Feasibility study of the deployment of levitated quantum optomechanical sensors for atmospheric observation (LEVITAS)

Executive Summary Report

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Ravindra Desai Animesh Datta James Bateman Daniel K L Oi
Rafal Gajewski

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1 Executive Summary

This feasibility study explores the development and application of levitated quantum optomechanical sensors for atmospheric observations, particularly in the context of Earth Observation (EO). The work, conducted by University of Warwick in collaboration with Swansea University and University of Strathclyde, evaluates the fundamental operating principles, conceptual and preliminary instrument design, performance, and recommended development roadmap for advancing optomechanical experiments from laboratory technology to space-qualified instrumentation.

The study first establishes the scientific rationale for the proposed optomechanical sensing technique, targeting gaps in neutral measurement capabilities. Conventional instruments like neutral mass spectrometers and accelerometers use indirect techniques and are therefore limited in resolution or operational range, particularly in low-density regimes of low earth orbit (LEO). Levitated optomechanical experiments on the other hand, leveraging dielectric nanoparticles monitored with quantum-limited precision, offer the potential to instantaneously detect individual particle impacts and measure the resultant moments of the underlying distribution function of the ambient medium (density, temperature, bulk velocity) with unprecedented sensitivity and accuracy. A set of target mission requirements is established for spacecraft operating in Low Earth Orbit (LEO). This atmospheric regime is of intense scientific interest due to the complex interactions between the upper atmosphere and the space environment. Furthermore, precise atmospheric drag measurements are essential in LEO both for advancing scientific understanding and for supporting operational satellites that require accurate orbit determination and prediction.

Building on these characteristics, a conceptual design outlines a compact "Levitodynamics for Interstellar Medium and Atmospheric Sensing" system termed LEVITAS, to utilise this micro-canonical measurement approach. The proposed system employs a laser for the nanoparticle trapping, millimetre-scale RF Paul traps, and a ram-facing aperture. LEVITAS is sensitive to a wide range of atomic and molecular species and able to resolve recoil events down to the Rayleigh scattering limit of 0.05 nm/s at high sampling rates. Technological components are assessed and specified, including nanoparticle dispensers, fibre lasers, photoreceivers and digital control systems. Key challenges towards implementation include vibration management and integration of optical and mechanical systems into a space-compliant instrument.

This conceptual design is then advanced into a preliminary instrument design through modelling of the system performance using Bayesian inference to extract impact parameters from nanoparticle motion. Multiplexing strategies, such as time-division tracking of multiple nanoparticles and optical lattice trapping, are identified as potentially significantly improving the sensing throughput and efficiency. Performance modelling demonstrates LEVITAS' ability to resolve multiple species (e.g., H, He, N, O) at various LEO altitudes (600–1000 km) with high precision. Even at low densities (down to below $10^4 cm^{-3}$); species composition, temperature (200–5000 K), and wind velocities ($\pm 1700 m/s$) can be inferred within seconds to minutes of observation. The sensor's sensitivity and accuracy even extends to rarefied distributions present in interplanetary space, with simulations resolving interstellar hydrogen and helium collisions at over 20 km/s. The refined design offers improvements in size, weight, and power (SWaP), with total power consumption estimated at 15-25 W and sensor head dimensions around 80×80×50 mm³. Technology readiness is assessed at TRL3, with clear paths to space qualification.

The findings are consolidated into a development roadmap, prioritising reaching TRL4 by 2026. Cost estimates focus on heritage hardware and modularity, while risk mitigation focuses on early experimental validation. LEVITAS aligns with missions such as ROARS (Revealing Orbital and Atmospheric Responses to Solar activity) and NASA's GDC (Geospace Dynamics Constellation), offering unmatched low-density capabilities as well as absolute measurement capability with zero in-flight calibration. LEVITAS also opens up the possibility for reliable detections of rare interstellar atoms and molecules, including noble gases and heavier elements, enabling studies of the Milky Way's composition and the origins of these species via stellar and Big Bang nucleosynthesis.

In summary, LEVITAS represent represents a novel and transformative sensor concept, bridging critical gaps in atmospheric and space science. By combining quantum optomechanics with precision engineering, LEVITAS achieves unprecedented resolution in challenging environments, from Earth's thermosphere to the Martian tenuous exosphere, through to the interstellar medium. This study provides both a strong conceptual foundation and a technical roadmap to further explore the utilisation of optomechanical experiments for space applications.

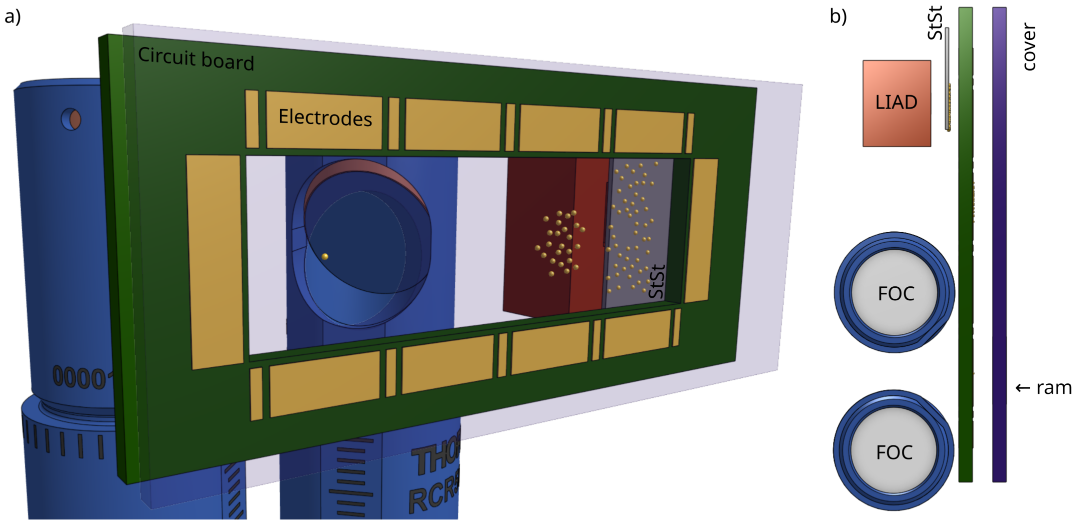

Figure 1: Illustration of the sensor head using the planar RF Paul trap and LIAD: (a) shows a perspective view while (b) shows a top-down view. The planar RF Paul trap is implemented using a **circuit board** comprised of a substrate and individually addressable **electrodes**. Nanoparticles are ejected by a **LIAD** laser directed at a Stainless Steel (**StSt**) substrate coated on one side with nanoparticles. These are captured into the RF Paul trap where they may be shuttled between regions and stored for transfer into an optical trap. For illustration we show a 2D vector resolving configuration, where two fibre-optic couplers (FOC) focus trapping light on a single nanoparticle exposed to **ram**; an arrow shows the direction of incident neutral species. A **cover**, semi-transparent in (a), shields the majority of the apparatus, with only a small circular region around the optical trap exposed.