Title:

G-Pisa gyrolaser after 1 year of operation and considerations about its use to improve the Virgo IP control

Title description

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Authors:

M. Allegrini, J. Belfi, N. Beverini, F. Bosi, G. Carelli, A. Di Virgilio, E. Maccioni, M. Pizzocaro, A. Porzio, U. Schreiber, S. Solimeno and F. Sorrentino

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Authors	**Institute**	**Signature**
Author 1	INFN-Pisa	
Author 2	University of Pisa, Physics Department	
Author 3	University of Naples, Physics Department	
Author 4	CNISM,	
Author 5	University of Florence, Physics Department	
Author 6	Forschungseinrichtung Satellitengeodaesie der Technischen Universitaet Muenchen - Fundamentalstation Wettzell -	

Summary

Introduction

Gyrolasers are inertial sensors, based on the Sagnac effect: let us consider two electromagnetic waves traveling in opposite directions in a closed path L, for example a ring with radius R; if the ring rotates with angular rotation Ω the two waves travel times t_+ and t_- are different

$$t_+=2\pi R(c+\Omega R) \text{ and } t_-=2\pi R(c-\Omega R) ,$$

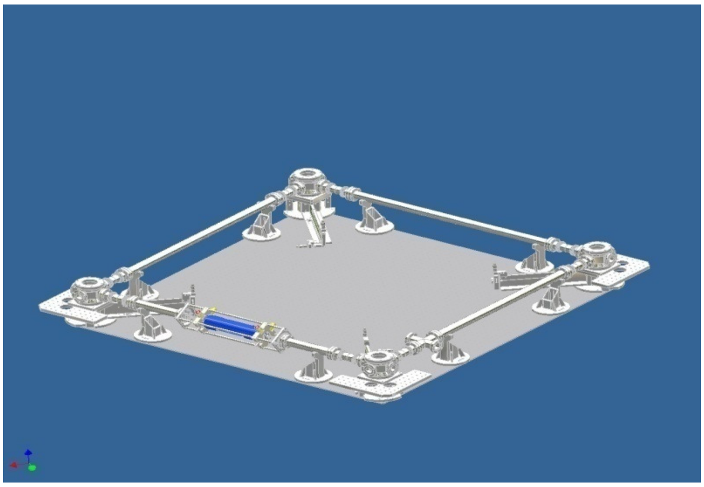
accordingly the path difference $\Delta L=c(t_+-t_-)\sim 4\pi R^2\Omega/c$ is proportional to the angular speed Ω.
A ringlaser or gyrolaser is a laser composed of a ring resonant cavity with active medium, working with two contra-propagating modes. If the ring rotates the two contra-propagating waves change their wavelength, the interference of the two modes, taken in one of the port of the ring, gives a beat frequency f which is proportional to Ω:

$$f=4\cdot A\cdot\Omega/(p\cdot\lambda),$$

where A is the area of the ring, p its perimeter, λ the light wavelength.

A lot of work has been done for the development of ringlasers by a collaboration among NewZealand (J. Stedman, University of Chrischurch) and Germany (U. Schreiber, TUM and Wetzell Laser Ranging Station), which so far has developed the most sensitive ringlasers. Several instruments are working at the moment with areas between 4 to 800 m^2, with high long term stability, used for geophysics and geodesy, with sensitivity in the range of 10^{-11} -10^{-12} rad/s/√Hz. G-Pisa has been done in collaboration with these two groups, with the aim of investigating middle size devices, important for possible applications and improvements of the Virgo suspensions.

Gyrolasers are based on resonant optical cavities; long term stability depends on the optical cavity itself. When the perimeter of the cavity changes the number of wavelengths inside the cavity changes and a mode jump is produced, and for a short time the instrument is blind. It then takes a few second to be back on (see. next paragraph). The gyrolaser G, 4m side gyrolaser built in Wettzell, in a underground controlled room, has been built in zerodur, namely a glass with expansion coefficient close to zero at 15 degrees centigrade. With less than 1 mode jump/year, it is thus remarcably stable, but rather expensive.
After the experience of G, a cheaper instrument called Geosensor has been developed. G -Pisa is an evolution of this model. Fig.2 shows one of the G-Pisa drawing. it is attached to a commercial breadboard, made of staninless steel, as the gyrolaser vacuum cavity itself. So far it has been working in horizontal position, but it could be positioned vertically as well. Fig.3 is a picture of G0, a ringlaser done with a similar mechanics, but attached vertically to the concrete made wall.



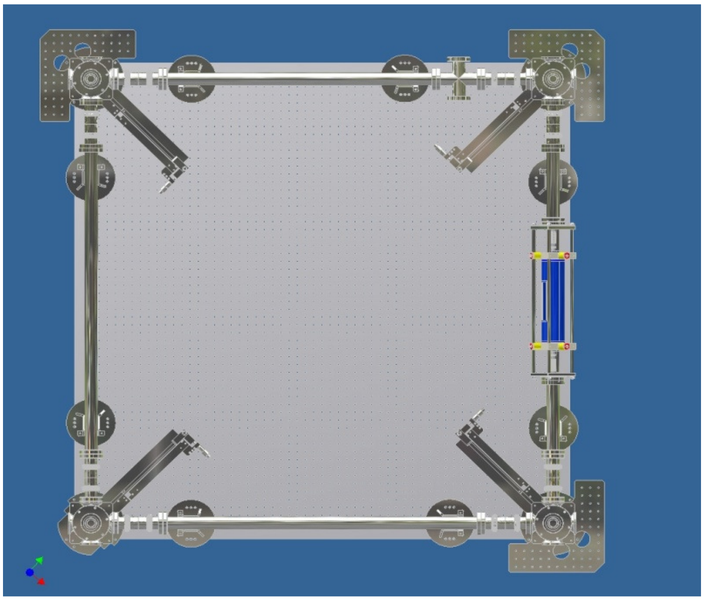


Fig1 Drawings of G-Pisa. G-Pisa has a stainless steel modular structure : 4 boxes, located at the corner of the square, contain the mirrors holders inside. The 4 boxes are connected by tubes, supported by vertical mounts. In the center of one of the tubes there is a pyrex insertion, a capillary with 4 mm internal diameter, approximately 15 cm long, which is the discharge chamber. The discharge chamber has micrometers necessary to allign the pirex capillary with the mirrors and the optical cavity. This design is flexible. G-Pisa can be scaled from 1.4 m down to 0.9m side with minor changes of the experimental set up. The mechanical system is attached to a stainless steel breadboard. Each box has a mechanical level used to align the optical cavity, 3 out of 4 have a support used for the optics : readout and controls.

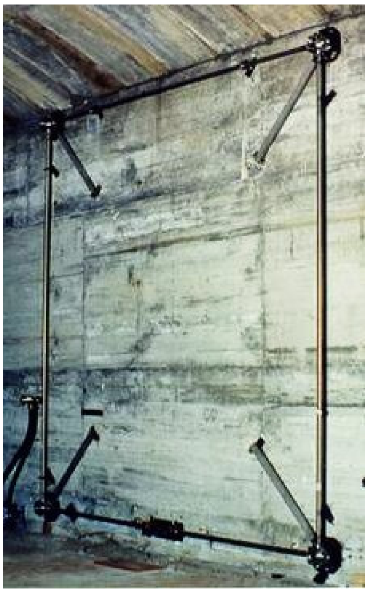
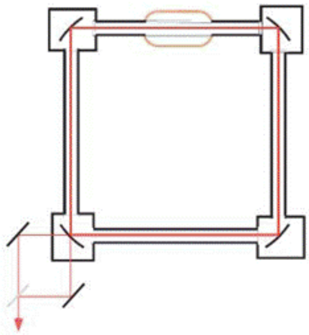


Fig. 3 G0 the gyrolaser which uses a design very similar to G-Pisa and mounted vertically in NewZealand

Inertial sensors, as gyrolasers and G-Pisa, are important to improve the performances of the test masse suspensions for future generations of gravitational wave antennas.



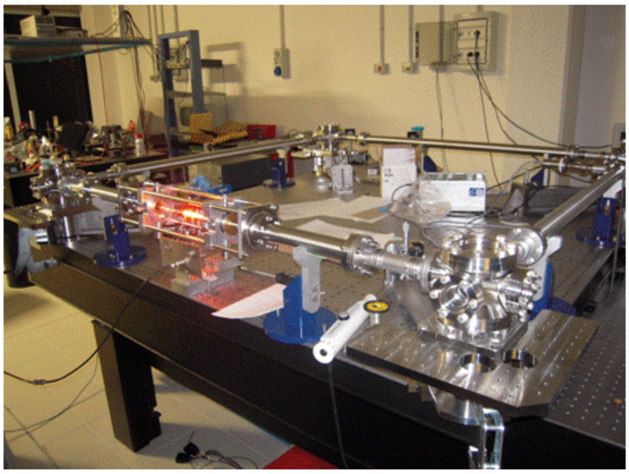


Fig.4 Top figure: schematic drawing of a gyrolaser: 4 mirrors define a squared loop, which is contained in a plane surface, all is contained in a evacuated tank filled with a mixture of He-Neon gas (approximately 7 torr). On the bottom left corner of the drawing the readout system is sketched: the two output beams are reflected by two mirrors and sent to a beam splitter, the two over imposed beams interference, detected by a photodiode (or photomultiplier) gives the Sagnac signal. Bottom: a photograph of the G-Pisa apparatus.

In G-Pisa, the Earth rotations gives a beat note of ~ 110 Hz, which is usually called Sagnac frequency, and is compatible with the latitude in Pisa and the size of our instrument (1.4 m side).
The Virgo Inverted Pendulum (IP) control is based on 3 linear accelerometers, which provide the signal to control the three translations and the rotation around the vertical axis. It has been already proposed to extend the control to the two tilt (pitch) modes, so far uncontrolled. The lack of this control causes troubles to the antenna sensitivity during severe weather conditions. The reduction of the low frequency angular motion of the interferometer mirror would facilitate the overall angular control and its importance could be even larger with improvements in the low frequency sensitivity. In the following we will not discuss the control itself, but will assume that the requirements for the IP control should be based on inertial sensors with sensitivity 10^{-8}-10^{-9} rad/$\sqrt{\text{Hz}}$ at 10 mHz.

Since July 2008 G-Pisa is operative and several measurements have been taken in different conditions. In the following we will discuss what we have learned and will try to answer the question if a gyrolaser similar to G -Pisa can be used to improve the performances of the Virgo Inverted Pendulum,
In this note the first paragraph shows several photographs of G-Pisa. The second pharagraph reports the sensitivity obtained so far by large ringlasers in general and by G-Pisa in particular, giving requirements for the device which should be used for IP control.
The third paragraph discusses the limits imposed by thermal noise on sensitivity.
G-Pisa has been compared with a mechanical 3-axis high sensitivity accelerometers, provided by V. Iafolla, the fourth paragraph reports the result of this analysis.
The fifth paragraph describes the characteristics of G-Pisa measured so far.
The sixth paragraph outlines the main design characteristics for a gyrolaser for the tilts control of the Inverted Pendulum of the Virgo SuperAttenuators (SA).
The seventh paragraph shortly addresses the possibility to use FOG.
At the end conclusions come.

1. A Tour around G-Pisa

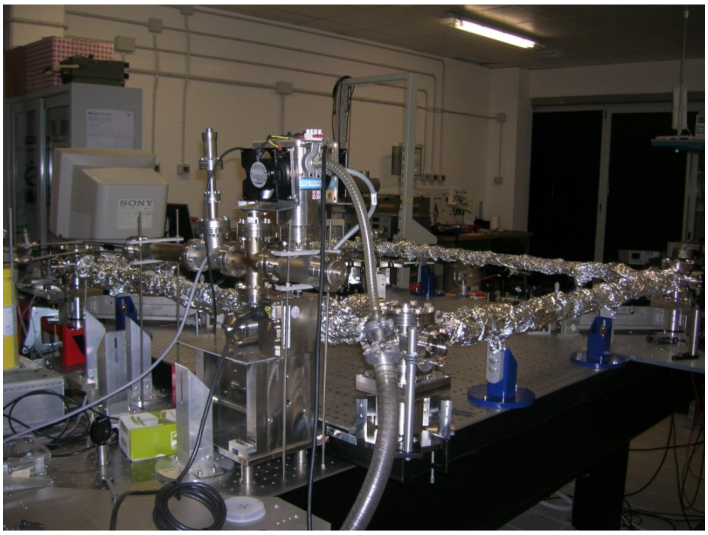


Fig.5 Overview of the gyrolaser on top of the breadboard on the optical table. The turbo pump and some of the vacuum circuit are visible

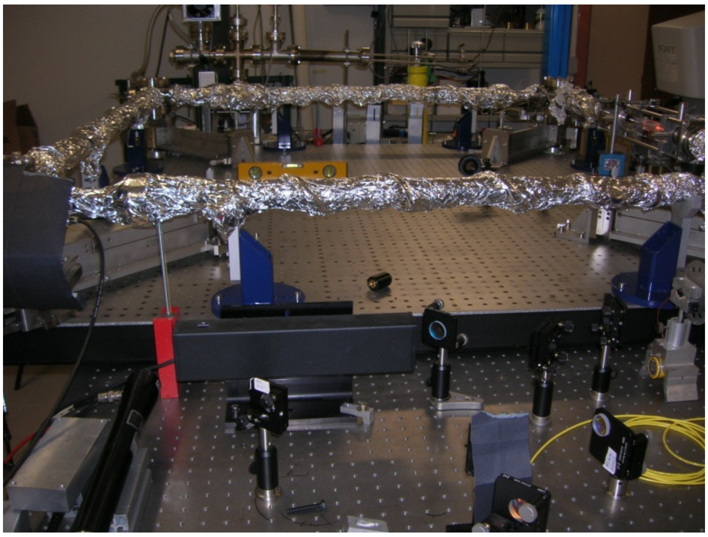


Fig.6 The gyrolaser, and in front of it the Fabry-Perot cavity to study the multimode operation and the frequency stabilized laser.

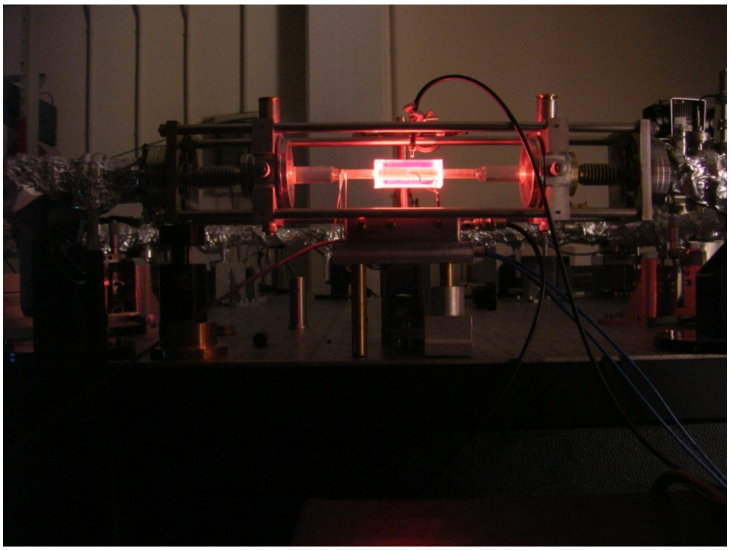


Fig.7 The discharge, the probe used to study the discharge. It is used to measure the Hydrogen contamination.

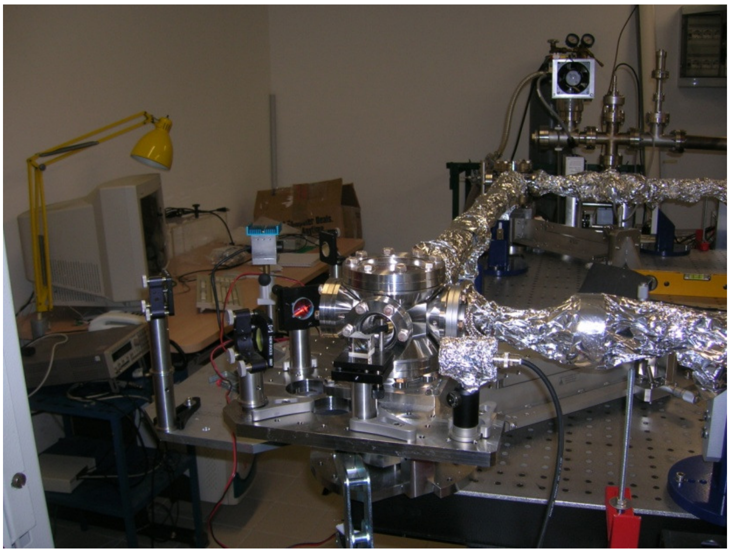


Fig. 8 The output signal circuit: the cube beam splitter is shown with the photodiode at its right

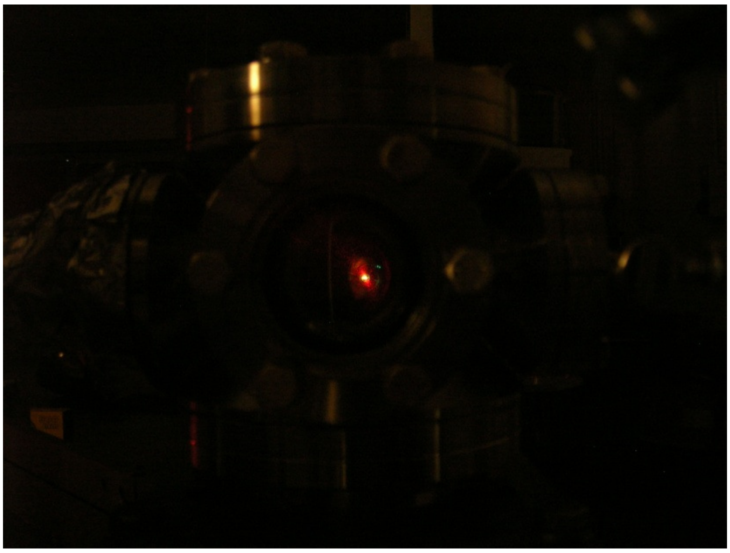


Fig. 9 A photograph of the light coming out from one of the corner mirrors.

2. Gyrolasers present sensitivity, shot noise limits and G-Pisa performances

Ringlasers are inertial sensors sensitive to angular speed. The output signal is the beat note frequency f, which is proportional to the angular speed Ω of the planar device. For a ring with area A and perimeter p; $f = 4$ A/(p λ) Ω, where λ is the wavelength of the light. Gyrolaser sensitivity is limited by the shot noise (sn), and the minimum measurable angular speed difference for a 1 second measurement is:

$$\Omega_{sn} = \frac{c}{2\pi KL}\sqrt{h\nu\mu\frac{T}{2P}}$$

where c is the speed of light, h is the Plank constant, ν the light frequency, μ and T the absorption and transmission of the mirrors of the gyrolaser, P the output power and K= 1.58 10^6 L a scaling factor for square ring cavities. It is important to point out that there is not much room for improvements : absorptions of good mirrors are around few ppm, the power of a gyrolaser cannot be increased by order of magnituds since the laser has to be set very close to gain threshold in order to have a clean monomode operation and to be far from cahotic regimes. Fig. 10 below shows Ω_{sn} as a function of the ring side At 10nW of power, three different curves are evaluated scaling the absorption: top curve bad mirros (10ppm), middle curve 1 ppm and lowest curve 0.1 ppm absorption.

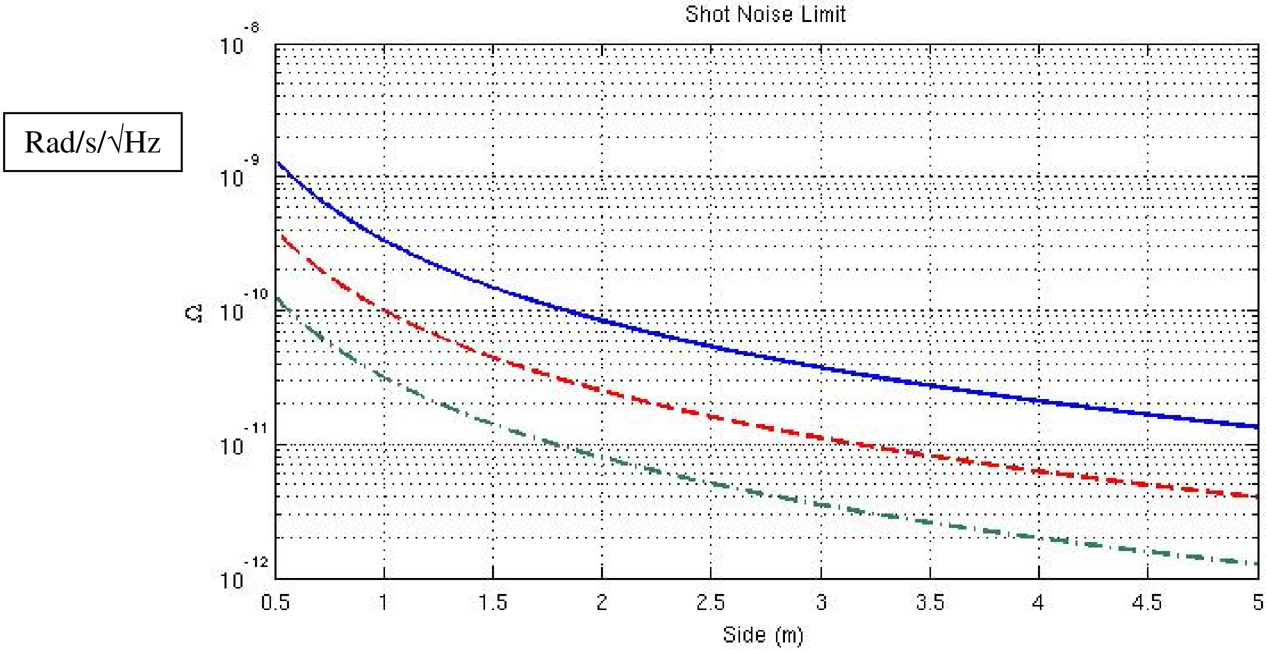


Fig. 10 Ω_{sn} as a function of the ring side, 10nW of power, top curve bad mirros (10ppm absorption), middle curve 1 ppm and lowest curve 0.1 ppm absorption.

The requirements for the IP control sets a device with side of the order of 0.5-1.2 m (middle curve) side. The main problem of gyrolasers is the backscattering, which can couple the two modes of the laser. In this case the two modes are said locked : they have the same frequency, there is not beat note, the Sagnac frequency disappears and the gyrolaser has no signal. The backscattering is reduced increasing the size of the ring.
For this reason square ring has to have side structure larger than 1m, at least with presently available mirrors quality. In summary, a 1m side device, located in Pisa has $\Omega_{sn}=10^{-10}$ rad/s√Hz, which is equivalent to an angular spectral sensitivity of about $2\cdot10^{-9}$ rad/√Hz at 10mHz. and the beat note f induced by the Earth rotation will be around 80 Hz.
The reconstructed differentiated phase $d\phi/dt$ of the output beat note is :

$$d\phi/dt= L/\lambda\ (\Omega_{Earth} \sin(\theta_0+\delta\theta(t))+\omega(t) + \text{shot-noise}$$

where θ_0 is the angle between the Earth rotational axis and the gyrolaser axis; if the device is horizontally arraged it is the local colatitude, $\delta\theta(t)$ is the jitter of θ_0 and $\omega(t)$ is the angular rotation to be measured.

G-Pisa is under study since July 2008, see paragraphs 4 and 5. The cavity is evacuated and filled with a 50% mixture of 2 isotopes of Neon (20 and 22), and Helium 1 :10. Total gas pressure is around 600pa.
The discharge is excited by a radio frequency. The original system was based on inductive discharge, which has been extensively tested worldwide. In our system we have adopted a

capacitive based excitation (see Fig. 7), which has the advantage of reduced electromagnetic induction. In G-Pisa the frequency of the discharge is 110MHz. No appreciable differences have been observed so far as a function of the excitation frequency or the inductive or capacitive based excitation methode. Each mirror box is equipped with a precise mechanical system to align the mirrors.

Typically the gyrolaser works well for 3-4 weeks, until the contamination due to Hydrogen outgassed from the walls becomes too high, and the system stops lasing. So, usually after 4 weeks the cavity is evacuated and refilled with a fresh gas mixture. The working time can be extended backing the mechanical structure and using passive getters pumps. At the moment we have backed our system and in the near future getters pumps will be used as well. Based of the experience of our German collegues, with this improvements (backing the tank and adding getter pumps) the gas lifetime is expected to increase its operation time to 3 months.

The stability of the mechanical system has proved to be very high, it is not necessary to adjust the mirrors continuusly, usually the alignment is done at each gas mixture refilling, and remains rather stable. Small range adjustement are performed on a daily bases in order to decrease the voltage threshold of the capacitive discharge of the laser.

Several measurements have been done in different conditions, and with different readout: using mirrors and beamsplitter as shown in fig.3 or using two single mode optical fibers forming a 2X1 coupler.

In fig.11 top a typical measurement is shown. The interruption after 100 seconds is due to mode jumping caused by temperature change. After 20 seconds the gyrolaser is back on. Fig. 11 bottom shows an enlarger view of the top curve, the oscillation due to the Earth rotation (the beat note for G-Pisa is 111 Hz) is well observable.

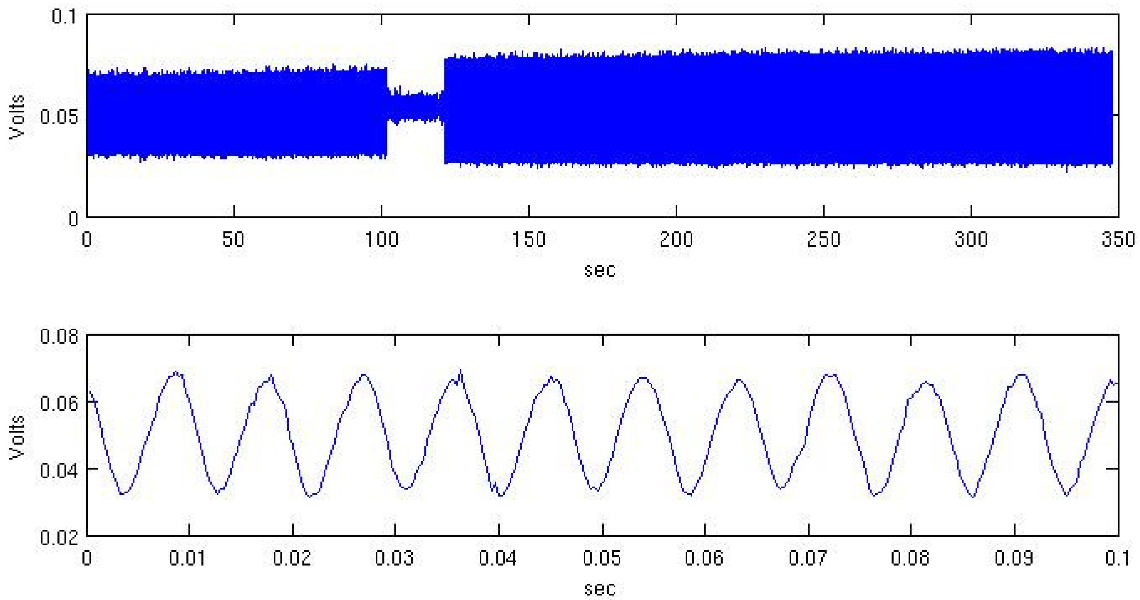


Fig.11 top curve: typical beat note due to the Earth rotation, about 110 Hz in G-Pisa, ad a function of time; a mode jump is taking place after 100 s. Bottom curve shows several cycles of the beat note.

The signal has been acquired with a standard ADC board (16 bits) and a Labview program.
We have used several methods to reconstruct the signal. The first method is to bandpass filter the data around the Sagnac frequency, take a few seconds and evaluate with an AR (Auto Regressive) algorithm the Sagnac frequency. Usually this method has a bandwidth below 20Hz, is very good to reconstruct very low frequency signals, very fast, so it can be used on-line. G-Pisa is a test instrument, it is an instrument to learn the technique more than to perform specific high sensitivity measurements, since it is located in a noisy environment. It is mounted on top of an optical table inside a standard research laboratory, without temperature stabilization; usually we acquire data for 1-2 hour and analyze the data off-line usind two different methods. The first method consists in using the inverse of the sin function: in this case amplitude fluctuations are removed normalizing each wave function to +/-1. The other extracts the phase using the Hilbert transform. In both cases the data are high pass filtered at 80Hz, with a standard 3 poles butterworth filter. The phase reconstructed is constrained between $+/-\pi$, using standard matlab routines (unwrap) or with other simple algorithm the phase is reconstructed as a function of the time; $\omega(\tau)$ is found differentiating the reconstructed phase and subtracting the Earth bias, which is a constant term. The two off-line methods have been compared with the on-line, based on the AR algorithm, and it has been checked that they are equivalent. The advantage of the off-line method is that the bandwidth is much larger, the response can be studied up to several kHz, depending on the acquisition rate, usually 3kHz for G-Pisa. The measured Earth angular speed Ω_{Earth} is consistent to what expected.
Measurements have been taken in different conditions, with and without optical fibers in the optical readout, different acquisition time, dampers of the optical table on and off (this changes the large low frequency resonance, which is around 1 Hz when the dampers are on). The best low frequency performance has been obtained in a late evening measurement. While the worse was done with optical fibers not well attached to the mechanical structure. Fig. 12 shows the power spectrum of the reconstructed $\omega(t)$ (Ω_{Earth} has been subtracted), when the environment was less noisy. The two parallel lines are the IP control requirements, the blue measurement is a factor 10 above the target at very low frequency, but it is the noise of the experimental set up, rather than the noise of the ringlaser. The noise above 10 Hz is probably affected by the power fluctuations and non linearities present in the system, while the low frequency one is a real motion, which depends on the experimental set-up and activities around the laboratory. In the same picture a typical power spectrum of G, the gyrolaser in Wettzell is shown. The sensitivity of Wettzell is well below the requirements for Virgo IP control, even taking into account a factor 3 in order to compensate the fact that G has 4 m side.

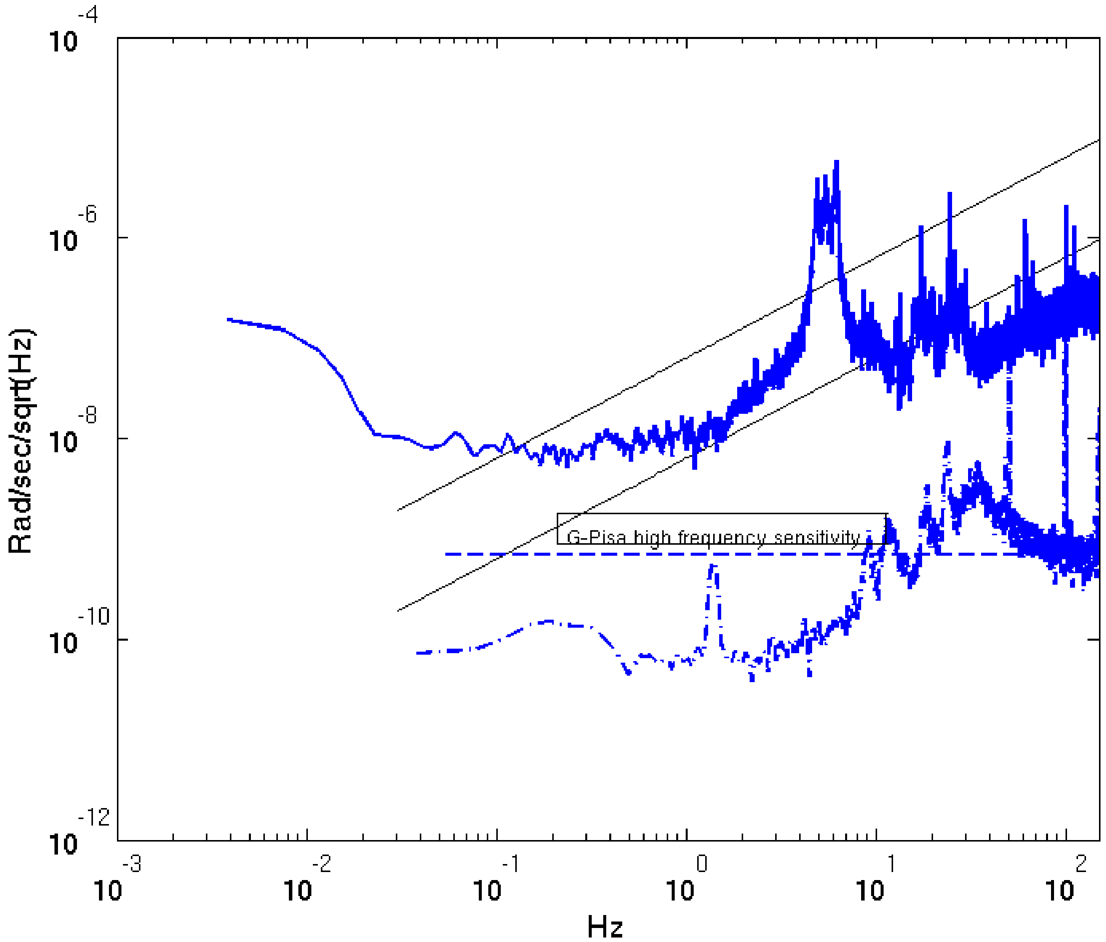


Fig. 12 Top continuous curve, one of the G-Pisa measurement with lower noise below 1 Hz (the large peak structure around 5-7 Hz is due to the optical table legs). Bottom curve, continuous-dotted line is a measurement taken with G, the 4m ring in Wettzel. The horizontal dashed line is the low frequency extrapolation of the sensitivity taken above 1Hz in G-Pisa data. The two parallel lines are the sensitivity requirements for the Virgo IP control.

Fig. 13 shows several measurements, taken in different conditions with the optical table isolated and not isolated from ground motion. The large peak around 2 Hz is due to the optical table rotation, which dominates when the table is vertically isolated. The best sensitivity curve has been taken at night, when the environmental noise is rather low.

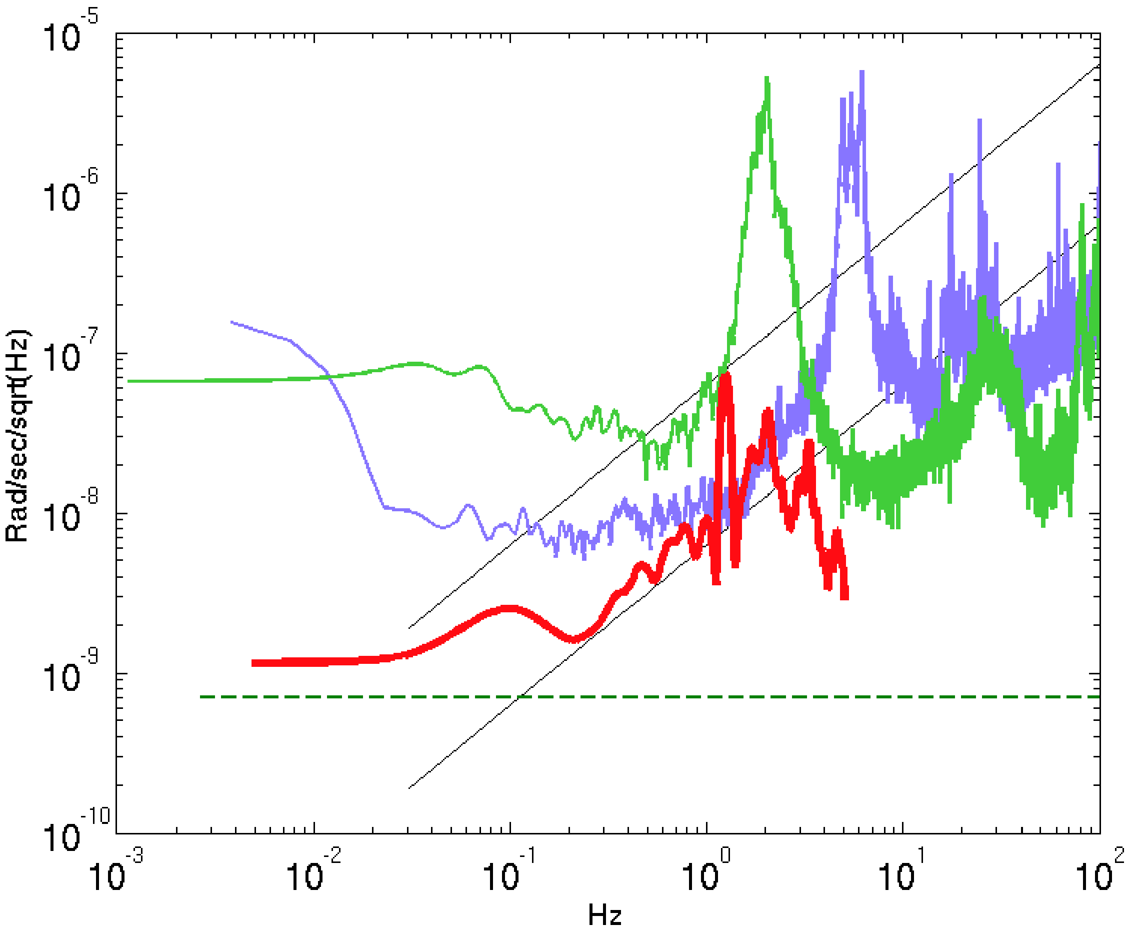


Fig13 Comparison among the best low frequency measurement with a typical spectrum taken with the optical table dampers working. The large peak around 2 Hz is a rotation of the whole optical table. The best measurement (in red and with 5Hz bandwidth) has been taken at night. The dotted green line is the low frequency extrapolation of the shot noise measured above 1.4kHz.

The blue line was one of the first measurement, taken in the evening. The large peaks region around 5-10 Hz was due to the optical table legs resonances, the table was not isolated with its vertical dampers.
The two beams coming out of the gyrolaser can be brought together to interfere in several ways, using a beam splitter or a prism. The use of optical fibers could have several advantages: it can be used to bring the light outside of a vacuum chamber in case the gyrolaser is positioned inside a vacuum chamber, as it should be if used for the Virgo IP control. We have checked that a two optical fibers system with integrated beam splitter can be used as well. In this case care has been used in order to isolate the fibers from vibrations. It has been checked that the low frequency response is the same, and the conclusion is that at the present level of noise of G-Pisa, i.e. about 10^{-9} rad/s/√Hz, an optical fiber system can be used to extract the Sagnac frequency.

We have investigated the response of our system at higher frequencies, which are usually less affected from noise. Fig.14 shows the very high frequency part of the spectrum, $7\cdot10^{-10}$ rad/s/√Hz, this noise level is compatible with the shot noise of our instrument and, extrapolated at low frequency, is well inside the limits of the IP control requirements (see green line in Fig. 13).

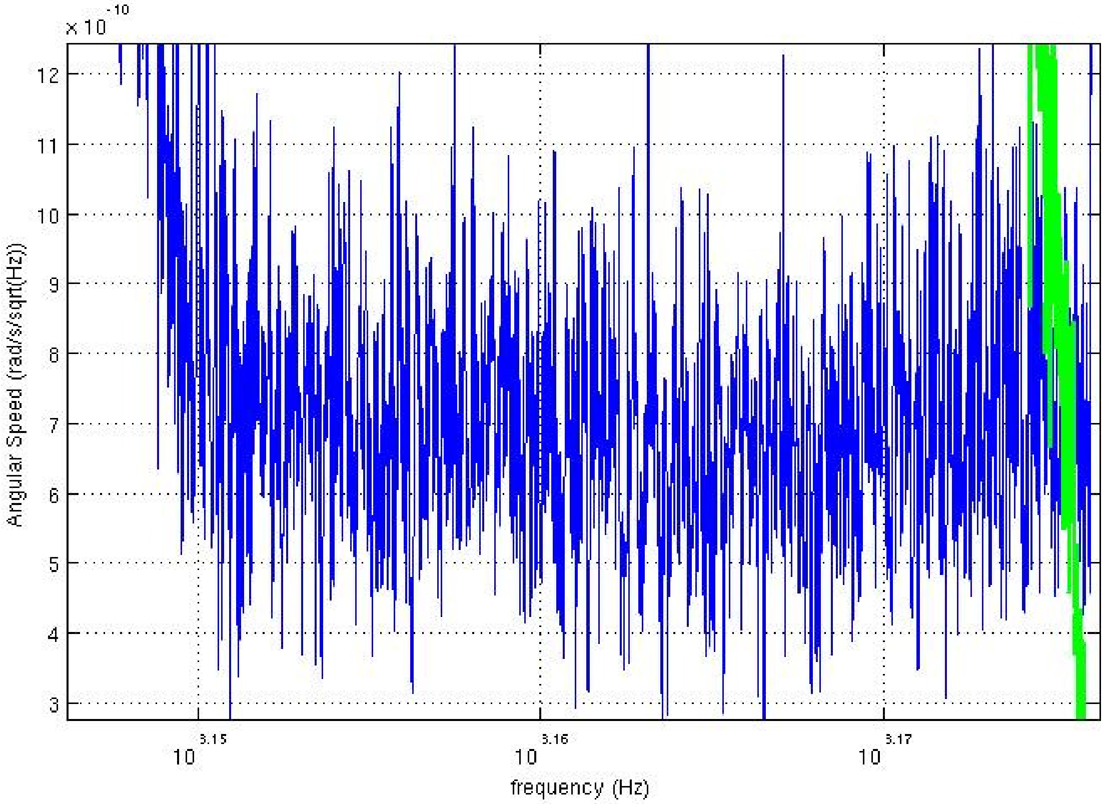


Fig. 14 Power spectrum at high frequency (~1400-1500 Hz)

We have performed a continuus run, monitoring the temperature, to investigate the effect of the temperature changes and the long term stability; 30 mode jumps per degrees have been measured, which is compatible with the stainless steel thermal expansion. The effect of such variation on the calibration of the Sagnac, which depends on the ratio area/perimeter, can be easily calculated to be about $2\cdot10^{-6}$. The spread of the measured Sagnac frequency is much larger than the effect due to temperature, and it is independent from temperature changes.

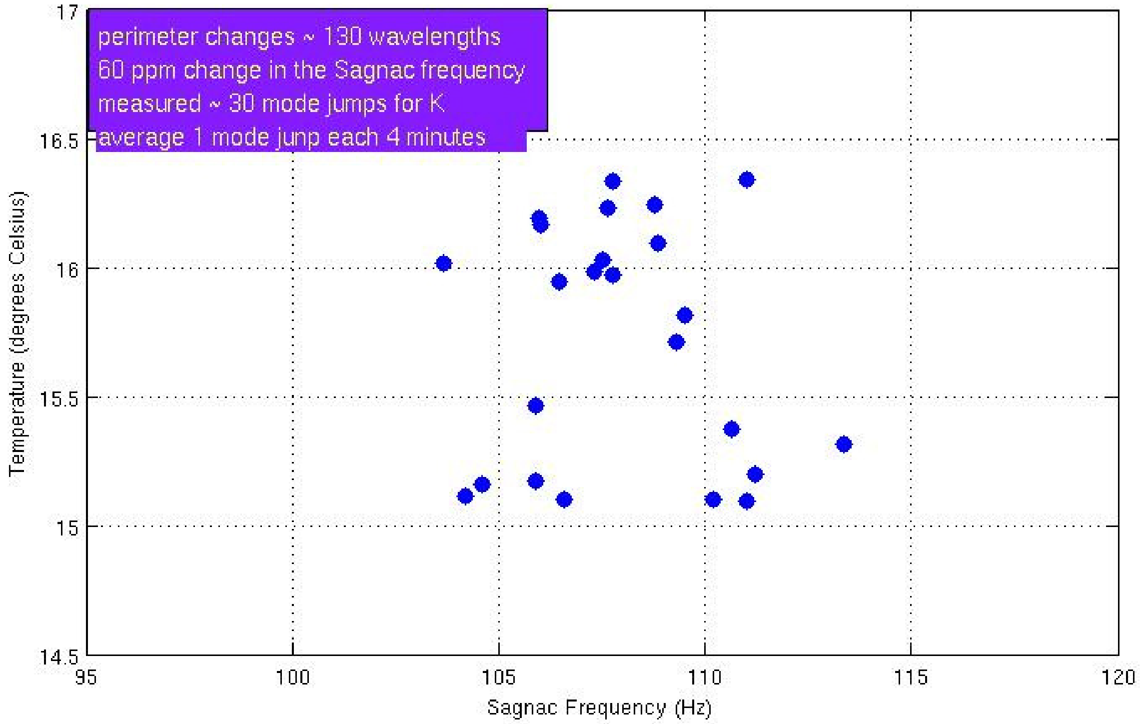


Fig.15 The Sagnac frequency versus the temperature of the laboratory

3. Short discussion about the mechanical vibration of the mirrors and the thermal noise in general

In a ring laser the two counter-propagating modes follow the same path, in this way several noise sources are reduced. The independent mechanical vibrations of each mirror do not affect the sensitivity since photons traveling in opposite directions feel the same vibration. Similar argument can be used for the path length changes due to density fluctuations of the gas mixture, filling the gyrolaser volume.

Mechanical vibrations of the structure around the gyrolaser axis, induced by thermal noise, will be detected by the instrument, and will be the limiting noise of the instrument. Let us give an order of magnitude of this noise source. The mechanical structure has several modes around its simmetry axis, to give an order of magnitude, let us consider the lower resonant mode. The whole structure has a momentum of inertia of roughly 162 kg m^2 (a ring with radius 0.9 and total mass of 200 kg), and resonance frequency 100 Hz, which are conservative values ; figure below shows the expected thermal noise, which has been evaluated applying the fluctuation dissipation teorem.

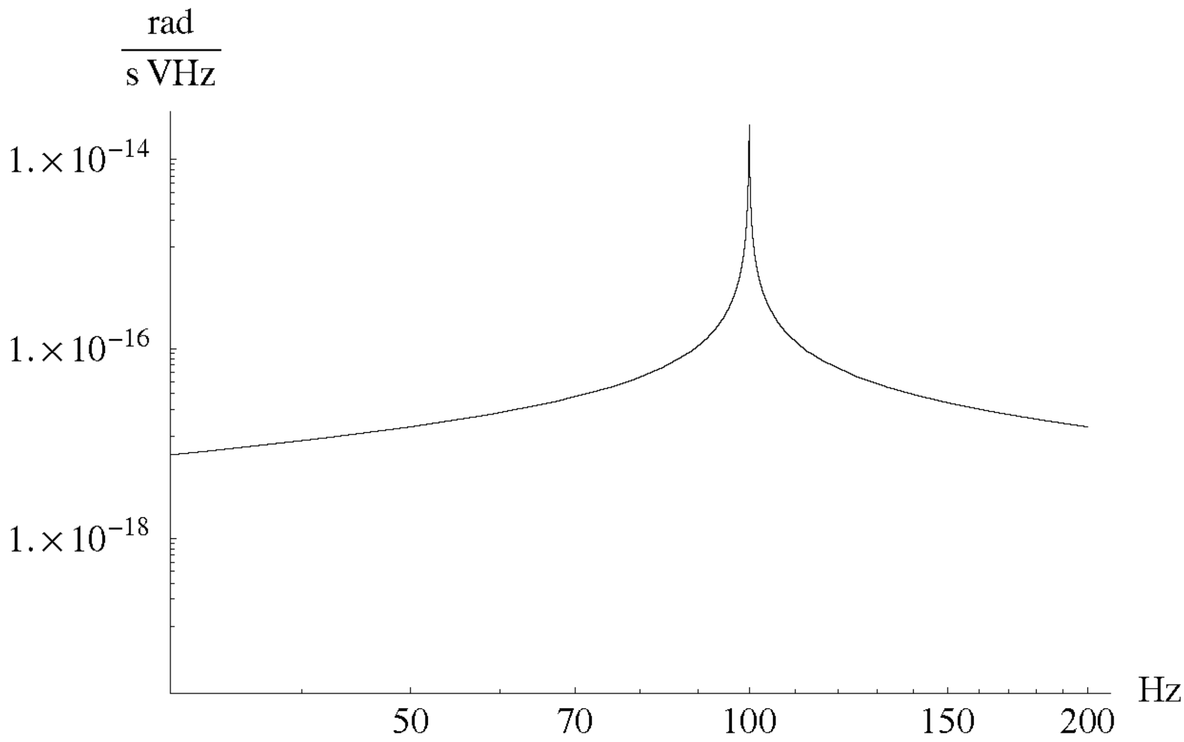


Fig. 16 Rough estimation of the rotational thermal noise.

Fig. 16 shows that the expected thermal noise is several order of magnitude below the present and near future sensitivity of such instruments.
In general large vibrations of the mirrors can affect the amplitude fluctuations of the two modes, changing the cavity set up and can affect the response through diffused light. Mirror vibrations, changing the distance among mirrors, change the area and perimeter of the instrument as well. A vibration δL induces a noise signal $\delta\omega = \delta L/L\ \Omega_{Earth}$; for example for δL=1μm, L=1 m, $\delta\omega$ is about 10^{-10} rad/s at the latitude of Pisa. This noise is not particularly important for a gyrolaser used to control the IP tilts, but it should be considered for more sophisticated measurements, as the LenseThirring effect detection.

4. Comparison between 3-axis sensitive accelerometer system and G-Pisa (in collaboration with V. Iafolla and E. Fiorenza)

The performance of G-Pisa has been compared with a very high sensitivity 3-axis linear accelerometers system, with high linear resolution up to 10Hz. The reconstructed phase is sensitive to Earth angular speed, which for our applications can be considered constant, to the angular speed ω of the gyrolaser itself and to the tilt respect to the Earth rotational axis, which enters in the measurement multiplied by Ω_{Earth}, i.e. depressed by a factor 10^{-5} , as reported above.

The accelerometers were located on the top of the ringlaser breadboard, off axis and close to the middle of one of the ring side, as sketched in fig. 17. In this way accelerometer 2 was sensitive to the coordinate y and to dω(t)/dt, accelerometer 1 to coordinate x and accelerometer 3 to the vertical coordinate. Since accelerometers have output proportional to the accelerations and to tilts, we have to take into account that accelerometer 1 is sensitive to θ(t). Accelerometer 3 is not as good as the others, and it should be sensitive to both tilts.

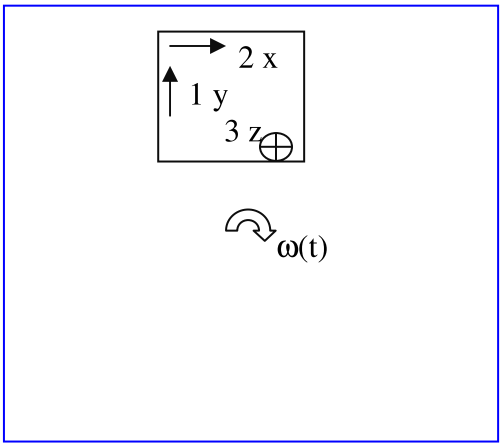


Fig. 17 Sketch of the relative position 3 axis accelerometric system and gyrolaser.

Figure above is a schematic view of the location of the 3-axis accelerometers inside the gyrolaser perimeter. The large square perimeter identifies the ringlaser, and the small box the 3-axis accelerometer. Accelerometer 1 is sensitive to the second time derivative of coordinate x, accelerometer 2 to the second derivative of y and 3 to the second derivative of the vertical z. Accelerometer 1 and 3 are sensitive to θ(t) and accelerometer 1 to dω(t)/dt.

The aim of the analisys is to understand if the noise level measured by the gyrolaser is of mechanical origin (i.e. is a real motion or a limit of the instrument), and measure the cross-coupling among orthogonal degrees of freedom

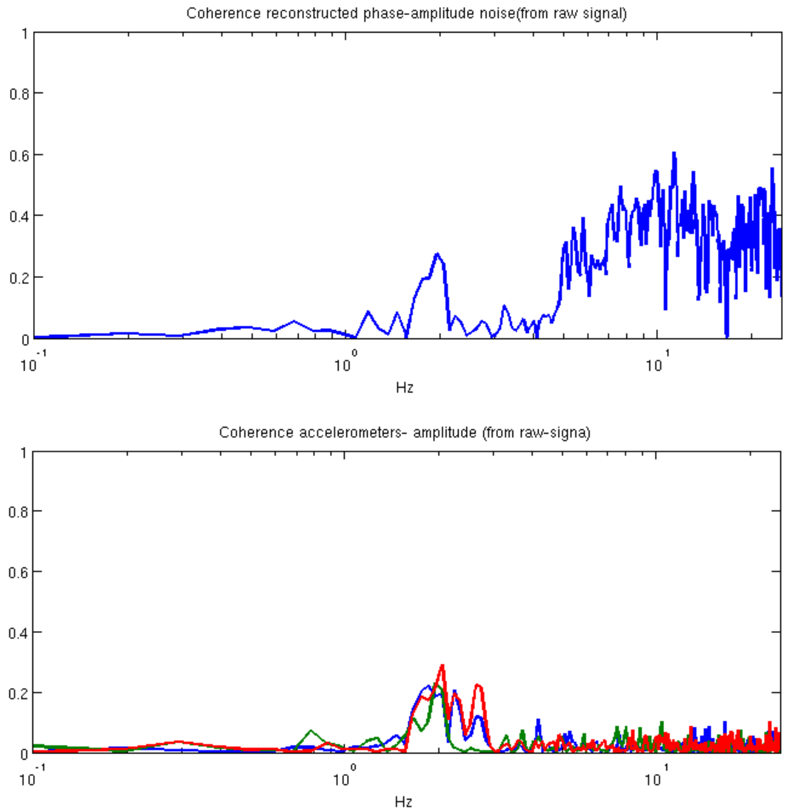


Fig. 18 Top coherence reconstructed ω(t) and amplitude noise of the laser

In the following the result of the analysis will be shown :
Fig.18 shows the coherence between the reconstructed ringlaser signal and the output power, which is betweenn 20% and 40% above 5 Hz, This is probably due to diffused light modulated by the mirrors vibration, which affects the output power and the response of the gyrolaser. The second figure shows the coherence between the accelerometers and the Sagnac, the coherence is rather poor, with the exception of the 2 Hz mechanical peak, where the optical table has a rotational resonance.

Fig. 19 shows the coherence between different accelerometers, couplings among accelerometers are clearly rather high up to 30Hz.

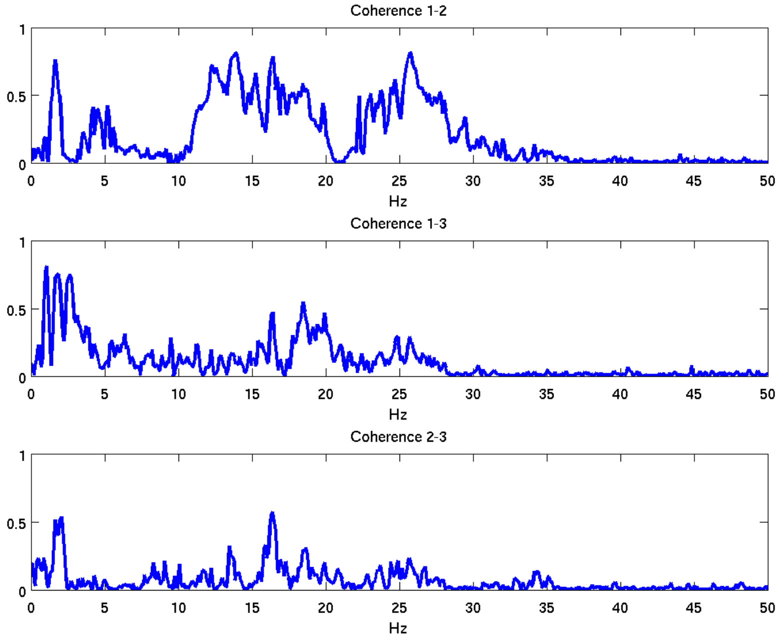


Fig. 19 Coherence among accelerometers.

It is important to point out that the mechanical accelerometers signals exhibits a rather large coherence among each other.

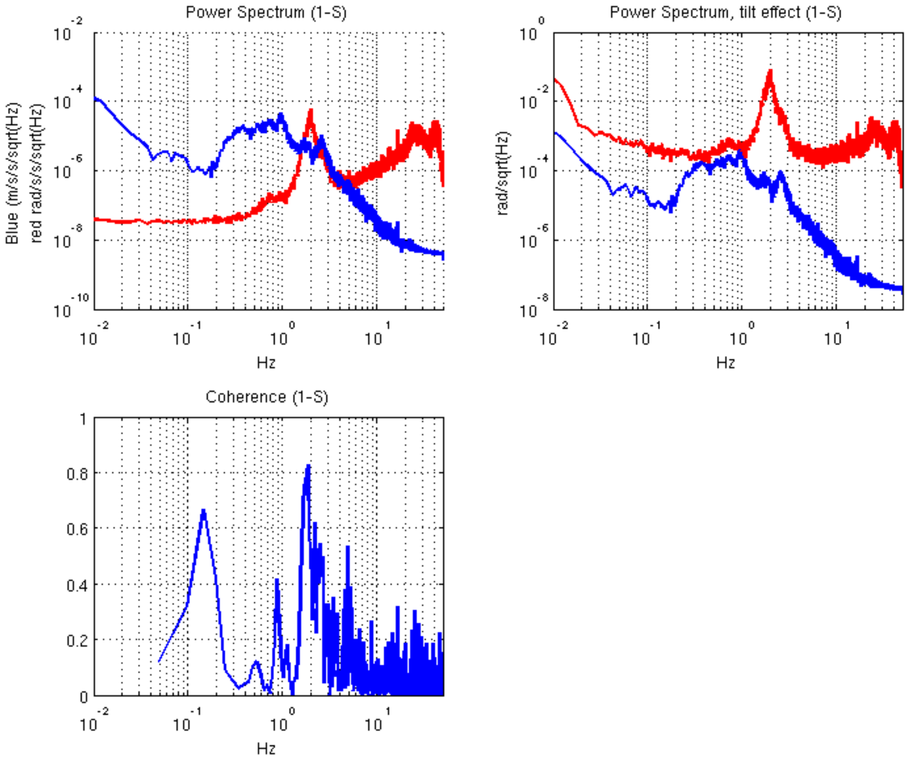


Fig.20 Top left linear acceleration evaluated with accelerometer 1 (blue) and Sagnac (red). Top right signals interpreted as tilts. Bottom coherence accelerometer Sagnac coherence

Let us compare each accelerometer with the gyrolaser output, the focus will be in the lower frequency region, taking into account that the large 2 Hz peak is due to the optical table mechanical resonance. Accelerometer 1 is not sensitive to ω, but it is sensitive to the tilt with the Earth rotational axis. Top left picture shows that the sagnac signal is inconsistent with tilt and motion around x, while top left shows that probably the region just below 1Hz could be due to tilt motion with respect to the Earth rotational axis. It is interesting the coherence peak near 0.1 Hz, where the accelerometer signal has a minimum, it could be a tilt motion, in a region where other noise sources dominates, since in fig. 20 up left the two curves are far apart .

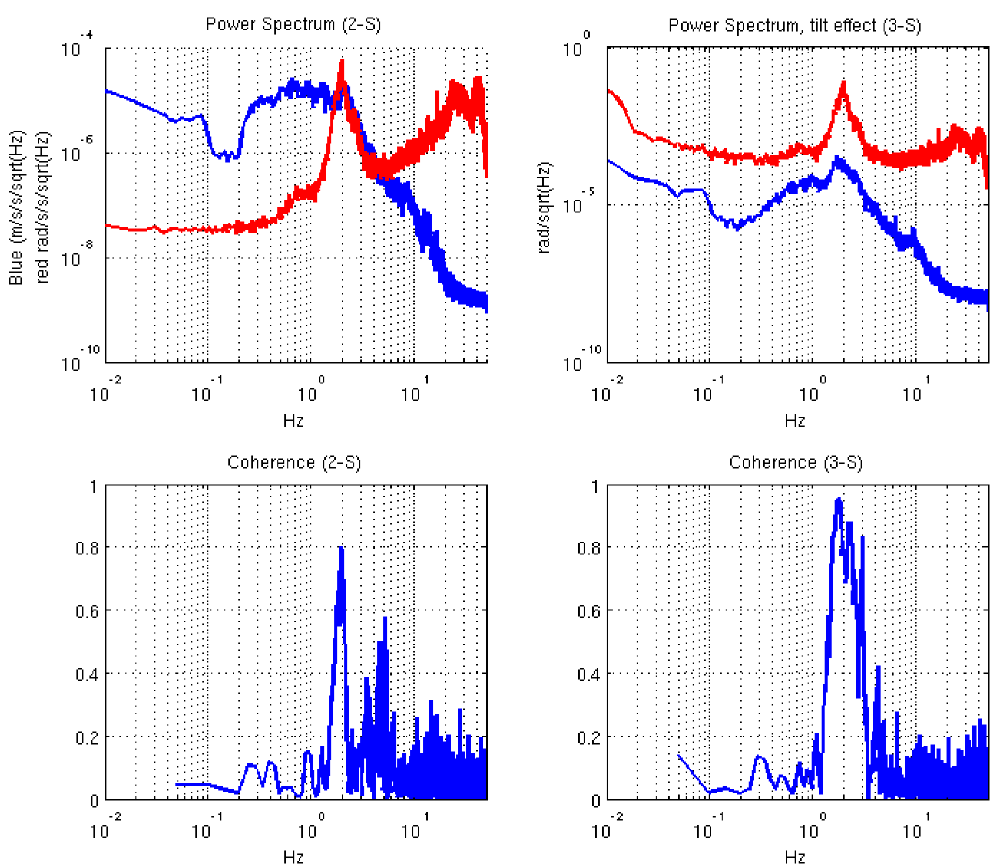


Fig. 21 Right comparison with accelerometer 2, top linear acceleration and Sagnac, bottom coherence between the two instruments. Left pictures : top tilts coming from accelerometer 3 and Sagnac, bottom the coherence among the two instruments.

Accelerometer 2 is sensitive to rotation ω(t), Fig. 21 up left shows that 2Hz peak is a rotation of the table. The comparison with accelerometer 3, the vertical one, is not giving more informations.

The two accelerometer 1 and 2 are more sensitive, in the following and upper limit on the cross coupling among ortogonal degrees of freedom in our gyrolaser will be given. In the picture are compared meters and radiants, but considering that the armlengths are of the order of 1 m, it is possible to say that the amount of signal of the Sagnac is a factor 100 below the accelerometers, considering that the average coherence is below 0.1, below 1Hz, it is possible to claim that the cross coupling among ortogonal degrees of freedom is below 0.1%.
In summary the analysis has shown that the large peak around 2 Hz is a rotation of the gyrolaser support, no clear evidence of signal induced by tilt motion ($\theta(t)$) has been seen, and the upper limit for cross coupling with 'unwanted ' signal seems below 0.1%. The nature of the low frequency signal is not clear, but it is probably real motion, we can try to improve the measurement taking more data in reduced disturbance condition, for example late evening.
Moreover the coherence among reconstructed Sagnac signal and amplitude variation of the power has shown that there is contamination, i.e. above 5 Hz some of the signal is at least in part correlated with amplitude fluctuation. This could be due to diffused light affecting the amplitude fluctuations and the Sagnac output.

5. Characterization of G-Pisa

Several measurements have been taken to know the behavior of the ring laser in function of its power and to investigate multimodal operation of the cavity. The mode structure has been detected injecting the output beams in a high finesse linear cavity. Stable operation has been checked to be possible from a monomode operation up to 4 modes, with an increase in output power by a factor ~3.
The first parameter is the contrast of the output signal, Fig.22 shows the contrast in function of the voltage given to the capacitive discharge which excites the laser. In order to compare measurements done in different condition, the voltage has been normalized by the threshold voltage, which has been constantly monitored.

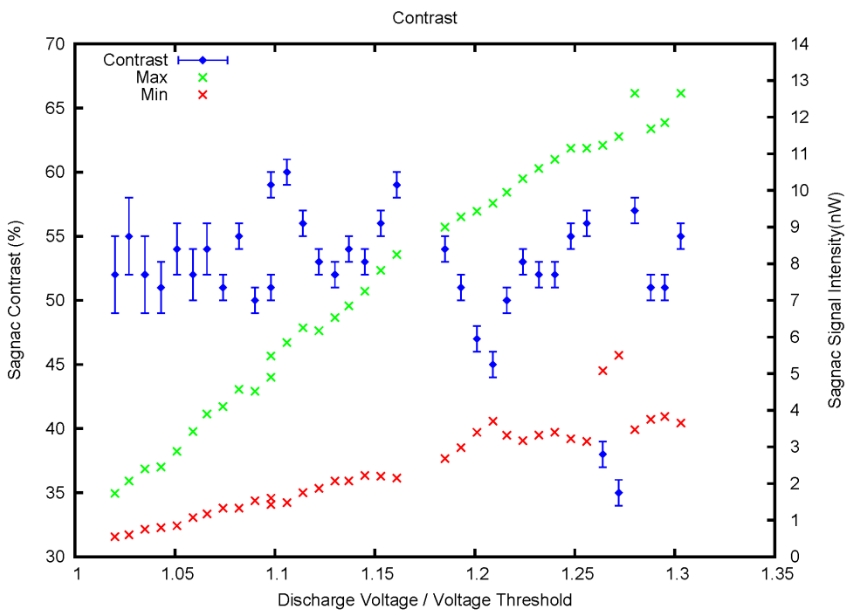


Fig. 22 Blue points, left scale: contrast in function of the normalized discharge voltage. Green and red are the maximum and minimum intensity of the signal.

The contrast is ~55%, and from 1 up to 1.1 normalized voltage it has been checked that the laser operate in monomode. The multimodal operation in general looks good, i.e. the different modes are locked in phase and the instrument gives a reliable Sagnac frequency, but when there are several modes quite often the operation is not stable, and sometime the output exhibits bad contrast.

Fig.23 shows the behavior of the intensity of clock wise and anticlock wise beams (measured as photodiode current), measured increasing (up) and decreasing (down) the voltage of the discharge.

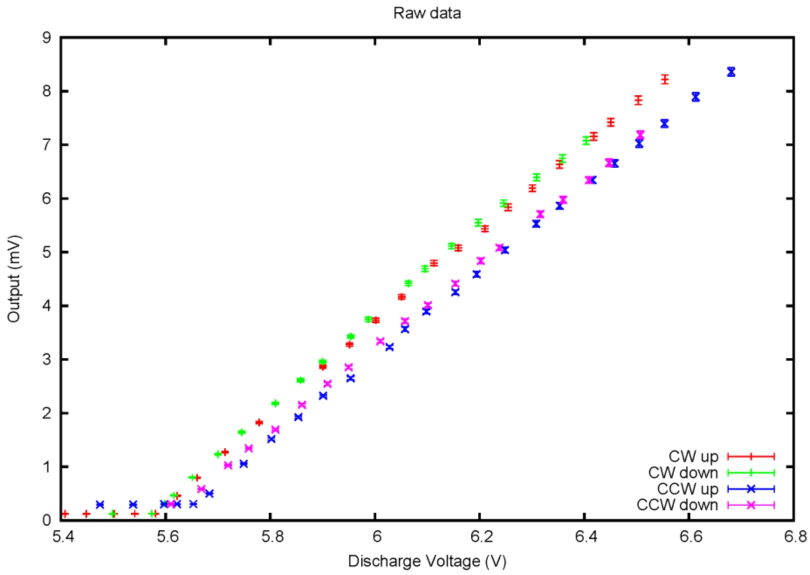


Fig. 23 Clockwise and CounterClockwise beams in function of the voltage applied to the discharge.

Clearly the two modes have different threshold and different slopes. Some hysteresis is evident as well, but the measurements is not good enough to show well the hysteresis, this point will be investigated more deeply in the future.

Hydrogen contamination is matter of concern, since when its level is too high the gyrolaser stops lasing. Fig. 24 shows the concentration of Hydrogen increasing in function of the time. The Hydrogen contamination is shown by means of the intensity of the H-line at 656nm, which is detected by a spectrometer. After approximately 3 weeks the contamination is too high and the gyrolaser stops lasing.

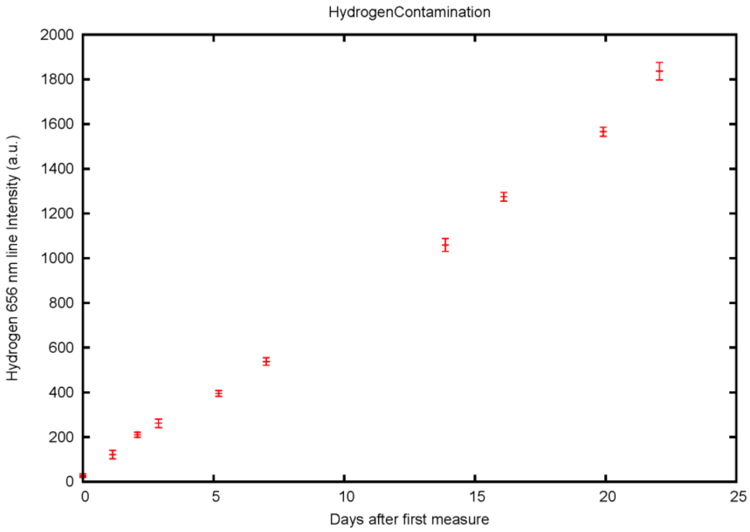


Fig. 24 Hydrogen contamination in function of time. This measurement refers to the vacuum tank not yet backed

6. Requirements for a gyrolaser for the IP control

The requirements for the IP is a sensitivity of 10^{-8}-10^{-9} rad/Hz at 10 mHz. The measurement has shown that gyrolaser has enough sensitivity. A direct low frequency measurement is not possible for G-Pisa with our present set up, but it is clear from the measurement taken in Wettzel with the gyrolaser G (see Fig. 12).

Mode jumps have been observed in our system and they depend on temperature changes. It is very important to avoid them if the interest is in very low frequency behaviour. At the moment we are developing an active perimeter control system, which could be implemented in the other GEOSENSORS as well, while it is not necessary for devices for the IP control. The jump rate has been evaluated to be 30 jumps/degrees, compatible with stainless steel thermal expansion. In our laboratory, in not controlled conditions, we got approximately in average 5-20 minutes of good signal, and about 20 seconds without signal. Inside the SA suspension vacuum tank the number of mode jumps will be very few per day. The temperature stabilization of the areas around the Virgo suspensions is 0.2 degrees, and should be at least 0.1 degrees inside the Virgo suspension ; so the number of mode jumps for a gyrolaser inside the Virgo vacuum towers is below 3 jumps per days. Since the number of jumps are very few, this should not be a problem for the IP control. It will be only necessary to provide a system which is able to understand when the gyrolaser is working properly and open the loop when a mode jump takes place, and close it as soon as the Sagnac signal is back.
The area of this gyrolaser should be larger than 1m^2, if possible even larger, taking in mind that the larger the better.

It is not straightforward to find a so large free space inside the vacuum towers, on the top of the bottom ring. The only solution seems to create a structure which supports the gyrolaser, which passes in front and behind the legs of the IP. This structure has to be taloired based on the actual free space of the bottom ring, moreover its rigidity have to be comparable to the one of a commercial breadboard.
An other matter of concern is the alignment of the gyros with the Earth axis, this implies that among 3 possible choices, one has to be avoided. An other point is the fact that 100 and 50 Hz, as Sagnac frequency, have to be avoided.
As far as necessary maintenance problem is concerned, so far in G-Pisa we have refilled the cavity each month, when the Hydrogen contamination was too high, but with a simple backing of the cavity and using getters it is possible to extend the lifetime of the ringlaser up to sever months.
Optical fiber system has been successfully used in G-Pisa, they could be of course very handy in this kind of applications, to bring the signals outside the vacuum chamber.

7. About FOG (Alexander Velikosetzev private comunication)

FOG are optical gyro based on long optical fibers, arranged in turns. They are commonly used for navigation, with sensitivity between 10^{-6} to few rad/s. So far the best sensitivity obtained by FOG is around 5 10^{-8} rad/s, which is not far from the requirements for the IP control. Improvements in the development of this instruments can be expected in the near future. FOG response is a function of dimensions indeed as well as number of fiber loops, a really sensitive instrument is feasible by increasing the number of coils. However there are other problems with FOGs, which should be addressed - temperature susceptibility and scale factor stability.

8. Conclusions

In almost one year of work we have acquired the necessary skill to operate with a gyrolaser. The device can run continuously, interruptions are due to mode jumps, which makes the instrument blind for few seconds. The Gyrolaser is highly unaffected by mirrors relative vibrations : it has been checked that our system is more than 0.5% insensitive to orthogonal degrees of freedom. The low frequency measured power spectrum (below 1 Hz) is around 10^{-8} ras/s/√Hz, which looks like real motion, while the sensitivity above 1.4 kHz is around $7{\cdot}10^{-10}$ rad/s/√Hz, compatible with the shot noise of the device. The best measurements below 0.1 Hz shows a power spectrum sensitivity very close to 10^{-9} rad/s/√Hz (see Fig. 13).
A system similar to G-Pisa, with at least $1m^2$ area (but larger is even better) seems good for the tilt control of the IP of Virgo. As far as the alignment with the Earth rotational axis is concerned, this is in principle always possible, more difficult is to find the necessary space on top of the bottom ring, it will not be possible to simply put the gyrolaser in between two legs of the IP, it will be necessary to design ad hoc a support structure attached to the bottom ring in two points and which passes in front and back to one leg, in this way the side would be a bit larger than 1m.

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