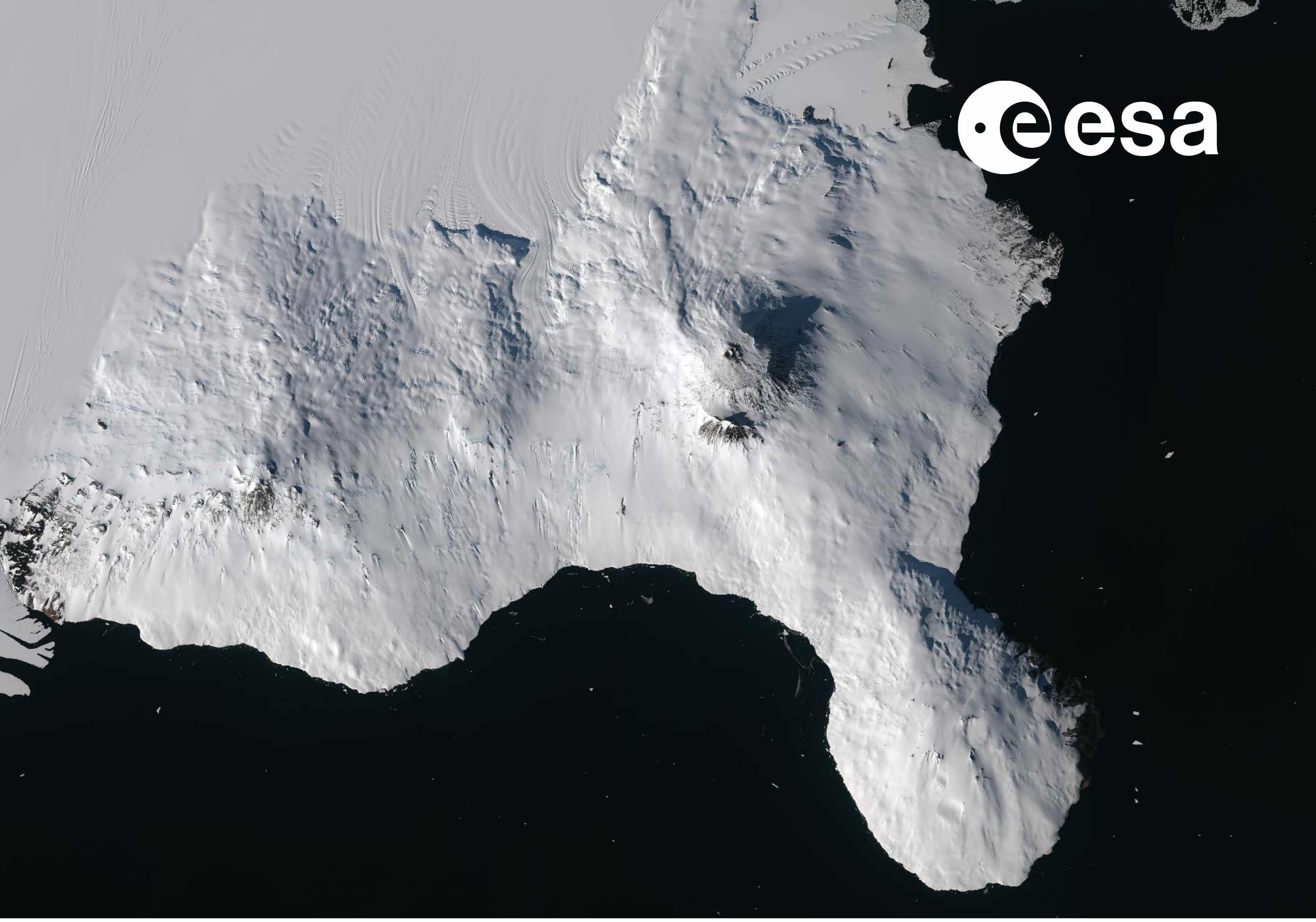

IMPACT ASSESSMENT OF ESA EARTH OBSERVATION EARLY R&D ACTIVITIES

Hybrid Atom Electrostatic System Follow-On for Satellite Geodesy

know.space

FINAL

January 2025

The need for cutting-edge measurement of essential climate variables has never been greater…

There is overwhelming scientific consensus that human activity is profoundly influencing Earth's climate and biodiversity. Tackling human-induced climate change is one of humanity's most pressing challenges, and one which can only be achieved through global cooperation.

Greenhouse gas emissions are already affecting weather patterns and climate cycles in every region across the globe, leading to extreme weather events with adverse impacts on food and water security, human health, our economies and society.[1] Therefore, the need for urgent action has never been greater. To inform policy and mitigation measures, it is vital to continually enhance modelling capabilities of Earth's energy imbalance (i.e. the difference between the energy reaching Earth, and the amount radiated back into space). This will help validate and improve the precision of existing climate models, allowing policymakers to set better informed targets, and implement the most effective policies for achieving them. In turn, this can build resilience and effective mitigation plans.

Satellite observations are revolutionising climate science, providing global coverage of climate variables, which complement ground-based and in-situ measurement tools. For instance, satellite gravimetry is an innovative technique that monitors sub-surface elements, using changes in the strength of gravitational fields. This technique can be used to study groundwater or sub-glacial water mass exchanges for example, enabling better modelling of water cycles and their contribution to sea level rise.[2] Beyond its role in improving climate science, satellite gravimetry for hydrological modelling also aids in understanding terrestrial water storage (TWS).[3] TWS measures the total amount of water on and in Earth's continental landmasses. This includes soil moisture and surface water, variables that are crucial in agriculture and drought monitoring.

Satellite gravity missions fill a crucial gap in understanding change across the entire Earth system, as they offer the only measurement technique which can monitor mass changes on a global scale.[4] They also gather data that is valuable for several of the six overarching science themes identified in ESA's EO Science Strategy, including 'The water cycle (ST-I)'

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[1] IPCC, (2023). *Climate Change 2023: Synthesis Report*. doi: 10.59327/IPCC/AR6-9789291691647

[2] Zahzam, N., *et al*. (2022). Hybrid electrostatic–atomic accelerometer for future space gravity missions. *Remote Sensing*, *14*(14), p.3273.

[3] Chen, J. (2019). Satellite gravimetry and mass transport in the earth system. Geodesy and Geodynamics, 10(5), pp. 402-415.

[4] Pail, R., (2023). Space Gravity Missions: CHAMP, GRACE, GRACE-FO, and GOCE, Satellite Projects. In *Encyclopedia of Geodesy* (pp. 1-9). Springer International Publishing.

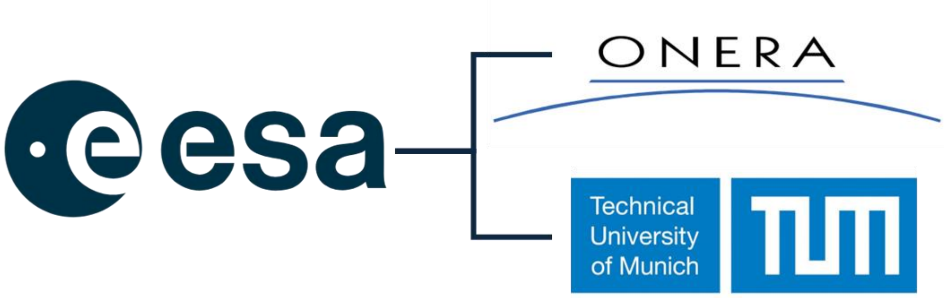
and ‘Energy fluxes (ST-III)’.[5] Examples of previous gravity missions include the ESA Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission, the NASA- and DLR-led Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow-on missions.

While satellite gravimetry has revolutionised climate modelling capabilities, the technique does have limitations. One key issue with data from the abovementioned missions is temporal aliasing – meaning the accuracy of data is limited by the orbit of satellites and the observation frequency. The performance of accelerometers in these missions is also a challenge, as noise levels have limited the accuracy of measurements to date, especially at low frequencies.[6]

… and next-generation accelerometers are being developed with ESA funding …

ESA have funded a project to develop a state-of-the-art accelerometer, which combines an electrostatic accelerometer with a novel quantum sensor based on cold atom interferometry to produce a hybrid concept. This project is being undertaken with the aim of the hybrid technology supporting a major future ESA space gravity mission. The system, which is a first-of-a-kind solution, could provide measurements with higher accuracies and improved resolution compared to existing electrostatic accelerometers, thereby enhancing the quality of data from future satellite gravity missions.

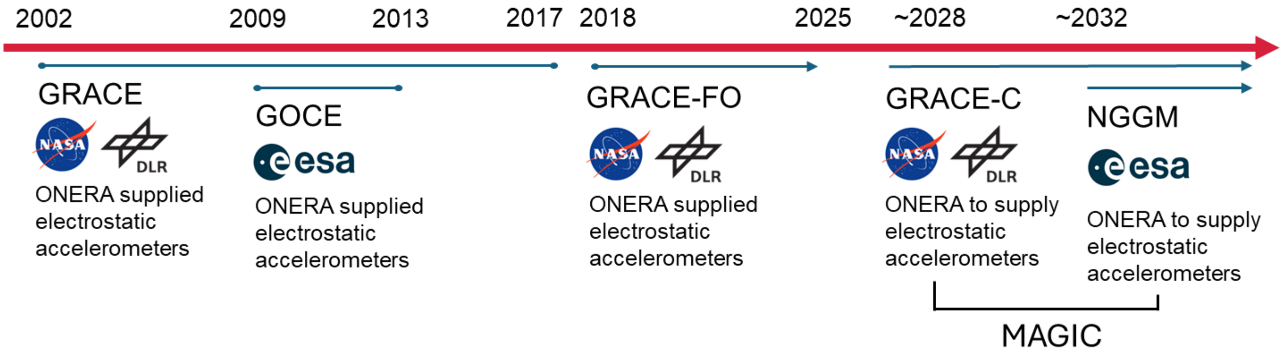
Team diagram outlining the project prime and subcontractor of the project



[5] European Space Agency. (2024). *Earth Science in Action for Tomorrow’s World- Earth Observation Science Strategy*.

[6] Haagmans, R., et al (2020). ESA’s next-generation gravity mission concepts. *Rendiconti Lincei. Scienze Fisiche e Naturali*, 31, pp.15-25.

Figure 1: Timeline of satellite gravity missions

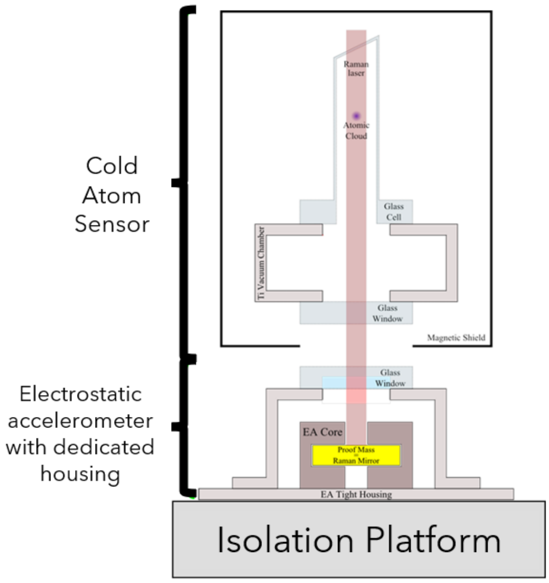


Source: know.space based on ONERA and ESA data

The consortium is led by ONERA (the French Aerospace Laboratory, France), who are global leaders in the field of electrostatic accelerometers. Their accelerometers were used in the above-mentioned GRACE missions, and they will support NASA's and DLR's GRACE-C mission, with a launch target 2028. ONERA have also been selected to provide the accelerometer for the ESA Next Generation Gravity Mission (NGGM) with a launch target in 2032, for which they were awarded with a €27.3m contract. By securing roles on GRACE-C and NGGM, ONERA's existing accelerometer technology will be used on all satellites in the NASA/ESA MAGIC mission.

This project leverages work that has been ongoing for a decade. ONERA have already begun development of the hybrid concept, which could support future missions by producing data with higher spatial and temporal accuracy. This was first formulated in a project for ESA between 2015-2016.

Figure 2: Diagram of an Electrostatic Accelerometer Hybridised with a Cold Atom Gravimeter



Source: ONERA

To advance the hybrid cold atom accelerometer concept, ONERA received €499,000 from ESA through the FutureEO programme.[7] This project, undertaken with partners from the Technical University of Munich (TUM, Germany), began in 2018 and has since resulted in technology developments, performance simulations and airborne testing in an aeroplane. The project team has also outlined a roadmap for future technology development and performance evaluations.

… which could help to overcome some of the greatest challenges in climate research and action…

Through this continued ESA support, ONERA are developing and testing a technology which, in the words of the project team, “holds the promise of substantially improving on current technologies”. [8] The system relies on a quantum sensor based on cold atom interferometry, which has only been used previously in laboratory settings for fundamental physics research. This project is helping to translate this system to first-of-a-kind space applications, which could help to provide absolute measurement and improved long-term stability performance for satellite gravimetry.

[7] The ESA FutureEO programme is a long-term initiative aimed at developing innovative EO technologies, missions, and applications. It focuses on developing research, including promoting the use of new observation techniques. By supporting early-stage research and development projects, and exploring novel mission ideas, FutureEO seeks to maintain European leadership in EO.

[8] Zahzam, N., *et al*. (2022). Hybrid electrostatic–atomic accelerometer for future space gravity missions. *Remote Sensing*, *14*(14), p.3273.

In doing so, the system could enable missions to monitor incoming and outgoing energy on Earth, giving precise information on Earth's radiative budget. This improved capability would provide evidence relating to global warming trends at unprecedented detail by understanding some of the key drivers, such as melting ice or warming oceans.

In turn, more accurate and timely data from these missions could support policy which enhances our resilience to extreme environmental events, and improves mitigation of the impacts of climate change. Examples include enhanced water resource management, glacial / iceberg monitoring, adaptation strategies in coastal areas, renewable energy optimisation (e.g. through prospecting hydropower or geothermal energy sources), and better early warning systems for flooding and extreme weather events. This benefit is in line with the strategic area of action 'from science to societal benefits' as identified in ESA's EO Science Strategy.[9]

… and delivering valuable socio-economic benefits

Alongside being a crucial enabler for future benefits relating to enhanced climate modelling in future satellite gravimetry missions, ESA support has led to tangible near-term benefits for the project prime (ONERA) and its subcontractor (TUM). These materialised benefits primarily relate to innovation undertaken within the project, as well as impacts on human capital, laying the potential for future knowledge spillovers.

Progressing technology development

Through ESA funding, the technological readiness level (TRL) of the hybrid accelerometer has been raised from TRL 3 to TRL 4, achieved through preliminary designs, performance simulations and experimental demonstrations. A roadmap for future development and testing has also been outlined.

ONERA highlighted the crucial role of ESA funding in de-risking and maturing their innovative hybridisation of an electrostatic accelerometer and quantum sensor based on cold atom interferometry. It has enabled the advancement of the technology from an initial concept to a system which has been validated in a (semi) relevant environment, therefore raising the technological readiness level (TRL) from 3 to a TRL of 4. The project undertook a successful test flight of the technology in an aircraft over Iceland. Despite testing not being undertaken in a space-specific environment, the test flight helped to demonstrate the accuracy of the

[9] European Space Agency. (2024). *Earth Science in Action for Tomorrow's World- Earth Observation Science Strategy*. Available at: https://esamultimedia.esa.int/docs/EarthObservation/ESA_Earth_Observation_Science_Strategy_issued_Sept_2024.pdf

gravimetry measurements using the hybrid concept device. The ONERA representative noted that this flight activity was attributable to ESA's support.

The project will continue progressing the technology, with aims to reach TRL 6 in the next five years. This will be achieved through follow-on ESA-funded and externally funded activities, including preparations for upcoming missions and the associated demonstration of the accelerometer in space. These follow-on activities are discussed in more detail in the below sections.

Strengthening competitiveness, visibility and leadership

ESA support has been crucial for increasing the visibility of cold interferometry applications. Through the project, ESA is helping to validate an emerging topic, while also helping ONERA to gain a first-mover advantage in the field.

ESA funding has aided ONERA in securing a leading role in the field of hybrid accelerometery, highlighted by ONERA leveraging ESA support to become the first to fly this technology on board a plane. This first mover advantage awards the organisation increased visibility and competitiveness within the field.

By enabling technology development in this emerging field, ESA support has raised the profile of ONERA's work in this area. As mentioned earlier, ONERA already supply state-of-the-art electrostatic accelerometers, offering a globally leading and highly competitive technology. However, in the view of the project manager, work on the hybrid concept was not widely known in the industry, and ESA has been a key factor in raising the visibility of this innovative technology. Through this project, and specifically ESA's support for it, recognition of the emerging hybrid concept's viability is growing. One example of this increased visibility includes the European Commission's (EC) interest in the project and ONERA's success in securing a follow-on contract with the institution to work on hybridisation within EC's Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometery – Pathfinder Mission Preparation (CARIOQA-PMP) project.

If further development of the hybrid concept unfolds as planned in the project roadmap, ONERA, and thus Europe, could maintain global leadership in accelerometery in the decades to come. Europe would secure a technological advantage in offering the most accurate measurements from satellite gravimetry, as ONERA are the only organisation currently pursuing space applications of this concept.

Positioning for future contracts and mission opportunities

Developments on hybrid accelerometery are positioning the project team for involvement in high profile gravity missions. To support this, ONERA has secured follow-on contracts with ESA and the European Commission to continue developing their hybridisation work.

Following on from this project, ONERA are in direct negotiation with ESA for a €200,000 project to continue developing the hybrid concept further. Given that the objective of this project is to use the hybrid accelerometer to support a future major ESA space mission, ESA funding is positioning European suppliers (e.g., ONERA) to deploy technology for this.

Through ONERA's next funding contract, the organisation has been tasked with collaborating with different industry stakeholders and universities to identify suitable partners for measuring the scientific output and performance of the technology. In this project, they also aim to derive the requirements of the instrumentation, which will further prepare the product for mission involvement.

As highlighted earlier, the project team has secured a follow-on opportunity for involvement in the EC's CARIOQA-PMP project. The ESA project was referred to as crucial for catalysing ONERA's involvement in this EC mission. The preparation project aims to develop a quantum accelerometer with the intent of future spaceflight under the Quantum Pathfinder Mission. It has a budget of €17m across the consortium within which ONERA will be involved in the hybridisation work.

Enhancing reputation and influence

ONERA already has a strong reputation in electrostatic accelerometery as global experts in the field, although their ability to influence the leading edge through cold atom accelerometery has been strengthened by ESA support, further benefitting their reputation.

As mentioned earlier, ONERA's global competitiveness in electrostatic accelerometers has contributed to the organisation's strong pre-existing reputation within this field. However, as the only organisation pursuing applications of cold atom interferometry beyond the laboratory, this project is helping to extend ONERA's reputation beyond electrostatic accelerometery and into the highly innovative field of hybrid accelerometery.

The project team's increasing reputation in hybrid accelerometery is exemplified by ONERA securing follow-on hybridisation work with the European Commission for CARIOQA-PMP. Furthermore, if this mission goes to plan, it presents an opportunity for ONERA to further increase their reputation and influence, as their hybrid accelerometer would have space flight validation. CNES (Centre National d'Études Spatiales, the French Space Agency) has also grown increasingly aware of the project and is showing support for the research and outputs.

The project representative reported that the project team often engage with potential partners, end users and suppliers whilst at outreach events such as conferences and workshops. These discussions increase the possibility of growing ONERA’s customer base – and mission involvement – which enhances the organisation’s reputation, as discussed above. Furthermore, these engagements can lead to follow on collaborations and new partnerships which foster innovation, can grow ONERA’s capabilities further and increase their influence in the field. They have also presented their hybrid accelerometer work at several conferences which, along with everything discussed above, grows recognition of ONERA’s project and the team’s prominence in the scientific community.

Fostering technical and project management skills

The innovative nature of ONERA’s hybridisation work has provided the team with technical upskilling, including for a co-funded PhD student working on the project. The team has also gained new project management skills by working with ESA and subcontractors.

ESA funding for the project is supporting eight jobs, five at ONERA and three at TUM, highlighting that the project is aiding the retention of the space sector workforce. The project team were able to develop and strengthen new technical skills through their access to ESA facilities and technical officer support. For example, the project team has applied their expertise in cold atom physics to create an integrated on-board system and are continuing to mature this to spaceflight readiness. This space application is not only new to the team developing it, but also to the wider field, highlighting the potential for further wide-ranging technical knowledge development.

A PhD student was also involved in the project, funded 50% by ESA and 50% by ONERA, offering them the opportunity to undertake applied hybrid accelerometer work for their thesis, focusing on the impact of satellite rotation on instrumentation. The project has provided valuable exposure to the space sector for the early career researcher, which could support their future career development. Furthermore, ESA directly supervised three months of the student’s PhD, during which they worked at the European Space Research and Technology Centre (ESTEC) with the ESA Technical Officer for this project. The student spent the time building an understanding of the stringent requirements of the space environment and its effect on systems and instrumentation, and was able to learn from ESA’s leading expertise in these areas. The opportunity provided to this student demonstrates how the project has supported routes for early career workers to gain direct exposure to space projects, which will ultimately contribute to helping strengthen the European space workforce in the longer term.

Some team members were regarded as having little experience working directly with ESA prior to this hybridisation project, and therefore have gained valuable insight into working with the Agency. Stakeholders mentioned that they had developed heightened awareness of the compliance and regulations required to move between phase 0, A and B. Some individuals involved had also not previously worked as a prime contractor (though ONERA as an organisation had), offering the opportunity for upskilling in project management.

This project also enabled some individuals at ONERA to build experience working with a subcontractor, strengthening project, client, and partner management skills. The activities planned for ONERA's follow-on funding with ESA involve multiple subcontractors, and thus valuable knowledge can be taken forward from the current project into their future work, improving efficiency.

The technical knowledge being developed within the hybridisation project could be beneficial for other departments in ONERA. The electrostatic team at ONERA are involved in ESA's Next Generation Gravity Mission (NGGM). While the hybridisation concept is distinct to the current ESA project, new techniques and lessons could be transferred to the electrostatic team to stabilise their electrostatic accelerometers and improve the accuracy of the data gathered. This shows the project supporting knowledge spillovers across the different departments at ONERA.

Supporting the publication of scientific research

There have been three publications developed by the project team and ESA technical officers linked to this ESA-funded project, which have accumulated a total of 104 citations, showing wider engagement from the scientific community with this novel field of research.

At least two research papers have been published by ONERA and its subcontractors directly related to their work on the ESA project. The first occurred in 2019 and was published in the journal *Advances in Space Research*.[10] The second was published in *Remote Sensing* in 2022.[11] Alongside these, ESA published a paper directly referencing the project work.[12]

[10] Abrykosov, P., et al. (2019). Impact of a novel hybrid accelerometer on satellite gravimetry performance. *Advances in Space Research*, 63(10), pp. 3235-3248.
[11] Zahzam, N., et al. (2022). Hybrid electrostatic-atomic accelerometer for future space gravity missions. *Remote Sensing*, 14(14), p.3273.
[12] Haagmans, R., et al (2020). ESA's next-generation gravity mission concepts. *Rendiconti Lincei. Scienze Fisiche e Naturali*, 31, pp.15-25.

These publications demonstrate that the project has added to the larger body of research in cutting edge fields and has helped translate research from fundamental physics into the applied space, climate science, and geophysics fields. Together these papers have accumulated 104 citations[13] , showing that ESA-funded research is reaching those in the wider scientific community, raising awareness of ONERA's (and Europe's) innovative research and capabilities.

Supporting knowledge spillovers into terrestrial and other sectors

Beyond the primary application for the hybrid concept, which is for a future satellite gravimetry mission, there are several areas of potential knowledge spillover, where this project could support new product development and terrestrial research.

While the project to date has been focused on de-risking and maturing the hybrid concept, ONERA have identified several areas where developments on the project could lead to spillovers and alternate use cases (although further development and commercialisation would be required). For instance, ONERA have highlighted that the cold atom sensors being developed through the project could have terrestrial spillover applications into navigation (by enhancing autonomous positioning measurements) and sub-surface detection (e.g. for archaeology and mining), through better resolution in measurement of gravity fields, which can detect underground elements more precisely. Moreover, as ONERA also have expertise in defence and fundamental physics research, there is opportunity for bi-directional spillovers and knowledge exchange between different research areas within the organisation, enhancing cross-sectoral innovation.

By supporting data of a higher spatio-temporal resolution and accuracy, the hybrid concept could also unlock the potential to develop new products for specific user domains (with further development and adaptation). For example, the hybrid concept could be incorporated to enhance operational services relating to early warning systems for extreme hydrological events (such as floods and droughts) and monitoring of geo-hazards (such as earthquakes, volcanoes, and tsunamis)[14]. In doing so, spillovers of the hybrid concept could enhance resilience to extreme events by improving mitigation (e.g. groundwater management) and response (e.g., evacuations, defences).

[13] As of December 2024.
[14] Zahzam, N., et al. (2022). Hybrid electrostatic-atomic accelerometer for future space gravity missions. *Remote Sensing*, 14(14), p.3273.

Would these benefits have been realised without ESA?

It is unlikely that the benefits achieved through this project would have been realised without the involvement of ESA, including the financial and technical support offered through the examined project and its precursors. While ONERA is already a leading provider of accelerometers for space gravimetry missions, this ESA-funded de-risking and technology maturing project for the next generation of hybrid accelerometer systems is essential to considerably improve future climate modelling data, which would otherwise be limited by the performance of current accelerometers.

This project is part of a series of early stages required to strengthen European capabilities and ensure technological non-dependence for future space missions. These steps provide crucial early progress in solidifying European technological leadership in the field, and will underpin the future development work required to achieve a fully flight qualified system in the coming decades.

> *"If ESA had not supported this, I do not think we would have the expertise we do today, and this innovative concept would not have the same visibility in the community. CNES and the European Commission are now showing support, and ESA has been key in getting that." - N. Zahzam, ONERA*

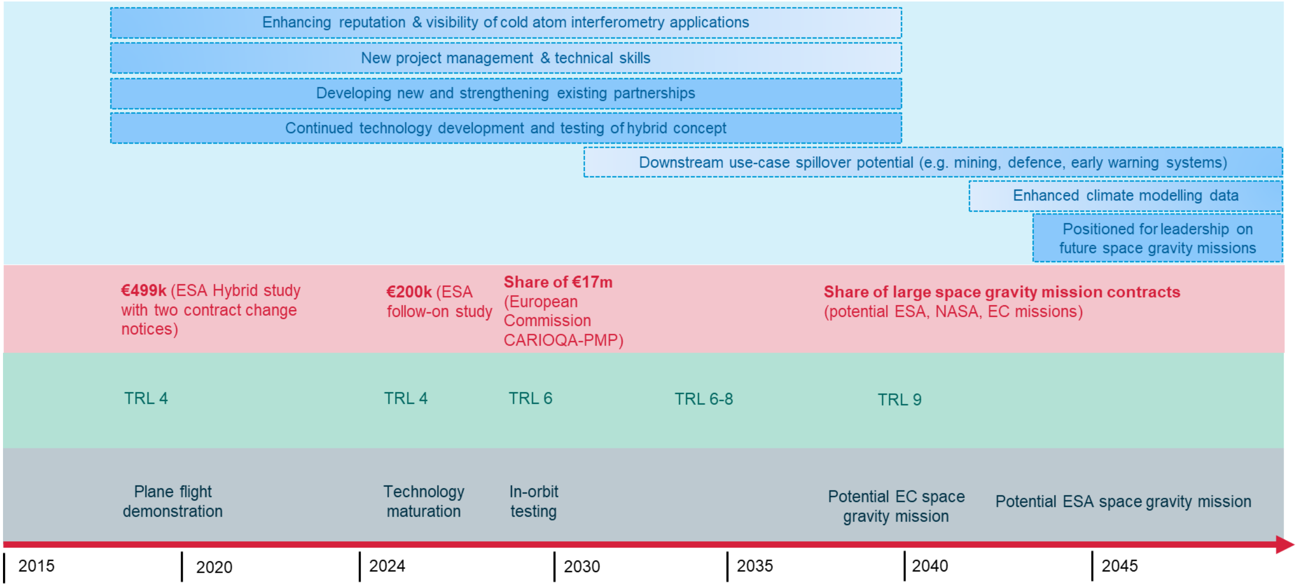
The tangible near term benefits described above would also not have been possible without ESA support. For instance, the technical and project management upskilling of ONERA staff is linked to their access to ESA facilities and technical officer support. This project may underpin impacts relating to new applications of the hybrid concept, which would not have materialised otherwise – however further development and commercialisation is necessary to exploit spillover opportunities. It is too early to estimate the magnitude of these future benefits, but several additional use cases (e.g. disaster response, monitoring of geo-hazards) have already been identified at this early stage.

Next steps: Further development, further benefits

The immediate next steps for ONERA are to derive the requirements of the hybrid technology for mission use. This will allow for the project team to continue technological developments on the hybrid concept through ESA follow-on support, as well as the European Commission CARIOQA-PMP project. As defined in their roadmap, the technology is planned to reach TRL 6 in the next 5 years, which would involve a system-level prototype being demonstrated in a relevant environment. ONERA will also work collaboratively with a larger range of academic partners to undertake simulations, and could expand their consortium to include companies, providing the opportunity to form new international partnerships, or strengthen existing ones.

If progress unfolds as planned, these developments should feed into future space gravity missions, while opportunities for other potential applications or products could also be explored over this timeframe (no concrete timelines for this have been confirmed yet). As ONERA are on track to be the first-to-market for this new hybrid concept, they will be well placed to secure mission roles and pursue new products and services in the following decades.

Figure 3: Overview of the timeline of the Hybrid Atoms project and the associated benefits



Source: know.space based on ONERA and ESA data

Key priority indicators

Programme	FutureEO
Country	France
Project cost	€499,000
Duration	2018-2022
Lead contractor	ONERA
Sub-contractors	Technical University Munich
TRL progression	TRL 3 to TRL 4
Spin-in into the space sector	-
Jobs supported	8 (5 ONERA, 3 TUM)
New collaboration with ESA	-
Partnerships created	-
Follow-on funding applied/secured	€200k ESA follow-on funding Share of €17m EC CARIOQA-PMP funding