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List of relevant mission parameters for future missions in space

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INTRODUCTION

We identified the mission parameters for

- Cold atom technology, which allow to perform interferometry with outstanding accuracy and resolution.
- Photon technology, which offer the possibility to create a global quantum communication and quantum internet.

IMPLEMENTATION

Cold atoms

Motivation: Cold atoms are one of the physical systems utilized to implement quantum technologies in space. They offer a well-controlled environment where employing interferometric effects leads to unprecedented precision sensing applications. Low-gravity environments elevate the precision of these systems even further, mainly due to the increasing free fall times. In addition, ultra-cold atomic condensates can be considered as macroscopic systems showing quantum effects. Thus, in combination with environments where relativistic effects become relevant, they present an attractive playground for testing fundamental physics. Furthermore, cold atoms interferometers can be used to enhance navigation systems, and aid geological exploration, or Earth observation.

Goals: cold atom interferometry with outstanding accuracy and resolution.

Cold atoms experiments have taken a long path from the laboratory environment and have been conducted in various harsh environments from drop towers, ships, aeroplanes, and sounding rockets, however, in following we focus solely on space-based projects. Three distinct *platforms* have been proposed for the cold atom experiment: parabolic sounding rockets (MAIUS), the International Space Station (CAL, BECCAL), and a miniaturized satellite (CASPA). Main limitations of space.

List of projects: *MAIUS [1], CAL [2], BECCAL [3], CASPA [4], CAI* (concept proposal) [5].

Parameter	**Description**	**Examples**
Cloud material	Type of atom (isotope)	MAIUS: Rubidium-87 CAL: Rubidium-87, Potassium-39, and Potassium-41 BECCAL: Rubidium-87, Potassium-39, and Potassium-41 (and enriched Potassium-40) CASPA: Rubidium-87
Cloud size	number of atoms in the cloud	MAIUS: 1- 5 x 10^5 CAL: 1.1 x 10^4 BECCAL: 1 x 10^6 for Rubidium, and 1 x 10^5 for Potassium, at least 1 x 10^4 for mixture of atoms; CASPA ~ 10^8
Chamber temperature	Atom cloud temperature during the experiment	MAIUS: ~ 100 nK CAL: 170 nK BECCAL: ~ 100 nK CASPA: 100 μK with a plan to reach nK range

Vacuum	Vacuum regime characterized by pressure in the chamber.	Ultra-high vacuum (UHV) system MAIUS: ~ 5 x 10^-8 Pa CAL: ~ 1 x 10^-8 Pa BECCAL: ~ 1 x 10^-8 Pa CASPA: <1 x 10^-7 Pa
Optics	distribution optics	Ruggedised telescope for delivery of laser light into the vacuum chamber. Imaging system. Optical subsystems (e.g. frequency doubler, Erbium Doped Fibre Amplifier)
Traps	apparatus used to hold atomic cloud	MAIUS: 2D, 3D magneto-optical trap CAL: 2D, 3D magneto-optical trap BECCAL: 2D, 3D magneto-optical trap, dipole trap CASPA: laser system with eight laser sources + Ioffe–Pritchard magnetic trap
Microgravity time	The duration of the experiment in microgravity environment	MAIUS-1*:* 6 minutes CAL: permanent BECCAL: permanent CASPA*:* permanent, max. experiment duration 30 min
Operation temperature range:	Temperature limits for electronic components. Heatsinks are employed to ensure the stability of the system.	MAIUS: 0 - +50°C CAL: delivery requirements similar to MAIUS BECCAL: delivery requirements similar to MAIUS CASPA: CubeSat -10 to +60°C ; Payload 0 to +40°C
Vibration:	The range of vibration frequencies the system has to withstand for launch qualification	MAIUS: in 3D for a 1 min duration per axis in freq. range 20 Hz to 2kHz; CAL: delivery requirements similar to MAIUS BECCAL: delivery requirements similar to MAIUS CASPA: NASA GEVS random vibration test (in 3D for a 2 min durations per axis in freq. range 20 Hz to 2kHz)

Orbit altitude	The altitude above ground level at which the experiment will be carried out	MAIUS: up to 260 km CAL: 370 km to 460 km (ISS) BECCAL: 370 km to 460 km (ISS) CASPA: 400-550 km (LEO)
Platform	The carrier of (physics package or payload) a subsystem where the experiments are to be performed.	MAIUS: Sounding rocket CAL: on board of ISS BECCAL: on board of ISS CASPA: CubeSat
Orbit maintenance	System used for controlling and correcting orbit altitude	MAIUS: n/a CAL: ISS Propulsion Module BECCAL: ISS Propulsion Module CASPA: no
Lifetime	Minimal planned duration of the project	MAIUS: ~ 11 min. CAL: ongoing since 2018 BECCAL: ongoing since 2018 CASPA: 6 months

Photons

Motivation: Paving the way towards global quantum communication and quantum internet.

Goals: The main goal is to implement a particular quantum key distribution (QKD) protocol. Additional goals of previous and current missions are to demonstrate the feasibility of new thermal or isolating designs, and investigate aging of the equipment in space, enabling iterative improvement for more robust and efficient future missions.

All the components of the system, as well as the overall engineered system undergo rigorous testing, including individual components and battery verifications, vibration, acoustic, radiation and qualification tests. The requirements imposed by space-qualification and platform of choice limit the range of mission parameters and in the following the minimum required parameters of the scientific mission are listed. The mission parameter is understood as the controllable value of the engineered system that directly influences the performance of the implemented protocol or experiment. Hence, following does not include parameters of supporting engineering subsystems such as avionic, solar cells, computational equipment, etc., although they might as well impose limitations on the performance of the quantum key distribution protocol.

The main parameter that determines the design of the optical payload is the *quantum communication protocol*. QKD protocols share a common goal, but there are a variety of approaches to how exactly they can be implemented, differing in preparation techniques, encoding, measurement types and assumptions made regarding used equipment to name a few. Predominantly a single protocol of choice is the well-studied discrete-variable two-decoy BB84 protocol []. Other employed protocols include E91 and BBM92. Furthermore, the mission can be suited to support multiple protocols, e.g. MICIUS satellite, operated by Chinese Academy of Sciences, can generate keys using decoy state BB84 or distribute two-photon entanglement between optical ground stations (OGS) realizing BBM92 protocol across 1120 km.

Generally, the performance of the QKD protocol can be seen in terms of the secure key rate that expresses the amount of bits that can be generated in a single round of the protocol (channel use) or per time unit. Practically it is limited by signal source *repetition rate* (currently employed sources have up to 100 MHz) or maximum detector count rate (single-photon detector on CubeSat platform requirement is at least 100 kHz). Already *the role of the satellite* in the communication protocol, i.e. the transmitter (requiring the source of the quantum signal states) or the receiver (carrying detectors) will govern the performance and the specifics of the optical payload design.

The protocol performance is upper bounded by *link efficiency* which describes the amount of losses the signal endures during transmission between communicating stations. For the OGS-transmitter and satellite-receiver configuration, a so-called uplink, link efficiency is observed in the range of -50 dB (NanoBob) to -62.7 dB (Q3), while the downlink (OGS-receiver and satellite-transmitter) is generally more efficient at the same orbit (starting with -37 dB for MICIUS, and lower values for small satellite missions). Among others, parameters that have direct impact on link efficiency are:

- *pointing accuracy* - a measure of optical angular re-alignment error (40 - 120 µrad for small, and 1-10 µrad for medium satellites);
- *pointing knowledge* - a measure of how well the position and orientation of the spacecraft is known (typically up to 30 µrad);
- *wavelength* of the optical signal beam (within near-infrared atmospheric transparency window 800-850 nm);
- *aperture size* - the diameter of the lens through which the light beam passes (related to the beam divergence at the transmitter, or collection area at the receiver);
- *minimum elevation angle* is the angle between the horizon and the slant range between OGS and the satellite, that bounds the communication window (commonly chosen around 20°, with bigger apertures allowing for smaller angles);

A very crucial parameter of space-based quantum communication is the spacecraft geocentric *orbit*. It bounds link efficiency and protocol performance, as well as defines mission lifetime, overall cost, radiation environment, and viewing geometry. The orbit can be characterized by using

- *type of orbit* usually defined in the range of altitudes from sea-level (majority of missions are set or planned on Low Earth Orbit with altitudes between 400 to 600 km);
- *the orbital period* is the time of spacecraft's single revolution around Earth (for aforementioned altitudes is 92-96 minutes).

The mission lifetime is the planned duration of the spacecraft operation. It is usually limited by maintenance cost, and electronics lifetime or nominal performance of optical equipment (e.g. transmitter gradual power loss, or wavelength shifts) in an orbit specific radiation environment. Planned lifetime for QKD satellites is around 2 to 3 years, but can be extended to 4 or 5 upon insignificant payload performance deviations.

Lastly, a distinction between the implemented systems is the choice of the carrier satellite size, which determines the launch mass (and consequently cost) that for already existing, undergoing or future missions ranges from a few kilograms for nanosatellites to hundreds of kilograms for medium-sized communication satellites.

List of projects: QUESS (Chinese Academy of Sciences) [6], CubeSat missions (SpooQy [7], QEYSSat [8], CQuCoM [9], SpeQtre, QUARC [10], UK QT Hub mission, QUBE [11], Q3 sat [12], NanoBob [13]), Deep Space Quantum Link (NASA) [14], Commercial missions (QKDSat by Arqit, QUARTZ by SES).

Parameter	**Description**	**Examples**
Lifetime	planned duration of the spacecraft operation (minimum set by electronics lifetime)	QUESS: 2 years, but extended to 4+ years CubeSat missions: [Q3: 1-2 years; NanoBob (uplink) 3 years - limited by radiation damage to the detectors]
Pointing accuracy	a measure of optical angular re-alignment error	QUESS: 0.5° CubeSat missions: [Q3: 40 µrad; QUBE- 1°; NanoBob - 50- 120 µrad (11-25 arcsec)]
Pointing knowledge	a measure of how well the position and orientation of the spacecraft is known	QUESS: ? CubeSat missions: [< 30 µrad (6 arcsec)]
Link efficiency	Depends on ground station, internal loss, weather, day/night	QUESS: 37 dB CubeSat missions: [Q3: (max) -62.7 dB; NanoBob ~ -50 dB]
Aperture size (SWaP)	the diameter of the lens through which the light beam passes	QUESS: 300 mm CubeSat missions: [Q3: 100mm; NanoBob 150 mm]
Repetition rate	number of signals sent per time unit	QUESS: 100 MHz CubeSat missions: [Q3: (OGS) 10MHz; NanoBob (detector limit) 100 kHz]
Wavelength	near-IR	QUESS: 848 nm CubeSat missions: [QUBE: 850 nm; Q3: 810nm; NanoBob: 800 nm]
Protocol	vacuum+weak decoy BB84 or six-state	QUESS: vacuum + weak decoy-state BB84 CubeSat missions: [QUBE: BB84; Q3: decoys-state BB84 , E91;

		SpooQy-1: entanglement measurement; NanoBob E91] QUARTZ: vacuum + weak decoy-state BB84
Orbital period	the time it takes a satellite to complete a single revolution around Earth	QUESS: ~ 96 min CubeSat missions: [QUBE: 94-97 min; Q3: 96min; Spooqy: 92 min; NanoBob ~ 96 min.]
Orbit altitude	altitude of the spacecraft above sea level	QUESS: 507 km CubeSat missions: [QUBE: 500-700 km; Q3: 500km; SpooQy: 408km; NanoBob Sun Synchronous at 584 kml QEYSSat: 600km;]
Classical communication	Rate (+ data loss and corruption?)	QUESS: 1Mbit/s (uplink) 4Mbit/s (downlink) CubeSat missions: [NanoBob up to 1 Gbit/s]
Minimum elevation angle	the angle between the horizon and the slant range between OGS and the satellite	QUESS: starts at 15° elevation ends at 10° CubeSat missions: [Q3: >30°;NanoBob elevations > 20°] QUARTZ: elevations > 20°

CONCLUSIONS

QTSpace organized several WG meetings to collect, discuss and compare information about mission parameters for several outstanding missions and proposals.

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