ANNEX B. STUDY DESCRIPTION

Quantum Metrology for Space-Based Tests of Gravitational Physics

Study Reference Number: 17-1201
Type of activity: Standard study (30k€)

Project Summary

Objective

This project studies the application of quantum metrology to enhance the precision of space-based gravitational physics experiments.

Target university partner competences

Quantum Theory, Quantum Metrology, Statistical Analysis, Photonics

ACT provided competences

General Relativity, Gravitational Wave Physics, Space-Based Interferometry, Geodesy

Keywords

Quantum Theory, Quantum Metrology, Statistical Analysis, Photonics, General Relativity, Gravitational Wave Physics, Space-Based Interferometry, Geodesy, Gravimetry

Study Objective

This study will assess how recent advances in the field of quantum metrology (e.g. as reported in [1,2,3,4] and for squeezed light interferometry in [5,6]) could be applied to improve the estimation of parameters in space-based gravitational physics experiments.

An example is the application of phase estimation for light ring gyroscopes [7] in frame dragging experiments similar to Gravity Probe B [8]. Tests of geodesic decoherence [9] can be improved with quantum metrology by measuring entanglement on trapped ion states [10]. Universities are encouraged to propose other more suitable, or analogous, examples to demonstrate what quantum metrology can offer for space-based experiments.

Background and Study Motivation

General Relativity (GR) has proven to be a highly successful theory, describing accurately the behaviour of massive bodies on large scales whose principal interaction is gravitational. However, its application on cosmological and microscopic scales, has proven famously problematic; the former due to unresolved questions on the nature of dark matter and dark energy, and the latter in a search for a quantum theory of gravity. As a result, experiments searching for deviations from GR and constraining alternative theories of gravitation are of great scientific interest [8,11,12,13].

Atomic Clock Ensemble in Space (ACES), which is scheduled to be launched in 2017, will bring a new generation of atomic clocks to the microgravity environment of the ISS to distribute a stable and accurate time base that will be used for space-to-ground as well as ground-to-ground clock comparisons [14]. Space Optical Clock, a potential follow-up candidate mission, aims to operate an optical lattice clock in microgravity [12]. The scientific goals of the mission are to perform tests of gravitational physics, such as the measurement of gravitational redshift, search for dark matter, and space-based relativistic geodesy at the sub-centimeter uncertainty level. Doing so requires the use of optical clocks with a fractional frequency instability of less than one part in 10^{17}.

The Laser Interferometer Space Antenna [11], or LISA, is another ESA candidate mission, proposed under ESA's gravitational universe science theme. LISA is a space based gravitational wave detector that will target waves in the sub-Hz to sub-mHz regime which are not accessible to ground based detectors. It will be composed of three heliocentric satellites in the configuration of an equilateral triangle, each side of the triangle will be used as a detector arm. A passing gravitational wave would then have the effect of inducing a relative acceleration between the satellites and modulating the frequency of the lasers through the Doppler effect. To achieve detection of such weak gravitational waves, LISA will measure a strain of one part in 10^{21}.

As illustrated in these examples, the non-Newtonian effects of GR are weak, at least when working within our solar system, as will, we expect, be the deviations from GR found in any alternative theory of gravitation. Space-based gravitational physics experiments will then need to measure physical parameters to great precision in order to discriminate between theories.

Given this demand for ever more precise measurements, experiments are now relying on quantum systems as probes of large-scale gravitational phenomena. In particular, the use of metrology for quantum systems has been proposed as a new approach to experiments, demonstrated for instance by Paris in 2009 [1].

In quantum metrology one uses the quantum properties of a system for highly sensitive measurements of physical parameters that do not correspond to observables [2]. These precise measurements are achieved by producing entangled states, having them interact with the system, and then measuring them [15]. In theory if maximally entangled states are used, the error of a measurement can be reduced by an additional factor of $\sqrt{\mathrm{N}}$, with N the number of measurements, compared to the scaling of a classical measurement.

Based on these developments, it is the objective of this study to carefully assess whether, and where, recent advances in the field of quantum metrology can be applied to improve the estimation of parameters in space-based gravitational physics experiments. As a guideline we list a few (far from exhaustive) examples of interest, but also encourage alternative suggestions: interference based gyroscopes [16] and atom trap entanglement for tests of geodesy [17]; light interferometry for acceleration [18]; and improvements to atomic clocks for measurements [19] of gravitational red-shift.

A terrestrial application of quantum metrology, to the LIGO platform, has already been studied [20]. It was found that the largest improvements to the experiment would come from increasing the optical power, to the point where quantum metrology methods would not apply. On the other hand, due to cost and technical restrictions on satellites, increasing the power of lasers beyond a certain point might not be a viable option for LISA so in this context one might expect quantum metrology to play a more useful role. However we note that, in practice, LISA will not be limited by the quantum limit as external noises will exceed the shot noise as sources of error.

The university is expected to describe a specific quantum metrology method to be applied to an existing, or novel, experimental technique for use in space based tests of gravitational physics. The improvement derived from adopting this method is then evaluated by estimating the change in statistical significance of the results of the experiment. Given that the time horizon for scientific missions is 15-20 years, universities are encouraged to use their insight into recent advances and trends to include likely developments and progress in quantum metrology.

Proposed Methodology

The study would be performed in close cooperation with the ACT. The following methodology is proposed, though universities can propose a different one alongside a justification of the alternative approach:

1. Identification, Trade-off, and Selection. A quantum metrology technique is proposed as a means of improving a type of space-based experiment. Following iteration with the ACT an appropriate space-based experiment is chosen (if relevant), and current techniques and expected accuracy are identified to serve as benchmarks.

2. Analysis. The theoretical improvement derived from applying quantum metrology will be analysed. The projected improvements are compared to a classical expectation of accuracy (if relevant) to help assess the feasibility of the experiment.

3. Roadmap. The identification of possible scientific and technological improvements that could help increasing the effectiveness of the technique. A summary of the findings into a baseline document on quantum metrology for space applications that could serve as reference for further work.

By the end of the study the following should be determined for a particular quantum metrology technique, applied to a possible space-based experiment:

- What is the best possible gain that can be achieved by using quantum metrology?

- Which reasonable technological advances were expected and needed in the foreseeable future to enable such experiments?

ESA/ACT Contribution

The ACT will contribute in several ways, depending on the needs and expertise:

- Expertise in general relativity and gravitational wave physics
- Expertise in condensed matter, quantum theory, and optics
- Reference data for ESA experiments

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