GWADW Online 2021

Gravitational Wave Advanced Detector Workshop

EINSTEIN TELESCOPE

Seismic studies at Sos Enattos, the Sardinian site for the Einstein Telescope

Luca Naticchioni (INFN Roma)

on behalf of the ET Sardegna site characterisation team

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Istituto Nazionale di Geofisica e Vulcanologia

Università degli Studi di Napoli Federico II

Gran Sasso Science Institute, School of Advanced Studies, Scuola Universitaria Superiore

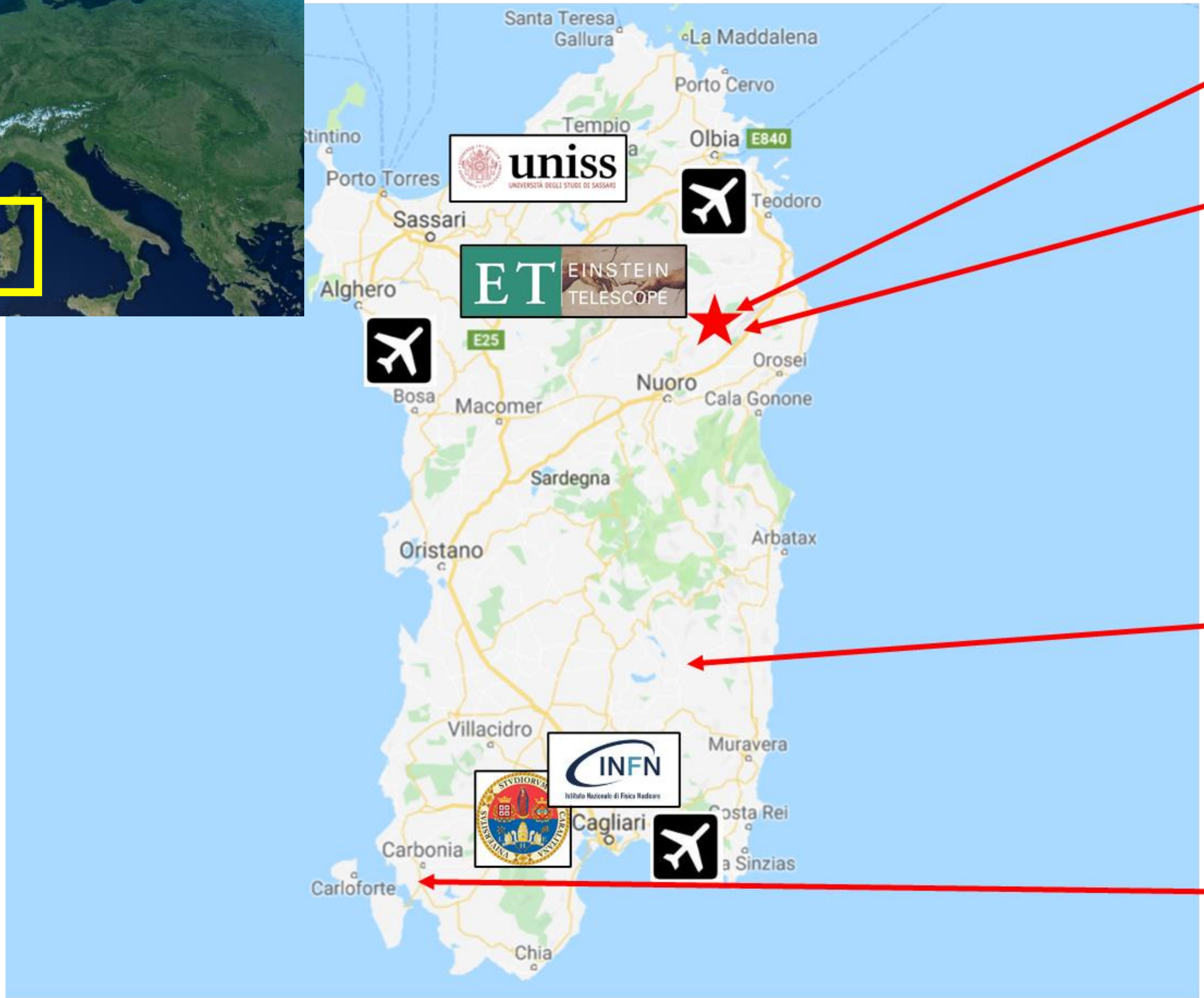
A. Allocca, T. Andric, D. Barrale, A. Berbellini, L. Boschi, E. Calloni, L. Cardello, A. Cardini, M. Carpinelli, A. Contu, R. De Rosa, A. Dell'Aquila, F. Dettori, L. Di Fiore, M. Di Giovanni, F. Dordei, D. D'Urso, L. Errico, V. Fanti, I. Fiori, C. Giunchi, A. Grado, J. Harms, E. Majorana, M. Marsella C. Migoni, L. Naticchioni, G. Oggiano, M. Olivieri, F. Paoletti, M. Punturo, P. Puppo, P. Rapagnani, F. Ricci, R. Romero, D. Rozza, G. Saccorotti, V. Sipala, I. Tosta, M.C. Tringali, L. Trozzo…

GWADW – 17th – 21st May 2021

Summary

- **Introduction: The Sos Enattos site in Sardinia**
- Characterisation of the Sos Enattos corner
- First 2-years results at Sos Enattos
- Characterisation of the other two corners
- Conclusions

The Sos Enattos site in Sardinia



Site access: 50' (85km) drive from Olbia airport (*SS 131 highway*)

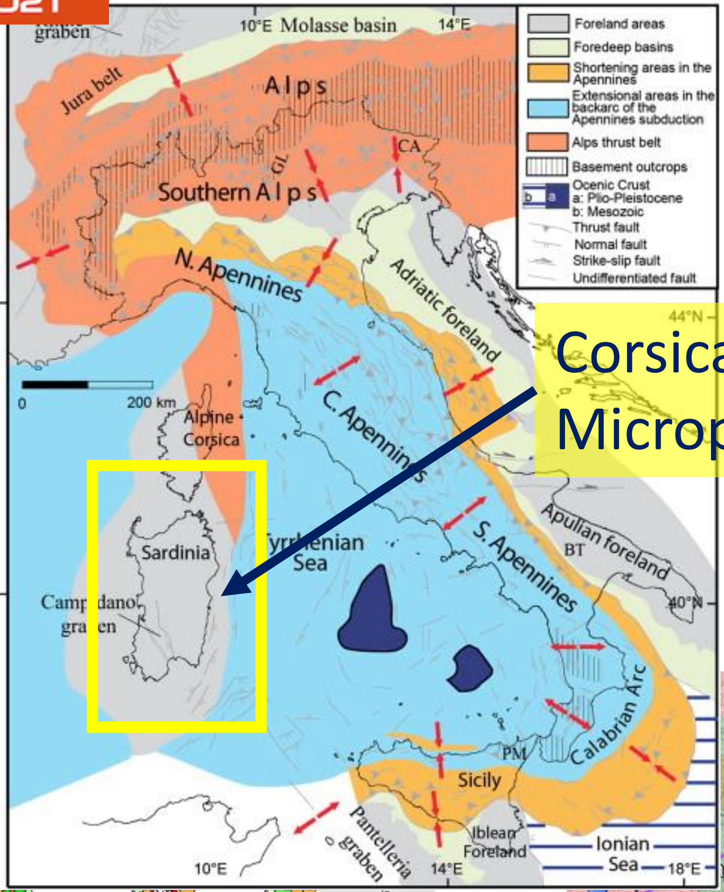
SarGrav underground laboratory

Sardinia Radio Telescope

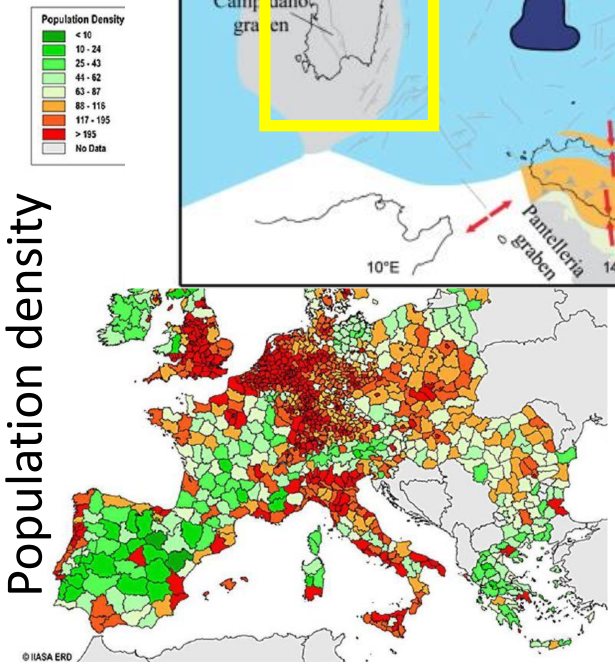
"ARIA" project (for Gran Sasso *Dark Side* DM det.)

The Sos Enattos site in Sardinia

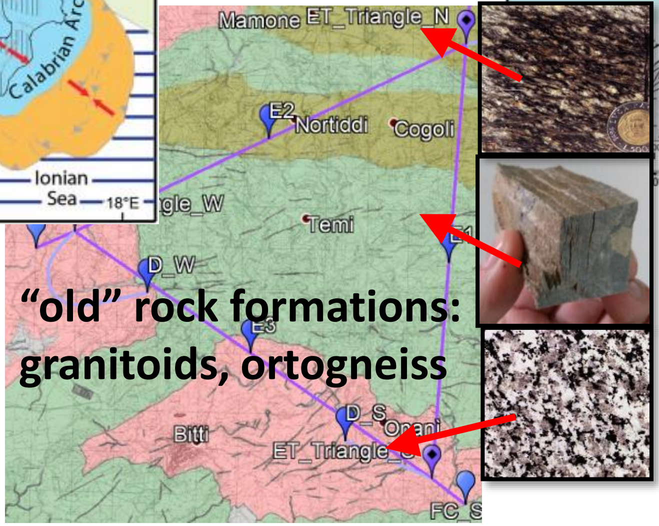
Geophysical frame



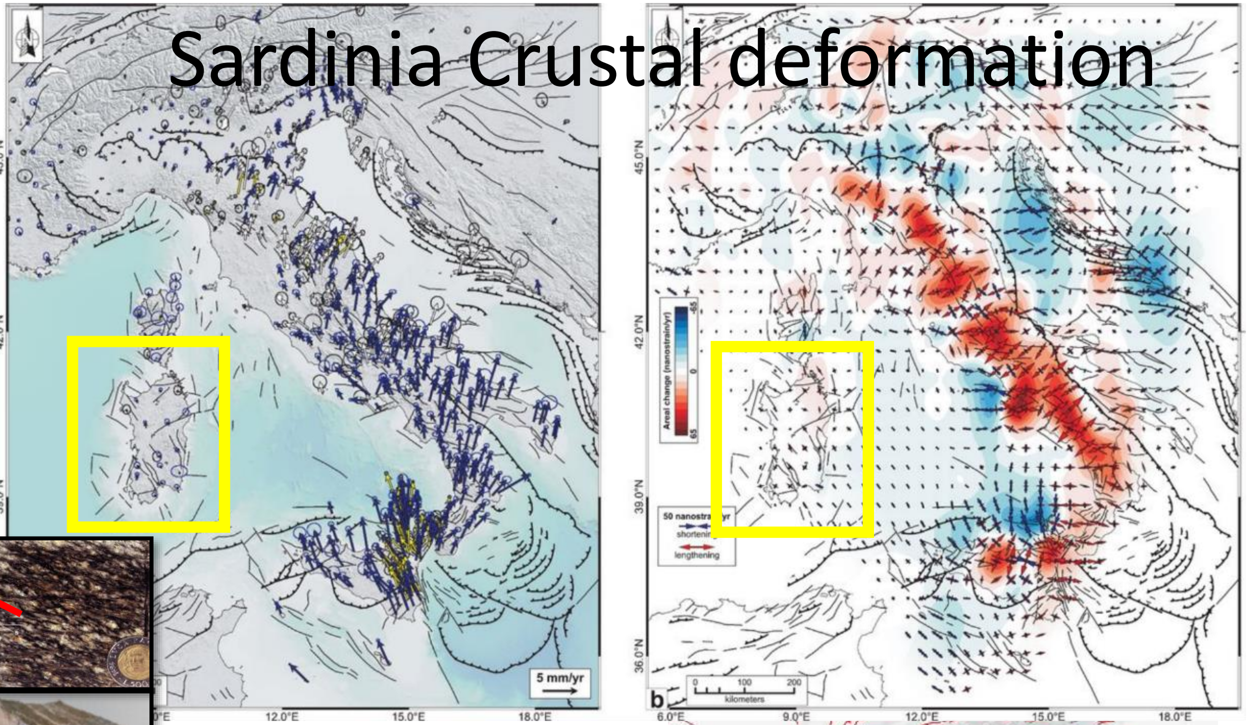
Corsica-Sardinia Microplate



Population density

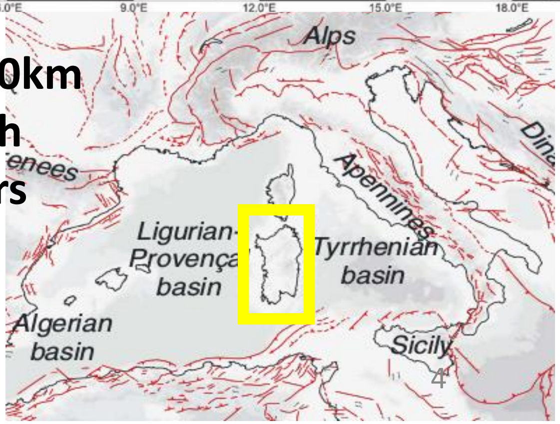


“old” rock formations: granitoids, ortogneiss

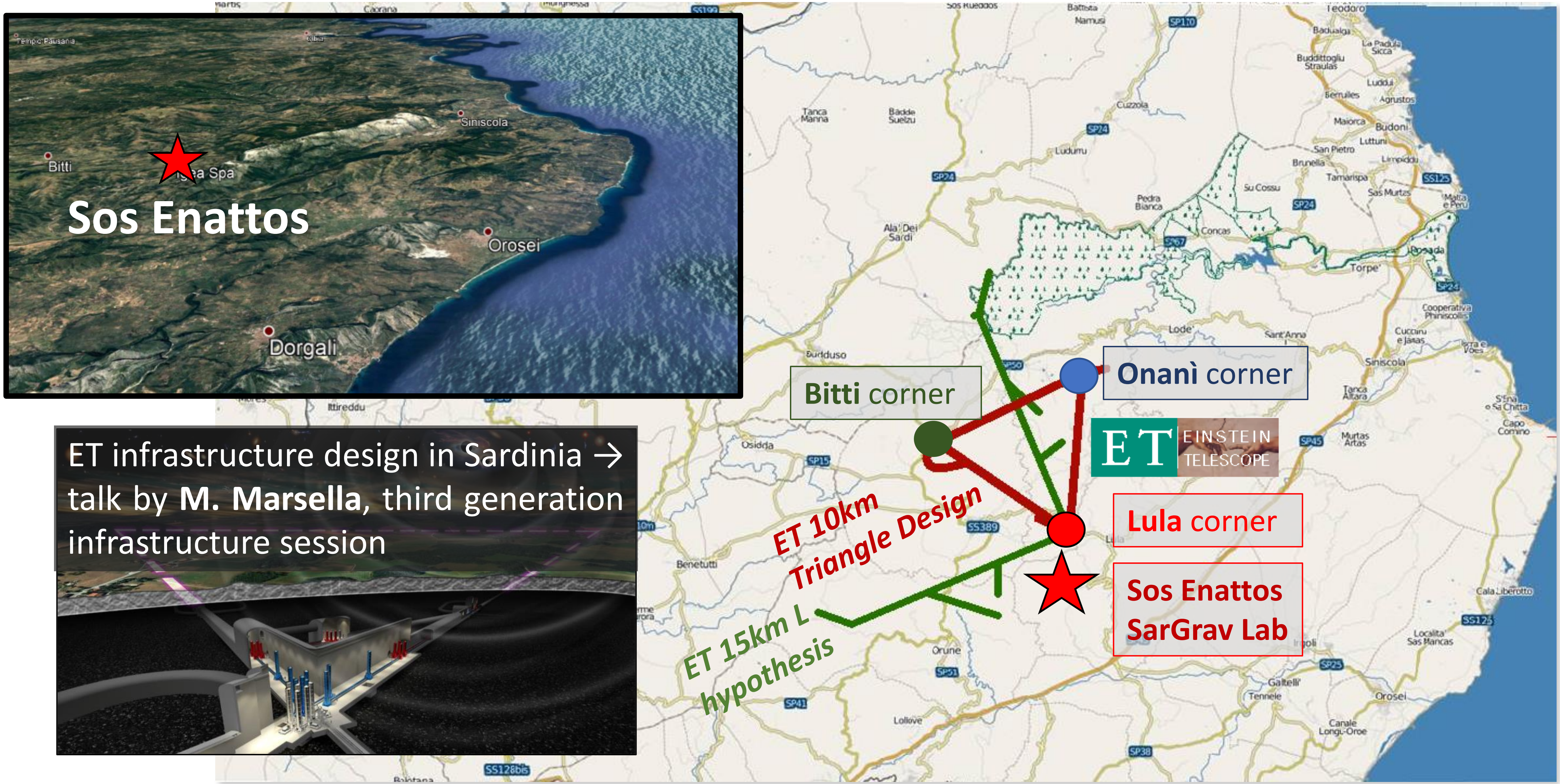


Sardinia Crustal deformation

10 earthquakes within 50km from Sos Enattos, all with M<2.5 in the last 40 years



The Sos Enattos site in Sardinia



ET infrastructure design in Sardinia → talk by **M. Marsella**, third generation infrastructure session

The Sos Enattos site in Sardinia

Sos Enattos former mine

- Maintained (by *IGEA SpA*) underground access via tunnels and shaft;
- Site studied in 2010-2014. **Long-term sensors deployment since March 2019**;
- Hosts the **SarGrav Laboratory** (→ talk by **D. D'Urso**, R&D facilities and plans session).

The Sos Enattos site in Sardinia

Ongoing site characterisation:

- **Seismic noise study** at the triangle corners (*Sos Enattos*, *Bitti* and *Onanì*);
- Other environmental noises in the area (magnetic, acoustic…);
- Local geology (rocks, groundwater…);
- Seismic field and Newtonian noise modelling at the site.

- ET requirements check;
- Site qualification;
- Possible site-dependent choices for the detector final design.

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Characterisation of Sos Enattos

Measurement stations at the Sos Enattos corner:

- **SarGrav surface Lab + Control Room**;
- **SOE0** (surface);
- **SOE1**, **SOE2**, **SOE3** (86m, 111m, 160m underground).

Instrumented stations

Sensors currently installed:

- 4 broadband triaxial seismometers (*Nanometrics Trillium 240* & *120 Horizon*);
- 2 magnetometers (*MF6-06*);
- 5(+3) short-period triaxial seismometers (*Nanometrics Trillium 20PH,* first seed of a transportable array);
- High Precision Tiltmeter (part of the *Archimedes* experiment @ SarGrav)
- Weather station (@ SarGrav Lab).

Work in progress: new sensors (seismometers and geophones, magnetometers, microphones) will be added to the network in the next months

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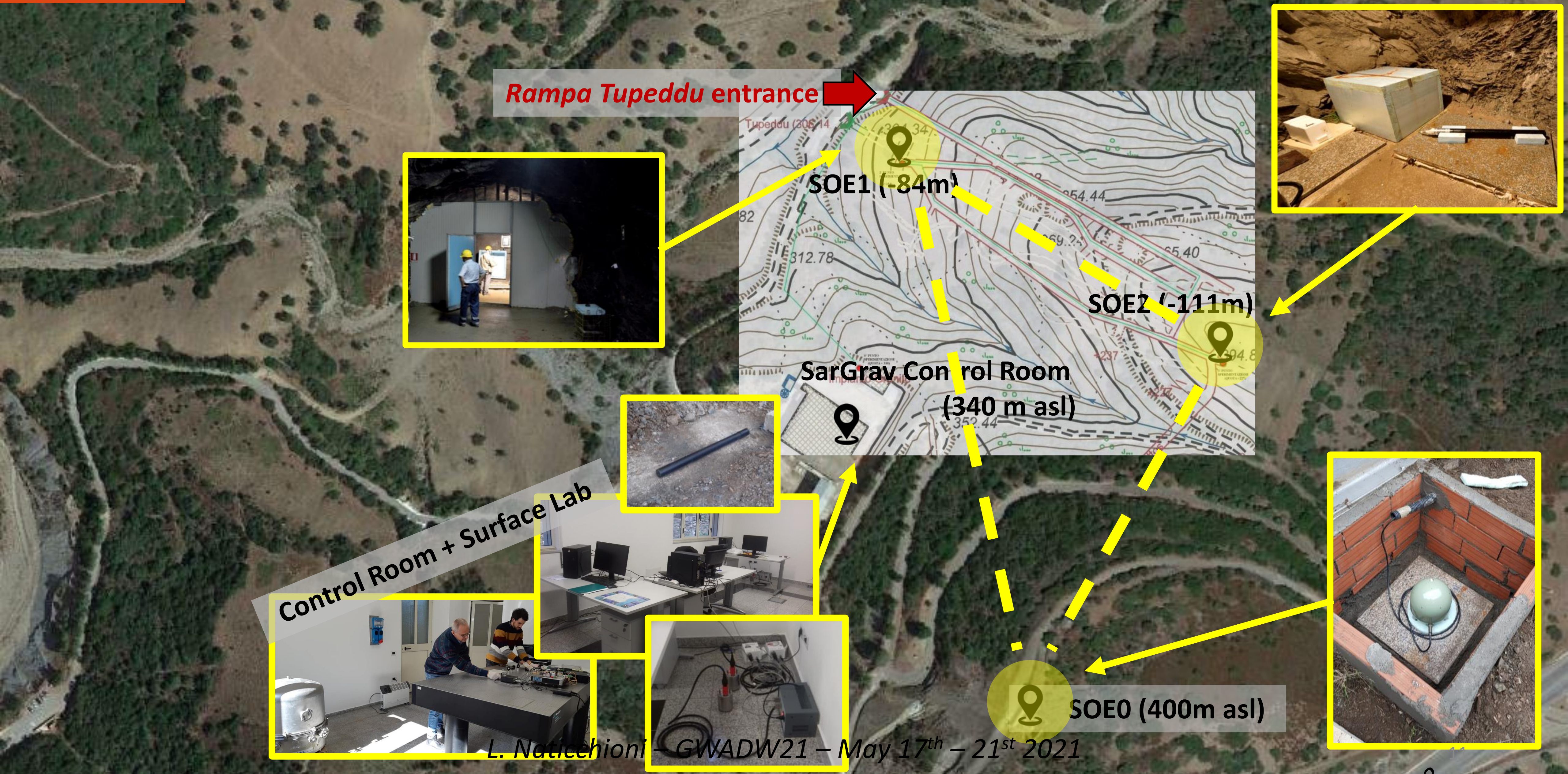
Sos Enattos measurement stations (2019-2020)

Sos Enattos measurement stations (2019-2020)

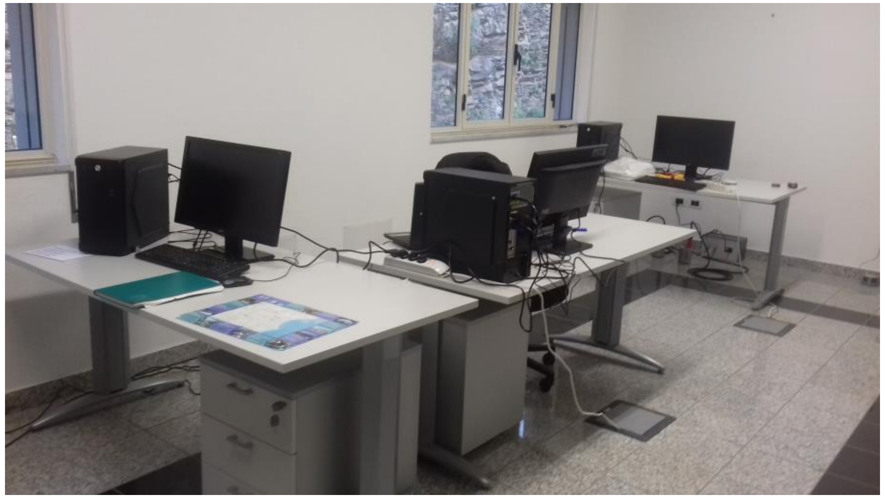


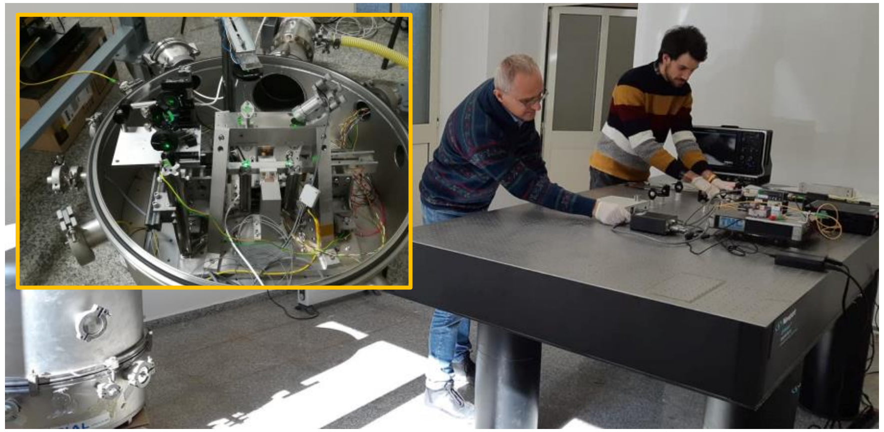
Sos Enattos measurement stations (since Aug. 2020)

Characterisation of Sos Enattos

SARGRAV surface lab & control room

MFS06 Magnetometer buried at surface close to the SarGrav control room





DAQs, Network connections, weather stations, *Archimedes* tiltmeter, T20 seismometers

Characterisation of Sos Enattos

SARGRAV surface lab & control room


New (large) experimental area in preparation

→ talk by **D. D'Urso**, R&D facilities and plans session

Characterisation of Sos Enattos

SOE0 station (*since December 2019*)

TRILLIUM 240s +
Taurus DAQ

Characterisation of Sos Enattos

SOE1 station (84m underground, *Mar. 2019 – June 2020*)

TRILLIUM 240s + Taurus DAQ

Characterisation of Sos Enattos

SOE1 station (84m underground, *since June 2020*)

TRILLIUM 120 Horizon + Centaur6 DAQ

DAQ input range reduced to 4Vpp (WRT 40Vpp standard settings);

→ Effective reduction of DAQ self noise in the few Hz band;

→ Measured noise floor hits the Earth Person’s Low Noise Model.

Characterisation of Sos Enattos

SOE2 station (111m underground, *since March 2019*)

Double wall + insulation box + *pasta-pot* insulation

TRILLIUM 240s + Centaur6 DAQ

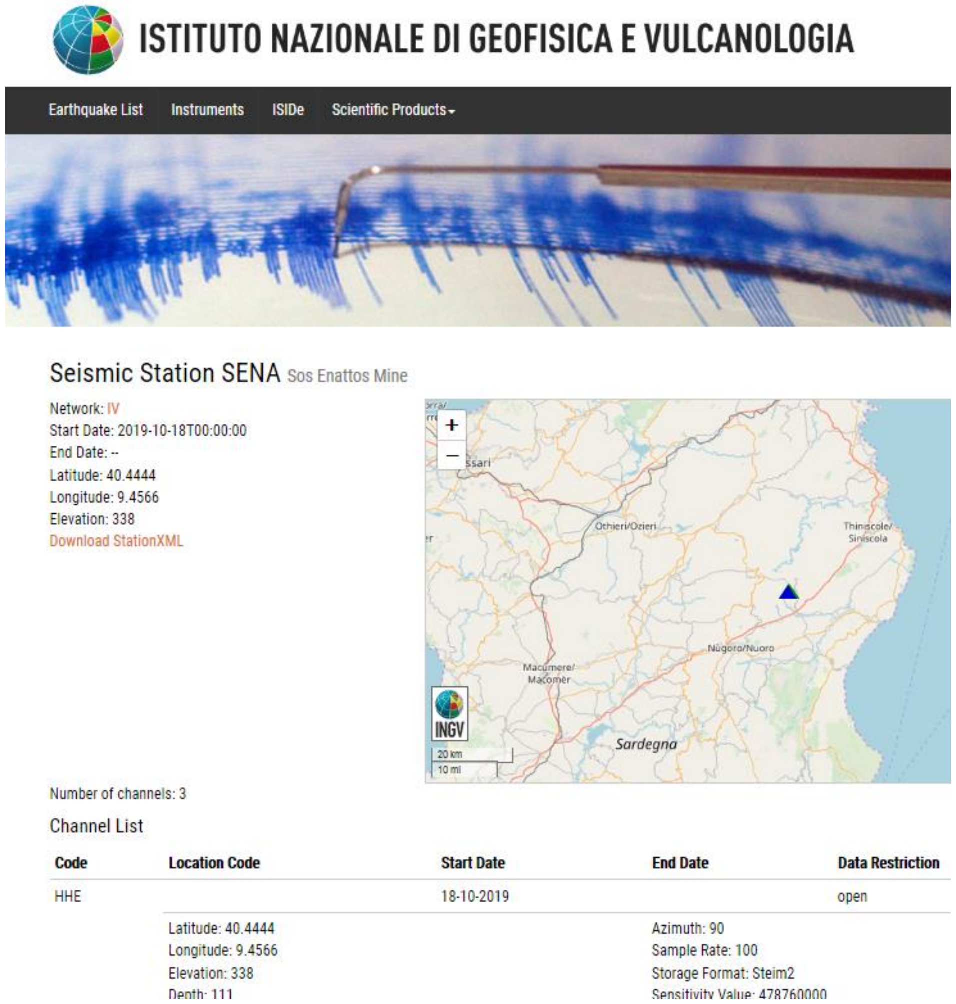
SOE2 station (111m underground, *since March 2019*)

Double wall + insulation box + *pasta-pot* insulation

Magnetometer MFS-06

Characterisation of Sos Enattos

SOE2 station (111m underground, *since March 2019*)



SOE2 station is integrated into the Italian national seismometer network of INGV (SENA station)

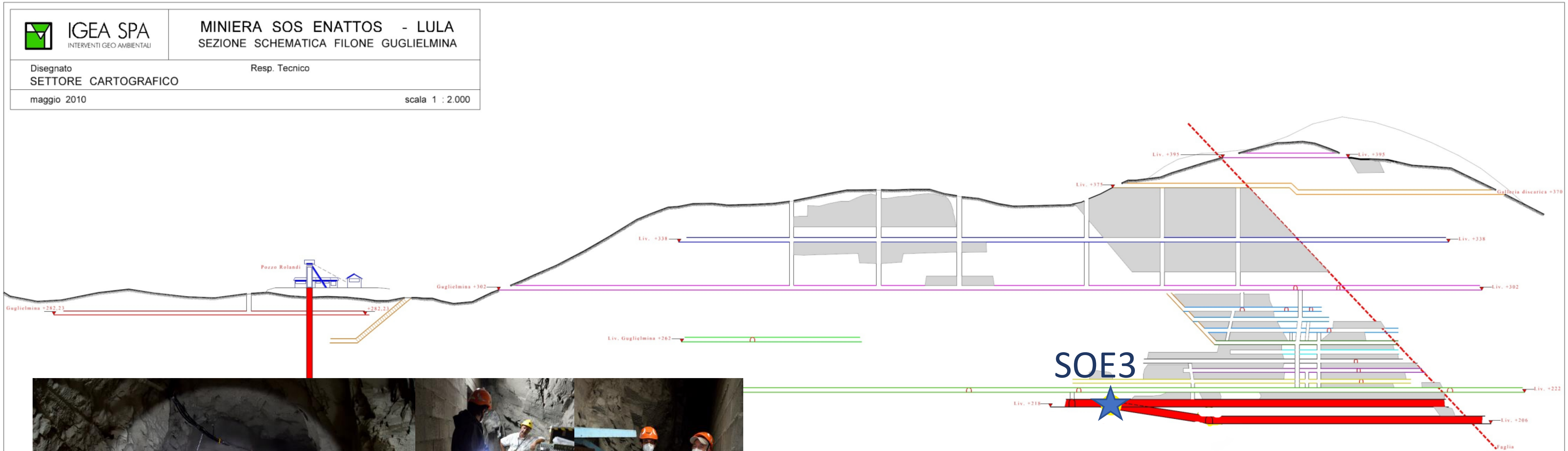
http://cnt.rm.ingv.it/en/instruments/station/SENA

Public data access

NB: standard DAQ input range in this network is 40Vpp

Characterisation of Sos Enattos

SOE3 station (160m underground, *since Aug. 2020*)



TRILLIUM 240 + Taurus DAQ

DAQ input range reduced to 4Vpp as in SOE1

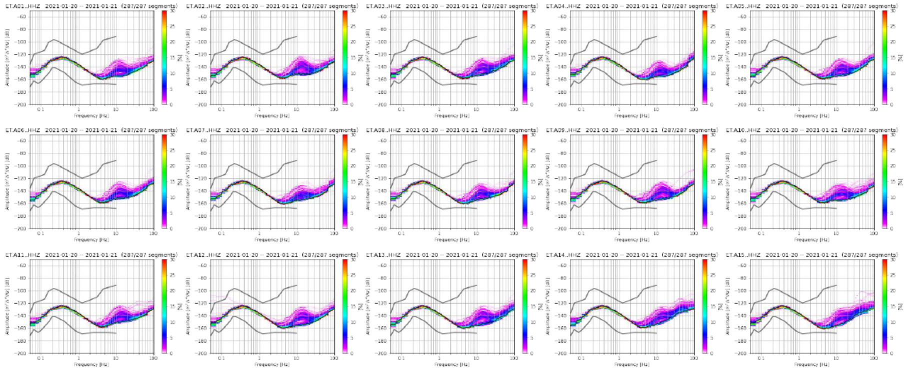
Taurus removed for maintenance on Feb 2021, to be re-deployed in May/July 2021

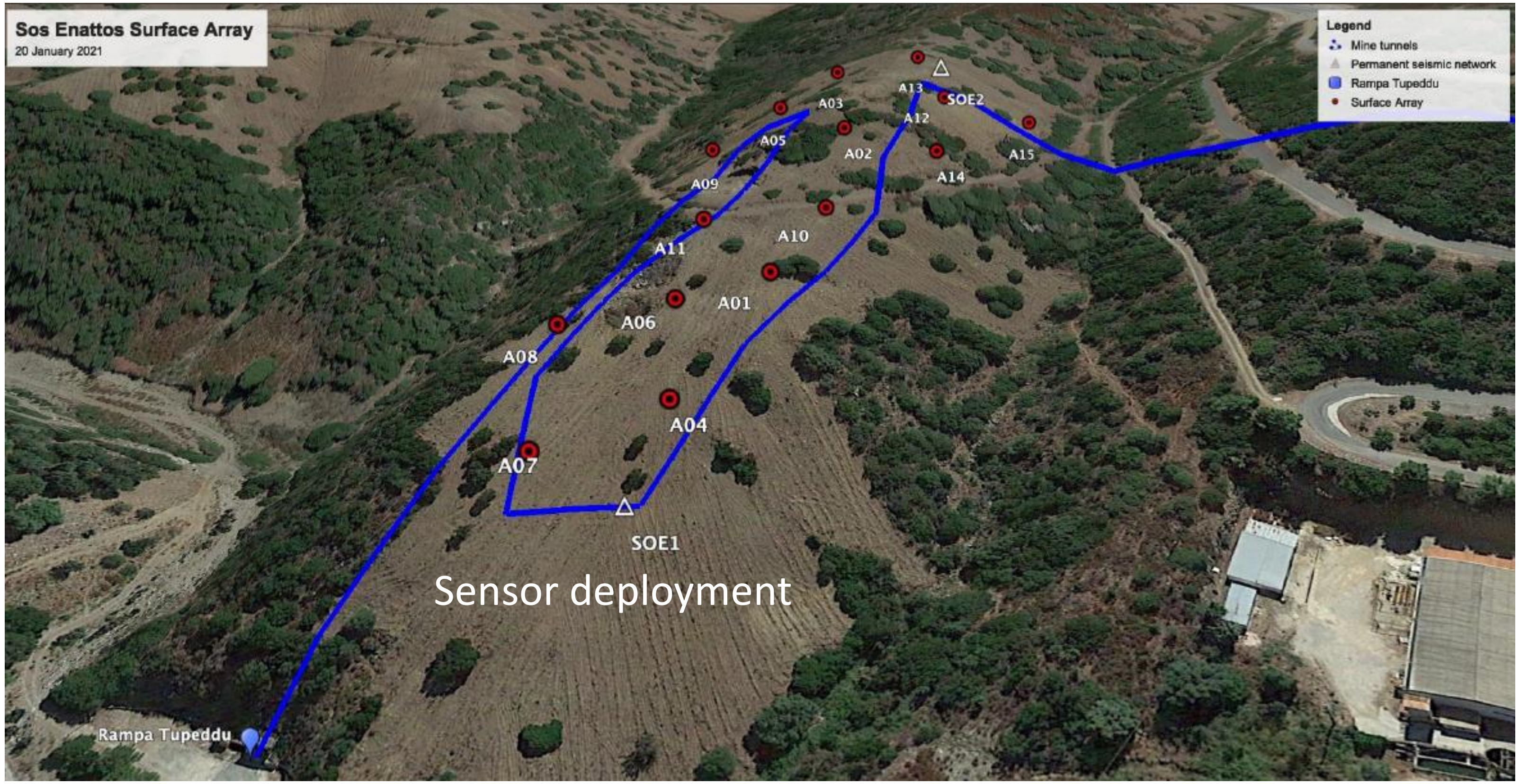
Characterisation of Sos Enattos

Surface Seismometers Array *Local noise sources and Noise modelization*

A surface array made of tens of seismometers (12 Trillium120 + 3 Trillium20 provided by INGV & INFN) have been installed at Sos Enattos in January-February 2021

Preliminary test





Sensor deployment

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First results at Sos Enattos

The results of the first 2-years of seismic characterisation at the Sos Enattos corner have been published in:

- L. Naticchioni et al., ***Characterization of the Sos Enattos site for the Einstein Telescope***, **JPCS** 1468, 2020
- M. Di Giovanni et al., ***A seismological study of the Sos Enattos Area – the Sardinia Candidate Site for the Einstein Telescope***, **SRL**, 2020 https://doi.org/10.1785/0220200186
- A. Allocca et al., ***Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency***, **EPJP**, 2021 https://doi.org/10.1140/epjp/s13360-021-01450-8

A Seismological Study of the Sos Enattos Area—the Sardinia Candidate Site for the Einstein Telescope

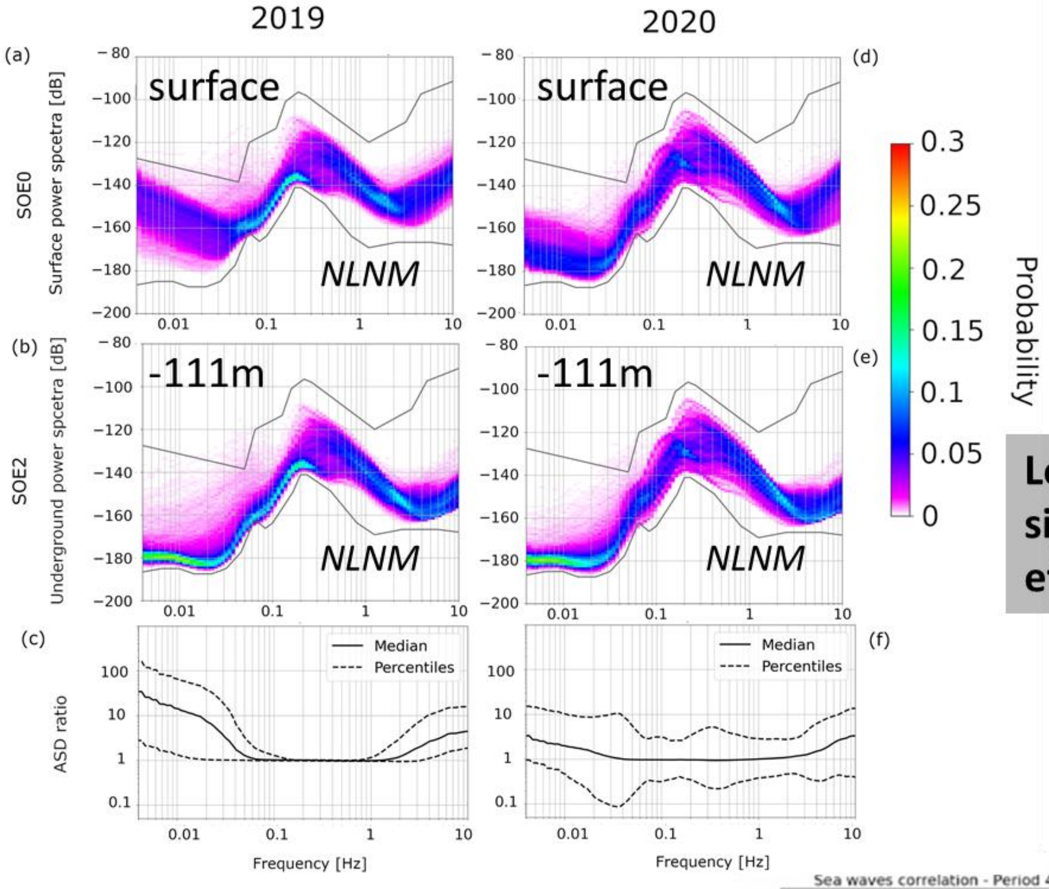
Matteo Di Giovanni[*1,2,3], Carlo Giunchi[1], Gilberto Saccorotti[1], Andrea Berbellini[4], Lapo Boschi[4,5,6], Marco Olivieri[4], Rosario De Rosa[7,8], Luca Naticchioni[9,10], Giacomo Oggiano[11,12], Massimo Carpinelli[11,12], Domenico D'Urso[11,12], Stefano Cuccuru[11,12], Valeria Sipala[11,12], Enrico Calloni[7,8], Luciano Di Fiore[7], Aniello Grado[13], Carlo Migoni[14], Alessandro Cardini[14], Federico Paoletti[15], Irene Fiori[16], Jan Harms[2,3], Ettore Majorana[9,10], Piero Rapagnani[9,10], Fulvio Ricci[9,10], and Michele Punturo[17]

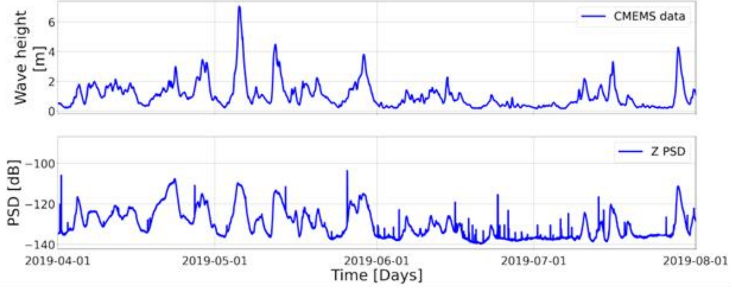
Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency

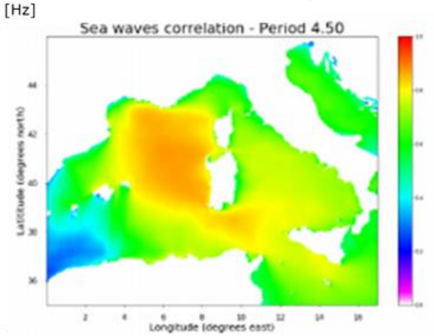
A. Allocca[1,2], A. Berbellini[3], L. Boschi[3,4,5], E. Calloni[1,2,a], G. L. Cardello[6,7], A. Cardini[8]. M. Carpinelli[6,7,9], A. Contu[8,10], L. D'Onofrio[1,2], D. D'Urso[6,7],

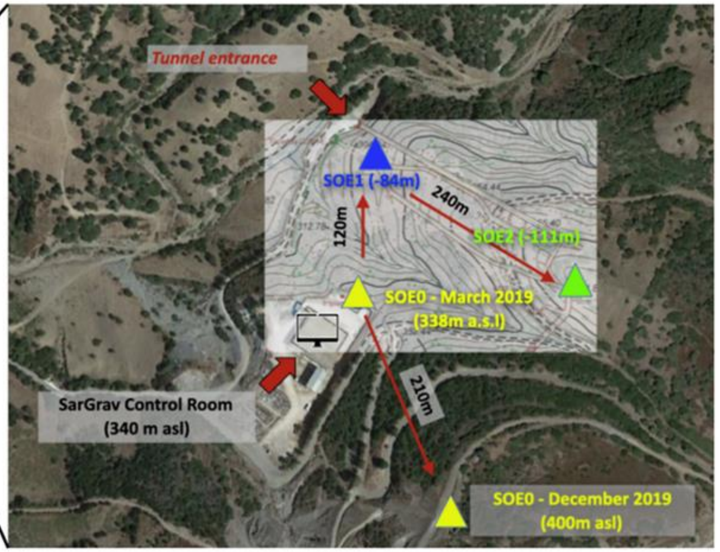
… another publication about the features of the seismic noise at the site is in preparation

First results at Sos Enattos

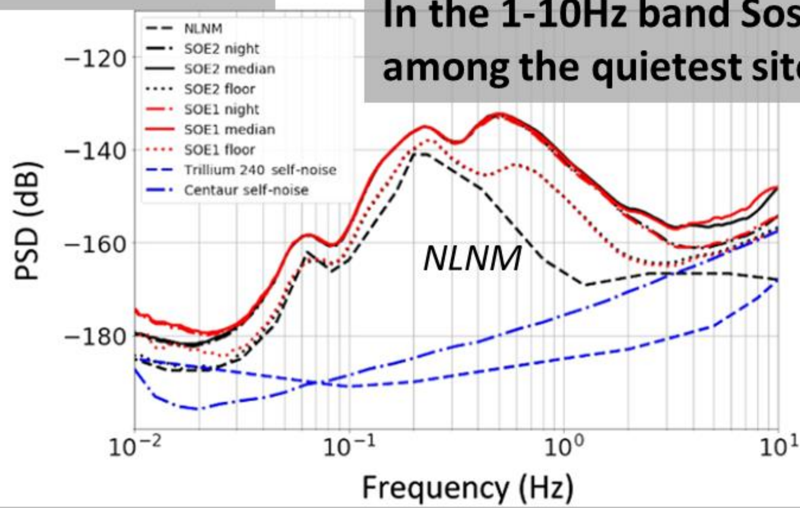








Low anthropic noise, no significant amplification effects



In the 1-10Hz band Sos Enattos is among the quietest sites in the world

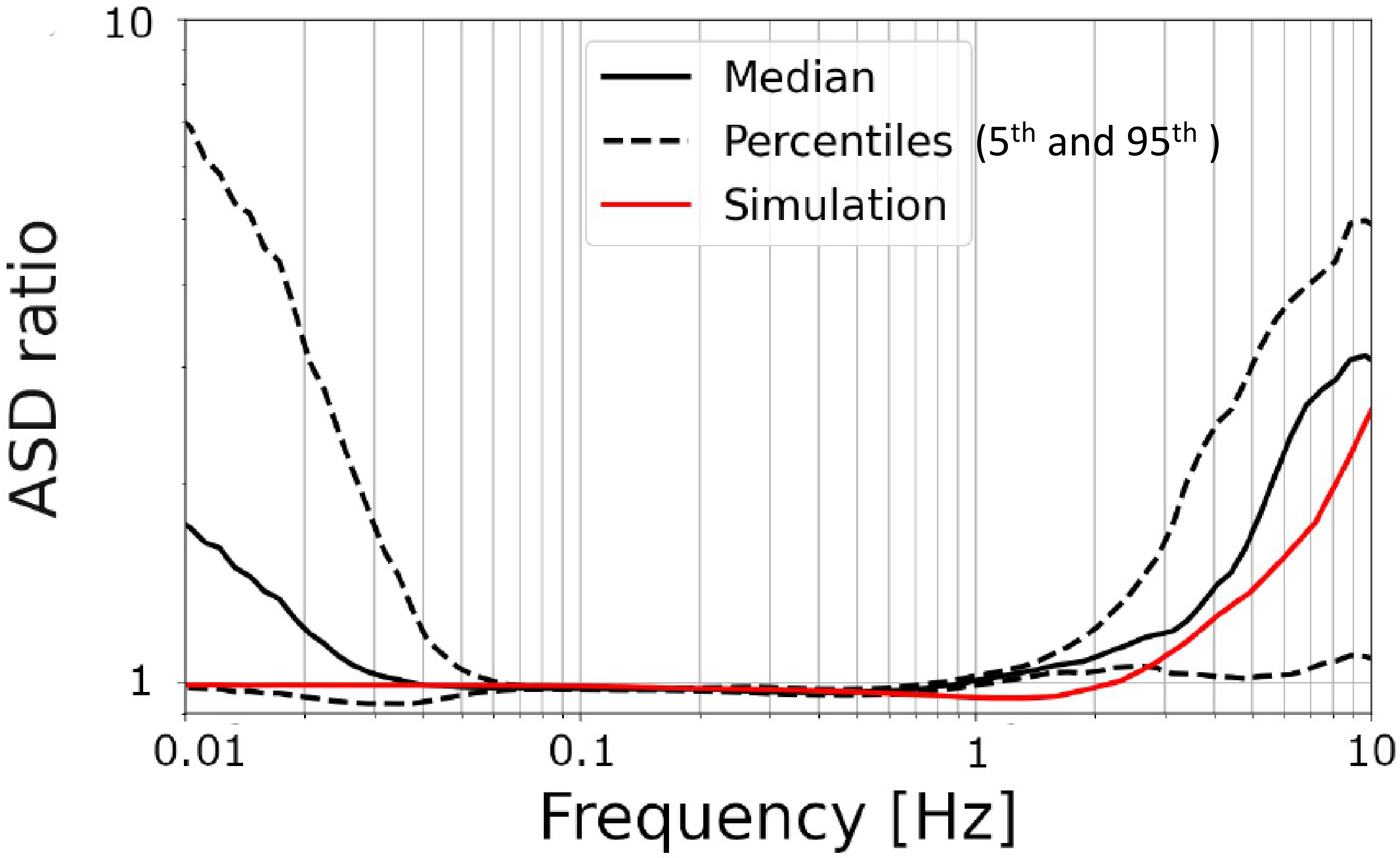
Microseisms correlation with NW 4.5s Med Sea waves

Seismological Research Letters (2021) 92 (1): 352–364

First results at Sos Enattos

Amplitude decay with depth significant only for f>2Hz, consistent with Rayleigh-wave propagation in local rocks

SOE0 (surface) / SOE2 (-111m vault)



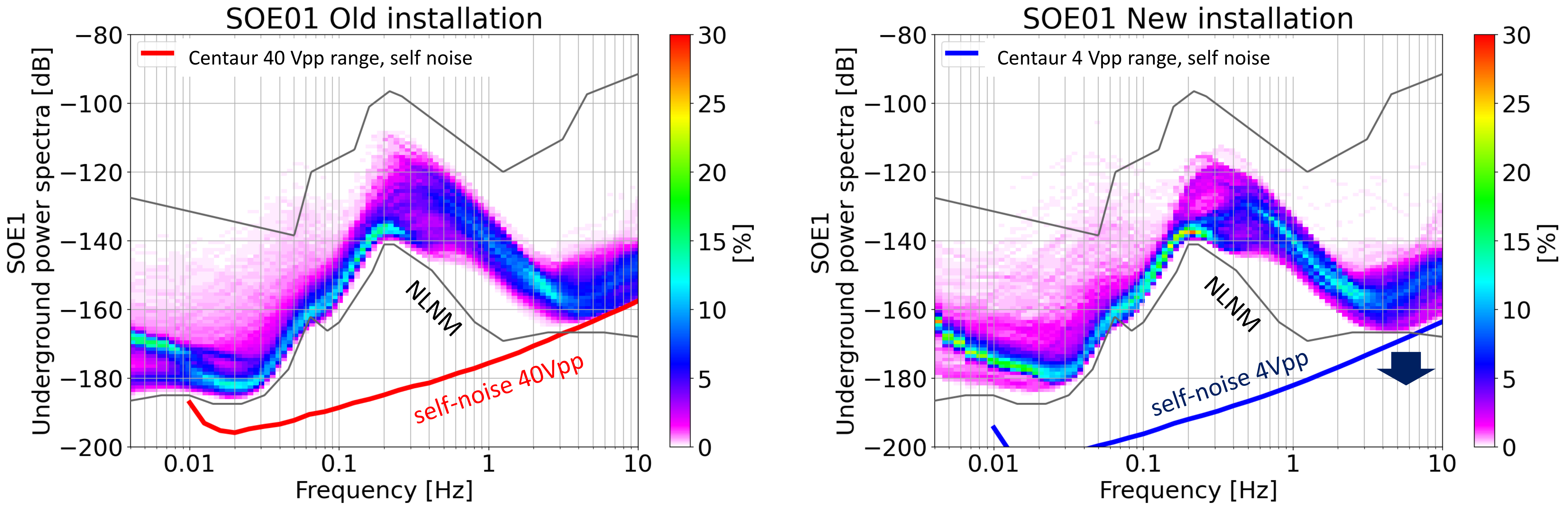
(5th and 95th)

Synthetic seismograms

Seismological Research Letters (2021) 92 (1): 352–364

First results at Sos Enattos

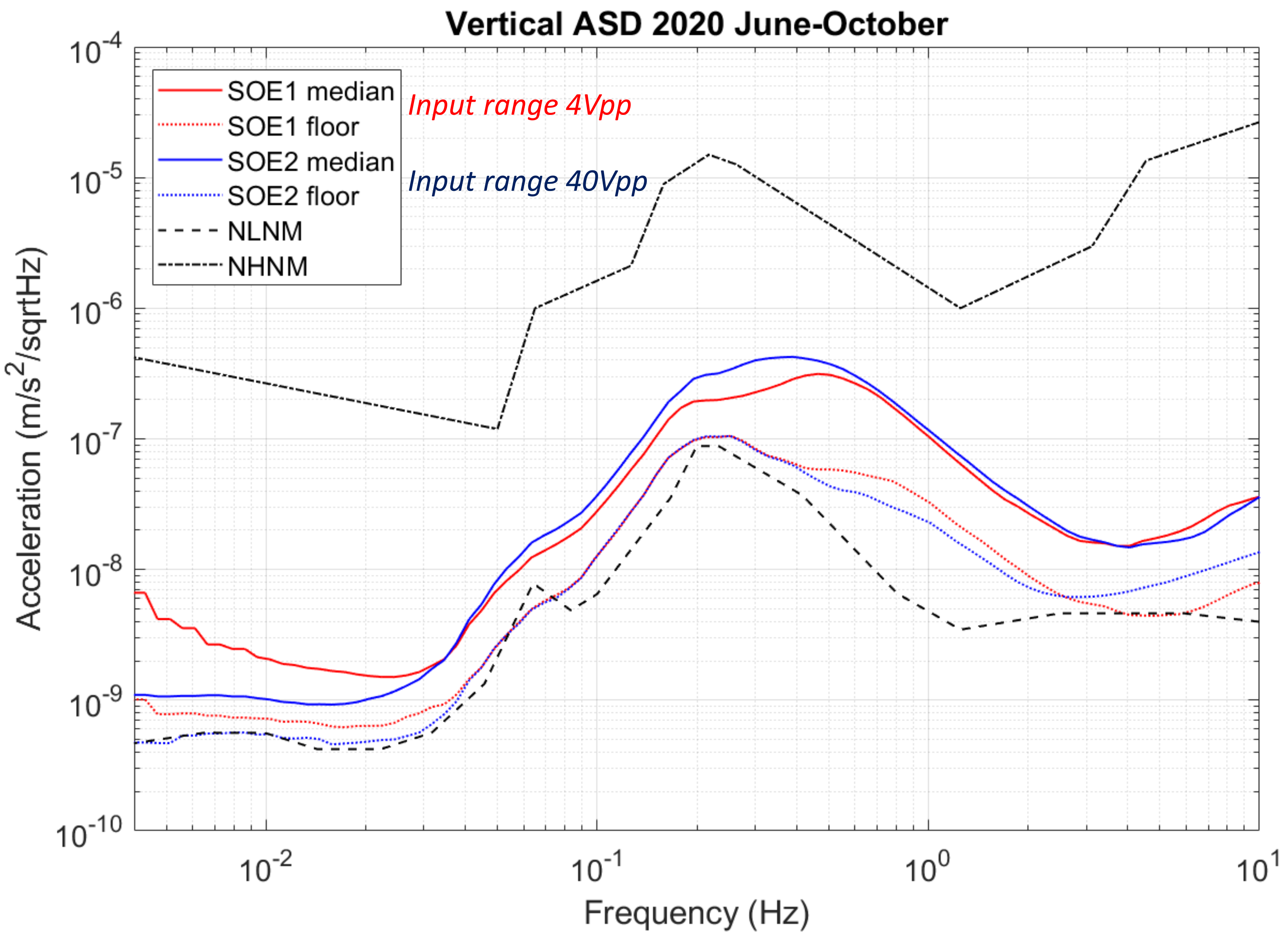
Reduced input range → reduced DAQ self noise → environmental seismic noise floor below the standard seismometer settings in few Hz band, **close to NLNM** (here SOE1, 84m depth)



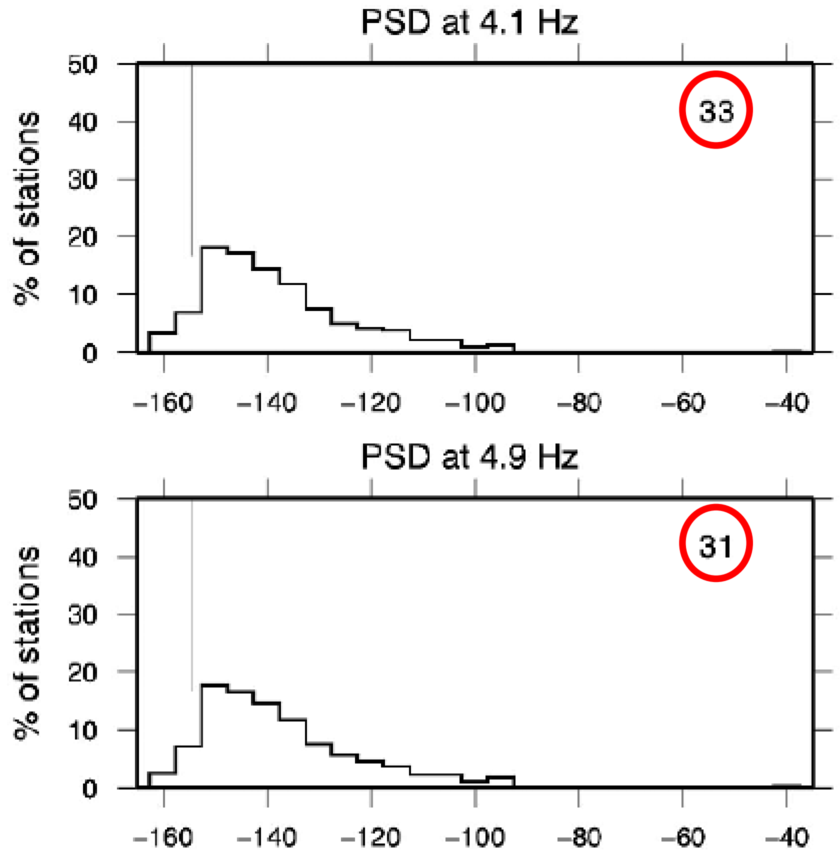
May to June 2020

June to August 2020

First results at Sos Enattos



SOE2 ranking among 445 stations of IRIS network



Seismological Research Letters (2021) 92 (1): 352–364

First results at Sos Enattos

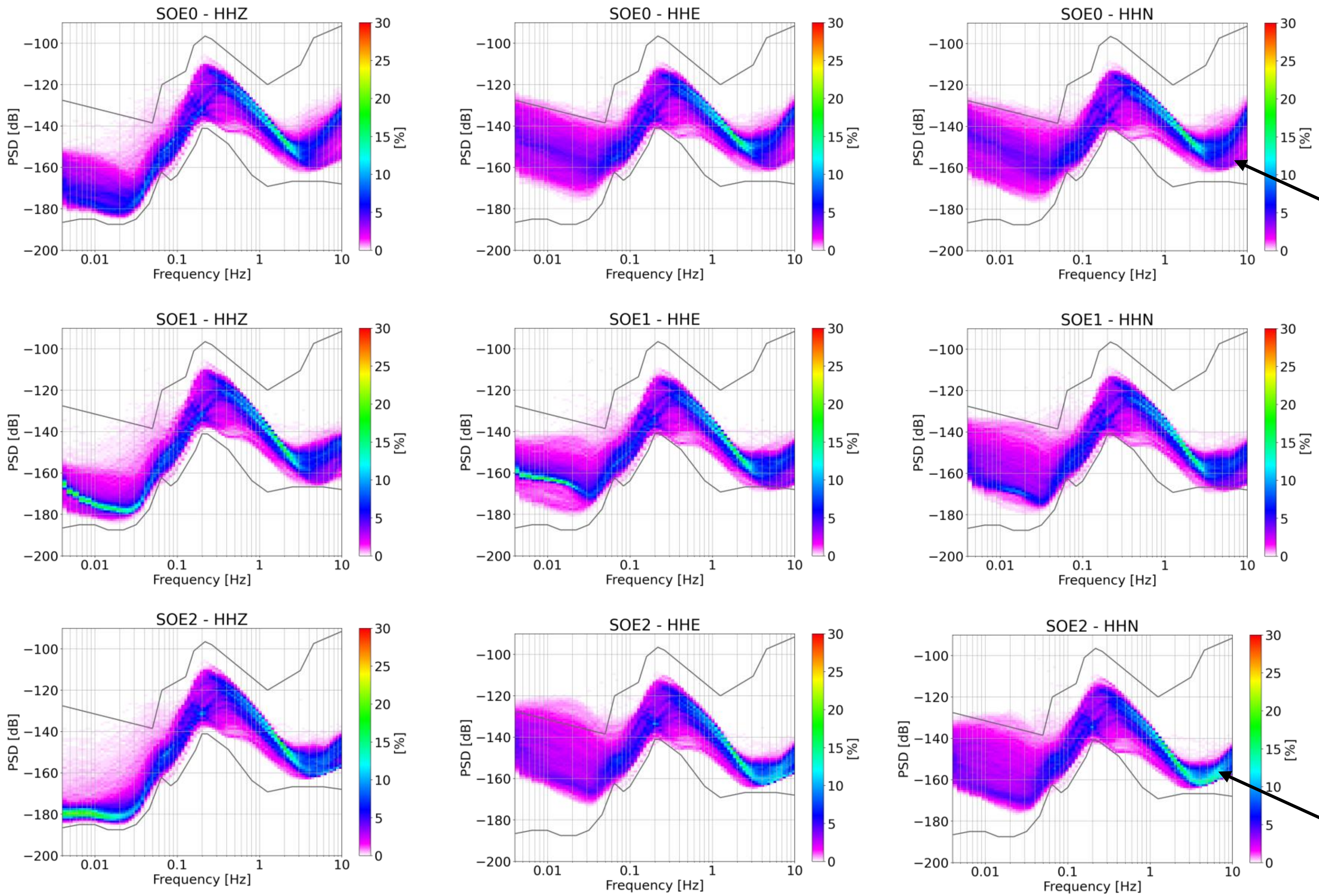
2021 data January-April

Vertical | Horizontal

SOE0 Surface

SOE1 -84m

SOE2 -111m



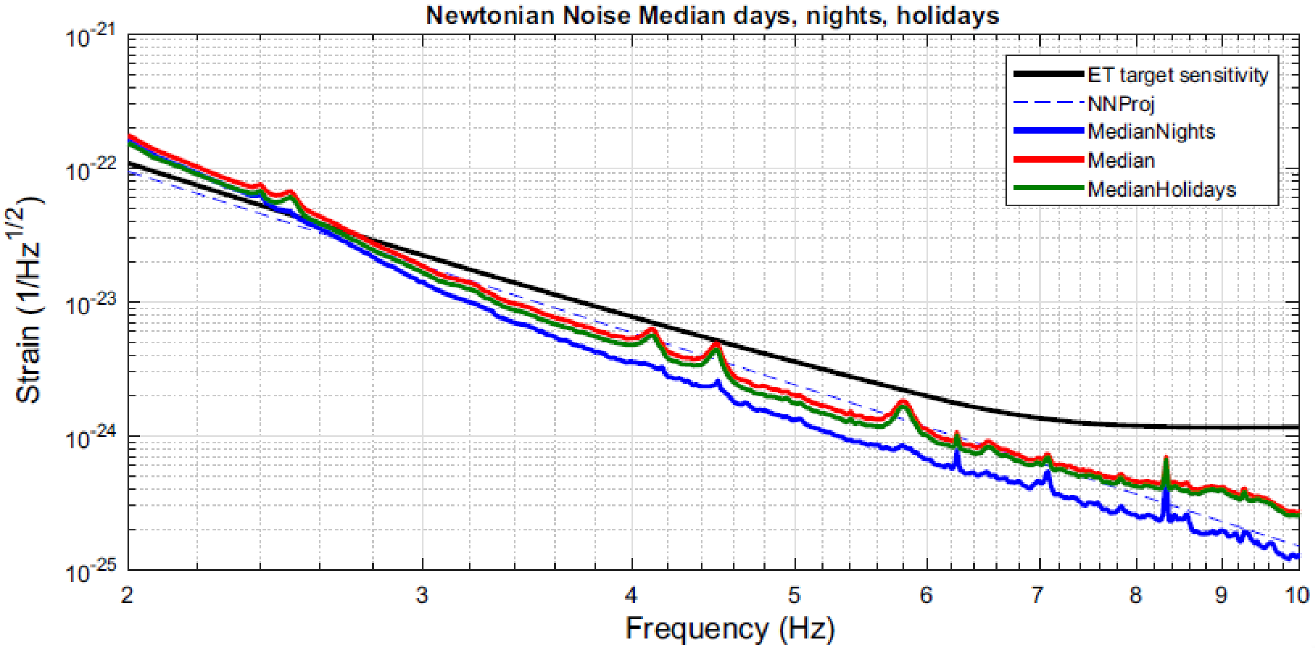
DAQ self-noise limit

DAQ self-noise limit

First results at Sos Enattos

Newtonian Noise & seismic glitches (based on 2020 data at SOE1)

Eur. Phys. J. Plus (2021) 136:511



Defining the Newtonian Noise ASD as:

$$\tilde{h}_{NN}(f) = \frac{4\pi}{3} G\rho_0 \frac{2\sqrt{2}}{L} \frac{1}{(2\pi f)^2} \tilde{x}(f)$$

Defining the Noise-to-Target Ratio of the Newtonian Noise in 1 minute window (~IMBH duration in ET band)

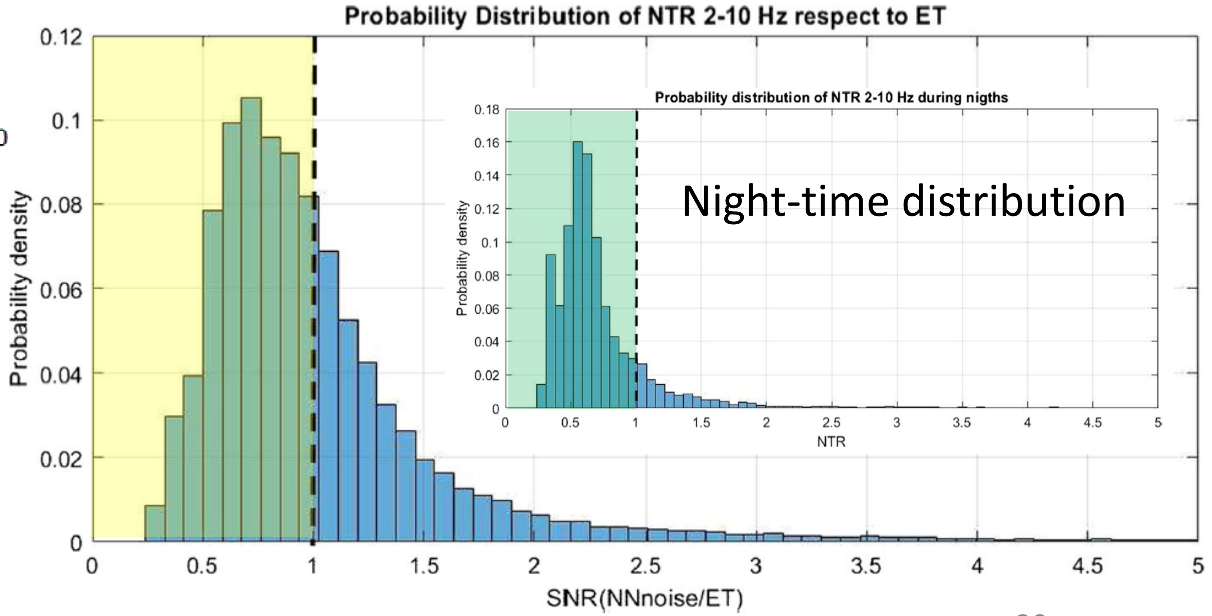
$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f} \int df \frac{\tilde{N} * \tilde{N}}{S_h}}$$

PSD of NN

PSD of ET sensitivity

P(NRT<1)=0.6 , considering only the nights: $P(NRT<1)_n$=0.86

→Need for moderate NN subtraction only for a limited time

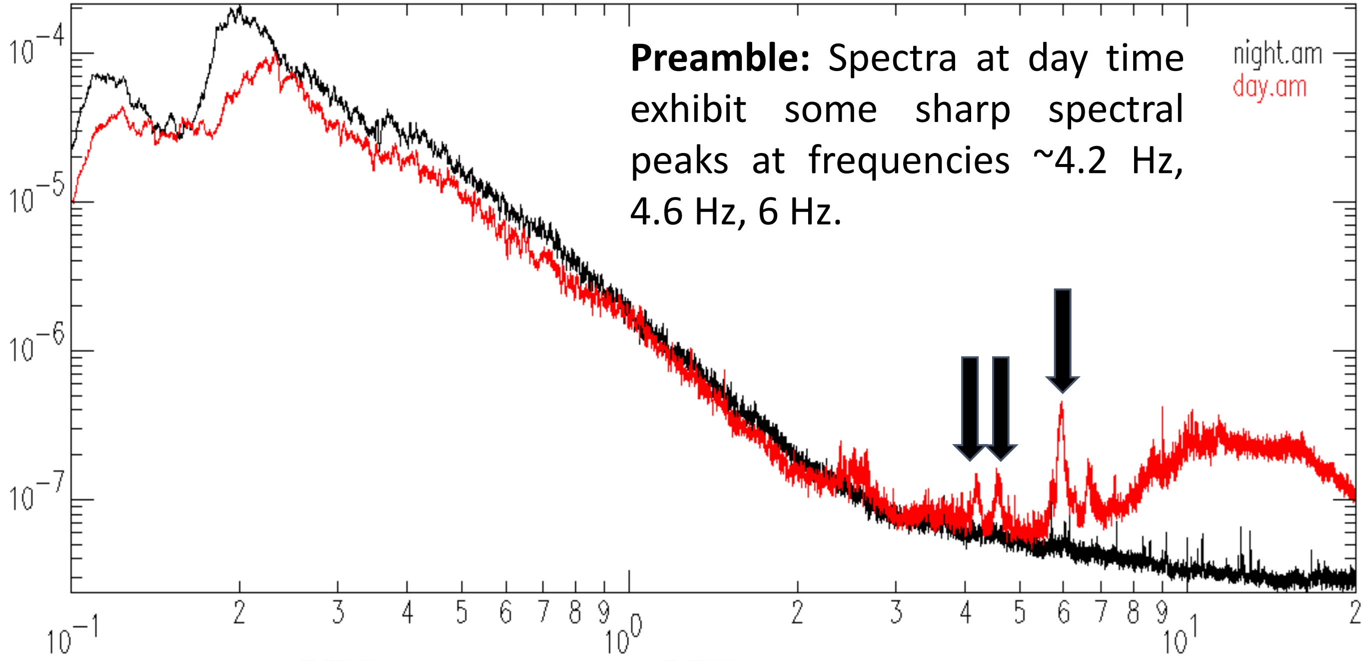


L. Naticchioni – GWADW21 – May 17th – 21st 2021

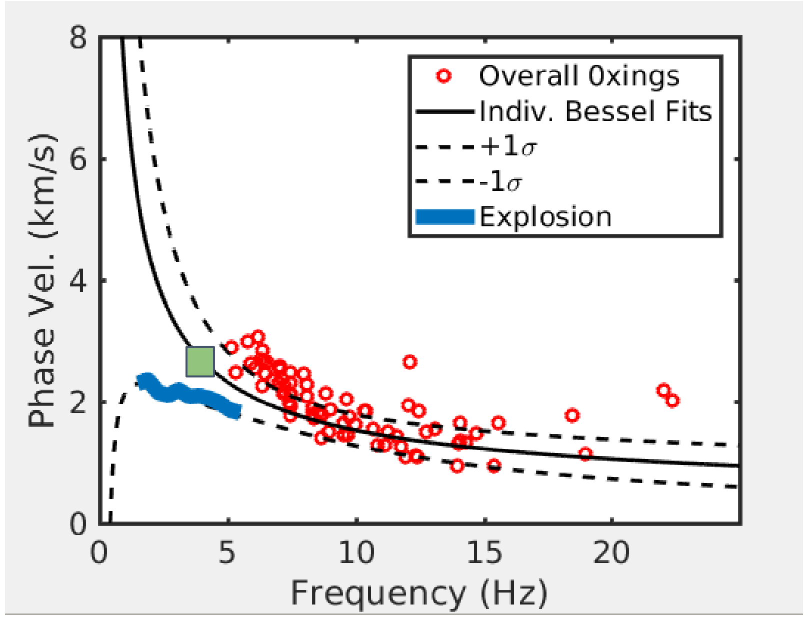
First results at Sos Enattos

Seismometer array results

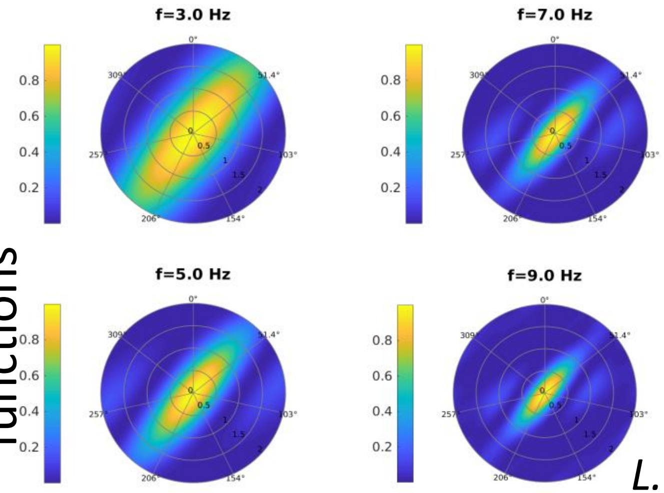
Array-stacked spectra:



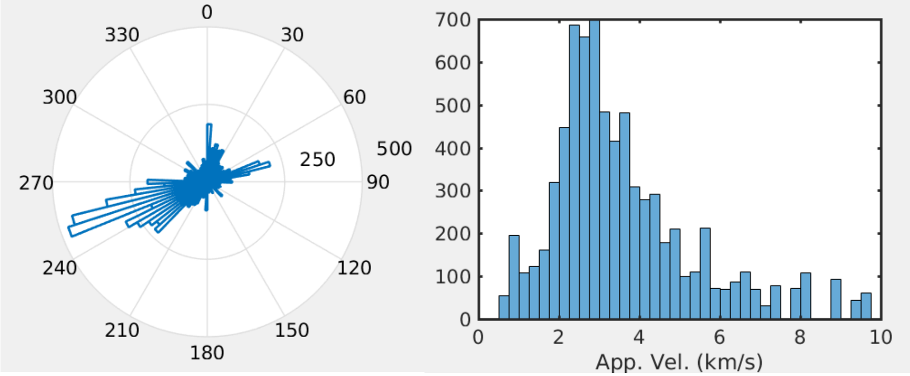
SPatial AutoCorrelation:



Array response functions



FK-Analysis

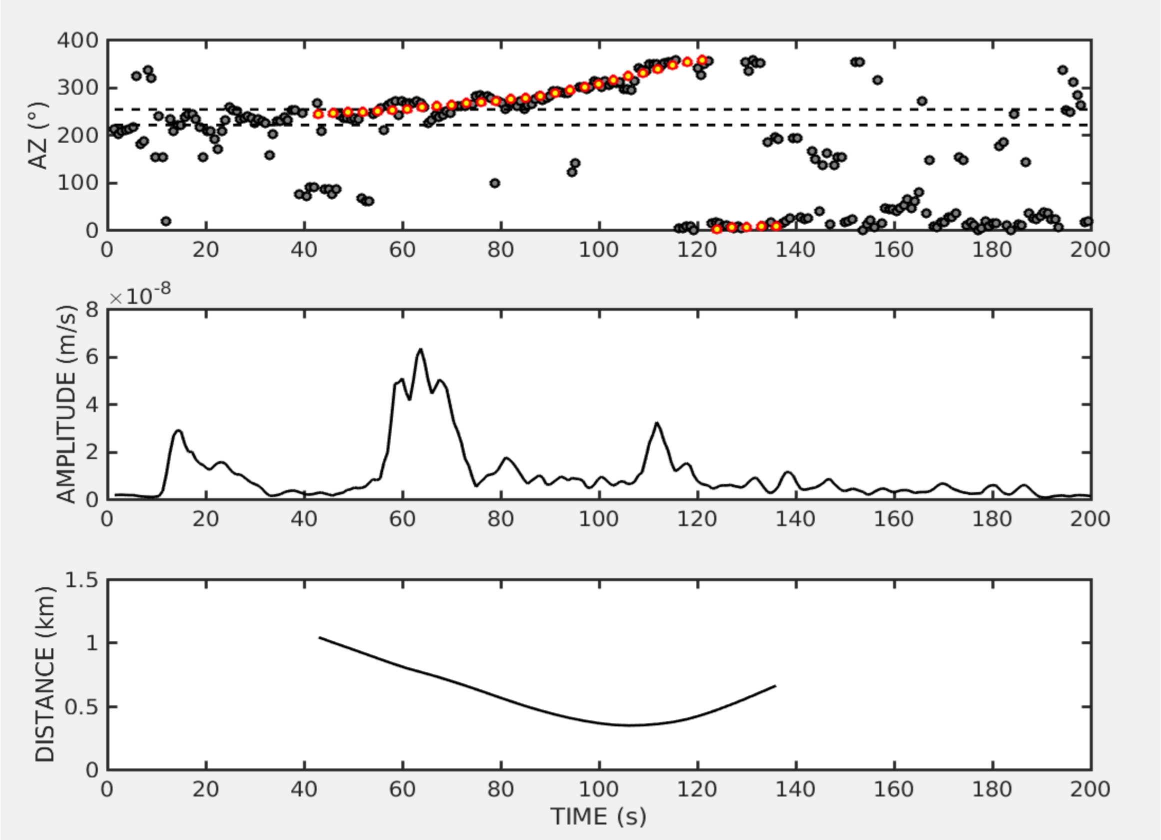


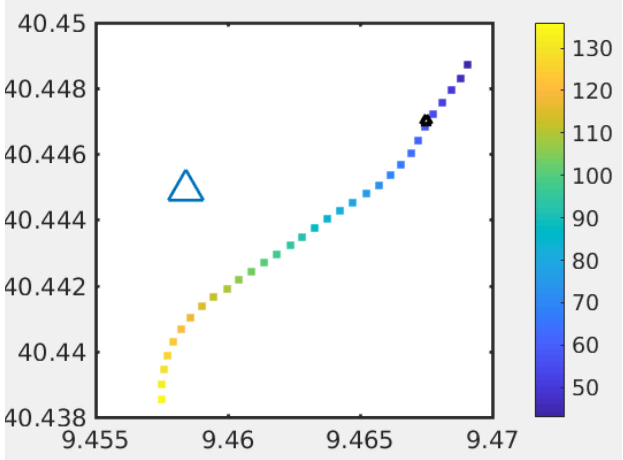
Not-isotropic wavefield
Peaks at f = 4-5 Hz
Propagation azimuths directed WSW (i.e., main sources located ENE of the array)
High velocities (~2.5 km/s)

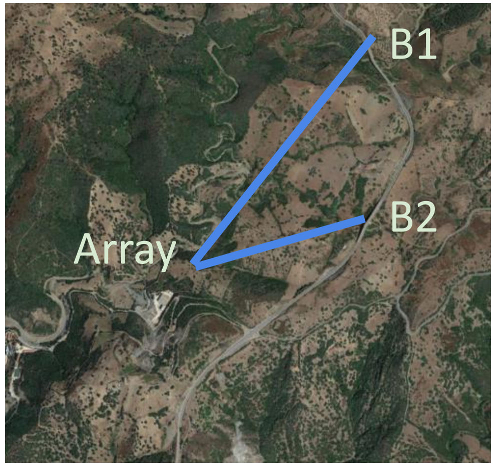
First results at Sos Enattos

Seismometer array results

Vehicle Tracking close to the site







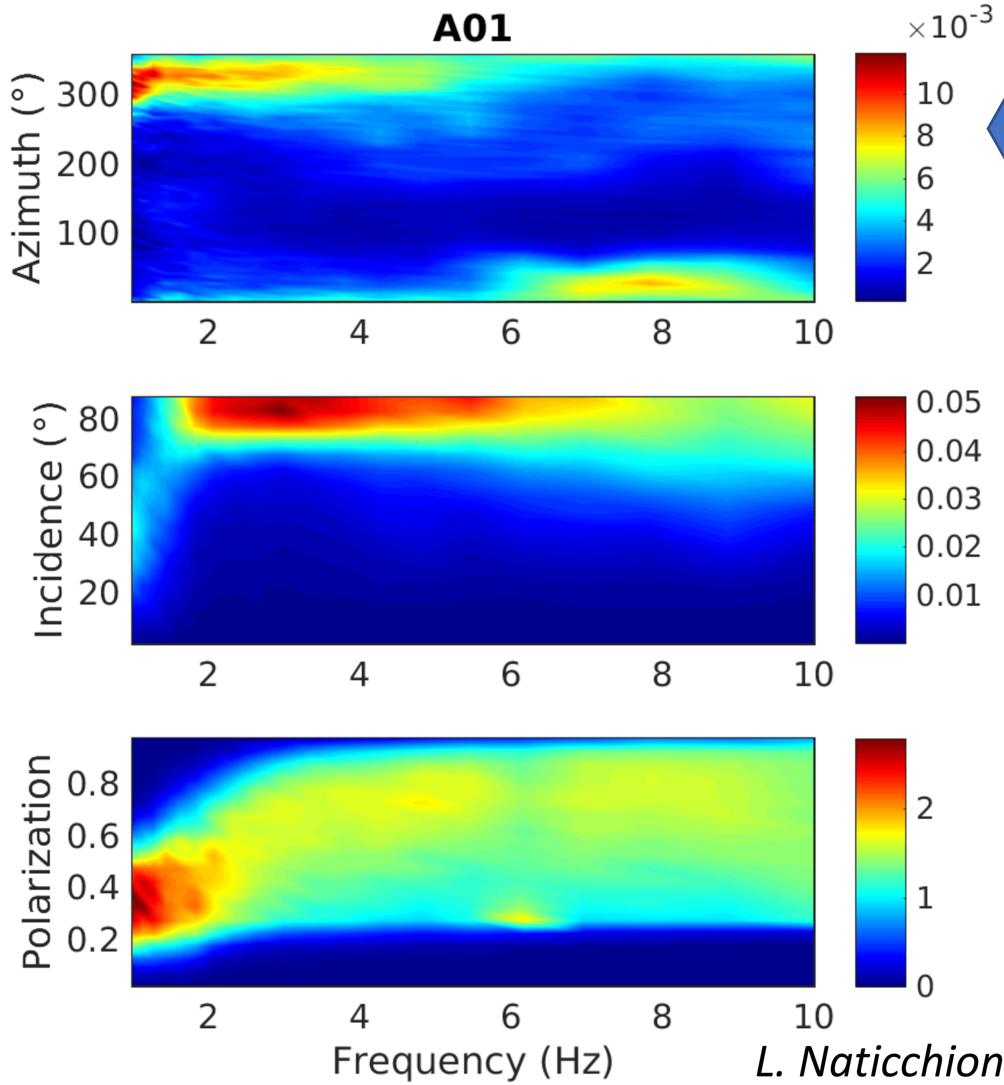
Time evolution of azimuth compatible with a vehicle traveling at 60 km/h southward along road SP73.

Largest signal amplitude is NOT associated when the vehicle is closest to the array, but when it traverses bridge B2

First results at Sos Enattos

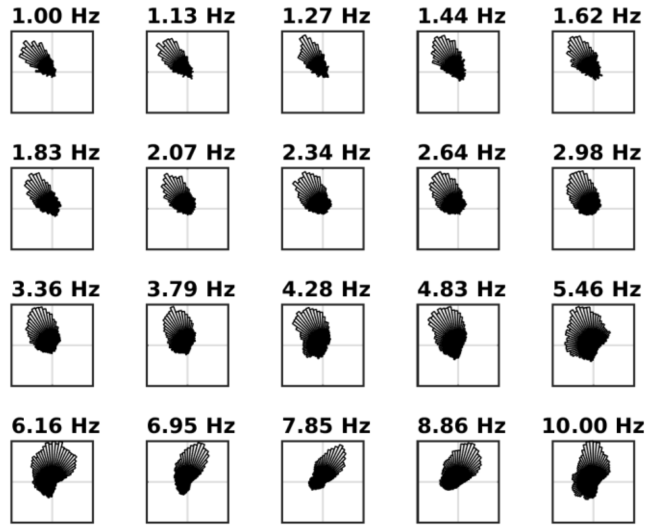
Seismometer array results

Polarization analysis



Probability density of particle motion Azimuth, Incidence Angle and Degree of Polarization as a function of frequency.

Polarization angle [0°- 180°]: the ellipsoid dips to East.
Polarization angle [180°- 360°]: the ellipsoid dips to West.

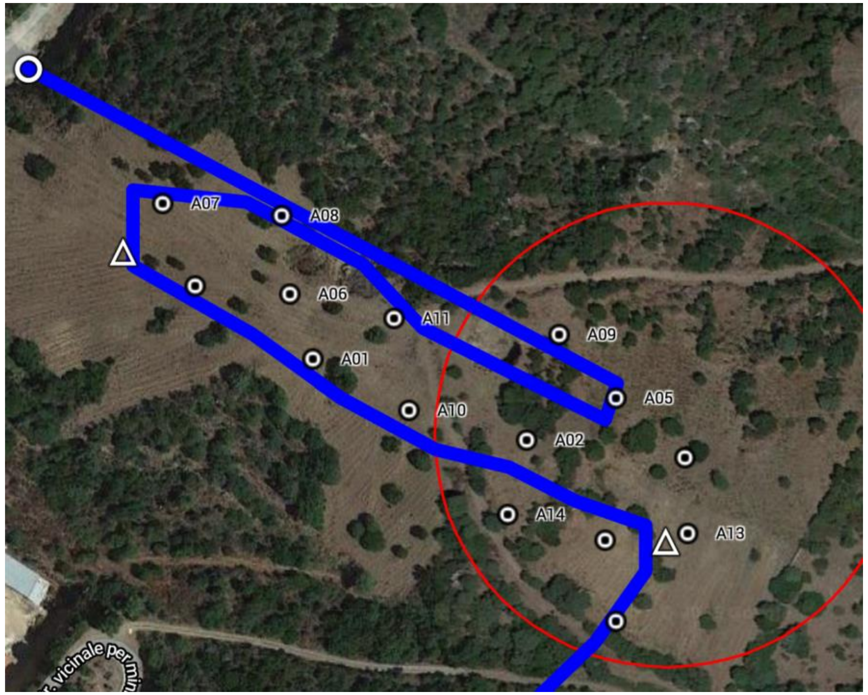


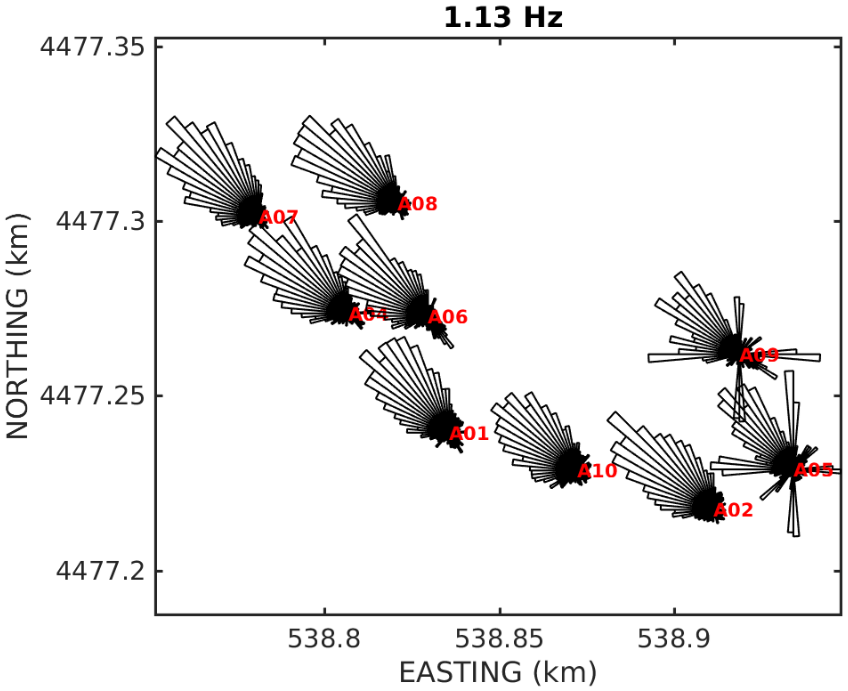
First results at Sos Enattos

Seismometer array results

Polarization analysis

At low frequencies, the polarization directions are rather uniform; they are oriented toward NW (see marine microseismic source).



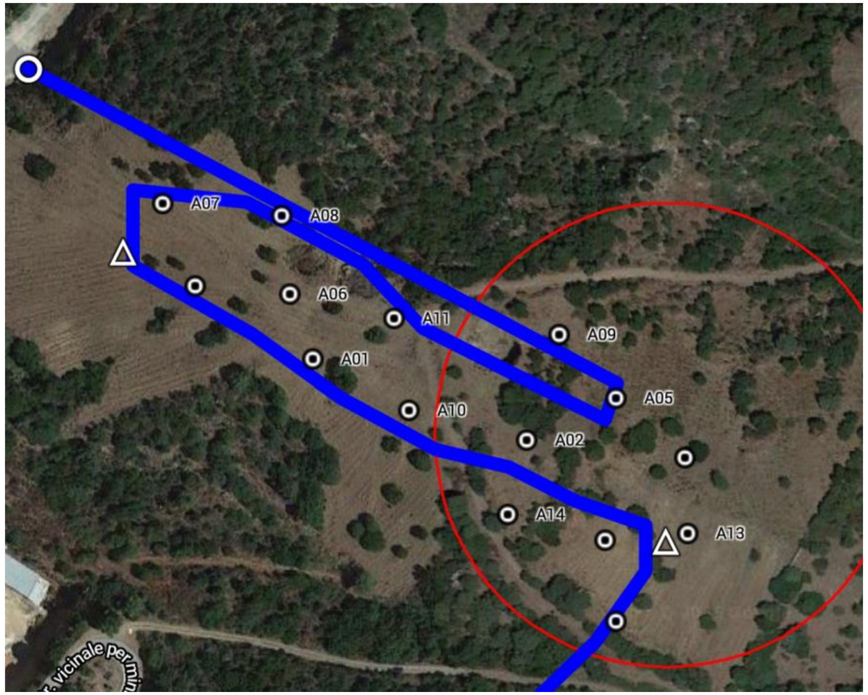


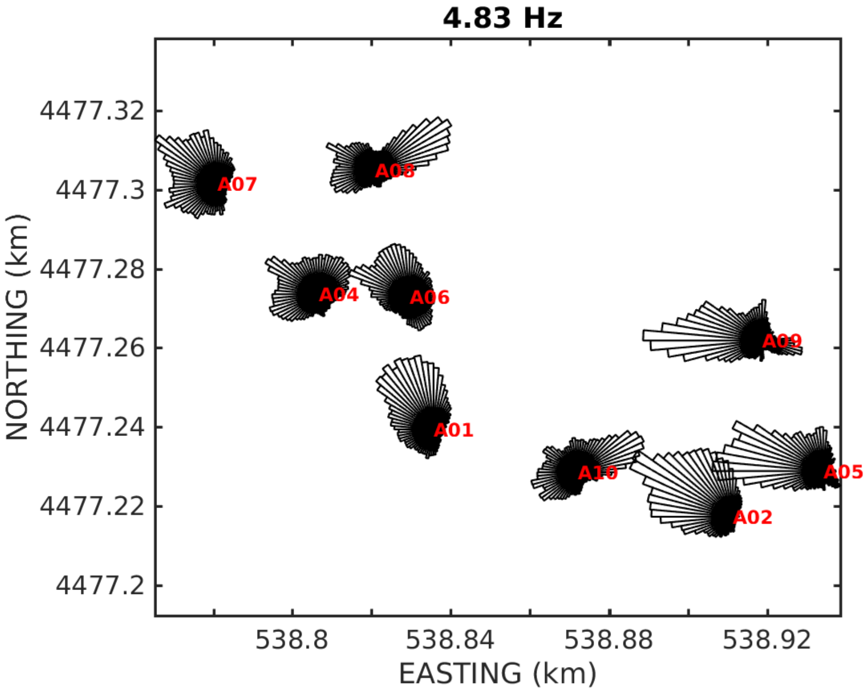
First results at Sos Enattos

Seismometer array results

Polarization analysis

At higher frequencies, the variability of polarization directions throughout the array deployment indicates a strong influence of topography.





First results at Sos Enattos

Very low electromagnetic noise observed at the site!

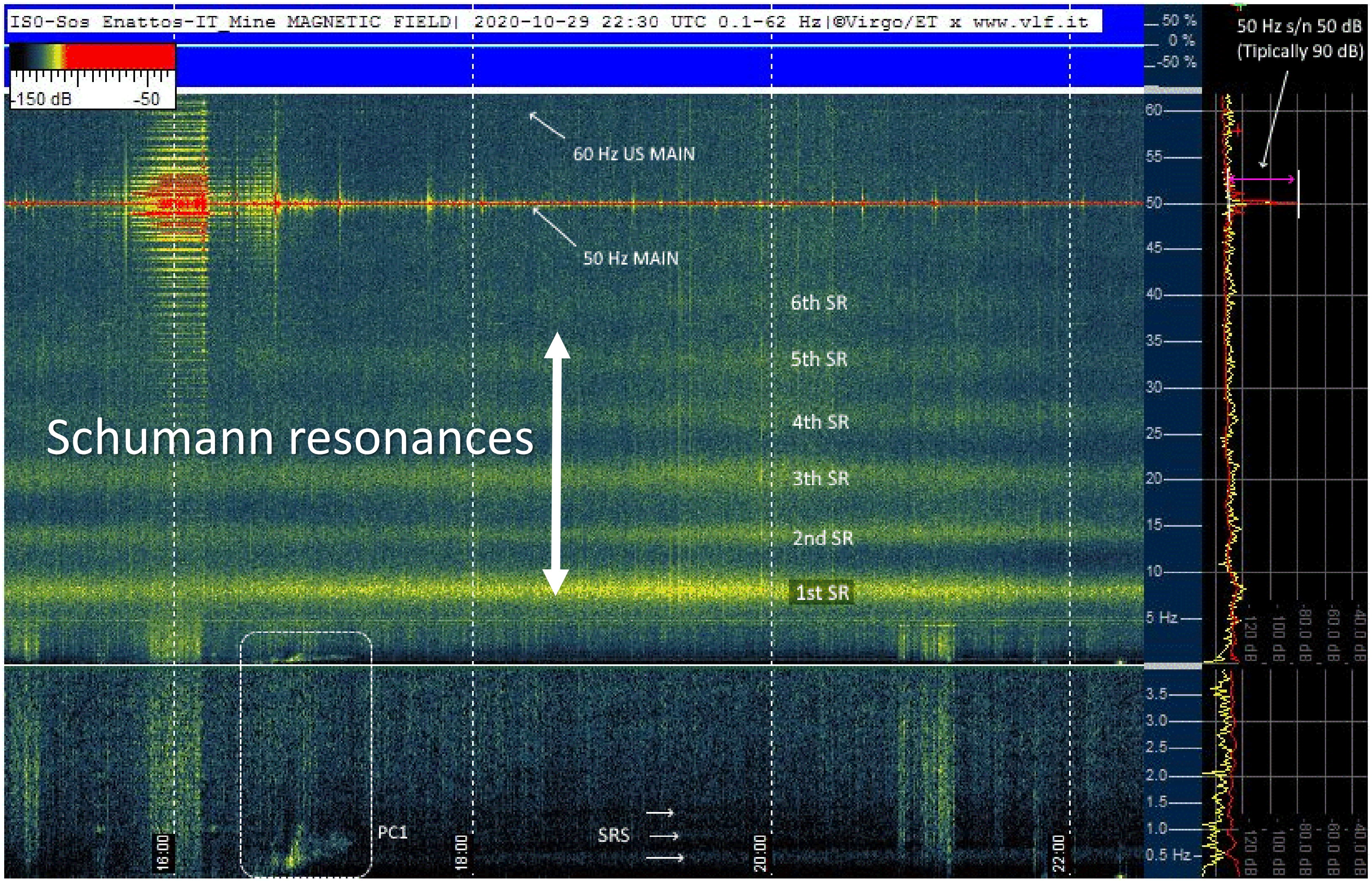


Image credit: R. Romero

SOE2 (underground) magnetometer.

Summary

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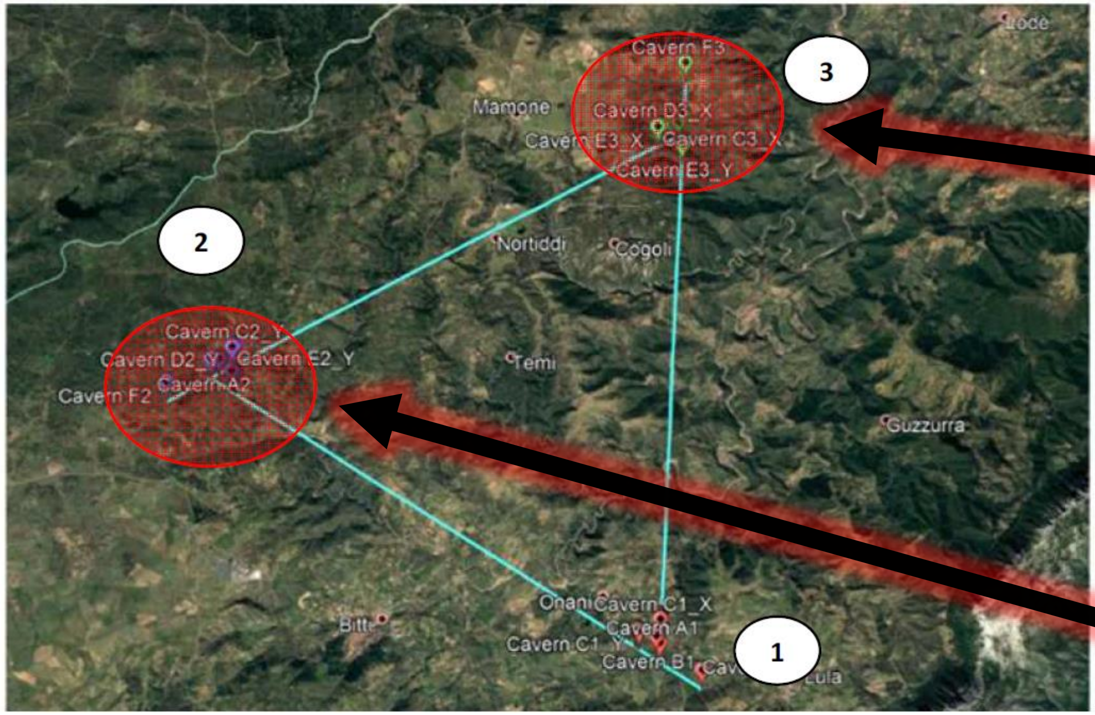
- ❑ Characterisation of the Sos Enattos corner
- ❑ First 2-years results at Sos Enattos
- ❑ **Characterisation of the other two corners**
- ❑ Conclusions

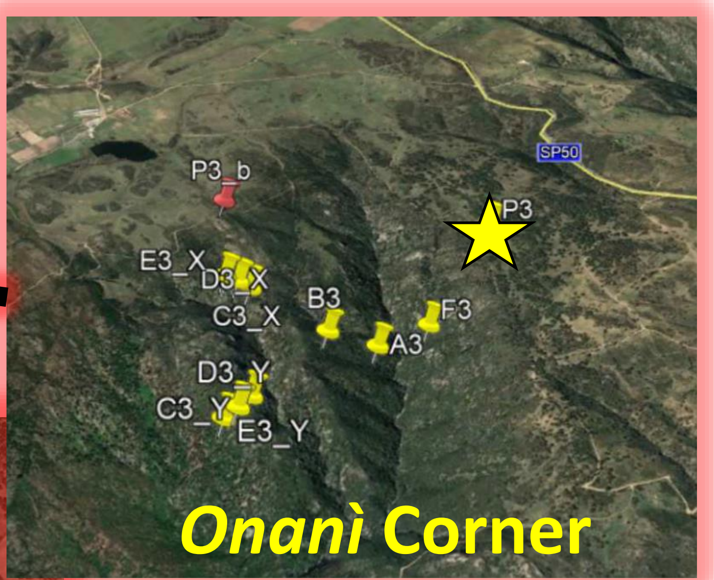
Characterisation of the corners

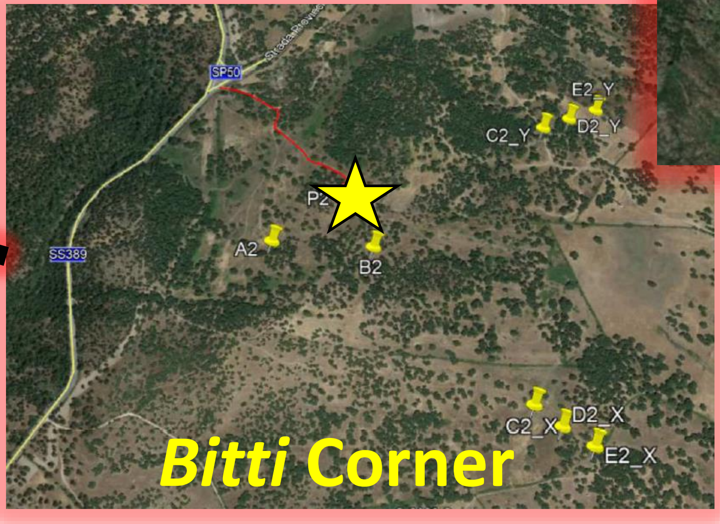
Surface and underground seismic and environmental measurements will start soon at the other two corners (named *Bitti* and *Onanì*).



***Lula* Corner**

Sos Enattos





★ : area for boreholes and surface arrays

: proposed locations for ET main caverns

Characterisation of the corners

Bitti corner,
borehole area

Onanì corner,
borehole area

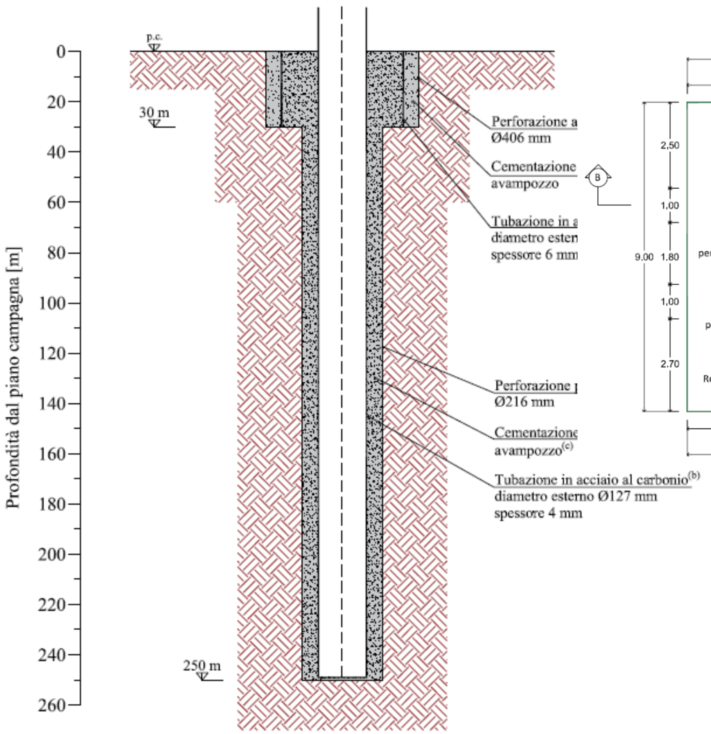
Characterisation of the corners

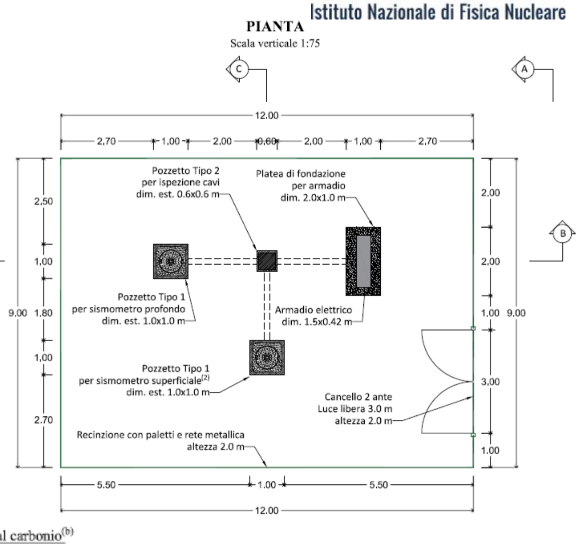
290m-deep boreholes at the two corners (P2,P3):

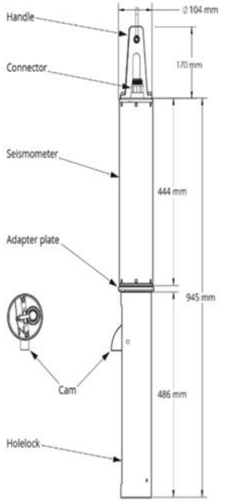
- **Excavation started at the Onanì corner. Boreholes will be completed by this summer**;
- Borehole sensor: *Nanometrics Trillium 120 BH Slim*;
- Surface sensor: *Nanometrics Trillium 120 Horizon*;

Surface measurements at P2, P3:

- **Active seismic**: vibroseis truck + seismometer array + opt fiber strainmeter;
- **Passive seismic**: 2-weeks long surface seismometer array (10x T20, 40x geophones + opt fiber strainmeter);
- **Environmental:** magnetometer and microphones;
- **Georesistivimetric** (groundwater) survey of the surrounding area.







Characterisation of the corners

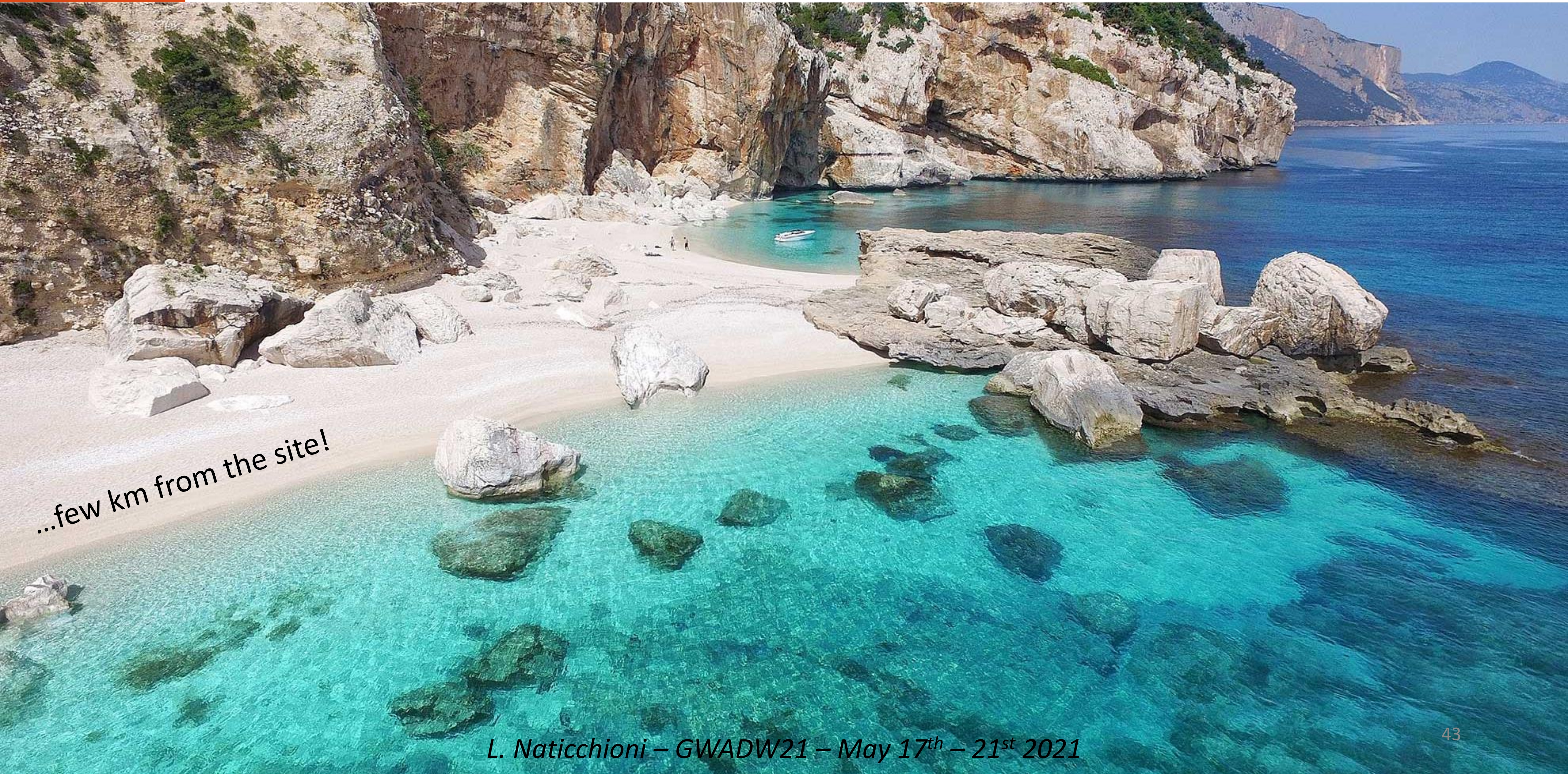
First borehole excavation started in P3 (Onanì corner) on April 27th

Conclusions

- **Long-term site characterisation is ongoing at the Sardinia site:** seismic and environmental monitoring at Sos Enattos, almost ready to start at the two corners (surface and boreholes);
- **Sinergy with SarGrav Lab activities;**
- **Public data (SOE2/SENA) + ET Repository (full data + analysis routines);**
- **First results: the seismic noise is very low** (close to NLNM), even at surface, due to no involvement in active tectonics (→low crustal velocity and crustal deformation) and to low population density (→low anthropic noise for $f > 1Hz$, at few Hz one of the quietest sites in the world);
- **Low environmental noise:** EM noise in underground stations is extremely low;
- **Good geomechanical properties of rocks, few groundwater, easy access** from existing airports/highway….

The Sos Enattos area is an optimal site for the Einstein Telescope!

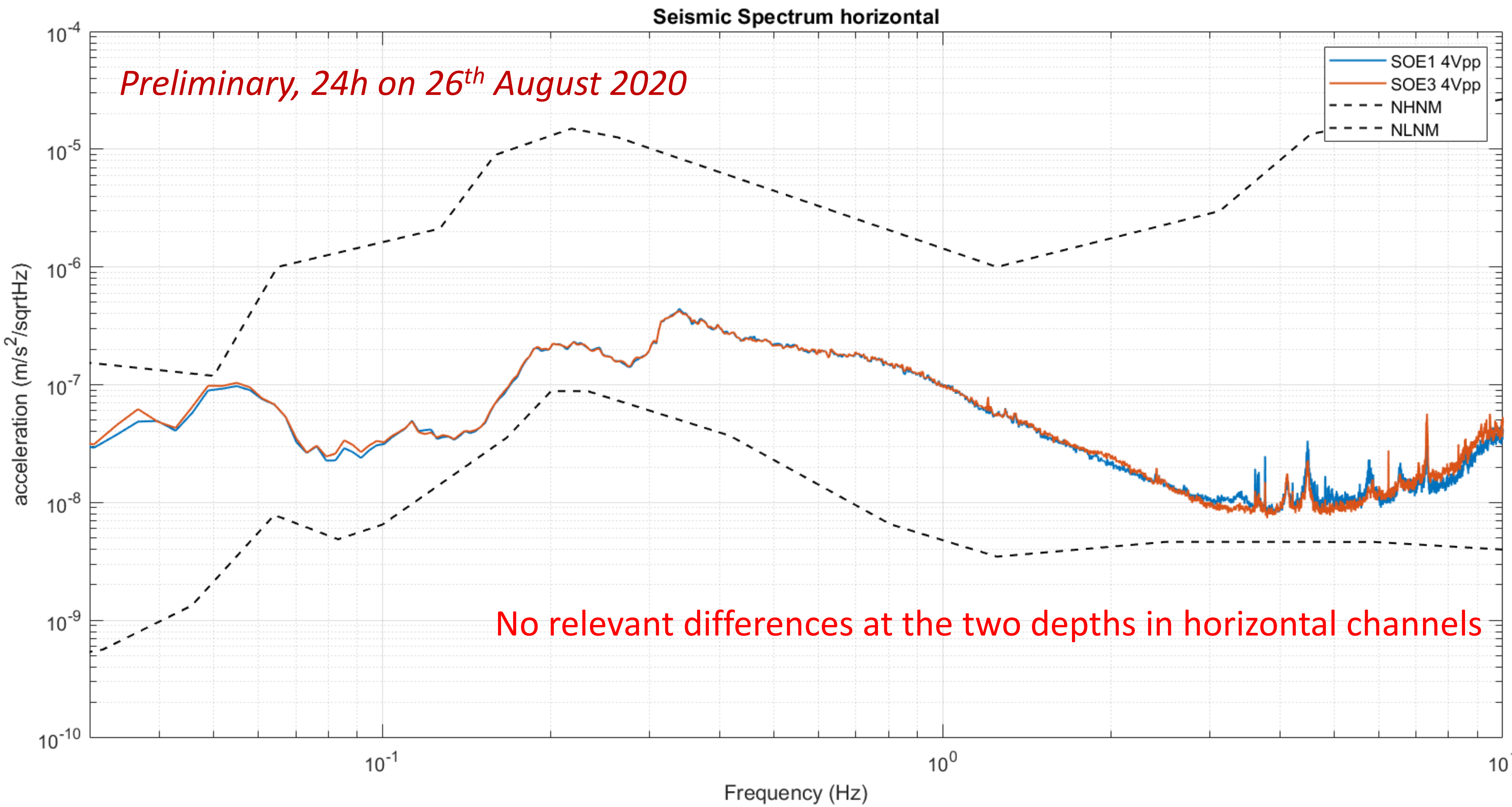
Thank you for your attention!



BACKUP SLIDES

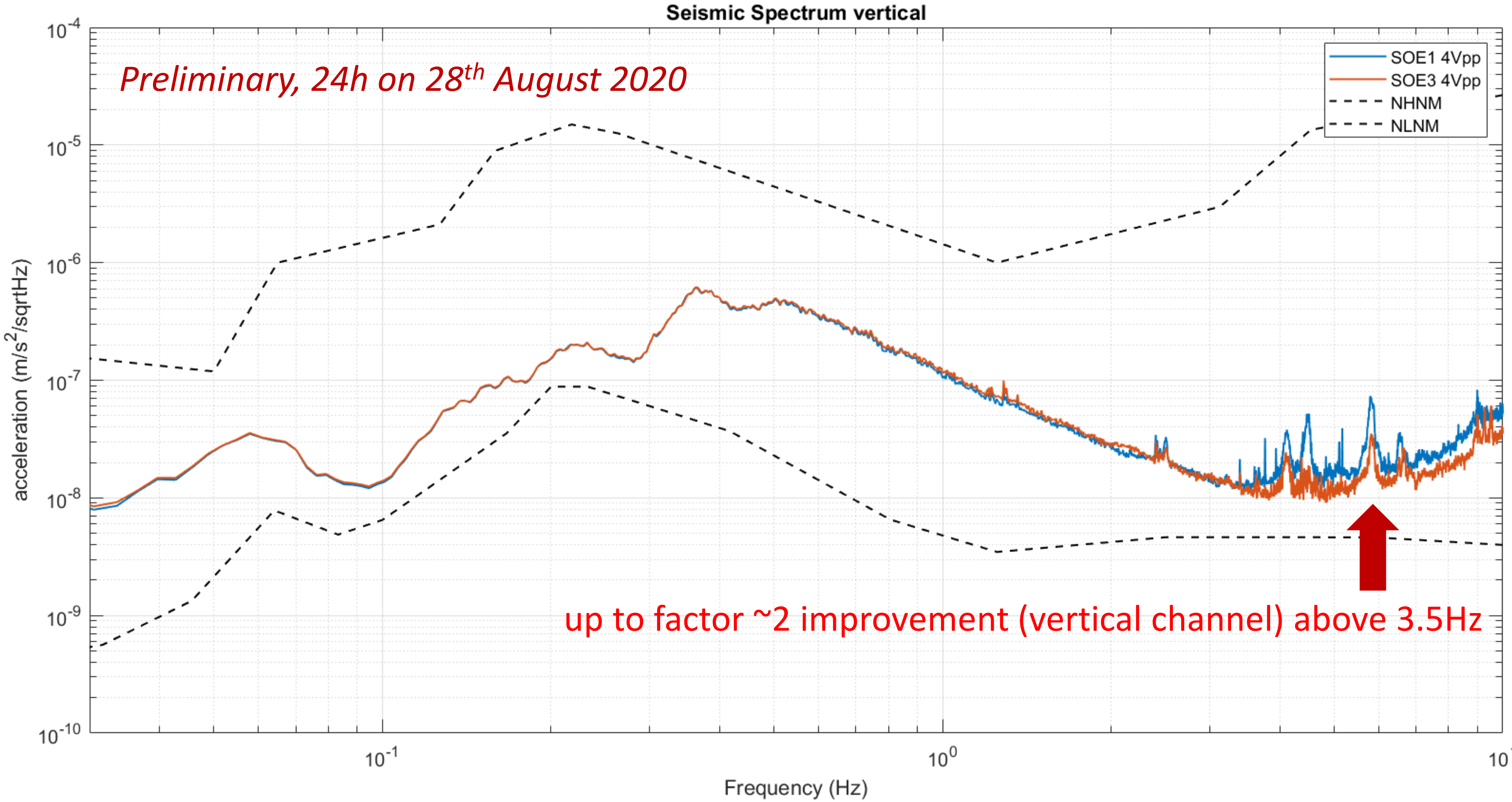
Sos Enattos site characterisation

SOE3 station (-160m) vs SOE1 station (-84m)



Sos Enattos site characterisation

SOE3 station (-160m) vs SOE1 station (-84m)

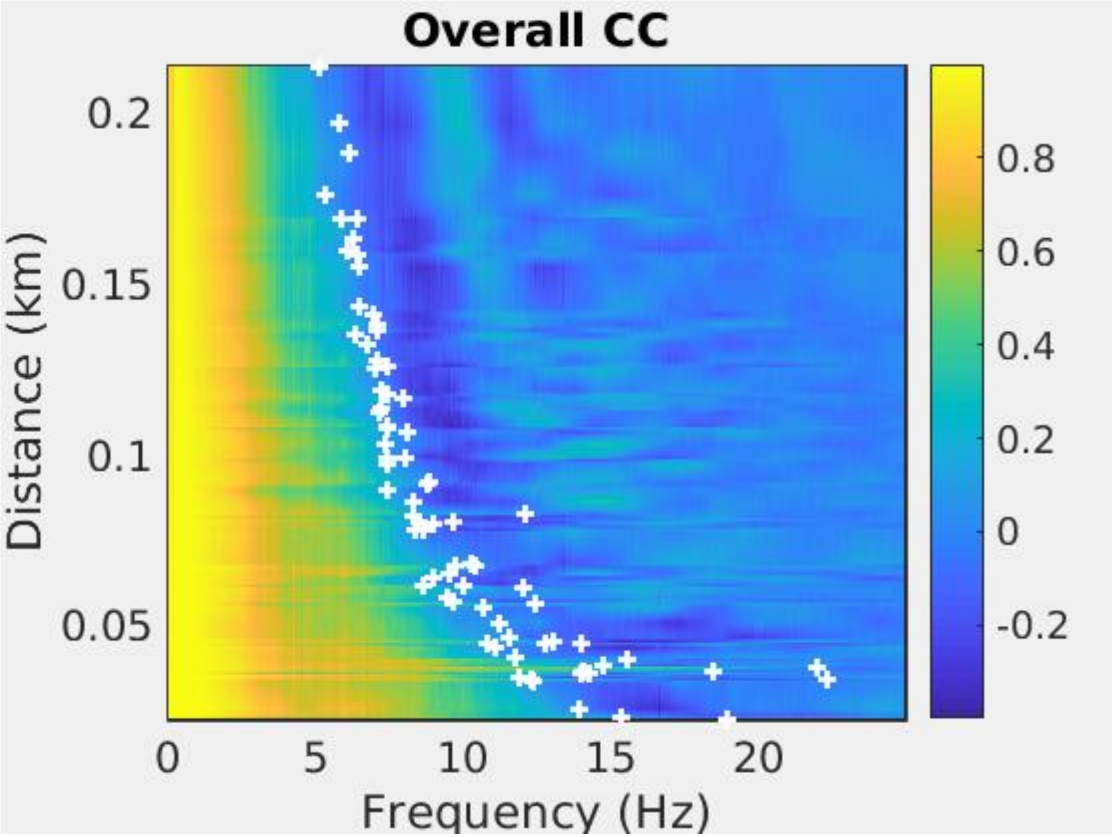


Sos Enattos site characterisation

ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

Credit: G. Saccorotti

SPatial **A**uto**C**orrelation - I



Under the hypothesis that the noise wavefield is **stochastic** and **stationary in time and space**, the relationship between spatial autocorrelation and phase velocity is:

$$C(f,r) = J_0\,(2\,\pi\,r\,f\,/\,c(f))$$

SPAC is derived at all the independent station pairs over the DC-25Hz frequency band.

Form the 1st zero-crossing, we derive c(f)

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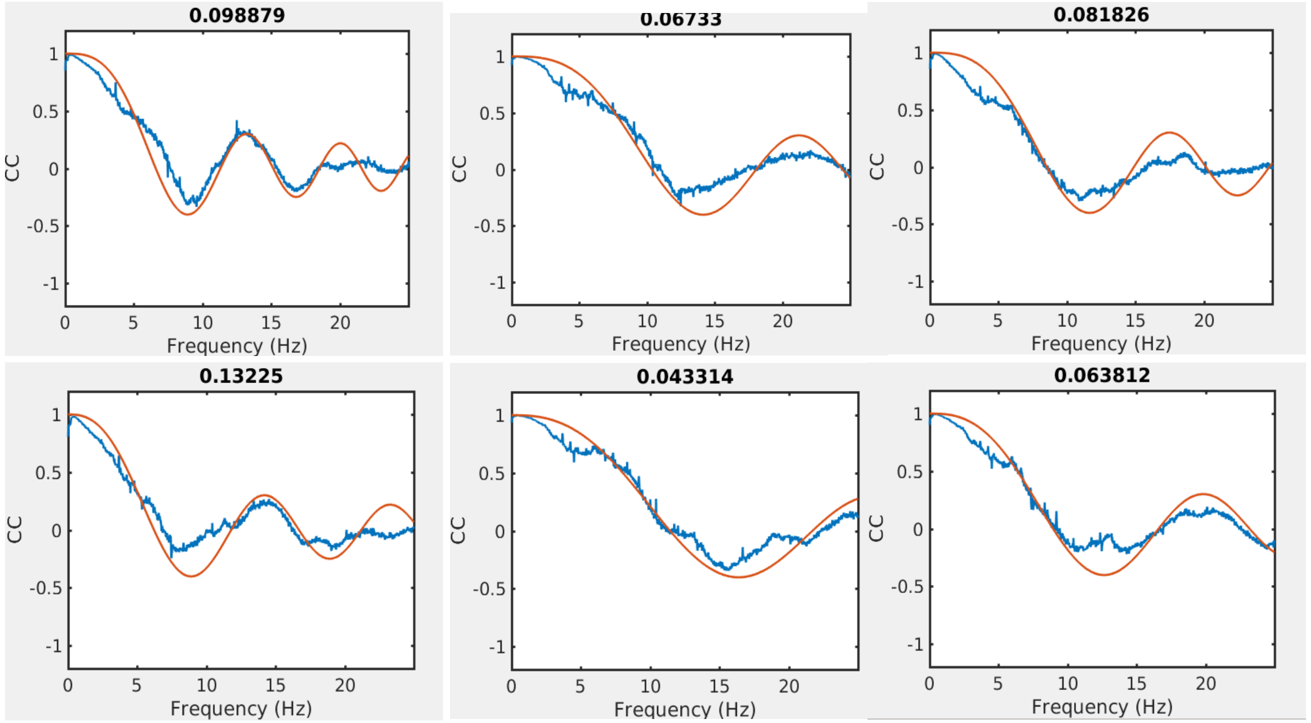
SPatial **A**uto**C**orrelation - II



Dispersion curves for individual CCs.

Red lines are the Bessel fits assuming dispersion follows a power law in the form:

$c(f)=A\, f^{-b}$

Sos Enattos site characterisation

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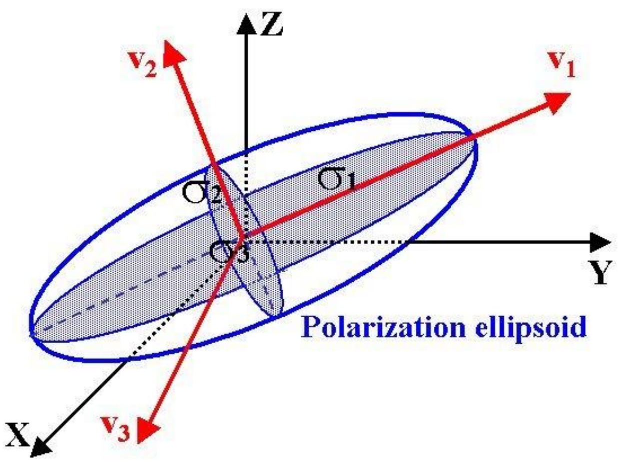
Polarization Analysis - I

Credit: G. Saccorotti

Recap: Seismometers record the 3 components (EW,NS,Up-Down) of ground motion.

Polarization Attributes are derived from the eigen-structure of the 3x3 covariance matrix evaluated over a given time frame.



The eigenstructure of the covariance matrix defines the axes of the polarization ellipsoid best fitting the 3C particle motion.

The amplitude of the **main eigenvalue** relative to the secondary ones defines the Degree of Polarization (or *rectilinearity*).

The eigenvector associated with the main eigenvalue defines the *polarization azimuth* (° from N) and *incidence angle* (° from the normal to the Earth's surface).

Sos Enattos site characterisation

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Polarization Analysis - II

Credit: G. Saccorotti

Polarization Analysis is conducted over subsequent time frames sliding along the 3C recordings, with 50% overlap.

The analysis is repeated over 20, log-spaced frequencies spanning the 1-10 Hz frequency interval. For each frequency, the signal is band-pass filtered using a 2-poles Butterworth filter with a bandwidth of 0.5 Hz.

The length of the time window for covariance estimates is set equal to 4 times the period associated with the lower frequency corner of the filter (e.g., if fmin=2 Hz, wlen=2s).

Polarization results are then filtered according to an amplitude threshold T, given by:

$$T = \text{mean}(\log_{10}(L))+\text{std}(\log_{10}(L))$$

where L is the largest eigenvalue of the covariance matrix.