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THE PRECISION LASER INCLINOMETER

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Abstract

Earth surface movements, like earthquakes or human-produced (cultural) noise, can induce a degradation of the instantaneous luminosity of particle accelerators or even sudden beam losses. In the same way the presence of seismic and cultural noise limits the detection capabilities of interferometric antennas used for the observations of gravitational waves.

This contribution discusses the importance of monitoring the effects of earth vibrations using a novel multi-purpose instrument, the Precision Laser Inclinometer (PLI). Few examples of recorded events are discussed along with ideas on PLI applications.

INTRODUCTION

The Precision Laser Inclinometer (PLI) is an instrument jointly developed at JINR in Dubna and CERN in Geneva to detect ground inclinations with high precision in direct angular measurement and as feedback sensor for high precision laser metrology instruments. The working principle was conceived back in 2012 [1–3] and, through iterative improvements, a stable working instrument was installed at CERN for continuous data taking since 2015 [4].

It was soon realised that the instrument has very high sensitivity to any angular ground motions from natural and industrial/human sources (cultural noise). During the years, a systematic study of all the components allowed an incremental improvement of the sensitivity to the levels achieved today.

DESCRIPTION OF THE INSTRUMENT

The PLI differs from conventional seismometers and inclinometers mainly due to the absence of mechanical constraints, as for example in case of usage of suspended masses in seismometers. That makes the PLI to be free from resonance frequencies over the full range of operational frequencies.

The Working Principle

The PLI working principle is based on the measurement of the movement of the laser beam reflected by a liquid mirror with the reflected beam detected by a position-sensitive quadrant photodetector.

Few ml of a liquid in a 5-cm diameter cuvette, resulting in a liquid level of around 3 mm, act as a liquid mirror. The cuvette is mounted on a common base with the laser and the quadrant photodetector. When the common base is tilted by earth angular oscillations of an angle θ, the liquid surface remains naturally flat, perpendicular to the local gravity direction, and the impinging laser beam is reflected at an angle 2θ as shown in Fig. 1.

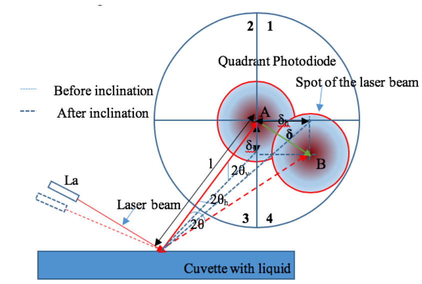

Figure 1: The laser beam spot and its displacement on the quadrant photodiode.

Figure 1 shows how the laser light reflected by the liquid is detected by a quadrant photodiode. This allows measuring the displacement in two directions. Linear combinations of the voltage output of the quadrants allows to determine the position of the spot and its movements up-down and left-right [2] .

It has been verified that the angular oscillations are such that the beam spot will remain in the sensitive area of the quadrant photodiode (5×5 mm^2) for any realistic seismic phenomena [5].

The Instrument

Based on the working principle and on the experience from years of running at CERN, being installed in the underground transfer tunnel TT1, the instrument has evolved through few prototypes until the establishment of a final technical specification and design. On this basis, a Production PLI (PPLI) has been produced with the introduction of a readout of the reference laser beam independent from the signal beam path, thus allowing to monitor and eliminate noise coming from the power fluctuations and from the angular wandering of the laser [6].

All the optical elements are mounted on a small base plate and this plate is inserted in a bigger container that is put under a moderate vacuum (~ 1 mbar) that allows to avoid air temperature gradient effects and air scattering for the laser beam [7, 8].

The readings from the two quadrant photodiodes for the signal and for the reference measurement are fed to eight independent 24-bit ADC channels with low input noise in the operational frequency range of the instrument. The impact of the readout ADC has been evaluated [9] as well as the maximum operating frequency has been measured [10]. Further improvements to the maximum operating frequency

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have been done and more refinements are under investigation, extending the upper limit towards 20-30 Hz to match the requirements from gravitational wave experiments for Newtonian-noise rejection [11].

A detailed accounting of the noise source has been documented in [6, 12], showing that the instability of the laser source and the angular wandering are small effects, but to be considered. These effects are monitored via the measurement of the reference signal that is unaffected by the liquid movements, i.e. from any tilt. The subtraction of the same linear combination of the signals from the reference photodiode allows to eliminate these sources of noise. A more detailed noise budgeting measurement is being organised using a dedicated test-bench.

Using a calibration system it is then possible to determine two calibration constants to convert the signal in volts into the angles in μrad for the vertical and the horizontal coordinates. The calibration system is integrated in the instrument with a one-arm external laser-interferometer [13].

THE EXPERIMENTAL DATA

Instrument Sensitivity and Seismic Events

The PLI has undergone few revisions between 2015 and 2019 and has been permanently taking data since March 2015 at CERN in the TT1 transfer tunnel in a very stable environment in terms of temperature and ground stability.

The instrument measures in real time the micro-seismic peaks in the Geneva area (Fig. 2) and any other seismic event, ranging from industrial noise from CERN and surroundings to earthquakes, both local and remote, spanning a wide range of magnitude and distance. The instrument is also sensitive to the Sun-Moon cycle [6].

The sensitivity of the PLI can be measured at any time and with very reproducible results. Analysing data over twenty four hours on a day with a relatively small level of micro-seismic peaks (< 0.1 rad) the minimal oscillations recorded indicate an excellent sensitivity going down to $2.4 \cdot 10^{-11}$ rad/$\sqrt{\text{Hz}}$ in the frequency range $[10^{-3}, 4]$ Hz (Fig. 2).

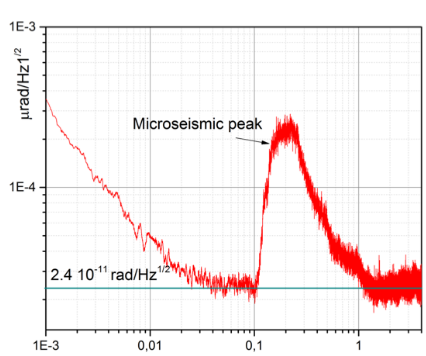

Figure 2: The spectral density of the micro-seismic oscillations in the Geneva area on a quiet day.

Local and very distant earthquakes are recorded by the PLI instruments along with their impact on the LHC luminosity, beam loss and orbit has been measured. The effects of small local earthquake, like events at distances around 200 km from CERN and of magnitude around $M_W = 3.0$, can provoke moderate beam losses and a decrease of around 2% of the instantaneous luminosity in one of the experiments. These perturbations are merely visible during the operation of the accelerator. Instead, for high-magnitude events even at large distances the oscillations of the LHC horizontal orbit can last very long time, even over one or two hours with a low frequency. As an example an earthquake with the epicenter on the Ascension Island, of magnitude $M_w = 7.1$ in 2016, provoked oscillations of the LHC horizontal orbit over a period of one hour [4].

Figure 3 shows the oscillations of the instantaneous luminosity in ALICE during the period of highest oscillations of the LHC horizontal orbit and how the PLI signal follows the same oscillations. The amplitude of the two signals has been rescaled to be plotted on the same arbitrary-units scale.

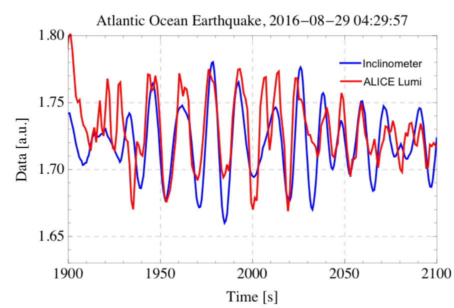

Figure 3: The effects on the ALICE experiment's instantaneous luminosity and on the PLI signal of a distant earthquake of magnitude $M_w = 7.1$ with epicenter on the Ascension Island.

A higher impact on the instantaneous luminosity in experiments is observed during strong earthquakes that are originated in Italy, the closest area to CERN with relevant seismic activity.

Figure 4 shows the PLI response (top plot) and the effects on the LHC horizontal orbit and on the instantaneous luminosity of the ATLAS and CMS experiments. The LHC orbit oscillates with the same behaviour as for the PLI, but it is more sensitive to the shear S-waves arriving with half-speed with respect to the compressional P-waves. The P-waves provoke a small-duration decrease in the instantaneous luminosity in CMS, while the arrival of the S-waves shows about a 40% drop for the ATLAS instantaneous luminosity during few seconds. The effect in CMS is significantly lower and this can be explained by the different collisions schema for the two experiments: the LHC beams arrive vertically to collisions in ATLAS and horizontally in CMS and this different behaviour, already observed also for distant earthquakes, indicates a higher sensitivity for ATLAS to shear and surface waves.

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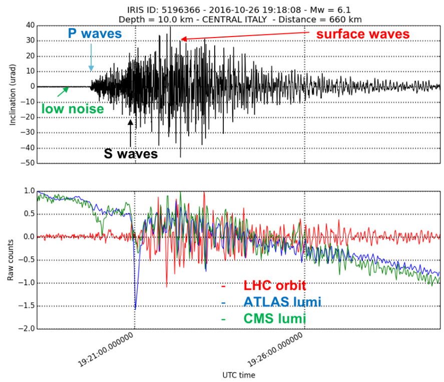

Figure 4: The effects of a $M_w = 6.1$ earthquake with epicenter in Central Italy at around 660 km from CERN.

Other Applications

Two PLIs have been installed in summer and fall 2019 at the Advanced Virgo Experiment [14]. The two PLIs have been taking data without interruptions since and have been included in the experiment dataflow at the end of 2019. The instruments monitor the seismic activity with the aim to be possibly providing in the future a feedforward signal and a veto trigger signal to be able to filter the seismic and wind-induced noise, among others, from the signal of the interferometer. This could enable the experiment to possibly enlarge the strain sensitivity towards lower frequencies [15–17].

In the context of this paper it is only possible to mention one important observation that was made at the end of December 2019 in occasion of a $M_W = 4.6$ earthquake with epicenter at 76 km from the Advanced Virgo Experiment. The PLIs signals are in complete agreement with the effects observed by a local seismometer and by the sensors on the Virgo mirror suspensions, however the PLIs also recorded a candidate prompt elasto-gravity signal [18–21] that has been detected several seconds before the arrival of the mechanical waves at the Virgo's site as shown in Fig. 5. The same type of signal has been observed in other occasions for near earthquakes in Croatia and Greece, opening new perspectives for the application of the PLIs as instruments in signal applications for very early earthquakes warnings. A detailed article about this argument is under preparation.

CONCLUSIONS

The Precision Laser Inclinometer is a novel instrument for measuring ground oscillations and vibration with high sensitivity. It has been proposed as an instrument to provide feedback and feedforward functionalities for the stabilisation of multi-TeV particle accelerators [4] and more recently as a high-precision early warning system for earthquakes.

The data recorded at CERN since 2015 and at the Advanced Virgo Experiment since 2019, show that the PLIs are able to monitor even low magnitude earthquakes and correlate with the behaviour of the LHC beams or the Virgo mirrors suspensions. Four units are being installed in service galleries around the ALICE and CMS experiments at LHC at CERN to monitor the effects of seismic noise on the LHC beams and also the long-term stability of the tunnel.

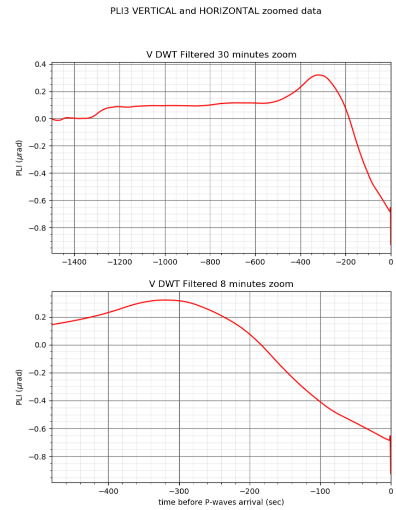

Figure 5: A candidate elasto-gravity signal in occasion of a $M_W = 4.6$ earthquake at 76 km from the Advanced Virgo experiment site.

Following the recent literature, a search for elasto-gravity signals was started and possible candidate signals have been detected from events in Italy, Croatia, Greece and Turkey, indicating that the sensitivity of the PLI allows to observe transient terrestrial gravity fluctuations even for moderate-magnitude events and that the two-dimensional capabilities of the PLI allow also to identify the direction of these signals with a precision between 1 to 3 degrees.

With respect to the classical approach of early earthquake warning systems, based on the early detection of the compressional P-waves traveling at double the speed of shear S-waves and surface waves, the detection of elasto-gravity signals allows increased warning time (minutes) and without the need of creating a network of sensors to identify the direction of propagation or to enable earlier detection using a sequence of sensors at increasing distances.

A new compact version of the Precision Laser Inclinometer is being developed for easier deployment with a significant reduction of the overall size and weight.

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REFERENCES

[1] V. Batusov, J. Budagov, and M. Lyablin, “A laser sensor of a seismic slope of the Earth surface”, *Phys. Part. Nucl. Lett.*, vol. 10, no. 1, p. 43, 2013. doi:10.1134/S1547477113010020

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[2] J. Budagov, M. Lyablin, and G. Shirkov, “The search for and registration of superweak angular ground motion”, *JINR Publications Applied researches*, p. E18-2013-107, 2013.

[3] J. Budagov *et al.*, “A laser based fiducial line for high precision multipoint alignment system”, *Phys. Part. Nucl. Lett.*, vol. 11, p. 286, 2014. doi:10.1134/S1547477114030042

[4] B. Di Girolamo *et al.*, “The Monitoring of the Effects of Earth Surface Inclination With the Precision Laser Inclinometer for High Luminosity Colliders”, in *Proc. 25th Russian Particle Accelerator Conf. (RuPAC’16)*, Saint Petersburg, Russia, Nov. 2016, pp. 210-212. doi:10.18429/JACoW-RUPAC2016-THCBSH04

[5] N. Azaryan *et al.*, “Position-Sensitive Photoreceivers: Sensitivity and Detectable Range of Displacements of a Focused Single-Mode Laser Beam”, *Phys. Part. Nucl. Lett.*, vol. 16, no. 4, p. 354, 2019. doi:10.1134/S1547477119040058

[6] N. Azaryan *et al.*, “Professional Precision Laser Inclinometer: the Noises Origin and Signal Processing”, *Phys. Part. Nucl. Lett.*, vol. 16, no. 3, p. 264, 2019. doi:10.1134/S154747711903004X

[7] N. Azaryan *et al.*, “The precision laser inclinometer long-term measurement in thermo-stabilized conditions (First Experimental Data)”, *Phys. Part. Nucl. Lett.*, vol. 12, no. 4, p. 532, 2015. doi:10.1134/S1547477115040056

[8] N. Azaryan *et al.*, “The temperature stability of 0.005 C for the concrete floor in the CERN Transfer Tunnel 1 hosting the Precision Laser Inclinometer”, *Phys. Part. Nucl. Lett.*, vol. 14, no. 6, p. 913, 2017. doi:10.1134/S1547477117060206

[9] V. Batusov *et al.*, “The sensitivity limitation by the recording ADC to Laser Fiducial Line and Precision Laser Inclinometer”, *Phys. Part. Nucl. Lett.*, vol. 12, no. 7, p. 813, 2015. doi:10.1134/S154747711507002X

[10] N. Azaryan *et al.*, “Determination of the maximum recording frequency by the Precision Laser Inclinometer of an earth surface angular oscillation”, *Phys. Part. Nucl. Lett.*, vol. 14, no. 6, p. 920, 2017. doi:10.1134/S1547477117060218

[11] J. Harms and H. J. Paik, ”Newtonian-noise cancellation in full-tensor gravitational-wave detectors”, *Phys. Rev. D*, vol. 92, p. 022001, 2015. doi:10.1103/PhysRevD.92.022001

[12] N. Azaryan *et al.*, “The compensation of the noise due to angular oscillations of the laser beam in the Precision Laser Inclinometer”, *Phys. Part. Nucl. Lett.*, vol. 14, no. 6, p. 930, 2017. doi:10.1134/S154747711706022X

[13] N. Azaryan *et al.*, “The innovative method of high accuracy interferometric calibration of the Precision Laser Inclinometer”, *Phys. Part. Nucl. Lett.*, vol. 14, no. 1, p. 112, 2017. doi:10.1134/S154747711701006X

[14] F. Acernese *et al.*, “The Advanced Virgo detector”, *J. Phys. Conf. Ser.*, vol. 610, p. 012014, 2015. doi:10.1088/1742-6596/610/1/012014

[15] G. H. Beker *et al.*, “Improving the sensitivity of future GW observatories in the 1–10 Hz band: Newtonian and seismic noise”, *Gen. Relativ. Gravit.*, vol. 43, p. 623, 2011. doi:10.1007/s10714-010-1011-7

[16] M. W. Coughlin *et al.*, “Implications of dedicated seismometer measurements on Newtonian-noise cancellation for Advanced LIGO”, *Phys. Rev. Lett.*, vol. 121, p. 221104, 2018. doi:10.1103/PhysRevLett.121.221104

[17] M. P. Ross *et al.*, “Towards windproofing LIGO: reducing the effect of wind-driven floor tilt by using rotation sensors in active seismic isolation”, *Classical Quantum Gravity*, vol. 37, p. 185018, 2020. doi:10.1088/1361-6382/ab9d5c

[18] J. Harms *et al.*, “Transient gravity perturbations induced by earthquake rupture”, *Geophys. J. Int.*, vol. 201, p. 1416, 2015. doi:10.1093/gji/ggv090

[19] M. Vallée *et al.*, “Observations and modeling of the elastogravity signals preceding direct seismic waves”, *Science*, vol. 358, no. 6367, p. 1164, 2017. doi:10.1126/science.aao0746

[20] M. Vallée and K. Juhel, “Multiple Observations of the Prompt Elastogravity Signals Heralding Direct Seismic Waves”, *J. Geophys. Res.: Solid Earth*, vol. 124, no. 3, p. 2970, 2019. doi:10.1029/2018JB017130

[21] J. Harms, “Terrestrial gravity fluctuations”, *Living Rev. Relativ.*, vol. 22, no. 6, 2019. doi:10.1007/s41114-019-0022-2