Optical polarization-based sensing and localization of submarine earthquakes

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Abstract: Optical polarization-based sensing is applied to multiple submarine cables around the world. Earthquakes are detected by their shear waves at the closest fiber section. Synchronized detection on multiple cables enables potential localization of major earthquakes.

1. Introduction

Submarine geophysical sensing is challenging due to the high cost of instrument deployment and maintenance. Fiber-optic sensing is providing a new opportunity by converting pre-existing fiber-optic cables into sensors. For example, ultra-stable laser interferometry (USLI) can measure micron-level total length changes of submarine cables caused by seismic shaking [1]. Distributed Acoustic Sensing (DAS) measures the longitudinal strain or strain rate over every few meters of a cable within a 100-km range [2-5]. Both USLI and DAS require substantial resources (e.g., specialty laser source and cavity, or dark fibers) to operate. Zhan et al. proposed a new sensing option, PolarSense, based on seismic perturbations to the status of polarization (SOP) of the regular telecommunication [6]. PolarSense has the obvious advantage of scalability but also suffers from the lack of source location information. In this contribution, we will report the latest research progress in PolarSense and how we can compensate for the limitation on source localization by using multiple cables.

2. Activation of PolarSense on multiple submarine cables

PolarSense uses the SOP of regular telecommunication signals to monitor earthquakes along cable [6]. Therefore, it does not require special instruments, dark fibers, or even dedicated channels, which makes it more scalable than other fiber sensing methods, such as DAS that requires dark fibers or USLI that requires specialty laser source and cavity. For the purpose of polarization multiplexing, modern telecommunication equipment for submarine networking is capable of measuring SOP at fine temporal sampling rate (e.g., 20Hz) and output them as data for sensing. Since the activation of PolarSense along the Google submarine cable Curie in 2020, which connects Los Angeles, US and Valparaiso, Chile, we have activated PolarSense on six additional cables (Figure 1). The data from all six cables are streamed in near-real time to Google Cloud Platform for storage and processing.

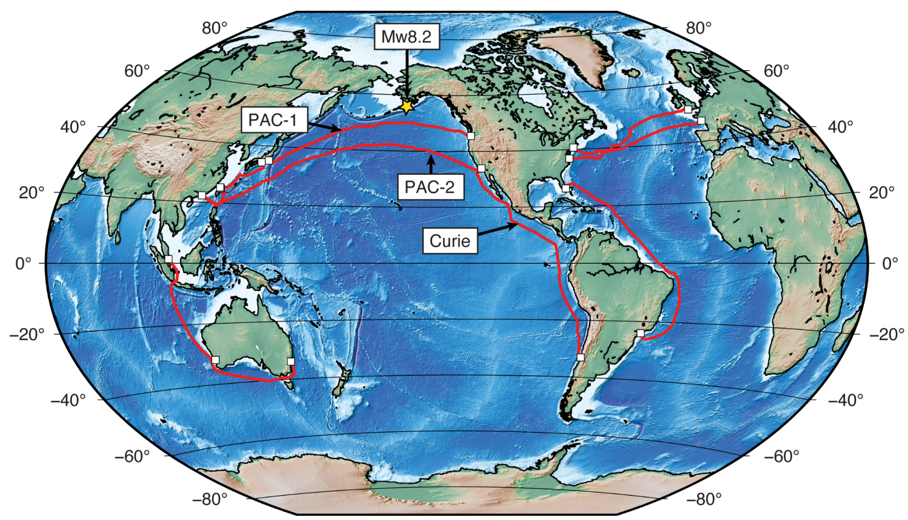

Figure 1. Submarine cables that have now activated PolarSense, with State of Polarization (SOP) data streaming in near real time to the Google Cloud Platform for further processing. The yellow star denotes the 2021 Chignik, Alaska M8.2 earthquake, which was detected by two cables in the Pacific: PAC-1 and PAC-2.

3. SOP earthquake detection by S waves

Earthquakes emit both compressional and shear elastic waves. The compressional P waves travel faster within the Earth and have smaller amplitudes. The shear S waves are slower but stronger. Identification of P and S waves on seismic records are critical to earthquake detection and localization using traditional seismic sensors. Because PolarSense makes integrated measurements along the entire cable, P and S waves from earthquakes do not produce sharp arrivals as distinct as on traditional seismometers. The identification of P and S waves is further complicated by the fact that the along-cable sensitivity of SOP may vary along the cable, due to differences in cable type (e.g., single-armored vs. double armored), fiber stress state (e.g., curved vs straight), and coupling to the seafloor. The travel time calculations may not have a unique distance. Zhan et al. assumed that the fiber section closest to the earthquakes contributed the biggest signals, but the assumption has not been tested rigorously [6,7].

Here we present a systematic compilation of SOP detections of earthquakes on the Curie and a Transpacific cable (PAC-1), which travel along relatively active subduction zones. In Figure 2, we sort the events by their distances to the closest points along the cable and align them by the earthquake origin time from the USGS NEIC catalog. The SOP earthquake signals are largely aligned with the predicted S wave arrival times based on the AK135 1D Earth model. In a few cases the P waves or the T wave appears to be detected based on the arrival time (T waves travel most of their paths as hydroacoustic waves in the ocean at 1.5km/s). This suggests that, in most cases, PolarSense detects earthquakes by the S waves at or near the fiber sections closest to the sources. This may not be surprising, because S wave amplitudes are generally bigger than P waves, and the wave amplitudes also decay as a function of distance due to geometrical spreading and attenuation. The sensitivity of the cable must not vary substantially over large scales, although small-scale variations may still exist. The consistent alignment with S waves also shows that the timing accuracy of SOP measurements has been substantially improved, compared to the shifts on the order of minutes in the early experiments reported by [6].

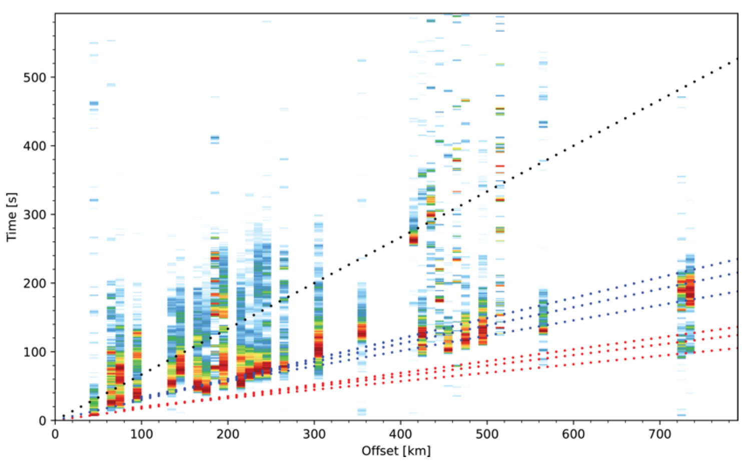

Figure 2. Record sections of SOP detections of earthquakes over the Curie and PAC-1 cables, which have the longest records. Each vertical stripe represents the stacked SOP power of earthquakes within a 10-km distance bin. The distance is calculated from an event to the closest point along the cable. The frequency band of the traces is 0.01-5Hz. The red, blue, and black dotted lines represent travel time predictions for P waves, S waves, T waves, respectively, based on the 1D AK135 model.

4. Towards event localization using multiple cables

With a more clear understanding of the wave type and sensing section, we attempt to address the major challenge of PolarSense, event localization, by using multiple cables. Because of the scalability of PolarSense, it is possible to turn large networks of submarine cables into seismic sensors. If an earthquake is detected by at least three cables with different geometry (orientation, location, path shape, etc.) and accurate clocks, then it is possible to use their differential travel times to triangulate the source location. Note that because PolarSense cannot yet localize the distance of perturbation along the cable by direction-dependent measurements [1], we need more than two cables for location, or more if the cable geometry is not favorable. Further development of distributed sensing capability along cable will substantially improve location accuracy.

With PolarSense activated on six cables globally during the last few months (Figure 1), the 2021 Chignik, Alaska M8.2 earthquake provided the first opportunity for us to test the localization idea using two Transpacific cables, PAC-1 and PAC-2. The Chignik earthquake is the largest event in Alaska since 1965. It ruptured a section of the plate interface along the Alaska subduction zone, where the Pacific plate subducts under the North American plate at about 64 mm/yr. The earthquake produced very strong shaking in the islands nearby but only generated a small tsunami of less than 0.5 m because of its depth at ~32km. NOAA issued the first tsunami warning about 5 min after the earthquake and canceled it after 3 hours.

At the closest points, the 2021 Chignik earthquake is about 580 km away from PAC-1 cable, and 1400 km from the PAC-2 cable (Figure 1). The SOP readings of both cables detected the event (Figure 3). Because of the integrated nature of SOP measurements, it is impossible to pick a sharp arrival time for either P or S waves. Knowing from Section 3 that the stronger SOP perturbation is most likely caused by S waves at the closest section, we measure the differential travel time of the envelope functions between PAC-1 and PAC-2 at the same frequency band (0.4-0.5Hz), which is about 150s as shown in Figure 3. Although we cannot uniquely locate the event with only two cables in this case, it is clear that the event must have happened to the north of PAC-1, consistent with the location of the event. The differential time also puts constraints on the distance between the two cables at the detection point, so the event cannot be near the western Pacific section where the cable separation distance is too short, or near the western coast of the US where the separation is too large (Figure 1).

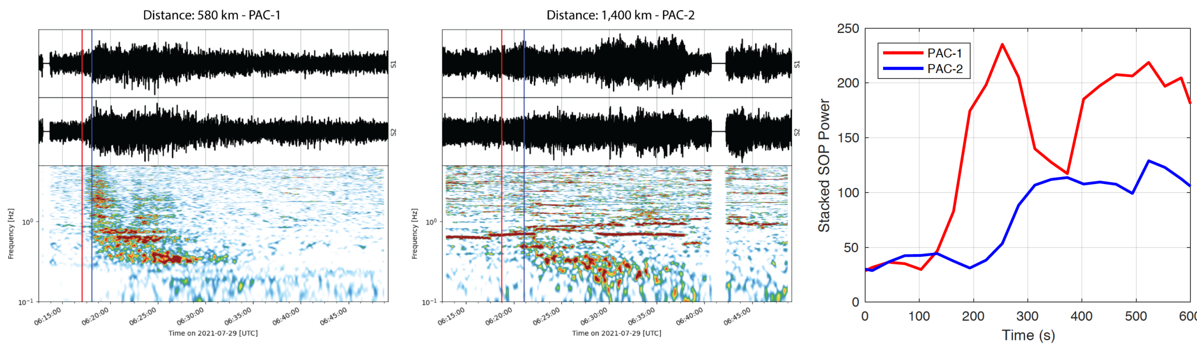

Figure 3. PolarSense detection of the 2021 Chignik M8.2 earthquake over the PAC-1 and PAC-2 cables. The top two traces in the left two panels represent the S1, S2 components of the Stokes parameters. The red and blue vertical lines are predicted P and S wave arrival times based on the distances to the closest points along the cables. The right panel shows the power of SOP perturbations stacked over the 0.4-0.5Hz frequency band, for PAC-1 and PAC-2, respectively. The earlier detection over PAC-1 is due to its closer distance from the earthquake.

5. Conclusion

Here we report the rapid expansion of PolarSense network over six additional long-haul submarine cables. By compiling event detections over the Curie and a Transpacific cable, we have verified that S wave is the main wave type being detected by SOP, and the assumption of main contribution from the closest fiber section is in general valid. We have also confirmed the improved clock accuracy, which makes it possible to jointly analyze SOP readings from multiple cables. Finally, we reported the first major earthquakes detected by more than one submarine cable using SOP and verified that their differential travel times can indeed provide useful constraints on earthquake location. This paves the way to use more than two cables to uniquely locate events in the future, thanks to the scalability of the PolarSense approach.

6. References

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