DETAILED REFEREE REPORT

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for the

Doctoral Dissertation

"Satellite Laser Ranging to Low Earth Orbiters for Orbit Validation and Determination of Global Geodetic Parameters"

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Introduction:

Space geodesy provides fundamental measurements of the shape, gravity field and rotation of the Earth and how these global parameters change with time. From this information we infer information about key parameters in the Earth system and how they evolve. Space geodesy also furnishes a precise terrestrial reference frame within which to anchor these observations of the Earth system. One of the principal techniques of modern space geodesy is Satellite Laser Ranging (SLR). The thesis by Ph.D candidate Darusz Strugarek seeks to improve the utility of SLR for measurements of these global geodynamic properties by demonstrating that they are accessible from processing SLR data to a suite of Low Earth Orbiting (LEO) satellites. The rationale is that more data is available from these LEO satellites, than from the higher LAGEOS satellites, that remain the core of the SLR contribution to the International Terrestrial Reference Frame (ITRF). In addition, through detailed analysis, the Ph.D candidate develops strategies to mitigate remaining systematic errors in SLR data, including target interaction effects, ranging-system effects, as well as potential errors in in situ meteorological data. In his Ph.D thesis, D. Strugarek successfully demonstrated, that the LEO satellites, that are tracked highly accurately by GNSS (Global Navigation Satellite Systems), can be exploited to make available much more data for scientific analysis. In addition, these data can provide new insights into the characteristics and performance of the SLR systems themselves. D. Strugarek in his analyses has also pushed the utility of SLR validation of GNSS orbits to a new level. By showing how different error sources, including elevation-dependent errors sources can be mitigated, D. Strugarek shows how SLR data can discriminate performance for GNSS orbits at a more detailed level than was the case previously. This application will be useful to validate or benchmark further model improvements in GNSS data analysis, and aid in the diagnosis of system anomalies. D. Strugarek's thesis is original, and a new, and original contribution to the field of space geodesy. The thesis is a welcome contribution as we look forward to future work that will entail multi-technique analysis of space geodesy data for helping to achieve the major goal of the Global Geodetic Observing System (GGOS): to provide a long-term global reference frame realization stable to 1 mm and 0.1 mm/yr.

Content and Review of the Individual Chapters:

Chapter 1: This short chapter provides an introduction and clearly sets out the central objectives of the dissertation research: to increase the spectrum of SLR data used for geodynamical analyses, especially for the reference frame, to characterize and to mitigate residual systematic errors in the SLR technique, and to improve SLR validation of GNSS-based satellite orbits. The foundational premise of the thesis is neatly encapsulated in Table 1, which points out that in terms of quantity, 76% of the SLR tracking is to active LEO orbiters, whereas only 13% of the tracking is to spherical geodetic satellites, including the LAGEOS satellites.

An underlying premise of the thesis is the availability and ubiquity of high-quality GNSS-based orbits for LEO satellites, at the level of 1-2 cm in the radial sense. It is important to point out that this level of precision is enabled not only because of the continued improvement in LEO GNSS receivers and methods of processing data, but also because we have available improved models of the Earth's static and time-variable gravity field from GRACE & GRACE FO.

Chapter 2: Chapter two describes the LEO missions whose SLR data are used in this thesis. The chapter also describes the retroreflectors used on these LEO satellite, sets out the principles of precise orbit determination for LEO satellites. In addition, the chapter provides an overview of the POD quality of the current suite of LEO orbiters, focused primarily on those that use GNSS. The chapter provides the necessary background material for the work described later in the thesis. I have a few comments:

(i) Section 2.3.1. Re GFO (GEOSAT-Follow-On), the GNSS system never worked properly, and the operational POD and ex post-facto precise POD was completed using altimeter crossovers and SLR data (*Lemoine et al., 2006, AIAA Paper 2006-6402, doi: 10.2514/6.2006-6402*).

(ii) Section 2.3.2 nicely describes the attributes of dynamic, reduced-dynamic and kinematic orbit determination. However, the description of the implementation of reduced-dynamics (just before equation 2.4) is probably particular to the CODE/Bernese software. Different groups and different POD softwares use slightly different strategies. Nonetheless, the central idea remains the same: that the density of tracking and robust observational geometry provided by GNSS allows the frequent adjustment of empirical parameters to absorb model error and come closer to a "true" orbit. Wu et al. (1991, J. Guidance Control and Dynamics, doi: 10.2514/3.20600), and Luthcke et al. (2003, Marine Geodesy, doi: 10.1080/714044529) respectfully, describe the reduced-dynamic POD implementation in the JPL/Gypsy and NASA GSFC GEODYN orbit determination softwares.

(iii) Section 2.3.3 provides an overview of the POD accuracy achieved for different orbiters, and who are some of the providers of these orbits. Regarding the 13 cm RMS of radial error cited for TOPEX, that was indeed the *pre-launch* requirement. Marshall et al. (1995, *J. Geophys Res-Oceans*) showed that the TOPEX orbits had achieved 2 – 2.5 cm radial orbit accuracy. With the availability of ITRF2005 and GRACE-derived Earth gravity models, further reprocessing possibly improved the radial orbit accuracy to about the level of 1.5 cm (Lemoine et al., 2006, AIAA Paper 6672, doi: 10.2514/6.2006-6672). Regarding the DORIS real-time orbit determination with the DIODE, Schrama (2017, Adv. Space Res., doi: /10.1016/j.asr.2017.11.001) showed that the NAV orbits had achieved about 3 cm RMS accuracy. Possibly with Sentinel-6A this has been further improved, however this has not yet been published.

I have the following question for the Ph.D candidate, D. Strugarek: *Given the types of LRAs flown on LEO orbiters, and his experience processing the SLR data for this dissertation with different SLR station configurations and systems, is there an existing LRA that produces lower or the lowest systematic error in the SLR data on a LEO satellite in the altitude range from ICESat-2 to Sentinel-6A?*

Chapter 3: This chapter provides an overview of satellite laser ranging, from a description of the measurement principles, a description of the ground stations, and how they operate, including the wavelengths and detectors that are used. The chapterprovides the prerequisite background understanding for the work described later in the thesis.

Here is some supplementary information regarding station operations (section 3.4).

(i) The use of an X Band radar for aircraft avoidance, which is indeed used at some sites, must be coordinated with other geodetic systems such as VLBI if they are collocated at the same site. At the Greenbelt station (operated by NASA), both the SLR and VLBI systems are programmed to not look in direction of the VLBI and SLR systems, respectfully. This is to avoid saturation and damage to the broadband feed on the VLBI antenna. It means that there is a visibility mask at Greenbelt for the SLR in the direction of the VLBI antenna. The impact on observations and geodetic results is probably small but probably should be kept in mind. Other stations might have visibility masks for similar or different reasons.

(ii) In section 3.4, the benefits of automated systems for SLR tracking are described along with a few examples at Wettzell and Zimmerwald. I would add that even a 'semi-automated' station can achieve improvements in tracking performance (number of observations), where semi-automated means being able to operate the station from an off-site location for a while such as an operator's home (Sven Bauer, Potsdam SLR station manager, personal communication).

This reviewer appreciates the conciseness and completeness of this chapter. One topic that might also be mentioned is the availability and use of full-rate data vs. SLR normal points. All the data used in this thesis refer to normal points that are constructed according to a defined (standard) algorithm, the Herstmonceux algorithm. However, work is under way to see if there are improved methods to construct normal points from full-rate data. There have been presentations to ILRS meetings and to the ILRS Quality Control Board (QCB), but at this point no definitive conclusion has been reached. The ILRS has requested for at least the last 5-7 years that stations archive their full-rate data (The kHZ stations supply only a decimated portion of their full-rate data). So for the observation period and satellites used in this study full-rate data should be available. Then, the question I pose is the following: *While I don't advocate a reprise of the work in this thesis using full-rate data, is there a way to make use of this resource to further elucidate and minimize systematic errors in modeling or processing SLR data?*

Chapter 4: Chapter presents a detailed overview of geophysical parameter estimation, as applied in this thesis work. In addition, the chapter lays out the mathematical and algorithmic foundations for the coordinate transformations, and the implementation of SLR-based validation and combination solutions for geophysical parameters. The subject matter is clearly presented and I could imagine the Ph.D candidate presenting this material in a professional setting such as a university or an "Ecole d'été". I have two comments and two small corrections on the presented material:

(i) Regarding the quaternions (section 4.1.5), the author correctly states the importance of modelling a satellite's proper attitude. However, firstly the attitude is needed for both the measurement model and the force model in POD processing. Secondly, while, we need the spacecraft body quaternions to model the general spacecraft orientation, we also need quaternions to model the orientation of the moving appendages (which include the solar arrays, but might also include steerable high gain antennae or SAR antennae).

(ii) As the Ph.D candidate explains, the geocenter is the manifestation at spherical harmonic degree one, of mass motion on the surface or within the Earth. Two points underscore the significance of the work undertaken in this thesis to obtain improved solutions for the geocenter. First, the geocenter represents a component of mass motion Is ***not*** observable by a mission such as GRACE or GRACE FO (Wu et al., 2012). So ideally we should obtain a geocenter solution from geodetic sources that has the accuracy and temporal resolution to complement the time-variable gravity solutions from GRACE [*Presently users of GRACE data rely on models to predict geocenter*]. A second point is that the geocenter is now considered important for precise orbit determination. Both the CNES and NASA GSFC include the geocenter models in their POD standards for altimetry satellite POD (e.g. https://sentinels.copernicus.eu/documents/247904/1848151/Sentinel-3-upgrade-POE-E-to-POE-F-orbit.pdf/da92a932-b727-46d4-bd52-eaa29e43bb89?t=1542186994000)

(iii) Section 4.3.2: Re the comment "spherical geodetic satellites do not need to model their attitude". Yes, this is probably true in most people's orbit determination softwares. However, a spin model is required to properly model thermal thrust effects due to Yarkovsky or Yarkovsky-Schach effects, which most people probably accommodate by estimation of empirical accelerations. (*See the presentation by David Lucchesi at the 2019 ILRS workshop for a detailed summary of this issue*). Couhert et al. (2018) expressed his concern that mismodelling this effect could impact LAGEOS-based solutions for the geocenter. Given what we know about how non-conservative force mismodelling can map into geodetic products from our experience with GNSS or DORIS data, it seems the SLR community should be concerned about this issue as well. So I think proper modelling of these nongravitational perturbations is an open issue for the community.

(iv) Also in Section 4.3.2, Re the sentence "Also they [the spherical satellites] do not use LRA corrections. I think that is a miswording. Rodriguez et al. (2019, J. Geodesy, cited in the section 4.3.3 of the thesis) after a laborious analysis derived a time-dependent station configuration-based and satellite-based Center-of-mass offset corrections for the spherical geodetic satellites. These new CoM offset corrections have been incorporated into the SLR analysis for ITRF2020.

Chapter 5: This chapter presents the core results obtained by D. Strugarek in his thesis work. The topics covered include (1) identification of systematic effects affecting SLR residuals; (2) detector-specific issues in satellite laser ranging to the Swarm satellites; and (3) elimination of systematic effects in SLR residuals to LEO satellites applied to the GNSS-based orbits of the Swarm satellites.

These are all first authored papers. All five papers have been submitted, undergone peer review and been published in high-impact scientific journals. The papers, and the journal impact factors are listed below. **For a Ph.D candidate to have this type of publication record for thesis-related work is unique and is a testimony that the originality of the thesis work that has already been acknowledged by the Ph.D. candidate's scientific peers.**

Strugarek et al. (2019a). "Characteristics of GOCE orbits based on SLR", Adv. Space Res., 63(1). **Impact factor: 2.1.**

Strugarek et al. (2021a). "Detector-specific issues in SLR to Swarm A/B/C satellites", Measurement, 182(109786**). Impact factor: 3.9**.

Strugarek et al. (2019b). "Determination of Global Geodetic Parameters using SLR measurements to Sentinel-3 satellites", 11(19). **Impact factor: 4.8.**

Strugarek et al. (2021b). "Determination of SLR station coordinates based on LEO, LARES, LAGEOS, and Galileo satellites". Earth, Planets, and Space, 73:87. **Impact factor: 2.3**

Strugarek et al. (2022). "Satellite laser ranging to GNSS-based Swarm orbits with handling of systematic errors". GPS Solutions. **Impact factor: 4.1**.

Here are some questions and comments regarding aspects of the above papers:

(i) *Concerning the Strugarek et al. (2019a) paper analyzing GOCE orbits and SLR data, is it possible to compare estimates of time biases with those that might be available from the Jason-2/T2L2 experiment? How is a time bias error, distinct from an error in modelling atmospheric drag?*

(ii) Regarding the Strugarek et al. (2021a) paper that analyzes SLR data to the Swarm satellites to isolate SLR detector-specific behavior and performance, this is quite an interesting analysis, and the first time this reviewer has seen LEO satellite data employed in this fashion to analyze the detector aspect of an SLR system. Possibly, the conclusions for the PMT detectors might need thought to be interpreted with some caution. The stations that have PMT detectors in these tests are predominantly the stations (Simiez, Kiev, Zelnchusksaya, Arkhyz) that have historically shown poorer performance over the years (compared to other stations in the ILRS), and there might be other parts of their ranging system that contribute to these results.

(iii) Regarding the Strugarek et al. (2019b, 2021b) papers, *is it possible to validate the improved coordinates (compared to the starting or apriori) using external tests such as site tie vectors by examining whether there is a reduction in the tie residuals (difference between Space Geodesy-determined coordinates at a collocated site minus the surveyed tie vector)?*

(iv) The Strugarek et al. (2022, submitted) paper presents quite an interesting method to reduce residual elevation and possibly azimuthal-dependent sources of system error. It would be quite interesting to apply this methodology to evaluate orbit quality for the altimeter satellites (the Jason satelites and Sentinels 3A,3B, & 6A) or to the GRACE & GRACE FO satellite orbits. *For the results in Figure 4 of the paper, the TB+G or TB+RB+G solutions, do the range of the residuals correlate or correspond to the estimate of the RMS of fit of the normal point to the high-rate data or to the so called "calibration RMS" given in the ILRS Performance Reports? In other words with these corrections, do the residuals now match the expectation for the intrinsic noise of the SLR data for given stations?*

Chapter 6 & Bibliography: Chapter 6 succinctly and clearly summarizes the main conclusions of the thesis. The cited bibliography is quite extensive and shows that the Ph.D candidate has a broad grasp and understanding of the field of satellite laser ranging. The Seitz et al. (2016) reference for DTRF2014 could be updated, since that group now has a journal paper published this year.

Seitz M. et al. (2022). "DTRF2014: DGFI-TUM's ITRS realization 2014", Adv. Space Res., 69(6), 2391-2420, doi: 10.1016/j.asr.2021.12.037.

Overall Assessment:

The Ph.D candidate, D. Strugarek, set out in this thesis to show that SLR data to active LEO orbiters could be employed for SLR reference frame realization, and the estimation of geodetic parameters, such as station coordinates, geocenter motion, LoD and pole coordinates. The objective was to develop strategies to use effectively the large quantity of LEO satellite SLR data, which presently is used mostly for orbit validation (and also for orbit determination in the case of the Jason & Sentinel-6A satellites), rather than for the reference frame. In the presented work, D. Strugarek has carried out meticulous and detailed analyses of SLR data, and he has shown that they carry the signature of different types of system errors that can manifest themselves with different dependencies. Importantly, he showed that the strategies of range bias estimation over a long time period, or estimation of a combination of range biases and troposphere biases, can mitigate these residual errors. He also demonstrated a strategy to use SLR data, filtered through the GNSS-determined orbits (*which become effectively roving ground stations*), for improvements in global geodetic parameters. Along the way, he has developed an approach to better use SLR data for validation of these many LEO science satellite orbits, whose requirements for orbit accuracy are becoming ever more stringent. This is particularly true for the altimeter satellites, where it would be quite useful to isolate and remove aberrant data-relaed or orbit-related signatures to make sure we can properly assess the orbit accuracy for satellites whose altimeter data is used to compute the changes in mean sea level.

This work will be quite useful as we contemplate multi-technique analysis of space geodesy data for improvement of the terrestrial reference frame, as has been contemplated by NASA and ESA in various mission proposals (e.g. GRASP, E-GRASP) and is under consideration once again by ESA in the scope of the mission proposal called GENESIS. The challenge is that the current approach for reference frame determination by the IERS (employed in ITRF2020 for example) relies on mono-technique analysis. We hope that this can change in the future, by the time the next ITRF realization is produced.

Another reason the work in this thesis is welcome is that as we strive to improve our ability to monitor the Earth system, and as the quality of GNSS orbit determination improves (e.g. through ambiguity fixing, better and mult-GNSS receivers) there is a need to better exploit the existing suite of SLR data. Finally, even though new SLR stations are coming on line (*i.e., the new ESA station in Tenerife which became operational in 2022* *or the new NASA SGSLR stations that will come on line starting in 2024)*, there will still be a need to exploit the long time history of SLR data to the current stations. In addition we will still need to monitor the performance of the new stations. Thus the techniques of system error mitigation shown in this thesis will be quite useful and needed for any scientific reanalyses that include older data.

In conclusion, I find that the work in this thesis is an original solution to a scientific problem. It is very clear that the Ph.D candidate has acquired a solid background knowledge in the field of satellite geodesy, specializing in the use of Satellite Laser Ranging data.

In my opinion, the doctoral dissertation fulfils the requirements for a doctoral degree, and that it demonstrates an original solution to a scientific problem, and it also demonstrates that the Ph.D candidate has the general theoretical background knowledge to independently conduct scientific research.

Final conclusion: Postive (sufficient)

Sincerely,

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