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

President: **Jürgen Müller**, Germany
Vice President: **Marcelo Santos**, Canada

http://quge.iag-aig.org

Terms of Reference

The novel developments in quantum physics of the previous decade, including new technologies and related measurement concepts, will open up enhanced prospects for satellite geodesy, terrestrial gravity sensing and reference systems. In close collaboration between physics and geodesy, this new IAG project shall exploit the high potential of quantum technology and novel measurement concepts for various innovative applications in geodesy.

Climate change often is reflected in mass variations on Earth. And, many mass change processes in the hydrosphere, geosphere and atmosphere are widely imprinted in gravitational data. However, gravitational data with better spatial-temporal resolution and higher accuracy is required, which can only be achieved by employing innovative quantum technology concepts. Highly stable and accurate reference systems provide the fundamental backbone to monitor the change processes in the Earth system, where clocks will play a central role in the future.

QuGe will serve as a unique platform for developing and evaluating those novel concepts and observation systems, where also further applications, like in exploration and navigation, may benefit. Technology development and space mission requirements have to be linked to geodetic and geophysical modelling in a synergetic way.

Optical ranging between test masses in satellites, atom-interferometric accelerometry and gradiometry, and chronometric levelling with clocks are the needed approaches to overcome the problems of classical concepts in geodesy. With these novel techniques, mass variations on almost all spatial and temporal scales can be observed with unprecedented accuracy and will serve as input for a multitude of applications in geosciences, from the monitoring of smaller groundwater basins and geodynamic effects to the observation of the complex global mass transport processes in the oceans.

The combination of expertise from quantum physics and geodesy in QuGe, integrating engineering skills and fundamental research, serves as an excellent basis to advance the frontiers of gravimetric Earth observation and the realization of reference systems.

Objectives

QuGe will put its focus on three major pillars

1) Atom interferometry for gravimetry on ground and in space (quantum gravimetry) will allow for a comprehensive set of applications, such as fast local gravimetric surveys and exploration, or the observation of gravimetric Earth system processes with high spatial and temporal resolution. In space, atom interferometry will enable accelerometry and inertial sensing in a modernistic way. The use of atom interferometry in hybrid systems with electrostatic accelerometers may allow to cover a wide spectral range for future inertial sensing and navigation. It will benefit satellite navigation, but also serve as a basis for developing the next generation of gradiometer missions (GOCE follow-on).
2) Laser-interferometric ranging between test masses in space with nanometer accuracy belongs to these novel developments as well, where technology developed for gravitational wave detection and successfully tested in the LISA/pathfinder mission is being prepared for geodetic measurements. GRACE-FO already demonstrates this new development. Even more refined concepts, like tracking a swarm of satellites, might be realized within the next years. Optical techniques may also be applied for test mass sensing in future accelerometers, and even combined to next generation gradiometry in space.

3) Frequency comparisons of highly precise optical clocks connected by optical links give access to differences of the gravity potential over long distances (relativistic geodesy). In the future, relativistic geodesy with clocks will be applied for defining and realizing height systems in a new way, locally as well as globally. As further application, clock measurements will provide long-wavelength gravity field information. Moreover, accurate clocks help to improve the accuracy of the International Atomic Time standard TAI. They are important for all space geodetic techniques as well as for the realization of reference systems and their connections. Another application example is the possible use of high-performance clock networks to support GNSS.

In all three research areas, along with the research on measurement systems and techniques, the analysis models have to be put on a sound theoretical basis. This requires dedicated geodetic and relativistic modelling of the various involved gravity field quantities and measurement concepts.

Structure

Working Groups:

WG Q.1: Quantum gravimetry in space and on ground
WG Q.2: Laser interferometry for gravity field missions
WG Q.3: Relativistic geodesy with clocks

Steering Committee

President: *Jürgen Müller* (Germany)
Vice-President: *Marcelo Santos* (Canada)
WG chairs: *see below*
Representatives of the four Commissions:
IAG Comm. 1: *Erricos Pavlis* (USA)
IAG Comm. 2: *Adrian Jäggi* (Switzerland)
IAG Comm. 3: *Federica Migliaccio* (Italy)
IAG Comm. 4: *Suelynn Choy* (Australia)
Representatives of Services:
IGFS: *Sylvain Bonvalot* (France)
GGOS: *Ulrich Schreiber* (Germany)
Members-at-large:
Wenbin Shen (China)
Gabriel Guimarães (Brazil)

Representative of External Bodies

Partly already proposed as members of the WGs. Additional members, e.g., from industry could be *A. Bresson* (ONERA), *S. Seidel* (OHB), *B. Desruelle* (MuQuans) and others.

Working Groups of the Project

The new WGs will closely collaborate with other components of IAG such as

- IAG SC 2.6 "Gravity and Mass Transport in the Earth System" (*Wei Feng*, Wuhan China)
- IAG SC 2.3 "Satellite Gravity Missions" (*Frank Flechtner*, Potsdam, *Matthias Weigelt*, Hannover, Germany)
- IAG Inter-Commission Committee on Geodesy for Climate Research – *Annette Eicker*, *Roland Pail*, Munich, Germany
- Further collaborations, e.g., with ICCT, IERS, WG on IHRF, JWG on IGRF, etc. will be fixed after start.

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

Chair: *Franck Pereira* (France)
Vice-Chair: *Michele van Camp* (Belgium)

Description

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 the 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 benefit 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 / space demonstrator (e.g. pathfinder) like atmosphere research, relativity tests, etc.
- Elaboration of synergies between 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 (preliminary)

R. Pail (TU Munich)
A. Landragin (Syrte Paris)
P. Bouyer (LP2N Bordeaux)
E. Rasel (LUH Hannover
C. Schubert (LUH Hannover)
T. Lévèque (CNES Toulouse)
O. Carraz (ESA)
L. Mondin (ESA)
A. Rülke (BKG Frankfurt)
M. Krutzik (HU Berlin)
F. Migliaccio (Univ. Milano)
M. Reguzzoni (Univ. Milano)

WG Q.2: Laser interferometry for gravity field missions

Chair: *Michael Murböck* (Germany)
Vice-Chair: *Bob Spero* (USA)

Description

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-FO was launched in May 2018 also carrying a Laser Ranging Interferometer (LRI) as demonstrator which is able to approach an accuracy of tens of nm for inter-satellite ranging.

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 for 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 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
- New concepts for future satellite gravity missions

Members (preliminary)

V. Müller (AEI Hannover)
G. Heinzel (AEI Hannover)
J. Kusche (Uni Bonn)
F. Landerer (JPL Pasadena)
D. Wiese (JPL Pasadena)
P. Bender (JILA Boulder)
G. Metris (OCA, France),
Ch. Le Poncin-Lafitte (Syrte Paris)
S. Jin (Shanghai China)
M. Rothacher (ETH Zurich)
B. Spero (JPL Pasadena)
C. Woodruff (JPL Pasadena)
F. Flechtner (GFZ Potsdam)

WG Q.3: Relativistic geodesy with clocks

Chair: *Gerard Petit* (France)
Vice-Chair: *Jakob Flury* (Germany)
Consultant from Physics: *Christian Lisdat*, Braunschweig, Germany

Description

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 0.1 m^2/s^2, transportable ones about 2 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 will include discussion about the feasibility to realize a datum by reference to a, e.g., 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. In cooperation with the two previous WGs, sensor fusion concepts will be discussed to utilize the different spatial integration characteristics of clocks and the other gravity sensors to disentangle local and extended signal sources.

In summary, the goals of this WG are using clocks 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 (preliminary)

N. Newbury (NIST Boulder)
A. Ludlow (NIST Boulder)
P. Delva (Syrte Paris)
P. Visser (TU Delft)
H. Margolis (NPL Teddington)
D. Calonico (INRIM, Torino)
C. Lämmerzahl (ZARM Bremen)
W. Shen (Wuhan, China)
U. Schreiber (GO Wettzell)
M. Santos (Uni New Brunswick)
S. Kopeikin (Uni Missouri)
N. Pavlis (NGA, USA)
P. Pottie (Obs de Paris)
S. Merlet (Obs. de Paris/Syrte)
E. Mazurova (MIGAIK, Moscow)
S. Stellmer (Uni Bonn)
J. Kusche (Uni Bonn)
Y. Tanaka (Tokyo Japan)
Hua Guan (WIPM, Wuhan, China)