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ESA Activities and Perspectives on Quantum Space Gravimetry

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ESA Activities and Perspectives on Quantum Space Gravimetry

Olivier Carraz *[a], Luca Massotti [b], Aaron Strangfeld [b], Arnaud Heliere [b], Ilias Daras [b], Pierluigi Silvestrin[b]
[a]RHEA for ESA, European Space Agency, ESA/ESTEC Keplerlaan 1, PO Box 299 NL-2200 AG Noordwijk, The Netherlands; [b] European Space Agency, ESA/ESTEC Keplerlaan 1, PO Box 299 NL-2200 AG Noordwijk, The Netherlands

ABSTRACT

In the past twenty years, gravimetry missions have demonstrated a unique capability to monitor major climate-related changes of the Earth directly from space – among others quantifying the melt of large glaciers and ice sheets, global sea level rise, continental draught and major flooding events. A Quantum Space Gravimetry (QSG) mission will provide corresponding Essential Climate Variables (ECV) with unprecedented quality compared to the initially demonstrated and already very successful missions like GOCE and GRACE (FO). To respond to the increasing demand of the user community for sustained mass change observations at higher spatial and temporal resolution, ESA and NASA are coordinating their activities and harmonizing their cooperation scenarios in an implementation framework, called MAGIC (MAss change and Geosciences International Constellation). In a future post-MAGIC mission, classical sensors can be combined with a Cold Atom Interferometry (CAI) instrument, or at a later stage a full quantum sensor could be employed. These Quantum Missions for Climate will reach sensitivities, which enable many applications addressing user needs with respect to water management and hazard prevention among others. Several studies related to these new sensor concepts were initiated at ESA, including technology development for different instrument configurations and validation activities. A new study has been initiated, the Quantum Space Gravimetry for Earth Mass Transport (QSG4EMT), with the focus on both, QSG mission architectures for monitoring of Earth's mass transport processes and the development of QSG user requirements.

Keywords: Atom interferometry, Quantum sensor, Gravity, MAGIC

1. INTRODUCTION

Sustained observations via dedicated satellite gravity missions (e.g., GOCE [1], GRACE [2] and GRACE-FO [3]) are crucial for monitoring the dynamic processes in the Earth system related to mass transport and for understanding their coupling mechanisms. Satellite gravimetry is unique in that it observes the entire integrated water column, allowing detection of variations in subsurface groundwater storage or subglacial water mass exchange. These are generally difficult to detect with other remote sensing techniques. It also contributes to the quantification of all relevant processes of the global water cycle, so that their contribution to sea level rise can be directly assessed. It is expected that future satellite gravity missions will provide enhanced sustained observations with higher spatio-temporal resolution and accuracies on one hand and new products that could directly be incorporated in operational services such as early warning of hydrological extremes and geohazard monitoring on the other [4]. Moreover, the improved measurements are also expected contribute to the improvement of ECV with unprecedented quality for groundwater as well as unique measurements on climate applications, Earth energy balance closure, sea level change, mass balance of ice sheets and glaciers and heat and mass transport.

The largest error contributor of state-of-the-art missions that monitor the time-variable gravity field (e.g. GRACE and GRACE-FO) is the effect of aliasing that results from the observation geometry and the resulting spatiotemporal sampling of the gravity signal. The ESA/NASA MAGIC mission concept, based on NGGM (Next Generation Gravity Mission) studies [5], is a well-designed satellite constellation that aims to tackle this limitation. The next largest error contributor with this architecture are the accelerometers. The ones used in gravity missions so far exhibit relatively high noise at low frequency. Analysis of GOCE-like architectures using gradiometers shows that the accuracy of state-of-the-art instruments is also orders of magnitude worse than what is required for observing temporal changes in gravity.

*olivier.carraz@ext.esa.int; phone +31 71 565 3714; esa.int

Following the example of MAGIC/NGGM, subsequent satellite gravimetry missions shall further improve the spatiotemporal sampling to a level that will require the exploitation of novel satellite sensor technologies, which need to go through technological maturation. QSG measurement techniques hold the promise of substantially improving on current technologies since they can provide absolute measurements with no drifts and thus lower noise at low frequencies. For example, CAI-based quantum sensors promise exceptional sensitivity under nanogravity conditions.

Earth Observation (EO) exploiting the “Second Quantum Revolution” covers several sub-domains in relation to potential sensing techniques (e.g. QSG, Quantum Magnetometry, Quantum Radio Frequency Sensing). Activities related to QSG have been performed for the last 10 years aiming at the next step advance in gravity monitoring and efforts continue to pursue the long-term goal of a Quantum Gravity Gradiometer (QGG) more performant than the classical gradiometer of GOCE [6]. For this, the ESA-developed QGG concept is a reference worldwide [7][8]. However, the near-term goal is to generate better gravimetry data for science and applications by improving current space accelerometry. Extensive studies and simulations have shown that an acceleration measurement sensitivity < 0.1 nm/s^2 is required to have a relevant impact [9][10]. Therefore the immediate next step is the demonstration of this level with CAI sensors. Such sensitivity can only be achieved in space, when the instrument is in free falling and allows long interrogation time. On ground, sensitivity up to 1 nm/s^2 has been proven and therefore any potential in-orbit demonstrations shall achieve a better sensitivity to allow confidence into implementation of a QSG. This goal is coherent with the overall development of MAGIC/NGGM since without a constellation even the most performant quantum sensor does not add value for EO due to the dominating geophysical sampling errors and since platform aspects remain largely similar. ESA has followed this direction across various Directorates for over a decade. and aligning discussions with the European Commission (EC) are ongoing, to define a related roadmap for a European QSG Pathfinder Mission. A mission statement and objectives for such European QSG Pathfinder Mission are under preparation with both ESA and EU Member States.

2. COLD ATOM INTERFEROMETRY AND RELATED INSTRUMENT CONCEPTS

Cold Atom interferometers rely on the wave-particle duality, which allows matter waves to interfere, and on the superposition principle. They can be sensitive to inertial forces. In a Chu-Borde interferometer the test mass is a cloud of cold atoms, which is obtained from a Magneto-Optical Trap (MOT) by laser cooling and trapping techniques. This cloud of cold atoms is released from the trap and its acceleration by external forces is measured using an atom interferometry technique. A Chu-Borde interferometer consists of a sequence of three equally spaced Raman laser pulses [11], which drive stimulated Raman transitions between two stable states of the atoms. In the end, the proportion of atoms in the two stable states depends sinusoidally on the phase of the interferometer, which is proportional to the acceleration of the atoms along the Raman laser axis of propagation in the reference frame defined by the Raman mirror. This Chu-Borde interferometer can be extended to any kind of inertial sensor such as a gravimeter [12], a gyroscope [13] or a gravity gradiometer [14].

In a double diffraction scheme (see Fig. 1) the Chu-Borde interferometer allows to enlarge the sensitivity by a factor of 2, and to suppress parasitic effects at first order such as the light shift or the magnetic field, as the atoms remain in the same internal state [15][16].

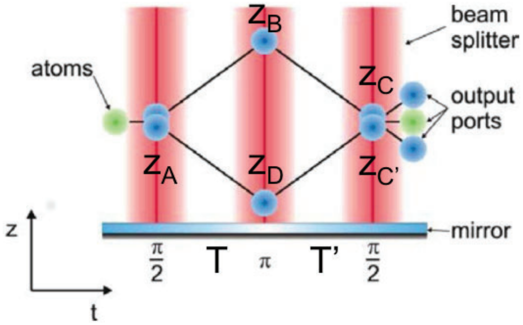

Figure 1: The double diffraction scheme for one cloud of atoms. Figure from [17]

CAI Interleaved Gravity Gradiometer Instrument:

It is possible to suppress non-gravitational forces by measuring different atom interferometers simultaneously [14][18]: Fig. 2 describes the gravity gradiometer concept in one dimension. This one-dimensional concept consists of measuring one diagonal element of the gravity tensor (V_{zz}). It can be extended to the other two dimensions to obtain all diagonal elements of the gravity gradient tensor. Full description of this instrument and a more detailed trade-off on the noise sources of the instrument have been done in [6][7].

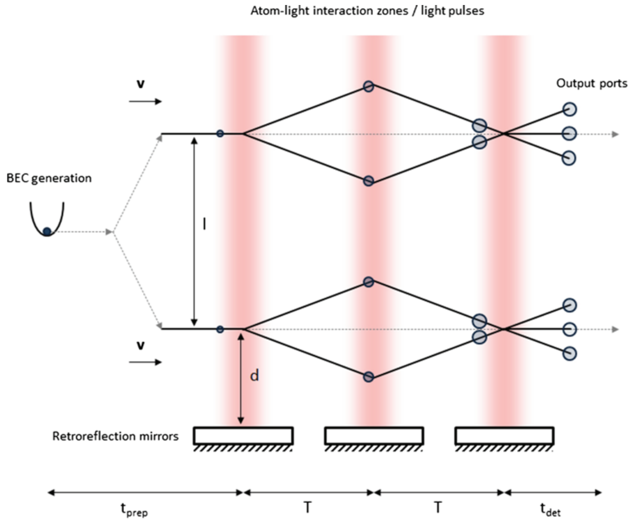

Figure 2: CAI Interleaved Gravity Gradiometer concept [8]

The concept of a CAI gravity gradiometer was further investigated in several ESA studies focusing on the instrument and mission concept as well as studies supporting technological developments needed for the instrument (vacuum chamber, laser system, etc.). Considering that the interferometer noise is limited by the quantum projection noise with $N=10^6$ atoms (i.e. an interferometer phase noise proportional to $1/N^{1/2}$ per shot), the performance expected for such an instrument is a white noise of 4.7 $mE/Hz^{1/2}$ in the frequency measurement bandwidth below 1/(2T), where T is the time between the laser pulses. Above 1/(2T) the sensitivity grows in $f^{1/2}$. This offers a large advantage over the electrostatic gravity gradiometer of the GOCE mission, which has a flat noise amplitude spectral density of 10−20 $mE/Hz^{1/2}$ in the frequency range 2−100 mHz and a large increase of the noise amplitude spectral density below 2 mHz. Mission simulations [8] suggest that a yearly mission with a CAI gravity gradiometer would provide the same or even better performance than the GOCE mission (Fig. 3), noting that not only the instrument performance, but also the duration of the mission and the altitude of the orbit are performance drivers. Although this concept may improve the mean gravity field knowledge of the Earth, it will still require and improvement of 2-3 orders of magnitude in the sensitivity instrument to be able to measure time variable gravity field [8].

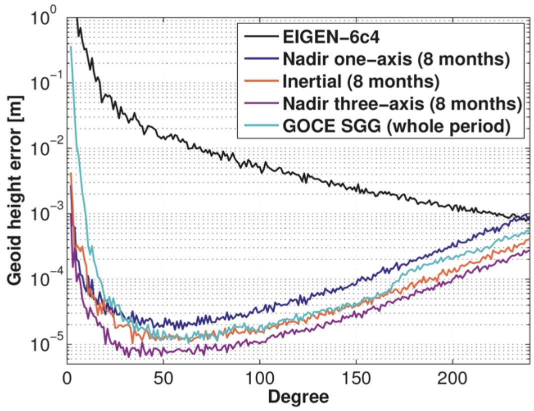

Figure 3: Comparison of geoid retrieval with different configurations. Duration of the mission was 8 months, compared to the full mission of 3 years for GOCE. 2 orientations for the spacecraft was considered, inertial mode (which relaxes constraints on the rotation) and nadir mode with one-axis (along z) instrument or 3-axis instrument. More information on [7][8].

Hybrid atom-electrostatic system for satellite gravimetry:

Another instrument concept is more suitable for MAGIC/NGGM type mission concepts based on a laser interferometer ranging system in a Low-Low Satellite-Satellite-Tracking (SST) configuration and measurement of non-gravitational forces. Inertial sensing technologies relying on electrostatic forces or on CAI are identified as very good candidates. Each of these two types of instruments have their own assets, which are, for electrostatic accelerometers (EA), their demonstrated short-term sensitivity and their maturity regarding space environment. For CAI the assets are, amongst others, the absolute nature of the measurement and a white noise spectrum even in the low frequency range and therefore no need for calibration processes. Leveraging the complementary properties, a hybrid sensor could improve the performance with reduced development effort compared to a full CAI approach. This technique can correct the spectrally colored noise of the electrostatic accelerometers in the lower frequency range. To realize this hybridization, the mirror used for Raman transitions should be placed on the proof mass [9]. Thus, the signal acquired by both instruments remains the same. Both signals can be compared and retroactively calibrate the EA for the low frequencies while maintaining the performances of the EA for the short-term measurements. The results of a proof of concept on ground are shown in Fig. 4.

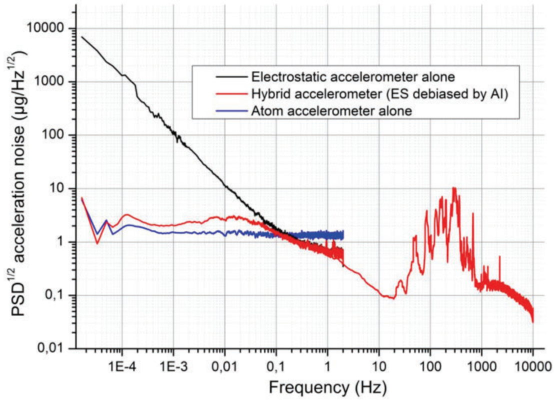

Fig. 4: Performance of the hybrid accelerometer during lab tests. ES: Electro-Static Accelerometer. AI: Atom Interferometer

The impact of a hybrid accelerometer on the time-variable gravity field retrieval is analysed in detail by [10], who finds that the low degree coefficients of the time-variable gravity field could be improved. However, it should be noted that the low degree coefficients are also affected by inaccurately modelled atmosphere and ocean mass transport, partly masking the improvements in the measurement system noise.

3. VALIDATION CAMPAIGN ACTIVITIES

A CAI gravimeter was tested during the CryoVex/KAREN airborne campaign over Iceland in 2017. The flight paths illustrated in Figure 5 included a first return flight from Akureyri to Snaefellsjoekull in the Northwest of Iceland and a grid pattern near Vatnajökull in the Southeast part of Iceland. Despite strong turbulences during the first return flight, the gravimeter's measurements of the outbound agreed very well with those of the return flight, where the differences indicate a measurement precision of 4−5 mGal. For the grid pattern, the airborne measurements showed a good agreement with existing on-ground measurements. The analysis of crossovers of the airborne measurements indicated that a precision of 2 mGal was reached. It was therefore concluded that the first airborne survey using a matter wave gravimeter was successful.

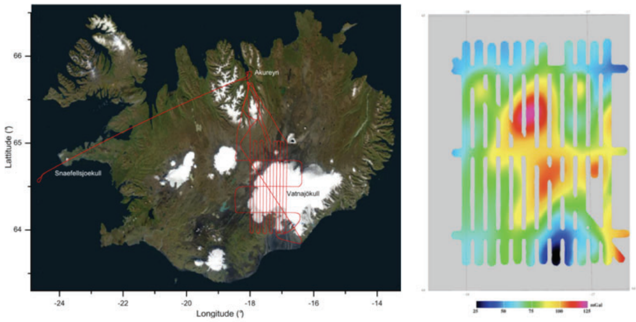

Figure 5: Flight paths over Iceland and gravity measurements.

Another flight gravity campaign was held in April 2019 with a CAI gravimeter previously developed by ONERA with the support of the French Defense Agency (DGA) and with the collaboration of the French Naval Hydrographic and Oceanographic Service (SHOM).This flight campaign is the result of collaboration between CNES, ESA, ONERA, DTU, SHOM, GET and SAFIRE.

Three different areas of interest were identified to realize gravity measurements:

- the **Bay of Biscay** to map a coastal area (interest of sea-ground transition),
- the **Pyrenees** to map a mountainous area,
- the **reference profile** off-shore of Brest used by SHOM for testing and calibrating their gravimeters.

During the flight gravity campaign three different gravimeters were operational, the ONERA GIRAFE 2 CAI gravimeter, the dynamic spring gravimeter TAGS from Lacoste&Romberg and the strapdown iMAR IMU. The last two gravimeters were operated by DTU.

The gravity flight campaign was a success since the CAI gravimeter GIRAFE 2 provided high performance measurements, improving those obtained during the previous flight campaign over Iceland in 2017. GIRAFE 2 seems also to be able to provide similar results as the state-of-the-art IMAR gravimeter with the additional benefit of offering absolute measurements (Fig. 6).

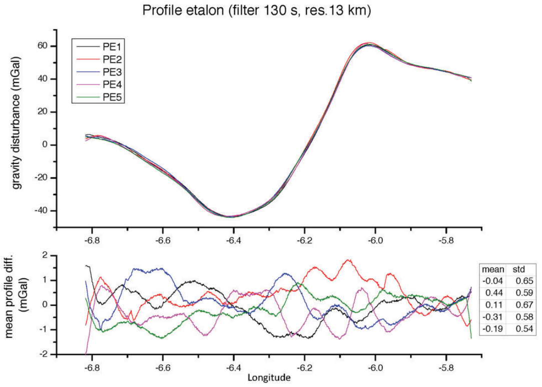

Figure 6: CAI gravity measurement along the reference profile

4. FUTURE ACTIVITIES

The (non-exhaustive) table below shows the QSG supporting activities, including some arising from non-EO applications, realised or planned within EOEP/FutureEO and corporate technology programmes.

Activity	Year	Status	Prime
Hybrid Atom Electrostatic System for Satellite Geodesy	2015-2016	Complete	ONERA (FR)
Study of Cold Atom Interferometry (CAI) Gravity Gradiometer Sensor and Mission Concepts	2015-2018	Complete	Syrte (FR)
Development of Cooling/Raman laser source with enhanced operational features	2016-2018	Complete	Muquans (FR)
Cold Atom Inertial Sensors: Mission Applications	2016-2019	Complete	TAS (IT)
All-optical diffractive element approach to compact, simple, rapid BEC creation in space	2017-2019	Complete	University of Strathclyde (GBR)
Hybrid Atom Electrostatic System for Satellite Geodesy Follow-On	2017-2021	Complete	ONERA (FR)
Hybrid, grating-MOT + magnetic chip trap, approach to compact high frequency BEC production in space	2018-	Ongoing	University of Strathclyde (GBR)
PhD Reaching Heisenberg limit for CAI detection	2020-	Ongoing	LENS (IT)
CAI-Common Optical Optimisation Laboratory (C-COOL)	2020-2022	Complete	LP2N (FR)
CASPA Atmospheric Drag Mission Study	2020-2021	Complete	Teledyne e2v (GBR)
CCN - Compact vacuum chamber for an Earth gravity gradiometer based on laser-cooled atom interferometry	2021-	Ongoing	RAL (GBR)
High Stability Laser Control Module	2021-	Ongoing	RAL (GBR)
Atom Interferometry Chamber for a Compact Gravity Gradiometer in Space	2021-	Ongoing	RAL (GBR)
Quantum Space Gravimetry for monitoring Earth's Mass Transport processes (QSG4EMT)	2022-	Ongoing	TUM (GE)
Development Of a Laser Frequency Stabilisation System For Future Quantum Gravimeter	2022-	Ongoing	iXBlue-MuQuans (Fr)

FutureEO is ESA's core Earth observation research and development programme, fundamental to laying the foundations for innovative space technologies, implementing state-of-the-art satellite missions, and delivering the scientific excellence of the future. MAGIC/NGGM, the first Mission of Opportunity in the FutureEO programme is a joint constellation with NASA, based on SST and precision classical accelerometry with two pairs of satellites. A QSG mission requires, and builds upon, the MAGIC development. The future activities will involve the development of the baseline concept for Bose-Einstein-Condensate (BEC)-based 3D hybrid accelerometers to advance on the QSG definition for near-term missions. A dedicated science study to explore the feasibility of QSG user requirements with candidate mission architectures with both concepts has just started: the Quantum Space Gravimetry for Earth Mass Transport (QSG4EMT).

This project will focus on the scientific assessment of satellite mission architectures that utilize QSG techniques to provide enhanced products of Earth's mass transport processes via directly measuring the temporal variations of the gravity field of the Earth. One of the major architecture options to be analysed is the Satellite Flight Formation (SFF), including Low-Low SST formations of tandem satellite pairs and High-Low SST single satellites formations. A search space of SFFs that consists of a constellation will be extensively analysed to minimize aliasing effects and explore the quantum sensors to their maximum potential. Different satellite payload options traditionally flying at satellite gravimetry missions will be analysed in addition to the quantum sensors. This can include, among others, inter-satellite ranging instruments by means of a laser interferometer, GNSS tracking, star cameras and traditional electrostatic accelerometers hybridized to the quantum sensor. In addition, satellite propulsion and coordination of orbits will also be extensively investigated. Quantum sensors to be considered are accelerometers and gradiometers of different design (e.g. 1-arm, 2-arm, 3-arm). A sensitivity analysis of different architecture options will be performed, which will also serve as an indication of desired accuracy levels for future QSG instruments.

The activities of this project will build upon technology studies of CAI gravity gradiometer and hybrid accelerometry, and scientific studies of Next Generation Gravimetry Missions that already exist in ESA since many years. The outcome of this project is directly relevant to the ESA/EC roadmap towards a European QSG mission with the EC goal of a pathfinder mission to precede the main mission within this decade. The project output will also complement the MAGIC Phase A activities for considering a QSG instrument as an opportunity payload. This will pave the future of Quantum Missions for Climate in the frame of the Space for Green Future Accelerator (See next section).

5. WAY FORWARD

The study of global mass transport phenomena via gravity field monitoring from satellite gravimetry provides important insights and crucial information to understand climate change, hydro- and cryosphere evolution, early warning of hydrological extremes, monitoring of geo-hazards among others. Previous and current space missions (e.g., GOCE, GRACE and GRACE-FO) have shown the great potential and uniqueness of observing mass distribution, change and transport from gravimetry in space.

The largest error contributor of state-of-the-art missions that monitor the time-variable gravity field (e.g., GRACE and GRACE-FO) is the effect of aliasing that results from the poor observation geometry and the insufficient spatiotemporal sampling of the gravity signal. The ESA/NASA MAGIC mission concept is a well-designed satellite constellation that aims to counter this limitation [19]. Moreover, accelerometers used so far in gravity missions exhibit relatively high noise at low frequency and are the next largest error contributor after the aliasing effects. Additionally, the accuracy of state-of-the-art space gradiometers are orders of magnitude worse than what is needed to observe temporal changes in gravity. Quantum Spaceborne Gravimetry (QSG) measurement techniques hold the promise of substantially improving on current technologies since they can provide absolute measurements with no drifts. A promising innovation, the Cold-Atom Interferometry (CAI)-based quantum sensor, promises increased sensitivity in space under nano-gravity conditions. This could fill the technological gap and help to increase the spatial and temporal resolution of mass transport products. Following the example of MAGIC, future QSG missions are expected to improve the spatiotemporal sampling to a level that will allow the exploitation of novel satellite sensor technologies (e.g. CAI gravity gradiometer).

In Agenda 2025 [20], ESA set out a vision for how Europe could seize the opportunity of the current revolution in space activities to help make a green, digitally safe and inclusive world. Central to this was a reinforced cooperation between ESA, its Member States and the European Union. In the summer of 2021, a High-Level Advisory Group, appointed by the ESA Director General, convened to discuss the priorities for this reinforced cooperation and on the ways to *accelerate the use of space in Europe*. This Advisory Group identified three main thematic areas of action and recommended ESA to adopt a new approach, called “Accelerators”, to reach this objective [21]. This approach was endorsed by ESA Member States during an Inter-ministerial Meeting in November 2021, which resulted in the Matosinhos Manifesto [22]. The three Accelerators are:

1. Space for a Green Future (S4GF)
2. Rapid and Resilient Crisis Response (R3)
3. Protection of Space Assets (Protect)

The S4GF Accelerator was supported by European leaders during the Space Summit that took place 16th of February 2022 in Toulouse, France [23]. It shall stimulate the development, deployment and use of advanced data, science, technology, applications and services for a sustainable life on Earth. The Accelerator shall provide European decision-makers, industry, and society with the support they need to reach the objectives of the energy transition and the green agenda, notably carbon neutrality by 2050.

There are four interacting development blocks within the overall framework of the S4GF accelerator, namely the Quantum Missions for Climate, the Digital Twin Earth Boost, the Green Transition Information Factories and the Accelerating de-carbonization element. The Quantum Missions for Climate element has the objective to deliver unprecedented data on key Earth processes, to enhance climate monitoring and cope with impacts on water cycle, e.g. ground- and soil-water changes (e.g., droughts, crop yield), extreme events like flash floods, sea level rise, and more.

In the European framework, the European Commission and ESA are collaborating on developing a European joint and harmonized QSG implementation roadmap for the smooth continuity between the various on-going and future planned gravimetry missions and the effective coordination between the EU players. All activities will ensure that the existing expertise developed by ESA, national agencies, and EU industries, including start-ups, are taken advantage of in a synergistically optimized manner. There is a clear intention that within this decade Europe should develop and test in orbit a QSG pathfinder mission based on CAI (Bose-Einstein Condensate technology). The objective would be to develop the capabilities of this key-technology including its potential for space gravimetry. The pathfinder should demonstrate the technology and highlight EU expertise and competence in QSG. Consequently, the pathfinder shall lead to a clear path for which the next step would aim (1) to improve technology and (2a) to perform scientific missions as well as (2b) to enhance existing or derive new application and services for EO Earth Observation. In the long term, Europe should put in place a QSG mission using multiple spacecraft embarking quantum sensors. To answer to policy- and user-driven needs, with appropriate spatial, temporal and quality performances, the goal would be to put in place an EU-driven geodesy mission satellite program, i.e., using QSG concept on multiple spacecraft embarking quantum sensors.

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