Space Operations and Astronaut Training

Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

DLR e. V. Space Operations and Astronaut Training
Oberpfaffenhofen, Muenchener Str. 20, 82234 Wessling, Germany

Prof. dr. hab. inż. Krzysztof Sośnica
Institute of Geodesy and Geoinformatics
Wrocław University of Environmental and Life Sciences
Ul. Grunwaldzka 55
50-357 Wrocław

Your reference
Your letter
Our reference

Your correspondent Oliver Montenbruck

Telephone 08153/28-1195
Telefax +49 8153 28-
E-mail oliver.montenbruck@dlr.de

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PhD Thesis Evaluation Radosław Zajdel

Dear Prof. Sośnica,

it is my very pleasure to serve as a reviewer for the doctoral thesis on “Determination of Global Geodetic Parameters Using the GPS, GLONASS, and Galileo Satellite Systems” presented by Mr Radosław Zajdel. Before being invited for this review, I have not met Mr. Zajdel in person or worked with him in a joint project, but was partly aware of his research through some of his publications issued over the past years.

Mr. Zajdel has chosen to submit his work in the form of a cumulative thesis that builds on a total of five peer-reviewed publications:

1. Zajdel R., Sośnica K., Dach R., Bury G., Prange L., Jäggi (2019) Network Effects and Handling of the Geocenter Motion in Multi-GNSS Processing, Journal of Geophysical Research: Solid Earth, 124(6). DOI 10.1029/2019JB017443
2. Zajdel R., Sośnica K., Drożdżewski M., Bury G., Strugarek D. (2019) Impact of network constraining on the terrestrial reference frame realization based on SLR observations to LAGEOS, Journal of Geodesy, 93:2293-2313. DOI 10.1007/s00190-019-01307-0
3. Zajdel R., Sośnica K., Bury G., Dach R., Prange L. (2020) System-specific systematic errors in earth rotation parameters derived from GPS, GLONASS, and Galileo, GPS Solutions, 24:74. DOI 10.1007/s10291-020-00989-w
4. Zajdel R., Sośnica K., Bury G., Dach R., Prange L., Kaźmierski K. (2021) Sub-daily polar motion from GPS, GLONASS and Galileo, Journal of Geodesy, 95:3. DO: 10.1007/s00190-020-01453-w
5. Zajdel R., Sośnica K., Bury G (2021) Geocenter coordinates derived from multi-GNSS: a look into the role of solar radiation pressure modeling, GPS Solutions, 25:1. DOI 10.1007/s10291-020-01037-3

All of these articles have been published in leading journals of the field that are renown for the overall quality of their articles, a thorough peer-review process, and high impact factors. In accord with common scientific practice, each of these publications includes contributions of multiple authors from the well-known research groups at University of Bern and Wrocław University of Environmental and Life Sciences, which evidences that Mr. Zajdel’s work is actively embedded into an international context. At the same time R. Zajdel has obviously taken the lead in the design, data analysis, writing, and interpretation of results in all cases, and provides convincing and trustable statements of intellectual ownership and his ability to perform high-quality research in all cases.

The collection of articles is complemented by a comprehensive book-style thesis report that provides an independent account of the research methodology and results written exclusively by the PhD candidate. The report starts with an overview of present Global Navigation Satellite Systems (GNSSs) highlighting the individual constellation design parameters as well as the diversity of spacecraft platforms that ultimately affects the capability to determine accurate orbits and geodetic parameter estimates. Furthermore, the introduction compares the role of GNSS for global geodetic observations with that of other space geodesy techniques and clarifies that GNSS can specifically contribute to observations of pole coordinates, variations in Earth rotation, and station coordinates, while limitations apply for the determination of geocenter motion and the scale of the terrestrial reference frame. Based on these introductory considerations the research scope is defined to investigate the potential contributions of the European Galileo system for improving GNSS-based geodetic parameter estimates and refinement of the terrestrial reference frame.

Following the introduction, the overall processing methodology is addressed in the second chapter of the thesis report. It starts with a generic description of multi-GNSS orbit determination and parameter estimation using the Bernese v5.2 software employed for this study. Here, key algorithms and the processing chain are described and the specific models, conventions and processing standards are documented for full traceability of the overall results. The explanations and depth of presentations are considered fully adequate for the purpose, with the possible exception of Sect. 2.2.3. where it is not fully clear how "system specific solutions" (as opposed to true single-constellation solutions) are obtained and how this approach affects the resulting parameter sets. Special attention is given to the discussion of the solar radiation pressure models using combinations of a priori and empirical parameterizations, which becomes important for both precise orbit determination and geodetic parameter estimation. Dedicated sections in the methodology chapter address aspects of reference frame realization, geocenter motion, and Earth rotation modelling in general. Given the commensurabilities of orbital motion, Earth rotation, and typical data arc lengths, a further section specifically addresses the occurrence of artificial periodic signals in the geodetic parameter series derived from GNSS observations. The potential impact of mismodelled tides, aliasing of sub-daily signal, resonances and long-term draconitic variations is discussed in detail, thus underlining the specific challenges of the authors' research.

In his third chapter, R. Zajdel provides a dedicated validation of orbit and Earth orientation products produced for his thesis. It complements the results presented in his five research papers and provides valuable background information for assessing and understanding the quality of those results. In particular the chapter assesses the impact of different radiation pressure models and empirical orbit parameterizations on orbit quality and estimated Earth orientation parameters. In general, the combination of a physics-based a priori model of solar radiation pressure in combination with a limited set of empirical parameters is identified as the most suitable approach for GNSS orbit modeling. Special attention is also given to satellite laser ranging as a completely independent technique for assessing the quality of GNSS orbit determination results.

The thesis report concludes with a synthesis of the five research papers and a summary and outlook chapter. A comprehensive bibliography reflects that the author is fully familiar with the state of the art in GNSS data processing and geodetic time series estimation, can put his work into context and gives proper credit to past and present work in the field.

Overall, the individual thesis chapter demonstrate the author's capability to discuss scientific problems and solutions in a clear and transparent manner. The text is logically structured and written in fluent language. The selected material and depth of the presentation is well chosen and enables readers to properly understand the background, study approach and achieved results. Throughout his report, Mr. Zajdel provides a clear line of arguments, puts his work into context of past and current research, and is able to provide convincing solutions to the research questions. The report demonstrates a great level of thoroughness in the conducted investigations, a profound background knowledge and substantial expertise in the field. Throughout all chapters, sophisticated, creative and professionally designed artwork is used to graphically illustrate key findings and to support explanations given in the text.

The journal publications included in the thesis have all undergone a thorough per review process, which may itself be taken as an independent evidence for high-quality and innovative research work presented by the author. The five articles may largely be divided into two groups. While papers 1, 2, and 5 address the determination of geocenter motion from GNSS and other space-geodetic techniques, papers 3 and 4 related to the GNSS-based determination of Earth rotation parameters. In the following summaries, I prefer to discuss the papers in topical order rather than the numerical order related to the times of publication.

Publication #2 covers the estimation of geocenter motion from satellite laser ranging (SLR) measurements of the LAGEOS satellites. It distinguishes itself from the other four articles by dealing with optical rather than radiometric observations and by processing observations from non-GNSS satellites. While this may, at first sight appear to be outside the main scope of the thesis, it is well justified in a wider context. In particular, the work provides a long time series of reliable geocenter coordinates from an independent source, which constitutes an important and independent reference for the assessment of GNSS-based geocenter estimates. The study provides a comprehensive investigation of SLR-based Earth orientation parameter estimates over an 8-year period. In particular, the impact of different station selection strategies is investigated and the relevance of network homogeneity and station quality is assessed. Furthermore, different approaches for constraining the station coordinates are investigated and discussed in great detail. Practical recommendations for choosing suitable SLR stations and for data screening are derived, which contribute to improved stability of the geodetic time series. Furthermore, the study highlights the need for ensuring a continued availability of high-grade SLR stations in all hemispheres, and the detrimental impact of losing even one or a few stations is evidenced.

In publication #1, R. Zajdel examines, how to properly handle the difference between the Earth's center-of-mass (relative to which the motion of satellites is referred) and the center of network (relative to which the observing stations are referred) in the processing of multi-GNSS observations. GNSS-based estimates of geocenter coordinates are found to agree better with SLR-based estimates when considering a large but inhomogeneous GNSS network with a higher density of IGS GNSS stations in Europe as compared to a smaller but more homogeneous network. This finding hints at similar network effects in SLR-based GCCs, since the present ILRS network also exhibits a notable imbalance in the geographical station distribution. For best repeatability of station coordinates a no-net-translation (NNT) constraint needs to be applied in the GNSS processing to avoid contamination of coordinate time series by geocenter motion. Consideration of GCC information from a priori models or other techniques does not help to improve the stability of station time series in the absence of an NNT constraint due to systematic differences in the technique-specific GSS estimated. Considering individual GNSS, the study confirms that all GNSS can, in principal, contribute GCC estimates, even though the formal errors are larger for constellations with three orbital planes (GLONASS, Galileo) than for GPS with its six-plane configuration. Despite a lower number of contributing satellites in the one-year analysis period, Galileo-only GCC estimates show a notable reduction in formal errors and mean offset from SLR than GLONASS-only solutions. Slightly lower Sun-elevations above the orbital planes and thus reduced correlations with empirical radiation pressure parameters as well as the beneficial contribution of two satellites in non-nominal planes are mentioned as potential explanations for the improved Galileo results. It would have been interesting, though, to also address and investigate the impact that ambiguity resolution has on the better performance of Galileo compared to GLONASS. Nevertheless, the study is thoroughly made and marks an important contribution to the understanding of GNSS-based GCC estimates and the benefit of multi-GNSS versus GPS only solutions.

Publication #5 further elaborates on multi-GNSS GCC determination with specific focus on the impact of different approaches to solar radiation pressure modeling. Previous studies in the field have already shown that a priori models for solar radiation pressure (SRP) can notably reduce the presence of spurious harmonic in geodetic time series for GPS and GLONASS. In the present work, a unified analysis of GCCs from up to three GNSSs is provided over a three-year period, which, for the first time, includes an essentially fully populated Galileo constellation. Due to the stretched body shape of the Galileo satellites and their unfavorable area-to-mass ratio, second-order harmonics of the orbit angle need to be considered in purely empirical SRP models for proper Galileo orbit modeling. Estimation of these parameters gives rise to notable correlations with the GCC z-component when simultaneously adjusting geocenter coordinates. In accord with earlier research, these correlations, and thus the formal errors are highest when two of the three orbital planes exhibit the same Sun-aspect angle. Use of an a priori box-wing model based on meta data published by the Galileo system provider allows for a reduced set of only five empirical SRP parameters and provides notably more stable GCC estimates. Obviously, however, the a priori models available for the three GNSSs are still insufficient to obtain fully constant GCC solutions with the SLR technique. While Zajdel's work itself does not contribute to actual improvements of such models, it presently provides the most comprehensive and transparent investigation of multi-GNSS GCC estimation considering the available a priori models and the parameterizations of empirical SRP contributions.

The impact of multi-constellation processing on GNSS-based estimation of pole coordinates and length-of day (LOD) is investigated in great detail in publication #3. Following a review of Earth orientation parameters estimates obtained by various analysis centers with thin the IGS multi-GNSS project, R-Zajdel presents the results of a 3-year processing of GPS, GLONASS, and Galileo observations. Similar to the GCC estimation discussed above, the single-constellation solutions are affected by spurious harmonics and the dependency of these artifacts on the employed SRP modeling strategy is examined for Galileo. Single-system Galileo solutions are found to perform better when using an a priori box-wing model and estimating a lower number of empirical parameters than in a purely empirical SRP parameterization. Still GPS, which uses six orbital planes is less susceptible to orbit modeling errors and achieves the best single-constellation ERP estimates. Further improvements can be achieved by combining all three constellations when using 1-day arcs, whereas, GPS-only and multi-GNSS solutions achieve an almost similar performance in comparison to the IERS-C04 reference. This comparison is possibly biased, though, by the strong contribution of GPS-based ERP estimates to the IERS multi-technique product.

Publication #4, finally addresses the problem of determining sub-daily polar motion from GNSS observations. Compared to other space geodesy techniques, GNSS offers a high temporal resolution and global coverage, which makes it a particularly promising technique for monitoring of such contributions. So far, however, analyses have focused in GPS only solutions which suffers from the near-commensurability of Earth rotation period and the orbital period. Likewise, the additional use of GLONASS has shown to be of limited benefit due to the lower number of orbital planes that may cause pronounced correlations with other estimation parameters and makes the solution sensitive to orbit modeling deficiencies. Even though Galileo suffers, in principle from a similar issue, the availability of a physical a priori model for the solar radiation pressure is again found to offer notable improvements over purely empirical SRP models. Im fact, the formal errors of the corresponding Galileo-only solutions of sub-daily polar motion approach those of GPS-only solutions, and allow for even further improvement in a true-multi-GNSS combination. The multi-GNSS solution also shows the best agreement with a reference time series based on daily IERS-C04 pole coordinates and sub-daily pole coordinate variations with tidal contributions and libration based on the IERS2010 model. For further analysis, the GNSS-based solutions derived by Zajdel are also compared against different external models of sub-daily pole coordinate variations derived from non-GNSS techniques. Indeed, the multi-GNSS solution shows improved consistency with the new Desai-Sibois model for selected tidal contributions than with the current IERS2010 model. A good consistency with VLBI based Gipson model, furthermore, hints at deficiencies in the libration terms of the other models.

Overall, all five publications constitute thorough and in-depth investigations of current research questions. They present important research results and valuable contributions to the body of knowledge. In particular, they pave the way for a consistent integration of the new Galileo constellation into GNSS derived geodetic products, which helps to mitigate known limitations due to the commensurability of Earth rotation and orbital periods in GPS-only products.

Specific questions, which I would request the candidate to answer in his oral defense, are listed here:

- In his thesis report, the authors repeatedly emphasizes the role of metadata (particularly phase center and patterns of the transmit antennas as well as surface parameters for radiation pressure models) for the high-quality contributions that Galileo can make to geodetic parameter estimation. What makes him confident that these parameters can actually be trusted and provide superior orbit and modeling measurement capabilities than empirically adjusted model parameters? While the Galileo has for sure published the most comprehensive set of metadata of all GNSSs, selected metadata are also available for GPS (e.g. antenna calibrations and radiation pressure models for GPS IIR satellites or BeiDou-2/3 antenna offsets) but have not shown obvious benefits compared to models adjusted from observations.
- The comparison of constellations in Sect. 3.3. of the thesis also highlights the superior clock quality of Galileo as a distinguishing factor. What is the relevance of this feature for the present work? How might stable clocks help to improve orbit determination and GNSS-based estimation of geodetic time series?
- Currently, GPS and Galileo are basically treated as independent constellations observed by a common set of monitoring stations. Given the availability of interoperable signals on the L1/E1 and L5/E5a frequencies, what would be necessary to treat GPS and Galileo as a single constellation with nine orbital planes and what benefit could be expected from such a processing?
- All GNSSs available today are radio navigation systems, which are inherently limited by the use of similar L-band radio signals and suffer from similar errors in their measurements (noise, multipath, etc.). Can the use of multiple GNSSs actually provide the substantial improvement in reference frame access desired by GGOS or would it need a fundamental change of technology to realize such improvements? Which technologies could you imagine?
- To what extent can GNSS be used for independent determination of a technique-specific terrestrial reference frame scale, and which specific contribution can the new constellations Galileo and BeiDou-3 make?

In my view, the doctoral dissertation clearly constitutes an original solution of complex scientific problem and shows general theoretical knowledge as well as the ability to independently conduct scientific work. It thus fulfils the requirements for a doctoral degree in particular under Article 13 of the Act of March 14, 2003 Ustawa o stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki (Dz.U. 2003 Nr 65 poz. 595 z późn. zm.).

Overall, I consider Radozław Zajdel a gifted researcher who has made important contributions already at an early stage of his research. His skills and expertise are likewise demonstrated in his thesis report and a remarkable number of journal and conference publications. Public recognition of his work is evidenced by various citation indices, which well exceed those of other researches at early stages of their career, as well as multiple awards and scholarships. As a member or coordinator of various IAG and ILRS working group, he ensures close interaction and lively exchange of ideas with the scientific community

Given the outstanding quality of Mr. Zajdel's work, I therefore recommend that the candidate should receive the PhD degree with honors.

Yours sincerely,

Oliver Montenbruck

Priv. Doz. Dr. rer. nat habil. Oliver Montenbruck