Measuring gravito-magnetic effects by multi ring-laser gyroscope

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The Design Study

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Measuring gravitomagnetic effects by a multi-ring-laser gyroscope

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We propose an underground experiment to detect the general relativistic effects due to the curvature of space-time around the Earth (de Sitter effect) and to the rotation of the planet (dragging of the inertial frames or Lense-Thirring effect). It is based on the comparison between the IERS value of the Earth rotation vector and corresponding measurements obtained by a triaxial laser detector of rotation. The proposed detector consists of six large ring lasers arranged along three orthogonal axes. In about two years of data taking, the 1% sensitivity required for the measurement of the Lense-Thirring drag can be reached with square rings of 6 m side, assuming a shot noise limited sensitivity (20 prad/s/$\sqrt{\text{Hz}}$). The multigyros system, composed of rings whose planes are perpendicular to one or the other of three orthogonal axes, can be built in several ways. Here, we consider cubic and octahedral structures. It is shown that the symmetries of the proposed configurations provide mathematical relations that can be used to ensure the long term stability of the apparatus.

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Basic Principles

- The Sagnac effect and the Ring-Laser
- Status of the art in short
- The LenseThirring effects and the proposed experimental set-up

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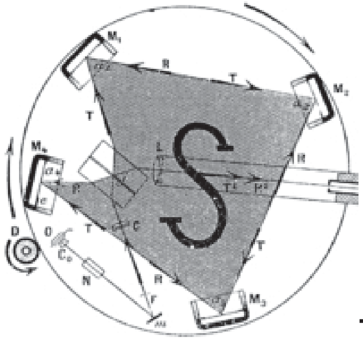
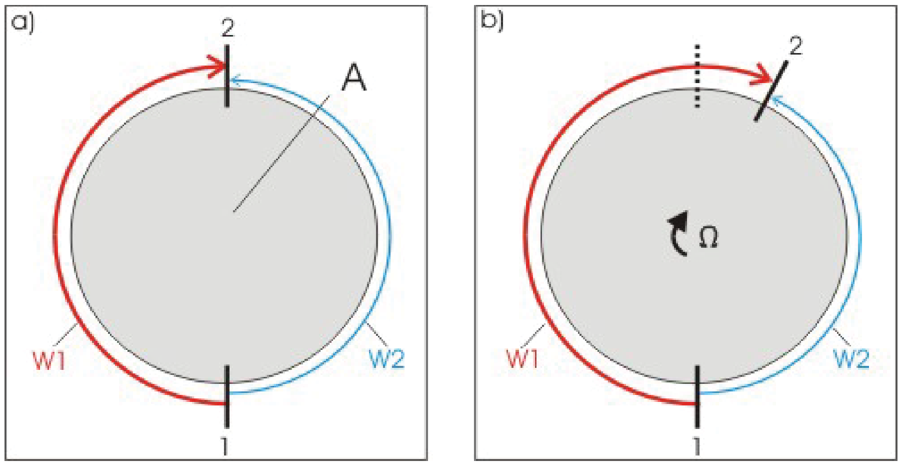
The Sagnac Effect



two beams conter-propagating inside a ring of radius R complete the path at different time if the ring is rotating with angular velocity Ω

$$\Delta t = \frac{4\pi R^2 \Omega}{c^2} \tag{1}$$



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Devices based on the Sagnac Effect

- fiber optics
- passive cavity
- active cavity (ring-laser, gyro-laser)

Several instruments have been developped for different purpose, in general inertial navigation (airplane, submarine...) and more recently for geophysics study.
Large frame RingLasers are the most powerful devices

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Our interest is in high sensitivity rinlaser, and its applications for General Relativity tests

in general, the light must follow:

$$g_{00}dt^2 + g_{rr}dr^2 + g_{\theta\theta}d\theta^2 + g_{\phi\phi}d\phi^2 + 2g_{0\phi}dtd\phi = 0$$

$$\delta T = T_+ - T_- \approx 2\oint \frac{g_{0\phi}}{g_{00}}d\phi \neq 0$$

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...and at first approximation

$$g_{0\phi} \cong (2\frac{j}{R} - R^2\frac{\omega}{c} - 2\mu R\frac{\Omega}{c})\sin^2\theta$$
$$g_{00} \cong 1 - 2\frac{\omega^2 R^2}{c^2}\sin^2\theta$$

where

$$\mu = G\frac{M_\oplus}{c^2} \approx 4.4 \times 10^{-3} m$$
$$j = G\frac{J_\oplus}{c^3} \approx 1.75 \times 10^{-2} m^2$$

Ω = angular velocity of ther Earth
ω = angular velocity of the instrument
θ = colatitude

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in a ring-laser the measured quantity is the beat note between the two laser modes

$f_b = \delta\nu/2 = \frac{c^2}{\lambda P}\delta T$

where P is the length of the path (Perimeter) for a ring laser attached to the earth

$\delta\nu = 4\frac{A}{\lambda P}[\Omega - 2\frac{\mu}{R}\sin\theta\hat{u}_\theta + \frac{GJ_\oplus}{c^2R^3}(2\cos(\theta)\hat{u}_r + \sin(\theta)\hat{u}_\theta)]$

- pure Sagnac term (Earth Angular Velocity)
- Geodetic (de Sitter)
- Gravitomagnetic Term (LenseThirring)

- The beat note has 3 terms: the Sagnac one, the de Sitter (Geodetic term) and the Gravitomagnetic one (LenseThirring)
- The Earth angular velocity is measured with very high accuracy by VLBI, which measures the Earth rotation with respect to the fixed stars

the Relativistic terms can be obtained by subctracting from the ringlaser data the Sagnac term measured by VLBI

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The relativistc effects at our latitude

- in order to subtract the Sagnac term, it is necessary $10^{-14} rad/s/$,which is equivalent to say that the Earth angular velocity has to be measured with accuracy one part in $10^9 - 10^{10}$ on the surface of the planet.
- So far, sensitivity and accuracy so high can be obtained by ring-lasers only. Very promising instruments based on cold atoms at the moment are not so powerful, and it is commonly assumed that they will not be able to reach such level in the next decades; by now experiments to measure the de Sitter term only have been recently proposed [kasevich et al.].

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Experimental Results for LenseThirring

- Gravity probe B (GPB) has obtained a 19% accuracy for the Lense-Thirring effect, and has measured the Geodetic precession (de Sitter) at the level of 0.28%. These results have been obtained considering the cumulative effect of many orbits and depend on the average gravitational field along one orbit. Knowledge of the gravito-electric field of the earth is needed (based on the measurements of the GOCE experiment).
- 10% accuracy has been obtained by measuring the precession of the plane of the orbits of the LAGEOS and LAGEOS II satellites using laser ranging. The same technique as above is being exploited by the LARES dedicated mission, started on February 13th 2012. The expected accuracy for the Lense-Thirring effect is in the order of $1-2\%$. Both the LAGEOS and LARES results depend on the knowledge of the gravito-electric field all along the orbits of the satellites (GRACE and GOCE experiments).

A Very Different Experiment

We stress that, being the whole proposed experiment fixed on the surface of the Earth, it has a constant gravito-electric (Newtonian) field so it does not need any modelling of the interior of the Earth or of the shape of the planet. Furthermore, all measurements are made in one and the same reference frame and there is no need of transporting time and space measurements from elsewhere. The experiment is fully local (a part for the comparison with VLBI data, as explained below); the tested gravito-magnetic field as well as the coupling between the angular velocity of the Earth and the gravito-electric field are the ones of the laboratory. There is no time and space averaging over scales bigger than the one of the laboratory.

Question: what is it possible to learn comparing the two kinds of experiments (Space/Earth)?

The experiments in space are based on the precession of physical gyroscopes induced by the gravitational field in its general relativistic form. Indeed the coupling of the angular momentum of a gyroscope with the gravitational field induces a torque depending on the configuration and on the features of the field. In the case of GP-B the angular momentum is the one of four spinning spheres; in the case of LAGEOS and LARES the angular momentum is the one associated with the orbital motion of the satellites. Our experiment instead exploits the anisotropic propagation of light in the screw symmetric space-time associated with rotating bodies. Our technique is thus complementary to the one used in space; furthermore it allows for a terrestrial location, provided the size and sensitivity of the ring-lasers is high enough.

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Limits of the RingLaser

The Shot Noise

$$\delta\omega_{sn} = \frac{cP}{4AQ}\sqrt{\frac{h\nu_l}{WT}} rad/s$$

Problems connected with the non linearity of the Laser: BackScattering

$$\begin{aligned}
\frac{2L}{c}\frac{\dot{E}_+}{E_+} &= \alpha_+ - \beta_+\sqrt{E_+} - \theta_\pm\sqrt{E_-} - 2r_-\frac{E_-}{E_+}\cos(\Psi + \varepsilon_-) \\
\frac{2L}{c}\frac{\dot{E}_-}{E_-} &= \alpha_- - \beta_-\sqrt{E_-} - \theta_\mp\sqrt{E_+} - 2r_+\frac{E_+}{E_-}\cos(\Psi - \varepsilon_+) \\
\omega_+ + \dot{\phi}_+ &= \Omega_+ + \sigma_+ + \tau_\pm\sqrt{E_-} - \frac{c}{L}r_-\frac{E_-}{E_+}\sin(\Psi + \varepsilon_-) \\
\omega_- + \dot{\phi}_- &= \Omega_- + \sigma_- + \tau_\mp\sqrt{E_+} - \frac{c}{L}r_+\frac{E_+}{E_-}\sin(\Psi - \varepsilon_+) \qquad ,
\end{aligned}$$

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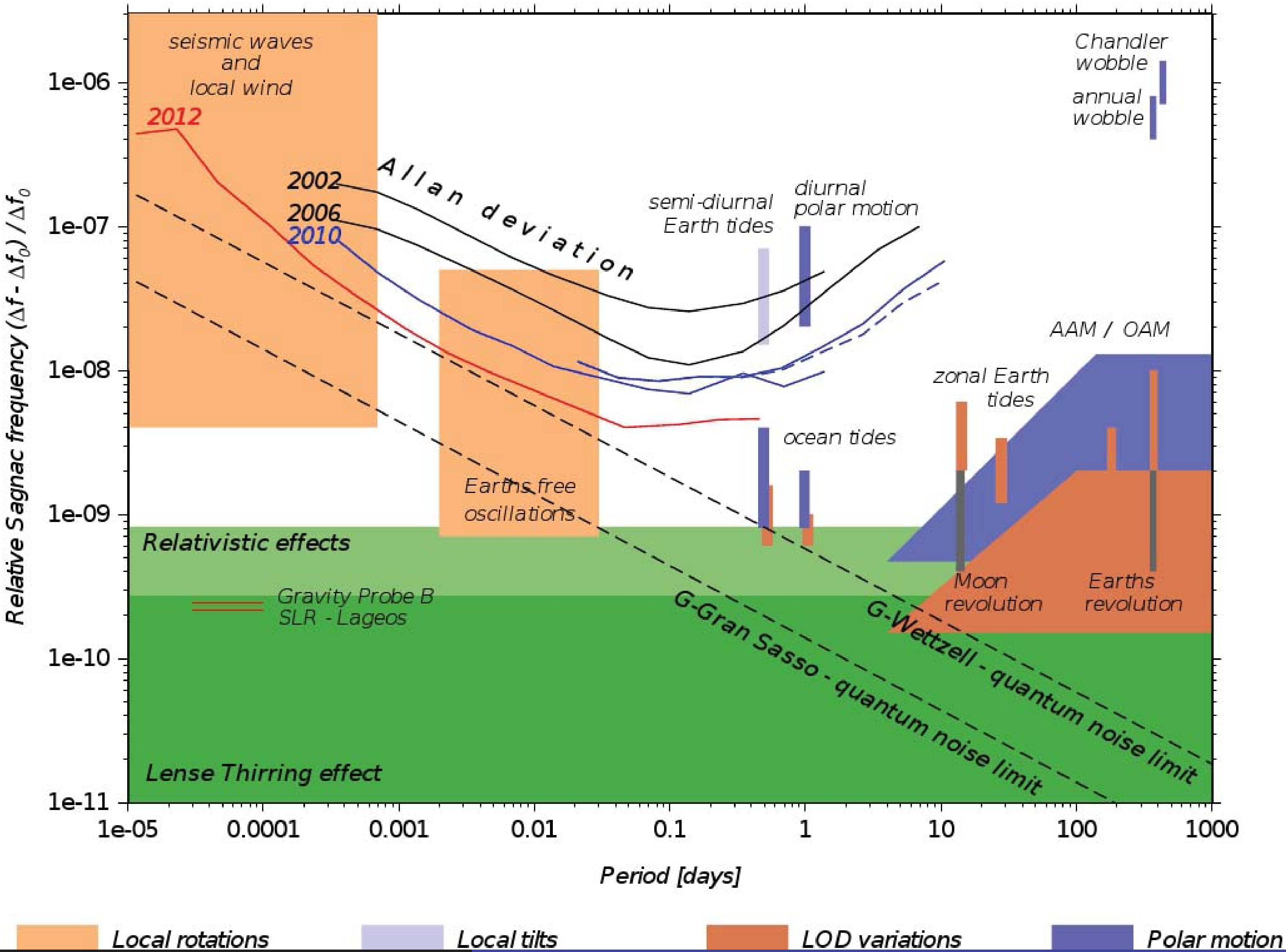
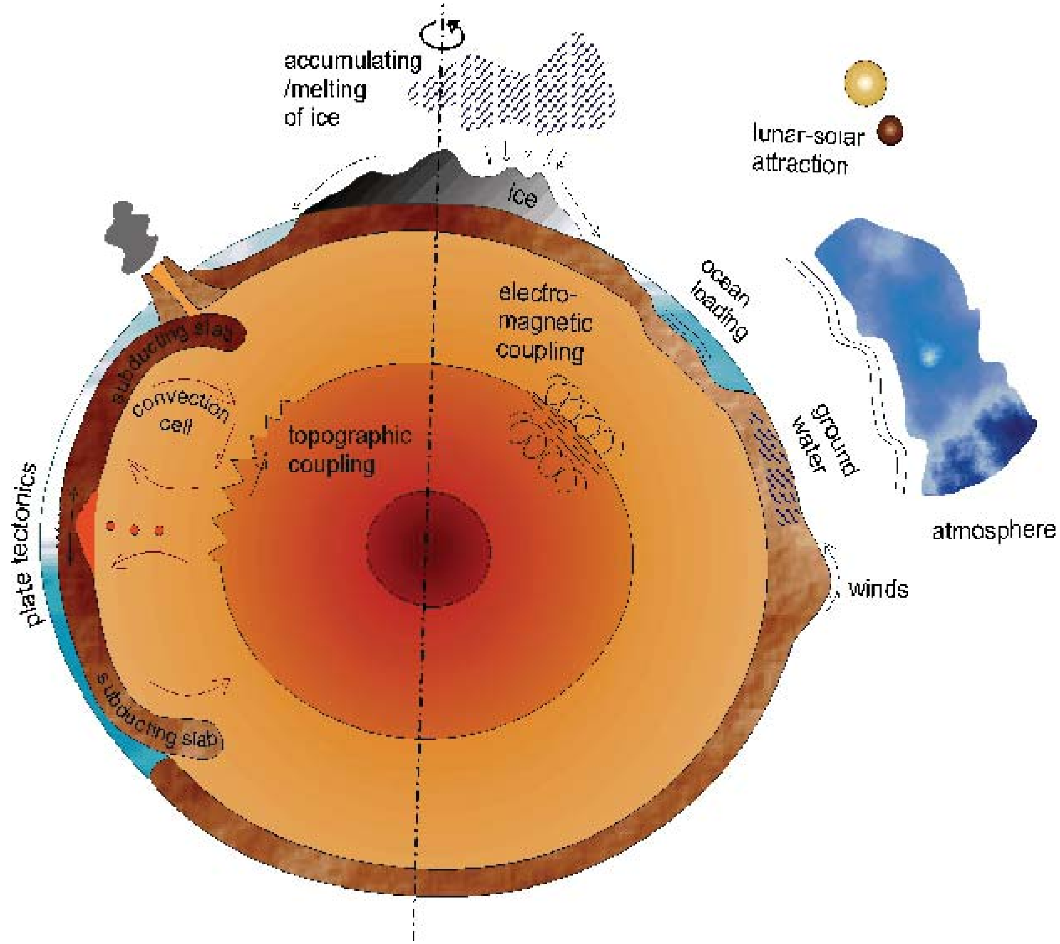
Status of The Art, known signals, recent measurements and requirements



The Environment

An apparatus directly linked to the Earth
Fundamental Physics, Geodesy and Geophysics



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Towards the LenseThirring measurement

- Ω is a vector, so at least 3 independent rings are necessary, we propose 6 parallel rings two by two, in order to have redundancy
- Underground Location, in order to be far away from the Earth crust, which is perturbed by atmospheric changes (pressure, wind, rain....)
- increase the sensitivity and the time of integration: larger rings (from 4 m to 6 m), and integration time from 4 hours to 1 day (underground location, reduce as much as possible problems coming from backscatter noise).

accuracy 1 in 10^{10}, necessary in order to cancel out the pure Sagnac term

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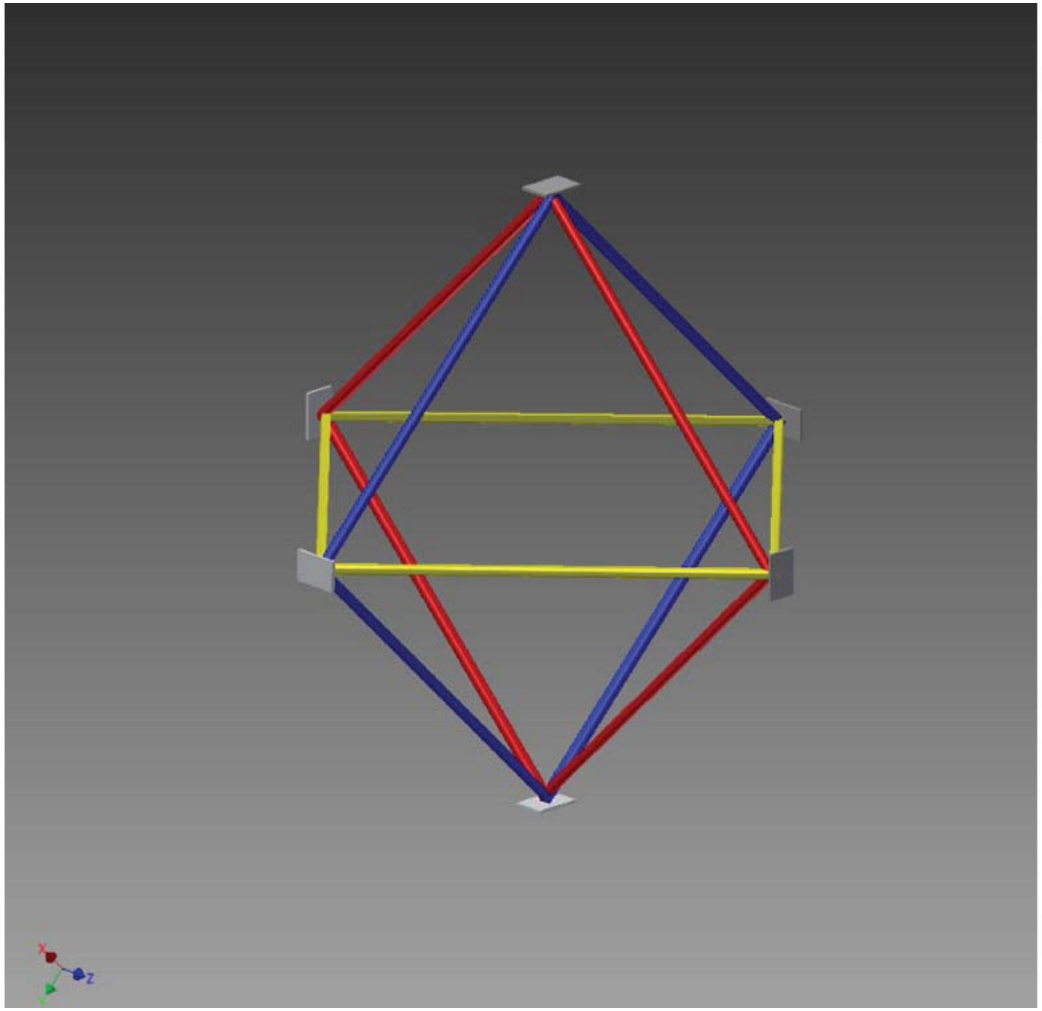
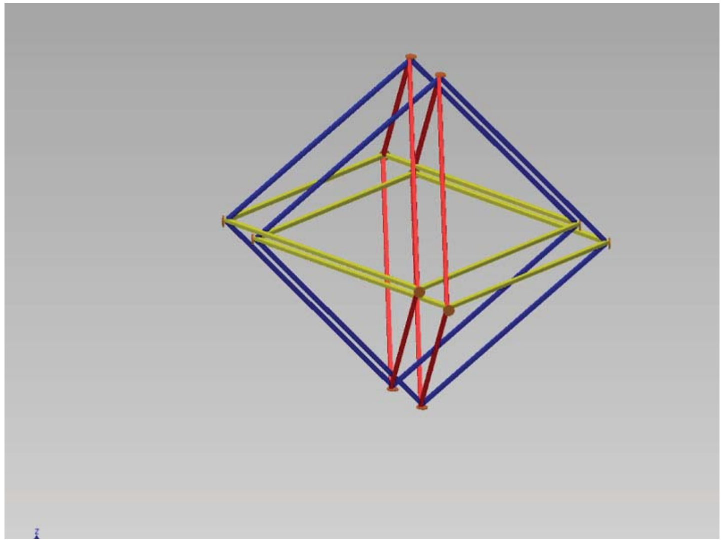
The Octahedron





The beauty of the Octahedron

the simmetries of an octahedron are very actractive

- mirrors along the diagonals of each rings are parallel, this implies that the diagonals can be Fabry-Perot cavities
- the cavities along the diagonals will give information on the relative alignment of the rings, through the observation of higher order modes
- each side of the rings can be independently measured, giving informations on the relative alignment. We are investigating the possibility of using Digital Interferometry.

suitable signals can be extracted in order to:

control the shape of the whole system

and monitor the relative angle between two rings

required accuracy $1 nrad$

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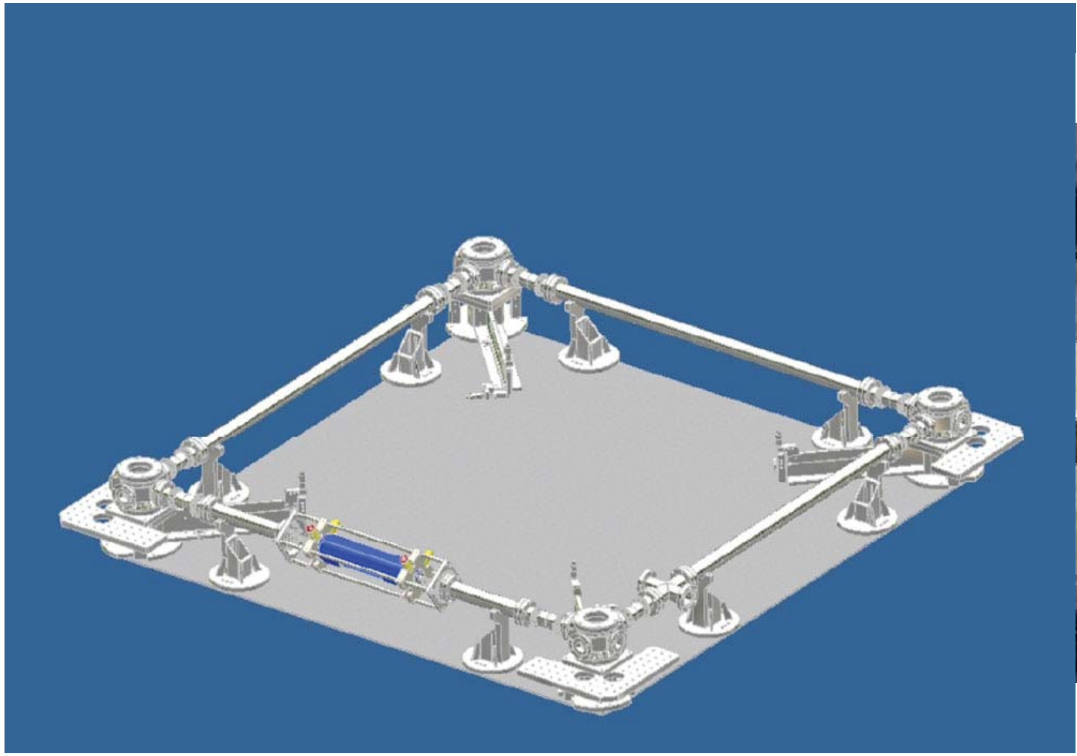
the mechanical design used for our prototype G-Pisa



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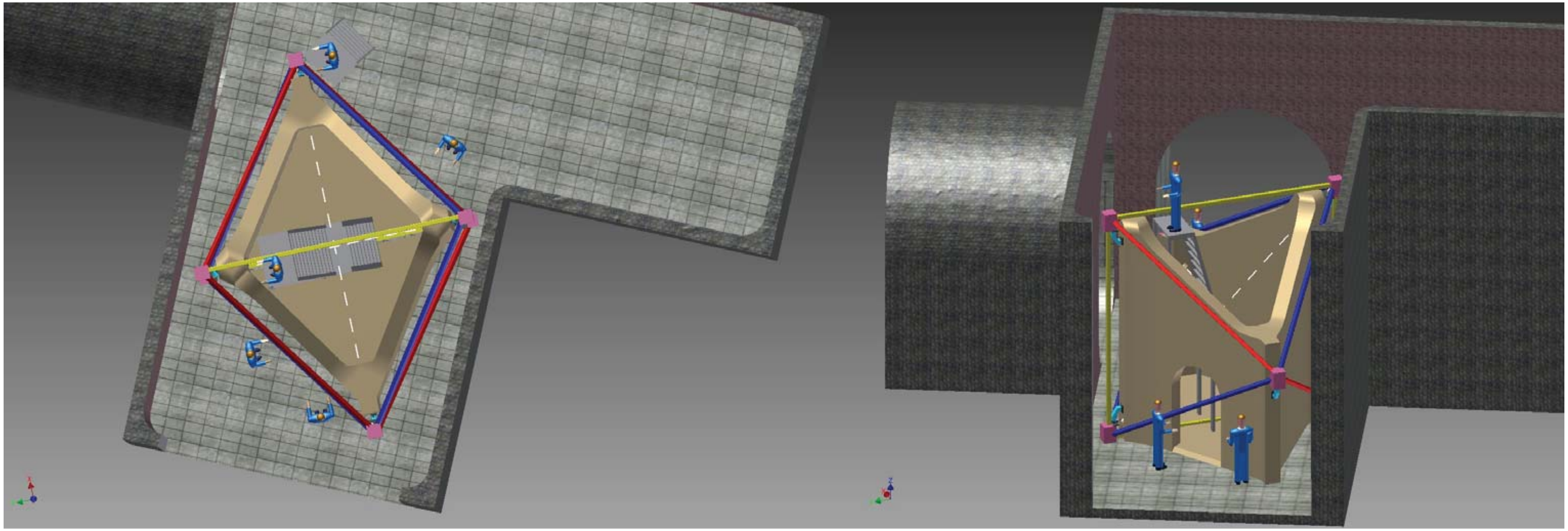
GINGER (Gyroscopes In GEneral Relativity, G-GranSasso)



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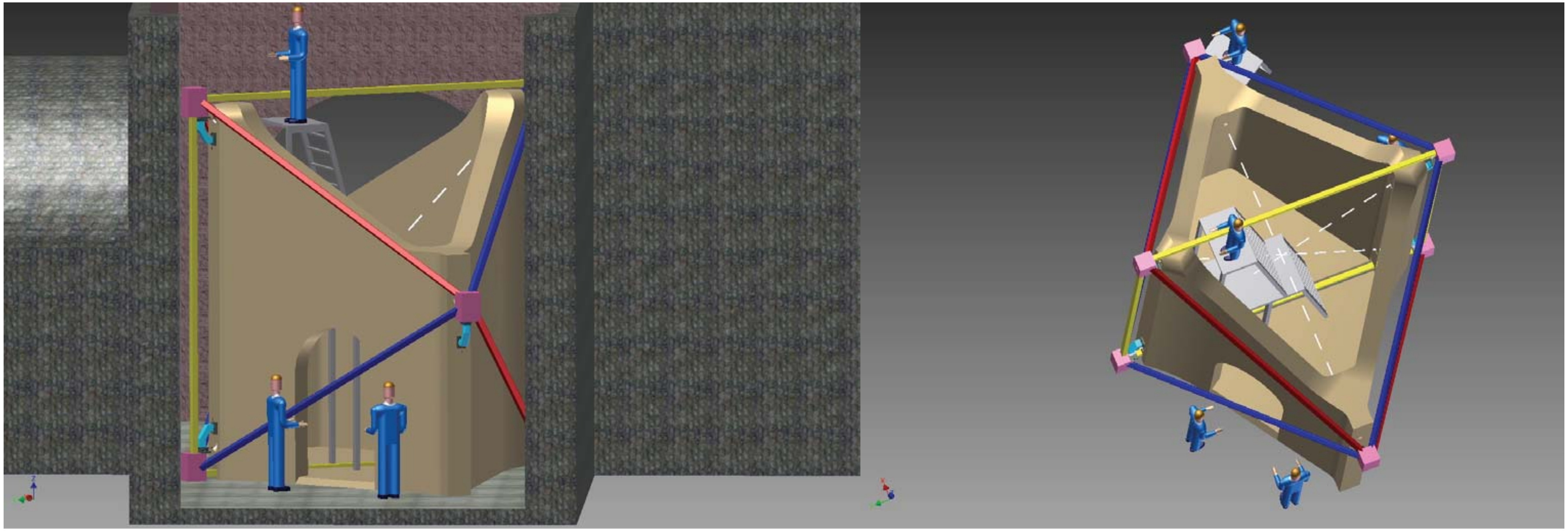

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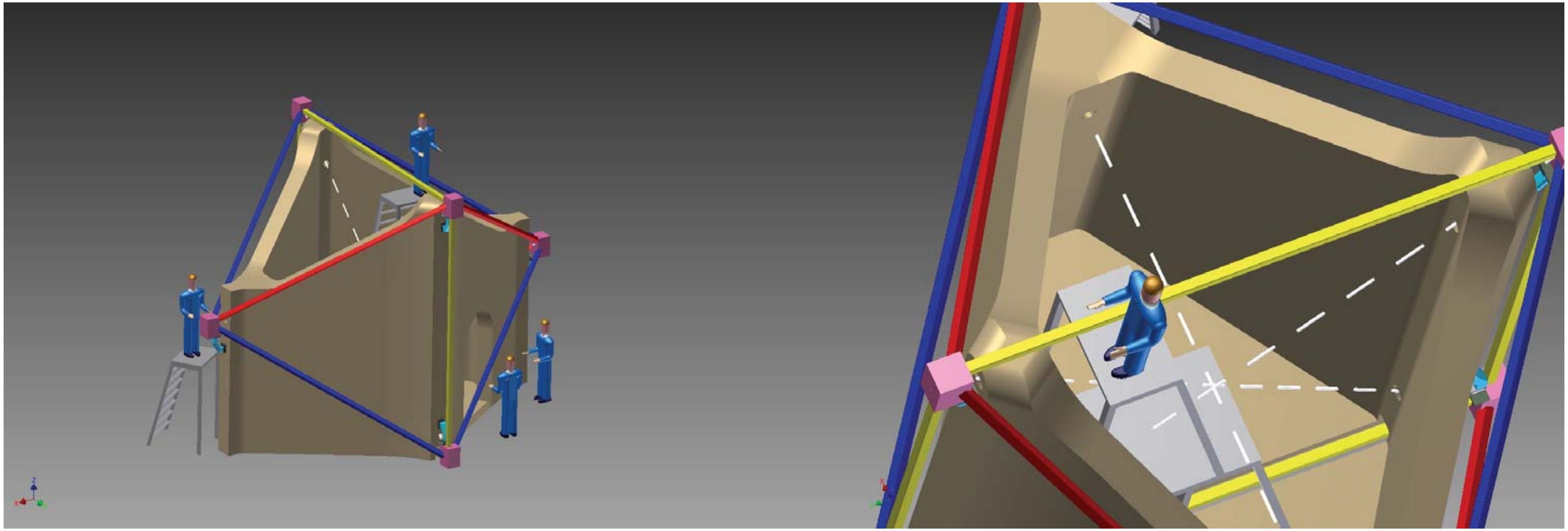

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Next Step: select a suitable Underground Location.....

- The GranSasso INFN National Laboratory (LNGS) could be a suitable location
- We plan to installe our prototype G-Pisa inside LNGS in 2013. Our prototype is a small one (1.35m side), it can show if the lab. is not adeguate as far environmental disturbances are concerning

 

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