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QTSPACE

DELIVERABLE 4.2

List of necessary technological requirements for future missions in space

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INTRODUCTION

Due to a wealth of commercialisation and prototyping activities led by the cold-atom and photonics communities, many of the existing challenges for the implementation of QT in Space are not insurmountable.

This deliverable describes how to build upon an already interconnected scientific and industrial community and what steps are needed to enable further cross-disciplinary networking and collaboration. Expanding the diversity of quantum experiments being performed in the optimal conditions of space and micro-gravity has clear benefits for the progression of our understanding of the universe and tangible economic and innovative outputs. We highlight these benefits and the need for a global effort to realise them.

We conclude this report work with a technical wish list detailing the technological advancements needed to enable space-based experiments with quantum systems.

IMPLEMENTATION

1. Environmental Control

The environment of space is not homogeneous, with variations in temperature, vacuum pressure and radiation. Although working in space allows for the exploitation of the vacuum and coldness of space, maneuvering experiments from the inside to the outside of the space platform is complex. The route for a ground-based experiment to become space ready is to translate all the subcomponents to space-hardened components, developing a new equipment where necessary.

1.1 Maintaining vacuum and environmental temperature

Setting up stable conditions for an experiment in space is very difficult due to the extreme thermal conditions the spacecraft will be facing when traversing through outer space [1, 2]. The solution is to add a passive shielding which reduces the impact of solar radiation on the thermal stability. Using a passive solution is particularly beneficial for a spacecraft than active cooling, which would require cryostats [3]. Cryostats and dilutions refrigerators cause vibrations, especially when one needs to go down in temperature [4, 5].

Additionally, keeping liquid helium in a container in a gravity free environment is a challenge on its own, which has been solved by the Gravity Probe B. The mission used a sponge mechanism inside a porous plug to prevent liquid helium sloshing and to control the pressure in the dewar [6, 7]. Finally, due to resource constraints in space, a limited supply of liquid Helium in an open cooling loop can drastically curtail the lifetime of a space mission and unaccounted heating sources can cause depletion even faster, leading to a potential abrupt end of the mission. Similar resource constraints apply to closed loops cooling systems on a space craft due to the combination of the high-power consumption and the limited energy budget for a space mission’s lifetime [8, 9].

Further technology constraints to take into account are:

- Measuring extreme vacuum is a challenge in itself [10, 11].
- Sealed devices use getter [12, 13].
- Vacuum packaging should also be taken into account [13–15].
- Spacecraft out gassing [2] can ruin pressure but can also be improved by the radiation shields [3].
- Best vacuum achievable 10^{-16} mbar in a facility at CERN - 7×10^{-17} mbar has been achieved at 4 K [16]; there are plans for the new PUMA project (antiProton Unstable Matter Annihilation), which will demonstrate storage and transportation of antimatter at pressures of 10^{-17} mbar.
- 10^{-10}-10^{-11} mbar is more at the space ready-side, but for low volume. For example, MAQRO requires less than 20 K environment temperature [17].

1.2 Mechanical Stability/Vibration Isolation/Alignment

Mechanical instability arises from two sources: the environment, or from movements inside the space craft. For environmental sources of vibration, atmospheric drag and solar wind can cause unwanted instabilities, which is why MAQRO is planned for an L2 orbit where there are reduced contributions from these noise sources [18, 19]. Vibrations within the experiment itself, for example, from cryostats require attention [20]. However, there are existing solutions used for Gravity Probe B and the Planck mission where closed loop cryostats show improved stabilization. It should be noted that closed loop cryostats also offer a longer lifetime compared with open loop ones. Although the helium leakage is unavoidable and amplified when there are sources of heat within the chamber, closed loop recycles the helium in a more conservative manner [21].

Lack of access to experiments once launched requires detailed understanding of how component and mounts change dimension between initial alignment, usually conducted at atmospheric pressure and at room temperature, to the final environmental conditions, e.g. cryostat temperatures or high vacuum. Out-gassing, flexure stresses and warping can all cause misalignment that is not easy to correct once the experiment is sealed.

- Vibrations from micro-propulsion system [1] where the force noise produced by LISA is not good enough for original proposal, but with longer free fall, larger fringes can be achieved when working with state of the art microthrusters. Acceleration sensitivity of MAQRO is between $1{-}100\times10^{-12}$ $m/s^2/Hz^{1/2}$ for the cavity.
- Tilt noise should be kept lower than 0.5 μ rad $Hz^{-1/2}$ [22].
- For free-fall interferometry, unwanted vibration can be accidentally applied during the grating/microwave pulse/detection stages.
- Length of time for measurements adds further requirements for stability/drift of instruments. For example, MAQRO requires around 100 s measurement time per data point [17]. For this reason, an accelerometer is a central prerequisite for MAQRO to prevent random relative motion between test particle and the spacecraft - two accelerometers are needed (one at the center of mass of the spacecraft). They have put forward the ONERA sensor in a cryogenic environment.
- Charge effects on free falling test-masses are another relevant issue [23].
- Depletion of nitrogen from cold gas micropropulsion system produces a deterministic gravitational drift typically several hundreds of fm s^{-2}/day [24].

2. Component Development

2.1. Miniaturisation

Miniturisation is becoming less of a barrier for getting things into space. SpaceX lowers cost of launch by ten times. Cubesats are opening up a lot of opportunity that is not so restrictive on size (going from 6U- 12U-24U). LISA limit is half a ton because it needs to reach the geostationary orbit. So orbit choice is also related. SWaP budget is still a driver for the further away orbits.

Elements to be considered are:

- Cold quanta (US) create cold atom parts and chambers [25, 26].
- Miniaturisation of vapour cells, where progress has been rapid due to GNSS use of rubidium cell frequency standards [27].
- Huge strides have been made on the sub-components required for atomic interferometry through a recent upgrade of the Cold Atom Lab on board the ISS - it is the first atom interferometer to operate in space. The Cold Atom Lab is approximately the size of a dishwasher [28].
- Space is expensive (size and mass have a 'cost'). Geostationary transfer orbit is the furthest orbit - so one wants high initial velocity therefore low mass. BECCAL is 350kg/320kg - but this mass comes not from the vacuum chamber (5kg) but from the sub-components - for example, the 16-17 lasers, and rack sized electronics (in-house built). The more functionality, the more number of parts, or requirements for upgrades.
- Small size/mass allows for piggybacking on missions. But it is a balance of money/political appetite.
- Additive manufacturing for space mission is required [29].

2.2. Optics/Photonics

The key elements to be considered are:

- Single mode fibers in space are feasible but if broken they need to be changed.
- InP PICs - miniturisation, radiation tolerant, CERN has been investigated [30, 31].
- In the DARWIN proposal [32] a roadmap was laid down, which included space-qualified delay lines to balance optical paths to nanometre accuracy and the use of single mode tested UHV, 10K, photon radiation and gamma radiation [1].
- Laser pointing [1] IR cavity finesse (high reflectivity coatings) of above 3×10^4. MAQRO suitable laser source: 1064 nm wavelength non-planar ring oscillator laser used by LPF and LISA. Laser sources NOT at mature TRL: 200 nm UV light source.
- Laser noise causes the same issues as it does on ground requiring either active feedback methods, referenced to stable frequency source, or single photon sources that are space qualified [33–35].
- FBH build lasers for many projects such as BECCAL and MAIUS [36].
- TESAT create TRL 9 lasers at 1550nm [37] already used for satellite to satellite communications. DLR building compact laser communication terminals for CubeSats (LCRT).
- Photonics for space up to TRL9 was developed [38].

3. Automation

3.1. Power consumption

MAQRO would require a solar array 680 W, similar to that used by Pathfinder [17], with the largest power consumption from data and diagnostics, and operating lasers. If a bake out of the heat-shield structure is required, this almost doubles the power consumption. QPPF has active cooling which requires more power consumption

3.2. Electronics & Control

Although some electronics can be sourced off-the-shelf, calm current operation may not be guaranteed, with bespoke requirements such as fast switching times not commercially available.

Sometimes one wants to use large chips. E.g. electronics, because of radiation issues like cosmic rays: a single cosmic ray could take out a transistor if it is made on small node size; on the other hand, one can have redundancy when working with small chips.

Electronics requirements can be quite different to drawing based, plug and play components such as vacuum chambers, with added cost in miniaturisation due to the high cost of developing and fabricating ASICs for low power and ruggarrised operation. STi work with space-related projects but it is within their remit.

Electronics, PCBs and software needs specialist companies to work on. Control software is especially needed. Power spectrums/FFT/big data storage e.g. random number generation needs Gb of storage Flash drives, SD cards are being used so some progress on this.

3.3. Particle trapping and launch/recapture

Optomechanics: there is a variety of particle loading and launch/capture methods [39–43].

MAQRO proposes to use transfer of particles through a hollow core photonic crystal fiber where loading and characterization is performed inside a buffer gas chamber, with optical guiding of the particle to outside of the spacecraft [17]. The storage of particles requires further thought due to heating of the internal test particle temperature (which cannot be higher than environment temperature) - low absorption materials are being considered, or, the use of each particle only once (held with light for short duration), or the use of non-optical methods for trapping, or to fill the hollow core photonic crystal fiber with a gas for sympathetic cooling - none of these have been demonstrated yet.

Sounding rocket, quantas, etc fully automated with no interference from ground (link to the people on board, astronauts or no one around at all, for satellites, astronaut time is expensive.

4. Quality Assurance/Environmental Testing

Some key elements are for implementing the MQRO proposal are:

- Vibration testing on preloaded LARES satellite and separation system [46].
- Controlling charges on surface of nanospheres [47, 48].
- Charging of dielectrics due to cosmic radiation [49] discharging particles is not enough. There might be some residual dipole moment [50].
- Optical surface potential mapping e.g. surfaces close to trapping potentials can skew them [51, 52]
- Radiation - single event failures on satellites (not as common on-board ISS because of shielding/protection).

Qualification is very expensive. Documentation easily becomes complex, even for screws; item costs can go up by ten times. Traceability is also important.

- The European Cooperation for Space Standardization (ECSS) is an initiative established to develop a coherent, single set of user-friendly standards for use in all European space activities.
- The European Centre for Space Law (ECSL) was founded in 1989 on the initiative of the European Space Agency. Its objectives are the improvement in space law research, education and practice in Europe.
- The Consultative Committee for Space Data Systems (CCSDS) is an international voluntary consensus organization of space agencies and industrial associates interested in mutually developing standard data handling techniques to support space research, including space science and applications. [53]
- The European Space Components Information Exchange System (ESCIES) is a repository for EEE parts information hosted by ESA, on behalf of the Space Components Steering Board, as part of the European Space Components Coordination.
- The European Preferred Parts List (EPPL) is a list of preferred and suitable components to be used by European manufacturers of spacecraft hardware and associated equipment. It is part of the ECSS system with an updated parts list released every year; for example, EPPL Issue 41 refers to 2020 [54].

CONCLUSIONS

The development of Space based Quantum Technologies requires a collaborative environment, involving space agencies, industries and academia.

Akin to another quantum technology, i.e. quantum computing, space-based quantum technologies are heavily dependent on heavy investments being made by private institutions and industry as its highly specialised and post-doctoral like workforce is generating a high cost basis to get started. Similar to how it has been proposed for quantum computing in [55] the space-based quantum technology sector would benefit from the establishment of quantum lighthouse hubs forming centres of excellence around the European research community in a close-knit relationship with industrial players to train the engineers and technicians for tomorrow's sprawling industries.

Furthermore, countries should focus on building the next generation manufacturing capabilities. Especially clean room infrastructure will be in high demand when it comes to scaling these quantum technologies. Easing the requirements for quantum technology startups to bid for public procurement projects, similar to how SpaceX created a new sector for commercial space flight in the US, will be of key essence.

Other elements to be considered are:

- Consortiums between academia and industry.
- Longer overarching project aim (instead of small standalone projects).
- Systems engineering and more training for physicists.
- Targeted funding incentives.

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