MaQuIS: Pioneering quantum space exploration to unlock Mars' interior and atmosphere

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Emily Warrender

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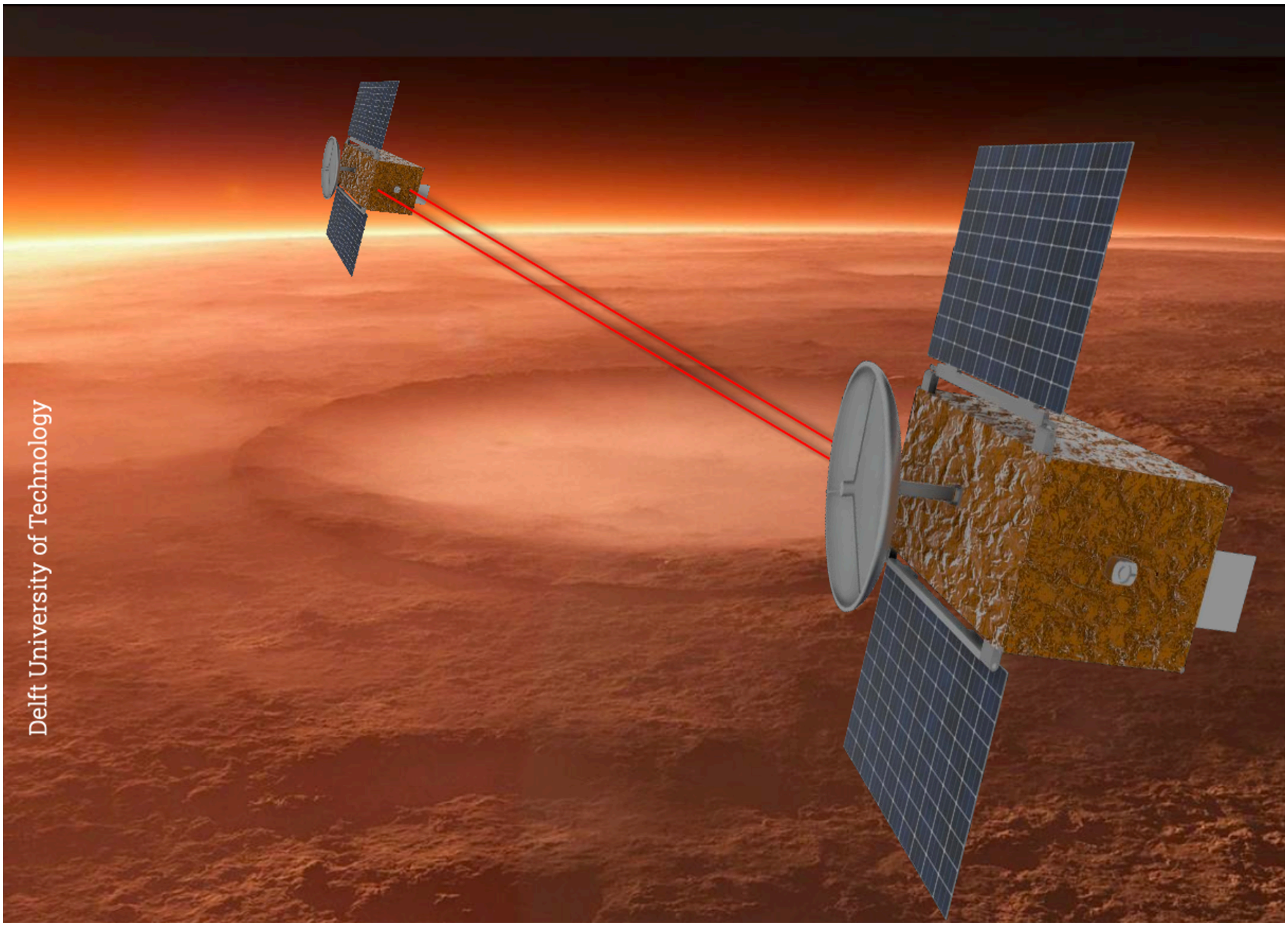

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B.C. (Bart) Root, an Assistant Professor at Delft University of Technology, discusses pioneering efforts in quantum space exploration aimed at unlocking the secrets of Mars' interior and atmosphere

The Mars Quantum Gravity Mission for Interior Structure and Atmosphere (MaQuIS) represents a transformative approach to understanding the Red Planet, uniting advanced quantum sensing technologies with a mission architecture proven through decades of successful satellite missions. By combining cutting-edge instrumentation with a robust spacecraft design, MaQuIS addresses one of the most compelling questions in planetary science: the internal structure, geodynamics, and atmospheric evolution of Mars.

The Mars Quantum Gravity

Mission for Interior Structure and Atmosphere Spearheaded by Delft University of Technology in collaboration with leading European research institutes, the mission concept is advancing rapidly, pushing the boundaries of space technology to enable a high-precision, global survey of Mars' interior and atmospheric dynamics.

Mars, long considered largely static, has revealed a dynamic interior in recent years. NASA's InSight mission detected ongoing tectonic activity, localised mantle plumes, and magmatic processes, suggesting Mars' interior remains active and may have contributed to the planet's atmosphere through mantle outgassing.

Understanding these processes is critical not only for reconstructing Mars' geological and climatic history but also for anticipating hazards and identifying potential resources for future robotic or crewed missions. MaQuIS addresses this challenge through a dedicated gravimetric satellite mission, capturing subtle variations in Mars' gravity field to reveal the hidden structure of the lithosphere, mantle, and subsurface reservoirs of water and volatiles.

MaQuIS can build on proven European and international satellite architectures, notably the GRACE mission to Earth and the GRAIL mission to the Moon. These missions demonstrated the power of inter-satellite laser ranging and precision accelerometry to map planetary gravity fields with exceptional spatial and temporal resolution.

MaQuIS advances this heritage by incorporating quantum sensing technology, specifically cold atom interferometers. These instruments provide absolute, drift-free measurements of acceleration, enabling the detection of minute variations in gravity that were previously inaccessible. Laboratory and orbital demonstrations confirm that these technologies are ready for high-precision planetary missions, marking a milestone for European leadership in quantum space applications.

The scientific goals of MaQuIS are ambitious yet achievable. The mission aims to:

1. Monitor Mars' atmospheric and volatile cycles –

   Gravity measurements, combined with sensitive onboard accelerometers, will quantify seasonal and interannual changes in polar ice masses, atmospheric pressure, and volatile transport. These observations will provide a complementary view on how Mars' CO_2, H_2O, and dust cycles evolve over time, informing climate models and atmospheric escape mechanisms.
2. Investigate the fate of ancient water –

   By tracking mass variations, MaQuIS will detect subsurface water reservoirs, potential briny layers, and polar ice dynamics. Combined with radar and altimetry, these measurements will refine estimates of the density and composition of layered deposits, improving understanding of Mars' habitability and resource potential.

3. Resolve Mars' interior structure –
   By mapping the static and time-variable gravity field to high spatial resolution, MaQuIS will constrain crustal thickness, lithospheric composition, mantle density, and porosity. This data will elucidate the thermal evolution of the planet and reveal active geodynamic processes such as mantle plumes beneath Tharsis and Elysium Planitia.

The mission architecture is designed for precision and efficiency. Two spacecraft will operate in a controlled formation, separated by 200 km, and connected by a bidirectional infrared laser interferometer operating at 1064-1550 nm. This approach leverages extensive European and international flight heritage, ensuring reliability while minimising technical risk.

Non-gravitational forces, such as atmospheric drag and solar radiation pressure, will be measured and removed using onboard accelerometers, while laser frequency noise will be stabilised using optical cavities and long-term reference techniques. Cold atom interferometers complement classical accelerometers, offering absolute, high-sensitivity measurements essential for long-duration missions.

Preliminary simulations demonstrate that MaQuIS can achieve unprecedented resolution of Mars' static and time-variable gravity field. The mission will operate at two altitudes: a low orbit at 200 km for high-resolution mapping of the static gravity field, and a higher orbit at 650 km for monitoring temporal variations. Time-variable gravity solutions generated over five-day, 30-day, and one-year intervals reveal the ability to detect regional-scale geodynamic activity, polar mass changes, and tidal responses, providing continuous global coverage not previously possible with other missions.

MaQuIS embodies a thoughtful approach to spacecraft design, prioritising mission longevity and data integrity. By minimising moving parts, the mission reduces vibration noise that could interfere with gravity measurements. Communications will rely on fixed or phased-array antennas, with onboard buffering and battery support to address constraints in solar array size and downlink capacity. Data will be transmitted using rates similar to GRACE, with potential enhancements through existing or proposed relay satellites, including Europe's emerging Lightship constellation.

The mission can be launched on an Ariane 6 A64 rocket. Both spacecraft will launch together, transit to Mars, and separate upon orbit insertion to achieve the required formation. With an expected operational lifetime of approximately four and a half years, MaQuIS will provide the European Union with a continuous, high-precision dataset of Mars' interior and atmosphere, supporting both scientific research and policy-relevant objectives in planetary exploration.

The strategic value of MaQuIS extends beyond scientific discovery. The mission positions Europe as a leader in quantum technologies applied to space exploration, fostering innovation that can spin off into terrestrial applications such as geodesy, climate monitoring, and navigation. It strengthens Europe's role in the international exploration of Mars, contributing to long-term planetary strategy and ensuring that European expertise and technology remain at the forefront of global efforts.

By providing high-resolution data on Mars' interior, atmosphere, and volatile cycles, MaQuIS supports future robotic and human missions, informing landing site selection, resource identification, and environmental risk assessment.

A milestone for European space policy and science?

In conclusion, MaQuIS could represent a milestone for European space policy and science. By combining quantum-enabled instrumentation, precision laser ranging, and a robust mission architecture, it promises to revolutionise our understanding of Mars' geodynamic and atmospheric processes.

The mission's outputs will provide policymakers with a scientific foundation for planning Europe's long-term presence in planetary exploration, while demonstrating leadership in quantum technologies, international collaboration, and high-value scientific return. MaQuIS is not only a mission to Mars – it can become a statement of Europe's ambition to lead the next era of planetary discovery.

Primary Contributor

Bart Root
Delft University of Technology
ORCID: 0000-0001-7742-1434