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Review of the doctoral dissertation

"Troposphere delay modeling in satellite laser ranging measurements to geodetic satellites"

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1. Formal and legal basis

The legal basis for conducting the doctoral procedure is Art. 14 sec. 2 of the Act of March 14, 2003 on academic degrees and scientific title as well as degrees and title in the field of art (consolidated text, Journal of Laws of 2017, item 1789). The formal basis for the review is the resolution of the Discipline Council of Civil Engineering and Transport of the University of Life Sciences in Wrocław (Uchwała Rady Dyscypliny Inżynieria Lądowa i Transport Uniwersytetu Przyrodniczego we Wrocławiu) of March 31, 2022.

2. General characteristics of the dissertation

The doctoral dissertation presented for review is an attempt to solve a very important, if not the most important problem for the Satellite Laser Ranging (SLR) technique, to improve the quality of observations. For over 20 years, the quality of SLR observations has not significantly improved, despite the introduction of many new technical improvements. All indications are that the main problem is the tropospheric delay, which in its current form is not accurate enough (the delay uncertainty is several mm). The best solution to this problem is to introduce two-color observations. Work in this direction was carried out at the end of the last century. Two-color observations would reduce the tropospheric delay error by 2-fold (Degnan, J. "Millimeter Accuracy Satellite Laser Ranging: A Review." Contrib. Space Geod. Technol. Geodyn. 1993, 25, 133–162). Unfortunately, it has not been possible to build a detector (Streak camera) so far, which would allow to obtain the distance between photons of two colors with sufficient sensitivity and accuracy for satellite observations. Attempts of two-color observations by laser stations at Zimmerwald (7810) and Concepcion (7405) (423 nm and 846 nm) failed to obtain satisfactory results due to the need to use two detectors for each color instead of one. Similar tests were recently carried out by the Wettzell station (8834) for 532 nm and 1064 nm.

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In the doctoral dissertation presented for review, to improve the tropospheric delay in SLR observations, the method of determining horizontal gradients was used for the first time in the literature, rightly assuming that the state of the atmosphere around the laser station is not symmetrical, as assumed by the currently used models, but depends on the azimuth. Such an assumption may significantly improve the distribution of tropospheric parameters around the station, and thus improve the quality of the results obtained by SLR. This method has been widely used with satisfactory results in Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI) techniques. A positive result of the dissertation would enable a significant improvement in the quality of the SLR observations, which is the key to the further various use of the results of this technique.

The main part of the dissertation are three thematically related articles, published in 2018-2021 in highly rated scientific journals distinguished in Journal Citation Reports (two for 140 points and one 100 points in the rating of MEiN), totaling 42 pages, containing 122 references. In all the papers, the PhD student is the first Author, according to the attached statements of the co-authors, he is also the Author with the majority share in all the papers. The work is preceded by preface and the abstracts in Polish and English, as well as a 46-page introduction to the topic, containing additionally 27 references, not included in publications.

The dissertation introduction in the first chapter provides some basic definitions about the International Laser Ranging Service (ILRS), research motivations and objectives. Chapter 2 deals with the applied research methods and data processing scheme, including the International Terrestrial Reference System (ITRS) and its realization, Earth orientation parameters (EOP), satellite orbits, perturbations in the satellite motion, including the Earth's gravity field and the geocenter motion. The next section briefly describes the parameters estimation using the least squares adjustment method and normal equations. The following parts contain a short description used in this work the Bernese orbital software (version 5.3) for SLR data, refractivity index for optical wavelengths, the concept of a mapping function and a bit more about modeling of tropospheric horizontal gradients and estimation of tropospheric delay from SLR observations. Mapping functions, very important for understanding the work, are also presented: Potsdam Mapping Function (PMF), Vienna Mapping Function (VMF30), ERA 5 model, and parametric model of horizontal gradients and its validation. The last subsection contains the estimation of tropospheric delay corrections from SLR observations, impact of the artificial 5 hPa pressure bias, and the impact of the Zenith Total Delay and range bias corrections on the determination of low-degree spherical harmonics of the Earth's gravity field. Most of these descriptions are presented in more detail in the three articles attached to the dissertation that constitute the basis of the doctoral dissertation. The third chapter of the introduction contains a brief description of these three basic publications in the form of introduction, summary and conclusions. Part of the introduction ends with conclusions and outlook for further use of the results of the work so far. All parts of the introduction are very important for better understanding attached articles. However, some subsections are too short and do not contain enough information.

In the main part of the work in the first article *(Drożdżewski M., Sośnica K. (2018). Satellite laser ranging as a tool for the recovery of tropospheric gradients. Atmospheric Research, 212, pp. 33-42, DOI: 10.1016 / j.atmosres .2018.04.028)* the authors present for the first time in the literature, the possibility of determining horizontal gradients of the tropospheric delay from SLR observations for the LAGEOS-1 and LAGEOS-2 satellites by using the method commonly used in GNSS and VLBI techniques. The idea of such solution, despite the very low data density for SLR, turned out to be effective. Determination of two parameters describing the northern (G_N) and eastern (G_E) components of the horizontal gradients of the tropospheric delay from the observation results allows for the determination of asymmetry in the tropospheric delay. The results were compared with the GNSS results for the co-located points from the SLR and the Numerical Weather Models (NWM). Good agreement of mean horizontal tropospheric gradients with GNSS (47%), with the hydrostatic part of horizontal gradients from the NWM (74%), and with the total part of horizontal gradients (54%) from the NWM was demonstrated. The distribution of deviations was analyzed, which for selected stations clearly shows the dependence on the azimuth. A much wider analysis based on the results of all stations operating in the period of 14 years 2002-2015 shows an improvement in the standard deviation for all 47 SLR stations after introduction of the assessment of horizontal gradients in the tropospheric correction. For nine core stations, the results of G_N and G_E signal amplitudes for GNSS and SLR were compared with the Vienna project GGOS Atmosphere model implemented since 2006 for the needs of GNSS stations, divided into hydrostatic part and total part. The results show a good agreement for all four solutions. The presented article also includes an assessment of the amplitudes and phase of horizontal gradients for selected stations and for four solutions depending on the station's location on the Earth's surface. The conducted analyzes indicate the possibility of determining horizontal gradients in the tropospheric delay from the results of SLR observations. All these activities show that the Author is well prepared to conduct scientific analyzes and draw correct conclusions.

Second article *(Drożdżewski M., Sośnica K., Zus F., Balidakis K. (2019). Troposphere delay modeling with horizontal gradients for satellite laser ranging. Journal of Geodesy, 93, pp. 1853-1866, DOI: 0.1007 / s00190 -019-01287-1)* further extends the previous work, mainly by comparing the results with the Potsdam Mapping Function model (PMF). This model based on the NWM is specially made by the team in Potsdam for all laser stations in the optical range. It was tested for the LAGEOS-1 and LAGEOS-2 satellites for 49 SLR stations operating in the period of 11 years 2007.0 - 2018.0. The presented in the paper tests were carried out for 11 core stations for three ranges; PMF, PMF with the first order of horizontal gradients, PMF with the first and second order of horizontal gradients. The tests included a comparison with the currently used Function Commonly Used for Laser Ranging model (FCULa) for the following parameters: standard deviations, station coordinates, Earth rotation parameters (pole coordinates and length-of-day (LOD)), geocenter coordinates. Tests were also carried out for the annual observations (2017) of the Sentinel-3A satellite, as an example for low satellites for which the number of measurements at low altitudes is much greater than for LAGEOS.

All tests showed a significant improvement in the results after the use of PMF models, the best results compared to the standard FCULa model were obtained for PMF with the first order of horizontal gradients. A significant improvement in the compliance of the pole coordinates determined from SLR with the determinations by the GNSS and VLBI techniques was also found. In general, the proposed method of determining tropospheric delay from the horizontal gradients provides much better results of SLR observations and should be widely used in the future. The development and verification of the presented method of determining tropospheric delays using PMF models is an important contribution of the Author in the effort to improve the quality of the SLR observations.

Finally, the third article *(Drożdżewski M., Sośnica K. (2021). Tropospheric and range biases in Satellite Laser Ranging. Journal of Geodesy, 95 pp. 16, DOI: 10.1007 / s00190-021-01554-0)* contains tests with artificially introduced pressure bias of 5 hPa for each observation of all stations, to show the effects of changing the results for three systematic parameters: range bias, tropospheric correction and vertical component of the station coordinates, and for a combination of these parameters. The tests were carried out for the observations of the LAGEOS-1 and LAGEOS-2 satellites made in the period of 9 years 2010.0 - 2019.0 using 7-day arcs. The results showed that only solutions with the evaluation of tropospheric corrections can deal with shifts in barometers at SLR stations and provide adequate estimation of station height. The paper also presents the relationship between systematic errors caused by range bias, tropospheric correction and station height error, and the impact of these errors on the repeatability of the station coordinates, the geocenter motion and the scale of the Earth's reference system. Determining the tropospheric correction ensures better stability of station coordinates and greater absorption of systematic errors of stations, it also shifts the scale and coordinates of the geocenter and low spherical harmonics of the Earth's gravity field.

Summarizing, the first article showed the possibility of determining the horizontal gradients of the tropospheric delay from SLR observations and their usefulness in improving the quality of the SLR technique, the second article introduces the Potsdam Mapping Function (PMF) of tropospheric delay and demonstrates the benefits in the quality of the results for; SLR deviations, station coordinates, geocenter coordinates and Earth rotation parameters, also demonstrated the benefits of using this model for the development of the results of the low Sentinel-3A satellite, the third article assessed systematic errors of stations in the form of constant range bias and elevation dependent tropospheric correction and their influence on the height, scale, geocenter coordinates and the second-degree gravity coefficients. Therefore, all three articles constitute a mutually complementary whole and respond positively to the dissertation's thesis.

3. Basic aims and thesis of the dissertation

The tropospheric correction is the main source of the errors in the SLR observations. The aim of the dissertation is to improve the tropospheric correction in SLR by introducing new models based on the asymmetric distribution of the atmosphere around the laser station and taking into account the influence of the tropospheric correction on the station's systematic errors.

The basic thesis of the dissertation is presented at the beginning of the introduction in the form:

"develop a method of the troposphere delay modeling for the SLR technique; investigate the impact of new troposphere delay models on geodetic parameters derived from SLR, such as station coordinates, geocenter coordinates, Earth rotation parameters, and gravity field coefficients; as well as account for elevation-dependent systematic errors in SLR observations."

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The thesis of the dissertation is clearly formulated, including methods of introducing new models to the results of SLR observations that ensure taking into account the asymmetry of the atmosphere around the SLR stations, verification of these models by determining geodetic parameters from SLR observations and introducing systematic error relationships such as range bias, tropospheric correction and the vertical component of the station coordinates.

The subject of the work is very important for the further development of the SLR technique. The introduction of the proposed solutions should ensure a significant increase in the accuracy of measurements and their better use for determining geodetic parameters and creating the terrestrial reference frame.

4. Substantive assessment

I consider the subject of the doctoral dissertation to be topical and very important for further improvement of the quality of the SLR observation results and obtaining better compliance of the determined parameters with the results of other techniques, such as GNSS and VLBI. The introduction of tropospheric delay taking into account horizontal gradients made it possible to more accurately determine the parameters determined by the SLR, primarily the coordinates of the stations. The applied methods of determining these corrections from SLR observations or from models based on numerical weather models (NWM) allowed to obtain the results at the appropriate level. The Author used an innovative approach to solving the dissertation's thesis. The topics presented should be further developed and implemented by the ILRS for general use by orbital analysis centers. Breaking down the aim of the work into several tasks carried out separately is a good solution, it provides answers to the presented thesis in a more detailed form. The work was written, except for some fragments, in a clear and understandable way. The dissertation thesis was proved by a detailed comparison of the results of determining geodetic parameters. This allowed to demonstrate that the introduction of the tropospheric delay using horizontal gradients significantly improves the parameters determined from the SLR observations, and the tropospheric corrections ensure better compatibility of the results with other space techniques, in particular with GNSS and VLBI. Numerous charts and tables illustrate the obtained results well. The work is supported by a well-selected and numerous bibliography, based mainly on the latest items.

Summarizing, the work showed the Author's competence in the field of satellite geodesy, the correct approach in the application of research methodology, and the performed analyzes and their interpretation deserve a distinction. It is worth emphasizing the innovative nature of the work, a large number of the developed results obtained with the Bernese orbital program modified for the needs of the study, their correct verification and the correct formulation of conclusions.

The next step should be to choose the best method of determining tropospheric corrections with the use of horizontal gradients and to verify the obtained results, mainly by assessing the compliance of the determined station coordinates. The end result would be to introduce these corrections to the ILRS calculations.

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5. Critical remarks and debatable matters

Apart from a very positive evaluation of the work, which corresponds to the dissertation thesis clearly, there are also, as in every work, critical remarks. The main comments and requests for clarification are listed below:

1. Two-color observations are only mentioned in a few short paragraphs in different parts of the work. It is a pity that there is so little information on this very important action for improving the tropospheric correction. Please explain in more detail the proposed two-color method and why this method was not implemented despite numerous attempts? How do you evaluate the future expected results of this method in comparison to the methods of determining horizontal gradients for the tropospheric delay?

2. Please provide which of the methods of determining the tropospheric delay from horizontal gradients presented in the doctoral dissertation is the most beneficial and you would recommend it for use in ILRS studies and why?:

determined directly from SLR measurements,
by using the Vienna Mapping Function model (VMF30),
by using the Potsdam Mapping Function (PMF), model PMF plus first order of horizontal gradients and model PMF plus second order,
by using the ERA 5 model,
by using a parametric model.

3. Can the introduction of the proposed tropospheric delay corrections ensure that the SLR meets the Global Geodetic Observing System (GGOS) conditions; 1 mm in station position and 0.1 mm/year in station velocity?

4. Lack of assessment of measurement uncertainty in the compared calculation results; are these compared sub-millimeter values realistic?

5. Why in the third article did not apply tropospheric delay corrections from horizontal gradients, only the standard model?

There are also a number of unavoidable minor editorial errors and mistakes, a dozen of which are listed below:
in the abstracts: the keywords in the Polish and English abstracts differ significantly,
word transfers in the Polish abstract are not correct,
in the chapter 1 of the introduction:
the wording "laser beam travel" is not correct, it should be "laser pulse travel",
atmospheric drag is not relevant for LAGEOS satellites,
Goddard Space Flight Center, should be NASA Goddard Space Flight Center,
CNES was not working with NASA, Starlette and LAGEOS were launched separately,
SEASAT was not observed by laser stations except for the first short period,
in the penultimate sentence of the paragraph "Ground segment", a comma instead of a dot and a reference in parentheses,
in the last sentence of this paragraph, instead of "up to 7 degrees" should be "up to 5 degrees",

in the chapter 2 of the introduction:
the post-seismic deformation model (PSD) is also used for several SLR stations,
no references in the text to Table 2.2 and Figure 2.3,
incorrectly used reference to non-existent Fig. 2.46 (probably should be Eq. 2.46),
in the first article:
station 7406 - large std results are from the 2010 earthquake in Chile (bias 3 cm), not technical issues,
station 7080 - the station is not located in a desert place, there is very high humidity around the station, making observations impossible at times (especially in the morning), McDonald station is an example of wrong reasoning due to the lack of knowledge of the station surroundings,
in the third article:
Fig. 3, are the graphs for LAGEOS-1 and LAGEOS-2 (especially for TRP + RGB + NEU) the same?

6. Final conclusion

I rate the presented work very highly. It is the next step in the process of improving the quality of the satellite laser ranging results. The subject of the work is in the discipline of civil engineering and transport. In my opinion, the Author has demonstrated excellent knowledge of conducting scientific research. This is also evidenced by the large number of his publications in reputable scientific journals. Taking into account the assessment presented above, I conclude that mgr inż. Mateusz Drożdżewski's doctoral dissertation "Troposphere delay modeling in satellite laser ranging measurements to geodetic satellites" meets the requirements for doctoral thesis in the light of the "Law on higher education and science" ("Prawo o szkolnictwie wyższym i nauce").

In connection with the above, I am asking for the acceptance of the doctoral dissertation and admission of the Author to public defense in the process of awarding a doctoral degree in the field of "Engineering and technology" (w dziedzinie nauk "inżynieryjno-technicznych") in the discipline "Civil engineering and transport" (w dyscyplinie "Inżynieria lądowa i transport").

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