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Éric Beucler, Mickael Bonnin, E. Diego Mercerat, Nathalie Favretto-Cristini, Anne Deschamps, et al..
Analysis of Seismic, Hydroacoustic and Acoustic Waves Recorded on the Shoreline in the Vicinity of
Shallow Underwater Explosions. AGU Fall Meeting, Dec 2022, Chicago, United States. hal-03925839

HAL Id: hal-03925839

<https://hal.science/hal-03925839>

Submitted on 11 Jan 2023

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Analysis of Seismic, Hydroacoustic and Acoustic Waves Recorded on the Shoreline in the Vicinity of Shallow Underwater Explosions

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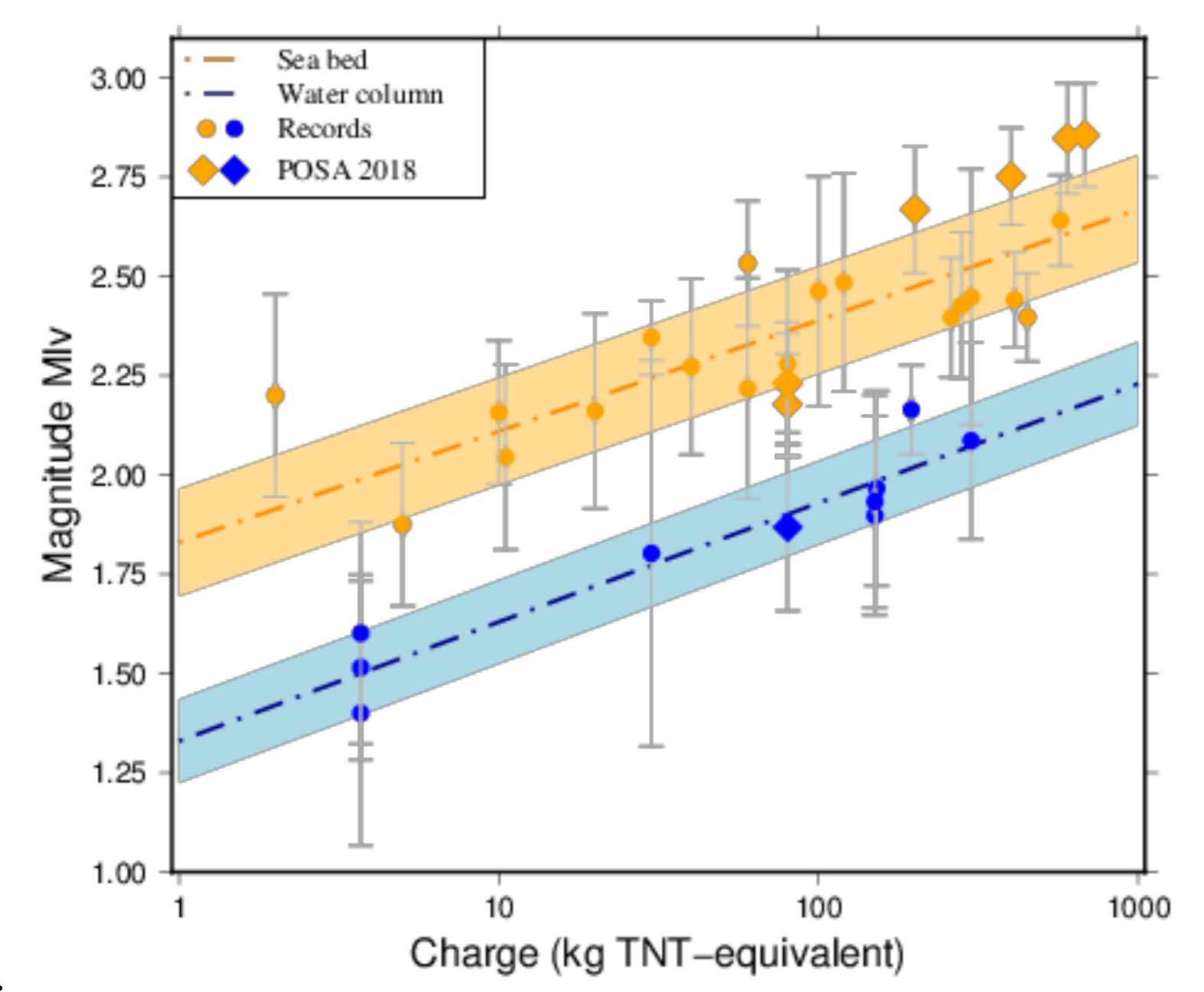
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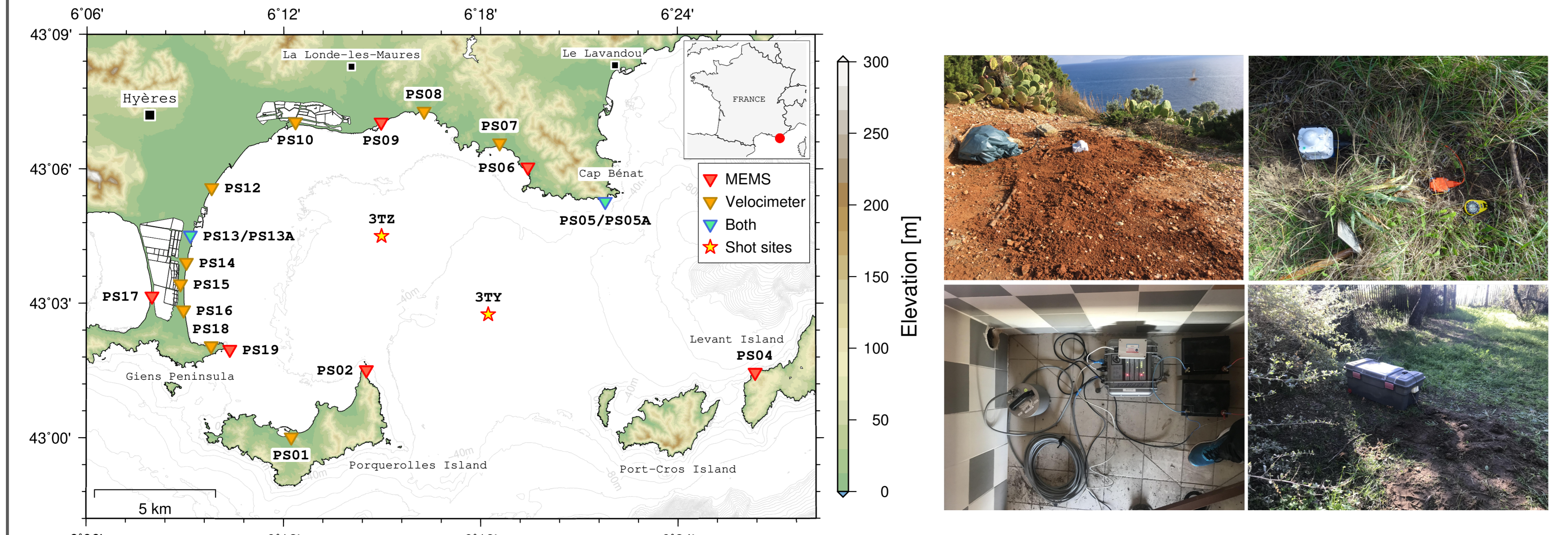
The French Navy Mine Warfare Office conducted a series of 8 calibrated underwater explosions in December 2018 in the Bay of Hyères, SE France. The charges were ranging from 80 to 680 kg TNT-equivalent weights and the generated mechanical waves have been recorded at 17 seismic stations (composed of velocimeters, accelerometers and/or Microelectromechanical system accelerometers) temporarily deployed within 10 km of the sources. The large sampling rate recordings (> 250 Hz) allow to clearly identify both seismic, hydroacoustic and acoustic waves on the shoreline. The hydroacoustic phases, mostly observed at the rocky sites, rapidly attenuate when propagating on land and seem to be conditioned by the bathymetry and the seabed sedimentary cover. The hydroacoustic onset times can be used very efficiently to infer explosion locations and origin times. The spectrum analyses and site response along the shore and inside a building (church) provide insights on the mitigation of the possible nuisance caused by the disposal of unexploded historical ordnance.

1. Introduction

The POSA project (étude de la Propagation des Ondes Sismiques d'origine Anthropique, 2015-2019) aimed to study the impact, inland, of the WWII unexploded ordnance (UXO) disposal operations of the French Navy along the French coasts. Several tens of UXO are detonated offshore every year to ensure the security of ships and divers. We performed two sets of experiments in 2016 and 2018 to derive magnitude to charge weight (kg TNT-equivalent) laws for the underwater explosions. We have obtained two laws (Favretto-Cristini *et al.*, 2022, see figure on the right): a law for UXO detonated on the sea bottom (orange in the figure) and another for UXO detonated in the water column (in floating barrels, blue in the figure). This study presents the analysis of the experiment conducted in December 2018 in the bay of Hyères, SE France, and, in particular on the high frequency signals recorded by 8 MEMS accelerometers. The 500 s.p.s. sampling rate configuration allowed us to observe hydroacoustic phases that bring interesting pieces of information for the mitigation of the UXO disposal nuisance inland and offshore.

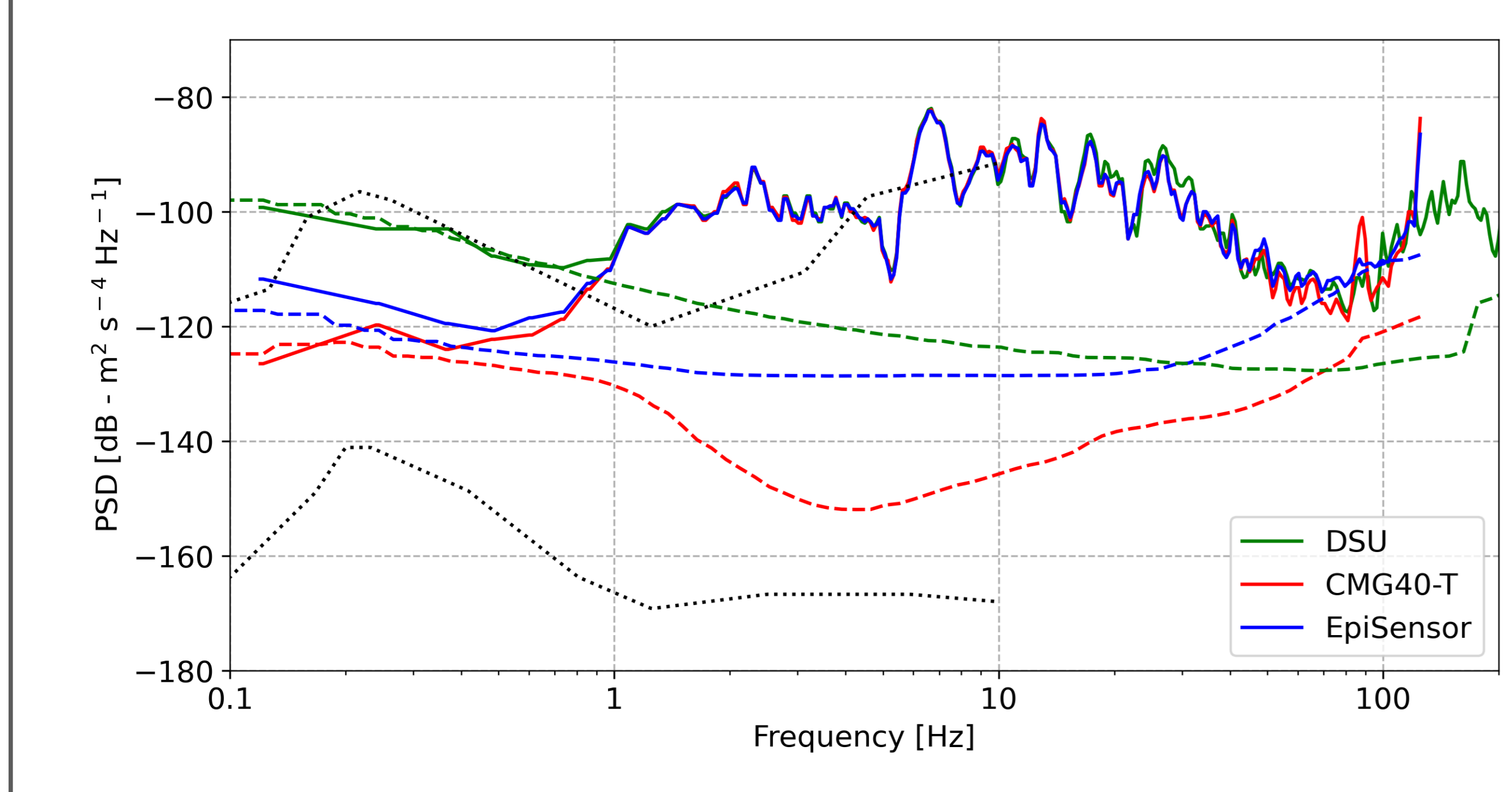


2. 2018 POSA experiment



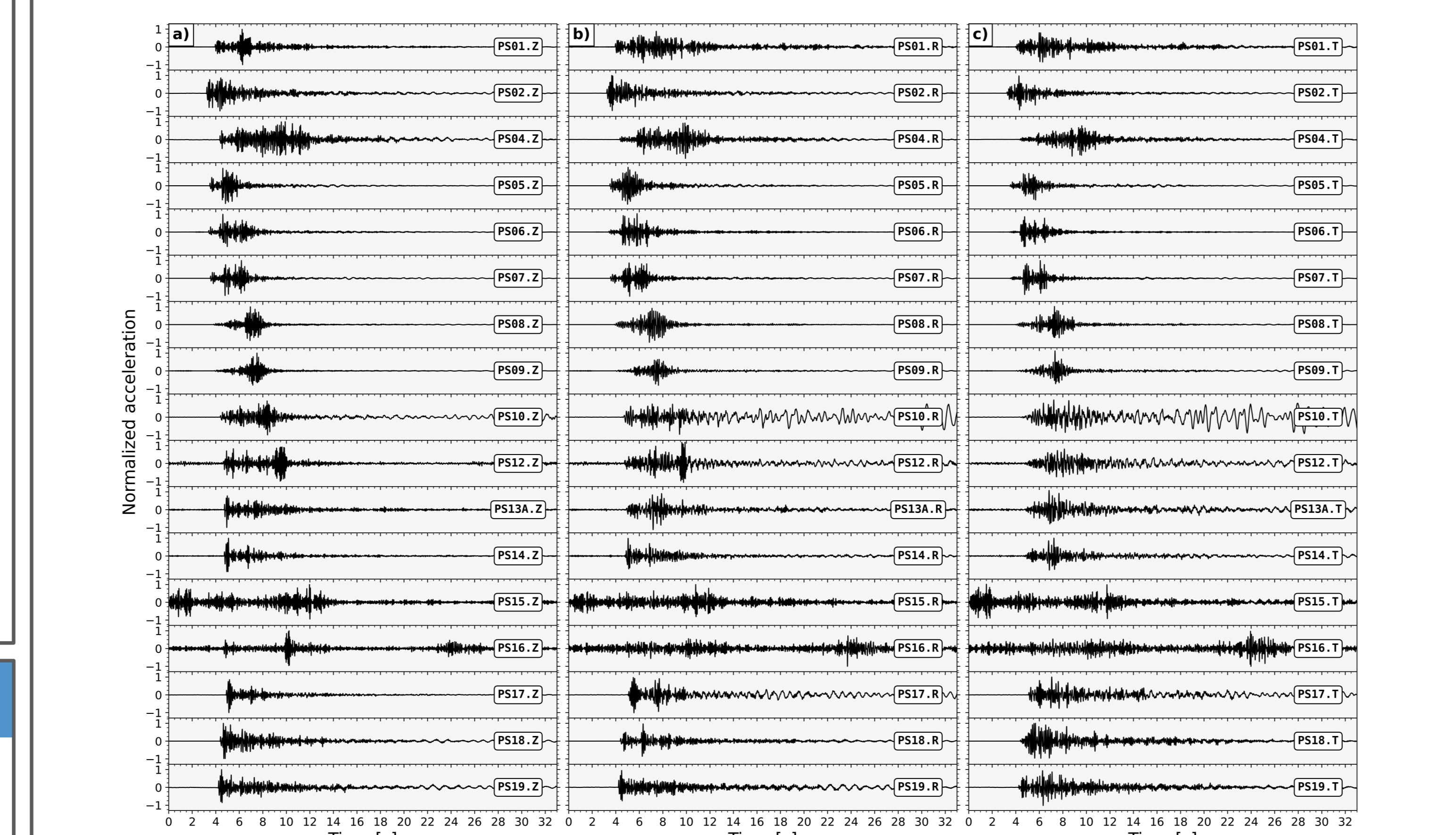
20 seismic sensors installed at 17 sites between December 11 and December 12 2018. 8 explosions triggered by the French Navy: 2 at the shot site 3TZ (S1 and S2) and 6 at the shot site 3TY. Charges loads were between 80 (S1, S2, S3 et S8) and 680 kg TNT-equiv. (S4). 7 shots occurred at the sea bottom (S1-S7) and the last one within the water column (S8). The experiment used 10 CMG40-T (250 s.p.s.), 1 ES-T (250 s.p.s.) and 8 Sercel DSU-428 MEMS accelerometers (500 s.p.s.).

3. Characterisation of the MEMS sensors

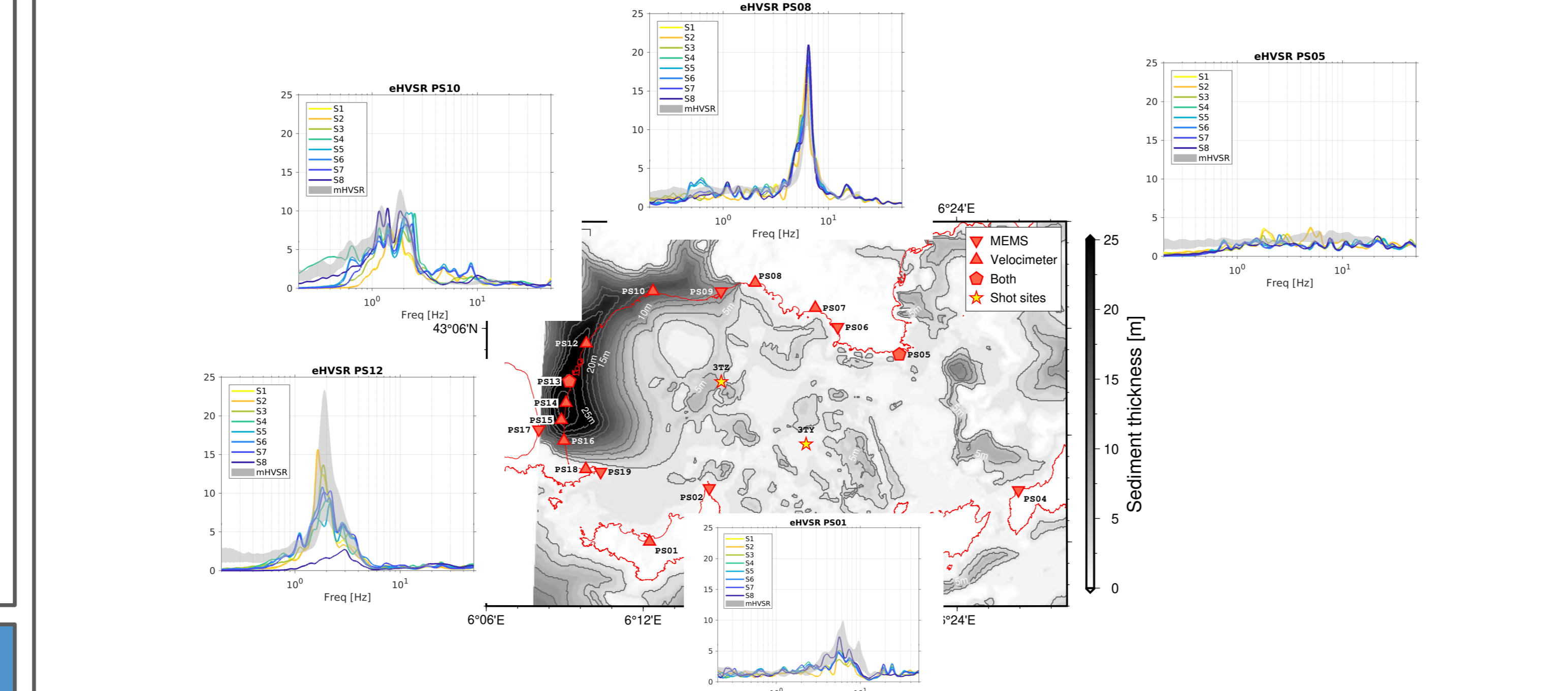


The POSA 2018 experiment was our first use of the SerCel DSU sensors. To estimate the performance of this sensor, we installed at the site PS05 a CMG40-T, an ES-T and a DSU. The figure on the left shows PSD computed on the continuous signal during the night of December 12 (dotted curves) and for shot S3 (80 kg TNT-equiv., solid curves). Though the self-noise of the DSU is high, the figure demonstrates that the DSU outperforms the ES-T above 20Hz for the signal of the explosion. In general the three sensors return coherent PSD between 1 and 20Hz

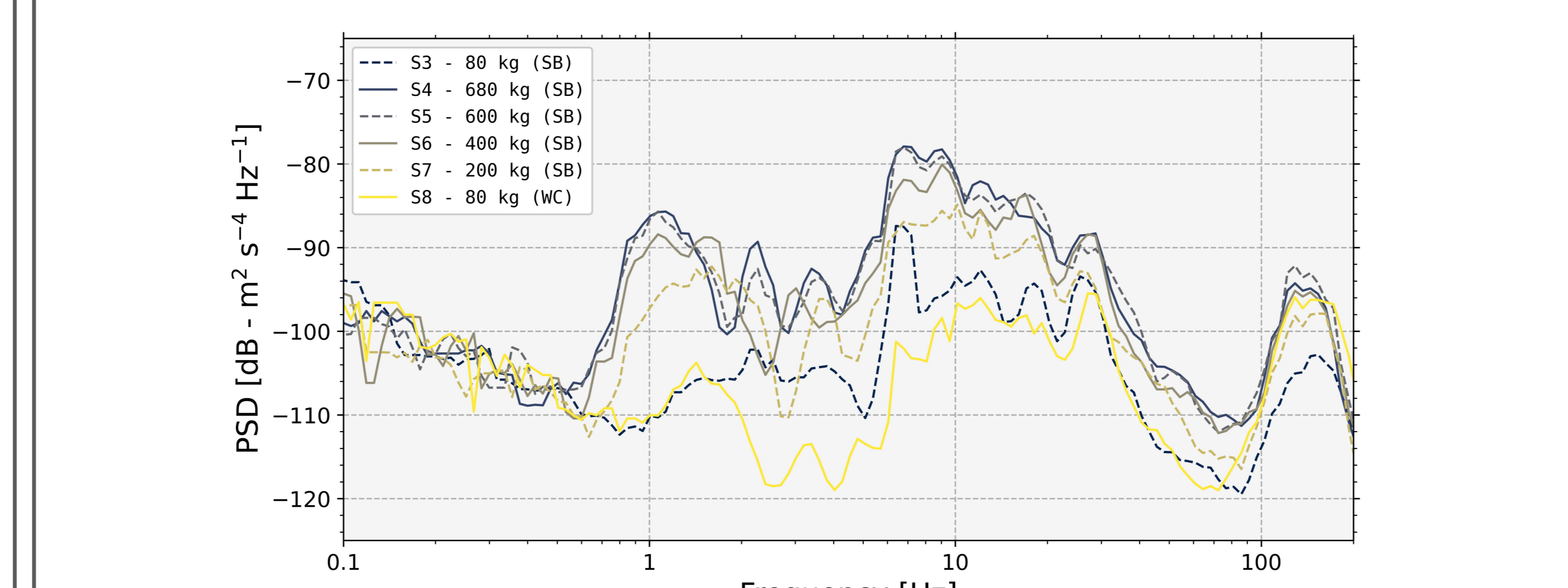
4. Seismic amplitude variability



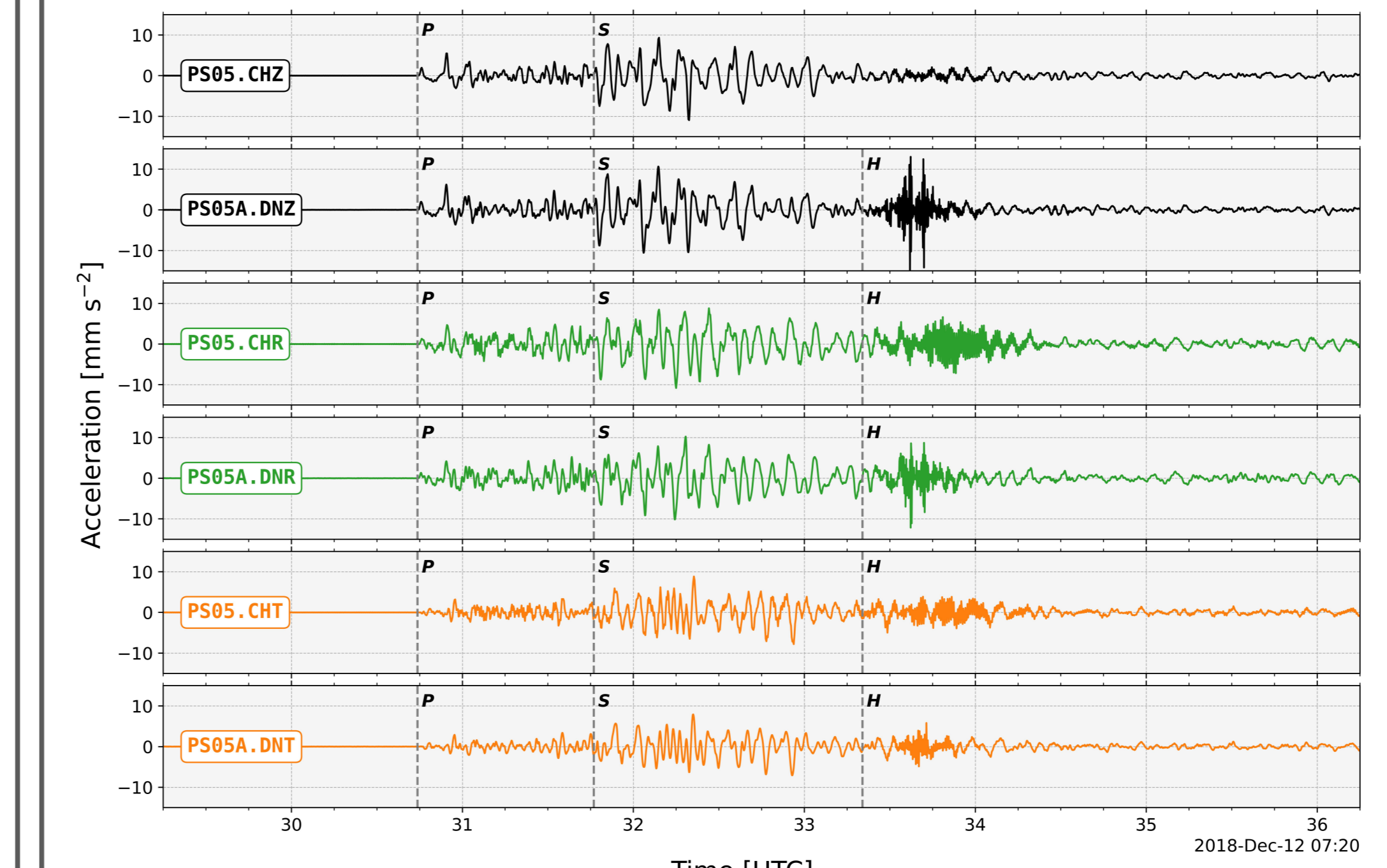
Waveforms and signal duration are very dependant of the nature of the rocks (solid rocks or unconsolidated sediments) at a given site. The figure above shows three-component signals at all the sites for shot S4 (680 kg TNT-equiv.). The figure below shows mHVSr and eHVSr at some sites. We can see that the sites on the western part of the area are associated with amplifications.



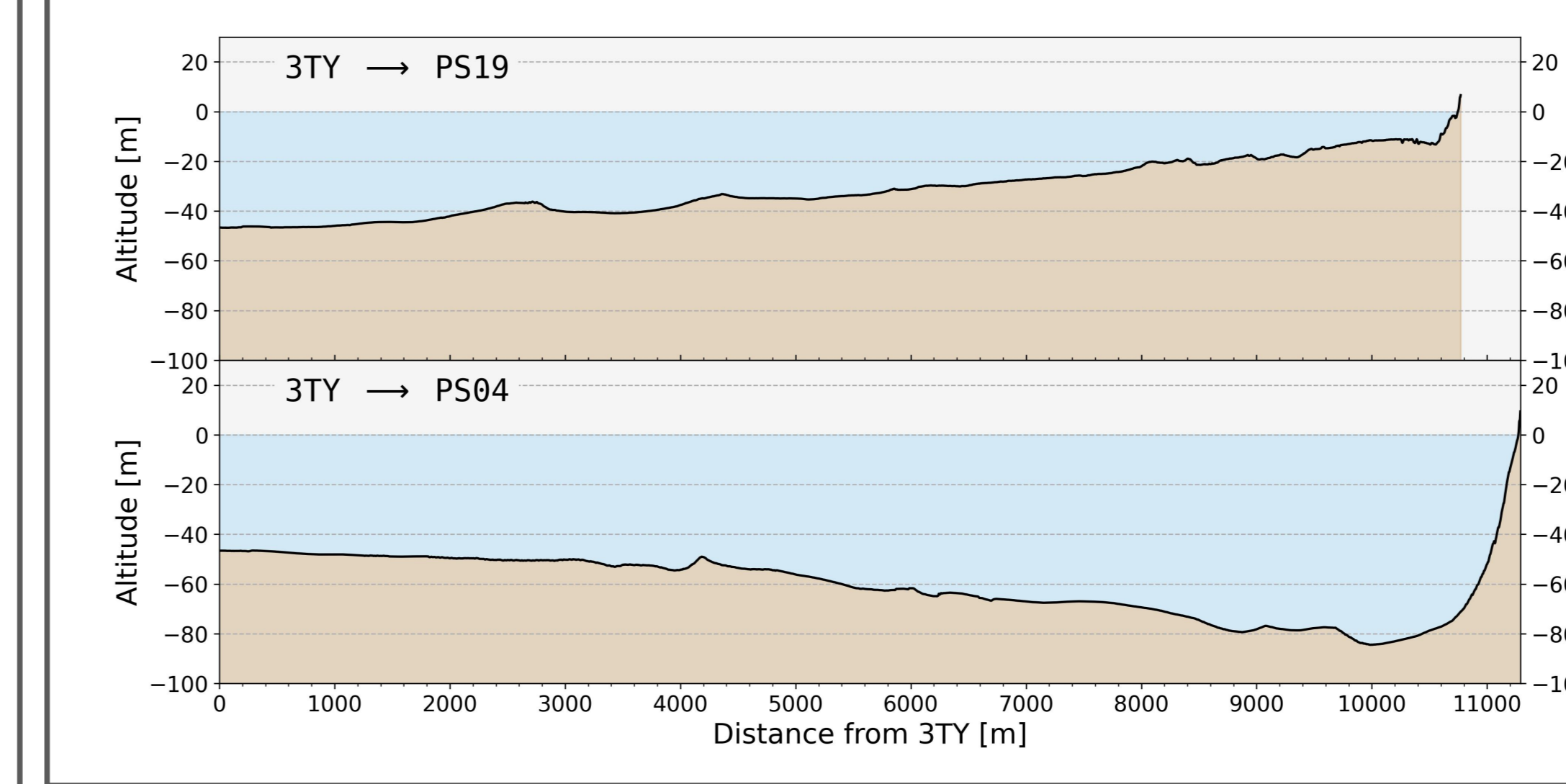
The spectrum of the explosion induced signals is dominated by a peak around 1Hz for the largest shots (surface waves), by a plateau between 5 and 20Hz (*P* waves) and by another peak near 100Hz (*H* phase). Figure below presents spectra of shots S3-S8 at PS05A (MEMS).



5. Observation of hydroacoustic signals



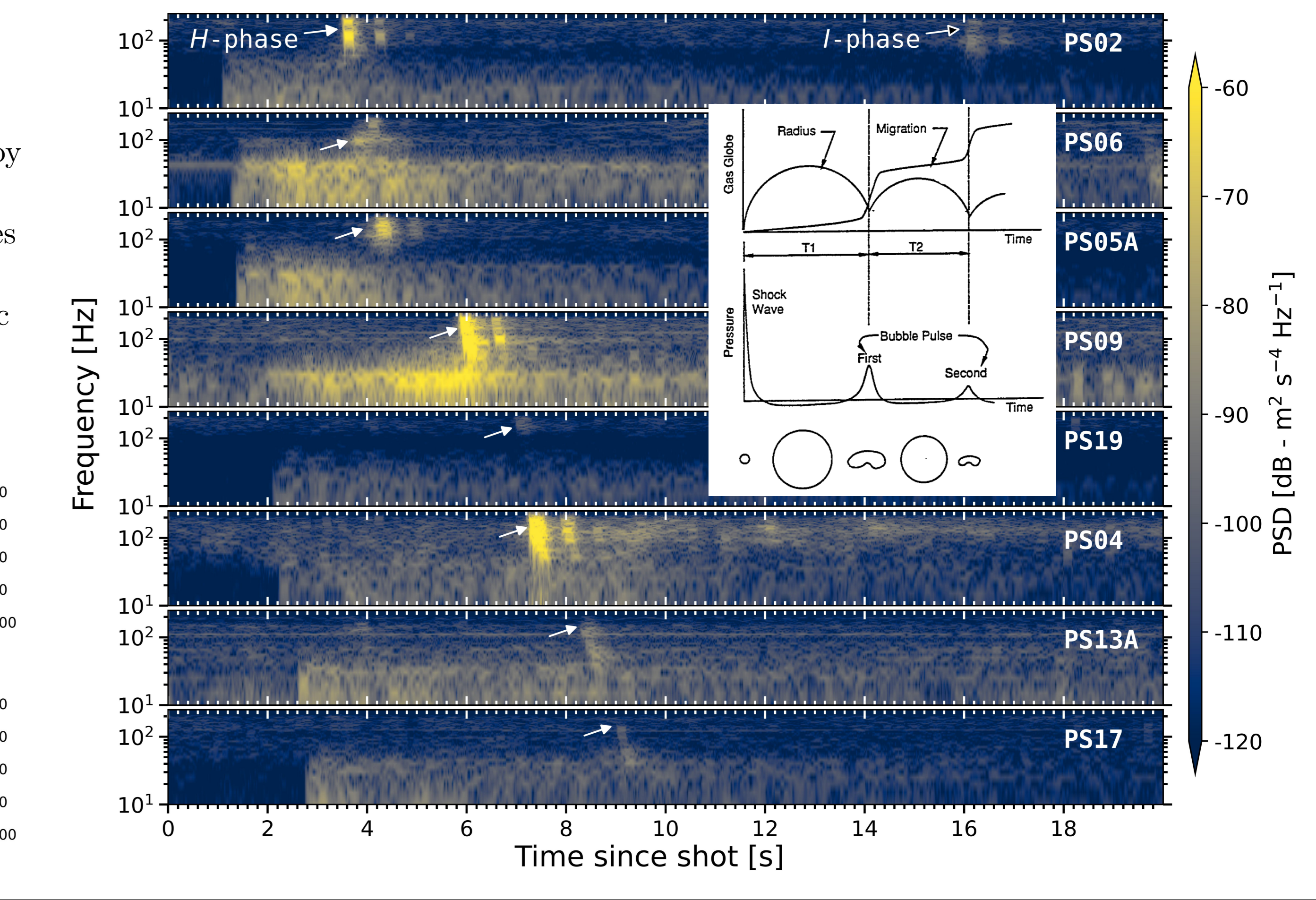
We can note on the spectrograms that the *H* waves are not recorded at all the sites with a MEMS sensor. We suspect that this is caused by the bathymetry of the bay of Hyères: to the West water depth is low near the shore (see profile for PS19 below) while water depth increases towards the East (see profile for PS02). This changes the distance at which the conversion from hydroacoustic to seismic wave occurs.



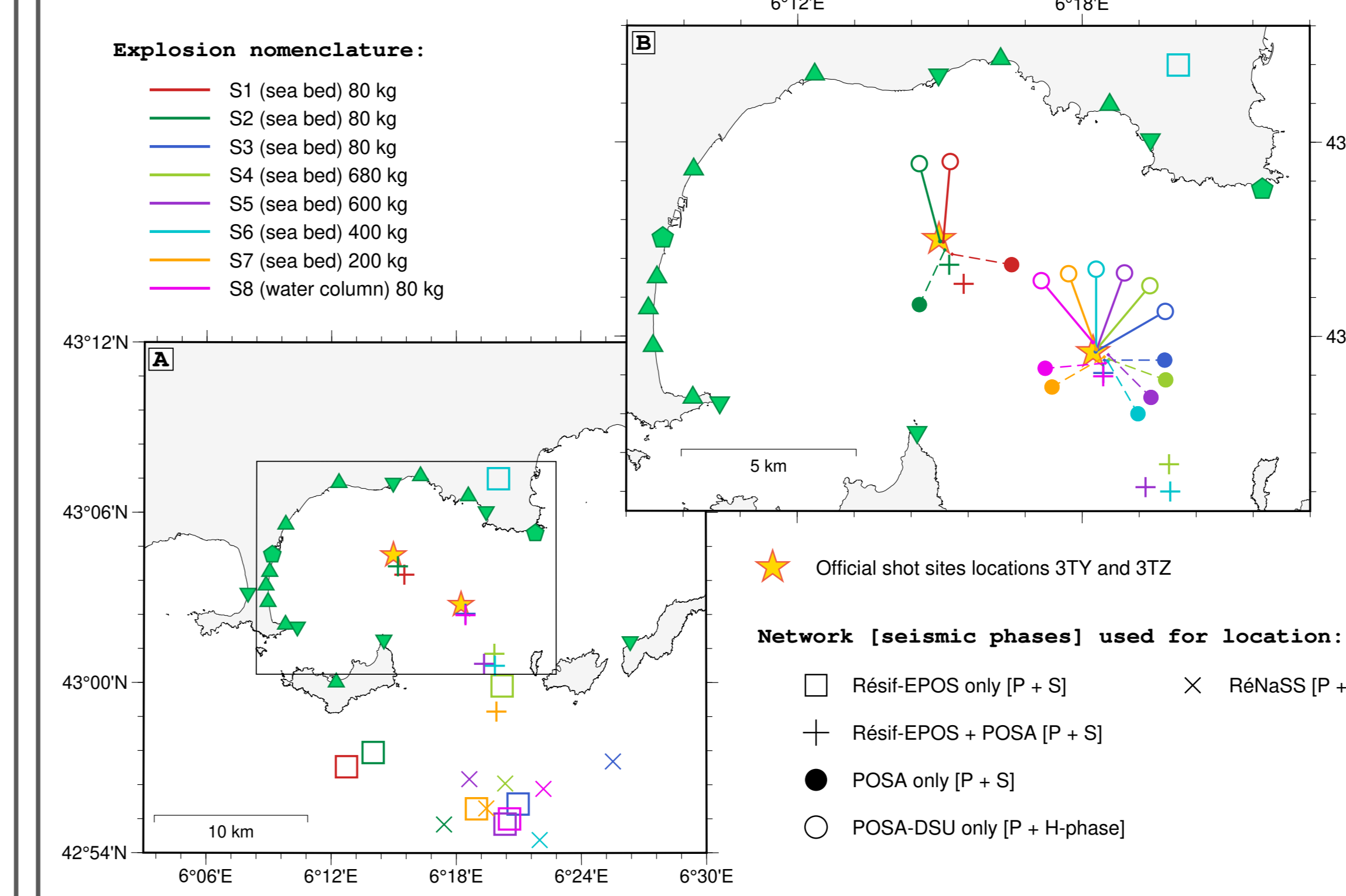
The use of sampling frequency > 250Hz (500 s.p.s. for MEMS) allows us to observe hydroacoustic (*H* phase of the figure on the left) and acoustic waves at PS02. Compare, in the figure on the left, the amplitude of the *H* phase for CHZ (250 s.p.s.) and DNZ (500 s.p.s.).

H phases are the most energetic wave packets (see spectrograms below) and the ones with the highest frequency content (> 100Hz). Their attenuation is low. At PS04 for instance, though body waves amplitudes are low, the amplitude of the *H* phase is as large as at PS02 which is twice closer from the source. We have also detected acoustic phases (*I* on the spectrograms) at station PS02.

Note that we can observe 3 *H* phase arrivals that correspond the expansion and contraction of the gas globe generate by the explosion in the water column (inset in the spectrogram, modified from Reid, 1996).



6. Localisation of the sources



Localisation of the sources using the French permanent network (network FR) located at more than 40km from the bay of Hyères results in mislocations of approximately 15km. The epicenters are systematically shifted towards the South. This is caused by the absence of permanent stations to the South of the bay. We have tested several inversion schemes and sets of data. We find that the best results are obtained using a MCMC bayesian inversion scheme using time arrivals of *P* and *H* waves. We obtain location errors of approximately 100m (open circles on the left).

7. Conclusion

The POSA experiment showed that UXO disposal operations along the French coasts generate hydroacoustic and seismic waves that may be perceived inland (at least with seismic instruments). Detonating UXO within the water column reduces seismic energy received at the shore but dramatically increases energy that propagates in the water column. This thus raises the question of the nuisance of the UXO disposal on the aquatic fauna. Moreover *H* phases are likely perceived by the population under favorable conditions. These investigations should therefore be pursued further.

Favretto-Cristini, N., Garlan, T., Morio, D., Demoulin, X., Arrigoni, M., Deschamps, A., Bonnin, M., Beucler, E., Mercerat, E. D., Ambrois, D., Schwab, R., Cristini, P. and Wang, P. 2022. Assessment of risks induced by countermeasures unexploded large-charge historical ordnance in a shallow water environment - Part I: real case study. IERE. J. of Ocean. Eng. 47(2), p. 359-373. doi: 10.1109/joe.2021.3111819
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 Research presented in this paper was part of the POSA program and supported by The French National Research Agency (ANR) and funded by DGA (French Ministry of Defense Procurement Agency) under reference Projct ANR-15-ASTR-0003 POSA
 The data from the POSA experiment are available from the Résoif-EPoS subservice (http://seismology.resoif.fr) with the code ZH.