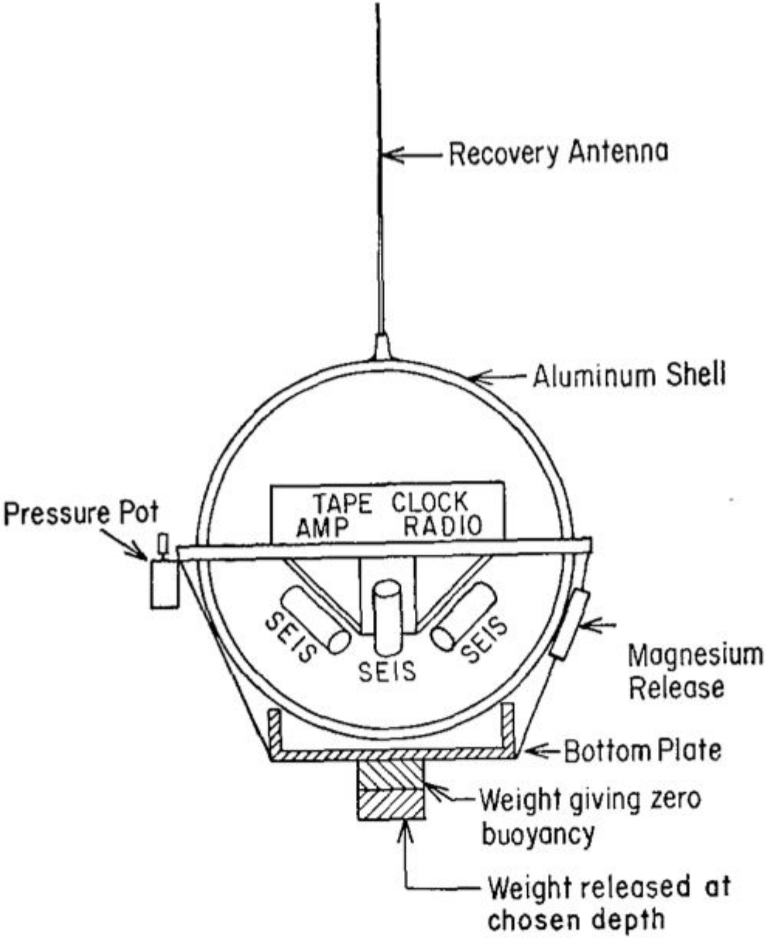
Earthscope-Oceans: Closing the Oceanic Coverage Gap for Seismology and Environmental Sensing

Frederik J. Simons

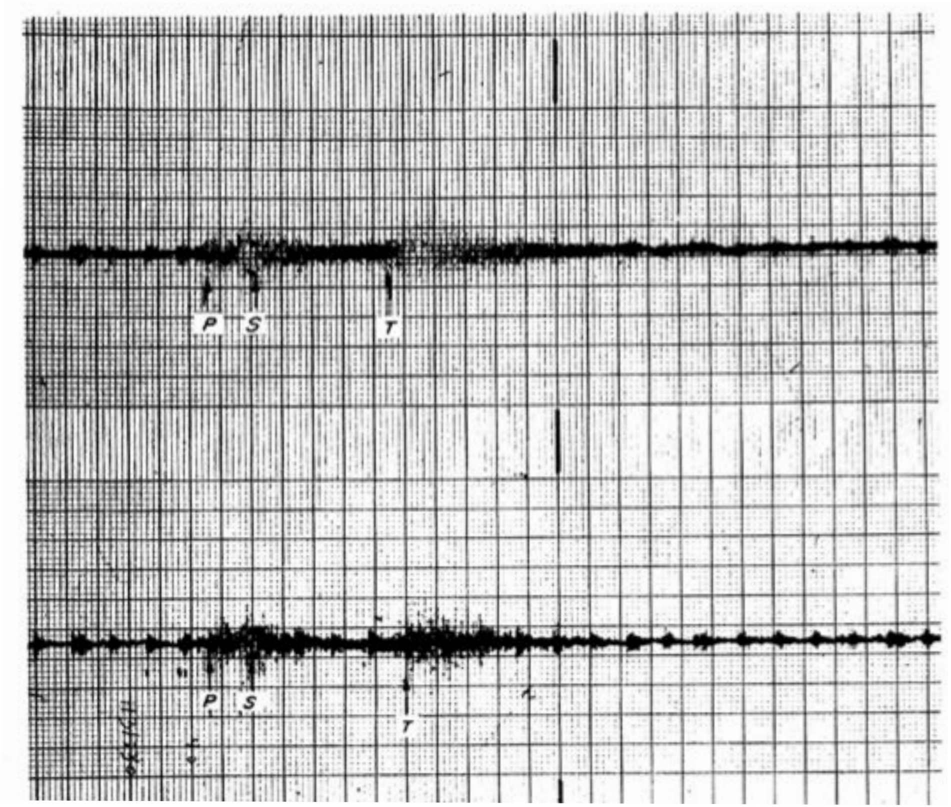
Yongshun John Chen
Joel D. Simon
Sirawich Pipatprathanporn
Sébastien Bonnieux
Jessica C. E. Irving
Masayuki Obayashi
Yann Hello
Karin Sigloch
Lucia Gualtieri
Tim Ahern
Guust Nolet

Fifty years ago



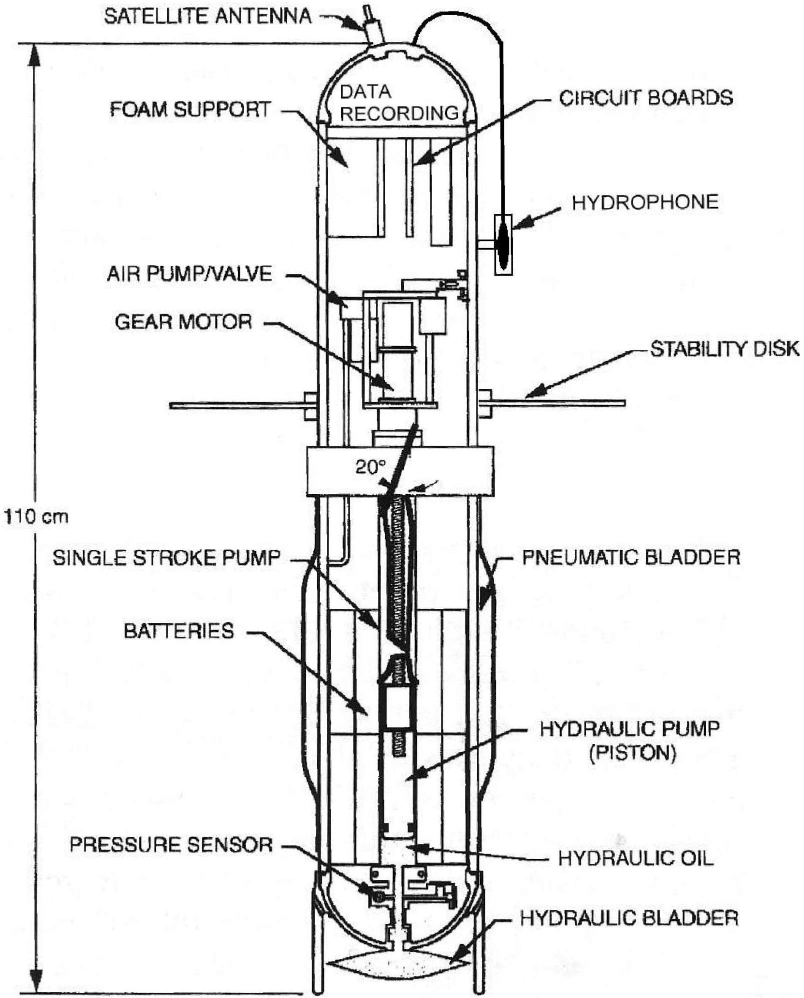
Bradner et al., 1970

Fifty years ago



Reid et al., 1973

Fifteen years ago

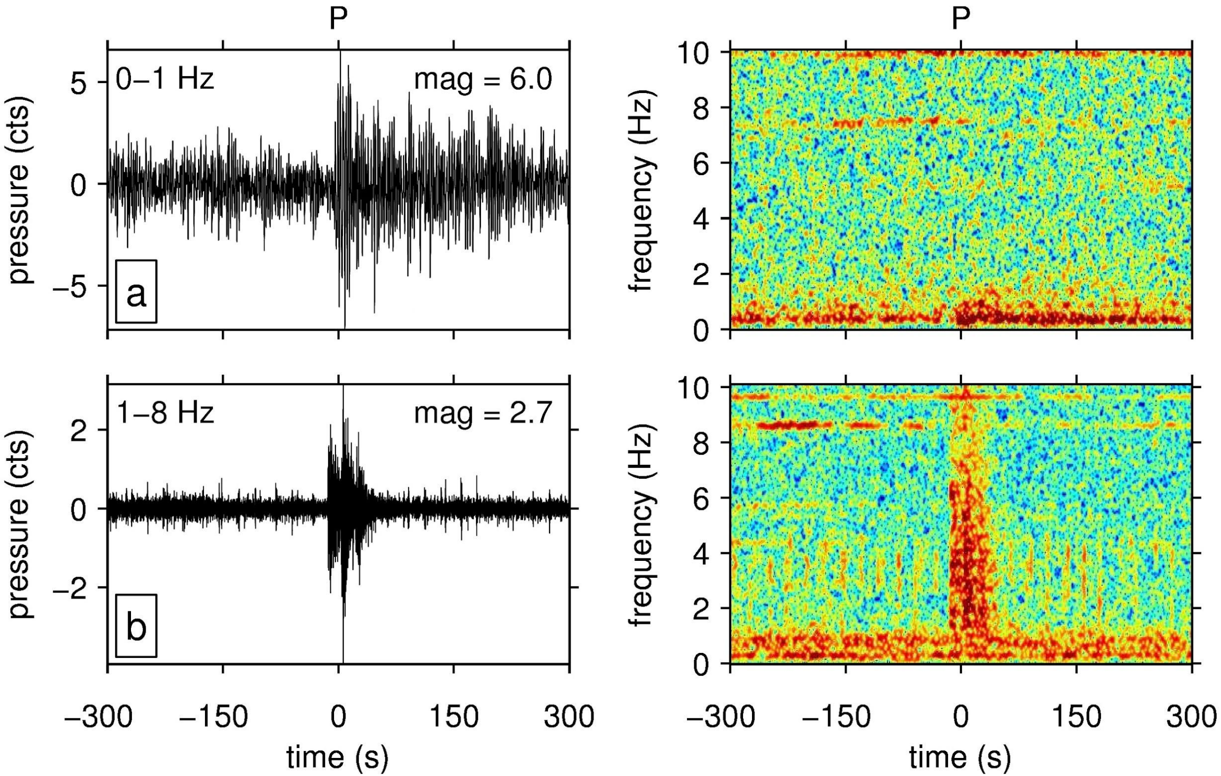


Simons et al., 2006

Fifteen years ago

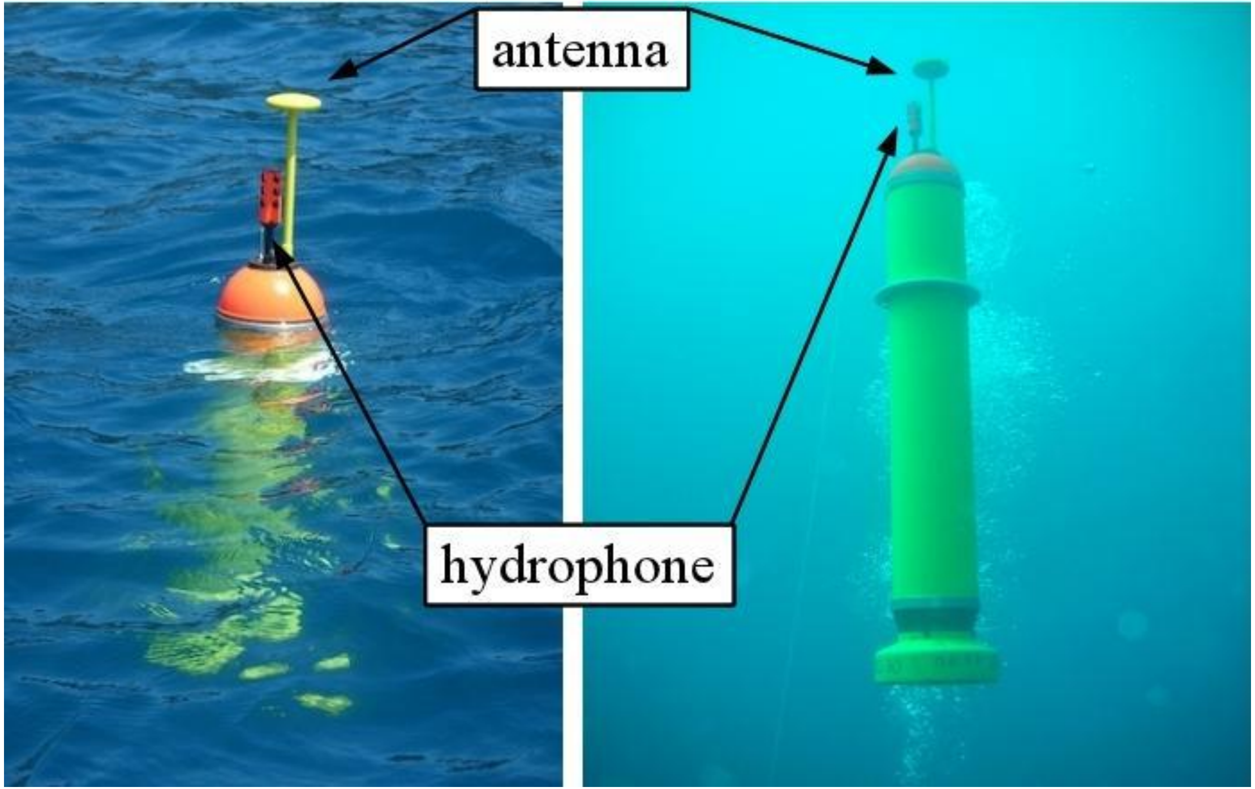
Simons et al., 2006

MERMAID-001



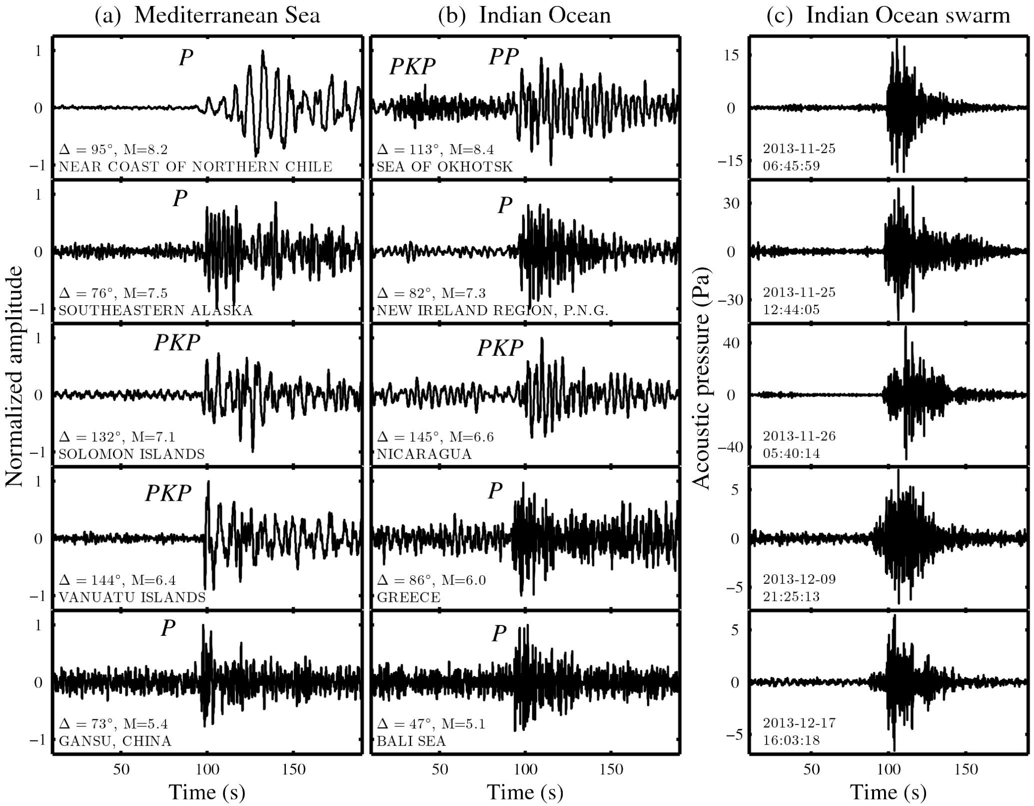
Simons et al., 2009

Ten years ago



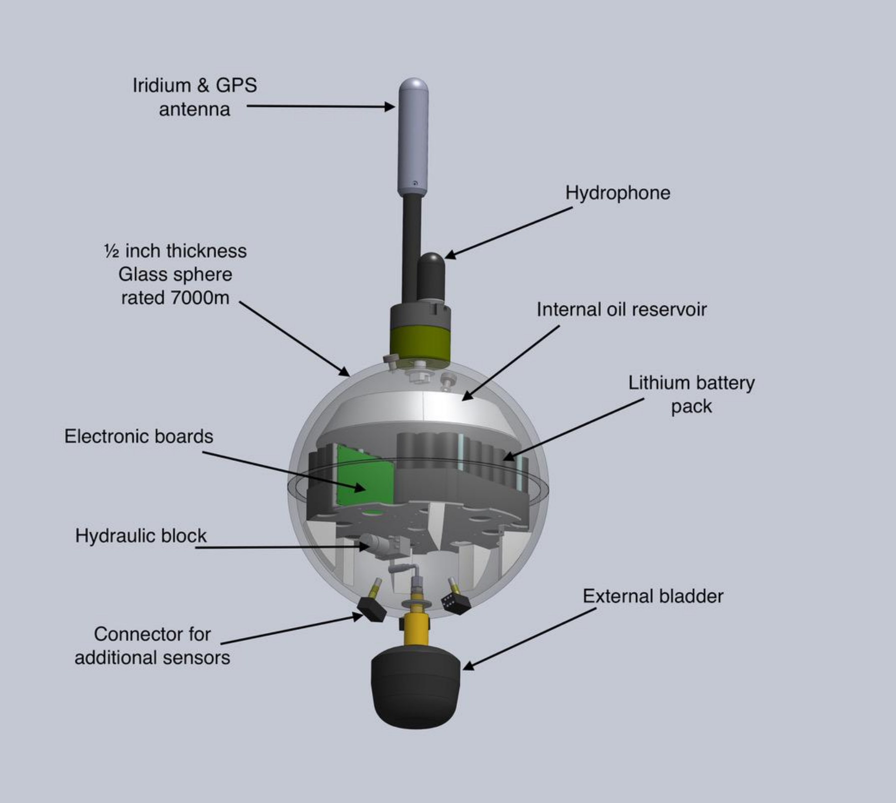
Hello et al., 2011

Ten years ago



Sukhovich et al., 2015

Five years ago



Hello & Nolet, 2020

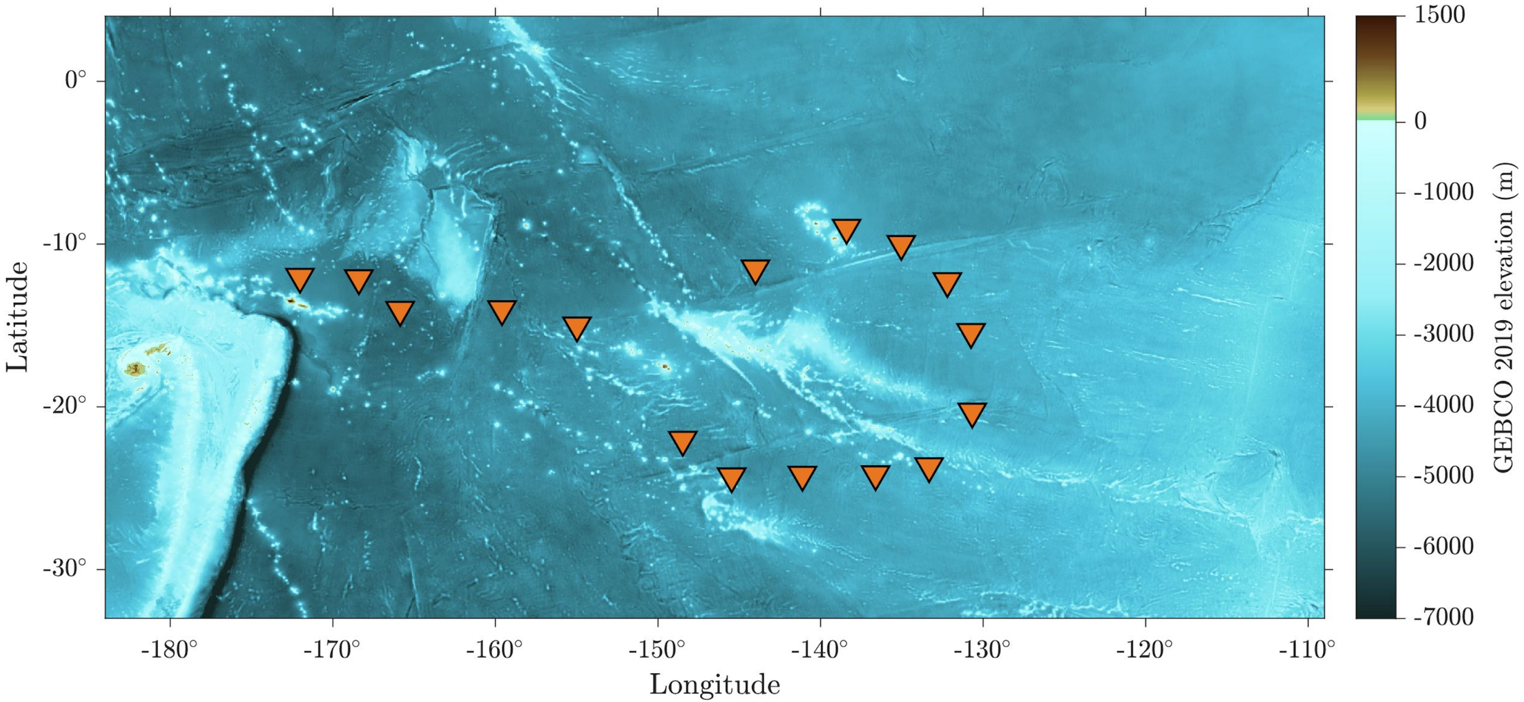
Three years ago

Simons et al., 2021

Coming to an Ocean near You!

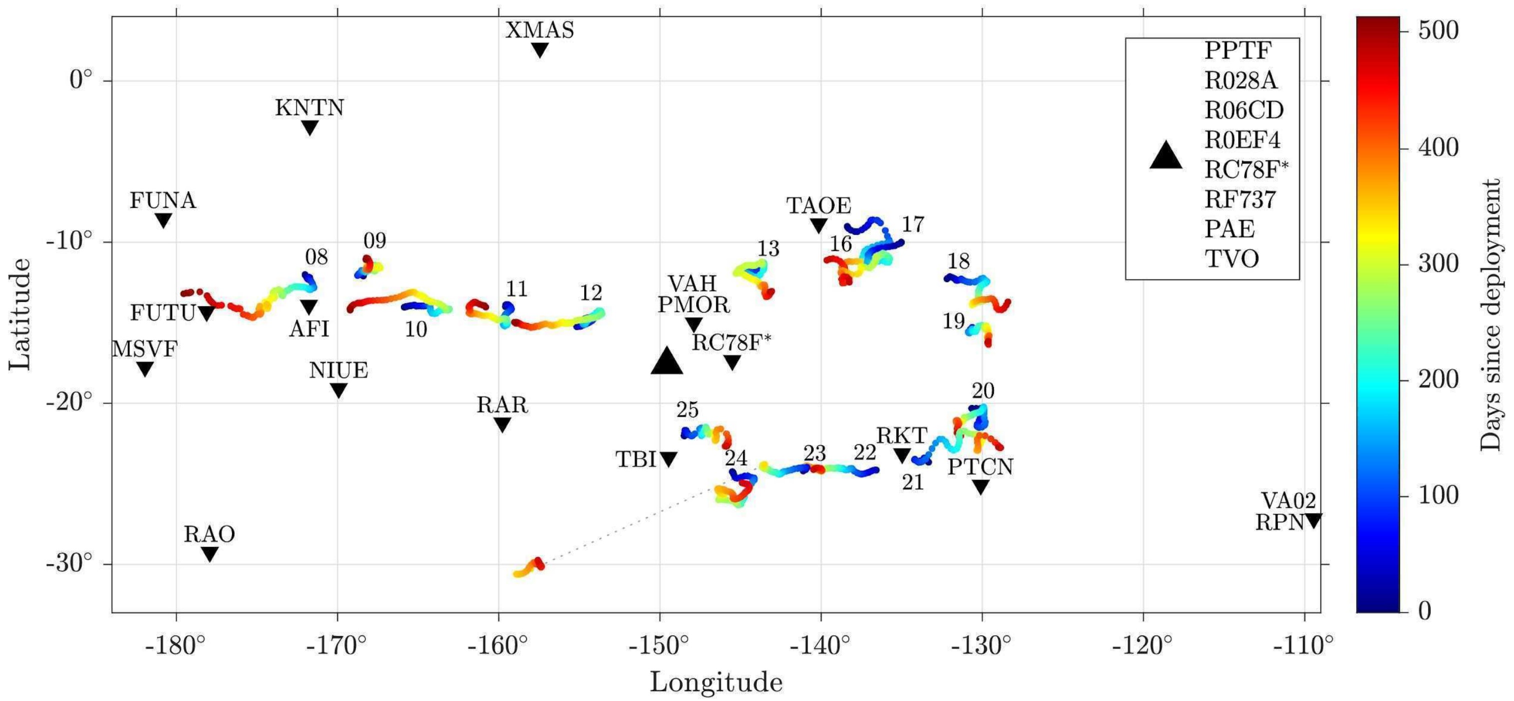
Simons et al., 2021

South Pacific Plume Imaging and Modeling — 1



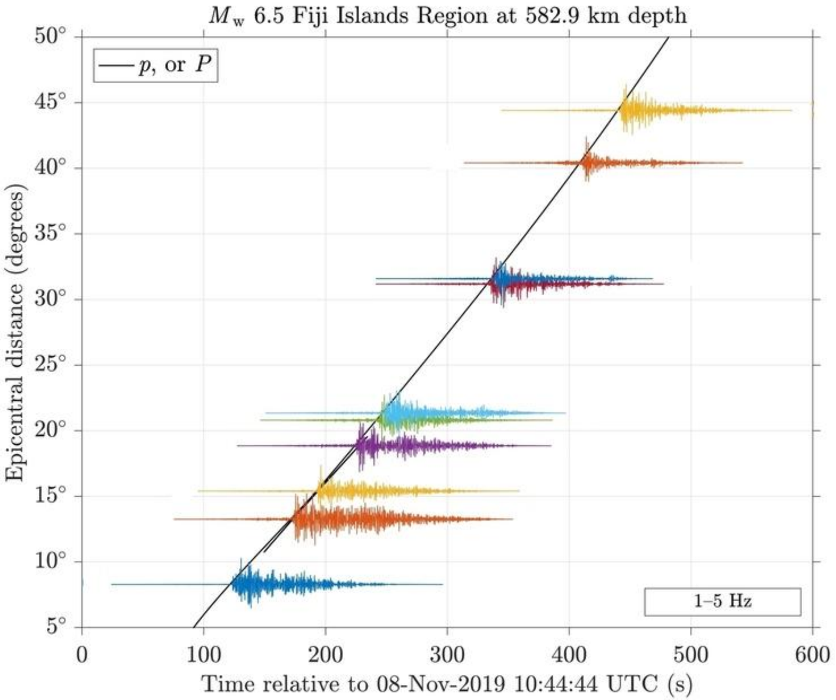
Simon et al., 2021

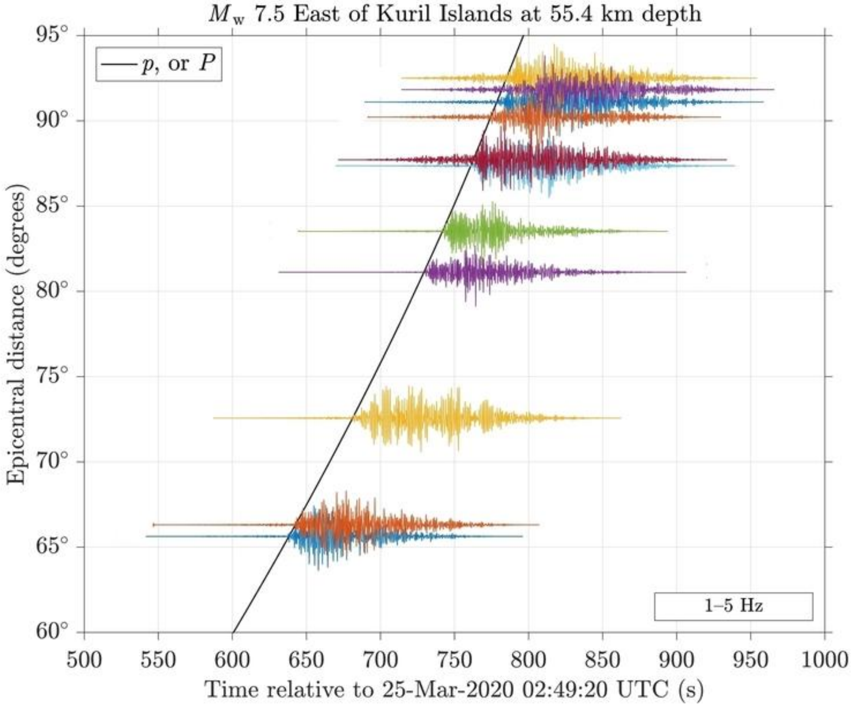
South Pacific Plume Imaging and Modeling — 2



Simon et al., 2021

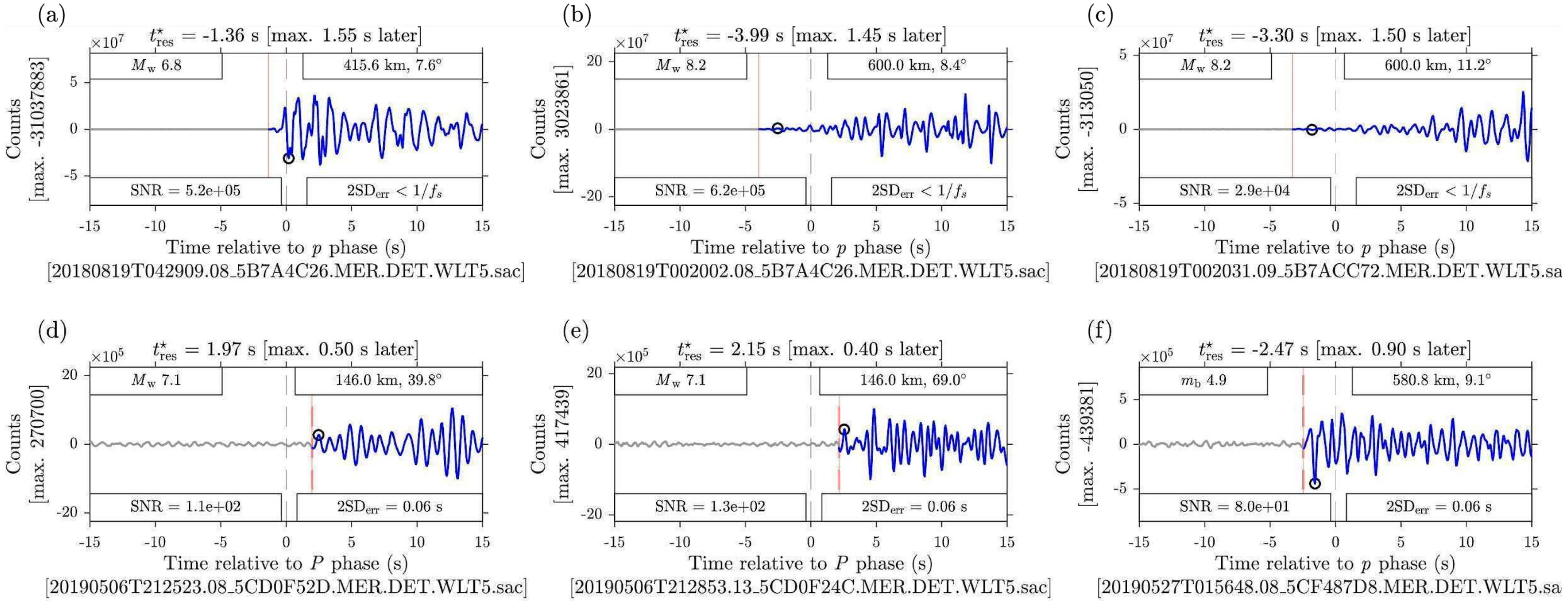
South Pacific Plume Imaging and Modeling — 3





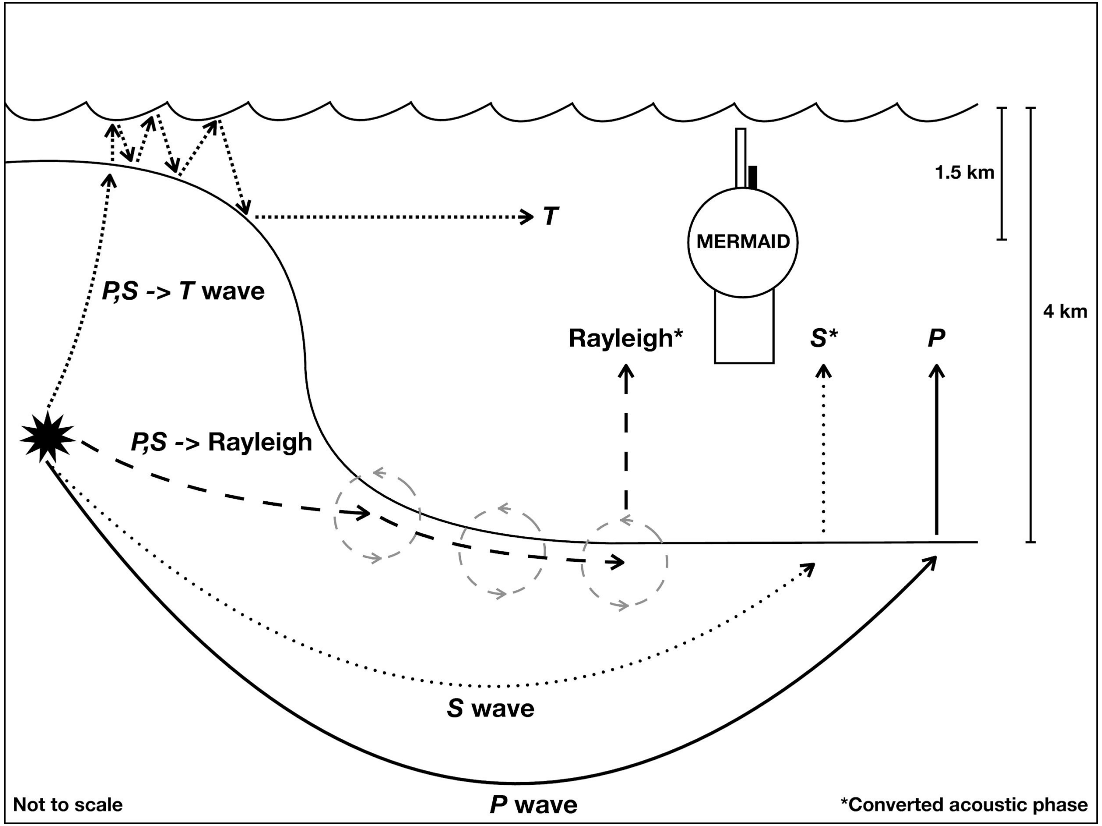
Simon et al., 2021

South Pacific Plume Imaging and Modeling — 4



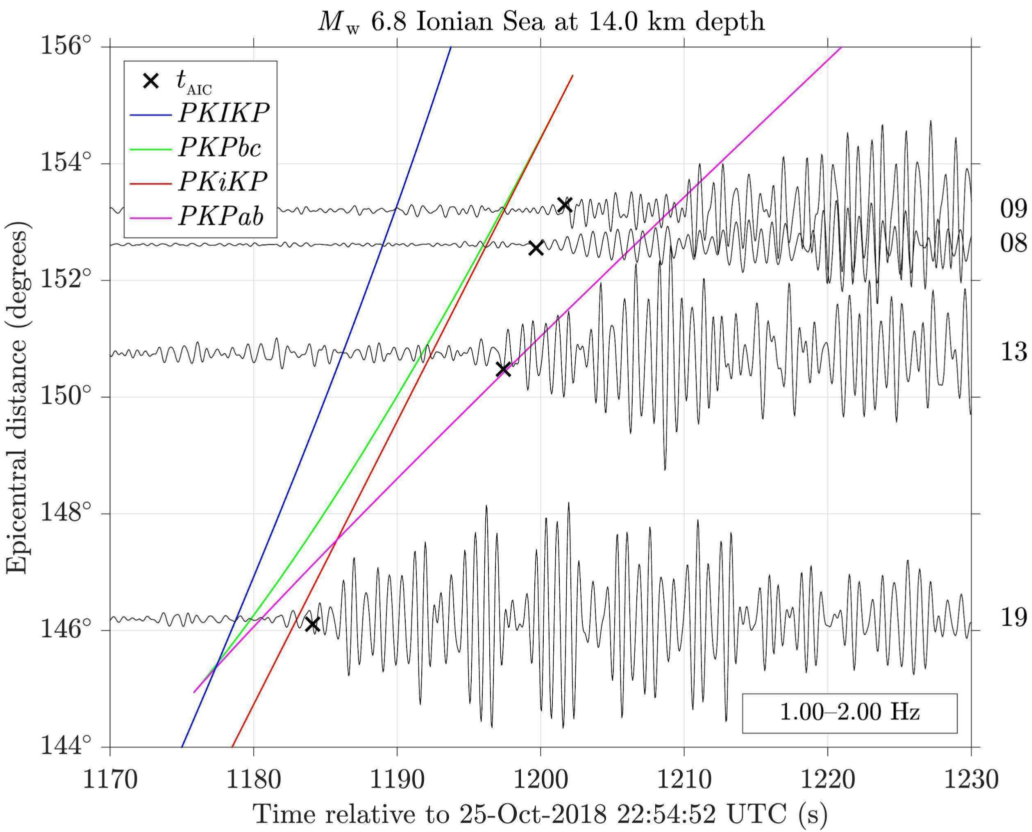
Simon et al., 2021

Beyond the first arrival — 1



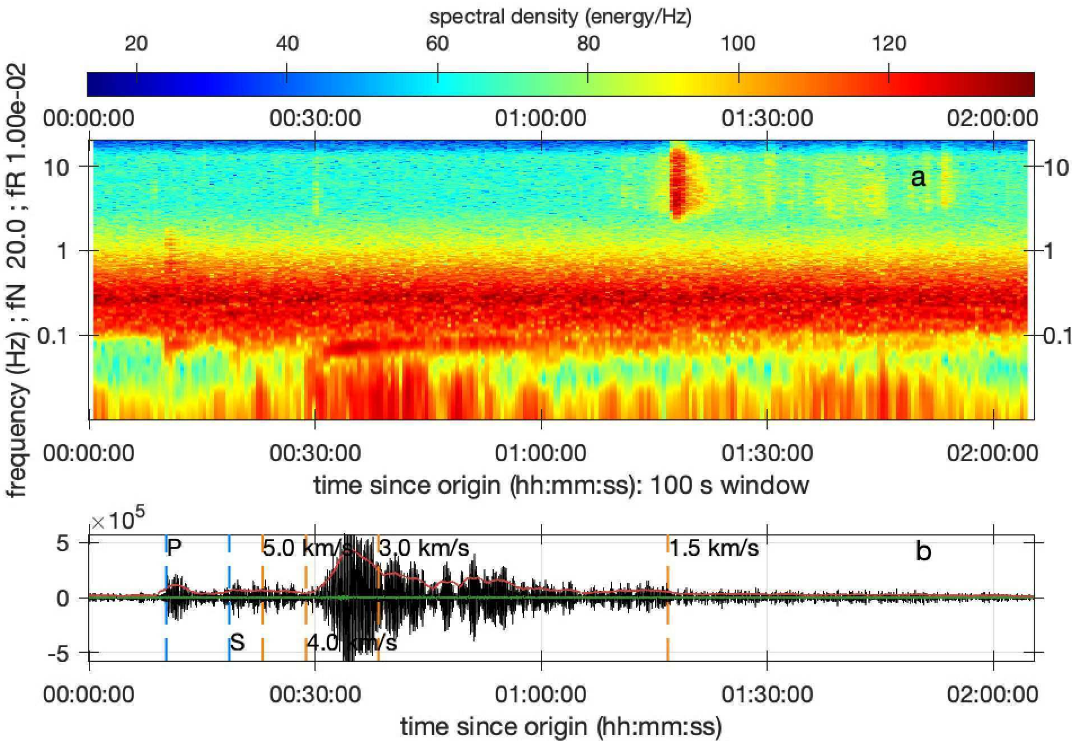
Simon et al., 2021

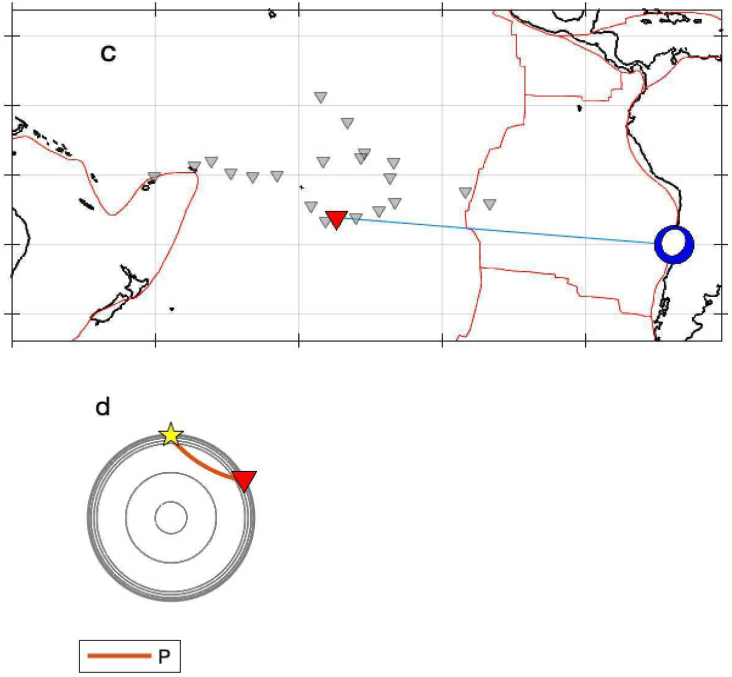
Beyond the first arrival — 2 Core phases



Simon et al., 2021

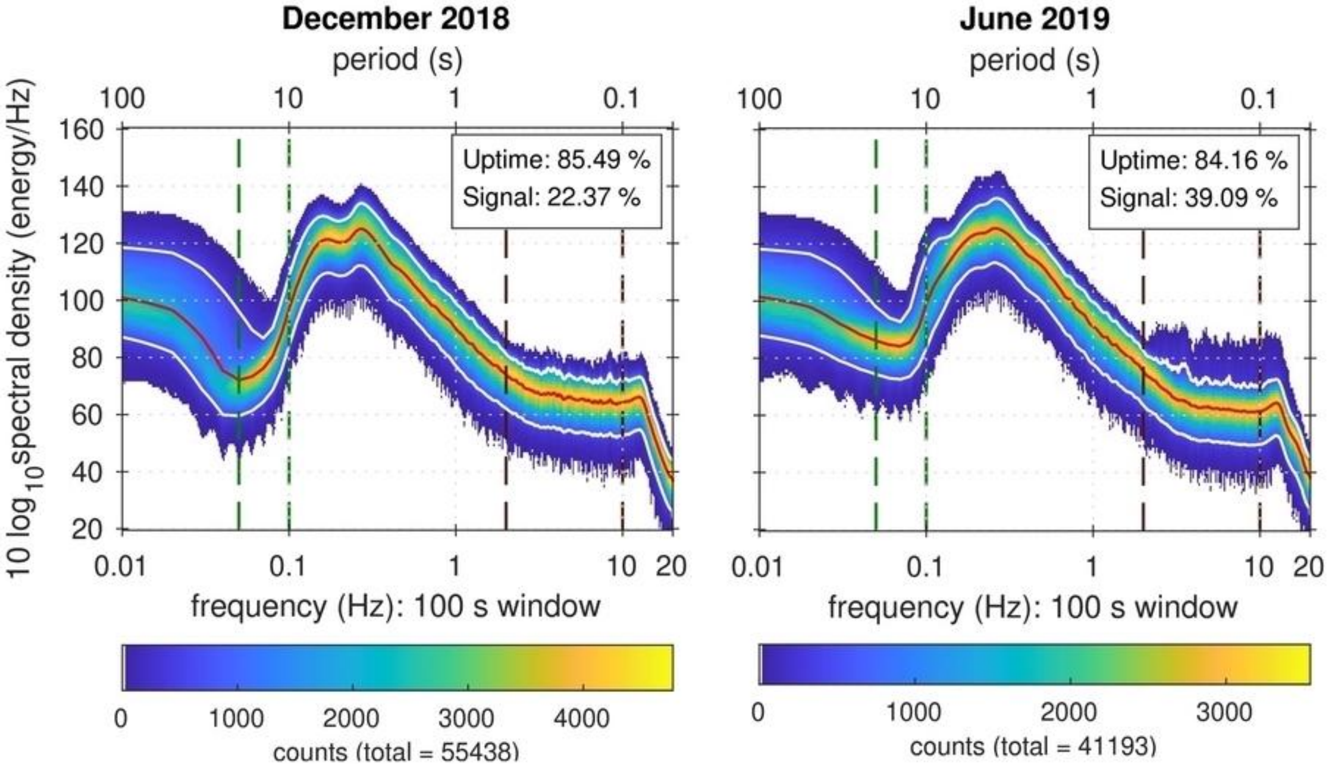
Beyond the first arrival — 3 Surface waves





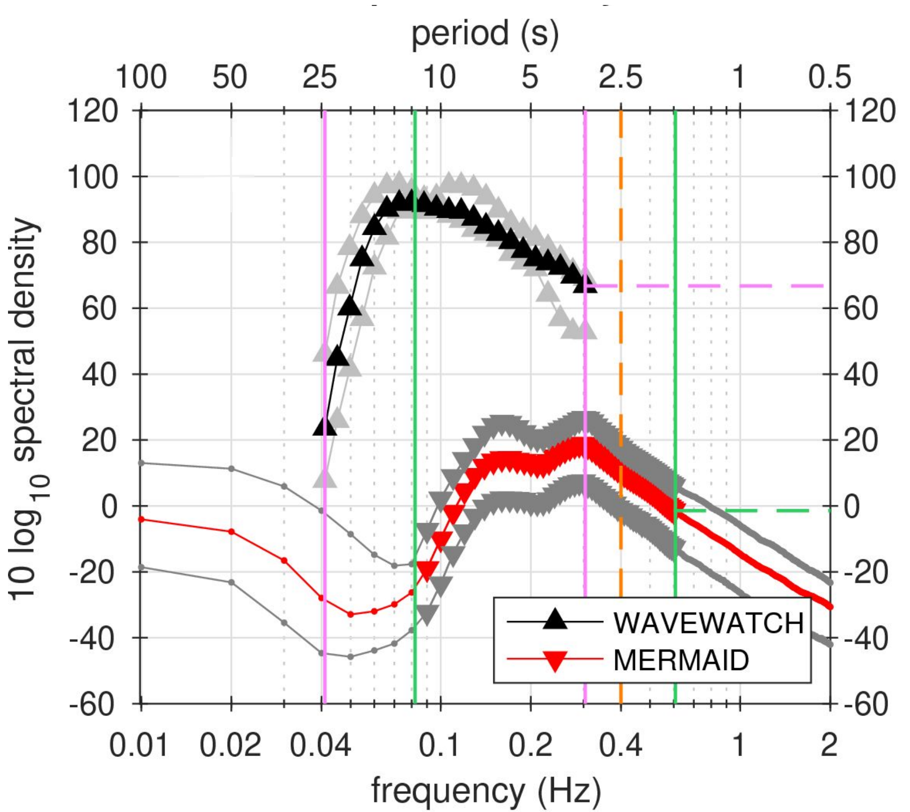
Pipatprathanporn & Simons, 2021

Noise — 1 Infrasonic ambient noise



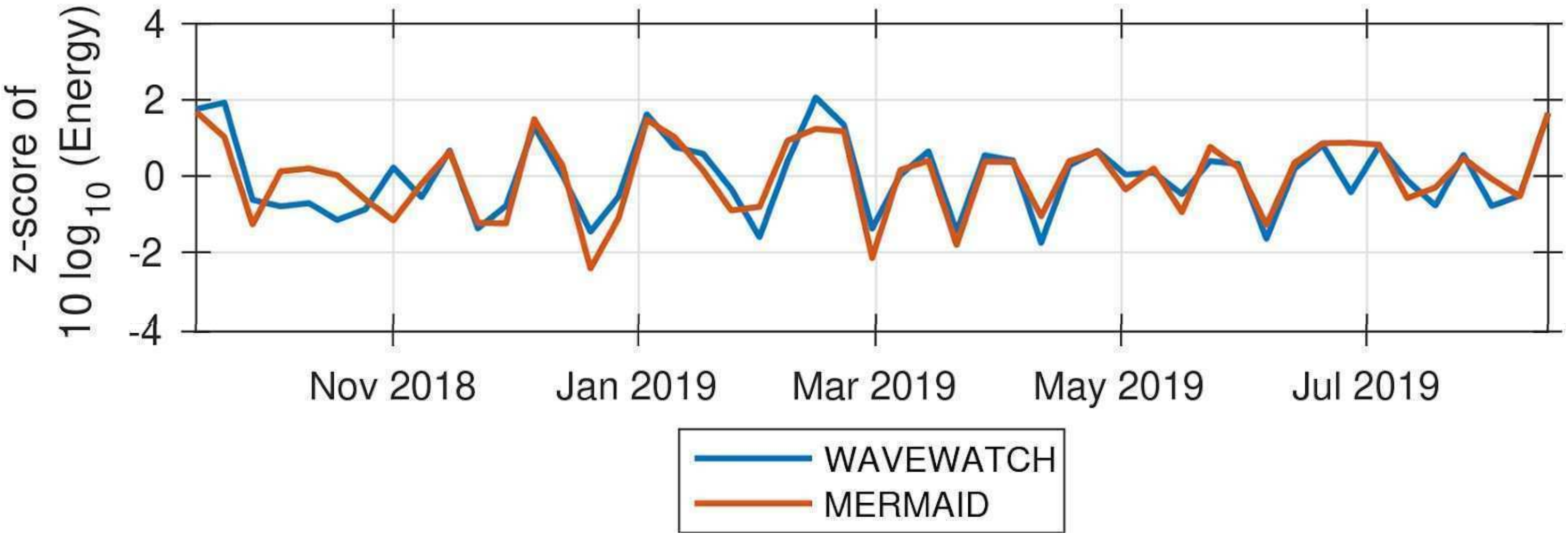
Pipatprathanporn & Simons, 2021

Noise — 2 Ocean gravity waves



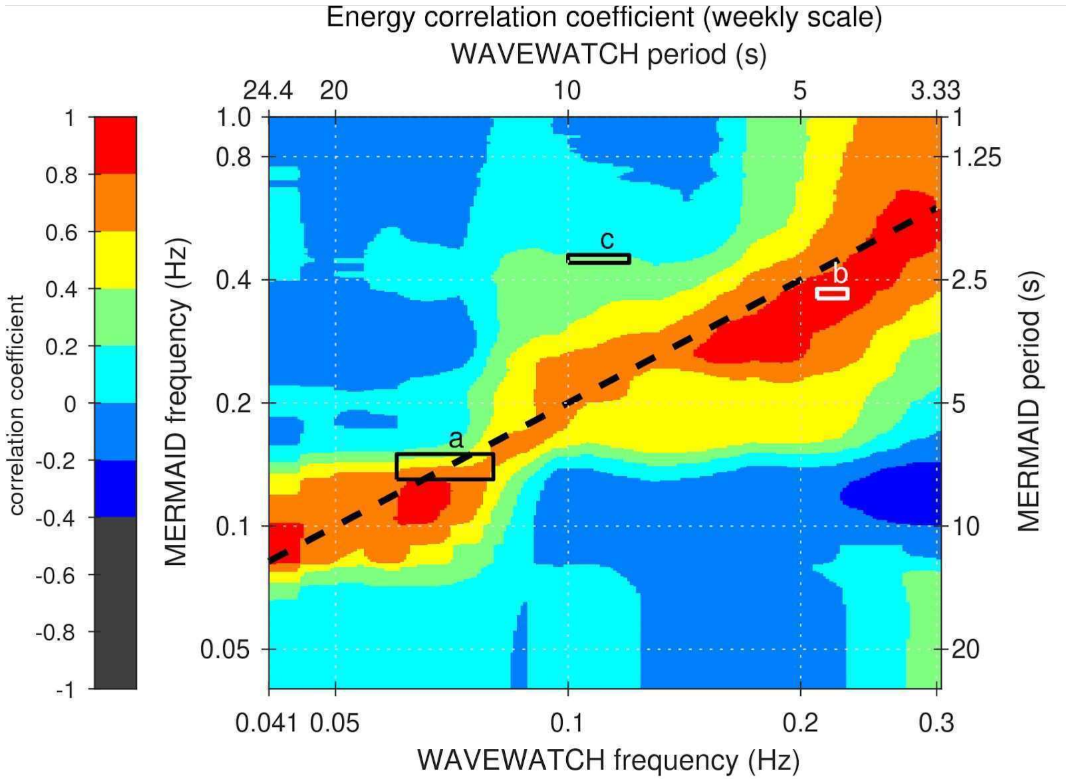
Pipatprathanporn & Simons, 2021

Noise — 3 Correlation at the doubling frequency



Pipatprathanporn & Simons, 2021

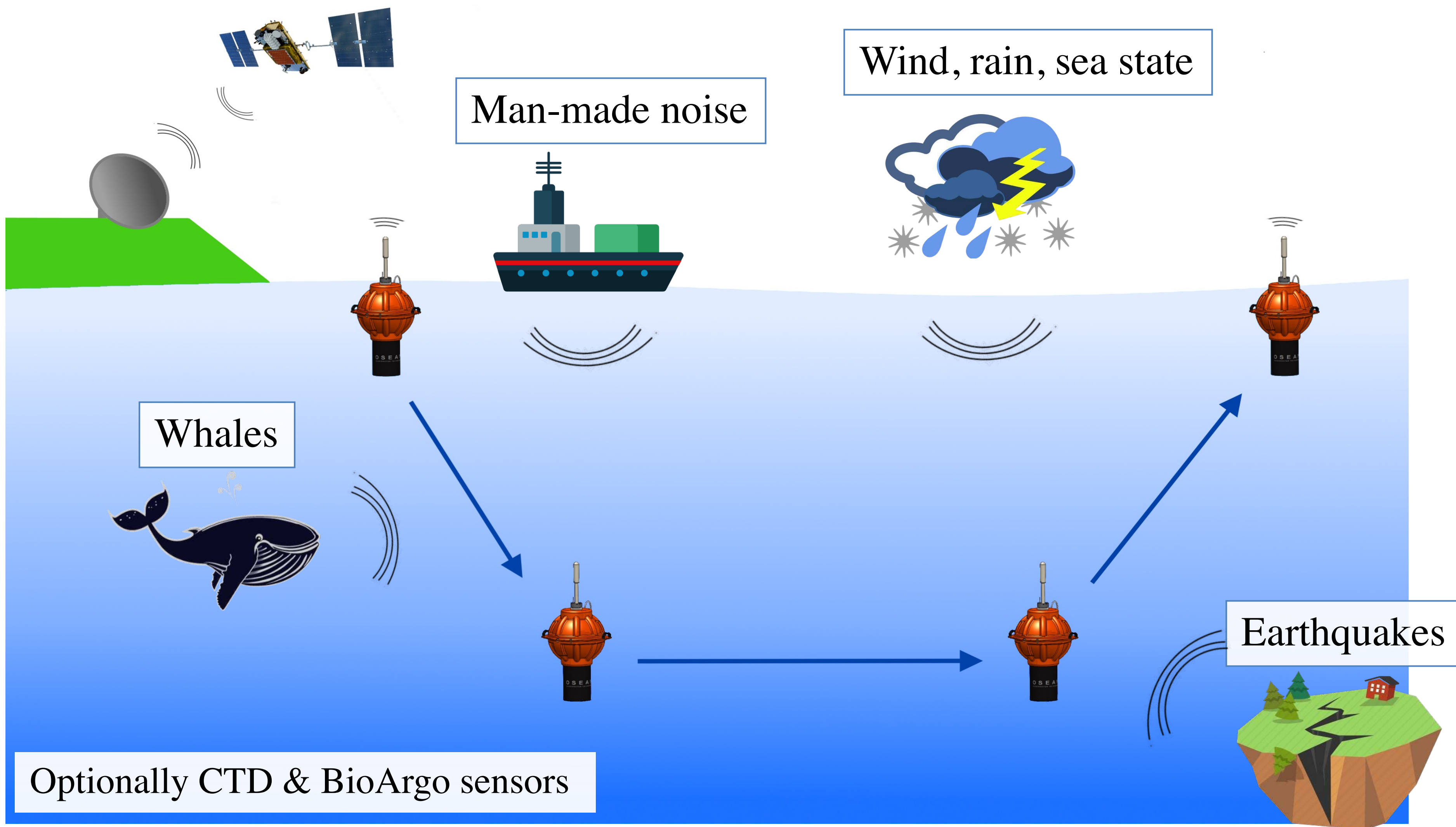
Noise — 4



Pipatprathanporn & Simons, 2021

MERMAID floats: key points

- **Seismo-acoustic** measurements in the **open oceans.**
- On an **ARGO-style float** – passively drifting at 1500m depth, 5+ years of recording, surfacing every few days to send data.
- Primary mission: record earthquakes. But "hears" all ocean noises.
- **Bigger batteries** than ARGO. Hardware & software support for **flexible addition of other applications** (phys/chem/bio…)
- First multi-disciplinary mission scheduled for 2024.

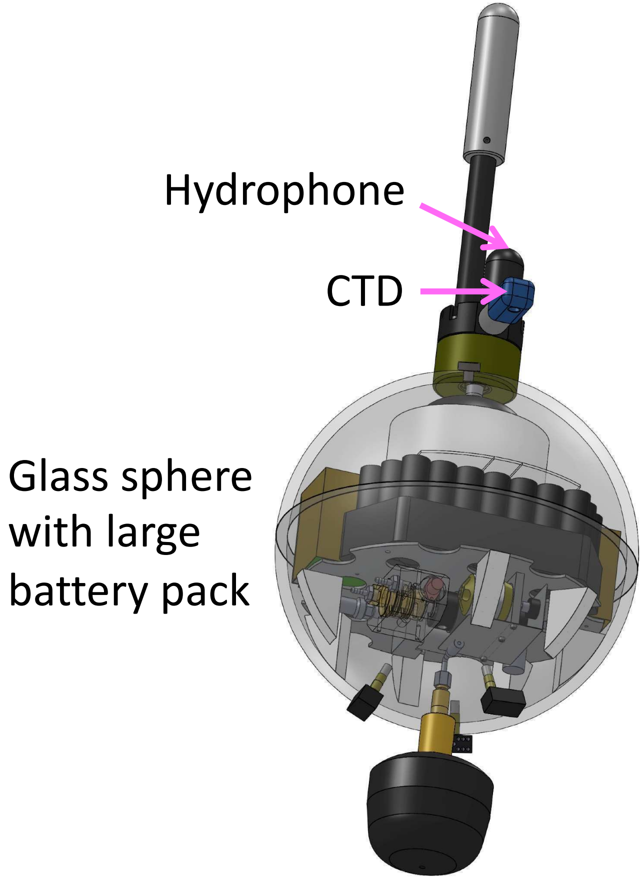


Man-made noise
Wind, rain, sea state
Whales
Earthquakes
Optionally CTD & BioArgo sensors

~75 MERMAIDS active since 2018.

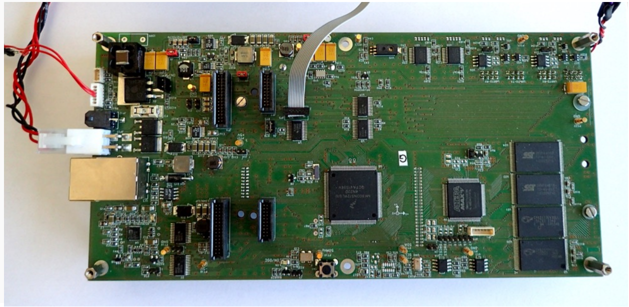
UN Decade Project EarthScope-Oceans
(earthscopeoceans.org)

Large batteries & flexible addition of sensors

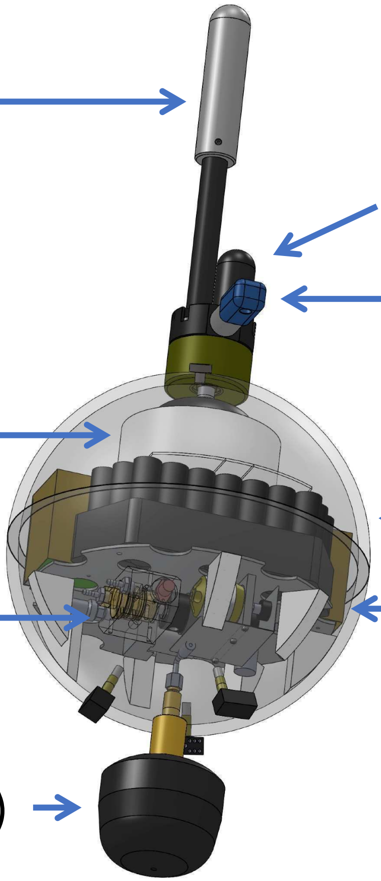


- Supports up to 8 sensors.
- Adding & testing applications through a high-level Domain Specific Language.

```
Mission:
   ParkTime: 7 days
   ParkDepth: 1500 meters

Coordinator:
   ParkAcqModes: helloFFT during 10 minutes every 1 hour

ContinuousAcqMode helloFFT:
Input:
   sensor: HydrophoneHF(20000)
   data: x(128)
   overlap: 32

Variables:
   Array spectrum(128)

RealTimeSequence main:
   spectrum = fft(x, 128, HANNING)
endseq;
endmode;
```

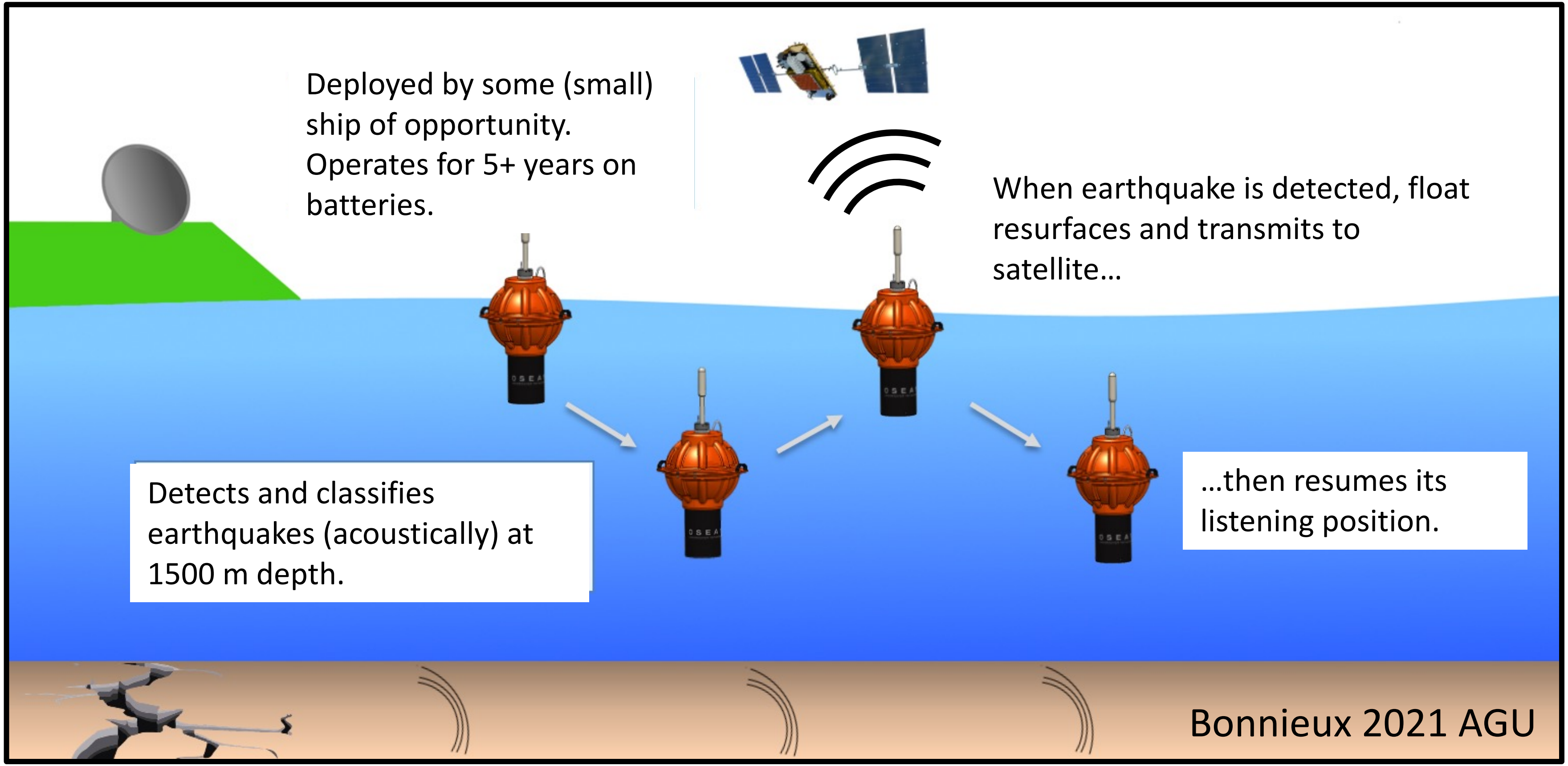


Components of a MERMAID float

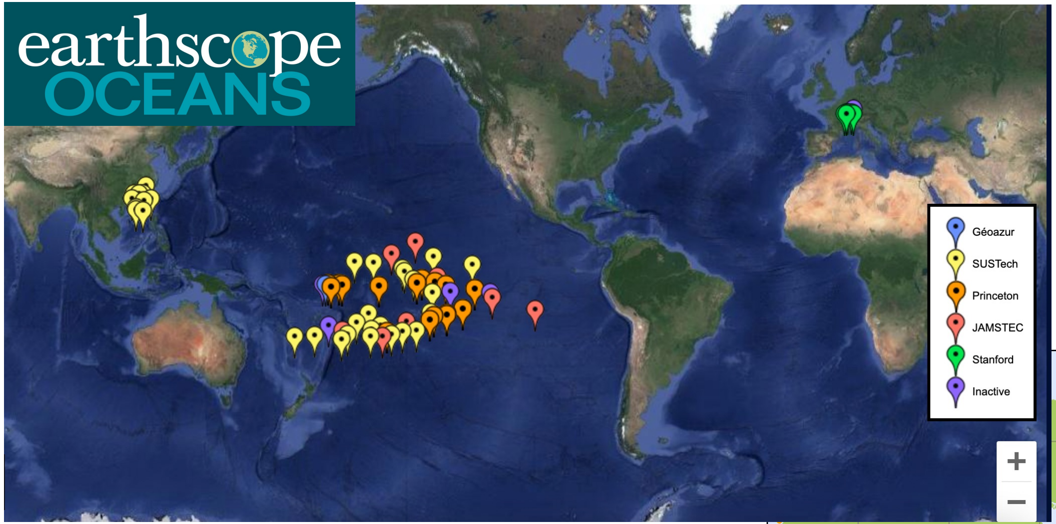


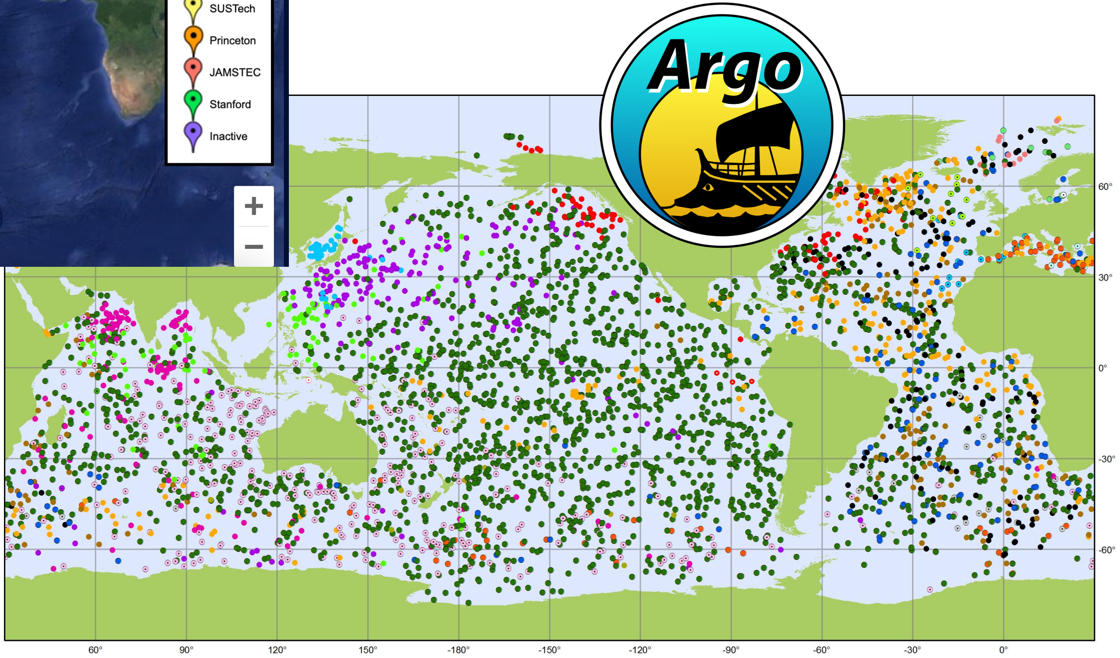
Developed by our group
in manufacturing partnership with
SME OSEAN.

Operation cycle of a Mermaid



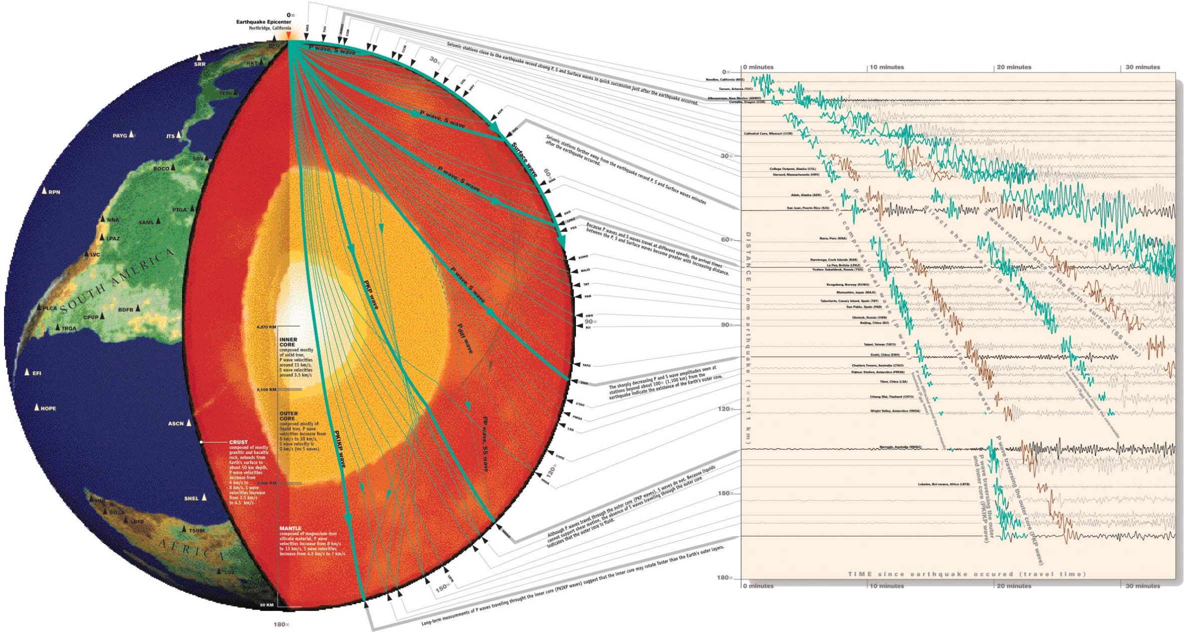
Current network, aiming for Argo-like coverage



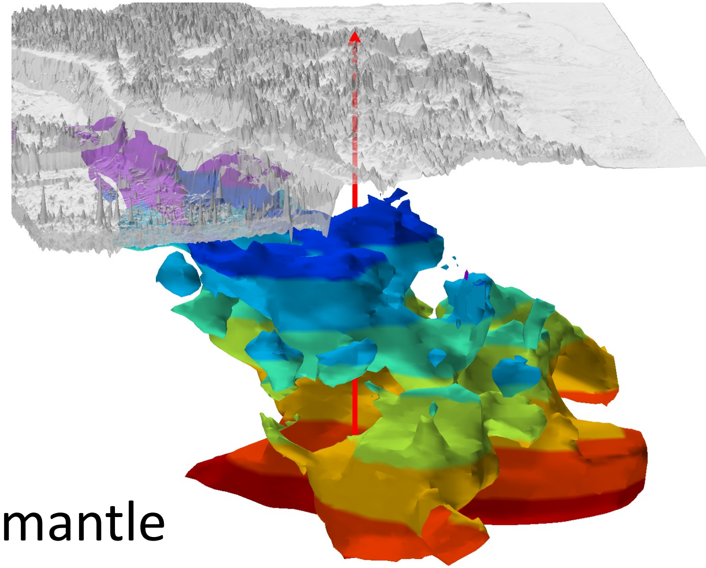


2021 2030 United Nations Decade of Ocean Science for Sustainable Development

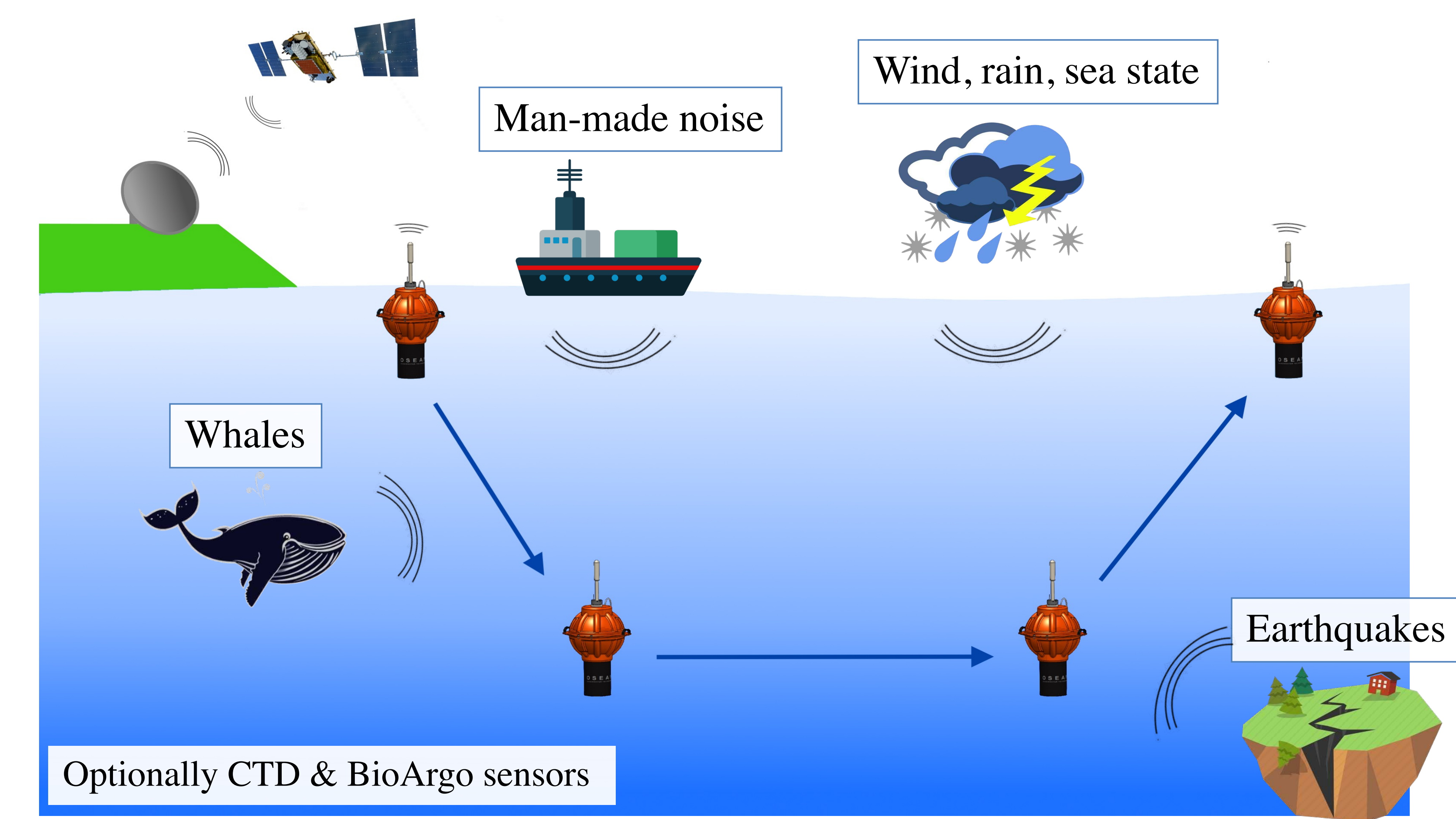
Basic quest: Seismograms from oceanic areas globally



Earthquakes recordable as seismograms

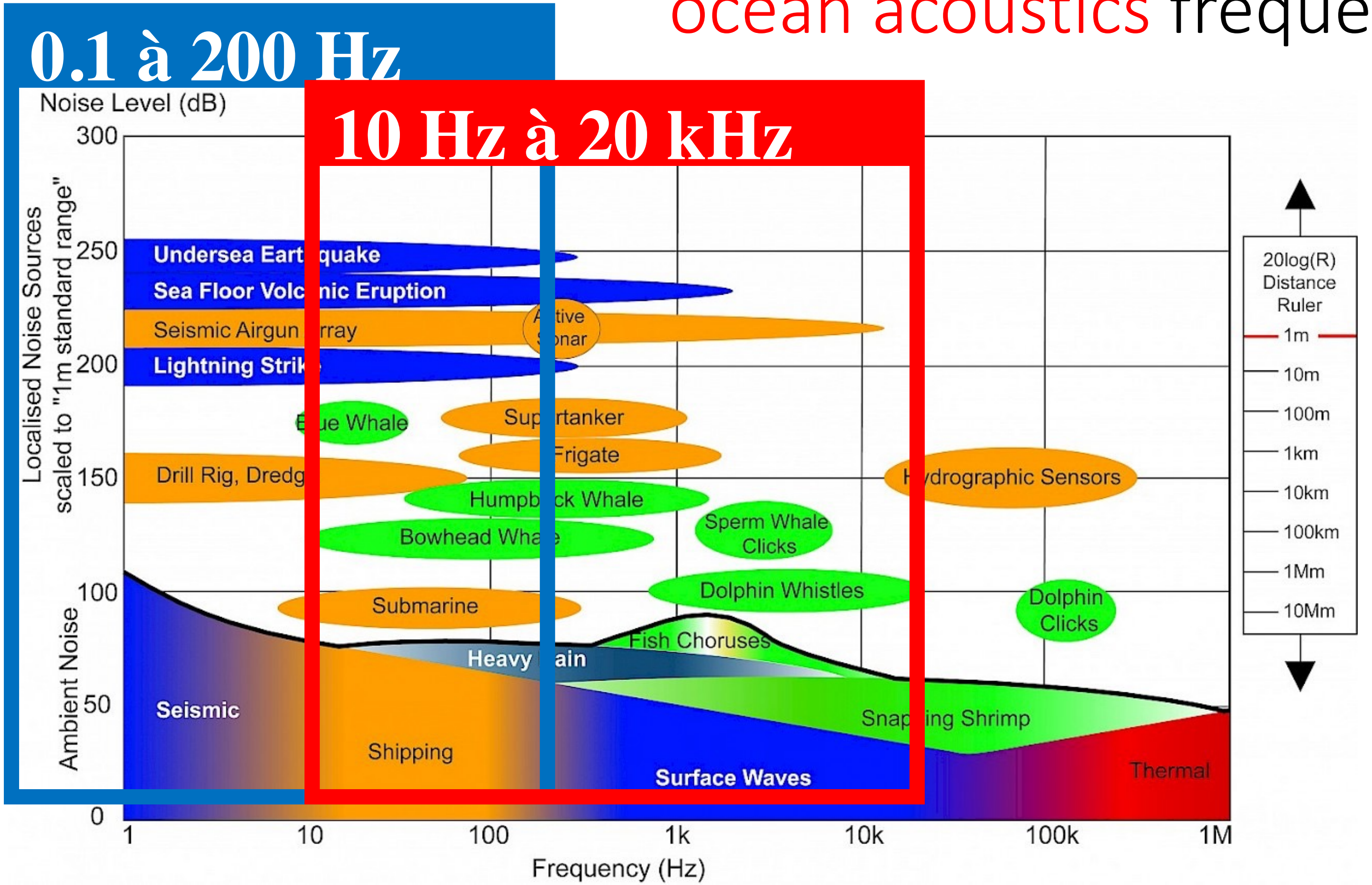


Tomographic images of the mantle



Wind, rain, sea state
Man-made noise
Whales
Earthquakes
Optionally CTD & BioArgo sensors

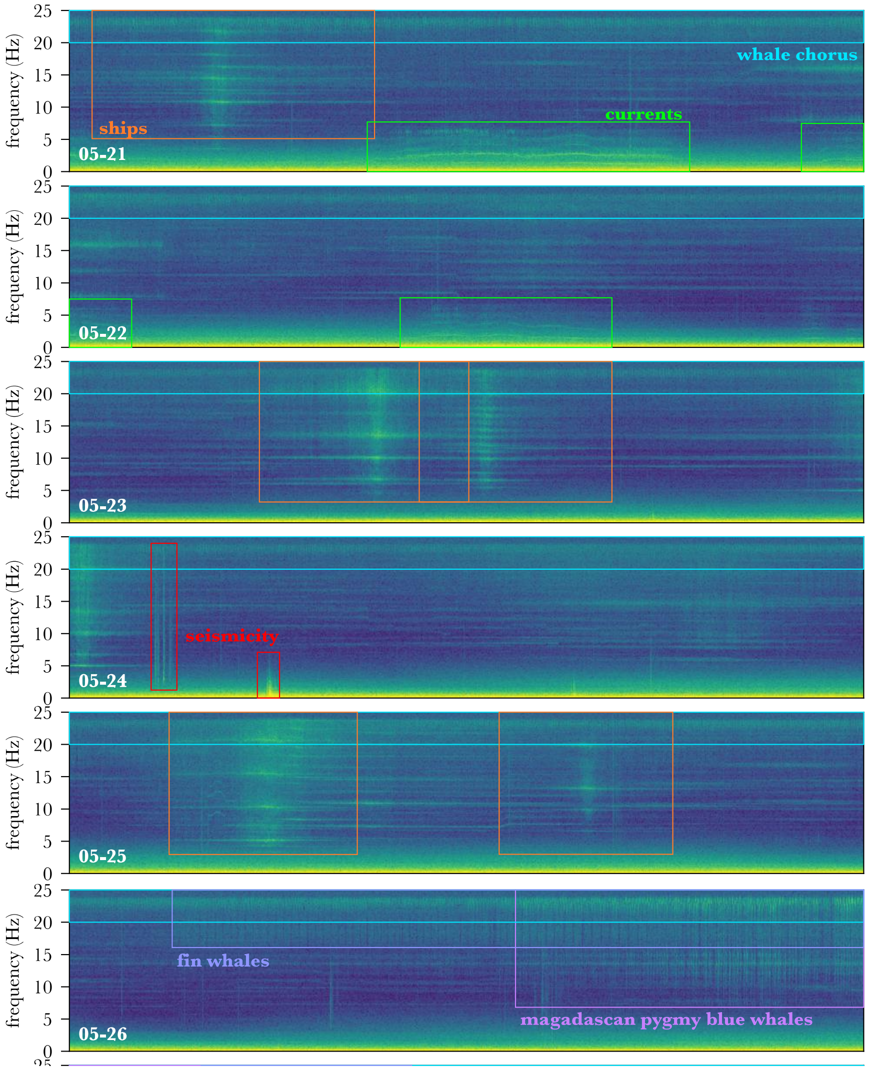
Two hydrophones targeting seismological and ocean acoustics frequencies.



www.ospar.org/work-areas/eiha/noise

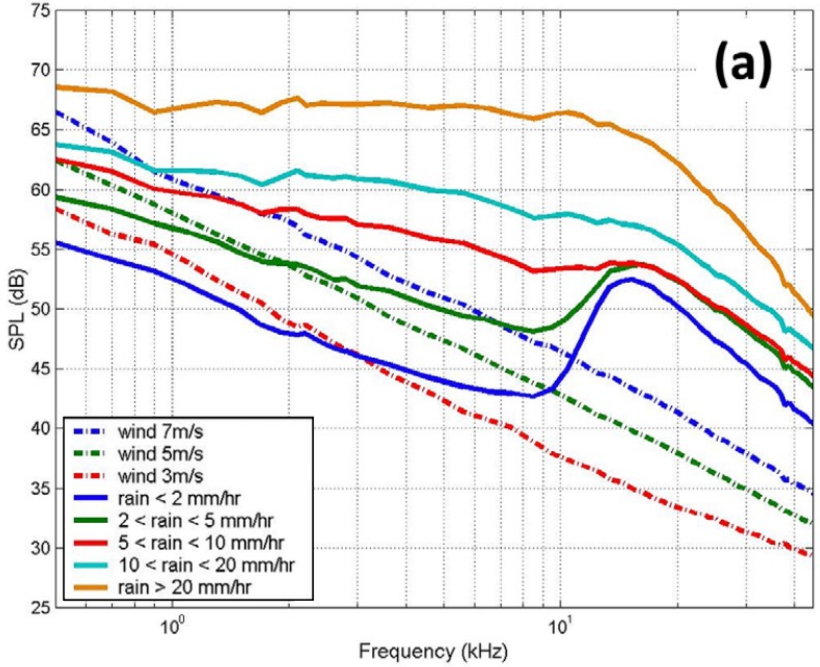
The targeted ocean sounds have long been recorded on ocean-bottom seismometers & hydrophones.

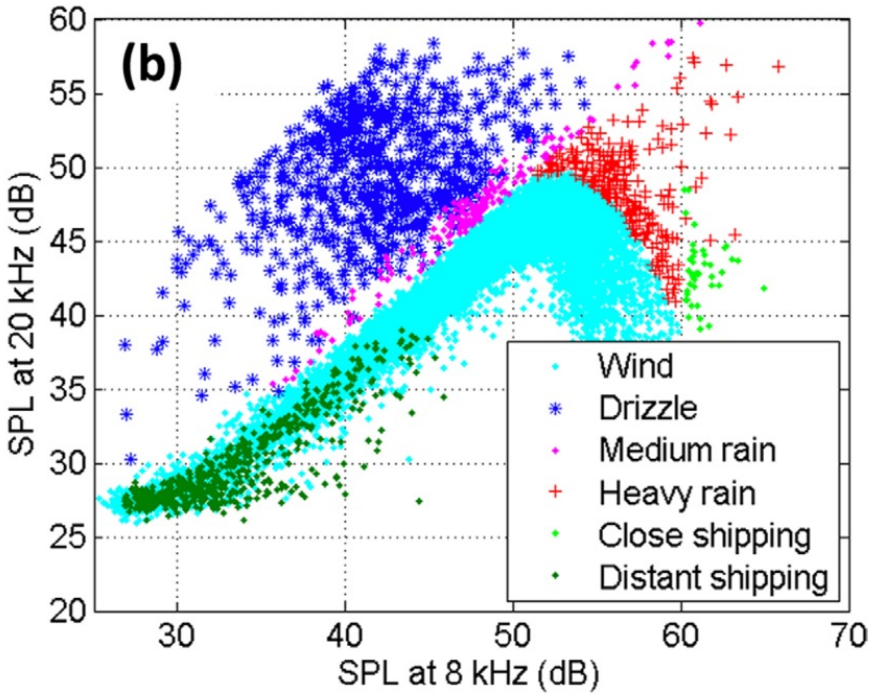
Six days of continuous spectrograms (21-26 May 2013) on an OBS' hydrophone near La Réunion island, southern Indian Ocean, shows transient signals of ship noise, various whale species, earthquakes and sea-bottom water currents. 5-25 Hz represents seismology's upper frequency limit, but ocean acoustics' "ultra-low" band.



Alister Trabattoni 2020 PhD thesis

In development: Embedded algorithm for acoustic proxies of wind, rain & sea state (MSc thesis I. Reinecke)





Yang, J., S.C. Riser, J.A. Nystuen, W.E. Asher, and A.T. Jessup. 2015. Regional rainfall measurements using the Passive Aquatic Listener during the SPURS field campaign. *Oceanography* 28(1):124–133.

Targeted application: Mapping ship noise in the open ocean.

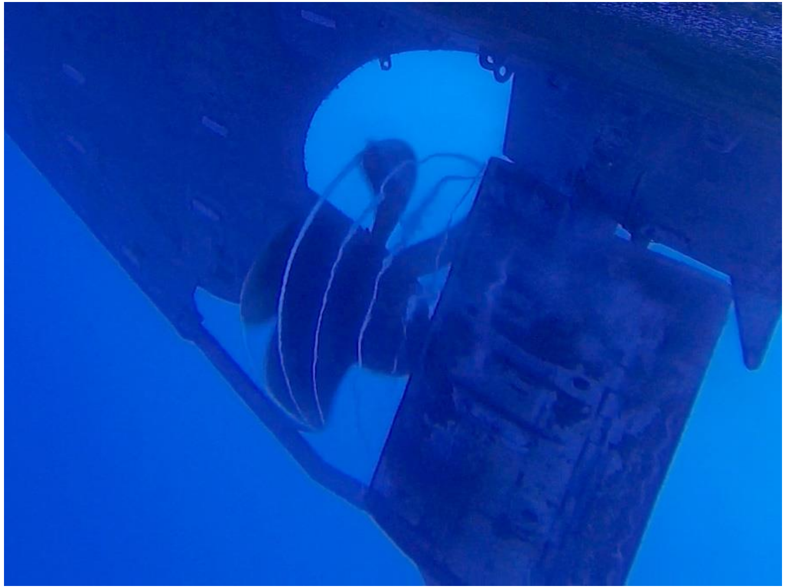


Figure 18. Cavitation generated by the propeller of the *R/V Meteor* during the RHUM-RUM recovery cruise. This phenomenon is due to a rapid pressure drop at the blade tips and produces high broadband acoustic noise.

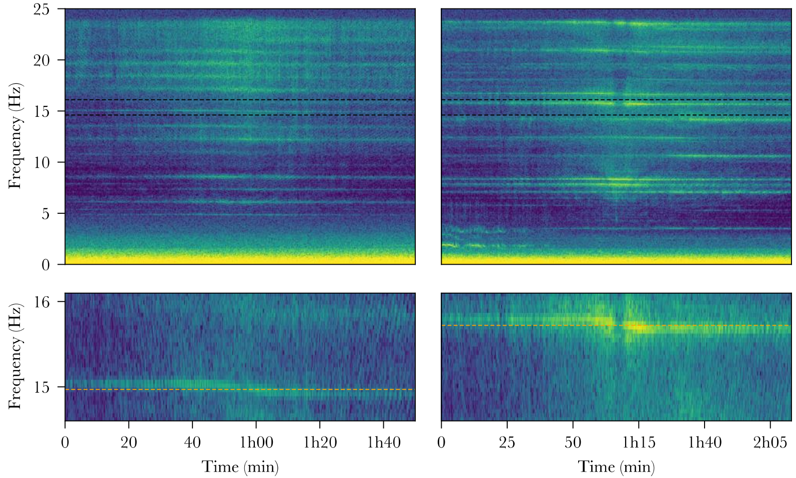


Figure 20. Examples of Doppler effects visible on hydrophone recordings of two ships passing near RR03. (a & b) Spectrograms when the two ships are at less than 30 km from the OBS. The first one (a) passes at about 3 km of the OBS and the second one (b) at about 6 km of the OBS. CPA time location is at the centre of the spectrograms. Different narrow-band peak structures can be observed for each ship corresponding to the activities of the propellers and blades. (c & d) Frequency zoom on the black dashed area: due to the Doppler effect the frequency peaks slightly shift around the true emitted frequency (extrapolated dashed orange line). The Doppler effect is null when the ship is travelling perpendicular to the OBS, hence at its closest point of approach.

Alister Trabattoni 2020 PhD thesis

Targeted application: Mapping whales in the open ocean.

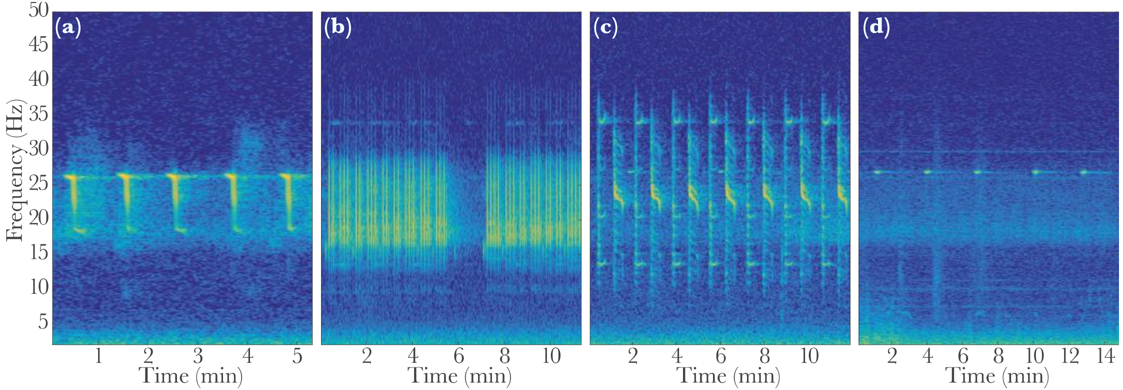


Figure 22. Different whale species recorded above the Southwest Indian Ridge during RHUM-RUM experiment, adapted from (Dréo *et al.* 2018). (a) Antarctic blue whale. (b) Fin whale. (c) Madagascan Pygmy blue whale. (d) Unknown P-call. Note that the fin whale on (b) stops singing around the 6th minute most likely to breathe at the surface. The duration of that break is characteristic of a species and is called the inter-series interval (ISI). Those recordings come from the few OBSs which were operating at 100 Hz. For other OBSs, the spectrogram is truncated at 25 Hz for DEPAS instruments and 31,25 Hz for INSU instruments.

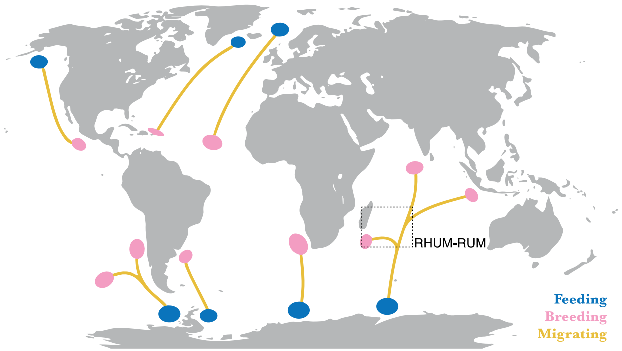
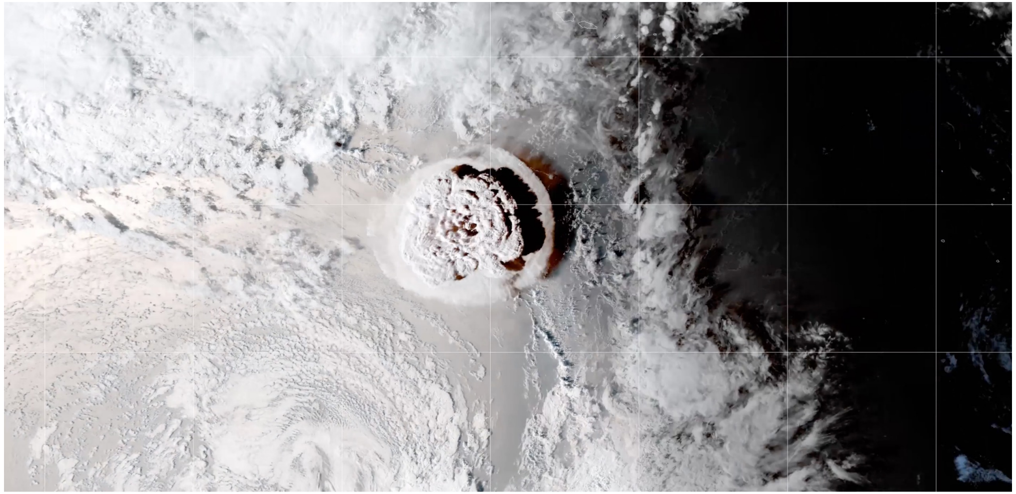


Figure 21. Migratory routes of blue whales. Other whales have different migratory routes, but the common pattern is to head to the Arctic/Antarctic in summer and to head to hot areas in winter. RHUM-RUM experiment is located on a breeding and migratory area, and a variety of species can be observed according to the period of the year. *Adapted from www.offthemap.travel*.

Various migrating whale species recorded on an ocean-bottom hydrophone near La Réunion .

Alister Trabattoni 2020 PhD thesis

Targeted applications: Underwater volcano eruptions (& tsunamis)



Hunga Tonga–Hunga Ha‘apai’s eruption was one of the most powerful on record. NASA Earth Observatory/NOAA/NESDIS/STAR

The Hunga Tonga eruption was recorded clearly by the current fleet of South Pacific MERMAID.

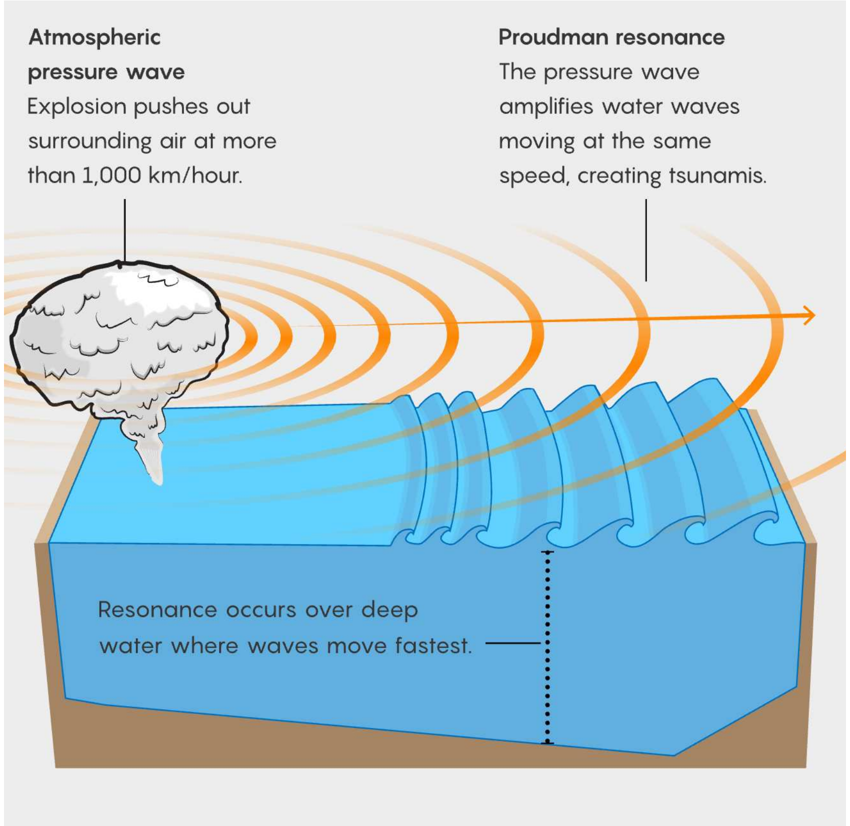


Image credit NASA / M. Sherman, Qanta magazine

Domain Specific Language “MeLa” implements applications, & hides the complexities of embedded programming.

In MeLa: **1** file / **20** lines of code

```
Mission:
    ParkTime: 7 days
    ParkDepth: 1500 meters

Coordinator:
    ParkAcqModes: helloFFT during 10 minutes every 1 hour

ContinuousAcqMode helloFFT:
Input:
    sensor: HydrophoneHF(20000)
    data: x(128)
    overlap: 32

Variables:
    Array spectrum(128)

RealTimeSequence main:
    spectrum = fft(x, 128, HANNING)
endseq;
endmode;
```

In C: **10** files / **442** lines of code

```
SRC_ROOT=src

CPPFLAGS+=-I$(SRC_ROOT)

LD_PATH=boards
######################################################################
SRC_SRC+=$(SRC_ROOT)/Coordinator_task.c
SRC_SRC+=$(SRC_ROOT)/shared.c

SRC_SRC+=$(SRC_ROOT)/Simple_task.c
SRC_SRC+=$(SRC_ROOT)/HydrophoneBF_task.c
```

```
void Coordinator_task(void* parametres) {
    init_board(0);
    Simple_semaphore = xSemaphoreCreateMutex();
    xTaskCreate(Simple_task, "Simple_task", 2048, NULL, 3, &Simple_task_handle);
    xTaskCreate(HydrophoneBF_task, "HydrophoneBF_task", 2048, NULL, 19, &HydrophoneBF
    while(1) {
        _update_mission_sequence();
        _wait_low_power_mode(1000);
    }
}
```

```
void HydrophoneBF_task(void * parameters){
    int32_t sample;
    int i = 0;
    xSemaphore = xSemaphoreCreateMutex();
    xSemaphoreTake(Simple_semaphore, portMAX_DELAY);
    vTaskSuspend(NULL);
    while (1) {
        sample = get_HydrophoneBF_sample();
        if (Simple_require_samples) {
            x_Simple_fill->data[i] = sample;
            i ++;
            if (i >= x_Simple_fill->len) {
                if (x_Simple_fill == &x_Simple_buff_1) {
                    x_Simple_process = &x_Simple_buff_1;
                    x_Simple_fill = &x_Simple_buff_2;
                }
                else {
                    x_Simple_process = &x_Simple_buff_2;
                    x_Simple_fill = &x_Simple_buff_1;
```

```
if (mission_step == DESCENT) {
    descent_cycle_time_s = getsdate() - descent_start_time_s;
    if (!Simple_is_running) {
        resume_Simple_task();
    }
}
else if (mission_step == PARK) {
    park_cycle_time_s = getsdate() - park_start_time_s;
    if (!Simple_is_running) {
        resume_Simple_task();
    }
    if (Simple_is_running) {
        suspend_Simple_task();
    }
}
else if (mission_step == ASCENT) {
    ascent_cycle_time_s = getsdate() - ascent_start_time_s;
    if (!Simple_is_running) {
        resume_Simple_task();
    }
    if (Simple_is_running) {
        suspend_Simple_task();
    }
}
else if (mission_step == SURFACE) {
    surface_cycle_time_s = getsdate() - surface_start_time_s;
    if (Simple_is_running) {
        suspend_Simple_task();
    }
    if (buffer_to_flush == true) {
        serialPrintString("Write on files\n");
        buffer_to_flush = false;
    }
```

```
void resume_Simple_task() {
    Simple_require_samples = true;
    ask_start_HydrophoneBF();
    vTaskResume(Simple_task_handle);
    Simple_is_running = true;
}
```

```
void suspend_Simple_task() {
    Simple_require_samples = false;
    ask_stop_HydrophoneBF();
    vTaskSuspend(Simple_task_handle);
    Simple_is_running = false;
```

Domain Specific Language “MeLa” checks & arbritrates the applications’ resource requirements.

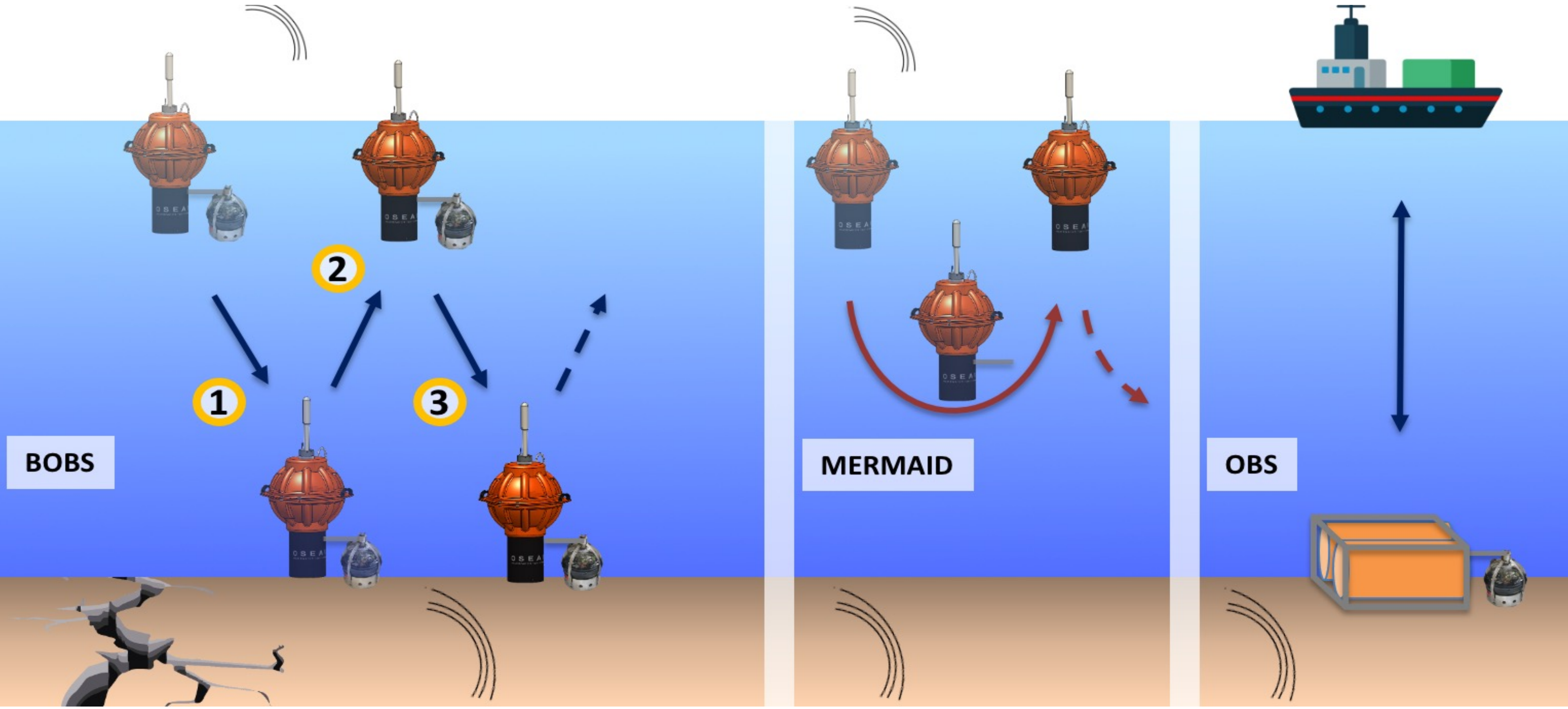
Success

Autonomy:
242 cycles
5.2 years

Energy consumption rate:

Mission step	Processor (%)	Sensors (%)	Transmission (%)	Actuators (%)
Descent	0.3	0	0	1.1
Park	33.3	37.7	0	0
Ascent	0.1	0	0	25.9
Surface	0	0	1.6	0

Perspective: deep (4000-6000m) and seafloor-landing models are in development.



Synergies sought with the ocean sciences

Perspectives include:

- Acoustics up to 20 kHz
- Non-acoustic measurements
- Bottom-landing float (built & tested)
- Descent to 6000 m depth (funded)
- YOUR application?