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 \( \theta \), the liquid surface remains naturally flat, perpendicular to the local gravity direction, and the impinging laser beam is reflected at an angle \( 2\theta \) as shown in Fig. 1.

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

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 ⋅ 10⁻¹¹ rad/√Hz in the frequency range [10⁻³, 4] Hz (Fig. 2).

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

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


