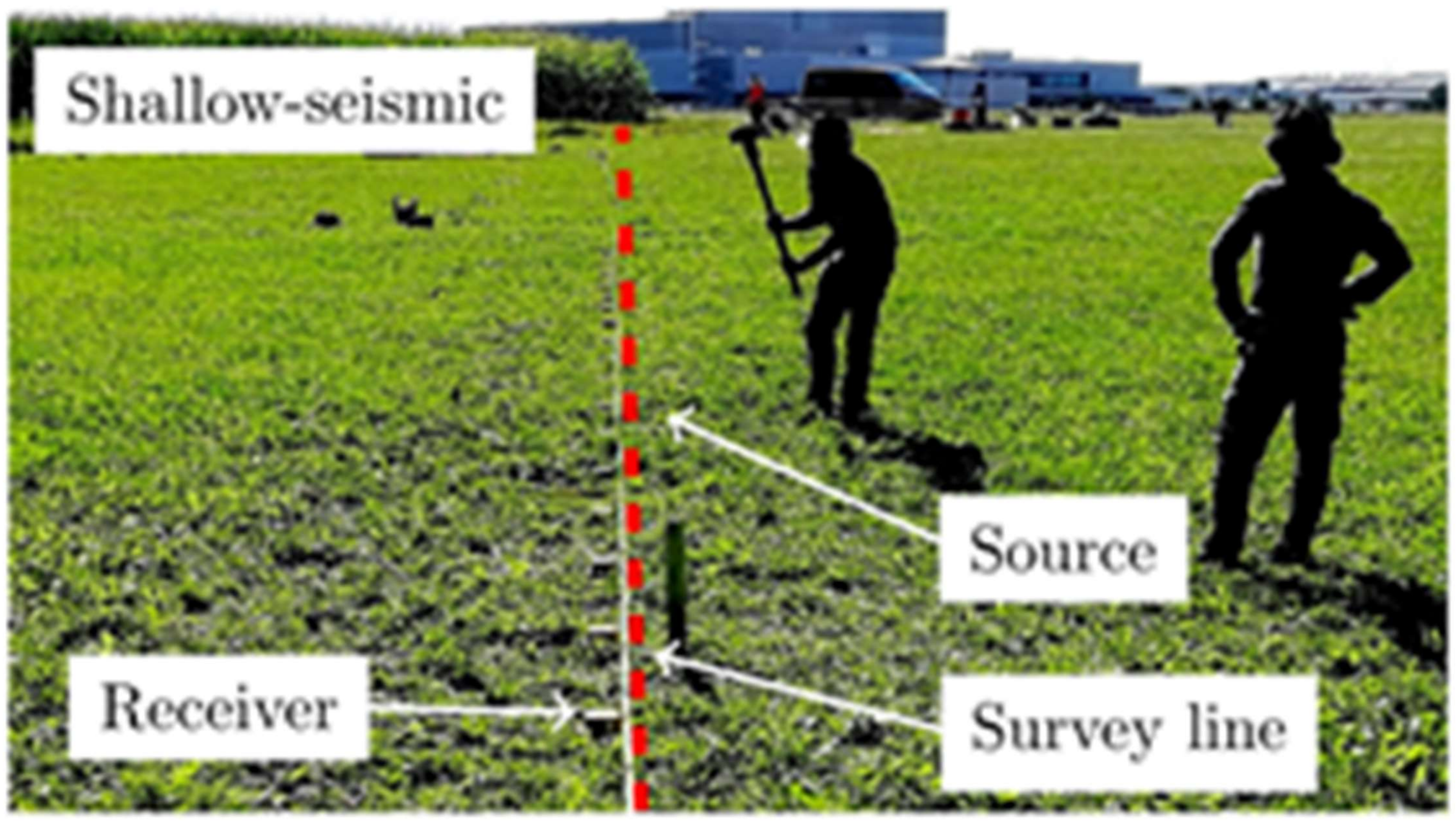
The near-surface zone within tens of meters below ground, also known as the critical zone, is closely related to human life. A full understanding of this area is quite important, thus attracting attention from fields such as urban construction, engineering exploration, environmental assessment, archaeology, hydrogeology and polar research. Ground-penetrating radar (GPR) and shallow-seismic methods are two geophysical techniques widely used in near-surface investigations.

As a consequence, independent full-waveform inversions (FWI, a way to reconstruct high-resolution subsurface models using information from the full waveform) of such data may provide inconsistent interpretation due to the non-uniqueness of the inverse problem and the inherent limitations of these geophysical methods. Hence, we developed a new method called *indirect joint petrophysical inversion* (JPI) to make best use of the complementary information and properties from different geophysical data.

Tan Qin, in collaboration with local GPI colleagues, colleagues from the University of Potsdam, and students from the international Geophysics Master's program at the GPI, took part in the field work. Shallow-seismic and multi-offset GPR data were collected at the Rheinstetten glider field in September 2021 (see Figure 1). The field work and later laboratory analyses were supported by the Geodetic Institute (GIK) and the Institute of Applied Geosciences (AGW), Engineering Geology, at KIT as well as the Leibniz Institute for Applied Geophysics (LIAG) in Hanover.

Indirect JPI was applied to the field data for the first time to reconstruct a high-resolution water-content model that highly agrees with measurements of borehole soil samples (see Figure 2). It not only successfully retrieved the Ettlinger Line, a V-shaped trench refilled with sand a few decades ago and invisible at the surface at this test site, as an anomaly of high porosity and high-water content, but also delineated a wet topsoil to its left and a slightly tilted layer to its right. Overall, this application demonstrates the feasibility of using indirect JPI to solve practical problems.

In November 2022, Tan Qin successfully defended his PhD thesis with highest honors. His thesis is publicly available from the KIT library at https://doi.org/10.5445/IR/1000152587



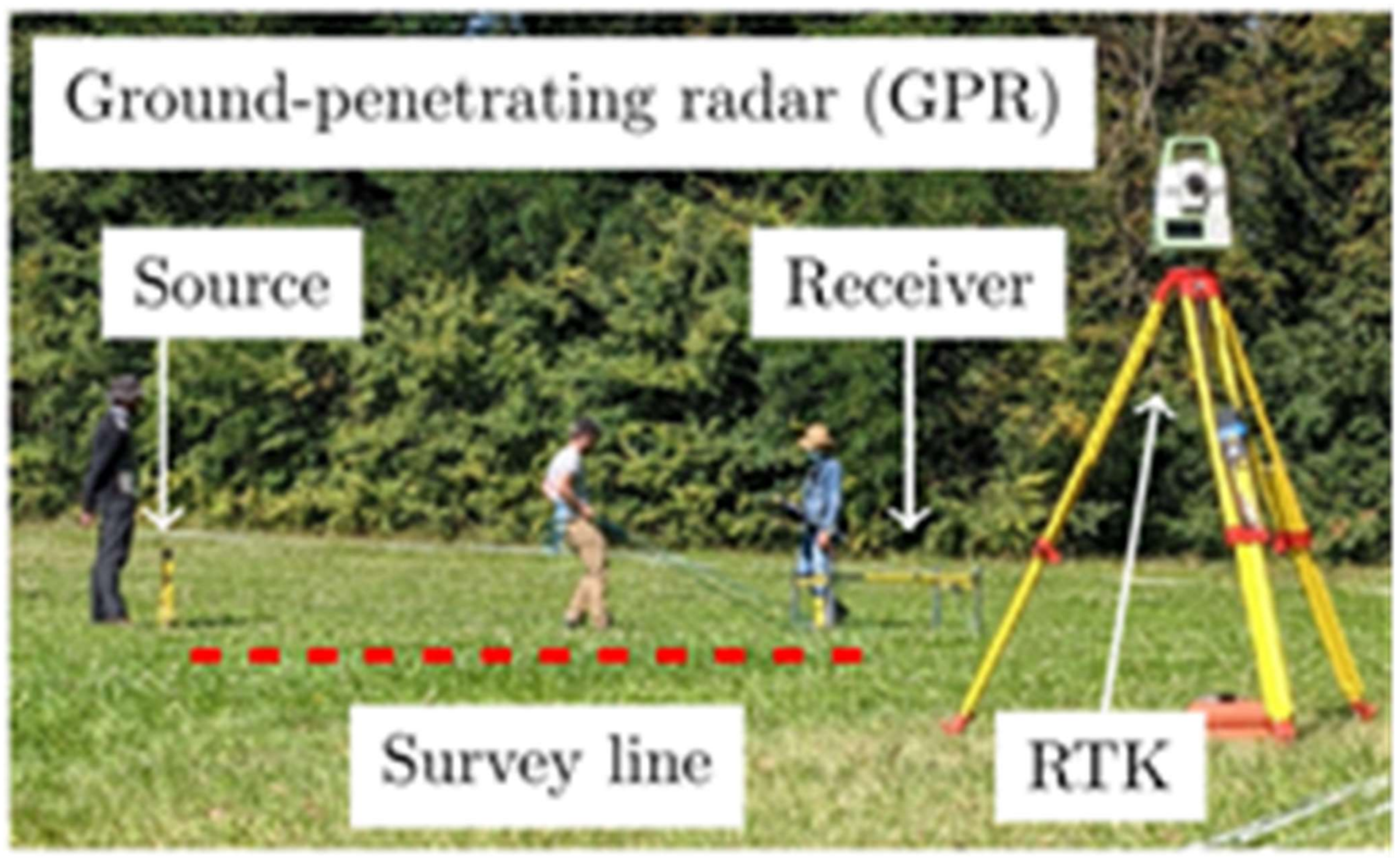


Figure 1: Field measurement at the Rheinstetten glider field. In (a) shallow-seismic measurements, the worker uses a hammer to hit a steel plate on the ground to generate seismic waves, and receivers are laid out along the survey line to record seismic data. In (b) ground-penetrating radar (GPR) measurements, the source generates electromagnetic (EM) waves and a worker moves the receiver along the survey line to record multi-offset EM data. The real-time kinematic (RTK) positioning tracks the coordinates of the receiver. Photo: Yudi Pan

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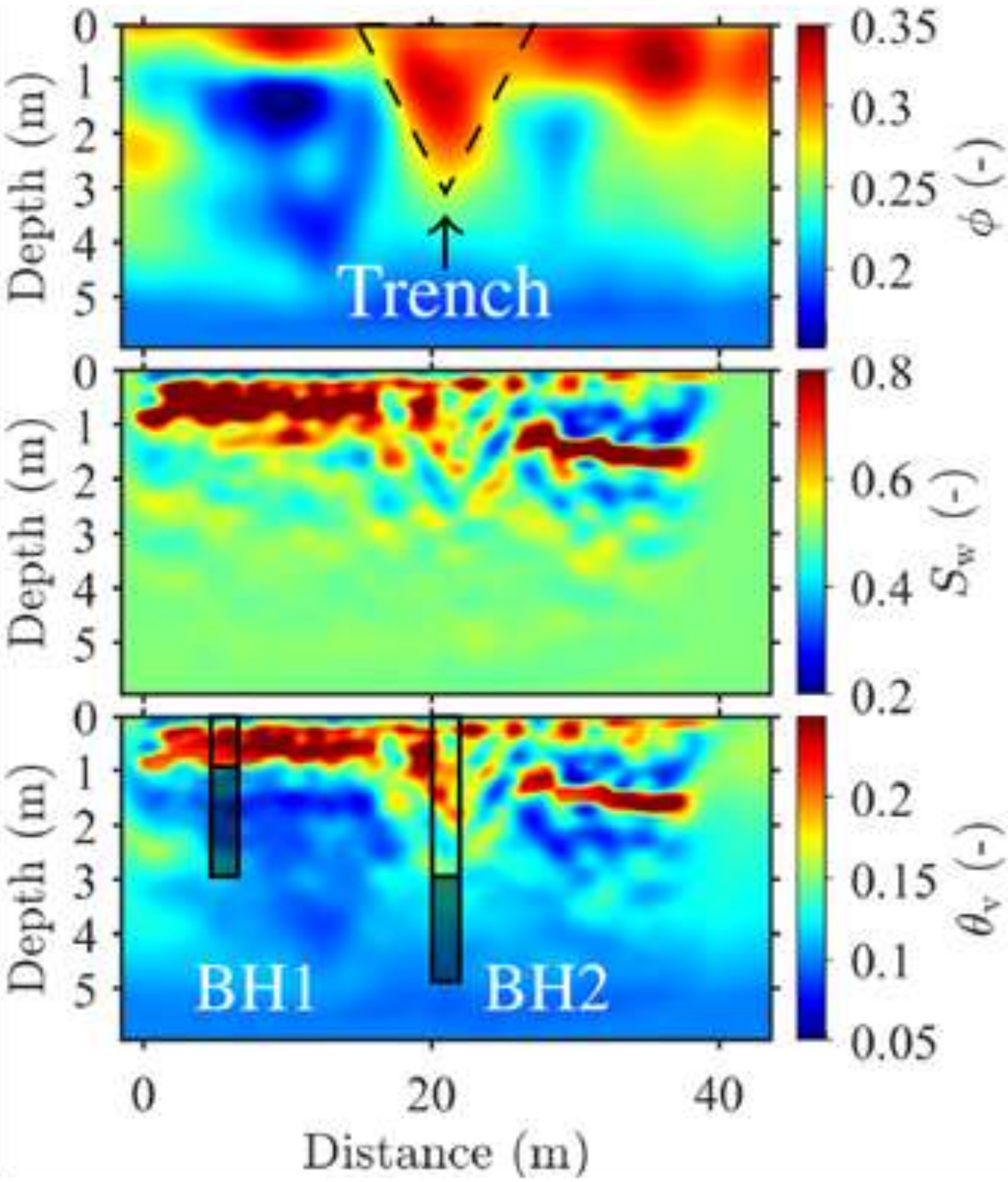

Figure 2: Petrophysical models (porosity, saturation and volumetric water-content model) reconstructed by indirect joint petrophysical inversion (JPI). The borehole histograms overlaid on the water content model are the gravimetric water content given by borehole soil samples, where the transparent and translucent areas exhibit high and low water content, respectively.

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Excellent results in course evaluations

The Geophysical Institute is well known for its good lectures and exercises. Typically, GPI courses rank fairly high in the mandatory course evaluations each semester. Hence, it comes as no surprise that summer semester 2022 was no different. Prof. Andreas Rietbrock won the department's course evaluation award in the category "Best lecture in Geophysics/Meteorology" for the lecture "Introduction to Geophysics II" in the Bachelor's program. Dr. Thomas Hertweck won the award in the category "Best exercise in Geophysics/Meteorology" for the exercises to "Theory of Seismics Waves" in the Master's program. Congratulations to both award winners!

Award ceremony on 4.11.22
Photo: Sonia Sortan

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REGULARIZATION IN TIDAL ANALYSIS

By Adam Ciesielki

We developed an innovative method for tidal analysis that overcomes the limitations of traditional approaches by adding model regularization, such as a priori grouping and fixed built-in models. The well-known tidal analysis program Eterna, which has become a de facto standard in the European tidal community, has its roots at KIT. In 1996 Hans-Georg Wenzel released his ‘Earth tide data processing package’ at the University of Karlsruhe, the predecessor of KIT. Schüller recently (2015, 2020) presented an extended and improved version called Eterna-X. Both programs seek model parameters for a priori defined groups of harmonics. The residual between the predicted tidal signal and the recording is minimized in a least squares sense, by linear regression effectively. Eterna 3.40 (Wenzel, 1997) seeks for factors with respect to the so-called Wahr-Dehant-Zschau, elastic a priori body tide model for the Earth. Eterna-X additionally allows for two inelastic models. All these programs assume that the variation of tidal admittance within each wave group is correctly expressed by the a priori model. The definition of groups is based on the “Rayleigh criterion”, not considering the actual resolution provided by the signal-to-noise ratio of the data. Hence, significant tidal contributions, whose response ratios are improperly assumed, cause a bias in the results of the tidal analysis. We solved this problem by avoiding a priori grouping in the new approach. All tidal harmonics in the catalog are free parameters in the inverse problem. However, many of them still are too close to each other in frequency or are too small in amplitude to be well constrained. Hence, the regression problem would become instable and many parameters would be strongly affected by noise. Therefore, the objective function for the regularized regression contains a model constraint. In the standard approach the objective function

$$\varphi(\vec{m}) = \left|\left|G_{123}\vec{m} - \vec{g}\right|\right|_2^2$$

is expressed by the data misfit only, where matrix G_{123} represents grouped harmonics (in-phase and quadrature) and the air pressure signal. The new approach, named RATA (Regularization Approach to Tidal Analysis), uses the full matrix with all available harmonics G_{2401} and applies a regularization term to the objective function

$$\varphi(\vec{m}) = \left|\left|G_{2401}\vec{m} - \vec{g}\right|\right|_2^2 + \alpha^2\left|\left|\vec{m} - \vec{m_r}\right|\right|_2^2$$

where α is a trade-off parameter and $\vec{m_r}$ is the reference model. All of the signals (G and $\vec{g}$) are bandpass filtered and tapered (cosine window) prior to the analysis in a consistent way. We analyzed 11.5 years gravity recordings from the superconducting gravimeter SG056 at the BFO (Black Forest Observatory, Schiltach). We seek a stationary tidal model in an iterative approach by updating the reference model guided by the inversion result of each iteration. To find the optimum values for the trade-off parameter, we investigate the two terms of the objective function for a range of values. The resulting misfit curve is shown in Fig. 1. The shape of the misfit curve and the scatter of model parameters indicated that overfitting is avoided if α > 60 in this case.

We consequently update the reference model until there is no significant benefit in data misfit. The model parameters for less constrained harmonics are kept at the inversion result for their well constrained neighbors. This way “data-driven” groups are inferred from significant harmonics in the inversion. Tides of different degrees are treated separately, forming “parallel” groups in the frequency domain. The stationary tidal response (gravimetric factors in the final model BF21) for tides of all degrees at the BFO

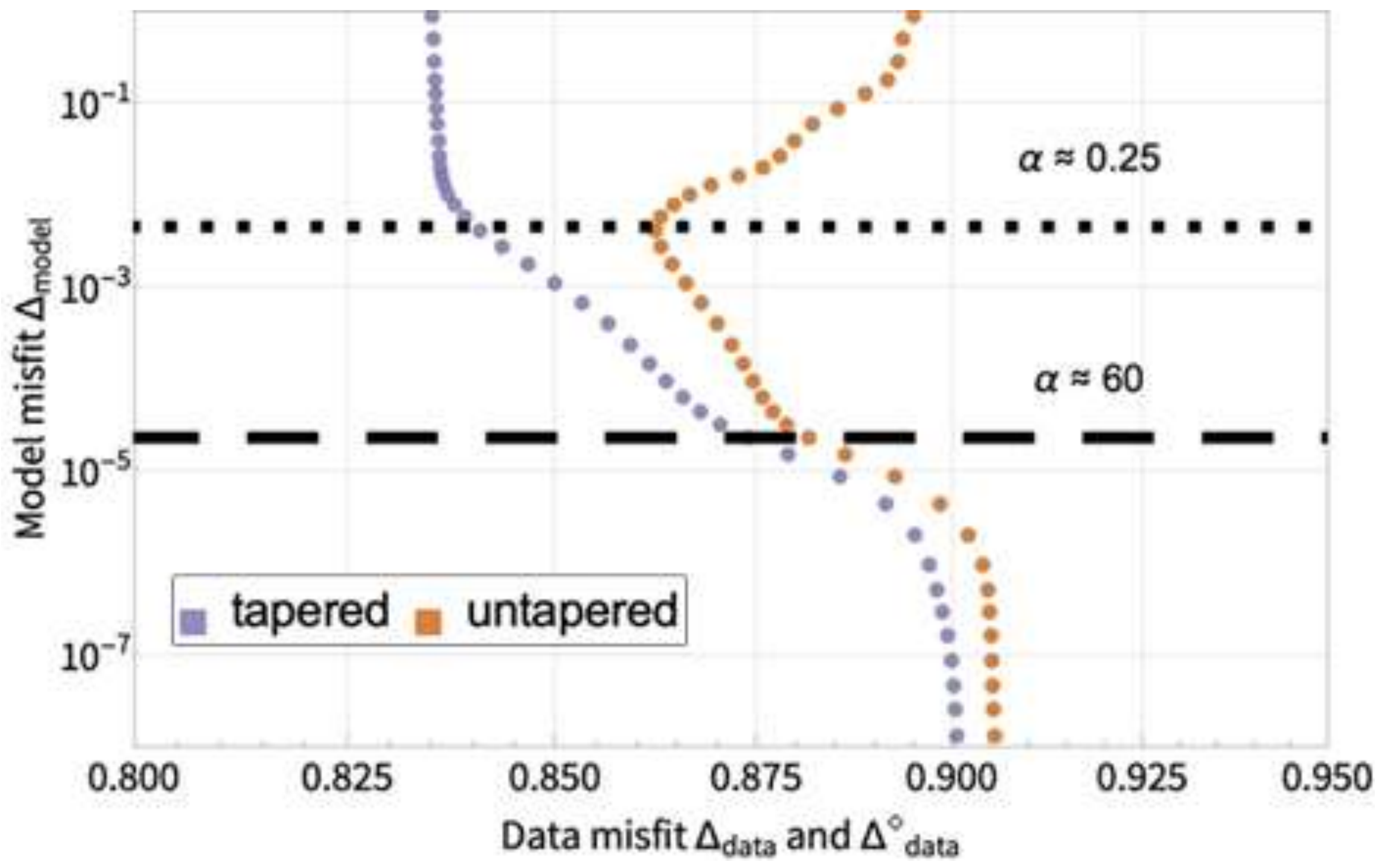

Figure 1: Two misfit curves representing solutions for tapered and untapered data

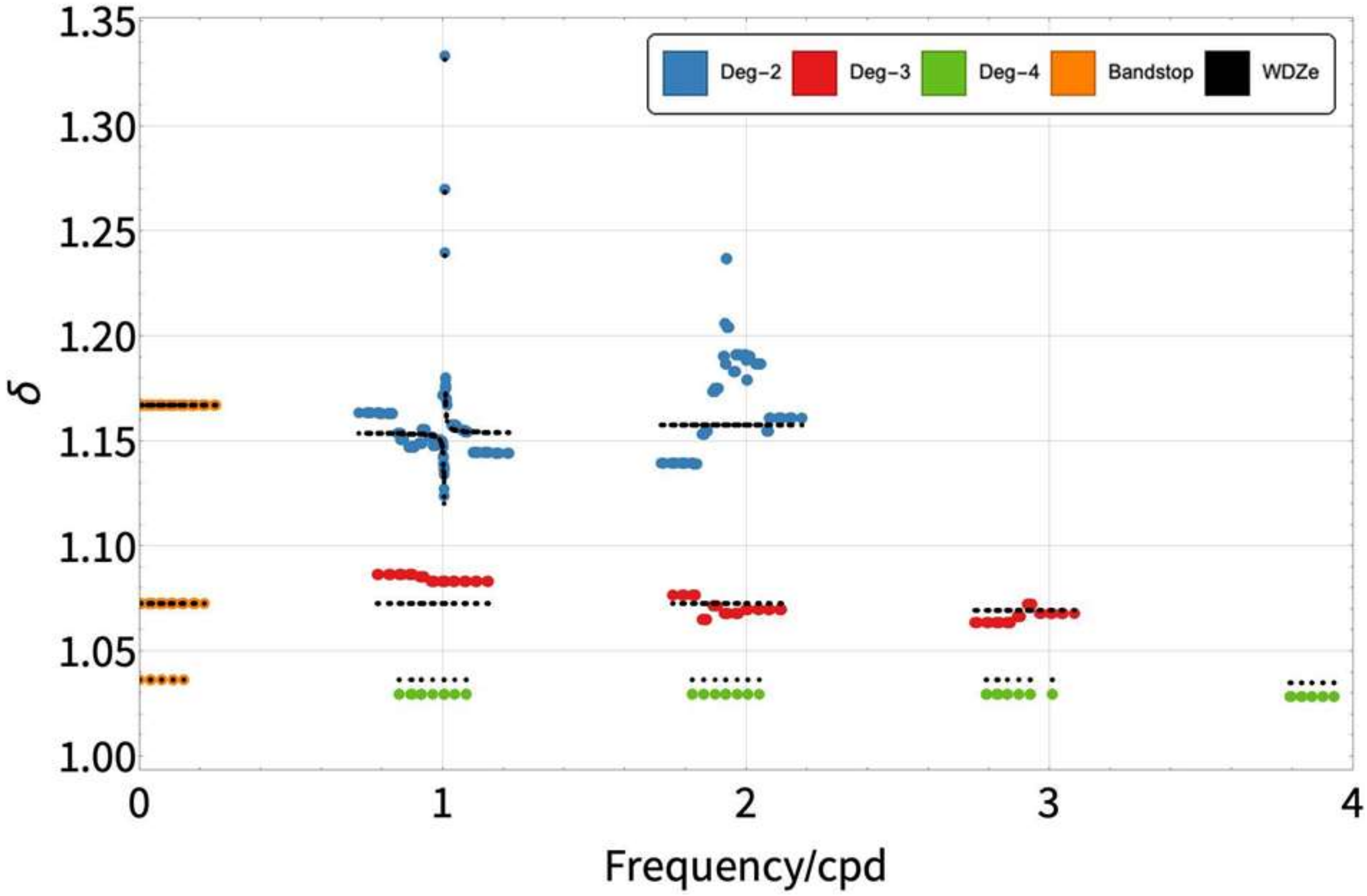

Figure 2: The stationary tidal response at BFO – gravimetric factors in the final model BF21

is shown at the Fig. 2. We obtained different frequency dependence of gravimetric factors of distinct degrees and found a resonance in the semi-diurnal band, which presumably is due to ocean loading. This provides higher resolution than would be expected based on the Rayleigh criterion in some cases.

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The analysis does not show clear evidence that more groups are resolvable. Harmonics with frequencies at frequencies below 0.5 cpd, which are outside the frequency band of the applied bandpass, remain in the analysis but their estimates stay at the reference parameters.

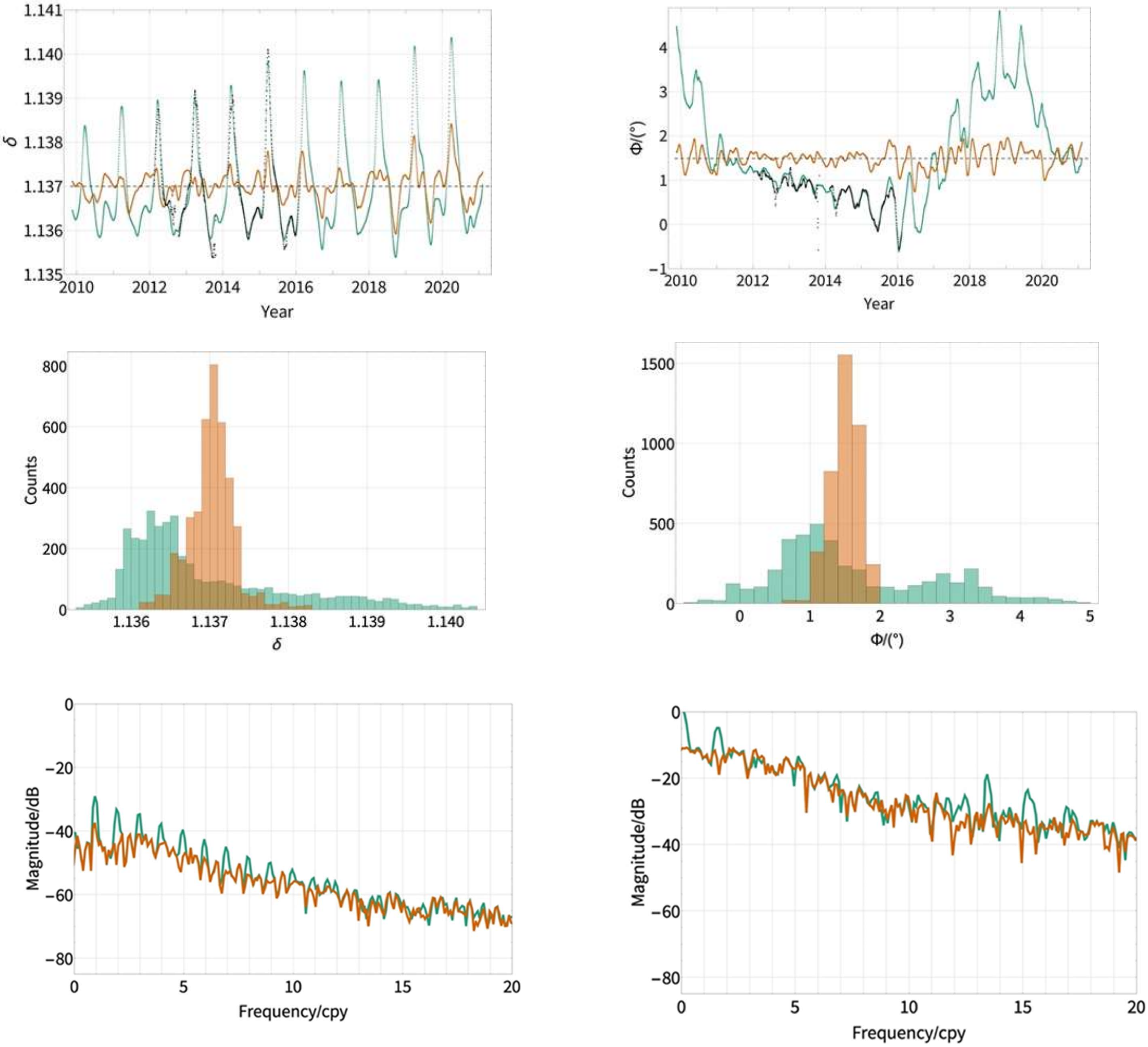

Figure 3: Results of the MWA for K1 factor (left) and L2 phase (right). Middle panels displays histograms, and bottom panel spectra of the corresponding MWA.

To validate the results, we used the moving window analysis (MWA) technique, with the resulting stationary model as the a priori analysis model. We compared this to the standard approach, which used Wahr-Dehant-Zschau analysis model. Windows of 90-days lengths were investigated with no regularization for 12 MWA-groups. Two demonstrative results, for groups K1 and L2, are shown together with histograms and residual spectra of the result in Fig. 3. The left panel displays the K1 factor, the right panel displays the L2 phase. The result based on the new BF21 analysis model is shown in orange, green dots show the results of the traditional approach, overlapped by black points representing results from Schroth (2018) for comparison. We clearly see that bias and beating patterns are significantly smaller, or almost vanish. This means the stationary BF21 model can capture the apparent temporal variations by appropriate tidal parameters within the MWA groups. In the group K1 this predominantly is due to the adjusted radiation tide S1, and for L2 the long-term variation is captured by an appropriate ratio between harmonics of different degrees.

The implementation of the algorithm as well as the data analysis was carried out by the author of the text. Thomas Forbriger, Walter Zürn, and Andreas Rietbrock contributed to the design of the analysis procedure and interpretation of the results. Two students, Daniel Hollarek and Konstantin Drach contributed to the RATA code development. A manuscript giving all details (Ciesielski et al. 2023) is in preparation for the Journal of Geodesy. Some gif files and pdf compilations, showing snapshots of model estimates under different α, are available here: https://nextcloud03.webo.hosting/s/najjk2J8NAd7iSN. They provide a demonstration of the method “at work”.

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Inter-Wind project – Seismic measurements on the Eastern Swabian Alb

By Laura Gaßner, Joachim Ritter

Within the Inter-Wind project we study emissions from wind turbines (WT) on the Eastern Swabian Alb near Geislingen an der Steige. There, we conduct interdisciplinary campaigns recording sound, ground motion and meteorological data at and in the settlements near the two wind farms. The recorded data is then an objective basis for evaluating noise reports issued by residents living at approximately 1 km distance from the wind farms during campaigns of several weeks. So far, two interdisciplinary campaigns were carried out at wind farm Tegelberg (3 WTs) and the village of Kuchen and one campaign at wind farm Lauterstein (16 WTs) and the village of Degenfeld (Figure 1). Both wind farms consist of the same WT type with 139 m hub height and 120 m rotor diameter.

Project partners are:
Environmental- and Social Psychology at the MSH Medical School Hamburg and Martin-Luther-University Halle-Wittenberg conducting interviews with residents
Stuttgart Wind Energy (SWE) at the Institute of Aircraft Design at the University of Stuttgart conducting sound measurements
Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) conducting weather measurements

Meteorological data is also recorded at two 100 m high meteorological masts at the WINSENT test site for WTs which is operated by ZSW in a few kilometers distance to wind farm Tegelberg (Figure 1). At the test site two research WTs are currently being erected. Here, two measurement campaigns were directed at recording data before the installation of the WTs for reference. The GPI also conducted additional measurement campaigns at each wind farm to estimate ground motion amplitude decay relations due to the eigen modes of the WTs and to study directional dependencies of emissions with a ring measurement. For these campaigns, recording instruments were provided by the Geophysical Instrument Pool Potsdam (Figures 1 and 2).

In general we find no increased amplitudes (sound or ground motions) that indicate significant immissions explaining the high number of affected residents at wind farm Tegelberg. However, it can be shown that noise reports are related to WT operation, with increased numbers of complaints during the night time and early morning hours, occuring at full operation or variable rotation rates of the WTs. Furthermore, acoustic and ground motion data are well correlated at frequencies above 12 Hz with signals of variable frequency related to the WT generators and gears (Figure 3).

Our research group presented invited contributions in the „Environmental Noise“ sessions at the „International Conference on Acoustics“ in South Korea in October 2022.

The project is supported by the Federal Ministry for Economic Affairs and Climate Action
based on a resolution of the German Bundestag (grant 03EE2023A-D).

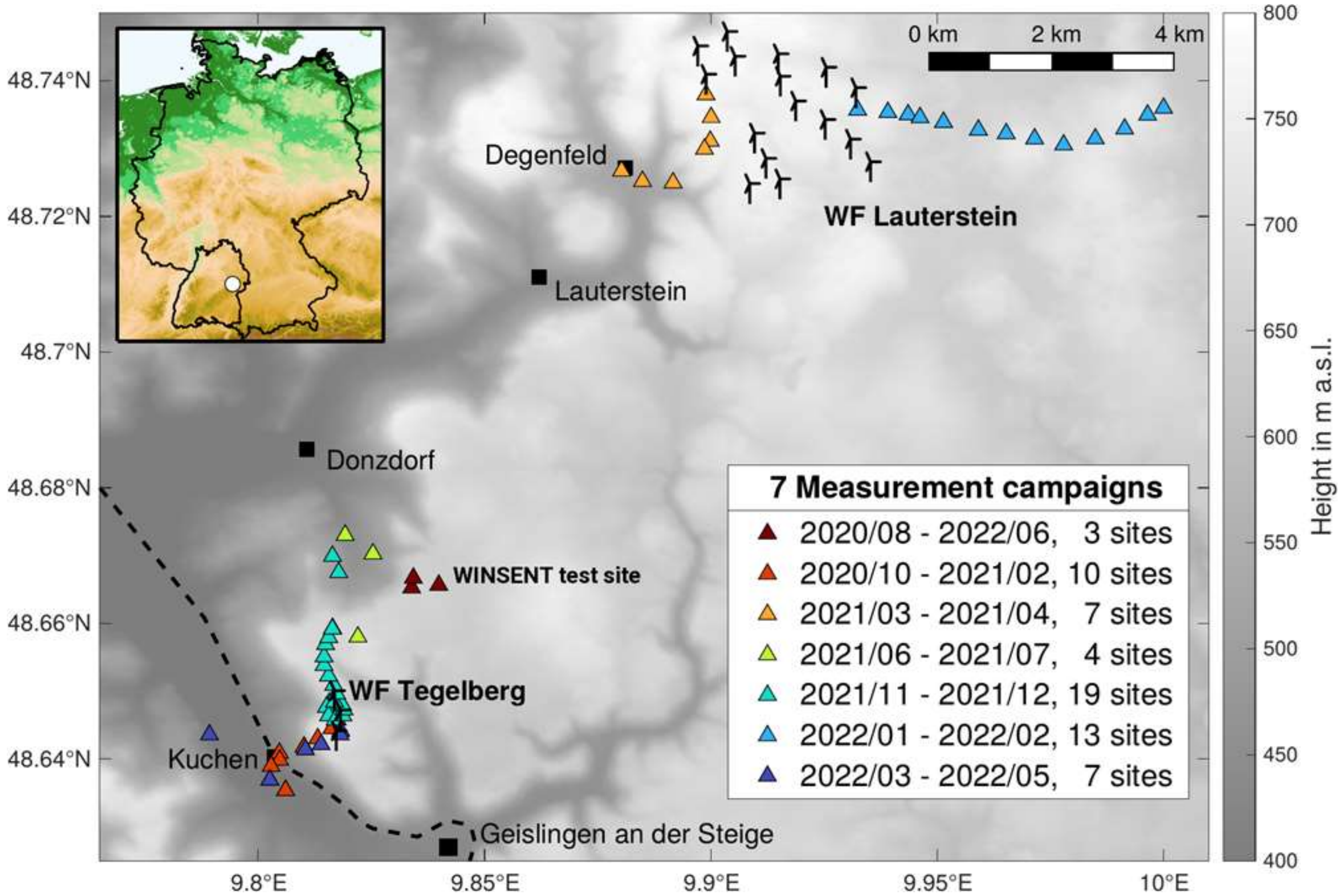

Figure 1: Overview of the measurement campaigns carried out in the years 2020 to 2022. Coloured triangles show the seismometer locations of the different campaigns. A final campaign is currently under way at wind farm Tegelberg and will last until February 2023.

Figure 2: Impressions from the installation of instruments at wind farm Lauterstein in January 2022 for a measurement line of 5 km length oriented towards the east of the WTs. One instrument was installed on the foundation of a WT, the other instruments on fields and forest ground. Photos: Laura Gaßner

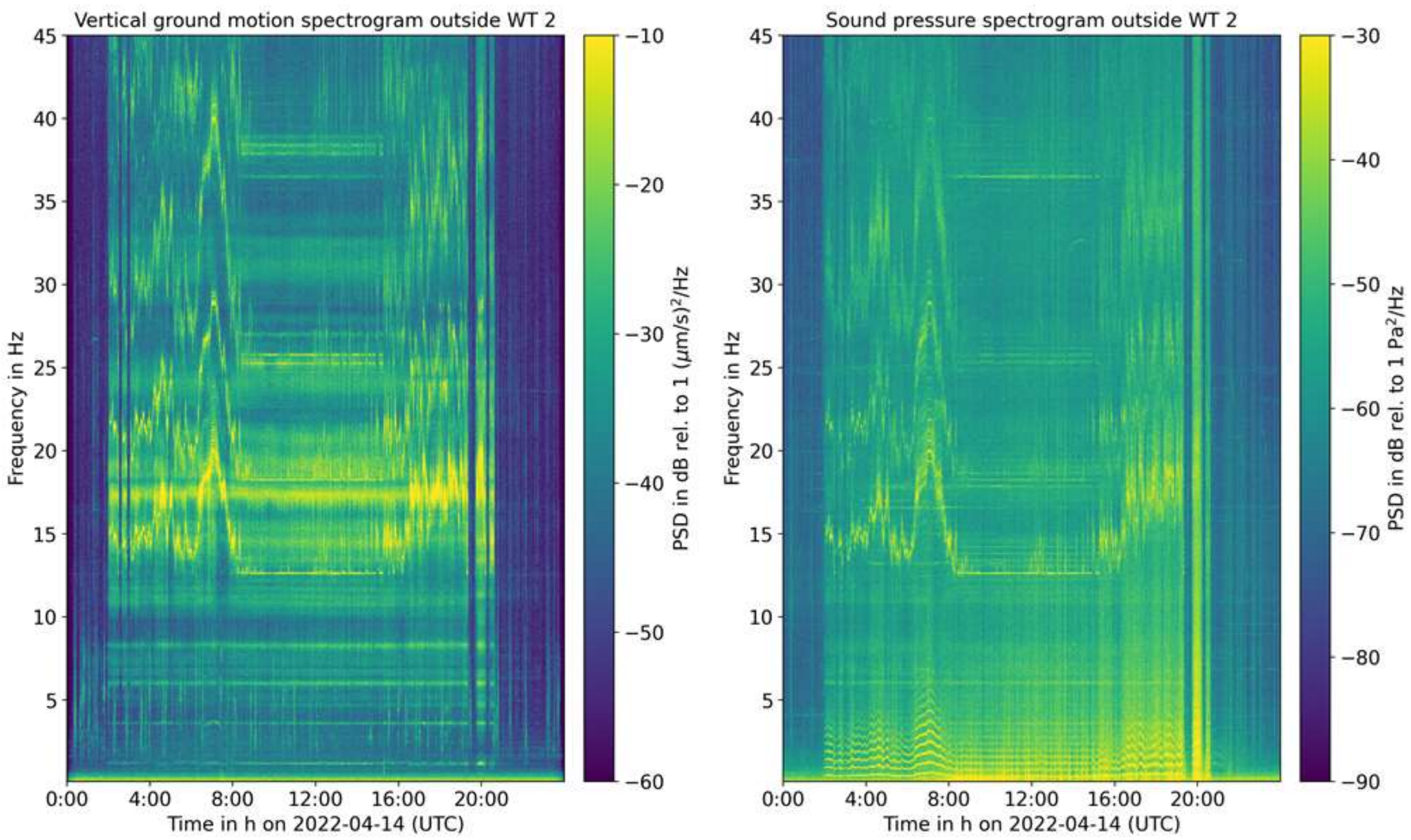

Figure 3: Spectrograms with ground motion velocity (left) and sound pressure (right) from 14th April 2022. For frequencies below 12 Hz the eigen modes (1.2 Hz, 3.6 Hz and 8.33 Hz) of the WTs are visible in the ground motion data. In the sound pressure data the primary multiples of the blade passing frequency (BPF) can be observed. Higher multiples of the BPF are observable in both data sets related to the WT generators and gears.

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In November 2022 M.Sc. ***Jack WOOLLAM*** successfully defended his PhD thesis.

Title: *Advances in Machine Learning for Seismic Event Detection*

Supervisors:
Prof. Dr. Andreas Rietbrock (KIT)
Prof. Dr. Joachim Ritter (KIT)

In November 2022 M.Sc. ***Tan QUINN*** successfully defended his PhD thesis.

Title: *Full-waveform inversion of ground-penetrating radar data and its indirect joint petrophysical inversion with shallow-seismic data*

Supervisors:
Prof. Dr. Thomas Bohlen (KIT)
Prof. Dr. Anja Klotzsche (Forschungszenrum Jülich)

Dario Eickhoff starts in SeisMET project

In summer 2022 our new project SeisMET started with a grant from the Vector Stiftung. Earlier in 2020, Mohsen Koushesh and Joachim Ritter detected acoustic signals from meteors travelling through the atmosphere in the recordings of the seismic network in the Eifel. The location of one source in the air correlated well with the trajectory of a fireball which was studied using optical data by astronomers. Now our new PhD candidate Dario Eickhoff intensifies these studies with the goal to develop a detector which is sensitive for meteor signals.

Sarah Mader starts in DB MISS project

In summer 2022 our new project DB MISS (data base for mitigating wind turbine noise at seismological stations) started with a grant from the state of North Rhine-Westphalia. Sarah will measure and analyse the ground motion emissions from large wind turbines (power >4 MW) to find parameters for the prognosis of such emissions.

WindForS

In spring 2022 Joachim Ritter was officially appointed in the scientific board of the WindForS - Wind Energy Research Cluster. WindForS combines the research efforts of 25 groups at seven universities and research institutions in southern Germany for studying wind energy. E.g., WindForS builds the WINSENT wind turbine test field on the eastern Swabian Alb.

RECENT PUBLICATIONS

In this section we would like to inform about recently published peer-reviewed journal papers authored by current members of GPI:

Gaßner L., Blumendeller E., Müller F.J.Y., Wigger M., Rettenmeier A., Wen Cheng P., Hübner, G., Ritter J. R. R., Pohl J.: Joint analysis of resident complaints, meteorological, acoustic, and ground motion data to establish a robust annoyance evaluation of wind turbine emissions.
Renewable Energy, Volume 188, Pages 1072-1093, ISSN 0960-1481, 202.
https://doi.org/10.1016/j.renene.2022.02.081.

Ritter J. R.R., Fröhlich Y., Sanz Alonso Y., Grund M.: Short-scale laterally varying SK(K)S shear wave splitting at BFO, Germany – implications of the determination of anisaotropic sturctures. J Seismol, 26: 1137-1156, 2022.

Schlömer A., Wassermann J., Friederich W., Korn M., Meier T., Rümpker G., Thomas C., Tilmann F., and Ritter J., 2022. UNIBRA/DSEBRA: the German seismological broadband array and its contribution to AlpArray – deployment and performance. Seis. Res. Lett., https://doi.org/10.1785/0220210287

Fröhlich Y., Grund M., Ritter J. R. R.: On the effects of wrongly aligned seismogram components for shear wave splitting analysis. Annals Of Geophysics, 6, Annals of Geophysics 65, 2022. https://doi:10.4401/ag-8781

Alaei N., Soleimani Monfared M., Roshandel Kahoo A., Bohlen T.: Seismic imaging of complex velocity structures by 2D pseudo-viscoelastic time-domain full-waveform inversion, Applied Sciences 12(15), 7741, 2022. https://doi.org/10.3390/app12157741.

Hertweck T.: Geophysical Tutorial: The significance of negative frequencies in Fourier transforms, The Leading Edge 41(3), 204-208, 2022. https://doi.org/10.1190/tle41030204.1.

Irnaka T. M., Brossier R., Métivier L., Bohlen T., Pan Y.: “3-D multicomponent full-waveform inversion for shallow-seismic target: Ettlingen Line case study”, Geophysical Journal International 229(2), 1017-1040, 2022. https://doi.org/10.1093/gji/ggab512.

Liu T., Bohlen T.: “Time-domain poroelastic full-waveform inversion of shallow seismic data: methodology and sensitivity analysis”, Geophysical Journal International 232(3) [in print], 1803-1820., 2023.https://doi.org/10.1093/gji/ggac414.

Qin, T., Bohlen T., Allroggen N.: Full-waveform inversion of ground-penetrating radar data in frequency-dependent media involving permittivity attenuation, Geophysical Journal International 232(1), 504-522, 2022.

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