# High resolution optical seismometer for real-time monitoring of ocean-bottom seismicity

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## LOKI: a dedicated embedded processing platform

### System architecture and operating principle

Designed and developed within the scope of PREST, LOKI is the latest generation of interrogator for extrinsic Fabry-Perot based sensor. From the early prototype, assembled from on-shelf instrumentation, deployed during at LSBB in Rustrel in 2012 (ANR LINES) , to the first embedded dedicated and rugged prototype GAIA, deployed offshore near Brest in 2018 and later offgrid at la Soufrière in 2019 (ANR HIPERSIS), We have worked continuously to improve resolution and versatility , while reducing size and power consumption.

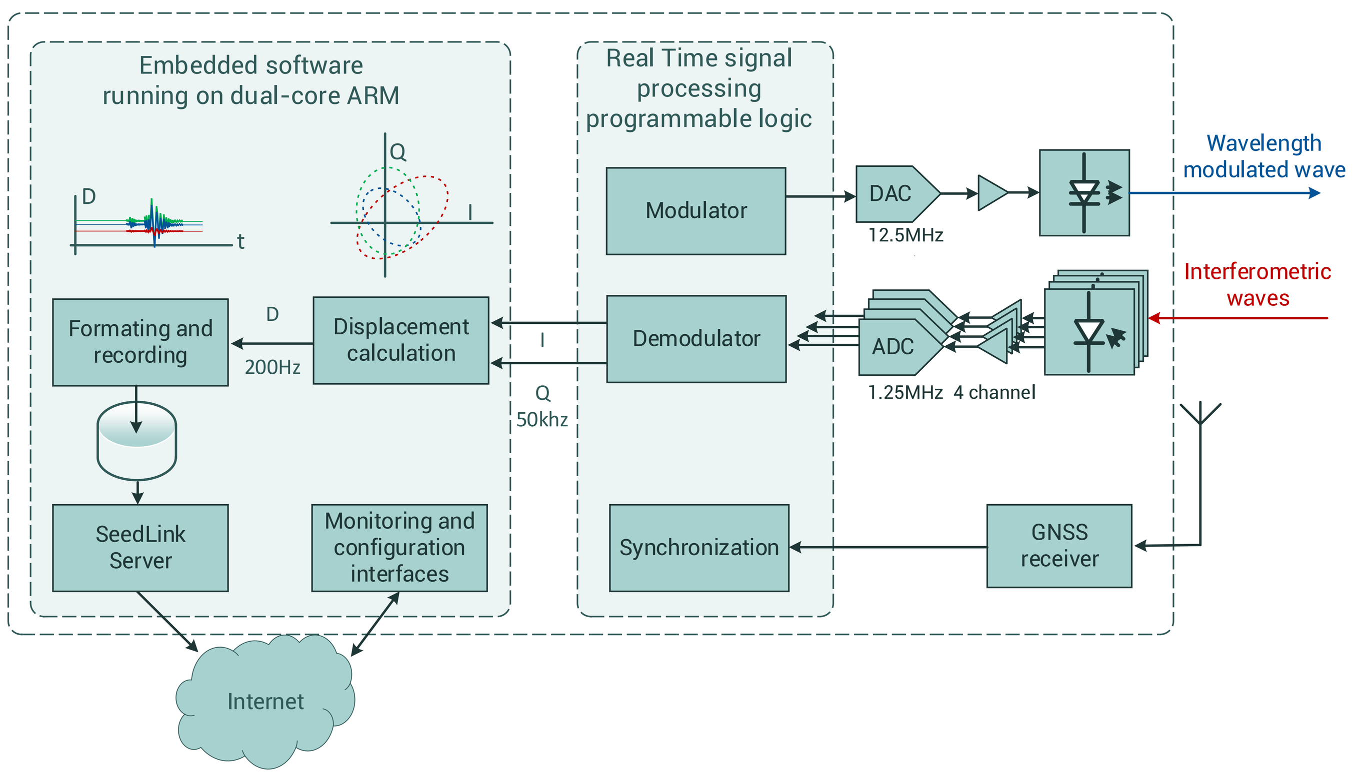
As the first fully in-house dedicated acquisition and processing platform, LOKI is a milestone. A combination of state of the art digitizers, tailored analog circuitry, embedded computing and programmable logic allow high performance real-time processing while maintaining high performance to Watt ratio.

Since June 2021, two of those last gen interrogators are continuously running in les Saintes and at la Soufrière providing the observatory network with measurements

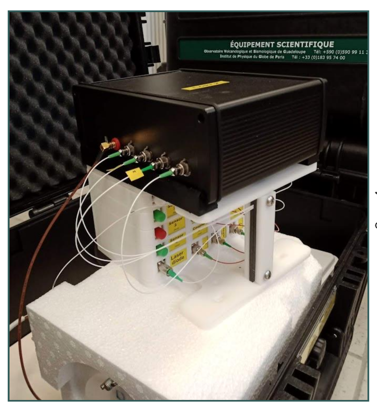
The optical measurement of the displacement of the mobile mass of the geophone, by FP interferometry, allows us to resolve the low-noise level of the Earth at periods down to 5s (2Hz geophone ). This performance is due to the innovative design of real-time algorithms that processes the double modulation signal of the laser frequency:

To boost measurement accuracy, the interrogator modulates the wavelength of the laser diode at a rather high frequency Fm (50 kHz). The cosine spectrum D(t) is actually centered on Fm, whereas the sine spectrum of D(t) is centered on 2x Fm – the first harmonic of Fm. Information is derived in part by a double synchronous demodulation. The instantaneous phase of resulting clarified signals contains a signature of the displacement. To decipher it, a real-time adaptive estimation algorithm (Kalman filter) followed by a phase unwrapping yields the distance D(t) of the mobile mass from the other side of the optical cavity. This seismometer and signal analysis presents very high-resolution characteristics, similar to those of the best commercial short period or medium band Seismometers.

**Fig-1: LOKI interrogator functional diagram**




### Performances and integration



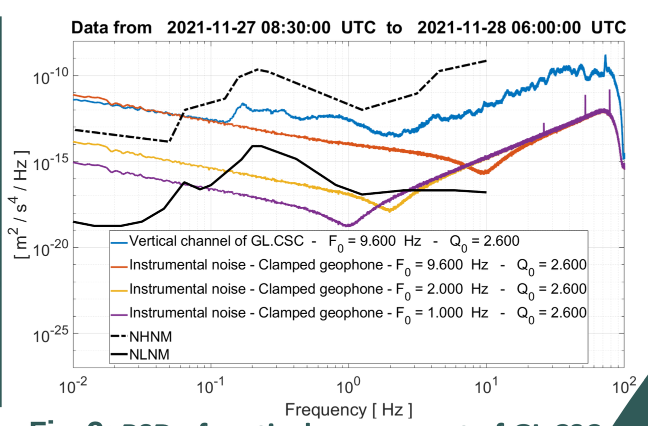
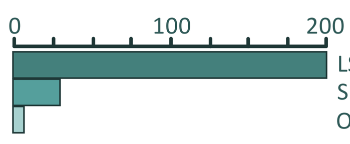



**Fig-2: PSD of vertical component of GL.CSC**
Summit of La Soufrière,Guadeloupe
and instrumental noise level
for different natural frequencies

**Fig-3: Power consumption reduction through the years**




### Key features

- High resolution
- Long range, up to 50km
- Versatile applications ( Displacement, tilt, strain )
- SeedLink compatible
- Low power, suitable for off-grid applications
- GNSS disciplined timestamping

HighRes · 50km · Versatile · SeedLink · Low power · GNNS Disciplined

## GHIP: a passive optomechanical geophone

### Mechanical design

The mechanics of the geophones, called « Geophone HIPersis » GHIP, used for this installation were entirely conceived, developed and characterized within the scope of ANR HIPERSIS.

Unlike the early works (ANR LINES), where on-shelf geophone were fitted with optical components, the GHIP as been design from scratch. Every part of the GHIP has been tailored with simplicity and robustness in mind.

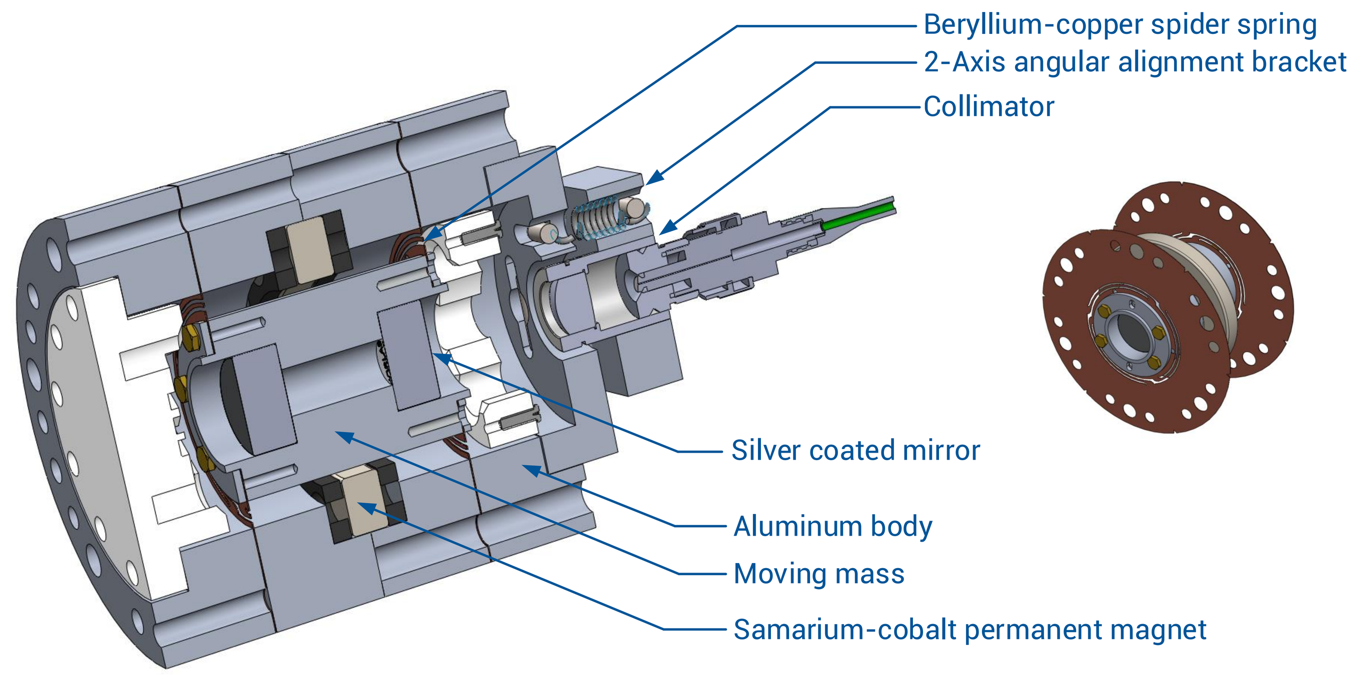
Intended to behave as close as possible to theoretical mechanical oscillator model the GHIP is a 10Hz mass-spider-spring system. This predictable behavior allow's an easy identification of its parameters, later used during deconvolution. A triaxial geophone is formed by fitting three of these oscillators orthogonally into a sealed container.

This 10 Hz natural frequency is high enough to withstand sudden motions while leveling or accidentally rotating the container—which could lead to the mechanical clipping of oscillators with lower natural frequencies (typically 1, 2, and 4.5 Hz).

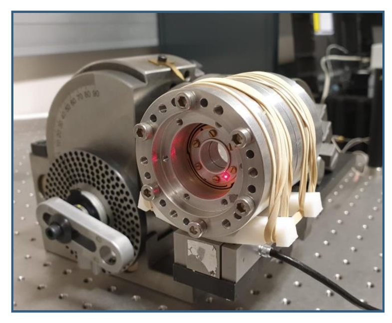
As no electronics is involved in the container, the oscillators are fully passive. Because their natural damping is very weak, we have employed a damping system based on eddy currents. We opted for samarium–cobalt annular magnets for their useful magnetic properties and particularly for their behavior as temperature changes. This choice not only stiffens the seismometer but also allows us to estimate the mobile mass position relative to the gravitational acceleration vector in case of rotation of the sensor container.

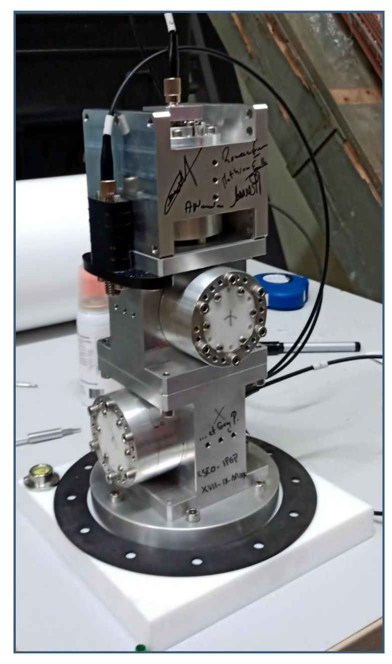
Each of the three sensor axial components is connected to one optical fiber, and a fourth fiber provides a reference optical signal, primarily to correct shared background optoelectronic noise.

**Fig-4: A cut through the mechanical design of the sensor**




### Vibrometric characterization setup and mechanical integration





### Key features

- Fully passive
- Heat resistant up to 150°
- Omni-tilt
- Low cost / expendable

Fully passive · Omni-tilt · Expendable · Heat resistant

Process · Sense

Designed and developed under the direction of Institut de Physique du Globe de Paris (IPGP), responsible for this axis in PREST, ESEOtech and Laboratoire d'Acoustique de l'Université du Mans LAUM) , this innovative instruments avoids many problems related to the usual deployment of electronics and energy on the seafloor.

Here, a purely mechanical seismometer, located at 40m depth underwater and 5 km south of Les Saintes, is connected by an optical cable to Terre-de-Bas (tourist office) where a laser interrogator allows remote measurement of its movements.

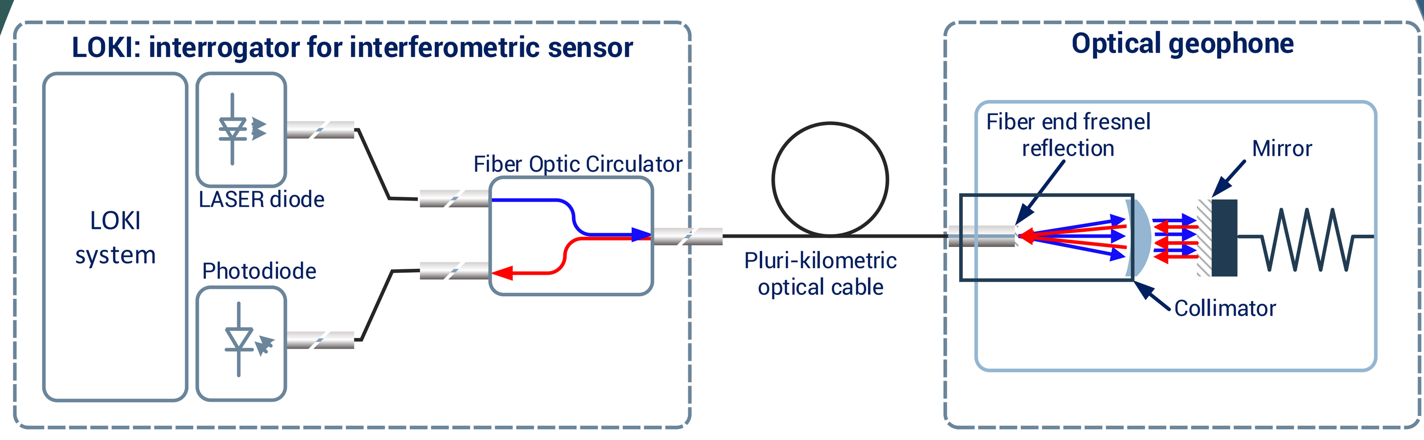



**Fig-6: Functional diagram of the high resolution optical seismometer**

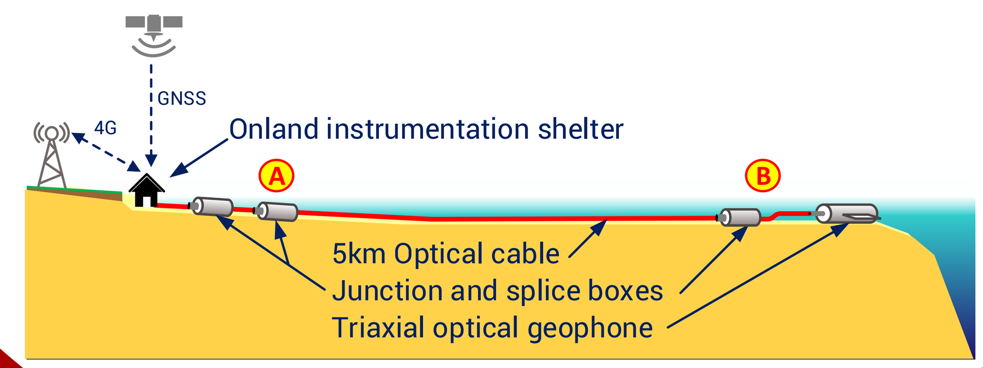
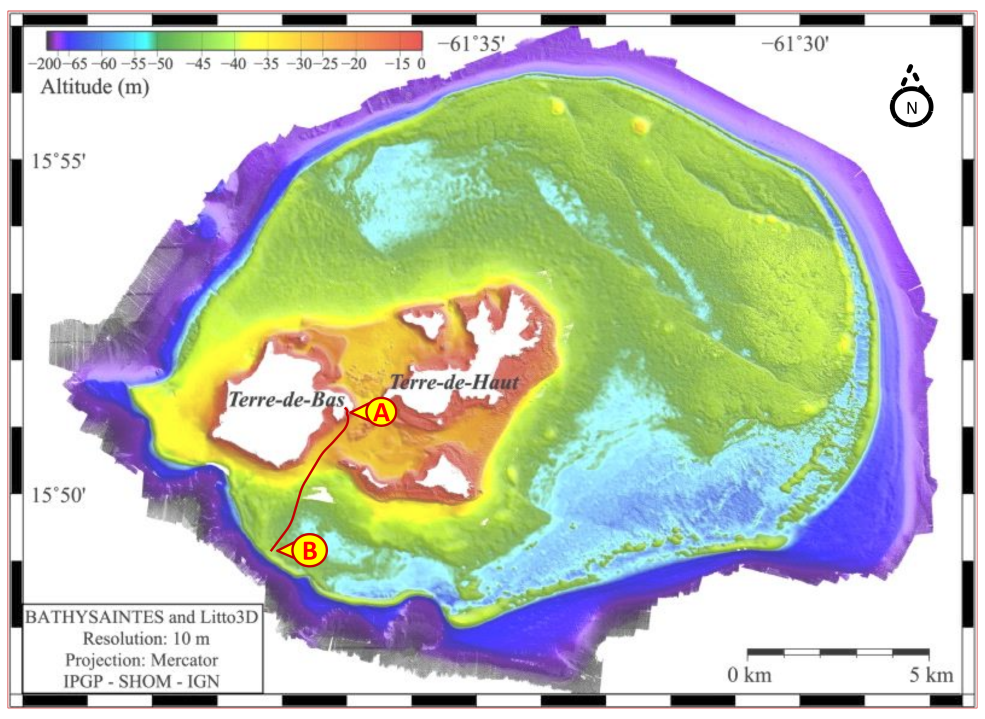



**Fig-7: Layout of les Saintes underwater observatory**

Deploy

## PREST: an ocean-bottom application

**Fig-8: High resolution bathymetry map of les Saintes archipelago and optical cable route**



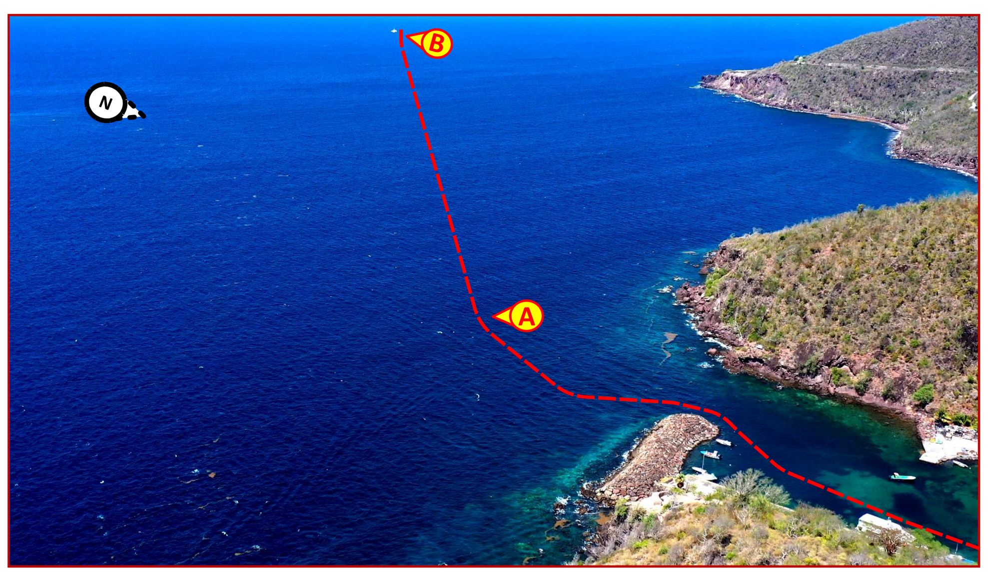
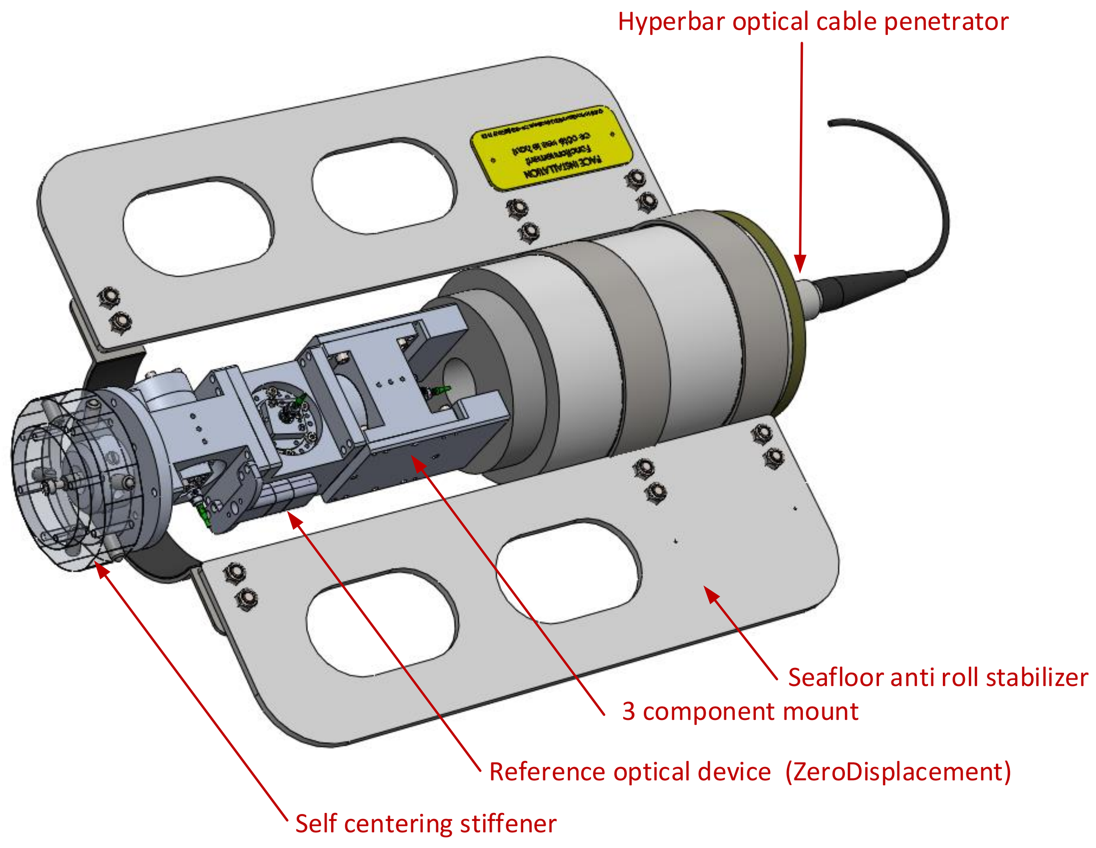



**Fig-9: Triaxial geophone fitted into a sealed marinized enclosure**




In June 2021, the FibroSaintes oceanographic campaign led by Géoazur (CNRS, Université de la Côte d'Azur) has conducted the installation of an innovative seismological station.
The station uses both a LOKI interrogator and a GHIP triaxial geophone linked by a 5 km long optical cable. The main optical cable was buried in the sediment between points A and B (Fig-8) where junction boxes are anchored.

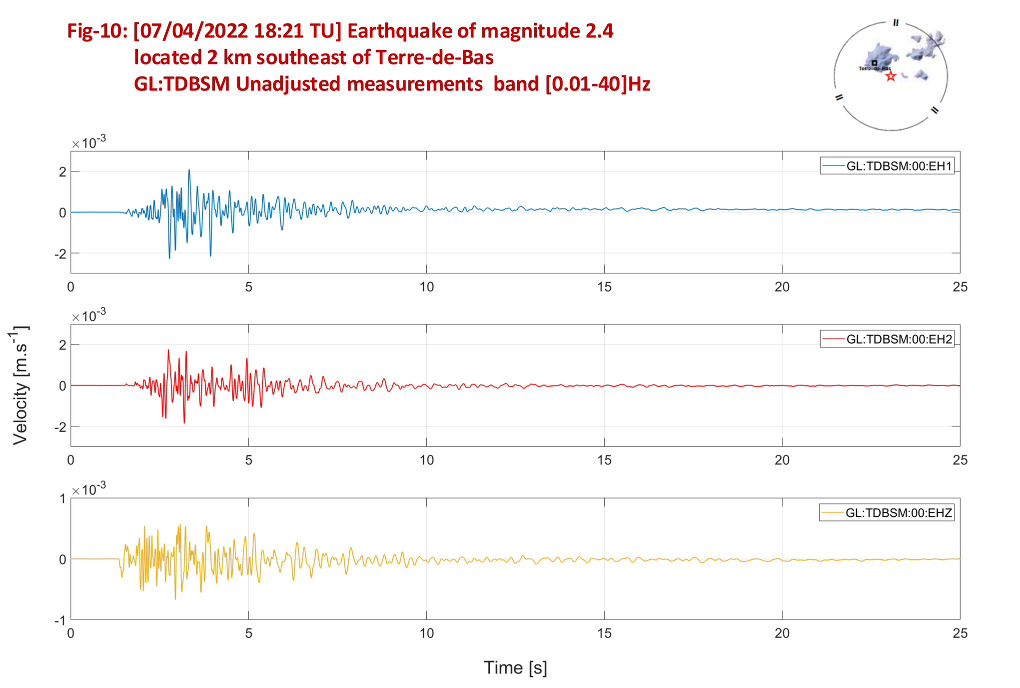
While the interrogator is installed ashore, the instrument is immersed at point B and connected to the fiber by an optical splice.

The installation of this underwater seismic monitoring observatory was carried out using the French oceanographic fleet vessel ANTEA (owned by IRD), operated by IFREMER.
The deployment required nearly 3 weeks of work at sea by experienced divers and engineers, but also ashore for the connection and protection of optical cable landing .

This was the first time a LOKI interrogator and GHIP triaxial geophone were installed together in real monitoring conditions.
To our knowledge, this is the first real-time ocean bottom optical seismometer ever installed.

Since then, the observatory has been operating continuously and is providing the observatory network with measurements, as shown in Figure 10, during a very local earthquake.

**Fig-10: [07/04/2022 18:21 TU] Earthquake of magnitude 2.4 located 2 km southeast of Terre-de-Bas GL:TDBSM Unadjusted measurements band [0.01-40]Hz**

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