Scientific Motivations of GINGER and its RoadMap

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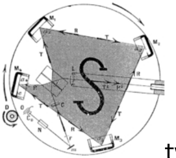
G-GranSasso (Angela Di Virgilio)

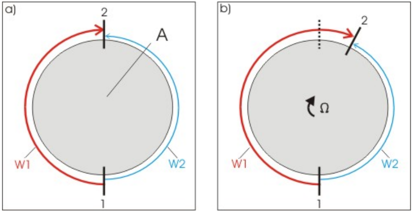
- The Sagnac effect and the Ring-Laser
- G in Wettzell
- GINGER (Gyroscope IN GEneral Relativity), LenseThirring effect at 1 %
- preliminary results of the first installation inside LNGS

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

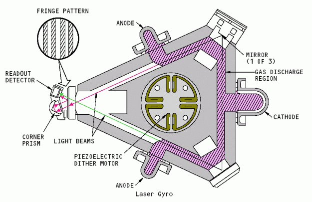
$$\Delta t = \frac{4\pi R^2 \Omega}{c^2} \tag{1}$$



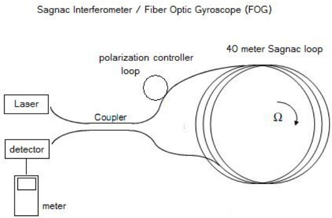
Devices based on the Sagnac Effect

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

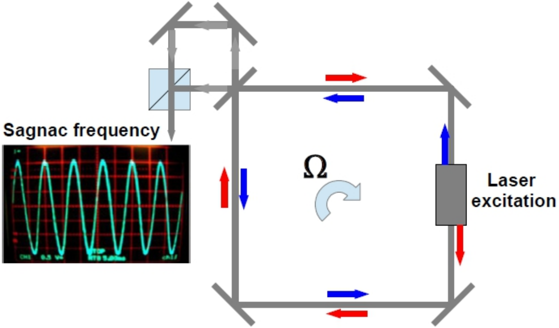
Several instruments have been developed for different purpose, in general inertial navigation (air-plane, submarine...) and more recently for geophysics study.
NOTE: the response is not affected by longitudinal vibrations since moving parts are not present



In general FOGs have applications when $10^{-4} rad/s$ is required, ring-lasers have higher sensitivity and accuracy



The Ring-Laser



When the cavity rotates with frequency Ω, the bit note, δf_{Sagnac}:

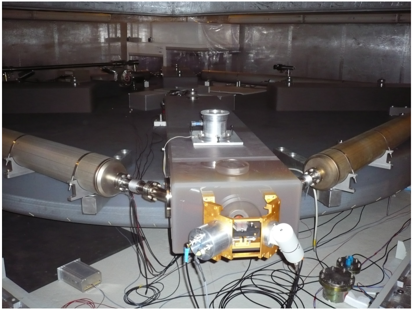
$$\delta f_{Sagnac} = K \; \Omega \cdot n$$

where **n** is the area vector and K is scale factor of the instrument, $K = \frac{4A}{\lambda P}$, λ is the wavelength, and A and P area and perimeter.

High Sensitivity RingLaser and G-Wettzell

There are few large frame(few m side) ring-lasers, in NewZealand, US and Germany

Geodesy and Geophysics

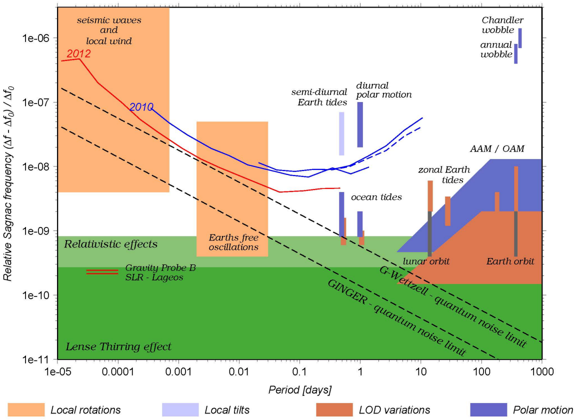


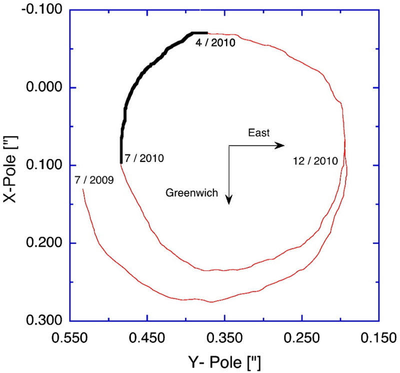
G in Wettzel is a monolithic device, a huge **'unique'** zerodur block, with mirrors optically contacted.

The Shot Noise of the RingLaser

The Shot Noise

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





U. Schreiber et al., PRL 107, 173904 (2011), highlighted and reported from Science, Nature Photonics News and Views, local newspapers in Germany and Italy as well

The data of G are combined with VLBI data (short term formal error reduced)

Limitation of the measurement

$$\Delta f_{Sagnac} = K_R(1+K_A)\Omega + \Delta f_0 + \Delta f_{BS}$$

K_R **resonator part**: depends from resonator geometry → $K_R = \frac{4A}{\lambda P}\left[1+\delta\left(\frac{A}{P}\right)\right]$

K_A **atomic part**: contribution of the active medium
(fluctuations of gain, pressure, gas temperature....)

Δf_0 **null shift**: due to amplitude non-reciprocities

Δf_{BS} **backscattering**: coupling of beams due to mirror impurities
or plasma inhomogeneities

Ω is the scalar product of whole vector $\mathbf{\Omega}$ with the normal $\mathbf{n}$ of the ring area

Problems connected with the non linearity of the Laser: BackScattering

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

we are developing Kalman filters to offline subtract backscattering

GINGER, Gyroscopes IN GEneral Relativity

In Collaboration with U. Schreiber (TUM), H. Igel (LMU) and JP Wells (ChristChurch NZ):
Geodesy-Geophysics-Fundamental Physics

in general, the light must follow:

$$g_{00}dt^2 + g_{rr}dr^2 + g_{\theta\theta}d\theta^2 + g_{\phi\phi}d\phi^2 + 2g_{0\phi}dtd\phi = 0;$$
$$\delta T = T_+ - T_- \approx 2\oint \frac{g_{0\phi}}{g_{00}}d\phi \neq 0$$

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:

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

$\Omega =$ angular velocity of ther Earth
$\omega =$ angular velocity of the instrument
$\theta =$ colatitude

in a ring-laser the measured quantity is:

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

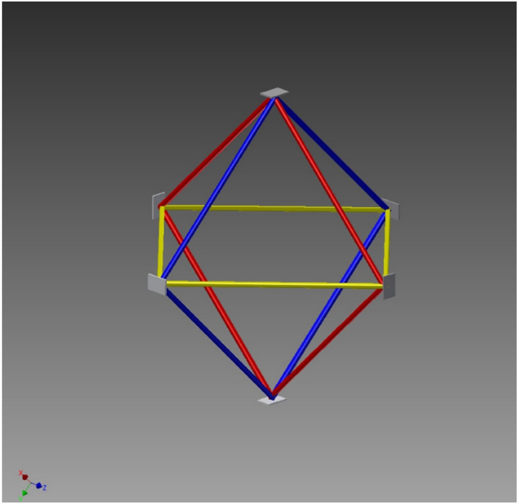
- pure Sagnac term (Earth Angular Velocity)
- Geodetic (de Sitter)
- Gravitomagnetic Term (LenseThirring)

- 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 measure 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

GINGER would be the first test (not considering the gravitational redshift measurements) of general relativity in one experiment on ground using light as a probe



What it is necessary to do in order to test GR

- Ω is a vector, so at least 3 independent rings are necessary, we propose 6 parallel ring 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 $6 - 10$ m)

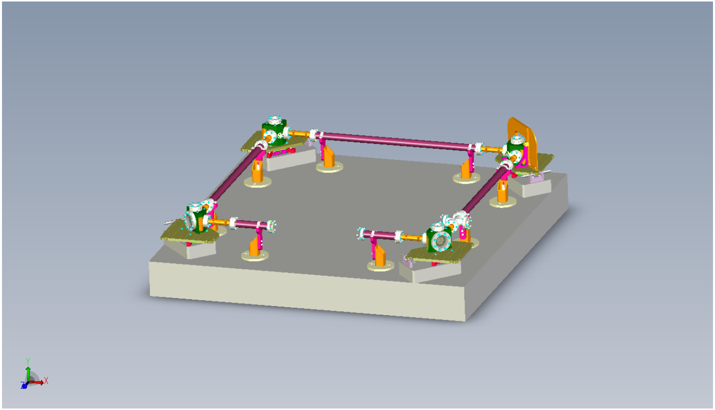
accuracy 1 in 10^{10}, necessary in order to cancel out the pure Sagnac term

The ring-laser has a mature technique, G Wettzell is a factor 4 far from what is necessary, but:

- tri-axial device
- increase as much as possible the integration time
- relative orientation of the planes must be monitored with nrad accuracy
- absolute calibration of the instrument

The heterolithic ring-laser

Necessary to make the 'heterolithic' structure as stable as the monolithic one G using control strategy. The new prototype GP2 in Pisa will be dedicated to this purpose and to investigate the systematics of the laser



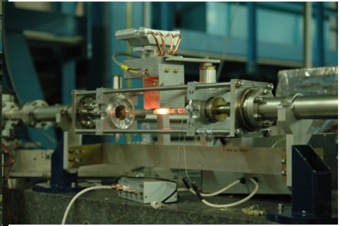
the LNGS installation

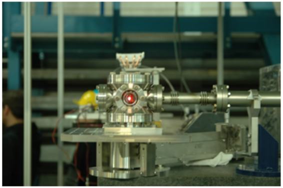
Our first prototype G-Pisa has been moved to LNGS last spring.
The aim of installation is qualify LNGS for GINGER

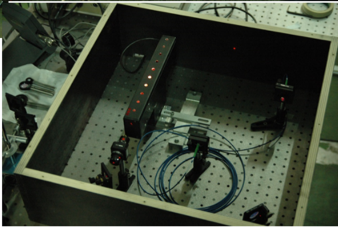
- first installation in Hall B, data taking ended in May
- restart data taking as soon as it will be possible to move it inside the ex Warp green cage
- in 2014 rearrange G-Pisa in order to form a 4m side ring-laser

in 2015 we should be able to say if LNGS is a good location

G-Pisa at LNGS (GINGERino)

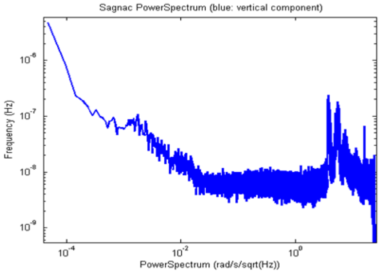




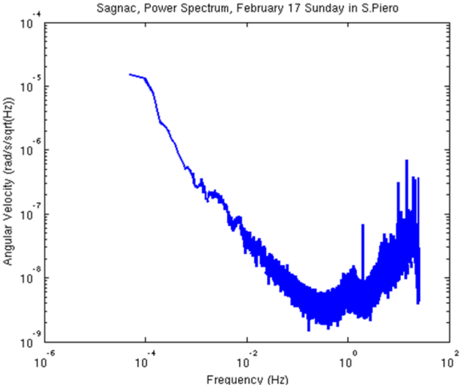


Main Characteristics

- Q of the cavity around 10^{11} (this depends on the mirrors, could be higher)
- PSD(noise floor) 4-5 nrad/s/sqrt(Hz) (sometime better...)
- Two seismometers are co-located (3 axis each)
- One nano-tiltmeter (2 axis)
- Few environmental monitors: temperature, pressure and humidity
- Below 10mHz the instrument is backscattering dominated



Typical PSD in S.Piero (Sunday February 17) and at LNGS



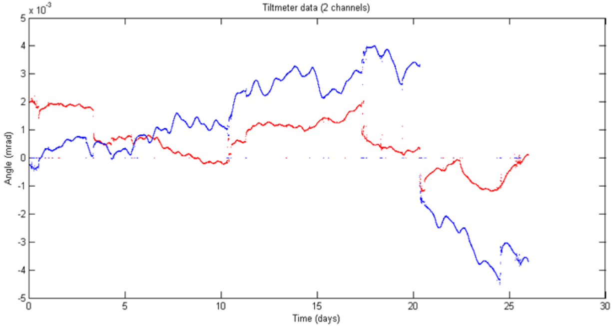
Some About TiltMeters
nrad

Environmental data

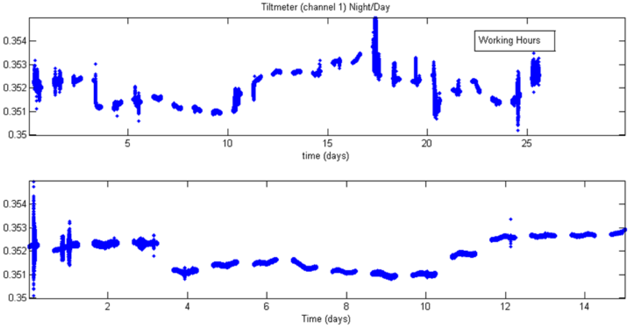
Stating time April 19, 0:00 UTC

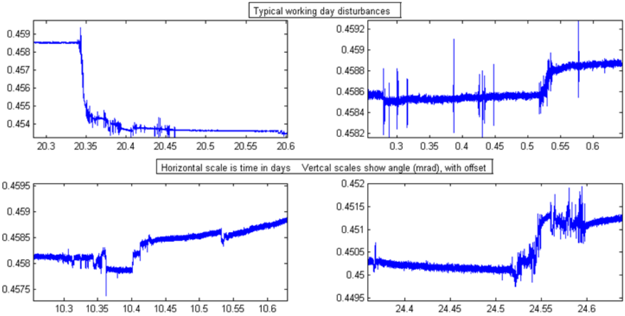
The Tiltmeter on top of the monument

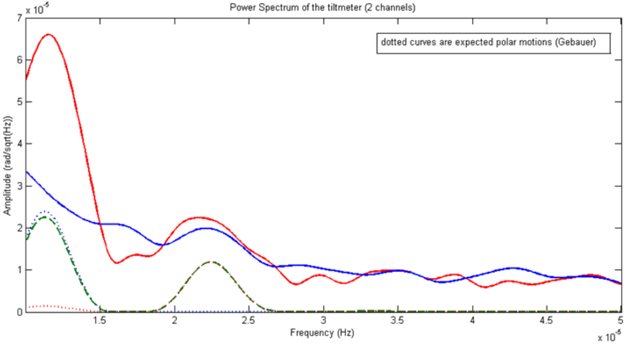
The Monument was not attached to the floor



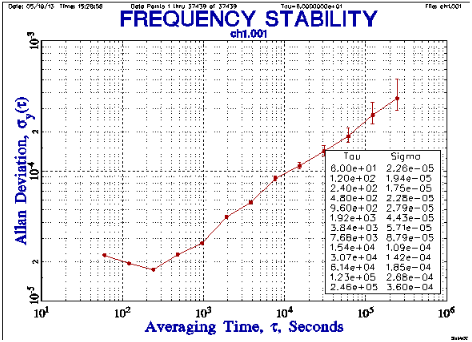
Tiltmeter data (2 channels)
x 10^-3
5
4
3
2
1
0
-1
-2
-3
-4
-5
Angle (mrad)
0
5
10
15
20
25
30
Time (days)


Tiltmeter (channel 1) Night/Day
Working Hours
0.354
0.353
0.352
0.351
0.35
5
10
15
20
25
time (days)
0.354
0.353
0.352
0.351
0.35
2
4
6
8
10
12
14
Time (days)

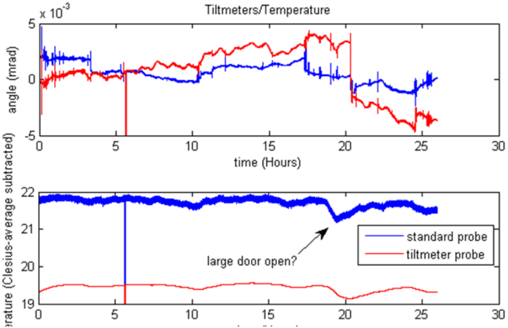

Typical working day disturbances
Horizontal scale is time in days   Vertcal scales show angle (mrad), with offset
20.3
20.35
20.4
20.45
20.5
20.55
20.6
0.459
0.458
0.457
0.456
0.455
0.454
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.4592
0.459
0.4588
0.4586
0.4584
0.4582
10.3
10.35
10.4
10.45
10.5
10.55
10.6
0.4595
0.459
0.4585
0.458
0.4575
24.4
24.45
24.5
24.55
24.6
0.452
0.4515
0.451
0.4505
0.45
0.4495

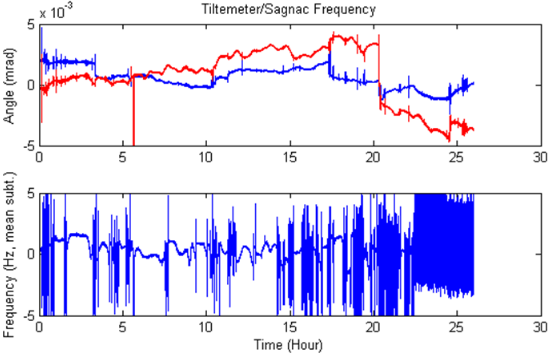

Power Spectrum of the tiltmeter (2 channels)
x 10^-5
dotted curves are expected polar motions (Gebauer)
Amplitude (rad/sqrt(Hz))
Frequency (Hz)
x 10^-5
0
1
2
3
4
5
6
7
1.5
2
2.5
3
3.5
4
4.5
5

Long Term TiltMeter stability working hours and big jumps have been eliminated



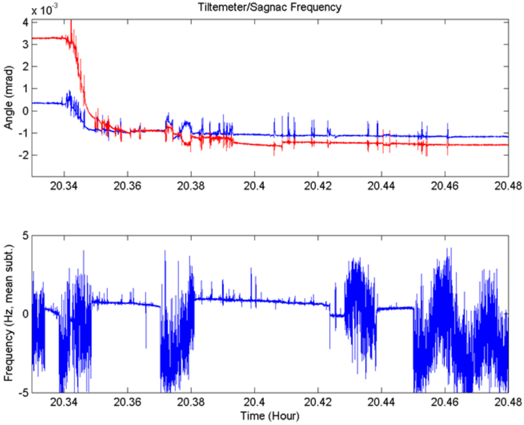
TIltMeter/Temperature-Monitors




Tiltemeter/Sagnac Frequency
x 10^-3
Angle (mrad)
5
0
-5
0
5
10
15
20
25
30
Frequency (Hz, mean subt.)
Time (Hour)

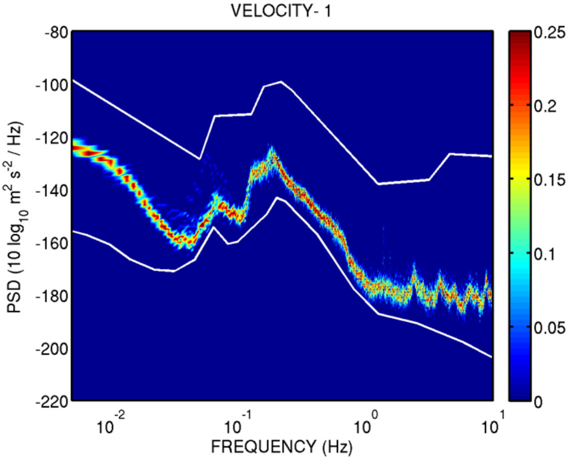
A detail

Is the monument moving with the tiltmeter?

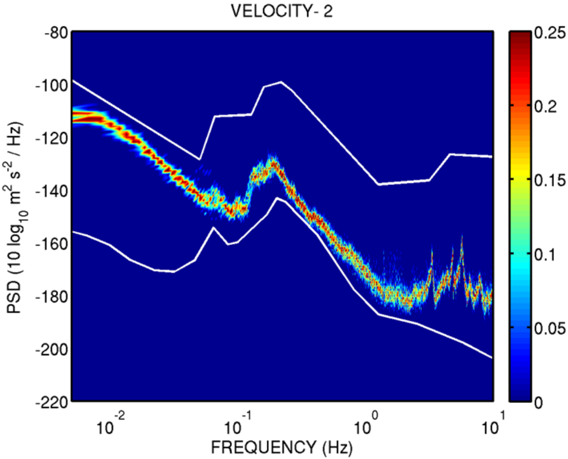


Seismometer STS-2 Streckeisen

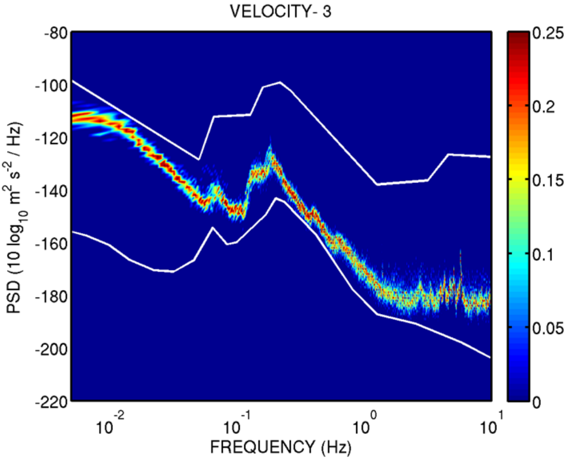
- ST-2 co-located with G-Pisa, on top of the granite table
- Confrontation with the USGS New Low Noise Model



G. Saccorotti INGV-Pisa

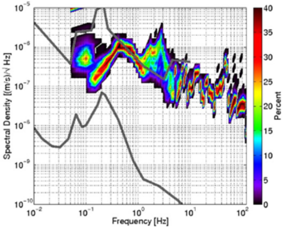


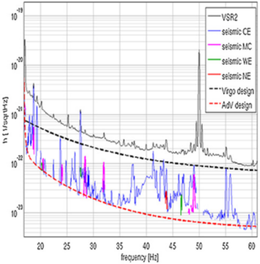
G. Saccorotti INGV-Pisa



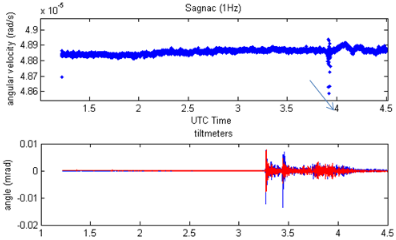
G. Saccorotti INGV-Pisa

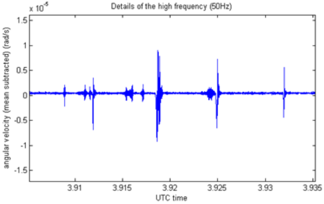
Typical PSD on the top surface (VIRGO)





EarthQuake April 19





Conclusions

- G-Pisa has been moved to LNGS with its equipment
- A first set of data (approx. 1 month) has been recorded
- The first set of data shows that LNGS is close to the typical LNM, this gives us a good motivation to go on with the measurements
- necessary to enlarge the ring up to 4m side (a factor about 9 improvement in sensitivity)
- together with our German colleagues we are working to make GINGER a reality