MELITE - Maritime Sea Laser Instrumentation for Tectonic Dynamics Exploration

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The NATO SPS Programme

NATO
OTAN
Science for Peace and Security (SPS) Programme

The **MELITE - Maritime Sea Laser Instrumentation for Tectonic Dynamics Exploration** has received funding by NATO in the framework of the **Science for Peace and Security (SPS**) Programme. Grant agreement no. G6137.

The SPS Programme promotes **civil** security-related practical cooperation based on scientific research, innovation and knowledge exchange. It links the scientific community to NATO through **civil** science cooperation that addresses emerging security challenges. Through SPS activities, civilians – including researchers, academics and experts – play an important role in helping the Alliance identify, understand and respond to vulnerabilities and threats.

Multi-Year Projects (MYP): Research and Development (R&D) projects that enable scientists from NATO nations and its Partner countries to collaborate on applied R&D and capacity building projects that result in new civil science advancements with practical application in the security and defence fields.

Advanced Training Courses (ATC): Enable specialists in NATO member states to share their expertise with trainees from Partner countries by developing tailor-made, modular courses.

Advanced Study Institutes (ASI): High-level tutorial courses organized to convey the latest developments in science and innovation to an advanced (PhD level) audience.

Advanced Research Workshops (ARW): Provide a platform for experts and scientists from different countries to share their experience, knowledge and perspectives on security-related topics.

SPS Key Priorities

- Emerging and Disruptive Technologies (EDTs)
- Environment, climate change and security
- Energy security
- Cyber defence
- Defence against hybrid threats
- more

The NATO SPS Programme

Who can apply?

All applicants must be affiliated with universities, research institutes, government entities, or non-profit institutions. For-profit companies are not eligible for SPS funding.
At least two researchers must be involved in the development of proposals: one in a NATO nation, and one in a Partner country.

NATO Countries

Albania, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Latvia, Lithuania, Luxembourg, Montenegro, Netherlands, the Republic of North Macedonia, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Türkiye, United Kingdom, United States.

Eligible NATO Partners

Algeria, Armenia, Australia, Austria, Azerbaijan, Bahrain, Bosnia and Herzegovina, Colombia, Egypt, Georgia, Iraq, Ireland, Israel, Japan, Jordan, Kazakhstan, the Republic of Korea, Kuwait, Kyrgyz Republic, Malta, Mauritania, the Republic of Moldova, Mongolia, Morocco, New Zealand, Pakistan, Qatar, Serbia, Switzerland, Tajikistan, Tunisia, Turkmenistan, Ukraine, United Arab Emirates, Uzbekistan.

The MELITE project

MELITE will study the real-time dynamics of such ultralong fiber lasers and their suitability for hydroacoustic sensing. The experimental characterization guided by theoretical modelling will provide the training data set for artificial intelligence (AI) based models to control the laser dynamics. Experiments will be carried out in a water tank to prepare the venue for the development of the first field trial to monitor the seismic activity of the Western Ionian Sea.

- Study the acoustic sensitivity of an ultralong fiber laser at 1560nm based on standard mono-mode fiber: artificial intelligence assisted laser design and modelling, experimental implementation, and sensitivity to environmental conditions.

- Develop an ultralong fiber laser at 1030 nm with few-modes propagation in a SMF-28 fiber: laser design, experimental characterization, and sensitivity to environmental conditions.

- Perform hydro-acoustics tests in a water tank and set out the basis for a field trial of an ultralong laser in a 25km long submarine fiber cable.

The MELITE SPS Key Priorities

- **Facilitate mutually beneficial cooperation on issues of common interest, including international efforts to meet emerging security challenges**

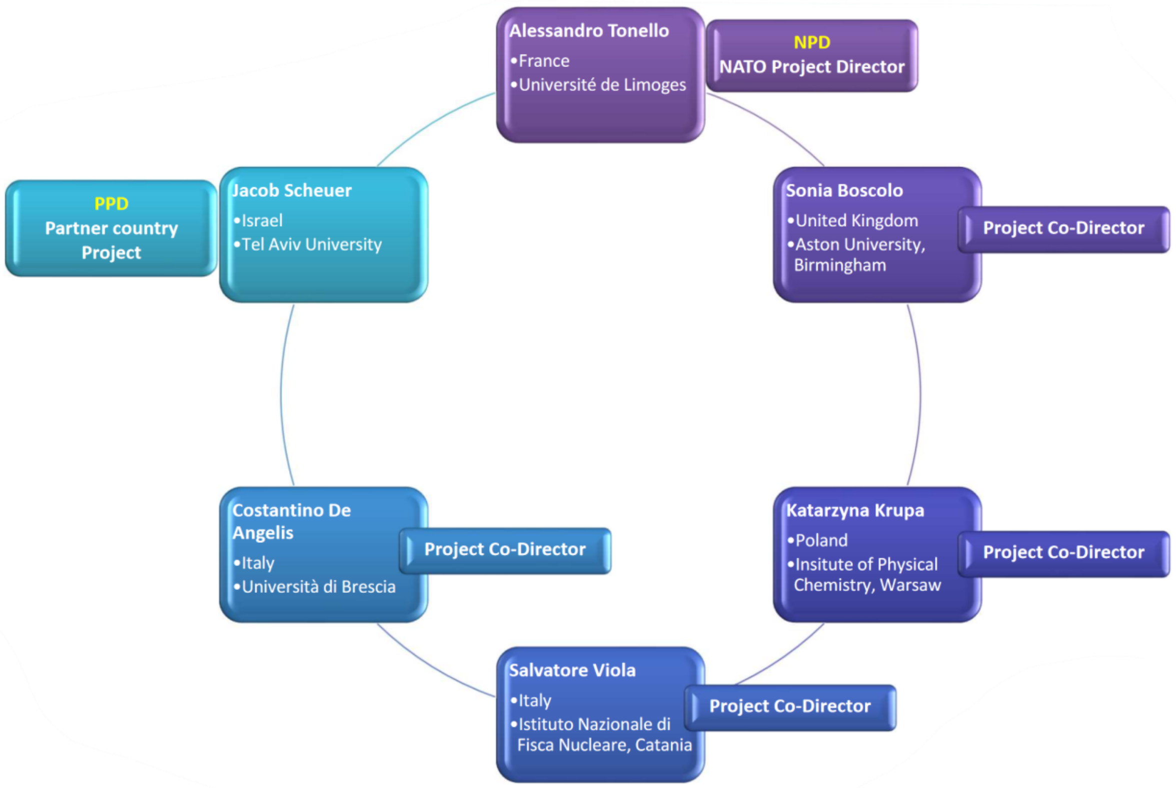
    a) Environmental Security

    b) Disaster forecast and prevention of natural catastrophes;

- **Enhance awareness on security developments including through early warning, with a view to preventing crises**

    a) Security-related Advanced Technology: Emerging technologies including nanotechnology, optical technology, micro satellites, metallurgy and the development of UAV platforms.

The MELITE Consortium



The MELITE Consortium - UNILIM

Dr. Alessandro Tonello

Nato Country **P**roject **D**irector

University of Limoges
XLIM Research Institute
Limoges, FRANCE

Research interests:
Multimode Non-linear Fiber Optics
Non-linear Optical propagation in presence of weak disorder
Ultralong fiber Lasers

The MELITE Consortium - TAU

Department of Physical Electronics, School of EE
Tel Aviv University, Tel Aviv, Israel

Prof. Jacob Scheuer

Partner Country **P**roject **D**irector

Research interests:
Metamaterials,
Ultralong-fiber lasers,
Sensing
Exceptional points in optics
Perovskites

The MELITE Consortium - ICHF

Dr. Katarzyna Krupa

Co-Director

Institute of Physical Chemistry,
Polish Academy of Sciences
Warsaw, Poland

Research interests:
Mode-locked fiber lasers
Multicolor light sources
Nonlinear effects
Real-time ultrafast dynamics
Spatio-temporal dynamics.

The MELITE Consortium - UNIBS

Prof. Costantino De Angelis

Co-Director

Department of Information Engineering
University of Brescia
Brescia, Italy

Research interests:
Numerical Modeling
Opto-thermal photonics

The MELITE Consortium - ASTON

Aston Institute of Photonics Technologies (AiPT),
Aston University
Birmingham, United Kingdom

Dr. Sonia Boscolo

Co-Director

Research interests:
Mathematical and numerical modelling of nonlinear photonic systems and devices.

Machine learning for the optimization and control of ultrafast nonlinear dynamics in fibre devices and photonic systems

Optical communication

The MELITE Consortium – INFN-LNS

Dr. Salvatore Viola

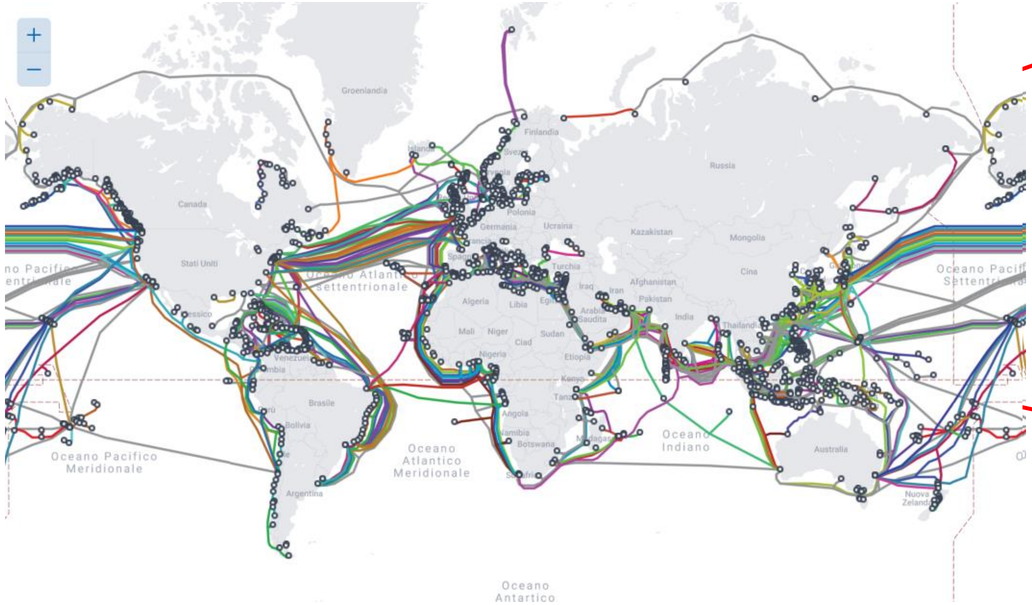
Co-Director

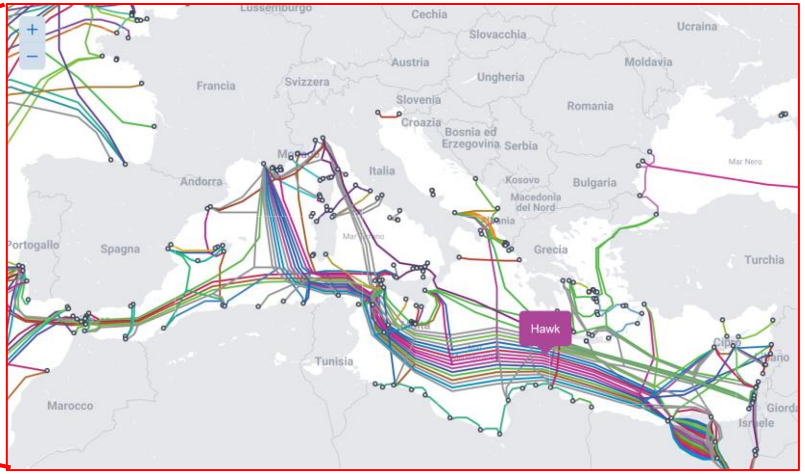
Laboratori Nazionali del Sud
Instituto Nazionale di Fisica Nucleare, LNS-INFN
Catania, Italy

Research interests:
Underwater acoustics
Signal processing
Remote sensing
Acoustic neutrino detection

Context

At present, there are more than 1.35 million kilometers of optical fiber cables installed undersea which power the internet. (487 global cables and 1304 unique landing stations)





https://www.submarinecablemap.com

Environmental sensing through underwater cables is becoming an important sector around the world

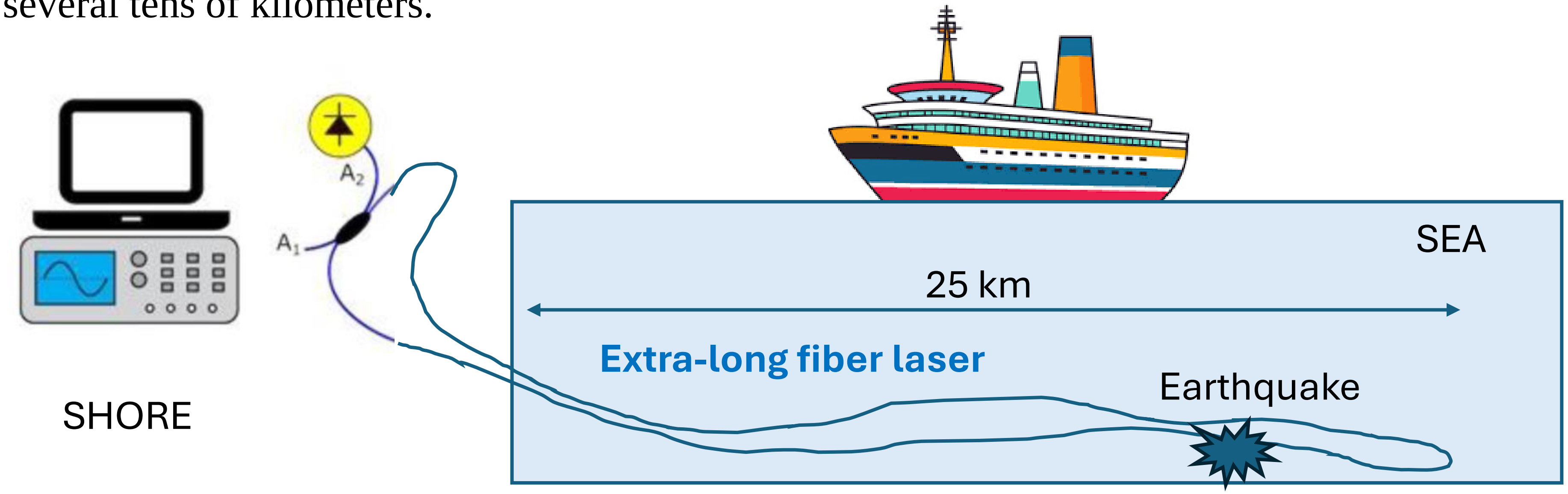
- Seismology
- Sea Life
- Tsunami warning

https://ella.link/geolab

Proposed solution

MELITE will establish a completely new way of exploiting the existing fiber-optic networks, that is, as sensing systems for environmental monitoring focused on early detection of natural disasters, biological diversity, and climate change

Project MELITE will explore the possibility of exploiting the installed fibers not used for communications, or dark fibers. Our proposed solution is to close the undersea fiber cable of some tens of kilometers in a loop, and then bring it to optical transparency by using one or more intra-cavity optical amplifiers, so to obtain a fiber laser with a cavity length of several tens of kilometers.



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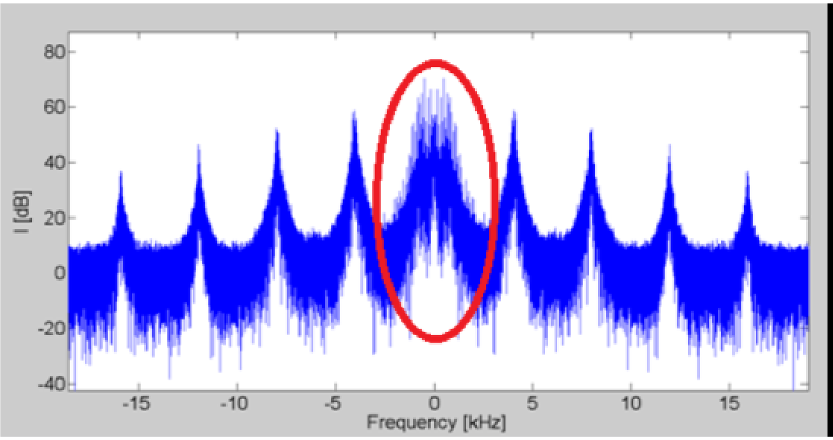
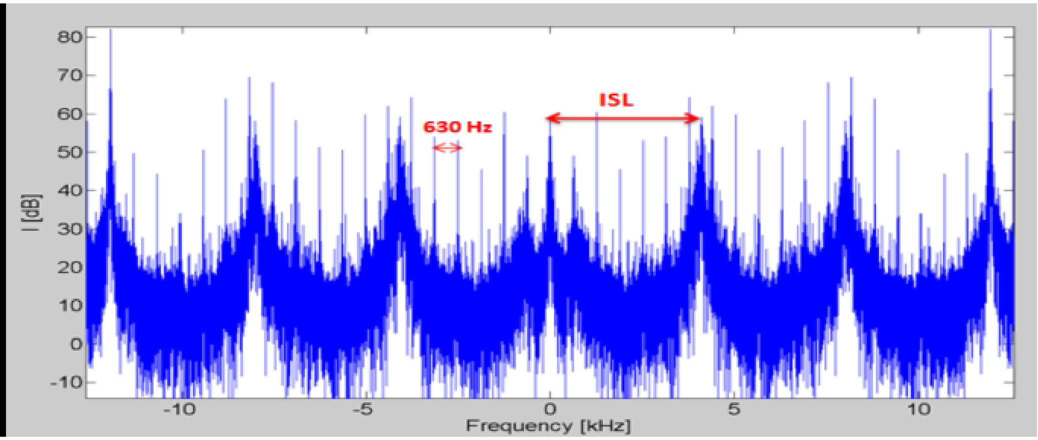


RF spectrum of a laser acquired in a laboratory environment when the laser is subject to a sound of 80 Hz: new frequencies appear (circled region).



Same laser subject to an acoustic tone at 630 Hz. ISL indicates the free spectral range of 4kHz: the fixed frequency sound induces a new RF comb.

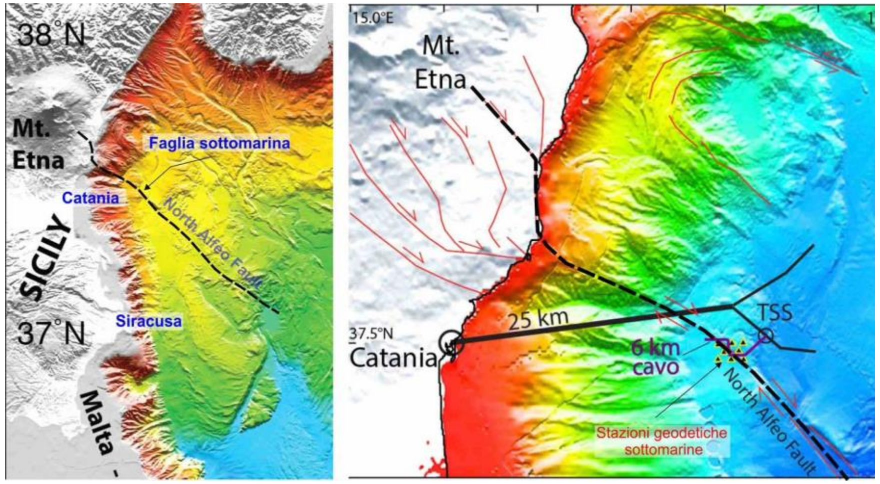
Why INFN?

Catania (2100 m water depth)
Multipurpose (including EMSO-ERIC)
25 km-long electro-optical cable 10 fibers, 6 conductors
divided among 2 CTFs (4 independent e.o. outputs)

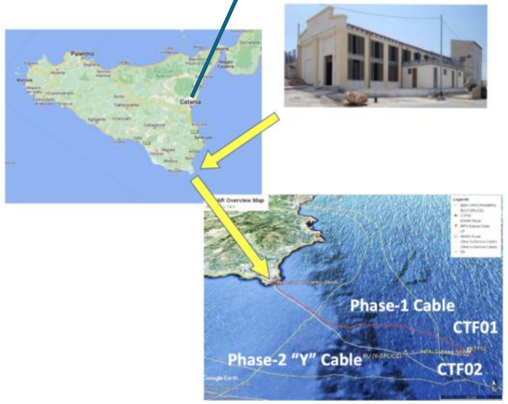
INFN's interest in marine sciences began in the early 2000s with studies on underwater acoustic detection in deep sea

- development of an acoustic positioning system for a km^3-scale Cherenkov neutrino telescope (KM3NeT)
- measurement of underwater background noise for studies on acoustic detection of Ultra High Energy cosmic neutrinos

INFN operates two underwater cabled deep sea infrastructure

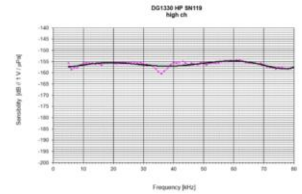


Capo Passero (3500 m water depth)
Multipurpose (including KM3NeT and EMSO-ERIC)
100 km-long electro-optical cable 20 fibers, 1 conductor (DC)
Cable Termination (5 independent e.o. outputs)
100 km-long electro-optical cable 48 fibers, 2 conductors (DC)
Cable Termination (16 independent optical and electrical outputs)



Shore Station at Capo Passero: direct **10 Gbit connection** to the EU optical network infrastructure for research

Real-time acquisition from the system infrastructure on the seafloor

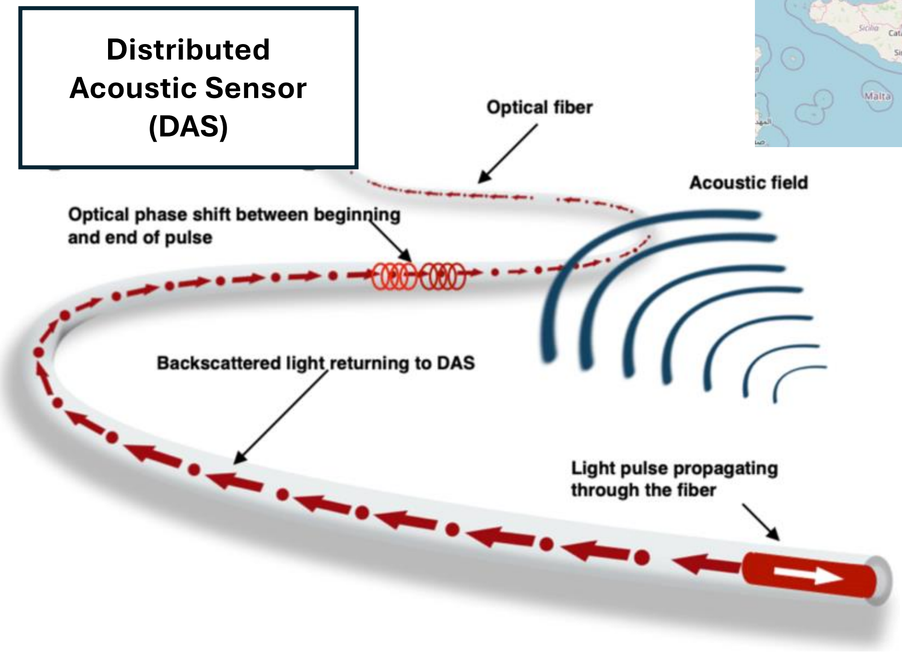


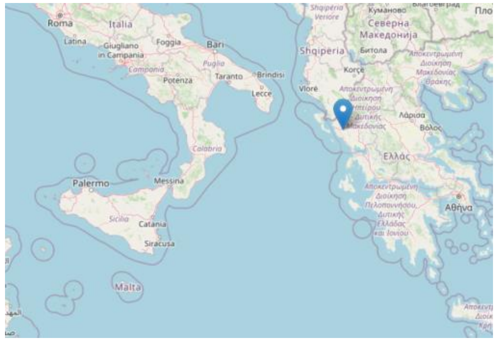
Co.l.mar. DG1330 Hydrophone:
- Two channels with different gain
- Wide frequency range
- High sensitivity, high dynamic range
- 24Bit, up to 216 kHz sample rate
- AES/EBU interface

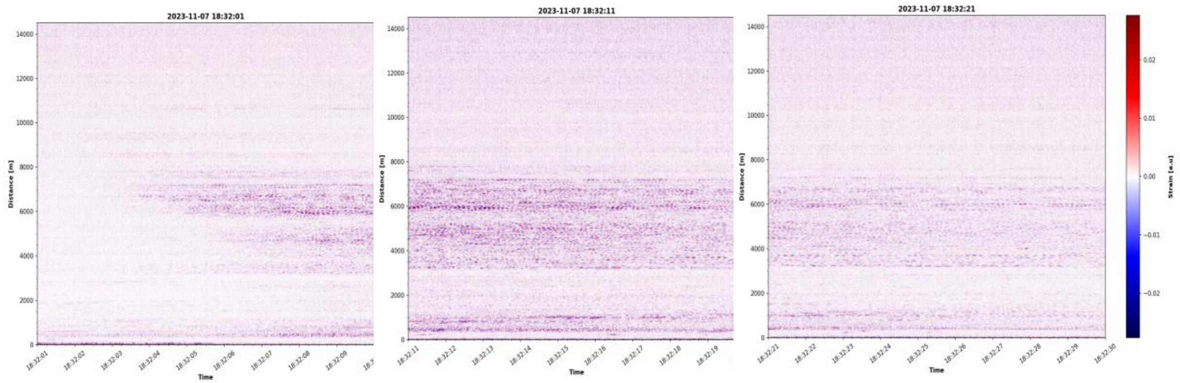
Both shore labs have direct 10Gbit connection to the EU network infrastructure for research

Fiber optic sensing @ INFN

Distributed Acoustic Sensing (DAS) technology is used to measure the dynamic strain rate along the whole length of the optical fibre, from the interferometric analysis of the back-scattered light. DAS technology has been tested as a new tool for monitoring the complex tectonic and volcanic interactions of Etna volcano from the summit to the sea floor.







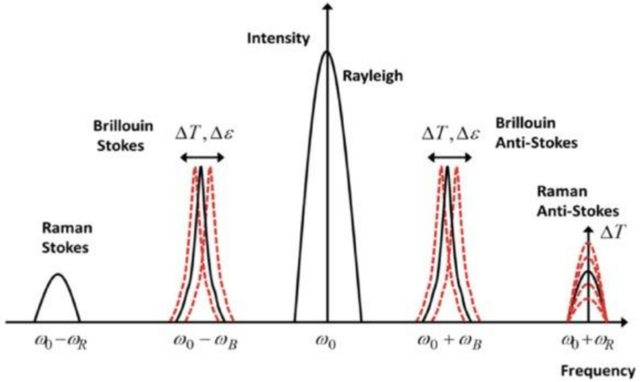
Submarine DAS strain rate record during of a M4.1 earthquake in Greece (07.11.2023) acquired through the 25 km long Catania Cable

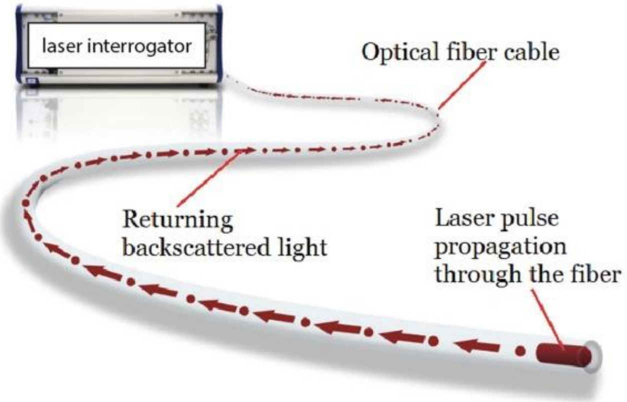
HORIZON EUROPE Geo-INQUIRE

LNS-INFN Catania, Italy

Fiber optic sensing @ INFN

Laser reflectometry (BOTDR - Brillouin Optical Time Domain Reflectometer), commonly used for monitoring structural health (bridges, dams, etc.), is being applied for the first time to the study of the movements of an active fault on the seabed.

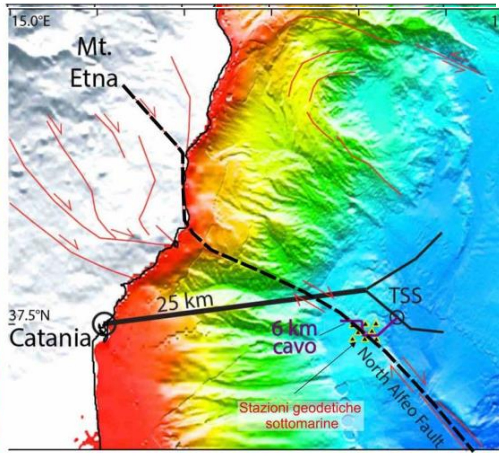


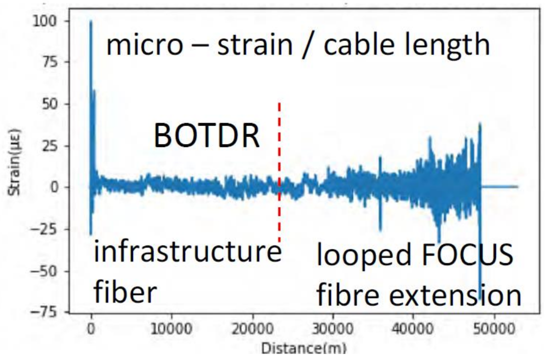


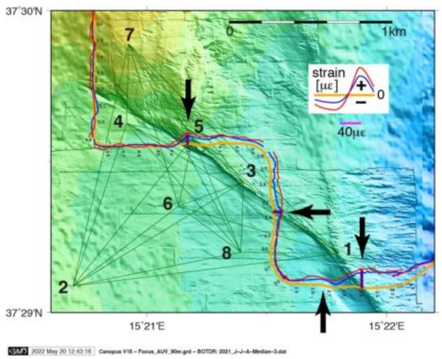
FOCUS ERC

European Research Council

GEO-OCEAN · GEOMAR Helmholtz Centre for Ocean Research Kiel · ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA · UNIVERSITÀ degli STUDI di CATANIA · INFN







Project structure

	YEAR 1				YEAR 2				YEAR 3			
Month	1 2 3	4 5 6	7 8 9	10 11 12	13 14 15	16 17 18	19 20 21	22 23 24	25 26 27	28 29 30	31 32 33	34 35 36
WP1: Ultralong fiber laser with Erbium-doped fiber amplifiers												
Task 1.1 Development of a 25 km long fiber laser at 1560nm (Architecture A)												
Task 1.2 Acoustic response of laser in Architecture A in dry environment												
Task 1.3 Role of polarization and bidirectionality in Architecture A												
WP2: Ultralong fiber laser with Ytterbium-doped fiber amplifiers												
Task 2.1 Design of Ytterbium amplifier architectures for few-mode UL laser (Architecture B)												
Task 2.2 Detection of the radio-frequency system and matching with models												
Task 2.3 Characterization of the laser dynamics and assessment of its suitability as a sensor												
WP3: Modelling, Signal processing and implementation of Artificial Intelligence												
Task 3.1 Numerical modelling of the amplification systems												
Task 3.2 Signal processing tools for real-time analysis of the RF spectrum												
Task 3.3 Data-driven deep learning approach												
Task 3.4 Model-driven deep learning approach												
WP4: Water tank trial in preparation of field trial												
Task 4.1 Acoustic response of laser Architecture A in a water tank												
Task 4.2 Acoustic response of laser Architecture B in a water tank												
Task 4.3 First field trial and first measurement of the RF signal and optical signal with polarisation analysis												
Deliverable		**Er laser in operation with numerical predictions**				**Acoustic characterization of Er laser with AI assistance completed**				**Test on acoustic and sensing properties of Yb laser with AI assistance completed**		**Acoustic characterisation in water tank completed**
Progress Reporting		**Milestone 1**				**Milestone 2**				**Milestone 3**		**Milestone 4 /Final report**

MELITE Project Budget

MELITE total budget: 350 k€
INFN budget: 36 k€

Category	Milestone	Milestone	Milestone	Milestone	Final	Total
Equipment	34.900					34.900
Training	1.000	5.400		5.400		11.800
Communication & Publication		9.000	8.500	9.000		26.500
Travel	11.800	27.010	25.300	20.500		84.610
Consumables	23.600	57.000	22.000	8.000		110.600
Other	7.000	8.300	8.300	7.000		30.600
Stipends	8.400	20.000	13.800	8.600		50.800
Total	**86.700**	**126.710**	**77.900**	**58.500**		**349.810**

Category	Milestone	Milestone	Milestone	Milestone	Final	Total
Tonello / France						
Equipment	3.000					3.000
Training	1.000	2.700		2.700		6.400
Communication & Publication		3.000	3.000	3.000		9.000
Travel	1.700	5.700	3.700	3.000		14.100
Consumables	3.000	6.000	3.000	3.000		15.000
Other	5.000	5.000	5.000	5.000		20.000
Stipends		1.600		1.600		3.200
Subtotal Tonello	**13.700**	**24.000**	**14.700**	**18.300**		**70.700**
Scheuer / Israel						
Equipment	23.000					23.000
Training						
Communication & Publication		3.000		3.000		6.000
Travel	2.800		5.600	2.800		11.200
Consumables						
Other	2.000	3.000	3.000	2.000		10.000
Stipends						
Subtotal Scheuer	**27.800**	**6.000**	**8.600**	**7.800**		**50.200**
Boscolo / United Kingdom						
Equipment	3.900					3.900
Training						
Communication & Publication						
Travel	3.300	6.610	3.300	3.300		16.510
Consumables	5.600					5.600
Other						
Stipends	5.400	10.800	10.800	5.400		32.400
Subtotal Boscolo	**18.200**	**17.410**	**14.100**	**8.700**		**58.410**
Krupa / Poland						
Equipment						
Training						
Communication & Publication						
Travel		6.700	6.700	6.700		20.100
Consumables	12.000	37.000	5.000			54.000
Other		300	300			600
Stipends	3.000	6.000	3.000			12.000
Subtotal Krupa	**15.000**	**50.000**	**15.000**	**6.700**		**86.700**
Viola / Italy						
Equipment						
Training						
Communication & Publication						
Travel	2.000	4.000	4.000	2.000		12.000
Consumables		11.000	11.000	2.000		24.000
Other						
Stipends						
Subtotal Viola	**2.000**	**15.000**	**15.000**	**4.000**		**36.000**
De Angelis / Italy						
Equipment	5.000					5.000
Training		2.700		2.700		5.400
Communication & Publication		3.000	5.500	3.000		11.500
Travel	2.000	4.000	2.000	2.700		10.700
Consumables	3.000	3.000	3.000	3.000		12.000
Other						
Stipends		1.600		1.600		3.200
Subtotal De Angelis	**10.000**	**14.300**	**10.500**	**13.000**		**47.800**

Summary

- At present, there are more than 1.35 million kilometers of optical fiber cables installed undersea which power the internet.

- MELITE will establish a completely new way of exploiting the existing fiber-optic networks, that is, as sensing systems for environmental monitoring focused on early detection of natural disasters, biological diversity, and climate change.

- While the MELITE project will target sensing applications in hydroacoustic by using submarine fiber cables to monitor tectonic dynamics, the outcomes of the project are expected to be of broad interest in that they will provide a general technology intelligence approach for the identification of alternative ways of exploiting installed optical fiber cables as sensors.

- The project will enable scientists of five different nations and six different research institutes to work together for exploring new avenues of laser fiber optics and to train young researchers

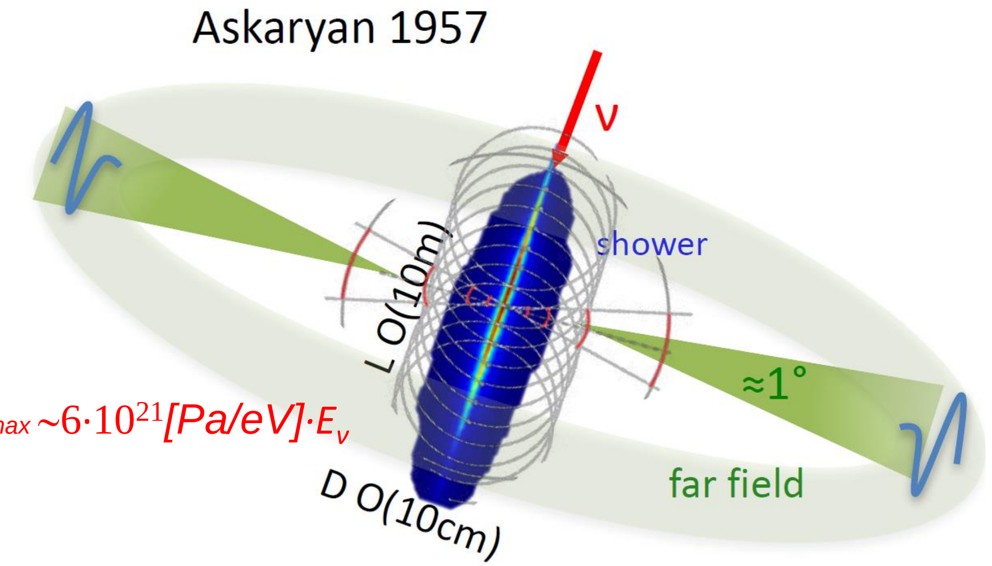
Perspectives

- Deployment of an innovative detection system based on ultra-long fiber laser in the Catania Test-Site (2000 m water depth)
  → Monitoring of an underwater site prone to numerous natural hazard issues due to high seismicity and the presence of Mount Etna, one of the biggest and active volcanoes in Europe, whose roots possibly sink down to seafloor
  → Contemporary monitoring of the same physical phenomena through different detection techniques:
    - Rayleigh scattering based distributed acoustic sensing (DAS) - GEOINQUIRE
    - Brillouin Distributed Strain Sensing (BDSS) – ERC FOCUS
    - Piezo-elettric acoustic antennas (IPANEMA / EMSO)
    - Ultra-long fiber laser (MELITE)

- Test of the technique on 100 km long electro-optical cable (Capo Passero – KM3NeT site)

Perspectives

- Patent production
- Exploit a possible use of ultra-long laser for underwater neutrino detection



$p_{max} \sim 6\cdot10^{21}[Pa/eV]\cdot E_\nu$

"Pen shaped" energy deposition region (20 m depth, 10 cm diameter)
Coherence:
$f \approx c_s/d \approx O(10\ kHz)$

Hadronic shower formation at interaction vertex
(if νe also an e.m. shower)

Hadronic shower carries≈ ¼ E_ν

Shower Development (LPM must be taken into account)

Sudden deposition of heat through ionization (10^{-8} sec)

Thermo-acoustic process dominant (10^{-5} sec):

Increase of temperature (C_p), Volume Expansion (β)

Bipolar pulses

$$p(\vec{r},t) = \frac{\beta}{4\pi\cdot C_p}\int \frac{dV'}{|\vec{r}-\vec{r}'|}\cdot\frac{\partial^2}{\partial t^2} q\left(\vec{r}', t - \frac{\vec{r}-\vec{r}'}{c_s}\right)$$

Thank you for the attention!