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The GINGER Project

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Abstract

GINGER (Gyroscopes IN General Relativity) is a project aiming at measuring the Lense-Thirring effect,, at 1% level, with an experiment on earth. It is based on an array of ring-lasers, which are the most sensitive inertial sensors to measure the rotation rate of the Earth. The GINGER project is still under discussion; the experiment G-GranSasso is an *R&D* experiment financed by INFN Group II, it is studying the key points of GINGER and at the same time developing prototypes. In the following the signal coming out of a ring-laser and the present sensitivity are described.The prototypes GP2 and GINGERino and the preliminary results are reported. This project is inter-disciplinary since ring-lasers provide informations for the fast variation of the earth rotation rate, they are used for the rotational seismology and for top sensitivity angle metrology.

Keywords: Gyroscope, Sagnac Effect, Gravitomagnetism, Rotational Seismology, Earth rotation rate

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1. Introduction

Ring Lasers Gyroscopes (RL) are top sensitivity devices widely used for measuring absolute rotation rates, exploiting the Sagnac effect. They are very reliable instruments, with extended bandwidth and very high duty cycle. Small size RLs are used for inertial navigation. The sensitivity increases with size. The most advanced RLs, devices with the area of tens of square meters, are used in seismology (rotational seismology), and in the geodetic community are considered the instruments able to measure the fast variations of the earth rotation rate (daily and sub-daily). The signal of a RL based on earth is proportional to the projection in the ring axis direction of the vector sum of the rotation rate of the planet, $\vec{\Omega}_\oplus$, plus the local rotation rate of the device, $\vec{\Omega}_l$. When the effects of non-Newtonian gravity are included an additional contribution appears; let us call it $\vec{\Omega}_{gr}$. Following General Relativity (GR), $\vec{\Omega}_{gr}$, at the highest orders, is in turn the sum of two contributions: the Lense-Thirring drag term $\vec{\Omega}_{LT}$ and de Sitter geodetic precession $\vec{\Omega}_{dS}$. These GR terms have modulus of the order $\sim 10^{-14}$ rad/s, nine orders of magnitude below the earth rotation rate. It is usually assumed that $\vec{\Omega}_l$, in an earth based laboratory is either negligible, with averaged value zero, or in case, could be modelled by other means. The present best sensitivity of a RL is $\sim 10^{-13}$ rad/s in one day of integration time [1], not far from the threshold to be crossed in order to detect the GR terms. The purpose of GINGER (Gyroscopes IN GEneral Relativity) is to measure the GR components of the gravitational field of the earth at 1% accuracy level, by means of an array of ring-lasers [2]. The first proposal based on an octahedral configuration [2] has been presented. The three-dimensional array would permit to reconstruct the modulus of the total angular rotation vector in the laboratory. The GR terms in this scheme would be evaluated by subtracting the earth rotation rate measured independently by the international system IERS ($\vec{\Omega}_{IERS}$). So far the gravitomagnetic field of the earth has been measured by space experiments, being the present accuracy limit $\sim$ 5%[5, 6]. The experimental objective of measuring Ω_{LT} down to 1%, is still challenging. GINGER would provide *the first measurement* of the General Relativistic features of the gravitational field, on the surface of the earth (not considering the gravitational redshift). Though not in free fall condition, it would be a direct local measurement independent from the global distribution of the gravitational field; not an average value, as in the case of the space experiments. The LenseThirring field depends on the latitude, and alternative theories predict different behaviour with the latitude.

At the moment the experimental set-up for the GINGER proposal is under discussion. Matter in discussion is if the 1% goal for the LenseThirring effect is really feasible, and if it is possible to proceed in steps with improved sensitivity and accuracy. As well different schemes are under discussion.

In the following the signal given by a ring-laser, the experimental work, and the main results of the two prototypes RLs GINGERino and GP2 will be shortly described.

2. Generalities

The RL is a laser with a ring optical cavity, where two counter-propagating modes circulate; the signal is the beat note in between the two beams coming out of the cavity, see fig. 1. Each RL is described by its scale factor S and its area versor $\vec{n}$, the response of the RL is the beat frequency f proportional to the scalar product between the total angular rotation vector Ω_T and the vector area of the ring optical cavity $f = S(\vec{\Omega}_T) \cdot \vec{n}$. The scale factor S depends on the geometry of the ring, $S = \frac{4A}{\lambda P}$, where A is the area and P the perimeter of the ring, λ is the wavelength of the light of the Laser. With an appropriate construction and location of the apparatus and for long enough integration time we may assume $< \Omega_l >$ to be negligible (or modellizable) even with respect to the GR terms, so that, in the framework of General Relativity (GR), we write $f = S(\vec{\Omega}_{\oplus} + \vec{\Omega}_{LT} + \vec{\Omega}_{dS}) \cdot \vec{n}$. For a detailed description of the RL signal with GR terms, interested readers are can see [2, 3, 4]. This general formulation of the RL frequency has been deduced assuming GR and the consequence is that the beat note expected from a RL contains three actual or effective rotations. The corresponding three axial vectors are coplanar, and contained in the meridian plane. The mutual orientations are fixed by the theory and depend on the latitude, see fig. 2.

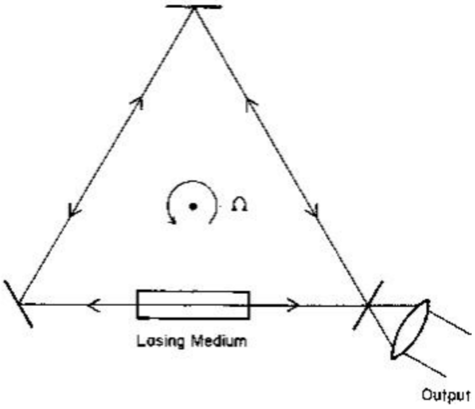

Figure 1: Typical RL scheme with rotation $\vec{\Omega}$, in this case the RL cavity is defined by three mirrors and has a triangular shape. Other shapes are feasible.

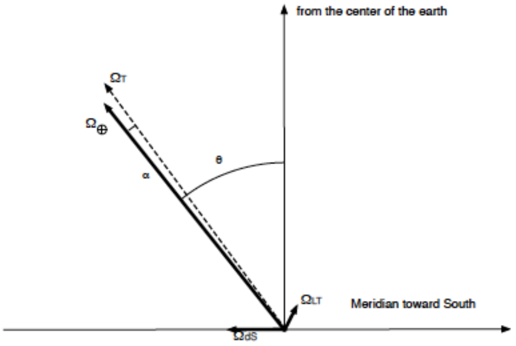

Figure 2: The three axial vectors $\vec{\Omega}_{\oplus}$, $\vec{\Omega}_{LT}$, and $\vec{\Omega}_{dS}$ are shown, with the relative orientation at the latitude of the underground laboratory of GranSasso (LNGS), following General Relativity. The angle α and Ω_T (dashed line) are shown as well. The graph is not on scale, it gives a pictorial view of the relative orientations of the different components, in the reality the modulus of $\vec{\Omega}_{\oplus}$ is 9 orders on magnitude bigger than the GR terms, and the angle α is $\sim 10^{-9}$ *rad*.

Fig. 2 shows the relative orientation of the relevant vectors at the latitude of LNGS. Each RL measures the scalar product of the vector sum $\vec{\Omega}_T = \vec{\Omega}_{\oplus} + \vec{\Omega}_{LT} + \vec{\Omega}_{dS}$ by the unit vector perpendicular to the surface of the ring, $\vec{n}$. The test of GR consists in extracting from the signal those contributions. There are two different approaches: a) to obtain with high accuracy the modulus of Ω_T as seen by the RL system, then subtract Ω_{IERS} measured with respect to the fixed stars; b) to manipulate equations in order to determine the GR terms.

Since the GR terms are 10^9 times smaller than $\Omega_{\oplus}$, the use of the modulus and Ω_{IERS} needs an accuracy of at least 1 part in 10^{10} in order to let GR terms emerge, and if we wish to go down to 1% in the measurement of the Lense-Thirring term, two more orders of magnitude in the accuracy are required. It is important to say that in this way the result is limited by the accuracy of the independently measured Ω_{IERS}. In fact, so far, Ω_{IERS} has reached about $10 \div 15 \mu s$ accuracy in the measurement of LoD (Length of the Day), which amounts to say that by this method it is barely possible to obtain $\sim$ 1 part in 10^{10}. Enhancements require to reduce the LoD error, however at present high improvements thereof are not foreseen. At this point it is important to remark that this measurement is relevant by its own for geodesy; in fact the RL system can provide the reconstruction of the modulus of $\Omega_{\oplus}$ independently from IERS, this of course requires a very high level of accuracy. It is expected to measure the short time variations of LoD, daily and sub-daily (IERS Annual Report 2014), while IERS can provide only measurements on time scale larger than a few days; in this case high level accuracy is not required.

As already said, in order to reconstruct the absolute value of $\vec{\Omega}_{\oplus}$, a three RLs system, arranged as an octahedron, has been proposed in 2011 [2]; this configuration has been extensively discussed in our previous papers. Such a system measures the projections of $\vec{\Omega}_T$ in all three spatial directions and reconstructs the norm of the vector combining together the different measurements. This approach allows the comparison of different co-located rings, giving the possibility of precisely measuring the systematics of the laser. The absolute orientation of the octahedron is not demanding; the basic requirements would be: each ring calibrated with very high accuracy, each i-it ring with versors $\vec{n_i}$ having the β_i with respect to the earth axis $\beta \geq 30^o$, and the relative angles between the different β_i monitored with $\sim$ nano-radiant accuracy.

Large area RLs are instruments shot-noise limited, the sensitivity is described by the minimum angular rotation which can be discriminated from the background $\omega_{ShotNoise}$, for a square device with 4 equal mirrors, we have:

$$\omega_{ShotNoise} = \frac{c}{2LQ}\sqrt{\frac{h\nu_{\lambda}}{P_{out} time}} \qquad (1)$$

where Q indicates the quality factor of the optical cavity, L is the side of the square cavity, $time$ is the integration time, ν_{λ} is the frequency of the circulating light, P_{out} is the output power, h is the Planck constant and c is the velocity of light. The quality factor Q depends on the total losses of the mirrors, side L of the square cavity; $\omega_{ShotNoise}$ improves with the second power of the side L.

To reconstruct the whole vector has several advantages: the statistics will be improved by using several devices since the shot noise of each ring is independent from the others; it provides the norm of the vector, which is a quantity invariant for changes of coordinates; the absolute orientation of each ring is not necessary, only the relative orientation is required. Co-locating more than three rings is a powerful tool to keep the systematics of an experimental apparatus under control. An array of at least four co-located rings would have the very interesting feature that the angular rotation vector could be reconstructed with different combinations 3 by 3. The comparison of the different results can give information on the systematics of the lasers. It must be stressed that the octahedron scheme proposed in 2011 is very powerful to fully reconstruct the local angular rotation, and allows redundancy, which is always welcome in this kind of experiment. The detection of the signal outside the meridian plane is also important to study the systematics of the laser, and for the investigation of Lorentz violations, since components outside the meridian plane, modulated with the earth rotation rate, could be detected.

Because of the difficulty of this test, which is based on very high accuracy and long term stability of the apparatus, we are investigating alternative solutions to the octahedron scheme.

The experiment G-GranSasso is carrying on experimental work with 3 prototypes: two RLs GINGERino and GP2, which will be described in the next sections, and the prototype GEMS which is at present under development by the GINGER associate group in Padova [7]. GEMS has the task to control the ring cavity geometry (shape and orientation), this prototype is based on a novel network of portable heterodyne interferometers, and it is capable of measuring the absolute distance between two retro-reflectors with a nominal accuracy better than 1 nm. First steps have been taken towards the realisation of this device and a starting prototype of distance gauge is under development and test [7].

3. GINGERino

GINGERino is shown in Fig. 3 (Top). It is 3.6 *m* in side and is located inside the deep underground INFN laboratory of the GranSasso[9]; its aim is to characterise the underground rotational seismic noise in view of the installation of the larger gyroscope array for fundamental Physics tests. It has been installed at the end of 2014, and the first data taking was started in spring 2015. Despite the fact that this device is an *R&D* prototype it is perfectly able to run continuously for days without any control of the cavity shape, thanks to the very quiet and thermally stable environment of LNGS. At present, the typical resolution is $\sim$ *tens* of *prad*/ for 500 *s* of integration time. This corresponds to a precision of 0.5 *ppm* on the earth rotation rate [9], fig. 5 shows the data of the latest run after backscattering subtraction. GINGERino has been able to detect the tiny ground rotations (around the vertical direction) induced by the passage of several tele-seismic waves in the frequency range between $(10^{-3} \div 1\ Hz)$ [10]. Standard seismometric equipment has been also installed on the laser cavity frame by INGV (Italian National institute of Geophysics and Vulcanology). This allows us to perform comparative analyses of rotations and translations and to have an insight on the surface wave propagation dispersion properties. At present the main limitation comes from the quality of the mirrors, in the next future top quality mirrors with total losses $\sim$ a few *ppm* will be installed.

4. GP2

The $10^{-13}\ rad/s$ sensitivity has been obtained with the monolithic prototype called G [1], located inside the geodetic station of Wettzell, in Bavaria. Its square optical cavity is realised on a very large slab of zerodur, closed at the corner by top-of-the-art super-mirrors kept in place by optical contact. Zerodur is a glass with zero thermal expansion coefficient. The rigid monolithic structure guarantees the long term stability of the scale factor of the RL G. G has demonstrated that for large enough ring-laser, once the geometry is under control, the output is shot noise dominated, accordingly the resolution increases with the square root of the integration time. It is not possible to build a ring array using monolithic zero expansion material in the required size, first by its cost, but essentially because of the lack of industrial facilities to work it; as well it is not possible to control the effective scale factors S of rings based on monolithic cavities, and it is very difficult to control the absolute orientation of $\vec{n}$. We have focused the experimental work on obtaining from a simple hetero-lithic

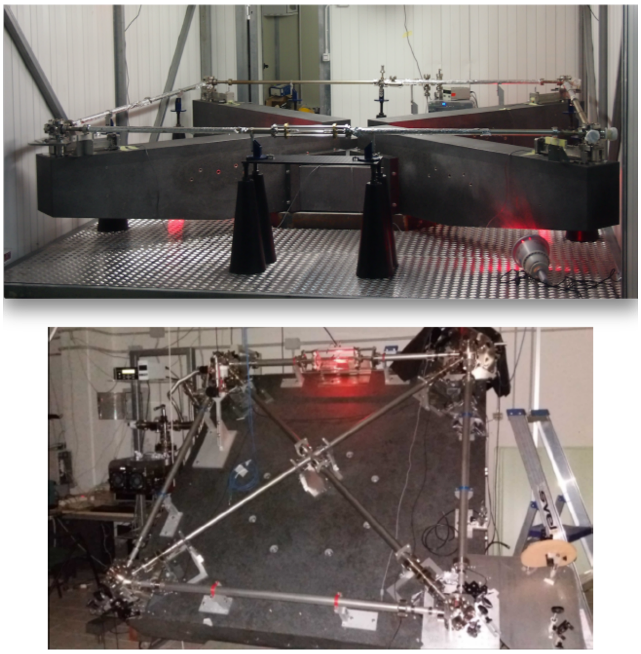

Figure 3: Top: GINGERino installed inside the underground laboratory of LNGS, it is a square ring-laser with side 3.6 *m*. Bottom: The prototype GP2, designed to develop the control to stabilise the geometry keeping fixed the length of the two diagonals. GP2 is aligned at the maximum Sagnac signal (plane of the ring perpendicular to the earth axis). This is the optimal choice for a test area to study the response of a RL, since in this way the influence of the local tilts are minimised.

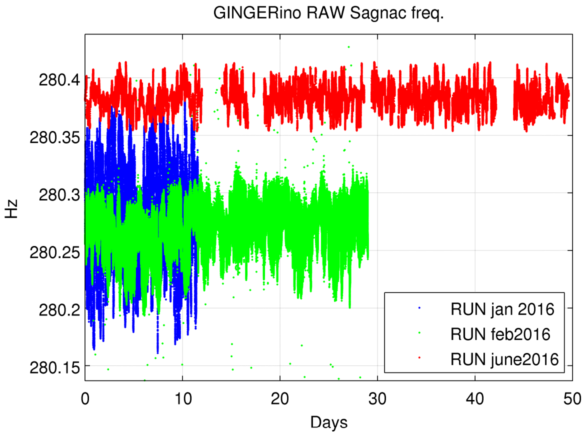

Figure 4: The three long continuous runs of GINGERino. The average frequency is consistent with the earth rotation rate, the scale factor and the orientation of the RL. The increase of the average Sagnac frequency, and its RMS amplitude reduction, is due to the improvement in the quality of the mirrors, which reduces the influence of the backscatter noise.

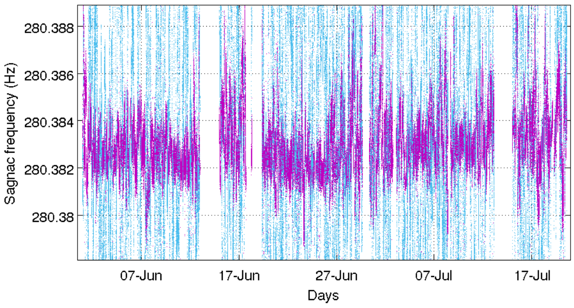

Figure 5: Raw data and backscattering corrected data for the run started on June 2016.

device the same performances of the monolithic one, controlling the geometry by means of the active control. Our prototypes are composed of 4 mirrors which can be moved by means of piezoelectric transducers. The error signals are taken utilising the diagonals of the square cavity, which form two independent Fabry-Perot cavities; standard metrological techniques are used to extract the error signals [8]. The external metrology GEMS under development in Padua is part of this active control scheme[7]. GP2 is the prototype devoted to the control of the geometry, it is operational since more than one year in the INFN section of Pisa. The first attempt [11] to control the geometry controlling the length of the two diagonals is at present under test, see fig. 6.

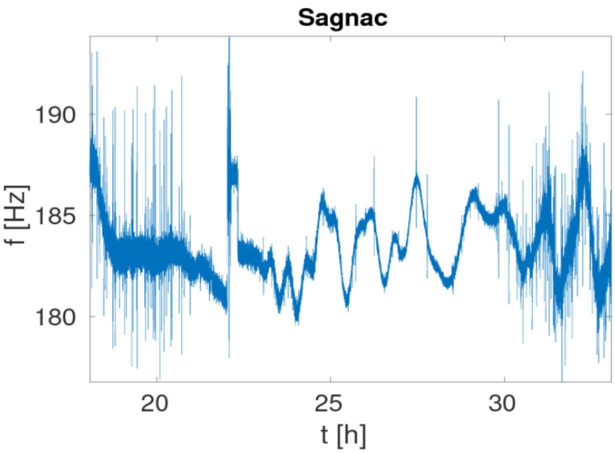

Figure 6: Continuous operation of GP2 with perimeter fixed controlling the two diagonals of the ring. The large changes of the output are due to the backscatter noise, which for GP2 are at present rather high, since the mirrors don't have losses higher than 10 *ppm*.

5. Ring-Lasers as tiltmeter and goniometer

The RL vertically oriented (versor area horizontally oriented) is a top sensitivity device able to measure tiny local tilts: in fact local tilts are local rotations $\vec{\Omega}_l$. In 2011 our old prototype G-Pisa has been installed inside the central area of the Virgo experiment, its measured sensitivity was of the order of $nrad/s$ [13].
RLs can be used as standard goniometers, the prototype G-LAS is under construction in collaboration with the Italian institute of standard (M. Pisani, INRIM, Turin), it is expected have a resolution of 5 $nrad$.[12]

6. Conclusions

The times of flight of two photons which follow a closed path (closed in the 3-dimentions space) bouncing around mirrors attached to the earth, is function of the rotation of the mirrors. The difference in time of two counter-propagating photons is proportional to the earth rotation rate (Sagnac effect) and contains as well terms 9 orders of magnitude lower, which come from General Relativity, specifically from the gravito-electric and gravito-magnetic effects (deSitter and LenseThirring).. G-GranSasso is an experiment of the INFN Commission II, it is aiming at pushing as far as possible the performances of RLs. These instruments have already demonstrated 10^{-13} rad/s sensitivity, which roughly speaking is one order of magnitude far from what is necessary to evidenziate on an earth based experiment the presence of the GR terms. Two RL prototypes have been built and are at present under study in Italy. In particular the prototype GINGERino is a large area RL located inside the underground laboratory of LNGS. Being located in a seismologically interesting area, GINGERino is considered of common interest for INFN and INGV. It is providing useful informations for the rotational seismology and the data are analysed in collaboration with INGV.

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