OPTICAL SEISMOLOGY

Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

Giuseppe Marra[1]*, Cecilia Clivati[2], Richard Luckett[3], Anna Tampellini[2,4], Jochen Kronjäger[1], Louise Wright[1], Alberto Mura[2], Filippo Levi[2], Stephen Robinson[1], André Xuereb[5], Brian Baptie[3], Davide Calonico[2]

Detecting ocean-floor seismic activity is crucial for our understanding of the interior structure and dynamic behavior of Earth. However, 70% of the planet's surface is covered by water, and seismometer coverage is limited to a handful of permanent ocean bottom stations. We show that existing telecommunication optical fiber cables can detect seismic events when combined with state-of-the-art frequency metrology techniques by using the fiber itself as the sensing element. We detected earthquakes over terrestrial and submarine links with lengths ranging from 75 to 535 kilometers and a geographical distance from the earthquake's epicenter ranging from 25 to 18,500 kilometers. Implementing a global seismic network for real-time detection of underwater earthquakes requires applying the proposed technique to the existing extensive submarine optical fiber network.

Although 70% of Earth's surface is covered with water, almost all seismic stations are on land. Underwater earthquakes of small intensity [moment magnitude (M_w) < 4] remain largely undetected because they are too weak to be measured with land-based seismic networks. This limits our ability to identify the source mechanisms of underwater seismic events and our understanding of the internal structure of Earth.

Underwater seismic sensors, such as ocean bottom seismometers (OBSs), have been widely used to study the physics of Earth (*1*), from earthquake dynamics to changes in volcanic structure (*2*), magma generation, and mid-ocean ridge development (*3*). These devices are deployed over geographically limited areas for temporary surveys, with data retrieved at the end of the campaign (*4–6*). Japan, the United States, and Canada have installed permanent arrays of OBSs close to earthquake-prone areas for research purposes and as tsunami alert systems (*7–10*). However, a permanent array of wired OBSs large enough to cover Earth's waters would be extremely expensive to install. Several more affordable solutions have been proposed (*11*, *12*), including potentially adding sensors in future submarine telecommunication repeaters (*13*). However, the existing submarine telecommunication network itself is a very attractive option for a global, real-time seismic network if the fiber itself is used as the sensing element. Such a fiber-based network should complement existing land-based seismometer and OBS networks, extending the coverage of underwater earthquake monitoring.

Submarine optical fiber cables are the backbone of international and intercontinental telecommunication. Since the first installations in the 1990s, the number of links has increased exponentially because of growth in the internet and mobile services. The current total length of submarine fiber cables is over 1 million km. In 2016 alone, ~100,000 km of cable were added to the existing network, and another 200,000 km are planned by mid-2018 (Fig. 1A) (*14*). Optical fibers can detect seismic events over kilometer-scale links by using distributed acoustic sensing techniques (DASs) (*15*, *16*). These techniques were developed by the oil and gas industry, for which they are currently primarily in use. DAS systems use back-scatter of the injected optical signal to extract information about local perturbations along the fiber. Because of the nonzero optical losses of the fiber, the signal-to-noise ratio of the returned signal decreases with the travel distance, currently limiting the usable range of this technology to <100 km. The feasibility of extending the DAS range to thousands of kilometers by using optical amplifiers along the link is yet to be demonstrated. Frequency metrology interferometric techniques can overcome the limitations of DASs. These techniques were initially developed by national metrology institutes (NMIs) for the comparison of next-generation atomic clocks. Metrological optical links up to 2200 km long already connect some of the largest NMIs in Europe, and network expansion is underway (*17–20*). Fiber links are usually installed in underground utility ducts, such as power or gas lines, or along motorways and are thus exposed to environmental noise. The induced noise is detrimental to atomic clock comparisons and suppressed by using active cancellation techniques (*21*). However, we can exploit the sensitivity to environmentally induced perturbations to detect seismic waves, vibration, and any other sources of acoustic noise. With these interferometric techniques, we can measure changes as small as a few femtoseconds in the propagation delay experienced by the laser light traveling in the fiber. This corresponds to micrometer-scale length changes that can be measured over lengths of fiber up to several thousands of kilometers. We achieve this level of sensitivity in just 1 s of measurement time using a laser stabilized to state-of-the-art Fabry-Pérot cavities made of ultralow expansion (ULE) glass (Corning) (*22*). Metrology-grade lasers generate phase-stable light over the entire propagation time through the fiber, which ensures that propagation time changes are attributed exclusively to the fiber.

Our experiments used light from a ULE cavity–stabilized laser that we injected at one end of a standard terrestrial or submarine optical link that consists of a fiber pair, one fiber used for each direction of propagation (Fig. 1B). The two fibers are connected at the far end of the optical link to form a loop so that the light returns to the transmitter after a round trip. We combined the injected and returned optical signals on a photodetector and measured their phase difference. The seismically induced phase changes of the returned optical signal detect local and remote earthquakes.

On 24 August 2016, an earthquake of M_w 6.0 struck in central Italy, followed by two more events on 26 and 30 October of M_w 5.9 and 6.5 respectively (*23*). These events were detected at the National Physical Laboratory (NPL) in Teddington, United Kingdom, while running frequency metrology experiments on an optical fiber link not intentionally designed to detect seismic waves. This 79-km-long fiber link (UK-L1) connects NPL in Teddington to a data center in the nearby town of Reading and is located at a geographical distance of ~1400 km from the epicenter of the central Italy earthquake. The phase fluctuations induced by the seismic event on the laser light propagating in the fiber link for the 30 October event are shown in Fig. 2A and compared with data from a seismic station (Swindon, GB.SWN1) located ~100 km away from the NPL end of the fiber link. The low sampling rate (one sample per second) prevented us from constraining the magnitude of the primary wave (*P* wave) that has a frequency spectrum extending to a few Hz. We detected several other teleseismic events with independently determined magnitudes of M_w 5.9 to 7.9 with epicenters in New Zealand, Japan, and Mexico. We achieved a higher signal-to-noise ratio on another 75-km-long optical link (UK-L2) in southeast England in late 2017. This link runs almost entirely in nonmetropolitan areas, which resulted in lower environmentally induced noise levels as compared with that of UK-L1. At the same time, the Istituto Nazionale di Ricerca Metrologica (INRiM) in Turin, Italy, established a 535-km link (IT-L1) between Turin and Medicina near the town of Bologna. The optical phase sampling rate for UK-L2 and IT-L1 was 100 samples per second. On 12 November 2017, we detected the M_w 7.3 earthquake on the Iran-Iraq border

[1]National Physical Laboratory, Hampton Road, Teddington TW11 0LW, UK. [2]Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, 10135 Turin, Italy. [3]British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, Scotland, UK. [4]Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy. [5]Department of Physics, University of Malta, Msida MSD 2080, Malta.
*Corresponding author. Email: giuseppe.marra@npl.co.uk

with both UK-L2 and IT-L1 links (Fig. 2B). We determined the arrival times for the *P* and *S* waves using the UK-L2 link, which were consistent with the first arrivals identified by using the nearby seismic station at Herstmonceux (GB.HMNX). Periodic environmental perturbations in the IT-L1 link made it difficult to resolve the *P* wave, but the following seismic perturbations were clearly visible.

The detection sensitivity of a terrestrial optical fiber link, like for seismometers, is primarily limited by surrounding man-made noise in the frequency range of interest for earthquake detection (0.1 to 20 Hz). We expected substantially lower background noise per unit length over submarine optical links. We conducted metrology experiments with an ultrastable laser source on a submarine link (IT-L2) in September 2017. During a 2-day measurement campaign on the 96.4-km-long submarine cable between Malta and Sicily, we detected a local magnitude (ML) 3.4 earthquake, with an epicenter 89 km away in the Malta Sea (Fig. 3A). We measured the optical phase perturbation and compared it with the displacement recorded by seismometers located within a few kilometers of each end of the fiber link (MN.WDD, Malta, and IV.HPAC, Sicily) (Fig. 3A). We observed a delay of ~2 s between the *P* wave detected by the link and the MN.WDD station. This delay is consistent with the travel distance between the seismometer and the Malta end of the fiber link at a speed of ~5 km/s, which we calculated from the delay observed between the MN.WDD and IV.HPAC seismograms. We clearly identified both *P* and *S* waves. We measured the root mean square level of environmental noise of the IT-L2 submarine link to be 8 and 5 times lower than the UK-L1 and UK-L2 links, respectively, in the frequency range of 0.1 to 20 Hz. In coastal areas, the ambient noise in this frequency range arises primarily from commercial shipping and local wind-sea, wave-wave, and wave-shore interactions. We expect a quieter environment for cables resting on the ocean floor in much deeper waters than the shallow depth (200 m) of the busy Malta-Sicily channel, allowing the detection of low-magnitude earthquakes on substantially longer links than IT-L2 (*24*). Submarine cables cross several seismically active areas, such as the North and Mid-Atlantic ridge and the South American Plate, North American Plate, and African Plate triple junction. Seismic monitoring of all these areas relies almost entirely on land-based seismic stations. Earthquakes of magnitude lower than 4 are largely undetected because they are too weak by the time they reach seismometers on the nearest island or mainland. Such earthquakes typically are detected only up to a few hundred kilometers from the epicenter and would affect a relatively small fraction of the submarine fiber links. A similar scenario, on a smaller scale, occurred for detection of the M_w 4.4 Parma, Italy, earthquake on the IT-L1 link in November 2017 that was also detected with nearby seismometers (Fig. 3B). Here, the epicenter was 25 km away from the nearest

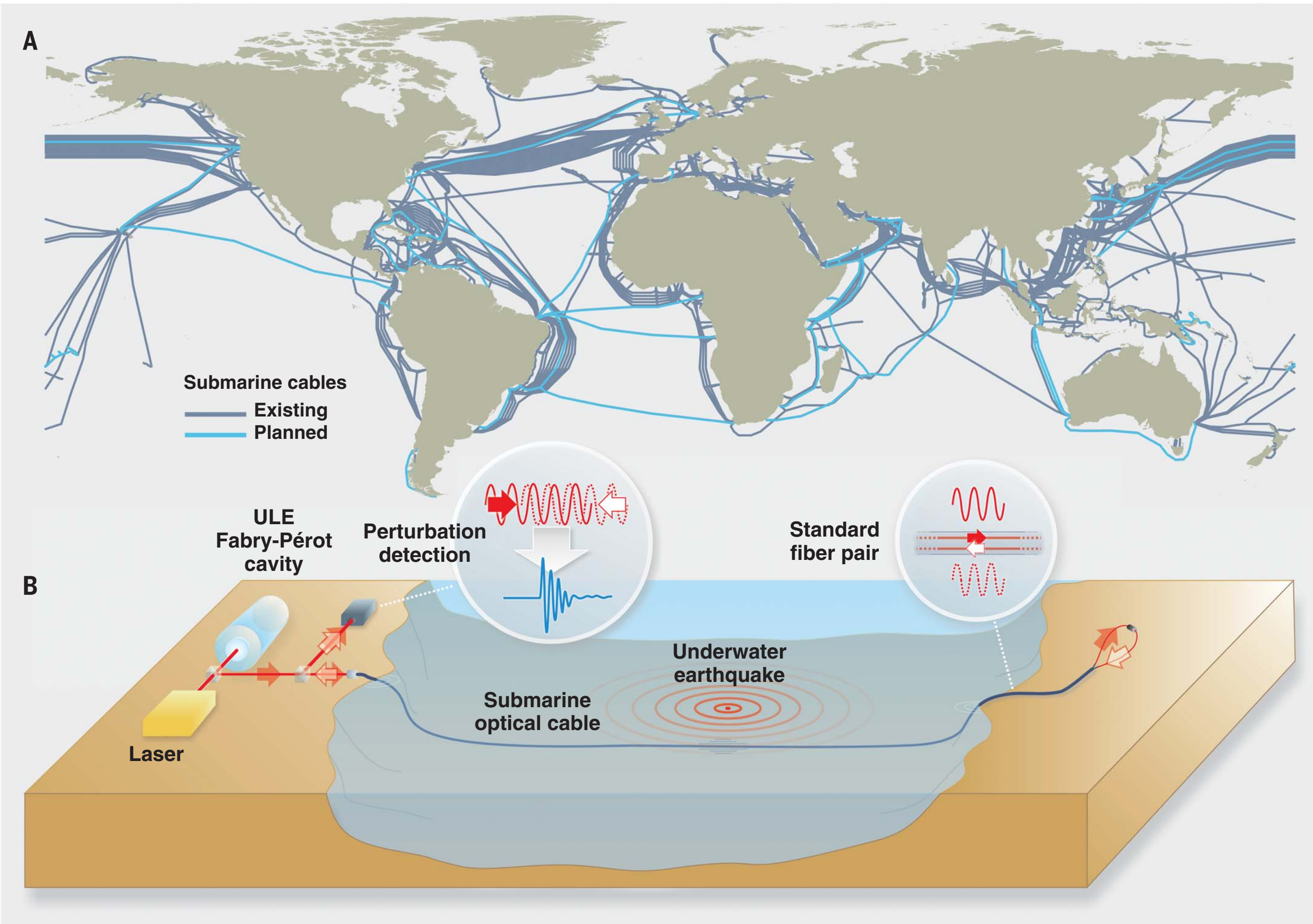

Fig. 1. Submarine telecommunication infrastructure and earthquake detection experimental setup. (**A**) Shown is an illustration of the existing and planned submarine telecommunication infrastructure. Optical frequency metrology techniques enable these fiber links to be used for the detection of earthquakes at the bottom of seas and oceans. [Map data are copyright of OpenStreetMap contributors; cable data are from TeleGeography's Telecom Resources licensed under Creative Commons ShareAlike.] (**B**) Illustration of the optical setup used in our experiments for measuring the seismically induced perturbation of the optical signal traveling in the fiber. The same principle was used for terrestrial and submarine fiber links (only the latter case is illustrated in the figure). ULE, ultralow expansion glass used to stabilize the laser frequency.

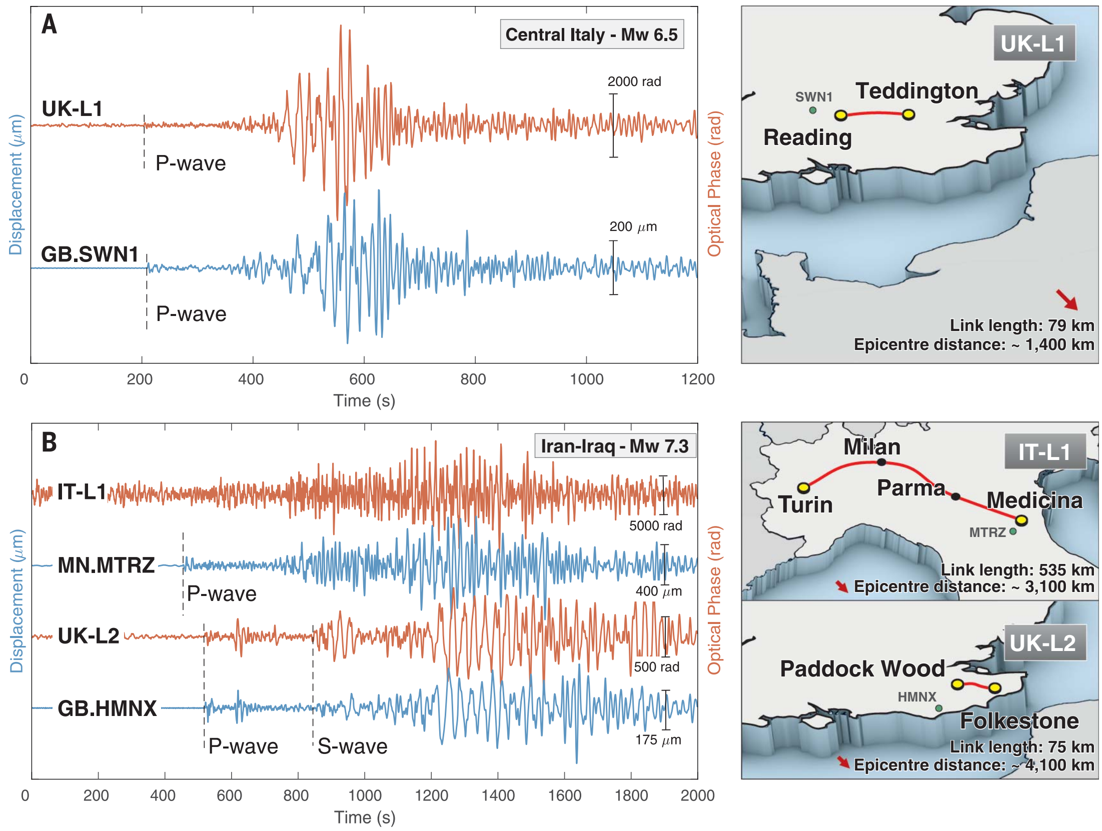

Fig. 2. Teleseismic events on terrestrial optical links. (**A**) Comparison between the seismically induced optical phase changes detected on the UK-L1 link and the signal from a seismometer in Swindon (GB.SWN1) for the central Italy earthquake on 30 October 2016. (**B**) Comparison between the phase changes detected on the IT-L1 and UK-L2 link with the signals from seismometers in Monterenzio (MN.MTRZ) and Herstmonceux (GB.HMNX) for the Iran-Iraq border earthquake on 12 November 2017. The north-south component has been used for all seismic station data.

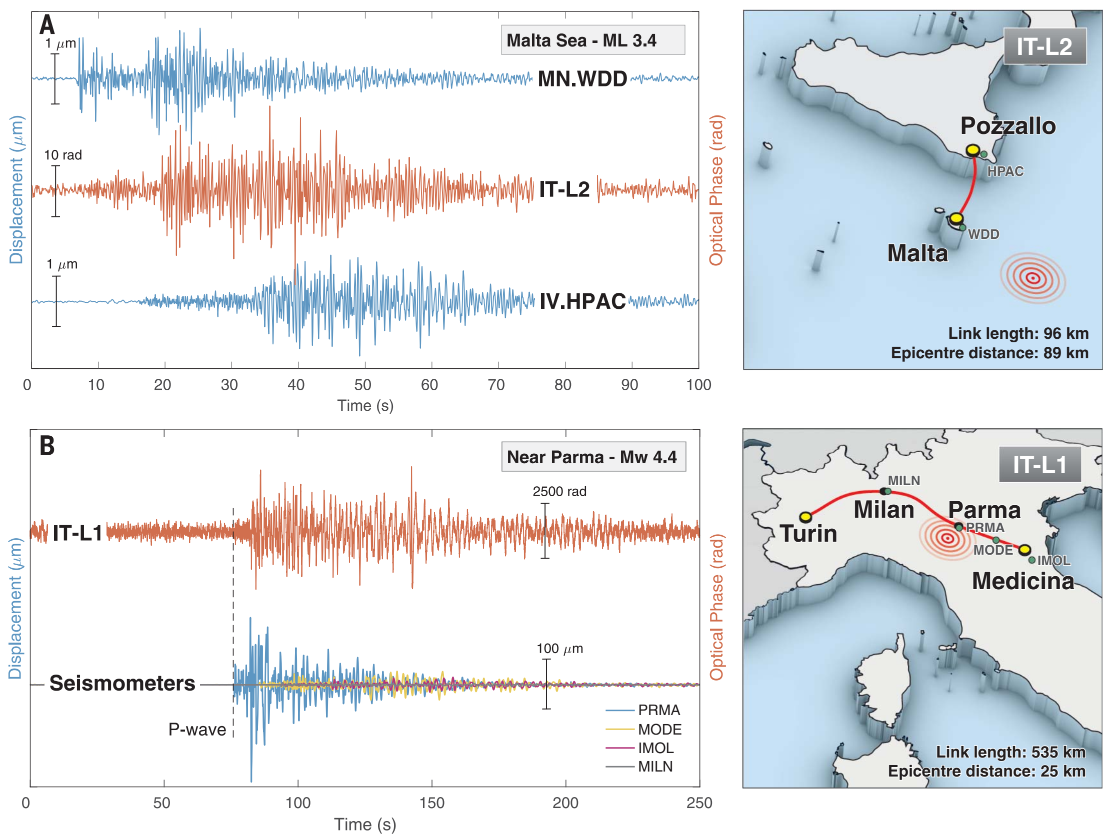

Fig. 3. Small-magnitude earthquakes on submarine and terrestrial links. (**A**) Seismic wave detected on the submarine IT-L2 link for the Malta Sea earthquake on 2 September 2017 compared with signals from seismometers located within a few kilometers of each end of the link. High pass filtering at 1.5 Hz has been applied to the optical signal so as to suppress a strong environmentally induced 1 Hz component that was present on the optical signal. The same filter has been applied on the signals from seismic stations. (**B**) Comparison between the phase changes detected on IT-L1 link and seismometers located close to four intermediate points along the link for the Parma earthquake on 19 November 2017. The north-south component has been used for all seismic station data.

section of the 535-km-long fiber link. We identified the time of arrival of the detected seismic wave, which corresponded to the smallest distance between the epicenter and the fiber link. This also leads to the highest amplitude of the detected signal, as confirmed with the seismometer traces.

We can determine the point at which the seismic wave reaches a fiber link by transmitting the laser light in both directions in a standard telecommunication fiber pair (Fig. 4A). We can measure the distance traveled along the fiber by cross-correlating the seismic signals recorded at each end of the link with a high-speed phase sampler. We used this technique in the laboratory to demonstrate proof of concept, in which we were able to identify the location of an environmental perturbation to within 1 km over 101 km of spooled fiber (*24*). The use of two fiber links, following different paths, allows the determination of the epicenter (Fig. 4B). The exact route of each fiber, required to calculate the epicenter, is normally known to within 1 km. Two line sensors (the links) eliminate the need for a third node to triangulate, as traditional seismology requires. Additional links improve the epicenter location accuracy and enable depth to be determined.

In contrast to seismometers, optical fibers are sensitive to seismic perturbations over their entire length rather than at a single point in space. The detected signal will be the result of integration of these perturbations. However, for earthquakes whose epicenter is at a distance shorter than the length of the link (as it would be in the case of small local earthquakes detected with transoceanic links), sections of the fiber far from the first point of contact of the seismic wave with the link will contribute only to a small degree to the detected signal, owing to the attenuation of the seismic wave with distance (this can be inferred, for example, from the seismometer traces in Fig. 3B for the Parma earthquake). The arrival time of the *P* wave, one of the most important parameters for earthquake characterization, is not affected by the distributed nature of the detection because only a small section of the link is perturbed upon its arrival. Also unlike seismometers, the signal detected by using optical fiber links is the result of the superimposition of perturbations along the three components of motion. Although the resulting signal from the distributed detection with optical fiber might require different analysis than that performed on seismometer data, crucial information can still be extracted and can prove invaluable from locations where no data can currently be obtained otherwise.

We used several optical fiber installations to detect local earthquakes and teleseisms and present a strategy for using the existing submarine telecommunications optical fiber infrastructure. Using existing cables should provide a cost-effective complement to ocean-bottom seismometers and further advance our understanding of the dynamic behavior of Earth's interior. The phase stability of metrology-grade lasers is sufficient to enable coherent measurements over fiber lengths well beyond 10,000 km, enabling measurement with transoceanic links. Fiber optic earthquake detection may be the preferred option for more remote areas such as the Arctic sea (*25*). We anticipate that submarine fiber networks could also be used for applications beyond seismic monitoring, from marine mammal migration tracking (*26*) to sea noise pollution monitoring, a growing matter of concern worldwide for its impact on marine life (*27*, *28*).

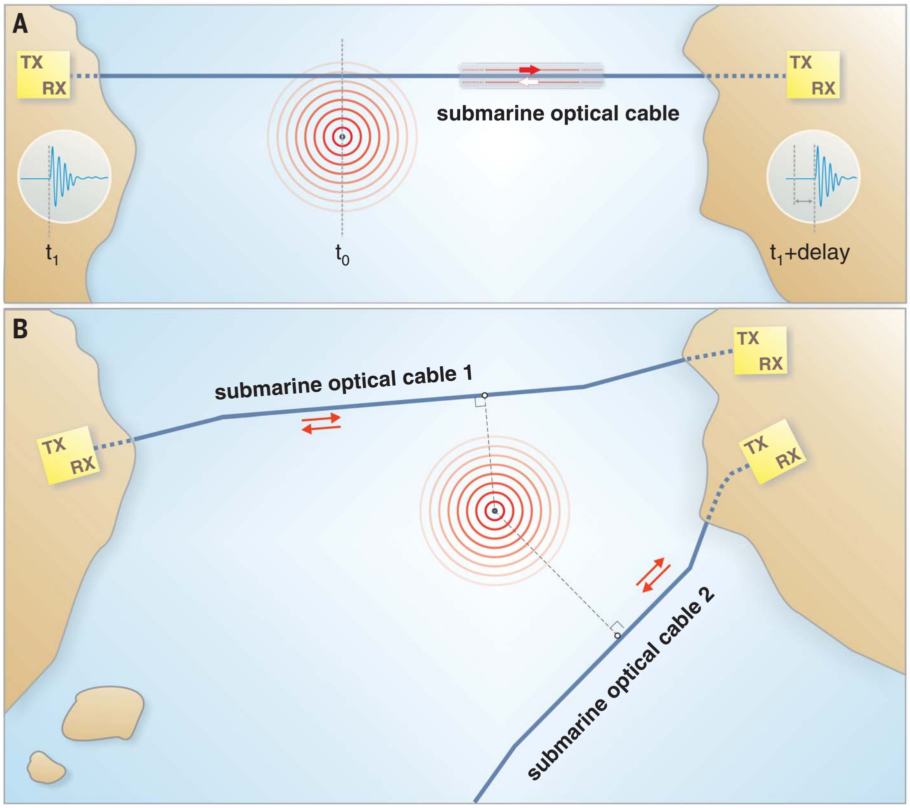

Fig. 4. Seismic event localization techniques. (**A**) Because of the finite propagation speed of the light in the fiber (~2 × 10^8 m/s), seismically induced optical phase perturbations will reach the two ends of a bidirectional fiber link at different times. The location on the optical fiber link at which the seismic wave first reaches it can be determined by calculating the delay difference by cross-correlating the received signals. Earthquakes located on either side of the link and along the axis perpendicular to the link will result in the same identified location along the fiber. By using two links, the location ambiguity can be resolved. (**B**) Localization of the epicenter by using two bidirectional fiber links. Simple geometry allows the coordinates of the epicenter to be found from the location of the point of first contact of the seismic wave along the fiber. TX, ultra-stable laser injecting light into the fiber; RX, optical detection and phase comparison unit. This unit measures the optical phase difference between the light generated by the local TX laser and that transmitted through the fiber link by the remote TX laser.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/361/6401/486/suppl/DC1
Materials and Methods
Figs. S1 to S5
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Data File S1
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Giuseppe Marra, Cecilia Clivati, Richard Luckett, Anna Tampellini, Jochen Kronjäger, Louise Wright, Alberto Mura, Filippo Levi, Stephen Robinson, André Xuereb, Brian Baptie and Davide Calonico

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Submarine fiber optic earthquake detection
Seismic networks detect earthquakes and are common on continents, where they are easy to install. However, most of Earth's surface is under the oceans, where placing seismometers is difficult. Marra *et al.* now find that ordinary submarine telecommunication cables can be used to detect earthquakes. Small strain changes associated with the passage of seismic waves were detected with laser light sent through in-use fiber optic cables by ultrastable lasers. This strategy could turn intercontinental fiber optic cables into ocean-bottom strain sensors, dramatically improving our ability to record earthquakes.
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