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Evaluation Doctoral Thesis of Grzegorz Bury:
Precise orbit determination of GNSS satellites
using microwave and laser ranging data

1. Background

Global Navigation Satellite Systems (GNSS) are an important space-geodetic observation technique. In addition to the fully operational GPS and GLONASS, two further global navigation systems are currently built-up, namely BeiDou and Galileo. As these new systems have different properties compared to the legacy systems, dedicated processing and modeling standards have to be developed. The most important error source of GNSS orbit determination is currently the modeling of the solar radiation pressure (SRP). An appropriate approach for SRP modeling is a box-wing model that requires knowledge about the dimensions and optical properties of the satellite.

In 2017, the GSA made available satellite metadata for the Galileo IOV and FOC satellites. The published areas and optical properties allow for the construction of a box-wing model to account for the perturbating accelerations due to solar as well as Earth radiation pressure. This physical modeling allows for a reduction of the number of empirical orbit parameters and reduces systematic errors like draconitic periods introduced by imperfections in orbit modeling.

All GLONASS, Galileo, BeiDou and QZSS satellites are equipped with retro-reflector arrays for satellite laser ranging (SLR). On the one hand, this technique allows for an independent validation of satellite orbits obtained from microware obervations. On the other hand, SLR allows for orbit determination of GNSS satellites solely based on SLR observations.

Whereas SLR allows for identifying systematic errors in GNSS satellite orbits obtained from microwave observations, there are also SLR-specific systematic errors. One of these errors is the so-called blue-sky effect. This effect is caused by the fact that SLR is an optic technique that requires a clear sky in order to track satellites. Clear sky conditions are usually accompanied by high air pressure. As a consequence, atmospheric pressure loading introduces a systematic bias in

the estimated stations height if it is not corrected for. Therefore, a correction is necessary for a consistent analysis of SLR and GNSS observations.
The thesis of Grzegorz Bury discusses SLR-only precise orbit determination, the impact of the blue-sky effect on geodetic parameters, and the performance of a box-wing model based on satellite metadata of the Galileo satellites.

2. Content of the doctoral thesis

The current work is a cumulative thesis based on four peer-reviewed papers. **Section 1** gives an overview about the basics of satellite orbit determination, adjustment theory, and the space-geodetic techniques GNSS and SLR. The observation equations of both techniques are discussed as well as gravitational and non-gravitational perturbation forces with a focus on solar radiation pressure and Earth radiation pressure (albedo as well as infra-red). Both are illustrated by several examples for GPS and Galileo satellites. Empirical as well as physical (box-wing model) approaches for solar radiation pressure modeling are introduced and selected results of both approaches are discussed. Measures for assessing the orbit quality are introduced and selected examples for Galileo orbit determination performance based on SLR as well as GNSS microwave observations are presented. Details on the globals systems GPS, GLONASS, BeiDou, and Galileo are given as well as differences and consistency issues for the GNSS and SLR observation techniques. **Section 2** summarizes the four peer-reviewed papers and discusses the most important conclusions. Finally, **Section 3** gives a short summary and outlook. Four key conclusions are presented.

Paper 1: Multi-GNSS orbit determination using satellite laser ranging, Journal of Geodesy, 2019, DOI: 10.1007/s00190-018-1143-1

SLR-only orbit determination of GNSS satellites, namely GLONASS, Galileo, BeiDou-2 MEO and IGSO satellites as well as the first QZSS satellite is the focus of the first paper of the thesis. The dependence of the orbit quality on the number of SLR observations, the number of SLR stations, their geographical distribution, the orbital arc length, and fixing dedicated parameters to their a priori values or estimating them is evaluated by comparisons with orbits computed from GNSS microware observations. It is demonstrated that precise orbit determination of GNSS satellites is already possible with a quite small number of 60 normal points if at least 10 stations are available that are well-distributed over the globe.

Paper 2: Impact of the Atmospheric Non-tidal Pressure Loading on Global Geodetic Parameters Based on Satellite Laser Ranging to GNSS, IEEE Transactions on Geoscience and Remote Sensing, 2019, DOI: 10.1109/TGRS.2018.2885845

This paper focuses on the so-called blue-sky effect for SLR. Amplitude and phase of annual signals in the atmospheric pressure loading corrections are analyzed. The station coordinate offsets introduced by the blue-sky effect are evaluated by comparing SLR solutions with and without correcting for atmospheric pressure loading. Furthermore, the impact on translation and scale parameters, the geocenter, as well as Earth rotation parameters is studied. The paper highlights the importance of this effect for a proper ananlysis of SLR data and consistent comparison or combination with GNSS microwave data.

Paper 3: Toward the 1-cm Galileo orbits: challenges in modeling of perturbing forces, Journal of Geodesy, 2020, DOI: 10.1007/s00190-020-01342-2

The empirical ECOM-2 model and a box-wing model based on the dimensions and optical properties published by the GSA are evaluated regarding their capability to model non-conservative forces for the Galileo IOV and FOC satellites. Orbit solutions with different ECOM paramerizations as well as different modeling options for albedo and infra-red radiation as well as power thrust provide the basis for this study. Analysis of amplitude spectra of different solutions allows for an assessment of systematic errors. The latter is also done based on an analysis of the estimated empirical parameters. The necessity of estimating dedicated parameters in the emprical approach is shown based on an analytical analysis of accelerations and satellite position error amplitudes. The external orbit accuracy is evaluated by SLR residuals. The most accurate orbits as evaluated by SLR are obtained with a hybrid approach utilizing the a priori box-wing model and a reduced set of three empirical parameters.

Paper 4: Accounting for perturbing forces acting on Galileo using a boxwing model, GPS Solutions, 2019, DOI: 10.1007/s10291-019-0860-0

The impact of a box-wing model based on the Galileo metadata published by GSA on the orbit quality as well as geocenter estimates is analyzed. The box-wing model is used to account for the perturbation forces due to solar radiation pressure as well as Earth radiation pressure (albedo and infra-red). The orbit quality is evaluated by orbit discontinuities between consecutive orbital arcs, SLR residuals, and orbit predictions. A hybrid approach consisting of the box-wing model as well as a reduced set of empirical parameters provides the best results and reduces systematic errors in SLR residuals as well as spurious signals in geocenter estimates.

3. Evaluation

The thesis is written in clear and precise English language and is in general well structured. Sole exception is the order of paper 3 and 4. I consider a flipped order more logical as paper 3

provides more detailed and spezialiced analysis than paper 4. The Figures and Tables are well readable and support the statements in the text. The sources of information are complete and referenced in a correct way.
The four peer-reviewed papers contributing to this thesis are published in highly-recognized scientific journals with a significant impact factor (5.63 for IEEE Transactions on Geoscience and Remote Sensing; 3.049 for GPS Solutions; 4.528 for Journal of Geodesy). The research questions of the papers are up-to-date and of high relevance for the geodetic community. In particular the improvement of Galileo orbit determination and prooving the usefulness of satellite metadata are an important research topic and the thesis is a signficant contribution to that.
The thesis is in general written in a concise and well understandable manner. However, Section 1.3.1 contains too much Bernese slang and cannot be understood by readers not familiar with that software package.
The GNSS and SLR observations techniques are introduced in a brief but consice manner. Only Section 1.5 suffers form the lack of an assessment of the SLR error budget. Such an assessment could contribute to a better understanding of the discrepancies seen between both techniques.
Satellite metadata plays an important role for the current thesis, as it provides the basis for constructing a box wing model. However, the availability of QZSS metadata is ignored. As QZSS is not topic of the papers, just a few sentences and references would be sufficient but the statement that Galileo is the only system with pulished metadata is not appropriate.
The scientific methods used are sound and well explained. Nevertheless, the overall orbit accuracy of 22.5 mm given in paper 3 is too optimistic as it is based on the radial SLR STD only. Along-track and cross-track errors are usually larger than radial errors and significantly contribute to the orbit quality.
An issue that has to be clarified before publication of the thesis is the inconsistency of the author contribution statement for paper 3. In Section 2.3 (p. 42), it is stated that the first author gave the idea for the paper but in the original paper, it is stated that Bury and Sosnica came up with the idea and all contributed to the design.
The appendix lists presentations given at well-established international conferences, where key results of the current thesis were presented. The author of the thesis in addition co-authored seven publications that are not part of the current thesis but were mostly published in highly-recognized scientific journals.

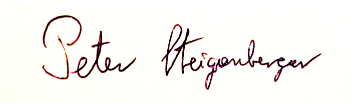
During the defence, the candidte should answer the following questions:

- What is the difference between precision an accuracy?
- What is a SLR observation?
- Which systematic errors do affect SLR (except for blue sky effect) and which order of magnitude do they have?

- How can inactive GLONASS satellites be tracked with SLR?
- What is the meaning of the dar blue bars in Figure 1.8?
- What is the accuracy and precision of the used APL corrections?
- Why is APL negligible for low-latitude areas?
- Who often do maneuvers of IGSO satellites occur?
- Which effects conrtribute to solar radiation pressure in addition to solar wind?
- Are the published optical properties of the Galileo solar panels compatible with Eq. 1.11?
- Which further satellite metadata would be required for an improved box-wing model compard to the one used in the thesis?
- What ist necessary to compute a 1 cm Galileo orbit?

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 that the PhD candidate should receive the **PhD degree with honors**.



Peter Steigenberger