

A laser gyroscope system to detect the gravito-magnetic effect on Earth

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Abstract. Ring lasers are inertial sensors for angular velocity based on the Sagnac effect. In recent years they have reached a very high sensitivity and accuracy; the best performing one, the ring Laser G in Wettzell (Germany), a square ring with 16 m perimeter, has reached a sensitivity of $12 \text{ prad/s}/\sqrt{\text{Hz}}$, very close to the shot noise limit inferred from ring-down time measurements. On this basis it is expected that an array of six square ring lasers of 36 m perimeter, can perform a 1% accuracy test for the measurement of the Lense-Thirring frame dragging after 2 years of integration time. Essential for this measurement is the comparison between the Earth angular velocity and orientation in space measured with the ring array and compared to the measurement series maintained by the International Earth Rotation and Reference System Service (IERS), which measures Earth Rotation and pole position with respect to remote quasars. It has been shown that the accuracy of G in Wettzell is limited by the low frequency motion of the near surface laboratory, which is of the order of several prad/s , roughly 100 times larger than the Lense-Thirring contribution. For this reason the entire experiment should be placed in a quite underground laboratory, where these perturbations are reduced. The feasibility to properly place such a device inside the GranSasso INFN National Laboratory has been investigated.

Ring lasers are very sensitive and accurate sensors of angular velocity. The ring laser equation [1] relates the frequency splitting δf of the two optical beams inside the ring interferometer with the experienced rotation rate Ω by the cavity and the orientation of gyroscope

$$\delta f = \frac{4A}{\lambda P} \mathbf{u}_n \cdot \Omega, \quad (1)$$

where A is the area of the ring, P is the perimeter, λ the laser wavelength and \mathbf{u}_n is the normal vector on the ring laser plane. The response R of a ring laser to the rotation rate Ω , in units of

rad/sec, is simply a rescaling of the frequency splitting by the scale factor $S \equiv \frac{4A}{\lambda P}$, i.e.

$$R \equiv \delta f / S = \mathbf{u}_n \cdot \mathbf{\Omega}. \quad (2)$$

General Relativity predicts that the stationary field of a rotating body is different from the static field produced by the same non-rotating mass. The difference is known as gravito-magnetism and consists of a drag of space-time due to the mass currents. The rotational frame-dragging effect is also known as the Lense-Thirring (LT) [2, 3, 4, 5] effect; the amplitude of this effect is function of the colatitude and orientation of the rings, at our latitude its value is of the order of few 10^{-14} rad/s. In the past, several authors have shown that ring lasers can be used to measure the Frame Dragging (Lense-Thirring effect or gravito-magnetic, GM) of the Earth [1, 6, 7].

The ring laser G in Wettzell (Germany) has shown that a sensitivity of $12 \frac{nrad}{s\sqrt{Hz}}$ can be achieved routinely [8, 9]; Fig. 2 shows the typical Allan deviation of G, some relevant geophysical signal are also identified in the same picture; Fig. 2 indicates that the best precision is obtained integrating the signal for several hours, while for longer integration times the sensor resolution degrades. This is mostly due to external disturbances, such as atmospheric loading effects, diurnal and seasonal temperature variations, wind effects and hydrologic variations causing interactions with the rock and soil beneath the ring laser monument. G is located at a depth of 4 m below the original terrain level. A proper underground location should substantially reduce ambient effects and hence allow for much longer unperturbed integration times. Figure 1 shows the east component of three different tiltmeters installed i) on a gravimeter pillar near the soil surface, ii) in 6 m depth, and iii) in 30 m depth. While the tiltmeter in 30 m depths clearly shows the periodic signal of the solid earth tides only, the tilt record of the instruments near to the surface is dominated by large non-periodic signals of hydrological, thermoelastic and barometric origin. Several investigations have shown that the site and the installation depths of tiltmeters has a major impact on environmental noise mainly caused by hydrology. It has been shown [10] that even in 100 m depths effects caused by hydrological changes are still detectable, but strongly reduced in comparison to a 50 m deep installation.

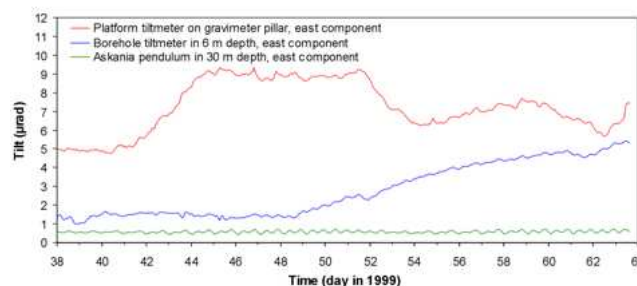


Figure 1. Measurement of local tilts as a function of depth in the Earth.

Recently this experimental problem has been addressed with more details, and the general scheme of an Earth experiment based on the most recent results on this field has been outlined [11, 12]. The Earth angular velocity is a vector, and as can be seen from eq. 1 each ring gives the projection of the velocity vector in its plane, accordingly 3 ring lasers, oriented along independent axis, are the minimum necessary for the fully reconstruction of the Earth angular velocity vector. An installation of 6 rings is necessary in order to have an independent cross-check on the performance (bias) of the ring lasers themselves and to

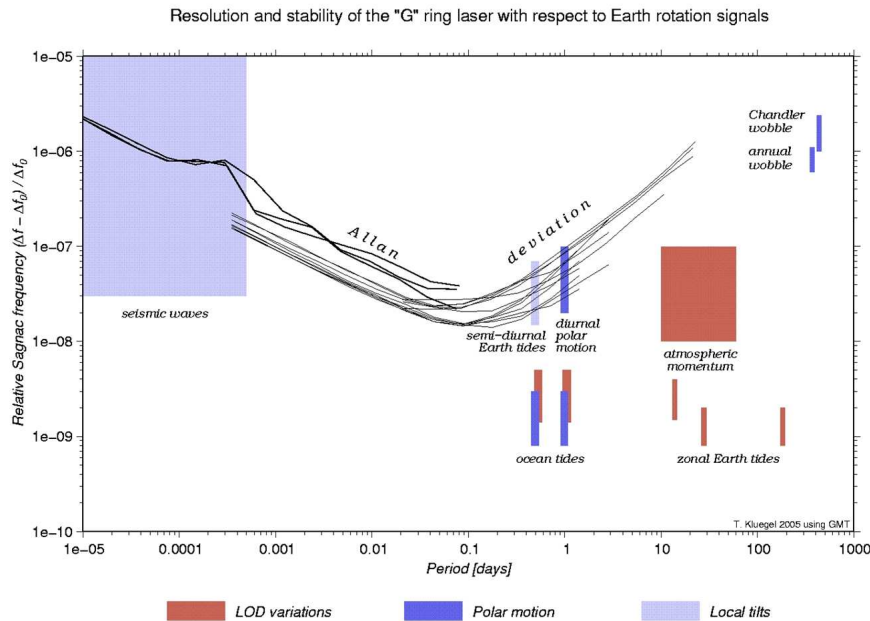


Figure 2. Resolution and stability of G, compared with Earth signals.

improve the signal to noise ratio. Strictly speaking, the ring-laser array measures the Earth rotation, the orientation of the Earth plus the Lense-Thirring effect, while the Very Long Baseline Interferometry (VLBI) measurements as maintained by the IERS provide Earth rotation and orientation only (<http://ivscc.gsfc.nasa.gov/>). Essential for our test is the comparison with the measurements of the VLBI quantities (length of day, and polar motion) provided by the IERS [13]. Considering that at our latitude, 45° degrees, the Lense-Thirring effect is 9 orders of magnitudes below the Earth rotation itself, the required accuracy in the measurement of ring laser arrays must be about 1 part in 10^{10} , in order to cancel out the Earth rotation component from the data produced by the ring lasers array.

The six rings can be arranged in different ways; the arrangement following octahedrons has several advantages; the six rings can be arranged putting the mirrors in the vertices of two different and equal octahedron, constructed closed to each other, in order to keep as much as possible the whole apparatus compact; see Fig. 3. The advantage of the octahedron is that the relative angle between different rings is $\pi/2$ rad, and the whole geometry can be controlled measuring the three diagonals. The three diagonals of the octahedron can form longitudinal Fabry-Perot cavities, giving the possibility to monitor the relative orientation of the rings and the distances between mirrors. As mentioned before, the experiment ought to be located in an underground facility, therefore we have investigated whether the proposed array could be contained inside node B of LNGS, where the ceiling height reaches 8 m, Fig: 4 shows one way of placing the octahedron inside node B. This location is the preferable one, since it is the part of the laboratory, which is dedicated to geophysical studies and at the same time it is an area of reduced human activity.

It appears that a system of 6 ring-lasers, each ring with 36 m perimeter, will be able to allow

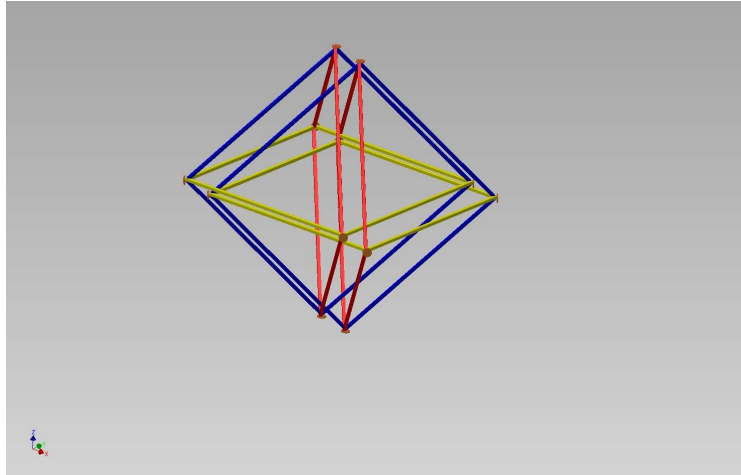


Figure 3. Six rings, two by two parallel, with mirrors on the vertices of two octahedron, constructed very close one to the other in order to reduce the dimension of the apparatus.

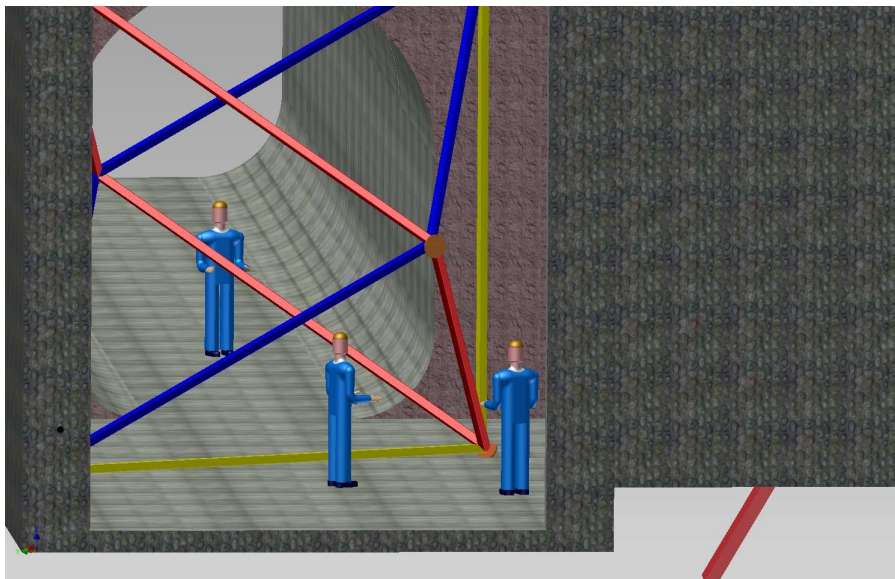


Figure 4. The ring laser system inside node B of LNGS, side view showing that passage between the two entrances.

the reconstruction of the Lense-Thirring effect with a precision of at least 10% in few months of data taking and 1% of accuracy seems feasible summing over a few years.

References

- [1] G.E. Stedman; *Rep. Prog. Phys.*, **60**, 615 (1997).
- [2] H. Thirring; *Phys. Z.*; **19** 204 (1918).
- [3] I. Ciufolini, E. Pavlis; *Nature*, **431** 958 (2004); I. Ciufolini et al; *Space Sci Rev*, **48** 71 (2009).
- [4] I. Ciufolini; *Class. Quant. Grav*, **17** 2369 (2000).
- [5] C.W.F. Everitt, et al; *Phys. Rev. Lett.*, **106** 221101 (2011).
- [6] G.E. Stedman, R.B. Hurst and K.U. Schreiber; *Optics Communications*, **279**, No. 1, 124 (2007).
- [7] M.O. Scully, M.S. Zubairy, M.P. Haugan; *Phys. Rev. A*, **24** 2009. (1981)

- [8] K. U. Schreiber, T. Klügel, J.-P. R. Wells, R. B. Hurst, and A. Gebauer; *Phys. Rev. Lett.*, **107** 173904 (2011)
Highlighted paper: <http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.107.173904>.
- [9] K.U. Schreiber, T. Klügel, A. Velikoseltsev, W. Schlüter, G.E. Stedman and J-P. R. Wells; *Pure and Applied Geophysics*, **166** 1485 (2009).
- [10] T. Jahr, G. Jentzsch, A. Weise; *Geodynamics*, **48** 126 (2009).
- [11] A.D. Di Virgilio, et al.; *International Journal of Modern Physics D*, **19** 2331 (2010).
- [12] F. Bosi et al.; *Phys. Rev. D*, **84** 122002 (2011).
- [13] Time series of the daily estimate of Earth rotation vector can be downloaded from
http://data.iers.org/products/176/11165/orig/eopc04_05.62now.