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In-Field Demonstration of Multi-Tech Sensing on Terrestrial Optical Data Network using State Of Polarization and Phase Monitoring

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Abstract *We implement a multi-technique seismic observatory on a live optical link in central Italy, using phase and state-of-polarization sensing coexisting with data traffic. Combining diverse fiber sensing and traditional tools enables turning telecom infrastructure into a resilient smart grid for interpreting complex and heterogeneous events.*

Introduction

Due to the increasing internet traffic demand, the optical data network infrastructure covers now large geographic areas with thousands of kilometers of deployed optical fiber. The perspective of turning such a large infrastructure into a pervasive sensing grid is attractive from many points of view. It could provide useful data for network health monitoring or geophysics analysis and would support the implementation of additional network services, increasing the operator revenues, the infrastructure added value, and the citizens quality of life. In particular, seismic sensing in coexistence with conventional data traffic would largely extend the traditional seismic stations network and contribute to earthquake early warning, localization and magnitude estimation functionalities. State of the art distributed acoustic sensing (DAS), leveraging on phase of back-scattered light, provides spatially-resolved and excellent accuracy[1], but it is expensive, has limited reach and typically requires dark fibers. Moreover, it generates a large amount of data, posing storage and management issues. Analysis of the state of polarization (SOP) and phase of data signals traveling into the fiber overcomes these issues and has already demonstrated the ability to sense seismic waves, although measuring the integrated effect over fiber length, which leaves the impact point on fiber unknown, if bidirectional measurements at high enough sample rate are not available.

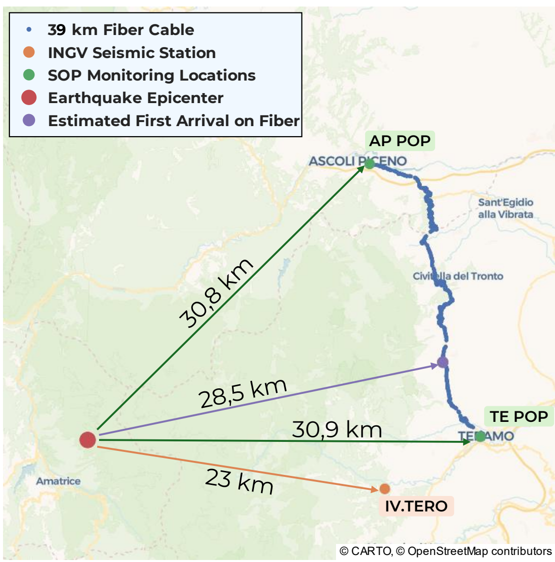


Fig. 1: Map of the experimental testbed - Case study EQ of 15-03-2025 11:40:31 (UTC) located near to Amatrice (42.6572, 13.3192) - [event-id: 41944002]

While phase analysis[2],[3] requires alien, high-coherence lasers, SOP monitoring can be achieved with minimum equipment overhead by analyzing Stokes vectors which are already computed in coherent receivers based on digital-signal-processing (DSP)[4]–[7]. However, transceiver SOP data is not easily accessible at adequate sampling rate due to the closed nature of proprietary DSPs, thus limiting its adoption on large scale.

We propose a third approach, that exploits polarized intensity-modulated, direct-detected (IMDD) signals, still widely available in modern networks as, for instance, optical supervisory channels (OSC), and a simple device based on a polarization beam splitter (PBS)[8] to observe the SOP fluctuations induced by external events on the two orthogonal polarization components[9]–[11]. This approach trades off sensitivity for scalability: despite limited sensitivity due to partial Stokes mapping, its low cost enables wide-scale deployment[12]–[14].While a PBS-based sensing device has already been reported in literature[15]–[17], it has not been employed in terrestrial production networks for earthquake detection.

In this paper we report on the deployment of a multi-tech seismic observatory based on PBS-

SOP analysis in conjunction with interferometric phase sensing, on a commercial optical data network with internet traffic. For assessing the earthquake detection sensitivity of both techniques, we compare our recordings with co-located conventional seismometers of the Italian Seismic Network. Our deployment showcases a hybrid seismic network in which different techniques concur to improve the overall monitoring ability and corroborate event detections, enabling at the same time advanced insight, more sophisticated data analysis, and robust event validation.

Experimental Setup

The in-field experimental activities have been carried out within the Fiber as a Sensor (FaaS) project and SENSEI European project[18], in collaboration with the Italian telecom operator Open Fiber, the Italian optical systems vendor SM-Optics, the Istituto Nazionale di Geofisica e Vulcanologia (INGV), and the Italian institute of Metrology (INRIM). The map of the experimental testbed is reported in Fig.1. Two PBS-based SOP Monitoring devices have been deployed in two points-of-presence (POP) of the production regional network operated by Open Fiber and located in the cities of Ascoli Piceno (AP) and Teramo (TE), an Italian area characterized by intense seismic activity. POPs are connected by a 39 km long fiber cable with bidirectional connectivity on separate fibers. In the same cable, an interferometric phase sensing system[2],[19] is deployed. The cable is mostly housed inside conduits along the road except for roughly 100 meters of aerial cable. Hence, SOP and phase measurements suffer from anthropic activity noise, reflecting realistic scenarios in terrestrial sensing. In contrast, the IV.TERO seismic station is taken as a silent reference since it is located roughly 8 km from the city of Teramo. The fiber sensing setup is reported in Fig.2. The two SOP sensing signals are generated by standard C-band 10G IMDD transceivers, then multiplexed to the the interferometric signal and existing online C-band WDM data channels by two reconfigurable add-drop multiplexers (ROADM) and propagated bidirectionally in separate fibers of same cable. After propagation, each PBS-SOP sensing channel is dropped by ROADM cards, bandpass filtered, and received by the sensing cards. The sensing card (Fig.2 inset) is a quarter-rack unit in size and is integrated into the WDM shelf apparatus, based on a low-power ARM CPU. Each received sensing channel passes through a TAP photodiode (not depicted in Fig.2) to measure the total optical received power (about -18 dBm in average). Then, the PBS splits the signal into its vertical and horizontal polarizations and sends them to a pair of transimpedance amplifier (TIA) photodiodes. The resulting electrical signals from the 3 photodiodes are sampled by three ADCs at $f_s = 120$ Hz with a resolution of 12 bits. The two devices are NTP-synchronized and timestamped in software, then, every 12 hours, data are stored on a remote server together with phase data. In post-processing, data sequences are interpolated at a lower sampling frequency of 100 Hz to mitigate the timestamp jitter.

Results

SOP data acquisition started in January 2025, producing roughly 300 MB of uncompressed SOP data per day. Among others, one of the project aims is to demonstrate event detection using a smaller sampling frequency and coarser resolution compared to other sensing systems. PBS-SOP and phase data are retrieved from the server and combined with seismometer data from the national seismic database. For each certified event, INGV reports the origin time, location, depth, and magnitude of the earthquake. We have collected the events located by INGV in the region from the start of measurements, and looked for signatures of these events in the SOP signal. As an example, Fig.3(a) shows timeseries of the three sensing approaches around the occurrence of a magnitude 2.0 earthquake located near the town of Amatrice (red circle in Fig.1). The estimated epicenter is 28.5 km away from the closest point of the fiber at a depth of 11 km, and is among the closest since the start of the acquisition one month earlier. We note that events of this magnitude are hardly felt by the population, and are below the

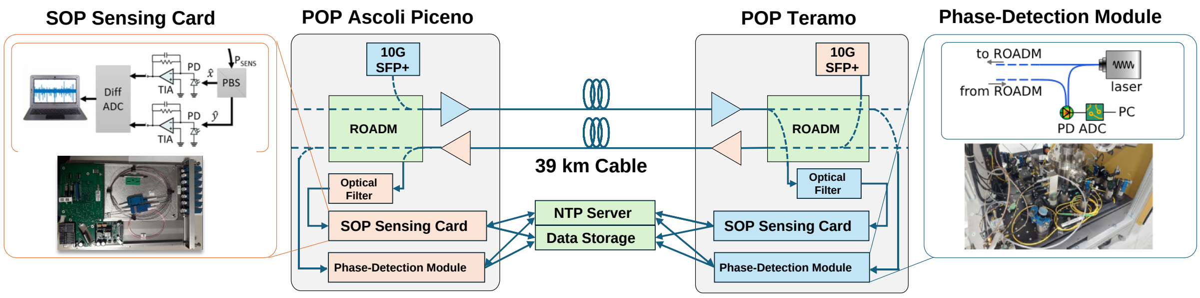
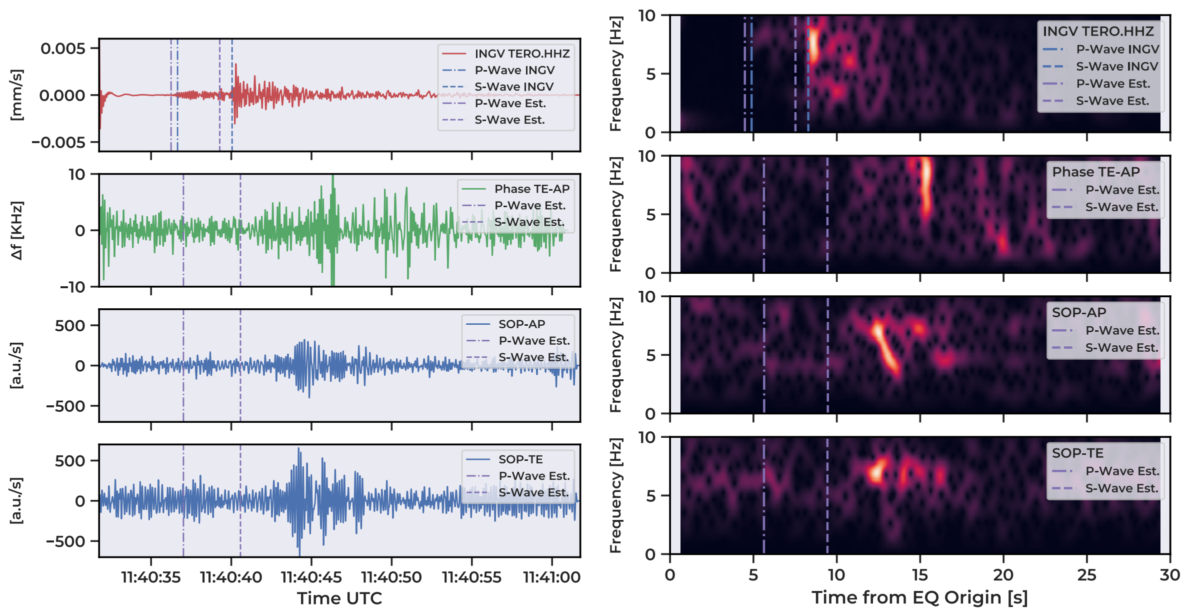


Fig. 2: (Left) Block diagram and real picture of the PBS-based SOP monitoring device. (Center) Block diagram of the experimental setup inside each POP. (Right) Block diagram and real picture of the interferometric phase sensing device.

official alert threshold. The figure shows the vertical velocity of IV.TERO (1st upper plot) deconvolved by the sensor response, the time-derivative of the interferometric phase recording (2nd plot), and the time-derivative of the differential voltage recorded on the two PBS outputs (3rd and 4th plots). Waveforms have been band-pass filtered with 16-th order Butterworth filter between 1 Hz and 10 Hz. Fig.3(b) displays the spectrograms of unfiltered signals. In addition, we calculate the theoretical arrival times of the seismic P- and S-waves at IV.TERO and to the closest point of the fiber using the AK135 model[20] available in the Obspy software suite[21]. For IV.TERO, the theoretical arrival times anticipate the measured ones by 0.4 and 0.77 seconds. Both phase and SOP measurements show time-aligned anomalies, although both occurring with a few seconds of delay w.r.t. their theoretical arrival time. Likely, the presence of disturbances of other origin (e.g. anthropogenic noise) occurring along the fiber hides the actual seismic signal in the fiber acquisitions. Indeed, earlier long-term analysis of interferometric phase data[2] carried out on several tens of earthquakes revealed that magnitude 2 events over 20 km from the fiber fall below the phase detection threshold.[2]. A similar analysis is being carried out for SOP recordings to assess its actual seismic detection sensitivity. In this respect, the availability of the two fiber sensing approaches, one of which already characterized, and conventional co-located seismometers, greatly supports the data analysis and interpretation, also identifying possible false-positive events.

Conclusions

We realized a distributed seismic observatory based on simultaneous phase and SOP analysis on a live optical data cable, showing continuous recording of integrated fiber deformations with low-cost equipment and modest data size. These features address the peculiar challenges set by the need for continuous and widespread seismic monitoring, where complexity and costs scale with network size. The location of our experiment ensures that a high number of candidate seismic events will occur in a few months of data collection, in a broad range of magnitudes and distances. This will enable to carry out statistically significant assessment of the seismic detection sensitivity of SOP analysis and to quantitatively characterize its spectral response also in comparison to phase analysis. Furthermore, the synchronous acquisition of SOP and phase data on the same fiber enables advanced analysis not possible otherwise, e.g. the investigation of the complex relationship between strain and deformation along different directions. Our multi-technique observatory contributes a diversified set of parameters which is highly relevant in view of deploying an intelligent, software-defined network architecture, able to orchestrate information from different sensors and take prompt, yet reliable countermeasures. Combined with telemetry data from discrete network elements (e.g. ROADMs and amplifiers), this multi-technique approach will improve not only seismic monitoring, but also supervision of the network operation, improving its robustness against failures, deterioration, and malicious events.



(a) Waveforms

(b) Spectrograms

Fig. 3: Experimental acquisitions. The estimated arrival times are computed at IV.TERO location for the seismic station, and at the estimated nearest point to the earthquake along the fiber cable path.

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