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Abstract. GINGER (Gyroscopes IN General Relativity) is a proposal aiming at measuring the Lense-Thirring effect with an Earth based experiment, using an array of ringlasers, which are the most sensitive inertial sensors to measure the rotation rate of the Earth. The long term stability of the apparatus plays a crucial role for this experiment, and an underground location is advantageous from this point of view. GINGERINO is a single axis ring laser located inside the Gran Sasso laboratory. Gingerino has demonstrated that the very high thermal stability of the underground laboratory allows a continuous operation, sensitivity well below fractions of nrad/s, and with a duty cycle above 90% even in free running operation, without stabilisation of the scale factor of the ring laser.

1. Introduction

Ring Laser Gyroscopes (RL) are high sensitivity devices widely used to measure absolute rotation rates, exploiting the Sagnac effect. They are very reliable instruments, with extended bandwidth and very high duty cycle, extensively used for inertial navigation. The output signal of the RL is the beat note of the two counter-propagating modes, the frequency of the beat note is called the Sagnac frequency f_S :

$$f_s = \frac{4\pi A}{P\lambda}\vec{n} \cdot \vec{\Omega}_T \tag{1}$$

where $\vec{n}$ is the area versor of the ring cavity, A is the area of the ring cavity, P the perimeter and λ is the wavelength of the light; the scalar factor S of the instrument is defined as $S = \frac{4\pi A}{P\lambda}$, it is purely geometrical; $\vec{\Omega}_T$ is the angular rotation which affects the RL cavity. If the RL is attached to the Earth crust, $\vec{\Omega}_T$ is the sum of the angular rotation of the Earth $\vec{\Omega}_\oplus$, local disturbances generated by human activity and by geophysical origin $\vec{\Omega}_L$, and the GR corrections which are seen locally as angular rotation vectors $\vec{\Omega}_{GR}$. The reader can find an extensive demonstration in literature [1, 2]. The GR terms are DC quantities and they lie in the meridian plane. The main terms are the geodetic and the gravito-magnetic ones. The geodetic one has been tested at a level better than 0.1%, at the latitude of 45^o it has an amplitude of about 10^{-13} rad/s, while the gravitomagnetic term, the LenseThirring (LT), is of the order of 10^{-14}rad/s. The two GR terms can be evaluated by comparing the measured modulus of Ω_T with the angular rotation rate measured by the international system IERS, which measures the cinematic Earth rotation rate by looking at a fixed star. The most sensitive RL is the Gross Ring G of the geodetic observatory of Wettzell, a square RL with perimeter 16m; it has demonstrated that RL noise level can achieve the limit of the shot noise of the light, and it has reached the sensitivity of 10^{-13} rad/s in one day of integration time, showing that the GR test is in principle feasible with larger RL and an increase in the long term stability of the apparatus in order to improve the integration time. Actually, the shot noise level in a RL decreases with the square of the side of the ring. The purpose of GINGER (Gyroscopes IN GEneral Relativity) is to measure the GR components of the gravitational field of the Earth at 1%, using an array of ring-lasers [1, 3]. So far the gravito-magnetic field of the Earth has been measured in space with an error at the level of$\sim$ 5% [4], and [5, 6], so the experimental objective of measuring the Lense-Thirring angular velocity Ω_{LT} with 1% is still challenging. GINGER would provide *the first measurement* of a GR 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.

GR is extremely predictive, allowing to compute the orientation and the amplitude of the LT term, that depends on the latitude of the observer. Note also that alternative theories of gravitation predict different dependences on latitude. Fig. 1 shows the mutual orientation of the various vectors for an assumed location of $\simeq 45^o$ latitude (as e.g. at the Gran Sasso laboratories (LNGS).

We have recently studied properties of an array composed of two RL [3], one oriented at the maximum signal and the other horizontal, providing all the specifications required in order to reach the 1% goal for the LenseThirring test. The RL at the maximum signal provides an excellent measurement of the modulus of the total rotation rate, while the combination with the horizontal one provides redundancy of measurements and a good measurement of the polar motion. In the following we discuss the connection with geophysics and our underground prototype GINGERINO.

2. Earth science and GINGERINO

The Earth is a solid body, as a consequence each perturbation produces translations and rotations. Adding rotational sensors to standard seismological devices, usually linear seismometers, gives the possibility to reconstruct the direction of propagation of the seismic waves and their phase velocity. Any tectonic motions are rotation with respect to the center of the Earth. In principle this could be an independent way to measure tectonic plate motions. RL is valuable for geodesy since it can monitor polar motion and the Earth rotation rate changes with high rate. Presently, it is considered the only instrument which can provide accurate measurements of the orientation change of the Earth axis in the time scale of the length of the day (LOD). The detectability of such signals depends on the sensitivity and the bandwidth of

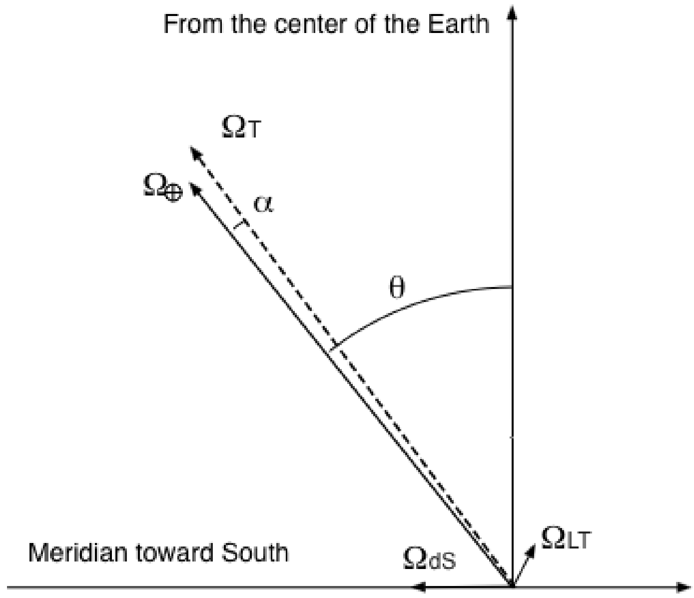

Figure 1. The three axial vectors $\vec{\Omega}_\oplus$, $\vec{\Omega}_{LT}$, and $\vec{\Omega}_{dS}$ are shown, with the relative orientation at the latitude of the underground laboratory of Gran Sasso (LNGS), following General Relativity. The 3 vectors lie in the meridian plane. The angle α and Ω_T (dashed line) are shown as well. The graph is not to scale, it gives a pictorial view of the relative orientations of the different components, in reality the modulus of $\vec{\Omega}_\oplus$ is 9 orders of magnitude bigger than the GR terms, and the angle α is $\sim 10^{-9}$ rad.

the instrument. Most of these signals are low frequency ones, from a few Hz below days and even longer. In principle, the RL has not a low frequency limitation in the bandwidth, limitation comes more on how the apparatus is deployed and on the reconstruction of the signal from the array. This is not a secondary point since most measurements require more devices, we deal with vectors so 3 components are required, and small errors in the relative orientation of different RL can limit the final sensitivity of the apparatus.
GINGERINO is shown in Fig. 2 . It is located inside the deep underground INFN laboratory of the Gran Sasso (LNGS) [7]; its aim was to characterise the underground rotational seismic disturbances. It was installed at the end of 2014, and the data taking started in spring 2015. Despite the fact that this device is an *R&D* prototype it is perfectly able to run continuously for months without any control of the cavity shape, thanks to the very quiet and thermally stable environment of LNGS, see Fig. 3. The low frequency part of the signal is affected by backscatter noise, due to the mixing between laser beams propagating in the two directions, this kind of disturbance can be off-line subtracted, Fig. 4 shows the typical residual angular rotation rate after backscattering subtraction [8]. At present, the typical resolution is $\sim 5 - 10$ prad/ for 1 hour of integration time. This corresponds to a precision better than 1 ppm on the Earth rotation rate. GINGERINO was 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), and a portion of the Marche-Abruzzo $2016 - 17$ Earthquake swarm. [9, 10, 11]. A standard seismometers station was also installed near by GINGERINO by the Italian National Institute of Geophysics and Vulcanology (INGV). This allows us to perform

comparative analyses of rotations and translations and to have an insight on the surface wave propagation dispersion function.

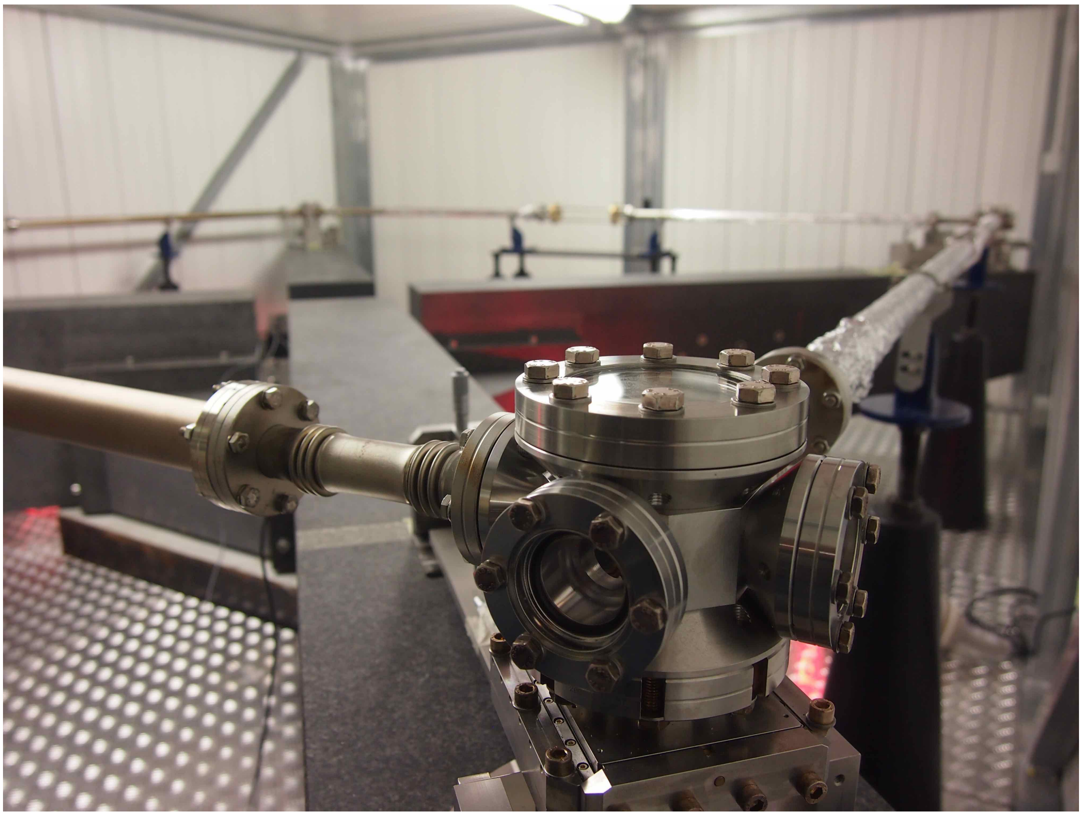

Figure 2. GINGERINO installed inside the underground laboratory of LNGS. It is a square ring-laser with side 3.6 m. It is based on the RL prototype called geosensor composed of 4 small vacuum tanks where the mirrors are installed and connected by vacuum tubes. The whole mechanics is in steel and supported by a granite monument attached to the bed rock in the center by a reinforced concrete block.

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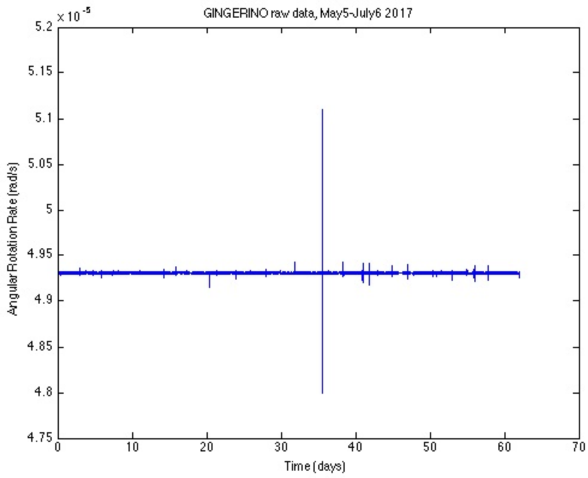

Figure 3. Typical raw data of GINGERINO, the Pizzoli Earthquake, M3.8, is visible, the DC level is compatible with the Earth rotation rate projected by a RL horizontally oriented at the latitude of Gran Sasso.

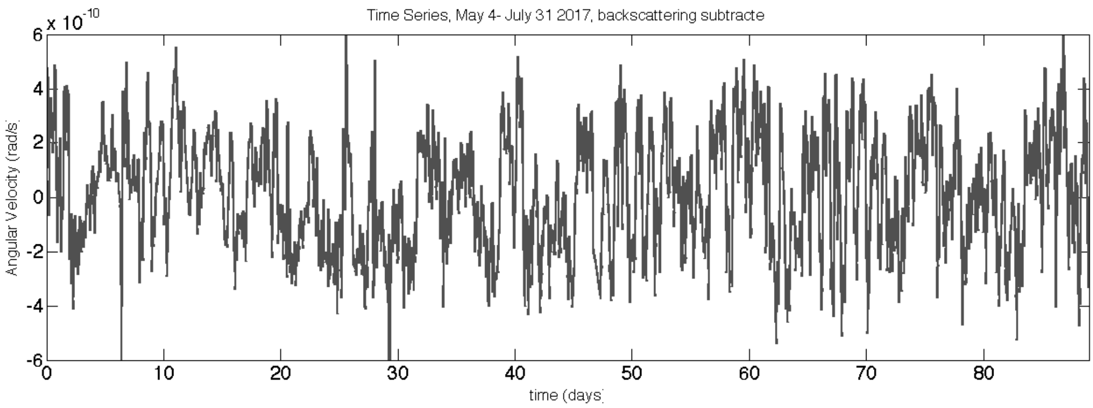

Figure 4. Backscattering noise limits the performance of RL, it can be reduced by improving the quality of the mirrors and can be to some extent reduced by off-line analysis. This picture shows typical residual angular rotation rate after the subtraction of the backscattering noise.

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