The GINGER project and status of the GINGERino prototype at LNGS

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Abstract. GINGER (Gyroscopes IN GEneral Relativity) is a proposal for measuring in a ground-based laboratory the Lense-Thirring effect, known also as inertial frame dragging, that is predicted by General Relativity, and is induced by the rotation of a massive source. GINGER will consist in an array of at least three square ring lasers, mutually orthogonal, with about 6-10 m side, and located in a deep underground site, possibly the INFN – National Laboratories of Gran Sasso. The tri-axial design will provide a complete estimation of the laboratory frame angular velocity, to be compared with the Earths rotation estimate provided by IERS with respect the fixed stars frame. Large-size ring lasers have already reached a very high sensitivity, allowing for relevant geodetic measurements. The accuracy required for Lense-Thirring effect measurement is higher than 10^{-14} rad/s and therefore Earth angular velocity must be measured within one part in 10^{-9}. A 3.6 m side, square ring laser, called GINGERino, has been recently installed inside the Gran Sasso underground laboratories in order to qualify the site for a future installation of GINGER. We discuss the current status of the experimental work, and in particular of the GINGERino prototype.

1. Introduction

The GINGER (Gyroscopes IN GEneral Relativity) project aims at measuring, for the first time in an Earth-based laboratory, the General Relativity (GR) precessions as the de Sitter and Lense-Thirring effects, by using an array of large ring lasers (RLs) [1]. The RL is widely used for the measurement of absolute angular rotations with respect the local inertial frame. RL technology has been applied so far to inertial guidance [2], angle metrology [3], geodesy [4] and geophysics [5]. The advancement of RL technologies has pushed the possibilities of such devices to unprecedented values of accuracy and precision, and ring lasers appear today as a most interesting apparatus to probe the structure of space-time of GR at the laboratory scale.

A RL exploits the asymmetric propagation of light along a closed space path in the gravitational field of a rotating body. It consists of a resonant optical cavity (triangular or square) in which two laser modes, counter-propagating over the same path, are excited. By the principle of Sagnac effect the frequencies of two laser beams shifts in response to angular

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rotation. The rotational information is detected by revealing the beams interference signal. The frequency difference between the two modes (Sagnac frequency) is given by [7],

$$f_s = \frac{4a}{\lambda p} \mathbf{\Omega} \cdot \mathbf{n} + f_{nr} \ , \tag{1}$$

where a is the area enclosed by the optical path, p is the optical path length (also known as "cavity perimeter"), λ is the light wavelength, $\mathbf{\Omega}$ is the rotational speed vector and $\mathbf{n}$ is the unit vector normal to the instrument plane. The scale factor $\mathcal{S}_F = 4a/(\lambda p)$ is a pure geometrical factor and it depends on the position of the optical elements (high-reflectivity mirrors) of the cavity. Here, f_{nr} represents the non-rotational contributions to the Sagnac frequency arising from non linear laser dynamics and backscattering, and represents a systematic error source that must be modeled and kept under control.

The large RL "G" [8] located in the Geodetic Observatory in Wettzell (Bavaria, Germany) has a square cavity with 4 m side. Because of its large size and strong stabilization of laser and cavity parameters, a resolution of the Earth angular velocity better than 2.5×10^{-13} rad/sec at about 4 hour of integration is now obtained. This is within a factor of 5 of the theoretical prediction of GR. G has demonstrated that the RL has a big potentiality in sensitivity. However, a further enhancement of the apparatus is also important, with special attention to the accuracy of the measurement by reducing uncertainties of f_{nr} term in Eq.(1). It is worth noticing that few co-located RLs arranged in a tri-axial system seems to be a viable way to improve the accuracy of rotation measurements. In fact, a tri-axial system of RL, as in GINGER, will provide a complete estimation of the laboratory frame angular velocity to be compared with the Earth's rotation with respect the "fixed stars" frame. This information is provided by IERS under the form of time series of Earth Orientation Parameters and Universal Time, determined by VLBI measurements together with data of GPS and DORIS satellites. IERS measures the Earth rotation rate with very high accuracy of $\simeq 3 \times 10^{-15}$ rad/sec, and a significative accuracy improvements is envisaged by VGOS (VLBI2010 Global Observing System) in the next years. The comparison between the two independent accurate measurements, made with IERS and GINGER, can put in evidence the Lense-Thirring and Geodetic terms. The redundancy of a tri-axial configuration, made up of at least 4 RLs, is crucial in eliminating local rotations by means of a linear combination of the Sagnac frequencies, and therefore in allowing us to estimate their f_{nr} contributions.

The plan of the paper is as follows. In Sect. 2, after the calculation of the Geodetic and Lense-Thirring terms, we report on the GINGER proposal and on the roadmap we devised to study some key issues of the project. In Sect. 3 we present some preliminary results of the GINGERino apparatus that we have installed at the Laboratories of Gran Sasso with the aim of characterizing the rotational noise of the site. Conclusions are eventually drawn in Sect. 4.

2. GINGER project

In proposing the GINGER experiment for the measure of relativistic effects due to rotating Earth, we have been driven by different motivations.

First, light is a good probe to measure the modification spacetime geometry with respect to Minkowsky flat metric. In fact, light is intrinsically relativistic, can be described by null geodetics which cover completely the space-time, and its propagation is affected in many ways by gravitation. Maxell's equations in curved space-time may be written as if they were valid in a flat space-time filled by a suitable optical medium. Thus, there exists an equivalence of optical media and spacetime Riemannian geometries that can be experimentally exploited [6].

Secondly, General Relativity has been tested so far in the Solar system, at planetary scales, by studying geodetic motions of test masses (free fall of planets, Earth orbiting satellites, etc), or the deflection of light from the sun. On the contrary, in the GINGER experiment the observer is in a non inertial motion, and the involved scales are few meters. In this way, we can test the local Lorentz covariance of GR at different scales, i.e. the independence of physical measurements from the observer accelerated motion.

Thirdly, GINGER is a relatively simple apparatus, and being on Earth, further improvements of its sensitivity and long term stability are feasible. In the future, other tri-axial RL arrays could be built in different laboratories. The comparison between them could provide data suitable to test alternative theories to GR (e.g. Horava-Liftshiz or Chern-Simon gravity) and/or measure PPN parameters with high accuracy.

Finally, we note that the tests of GR using GINGER do not require a global model of the Earth gravity as required by the space measurements based on the tracking of satellite orbits. For instance, using LARES and LAGEOS satellites, the measure of Lense-Thirring at 1% of accuracy requires the Earths gravity models obtained by the GRACE project. For these reasons, space and Earth based tests of GR are complementary: the latter can also be used for testing PPN parameters related to non-free fall motions.

2.1. Gravitomagnetic effects in General Relativity

The relativistic response of a RL has been calculated many times in the literature (see e.g. [1]) starting from the metric near the Earth surface, which is the solution of the linearized Einstein equations in vacuum for a rotating body. Neglecting the f_{nr} term in Eq. (1), the Sagnac frequency can be written as

$$f_s = \frac{4a}{\lambda p}\ (\mathbf{\Omega}_\oplus + \mathbf{\Omega}_G + \mathbf{\Omega}_B) \cdot \mathbf{n} \tag{2}$$

where the effective angular velocity vector is the sum of 3 contributions: i) the kinematic Earth rotation vector as measured by IERS or Sagnac term $\mathbf{\Omega}_\oplus \equiv \Omega \mathbf{u}_\oplus$, ii) the pure mass contribution or Geodetic term

$$\mathbf{\Omega}_G \equiv -2\frac{GM}{c^2R}\Omega_\oplus \sin\theta\ \mathbf{u}_\theta\ , \tag{3}$$

and iii) the Earth angular momentum contribution or Lense-Thirring term

$$\mathbf{\Omega}_B = \frac{G}{c^2R^3}\left[\mathbf{J}_\oplus - 3(\mathbf{J}_\oplus \cdot \mathbf{u}_r)\mathbf{u}_r\right]\ ; \tag{4}$$

here $\mathbf{R} \equiv R\mathbf{u}_r$ is the position of the laboratory with respect to the center of the Earth, $\mathbf{J}_\oplus \simeq (2/5)MR^2\mathbf{\Omega}_\oplus$ is the angular momentum of the Earth approximated as a rotating rigid sphere of radius R, mass M, moment of inertia $I_\oplus = (2/5)MR^2$, the unit vector $\mathbf{u}_r$ is along the radial direction, and $\mathbf{u}_\theta$ is along the local meridian in the sense of increasing colatitudes. Using Earth mass, rotation rate and radius, we have that Geodetic and Lense-Thirring terms are both of order $\sim 10^{-9}$ with respect to the Sagnac term.

2.2. Key issues of GINGER

The GINGER apparatus will consist of an array of ring lasers arranged in a tri-axial configuration. The expected sensitivity of GINGER can be extrapolated starting from the record of sensitivity and long term stability already obtained by "G" in Wettzell geophysics observatory [8]. To reach the GINGER goals, we need to improve the "G" performances along the following experimental lines, as discussed in ref. [1] :

- Reduction of the shot noise level by enlarging the RL side L from 4 to $8 \div 10$ m. It can be shown that for equivalent mirrors, the sensitivity increases as $\sim L^5$ [7].

- Improvement of the long-term stability to 1 day by monitoring and controlling the laser operative parameters and the RL environment. A deep underground location of the RL array is recommended to reduce surface noise due to changing weather patterns and local atmospheric hydrological effects.
- Stabilization of the geometrical scale factor by means of an effective active control of the RL geometry, i.e. the vectorial area and perimeter associated to the laser beams of a RL cavity. The relative variations of scale factors and angles among RLs must be controlled at the level of one part in 10^{10}.
- Correction of the nonlinear laser dynamics terms. In fact, non linear laser dynamics introduces nonreciprocal effects consisting in a null-shift term in the laser gyroscope responses. To achieve the required accuracy, an estimate of these contributions must be implemented. The redundancy of RL array allow us to cancel in a linear combination of the Sagnac frequencies any rotation source (geophysical, geodetical or local), and therefore to estimate the non rotational contributions to the Sagnac frequencies at the level of the geometry control.
- A RL array allows for the reconstruction of the modulus of the Earth rotational speed independently of the knowledge of the absolute orientation orientation of the array with respect the "fixed star" frame. The proposed RL array for GINGER is a set of 6 mirrors arranged in an octahedral configuration, which defines three mutually orthogonal nested RLs. The octahedral configuration could also provide a strong control on the geometry by locking the three Fabry-Perot cavities along the octahedron diagonals to an identical value. As already pointed out, redundancy is essential, and so we may add to the octahedron another RL oriented almost parallel to the Earth rotation axis $\mathbf{u}_\oplus$.

3. Status of GINGERino

GINGERino is a test apparatus with the main purpose of studying the low frequency rotational motion of the LNGS, in order to validate this site for the future installation of GINGER. GINGERino is located south of the node B, far from human activities occurring in the laboratory. This apparatus should be able to measure the polar motions and other relevant geodetic signals associated to Earth rotations, as well teleseismic events and micro-seismic activity of the Earth that are relevant for geophysics. GINGERino is made of a square optical cavity of 3.6 m side formed by four high reflectivity mirrors. The cavity is mounted on a cross granite structure rigidly linked to the underlying bedrock. The experimental instrumentation is completed by two seismometers (provided by INGV), two nano-tiltmeters and several environmental monitors (temperature, humidity, pressure etc). GINGERino is enclosed in an isolating box with a temperature that can be set in the $13 \div 16$ °C range. The temperature is not yet actively controlled; however, it remains stable at the level of fractions of degrees, with a relative humidity of the order of 60 %. The basic hardware of GINGERino has been completed at the beginning of 2015. Since then, several mechanical improvements have been adopted in order to make stiffer the supports of the cavity mirrors and discharge, and to isolate the instrument from the vibration of the box which, in its turns, isolates acoustically the whole apparatus. Fig. 1 shows a picture of GINGERino experimental setup. The data acquisition is based on a NI PXI system. The relevant signals from the RL (monobeam intensities, interferogram, gain monitor and UTC synchronization signal) are acquired at 5 kHz, while the auxiliary channels (temperature, humidity, local tilts, etc.) are acquired at 1 Hz. Data files are created hourly, and sent to a PC, which takes care of copying the files directly to our storage area in Pisa for subsequent analyses.

So far a consecutive data set of more than a week has been acquired. The preliminary analysis has shown a sensitivity about 0.1 nrad/s for 1 second of integration time, compatible with the

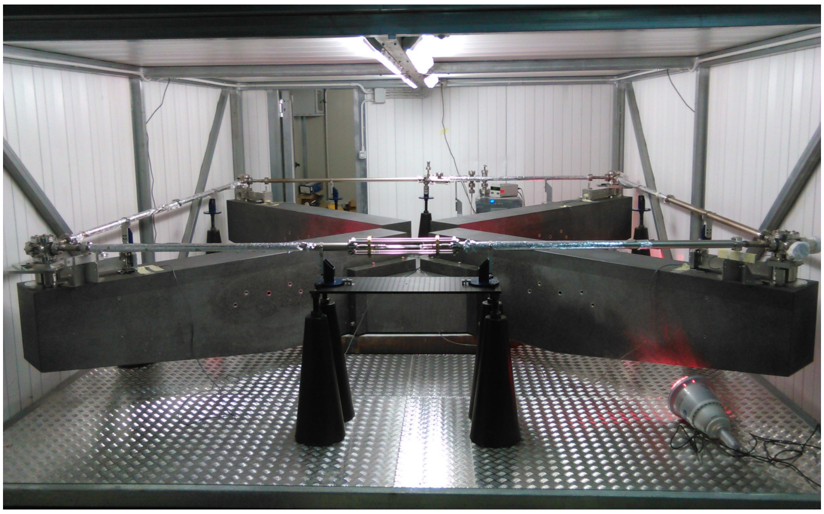

Figure 1. A picture of the GINGERino apparatus at LNGS. The insulating box, the cross granite structure, and the laser discharge are clearly visible.

shot noise level [9]. At present, the main limitation comes from the backscatter noise due to mirror losses, which are a factor of 10 higher than losses of top quality mirrors and limit the ring-down time to 250 μsec. To fix this problem, a new set of mirrors will be installed at the beginning of 2016.

4. Conclusions

Large size RLs are very high precision gyroscopes, which provide useful information for Geodesy and Geophysics, and can also perform interesting test of GR by measuring the local space-time geometry. The GINGER apparatus consists of an array of at least 4 RL with an heterolithic design, capable to measure locally the Lense-Thirring and Geodetic effects. The GINGER requirements to enter in the realm of GR tests can be summarized as: i) a sensitivity of 10^{-14} rad/sec in measuring the Earth rotation; ii) a long term stability of $\sim$ 1 day; and iii) a relative accuracy of 1 part in 10^{10}. To further investigate these 3 key issues, we are conducting experimental activity in stabilization of the single RL geometry, control of the relative angle among different RLs in the array, and correction of the non linear laser term in the Sagnac frequency [10, 11, 12, 13]. We expect to characterize LNGS site and complete our investigations in about one year, after that time the GINGER realization will be discussed.

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