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Review of the doctoral thesis submitted by
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on

„Research on natural and anthropogenic seismicity with the high-frequency GNSS observations"

The formal basis of this review is a letter from the Chair of the Scientific Council of the Discipline Civil Engineering, Geodesy, and Transport of the Wroclaw University of Environmental and Life Sciences no. IDDD.0000.4100.4.2023 from 15th of May 2023.

Thesis structure

The presented dissertation is a thematically coherent collection of four articles published in peer-reviewed scientific journals:

1. **Kudlacik Iwona,** Kapłon Jan, Bosy Jarosław, Lizurek Grzegorz (2019). *Seismic phenomena in the light of high-rate GPS Precise Point Positioning results*. ***Acta Geodynamica et Geomaterialia***, 15 (1), 99–112. DOI: 10.13168/AGG.2019.0008, IF=1.000 (70%)
2. **Kudłacik Iwona**, Kapłon Jan, Lizurek Grzegorz, Crespi Mattia, Kurpiński Grzegorz (2021). *High-rate GPS positioning for tracing anthropogenic seismic activity: The 29 January 2019 mining tremor in Legnica-Głogów Copper District, Poland* ***Measurement***, 168 (September 2020), 1–9. DOI: 10.1016/j.measurement.2020.108396, IF=5.131 (70%)
3. **Kudłacik Iwona**, Tymińska Anna, Lizurek Grzegorz, Kapłon Jan, Paziewski Jacek (2023). *High-rate GNSS data in seismic moment tensor inversion: application to anthropogenic earthquakes.* ***Geomatics***, **Natural Hazards and Risk**, IF=3.922 (40%)

4. **Kudłacik Iwona**, Kapłon Jan, Kaźmierski Kamil, Fortunato Marco, Crespi Mattia (2023). *First feasibility demonstration of GNSS-seismology for anthropogenic earthquakes detection* (in review: **Scientific Reports**) IF=4.997 (70%)

The articles were written in English and have been published in (or submitted to) good and very good scientific journals indexed by Journal Citation Reports, including three journal [**2-4**] with a high Impact Factor. However, the fourth [**4**] manuscript is still in the review process. The Candidate is the first author in all the articles, having a dominant contribution varying from 40% to 70%. The first supervisor coauthored all manuscripts, while the second one coauthored manuscripts [**1-3**]. The articles were published during the 2019-2023 period.

Apart from the articles, the thesis consists of a very comprehensive and detailed self-report, in which the Candidate presented the aim and motivation for the research, the background of the research, the current state-of-the-art in GNSS data processing and GNSS seismology, her methods, results, and the final conclusions together with outlook for future studies – totaling of 87 pages including references. Moreover, she provided comprehensive summaries of all four articles presenting her results. Finally, she included copies of all the articles. The overall structure of the thesis is clear and well-designed. The language is also clear, and understandable, the English is good and clear. The structure of the sentences is correct and it makes the text easy to follow and understand. The editorial level of the thesis presents a high standard fulfilling requirements for a doctoral thesis.

Aim and methods

I have to admit that the self-report is really very comprehensive, and this is quite rare in case theses being collections of articles. It starts (Chapter 1) with the motivation and introduction, where the Candidate presents the gap in the current research in GNSS seismology and formulates the aim of the Ph.D. thesis: to propose the procedures for retrieving the short-term vibrations of small-magnitude anthropogenic earthquakes from the HR-GNSS observations. There are also defined four specific goals of the study, namely:

- to evaluate different approaches to HR-GNSS observations processing;
- to explore the denoising procedures and determine the methodology for reducing the noise in the HR-GNSS time series;
- to investigate the possibility of detecting the co-seismic signal in the HR-GNSS time series;

• to include the HR-GNSS data to the estimation of seismic event parameters.

In my opinion, the aim of the thesis is correctly formulated, it is based on the identified gap in the current knowledge and research and concerns contemporary topics. Indeed, small-magnitude anthropogenic earthquakes are not very well studied using high-rate GNSS, which is primarily used for structural health monitoring. There are just several early studies published on this topic, while most of the studies concern strong, natural earthquakes.

The second Chapter 2 provides the background and the current state of research in GNSS and seismology, in particular, in GNSS seismology. The candidate describes the characteristics of the seismic sources and the classification of the earthquakes and discusses the seismicity in Poland. Then, the current methods of GNSS data processing are described, for both DD and PPP approaches.

However, section 2.2 misses references in many instances. The statement that the tropospheric delay varies faster and more frequently than the ionospheric one is not correct. Moreover, the ionospheric delay can only be compensated to some extent by applying ionospheric models. Some acronyms are introduced several times, e.g., IGS on page 22 (and with no proper references). The need for the application of differential code biases in DD processing is questionable. Also, at this point observable specific biases are commonly used instead of DCB.

A very important and interesting section 2.3 introduces the reader to the GNSS seismology research field. The candidate discusses the advantages and limitations of the GNSS technique in the applications in seismic studies, in particular in the comparison to standard seismic sensors based on accelerometers. She also introduces and discusses the novel variometric (GNSS-based) approach providing directly station velocities, which was developed at La Sapienza University. In this section, the Candidate correctly defines the main limitation of GNSS in seismic studies – the noise in GNSS-derived position time series. She discusses different possible sources of the noise and then focuses on the mitigation methods. In particular, she introduces the Butterworth filter, discrete wavelet transform, and principal component analysis combined with the wavelet transform. Some examples of data filtering using the abovementioned methods are also presented and discussed. Noise reduction to a single-millimeter level is demonstrated. The final part of Chapter 2 concerns methods for tremor detection and characterization. The most frequently used algorithms and methods are reviewed, and their limitations in small-amplitude earthquake applications are discussed. This section provided the methodological foundations for the presented research, it also confirms that the applicant knows and understands the limitations in the current state-of-the-art in the GNSS seismography. I find this section a very important part of the thesis. One note - the Japanese GEONET network consists of over 1300 stations – not 80 as stated on page 26.

Research and results

Chapter 3 describes the investigations and results within this thesis, which were published in the four manuscripts constituting the thematically coherent collection being the doctoral thesis. It is very well written and nicely orders research published in the articles. It presents the data used, methods applied, obtained results, and validation of the results in comparison to the existing "classic" methods. Since the basis for this thesis is a collection of research articles, I give my opinion on the content of the articles. This is because, as expected, Chapter 3 basically reproduces the results from the articles. Moreover, Chapter 4 provides summaries of the articles with statements on the actual contribution from the Candidate.

Paper [**1**] starts the investigations and studies three naturally originated moderate to strong earthquakes using a high-rate PPP approach. The obtained station motion time series are compared with the results of the seismometers, using several pairs of GPS/SM stations. The candidate sees the necessity of the filtration of GPS-derived displacement time series. After some tests, the Butterworth filter was selected as the most efficient. The final correlation coefficients between the displacements from PPP and seismometers are in good agreement, confirming that high-rate GPS can reliably produce earthquake-generated waveforms. This paper is a basis for establishing the procedure for determining short-term deformations with GPS observations.

Paper [**2**] adopts the methodology developed and tested in [**1**] for analysis of low-magnitude and low-amplitude anthropogenic tremor in the LGOM area. Moreover, this study compared the results of DD and PPP approaches and it is based on 10 Hz GPS data. In this contribution, the peak ground displacements are compared between, DD, PPP, and SM solutions. Moreover, additional coherence analysis in the frequency domain is provided, and I find these spectral analyses very valuable. Finally, the Candidate made a successful attempt to detect the mining tremor in the GPS position time series. The main value of this article is the confirmation that the GNSS-seismology methods (both DD and PPP) may be successfully applied to the detection and study of the anthropogenic tremor provoked by underground mining activity. One comment – earlier studies on the application of HR-GNSS to anthropogenic low-magnitude tremors carried out in Poland were already published in 2020 by Paziewski et al. (DOI:10.1016/j.measurement.2020.108236). Nevetheless, this contribution is cited in the article [3].

Paper [**3**] also focuses on the LGOM area and analyses two events with low magnitudes of 3.7 and 4.0. Again, SM and GNSS results are compared. This time GNSS PPP results are derived with the RTKLib software and the CSRS-PPP online system, finally using also Galileo system data. This manuscript extends the research with the studies on seismic moment tensor inversion based on combined GNSS and SM data. The influence of the relative location of the monitoring stations is also investigated. It was also demonstrated that the MT can be reliably determined with GNSS data in case of a weak/sparse SM network. This is an important step in the presented studies, allowing for better characterization of the mining tremors.

Paper [**4**] presents very comprehensive research on anthropogenic seismicity and it is clearly based on the results and experience gained in the first three studies [**1, 2, 3**]. It greatly extends the research and provides a full and comprehensive methodology that may be applied in practical applications. The Candidate applies dedicated, nd advanced GPS+Galileo PPP processing methodology (WARP) as well as the innovative variometric approach. To further reduce the noise in the GNSS time series, she introduces advanced multiresolution analysis and decomposition based on wavelet transform (MRA-IQR filtering). In the second section of this study, she introduces an innovative procedure to detect the first motion of the tremor. Finally, she confirms the ability to detect the tremor events of low PGD of only 2 mm using her own seismo-geodesy methods. This manuscript presents the final advancement of the thesis and sums up the scientific findings of the presented research. It presents the complete procedure applicable for anthropogenic seismicity monitoring and studies.

Finally, Chapter 5 of the self-report presents conclusions and an outlook for future studies. The Candidate concludes that HR-GNSS methods are applicable for small-magnitude anthropogenic earthquakes, providing an advanced filtration of the derived position time series. She notes the high efficiency of the estimation of the mining tremor parameters and emphasizes real-life scenarios analyzed in the study. According to the Candidate, future studies shall include refinements and advancements in GNSS data processing methods as well as a combination of GNSS and SM data. Further improvements in the data filtering procedures and analyses are also needed, including the application of modern machine learning methods.

Opinion on the research presented in the thesis

As I already mentioned, the structure of the thesis, i.e., the self-report, is well-designed, which makes it easy to follow the research of the Candidate. It follows the classic order and it is well-written. It covers the studies carried out and presented in the articles. Indeed, the self-report is very extended and detailed, so the reader can learn the state-of-the-art, gap in the current research, the background and research methods applied, and finally the results and conclusions. Basically, the reader may learn the whole scope of the thesis by reading just the self-report part. Of course, copies of all four manuscripts are also provided with their extended summaries. Since the articles have coauthors, the Candidate provides statements on her actual contribution.

As for the research, the whole thesis is arranged in a logical way, starting with article [**1**], where the Candidate studies strong earthquakes and provides her procedure for obtaining short-term deformations with 1 Hz GPS data. The results are verified by the comparison to the SM measurements. Then, in [**2**] she adopts her methodology to a low-magnitude and low-amplitude anthropogenic earthquake. Here she also uses real measurements. Then, in [**3**] the Candidate applies her further developed method to the characterization of weak mining tremors. Finally, in [**4**], taking advantage of the experience gained in the earlier studies, she proposed a well-developed and comprehensive methodology for the detection and characterization of tremors caused by mining activity. It is worth noting that the methodology is based on HR multi-GNSS (GPS+Galileo) data only.

In my opinion, the Candidate correctly defined the gap in the current research, then she formulated the aim of the thesis with the goal of filling that gap. During her studies, she presented solid research based on her own methodology. The presented research required a broad knowledge of HR GNSS data processing, seismology, and advanced time series filtration. The logic behind the research in this thesis can be easily followed. Her results are original, based on actual measurements, and confirm the applicability of the methods, which surely can find practical applications for the monitoring of the mining areas, not only in Poland but in the world. The main achievement of the Candidate is the development of her own methodology of applying HR GNSS data to the detection and characterization of the short-term vibration caused by low-amplitude anthropogenic tremors, its validation, and practical application. Moreover, the results were published in good and very good peer-reviewed scientific journals. This additionally confirms the high level of the research.

Specific questions to the Candidate

1) What, in your opinion, is the main source of the noise in the GNSS-derived position time series?
2) What advancements in GNSS data processing may further improve the quality of the position time series?
3) As for the SM and GPS/GNSS displacement correlation studies – how the time of SM and GPS observations was synchronized? I understand that GPS data is provided in the GPS time system, but what about SM data?
4) Why signals from the BDS3 system were not applied in the study?
5) Why do you think the tropospheric effects on GNSS signal vary faster than the ionospheric ones (p. 21)?
6) Is it really possible to fix the carrier phase ambiguities using PPP model provided in eq. 9 (page 25)?
7) Why inconsistent geodetic products were used when processing GPS data with GAMIT? I mean the mix of CODE and UPC ones?
8) Why simple Klobuchar ionosphere model is used in the variometric approach?

Final conclusion

This is my opinion that MSc Eng. Iwona Kudłacik reached the goal defined in the thesis, and the presented thesis fulfills the requirements provided in the Act of 14 March 2003 on Academic Degrees and Titles and Titles in the Field of Arts. Therefore, I request that the thesis be admitted to public defense.

Furthermore, taking into account the quality of the self-report and the scientific value of the study, I make the request the doctorate be awarded with distinction.

Signed by /
Podpisano przez:

Paweł Wielgosz

Date / Data:
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