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Report on Doctoral dissertation
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Precise Orbit Determination of GNSS satellites using microwaves and laser ranging data
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1) Presentation of the doctoral dissertation

The PhD document is a collection of four peer-reviewed articles published as first author in major scientific international journals, all related to the same research theme and provided in full in Appendix A.
First, an introduction provides sufficient background to the readers, introducing the major concepts and current scientific challenges. This includes a short presentation on GNSS (Global Navigation Satellite systems) orbit determination and its current limitations, a presentation of the current GNSS satellites, in particular including detailed discussion on the American GPS (Global Positioning System) navigation system and on the European Galileo system. A similar discussion is also provided on SLR (Satellite Laser Ranging), which is of key interest for this PhD thesis. For each of the four published articles, a brief summary is provided. Finally, some conclusions, summarizing the work performed during the four-year PhD programme done at Wroclaw University. Some conclusions are then discussed.

2) Scientific background and objectives

Since the late eighties, navigation satellite systems such as GPS have revolutionized several scientific disciplines such as geodesy. Most accurate results are obtained when using a posteriori orbits using state-of-the-art modelling and analysis methods. More recently, the European system Galileo has been launched, allowing scientists to use an extended constellation of satellites. Some of these satellites are equipped with retroreflectors, allowing accurate range measurements between ground tracking stations and these satellites. The goal of the PhD is to investigate how these Satellite Laser Ranging (SLR) data can be used to provide an external validation of the GNSS orbit determinations or to derive some independent precise orbits.

3) Evaluation of the doctoral dissertation

First of all, it is important to note that the four accepted papers have been published in major journals, well-recognized within the geodetic community: IEEE Transactions on Geoscience and Remote Sensing (IF: 5.630), Journal of Geodesy (IF: 4.528, official journal of the International Association of Geodesy), and GPS Solutions (IF: 3.049). Finally, in Appendix C, a list of seven peer-reviewed articles published as co-author on related subject in major scientific journals is given. This must be recognized as a major achievement done within a four-year period, taking into account the current worldwide emulation to publish on these subjects.

The current text, while sufficiently focused and brief, is well-written and goes to the point, explaining what is currently known, what is still subject to possible improvement and discussing the current scientific limitations. The scientific goals are well explained since the very beginning and I would recommend future PhD students to read such a document for a complete background on this subject. Some historical background is also provided and discussed in a worldwide perspective. Figures are of ex excellent quality and used appropriately. Equations are given when needed and discussed with care. The bibliography is well-selected and includes key papers without being too long. The selection of the papers is appropriate, showing a good knowledge on the scientific literature on these topics.

The scientific discussion addresses the identification and possible mitigation of some systematic errors, such as those coming the current limitation in modelling of the perturbing forces. This is usually quite a challenge, as systematic errors are, by definition, more difficult to identify and are often under-estimated in many types of data processing. The different uses of SLR data for validation of the GNSS orbits or for POD determination are presented in full details. Emphasis is made on internal and external validations of current POD results. This current research is then strongly linked to state-of-the-art research activities among many groups in the world for GPS POD determination. It also fits well within a major project of the International Association of Geodesy: GGOS (Global Geodetic Observing System). In particular, the topic is in phase with an on-going international investigation looking at the importance of co-location in space (by opposition to co-locations of different space techniques in the same place for tracking purposes). The conclusions of this research may then drastically change the way geodesy determines the International Terrestrial Reference Frame (ITRF), which is the basis of all type of geopositioning and georeferencing.

4) discussion on published articles

Article 1: Multi-GNSS orbit determination using satellite laser ranging (Journal of Geodesy)

Unlike being used as validation data (control points), the SLR data are used here to estimate an independent orbit for some of the GNSS satellites. This was possible, thanks to an intensive GNSS-tracking campaign (LARGE) organized by the International Laser Ranging Service (ILRS). The obtained results could then be a good estimation of possibilities offered in the future when the full ILRS tracking network will using tracking station of new generation. The author demonstrates that the amount of observing SLR data and the geographic distribution of the SLR tracking stations are key criteria for the quality of such orbits. The length of the considered orbital arc is also discussed.

Article 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)

In the last few years, there is on-going scientific discussion trying to understand why station position coordinate time series from different geodetic techniques show different periodic (mostly annual or semi-annual) signals and if some corrections such as the non-tidal pressure loading should be applied at the observation level (per data point) or in post-processing mode (per day or per week). As there is currently no clear answer to that question, the article is very

timely and provides some answers. The fact that SLR stations, unlike GNSS stations, do not provide continuous observations may create some systematic effect, called "blue-sky" effect, as SLR observations are mostly obtained during good atmospheric conditions. This effect is quantified on different types of geodetic results: station coordinates, geocenter motion, Earth rotation parameters, GNSS orbits. This is a good reference for future work. The need to apply the same Atmospheric Non-Tidal Pressure Loading (ANPL) models consistently by all geodetic technique is strongly recommended in this article, which, unfortunately, is not the option used until now.

Article 3: Toward the 1-cm Galileo orbits: Challenges in Modeling of Perturbating Forces (Journal of Geodesy)

This article focused on the recent Galileo satellites and investigate the effect of using different types of solar radiation pressure, albedo and infra-red models, specifically looking for systematic effects on the geodetic results. A proposed model is provided in this article and fully tested using different approaches and can be used by other groups.

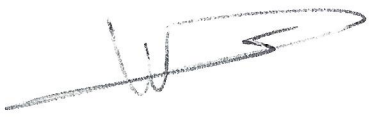
Article 4: Accounting for Perturbating Forces Acting on Galileo Using a Box-Wing Model (GPS Solutions)

This article is the logical continuation of article 3 and provides an overview of data analysis strategy used when estimating precise orbits of Galileo satellites. As the model used are semi-empirical (some parameters need to be estimated after processing some of the data), the difficulty here is to assess to what point these models need to be refined: too few parameters will not allow a proper fitting of the data, too many parameters may create over-parameterization, which could then lead to new types of systematic errors. This article proposes some first recommendation to scientists, in particular to the few analysis centers of the International GNSS Service (IGS). This is important, as this not yet any IGS official orbit available based on the MGEX observation data set. In particular, ECOM2 model is strongly recommended as it supersedes ECOM1 model.

5) recommendation

Consequently, for all these reasons, I recommend, without any reservation, to accept the present thesis of Grzegorz Bury as PhD work. In case a mark is required, I suggest to rank this work with the following grade: **With highest honors**

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.)*.



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