SIGRAV, Urbino, September 7, 2021

GINGER

Angela D. V. Di Virgilio for the GINGER Collaboration

September 7, 2021

RLG: a tool for Fundamental Physics

- Absolute Rotational degree of freedom

as a tool to investigate Nature

- ring laser gyroscope
General Relativity and Lorentz Violation

time difference and interferometry -> long term and fast response, huge sensitivity and dynamic range

- Earth based experiment

Repeatability and focus on physical laws: 'Valid here and now' not isolated and very rare natural phenomena far from the observer (in distance and time)

RLG a very special instrument

- unattended continuous operation for months
- typically sub-prad/s sensitivity in 1 second of measurement
- very large bandwidth, fast response, in principle as fast as milli-seconds
- very large dynamic range. Since it is based on frequency measurement, the same device can record sub-prad/s variations and strong signals from near by earthquakes
- they can be oriented at will in order to reconstruct in 3D the angular rotation vector

RLG and Fundamental Physics

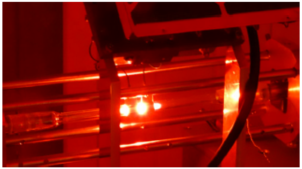
- The key point is the sensitivity
- the watershed to be useful to fundamental physics is to reach and go below 10^{-14}rad/s (measure $\Omega_\oplus$ down to 1 part 10^9).

GINGERINO has recently demonstrated a noise floor compatible with 0.1prad/s

NEWS INFN

03 GIUGNO 2021

GINGERINO MISURA LA VELOCITA' DI ROTAZIONE E IL CAMPO GRAVITAZIONALE DELLA TERRA



È possibile **misurare con precisione la velocità di rotazione della terra a partire dall'analisi delle differenze con cui i segnali luminosi con traiettorie opposte si propagano**. A sostenerlo, un articolo apparso l'8 maggio sulla rivista Springer EPJC, in cui sono raccolti i risultati relativi all'ultima analisi condotta su dati acquisiti su un lungo periodo da **GINGERINO, un interferometro laser, comunemente chiamato laser ad anello (Ring Laser Gyroscope), ospitato nei Laboratori Nazionali del Gran Sasso**. Lo studio ha infatti evidenziato la capacità dell'apparato di fornire, con un'accuratezza oltre le aspettative, valori della velocità angolare della Terra concordi con quelli ottenuti da sofisticati sistemi satellitari e da interferometria astronomica, oggi impiegati per monitorare i parametri legati alla rotazione del nostro pianeta. **L'esperimento si inserisce nell'ambito delle attività di**

- GINGER is a project based on a RLG array, underground, isolated from external disturbances, to directly measure the Lense Thirring effect on the Earth
- Lense Thirring (and de Sitter) acts on the RLG as angular rotation vector summed to the Earth rotation rate.
- kinematic component independently measured by IERS with very high accuracy
- Main difference with existing measurements: fixed latitude, not averaged. Not required: synchronization of different clocks and independent gravity map.
- discriminate among different theories, minimising modeling

- de Sitter and Lense Thirring effects, function of the latitude **(multisite approach would be advantageous)**, independent from the gravity map of the Earth.
- Lorentz Violation, in the SME framework
- Gravitational waves exciting the Earth quadrupole moment
- space-time structure in the noise spectral density

Salvatore Capozziello

sensitivity windows $10^9 - 10^{13}$, low rate, DC and accurate, IERS required.

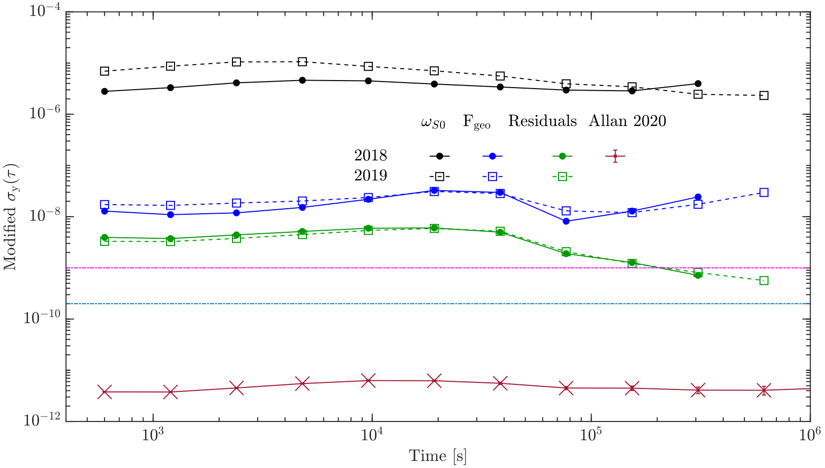
Jay Tasson

1 part 10^9 or better, fractions of hours

...here sensitivity is never enough..

sensitivity better than 1 part 10^{12} at 1 hour frequency.very high frequency, MHz and high accuracy.

Compare sensitivity and physics



Basic of the measurement

$$f_S = \frac{4A}{P\lambda} \hat{n} \cdot \overrightarrow{\Omega}$$

- A area, and P perimeter of the ring, λ wavelength
- output: scalar product between Ω and the ring area versor
- accuracy depends on geometry, which can be monitored by standard optical techniques

main difficulty is the subtraction of the kinematic component (9 orders of magnitude higher than the signals we are looking for)

-control/monitor the geometry
-ring shape close to regular polygon with error of fractions of micrometer

-RLG at maXimum signal to recover the angle of the other rings
-alignment of RLX close to ideal down to fractions of micro-rad

GINGER: interdisciplinarity

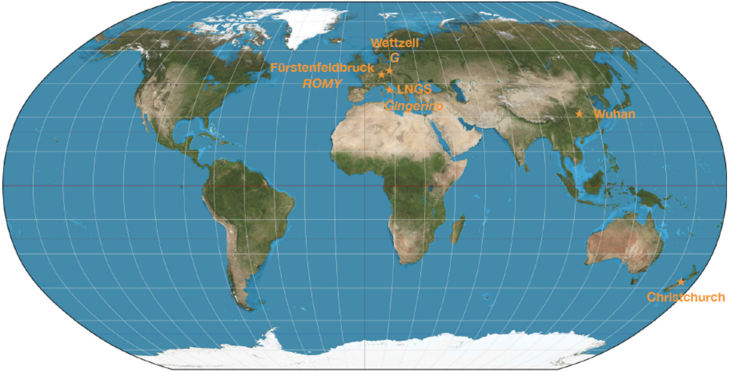
GINGER is not specialised to some specific feature of physics, it monitors the absolute rotational degree of freedom of the Earth crust in one point, as a consequence it provides data useful for geophysical and geodesic investigation.

In turn we can use those signal to investigate the apparatus.

We have prepared and addendum to the TDR, to summarize the impact in fundamental physics, geophysics and geodesy, a 'living summary'.

High sensitivity RLG gyroscopes

Large-frame optical gyroscopes in the world



In Germany are operative: G, which has been already productive for geodesy and ROMY (ERC) of the geophysical observatory of Baviera, a 4 RLG array with 36m perimeter.

GINGER: the Collaboration

INFN Pisa
<u>*Angela D.V. Di Virgilio*</u>
Fabio Morsani
Giuseppe Terreni

UNIPI
Andrea Basti
Nicolò Beverini
<u>Giorgio Carelli</u>
Donatella Ciampini
Francesco Fuso
Enrico Maccioni
Paolo Marsili

GSSI
Umberto Giacomelli

INFN Napoli
CNR-SPIN
<u>Alberto Porzio</u>

UNINA
Carlo Altucci
Francesco Bajardi
Salvatore Capozziello
Raffaele Velotta

UNISA
Gaetano Lambiase

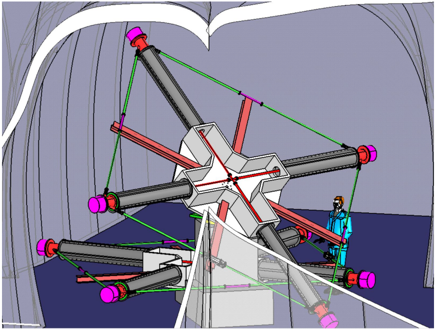
INFN LNL
<u>Antonello Ortolan</u>
POLITO
Matteo Luca Ruggiero

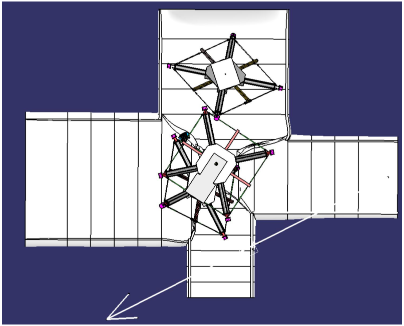
INFN LNGS
INGV
Thomas Braun
<u>Gaetano De Luca</u>
Giuseppe Di Stefano
Roberto Devoti
Aladino Govoni

UNIVAQ
Francesco Dell'Isola
Ivan Giorgio
Marco Tallini

UNISS
Emilio Barchiesi
Emilio Turco

GINGER: the apparatus





General rules of the mechanics

- Experimental setup contained inside a closed box
- thermal stability and avoid gradients
- rigid
- homogeneous materials and cylindrical symmetry
- minimize the points in which seismic motion impacts
- reduce coupling between mirrors

- underground location provides excellent thermal stability with reduced day night effects
- to push above 50Hz the proper mode of the structure
- unattended operation and far from anthropogenic noise
- proper selection of components
- utilize the symmetry of the system to reduce to second order the typical causes of instability

we have demonstrated that using RLX the measurement is limited by the noise of the RLG

RLX: the RLG at maXimum signal

- RLX is oriented at maximum Sagnac signal, insensitive to local tilts and provides the absolute value of Ω_T, necessary to reconstruct the orientation of the other RLG
- the misalignment of RLX with respect to the rotation axis determines the sensitivity limit.

GINGER: steps toward final sensitivity

- step 0, 1 part in 10^{9} ($7\text{x}10^{-13}$ rad/s);
- step 1, 1 part in 10^{10} ($7\text{x}10^{-14}$ rad/s);
- step 2, 1 part in 10^{11} ($7\text{x}10^{-15}$ rad/s);
- step 3, 1 part in 10^{12} ($7\text{x}10^{-16}$ rad/s);
- step 4, 1 part in 10^{13} ($7\text{x}10^{-17}$ rad/s), this amounts to the 0.1% test of GM effects.

step 0 alignment at 310^{-5}rad
step 1 ....10^{-5}rad
....
step 4 ....310^{-7}rad
NOTE: data suitable for geophysical and geodesic investigation since the beginning

Why so few: The problem of the RLG

The use of the active cavity is extremely advantageous, but has the drawback that the response is affected by the non linear laser dynamic. We have elaborated an original analysis technique which takes into account the laser dynamic, and reconstruct ω_s using the available signals of the laser: the beat note ω_m, the intensities of the two laser modes (DC and at ω_m) and their relative phase.

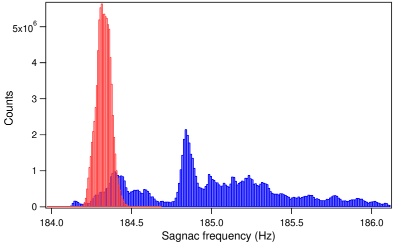


Figure: Distribution of the signal of GP2, with and without taking into account the dynamic of the laser

Eur. Phys. J. C (2019) 79: 573.
Eur. Phys. J. C (2020) 80: 163

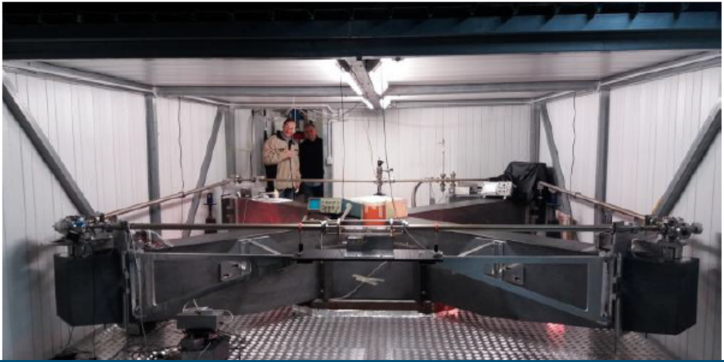
Available signals

'

Signals:

Gyroscope signals: beat note ω_m, amplitude of the two modes I_1 and I_2, amplitude of the two modes at the beat note frequency IS_1 and IS_2, relative phase ε, power at the discharge GM

Environmental signals: Temperature, Pressure, Tiltmeter ξ_1 and ξ_2



The Earth: natural test-beam

- RLGs are sensitive to the Earth global rotation (Ω_{geo}) and its variations: polar motion, Annual and Chandler wobbles, tides, crust deformations etc, all measured with very high accuracy by the international system IERS.
- This provides a "natural test beam" to investigate the characteristics and the sensitivity of GINGERINO.
- The true Sagnac signal ω_s is recovered taking into account the laser dynamic, and assuming that it is $\omega_s = \omega_{geo} + \omega_{local}$, where ω_{geo} indicates the scalar product of the total variations of the Earth with the RLG area vector, ω_{local} the signals of local origin, related to temperature fluctuations and local tilts.
- ω_s, ω_{geo} and ω_{local} are identified using linear regression and standard statistical means based on minimum square
- weak points of the apparatus and the sensitivity are investigated.

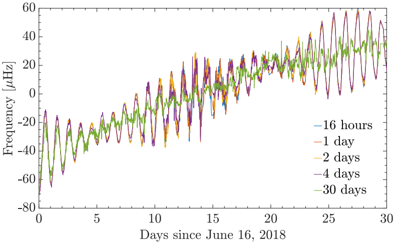
Linear regression

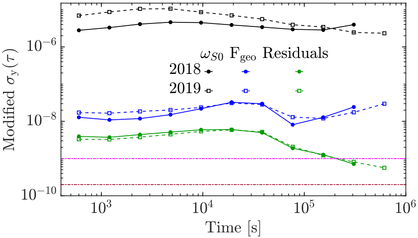
GINGERINO is running in a continuous basis, unattended and free running since 2017. We know that inside its data the global signal $\Omega_\oplus$ (independently measured by IERS, F_{IERS}) is contained. It contains also local disturbances ω_{local}, in principle due to geophysical phenomena or instrumental. Aim is to identify ω_{local} with a linear regression using the laser dynamic, the available environmental signals, temperature, pressure and tiltmeters signals $\zeta_{1,2}$ to reconstruct the global signal F_{IERS}.

$$\omega_s = CAL \cdot F_{IERS} + LD_T\mu + \omega_{local}$$
$$F_{IERS} \propto \vec{A} \cdot < \vec{\Omega}_\oplus > + CW + PM$$
$$\Omega_\oplus = < \Omega_\oplus > + \Delta\omega_3$$

CW and PM indicate the effect of the Annual and Chandler wobble and the daily polar motion. IERS data are used to cross calibrate and evaluate the absolute orientation and the effective scale factor SF in an arbitrary point T_0, to evaluate CAL.

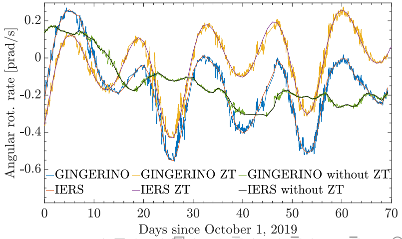
Phys. Rev. Research 2, 032069(R) – 2020



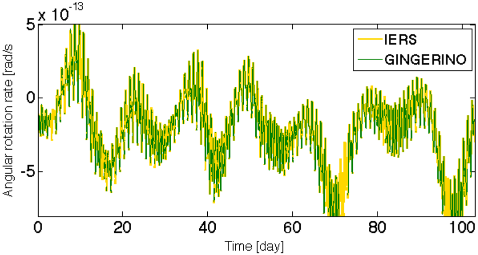


sensitivity limit 40 frad/s after 3.5 integration days: meaningful for GR test and Lorentz violation study. Please note that MAD is still decreasing.

F_{geo} is F_{IERS} reconstructed by the linear regression.

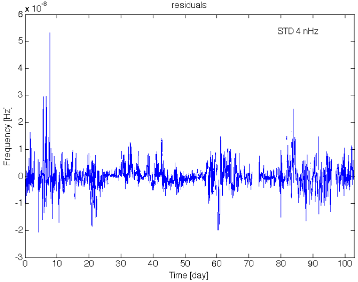


$\zeta_{1,2}$ plays a dominant role in the identification of ω_{local}. More explanatory variables are added to the linear regression, obtaining:residuals gaussian distributed, typically STD $10 - 4$nHz (below frad/s) estimation of the sensitivity limits using two sinusoidal signals added to the signal and to the LR: period 40 and 0.5 days, sensitivity of the order of 0.3nHz (0.01frad/s).

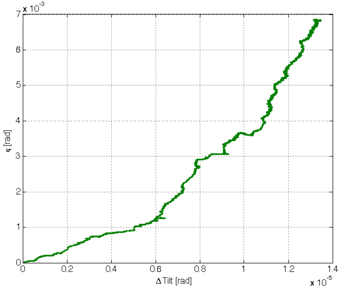


The disturbances have instrumental origin

Typical residuals, STD 4nHz.



ω_{local} is instrumental, when the monument tilts the mechanical structure of GINGERINO rotates. Improvement of the heterolithic mechanical design required.



Very important to remark

- IERS provides the local angular rotation with wobblers, tides and deformations. The analysis method is not predictive, but it is good to investigate the apparatus.
- The level of precision with which the different terms of the linear regression, and the residuals indicate 0.1frad/s sensitivity.
- **my main concern about our result is that: it looks too good....**

Fundamental limit problem

The debate around RLG sensitivity is still active, mainly focusing to very small RLGs; so far the limit for large frame, high sensitivity RLGs is considered to be the shot noise due to spontaneous emission of laser atoms. The sensitivity we observe is a factor 1000 below the shot noise due to spontaneous emission of the laser atoms. This noise is phase noise, but the Sagnac signal is the frequency. At present we are studying the problem.

the GINGER proposal

- We have concluded our preliminary work toward GINGER and submitted the GINGER proposal to the CSN2.
- The first target was 1% of the Lense Thirring, the speculation about the sensitivity indicates the feasibility of 0.1%, a factor 10 improvement.
- The main difficulty is to subtract the Earth kinematic components, this implies to constantly have the absolute orientation of the RLG.
- The RLG at maximum signal has the advantage to be insensitive to small orientation changes, and using its data it is possible to monitor the orientation of the other RLG of the array with respect to the absolute orientation of the total angular rotation vector.

The RLG at the maximum signals provides $|\Omega_\oplus|$ and the relative orientation of the other two RLG with the Earth rotation axis.