Sub-Hertz Spectral Analysis of Polarization of Light in a Transcontinental Submarine Cable

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Abstract *We report on a field-trial over the Curie cable connecting USA to Chile. We detected environmental changes through measurements of polarization of light. Seismic waves stemming from moderate-size earthquakes caused perturbations in the 0.5-3Hz range, suggesting that transcontinental cables may be used to detect earthquakes.*

Introduction

The ubiquitous cloud computing paradigm is driving a revolution in optics[1]. To accommodate the massive growth while limiting the total cost of ownership (TCO), open line systems gained great interest both in terrestrial and subsea systems[2,3]. In this paper, we report the results of a field experiment over the Curie cable system. With a total length of 10,500 km, Curie connects Los Angeles, USA to Valparaiso, Chile (Fig.1).

During a field trial we were able to detect mechanical perturbations in the cable through the monitoring of the states of polarization (SOP) of light estimated by the adaptive filters of the DSP-enabled coherent receiver. By analyzing the Stokes vectors we were able to detect the seismic waves caused by multiple earthquakes, including the magnitude (Mw)7.7 earthquake near Jamaica on 01/28/2020, and several moderate-size earthquakes closer to the cable offshore Chile or on the East Pacific Rise.

Curie Submarine Open Cable

The Curie systems is an example of the Open Cable paradigm[2,3]. The cable was accepted based on the Generalized SNR (GSNR) measured by the wet-plant vendor. The submarine line terminal equipment (SLTE) includes photonic commons on which we can connect 3rd-party capacity from different vendors. Each vendor can use their linecards to characterize the system and can report it in terms of GSNR. The unique appeal of referencing to GSNR is that different vendors, using different hardware, can come to the same conclusion in regard to the cable optical performance and its supported capacity. After the characterization, the system was loaded with a combination of 200 Gb/s and 300 Gb/s channel rates, with channel spacing ranging from 50 GHz to 75GHz. In this configuration we ran a series of stability tests and from the analysis of all performance monitoring parameters we discovered something unexpected.

State of polarization monitoring and analysis

Exploiting advanced monitoring capabilities exposed by the DSP-enabled coherent receivers,

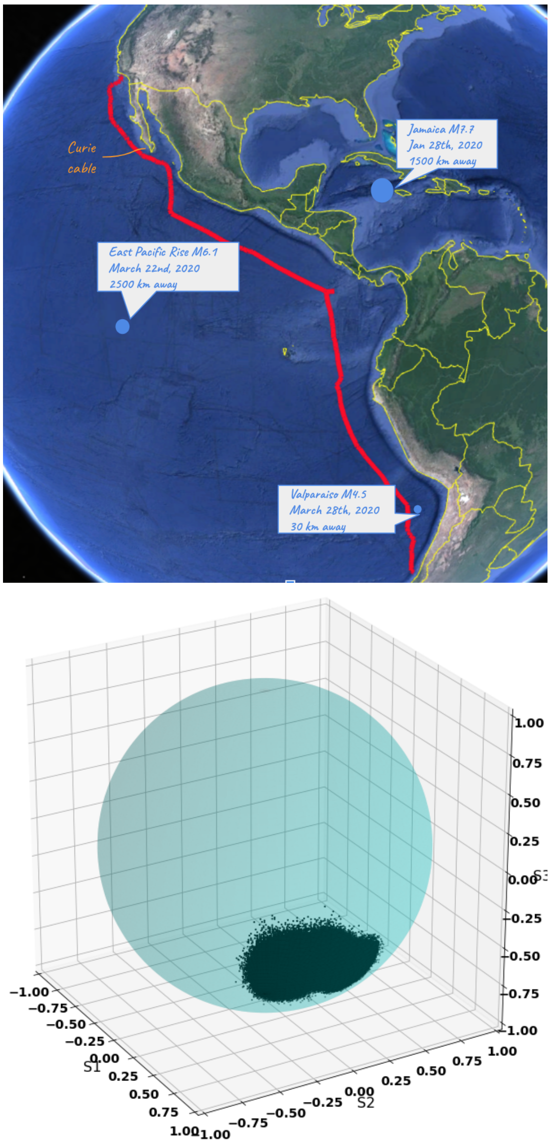

Fig. 1: CURIE Submarine Network with three earthquakes detected through changes of SOP (top) and the trajectory of polarization measured at LAX over 24h on Jan. 30th shown on Poincare sphere for channel 1548.7 nm (bottom).

we were able to continuously monitor the state of polarization of the transmitted light signals with an average sampling period of ~60 ms. The polarization demultiplexing algorithm that tracks the SOP of the received signal can log its Stokes parameters vector, and no special purpose

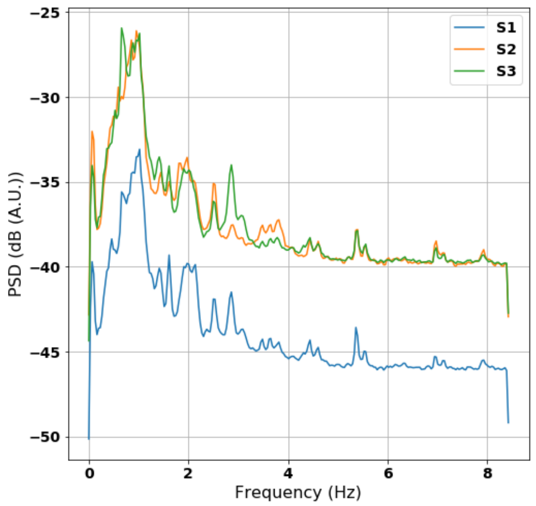

Fig.2: PSD of the Stokes parameters over a 24 hour window during Jan. 30th

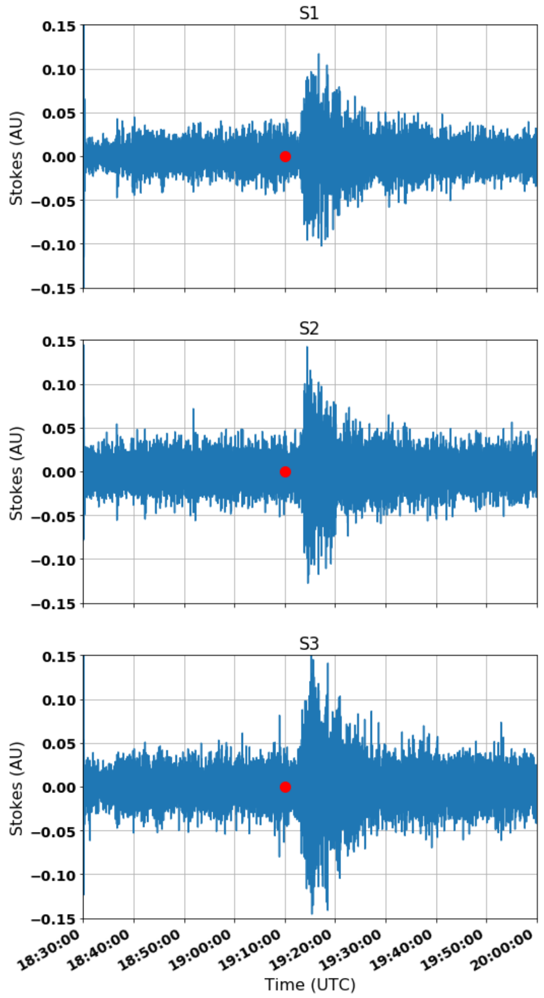

Fig. 3: S1(t), S2(t), S3(t) filtered with 0.1...0.5 Hz window, measured at LAX for channel 1548.7 nm. 90-min data around 2020-01-28 correlate to Jamaica 7.7M earthquake 19:10 UTC (red dot in figure).

hardware was used in the experiment. The data collection spanned several months and the collected Stokes parameters vectors were stored and streamed to a remote Cloud computing instance for data analysis. All collected samples

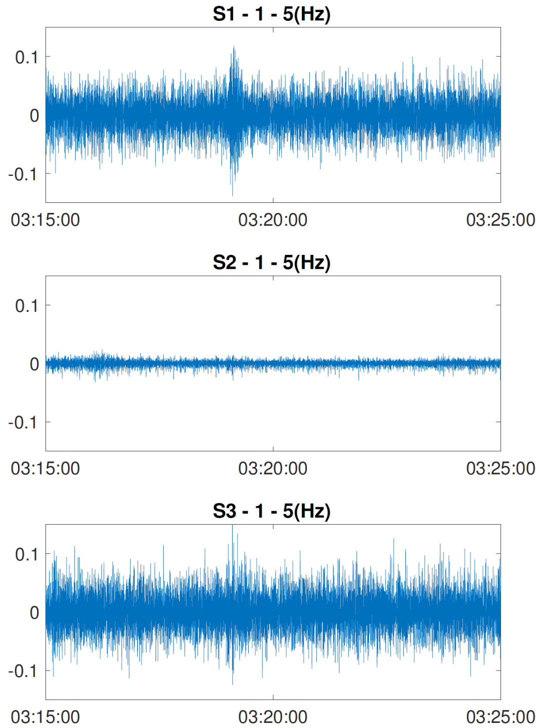

Fig. 4: Detection of a M4.5 earthquake (2020-03-28 03:18:37 UTC) close to Curie cable (Figure 1) in the 1-5 Hz frequency band.

were timestamped using a UTC reference provided by Google's TrueTime APIs. Data reported in this paper have been collected on a single channel centered at 1548.7 nm operating at data transmission rate (a) 300 Gb/s, and transmitted from Valparaiso to Los Angeles; (b) 100 Gb/s after round trip Los Angeles - Valparaíso - Los Angeles with a total path of 21,000 km.

Fig.1 shows the polarization data after 10,500 km plotted over the Poincare sphere of a 24 hour window during Jan.30th. SOP changes with averaged angular rotation rate about 0.6 rad/s, showing Maxwelian distribution of angular rotation speed. 24-hour stability of SOP shown in Fig.1, where polarization stays within < 0.2 sr. The state of polarization for submarine cable is substantially more stable than for terrestrial cable and aerial cable, where temperature fluctuation and wind cause abrupt changes of polarization parameters[4,5].

To better discriminate different signal components, a spectral analysis of Stokes parameters was performed. Power spectral density of the signal was estimated using Welch's method, considering Stokes traces over 24 hours and shown in Fig. 2. A 1 Hz band dominates in the spectrum with a signal-to-noise ratio larger than 15dB. Multiple smaller peaks in the sub-Hz area and few Hz part of the spectrum are visible, less than 4 dB above the noise floor.

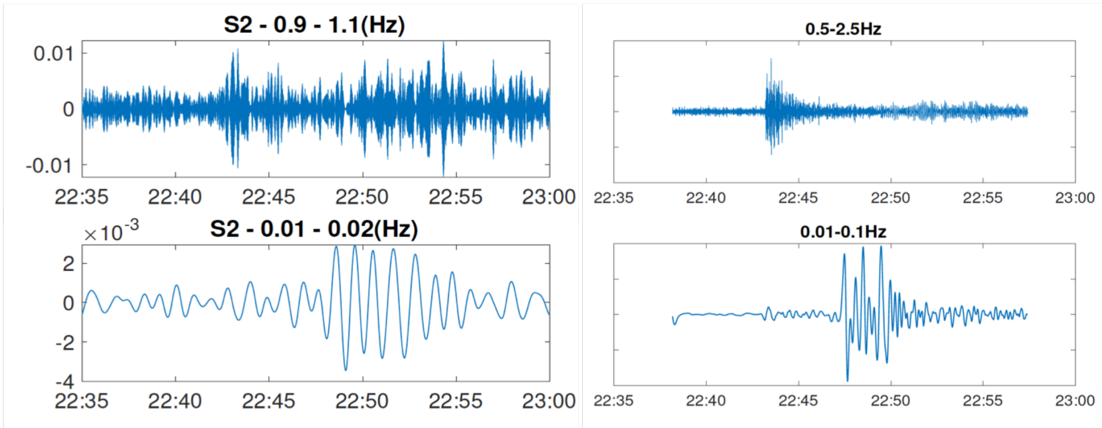

Fig. 5: Stokes parameters (left) together with conventional seismic station TLIG seismograms (right) for 2020-03-22 Mw 6.1 earthquake. High frequency near 1 Hz (top) and low frequency surface wave 0.01-0.02 Hz (bottom)

Several contributions into spectrum shown in Fig.2 originate from coherent transponder control loops, stochastic nature of polarization changes in long optical fiber, but also environmental effects. The goal of this paper is to report the ability to detect spectral components of optical polarization, which correlate in time with earthquakes along Americas West Coast transcontinental submarine cable CURIE.

Detection of earthquakes

Our first detection of an earthquake was on Jan 28, 2020, the Mw 7.7 Jamaica earthquake, over 1,500 km away at the closest point along the Curie cable. In the frequency band of 0.1Hz to 0.5Hz, S1, S2, and S3 all showed strong perturbations around 19:15, Jan 28, 2020 (Fig.3), which correlates well with the expected arrival time of the seismic waves from the M7.7 Jamaica earthquake. The SOP perturbations lasted over 10 min, substantially longer than the duration of strong seismic waves at any given location along the cable. This is because the SOP perturbation is an integrated measurement along the total length of the cable. As the seismic waves propagate, they perturb cable sections further away.

In the months following the Jamaica earthquake, we have also detected multiple moderate-size (M5~6) earthquakes, both at shorter distances (<100km) and 2,000 km from the cable. We report here two instances on March 22nd and March 28th 2020.

On March 28th, 2020, a M4.5 earthquake occurred offshore Valparaiso, Chile, only 30 km away from the Curie Cable at the closest point (Fig.4). The event produced a clear but short pulse of SOP perturbations on S1, potentially because the shaking intensity decayed rapidly along the cable for the relatively small event.

In this case, the response of SOP to the earthquake shaking is broadband. For the March 22nd, 2020 M6.1 earthquake on the East Pacific Rise (~2,000 km away from the Curie cable) we observed clear perturbations both around 1Hz and 0.01-0.02Hz, with timing consistent with observations made on seismic station TLIG at a similar distance (Fig 5). Note that the low-frequency surface waves are about 5 min later than the high-frequency P waves, as expected f rom their different paths within the Earth.

Conclusions

We discussed sub-Hertz spectral analyses of polarization of light in the context of a field trial with commercial transponders over the Curie cable. Limited test data today prevent us from more conclusive evidence on mechanisms and physics of our preliminary observations. Analyzing Stokes vector traces we detected polarization perturbations well matching several earthquakes in Jamaica, Chile, and East Pacific Rise. This finding demonstrates the potential of using traditional optical networking equipment as a scalable seismic sensing mechanism. More work is required to understand the mechanisms of conversions of seismic energy to polarization variations, to better fingerprint events and possibly realize early warning systems for earthquakes and tsunamis for wider societal benefit.

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