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Ring laser gyroscopes in the underground Gran Sasso Laboratories

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Abstract. **Gyroscopes IN GEneral Relativity (GINGER) is a proposed experiment with the aim of measuring the gravito-electric (known also as De Sitter effect) and gravito-magnetic effects (or Lense–Thirrings effect) in a ground laboratory, foreseen by general relativity, through an array of large dimension ring laser gyroscopes. The site is located inside the Gran Sasso laboratories (LNGS) of INFN, under more than one thousand meter underground, well protected from surface perturbations. GINGERINO is a square ring-laser prototype with 3.6 m side, which has been built to investigate the level of noise of this site. GINGERINO has already completed its task, showing the advantage of the underground location. It cannot reach the sensitivity suitable for the fundamental physics measurements, but it can provide important data for geophysics and seismology. Its high sensitivity in the frequency band of fraction of Hz and its location in a seismically active area make it suitable for seismology studies. It recorded a sequence of central Italy earthquakes in the autumn of 2016 and many other events both from near field and from far field. The analysis of 90 days of continuous operation shows that its duty cycle is higher than 95%, with a quantum shot noise limit of the order of 10^{-10} rad s^{-1} $Hz^{-1/2}$.**

Keywords: *laser gyroscope, Sagnac effect, Lense–Thirring effect, length of the day, polar motion, rotational seismology.*

1. Introduction

George Sagnac [1] showed in 1913 that light travelling along a closed-ring path in opposite directions allows one to measure the rotational speed of the ring structure with respect to an inertial frame. A few years later Michelson [2] was able to measure the Earth rotation rate with a very large interferometer some hundred metres in size.

The effect was easily explained by a classical model. Let a polygonal ring interferometer of area A (as defined by the mirrors steering the two counterpropagating beams) rotate at an angular frequency Ω in an inertial frame. Due to the cavity rotation, the beam propagating in the rotation direction will spend more time to complete the optical path; the opposite will happen to the other beam. This occurrence produces a phase difference, $\Delta\phi = 8\pi\Omega A\cos\theta/\lambda c$, where λ is the radiation wavelength, c the speed of light, and θ is the angle between the rotation axis and the optical path axis. George Sagnac thought that this result disproved the theory of relativity, but it is not true! A rigorous approach made in the frame of the theory of general relativity confirms the result [3].

The invention of a laser provided the coherent radiation source suitable for applications. Moreover, it is possible to modify the operation scheme by inserting the laser active medium inside the ring optical cavity. In this configuration, the difference in the optical length of the round trip in the two directions is translated to a difference in the frequencies of the laser emission, which can be measured by combining the two beams on a photodetector. The beat note, named Sagnac frequency, is then linearly related to the value of Ω by $f_{\mathrm{Sagnac}} = 4\Omega A\cos\theta/\lambda p$, where p is the ring optical path [3].

First demonstration of ring laser gyroscopes based on the Sagnac effect was already reported in 1963 [4]. This was the beginning of a strong technological effort. Since an optical gyroscope has no moving mechanical part or massive test masses, in principles it is completely insensitive to translational motion or to the gravity field. It was then the ideal solution for inertial navigation.

Commercial ring laser gyroscopes (RLGs) are usually single longitudinal mode He–Ne lasers operated at a wavelength of 632.8 nm in aircraft navigation applications. The laser gyroscopes used for inertial navigation usually have an area of < 0.02 m^2 corresponding to a perimeter of 30 cm or less. Best sensitivity is around 5×10^{-7} rad s^{-1} $Hz^{1/2}$ with a long term drift as low as 0.0001deg h^{-1} (~ 0.5 nrad s^{-1}). A set of three mutually orthogonal rings provides the full 3-dimensional rotational information. This is good for navigation, but not enough for other applications in geodesy, in seismology, and, more generally, in Earth Sciences.

A problem of a laser-gyro is the phenomenon of mode lock-in between the counterpropagating beams, due to the backscattering on all the intracavity optical surfaces that couples the two beams. As indicated by the equation of the coupled oscillators, this makes that, at low values of Ω, eventually the two oscillation frequencies are locked together. This dead zone is typically much wider than the potential sensitivity of the device. The problem was solved in some way by a mechanical dithering that makes the gyro vibrate.

Starting with the last years of the 20th century, thanks to the great improvement in mirror manufacturing, it was possible to build large frame ring lasers. Since sensitivity increases linearly with dimension and backscattering reduces as the fourth power of it [3], by using mirrors with reflectivity of the

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order of 99.999 % with optical laser resonators larger than 0.5 m^2, the Earth rotation rate is large enough to unlock the frequencies of the two counterpropagating beams. The state of the art record of precision is achieved by the ‘Gross’ ring (G) in Wettzell (Germany), a square ring laser of 4 m side build on a monolithic block of Zerodur, so that the geometry stability of the ring is obtained in purely passive way. Its precision is better than some fractions of prad s^{-1} [5].

To improve sensitivity, it is necessary to increase the ring dimension. However, it is not possible to scale at larger dimensions the design of G. Moreover, a single gyroscope will measure only one component of the rotation velocity vector. At least three rings with different orientations are necessary to obtain the full information.

2. GINGER proposal: general relativity test and geodetic applications

A proposal for the construction of an array of RLGs with a sensitivity large enough to observe the effects expected by general relativity in a terrestrial laboratory, has been presented in 2012 [6] and updated in 2017 [7], named with the acronym GINGER (Gyroscopes IN General Relativity). It foresees to locate the array inside the INFN Gran Sasso National Laboratories (LNGS), one thousand metre underground, far from surface perturbations.

The general relativity effects are related to the deformation of the local metric due to the Earth gravitational field (De Sitter or geo-electric effect) and to the Earth angular momentum (Lense–Thirring or geo-magnetic effect). Their observation requires an instrumental accuracy better than 10^{-14} rad s^{-1}. A level of accuracy better than a few 10^{-14} rad s^{-1} offers also the possibility of measuring fundamental geodetic parameters related to the Earth rotation (the so-called length of the day and polar motion), giving information on the correlation between the co-rotating Earth centred reference system and the Cosmic inertial one. This information could integrate the data of the length of the day (LOD), produced from the International Earth Rotation Service (IERS) by fitting through a complex elaboration the Very Large Baseline Interferometry (VLBI) observations of the signals that arrive from the billions light-years far quasars. It is worth noting that the VLBI gives a very accurate measure of the sidereal day, but cannot produces sub-daily information on the Earth rotation rate, which instead can be obtained by the RLG. The RLG data might then integrate usefully VLBI. We note that the present sensitivity level of G is not so far from the required one. Indeed, it has been demonstrated in [8] that, also in the present situation, the integration of data of G reduces, in some cases, the error of the fit.

A complete information about the rotation rate (length of the day) and rotation axis orientation (polar motion and Earth tides) requires a tri-axial array of RLGs. The difference between the Earth rotational rate as measured by VLBI (in the inertial cosmic frame) and by RLGs (in the Earth centred co-rotating frame) will give the opportunity of evaluating the relativistic contributions [9]. Following the proposal [7] a first RL will be oriented parallel to the Earth rotation axis, i. e. with $\theta = 0$ so that the Sagnac frequency is at a maximum. In this way, an error in orientation does not affect at the first order the accuracy in the rotation rate value, giving the opportunity of achieving a relative accuracy of the order 10^{-10} with an accuracy in orientation of the order of ~10 mrad. The other two rings will be oriented in horizontal and vertical plane to simplify the metrology for measuring the relative angle between the RLGs. This two RLGs will measure the evolution of the Earth axis orientation with respect to the celestial inertial frame, giving the value of the components of the Polar Motion and the local contribution of the Earth tides in the N-S and in the E-W directions. We highlight that the information on daily evolution of polar motion is of paramount interest in geodesy, since it cannot be obtained through VLBI.

3. Gingerino and seismological applications

A first step in this direction was the installation in LNGS of Gingerino, a test ring 3.6 m in side that has been installed in order to validate the Gran Sasso site from the point of view of the seismic noise. A detailed presentation of the apparatus and of the co-located seismological station is given in [10]. This apparatus, however, for its sensitivity and for its location near an active seismic region, proved itself to be a powerful instrument for seismology.

In seismology, translation and strain are routinely observed by inertial seismometer and by strain metres. 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 observables at different sites allow one to estimate the local underground velocity structure, which is of high interest in geophysical studies. Rotational signals induced by seismic waves have quite a 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^{-1}, while micro-seismic rotational background noise (around 0.1 Hz) is expected to be smaller than 10^{-10} rad s^{-1}. Large frame RLGs have demonstrated an unrivalled sensitivity level. Impressive data were collected on G, but also Gingerino showed very interesting results. Gingerino is in the furthest part of the cave and shows an excellent long-term stability, even without active stabilisation, due to the thermal stability of the environment. A high-sensitivity bi-axial tiltmetre and a broad band seismometer are positioned on its frame. It demonstrated a remarkable reliability, by taking data continuously for almost 100 days in 2017 completely unattended, with a duty factor better than 90 % and a relative stability better than 10^{-6} over one day [11]. Improvements of the apparatus are in progress. A new set of mirrors with better performance has been recently installed, and the analysis procedure has been improved integrating our previous work on

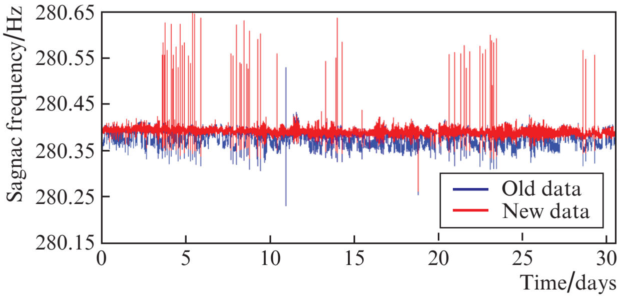

Figure 1. Comparison between the old and the new data analysis over 30 days. The record starts on 16 May 2018 at 0.00.00 UTC. The measured Sagnac frequency, compared with the value expected for a RLG lying on a horizontal plane at the latitude of Gran Sasso Laboratories (42° 25′), is consistent with a Gingerino inclination of the order of 1.5 mrad in the North direction.

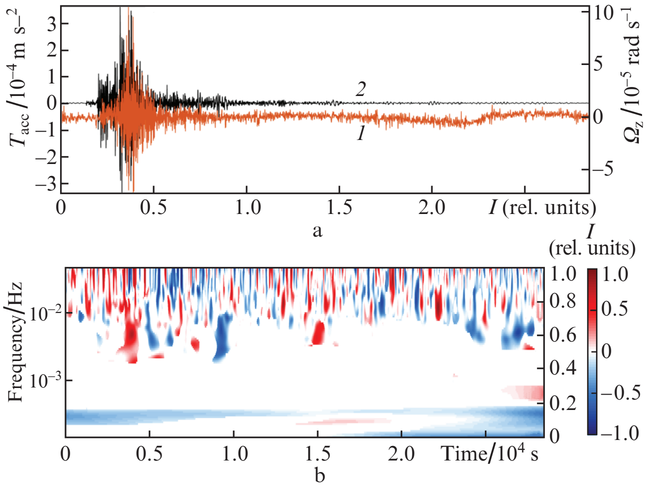

Figure 2. Love waves trains observed after the MW 8.1 Tehuantepec earthquake by Gingerino and by a collocated broadband seismometer: (a) superposition of vertical rotation rate Ω_z (*1*) and transverse acceleration T_{acc} (*2*) according to the theoretical back-azimuth ThBAZ = 305.0°; (b) wavelet coherence of the above signals showing the onsets of the G1,G2 and G3 Love wave trains.

Kalman filter technique [12] by using an analytic approach. Figure 1 compares the new procedure [13] with the old one. Besides the reduction of the noise amplitude, it is worth noting the shift upwards of the Sagnac frequency, in agreement with the expected value. This demonstrates the effectiveness of the procedure in correcting the frequency pulling due to the backscattering of the laser radiation on the cavity mirrors [3].

The present performance is well suited for seismological observation. In the autumn of 2016 Gingerino detected the Central Italy seismic sequence, as described in detail in [14], giving useful information about local seismic wave velocity profiles and providing the definition of the back-azimuth of the waves. This represented the first rotational observation and analysis of earthquakes in near field through RLGs.

Observations at a tele seismic distance are common for the Gingerino. At the present status of sensitivity we can detect any earthquake with magnitude below 7 occurring at depths lower than 20 km. The strongest recorded event during the instrument history is the magnitude MW 8.1 one that occurred in Tehuantepec (Mexico) on 8 September 2017.

It is common practice in rotational seismology to assume, for large and distant events, the plane wave approximation for the propagation of the generated seismic waves. Under this assumption and for our setup (observations of rotation rate around a vertical axis) we can directly compare the surface Love waves arrivals as recorded by a rotational sensor and a broadband seismometer in order to extract the direction of the wavefield and the phase velocity of Love waves at the observation site. Longer period surface waves ($T > 50$ s) are excited by large and shallow events that are not so frequent; for this reason, the event is so important for our seismological studies.

Analysing these large events, as already observed by [15] in a similar setup (the G-ring in Wettzell), it is possible to observe the Love wave trains that propagate on the Earth surface along the great circle that connects epicentre to station. In our case we make use of wavelet coherence to highlight (Fig. 2) a region of high coherence in the expected period range (120–280 s), corresponding to the expected onsets of

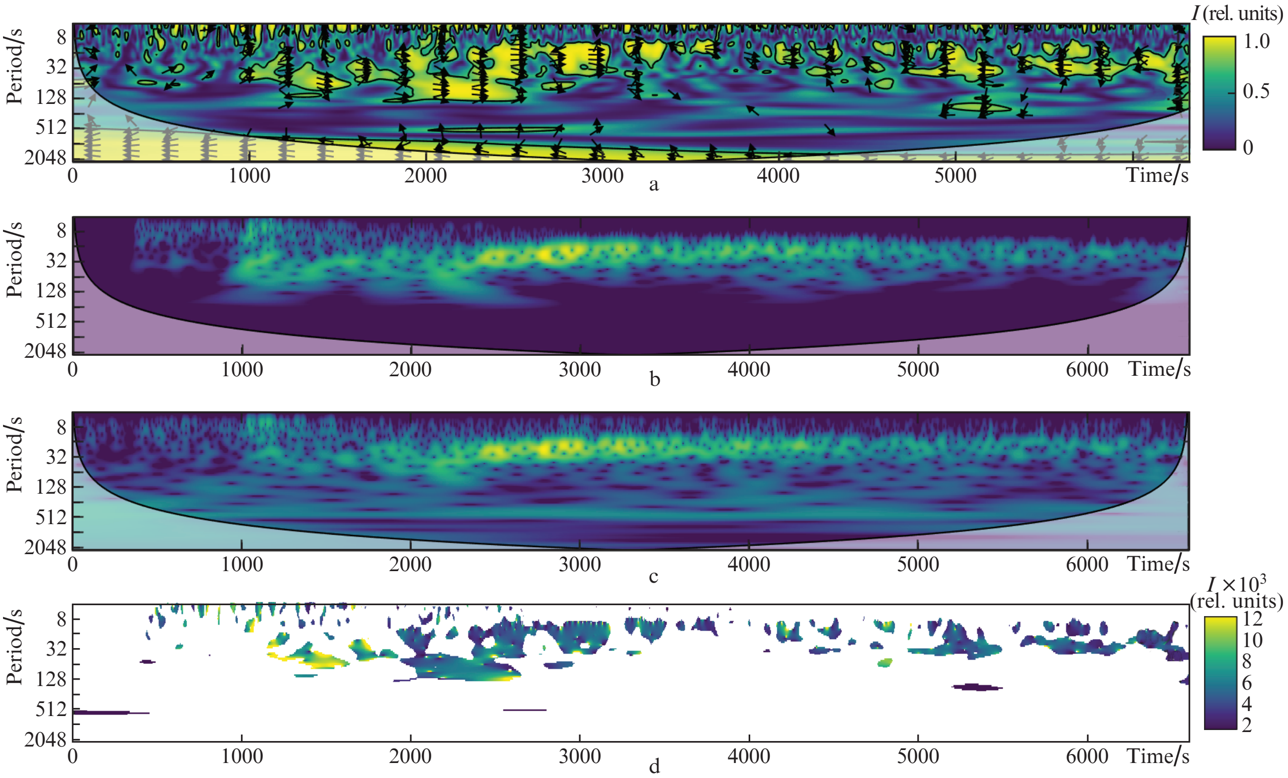

Figure 3. Time-frequency analysis of signals shown in Fig. 2: (a) relative phase of the two signals; (b) wavelet power spectrum of transverse acceleration; (c) wavelet power spectrum of rotational signal; and (d) phase velocity map.

the G1, G2 and G3 Love waves trains (that is the time of arrival of the direct wave, of the wave that is arriving travelling along the great circle in the opposite direction, and again of the direct wave after a complete turn around the globe). We remark that this is the first time after the work in [15] that similar observations are reported in seismology.

With the assumption of the great circle propagation for the surface waves, we orient the horizontal traces of the seismometer according to the radial/transverse reference system, so defining the transverse acceleration component. For this study, after [16] we use the wavelet decomposition of the two signals. In this approach the amplitude ratios of the coherent parts of the two signals give a time-frequency dependent phase velocity estimation that we report in Fig. 3. From the top of Fig. 3 we show the superposition of the acceleration/rotation rate signals, the phase relation map that we use as a phase mask to select the area where the phase velocity estimation is meaningful, the two wavelet power spectra and finally a phase velocity map where the velocity is mapped in colours as reported in the colour map, the measured values are consistent with the expected ones from the global velocity models e.g. PREM [17].

4. Conclusions

The Gran Sasso site has been validated for the installation of an array of large frame RLGs for general relativity test and geodetical applications. The apparatus has demonstrated an impressive reliability, working unattended continuously for many months. The implementation of new mirrors with better quality and a new analytical processing of the data have improved the long term stability and accuracy of the apparatus. Moreover, the observation of seismic events, both related to local earthquakes and to strong teleseisms, hase allowed one to obtain important seismological information.

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