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External Review Report on Doctoral Thesis of Mr Dariusz Strugarek: "Satellite Laser Ranging to Low Earth Orbiters for Orbit Validation and Determination of Global Geodetic Parameters"

1. Scientific Achievement

Mr Strugarek's PhD study focuses on precise analysis of SLR observations to LEO satellites. In comparison to spatially homogeneous onboard GNSS tracking data, SLR observations from ground laser stations all over the world are more complicated with station-specific issues especially when sub-cm accuracy is required. He has carefully looked into a variety of possible error sources.

Whereas SLR observations of active LEO satellites have often been used only as external validation of microwave-based orbits, his attempts to use them for improving the quality of geodetic products should be highly rated.

Mr Strugarek has published as many as five first-author papers in four years, including the GPS Solutions one (Paper A.5) which was notified later as accepted. Such high productivity at such an early stage of his career is truly remarkable, and I look forward to further achievement in his promising career.

2. Comments and questions

Mr Strugarek's studies have focused on a challenging and important issue – maximizing the use of LEO-SLR data. As he pointed out, only a limited number of spherical satellites have been used for geodetic purposes in the international mainstream projects, and the usefulness of SLR data to LEO satellites had not been fully investigated. It's good to learn that as much as 76 percents of SLR observations are for active LEOs. I sincerely hope that his studies (combined with his future studies) will have a positive impact on the analysis and observing strategies of the SLR community.

Here are the key questions that I would like to discuss with Mr Strugarek. Each of the published papers has already been peer-reviewed, and therefore I try to ask comprehensive questions throughout his works. Some of them are beyond the scope of the papers and also the thesis, but will be beneficial for global geodesy.

- It is not clear how the LEO LRA corrections (Fig 2.8 and Fig 2 of Paper A.2) were calculated. Montenbruck and Neubert (2011) presented two typical cases: a nearest case (~multi-photon, leading-edge detection) and a multi-prism case (~single photon) - which was chosen in each of his studies? A multi-photon pattern or a single photon pattern should be applied according to the operation policy of each SLR station. Also, were these angular-dependent collections actually applied to all of the LEO-SLR analyses (stated so in Paper A.2 but how about others)?
- I understand what can be gained from orbit-fixed solutions of LEO-SLR data. On the other hand, they are heavily dependent on the microwave-based LEO orbits, the microwave-based GNSS orbits and also the microwave-based GNSS station coordinates. I am wondering which of the findings can be real additional input to the geodetic products, from a viewpoint of external users who do not care about each geodetic technique.
- The quality of LEO orbits was investigated through beta-angle dependence and spectral analysis of geodetic products. These methods have been indeed useful for GNSS satellites, but are these checks sufficient to detect possible errors of dynamically complicated LEO orbits?
- In some of his papers (e.g. A.1), remaining systematic O-C trends are attributed to station time bias. Time bias is not separable from the along-track offset error of satellite orbits. In a healthy SLR station, the time tag should be much better than 1 microsecond where anomalies are sometimes reported. I am skeptical about the result from a single satellite (or a single series of satellites). A consistent, satellite-independent time bias should be provided, or it should be matched with ILRS Data Handling File.
  - https://ilrs.gsfc.nasa.gov/docs/2020/ILRS_Data_Handling_File_200427_ANNOTATED.snx.pdf
- Will it be possible to extend the series of his studies toward more comprehensive projects such as:
  - Find the best mix of SLR satellites for various geodetic products. Sosnica et al. (J Geod, 2014) presented the usefulness of Starlette, Stella and Ajisai for TRF, and I am keen to learn what can be achieved by the combination with Paper A.4, for instance.

- Evaluate the different types of LEO-onboard GNSS antennas/receivers. The differences between kinematic solutions and reduced-dynamic solutions were mainly discussed, but I am wondering any instrument-specific trend or behaviour can be found by combining the LEO-SLR studies.

- Will future SLR stations need a LAGEOS- and GNSS-tracking capability? Without it, much more SLR stations and a denser tracking network are envisaged because an SLR station can be much smaller, much cheaper, and possibly easy to operate especially if it can be an eye-safe system with a low energy laser.

3. Recommendation

The thesis is nicely structured and written in good English. There is no question about Mr Strugarek's high skills in precise data analysis, and his cutting-edge scientific achievements are more than equal to the level of the international researchers in today's competitive geodetic community.

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.).

I recommend Mr Strugarek should receive the PhD degree with great honours.

Best regards,

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