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Sagnac gyroscopes, GINGERINO, and GINGER

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Abstract. GINGER (Gyroscopes IN GEneral Relativity), based on an array of large dimension ring laser gyroscopes, is aiming at testing on Earth General Relativity effects, like the gravito-electric and gravito-magnetic effects (also known as De Sitter and Lense-Thirring effects) and the Lorentz violation. The sensitivity is a function of the size and of the losses of the ring laser optical cavity. In this kind of measurement long term stability is matter of concern, and underground location is desirable for its natural thermal stability and for being isolated from atmospheric disturbances. Considering the present sensitivity of the RLG prototype GINGERINO, and assuming total losses of 6 ppm, a 40 m perimeter and 1 day of integration time, a sensitivity of the order of frad/s could be achieved. The construction of GINGER is at present under discussion.

1. Introduction

The Sagnac effect states that the difference of time of flight of two light beams counter-propagating on a closed path is proportional to the angular rotation rate of the frame [1]. In a more general manner we can say that the two counter-propagating beams provides information on any non reciprocal effect they encounter in the clockwise and counterclockwise paths, the angular rotation rate is one of the main cause of non reciprocity, and usually it is the dominant one. The general formula is

$$\Delta\phi = \frac{8\pi A\Omega}{\lambda c}\cos\theta \ , \tag{1}$$

where $\Delta\phi$ is the difference in phase of the two output waves, A is the area enclosed by the optical path, λ the radiation wavelength, θ the angle between the area versor of the ring and the rotation axis defined by the angular velocity vector $\vec{\Omega}$, and c the velocity of light; here $K_0 = \frac{8\pi A}{\lambda c}$ is a scale factor relating the phase difference to the angular velocity. So far several different probes have been utilised to exploit the Sagnac effect, namely photons, atoms and super-fluid helium [1]. Here we limit the discussion to high sensitivity apparatuses using optical photons, which have the obvious advantage of being insensitive to gravity variations. The closed path can be

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an optical fiber coil or a ring Fabry-Perot cavity[1]. The devices based on resonant Fabry–Perot ring cavities can be passive or active. In the passive devices the resonant cavity is interrogated by injecting a laser radiation emitted from an external source (Passive Ring Cavity (PRC)); in the active one the ring cavity contains the active medium and a laser emission is generated in the two directions (Ring Laser Gyro (RLG) or active ring cavity (ARC)) [2]. In both cases, the Sagnac frequency f_s between the two counter-propagating beams, is related to $\vec{\Omega}$ by

$$f_s = S_0 \Omega \cos\theta,\ S_0 = 4\frac{A}{\lambda L}\ , \tag{2}$$

where L is the perimeter and S_0 the geometrical scale factor. This is advantageous since the frequency measurement is extremely accurate and provides large dynamic ranges. Moreover, S_0 can be more efficiently stabilised, since it is proportional to A/L. Due to elastic deformations of optical cavity, this ratio can change with time. However, building the apparatus in order to have this ratio close to a saddle point, the requirement on the long term stability of S_0 becomes accessible.[2]

So far, atom based gyros have reached 0.3 nrad/s in 3 hours integration time, while the best RLG has a sensitivity of 10 prad/s in 1 second integration time, and can reaches 0.25 prad/s in 3 hours integration time [3]. People are still working to optimize the PRC sensitivity, at present the record is nrad/s in 1 second integration time [4]. In principle a RLG apparatus can be operated also as PRC, which is a very important feature to validate top sensitivity tests, and to investigate systematic.

These devices have applications in geodesy, in geophysics and in General Relativity (GR) tests [2]. Our proposed RLGs array, GINGER, has the aim of testing the Lense–Thirring effect at the level of 1% [5, 6, 7], *which would be the first measurement* of a *GR* dynamic effect of the gravitational field on the Earth surface, beside the gravitational red-shift. Though not in free fall condition, GINGER would perform a direct local measurement, independent from the knowledge of the map of the Earth gravitational field, and not an average global one, as in the case of space experiments, making possible several new tests of relativistic gravitational theories [8]. In the preparatory phase, solutions for the scale factor stabilisation has been provided [9], and new data analysis method has been developed to correct the non linearity induced by the laser dynamics[10]. GINGER has to push the relative sensitivity of the Earth rotation rate measurement from the present 3 parts in 10^9 down to 1 part in 10^{12}, corresponding to a sensitivity level of 10^{-16}rad/s. The principle of the GR test is rather simple: the GR effects on the apparatus take the form of two extra angular rotation vectors (i.e. de Sitter and Lense–Thirring effects) in the local meridian plane. The RLG array measures a total angular rotation rate which is the vectorial sum of the kinematic Earth rotation vector $\Omega_\oplus$, and the two GR contributions. Since International system IERS measures $\Omega_\oplus$ with the required accuracy, and the de Sitter term is very well known, the Lense–Thirring term can be evaluated. GINGER could also provide important tests on Lorentz violation to improve the present limits, following the recent suggestion by Jay Tasson [11].

2. From GINGERINO to GINGER

In 2015 GINGERINO has been installed inside the underground laboratory of Gran Sasso. It is a 14 m perimeter RLG based on a simple mechanical structure in order to qualify of the location for high sensitivity apparatus as GINGER. In spite of the fact that its mechanical apparatus followed an old design affected by several flaws, and the absence of an active control

[1] This two concepts have been and still are widely used in inertial navigation gyroscopes.

[2] Very low frequency rotational signals are the focus of this kind of research, so that long term stability is a key point.

of its dimension, GINGERINO is able to run unattended for months, with a duty cycle higher than 95% and a sensitivity below 0.1nrad/s in 1 s. In part the success of GINGERINO depends on the high thermal stability of an underground location. In addition, the location in a active seismic region makes it a very useful tool for seismological study [12]. For testing Lense-Thirring effect, which is a DC signal, it is of paramount importance to achieve high accuracy at a very low frequency. For this purpose it is extremely important to take into account the laser dynamics, which is highly non linear. For this purpose the data analysis requires the use of diagnostic signals, collected together with the Sagnac interferometric signal, namely the intensities of the two counter-propagating laser beams and the plasma discharge intensity. In 2011, the first attempt to take into account the laser dynamics was done using a Kalman filter on the data of G-Pisa, our first RLG prototype. This first attempt has clearly shown that the laser dynamic affects the accuracy of the instrument, not the only its sensitivity. The Kalman filter for data reduction was quite cumbersome and CPU time consuming. Starting from this first experience, recently we have developed a new purely analytical approach to highly reduce the laser disturbances. [10]. To validate the data analysis procedures, we have used the data of our prototypes GP2 and GINGERINO. The improved analysis scheme decreases more than one order of magnitude the noise level, and we have shown with our prototype GP2 data that the mean value of the angular speed bias is pushed closer to the expected Earth rotational rate. It is worth noticing that GP2 is located in Pisa, and oriented at the maximum Sagnac signal, i.e. the optimal alignment to provide the modulus of Earth angular velocity. GP2 is dedicated to the improvements of a RLG apparatus, as the tests of the scale factor control, and the development of tools to remotely operate a RLG [9]. The prototype GINGERINO is operative inside the Gran Sasso laboratory on a continuous basis, the data are utilised for geophysical studies providing an excellent playground to refine as much as possible our new analysis schemes. All these results give us the motivation to proceed with the GINGER project.

3. GINGER project

The RLG is a shot-noise limited instrument. Its sensitivity limit ω_{sn}^{μ} can be expressed as amplitude spectral density[2] in function of the measurement time t, h_p the Planck constant, ν_λ the frequency of light, Q the optical cavity quality factor, and P_μ the total power dissipated in the cavity (i.e. $P_\mu = \mu P_{in}$, assuming μ the total losses of the cavity and P_{in} the intra-cavity power). In the ideal case in which $A/L = l/4$, being l the side length of the square ring cavity, and expressing the quality factor $Q = \frac{2\pi l f_\lambda}{c\mu_s}$, the original formulation can be rewritten defining $\mu_s = \mu/4$ the total losses of each mirror(four in our case) and assuming that no other loss mechanism is present, [3] obtaining:

$$\omega_{sn}^{\mu} = \frac{c^2}{4\pi l^2}\sqrt{\frac{h_p \mu_s}{\nu_\lambda P_{in} t}} \quad , \tag{3}$$

showing that ω_{sn}^{μ} scales as the second power of the side length l and the square root of the losses μ. The larger is the ring the lower the shot noise limit. Compact rings are however advantageous in term of stability. At present RLG with side between 4 and 10 m have been built and successfully operated. ROMY, the RLGs array operative in Germany, is composed of equal equilateral triangular rings with 36 m perimeter. Fig. 1 shows that a RLG integral with the Earth crust could fulfill the Earth rotation rate measurement with precision 1 part in 10^9 in 1 hour integration time. Fig. 1-A shows the shot noise sensitivity limits, starting from the state-of-the-art (mirrors produced by FIVE9) of 10 prad/s $Hz^{-1/2}$, with $\mu = 6$ppm, assuming a reduction of the losses per mirror down to 1.5ppm: Similar conclusion could be done

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[3] For instance, this implies that losses associated with the discharge tube of the laser are negligible.

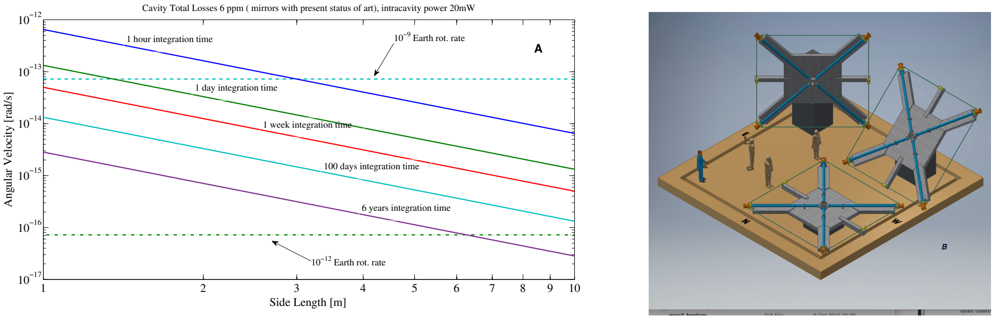

Figure 1. A: Sensitivity limit in function of the RLG side length, assuming 6 ppm total losses of the cavity (present best mirrors), internal power 70mW (output power 20nW, mirror transmission 0.3 ppm). The two GINGER targets, expressed as fraction of Earth rotation rate, are over-imposed. B: Pictorial view of the GINGER experiment at 45° latitude.

for the angle variation measurement, but it is clear that with a single RLG it is not possible to discriminate among variations of rotation or angle. For that purpose and array of RLGs is necessary. The configuration of GINGER [7] as shown in Fig.1-B allow a full determination of the rotation vector without requiring an independent measurements of the relative angles between rings. Where to build GINGER in Italy is presently under discussion. It was proposed to the Gran Sasso laboratory, but an alternative location can be the SAR-GRAV underground laboratory, which is under construction in an old mine of Sos Enattos in Sardinia. In conclusion, GINGER is highly interdisciplinary, providing the measurement of the ground rotational motion, for seismology, and the measurements of the fast variation of the Earth angular velocity and axis orientation.

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