Title:
Development of an Absolute GNSS Antenna Field Calibration System

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Level of study or work: PhD

Information about you (and your team): Antonio Tupek was born in 1992 in Zagreb, Croatia. He completed his bachelor's (BSc) and master's (MSc) studies in Geodesy and Geoinformatics at the Faculty of Geodesy of the University of Zagreb, from 2011 to 2016. In 2018, he furthered his commitment to advancing geospatial sciences by enrolling in a PhD program at the Faculty of Geodesy, University of Zagreb, focusing on developing of a new GNSS receiver antenna absolute field calibration method and system thereby advancing GNSS positioning. In February 2024, he successfully defended his doctoral dissertation, titled "Development of an Absolute GNSS Antenna Field Calibration System", and was awarded the academic degree of Doctor of Philosophy (PhD).

He currently works as a postdoctoral researcher at the Chair of Instrumental Technique of the Institute of Applied Geodesy of the University of Zagreb – Faculty of Geodesy in Zagreb, Croatia. His research interests encompass geodetic instruments and geodetic metrology, deformation analysis, GNSS, and GNSS data processing, with a particular emphasis on GNSS antenna calibration.

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Area of interest

To obtain high global positioning accuracy, Global Navigation Satellite Systems (GNSS) receivers are essential sensors. Thereat, all influential factors and error sources must be understood and appropriately accounted for. One such key influence and error source is the GNSS receiver antenna phase centre (PC) model. Because, due to the antenna's design characteristics and electromagnetic properties, its PC changes with respect to the incoming signal's direction and frequency. Such variations cause significant range errors and decrease positioning accuracy (Baire *et al.*, 2014). Therefore, adequate corrections known as phase centre corrections (PCCs) need to be applied, and individual GNSS antenna calibration is needed.

The antenna calibration topic is currently of high interest to the global GNSS community. With the development and modernization of GNSS and the availability of new GNSS signals, the need for their calibration emerges. Today, the lack of consistent multi-frequency multi-GNSS PCC models is one of the most challenging issues (Kröger *et al.*, 2021). Furthermore, this topic has high scientific and practical relevance to the Republic of Croatia because none of the GNSS antennas of the Croatian Positioning System (CROPOS) are individually calibrated.

The doctoral research objectives can be summarized as follows: development of a new GNSS antenna calibration system, contributing calibration data and results to the global GNSS community, further improvement of CROPOS, and enhancing GNSS positioning overall.

Approach to the problem

The GNSS receiver antenna calibration system developed as part of the doctoral research is an *absolute field* calibration system based on the utilisation of a 6-axis Mitsubishi industrial robot. The developed calibration methodology is based on the concepts of *absolute calibration*, whereby the PCC model of the calibrated antenna (AUT) is determined completely independent of the reference antenna (REF). According to the developed methodology, the industrial robot is used for fast, efficient, and precise spatial rotations of the calibrated antenna, ensuring homogeneous observation coverage of the entire antenna hemisphere. A conceptual representation of the developed calibration system is given in Figure 1 and an on-site calibration set-up in Figure 2.

Software-wise, the newly developed calibration system consists of three main modules, namely: the main Antenna Calibration Module (ACM), the Time Synchronization module (TiSy), and the PCC estimation module (PEM). All software modules are results of the doctoral research and are custom-built using the Python programming language.

A new time synchronization method of the calibration system, based on the one pulse-per-second (1PPS) signal and its corresponding 1PPS Time Tag message, has been developed to ensure temporal alignment of all hardware and software parts of the system as well as registered carrier-phase measurements.

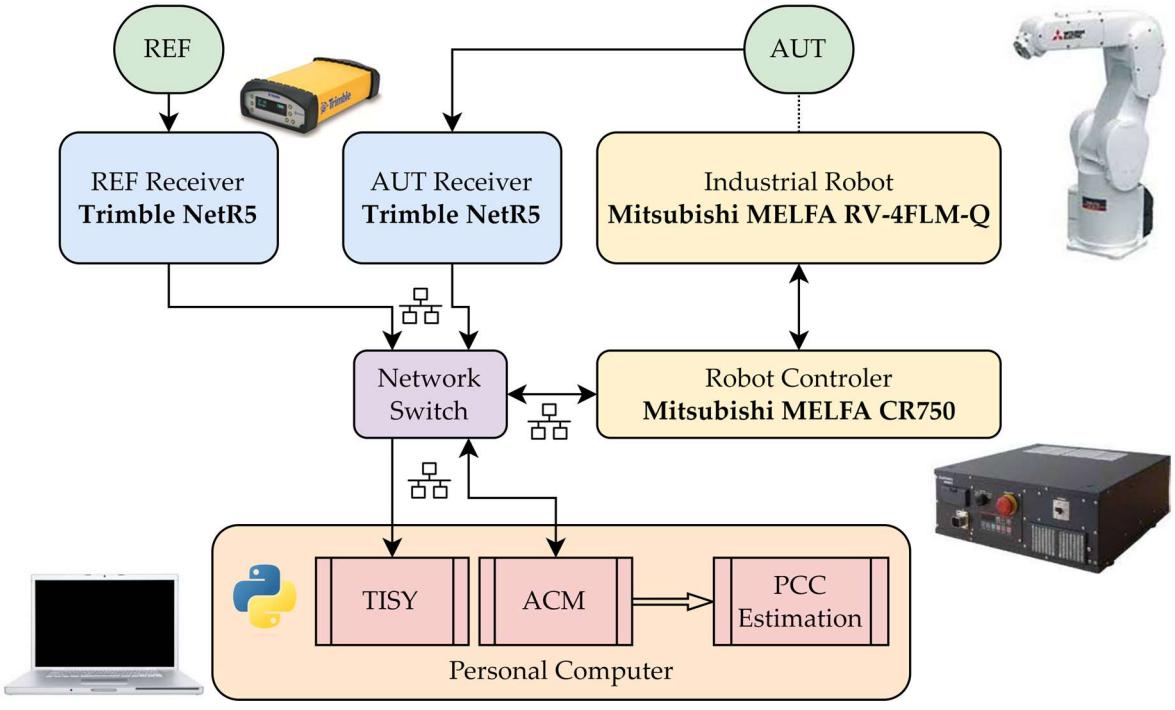

Figure 1. Concept of the developed GNSS antenna calibration system.

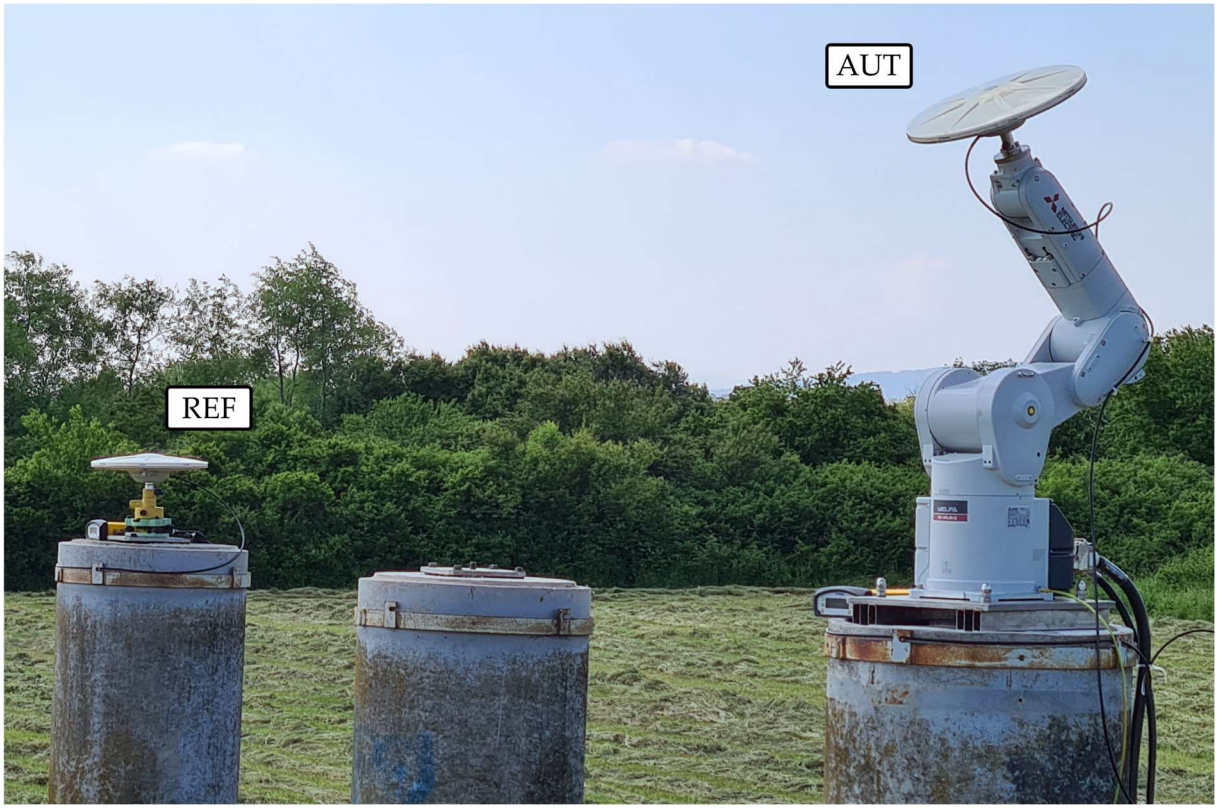

Figure 2. GNSS antenna calibration system during operation; REF – reference antenna, AUT – antenna-under-test (calibrated antenna).

The new GNSS receiver antenna PCC model creation methodology presents one of the key parts of the newly developed calibration system and is one of the main scientific contributions of the doctoral research. At its core, the PCC estimation method is based on triple-difference carrier-phase measurements and their mathematical parametrization by spherical harmonics (SH). SH resolution of degree and order 8 has been chosen as optimal and is implemented in the system.

Results, conclusions and next steps

The development of the new GNSS receiver antenna calibration system was successful, enabling individual antenna calibration, i.e., antenna PCC modelling (Figure 3). During the analysis stage, the system underwent extensive tests and was validated at multiple levels.

Experimental research results confirmed that a time synchronization uncertainty of 1.0 millisecond was achieved, fully satisfying the calibration system requirements. Furthermore, by comparison with independent individual calibration results obtained by Geo++ GmbH in Germany, the accuracy of antenna calibrations was determined. Analysis results confirmed that sub-millimetre dual-frequency GPS calibration accuracy has been achieved. Also, short baseline test results have confirmed that antenna calibration with the developed system leads to approximately 3.5 times greater baseline accuracy compared to the IGS (International GNSS Service) type-mean PCC models. Moreover, results indicated an approximately 23% increase in GNSS network accuracy.

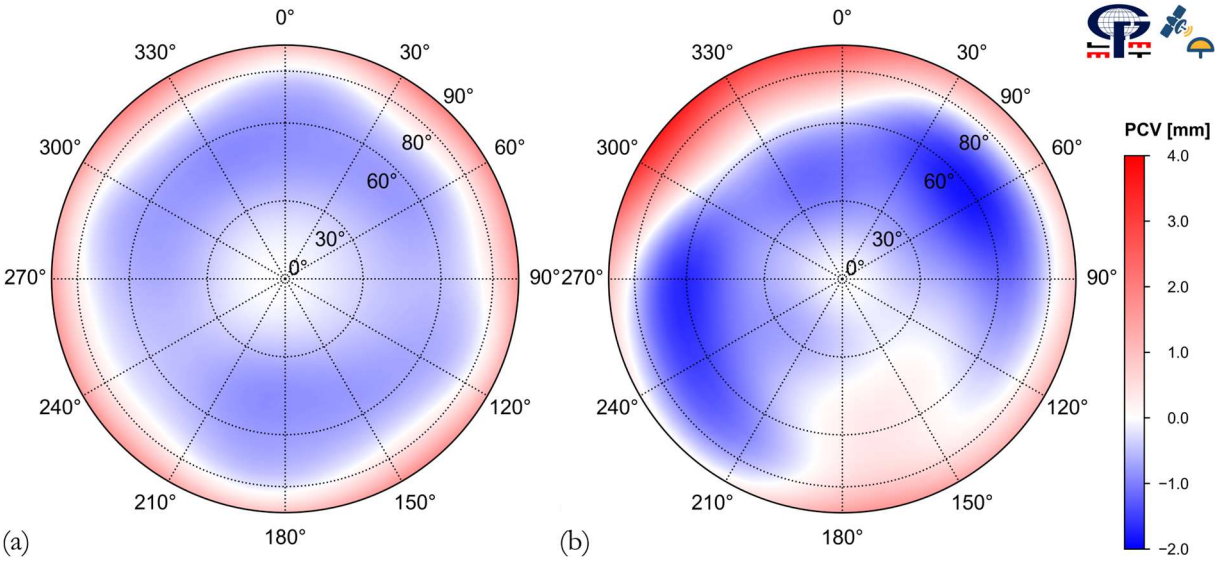

Figure 3. Results of individual calibration for antenna Leica AX1202GG for: (a) GPS L1; (b) GPS L2 frequency.

Overall, based on the gained research results, it is concluded that all proposed research hypotheses presented in the doctoral dissertation are accepted. The newly developed GNSS receiver antenna calibration system provides meaningful antenna calibration results and enhances GNSS positioning accuracy.

Future research and calibration system development will primarily be focused on expanding the newly developed system to incorporate multiple frequencies and all other global navigation satellite systems, primarily the European Union's Galileo.

References

Baire, Q., Bruyninx, C., Legrand, J., Pottiaux, E., Aerts, W., Defraying, P., Bergeot, N., Chevalier, J.M. (2014): *Influence of Different GPS Receiver Antenna Calibration Models on Geodetic Positioning*. GPS Solutions, 18, 529–539.

Kröger, J., Kersten, T., Breva, Y., Schön, S. (2021): *Multi-frequency multi-GNSS receiver antenna calibration at IfE: Concept – calibration results – validation*, Advances in Space Research, 68, 12, 4932–4947.

For more detailed information regarding the developed GNSS antenna calibration system, calibration methodology, and results, please refer to the following applicant's scientific publications resulting from the doctoral research:

Tupek, A. (2024): *Development of an Absolute GNSS Antenna Field Calibration System*, Doctoral dissertation, University of Zagreb, Faculty of Geodesy, Zagreb. Available at: https://repozitorij.geof.unizg.hr/islandora/object/geof:40.

Tupek, A., Zrinjski, M., Švaco, M., Barković, Đ. (2023a): *GNSS Receiver Antenna Absolute Field Calibration System Development: Testing and Preliminary Results*, Remote Sensing, 15, 18, 1–21.

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Tupek, A., Zrinjski, M., Barković, Đ., Špoljar, K. (2024): *Absolute GNSS Receiver Antenna Calibration at the Faculty of Geodesy – University of Zagreb*, Conference Proceedings, 9th International Conference Contemporary Achievements in Civil Engineering 2024, April 25–26, Subotica, Serbia, 1–12.

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