GINGER
AND GINGERINO
Angela Di Virgilio, INFN-Pisa

Gyrosopes IN GEneral Relativity
Lense Thirring effect, on Earth, 1% precision
Ring laser measures absolute angular velocity
(Sagnac Effect)
LAY OUT OF THE TALK

• A bit of history
• The present situation
• GINGER: the main problems and the proposed solution
• GINGERINO
Sagnac Interferometer (1913)

Rotation Rate: 2 rev. per sec.

observed Fringe Shift:

\[
\delta \phi = \frac{8\pi A}{\lambda c} n \cdot \omega
\]

with \( A = 0.086 \text{ m}^2 \) this turns out to be \( 0.07 \pm 0.01 \) fringes

Georges Sagnac was the first to correctly combine theory with experiment. We also acknowledge the experimental skill to build a sufficiently stable apparatus.
Sagnac effect

\( \Delta t_{\text{Sagnac}} = \frac{4 A \vec{\Omega} \cdot \vec{n}}{c^2} \)

Advantages

- No moving masses
- No signal for a linearly accelerating reference-frame
- \( L > 1 \text{ m} \rightarrow \) Earth rotation is the bias

Quantum limit

\[ \delta \Omega_{\text{shot}} = \frac{c P}{4 AQ} \left( \frac{h \nu T}{2 P_{\text{out}} t} \right)^{1/2} \]

- Low cavity losses
- High power
- Large size
The Sagnac Effect and the ring-laser

\[ f_{\text{Sagnac}} = \left| f_{\text{CW}} - f_{\text{CCW}} \right| = \frac{4\vec{A} \cdot \vec{\Omega}}{\lambda p} \]
Industry is active in developing RL since more than 50 years, especially for navigation, submarines and drones.

Fig. 9.10 Laser gyroscopes: (a) ring laser gyro (RLG); (b) fiberoptic gyro.

https://www.youtube.com/watch?v=-HzmxW3Jll8
• Large frame ring lasers are top sensitivity devices to measure absolute angular velocity

• Routinely they measure tens of pico-rad/s, present record $10^{-13}$ rad/s in 1 day

• Very low frequency measurements are of primary importance for geophysics and geodesy, for this reason 2 installations have been realized in Germany (G and ROMY)
G - Ring the currently best performing gyro

- Perimeter: 16 m
- Area: 16 m²
- FSR 18.75 MHz
- \( \Delta \nu_L \approx 274 \ \mu \text{Hz} \)
- 5 ppm total loss
- \( Q = \omega \tau \approx 5 \times 10^{12} \)
- 6.5 mB gas pressure in order to avoid multi-moding
Seismology built and on
GINGERINO: SOME DATA WILL BE SHOWN AT THE END OF THIS TALK

LET US DISCUSS NOW THE TEST OF GR, THE LENSE-THIRRING EFFECT AT 1%
The deSitter and LenseThirring terms are equivalent to an extra rotation 9-12 orders of magnitude below the Earth rotation rate.

\[ f = \frac{4A}{\lambda P} \left[ \Omega_\oplus - \frac{2m}{r} \Omega_\oplus \sin \theta \hat{u}_\theta + \frac{G I \Omega_\oplus}{c^2 r^3} (2 \cos \theta \hat{u}_r + \sin \theta \hat{u}_\theta) \right] \cdot \hat{u}_n = S (\Omega_\oplus + \Omega_{dS} + \Omega_{LT}) \cdot \hat{u}_n. \]

The probe is a vector which can be oriented at will.
The quantity to measure is the angular rotation vector.
The output is the scalar product between the two vectors.

$S$    geometrical scale factor
$n$    area versor
Beat frequency Scalar product $n \cdot \Omega$
The measurement of the Lense-Thirring effect implies to measure the modulus of the Earth rotation rate with an accuracy $1 \text{ part in } 10^{12}$ and subtract the measurement done by IERS, which contains the only kinetic term

1) One RL at maximum signal, with an angle with the Earth rotation rate small enough

2) An array of RL, but the angles between relative angles must be monitored with prad accuracy
Simplified apparatus, A. Di Virgilio et al: GINGER: a feasibility study

DOI 10.1140/epjp/i2017-11452-6
**RELATIVITY**

Proving Einstein right using the most sensitive Earth rotation sensors ever made

A new study use the most precise inertial sensor available to date to measure whether Earth partially drags inertial frames along with its rotation

---

**PLASMA PHYSICS**

X mode Doppler Reflectometry k-spectral measurements in ASDEX Upgrade: experiments and simulations

Doppler reflectometry is a microwave backscattering diagnostic for measuring flows and density fluctuation spectra in fusion plasmas. One longstanding problem is the discrepancy between the Doppler spectrum and the density fluctuation spectrum from turbulence simulations: The red "GENE" curve has its knee at a different wavenumber compared to the experimental Doppler measurements. The knee position is intrinsic to the turbulent drive mechanism and should be the same in both.

We coupled the sophisticated plasma turbulence code GENE to the fullwave code IPF-FD3D to model the scattering and the power response of the reflectometer in the presence of realistic turbulence. Dashed lines in the figure are the result

![Image of Earth and stars](image_url)

*Physicists have now found a way to measure Earth's rotation in an extremely accurate way (© Fotolia).*

Einstein's theory of gravity, also referred to as General Relativity, predicts that a rotating body such as the Earth partially drags inertial frames along with its rotation. In a study recently published, a group of scientists based in Italy suggests a novel approach to measuring what is referred to as frame dragging.
• The combination of 1 RL at maximum signal, 1 horizontal and the other with a different angle outside the meridian plane has several interesting features and it does not require the high sensitivity measurement of the relative angle between the two RL

• The RL at maximum measures the modulus

• The combination of the two RL provides a very sensitive measurement of the angle between the horizontal RL and the Earth rotation axis (this makes feasible the study of polody)
EXPERIMENTS ON GOING IN ITALY

- *Scale factor control, control of the geometry GP2*

- *Observation of the perturbations affecting the underground laboratory of LNGS*
G IS MONOLITHIC, OUR PROTOTYPES ARE HETERO-LITHIC

• Long term stability and control of the geometry of the ring is the key point

• We have found a suitable control strategy, which is under test with the prototype GP2 in Pisa
Multi-resonator stabilization

Control IDEA

- Lock opposite mirrors distances (diagonal Fabry-Pérot ITFs) \([E1, E5], E2\]
- Optimize the residual 4 quadratic d.o.f.
- \([E3(-), E4(-), E5(+), E6(+)]\) the looking at the perimeter length

Reference laser

- He-Ne/\(_2\) laser primary frequency standard
- \(\mu\)-lens coupled cw diode laser probe laser

Deformation quasi-normal modes
Comparison Sagnac signals with different lock

Sagnac

- perimeter lock
- diagonals lock
GINGERino: deep underground ring laser

GINGER-ino (INFN-LNGS)+ Seismometers (INGV)

He-Ne laser at 633 nm
Square cavity, L=3.6 m
Mirrors r.o.c= 4 m
Earth rotation Sagnac bias: fs=280.4 Hz
• **GINGERINO has already proved that underground laboratories provides very high thermal stability and quiet environment**

• **It is now working in a continuous basis to provide data to geophysics**
TYPICAL SENSITIVITY

**Figure 3.** Angular velocity linear spectral density of GINGERino during the February 2016 run. Power spectral density is estimated from the raw data interferogram.
BEST ALLAN, WITH PARTICULAR CARE IN SELECTING THE DATA
GINGERINO CAN DETECT VERY HIGH ANGULAR ROTATION SIGNALS

The Visso M 5.9 earthquake, probably the largest seismic rotational signal ever recorded

Ω Earth

A. DI VIRGILIO, QFC2017 PISA
M8!
CONTINUOUS DATA TAKING
SINCE MAY 3 2017, DUTY CYCLE > 97%

Pizzoli M3.8, June 9, 2017
RING LASER AND GEODESY

• The top sensitivity ring is the Gross Ring G at the geodetic station of Wettzell

• The main purposes for geodesy are the daily and subdaily variations of the length of day (LOD) and the earth axis variations, two open questions of the geodesy
Ringlaser Measures Eigenmodes of Earth

- Observed eigenmodes of the ringing Earth, stroked by the Tohoku-Oki earthquake

Gross ring G Wettzell

Igel et al. 2011
CONCLUSIONS

- Large frame ring lasers are based on a mature technique

- High sensitivity and long term stability make RL able to investigate the very low part of the spectrum, providing remarkable measurements for general relativity, geodesy and geophysics

- They can measure locally global quantity

sensitivity & stability
key points to access very low frequency signals
Underground-Stability