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ORIGINAL ARTICLE

Performance of "G-Pisa" ring laser gyro at the Virgo site

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Abstract The ring laser gyroscope "G-Pisa" has been taking data inside the Virgo interferometer central area with the aim of performing high sensitivity measurements of rotations in the vertical as well as in the horizontal orientation. We discuss the main characteristics of the instrument, describing its mechanical design and presenting the measured sensitivity limit. By applying a simple effective model for the laser gyroscope, we show that the stability of the sensor above 10 s of integration time is mainly limited by backscattering effects. The horizontal rotation rate signal is also compared with the signals recorded by the Virgo environmental monitoring system and by a biaxial mechanical tiltmeter rigidly fixed on top of the gyrolaser mounting frame.

Keywords Laser gyroscope · G-Pisa · Horizontal rotations

1 Introduction

The continuous monitoring of the environment plays a crucial role in the field of the gravitational waves detectors since it allows to identify and localize the noise sources. High sensitivity monitoring the ground rotational motion in the

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seismic frequency range (5–500 mHz) (Acernese et al. 2010; Losurdo et al. 2006) is of course important. For the Virgo gravitational waves interferometer (Accadia et al. 2011), the ground rotations around the horizontal axes (tilts) are important. Mainly during severe weather conditions, the local rotations are a source of excess noise in the control system of the inertial suspensions, since, up to now, the tilt control of the first stage of the test masses suspension (Inverted Pendulum) has not been implemented for lack of a suitable sensor. The use of very sensitive pure-rotation sensors is then expected to improve the low-frequency performance of the gravitational antenna. Ring laser gyroscopes (Stedman 1997) are good candidates for this task. Presently, they are one of the most important instrument in the field of inertial navigation and precise rotation measurements. They have high resolution, excellent stability, and a wide dynamic range. Furthermore, no spinning mechanical parts are required, so these sensors can be manufactured in a very robust way and with a very high rejection of linear cinematic and gravitational accelerations from the rotational signal. Very large perimeter ring laser gyroscopes have found application in Geodesy, and General Relativity tests seem feasible in the near future (Di Virgilio et al. 2010a; Bosi et al. 2011). In the last years "G" (Schreiber et al. 2009), a monolithic structure of zerodur (a glass–ceramic with ultra-low thermal expansion coefficient) supporting a squared cavity 4 m in side, operating by the Geodetic Observatory of Wettzel (Germany), was able to detect very small rotation signals like the twice-daily variations of the earth rotation axis due to solid earth tides (Schreiber et al. 2003) and the nearly diurnal retrograde polar motion of the instantaneous rotation pole caused by the lunisolar torques (Schreiber et al. 2004). Comparable results have also been obtained by the New Zealand ring laser research group. Inside the underground laboratory located in Cashmere, Christchurch, New Zealand, operates the world largest gyrolaser: the "UG2", a rectangular cavity 21×40 m (Hurst et al. 2009).

Since 2008, a square-cavity gyrolaser, named "G-Pisa" (Belfi et al. 2010), 1.35 m in side, is operative and a sensitivity of some (nrad/s)/$\sqrt{\text{Hz}}$ in the range 10–100 mHz (Di Virgilio et al. 2010b; Belfi et al. 2011) has been demonstrated. On June 2010, "G-Pisa" has been installed inside the Virgo central area, few meters apart from the beam splitter and the two input mirrors of the 3-km Fabry-Pérot cavities, with the main purpose of performing in situ measurement of the tilt motions. The gyroscope has been operated in the horizontal plane configuration (measuring rotations around the vertical axis) until December 2010. On February 2011, the laser plane has been positioned in the vertical position, so to measure the rotations around the Virgo interferometer north–south arm. The required sensitivity for the next generation of the Virgo antenna is at the level of 10^{-8} rad/$\sqrt{\text{Hz}}$ in the range 5–500 mHz (see: The Virgo Collaboration, 2009 Advanced Virgo Baseline Design, Virgo note VIR-027A-09 (26 May 2009)). In the following, we will give a brief description of the gyrolaser working principles, describe the experimental apparatus, and present some experimental results concerning the comparison between the rotation signals detected by "G-Pisa" and co-located sensors dedicated to the suspensions control and to the monitoring of the Virgo environment.

2 Basic principles of gyrolasers

The principle of operation of a ring laser gyro is based on the Sagnac effect. Two optical beams counter propagating inside the same ring resonator require different times to complete a round-trip. This time difference is proportional to the angular velocity of the local reference frame measured with respect to an inertial reference frame. In the case of a rotating active laser interferometer (gyrolaser), the required resonance condition for sustaining the laser action implies a different optical frequency for the two beams. This difference in frequency is proportional to the rotation rate, and it is measured combining the beams outside the ring and by measuring their beating frequency. The expression for the optical frequency difference (Sagnac frequency) f_S for a ring laser of perimeter P and area A takes the following form:

$$f_S = \frac{4A}{\lambda P}\mathbf{n}\cdot\Omega, \tag{1}$$

where A is the area enclosed by the optical path inside the cavity, P the perimeter, λ the optical wavelength, and $\mathbf{n}$ the area unit vector. The larger is the ring size, the easier the detection of the Sagnac frequency. Large size also mitigates the effects of lock-in, a major problem with the small size active ring lasers. Lock-in is the tendency (typical of coupled oscillators with close eigenfrequencies) of the counter-propagating laser beams to frequency lock, preventing any rotation measurement. The coupling arises in ring laser usually because of backscattering: Part of radiation of both beams is scattered in the counter-rotating direction. Unlike the small ring lasers used for navigation systems, large gyros easily detect the Earth rotation, which provides a nearly constant background rotation rate. The Earth contribution is enough to bias the Sagnac frequency of the gyrolaser described in this paper. Measuring the local rotations with a resolution at the level of some nrad/s implies to resolve the Earth rotation rate at the level of one part in 10^5.

3 Experimental setup

The advantage of middle-sized ring lasers is that they are easily transportable and yet can reach sensitivities of some (nrad/s)/$\sqrt{\text{Hz}}$ in the seismic frequency range. The experimental setup of the laser gyroscope is shown in the pictures of Fig. 1 in the two possible operational configurations for the measurement of the vertical and horizontal rotations. A 180 mm thick and 1.50 m in side square granite slab sustains the whole mechanical ring and defines the laser cavity reference frame. A steel armed reinforced concrete monument has been designed and realized, which is able to sustain the granite table both horizontally and vertically, in order to measure the rotations around the vertical, or around the horizontal direction. A steel flange is embedded at the center both of the upper side and of the lateral side of the concrete monument, in order to firmly hold the granite table. The weight of the concrete monument is about 2 tons, while the granite table is about 1 ton. The weight of the whole structure has to guarantee a good contact with the floor. In order to improve this contact as much as possible, a liquid, fast-setting, concrete has been used to fill cracks and gaps between the floor and the monument

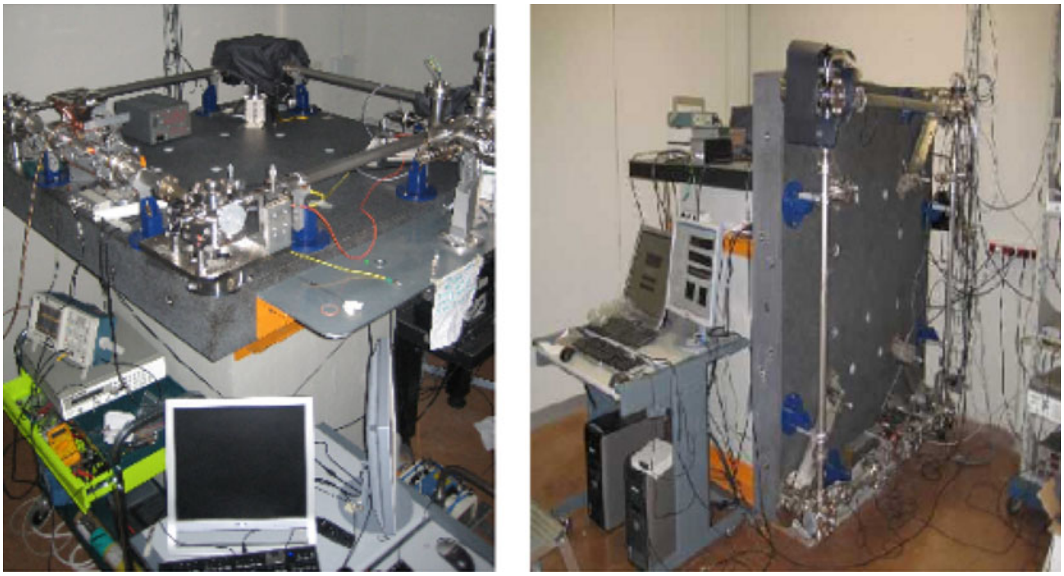

Fig. 1 The two operational configurations of the experimental setup

basis. The optical cavity design is based on the GEOsensor (Schreiber et al. 2006) project. As stated before, it is a square optical cavity, 5.40 m in perimeter and 1.82 m^2 in area, enclosed in a vacuum chamber entirely filled with the active medium gas. The vacuum chamber has a stainless steel modular structure: Four boxes, located at the corners of the square and containing the mirror holders inside, are connected by pipes through flexible bellows, in order to form a ring vacuum chamber with a total volume of about 5×10^{-3} m^3. The mirrors are rigidly fixed inside the boxes, which are rigidly fixed to the granite table. The mirrors alignment can be adjusted thanks to a micro-metric lever system that allows to regulate the two tilt degrees of freedom of each box. A fine movement of two opposite placed boxes along one diagonal of the square is also possible. This is provided by two piezoelectric transducers that allow the servo control of the laser cavity perimeter length (Belfi et al. 2010, 2011). There are no optical elements inside the ring cavity, and the vacuum chamber volume is entirely filled with a mixture of He and a 50% isotopic mixture of ^{20}Ne and ^{22}Ne. The total pressure of the gas mixture is set to 560 Pa with a partial pressure of Neon of 20 Pa. The active region is contained in a pyrex 4-mm-diameter tube, where a plasma is generated by a RF capacitive discharge; the pyrex capillary is inserted at the middle of one side of the ring. Getter pumps are used to keep low the hydrogen contamination of the active gas. The typical power of a single output beam is around 10 nW. In order to avoid undesired intensity fluctuations provoking transitions to multimode regime or the extinction of the laser beam, we have implemented a closed-loop stabilization of one single-beam intensity (Belfi et al. 2011).

4 Data acquisition and analysis

"G-Pisa" has been running unattended for several months in the horizontal as well as in the vertical orientation. The data from the gyro-laser are acquired and stored continuously by the Virgo data acquisition system. The Sagnac beating signal and the two single beam intensities are acquired at the rate of 5 kSample/s so that it is possible to reconstruct the rotation rate nominally up to 2.5 kHz. In addition, a local PC provides the evaluation of the instantaneous Sagnac frequency as well as other information about the ring, as the correction signal for the perimeter control. The timing is provided by the Virgo central timing system (Acernese et al. 2007), based on GPS. The digital control system of the perimeter can be operated from remote, via a VNC connection, and the behavior of the instrument can be checked without accessing the Virgo central area. The

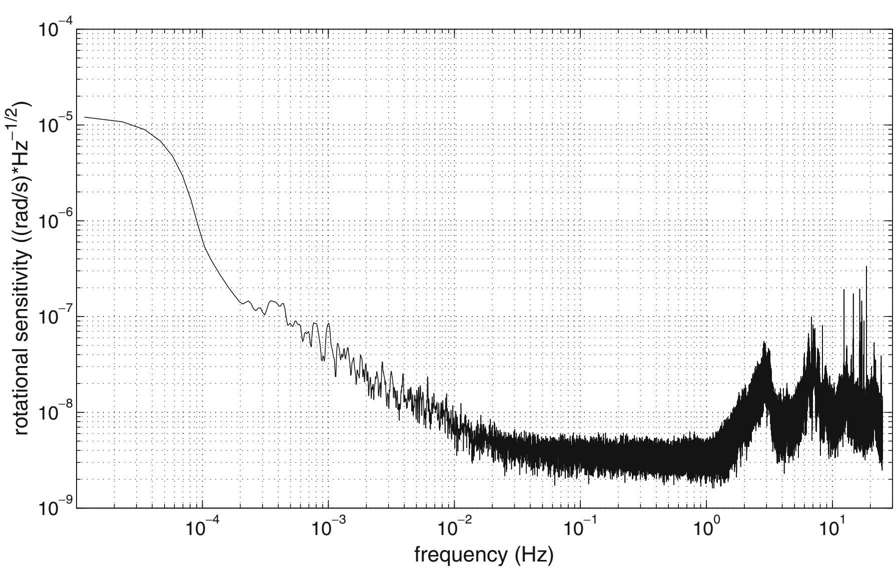

Fig. 2 Typical angular velocity sensitivity of the gyroscope operating in the vertical plane configuration

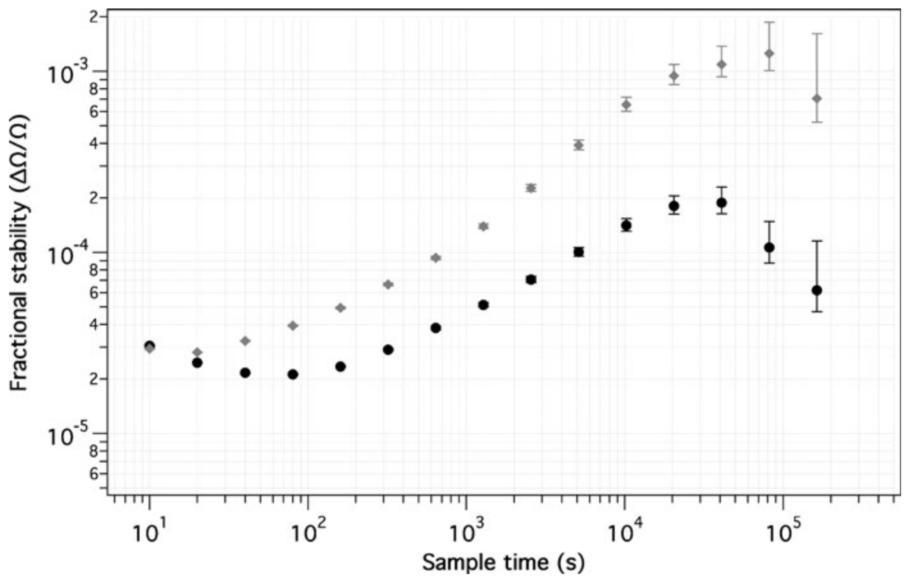

Fig. 3 Allan deviation for the raw data (*gray*) and the data processed with the algorithm based on the error model presented in Belfi et al. (2011) (*black*)

acquired data are post-processed by correcting the measured beating frequency from the systematic errors induced by the laser dynamics. So far the dominating noise source in G-Pisa is given by the backscattering contribution to the Sagnac frequency. A detailed description of the technique we adopt for the correction of the systematic effects induced by the laser dynamics is reported in Belfi et al. (2011).

5 Rotational sensitivity and frequency stability

The typical tilt sensitivity, for the vertical plane configuration, is shown in Fig. 2. The level of sensitivity observed in the vertical configuration is qualitatively very close to the one observed when the gyro is operated in the horizontal configuration (Belfi et al. 2011). Figure 3 gives the Allan deviation for the raw data and for the

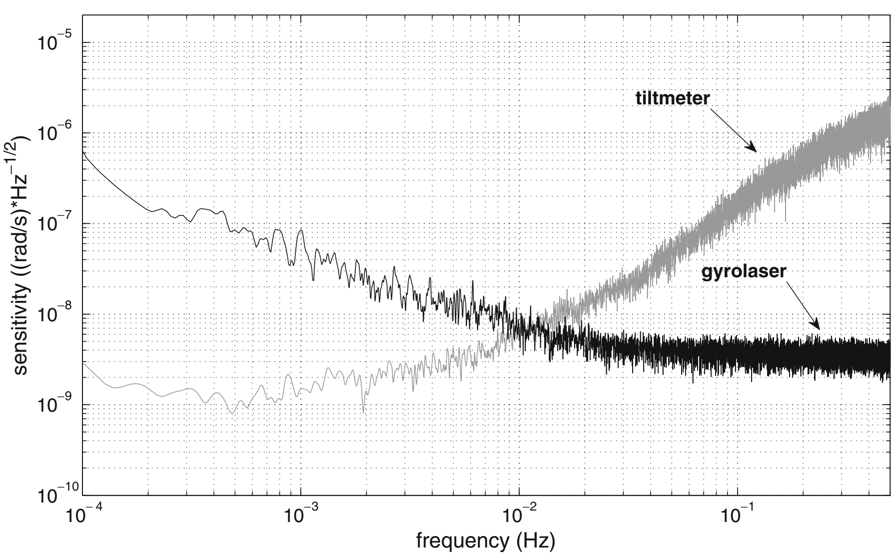

Fig. 4 Comparison between the sensitivities of one channel of the tiltmeter and the gyrolaser. The tiltmeter signal has been converted to angular velocity. The two axis of the mechanical tiltmeter have been oriented along the north–south and west–east Virgo directions

data corrected from the contribution given by the laser dynamics (mainly backscattering induced frequency pulling).

6 Comparison with environmental signals

We have installed a two-channel, high-resolution, mechanical tiltmeter (provided by E. Lipmann; http://www.l-gm.de/) on the top of the granite slab sustaining the vertically mounted ring laser. This kind of mechanical tiltmeters has been demonstrated to be fundamental for correcting the data of "G" (Schreiber et al. 2009) (detecting vertical rotations) from the local ground tilts. In the case where "G-Pisa" operates in the vertical-plane configuration, there is the possibility to directly compare its rotation estimate with the tiltmeter estimate of the same rotational degree of freedom. We will provide in the following a preliminary comparative analysis between the angular rate signal of the laser gyroscope, the signal provided by tiltmeter, and the local linear accelerations from a tri-axial accelerometer. Figure 4 shows the measured sensitivity limits for the tiltmeter and the laser gyroscope; the tiltmeter is extremely sensitive at very low frequency, while "G-Pisa" has a higher sensitivity at higher frequencies (cross frequency around 10 mHz). In Fig. 5 is presented the coherence function between the longitudinal accelerations detected by a tri-axial accelerometer (ES-T force–balance episensor), located few meters aside the gyrolaser setup, and the two channels of the mechanical tiltmeter. A significant level of coherence is observable between the co-orientated channels of the two instruments in the range of frequencies between 250 and 500 mHz. On the other hand, the coherence between the gyrolaser and the linear accelerometer (Fig. 6), as well as the coherence of the gyrolaser with the tiltmeter (Fig. 7), has no significant frequency components. This fact can be ascribed to the rejection

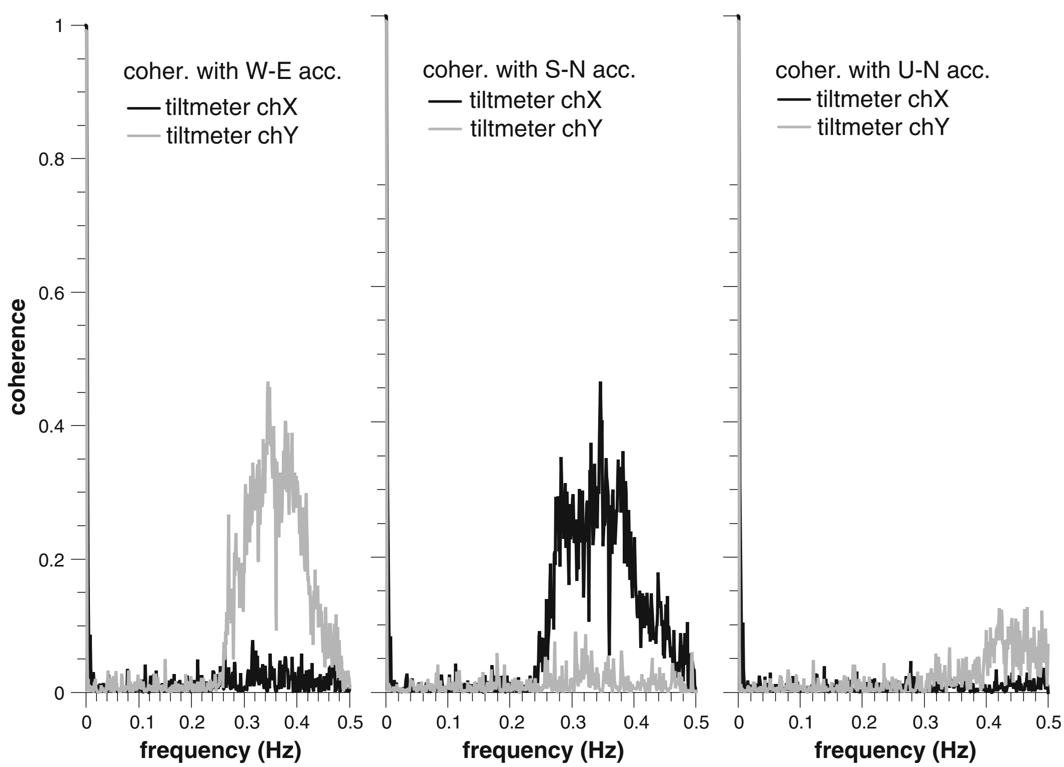

Fig. 5 Coherence between the tiltmeter channels and the different components of the episensor accelerometer (*W–E* west–east, *S–N* south–north, *U–D* up–down). The coherences are calculated over a time period of 24 h starting at 00:00 am of the 15 of July 2011, with a time window of 1,024 s and 50% overlap

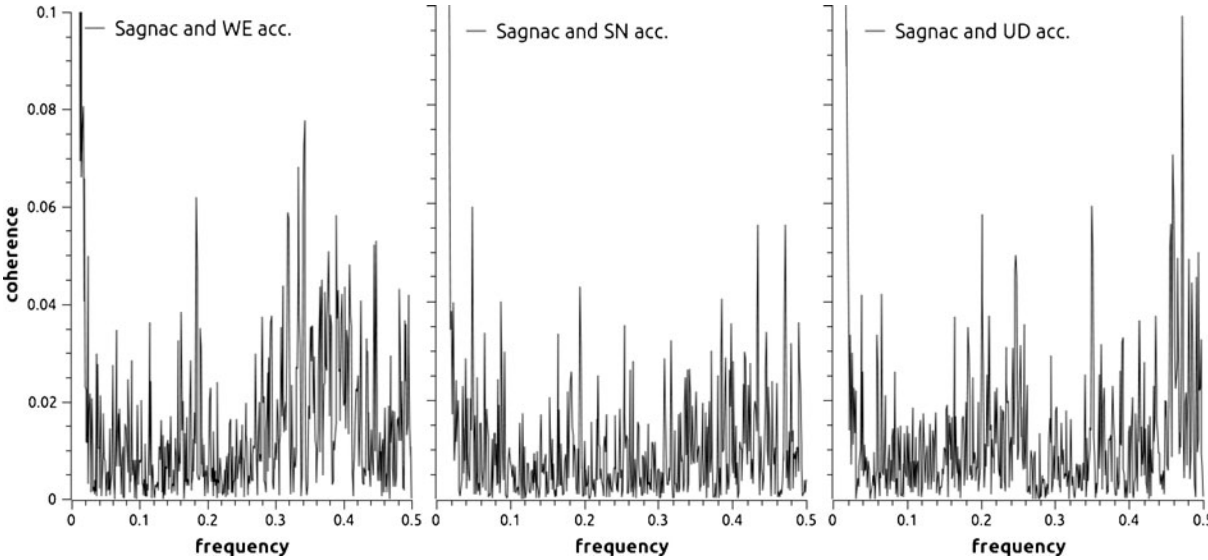

Fig. 6 Coherence function between the gyrolaser and the different components of the episensor accelerometer (*W–E* west–east, *S–N* south–north, *U–D* up–down). The coherences are calculated over the same time period and with the same parameters of Fig. 5

of the linear acceleration by the optical device. In the following, we show the comparison of the gyrolaser data with some environmental monitors. The Virgo interferometer has several very sensitive linear accelerometers and position sensors, which measure the displacement of the top part of the Virgo suspension. On top of each tower, three of such linear accelerometers are positioned, allowing the reconstruction of the two horizontal translations and of the rotation around the vertical axis. The linear displacement sensors, called linear voltage differential transformer (LVDT) are located close to the accelerometers. They measure the position of the top stage with respect to the ground. The top stage longitudinal motion is actively controlled and the feedback loop uses

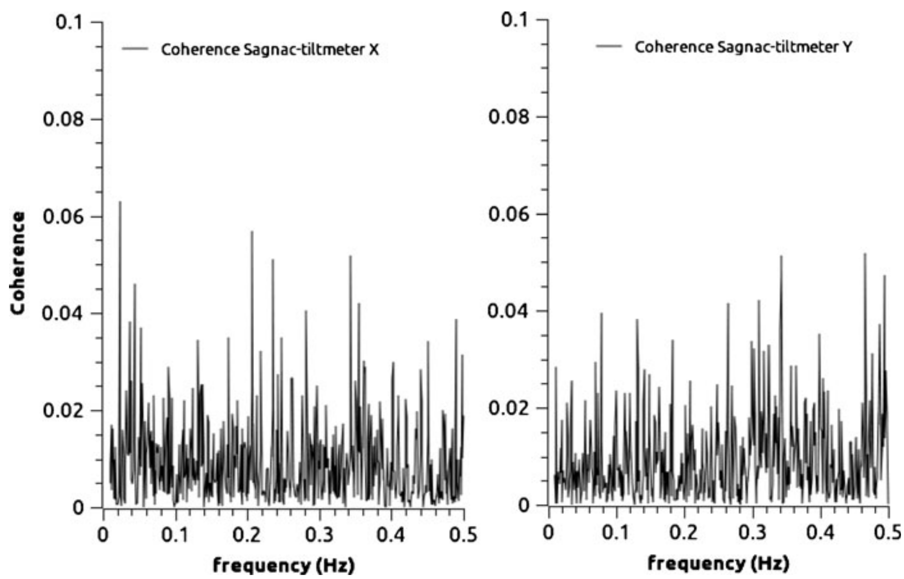

Fig. 7 *Left* coherence function between the tiltmeter X channel and the Sagnac frequency; *right* coherence function between the tiltmeter Y channel and the Sagnac frequency. The coherences are calculated over the same time period and with the same parameters of Fig. 5

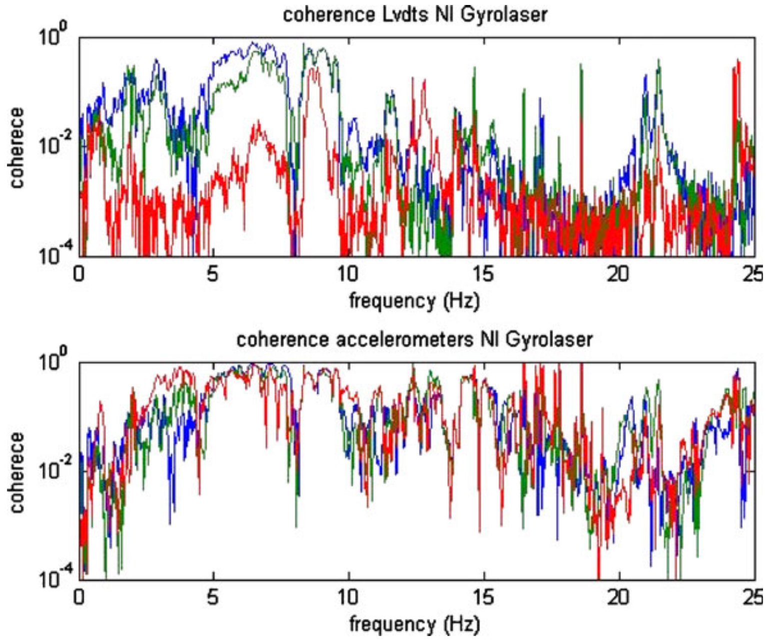

Fig. 8 *Top* coherence between the gyrolaser and the LVDTs of the North Input tower measuring the displacement of top part of the suspension with respect to the ground. *Bottom* coherence between the gyrolaser and the linear accelerometers of the North Input tower. *Blue* E–W translation, *green* N–S translation, *red* rotation around the vertical axis

as sensors the accelerometers above some tens of millihertz and on the LVDTs below this frequency. Figure 8 shows the coherence between the Sagnac and the three reconstructed coordinates of the top stage of the North-Input tower of Virgo. As it has been said in the introduction, strong wind is a cause of excess noise in this control system due to the coupling of the accelerometers to the tilts. This fact can be easily checked with our gyro. Figure 9 compares the standard deviation of the gyro-laser data with the data coming from the Virgo's wind monitor, and the correlation is evident. Figure 10 shows the spectrogram of the gyrolaser signal over several days. It is clear that the strong wind causes an excess of noise. The highlighted patterns in the sub-hertz region correspond to a particularly strong wind activity at Virgo site.

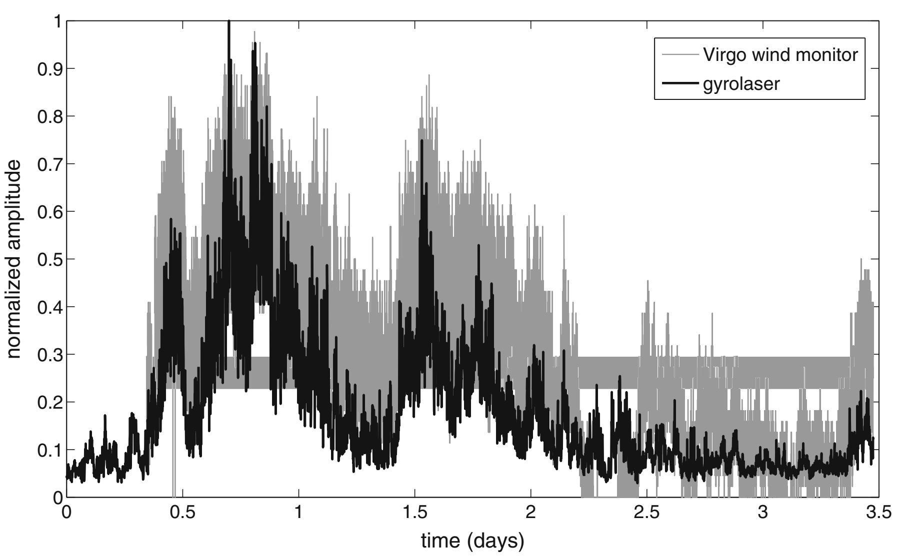

Fig. 9 *Black* normalized standard deviation for the measured Sagnac frequency. *Gray* normalized rms wind intensity measured by the Virgo's anemometer

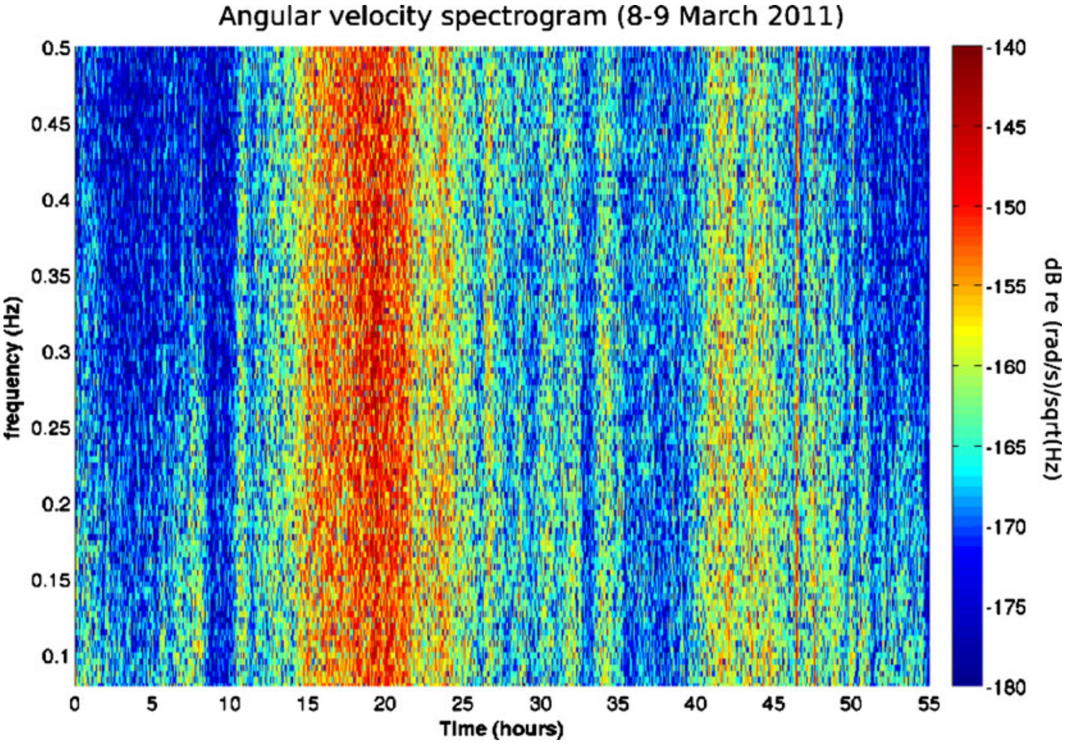

Fig. 10 Spectrogram of the Sagnac signal (sampled at 1 Hz) for a period of about 2 days

7 Conclusions

The ring laser G-Pisa, active-controlled in frequency and power, exhibits a sensitivity at the level of some ((nrad/s)$\sqrt{\text{Hz}}$) and an almost continuous duty cycle for the two main orientations: horizontal and vertical. We have presented the measured sensitivity limits and the Allan variance for the raw data and the data corrected for the laser dynamics effects. Backscattering is by far the dominant source of noise and can be effectively corrected below 10 mHz by using an error model for the sensor. A preliminary study of the coherences between the gyrolaser signal, some environmental sensors, and a mechanical nano-tiltmeter is given. We also observed that the fluctuation of the gyrolaser signal is amplified up to a factor of 10 during windy days. From all said in the present paper, due to its high sensitivity and duty cycle, a middle-sized gyrolaser represents a suitable tool for the monitoring of the gravitational waves antennas environment. Our ring laser demonstrated as well the sensitivity required by the suspensions improvement foreseen for AdVirgo.

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