Laboratory tests of a high-precision laser interferometry readout for the GG experiment in space

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***Abstract*—On 25 April the Microscope satellite was successfully launched to test the weak equivalence principle, which is the founding pillar of General Relativity, to to 1 part in 10^{15} (100-fold improvement). A possible violation will potentially be a major discovery and call for urgent checking. The GG ("Galileo Galilei") satellite experiment can do that with one hundred times better precision, to 10^{-17}. To do that GG is required to measure the relative displacements of two concentric test cylinders with a precision of about half a picometer at the frequency of $1\,\mathrm{Hz}$. A laser interferometry gauge has been designed for this purpose and is under development at INRIM with a required noise level of $\frac{1\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ at $1\,\mathrm{Hz}$. We report recent experimental results which demonstrate that the requirement can be met with a free running laser (no frequency lock needed) and consequent reduced complexity.**

I. Introduction

In a gravitational field all bodies fall with the same acceleration regardless of their mass and composition. This is the Universality of Free Fall-UFF (also known as the Weak Equivalence Principle-WEP). As stated by Einstein in his 1916 paper "*The foundation of the general theory of relativity*"[1], this 'fact of nature' is at the foundation of the General theory of Relativity (GR) and must therefore be firmly supported by experiments. In 1916 Einstein brought as experimental evidence the best tests of his time carried out in Budapest by Loránd von Eötvös and his group, referring to the great accuracy of these tests in a specific footnote of his paper. The results of Eötvös were indeed astonishing. While all his predecessors since Galileo had suspended different test masses from pendulums, Eötvös had the great intuition of coupling them by suspension on a single torsion balance, and in so doing improved the precision of the test by three orders of magnitude.

One century later the best controlled laboratory tests of UFF-WEP are still provided by torsion balances, now rotating in order to modulate the signal and up-covert its frequency to higher values (the higher the better) where thermal noise, electronics noise and other noise sources are known to be smaller. In a remarkable series of experiments with slowly rotating torsion balances the Eöt-Wash group of Eric Adelberger at the University of Washington has confirmed UFF-WEP to 1 part in 10^{13} in the gravitational field of the Earth [2], [3]. A similar result has been obtained for the Moon and the Earth falling in the gravitational field of the Sun by laser ranging to the retroreflectors left by the astronauts on the surface of the Moon ([4], [5]).

Gravity is the only fundamental force of nature to obey the equivalence principle. The equivalence principle is therefore at the crossroad between General Relativity and the Standard Model of particle physics, and for this reason a huge amount of theoretical work has been carried out in trying to establish at which level a breakdown –if any– should occur. Till now these efforts have failed to provide us with a firm target. Thus, similarly to Einstein and Eötvös one hundred years ago, we consider the best tests available and how they can be further improved,

A violation of UFF-WEP would signal that either GR needs fixing, or a new force of nature has been found. Either way it would be a scientific revolution. This is why experimentalists have tried to test it with better and better precision whenever the possibility for an improvement has arisen.

Tests of the Universality of Free Fall are quantified by the fractional differential acceleration

$$\eta = \frac{\Delta a}{a} \tag{1}$$

between two test masses of different composition as they fall in the gravitational field of a source body with the average acceleration a (the "driving signal"). The physical observable quantity is the differential acceleration Δa of the falling masses relative to each other, pointing to the center of mass of the source body (e.g. the Earth). For UFF-WEP to hold it must be $\eta = 0$; the lower the value of η, the more sensitive is the test.

For the same experimental sensitivity to Δa, the higher the driving acceleration a (at the denominator of (1)), the more sensitive is the test. If the test masses are suspended inside a satellite orbiting the Earth at low altitude rather than being on a torsion balance on the ground, the gain due to the driving

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signal alone is by a factor of: $8\,\mathrm{ms}^{-2}/0.016\,\mathrm{ms}^{-2} \simeq 500$. This is why a torsion balance-type experiment in space is expected to considerably improve UFF-WEP tests in the field of the Earth.

The Microscope satellite experiment [6] has been successfully launched on 25 April 2016 and plans to reach 10^{-15}, which would improve the torsion balance tests by a factor of one hundred. Should Microscope demonstrate a sensitivity better than 10^{-13} and report a possible violation, this will potentially be a major discovery and call for urgent checking with a more precise experiment. GG ("Galileo Galilei") [7] can achieve that with one hundred times better precision, to 10^{-17}.

More recently, considerable activity has been devoted to testing UFF-WEP with Galileo-like mass dropping tests using cold atoms. They have reached 10^{-7}, while the best drop test carried out at CERN in the early 90s with macroscopic masses has reached $7 \cdot 10^{-10}$ [8]. Attempts to improve cold atoms drop tests in space by almost 8 orders of magnitude, to reach $2 \cdot 10^{-15}$ in low Earth orbit (where indeed the signal is slightly weaker than it is for bodies dropped on the surface of the Earth) are found to hit the uncertainty limits of Heisenberg's principle, in essence because of the small number of atoms compared to Avogadro's number (see [9] and references therein).

In order to meet its goal GG will be equipped with a laser interferometer readout with a noise level of $\frac{1\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ at $1\,\mathrm{Hz}$.

The paper is organized as follows. Sec. II is a brief summary of the key features of the GG experiment in space, to show how it can improve Microscope's results by two order of magnitude while being, like Microscope, an experiment at room temperature. Sec. III reports some laboratory results obtained recently in developing the GG laser gauge. They are summarized in the Conclusions, where it is stressed that they are close to the mission requirements, and that these requirements can be met with a laser gauge of reduced complexity as compared to the one currently flying on LISA Parhfinder.

II. Key features of the GG space experiment: how to reach 10^{-17} at room temperature

In both Microscope and GG the test masses are (nominally) concentric test cylinders. This is because, as shown in (1), the sought for violation signal is a differential acceleration pointing to the center of mass of the Earth; it therefore competes with classical differential accelerations due to the non uniformity of the gravitational field (known as gravity gradient or tidal effects). These effects may mimic a violation and grow linearly with the offsets between the centers of mass of the test cylinders; hence, the better the test cylinders are centered, the more sensitive they are to UFF-WEP violations.

The other key ingredient of these experiments is rotation. Torsion balances have demonstrated that up-convertion of the signal to higher frequencies –achieved by rotating the apparatus relative to the source body (the Earth in our case)– is a crucial asset, because thermal noise and electronic noise are lower at higher frequency. The higher the rotation frequency, the higher the frequency at which the signal is detected, the better.

This is where GG differs from Microscope. In Microscope the test cylinders are sensitive in 1D, along their symmetry axis. At a first glance, dealing with one dimension only should make things easier. It is not so when it comes to modulating the signal. The only way to modulate a signal acting along the sensitive/symmetry axis of the test cylinders is by rotation around an axis perpendicular to it. However, it is well known in classical mechanics that an axisymmeric body is stable to small perturbations only when rotating around the axis whose principal moment of inertia is distinct from the other two. Therefore, if in space the test cylinders can be arranged to be sensitive in the plane perpendicular to the symmetry axis, then modulation is provided by rotation around the symmetry axis, and it is stable. This is why in GG the symmetry axis of the concentric test cylinders has been turned by $90°$, and they have been coupled to form a beam balance with the beam along the symmetry axis and sensitive to differential accelerations in the plane perpendicular to it. Then, rotation around the symmetry axis at $1\,\mathrm{Hz}$ modulates the signal at this high frequency (3 orders of magnitude higher than in Microscope) while also ensuring passive stabilization of the satellite's attitude by one-axis rotation. The fact that in space the satellite constitutes an isolated system is thus fully exploited in GG: once it has been set in rotation at the start of the mission, it does maintain it simply by angular momentum conservation. Unlike rotating lab experiments, which have a rotating and a non rotating part (rotor and stator) with bearings in between them and a motor to keep the system rotating, the whole GG satellite is in passive rotation –similarly to an axisymmetric celestial body– there is no motor, no bearings and none of the noise sources related to them which are well known to plague all rotating lab experiments, including the GG laboratory prototype.

Once rotation occurs around the symmetry axis, it is a simple physics exercise to show that a spin frequency higher than the natural ('critical') oscillation frequency of the test cylinders ensures that the original offset between their centers of mass as achieved by construction and mounting is reduced, by an amount equal to the ratio of the natural-to-rotation frequency squared. This is the the well known self-centering property, which holds by physical laws at rotation frequencies above the critical frequency ('super-critical' regime).

A sketch of the GG spacecraft with the test cylinders visible at its center of mass is shown in Fig. 1 (to scale).

A sketch showing the violation signal expected in the sensitive plane of the GG test cylinders as they orbit around the Earth is shown in Fig. 2 (clearly not to scale). This figure depicts in red the laser rays (at $120°$ from one another) of the interferometry gauge which has been designed in order to read the relative (differential) displacements between the centers of mass of the two cylinders such as those expected in case of a violation. Two similar laser gauges are located one above and one below this one (symmetrically) for redundancy as well as for monitoring any small inclination of the symmetry axes. As described in the figure caption, the laser gauge rotates with

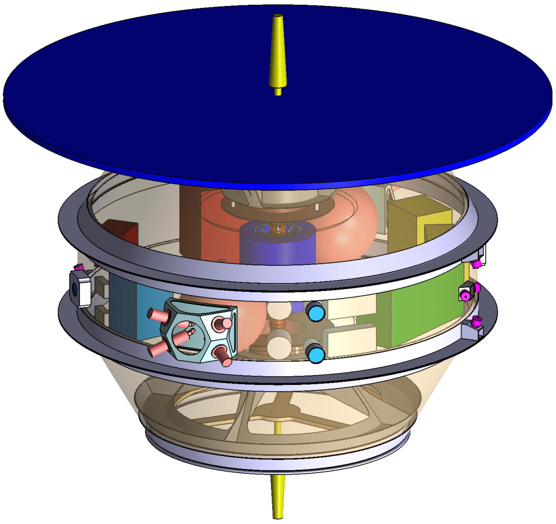

Fig. 1. The GG spacecraft ($\simeq 1.5\,\mathrm{m}$ width and $\simeq 1.2\,\mathrm{m}$ height) enclosing below the solar panel, in a nested arrangement similar to a russian doll, the PGB intermediate stage (depicted as a transparent cylinder, serving as test mass for drag-free control and to accomodate ancillary items, such as thermal blankets and readout electronics and components) and the co-axial test cylinders, all with cylindrical symmetry and to be passively stabilized by one-axis rotation around the symmetry axis at the spin frequency of $1\,\mathrm{Hz}$. It is designed to fly in high-inclination sun-synchronous orbit (solar panel synchronous with the Sun) at about $630\,\mathrm{Km}$ altitude around the Earth. (Figure to scale)

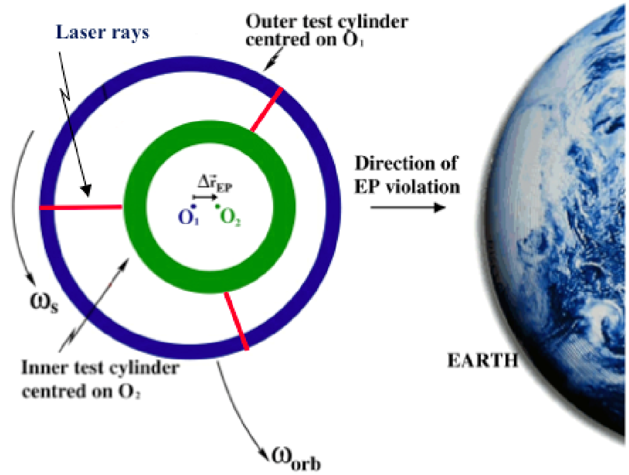

Fig. 2. Section of the GG coaxial test cylinders (of different composition) in the plane perpendicular to the spin/symmetry axis as they orbit around the Earth and in the case in which the sensitive plane coincides with the orbit plane (violation signal maximized). The centers of mass O_1, O_2 of the test cylinders are displaced from one another because of a violation of the Weak Equivalence Principle in the gravitational field of the Earth (e.g., the inner cylinder is attracted by the Earth more than the outer one because of its different composition). Under this (differential) force the test cylinders, which are weakly coupled by mechanical suspensions, reach equilibrium at a displaced position $\Delta\vec{r}_{EP}$ where the new force is balanced by the weak restoring force of the suspension, while the bodies rotate independently around O_1, O_2 respectively. The laser intereferometer gauge co-rotates with the test cylinders (and the whole GG satellite) at $1\,\mathrm{Hz}$. While the displacement vector $\Delta\vec{r}_{EP}$ keeps pointing to the center of mass of the Earth and changes its direction with the orbital frequency of $\frac{1}{5800}\,\mathrm{Hz}$, the laser gauge reads its size at the much higher spin frequency of $1\,\mathrm{Hz}$. This is how the signal is up-converted to higher frequency (by a factor 5800) where thermal noise and electronics noise are much lower (Figure not to scale).

the whole GG system at $1\,\mathrm{Hz}$ while the displacement signal $\Delta\vec{r}_{EP}$ caused by a violation points to the center of mass of the Earth during each orbital period of about $5800\,\mathrm{s}$; as a result, up-conversion of the signal frequency by a very large 5800 factor is ensured.

At the high frequency that the signal has been up-converted to, thermal noise from internal damping is much lower; the reduction has been quantified [10] and once all sources of thermal noise are taken into account the integration time required to reach the 10^{-17} target of GG is of a few hours only [11]. This holds at room temperature and there is no need to invoke cryogenics.

III. A LOW NOISE LASER INTERFEROMETER READOUT FOR GG: PRELIMINARY EXPERIMENTAL RESULTS

For test masses orbiting the Earth at an altitude $h \simeq 630\,\mathrm{km}$ detection of a violation at $\eta = 10^{-17}$ requires to be sensitive to a differential acceleration $\Delta a_{EP} = \eta g(h) \simeq 8.1 \cdot 10^{-17}\,\mathrm{ms}^{-2}$ ($g(h) \simeq 8.1\,\mathrm{ms}^{-2}$ being the local gravitational acceleration from the Earth at the orbiting altitude). The GG test cylinders are weakly coupled in the plane perpendicular to the spin/symmetry axis with a natural frequency of oscillation (in differential mode) $\omega_n \simeq 2\pi/540\,\mathrm{rads}^{-1}$. Hence, the target acceleration signal Δa_{EP} would result in a relative displacement of the two cylinders one with respect to the other $\Delta r_{EP} \simeq \frac{\Delta a_{EP}}{\omega_n^2} \simeq 0.6\,\mathrm{pm}$.

A readout whose noise is so low that it can measure this differential displacement signal in a few seconds allows the very small thermal noise and short integration time of GG to be fully exploited: a large number of measurements, all to the target precision, can be performed during a space mission of limited duration allowing us to carefully check for systematic errors, similarly to what scientists do in laboratory tests on Earth.

An adaptation to GG of the heterodyne laser gauge developed at JPL for SIM (Space Interferometry Mission), with a noise level of $\frac{1\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ at the GG signal frequency of $1\,\mathrm{Hz}$ was proposed in 2010 by Mike Shao [12].

The laser gauge designed for GG has been presented in [13]. As suggested by [12] it is based on spatial separation of the two arms of the interferometer, rather than polarization separation. In [13] we have investigated the error-source due to diffraction and consequent crosstalk between the two optical paths, and reported the results of laboratory tests showing how this error can be taken care of and made unimportant.

Here we report more recent laboratory results on measurement noise and frequency noise.

The Power Spectral Density (PSD) of the measured displacement noise as obtained with a preliminary set-up is reported in Fig. 3, expressed in $\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$. We used a fiber laser with $\lambda = 1533\,\mathrm{nm}$, high spectral purity, thermally stabilized, and a few mW power. The heterodyne frequency was $200\,\mathrm{kHz}$. The laser was free-running (i.e. it was not locked to some stable frequency for stabilization) and the set-up was not optimized for compactness.

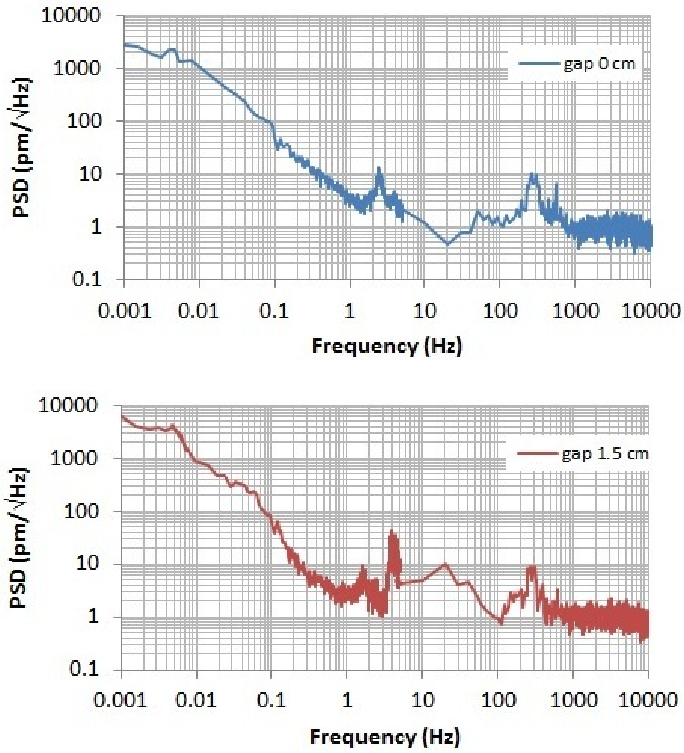

Fig. 3. Power Spectral Density (PSD) of the displacement noise measured by the interfrerometer in the case of $0\,\mathrm{cm}$ gap (top plot) and $1.5\,\mathrm{cm}$ gap (bottom plot) between the targets. At the $1\,\mathrm{Hz}$ frequency of the GG signal the noise is $\simeq \frac{3\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$, only a factor 3 above the requirement, and there is no indication of higher noise with $1.5\,\mathrm{cm}$ gap. For the noise limiting factors at various frequencies see text.

In order to evaluate the effects in our case of the lack of frequency stabilization of the laser we tested two cases: one with zero and another with $1.5\,\mathrm{cm}$ nominal gap (spatial separation) between the targets that the two arms of the interferometer are aiming to. It is known that for large optical path differences the frequency stability of the laser becomes relevant and it may be necessary to lock the laser to a very stable frequency, which is not desirable for an experiment in space whose complexity and cost should be limited as far as possible. In GG the nominal gap (between the outer surface of the inner cylinder and the inner surface of the outer one, i.e. the optical path difference) is $2\,\mathrm{cm}$. From Fig. 3 we notice the following:

- At $1\,\mathrm{Hz}$ we read $\simeq \frac{3\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$, a noise level only a factor 3 above the GG requirement.
- There is no indication of a noise increase when the targets are $1.5\,\mathrm{cm}$ apart (instead of zero), which means that the measurements are not affected by laser frequency noise. With $2\,\mathrm{cm}$ nominal separation in GG it is expected that we can meet the requirement with a free running laser, without providing laser frequency stabilization.
- Below $1\,\mathrm{Hz}$ the noise increase (up to several $\frac{\mathrm{nm}}{\sqrt{\mathrm{Hz}}}$ at $1\,\mathrm{mHz}$) is due to thermo-mechanical drifts, not to the interferometer.
- In the frequency range $1\,\mathrm{Hz} < \nu < 1\,\mathrm{kHz}$, the measurement is limited by acoustic and vibration noise.
- Above $1\,\mathrm{kHz}$ the measurement is limited by electronics noise at the level of $\frac{1\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ (this noise is not due to the environment).

The displacement noise of the interferometer depends (particularly for large optical path differences) on the frequency noise of the laser. A measurement of the frequency noise for the free-running diode laser RIO Orion with wavelength $\lambda = 1542\,\mathrm{nm}$ was reported in [14], where the advantages of locking the frequency of the laser to acetylene have also been measured. In Fig. 4, taken from their paper, we can see that at $1\,\mathrm{Hz}$ the frequency noise is slightly below $10^4\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ and its reduction in case of locking is by almost two orders of magnitude.

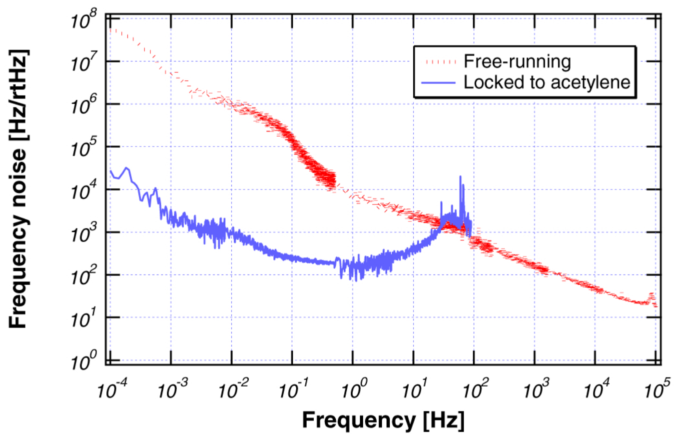

Fig. 4. This figure (taken from [14]) shows the frequency noise as measured by the authors without (red curve) and with (blue curve) stabilization of the laser frequency.

The frequency noise can be obtained by measuring the frequency difference of two similar free-running lasers. However, the measurement of the frequency difference of two similar lasers may hide common mode effects –such as thermal drifts– which would obviously affect the measurement when using one individual laser. In order to make sure that the measured frequency noise of the free-running laser does not cancel any common mode noise we have measured the absolute frequency with the optical frequency comb of INRIM (the Italian Metrology Institute in Torino) directly traceable to the realization of the SI second, which measures the laser frequency with high accuracy. Our results are reported in Fig. 5 and turn out to be comparable with those of Fig. 4 (red curve), thus confirming that this is the real long term frequency stability of the RIO Orion free-running laser. In particular at

1 Hz the frequency noise is $10^4\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$, only slightly higher than the value measured by [14] and shown in Fig. 4.

We have measured the same level of frequency noise also for the fiber laser at $1533\,\mathrm{nm}$ used for the interferometer that has yielded the displacement noise reported in Fig. 3. It is therefore concluded that the displacement noise required for the GG laser gauge does not need the frequency of the laser to be stabilized.

A heterodyne laser interferometer is currently flying on the LISA Pathfinder (LPF) mission of ESA. It is required to have low noise down to $10\,\mathrm{mHz}$, with values from $\frac{6\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ to about $\frac{50\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ at $10\,\mathrm{mHz}$. The test masses are about $38\,\mathrm{cm}$ away and the requirements are met with a frequency stabilized laser [15].

It is apparent that the high $1\,\mathrm{Hz}$ frequency that the GG signal has been up-converted is crucial in making the laser gauge less demanding.

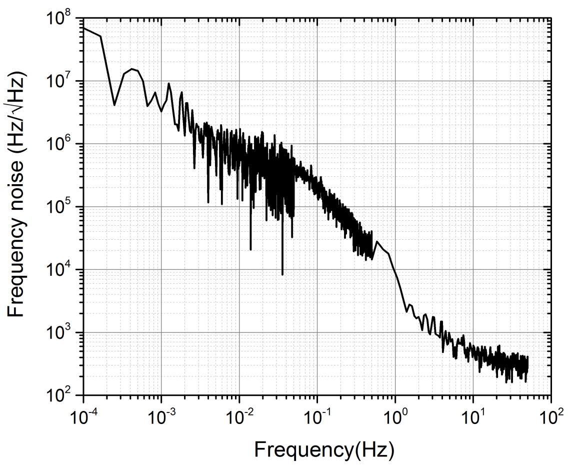

Fig. 5. Power spectral density of the frequency fluctuations of the free-running diode laser RIO Orion at 1542 nm. It has been obtained by measuring the absolute frequency with the optical frequency comb of INRIM (the Italian National Metrology Institute in Torino) directly traceable to the realization of the SI second, so as not to be affected by common mode noise. It is comparable to the frequency noise measured by [14] and shown in Fig. 4 (red curve)

We also note that in GG the effect of frequency noise should be mitigated by the use of split CCRs (Corner Cube Reflectors). CCRs are known to be very effective in reflecting back the laser rays along the same direction. In GG interference occurs between laser rays reflected from the outer test cylinder and the inner test cylinder. The solution is a CCR split into two parts, to be embedded in each test cylinder (as described in [13], Fig. 8). The first part reflects light back from the outer test cylinder; being truncated it lets another, spatially separated (inner) laser ray pass through, so as to reach the inner test cylinder and be reflected back by the remaining part of the CCR embedded in it. This makes the actual path difference between the interfering laser rays smaller than the nominal one, which helps in reducing the effects of frequency noise. Note that, as sketched in Fig. 2, each laser gauge has three such split CCRs, at 120° from each other so as to recover the relative displacement of the centers of mass of the two cylinders.

Future laboratory work will be devoted to reducing noise by a factor 3 at $1\,\mathrm{Hz}$, in order to reach $\frac{1\,\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ at the GG signal frequency, and to obtaining it with a compact interferometer set-up. Compactness is expected to reduce some noise sources due to the environment. Other laser wavelengths (such as $\lambda = 1064\,\mathrm{nm}$) will also be tested.

It is worth mentioning that during the evaluation of GG as one of the proposals shortlisted for the medium size mission M4 of ESA in 2015, the SARP - Science Assessment Review Panel appointed by the Agency raised the issue of cross talk between the two optical paths of the interferometer. Specific laboratory tests have been performed, whose results have been reported in [13], Sec. IV, showing that this issue is not critical.

Another issue raised by SARP in its final report was the impact of the rotation of the Earth on the rotating test cylinders or the laser interferometer if considered in the framework of General Relativity rather than Newtonian mechanics. The concern was that a general relativistic effect, if not recognized as such, might be misinterpreted as due to a violation. Since then the general relativistic effects of rotation on the centers of mass and the spin axes of the test cylinders have been carefully calculated, and found to be irrelevant by several orders of magnitude [16].

As far as the laser interferometer is concerned, rotation may result in a spurious displacement because of the Sagnac effect (similarly to a laser gyro) if the laser rays which are separated and then recombined enclose a non zero area whose normal is aligned with a non-zero component of the rotation velocity vector (laser rays travelling along the sense of rotation or opposite to it would have different flight times, thus yielding a spurious displacement).

If the interfering laser rays are perfectly aligned the area enclosed from separation to recombination is zero, hence there is no spurious displacement. If the alignment is not perfect the situation is sketched in Fig. 6 and the resulting spurious displacement is $\Delta x \simeq \frac{\omega_{spin}}{c} 2A$. With a conservative $10\,\mu\mathrm{m}$ misalignment, it amounts to about $4 \cdot 10^{-14}\,\mathrm{m}$ (see Fig. 6) which is more than 2 orders of magnitude below the target displacement signal. In addition, only time variations of the spin frequency close to the spin/signal frequency do matter (a constant bias doesn't matter), yielding an even smaller effect.

In any case, the GG laser gauge is designed to make this effect nominally zero even in the presence of a non-zero misalignment: by arranging the lasers so that the rotation velocity vector has no component perpendicular to non-zero area resulting from the misalignment there is (nominally) no Sagnac effect. In reality, it is reduced even further.

IV. Conclusions

General relativity is founded on the universality of free fall and the weak equivalence principle. A violation would imply either that GR must be amended, or that a new force of nature has been found. Either way, it would be a revolution in physics.

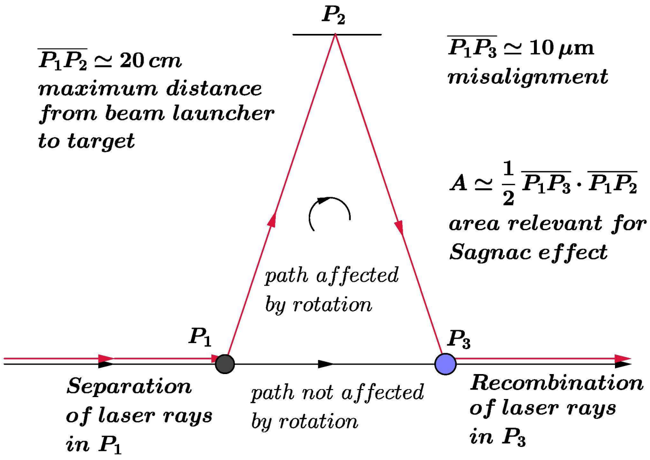

Fig. 6. The sketch shows how a misalignment of the laser rays of the interferometer combined with the rotation of GG gives rise to a spurious displacement because of the Sagnac effect. The figure is not to scale (the misalignment has been greatly exaggerated to make the enclosed area visible).

On 25 April 2016 Microscope has been launched to test UFF-WEP to 10^{-15}, with an improvement upon the current best tests by a factor of one hundred. Report of a violation would potentially be a major discovery and call for urgent checking. GG can achieve that with one hundred times better precision, to 10^{-17}.

In GG rotation around the symmetry axis of the concentric test cylinders at 1 Hz up-converts the target violation signal from the low orbital frequency to the much higher spin frequency of the satellite, where thermal noise is lower. The target violation signal of GG is a 0.6 pm relative displacement of the test cylinders pointing to the center of mass of the Earth. Being up-converted to 1 Hz it is read by a laser interferometry gauge with $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ noise at 1 Hz. The laboratory tests reported here show a noise level only a factor of three above the requirement, obtained with a free-running laser. The frequency noise of the laser has also been measured (absolute frequency measurement). Comparison with the laser interferometer currently flying on LISA Pathfinder shows that the GG laser gauge is much less demanding, due to the high frequency of the target signal and the smaller optical path difference to be measured.

Co-rotation of the whole GG satellite as an isolated system in space by conservation of angular momentum (similarly to an axisymmetric celestial body) avoids the known dangers of rotating experiments on Earth, particularly for the laser gauge.

Work is ongoing in order to reduce the measured displacement noise by a further factor of three, to fully meet the requirement, to achieve it with a compact set-up and to test the CCRs as designed.

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