Astro2020 Science White Paper

Space-Based Measurements of G

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
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1 Introduction

A precise determination of Newton's constant of gravitation G is critically important for many precision measurements relevant to NASA astrophysics and fundamental physics missions. Examples include tests of postulates and predictions of special and general relativity theory using time dilation, the equivalence principle, and gravitational observations with long distance laser ranging and radio tracking. In many astrophysical processes, mass, G, distance and time are coupled. With better tools today such as ultra-accurate atomic clocks, sensors, and multi-messenger observations, an independent higher precision measurement of G can put tighter constraints on many measurable quantities for astronomical objects: e.g. stars, exoplanets, and black holes. Furthermore, some alternatives to dark matter expect variations in the magnitude of G which could be detected in space-based experiments [1]. Having a more accurate value for G could be the first step to detecting such variations, and thereby finding traces of new physics to help solve outstanding questions regarding a quantum theory of gravity, super-unification, better strings and loops, etc.

We propose a new, low-cost, state-of-the-art space experiment for measuring G within a 3U+ CubeSat. The experiment builds upon PI D'Urso's experience in an innovative ground-based effort for measuring G. In D'Urso's experiment, the oscillatory motion of a diamagnetic microsphere test mass in a high-vacuum, gravito-magnetic trap is monitored over the timescale of days. Carefully constructed field masses are then added, whose gravitational potential is well known, and the experiment is repeated. The phase difference between the two experiments encode G. Moving the experiment to low-Earth orbit (LEO) has the potential to reduce systematic errors caused by nearby gravitational sources, and would represent a marriage between a state-of-the-art physics experiment from U.S. academia and the new business model from the U.S. space industry. This mission would bring extraordinary STEM and leadership opportunities for young astrophysicists and physicists in U.S. universities and national laboratories working side-by-side with young engineers from the U.S. space industry.

In the following sections, we will present the current state-of-the-art measurements of G on the ground and a preliminary small satellite mission concept with key parameters and a component-level technology readiness evaluation.

2 Measurements of G

Not only are high-precision measurements of G difficult, but as illustrated in Fig. 1, our most precise measurements disagree to extreme significance [2, 3, 4]. Such enormous discrepancies reflect either a core misunderstanding of systematic errors in some experiments to date, or tantalizing evidence of new physics (e.g. [5]).

Based on their reported uncertainties, the leading two techniques for measuring G at this time are the angular-acceleration-feedback (AAF) and time-of-swing (TOS) methods. Both of these techniques involve a Cavendish-inspired torsion pendulum, but with improvements added to reduce or remove systematic errors. In the AAF method (e.g. [6, 7]), a torsion pendulum is accelerated to a constant rotation on a turntable. Equally spaced from the pendulum at opposite

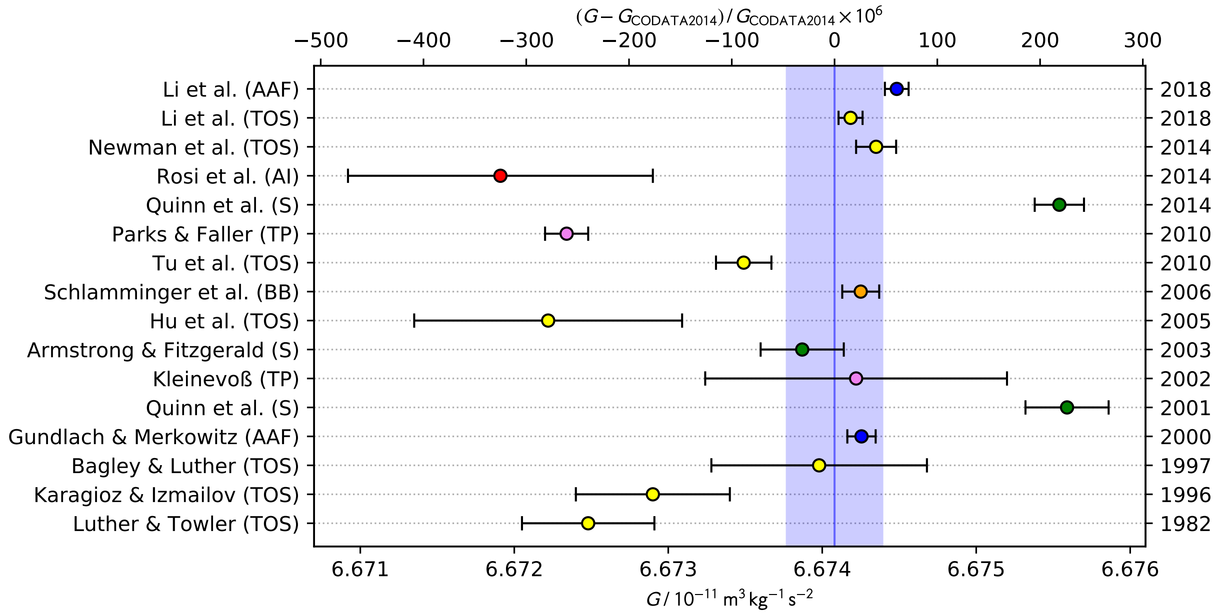

Figure 1: Measurements relevant to the 2014 CODATA value of G [2] and two new measurements from 2018 published together [6]. The shaded band represents the 2014 CODATA value $\pm$ the standard uncertainty. The measurement method for each result is indicated in parenthesis after the authors, with AAF $=$ angular acceleration feedback, TOS $=$ time of swing, AI $=$ atom interferometry, S $=$ servo, TP $=$ two pendulums, and BB $=$ beam balance. Points for measurements with the same technique are shown filled with the same color. The year of publication of each result is shown on the right.

sides of the turntable, two spheres with known masses and mass densities (the field masses) induce a gravitational torque on the pendulum masses, causing the pendulum to oscillate. Next, the turntable's angular velocity is varied via a feedback mechanism to cancel this gravitation-induced oscillation, and the angular acceleration of the turntable is measured to obtain G. The TOS method (e.g. [6, 8]) also frequently uses a torsion pendulum, but instead of using feedback to eliminate twisting of the fiber, the torsion pendulum is allowed to oscillate. The frequency of oscillation is measured with the field masses in two positions relative to the torsion pendulum, and the difference in frequencies is used to calculate G. Despite centuries of refinements in measurement techniques [9] and concerns about the properties of torsion fibers (e.g. [10]), the torsion pendulum is still a core component of most of the precise measurements of G.

With the impressive progress in using cold atoms for atom interferometry (AI) experiments, including gravimetry (measuring little g) [11], it might be expected that AI-based measurements would dominate precision measurements of G. Instead, measurements of G using AI do not yet claim precision competitive with mechanical measurements. For example, the measurement of Rosi et al [12] possesses one of the largest errors of all modern, state-of-the-art experiments. It measures G with a gravity gradiometer [13], which measures the apparent spatial variation in g due to a field mass. Since the earth's gravity also creates a gradient in g, two configurations of the field mass must be used. The reported systematic uncertainty in this measurement is dominated by uncertainty in the atomic cloud geometry; this may indicate a fundamental experimental challenge with identifying the location and motion of such a dilute test mass.

Faced with such large discrepancies in existing results, there is clearly a need for new measurement techniques to produce competitive measurements of G with much reduced *and unique* systematic uncertainties [14]. The wide spread of results from torsion-pendulum measurements makes it unlikely that incremental improvements in current experiments will resolve the problem.

3 The Next Step for G

Recently, an ambitious plan has been proposed to measure G in deep space [15]. The approach uses the "gravity train" mechanism, where a small test mass oscillates harmonically in a tunnel through a larger spherical field mass (like dropping a ball into a hole drilled all the way through the earth). Under the appropriate conditions, the test mass exhibits stable oscillatory motion with a period of oscillation depending on G and the field mass distribution. In such an experiment, G could be determined simply by measuring the oscillation period of the test mass; Feldman et al [15] suggest a possible measurement resolution of 63 ppb, an improvement of over two orders of magnitude relative to current measurements.

This deep space measurement of G faces numerous hurdles, both technical and practical. The cost of launching to deep space, particularly with a two-part spacecraft flying in formation as proposed, is potentially prohibitive on its own. Serious technical challenges with the proposed experiment include the effect of patch charges on the field mass and initial release requirements for the test mass of less than 10 mm per day of transverse velocity, almost two orders of magnitude smaller than the release specification for LISA Pathfinder.

Here, we suggest modifications to the gravity train experiment to make it practical in low earth orbit (LEO) as the payload of a CubeSat (ideally restricted to 3U+ size). The initial goal of the mission would be a state-of-the art 10 ppm measurement of G, with further improvements over an extended time. The revised experiment would add a two-dimensional magnetic trap (similar to those demonstrated on earth for diamagnetic particles [16]) to relax the stringent release conditions for the test mass in the deep space measurement, while also making the system more tolerant of the perturbations in LEO. While the goal of this white paper is not intended to provide a comprehensive mission design, we would like to provide a preliminary design, identify high risk elements for low cost small satellite mission, and provide conceptual risk mitigation strategies.

The magnetic trap would consist of a two-dimensional quadrupole field, produced by a permanent magnet array in a cylinder surrounding the (~ 1 cm diameter) cylindrical vacuum chamber in which the test mass oscillates (see Fig. 2). The magnets could take the form of a Halbach array [17], which is compact, strong, and can be surrounded by a ferromagnetic shield to keep out external fields and contain the trapping field. The diamagnetic test mass (made of e.g. silica and with a diameter of ~ 1 mm) would be confined by the trap in two dimensions, but free to oscillate within the field mass in the third direction, over a length of at least 1 cm (out of a total trap length of ~ 10 cm). As with the original gravity train method, the period of oscillation in this third dimension can be used to determine G. Chip-scale atomic clocks can provide the period measurement at a few parts per billion accuracy with 100-200 mW power consumption [18, 19].

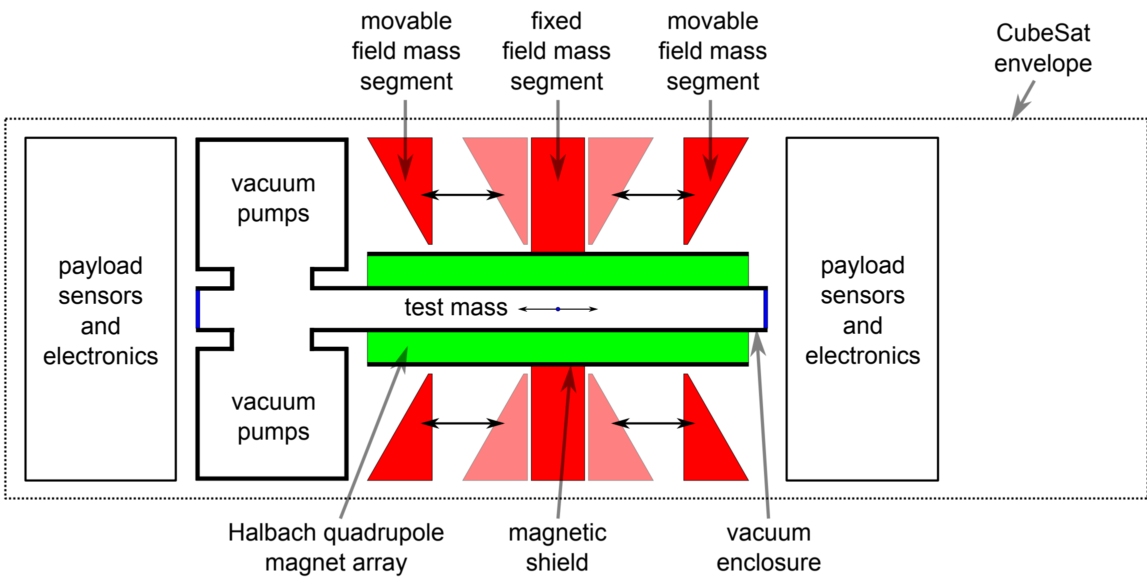

Figure 2: Conceptual diagram of the LEO 3U+ CubeSat. The vacuum enclosure, magnetic shield, and field mass segments are cylindrically symmetrical around the horizontal axis, which is also the axis of the 2-D quadrupole magnet. The test mass oscillates horizontally, and the period of oscillation is recorded with the movable field mass segments in two positions. G can be determined based on knowledge of the movable field mass geometry and measured oscillation periods.

The penalty associated with adding the 2-D magnetic trap is that imperfections in the magnets may modify the G-determining oscillation period of the test mass. The solution is to employ the same strategy used in the traditional time-of-swing method: measuring the oscillation period with two configurations of the field mass. With this approach, only the change in oscillation period of the test mass when the field masses are moved is used to determine G. Unwanted forces which act on the test mass and may alter its oscillation period but do not change when the field mass is reconfigured do not lead to any systematic error. This approach has the added benefit of mitigating the primary systematic error due to patch charges, a significant concern in the original gravity train approach. Reconfiguration of the field mass will require a segmented field mass, and parts of it will have to move a significant distance (> 1 cm). While a moveable structure adds unavoidable mission complexity, volume and cost, it can be realized by carefully architecture design using off-the-shelf motors consuming 1-2 W.

The test mass would be contained in a cylindrical vacuum chamber with an optical window on each end, radially surrounded by the Halback quadrupole magnet and then a ferromagnetic shield cylinder. The segmented field mass, likely taking the form of three rings, would surround the shield, with e.g. the two outer rings movable along the axis from near the center of the test mass oscillation range to the outer edges of the vacuum chamber. The entire CubeSat would need to be rotationally stable (no tumbling) and would require low-bandwidth communications with the ground for transferring data. Power would be required for guidance, electronics, lasers, pumps for the vacuum chamber, and moving the field masses (which will be stationary for at least one day between moves); all these have modest power requirements. The weight of the payload will be dominated by the Halbach magnet array and the field mass. Optimizing these will require further study, but staying within the usual CubeSat mass budget (4 kg for a 3U CubeSat) appears plausible.

The test mass must move in ultra-high-vacuum to minimize damping. In ground-based experiments, this is achieved by high power, high volume, mechanical and turbomolecular pumps, assisted by an ion pump and titanium sublimation pump. For space flight, we can use passive getter pump technology and a highly bakeable vacuum system design. Compact, low power ion pumps with 1-2W power consumption can serve as auxiliary pumping operating only as needed. This enables a primary zero power consumption for the vacuum system.

Although most of the system calibration can be done on the ground before launching, several in-flight calibrations are necessary due to variations in the thermal environment in space. Multiple temperature sensors would be attached to the field mass. The positions of the field mass segments as well as the position of the test mass would all be measured optically, e.g. with low power commercial off-the-shelf low power short-distance LIDAR sensors and/or CMOS/CCD detectors.

The release and loading process of the test mass is the highest risk in the proposed concept. If the test mass is left free in the vacuum chamber during the whole launch sequence, it might bounce around, damage the chamber or test mass, and might have too much kinetic energy to settle into the center of the vacuum chamber in a reasonable time. A better approach would be to carefully release the test mass once the satellite has reached a vibration-free environment in the orbit. One possibility is to use thin-wire thermal release technology, similar to that used in single-ion clocks, to keep the release power consumption to milliWatt levels. Multiple such wires could be installed to increase the number of chances for test mass loading. Radiation pressure and feedback control (which we use in ground-based experiments [16] can be used to adjust the initial amplitude of oscillation. Developing and testing the release and manipulation systems will be challenging on the ground because the magnetic trap will not be strong enough to levitate the test mass in earth's gravity.

In summary, we suggest a new measurements of G in a 3U+ format CubeSat in LEO, with a total mass of 4 kg, < 10 W power consumption and a initial target of measuring G to 10 ppm. After a proof-of-concept demonstration, future revisions could aim for improved precision of 1 ppm or less, possibly using a larger field mass in a 6U or 12U design.

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