IAG Project - Novel Sensors and Quantum Technology for Geodesy (QuGe)

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Vice President: Marcelo Santos (Canada)

QuGe website - www.quge.iag-aig.org

1 Terms of Reference

The advancements in quantum physics over the past decade have ushered in a new era of possibilities, particularly in satellite geodesy and terrestrial gravity sensing. The IAG Project Novel Sensors and Quantum Technology for Geodesy (QuGe) harnesses these breakthroughs alongside innovative measurement concepts. It is a collaborative project between physics and geodesy, which aims to leverage quantum technology's potential for a myriad of groundbreaking applications in geodesy. Changes in the Earth system manifest in mass variations, spanning the hydrosphere, geosphere, and atmosphere. These changes are intricately linked to gravitational data, necessitating higher resolution and accuracy, the highest are achievable only through quantum technology. Stable reference systems, crucial for monitoring Earth's dynamic processes, rely heavily on precise timekeeping, marking clocks as pivotal components in future endeavors. The QuGe project stands as a unique platform for developing and testing novel concepts and observation systems, with potential applications extending to exploration and navigation.

Synergies of technology development with geodetic and geophysical modeling are imperative. Optical ranging, atom-interferometric accelerometry, and chronometric levelling are proposed methods to overcome limitations in traditional geodesy [1]. These innovative techniques promise unparalleled accuracy in observing mass variations across various spatial and temporal scales, thus, facilitating applications ranging from groundwater basin monitoring to understanding global mass transport in oceans.

QuGe, with its fusion of quantum physics and geodesy expertise, bridges engineering prowess with fundamental research, propelling the boundaries of gravimetric Earth observation and reference system realization.

1.1 Objectives

The objectives are grouped into three primary areas, reflecting its working groups:

1. Atom interferometry for ground-based and space-based gravimetry (quantum gravimetry) will offer a wide range of applications. This includes rapid local gravimetric surveys, exploration activities, and the monitoring of gravimetric Earth system processes with exceptional spatial and temporal resolution. In space, atom interferometry will revolutionize accelerometry and inertial sensing. Combining atom

interferometry with electrostatic accelerometers in hybrid systems could broaden the spectral range for future inertial sensing and navigation endeavors. Its impact will extend to satellite navigation enhancement and the development of next-generation gradiometer missions (such as GOCE follow-on).

2. Laser-interferometric ranging between test masses in space, with nanometer precision, represents another groundbreaking development. This technology, originally designed for gravitational wave detection and validated in missions like LISA/Pathfinder, is being adapted for geodetic measurements, as demonstrated by GRACE-FO. Further refinements, such as tracking satellite swarms, may become feasible in the coming years. Optical techniques may also find application in future accelerometers for test mass sensing and advanced space-based gradiometry.
3. Frequency comparisons of highly precise optical clocks interconnected via optical links offer insights into differences in gravity potential over significant distances (relativistic geodesy). In the future, relativistic geodesy employing clocks will re-assess how height systems are defined and realized, both locally and globally. Clock measurements will also furnish long-wavelength gravity field data and enhance the accuracy of the International Atomic Time standard (TAI). They are crucial for all space geodetic techniques and for establishing and connecting reference systems. Additionally, high-performance clock networks could support Global Navigation Satellite Systems (GNSS).

In all three research domains, alongside with the advancements in measurement systems and techniques, it is imperative to establish robust theoretical foundations for analysis models. This necessitates dedicated geodetic and relativistic modeling of the various gravity field parameters and measurement concepts involved.

1.2 Program of Activities

The IAG project QuGe fosters and encourages research in the areas of its working groups by facilitating the exchange of information and organizing workshops and sessions, either independently or at major inter-disciplinary conferences such as EGU, AGU, COSPAR, IAG Scientific Assembly and Symposia, and IUGG General Assembly. QuGe will endeavour to improve its visibility and demonstrate the benefit of the new technologies in geodesy and beyond.

Within its scope, QuGe will continue contributing to related research activities and missions studied and pushed forward by NASA, ESA, EU and national programs on the use of quantum technology. Examples are the missions MAGIC, CARIOQA, ACES. QuGe will strengthen the contacts to industry, enabling good exchange with science, while the major focus of QuGe will remain on research.

The activities of its working groups, as described below, constitute the activities of the Project, which will be coordinated by the Steering Committee and summarized in annual reports to the IAG Bureau.

Project QuGe and its WGs will closely collaborate with other components of IAG such as specific Joint Study/Working Groups of the IAG commissions, ICCC and ICCT as well as with related services like IERS. Moreover, representatives of external bodies (e.g., from industry or research institutions) will collaborate in the WGs.

1.3 Structure

Working Groups

WG Q.1 Quantum gravimetry in space and on ground
Chair: Franck Pereira (France)
WG Q.2 Laser interferometry for gravity field missions
Chair: Samuel Francis (USA)
WG Q.3 Relativistic geodesy with clocks
Chair: Jakob Flury (Germany)

1.4 Steering Committee

The steering committee will meet at least twice per year.

- President: Jürgen Müller (Germany)
- Vice President: Marcelo Santos (Canada)
- Chairs of WG Q.1: Franck Pereira (France), Marvin Reich (Germany)
- Chairs of WG Q.2: Samuel Francis (USA), Kirk McKenzie (Australia)
- Chairs of WG Q.3: Jakob Flury (Germany), Pacôme Delva (France)
- Representative of IAG Comm. 1: Urs Hugentobler (Germany)
- Representative of IAG Comm. 2: Srinivas Bettadpur (USA)
- Representative of IAG Comm. 3: Rebekka Steffen (Sweden)
- Representative of IAG Comm. 4: Allison Kealy (Australia)
- Representative of Early Career Scientists: Öykü Koç (Italy)
- Representative of IGFS: Sylvain Bonvalot (France)
- Representative of GGOS: George Vergos (Greece)
- Representative of IHRF: Laura Sánchez (Germany)
- Member at large: Wenbin Shen (China)
- Member at large: Claudia Tocho (Argentina)

2 Working Groups

WG Q.1: Quantum gravimetry in space and on ground

Chair: Franck Pereira (France)
Vice-Chair: Marvin Reich (Germany)

Terms of Reference

On ground, quantum sensors based on matter wave interferometry with cold atoms are very well suited for rapid and very precise gravity sensing. They can be used as registration instruments and as absolute gravimeters with sub-µGal accuracy. Mobile devices are developed for field campaigns and large-scale stationary devices for achieving extreme precision. While the former enable new strategies for local and regional gravity surveys, the latter will provide a new gravity standard in the future. In space, the long-term stability and low noise level of quantum sensors will allow improving the spatial gravity field models in GOCE-type gradiometer missions. The determination of mass transport processes on Earth at low and medium degrees in GRACE-type missions will benefit from quantum accelerometers providing measurement of the specific non-conservative forces. In addition, hybrid systems (i.e. a combination of electrostatic and atom-interferometric accelerometers) can cover a wider spectral range, which will greatly support navigation and inertial sensing on ground and in space. The goal of this WG is to elaborate the major benefits and most promising applications of atom interferometry for gravimetry and inertial sensing in space and on ground.

Objectives

- Terrestrial quantum gravimeters and applications scenarios (including airborne and marine instruments);
- (Hybrid) accelerometers for space missions and spacecraft navigation;
- Atom interferometric gradiometry;
- Elaboration of further applications (like atmosphere research, relativity tests, etc.) and corresponding space demonstrators (e.g., pathfinder missions);
- Elaboration of synergies among different science topics in a single mission (Earth observation and fundamental physics, navigation and space exploration, several scenarios for Earth observation, e.g. gravimetry, atmospheric research and magnetometry).

Members

Franck Pereira (France); Chair
Marvin (Reich); Vice-Chair
Roland Pail (Germany)
Ernst Maria Rasel (Germany)
Thomas Lévèque (France)
Oliver Carraz (Netherlands)
Steffen Schön (Germany)

Yuichi Imanishi (Japan)
Jeffrey Kennedy (USA)
Shuqing Wu (China)
Nan Yu (USA)
Andre Gebauer (Germny)
Markus Krutzik (Germany)
Bastian Leykauf (Germany)
Ashton Flinders (USA)
Rainer Dumke (Singapore)
Nassim Zahzam (France)
Przemyslaw Dykowski (Poland)
Brynle Barrett (Canada)
Federica Migliaccio (Italy)

WG Q.2: Laser interferometry for gravity field missions

Chair: Samuel Francis (USA)
Vice-Chair: Kirk McKenzie (Australia)

Terms of Reference

GRACE has excellently demonstrated the great potential of inter-satellite tracking to determine time-variable gravitational signals which are related to mass transport processes in the Earth system. Examples are ice mass loss in Greenland and Antarctica, ground water loss in Asia, droughts in USA, quantification of the global water cycle, mass contribution to sea level rise, mass variation due to land uplift in North America and Scandinavia, or mass changes related to earthquakes. To increase the resolution and to extend the time series, GRACE Follow-On (GRACE-FO) was launched in May 2018, carrying as demonstrator a Laser Ranging Interferometer (LRI) which is able to approach an accuracy of tens of nm for inter-satellite ranging.

The GRACE-FO LRI continues to operate in-orbit with performance well below requirements. No signs of optical contamination or degradation have been seen after 5 years of operation and there have been few unplanned interruptions to tracking. Gravity fields derived from LRI are consistent with those derived from primary microwave instrument, while offering improved performance at high frequencies. The LRI will be the primary instrument on the NASA/ DLR GRACE Continuity (GRACE-C) mission. Optical sensing of the motion of test masses in the gravitational field with nanometer accuracy and beyond can be realized in various measurement concepts such as in ranging between satellites like in GRACE-FO or future swarms of satellites. Further concepts apply LRI for sensing single test-mass motion (accelerometry) or multiple test-mass constellations within one satellite (GOCE-type gradiometry). The overall goal of this WG is to study novel concepts including optical sensing for inter-satellite tracking, accelerometry and gradiometry, and its applications for next generation gravity field missions.

Objectives

- Interferometric Laser Ranging between swarms of satellites;
- Accelerometry with optical readout and application scenarios;
- Gradiometry with optical readout;
- Hybrid sensors and measurement concepts;
- New concepts for future satellite gravity missions.

Members

Samuel Francis (USA); Chair
Kirk McKenzie (Australia); Vice-Chair
Michael Murböck (Germany)
Robert Spero (USA)
Vitali Müller (Germany)
Gerhard Heinzel (Germany)
Jürgen Kusche (Germany)
Felix Landerer (USA)
David Wiese (USA)
Peter Bender (USA)
Gilles Metris (France)
Christophe Le Poncin-Lafitte (France)
Shuanggen Jin (China)
Christopher Woodruff (USA)
Brent Ware (USA)
Frank Flechtner (Germany)
Markus Hauk (Germany)
Thomas Papanikolaou (Denmark)
Andrew Wade (Australia)
Emily Rose Rees (Australia)
Clément Courde (France)
Julien Chabé (France)
Julie Rolla (USA)

WG Q.3: Relativistic geodesy with clocks

Chair: Jakob Flury (Germany)
Vice-Chair: Pacôme Delva (France)
Consultant from Physics: Christian Lisdat (Germany)

Terms of Reference

Optical clocks are sensitive to the gravity potential in which they are operated. The comparison of two clocks will reveal a frequency offset from the value expected from side-by-side comparisons, that can directly be related to the potential difference between both clocks. The best optical clocks now reach resolutions of better than 0.1 m^2/s^2, transportable ones about 1 m^2/s^2. They can be achieved already after few hours of averaging.

We will evaluate how this technique can be used to generate unified and long-term stable height networks and reference systems. This includes discussing the feasibility of realizing a datum by reference to e.g., a space-borne clock with ideally negligible gravitational interference. Future clock networks might also be used as ground-truth for space missions or even to bridge gaps in satellite observations.

Other aspects to be addressed are the application of observed time-variable signals in de-aliasing of satellite observations. Sensor fusion concepts will be discussed to utilize the different spatial integration characteristics of clocks and other gravity sensors so as to disentangle local and extended signal sources.

In summary, the goal of this WG is to use clock measurements for determining differences of physical heights and gravity potential for various geodetic applications.

Objectives

- Clock networks for unification of height systems;
- Gravity field recovery on ground;
- Application to realize reference systems, including dedicated space clocks;
- Further applications (height/potential variations);
- Potential satellite missions for long-wavelength gravity field recovery, including optical links for comparing the space clocks.

Members

Jakob Flury (Germany); Chair
Pacôme Delva (France); Vice-Chair
Christian Lisdat (Germany)
Claude Boucher (France)
Davide Calonico (Italy)
Pascale Defraigne (Belgium)
Ropesh Goyal (India)
Jochen Kronjäger (Germany)
Hua Guan (China)
Chris Hughes (UK)
Sergei Kopeikin (USA)
Jürgen Kusche (Germany)
Claus Lämmerzahl (Germany)
Marie-Françoise Lequentrec (France)
Guillaume Lion (France)
Andrew Ludlow (USA)
Helen Margolis (UK)
Elena Mazurova (Russia)
Nathan Newbury (USA)
Bijunath Patla (USA)
Nikos Pavlis (USA)
Paul-Eric Pottie (France)
Ulrich Schreiber (Germany)
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Simon Stellmer (Germany)
Yoshiyuki Tanaka (Japan)
Giulio Tagliaferro (France)
Pieter Visser (Netherlands)

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