ΑΡΙΣΤΟΤΕΛΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΟΝΙΚΗΣ
ΤΜΗΜΑ ΑΓΡΟΝΟΜΩΝ ΚΑΙ ΤΟΠΟΓΡΑΦΩΝ ΜΗΧΑΝΙΚΩΝ
ΤΟΜΕΑΣ ΓΕΩΔΑΙΣΙΑΣ ΚΑΙ ΤΟΠΟΓΡΑΦΙΑΣ
ΕΡΓΑΣΤΗΡΙΟ ΜΕΛΕΤΗΣ & ΕΦΑΡΜΟΓΩΝ ΤΟΥ ΠΕΔΙΟΥ ΒΑΡΥΤΗΤΑΣ - GRAVLAB
Γεώργιος Σ. Βέργος
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SCHOOL OF RURAL & SURVEYING ENGINEERING
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George S. Vergos
Associate Professor

Thessaloniki, March 04, 2020

Department of Mine Surveying and Geodesy
Faculty of Mining Technology
St Ivan Rilski University of Mining and Geology
Prof. Boyan Kamenov St.
Sofia, Bulgaria

Review Report

Dear Colleagues,

After the formal invitation by the Department of Mine Surveying and Geodesy in December 13, 2019 and the invitation by Prof. Dr. Eng. Ivaylo Koprev in January 22, 2020, I was assigned as an external reviewer of Mr. Othman Al-Kherayeff's PhD Thesis in partial fulfillment of his Dr of Philosophy degree. Following this invitation and the supply of Mr. Al-Kherayeff's PhD Thesis, Extended Summary, CV, Publications and MSc, I have completed the following review of the candidate. The review is structured in terms of the usual academic formalities, with the initial presentation of the candidate at start, followed by the review and main structure and findings of the PhD thesis. At the end follows my main conclusive remarks and final statement.

Cordially,

Dr. Georgios S. Vergos
Associate Professor
Department Head
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PhD Thesis review

Geodetic Earth Observations Combination for Vertical Reference System Definition – A Case Study for the Kingdom of Saudi Arabia Vertical Datum and Vertical Reference Frame

Candidate: Dipl. Eng., M.Sc., Othman Al-Kherayeff

Reviewer: Prof. Dr. Georgios S. Vergos

Contents

1. Overview of the Report

The herein form the PhD Thesis review of Mr. Othman Al-Kherayeff in partial fulfillment of the Degree of Doctor of Philosophy. The structure of this review report is as follows:

- Analysis of formal documents received by the Department of Mining Surveying and Geodesy
- Brief overview of the PhD Thesis
- Overview and review of the provided PhD Thesis extended summary
- Presentation and review of the provided author publications
- Review of other documents related to the candidate
- Comments and remarks on the thesis proofreading
- Review of the candidate profile and current status
- Scientific and Research Achievements of the Candidate
    - Thesis structure and Chapter review
    - Thesis objectives, concepts, methodology and results
    - Thesis practical aspects
- PhD Thesis critical remarks
- Analysis of PhD Thesis contributions
- Conclusive remarks
- Final statement and assessment

2. Analysis of formal documents received by the Department of Mining Surveying and Geodesy

In the frame of the PhD Thesis defense, I have received the following documents, referring to the Candidate:

- PhD Thesis
- Extended Summary of the PhD Thesis
- Mr. Al- Kherayeff's CV
- Mr. Al- Kherayeff's List of Publications
- Mr. Al- Kherayeff's order of enrollment at the University of Mining and Geology "St. Ivan Rilski" – Sofia
- Mr. Al- Kherayeff's transcript in the frame of an MSc at the School Military Service, Royal Engineers.

In the following, a more analytical description of the aforementioned documents is given.

2.1. PhD Thesis

The PhD Thesis entitled "Geodetic Earth Observations Combination for Vertical Reference System Definition – A Case Study for the Kingdom of Saudi Arabia Vertical Datum and Vertical Reference Frame" is composed by 211 pages and is written in the normal thesis nomenclature divided in the Prefaratory pages, main body and bibliography. In the Prefaratory pages, one can find the Table of Contents, List of Tables and List of Figures. The Thesis encompasses 21 Tables and 90 Figures while it contains 3 Appendices.

2.2. Extended Summary

The provided PhD Thesis Extended Summary is 53 pages long and is composed of six chapters, basically following the structure of the PhD Thesis itself. The main part of the extended summary is devoted to the presentation of the numerical results (Chapter V of the summary, 15 pages) and the Conclusions and Contribution (Chapter VI of the summery, 5 pages). This is to point out that the summary is self sufficient and manages to present in a coherent and clear way both the numerical results carried out and achieved as well as the main conclusions of the PhD Thesis, and the contributions to VRF definition, HSU and IHRS realization and prospects of modern-day combination schemes proposed by the candidate.

2.3. Relevant Publications

The candidate has submitted four publications in support of the research work performed during his PhD studies.

- Al-Kherayef O, Vergos GS, Grebenitcharsky RS (2019) Improvement of Kingdom of Saudi Arabia Vertical Datum by Tide Gauge & Satellite Altimetry Data and GNSS observed ellipsoidal heights. Presented at the 2019 IUGG General Assembly, Session G02 "Static Gravity Field and Height Systems", July 8 – July 18, Montreal, Canada.

  This is a poster presentation closely related to the theoretical and numerical results of the PhD Thesis as it refers to the combination of satellite altimetry, GNSS and levelling data (Section 5.B) in order to determine the SST at the TG locations over KSA (Strategy 2 in the Thesis). In the same work, the WL-MRA concept is presented as a tool to analyze TG data.

- Al-Kherayef O, Grebenitcharsky RS, Minchev M (2019) Improvement of Kingdom of Saudi Arabia National Vertical Reference Frame definition by all available classical and new geodetic Earth observation data: A case study. Presented at the 2019 IUGG General Assembly, Session G02 "Static Gravity Field and Height Systems", July 8 – July 18, Montreal, Canada.

  This is a poster presentation closely related to the theoretical and numerical results of the PhD Thesis as it refers to the multi-Vertical Regional Datum (m-VRD) problem and its implementation with all GGMs (Strategy 2 in the Thesis) as well as available geodetic data over KSA for the definition of the KSA VRF (Strategy 3 in the Thesis).

- Al-Kherayef O and Grebenitcharsky RS (2019) The Kingdom of Saudi Arabia Geodetic and Vertical Reference Frames – the main components of National Spatial reference System. Presented at the 2019 EUREF Symposium, May 23-25, Tallinn, Estonia.

  This is an oral talk closely related to Chapter 4.A of the thesis where the geodetic infrastructure of the Kingdom is presented. It basically outlines all input data used for the numerical work in the PhD Thesis.

- Al-Kherayef O, Valchinov V, Grebenitcharsky RS, Valcheva S, Al-Muslmani B, Al-Rubaia U (2018) Refraction coefficient determination and modelling for the territory of the Kingdom of Saudi Arabia. In Proceedings of the FIG Congress Embracing our smart world where the continents connect: Enhancing the geospatial maturity of societies, Istanbul, Turkey, 6-11 May 2018, ISBN 978-87-92853-78-3, ISSN 2308-3441.

  This is a conference proceedings paper where all the theoretical and numerical work referring to the determination of the refraction coefficient over the KSA is presented. It thus relates closely and gives the necessary material described in Chapter 4.C and Chapter 5.A of the Thesis.

2.4. Other Documents – Candidate General Information

The other documents, complementary to the above, are the aforementioned order of enrollment at the University of Mining and Geology "St. Ivan Rilski" – Sofia and transcript in the frame of an MSc at the School Military Service, Royal Engineers. They show the successful completion of the MSc studies of the candidate and the acquisition of the PhD Candidate status.

The candidate's CV provides in a coherent and concise way the professional and academic progress over the years, as well as the continuous professional occupation in strictly surveying and geodetic works. The combination of the academic and professional career of the candidate with his publication record from 2014 onwards, show the natural flow to a PhD candidacy in a field close to his main interests. Since 1993, and especially after 2000, he has participated in major conferences worldwide on all aspects of modern geodesy (geometric, satellite, physical, GNSS) while he has given attention to more application-oriented Symposia like those organized by FIG. He himself contributed to the organization of the 2013, 2015 and 2016 annual Geodetic Conferences in KSA, Finally, he employment record shows a natural evolution from the practical aspects of surveying and cartography (early '90s), to the formation of the geodetic infrastructure in KSA ('00s) and the implementation of high-level geodetic projects realizing the GRF, VRF, CORS and geoid in the Kingdom.

2.5. Comments and remarks on the paperwork

In general the PhD Thesis is of high-quality in both the use of the English language and structure. It has an intuitive way of communicating the basic goals, assumptions made, theoretical concepts needed for its conclusion and summary of data used. It is especially important to mention that, despite the usual concept in many PhD Theses of coping and repeating basic theoretical concepts in satellite and physical geodesy, the present thesis is direct and to the point. This means that it gives the absolutely basic theoretical concepts needed in support of the numerical experiments carried out, without repeating lengthy formulas and known concepts which can be found in any given geodesy graduate handbook. On top of that, the theoretical part of the Thesis is self-sufficient, in the sense that nothing needed in terms of the theoretical concept is missing. This is real good evidence of the mastery of the candidate in the field that he aims to tackle and the self-consistency and integrity of the PhD Thesis itself. Moreover, the results achieved are supported by the preceding theory and are replicable and justifiable. The Tables and Figures are well presented and of high-quality, contributing to the high-quality of the Thesis.

3. Scientific and research achievements of the doctoral student

The main body of the PhD Thesis is composed of five main chapters with many sub-sections in each one.

Chapter 1 "Introduction" provides the general background of the thesis, i.e., it sets the problem statement, main research tasks and proposed solutions of the problem. It is composed of two main sections and a conclusive one acknowledging that the thesis is based on already published results in research publications.

Chapter 2 "Geodetic Background" is composed of 5 main sub-chapters which present the basic mathematical background needed in support of the research work presented. Section 2.A presents the basic concepts of coordinate systems in geodesy and Section 2.B presents fundamental aspects of the physical shape of the Earth , a.k.a, Earth's gravity field, natural heights and the geopotential. Section 2.C forms the main conceptual mathematical background of the PhD Thesis, since orthometric, normal, geoid and quasi-geoid heights are presented, while the basic concepts of height systems and projections is given, with emphasis on past, current and future concepts for vertical reference systems (VRS) and frames (VRF) realization. Section 2.D focuses on the contribution of geodetic observations, i.e., gravity, precise levelling and tide-gauge data towards the realization of a VRS into a VRF. Of main importance for the novelty of the PhD Thesis is Section 2.E, where the contribution of satellite altimetry and airborne gravity data to the determination of the VRF is outlined, as such data do not participate to the traditional modeling of the VRFs.

Chapter 3 presents available methodologies (Section 3.A and 3.B) to solve boundary value problems and emphasizes the application of spherical harmonic analysis, in the frame of global geopotential models (GGMs), and Stokes' integral formula for local geoid determination. Then the analysis of GGMs in surface spherical harmonics is presented, along with an analysis of the spatial interpretation in terms of degree and order of expansion. Section 3.B finishes with a brief presentation of the recent missions of CHAMP, GRACE and GOCE. Section 3.C is dedicated to the theoretical and numerical presentation of results on the determination of the refraction coefficient for precise leveling. First the theoretical background is presented and then results over KSA are given in Table 3.2. Section 3.D describes another novel part of the thesis, which refers to the use of wavelet (WL) mutli-resolution analysis (MRA) to tide-gauge data. This step is quite important as steps and discontinuities in the TG data can result in increased errors in VRF determination when combined with altimetry and local gravity information. Chapter 3.E focuses on another novel approach followed in the thesis which refers to the combination of available multi-satellite altimetry data, local GNSS/Levelling observations, local high-accuracy level campaigns, local gravity and GGMs in order to determine potential differences for all KSA BMs relative to the zero-level point of the country and to the IAG-adopted optimal W_o representing a global geoid with $W_o = 62636853.4\ {}^{m^2}/_{s^2}$ thus realizing the IHRS/IHRF. Section 3.F summarizes the previous ones and presents the methodological concept for the (novel in this Thesis) so-called multi-Vertical Regional Datum (m-VRD) problem. It should be stressed that this section is extremely important for the thesis under review, as it manages to provide the overall methodology and different approaches for the VRF unification and regional VRF determination for the entire Kingdom, as well as to unify the KSA VRF to the IHRS/IHRF. Chapter 3 finishes with a recommendation for the future realization of the KSA VRF, once all current ongoing geodetic projects are finalized.

Chapter 4 provides an overall comprehensive description of the data used for the numerical results of the thesis. A presentation of the KSA National Geodetic Infrastructure (NGI) is given in Section 4.A, with detailed analysis of the KSA SANSRS and KSA-NGNs in 4.A.1. Section 4.A.2 gives a detailed presentation of the geometric (KSA-GRF17), CORS (KSA-CORS), vertical (KSA-VRF14) datum definitions and the National Gravity (NGN) and Vertical (NVN) networks. Finally, the adopted geoid for the Kingdom is outlined (KSA-GEOID17) along with the available airborne gravity anomalies.

Finally, Chapter 5 presents the numerical results of the PhD thesis. Section 5.A focuses on the determination of the refraction coefficient, Section 5.B refers to the numerical results for VRF determination and HSU using altimetry and TG data and finally Section 5.C provides the numerical solutions for the m-VDP problem based on all three presented approaches.

Chapter 6 summarizes the thesis results, proceeds to recommendation and makes proposals for future work.

The PhD Thesis is accompanied by three Appendices, one on the interpretation of low-degree spherical harmonics, one GGMs and a final one on definitions.

The PhD Thesis is of high-quality in both the use of the English language and structure. It has an intuitive way of communicating the basic goals, assumptions made, theoretical concepts needed for its conclusion and summary of data used. In terms of the goals set, the main aim is clearly set from the beginning (Section 1.2.1) as: "*Having many different types of collocated geodetic observations at a TG station would allow the computation of geopotential values and numbers and the orthometric heights of a BM from the TG Network to be determined up to the highest possible accuracy requirements*".

From that aspect, the main goal is, given the existence of this wealth of information how can one integrate, assimilate and combine them in a coherent, rigorous and theoretically sound way to determine, given the different stochastic characteristics of each one, the vertical reference system and frame of a country. This has been crystal clear from the beginning of the Thesis and forms the basis for the next three main pillars of the work, i.e., presentation of theoretical aspects and methods used, data employed and their error characteristics, and finally numerical experiments carried out for the realization of the Thesis goal. Therefore, the conformity of the overall Thesis structure is guaranteed being presented in a coherent and unified way.

I have thoroughly checked the mathematical expressions throughout the PhD Thesis and found them suitable and correct, with proper credit given to related work. As mentioned in section 2.5 above, the thesis manages in a simple, straightforward and complete way to give the absolutely basic theoretical concepts needed in support of the numerical experiments carried out, without repeating lengthy formulas and known concepts which can be found in any given geodesy graduate handbook.

To my personal knowledge and perspective, the overall concept presented and the work carried out, is a first ever try to combine in a coherent way all this multitude of data and information and try to reach a high-accuracy determination of the KSA VRF and its connection to the WHS in terms of both height and potential differences. Moreover, the use of the WL-MRA concept to analyze TG data and make

them compatible with the 30+ years altimetry record, shows the strength of spectral methods and how they can be optimally combined with collocation in order to take advantage of heterogeneous data for VRF determination. Finally, the concept of the m-VDP problem is presented for the first time in such a coherent way referring to one regional Multiple LVDS based on several TG stations linked through different, heterogeneous and of varying quality data.

The research contributions of the candidate are very well and clearly presented in Chapter IV, Section 2 where they are analyzed extensively in terms of contributions to:

- The development of the methodology for improved VRF determination
- The Definition of the new concept of m-VDP and its numerical solution, evaluation and validation
- The determination of the offset between TGs solely from altimetry
  and
- The fact that based on the realization of the KSA VRF with the m-VDP and the combination of heterogeneous data no offset between the two coasts of the Kingdom exists.

4. Critical remarks

No major critical remarks on the PhD Thesis.

Given all the research work carried out during the last decade within IAG, starting from GOCE and continuing to the IHRS, one major question stemming from the thesis is:

"The presented scenario and scheme can be considered a laboratory one, given that the data wealth, availability and quality is (most probably) unique worldwide. How does the candidate propose that similar problems, i.e. definition of the VRFS/VRF, connection of local VRFs to a regional one and contribution to the IHRF, can be addressed elsewhere? What is the proposed data setup, methodology to be applied, quality control and results that can be achieved?

In most countries gravity data are insufficient and data back to the '50s, with accuracies to the 3-5 mGal level. GNSS is scarce and does cover only low-terrain regions. Levelling shows significant tilts and the original temperature and gravity information (if collected in sync) is not available, while information on tidal corrections are absent. Islands are not connected to the mainland. What should be a proposed scenario for such a real world case?"

5. Contributions of the PhD Thesis

As already mentioned, the research contributions of the candidate are very well and clearly presented in Chapter IV, Section 2 where they are analyzed extensively in terms of contributions to:

- The development of the methodology for improved VRF determination
  This contribution is significant and novel, as it has only been attempted during the last 4 years worldwide. The thesis proposes adequate and specific recommendations how the developed

methodology can be efficiently utilized for geo-potential numbers/orthometric heights and their accuracy estimations. Moreover, it reaches a mean value of the SST estimates between altimetry and TG data at the 1.6 cm level, resulting in an average shift across the country at the 7 cm level only. Given the extend of the country in the west-east direction (~2500 km) this is a result of astonishing relative accuracy.

- The Definition of the new concept of m-VDP and its numerical solution, evaluation and validation.
  To the reviewer's knowledge this is the first practical definition of this vertical datum problem, while it is the first time its has been proven that the m-VDP definition if reliable, i.e., it results in consistent results, which introduce small biases and tilts in the defined VRF. This has been possible in the frame of the present thesis, given the high-quality data and proper processing carried out by the Candidate.

- The determination of the offset between TGs solely from altimetry
  In the frame of the thesis a complete set of altimetry data spanning over 30+ years has been considered. They have been used to determine, without any other external information, height and geopotential differences between the KSA TGs, which when compared with TG GNSS and levelling data show astonishing coherence and agreement.

- The fact that based on the realization of the KSA VRF with the m-VDP and the combination of heterogeneous data no offset between the two coasts of the Kingdom exists.
  This is a very important contribution, since it shows that not only the proposed methodology can be applied to define a new VRF for a country, but it can be also used in order to eliminate long lasting tilts in existing VRFs due to systematics in levelling data and inconsistences in the combination of TG MSL records.

Finally, it is important to point out that the above main contributions, have not only theoretical value but also practical ones. As already mentioned, IAG is striving during the last decade to formulate, design, define and implement an IHRF and provide the ties between local and regional VRFs among neighboring countries and to the WHS. In that sense, the present PhD Thesis has clear applications to nowadays geodetic research and surveying applications. It can be utilized in large scale engineering works, spanning countries and continents, while it can assist islandic nations to connect their local realizations of many VRFs to a common, coherent, consistent and accurate national datum. Finally, the proposed approaches, and most importantly the m-VDP can be used in order to study and identify existing offsets and tilts in the current vertical datums, and practically eliminate them, thus providing unbiased and free of long-wavelength errors heights.

6. Conclusive remarks

The PhD Thesis is of high-quality in terms of the scientific content, the presented material, the theoretical background, the numerical results, the use of the English language and structure. It has an intuitive way of communicating the basic goals, assumptions made, theoretical concepts needed for its conclusion and summary of data used. In terms of the goals set, the main aim is clearly set from the

beginning. To my personal knowledge and perspective, the overall concept presented and the work carried out, is a first ever try to combine in a coherent way all this multitude of data and information and try to reach a high-accuracy determination of the KSA VRF and its connection to the WHS in terms of both height and potential differences. The concept of the m-VDP problem is presented for the first time in such a coherent way referring to one regional Multiple LVDS based on several TG stations linked through different, heterogeneous and of varying quality data. It has not only research novelty and merit, but also direct practical applications.

7. Final statement

Based on the above review, the PhD Thesis of Mr. Othman Al-Kherayeff meets the quality criteria and requirements foreseen for a Doctoral work. I would therefore recommend, with flying colors, to the scientific jury to award to Mr. Othman Al-Kherayeff the degree of Doctor of Philosophy (PhD degree).

March 04, 2020

Prof. Dr. Georgios S. Vergos

Залитаване на данни
съгласно Сл. 2 от ЗЗЛД