



# CARIOQA Quantum Pathfinder Mission for Space Weather Research

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## Abstract

The Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry (CARIOQA) Quantum Pathfinder Mission aims at demonstrating a quantum technology-based accelerometer in space as a precursor for a later use onboard a satellite gravimetry mission. A dedicated satellite will be launched for the Pathfinder Mission in the early 2030s to raise the technology level of the required technologies for applications on operational missions. The Phase A study to investigate the feasibility of this mission has concluded and the Phase B started in October of 2025. We present studies from the Phase A on the relationship between available models of the atmospheric conditions in low Earth orbits and the instrument and satellite design. We examine the impact of drag models on the development of requirements to fulfil the mission objectives. In addition to the demonstration of the functionality of the quantum sensor, the Pathfinder Mission will provide accelerometer measurements in low Earth orbits for the expected mission lifetime of three years. As a scientific objective of the mission, this dataset will be used to derive parameters like thermosphere density or atmospheric crosswinds.

## Keywords

Accelerometer · Density · Pathfinder mission · Quantum sensor · Thermosphere

## 1 Introduction

Satellite gravimetry missions like the Gravity Recovery and Climate Experiment (GRACE) and its successor mission GRACE-Follow On (GRACE-FO) have an invaluable contribution to our understanding of mass transport on the Earth (Tapley et al. 2004; Landerer et al. 2020; Chen et al. 2022). These missions, consisting of two identical satellites in the same orbit with an along-track separation of approximately 200 km, typically provide monthly gravity field solutions based on intersatellite ranging. Satellite gravimetry data is used in monitoring global climate change (Tapley et al. 2019), estimating total waterstorage variations and sea level

change on a regional level (Boergens et al. 2020; Manche et al. 2021), and in studying the Earth's interior (Mandea et al. 2020). The applications of satellite gravimetry data are today limited in spatial and temporal resolution by temporal aliasing, which is due to undersampling of rapid mass variations in the atmosphere and ocean, as well as instrumental errors, mostly due to the missions' intersatellite ranging system and accelerometer performance. The accelerometers onboard each satellite play a key role in removing the effect of non-gravitational accelerations from the intersatellite ranging observations. Accelerometers based on quantum technologies have the potential to surpass classical electrostatic accelerometers performance due to white noise behavior in a broad bandwidth compared to the colored noise in electrostatic accelerometers in lower frequencies. This will benefit gravity field recovery as it reduces one of the current limiting factors of GRACE and GRACE-FO

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(Abrykosov et al. 2019; Lévêque et al. 2021; Zingerle et al. 2024; HosseiniArani et al. 2025).

The Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry (CARIOQA) Quantum Pathfinder Mission (Lévêque et al. 2023) is a dedicated satellite mission designed to test a one axis quantum accelerometer in a space environment in order to raise the Technology Readiness Level (TRL) of key components to TRL 8. The overarching goal of CARIOQA is the development of key technologies of a quantum accelerometer to be deployed on a future satellite gravimetry mission comparable to GRACE-FO. Currently, the European Union is funding different phases of the Pathfinder Mission in the Horizon Europe funding programme involving partners from industry, academia and the French and German space agencies.

The recently concluded CARIOQA Phase A study (CARIOQA-PHA<sup>1</sup>) investigated several mission objectives addressing the functionality of the quantum accelerometer as well as scientific applications of Pathfinder Mission data. These studies involved implementing a 3D model of the satellite as the design evolves during the project. The 3D model is used to simulate realistic non-gravitational accelerations acting on the satellite for orbit propagation. Additionally, the simulated acceleration and orbit data is used to investigate mission objectives and define requirements on the quantum sensor and satellite. These simulations rely on a number of models to calculate the non-gravitational accelerations, e.g., for solar radiation pressure (SRP), the atmosphere and Earth albedo.

In this paper, we focus on the application of Pathfinder Mission data for thermosphere density recovery. In Sect. 2 we give a brief overview on the CARIOQA project and the new technologies involved. The application of accelerometers for research of the upper atmosphere is described in Sect. 3. The mission simulations and results are presented in Sects. 4 and 5.

## 2 CARIOQA Quantum Pathfinder Mission

The basic concept of the CARIOQA Pathfinder Mission was described by Lévêque et al. (2023) as the result of a Phase 0 study. The first phase of the project, which was funded by the European Union, is the CARIOQA Pathfinder Mission Preparation (CARIOQA-PMP<sup>2</sup>), which started in December 2022 for a duration of 40 months. The consortium of CARIOQA-PMP consists of 16 partners from five member states. The main objectives of CARIOQA-PMP are the development of a quantum accelerometer engineering

model and a roadmap for the implementation of a future Quantum Space Gravimetry Mission (QSG). These objectives are accompanied by a scientific study on the design of the Pathfinder Mission and a follow up QSG Mission, to support and justify design decisions in the development of the quantum accelerometer. The development of the Pathfinder Mission is divided into phases according to ECCS-M-ST-10C (ECCS 2009).

CARIOQA-PHA started in January 2024 for a duration of 18 months in parallel to CARIOQA-PMP with a consortium consisting of six partners from four member states. The industry partners responsible for the quantum accelerometer and the satellite were part in both CARIOQA-PMP and the Phase A study. Results achieved and decisions made in the Phase A study, e.g. orbit choices or satellite geometry, were also shared with the partners of the CARIOQA-PMP scientific studies on (Post-)Pathfinder Mission applications to reflect the progress of the overall CARIOQA program. During CARIOQA-PHA the Mission Requirement Document (MRD) and other documents central to the deployment of the Pathfinder Mission were developed. These documents will be refined in the phases following Phase A.

CARIOQA Phase B (CARIOQA-PHB<sup>3</sup>) with a duration of 24 months started in October 2025 with 14 partners from five member states. During CARIOQA-PHB the preliminary definition of the mission and instrument will be finalized. Pre-development activities of critical components of the quantum accelerometer identified in earlier phases will be carried out to raise their TRL to TRL 6. The feasibility of achieving the defined mission objectives by the chosen Pathfinder Mission and instrument design will be studied in Phase B prior to entering the next phase of the mission.

### 2.1 Quantum Accelerometer

The instrument onboard the Pathfinder Mission will be a one axis quantum accelerometer utilizing Rubidium in a Bose-Einstein Condensate oriented in the along track direction of the satellite. This will enable the measurement of the non-gravitational accelerations mainly due to atmospheric drag, which is the dominant disturbing force in any direction, thus providing the largest signal to measure. A Mach-Zehnder like atom interferometer using ultra cold Rubidium atoms which interact three times with Raman laser beams in a double diffraction configuration realise the acceleration measurement (HosseiniArani et al. 2024). The measurement principle depends on immutable atomic properties and the ability to generate specific frequencies tuned to transitions between atomic states. Neglecting higher order terms the atom interferometer phase shift  $\Delta\Phi$  due to the acceleration  $\mathbf{a}$

<sup>1</sup><https://doi.org/10.3030/101135075>

<sup>2</sup><https://doi.org/10.3030/101081775>

<sup>3</sup><https://doi.org/10.3030/101189541>

depends on the geometry of the laser beams interacting with the atoms expressed in the vector  $\mathbf{k}_{\text{eff}}$  and the time interval between the Raman laser pulses  $T$ :

$$\Delta\Phi \approx 2\mathbf{k}_{\text{eff}}\mathbf{a}T^2. \quad (1)$$

Increasing the time interval  $T$  will also increase the sensitivity of the instrument. While mobile terrestrial instruments are limited in  $T$  in the range of a few tens of milliseconds to about 250 ms (Antoni-Micollier et al. 2024; Freier et al. 2016) due to instrument size, a satellite in free fall enables much longer times  $T$ . The limit on  $T$  in space is set, e.g., by the expansion of the atomic cloud or the dynamic range of the sensor. As the atom interferometer measures a phase between 0 and  $2\pi$ , a phase ambiguity occurs for accelerations exceeding a certain range during and between measurements. Therefore,  $T$  needs to either be limited or a hybridisation with a classical electrostatic accelerometer needs to be implemented (Knabe et al. 2023). A hybridisation scheme is not foreseen for CARIOQA. The standard atom interferometer time interval  $T$  will be 1 s with the possibility to extend  $T$  for testing. The sample interval of the instrument will be 4 s consisting of time for the preparation of atoms,  $2T$  for the measurement and detection after the measurement. The design of the quantum accelerometer and the system architecture are described in more detail in Lévêque et al. (2023).

## 2.2 Mission Objectives

The main objective of the Pathfinder Mission is the demonstration of the functionality of the quantum accelerometer in space. The acceleration measurement should also be representative of the environment of a satellite gravity field mission. In addition to these technical mission objectives, including the demonstration of differential acceleration measurements by splitting the initial atom cloud, science objectives were defined exploiting the data recorded during the mission. These objectives include gravity field recovery by high-low satellite to satellite tracking (hl-sst) and the calculation of parameters of the atmosphere. While gravity field recovery from hl-sst might benefit from an improved accelerometer in the determination of the very low coefficients of the gravity field, observation of density greatly benefits from accelerometer measurements compared to, e.g., orbit data only. Additionally, the quantum accelerometer performs absolute measurements potentially providing new insights compared to classical electrostatic accelerometer measurements, for example investigating scale factors and bias of existing density models.

**Table 1** Orbit scenarios at the end of the Phase A

| Shape      | Altitude         |
|------------|------------------|
| CIRCular   | 500 km           |
| ELLIPtical | 400 km to 700 km |

## 2.3 Preliminary Mission Design

The mission objectives and additional requirements lead to the identification of several candidates for the orbit of the Pathfinder Mission. The two orbit choices listed in Table 1 remained after the end of Phase A with a decision to be taken in Phase B. Key parameters of the instrument were already defined in CARIOQA-PMP and further refined in Phase A. A preliminary satellite design addressing the mission objectives was also developed during Phase A. Both prevailing orbit options can be flown with the same satellite design. The rotation of the satellite about the cross track axis on the ELLIP orbit also changes along the orbit compared to the CIRC option. The quantum accelerometer is equipped with a tilting mirror rotation compensation system (Beaufils et al. 2023), which needs to be able to compensate different rotation rates based on the satellite position along the ELLIP orbit while compensating a constant rotation rate on the CIRC orbit is sufficient (Meister et al. 2022). Other requirements on the mission design are related to a reduction in weight and cost of the satellite. Examples of these decisions are: (i) a sun synchronous orbit with a minimised eclipse period was chosen to reduce the weight of batteries or (ii) the orbit should enable a natural deorbiting in accordance with the French Space Operations Act (Loi relative aux Opérations Spatiales<sup>4</sup>) to reduce the need for a (dedicated) propulsion system and thus save weight.

## 3 Accelerometry for Space Weather Research

Knowledge of the upper atmosphere benefits a variety of applications. Atmospheric drag models are used in orbit propagators to calculate the orbits of satellites and space debris. With an increase in satellite numbers especially in low Earth orbit, precise orbit determination and forecasts will be essential to ensure the safety of spacecraft in the future. Within mission planning activities, these models affect the design of a satellite and are considered when estimating the mission lifetime or fuel consumption. In-situ observations of

<sup>4</sup>The applicable regulations are yet to be determined. LOS was the basis for the Phase A study, see <https://spacecare.cnes.fr/>. Other potentially applicable regulations are, e.g., the Space Debris Mitigation Guidelines by the IADC (2025) or the Space Debris Mitigation Requirements by ESA (2023). Final regulations depend on launch date and satellite operator.

**Table 2** Satellite mass and area projected in the along and cross track direction

|       | CARIOQA            | GRACE-FO           | Swarm              |
|-------|--------------------|--------------------|--------------------|
| Mass  | 500 kg             | 600 kg             | 470 kg             |
| Along | 0.9 m <sup>2</sup> | 1.0 m <sup>2</sup> | 0.8 m <sup>2</sup> |
| Cross | 4.2 m <sup>2</sup> | 2.4 m <sup>2</sup> | 3.2 m <sup>2</sup> |

atmospheric parameters contribute to our understanding of processes in the upper atmosphere. The observation during extreme events, like solar flares and geomagnetic storms, can improve the prediction of space weather and the analysis and processing of electromagnetic signals, e.g., from GNSS. In the context of the GRACE and GRACE-FO mission, atmosphere data products are also used for accelerometer calibration (Wöske et al. 2019) and an accelerometer data transplant for the GRACE-D satellite (Huckfeldt et al. 2024). The accelerometer data transplants replaces the less accurate measurements on the GRACE-D accelerometer with an artificial data product based on GRACE-C measurements and a combination of environmental models.

In the activities of developing the Pathfinder Mission the requirements of the quantum accelerometer are in part derived from studies modelling the expected signal amplitude and variation thereof on the different orbits investigated. To ensure the ability of the proposed quantum accelerometer to measure the full acceleration signal, i. e., do phase ambiguities occur while using a certain atom interferometer interval  $T$  (cf. Sect. 2.1 and Eq. 1), realistic simulated accelerations are necessary. These accelerations can be simulated considering the 3D shape of the satellite, its mass and environmental models on the orbit (cf. Sect. 4). The alternative to the modelling of the satellite environment in orbit is the comparison with accelerometer data from other satellite missions. While the CIRC scenario (Table 1) is similar to the GRACE(-FO) mission and the area in the along track direction and mass are also similar (cf. Table 2), the ELLIP scenario lacks directly comparable missions.

Satellite missions equipped with accelerometers, mostly satellite gravimetry missions and the Swarm mission, have been used to derive the density as well as crosswinds on the satellites orbit (Mehta et al. 2017; Siemes et al. 2023). In case of the Swarm mission the accelerometer data is replaced with GNSS derived accelerations due to the performance of the accelerometers (van den IJssel 2020). The process also relies on detailed satellite geometry (March et al. 2019).

The thermal density  $\rho$  is calculated from the accelerometer observations  $a_{\text{obs},x}$  in the along track direction reduced by the impact of solar radiation pressure, Earth albedo and infrared radiation (Doornbos 2011):

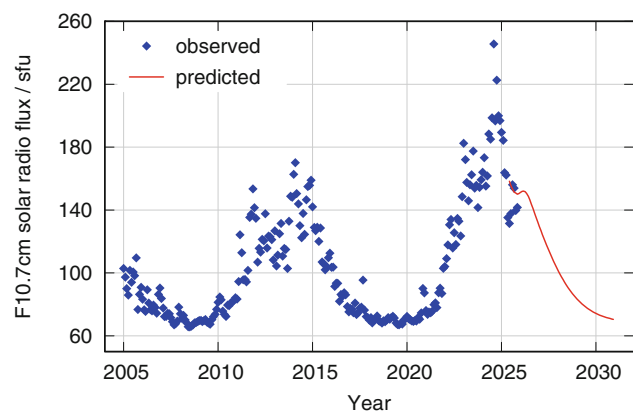
$$\rho = \frac{2m}{A_{\text{ref}} v_r^2} \frac{a_{\text{obs},x}}{C_{a,x}}. \quad (2)$$

The mass of the satellite  $m$ , the area  $A_{\text{ref}}$  of the satellite projected in the along track direction and the aerodynamic coefficient  $C_{a,x}$  projected in the along track direction and velocity relative to the atmosphere  $v_r$  are also required. The velocity  $v_r$  is the sum of satellite velocity, the velocity of the atmosphere corotating with the Earth and the horizontal wind. Splitting  $v_r$  in Eq. (2) into its components and solving for the horizontal component projected in the cross track direction provides the crosswind. TU Delft publishes data products and 3D satellite models based on these mission (TU Delft 2025). The Drag Temperature Models provided by the French space agency are combined models taking additional satellite missions and observations into consideration to provide atmosphere parameters for an altitude up to 1500 km (Bruinsma and Boniface 2021).

In general, density data measurements are sparse in all altitudes (Bruinsma et al. 2023) and dedicated mission concepts based on cube sats are proposed to increase the data availability (e.g. Siemes et al. 2022). In the altitudes of interest for satellite gravimetry missions such measurements would directly benefit future missions for accelerometer calibration and data transplants. The orbits considered for the Pathfinder Mission will cover this altitude. In addition to the quantum accelerometer it will also be equipped with a multi-frequency GNSS receiver as a comparison to the cold atom interferometer and to determine wind. The feasibility of density and wind determination by the Pathfinder Mission depends on the amplitude of the drag component and the sensors available, which will be described in Sect. 5.

## 4 Pathfinder Mission Simulation

The Pathfinder Mission will launch in the early 2030s at the start of the solar minimum. Figure 1 shows the observed and predicted F10.7cm solar radio flux as indicator for



**Fig. 1** F10.7cm solar radio flux monthly observation and prediction (Data: NOAA SWPC 2025)

**Table 3** Simulation setup

|  |  |
|--|--|
| Non-gravitational force modelling      | FEM based on 3D model                            |
| Solar radiation pressure               | Pointlike sun with eclipse modelling             |
| Atmospheric drag                       | NRLMSISE-00<br>( $F_{10.7} = 115$ , $A_p = 13$ ) |
| Earth albedo and IR, thermal radiation | Not included                                     |

solar activity. Low solar activity is also the cause of lower atmospheric drag resulting in the lowest input acceleration at the start of the mission. The simulations presented here were carried out with larger parameters due to increasing solar and atmospheric activity (see Table 3 and Schilling et al. (2025) for data) representative for the end of the mission.

The satellite and orbits were simulated in VENQS, the Virtual Environment for New Quantum Sensors (VENQS 2025; Chand et al. 2025). This software, developed at DLR, allows users to calculate satellite orbits based on the Earth’s gravity field and the 3D geometry and moment of inertia of the satellite. The 3D model of the satellite is divided into patches for a Finite Element Method (FEM) approach to calculate the forces acting on each individual element. Disturbing forces acting on the satellite can be simulated based on environmental models at orbit altitude including SRP, atmospheric drag, Earth albedo and infrared radiation, and satellite thermal radiation. Surface properties of the satellite can also be considered. For this study, the satellite from the CARIOQA Phase 0 (L  v  que et al. 2023) was implemented in VENQS but only the dominant perturbations due to SRP and drag were considered. Figure 2 shows the satellite model as an example for the calculation of SRP. The elements shown in yellow are illuminated by the sun and the force due to SRP is calculated for those elements while the blue elements are shadowed.

The sun synchronous orbits listed in Table 1 including attitude control to realize a nadir pointing mission were simulated with the parameters given in Table 3. The orbital parameters were the result of the mission analysis performed by the industry partner GMV. Models, e.g. the atmospheric drag model NRLMSISE-00 (Picone et al. 2002), and parameters used in VENQS and the mission analysis were agreed upon and results for a common epoch were compared between partners to ensure a common basis for the simulations in CARIOQA-PMP and the Phase A. Predicted orbits and non-gravitational accelerations for various scenarios were provided to partners developing the instrument. Software for the simulation of the quantum sensor (e.g. SQUID, Struckmann et al. 2024) was then used to evaluate the sensor performance based on a realistic satellite environment.

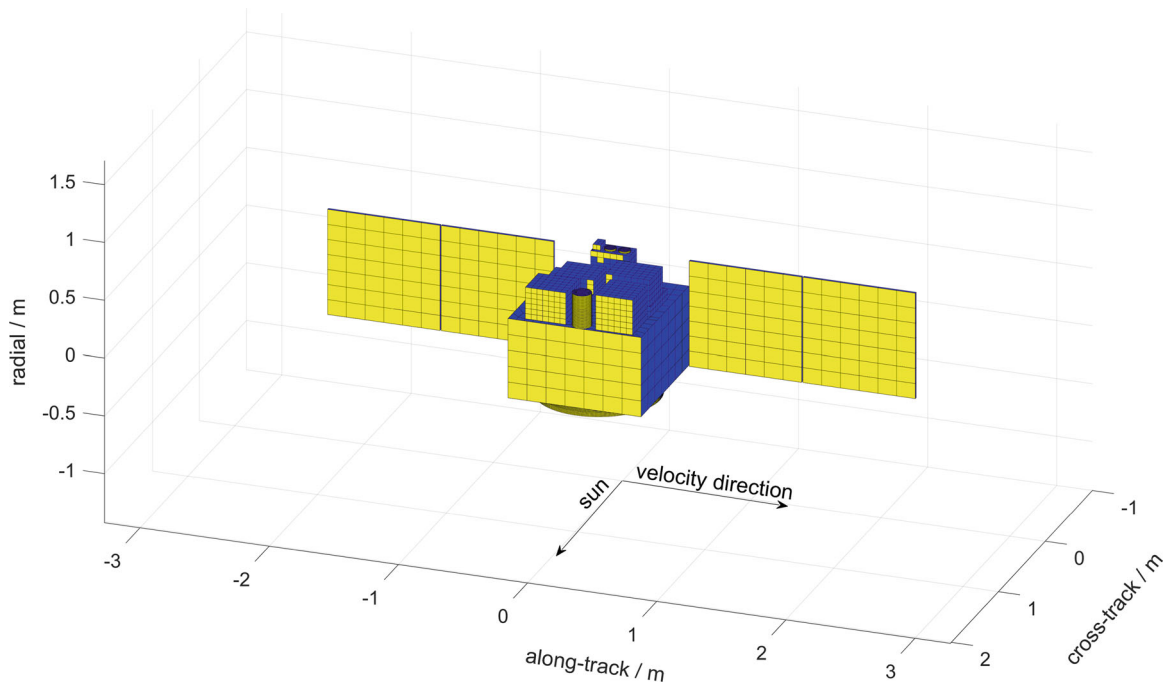
## 5 Results

The non-gravitational acceleration from SRP and atmospheric drag in the along-, cross- and radial direction were simulated as these are the dominant forces acting on the satellite. For this study the along- and cross-track directions are of interest to evaluate the accelerometer performance and the potential benefit for density and crosswind retrieval. The radial direction, dominated by Earth’s albedo and infrared radiation, is not examined here in detail.

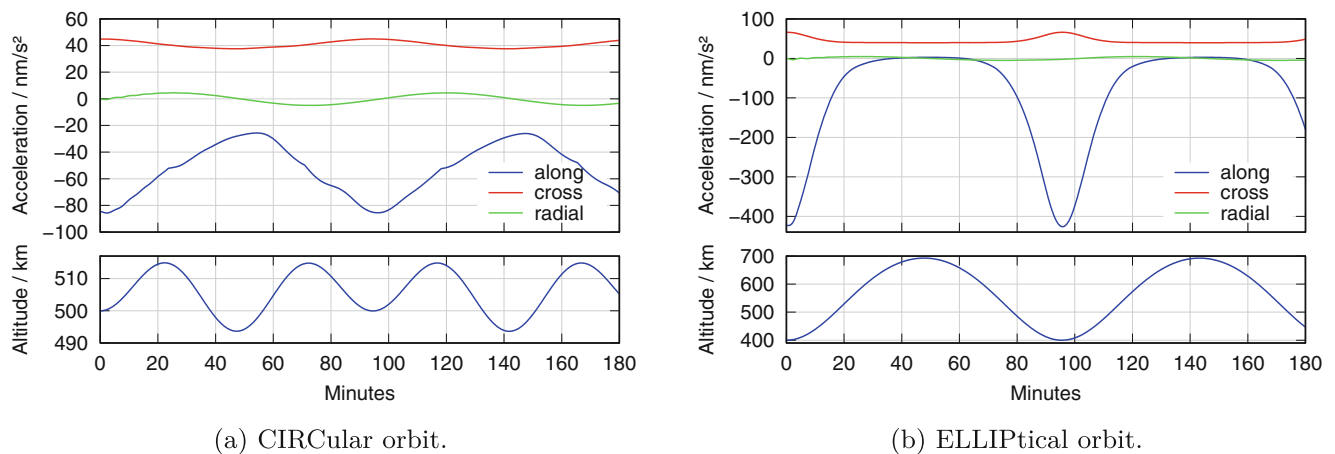
In Fig. 3 the simulated non-gravitational accelerations are presented for the CIRC and ELLIP scenario (cf. Table 1) on two orbits. The bottom plots of Fig. 3 show the satellite altitude. For the CIRC orbit in Fig. 3a the non-gravitational acceleration in the along track direction varies by a few tens of  $\text{nm/s}^2$ . The estimated dynamic range of the sensor based on Eq. (1) and an atom interferometer time interval  $T = 1 \text{ s}$  is approximately  $10 \text{ nm/s}^2$  to keep the atom interferometer phase shift  $\Delta\Phi$  well below  $\pi/2$ , i. e. centered on the linear slope of a sine wave. Adding an additional phase shift to the last Raman laser beam can compensate the acceleration measured to implement a phase tracking scheme to always operate the atom interferometer mid fringe. This way the dynamic range of the sensor only needs to cover the acceleration change of two consecutive measurements and not the total amplitude of accelerations along the orbit. The non-gravitational acceleration in the cross track direction is dominated by SRP and shows only minimal variation due to atmospheric drag of about  $8 \text{ nm/s}^2$  along one orbit.

Figure 3b shows the same results for the ELLIP scenario. As the satellite reaches lower altitudes (bottom plot of Fig. 3b) the maximum amplitude of non-gravitational accelerations in the along track direction is much larger. In addition at apogee, the non-gravitational acceleration is very low, which supports one of the mission objectives because it is beneficial to determine the noise level of the quantum accelerometer. The non-gravitational acceleration in the cross track direction is also dominated by SRP with only little change along the orbit but with larger variation due to atmospheric drag at lower altitudes.

Figure 4 presents the amplitude spectral densities (ASD) of the simulated non-gravitational accelerations for 24 hours in the along and cross track direction for both orbit scenarios. Additionally, two colored lines indicate the performance of a multi-frequency GNSS receiver similar to, e.g., Swarm with a 1 cm error (van den IJssel et al. 2016) and a lower performance GNSS receiver with a 1 m error.



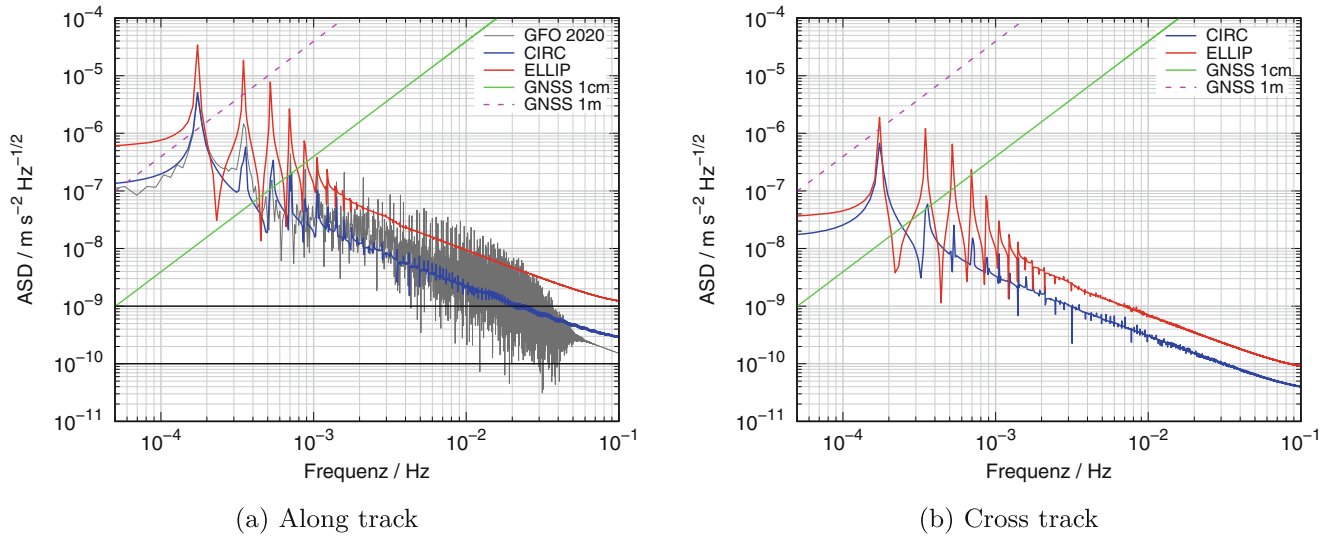
**Fig. 2** CARIOQA Phase 0 Satellite design implemented in VENQS



**Fig. 3** Simulated non-gravitational acceleration (sum of SRP and atmospheric drag) for the CIRC and ELLIP orbit

For the along track direction, shown in Fig. 4a, the minimum requirement of the quantum accelerometer of  $10^{-9} \text{ nm/s}^2/\sqrt{\text{Hz}}$  for the Pathfinder Mission and the best case scenario of  $10^{-10} \text{ nm/s}^2/\sqrt{\text{Hz}}$  are indicated as black lines. The main frequencies visible in the ASD are the orbital period and multiples thereof. The amplitudes for the ELLIP scenario are higher than those for the CIRC orbit. For comparison the ASD of the GRACE-FO accelerometer data product (ACT1B, Wen et al. 2019) for the date 10.01.2020 and satellite GRACE C is shown in grey. The altitude of the satellite was at approximately 500 km at the time. Considering mass and surface area of the Pathfinder satellite and GRACE-FO (cf. Table 2) but higher solar activity

compared to the year 2020 (see Fig. 1), the results for the CIRC scenario are comparable to real GRACE and GRACE-FO missions in a similar altitude. This supports the mission objective of the Pathfinder Mission to provide a comparable environment to satellite gravimetry missions. The signal amplitude between  $10^{-4} \text{ Hz}$  to  $10^{-3} \text{ Hz}$  of the ELLIP orbit is comparable to a GRACE orbit of the year 2014 at an altitude of approximately 420 km (not shown in Fig. 4a for clarity) making the ELLIP orbit also a valid choice of a representative satellite gravimetry orbit for the evaluation of the instrument. The 1 cm GNSS solution would also allow a comparison between GNSS derived accelerations and the quantum accelerometer at least in a



**Fig. 4** Amplitude spectral densities of non-gravitational accelerations in along track (left) and cross track (right) direction with estimated GNSS errors and upper/lower limits of accelerometer performance

limited bandwidth. This contributes to the verification of the instruments' performance.

The cross track direction, shown in Fig. 4b, features lower amplitudes in the spectrum compared to the along track direction for both orbits. The amplitude and change thereof is also larger on the ELLIP orbit due to variable crosswinds at different altitudes. Accelerations derived from the 1 cm GNSS receiver would still be able to recover the wind component by averaging 20 min to 30 min on the ELLIP orbit.

This part of the CARIOQA-PHA study relied on the Phase 0 satellite design, which was a starting point concerning size, weight and power consumption of a preliminary instrument design. During Phase A and all the more during the following phases, the instrument as a main driver for the satellite will be further developed. Therefore the satellite design is also not finalized but certain assumptions can be made considering the future development and the applicability of current results.

The size and mass of the satellite is limited by the space required to house the instrument and other subsystems with solar panels providing the necessary power as a lower boundary. The upper boundary considering satellite size, thereby limiting, e.g., size of solar array or instrument volume, is the available space of the launch vehicle. Currently, there are multiple European launch options available, e.g. Vega-C (dual passenger) or Ariane 6 (multiple launch service) as well as developments in the New Space sector, for the Phase 0 satellite design. Most options also allow for an increase in size and mass of the Pathfinder satellite compared to Phase 0.

As this study relies on the satellite geometry (area projected in a direction derived from a 3D model considering the

satellite attitude) and mass, variations of these two parameters will also change the accelerations measured by the quantum accelerometer. While a very low input signal for the accelerometer is desirable for certain tests of the instrument, applying environmental models to calculate corrections and other mitigation strategies are already considered now in the planning of the science program of the mission. The impact on the Pathfinder Mission objective, demonstrating a quantum sensor in space, and secondary objectives, e.g. contributing to models of the upper atmosphere, is not affected by this potential increase in acceleration signal. Other aspects, e.g. mission lifetime, are part of mission analysis activities of the Phase B study.

The study presented here uses model data with a low temporal resolution compared to the data rate of current and future accelerometers. At the current state of the project, where key parameters of the instrument are fixed, the main interest is in the overall expected signal amplitude on different orbits and on time spans covering consecutive measurements. For scenarios like the CIRC orbit also GRACE(-FO) accelerometer data products are utilized in evaluating the required dynamic range of the instrument and other aspects of the instrument. The impact of acceleration changes during a single and consecutive quantum accelerometer measurement is described, e.g., by Knabe et al. (2023).

## 6 Conclusion

The CARIOQA Pathfinder Mission is the first step to equip future satellite gravimetry missions with a quantum accelerometer by demonstrating the technology on a dedicated mission in space. The recently concluded Phase

A study defined and investigated several mission objectives and scientific applications of Pathfinder Mission data. Two orbit options fulfilling the mission requirements while being flown with the same satellite design are the result of the Phase A and were investigated here. Models of the satellite environment play a vital role in this process to simulate the expected signal on different orbits also considering the geometry of the satellite. Key parameters of the instrument were defined based on the expected signal to achieve the desired performance level.

Once in orbit, the Pathfinder Mission can also contribute to the improvement of the environmental models. The acceleration measurements in the along track axis are comparable to the GRACE(-FO) mission data which can then be used to derive the density along the Pathfinder Mission orbit. The actual quality of such a data product depends on the orbit chosen for the mission because the accelerations on the elliptical orbit will be at or below the sensors noise level during part of the orbit. As no cross track accelerometer axis will be available, only GNSS derived accelerations can be used to generate a crosswind data product. In a processing scheme similar to crosswind data products generated from Swarm mission data, a low temporal resolution wind product can be envisioned for the Pathfinder Mission.

## Declarations

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**Data Availability** GRACE(-FO) data is available at the [Information System and Data Center \(ISDC\)](#) of the Helmholtz Centre for Geosciences (GFZ). F10.7cm radio flux data is available at the [Space Weather Prediction Center](#) of the National Oceanic and Atmospheric Administration (SWPC). Data simulated in this study is available on Zenodo (DOI: [10.5281/zenodo.17580678](https://doi.org/10.5281/zenodo.17580678)).

**Competing Interests** The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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