GINGERINO and the GINGER project

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GINGER (Gyroscopes IN GEneral Relativity) is a project based on an array of large dimension ring laser gyroscopes, which is aiming at measuring in a ground laboratory the gravito-electric and gravito-magnetic effects (also known as De Sitter and Lense-Thirrings effect), foreseen by General Relativity, and proposed at the underground Gran Sasso laboratory (LNGS). The geometry control to keep constant the scale factor and the optimal orientation of the array have been studied. GINGERINO, a square ring-laser prototype built inside LNGS, has shown the advantages of an underground location for GINGER. At present, it is the only high sensitivity laser gyro running unattended in a seismically active area. It recorded the large signals of the sequence of the central Italy 2016 earthquakes and microseismic signals of the Mediterranean area five orders of magnitude smaller. The analysis of 90 days of continuous operation shows that its duty cycle is higher than 95%, with noise limit of the order of 10^{-10} (rad/s)/$\sqrt{Hz}$.

1. Introduction

The Sagnac effect has been discovered by Georges Sagnac more than 100 years ago, and states that the difference of time of flight of two light beams counter-propagating inside a closed path, is proportional to the angular rotation rate of the frame.[1–3] Usually the closed path is an optical fiber coil or a ring Fabry-Perot cavity composed by $3 - 4$ mirrors. The device can be passive or active: passive is when the resonant cavity is interrogated injecting light from the outside; active when it contains an active medium, and the device is itself a laser emitting along two counter propagating modes, in this case it is called Ring Laser Gyro (RLG).[4] RLGs based on large frame ring cavities, with perimeters of several meters, are at present the most sensitive angular rotation sensors based on Earth. They have been built for geodesy, geophysics and for General Relativity (GR) tests[1] (for geophysics see $https : //www.geophysik.uni - muenchen.de/ROMY/$). Since 2011 we are studying the feasibility of the Lense Thirring test at the level of 1%, with an array of large frame RLGs,[5–7] studying in details the orientation of the RLGs in order to define the specifications of such apparatus. At the same time several tests have been pursued in order to define and test in details the geometry control and the data analysis. It is necessary to push the relative sensitivity of the Earth rotation rate measurement in the range from 3 parts in 10^9 (present record[8]) up to 1 part in 10^{12}, this is equivalent to reach the sensitivity level of 10^{-16}rad/s. It is necessary to point out that this measurement is even more demanding since it requires very high accuracy. At present, the accuracy limit is certainly at least 10 times worst than the sensitivity limit. RLG consists of a laser with a cavity comprising of three or four mirrors, depending if the cavity is triangular or square, rigidly attached to a frame; the two counter-propagating cavity modes have slightly different frequency, and the beat note f_s of the two beams is proportional to the angular rotation rate Ω felt by the ring cavity.

$$f_s = S\Omega\cos\theta \qquad (1)$$
$$S = 4\frac{A}{\lambda L}$$

where A is the area of the ring cavity, L is its perimeter, λ the wavelength of the light, and θ the angle between the area versor of the ring and the rotation axis. Considering RLG attached to the Earth crust, horizontally aligned (*i.e.* area versor vertical) θ is the colatitude angle, while for RLGs aligned at the maximum Sagnac signal (*i.e.* area versor along the Earth rotation axes) $\theta = 0$. Eq. (1) connects Ω with the scale factor S, which depends on the geometry, and the wavelength λ. RLGs have large interest in fundamental physics to study the property of the gravito-magnetic field, and they have been proposed in the past for axion search and Lorenz invariance violation.[9] GINGER would provide *the first measurement* of a *GR* dynamic effect of the gravitational field on the Earth surface (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 and not an average value, as in the case of space experiments. It is important to point out that this kind of measurement depends on the angular momentum of the Earth, so it provides a way to check whether dark matter is nearby rotating. There are space based project to further develop the gravito-magnetic measurements in space to test the presence of dark matter.[10] The measurement is based on properties of the velocity of light and on the measurement of the frequency, ensuring fast response, large bandwidth, and a huge dynamical range. For example GINGERINO, our RLG prototype at LNGS, has recorded microseismic events in the range of fraction of nrad/s and high magnitude nearby earthquakes[11] 5 orders of magnitude higher. Fig. 1 shows the typical lay-out of a square cavity RLG. The

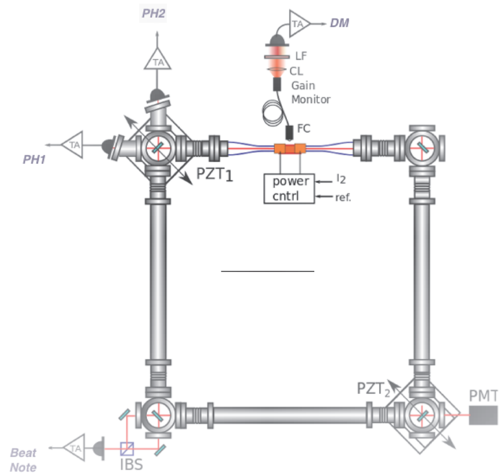

Fig. 1. Typical scheme of RLG with a square ring cavity.

four mirrors are placed at the corners of the square ring, each contained inside small vacuum chambers connected by steel pipes. The whole setup is vacuum tight and filled with Helium and an isotopic 50/50 mixture of ^{20}Ne and ^{22}Ne. The r.f. discharge, located in one of the side, generates the laser plasma. In most of the cases, piezoelectric actuators are utilised to translate the mirrors, allowing a control of the RLG perimeter length. The Sagnac beat note signal is observed at one corner (bottom-left) by superimposing the two output beams on a photodiode. At the top left corner two amplified photodiodes monitor the clock-wise (cw) and the counter clock-wise (ccw) output beams optical power (mono-beam photodiodes). Another photodiode monitors the fluorescence from the discharge, filtered around 633nm by an interference filter, providing a rough indication of the density of excited atoms in the laser upper state. In normal operation, plasma discharge is electronically controlled in order to keep as much as possible constant the optical power of one of the two mono-beams. All these signals are acquired by an ADC card at a frequency rate of a 5 kHz, suitable to allow their reliable reconstruction from DC up to the Sagnac frequency.

2. GINGER

The effects of the gravito-magnetic (Lense-Thirring, LT) and gravito-electric (de Sitter, dS) fields are observable by the gyro as angular velocity $\mathbf{\Omega_{LT}}$ and $\mathbf{\Omega_{dS}}$, that combine with $\mathbf{\Omega}_{\oplus}$, the Earth angular velocity, seen in the Cosmic inertial frame. GR is extremely predictive, allowing to compute the orientation and the amplitude of Ω_{LT} and Ω_{dS}, in function of the latitude of the observer. Note also that several alternative theories of gravitation predict different dependence on latitude; so that a direct observation would, perhaps, discriminate between different theories.[12] Fig. 2

shows the mutual orientation of the various vectors for $\simeq 45^o$ of latitude (as e.g. at the GranSasso laboratories, LNGS).

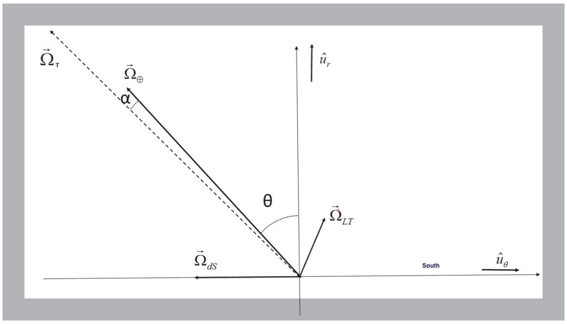

Fig. 2. The three axial vectors $\vec{\Omega}_\oplus$, $\vec{\Omega}_{LT}$, and $\vec{\Omega}_{dS}$ are shown, with the relative orientation at the latitude of the underground laboratory of GranSasso (LNGS), following General Relativity. The angle α and Ω_T (dashed line) are shown in the picture. The graph is not to scale, it gives just a pictorial view of the relative orientations of the different components. In reality, the modulus of $\vec{\Omega}_\oplus$ is 9 orders on magnitude bigger than the *GR* terms, and the angle α is of the order of $\sim 3.5{\cdot}10^{-10}$ rad at the latitude of 45^o.

The idea is to measure the total angular velocity seen by the gyros array and to evaluate the GR terms comparing the results with the measurement done by the international system IERS (International Earth Rotation and reference System), which independently measures the kinematic term $\Omega_\oplus$. The problem of the Lense-Thirring test is a very general one, similar to any effect induced by geophysical phenomena; it is particularly challenging since it is a DC effect, and not only sensitivity is required, but also accuracy. The main points of the GINGER apparatus are the following:

- reconstruct with very high precision a vector in the space using the information of the projectors, Eq. 2 shows that the geometry of the apparatus must be controlled, in particular the ratio $\frac{A}{P}$, the wavelength λ and the variation of the absolute inclination $\delta\theta$;
- in general at least 3 independent gyros, 4 or more would be better for redundancy;
- it is necessary to study the noise related to any kind of variations of the apparatus, in particular all geophysical signals.

The main difficulty is the required accuracy, because it is necessary to distinguish a DC signal $9-10$ orders of magnitude smaller than the dominant signal $\Omega_\oplus$. It has been shown that in general the signal can be reconstructed combining the different RLG of the array,[6] but the relative angles between the different RLGs must be known with adequate accuracy. This means accuracy in the relative alignment of the RLGs of the order of nrad or better. One technique suitable to monitor with nanometer accuracy the distance between the mirrors has been tested.[13] Utilising the natural symmetry of the problem it is possible to mitigate the requirement of the relative alignment. It has been shown that aligning one of the RLG at the maximum signal and the other horizontally or vertically it is possible to evaluate the angle between the two and solve the problem.[7] The RLG aligned at the maximum signal, so with area versor along the Earth rotational axis, has the interesting property that delivers the modulus of the total angular velocity and is at first order insensitive to local tilts. In principle it delivers the variations of the modulus of $\Omega_{\oplus}$, or equivalently the Length of Day (LoD). The details of the specification have been published.[6,7] Fig. 3 shows a picture of GINGER with 3 independent RLG, the location may be node B of LNGS, an area far apart from the main experiments. The exact dimension of the ring laser resonators has not been decided yet, but they will be squared structures with side length of $5 - 6$ meters.

Fig. 3. Pictorial view of the GINGER project.

3. GINGERINO and work toward GINGER

Large effort has been pursued in Italy toward GINGER. Presently the most performing RLG is "G", situated at the Geodetic Observatory of Wettzell in Germany; it is composed of a monolithic structure, a rigid block of Zerodur with mirrors optically contacted in order to have a geometry fixed by construction. It is evident that such a structure cannot be extended to form a three axial array. Hetero-lithic mechanical structures have to be used instead, and in this case an electronic control is necessary in order to keep constant the geometry. A suitable control scheme to keep constant the scale factor has been studied and tested.[14–16] It is a well known fact that RLGs are affected by non linearity of the laser, and, in particular, optical back-scattered noise. In 2012-2014 Kalman filters have been successfully applied,[17,18] more recently we have developed a novel analytical technique to reconstruct the Sagnac frequency avoiding laser systematic.[19] Fig. 4 shows the time behaviour of the data of GP2, analysed with the standard method and with the new one. GP2 is a square ring laser with side of 1.6m, aligned at the maximum Sagnac signal and presently working in Pisa for test purposes.[16] Gingerino is a test RLG

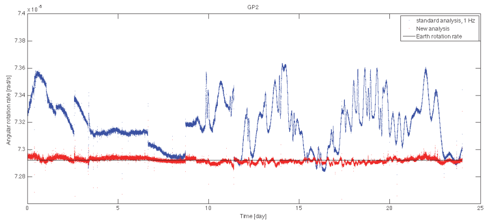

Fig. 4. One day of data of the prototype GP2 analysed with the standard method and the new one, the black line is the expected Earth angular rotation rate. GP2 is the RLG prototype with 6.4m perimeter, aligned at the maximum Sagnac signal.

3.6 m in side, installed at LNGS since 2014. In seismology, translation and strain are routinely observed by seismometer and strain meters. However, a full description of the ground movements requires also the acquisition of a third type of information, namely rotations. In particular, co-located translation and rotation sensors allow to estimate the local underground velocity structure, which is an information of high interest in geophysical survey. Rotational signals induced by seismic waves have a quite small amplitude. A strong seismic wave with a linear acceleration of 1 mm/s^2 produces a rotation velocity amplitude of some 10^{-7} rad/s, while micro-seismic rotational background noise (around 0.1 Hz) is smaller than 10^{-10} rad/s.[11,20] GINGERINO has shown the advantage of the underground location, since it is the first large frame hetero-lithic RLG, which operates continuously unattended with high sensitivity and with 95% duty cycle.[21] It has also shown that the local tilts on long time are below μrad,[7] this is an important parameter for the installation of a RLG at the maximum signal. GINGERINO is taking data for seismology, so at present inside LNGS there is one of the few seismic station allowing to record at the same time both the three translation components and the rotation angle.[11,20] Besides, GINGERINO is a very useful tool to develop new analysis technique, to investigate the very low frequency signals and to test all the equipment to remotely control and operate on the apparatus.

4. Conclusion

A large experimental work has been pursued toward GINGER, the array of RLGs designed to detect on ground the Lense-Thirring effect at 1% precision. Geometry control of each independent RLG, study of the optimal orientation of each RLG of the array, and reconstruction of the angular rotation rate taking into account the systematic of the laser. GINGERINO has been realized to validate LNGS for this experiment, and it has shown the advantage of an underground location far from atmospheric perturbations and large thermal variation. In fact it is the first high sensitivity RLG based on a hetero-lithic mechanical structure operating with 95% duty cycle and with a sensitivity of the order of 10^{-10}rad/s. It has detected microseismic signals of the order of 10^{-10} rad/s and large teleseismic events 5 orders of magnitude larger. It is the first and only RLG operative in one of the Mediterranean most important seismically active area.

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