

From data acquisition to noise mitigation, environmental sensor arrays in Gravitational-Wave Observatories



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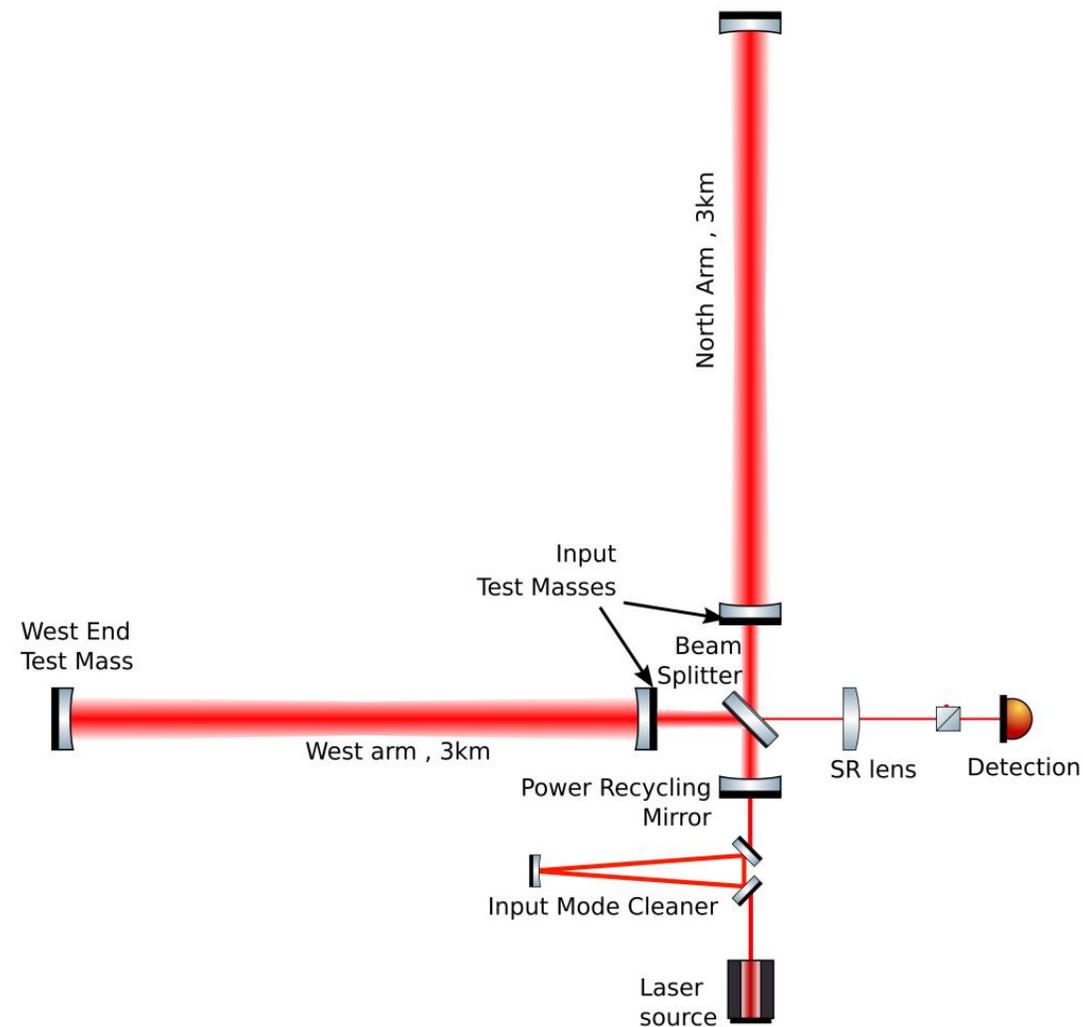
**ASTRONOMICAL
OBSERVATORY**
UNIVERSITY OF WARSAW

Astronomical Observatory of the University of Warsaw

Nicolaus Copernicus Astronomical Center Polish Academy of Sciences

The Virgo Collaboration

- Laser interferometer, 3-km arms
- Mirrors suspended



Environmental Noise Sources

Gravitational-wave observatories measure extremely small distortions of spacetime produced by astrophysical events such as binary black hole mergers and neutron star collisions

Noise Sources

- seismic motion, acoustic noise, atmospheric pressure fluctuations
- magnetic fields, human activity

Time Synchronization

- Coherent analysis of signals across sensors
- Wavefront reconstruction
- Accurate phase comparison

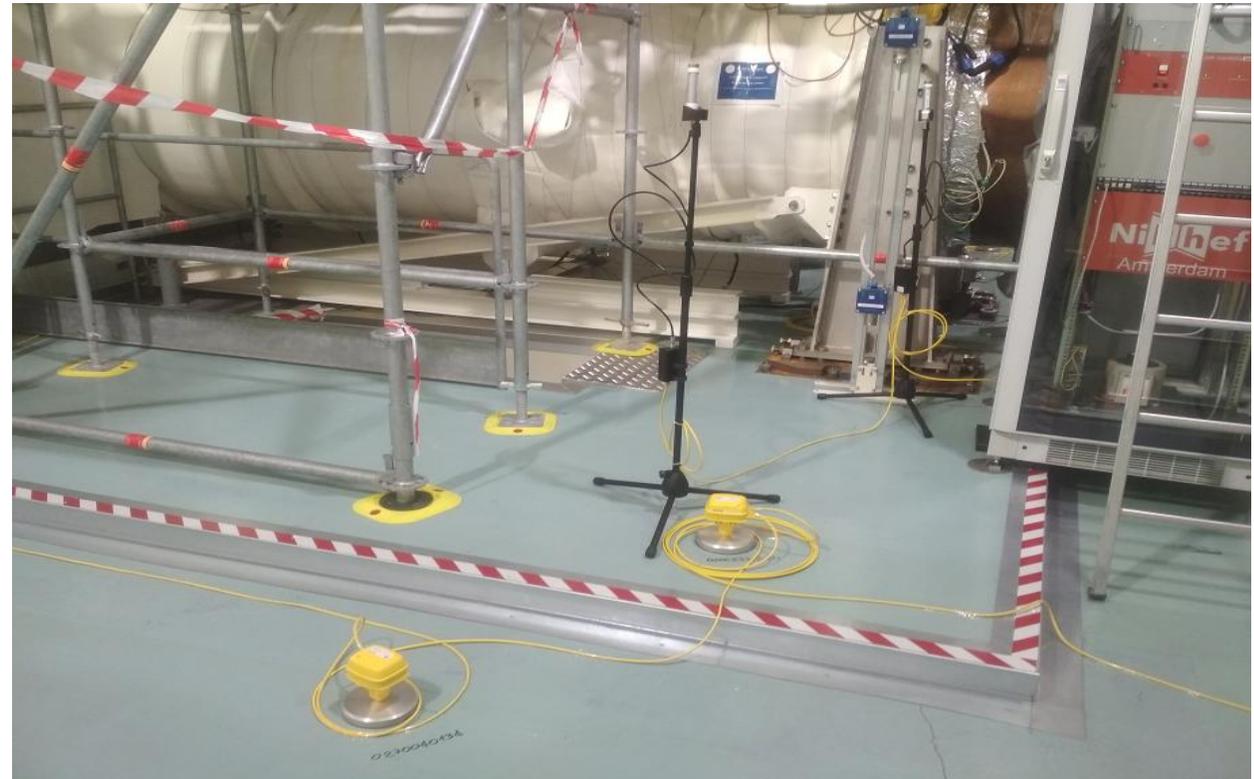
Precise timing is critical for environmental sensor arrays

Current Status - 2026

Installed sensors in **NEB, WEB, CEB** buildings:

- 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



New and Old seismic sensor

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



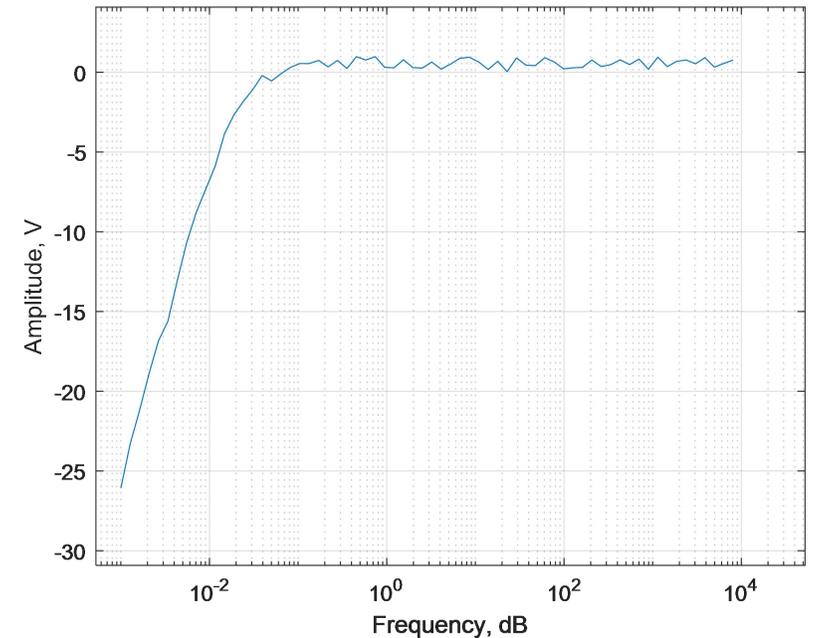
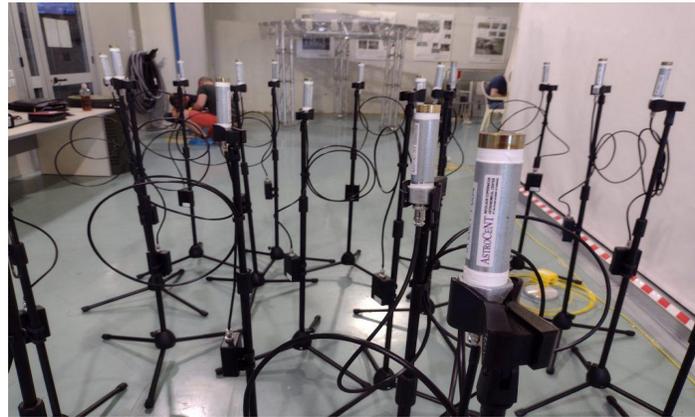
New sensor



Infrasound sensors (microphones)

- Developed sensor
- Frequency range from 0.04 Hz to 120 Hz (commercial devices starts from 0.09 Hz to 15 kHz)
- Sensitivity: 26 mV/Pa (commercial devices 8 mV/Pa)
- Distortion max. 1 dB

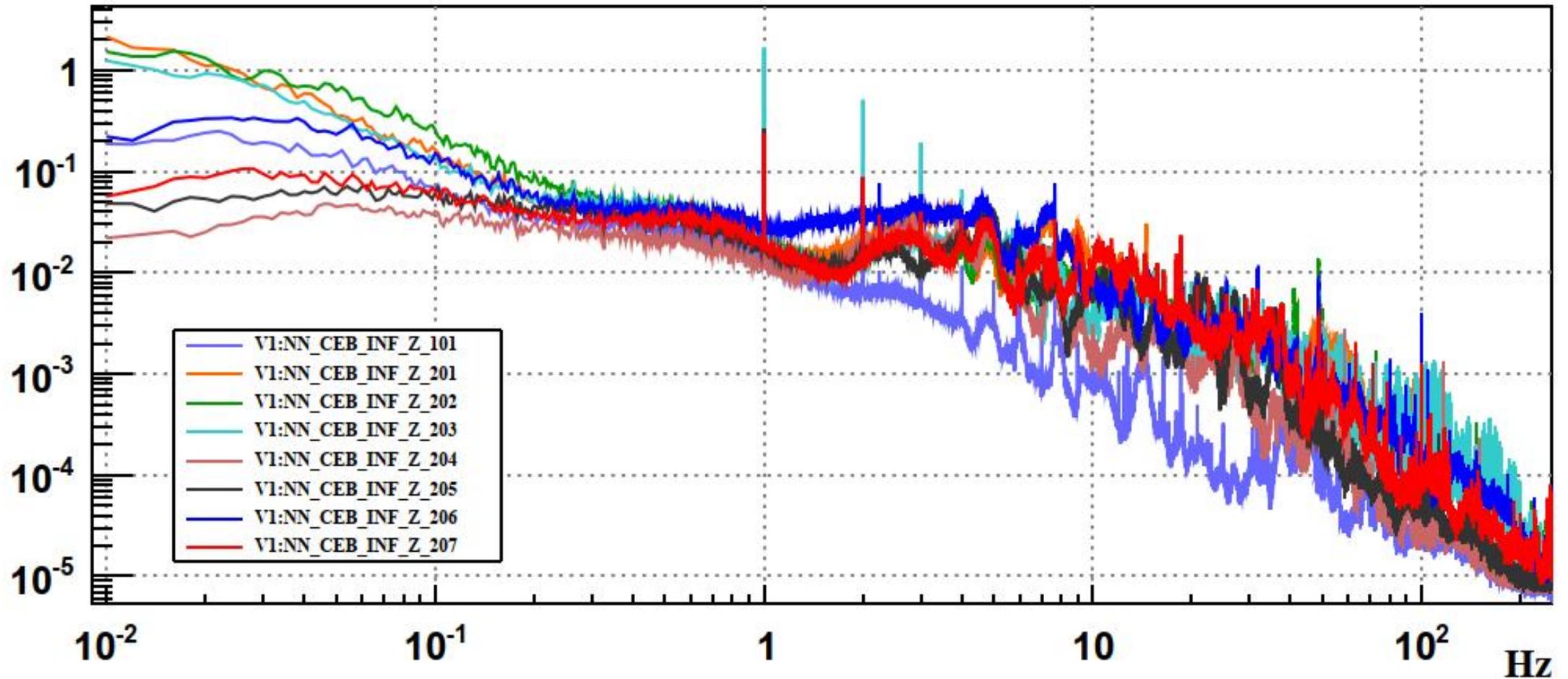
New version (final release)



Prototype

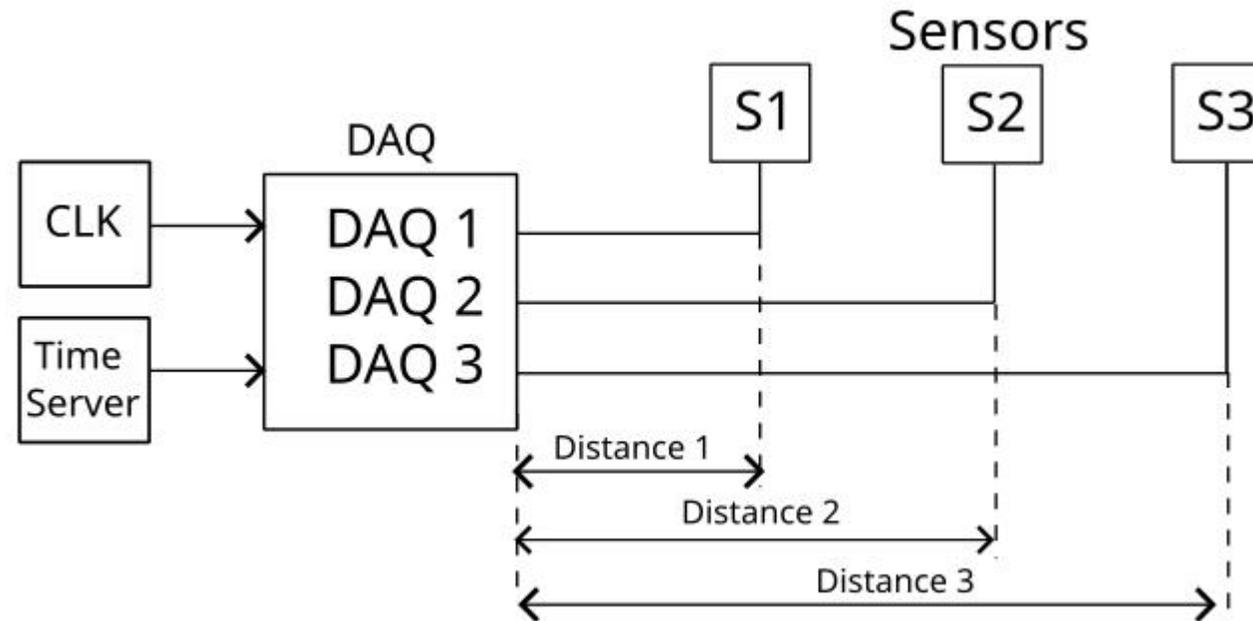


Infrasound signal from CEB building VIRGO



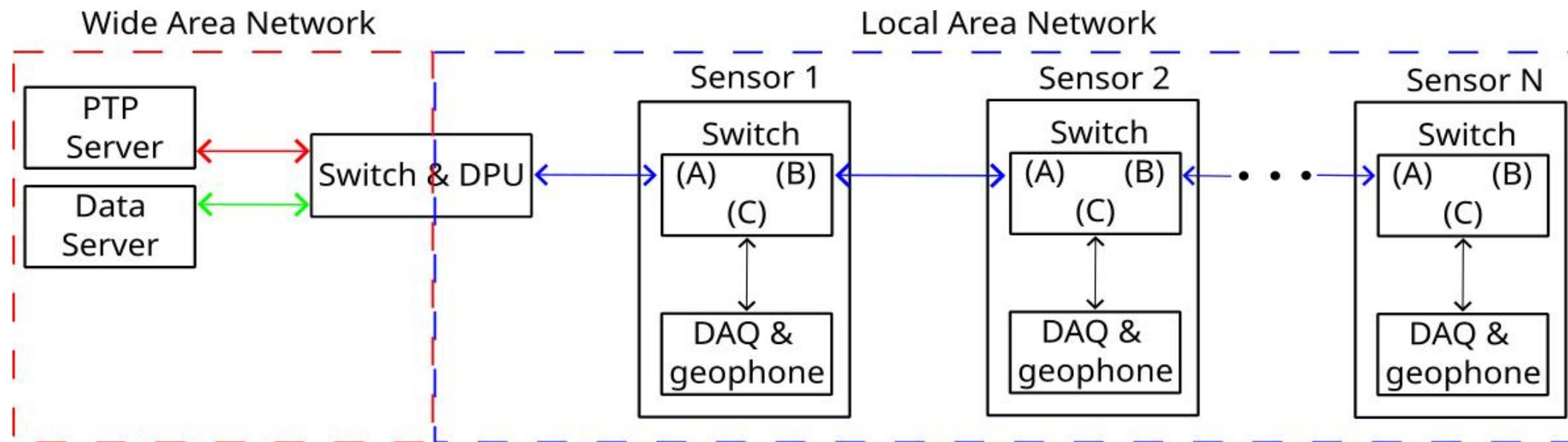
Typical local data acquisition system

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



Second generation of seismic sensors

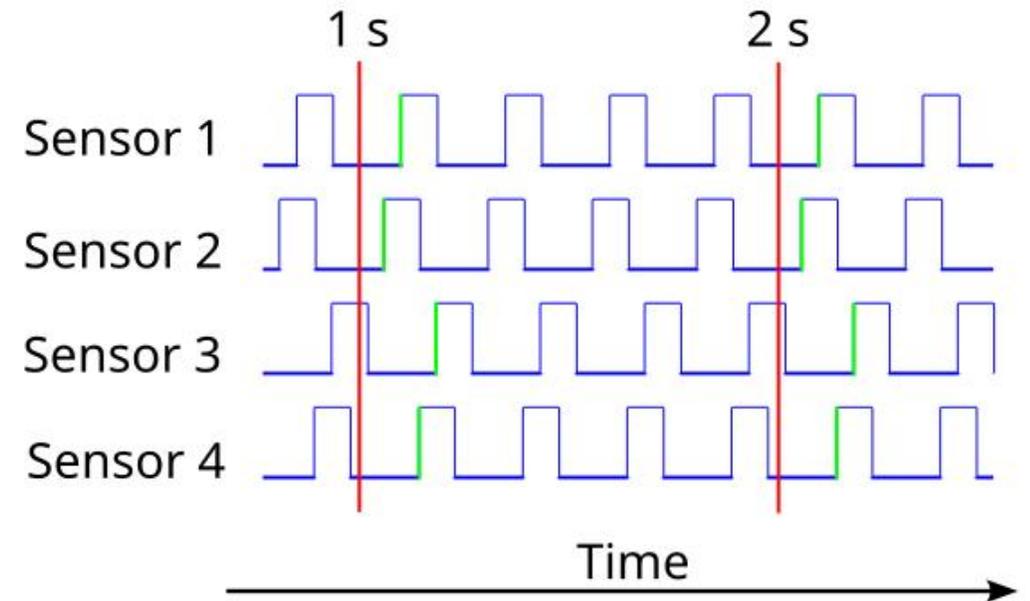
- Power supply, PoE++ (upgraded to 200 W per channel)
- Connections ethernet 1000 MB/s
- Synchronisation via Time Server -> PTP (Precision Time Protocol) 1588v2 (IEEE 1588-2008)



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
- This drift directly degrades correlation and coherent signal analysis
- The signal sampling phase must therefore be synchronized across all sensors
- Synchronization can be achieved using external pulse (e.g., 1 PPS) or network-based methods (e.g., PTP)

$$\Delta t(t) = t \cdot \frac{\Delta f}{f}$$



PTP - Timestamp Exchange and Clock Offset Estimation

- These timestamps allow the system to estimate both the clock offset between devices and the network delay
- The delay is used for adjusting the clock offset of the Slave

T1 – time when the Sync message leaves the master

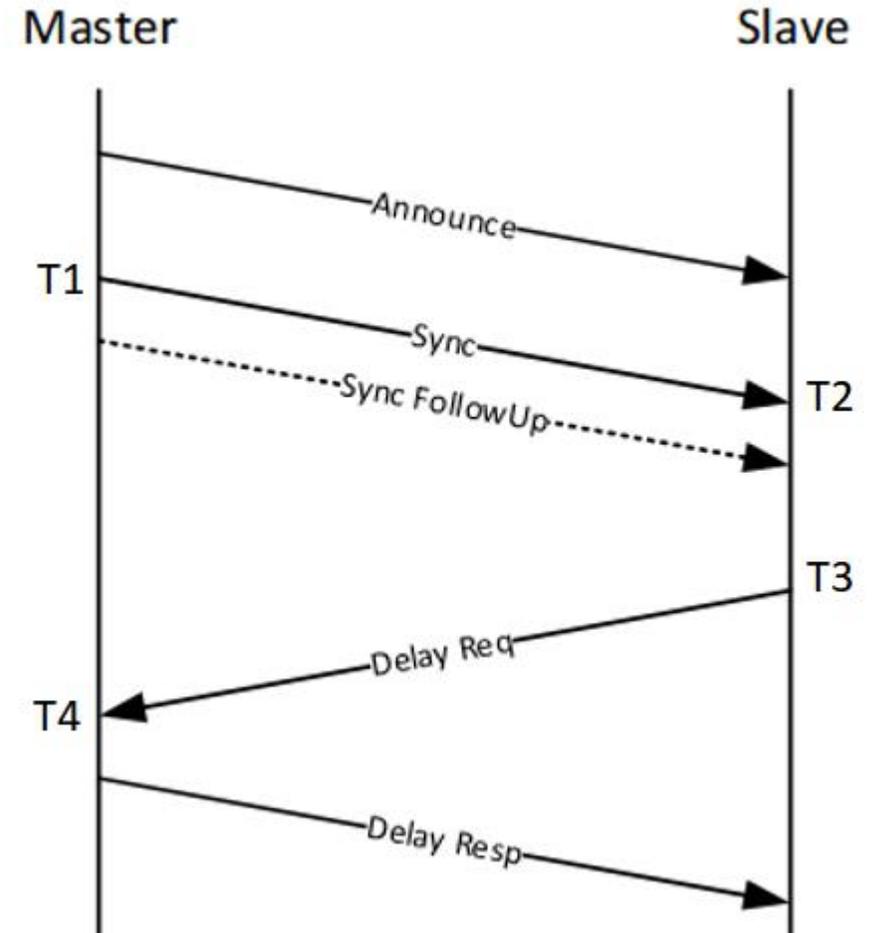
T2 – time when the Sync message is received by the slave

T3 – time when the Delay Request message leaves the slave

T4 – time when the Delay Request message arrives at the master

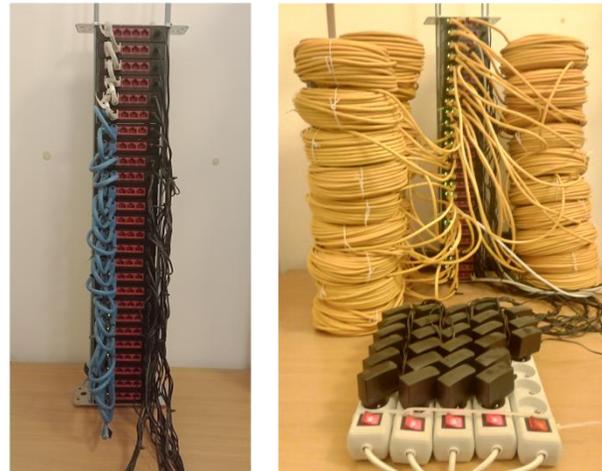
$$\text{Delay} = \frac{(T2 - T1) + (T4 - T3)}{2}$$

$$\text{Offset} = T2 - T1 - \text{delay}$$

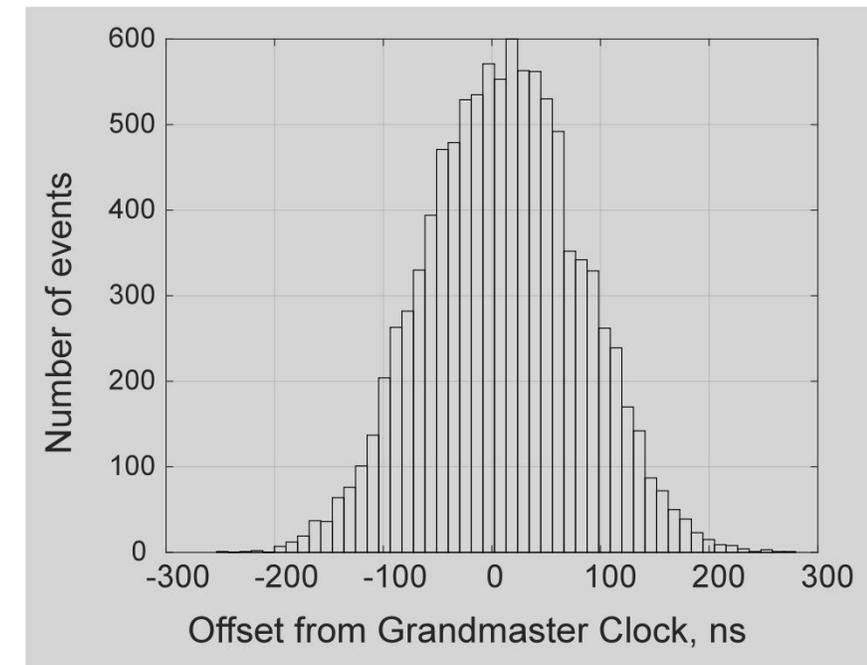


Clock Synchronization with PTP tests

- Tests conducted over a chain of more than 24 Ethernet switches
- Using 23 links of 30 m cables, demonstrated synchronization stability sufficient for coherent data acquisition.
- The measured software synchronization offset ranged from -200 ns to $+200$ ns.



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Summary

- The next generation of seismic sensors are more sensitive sensors from 177 mV (old) to 2 V m/s (new) and a wider frequency range starting at 2 Hz
- Important is the integration of power delivery and data transmission, often realized through unified data acquisition systems
- Precise timing is critical for environmental sensor arrays

Thank you for your attention
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