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Assessment report on the Doctoral Dissertation

Determination of Global Geodetic Parameters Using the GPS, GLONASS, and Galileo Satellite Systems

Submitted by Radoslaw Zajdel

The doctoral thesis is written in English with an Abstract in English and Polish. It contains five chapters and in Annex A five peer-reviewed scientific papers with Mr. Zajdel as main author, published between 2019 and 2021 in highly recognized international journals. Further contents are a Bibliography and Annex B with a curriculum vitae and a formal declaration of the author.

The doctoral thesis deals with the very complex and comprehensive field of determining the various geodetic parameters of Global Navigation Satellite Systems (GNSS) that have been developed, brought in full operation, and continuously improved during the last three decades. It is a very good thesis in general, discussing several critical issues in global geodetic parameters, such as geocenter coordinates, the terrestrial reference frames, and satellite orbits in the multi-GNSS era, especially the contribution of the Galileo system which plays a significant role in the work of Mr. Zajdel.

Throughout his dissertation Radoslaw Zajdel covers a broad range of aspects of GNSS applications and treats also the other space geodetic techniques, such as SLR, VLBI, and DORIS. In the first introductory part of the thesis, i.e. within the first two chapters, the author provides the basics of the methodology how to process GNSS data, whereas chapter 3 contains a first validation of this methodology.

In the second part of the thesis (Annex A) the candidate covers several special topics concerning the determination of geodetic parameters that are treated in terms of theory as well as in terms of numerical modelling and parameter estimation. All five papers have been published in internationally widely recognized scientific journals that prove the candidate's scientific excellence. The required

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originality of the scientific approach is plausibly documented within these publications. The fact that all included papers were written by the candidate as first author supports the assumption that the major research work of the dissertation was conducted in adequate independence, but in fruitful cooperation with his supervisors, colleagues, and international partners. The other peer-reviewed publications to which Radoslaw Zajdel contributed as a main author or co-author demonstrates the ability for national and international collaboration and for applying his expertise also to other scientific problems beyond his primary subject.

The international scientific activity of the candidate is further accented by memberships in scientific committees and working groups of international associations and services (e.g. IAG and ILRS) and numerous participations, including poster or oral presentations, in international conferences. The rapporteur can confirm that Mr. Zajdel – in spite of his relatively young age – is already recognized by GNSS experts worldwide. The CV of Radoslaw Zajdel gives a very extensive list of his work experience and scientific research projects to which he contributed, and the ability to carry out excellent research can be undoubtedly attested to the candidate.

Here are a few more detailed questions and comments; some of them should be considered for the final version of the thesis after revision.

1. Page 8, table 1.2. This table is kind of misleading. We should distinguish between what the technique can provide and what is currently used to generate the product (e.g., IERS EOP).
    - For LOD, VLBI can certainly provide good estimates, so it should be a full circle, not half a circle.
    - The DORIS might not provide very good tropospheric delay due to the weak geometry, but it is still able to give good ionosphere information from the globally distributed stations (~60).
    - VLBI provides reliable long-term troposphere information thanks to the stable radio telescope performance in decades, which cannot be given by any other technique. Satellite altimetry also provides good troposphere products in the open-ocean region with global coverage.
    - Page 8, 6th line. GNSS does provide precise short-term LOD estimates, but SLR LOD is not that good, as also shown in this thesis (page 131, table 9). VLBI can provide continuous UT1-UTC from the daily intensive sessions.
    - How to explain the contributions of different techniques in the “sea level” column? More information should be given.
    - Nevertheless, this table needs more explanations.
2. In section 1.1, it is worth to also (at least briefly) describe BDS after Galileo, even though BDS is not the focus of this thesis.
    - What are the potential benefits/problems of the BDS constellation, a combination of GEO+IGSO+MEO? Currently we have more than 30 BDS satellites available.
    - How about the capability of the Bernese software in processing BDS?
3. In section 2.2.2 the author gives the basic theory of least-squares adjustment. As the 3-day arc solution is used in this thesis, it is also worth mentioning the theory for the normal equation stacking with different initial values, which is not the same as the equations in sequential least-squares adjustment on page 22.
4. Page 37, Figure 2.8.
    - How to explain the geocenter coordinate GCC-Z from the MIT product? It shows less scatter than other ACs and smaller (semi-)annual signals.

- What are the process strategy changes of COD and GFZ in 2015?

5. Page 40-41. Always remember the long-term bias whenever talking about the satellite techniques in deriving LOD.
6. Page 67. This is a very good and detailed table.
   - For the orbit quality, it is worth mentioning that for GLONASS the FDMA makes it difficult to fix ambiguities, resulting in the bad orbit quality.
   - For the future GPS-III, will the SLR-GNSS space tie be available?
7. Page 100, 4th paragraph. In the over-constrained solution "SOL-I", the GCC is not estimated but the NNT is applied. The author mentioned "however the satellite clocks are not estimated in this processing.", what does this mean? Are the clocks fixed to some value? It would be interesting to have a look at the parameters that absorb GCC.
8. Page 106, table 4. SOL-NG has the "worst" coordinate repeatability, which is obviously caused by ignoring GCC, as GCC goes to the common part of all station coordinates. This does not mean the solution is "bad". If we do the Helmert transformation and check the residuals, then the repeatability will be ok.
9. Page 129, table 8. How to explain the -80/120 µs/day MEAN/STD values of SLR LOD? Especially the negative systematic bias? Later on page 130, 2nd paragraph, the author mentioned "Because of the PWL parameterization and rigid constraining for the middle UT1-UTC value, there are almost no differences between the particular solutions in the case of the LoD estimates." If only one epoch of the UT1-UTC PWL function is fixed, that does not influence the LOD estimates and cannot explain the similar values of different solutions. My assumption is that LOD is not sensitive to the network distribution, or at least not as sensitive as polar motion, as LOD reveals more about the network east-west distribution.
10. Page 130, 1st paragraph of 3.4. The author mentioned "The SLRF2014 scale is consistent with the ITRF2014 scale which is based on the combination of long-term SLR and VLBI solutions." This statement might not be very accurate. The scale discrepancy between ITRF2014 and SLR/VLBI-only scales is well-known.
11. For the A2 paper, it is interesting to see the network effect in SLR solutions. However, it should be noticed that the SLR solutions with only LAGEOS satellites are not good enough to determine ERP, especially polar motion, which really needs a good station distribution. To investigate the SLR contribution to determining ERP, utilizing the observations to GNSS/LEO satellites will be more beneficial.
12. Page 145. The improved polar motion rate precision in the 3-day solution derives not only from the longer orbit arc. The between-day continuity constraint on polar motion improves the rate precision more. This should be emphasized.
13. Page 146, Figure 7. It seems that for Galileo, the 3-day solution has larger LOD drift than the 1-day solution, e.g., the yellow "GAB" solution. For other systems, the 3-day solution usually shows smaller drift than the 1-day solution. How to explain this?
14. Page 146-147. The accumulated LOD results of the Galileo solution in Figure 8 show that Galileo has the smallest drift, but the amplitude spectra figure (Figure 9) also shows that Galileo has larger amplitude than GPS/GLONASS. How to interpret this result?

15. It is quite interesting to see the investigation on sub-daily ERP derived from multi-GNSS in paper A.4 where the author addresses several aspects. One question is about the constraint applied on the piece-wise-linear (PWL) function which is used to model sub-daily ERP. Is there any constraint applied or not? If yes, what are the numbers? This will have a critical impact on the sub-daily ERP estimates.

16. One minor correction on page 4, section 1.1.2, 5th line of 2nd paragraph, "which allow an for independent orbit validation …", should be "which allow for an independent orbit validation …".

17. In the paper "*Impact of network constraining on the terrestrial reference frame realization based on SLR observations to LAGEOS*", it is generally acknowledged that the observation number might vary significantly between different stations. Are the non-core stations that are eligible for datum constraints always have enough observations? In other words, what about the long-term observing and technical performances of these stations? (listed in the second paragraph of the section "4 Conclusions", page 132)

18. Regarding the multi-GNSS sub-daily ERP determination in the paper "*Sub-daily polar motion from GPS, GLONASS, and Galileo*", the 1-day and 3-day arcs are investigated. How about using longer arcs? For instance, to stack weekly (or even monthly) normal equations, will the sub-daily estimated parameters get more stable?

19. In the multi-GNSS sub-daily ERP paper, the empirical sub-daily model is derived using the 2-h sampled estimates. Can this empirical model be further applied, e.g., in the GNSS POD solution? Can we expect any improvement of the orbit quality?

20. The investigation of solar radiation pressure (SRP) modeling on multi-GNSS GCC estimates, e.g., paper "*Geocenter coordinates derived from multi-GNSS: a look into the role of solar radiation pressure modeling*", leaves open whether the SRP modeling strategy in the eclipse season will have an impact on the GCC estimates. Currently the SRP modeling in the eclipse season is not perfect, so probably this is worth to be investigated.

21. One of the major focusses of this thesis is the contribution of the Galileo constellation. The Galileo satellites are equipped with super stable satellite clocks; thus, the clock modeling is available in the POD solution. Can we expect any improvements in GCC and sub-daily ERP estimates from clock modeling? For instance, if we assume a linear clock in the 24-hour arc, the sub-daily signals will be forced into the satellite orbit and/or sub-daily ERP. This might (1) improve the solution by better separating different signals, or (2) degrade the solution by forcing the "real" clock signals into orbit.

22. The current multi-GNSS processing assumes identical parameters for station coordinates, receiver clocks, and tropospheric delays between different systems. However, due to the different signal frequencies, there might be systematic discrepancies. The receiver antenna phase center offset and variation (PCO and PCV) also do not distinguish between different systems, which will lead to further systematic effects. What are potential solutions to handle these issues?

23. In the data processing part, i.e., table 2.1 on page 17, higher-order ionospheric delay corrections are applied. The CODE's global ionosphere map (GIM) model is used for the total electron content (TEC) calculation. Which model is used to describe the geomagnetic field? Maybe the international geomagnetic field (IGRF)?

24. Further on table 2.1, page 17. The description of the inter-system biases is rather ambiguous. In the "Intersystem translations" item it is explained as: "Station-specific Galileo-GPS intersystem translation parameters for receiver antenna vector and troposphere bias (Schaer and Dach, 2010)"

where the reference goes to "*Schaer, S. & Dach, R., Biases in GNSS analysis. In: IGS Workshop. Newcastle upon Tyne, United Kingdom, 2010*."

- I am actually confused, because the reference talk (http://www.acc.igs.org/biases/signal-biases_igsws10.pdf) only addresses differential code bias (DCB), inter-system bias (ISB), and inter-frequency bias (IFB), so only frequency-related biases. I cannot find anything related to the "receiver antenna vector" or "troposphere bias".
- It is also not very common to use this kind of "translation parameters for receiver antenna vector", because in this way we are applying the network transformation between the two systems. But in all the analyses of the thesis it is very clear that both systems use the same ERP/GCC.
- The "intersystem translation parameters for … and troposphere bias" is also not commonly adopted in multi-GNSS processing because if we apply the troposphere bias (e.g., one ZTD bias per station per day), we are weakening the solution by over-parameterization.
- We actually only consider the ISB/IFB, estimated as either daily constant or time-varying function (piece-wise-linear, or epoch-wise white noise).
- Nevertheless, the inter-system biases and differences are critical in multi-GNSS processing and should be better explained.

Overall assessment

There is no doubt that the candidate provided an original solution of a scientific problem and acquired deep but also broad knowledge in the topic of the thesis. The layout of the dissertation looks quite perfect, the bibliography is rather complete, the methods used in the analysis are well described. The discussion of the results and potential applications of the obtained results are sound and solid. Thus, the final conclusion for evaluation of the thesis is:

Positive (sufficient) with honors (outstanding)

The reviewer suggests to provide the grade "*with honors*" as the thesis goes far beyond a normal PhD thesis in this particular field, the five papers have been published in top international journals, and the candidate has proven his scientific excellence in numerous conference participations and successful international collaborations.

Final recommendation

In my opinion, the doctoral dissertation 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.).

Yours sincerely,

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