AAPG2021	BRUIT-FM		PRC
	Wayne CRAWFORD	Duration: 48m	593 k€
CE01: Terre fluide et solide			

BRUIT-FM: seismic noise on and from the seafloor

Partner	Name	First name	Current position	Role & responsibilities in the project (4 lines max)	Involvement (person.month) throughout the project's duration
IPGP	*CRAWFORD*	*Wayne*	*Dir Rech CNRS*	*Coordinator and WP1 Leader WPs 2 & 4 co-Leader*	*21*
IFREMER	*KER*	*Stephan*	*Cadre de Recherche IFREMER*	*Partner's scientific leader WP4 co-leader*	*12*
iXblue	*GUATTARI*	*Frederic*	*Director*	*Partner's scientific leader WP 3.3 co-leader*	*2,5*
IPGP	*STUTZMANN*	*Eléonore*	*Physicien*	*WP3 Leader, WP2 co-Leader*	*18*
IPGP	*BARRUOL*	*Guilhem*	*Dir Rech CNRS*	*WP5 leader, WP2 co-leader*	*18*
IPGP	*XXXX*	*XXXX*	*PhD student*	*Doctoral researcher, WP3*	*36*
IFREMER	*XXXX*	*XXXX*	*postdoc*	*PostDoctoral researcher, WP4*	*18*
IPGP	*XXXX*	*XXXX*	*ingenieur (hired)*	*Data processing, WPs 2 & 5*	*20*
IPGP	*FARRA*	*Veronique*	*Maitre de Conf*	*WP3: Global noise*	*4*
IFREMER	*ARDHUIN*	*Fabrice*	*Dir Rech CNRS*	*WP3: Global noise modelling*	*2*
IFREMER	*DUVAL*	*Laurent*	*Chercheur Invité*	*WP3: signal processing*	*2*
IPGP	*SCHIMMEL*	*Martin*	*Researcher*	*WP3&4: Noise removal*	*4,7*
IPGP	*MARS*	*Jerome*	*Professor*	*WP4: Signal Processing*	*2*
IPGP	*OLIVIER*	*Michel*	*Professor*	*WP4: Signal Processing*	*2*
IPGP	*RIVET*	*Diane*	*Physicien Adjoint*	*WP4 : DAS applications*	*2*
IPGP	*STEHLY*	*Laurent*	*Asst Professor*	*WP4: Ambient noise applications*	*2*
IPGP	*DANIEL*	*Romuald*	*Ing Recherche*	*WP4: Rotational seismometer*	*2*
IPGP	*BESANCON*	*Simon*	*Ing d'etudes*	*WP4: Rotational seismometer*	*2*
IFREMER	*PELEAU*	*Pascal*	*Engineer*	*WP4: Rotational seismometer*	*2*
IFREMER	*GUYAVARCH*	*Pierre*	*Engineer*	*WP4: Rotational seismometer*	*2*
IPGP	*WEBB*	*Spahr*	*Professor*	*WP4: Noise removal*	*1,5*
IPGP	*SAMARAN*	*Flore*	*Asst Professor*	*WP5: Biological sources*	*3,5*
IPGP	*KINDA*	*Bazile*	*Researcher*	*WP5: noise pollution*	*3,5*

Any changes that have been made in the full proposal compared to the pre-proposal

The LOPS partner was integrated into the IFREMER-GM partner. The 3 doctoral researchers were transformed into 1 doctoral, 1 postdoctoral and 1 engineer, according to the specific needs of the Work Packages. A "Full Seafloor Spectrum" Work Package was added to cover data collection and validation as well as scientific aspects (noise levels, catalog of sources) that cross the three main Work Packages.

I. Proposal's context, positioning and objective(s)

a. Objectives and research hypothesis

BRUIT-FM is a multidisciplinary project to identify and exploit the signals hidden within broadband seafloor seismological "noise". Our goal is to catalogue the different noise sources, understand their contributions to local and global seismological noise and to enhance individual signals by removing others.

According to the Oxford English Dictionary (OED), "noise" is fluctuations or disturbances which are not part of a wanted signal or which interfere with its intelligibility or usefulness. In seismology, 'noise' often represents all non-earthquake related signals. In this proposal, we refer to non-earthquake signals as "seismological noise" and use the OED definition when dealing with specific, non-earthquake signals.

Marine seismology has made huge technological advances in the past few decades and ocean bottom seismometer (OBS) data is becoming broadly distributed through open data centers using standardised FDSN Web Services. These data can not yet be fully exploited by the seismological community, because of their relatively high seismological noise levels. We propose that **this noise, properly understood and treated, is not a hindrance to seismological study but rather a rich source of seismological, oceanographic, environmental, biological and cultural signals**, including storms, ocean waves, seafloor currents, ship engines and sonars, marine animals, landslides and icequakes (**Figure 1**).

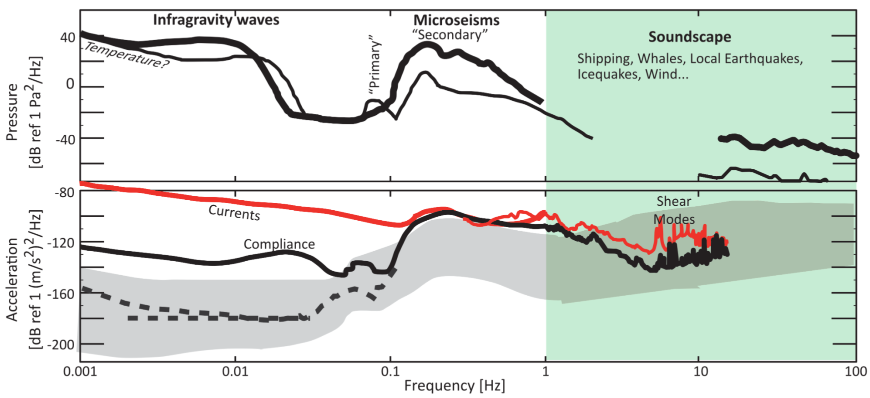


Figure 1: Seafloor seismometer spectra. Green region is the "soundscape" band. Top: Pressure. Thick lines are relatively high, thin relatively low values. Bottom: Acceleration. Red line = horizontal channels, black lines = vertical. Dashed black line is cleaned spectra[Crawford & Webb [2000]. Grey background: Global seismometer noise bounds [Peterson et al., 1993; Wolin & McNamara, 2020]. Spectral lines derived from Bradley et al. [1997], Crawford et al. [2006], Webb [1998], McDonald et al. [2008], Hildebrand [2009] and Deen et al. [2017].

Most of our work will be done using autonomous or cabled OBS data. Newer technologies such as DAS can revolutionise ocean bottom sensing by providing dense, real time networks, but they cannot replace the 3D wave-field and deploy-anywhere capabilities of OBSs. Our project will share processing techniques and signal levels with projects using DAS, such as the ANR MONIDAS project, which should be very useful in calibrating their systems.

The work is divided into three parts :

- **Global seismic noise**, to understand the ocean-induced sources of seismological noise, both at the seafloor and on land; (WP3)
- **Signal separation and noise removal** at seafloor stations, using our physical understanding of the noise sources and advanced signal processing techniques; (WP4)

- **Seafloor soundscape**, to characterise seismological, environmental and anthropogenic signals at frequencies > 1Hz, including earthquakes, storms, marine fauna, shipping and icequakes. (WP5)

1. Understanding and modelling oceanic sources of global seismic noise

Seismic noise at land and on the seafloor is generated primarily by the atmosphere-ocean system, with different mechanisms in the different frequency bands. Each component of the seismic noise field varies over time and space [e.g., **Stutzmann et al.** 2012]. The low-frequency seismic noise spectrum is separated into secondary microseisms (0.1-0.3 Hz), primary microseisms (0.05-0.1 Hz) and hum (0.003-0.05 Hz). **Secondary microseisms** are generated by interactions among ocean waves travelling in opposite directions and have double their frequencies. They are recorded worldwide at terrestrial stations but can be recorded *in-situ* from the ocean floor beneath active storms (**Davy et al.,** 2014, 2015). **Primary microseisms** are generated by interactions between ocean waves and the seafloor and have the same frequencies as the ocean waves. **Seismic hum** is created by the interaction of infragravity waves and the sea floor. This low frequency signal is weak but nevertheless large enough to excite Earth's free oscillations, which can be detected on high quality Broadband OBS (BBOBS) data (**Deen et al.**, 2017).

An integrated understanding of this noise was developed in the framework of the ANR "MIMOSA" project, (2015-2019, PI E. **Stutzmann**), in which members of the current proposal modelled seismic noise recorded on land in the frequency band 0.005-0.3 Hz, based on ocean waves and several mechanisms (**Ardhuin et al.**, 2015, **Farra et al.**, 2016, **Gualtieri et al.**, 2019, **Deen et al.,** 2017). This model was an important step forward but can still be improved (**Meschede et al.**, 2017). Finally, the amount of Love waves has never been investigated at the ocean bottom and the source mechanism is still debated (Ziane and Hadziioannou, 2019, Sethi., 2019, Gualtieri et al., 2021).

Since the sources of the broadband seismic noise are oceanic, seafloor data are crucial to better characterising and quantifying their distribution and intensity. Seafloor noise has never been quantitatively modelled and we will first need to separate the contribution of distant wave sources from those due to local effects such as currents or infragravity-waves passing above the stations.

We will also study the variability of the noise sources over time and space using the different sensors: seismometers, pressure sensors, rotational sensors, to 1) understand the sources of variations of seafloor noise, 2) propose an integrated model of the sea floor noise and 3) identify the sites and seasons most amenable to seafloor ambient noise experiments. To improve source and site characterisation, we will use machine-learning algorithms to classify signals recorded at each site.

2. Seafloor seismological signal separation and noise removal

An OBS recording is the superposition of a broad spectrum of signals created by solid earth, ocean wave, biologic and anthropogenic sources. These signals can be very different in amplitude, duration and frequency content but they also can overlap, making them hard to isolate from each other. For instance, infragravity ocean waves in the frequency bandwidth 0.003-0.03 Hz can be used to study subsurface structure (**Crawford et al.**, 2002), but they mask seismological signals in this same frequency band (**Webb**, 1998; **Webb & Crawford**, 1999). Similarly, whale calls can interfere with seismological signals at ~20 Hz and seafloor currents generate noise across the measurable frequency band (Duennebier & Sutton, 1995; **Crawford & Webb**, 2002; Li et al., 2020).

Methods developed to isolate seafloor seismological signals have already been used to enhance earthquake studies and reveal earth's background free oscillations (**Crawford et al.**, 2006; Ball, et al. 2014; **Deen et**

al., 2017). Better measuring and separating these signals are crucial for seismological studies, for understanding the generation of global noise and for quantitatively characterising the oceanic soundscape.

We propose to improve the state of the art in separating signals present in OBS records using a multi-sensor and multicomponent approach using advanced signal processing techniques. Previous approaches developed for improving seismological signals on the vertical channel used the fact that seafloor current and compliance signals predominate on another channel (horizontal and pressure component, respectively). We will go further in the exploitation of this multi-sensor capacity of OBS instruments.

First, we will improve multi-sensor capacity by physically incorporating a new sensor in the instrument: a rotational seismometer, enabling us both to better measure the rotation signal generated by bottom currents and to investigate separating seismic signals, for example Love waves. iXBlue, a world leader in navigation, positioning and imaging systems, has developed a high-resolution rotational seismometer that can be integrated into the INSU-IPGP BBOBS. It has the best combination of size/sensitivity/power currently possible for a BBOBS, with 4-5 nrad/s/sqrt(Hz) sensitivity from 0.001-200 Hz and 3W power consumption. Its noise floor level, when converted to horizontal noise levels (**Figure 2**) is at or below that of seafloor sites at all relevant periods and below that of buried sites for periods greater than 80s. We will install a blueSeis-1C on the gimbaling system of a broadband (Trillium T240) seismometer from the INSU-IPGP national OBS facility. We will conduct laboratory and shallow water evaluations, then we will deploy the system on the ocean floor for one month, to investigate improvements in seafloor data.

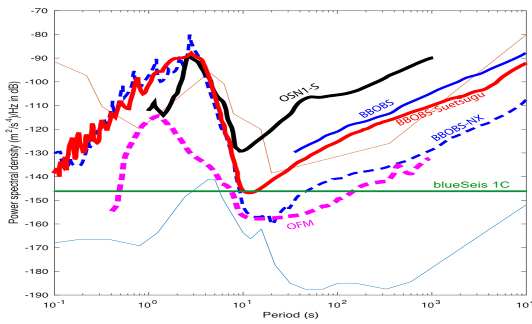


Figure 2: Horizontal component noise levels observed at and beneath the seafloor, compared to blueSeis 1C self-noise level (green). Dashed lines are buried stations. The near-constant slope above ~10 s is caused by tilting due to seafloor currents. Sources: Crawford et al. [2006]; Beauduin & Montagner [1996]; Sutton & Barstow [1990]; Shiobara et al. [2013]; Suetsugu & Shiobara [2014].

Second, we will improve signal processing techniques used to enhance the quality of seismological signals. We will start by revising the reference, transfer function, technique by applying: 1) more critical **data window selection** based on improved attributes (e.g., **Schimmel and Paulssen** (1997), **Schimmel et al**. (2011)); 2) more critical **solution selection** using *a priori* forms of the transfer function based on physical models; 3) improvements to the conventional transfer function using analytic signal theory.

We will also adapt non-linear adaptive subtraction techniques developed for active seismic multiple removal, which overcome some of the limitations of the linear transfer function approach (**Ventosa et al.** 2012, **Pham et al.** 2014). Finally, we will test other source separation techniques, including component rotation, machine learning, broad source separation methods relying on very-limited modelling assumptions (e.g. **Ning et al.**, 2014) and methods recently developed for the Mars InSight project [Garcia et al., 2020; Kenda et al., 2020].

We will compare the efficiency and effectiveness of the different approaches, analyse the differences and create open-source software using the most effective approach(es).

3. The seafloor soundscape

The seafloor **high frequency band** (above 1 Hz) is rich in signals from earthquakes and ocean waves, but also from biological, human and environmental activities. Acoustic waves travel efficiently through the water column but are challenging to separate into their biophony, geophony and anthropophony components, particularly in a world dominated by the continuous local and global ocean wave dynamics. OBSs can provide important data concerning **environmental, economic and societal issues** if we can understand and decipher the origin of these signals.

Using available data from recent OBS deployments, we aim to better understand and constrain noise sources recorded on the seafloor and to create synergetic links between disciplines such as ecology, bioacoustics and seismology. To promote and facilitate this synergy, BRUIT-FM proposes to **catalog available data** from the various oceans and to quantify the ambient sound levels and seismological noise components as well as their regional and seasonal variations. Typical sound signatures will then be investigated to better constrain their origins. We propose to then analyse in greater detail some ubiquitous sound sources: whales, ships and ice.

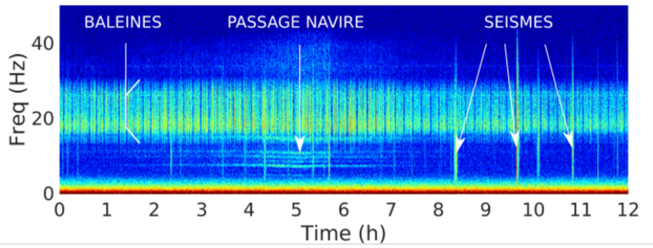


Figure 2: Seismo-acoustic soundscape recorded by an OBS from the RHUM-RUM experiment in the Indian Ocean, showing close cohabitation of earthquake ("SEISMES"), ship ("NAVIRE") and whale ("BALEINE") signals

One under-exploited application of OBS data is monitoring **submarine fauna** that emit sounds and calls in the recording band of OBS seismometers and hydrophones. OBSs can detect several baleen **whale species** emitting calls in the 1-100 Hz band, which allowed us to quantify their seasonal distribution in the western Indian Ocean (**Bouffaut et al.**, 2018) and to track them over parts of the OBS network where inter-station distances were small enough (i.e. <50km) (Dreo et al., 2019). The large number of OBS data available for this application is a real opportunity to develop and respond to scientific questions concerning whale populations, migrations, basin-specific calls and, ultimately, population density. The strong and unique whale call signal may even allow them to be used for crustal imaging (Kuna & Nabelek, 2021).

OBS data can also be used to ground truth **ocean sound pollution** models. The European Union MSFD « "Marine Strategy Framework Directive" 2008/56/CE requires state members to guarantee and monitor the ecological state of the oceans. Anthropogenic underwater noise is clearly identified as a pollution that needs to be monitored to reduce its impact on marine life. In the 1 to 100 Hz frequency band, anthropogenic noise pollution comes from marine traffic, geophysical prospection, military operations and underwater works. Noise modelling is widely used at basin scales in this community, but seafloor measurements using existing datasets will provide precious ground truth (**Kinda et al.**, 2018) at low cost.

OBSs can be used to **detect, locate and track moving noise** sources. A recent IPGP-DGA thesis (Trabattoni, 2021) demonstrated that **ship noise** can be used to accurately locate and orient an OBS on the ocean floor using the vessel's location indicated by its AIS (Automatic Identification System) and that OBSs can detect and locate moving sound sources such as surface vessels and whales, without any *a priori* information. This development has important **economic and societal potential**, for example in detecting illegal incursions of AIS-disabled vessels into an EEZ or characterising whale populations and migrations to better understand the impact of anthropogenic noise on them. Real time monitoring will be possible in the very near future using ocean floor cables, but we must first identify and understand the various noise sources in order to correctly develop these systems.

Finally, OBSs may also record **cryoseismic activity** emitted from polar events, even at large distances. These events occur particularly in the coastal areas of Antarctica, where glacial outlets and ice shelves create huge icebergs that interact with each other and with the ocean bottom, generating monotonic tremors (Müller et al., 2005; Macayeal et al., 2008) that can propagate across ocean basins. Detecting and characterising cryoseismic events at the ocean bottom may provide a new way to monitor polar ice discharge.

b. Position of the project as it relates to the state of art

State of the art in understanding seafloor and terrestrial noise

Some mechanisms for the generation of microseisms and infragravity waves have been known for decades (Longuet-Higgins, 1950, Hasselmann, 1963), but an integrated understanding of the noise in the broadband frequency range 0.002-0.3 Hz was only recently developed, in the framework of the ANR "MIMOSA" project (2015-2019) and based on different mechanisms involving ocean waves. This model reproduces only half of the observed sources in the secondary microseism frequency band (**Meschede et al.**, 2017) and can be improved. One important unknown parameter is the amount of ocean waves reflected at the coast. Seafloor seismic noise has never been similarly modelled and OBS data will enable us to improve the global source model

Love waves also exist across the ambient seismic spectrum but their generation mechanism is still debated. They cannot be directly generated by oceanic sources, so a conversion mechanism must be found. Possibilities include crustal heterogeneities (Ziane and Hadziioannou, 2019), slope discontinuities (Sethi, 2019) and 3D structure (Gualtieri et al., 2021). The use of ocean bottom seismometers, pressure sensors and rotational sensors will enable us to investigate and quantify the amount of Love waves. This would be of particular interest in the vicinity of a cyclone for understanding the generation mechanism.

An accurate model of broadband sources may also significantly improve the resolution obtainable using "ambient noise" seismology, by allowing the calculation of finite-frequency noise correlation sensitivity kernels (Tromp et al., 2010).

State of the art in removing seafloor noise

Seafloor noise is presently removed from seafloor vertical seismometer data using transfer function techniques, noise-minimising component rotation, instrument shielding and sensor burial . The transfer function and component rotation techniques (Ball et al., 2014, Bell et al., 2015), now available as Open Source software (https://nfsi-canada.github.io/OBStools/atacr.html), are small improvements on techniques developed by **Crawford & Webb** (2000). Burial can reduce horizontal noise by up to 30 dB (Beaudoin & Montagner, 1996; **Crawford et al.**, 2006; Shiobara et al., 2013), but is time-consuming and expensive. Shielding may also reduce noise levels (Janiszewski et al., 2020), but makes for more cumbersome instruments and thus has been limited to smaller wide-band sensors. Relevant seismological noise reduction methods have also recently been developed for the Mars InSight mission (Garcia et al., 2020; Kenda et al., 2020).

Pillet et al. (2009) suggested that a sensitive tiltmeter or horizontal seismometer could be used to greatly improve low-frequency horizontal data. Lindner et al (2017) showed that rotational information from a fiber optic gyroscope could be used to reduce horizontal noise levels at a shallow North Sea site, but the site was much noisier than the seafloor norm, the rotational sensor consumed too much to be practical energy (28 W, compared to < 1W for a BBOBS) and the gyroscope's sensitivity was only adequate for very noisy sites. The recent technological developments in rotational seismology provide unique opportunities for progressing in this direction.

State of the art in categorising soundscape noise

The high-frequency side of the ocean bottom seismic spectrum (1-100Hz) corresponds to the ultra-low frequency (ULF) band of hydro-acoustics. This domain is generally studied using hydrophones, which can sample the signal at high rates but provide only a scalar value of the local pressure, requiring instrument networks to locate and track sources. The seismometer and hydrophone of a single OBS provide a 4-component vectorial measurement of the full medium displacement and, therefore, the possibility of analysing the polarisation of the acoustic/seismic waves, opening new ways to detect, locate and track sources. This seismology/hydroacoustics overlap in the 1-100 Hz frequency band provides a unique opportunity to create links between communities working in the biophony and anthropophony domains. Sub-seafloor imaging using whale calls (e.g., Kuna and Nabelek, 2021) is an example of new perspectives arising from multidisciplinary study of the full OBS spectrum.

Baleen whales are usually detected by hydrophones moored for military or hydro-acoustic purposes (Mellinger et al. 2007). In the deep ocean, hydrophone are usually positioned in the SOFAR channel, at 1000-1500 m depth (e.g., Fox et al., 2001; **Samaran et al.,** 2013; **Leroy et al.**, 2016, 2018; **Tsang-Hin-Sun et al.,** 2015) requiring moorings that are complex to deploy and maintain. Moreover, hydrophone networks are often deployed in a sparse array limiting the possibility of locating and tracking whales. OBSs can be used to detect and track whales from the ocean bottom (e.g., Dunn and Hernandez 2009; Wilcock, 2012; Harris et al., 2018). We will investigate the benefits and limitations of 4-component OBS data for tracking whales and other animals (**Bouffaut et al.,** 2018**; Dréo et al.,** 2019), to open bridges to the bio-acoustic community and to better exploit the masses of existing ocean-bottom data.

Ships have been detected from OBSs at distances up to 100 km and have been tracked by isolated 4-component OBSs (**Trabattoni et al.**, 2020). We will further explore the use of ship noise for sub-seafloor imaging, as proposed by Trabattoni (2021). **Noise pollution levels** in the Indian Ocean were studied by the French Naval Hydrographic and Oceanographic Service (SHOM) using data from the RHUM-RUM experiment (**Kinda et al.,** 2018). We will extend this collaboration to other ocean basins.

Ice-induced signals are clearly recorded at large distances by hydrophones moored in the SOFAR channel (e.g., **Royer et al.,** 2015) and as T-waves on terrestrial island stations (Talandier et al., 2002). They are probably recorded by OBSs at large distances but this is poorly documented. We propose to combine cryoseismic signal analysis at distant OBSs with near-field data from a rare OBS deployment in Antarctic coastal areas(IPEV-funded SEIS-ADELICE project, PI **G. Barruol**). This deployment in front of the floating tongue of the Astrolabe glacier will record signals from glacier crevassing and gliding, tide and swell, icebergs and sea-ice dynamics and from the bio-acoustic landscape of this coastal area, providing a near field baseline for what is recorded in the far field.

c. Methodology and risk management

The project is divided into 5 Work Packages (WPs). WP1 coordinates and manages the project, WP2 handles common data and signals between the primary scientific packages, and WPs 3-5 are the primary scientific packages. We name the leader(s) of each WP and Task in parentheses. **Table 1** presents a preliminary list of the datasets of interest, which we will detail and expand in WP2. Most of the data are publicly available on FDSN-compatible data centers and we are active collaborators on the others: the "embargoed" datasets will become publicly available after the embargo period.

Name	Location	# stations (BB)	min/max freq (Hz)	Duration	Availability
Gorda	NE Pacific	40 (2)	0.001 / 40	2 years	public
RHUM-RUM	Indian	40 (40)	0.001 / 50	1 year	public
MAYOBS	Indian	6-12 (1)	0.1 / 100	2 years	embargoed
EMSO-MOMAR	N Atlantic	5 (1)	0.001 / 50	14 years	embargoed
AlpArray	Ligurian Sea	35 (35)	0.001 / 40	0.6 years	embargoed
PiLAB	C Atlantic	40 (40)	0.001 / 40	1 year	private
Ocean Obs. Initiative	NE Atlantic	7 (3)	0.001/100	6+ years	public
SEIS-ADELICE	Antarctica	5(2)	0.1 / 100	1 month (4), 1 year (1)	embargoed

WP 1	**Coordination, Management and Dissemination**	Start: M1	End: M48
WP leader: Crawford (IPGP)			
Contributions (PM)	IPGP: 9,8	IFREMER: 2,7	iXBlue: 0.2
Tasks			
T1.1	Administrative management, coordination (Crawford)		
T1.2	Financial management (Crawford)		
T1.3	Promotion of internal communication (Ker, Crawford)		
T1.4	Writing/implementation of Open Science guidelines & Data Management Plan (Crawford)		
T1.5	Project dissemination (Crawford, Barruol, Stutzmann)		
Deliverables			
D1.1	Kick-off Meeting	M1	
D1.2	Open Science guidelines	M6, M30, M48	
D1.3	Periodic and final reports	M12, M24, M36, M48	
D1.4	Dissemination report	M48	

WP1 will animate collaborations between participants and WPs. A management committee consisting of one representative of each partner will ensure that the funds are appropriately expended and that temporary posts are properly advertised and are selected in a timely manner. We will share and evaluate scientific results and work advancement at biannual meetings. A small operations budget will allow us to invite outside researchers to participate in these meetings.

The Data Management Plan (DMP) will be based on putting and retrieving data to/from FDSN-compatible data centers (RESIF if collected using French instruments). Enhanced data will be proposed to the data center: if it cannot distribute the data, the DMP will specify how to make it publicly available.

Open Science guidelines will reiterate ANR-required guidelines for publications and specify rules for making available codes developed during the project (publication of all software on an open-software site (e.g. GitLab) and distribution of operating software on open-software deployment sites (e.g., PyPI).

WP 2	Full Seafloor Spectrum		Start: M1	End: M48
WP leaders: Crawford, Barruol, Stutzmann (IPGP)				
Contributions (PM)	IPGP: 17,4	IFREMER: 1,0	iXBlue: 0,0	
Objectives ● Establish a catalogue of existing data (by oceans and world regions) and how to access them. ● Establish a catalogue of ocean bottom noise signals and their sources. ● Determine the seafloor pressure noise floor.				
Tasks				
T2.1	Dataset selection and validation (Crawford, Stutzmann, Barruol)			
T2.2	Pressure noise bounds (Crawford)			
T2.3	Noise source catalog (Crawford)			
Deliverables				
D2.1	Catalogue of available OBS data and characteristics		M12	
D2.2	Low and High noise reference levels for OBS		M36	
D2.3	Seismological noise source catalog		M44	

This WP consolidates the cross-WP tasks of dataset selection and validation, reducing work in each WP and choosing datasets with more cross-WP interest. This WP will also quantify seismological noise levels and compile a a full-spectrum vision of the results of WPs 3-5.

Task 2.1: Dataset identification and validation

- 2.1.1: Catalogue existing databases and their characteristics (access method, region, sensors, seasons...)
- 2.1.2: Evaluate the interest of each dataset according to the needs of WPs 3-5
- 2.1.3: Select data sets based on the above criteria
- 2.1.3: Validate data access and specify the access method for each selected data set

Task 2.2: Pressure noise bounds For the chosen data sets and other large or spatially isolated datasets, we will confirm instrument responses and calculate Probabilistic Power Spectral Densities to determine upper and lower bounds of seafloor pressure signals.

Task 2.3: Seismological noise source catalog: Combining the noise sources identified by WPs 3-5 with other sources in the scientific literature..

WP 3	The Generation of Global Seismological Noise		Start: M6	End: M44
WP leader: Stutzmann (IPGP)				
Contributions (PM)	IPGP: 40,0	IFREMER: 4,7	iXBlue: 0,0	
Objectives ● Develop an integrated model of broadband (0.02-1 Hz) seafloor noise validated by measurements ● Better understand the physics of the sources of broadband noise and the noise floor in this frequency band ● Improve the quality of ambient noise data selection for compliance analysis ● Provide a catalogue of broadband sources that can be used for tomographic application				

Tasks		
T3.1	Sources and effects of spatio-temporal variations in seafloor noise: (Stutzmann)	
T3.2	Sources of seafloor/global noise: (Stutzmann)	
T3.3	An integrated seafloor/global noise model (Stutzmann, Ardhuin)	
Deliverables		
D3.1	Catalog of wave-generated noise sources	M36
D3.2	Scientific Articles	M12-48

This WP will develop an integrated model of seafloor and land seismological noise validated by measurements. We will use broadband datasets from the Pacific, Indian Ocean and Atlantic oceans to generate noise models and evaluate the key features of each ocean. Tasks are:

Task 3.1: Spatio-temporal variations in seafloor noise, both sources and effects.

- T3.1.2: Variations of infragravity waves. Static (compliance) & dynamic (seismic wave) effects.
- T3.1.1: Variations of currents and other noise sources. Using topographic current models and seafloor spectra.

Task 3.2: Sources of seafloor/global noise

- T3.2.1: Data cleaning.. Remove local effects using tools developed in WP4
- T3.2.2: Quantify variability in three principal frequency bands. Use spectrograms and polarisation analysis to quantify the intensity and azimuth variability of the sources in the primary microseism, secondary microseism and infragravity wave bands. Analyze datasets from three oceans to locate sources and analyse in detail the strongest sources.
- T3.2.3: Classifying the sea floor signal using machine-learning algorithms. Starting with primary and secondary microseisms, which record characteristic signals related to ocean wave dispersion, we will identify source clusters and investigate wave origin using algorithms such as blind source separation (Comon & Jutten, 2010, Moni et al., 2013, **Meschede et al.**, 2019), and classify signals using machine learning (**Malfante et al.** 2018a, 2018b).

Task 3.3: An integrated seafloor/global noise model

- T3.3.1: Improving modelling tools. The current microseism and hum modelling tools were developed for seismic surface and body wave noise on land. We will modify the station site effect to account for the reverberation of acoustic waves in the water column and possibly also in the sediment layer, separately considering body and surface waves.
- T3.3.2: Modelling seafloor seismic noise between 0.003 and 1 Hz. We will model the Pacific, Atlantic and Indian ocean data sets and analyse the data fit, progressively improving the model as indicated by the fit.
- T3.3.3: An integrated model of sea floor noise. Based on the above models and physical mechanisms.

Risks: Risks are fairly low as we developed the techniques and know in what areas they can be improved or modified to apply to the seafloor environment.

WP 4	Seafloor signal separation and noise removal			Start: M2	End: M44
WP leaders: Ker (IFREMER), Crawford (IPGP)					
Contributions (PM)	IPGP: 34,5	IFREMER: 31	iXBlue: 2,3		
Objectives ● Increase sensitivity to low-frequency seismological signals (normal modes, teleseisms…) ● Improve the quality and depth penetration of ambient noise and compliance techniques ● Better understand the sources of noise and the noise floor in this frequency band					
Tasks					
T4.1	Reducing horizontal noise using a rotational seismometer: (Crawford, Guattari)				
T4.2	Signal separation/removal techniques: (Ker, Crawford)				
T4.3	Separating seismological and biological signals (Ker, Duval)				
Deliverables					
D4.1	Report on rotational seismometer integration in BBOBS			M12	
D4.2	Open source software for noise separation and removal			M24-48	
D4.3	Catalog of seafloor noise sources			M36	
D4.3	Scientific articles			M24-48	

This WP applies advanced signal processing techniques to separate signal/noise sources and tests the use of a new rotational sensor.

<u>Task 4.1: Reducing horizontal noise using a rotational seismometer</u>
We will investigate reducing seafloor horizontal noise levels using the iXblue blueSeis-1C rotational seismometer. This task is divided into sequential subtasks: 1) <u>Conception</u>. Mechanical analysis of integration of blueSeis-1C into INSU-IPGP BBOBS; 2) <u>Manufacturing:</u> Construction of blueSeis-1C and modified BBOBS parts; 3) <u>Installation of the rotational seismometer in a BBOBS</u>; 4) <u>Calibration table evaluation</u>. Using iXblue's state of the art 3-axis calibration table; 5) <u>Analysis of results</u>. Compare calibration table tests with predicted noise level improvements. Modify installation and retest if needed; 6) <u>Near-shore test:</u> Deployment offshore Brest to validate instrument and obtain high-current data; 7) <u>At-sea test</u>. Leverage yearly month-long expeditions by the OBS team to the deep seafloor Lucky Strike volcano. We will request a 1-day cruise extension for summer 2023 or 2024; 8) <u>Analysis and scientific article</u>.

<u>Task 4.2: Signal processing techniques for signal separation and noise removal</u>

This task will be run in collaboration between IPGP and IFREMER with the support of a postdoctoral researcher specialised in signal analysis/processing and a broad group of signal processing experts from ESIEE, iXBlue, GEO3BCN and GIPSA-Lab.

- <u>4.2.1 Revisiting the transfer function approach</u>. Develop new methods to determine the transfer function, using critical data window and solution selection as well as improvements to the conventional transfer function using analytic signal theory.
- <u>4.2.2 Signal separation based on adaptive template subtraction</u>. We will adapt a family of short templates (obtained by recording, modelling or learning) on longer signals. We will develop shaping

filters in a spectrogram or wavelet domain to perform a fast optimisation of template adaptation in amplitude, time and frequency.

- 4.2.3: Physics-based noise removal Compare the effectiveness of the above techniques with methods based on the known physical relations (for example, optimised sensor reorientation)
- 4.2.4 Frontier techniques: In environments where strong scattered and non-stationary background noise is present, we will investigate broad source separation methods relying on very-limited modelling assumptions (e.g. **Ning et al.**, 2014).

Task 4.3: Separating seismological and biological signals

We will develop an approach to separate simultaneous seismological and whale call signals in the shared frequency band around 20 Hz, including the challenging chorus footprint (**Bouffaut et al.**, 2018). We will use recently developed signal deconvolution/restoration techniques (SPOQ) using sparse non-convex norm-ratio penalties (**Cherni et al.,** 2020) to characterise the overlapping signals using robust statistical measures (moments and moment ratios) to enhance their differences and assist their separation.

Risks: Task 4.1 risks are 1) inability to integrate the rotational seismometer into the BBOBS seismometer sphere or 2) less horizontal noise reduction than predicted. These risks will be evaluated in the first 2-5 subtasks, before the major cost and personnel items are engaged. The risk of the technique not working is low, as the relation between horizontal signal and rotational measurements has already been demonstrated for a less sensitive rotational seismometer using the same technology [Bernauer et al., 2018]. Task 4.2 is relatively low risk: We know the existing methods very well and have identified weaknesses that we can improve on. We will quantify improvements, limitations and benefits using synthetic and measured data. Task 4.3 is high-risk, high-reward. It uses few resources and failure has no impact on other tasks.

WP 5	**The seafloor soundscape (> 1 Hz)**			Start: M8	End: M44
WP leader: Barruol					
Contributions (PM)	IPGP: 41,0	IFREMER: 0,0	iXBlue: 0,0		
Objectives ● Explore and exploit sources to study non-seismic subjects (marine mammals, ship tracking, icequakes, ocean currents…). ● Explore how each soundscape signal may be improved.					
Tasks					
T5.1	Whale sources (coordinator: Samaran, CDD)				
T5.2	Noise pollution (Kinda)				
T5.3	Ship noise (Barruol, CDD)				
T5.4	Cryoseismic signals (Barruol, CDD)				
Deliverables					
D5.1	Catalog of soundscape noise sources			M36	
D5.2	Scientific Articles and Reports			M12-48	

This WP investigates specific phenomena associated with seismological noise sources: whales, shipping, icequakes and underwater noise pollution. These are exploratory tasks to identify these sources and investigate what can be learned about them using OBS recordings, in collaboration with bio-acousticians,, noise modellers and submarine acousticians. We will investigate the specific soundscapes of various oceans and latitudes. Developments performed for ship detection and tracking (**Trabattoni et al.,** 2020) such as acoustic intensity, azigram and cepstrum analyses will be applied - and adapted if necessary - for whales. Tools developed in WP4 will be used to improve soundscape signals.

Task 5.1 - Whales: We will analyse the ability of OBS to provide observations baleen whales, to provide new insights into their ecology and to assess their conservation status. We will use datasets from regions where passive acoustic monitoring of baleen whales is almost absent (e.g. southern Atlantic Ocean, middle and south Pacific), to complete research conducted by the Acoustic Trends Steering group of the **International Whaling Commission** (IWC) Southern Ocean non lethal Research Partnership. We will focus on the occurrence and distribution of the endangered blue and fin whales, their seasonal migration patterns and their acoustic behaviour on the ocean basin scale.

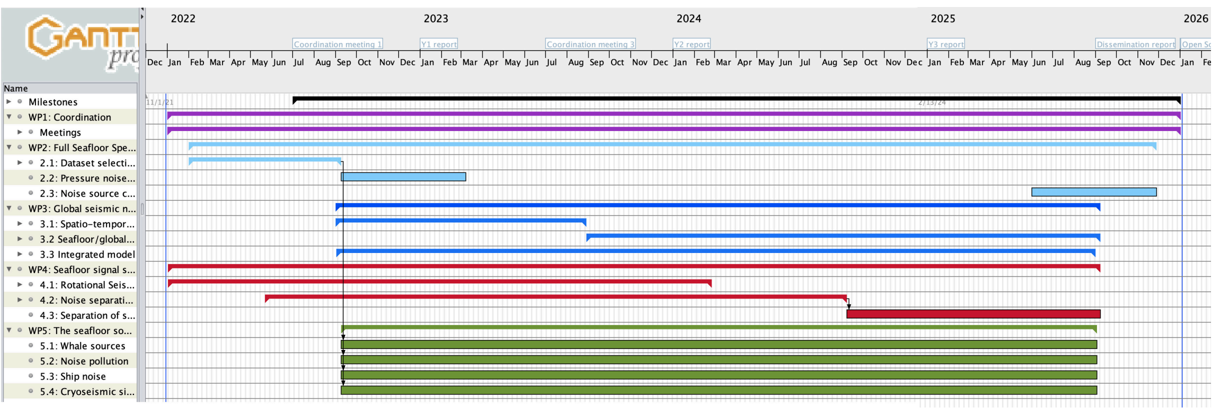
Task 5.2 - Noise pollution : Long-term OBS data will be used to ground truth noise models in several ocean basins, especially for shipping noise. We will focus on the North Atlantic and Indian Oceans where shipping noise may dominate [1-100]Hz ambient noise. We may also statistically study the distribution of marine animals as a function of noise levels.

Task 5.3 - Ship : We will use OBS data to characterise ship noise and investigate the ability of OBSs to passively detect, decipher and track moving sources. We will investigate imaging solid-earth structure using ship noise.

Task 5.4 - Icequakes : We will search for ice tremor signals on OBS data. Where possible, we will compare ocean bottom detections with hydro-acoustic observations. We will complement this approach with data acquired by a few OBSs deployed offshore Antarctica starting in January 2022 (SEIS-ADELICE cryo-seismic experiment).

Risks: Accessing data is no risk: high frequency (1-100 Hz) data from numerous OBS experiments in various oceans are available on FDSN-compatible data centers. Improving soundscape signals from the processes developed in WP4 is at no risk for the rest of the project. The richness of the OBS data in the high frequencies ensures that noise sources will provide many new promising and original research fields. Using data from OBSs in Antarctica coastal waters is high risk / high gain, but this risk is primarily supported by another project (SEIS-ADELICE, PI G. Barruol) and any problem would not impact other BRUIT-FM tasks.

GANTT DIAGRAM



II. Organisation and implementation of the project

Our team is composed of experienced researchers who have made major contributions to ocean bottom compliance analysis, oceanic tomography, ambient seismic noise modelling, terrestrial and ocean-bottom microseismic noise observations, seismic data analysis and signal processing. Several members (W.C., E.S, G.B., M.S, F.A.) have long lasting collaborations with more than 25 joint papers. The WP3 team has worked successfully together on the ANR "MIMOSA" project. The WP4 team has the experience and breadth necessary to develop innovative signal separation and noise reduction techniques: W.C. developed the original noise reduction technique, E.S specializes in broadband seismological noise, J.M., L.D. M.S, O.M., and S.K. have extensive experience in signal processing and have worked on land, oceanic and planetary geoscience signals using techniques including Source Separation, Artificial Intelligence and Machine Learning (e.g., **Malfante et al.** 2018a, 2018b). The WP5 team brings together seismologists (G.B., L. S.), bio-acousticians (F. S.), noise modelers (B. K.) and promotes links to and collaborations with domains concerned by the seafloor soundscape and new technological developments such as DAS (D. R.)

iXblue is a leading manufacturer of high technology hydrographic and underwater positioning instruments. The blueSeis project develops state of the art rotation measurements for geoscience applications, including the first portable rotational seismometer, developed in partnership with LMU Munich through the ERC "ROMY" grant (Prof. Doc. H. Igel). They also have experience in separating rotational and translational seismological measurements that should be invaluable to WPs 3 and 4.

A doctoral student will work principally on WP3. A postdoctoral researcher specializing in signal processing will work on WP 4 and the machine learning aspects of WP3. An engineer hired for the project will work on validating the data sets and establishing a pressure noise limits model (WP2) and data processing for the soundscape studies (WP5). Four Masters stipends, one each for WPs 3 and 4 and two for WP5, will help us to train younger students and to evaluate the doctoral candidates for WP3.

The results will be presented at national and international congresses (AGU, EGU) and published in scientific articles that will be distributed openly via HAL. Software will be distributed on open-access software archives (GIThub or GITlab, for example) and on international seafloor seismology sites currently under discussion between international actors. Software will be presented and demonstrated at European and international workshops (ENVRI-FAIR, ISC) and Training Networks.

a. Scientific coordinator and its consortium / its team

Dr. Wayne Crawford is a CNRS researcher specialising in broadband ocean bottom seismology. He developed the seafloor compliance method and the first methods for removing tilt noise from BBOBS data. He contributes to Open Science by leading the development of RESIF's marine-seismology data node and European-level infrastructure projects to integrate OBS data onto FDSN-compatible data centers (EPOS and ENVRI-FAIR Research Infrastructures). He is the director of the INSU-IPGP national OBS facility.

Dr. Stephan Ker is a research geophysicist at IFREMER, France. He is specialised in exploration seismology. He developed deep-sea acquisition techniques and new signal processing techniques for seismic data analysis.

Frederic Guattari is a senior expert in Fiber-Optic Gyroscope technology and has deposited more than 12 patents. Starting in the iXblue R&D team 12 years ago, after graduating the "Ecole des Mines" Nancy in engineering and obtaining a Masters 2 in "Laser et Matière", he leads the 'blueSeis' product line dedicated to ground motion measurement.

Prof. Eleonore Stutzmann is a professor (CNAP Physicist) and head of the IPGP seismology group. She has made significant contributions on understanding broadband noise sources, modelling seismic noise, and seismic tomography with geodynamic interpretations. She develops new signal processing methods for seismic applications. She coordinated the ANR MIMOSA noise modelling project and she is IPGP's PI for the SPIN International Training Network.

Dr. Guilhem Barruol is CNRS research director specialised in mantle imaging, seismic anisotropy and environmental seismology. He led the PLUME and RHUM-RUM amphibious seismic experiments, which investigated microseismic noise, seismic hum, ship and whale detection and tracking. He is PI of a cryo-seismic experiment in Antarctica (IPEV SEIS-ADELICE, 2019-2024).

Collaborators:

Dr. Martin Schimmel (GEO3BN, Spain) is a research geophysicist whose work focuses on observational seismology with an emphasis on the detection and identification of weak-amplitude signals, and seismic monitoring and imaging studies using active and passive data to constrain structure at different scales.

Dr. Flore Samaran (ENSTA-Bretagne) is a research scientist focusing on cetacean bioacoustic and long-timescale passive acoustic monitoring to study the behavior and ecology of elusive marine mammals.

Dr. Bazile Kinda (SHOM-Brest) is a research scientist in underwater acoustics modelling and noise measurements. He is the national coordinator for the underwater noise monitoring program within the EU MSFD.

Dr. Fabrice Ardhuin is senior researcher in oceanography at LOPS - CNRS, France. He has developed numerical models for wind-generated ocean waves and their associated sources of microseism and microbaroms in the range 0.003 to 1 Hz.

Dr. Laurent Duval (ESIEE Paris) is a research engineer and project manager in signal processing and data science. His research focuses on developing sparse and robust data processing methods, using convex and non-convex optimization, notably with applications to analytical chemistry and geosciences.

Dr. Jerome Mars (GIPSA-Lab) is a Professor at Grenoble-INP and was head of the Grenoble GIPSA-Lab from 2016 to 2020. His research interests include statistical signal processing and source separation and his latest work focuses on underwater acoustics and geoscience data analysis.

Dr. Olivier Michel (GIPSA-Lab) is a Professor at Grenoble-INP. His research focuses on applications of signal processing to physical problems. His research topics include information theory, compressive sensing approaches for multiple sensors and causal dependence estimation.

Dr. Veronique Farra (IPGP) is a senior researcher at IPGP (Assistant physicist, CNAP) and expert in seismic wave propagation and ray theory.

Dr. Diane Rivet (Geoazur) is a research physicist who studies Machine Learning and Distributed Acoustic Systems (DAS) and will coordinate with DAS-related projects.

Dr. Jean-Yves Royer (UBO) is a research director at the European Institute for Marine Studies (Brest). He has made major contributions in numerous fields of marine geology and geophysics and currently directs the French SOFAR channel hydrophone facility and its research orientations/projects.

Dr. Laurent Stehly (ISTerre/UGA) is a research scientist who has made pioneering contributions to the field of ambient seismology.

Prof. Spahr Webb (LDEO, USA) has pioneered signal and noise studies in seafloor seismology, pressure and electromagnetic measurements and developed several seafloor geophysical instruments.

Pascal Pelleau (IFREMER REM-GM) is the lead engineer of the IFREMER OBS facility

Pierre Guyavarch (IFREMER REM-GM) is an engineer of the IFREMER OBS facility

Romuald Daniel (IPGP-CNRS) is the lead engineer of the INSU-IPGP OBS facility.

Simon Besancon (IPGP-CNRS) is an electrical/operational engineer of the INSU-IPGP OBS facility.

Implication of the scientific coordinator and partners' scientific leaders in on-going project(s)

Name of the researcher	Person.month	Call, funding agency, grant allocated	Project's title	Scientific coordinator	Start - End
Wayne CRAWFORD	5	European Union	ENVRI-FAIR	A. PETZOLD	2019-2022
	1	INTERREG	PREST	V CLOUARD	2017-2021
	2	European Union	EPOS SP	D MERCURIO	2020-2022
Stephan KER	3	ANR	BLAME	V. RIBOULOT	2018-2022
	3	European Union	DOORS	A. STANICA	2021-2024
Frederic GUATTARI	14	H2020	PIONEERS	R.F. GARCIA	2019-2022
	2	H2020	IQLev	P. BACK	2020-2023

b. Implemented and requested resources to reach the objectives

1. Partner 1: IPGP

Staff expenses are 1 doctoral fellowship (122k€), 20 months engineer (105k€) and 8k€ for 4 masters student indemnities.

Instrument and material costs are 8k€ computer equipment for the engineer and doctoral researcher.

Outsourcing / subcontracting costs are 12k€ in publication charges, 20k€ to install the rotational seismometer in an existing BBOBS, 12k€ for Antarctic OBS deployments, 8k€ for transportation to/from BBOBS and OBS experiments, and 5k€ participation fee for the IPGP computational cluster.

General and administrative costs & other operating expenses are 41.6 k€ for travel and 41k€ for 12% environmental costs. Travel expenses cover 8 1-week missions to work with Schimmel in Barcelona (8k€), WP1 travel and meeting costs (9,6k€) and participation in 4 European and 4 international workshops/symposia (24k€).

Partner 2: IFREMER Geosciences Marines

Staff expenses are 93k€: 40% of 16 months permanent researcher and 18 months postdoctoral researcher.

Instrument and material costs are 3.2k€: 40% of 4k€ computational equipment for the postdoctoral researcher and 4k€ for the BBOBS test at Brest

Outsourcing / subcontracting costs are 5,2k€: 40% of 6k€ in publication and inscription charges, 4k€ for the ship used for the Brest BBOBS test, and 3k€ for equipment transportation

General and administrative costs & other operating expenses are 69,5 k€: 40% of 24k€ for travel, 146,5k€ in personnel overhead (68%) and 3,2 k€ other overhead (7%) Travel costs cover collaboration voyages between Duval and Ker (4,8 k€), travel to project meetings (4k€), postdoctoral missions between Brest (IFREMER) and Paris (IPGP, ESIEE (5,2 k€)), 3 EGU and 1 AGU meeting participations (10 k€).

Partner 3: IXblue

Staff expenses are 30% of 62,5k€ for: 2 person-months Guattari (supervision), 50 days mechanical engineer to match the BBOBS structure; 5 days support engineer for shake table test; 50 days FOG engineer to adapt the design to the mechanical setup; 15 days optical technician to manufacture the prototype.

Instrument and material costs are 30% of: cost for optical fiber (1,8k€), mechanical parts (15k€) and otpo-electronic parts (4k€).

Not charged: **Building and ground costs** (there are 44 days of building/installation in the workshop).

General and administrative costs & other operating expenses are 30% of: 4k€ travel and missions and 44,2k€ administrative management & structure costs.

Requested means by item of expenditure and by partner

		Partner *IPGP*	Partner *IFREMER-GM*	Partner *iXblue*
Staff expenses		235 000€	93 022€	18 750€
Instruments and material costs (including scientific consumables)		8 000€	3 200€	6 677€
Building and ground costs				
Outsourcing / subcontracting		57 000€	5 200€	
General and administrative costs & other operating expenses	Travel costs	41 600€	9 600€	1 284€
	Administrative management & structure costs**	40 992€	59 864€	12 750€
Sub-total		**382 592€**	**170 887€**	**39 461€**
Requested funding		**592 939€**		

III. Impact and benefits of the project

This project will have important impacts in seafloor seismology and marine geophysics and environmental studies, including a better understanding of seismological noise at the seafloor and better extraction of desired signals from seafloor datasets. The improved signals should improve low frequency seismological studies including compliance studies and earthquake and ambient-noise tomography. These improvements should allow better characterisation of the lithosphere, upper asthenosphere and their boundaries, which could have important societal implications, for example, in the case of ocean bottom permanent observatory for the deep melt source for the Mayotte volcano-seismic event.

The project should also improve the modelling of ocean bottom and land seismic data, providing key independent constraints on ocean wave models. Improving the accuracy of these models is crucial for long-term monitoring of ocean activity related to global warming.

The project will provide important constraints on the detection and tracking of non-traditional targets in the ocean, including shipping, marine mammals, landslides and icequakes, and it may provide important information on the generation of large low-frequency waves that present a threat to coastlines. Seismology is becoming an important discipline to characterise our environment. Improved data acquisition and signal characterisation will allow seismology to attract and interact with scientists from other disciplines (ecology, biology, oceanography, acoustics, glaciology…), stimulating the development of interdisciplinary frontier projects.

Expected publications:

WP2: Seafloor ambient pressure: sources and typical levels;

WP3: Variability in seafloor seismological noise levels as a function of space and time; Classifying seafloor seismological noise sources using machine learning; An integrated seafloor/global noise model.

WP4: Reducing low frequency horizontal noise using a rotational seismometer; Separating low frequency noise sources in seafloor seismological data; The low frequency limit for seafloor ambient noise tomography; Separating whale and seismic sources in the same frequency band.

WP5: Cryoseismic noises in shallow Antarctic environment; Whale and ship detection and tracking; Noise pollution monitoring.

WP2-5: Characterizing environmental, human, and seismologic sources for seafloor seismological noise

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