Seismic sensors and infrasound microphones

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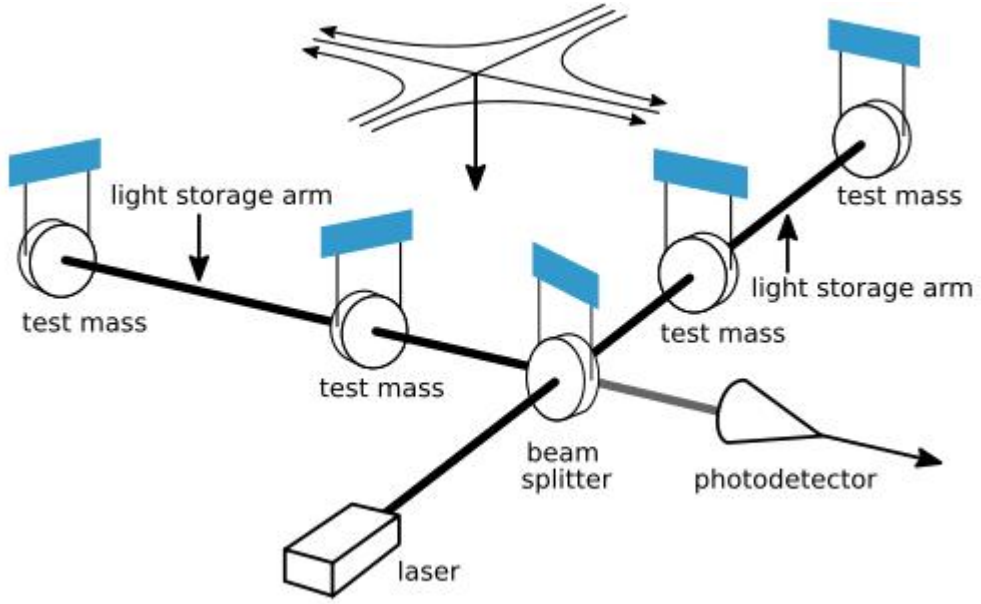
Seismic Sensor Development for Gravitational-Wave Detectors

- Motivation: Newtonian Noise
- Newtonian noise is caused by time-varying gravitational fields generated by seismic and atmospheric density fluctuations, which directly perturb the interferometer's test masses



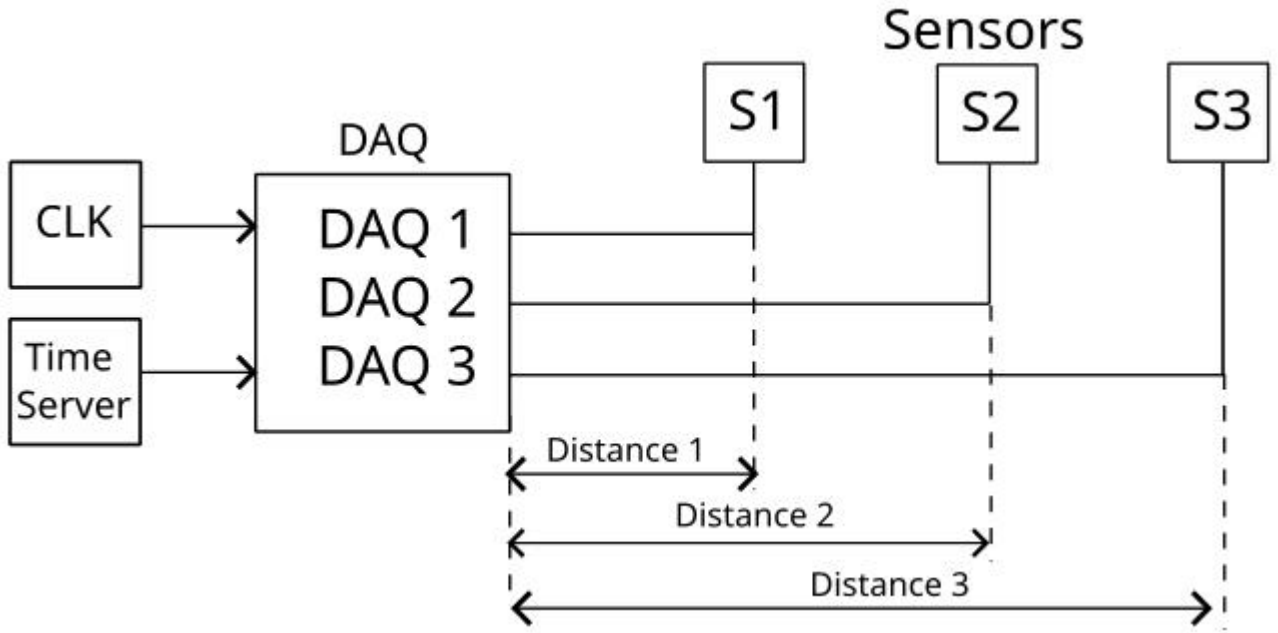
en.wikipedia.org/wiki/Gravitational-wave_observatory

www.virgo-gw.eu/science/detector/

- Direct gravitational coupling to the suspended test masses
- Relevant at low frequencies

Typical local data acquisition system

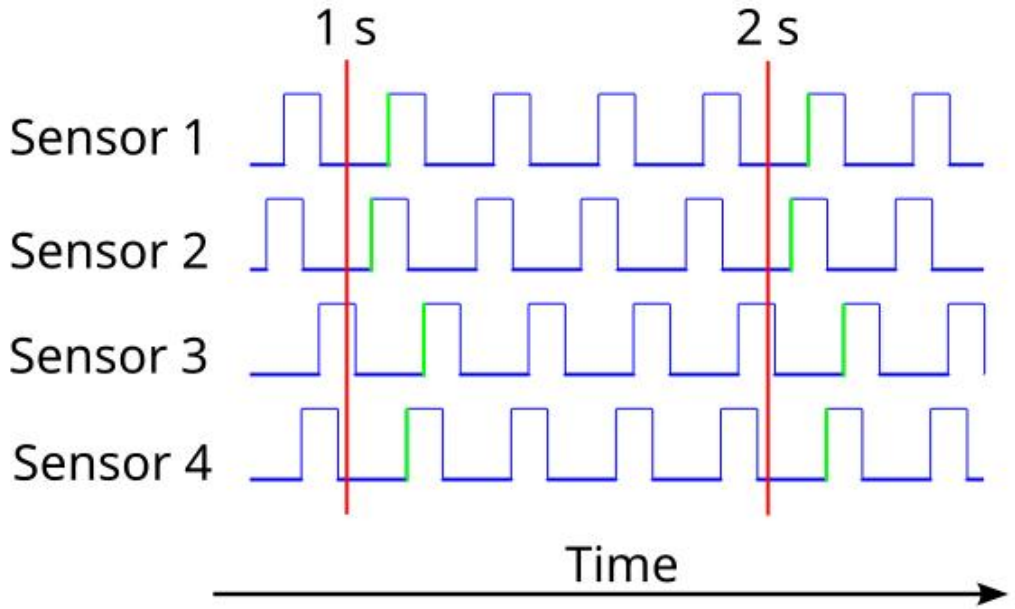
- A single data acquisition system
- An analog signal from each sensor connected to the DAQ system
- External noise degrades signal quality



Clock drift in distributed coherent sampling

- Typical oscillator stability is on the order of ±10 to ±50 ppm
- Frequency differences between local clocks lead to time drift between acquisition nodes (sensors)
- The timing error can reach several microseconds within seconds and increases over time

```
sensor 1 d0 d1 d2 d3 d4 ... dN
sensor 2 d0 d1 d2 d3 d4 ... dN
sensor 3 d0 d1 d2 d3 d4 ... dN
sensor 4 d0 d1 d2 d3 d4 ... dN
sensor 5 d0 d1 d2 d3 d4 ... dN
sensor 6 d0 d1 d2 d3 d4 ... dN
sensor 7 d0 d1 d2 d3 d4 ... dN
sensor 8 d0 d1 d2 d3 d4 ... dN
```

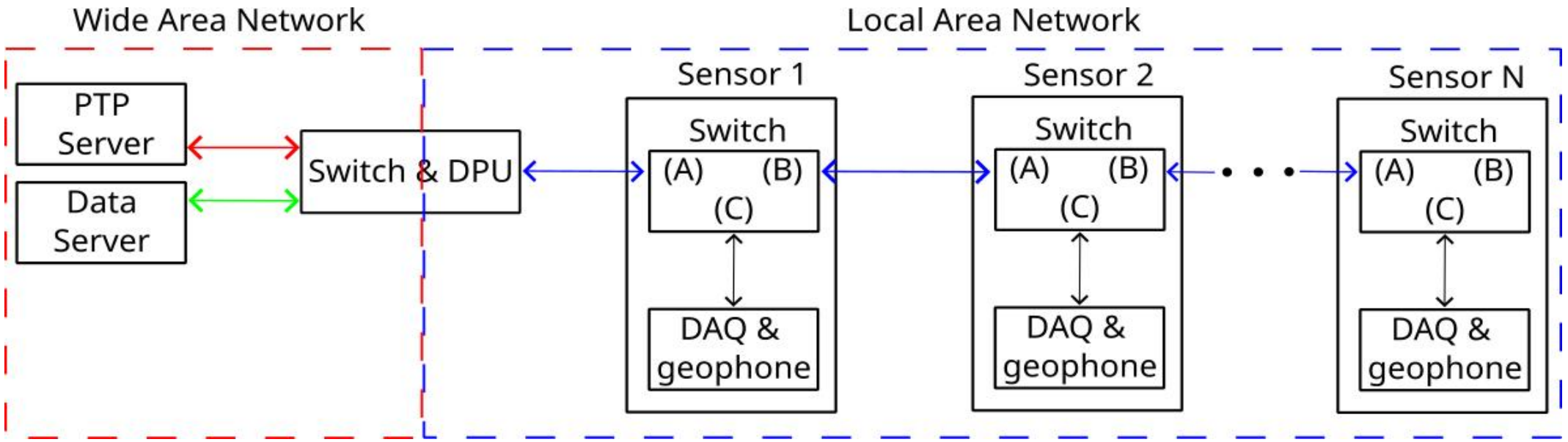


Sensors - Indoor and Outdoor

- A complitly different design approach, to the deployment environment and system integration requirements
- **Indoor sensors**: networked sensing nodes with shared power and communication infrastructure (e.g., PoE), synchronized via a dedicated 1PPS signal or Precision Time Protocol (PTP)
- **Outdoor sensors**: designed for harsh environmental conditions, including wide temperature and humidity variations, with autonomous power supplies and independent GPS-based time synchronization

Second generation of seismic sensors

- Power supply, PoE++ (upgraded to 200 W per channel)
- Connections ethernet 1000 MB/s
- Synchronisation via Time Server -> PTP (Precision Time Protocol) 1588v2 (IEEE 1588-2008)



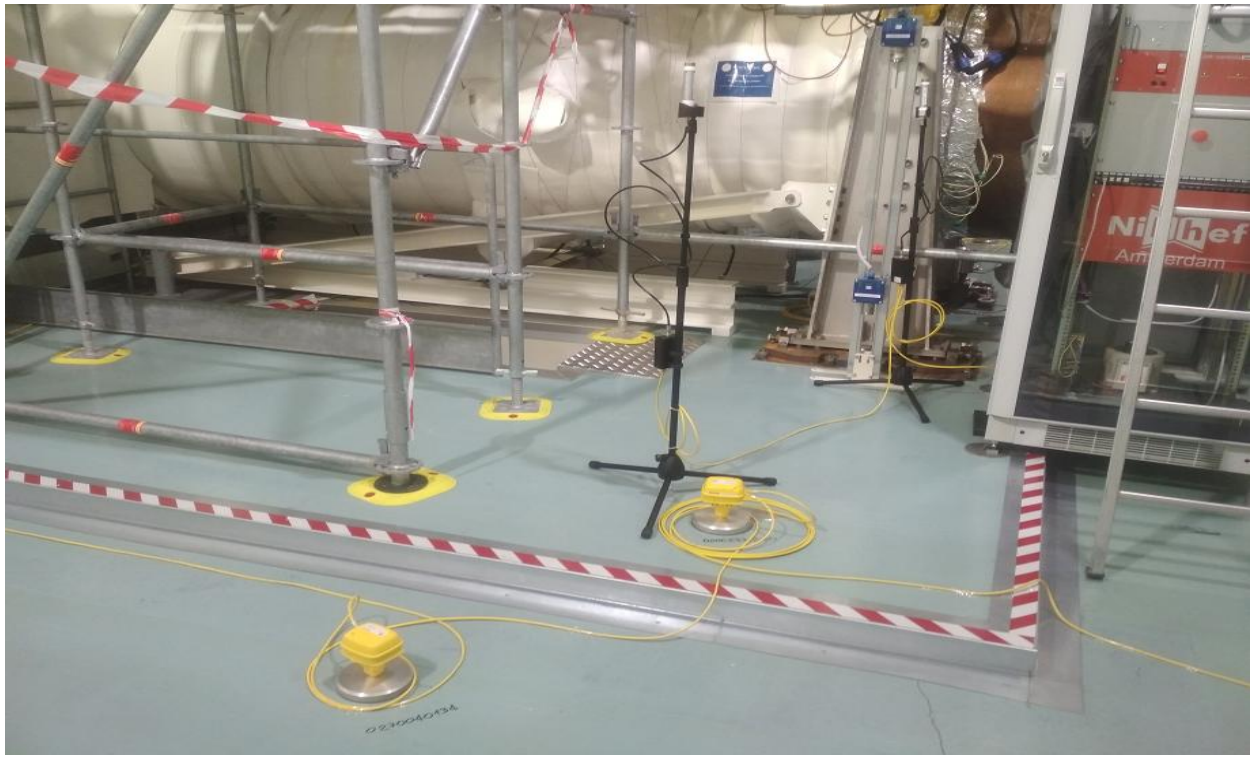
Current status of sensors at VIRGO

Installed sensors in **NEB, WEB, CEB** buildings from 2019/2020:

- CEB 85 (55 seismics + 30 infrasounds)
- NEB 38 (30 seismics + 8 infrasounds)
- WEB 56 (30 seismics + 26 infrasounds)

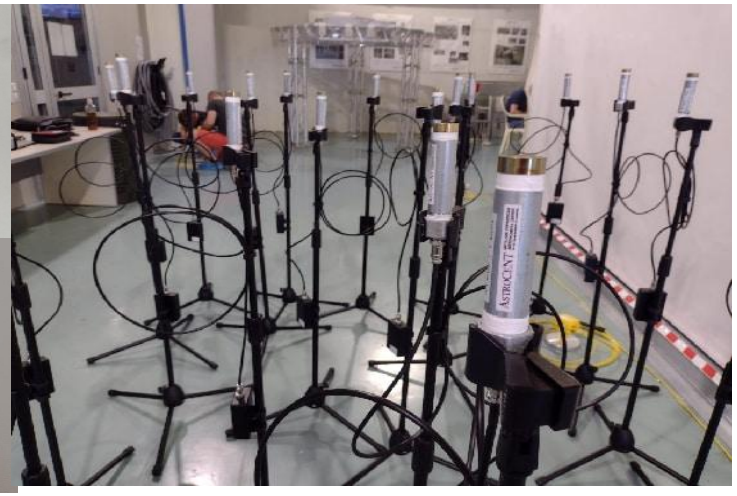
Total 179 seismic (115) and infrasound (64) sensors

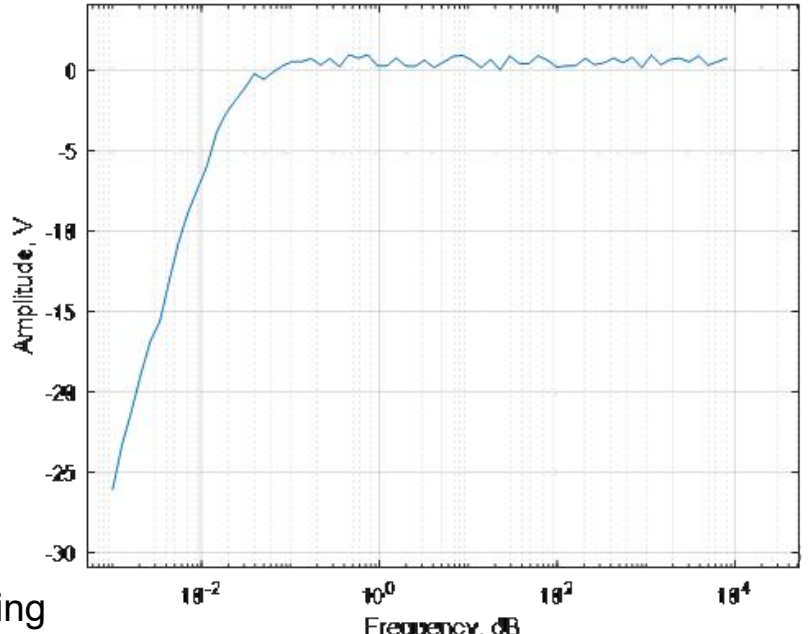
Also more than a dozen more are planned to be added



Infrasound microphones

- Developed to meet Virgo's requirements for infrasound monitoring and the characterization of environmental acoustic noise
- Designed to measure low-frequency infrasound noise and atmospheric pressure fluctuations
- Frequency range from 0.04 Hz to 15 kHz (commercial devices starts from 0.09 Hz to 20 kHz)
- Sensitivity: 26 mV/Pa (commercial devices 8 mV/Pa), distortion max. 1 dB





Infrasounds stations in Sardynia

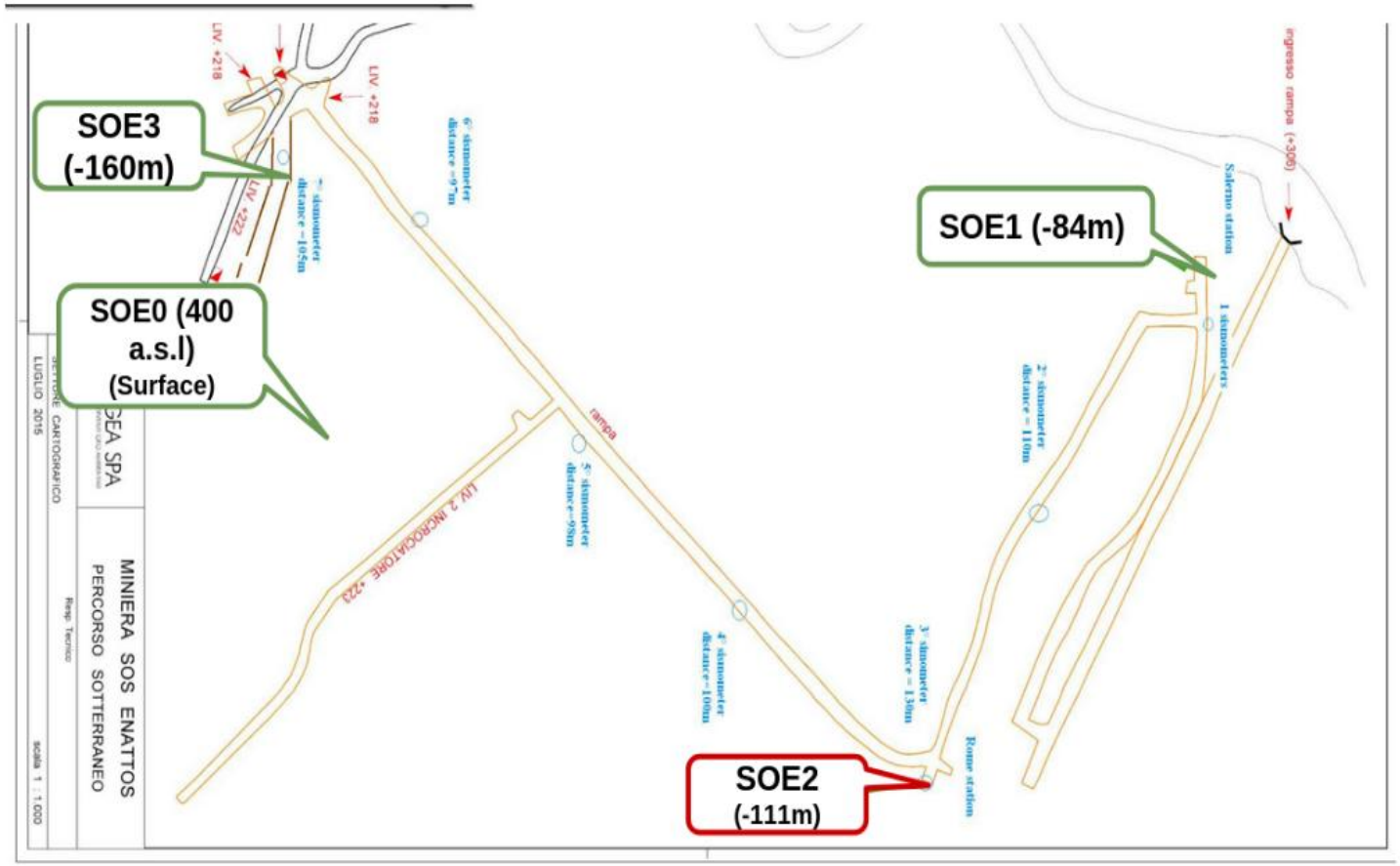
ST0 - Surface Station

SOE1 Underground station

Sites

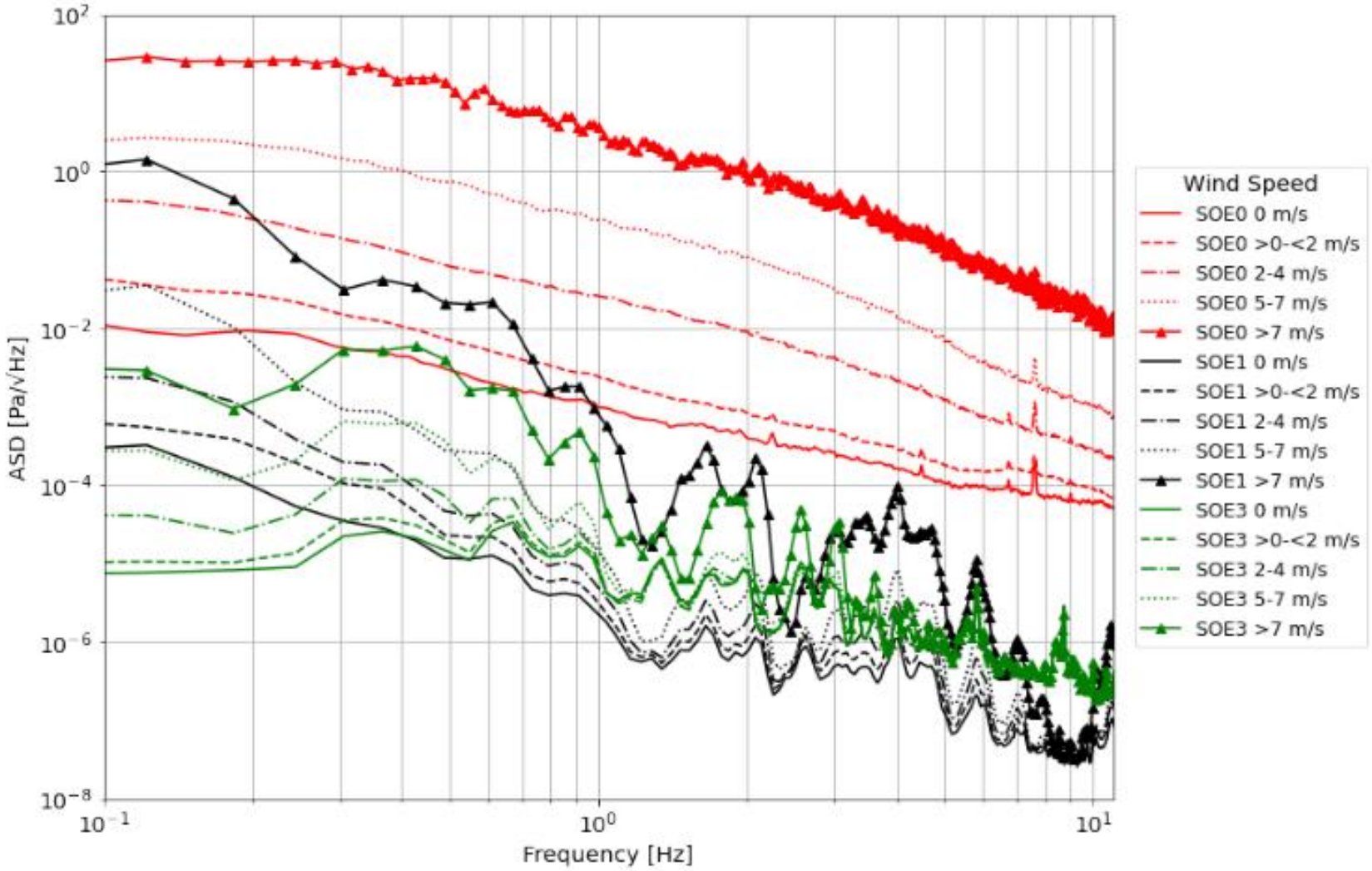
- **SOE0:** surface station
- **SOE1:** shallow installation
- **SOE3:** underground station (~160 m depth)
- Continuous monitoring from around **2022/11 to 2024/09**

Microphone locations



Wind speed dependence

- **Dominant control parameter** across all sites
- SOE0: several orders-of-magnitude rise between calm and >7 m/s winds
- SOE1: similar but weaker response
- SOE3: least sensitive yet systematic increase



Seismic sensors, then and new

Seismic sensors:

- Ethernet based seismic sensor
- The previous version unfortunately is not 100% compatible with ethernet standard, it requires additional power supply and synchronization in the ethernet cable RJ45)
- New generation sensor 100% compatible with Ethernet standard, powered by PoE+ (+48 V), 1 Gb ethernet, synchronization by clock from PTP server

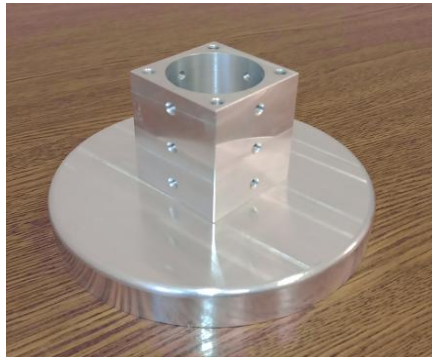
Old sensor

New sensor

Seismic sensors

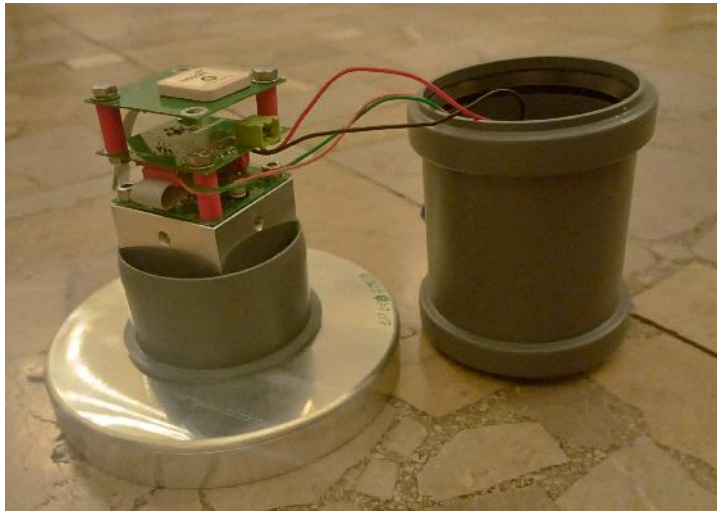
The single seismic sensor consists of:

- a geophone sensor
- mechanical components for its construction
- and an ethernet data acquisition system

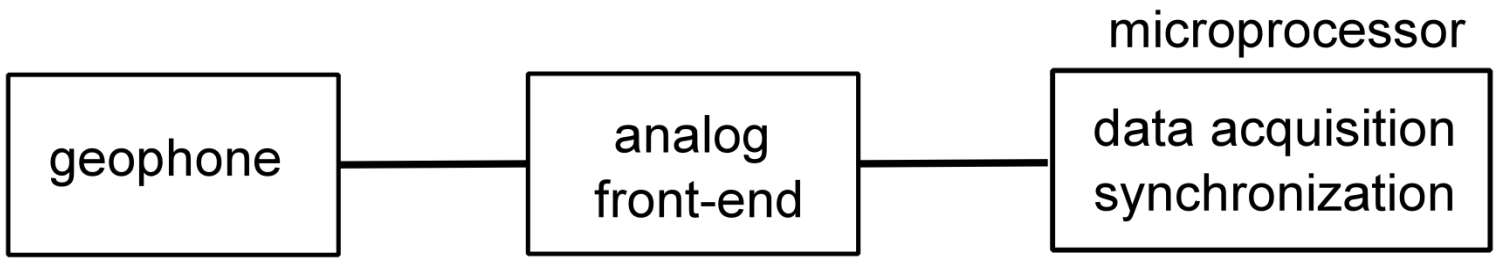


Outdoor sensors

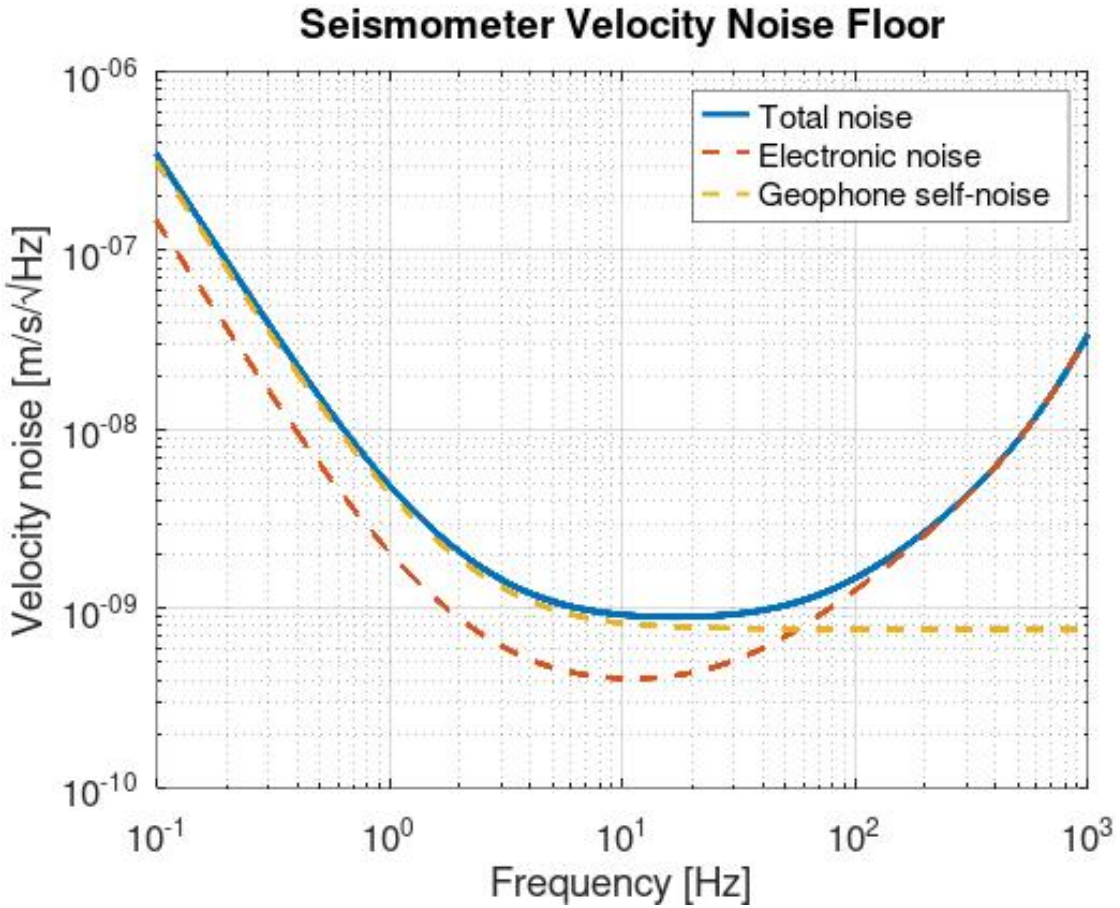
- Independent sensor
- Self synchronized (GPS synchronized)
- Independent power supply
- Waterproof casing

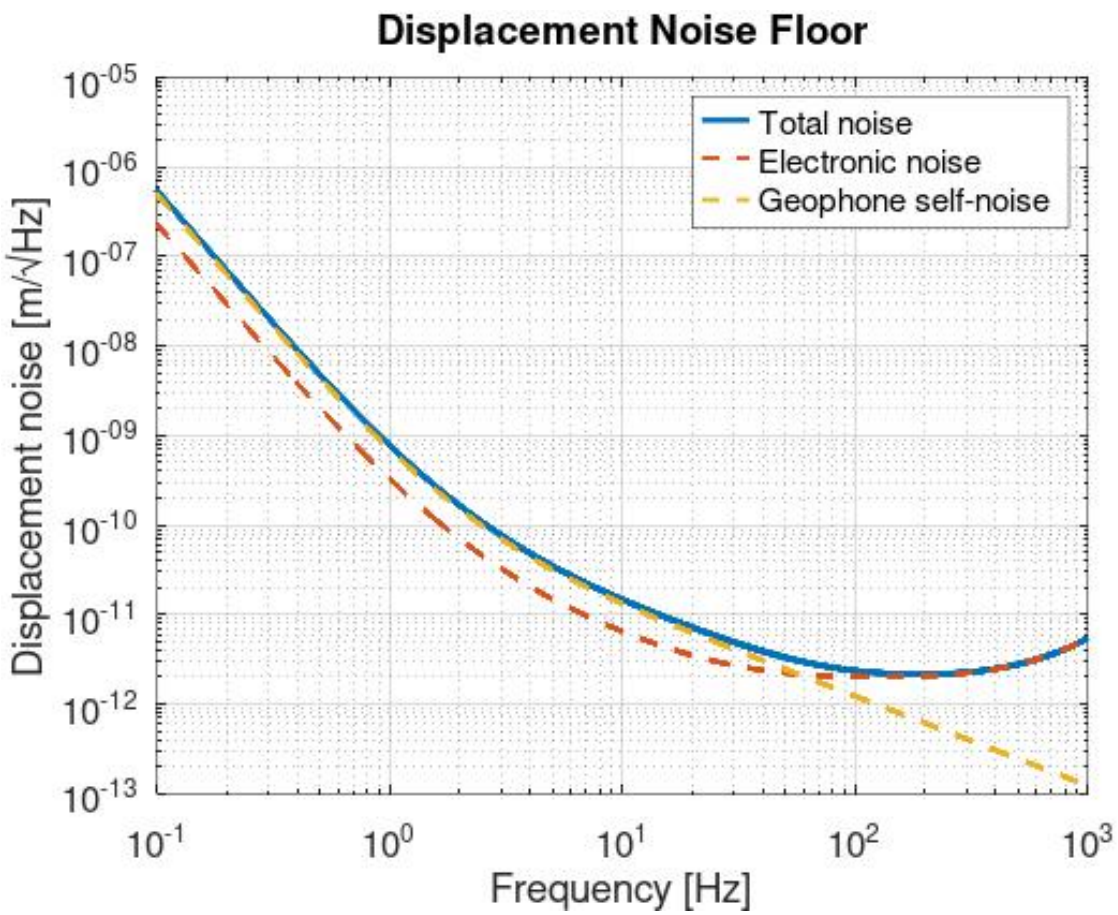


- Signal flow diagram

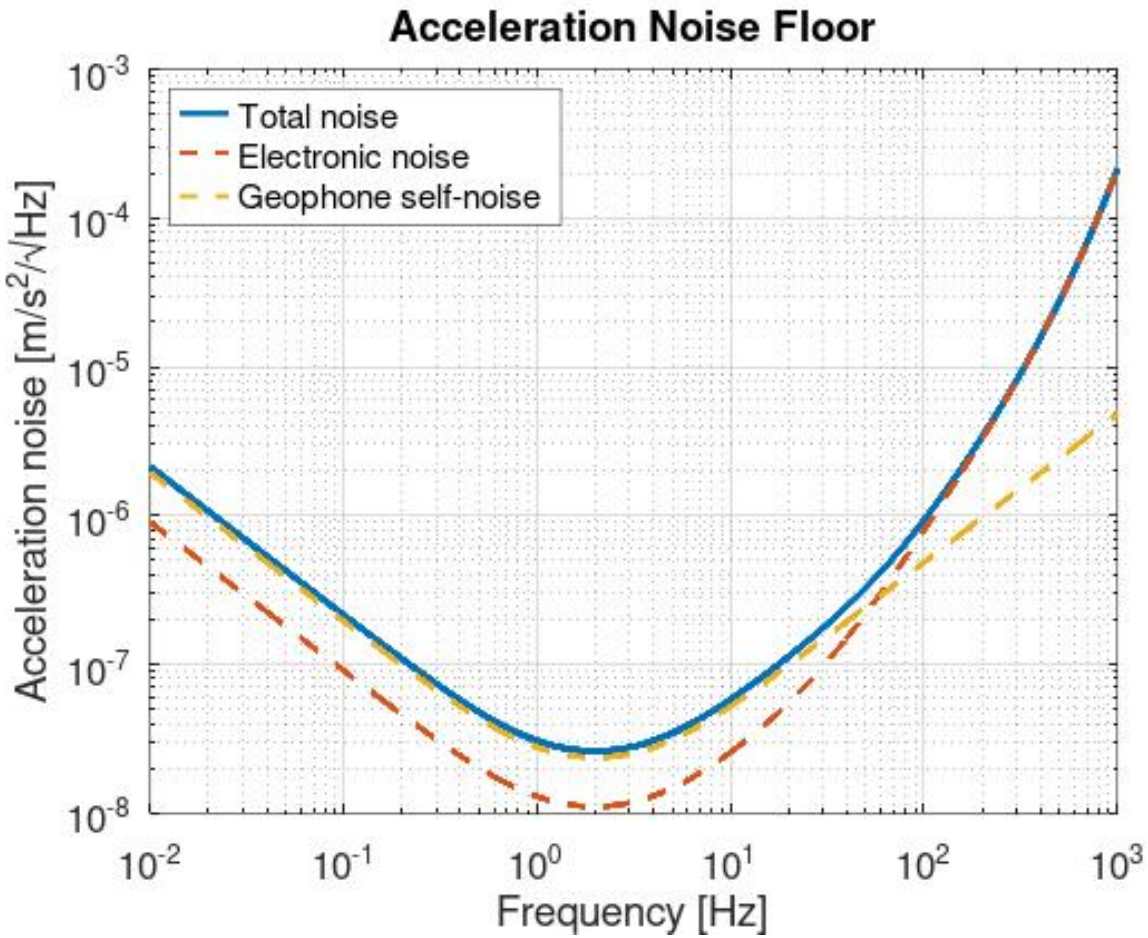


Sensor noise floor



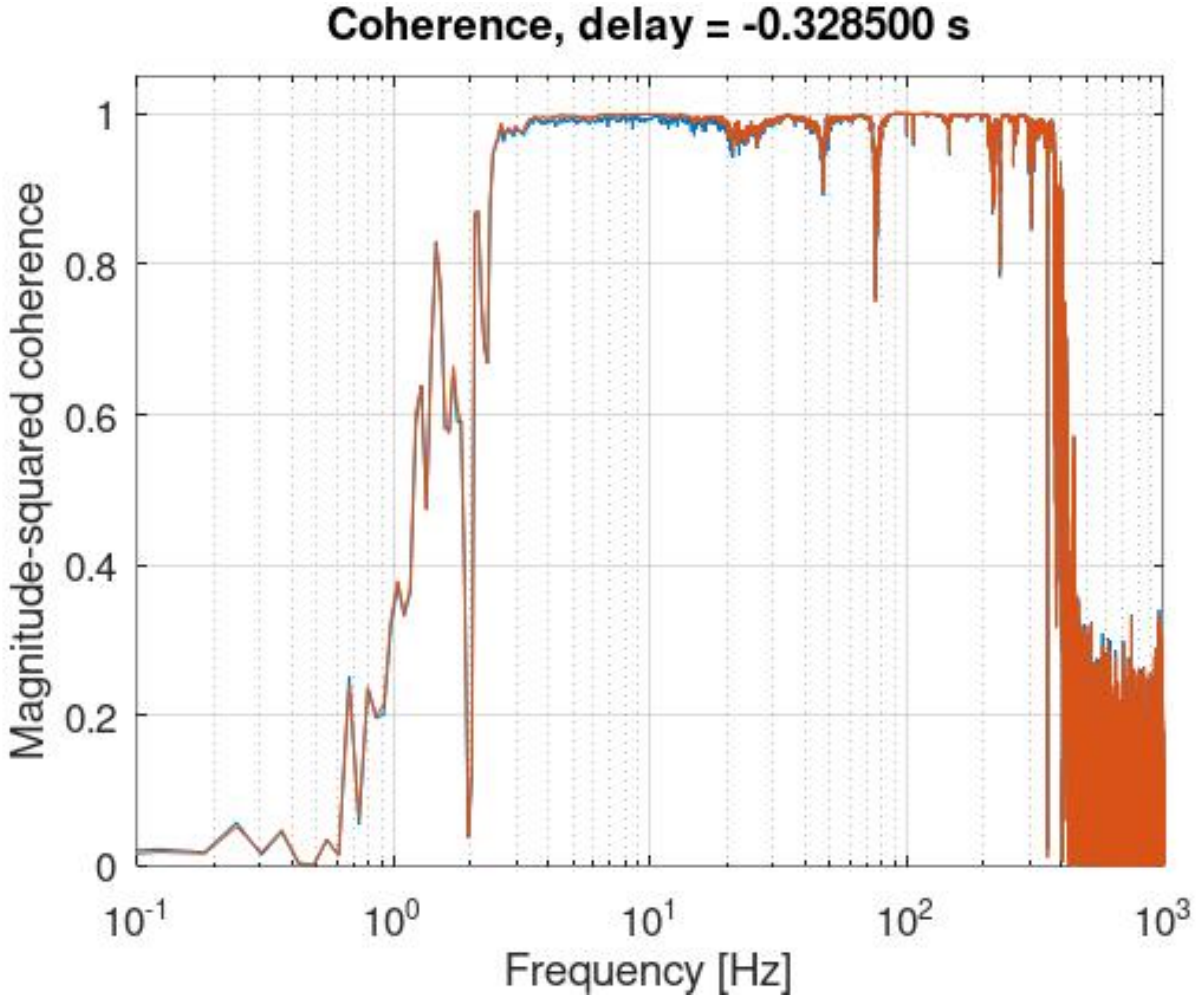


Sensor noise floor



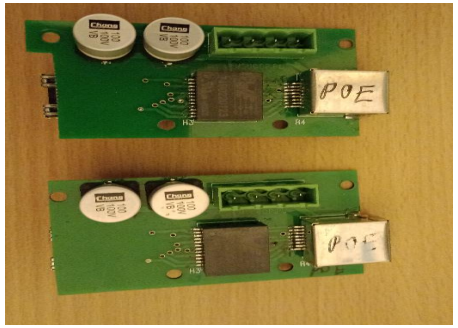
Coherence between sensors

Geophone 2.0 Hz ... closer to 2.5 Hz



DPU Data Processing Unit - tests

- We have assembled 5x DPU
- single ethernet PoE++ testers



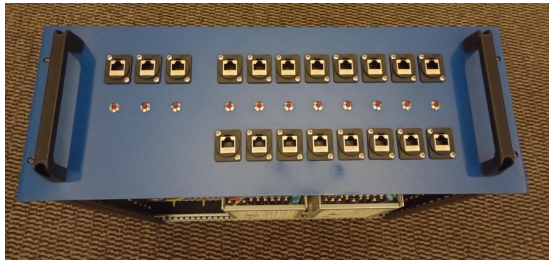
- power supply load tester (200 W)

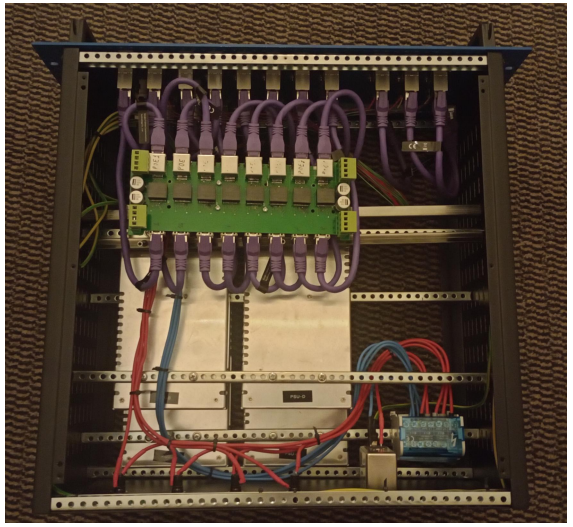
typically single switch 65 Ω (48 V, only 33.3 W)

Cable length 20 m, load 200 W, 48 V

cable cat., voltage drop across the cable

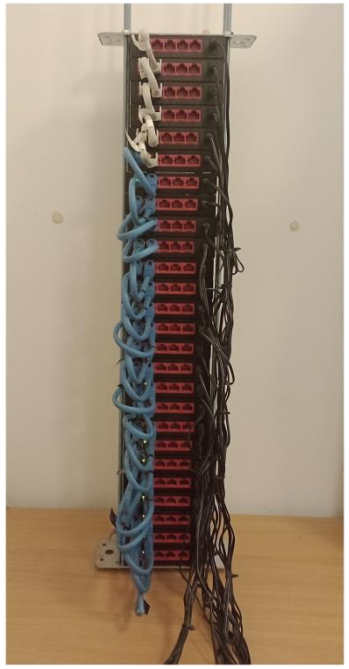
- cat. 5e 8 V
- cat. 6 8 V
- cat. 6a 4 V

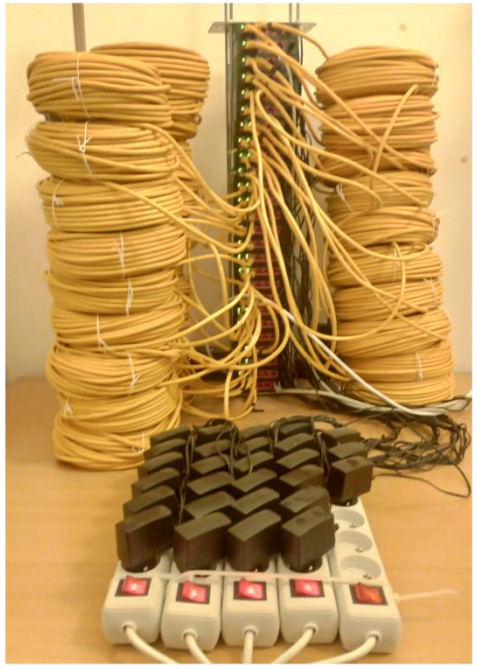


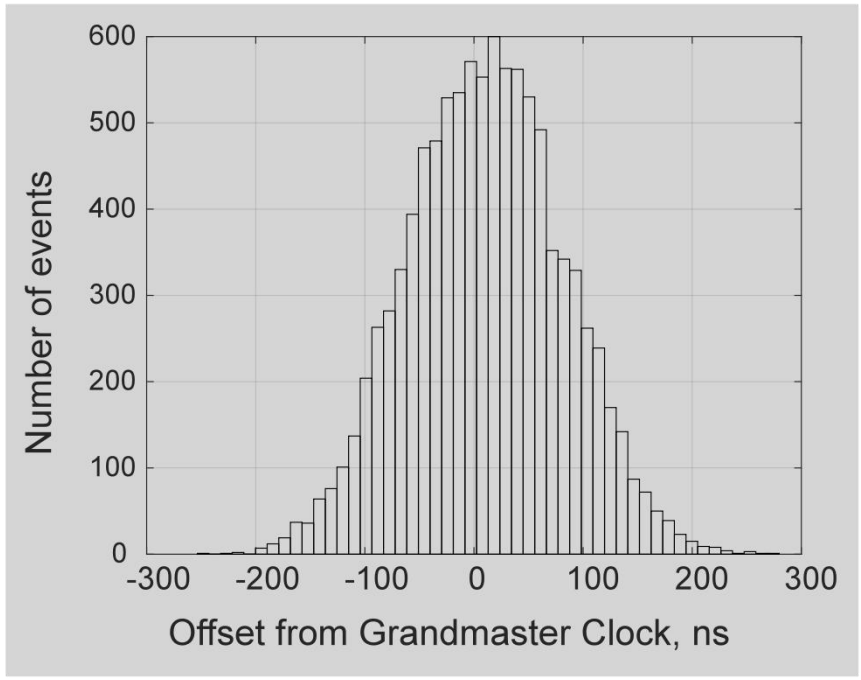


Clock Synchronization Test

- Tests conducted over more than 24 chained switches
- demonstrated synchronization stability sufficient for coherent data acquisition
- software synchronization offset from -200 ns to +200 ns







Summary

- OAUW + CAMK are preparing 200 new seismic sensors for VIRGO, including 10–20 external sensors and 180–190 internal sensors - Installation planned for 2027
- The next generation of seismic sensors are:
  - more sensitive sensors 10x and
  - have a wider frequency range starting at 2 Hz (4.5 Hz old)
- Unification and standardization: important is the integration of power delivery (PoE) and data transmission (ethernet), clock distribution (PTP protocol)

Thank you for your attention

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