The observation with high accuracy of the rotational motion of Earth crust motion is of large interest in different fields of scientific research. Rotation and angle measurements are of great importance for different fields of scientific research: the General Relativity provides terms of rotation originated from the kinetic term, Earth science studies the earth’s angular velocity and all its variations, tides and all its perturbations, the normal modes of Earth, the angular perturbations associated with the movement of the plates, the deformations of a hydrological, volcanic nature or connected to anthropic activities, without neglecting the rotational signals produced by the earthquakes that bring relevant information complementary to the classical linear seismology. In particular, the measure of low frequency rotation components has a very large potential in applied geophysics and risk evaluation for monitoring the movements of the fluids in the underground and the soil subsidence, due to industrial activity, like natural gas extraction and stocking in geological reservoirs, geothermic fields cultivation or the proposed methods of geological trapping of CO₂.

Only recently this kind of measurements are becoming available. In the past, direct measurement of seismic rotations has been ignored for a long time because rotational effects were
thought to be too small for the existing instrumentation. However, in the last decades large frame ring laser gyroscopes (RLG) have demonstrated the capability of sensing the rotational ground motion with a very high resolution. This has open new perspectives in seismology, since the simultaneous observations of ground rotations and translations can improve the interpretation of the seismic data, by the correction of the tilting systematic errors of the traditional seismic sensors and by allowing tomographic reconstruction of the seismic velocity profile beneath the observation site (Bernauer et al., 2009).

A RLG exploits the Sagnac effect: if a ring laser, operating in a single mode, rotates with respect to an inertial reference system, the radiation beam traveling in the rotation direction sees a round-trip path longer than the counter-propagating one. As a consequence, the stationary frequencies of the radiation emitted in the two directions differ by a quantity, called Sagnac frequency, that can be directly measured by beating the two radiation beams on a photodiode. The Sagnac frequency $f_{\text{Sagnac}}$ is related to the rotational speed $\Omega$ by a simple geometric factor:

$$f_{\text{Sagnac}} = \frac{4 A \Omega}{\lambda p} \sin \theta$$

where $p$ is the length of the perimeter of the cavity, $A$ is the area included in it, $\lambda$ is the laser wavelength, and $\theta$ is the angle between the rotational axis and the normal to the RLG plane. The fact that the proportionality factor is purely geometrical is of paramount importance, since the geometry of the apparatus can be controlled.

Ring lasers have high resolution, excellent stability, high duty cycle and a wide dynamic range. Furthermore, no movable mechanical parts are required, so these sensors can be manufactured in a very robust way and with a very high rejection of linear kinematic or gravitational accelerations. The best RLG operating at the moment is the Großring G, which is located in the Bayern geodetic observatory in Wettzell (Schreiber and Wells, 2013). It is a square ring laser with 4 m side, mounted on a monolithic structure made of Zerodur (a glass with practically null expansion coefficient). G has achieved a resolution near to the quantum noise limit, in about $10^4$ s of measurement time, reaching an optimal sensitivity better than $10^{-13}$ rad s$^{-1}$. Thanks to its sensitivity, it allowed the observation of terrestrial tides, of polar motion, of Earth free oscillation modes, of rotational microseismic noise, and the evaluation of the length-of-the-day competitive with VLBI. At longer times, G is limited by random walk noise, but its stability is anyway good enough to carefully estimate the long-term fluctuation of the orientation of the rotation axis of the Earth (the Chandler wobble).

Our group in Italy is active in this field since almost 10 years. Our main purpose is to push the sensitivity of such apparatus in order to test the Lense-Thirring effect foreseen by General Relativity at the level of 1% with and Earth based experiment. Since 2010 a RLG apparatus, called G-Pisa, with a square optical cavity of side 1.35 m was installed near VIRGO gravitational antenna. During its operation, it detected many earthquake signals, among which the 2011 M$_{w}=9.0$ Sendai-Honshu earthquake (Belfi et al., 2011, 2012). Gingerino is an evolution of G-Pisa, with a side of 3.60 m that we have installed in the INFN underground GranSasso Laboratories (Belfi et al., 2017). This apparatus cannot compete with G as resolution, since it is based on a simple and cheap heterolithic structure done in steel and not in Zerodur, but it has however demonstrated a shot-noise limited sensitivity in the range of $10^{-10}$ rad/s at 100 s. The noise power spectrum of the apparatus is shown in Fig.1. Mirror quality limits at present the performances of the instrument. This RLG is presently flanked by a long-period seismometer installed by INGV that is inserted in the national seismic network. It is operative since the beginning of 2016, and in this period it has observed many seismic events, included many regional earthquakes of the recent Umbria seismic swarm. A detailed analysis of the data related to these events is the object of another communication in this GNGTS meeting, by A. Simonelli. At the present days, Gingerino is operative completely unattended from the beginning of May 2017. The underground location provides a rather high natural thermal stability, and reduced impact of weather condi-
tions and anthropic disturbances. At present, it exhibits a very high duty cycle (>95%). Fig. 2 shows the record of two months. The spikes in the record correspond to earthquake events. The analysis of later data is in progress.

Both laser cavities of G and Gingerino lie in the horizontal plane and measure rotation around the vertical axis. To fully exploit rotational information, it is however necessary to reconstruct the full 3-dimensional angular velocity vector. Indeed, a single RLG cannot distinguish between a rotational speed (changing $\Omega$) around its axis and an angular tilt of the axis (changing $\dot{\theta}$). ROMY, a large tridimensional array of four triangular RLG built near Munich for seismic study thanks to an ERC grant, is presently in commissioning. It is expected to achieve a very high sensitivity in the bandwidth up to a few hundred seconds useful for seismic application.

In setting up a RLG array it is necessary to carefully consider several requirements, for example it should be noted that a RLG needs to work properly of a bias rotation that is given by Earth. Then, not every RLG axis orientations are suitable; in particular the orientation near orthogonal to Earth axis are forbidden.

Exploiting the expertise that we have gained by the operation of Gingerino and of the other RLG GP-2 that is operating in the INFN Pisa laboratories, we have now developing the project for the construction of a new RLG array (Di Virgilio et al., 2017). This array will include a RLG oriented with its axis parallel to the Earth rotational axis, a second one lying on the horizontal plane, a third one with the axis outside the meridian plane. A part the orientation, the RLG should have identical geometry. A fourth RLG could be added to increase by redundancy the accuracy. The target is to allow a very precise identification of the direction of the signals, using a new design much more cost effective, achieving a noise equivalent level beneath $10^{-11}$ rad/s/$\sqrt{\text{Hz}}$ up to 1 day of integration time and extending the observation to three dimensions. The very large bandwidth of the sensitivity, extended from acoustic frequencies down virtually to the DC, can produce information on a lot of phenomenologies. The comparison of the data produced by the existing RLG is Europe (the G ring of Wettzell and the array ROMY, 4 RLG) will provide unique information of geophysics and geodesy.

The array we are studying and proposing will give also important geodetic information. The first RLG, oriented parallel to the Earth rotational axis, will directly test the Earth rotation rate $\Omega_T$. In this configuration in (1) is $\dot{\theta}$=0 and the Sagnac frequency is at its maximum value. Then, possible slight misalignment will affect the accuracy of $\Omega_T$ only at the second order, and an accuracy better of 1 ppb can be achieve by controlling the orientation at $3 \times 10^{-5}$ rad. Such an accuracy on $\Omega_T$ value results competitive with the present measurements of the length of the day (LOD), which is made through VLBI (Very Large Baseline

![PSD May-June 2017, GINGERINO, backscattering subtracted](image1)

**Fig. 1 - Noise power spectrum of Gingerino.**

![PSD May-June 2017, GINGERINO, backscattering subtracted](image2)

**Fig. 2 - Record of two months of the Sagnac frequency of Gingerino, from 2017 May 4th, up to June 6th. The spikes in the record correspond to earthquake events. The biggest one is the Mw 3.8 Pizzoli (AQ) earthquake on June 9th.**
Interferometry) and GPS satellite constellation, and requires very complex modelling and provides data with delay of some days. The comparison with RLG and VLBI data will validate RLG operation. A unique feature of the RLG array will be to provide almost immediately available the direct information on sub-daily fluctuation of Earth rotation rate, at the same time the array will provide information of the variation of the rotational axis. VLBI makes its observation in the cosmic inertial reference system, while RLG measure the rotation rate in the local co-rotating reference system. Following General Relativity theory, this introduces a slight difference between the two measurements that we intend to put in evidence at a level of accuracy around some 0.1 ppb. A RLG oriented at the maximum Sagnac signal is not sensitive to the angular fluctuation of the terrestrial axis orientation (polar motion). this information can be obtained by the other RLG of the array.

References:
Schreiber K.U., and Wells J-P. R.; Large ring lasers for rotation sensing; 2013: Rev. Sci. Instrum. 84, 041101