Fiber optic hydrophone development for an acoustic neutrino telescope

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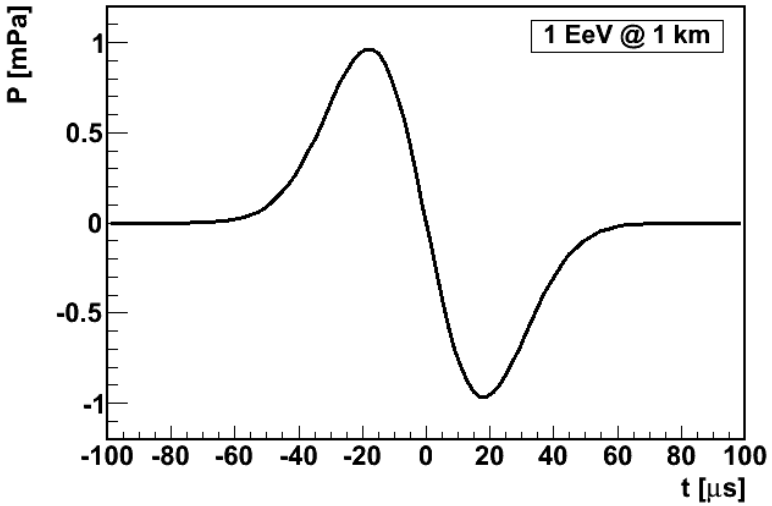
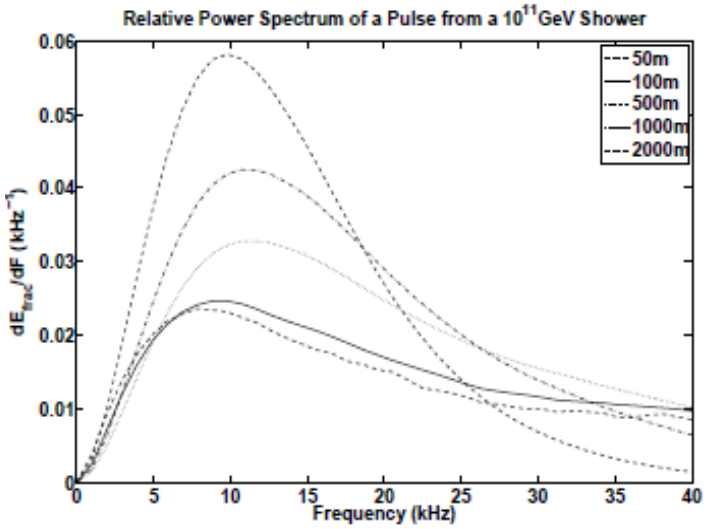
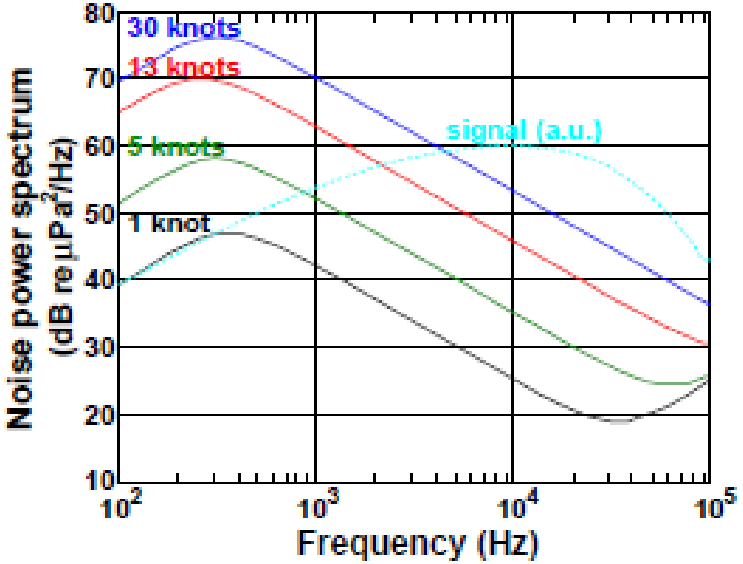
Neutrino signal

Understanding of the signal is of prime importance





Bevan et al 2007



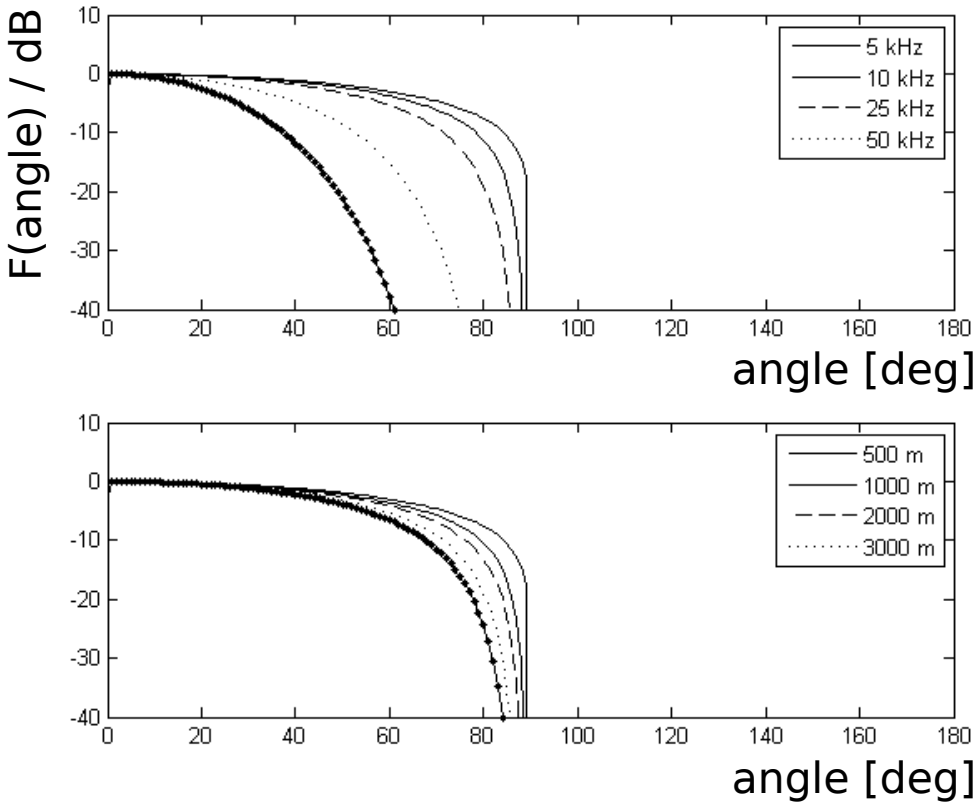
Lehtinen et al 2001

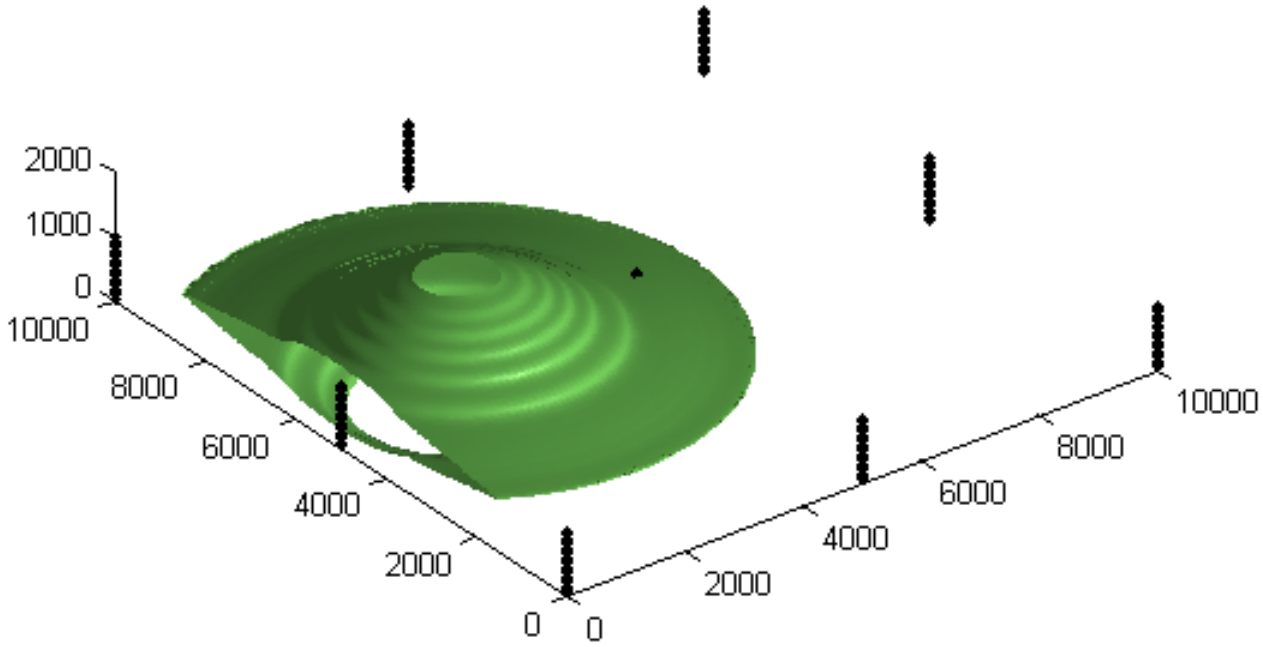
Neutrino signal:

- Bipolar pulse
- Spectrum peaks at ~5-10 kHz, but compared to sea-states, a frequency range beyond the peak is desirable

Vertical distribution ambient noise

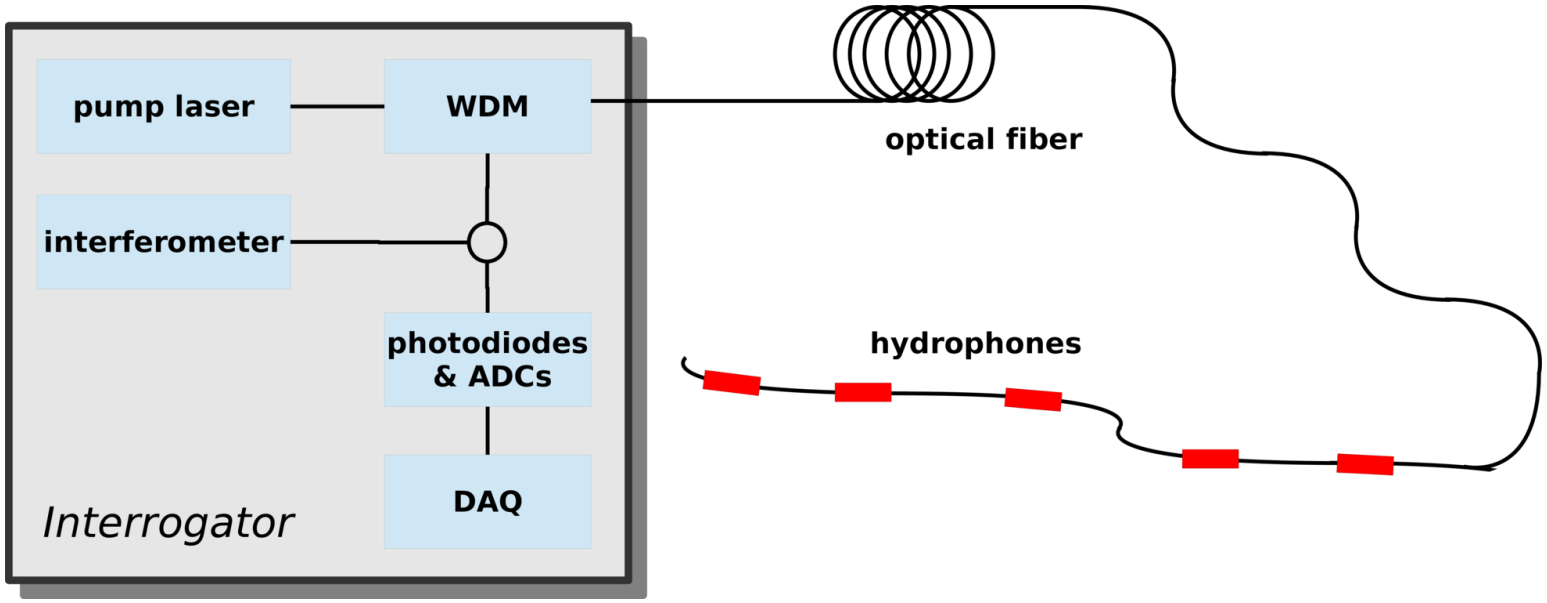
Theoretical deep-sea vertical angle distribution



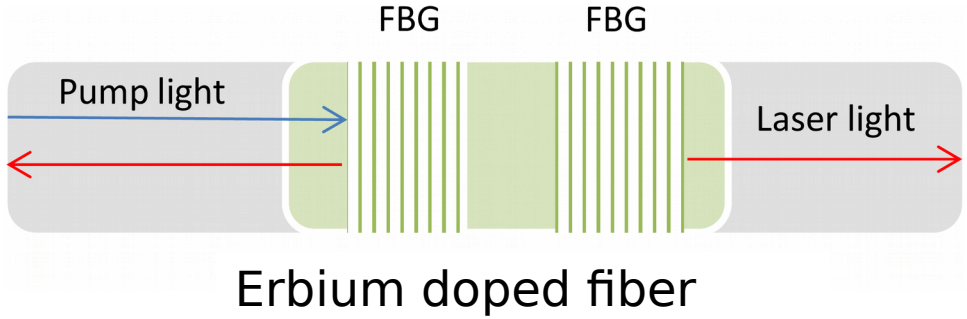


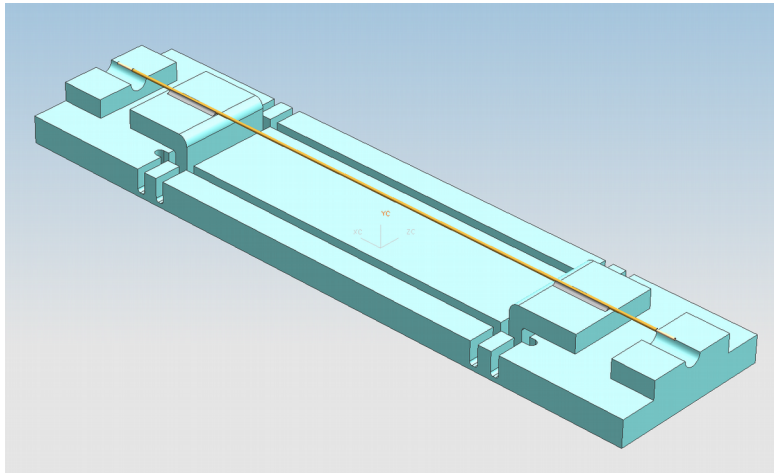
- Increase sensitivity with about 20dB using a filter on the direction of noise
- Need to construct a phased array to benefit from this method
- Many sensor close together

Fiber optic hydrophone recap



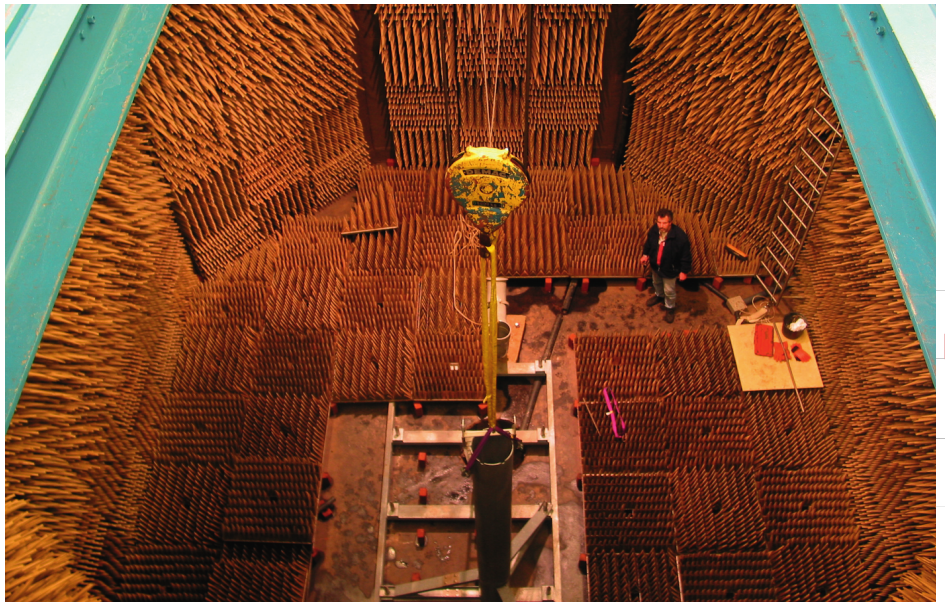
Three components:
1) Hydrophone sensor
2) Optical fiber
3) Data acquisition system

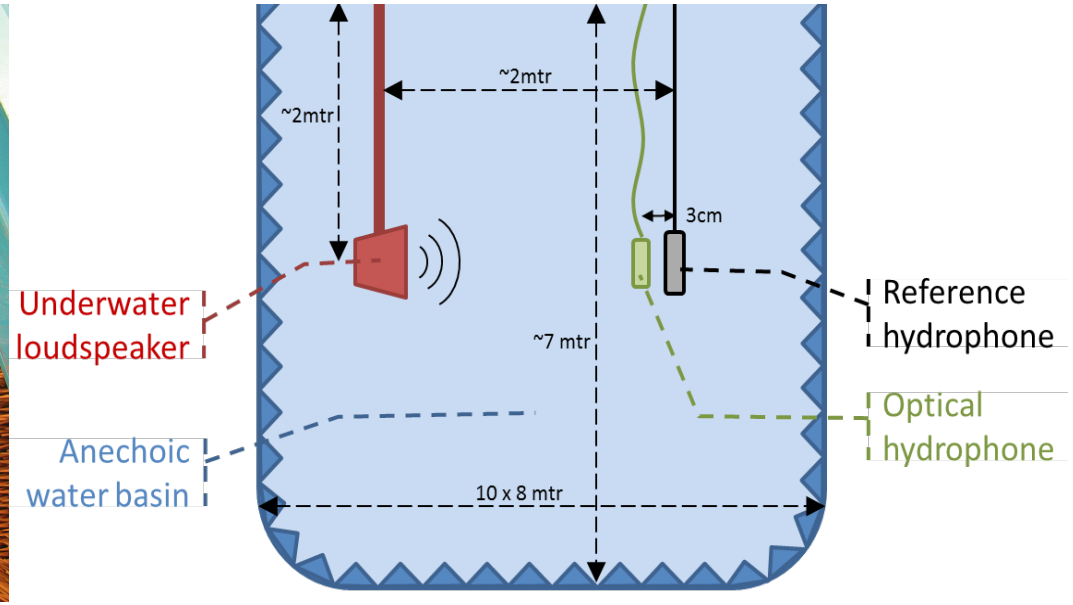




Experimental setup

- Using an anechoic basin at TNO (acoustically isolated).
- Dimensions of the basin: 8x10x8 m^3. Basin should be large to avoid echos mixing with the signal.
- Using commercial and well calibrated hydrophone as a reference.

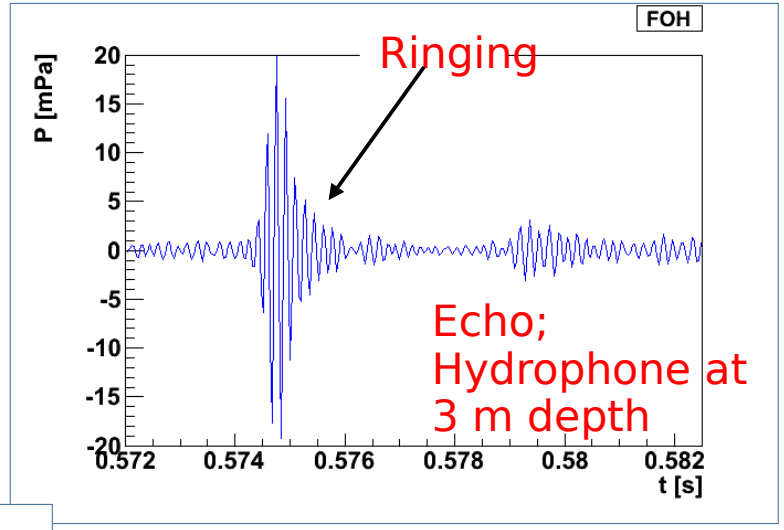


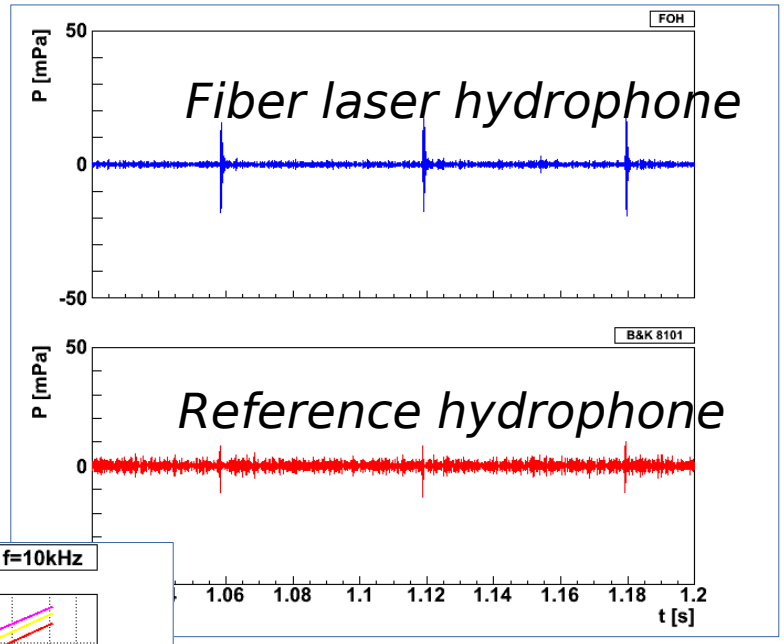


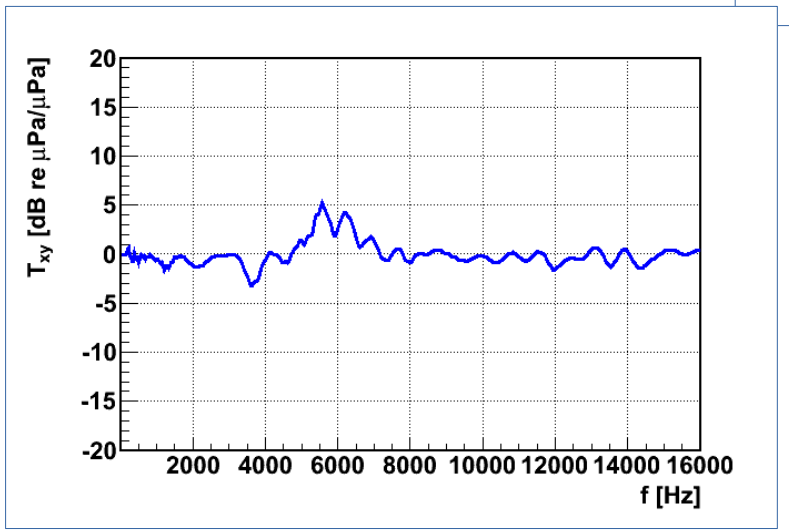
Fiber optic hydrophone recap

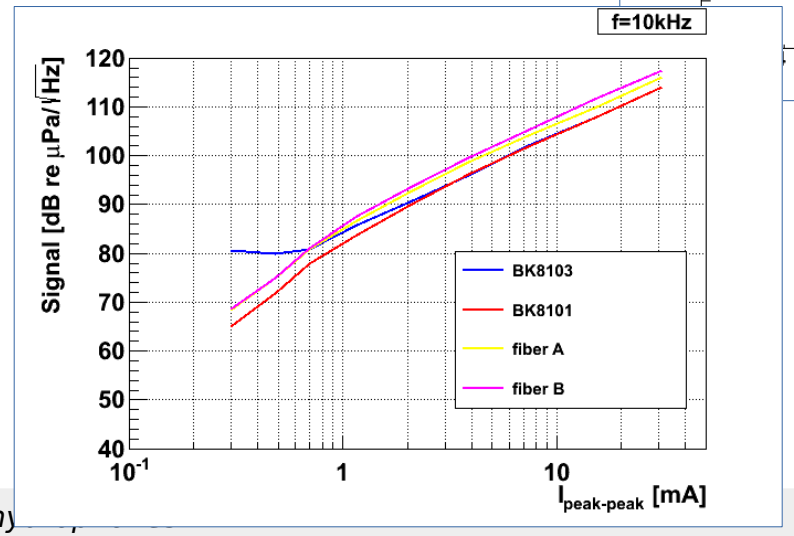
Results:

- Sensitive to DSS0
- Up to 16-20 kHz
- Modest resonance peak









Where to go from here…

To do list:

- *Increase of frequency range from up to 50 kHz*
  - Increasing frequency range while maintaining high sensitivity is challenging
  - Smaller fiber diameters could help to increase the sensitivity

- *Multiplexing:*
  - Time domain multiplexing (TDM) vs Wavelength domain multiplexing (WDM)

- *Pressure compensation*

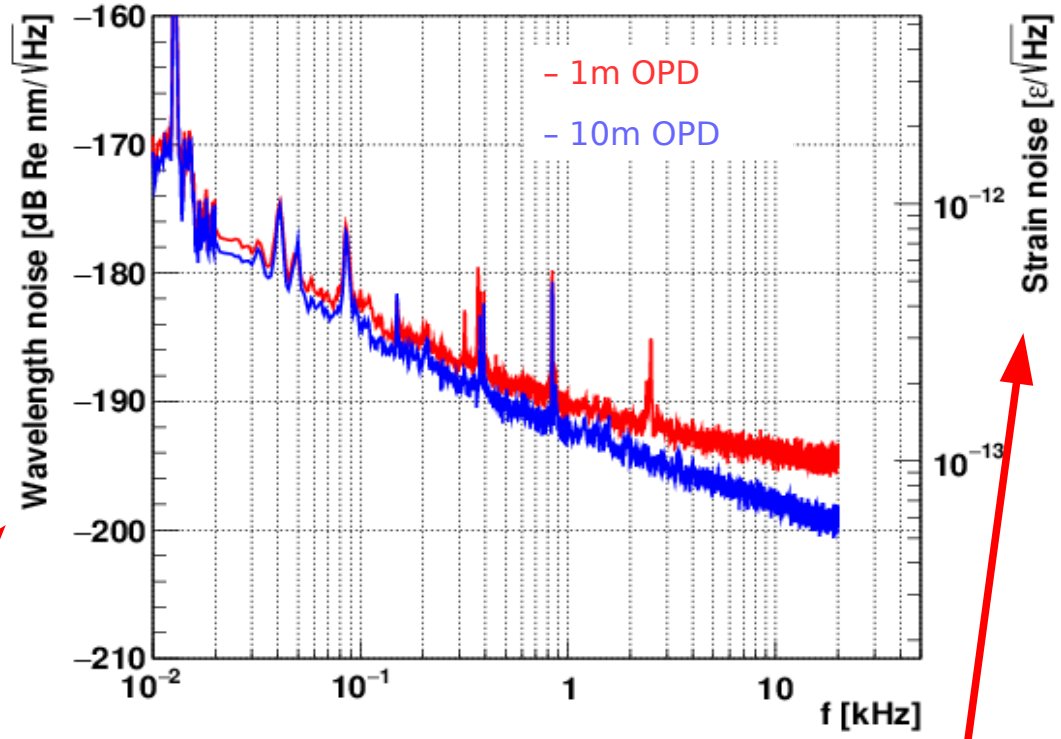
- *Laser pumping and read out over large distances*

- *Manufacturability, industrialization*

Redesign of the system

Sensitivity @ high frequency

- Self noise measured in an acoustically and vibration isolated environment.
- Performance expressed in wavelength noise and strain noise.



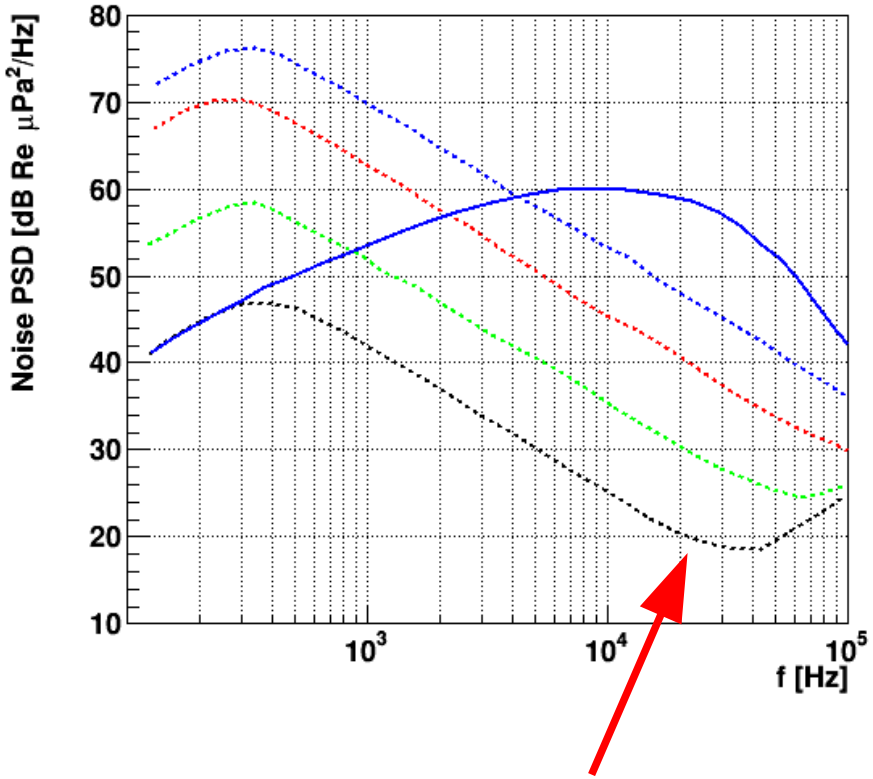
$$\phi = \frac{2\pi}{\lambda} OPD$$

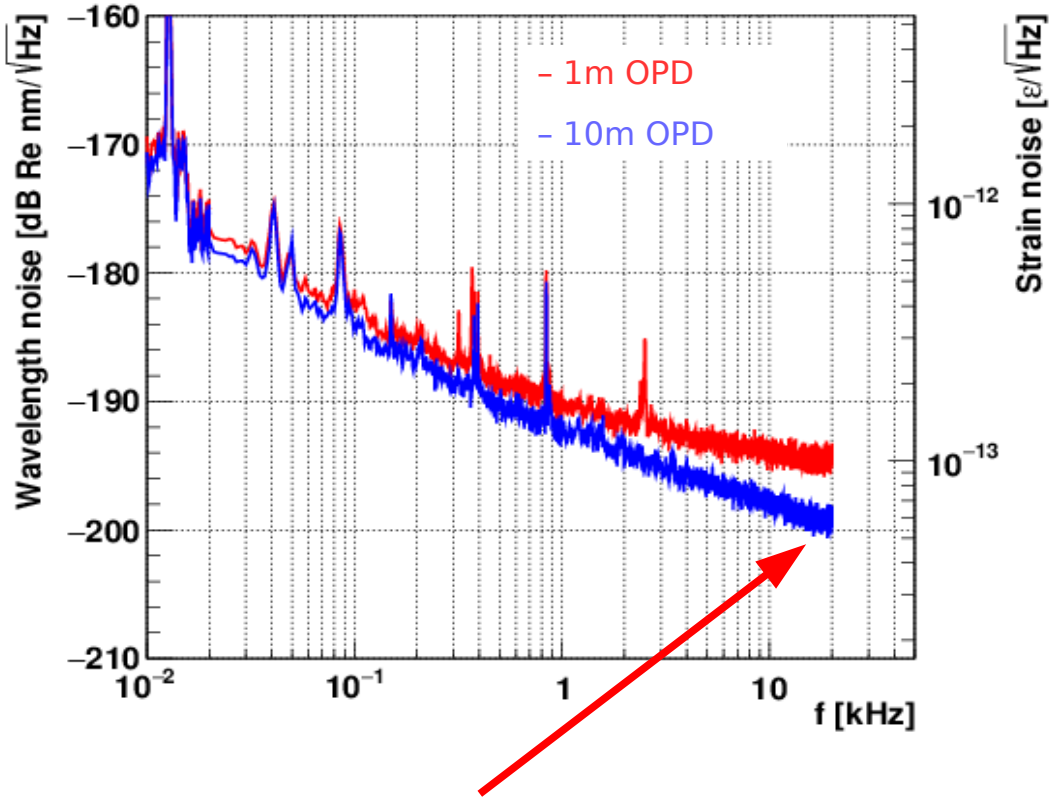
$$\frac{\Delta\phi}{\Delta\lambda} = \frac{2\pi}{\lambda^2} OPD$$

Conversion to strain using photo-elastic coefficient

$$\frac{\Delta\lambda_B}{\Delta\varepsilon} = (1 - p_e)\lambda_B = 1.2 \left(\frac{\mathrm{pm}}{\mu\varepsilon}\right)$$

Sensitivity @ high frequency





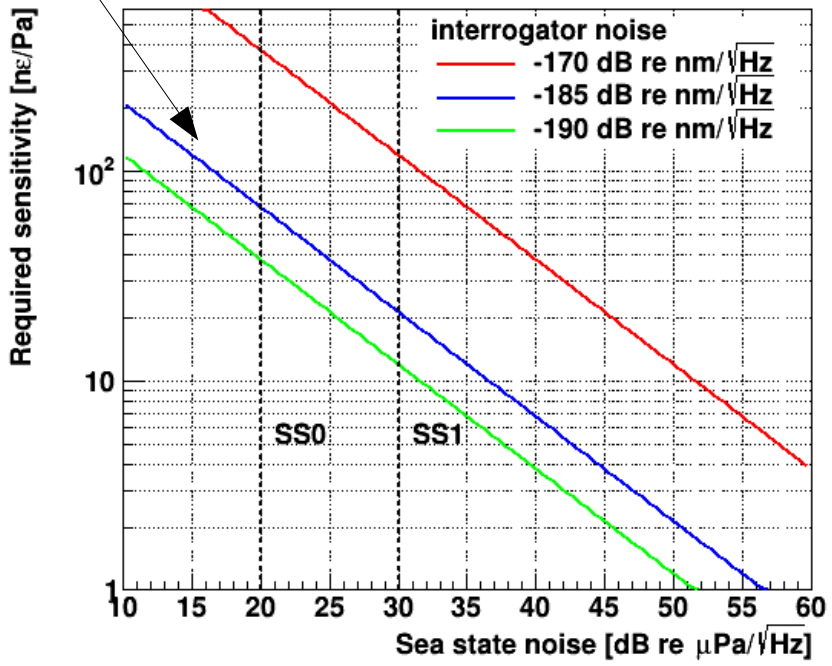
- Use the *sea state noise* and *interferometer noise* as input design of the *transducer*:
  η > 60 nε/Pa
- Lower interrogator relaxes requirement on the strain sensitivity
- Lower sea state noise at higher frequencies → higher strain sensitivity required

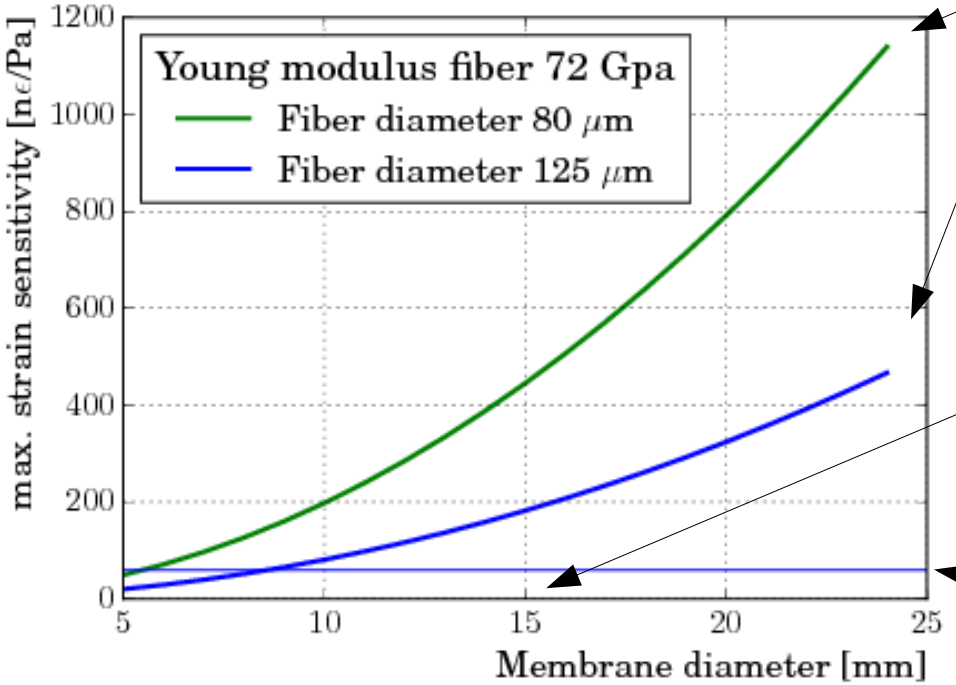
Theoretical limit on strain

Limit on the strain sensitivity

- Sensitivity is determined by the ratio of diameters of the transducer and the optical fiber.
- Diameter of the diaphragm is about 15 mm while the diameter of the fiber is about 125 μm.

Nominal performance





All pressure is converted to strain

Half-wavelength @ 50 kHz

required

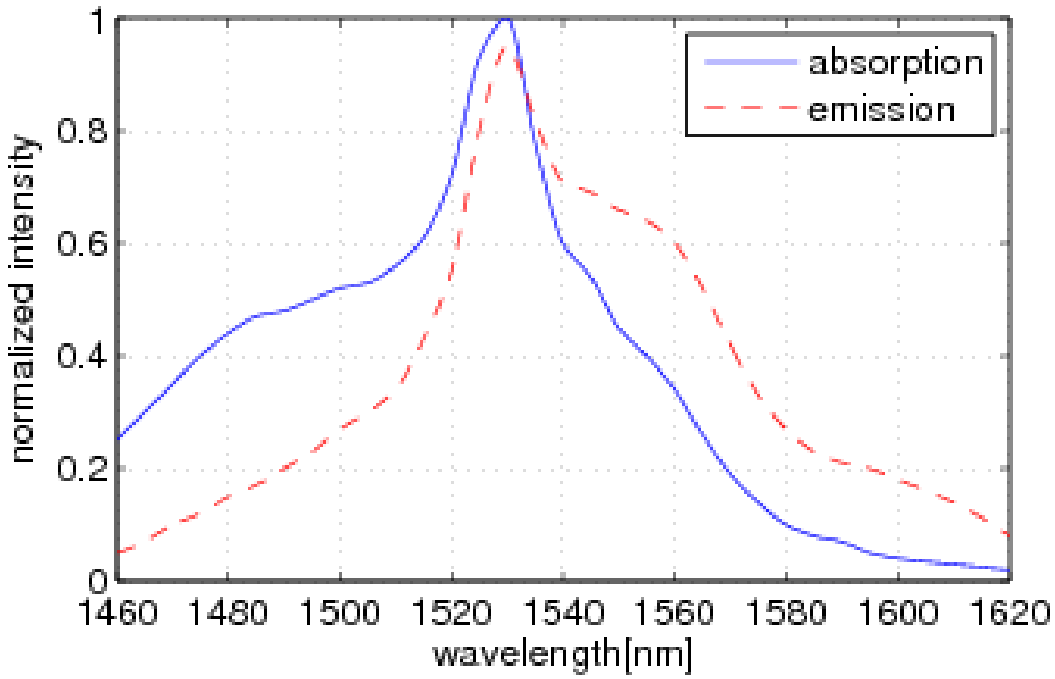
WDM vs TDM

- Wavelength domain multiplexing(WDM) vs Time domain multiplexing (TDM):
  - WDM requires a dedicated interometer for each sensor on the fiber
  - TDM: samples are distributed over >1 sensor: Reduced duty cycle

WDM:

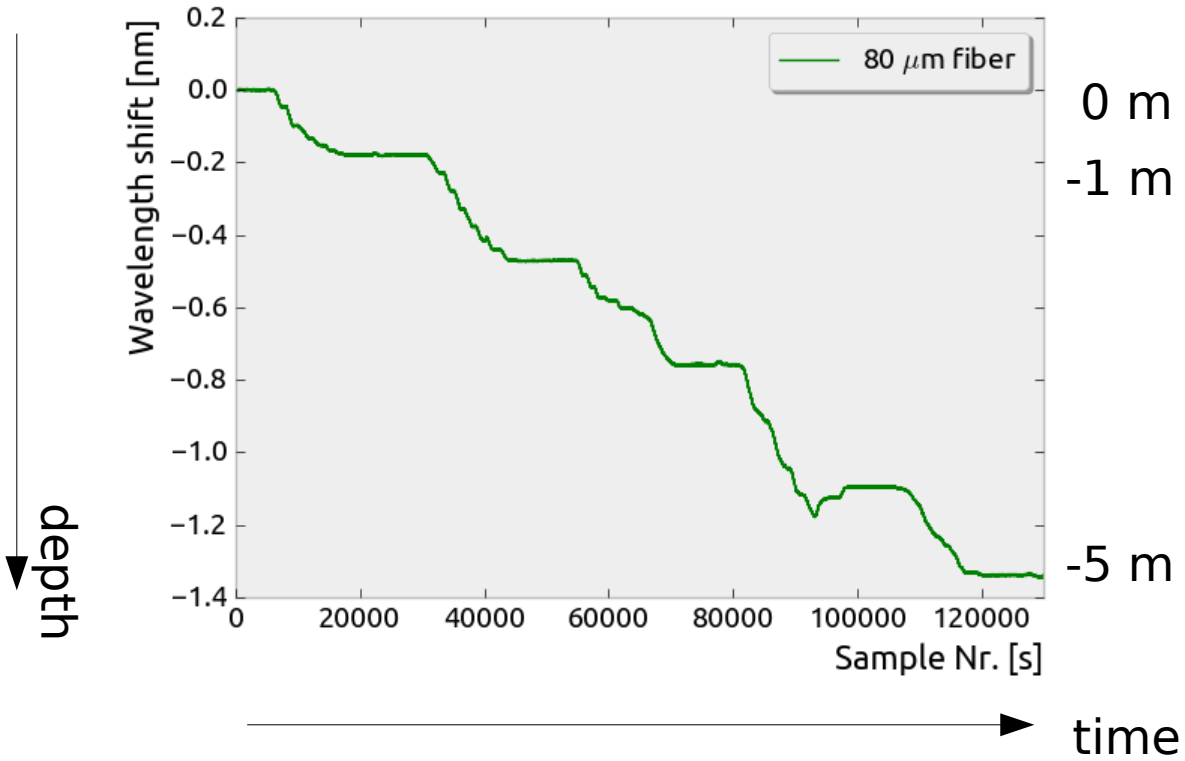
- Erbium spectrum determines what wavelength range to be used.

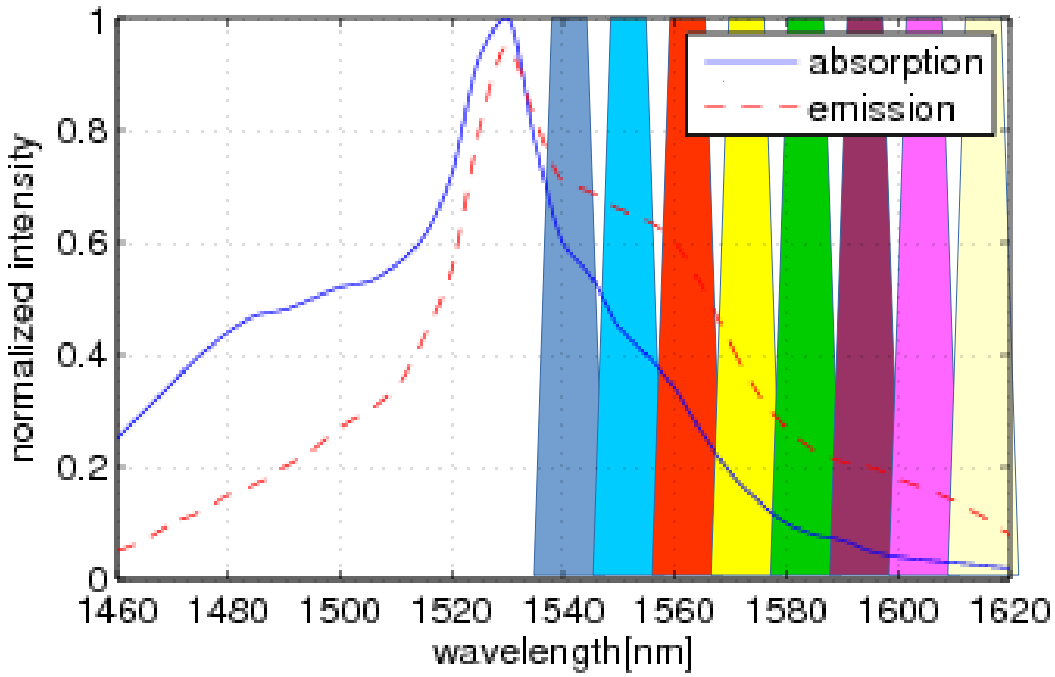
  Emission > absorption, so *λ > 1530 nm*



Wavelength domain multiplexing

- WDM: Each of the sensor falls in a dedicated filter band of the WDM
- Studies are needed how wide the filter bands should be.
- Wavelength shifts with depth. Is required to be stable..

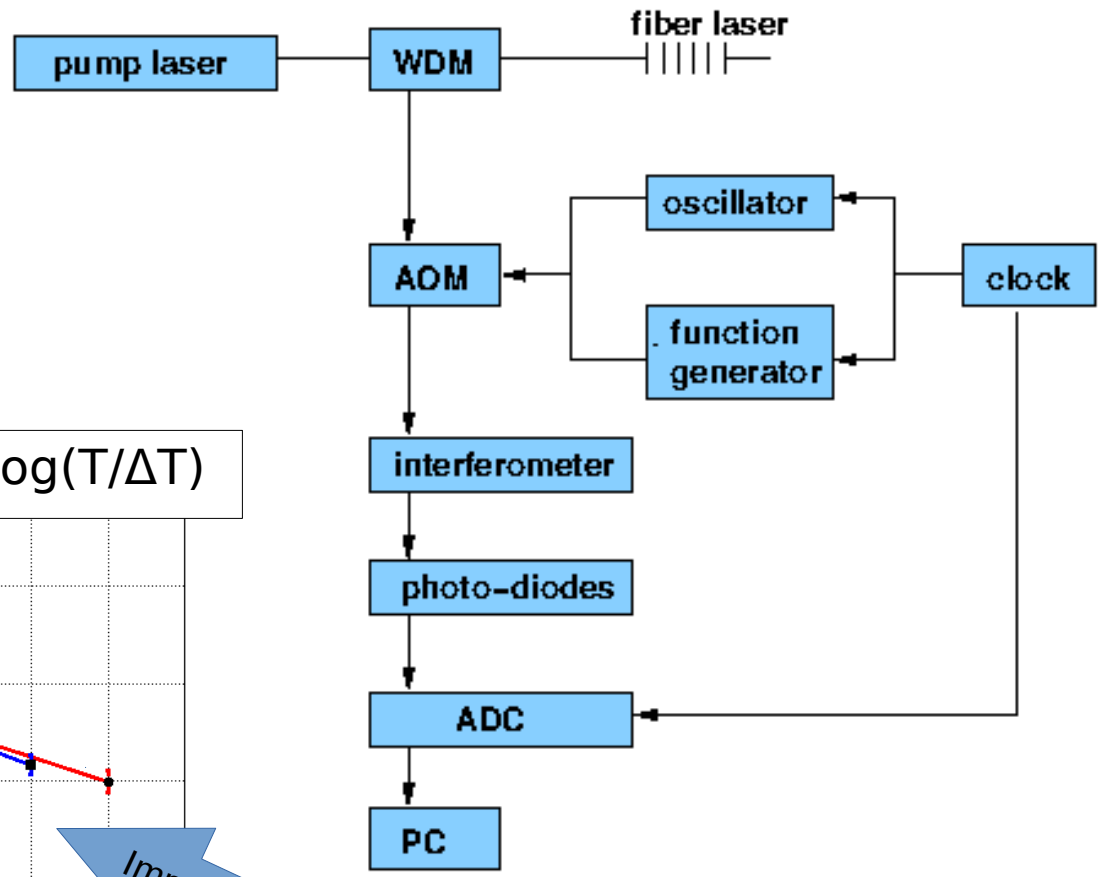


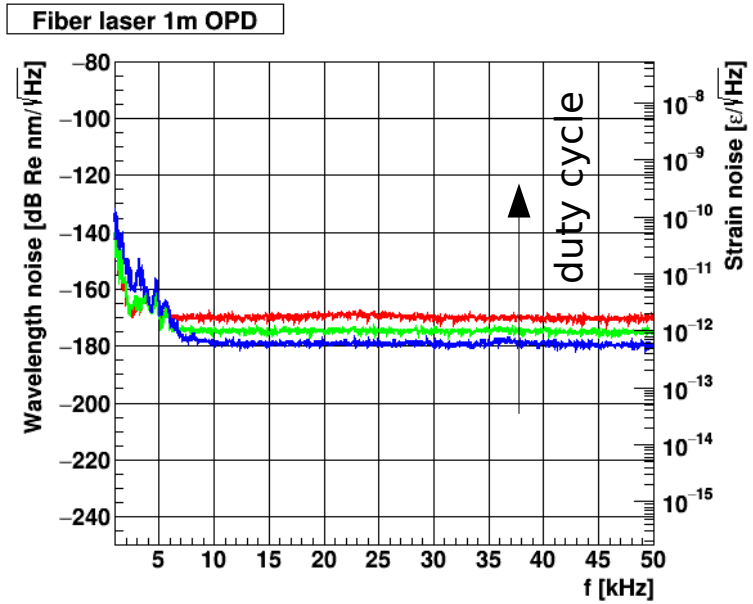


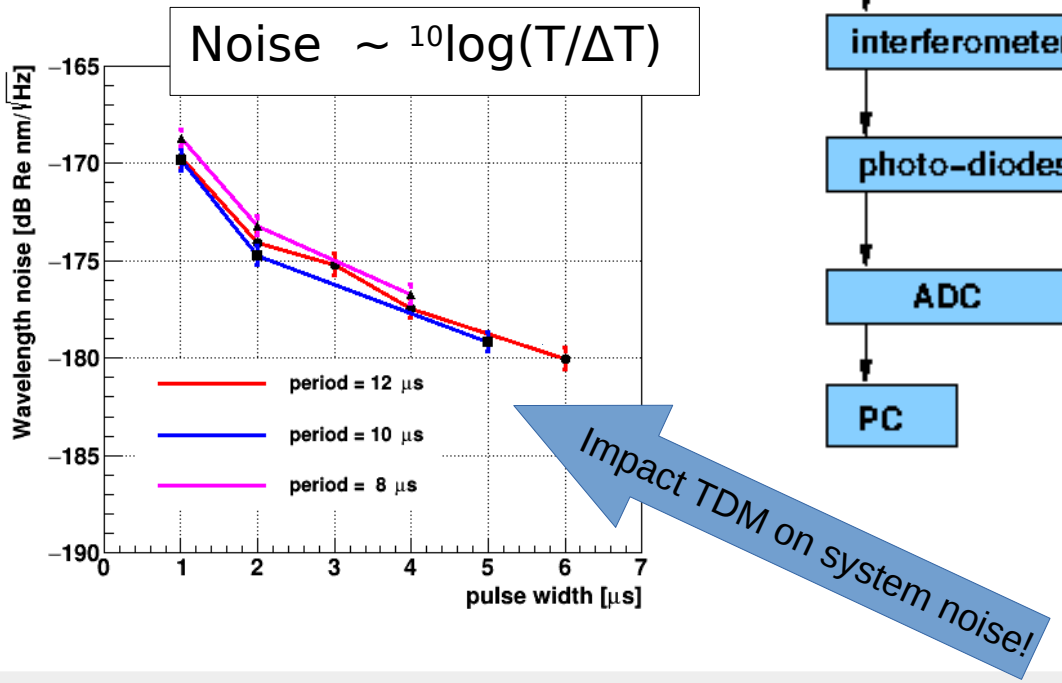
Time domain multiplexing

Time domain multiplexing:

- Insert an acoustic optical modulator in the acquisition system
- Reduce the duty cycle when sampling the signal

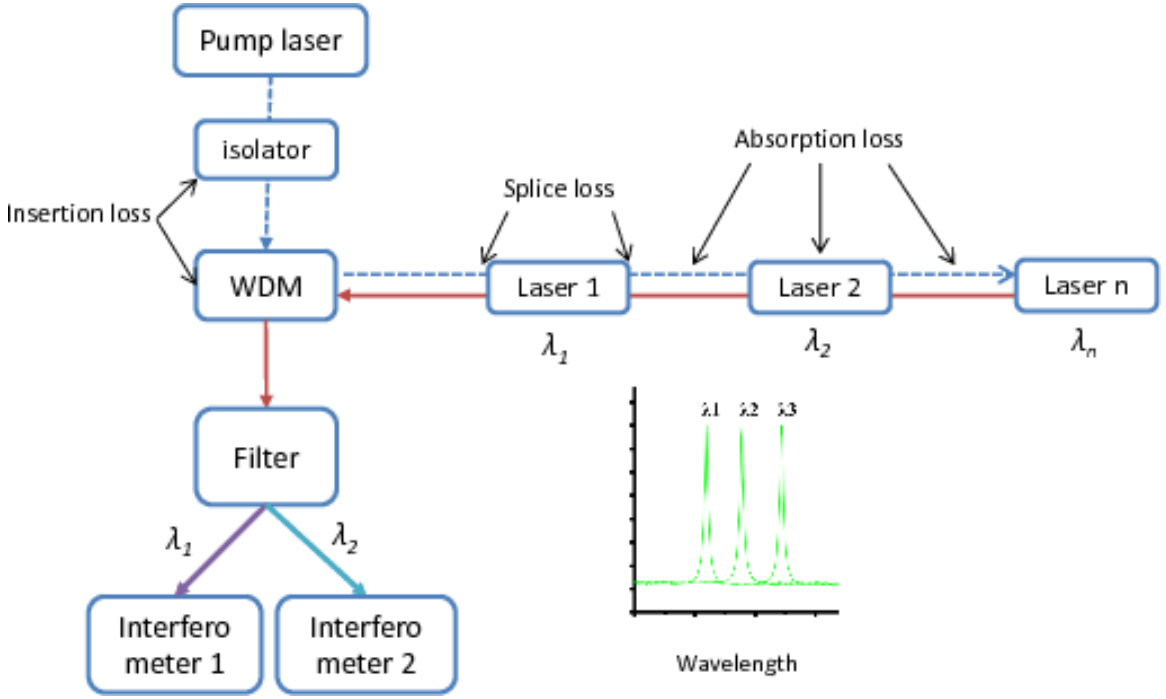


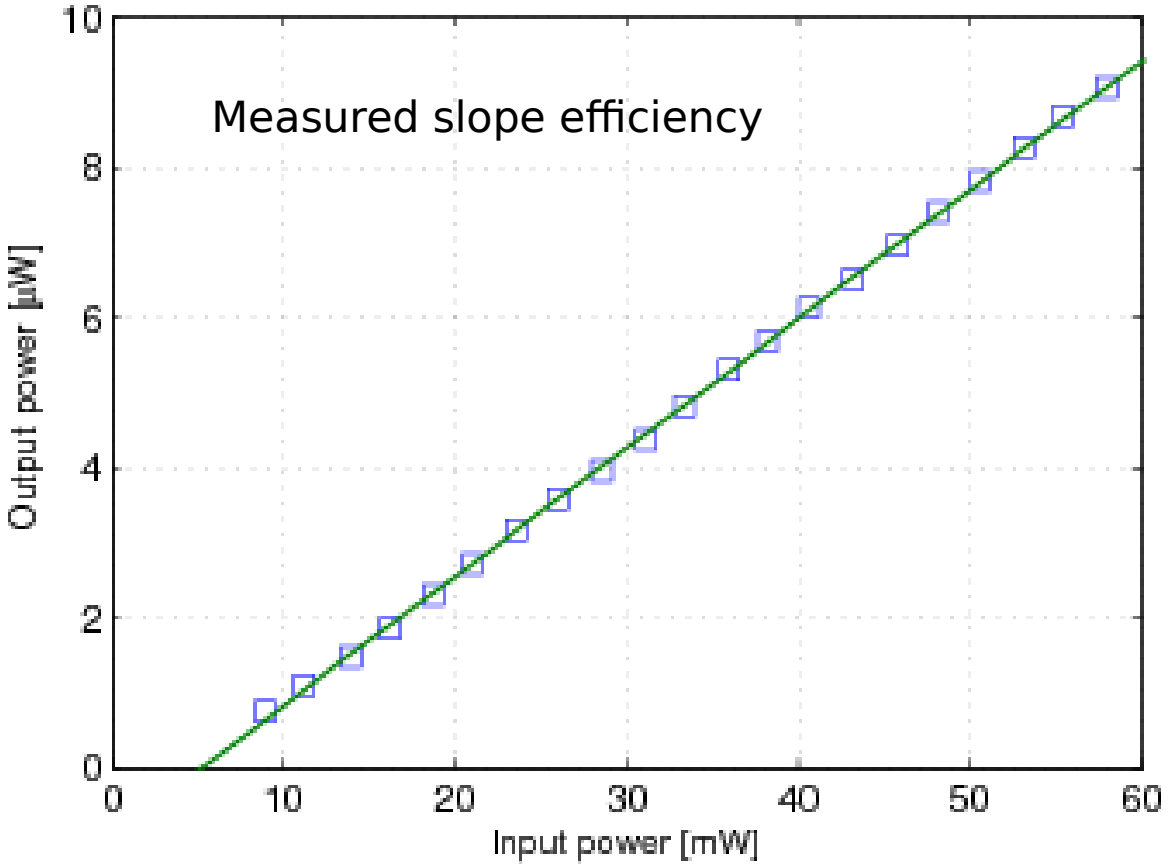




Multiplexing sensors

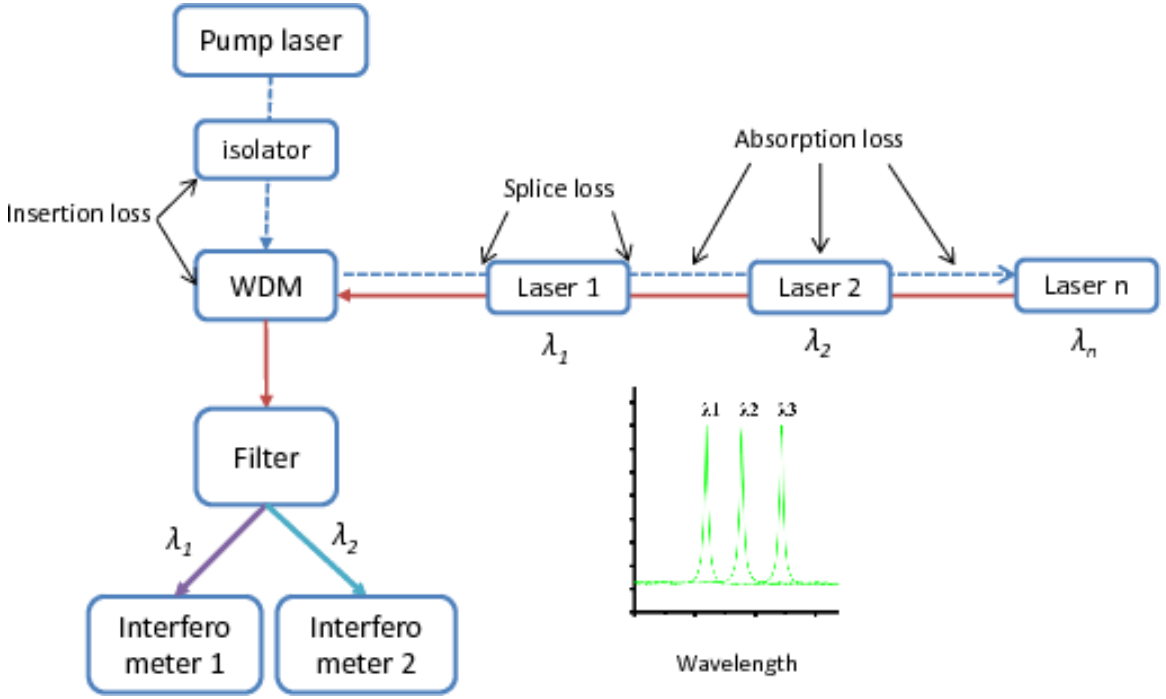
- Calculations on required power and pumping schemes
- Requirement: 10 μW signal at the interrogator
- Introduce: absorption in the fiber and the laser, splice losses, slope efficiency

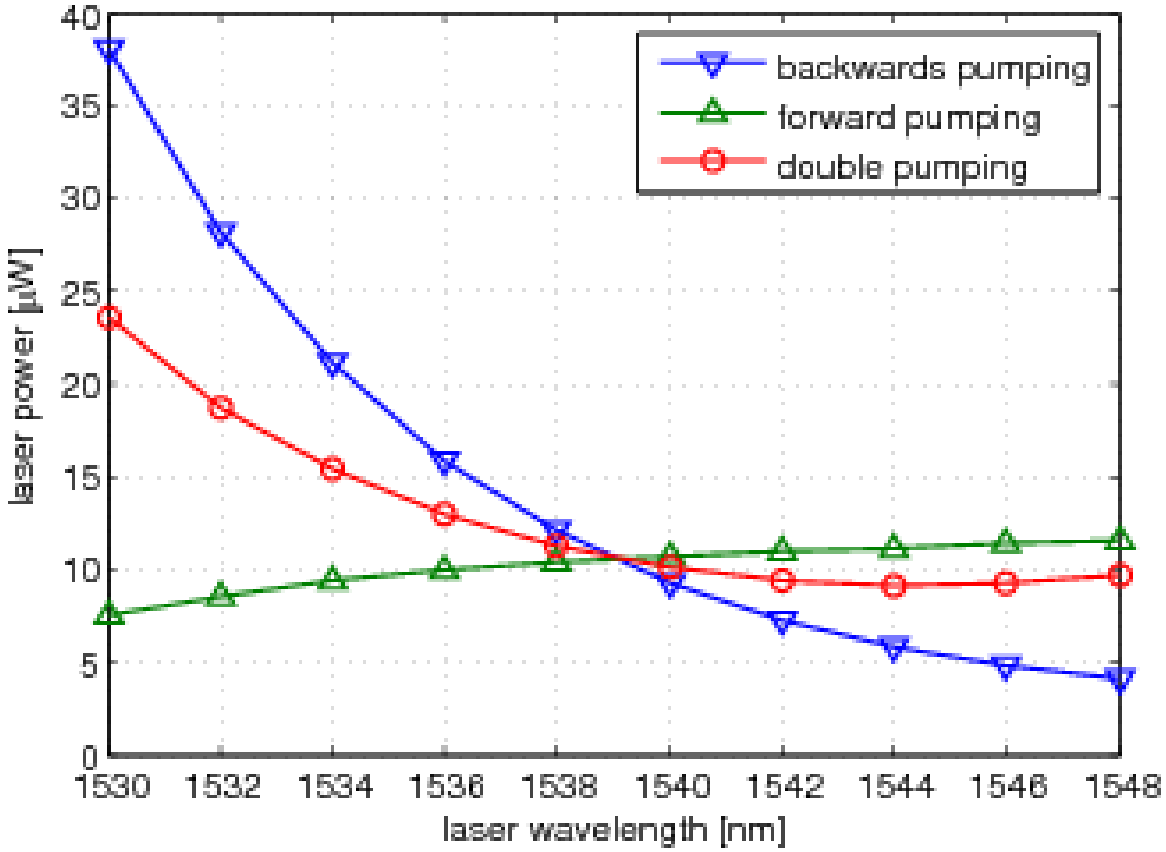




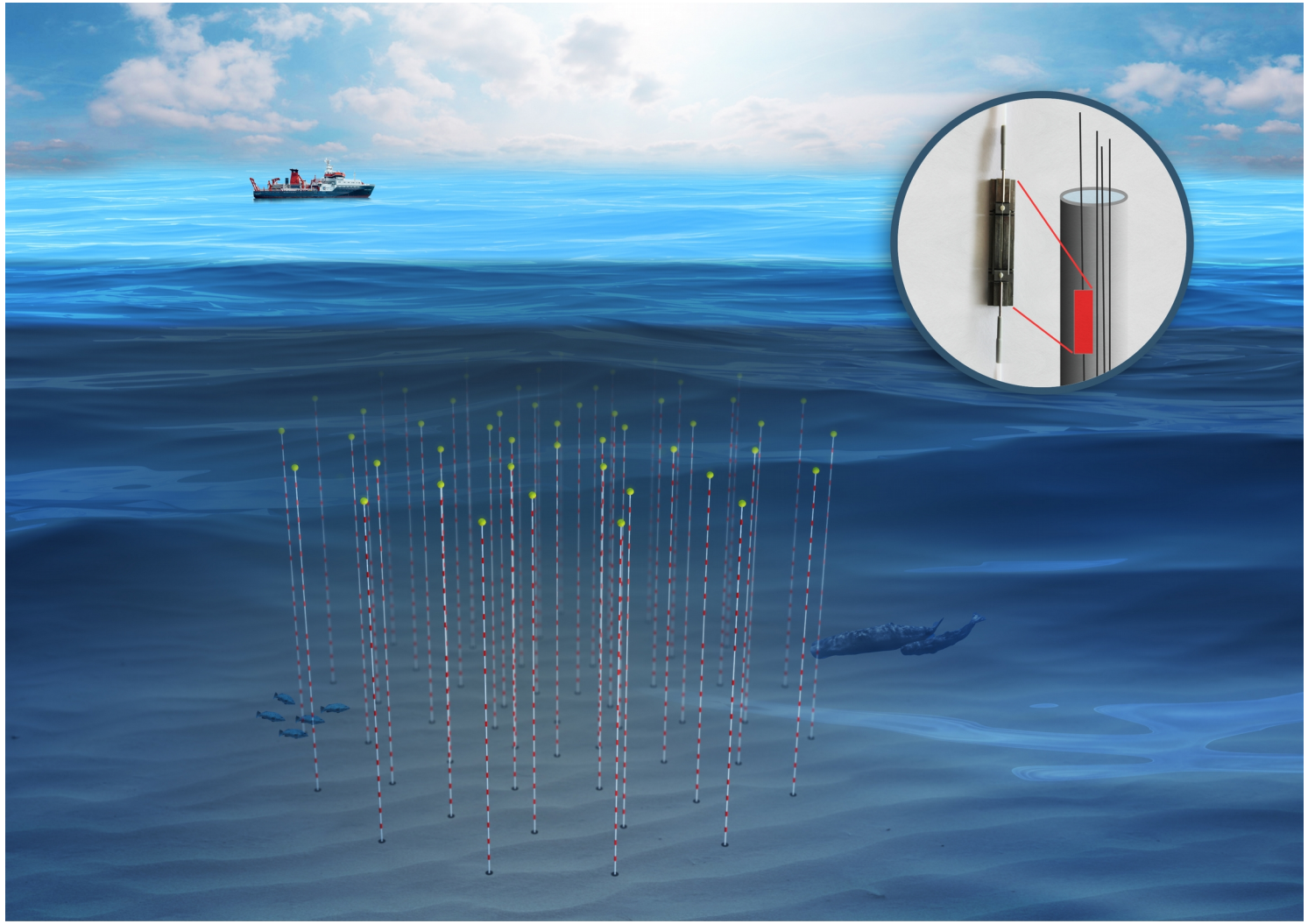
Multiplexing sensors

- Calculations on required power and pumping schemes
- Requirement: 10 μW signal at the interrogator
- Introduce absorption in the fiber and the laser, also splice losses



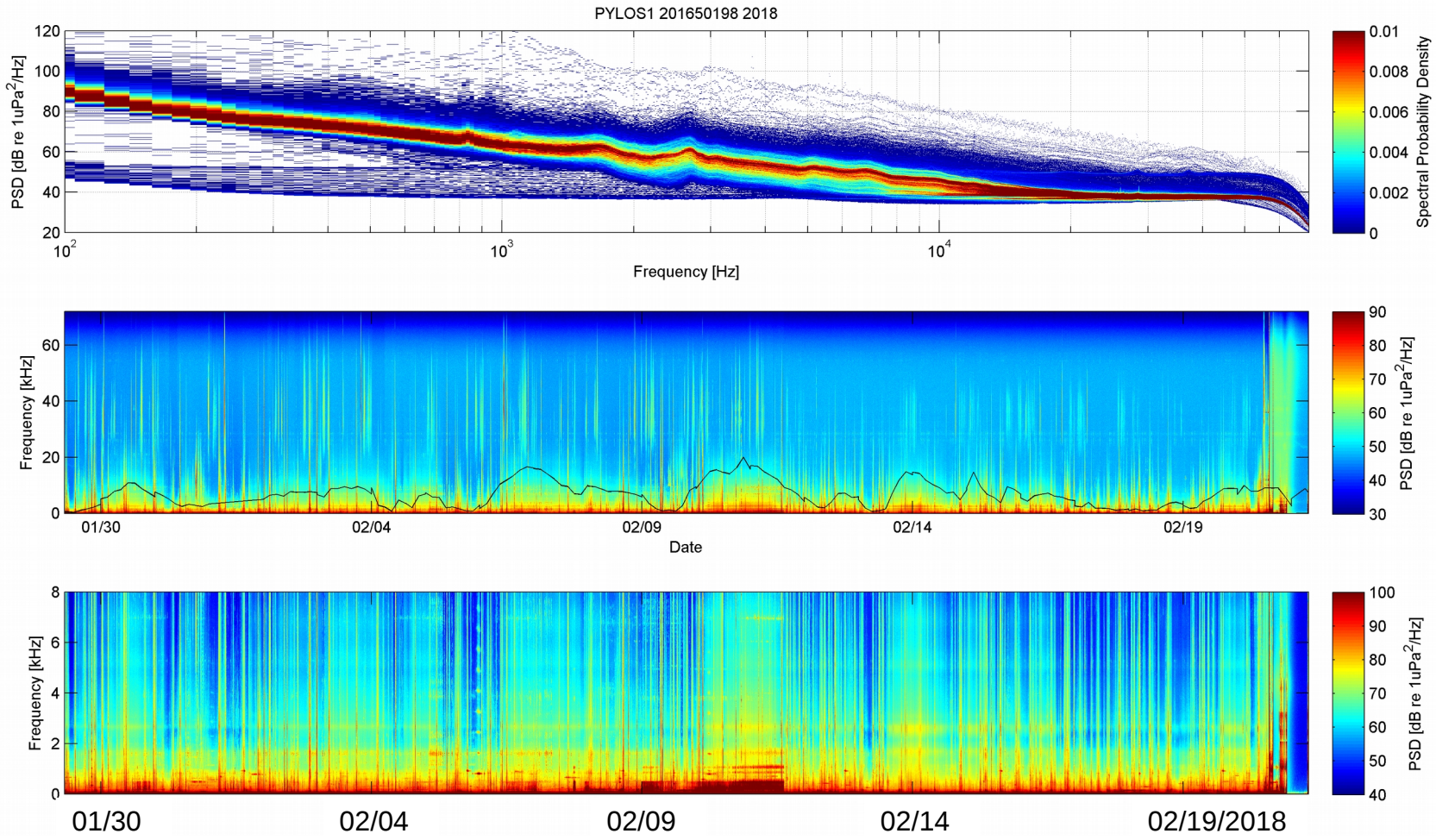


An acoustic neutrino telescope



> 100 strings,
> 1000 hydrophones,
> 100 km^3

Pylos site characterization



- Loggerhead DSG-ST ocean acoustic data logger at a depth of 850 and 1350 m
- Three weeks of continuously data taking: many ‘bottlenoise dolphins’, analysis ongoing

...meanwhile

Interesting developments:
Recent deployment of a data center
by *Microsoft* off the coats of Scotland.

Interrogators in here?

Photos by Scott Eklund/Red Box Pictures

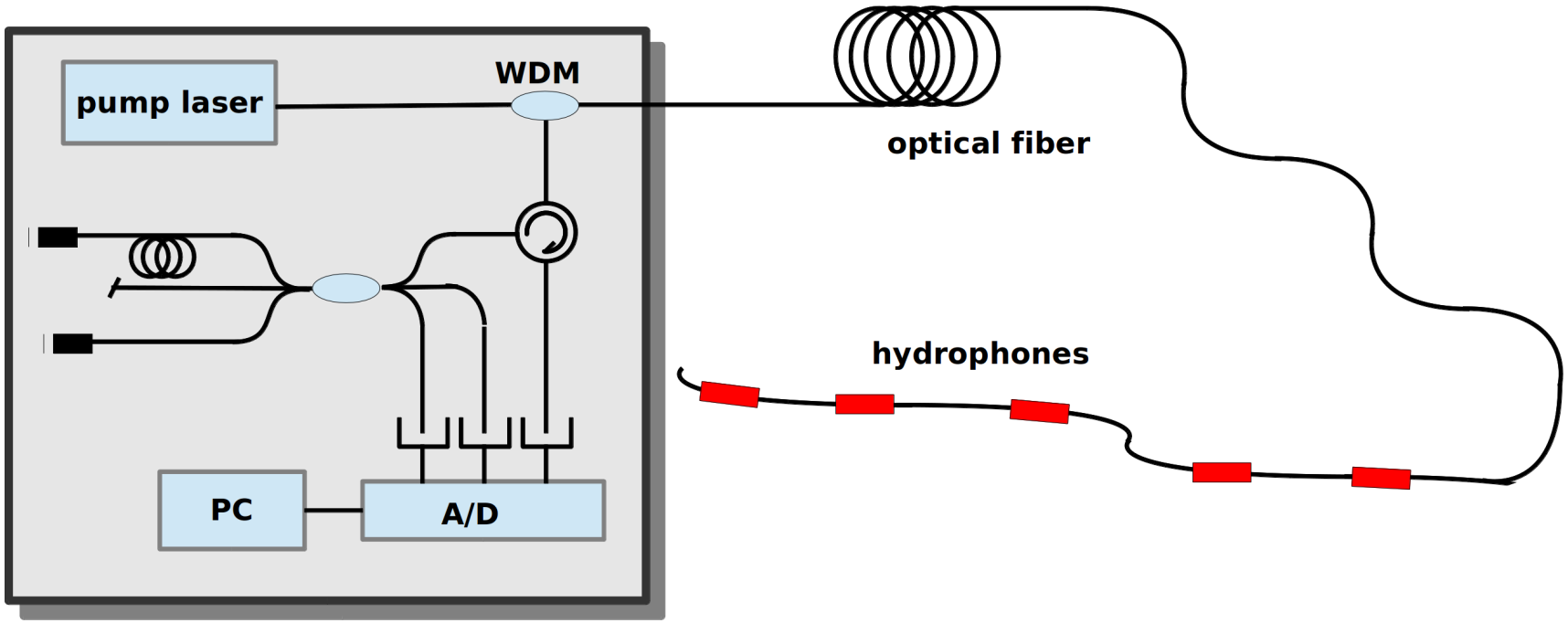
Summary and conclusions

- Present status:
  - System is working up to with required sensitivity, i.e sea state sensitivity
  - All tools at hand for further development.
  - A kick-off of the Greek site characterization.

- Future directions:
  - Improving and tailoring of the system to neutrino detection:
    - Frequency range and pressure compensation
  - Building the first prototype string
  - Extensive characterization of a suitable site

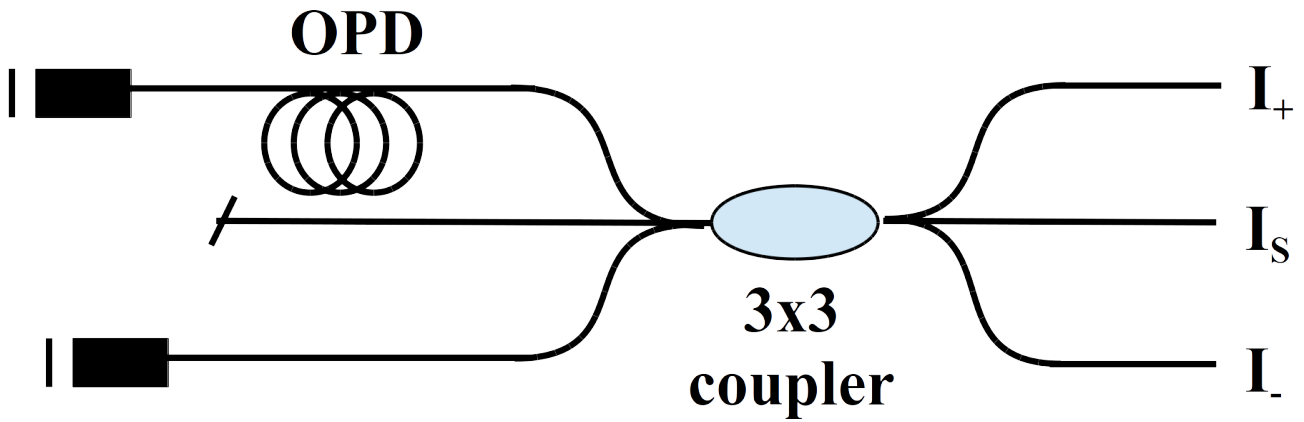
Backup

Interrogator



- 3x3 interferometer: *coupler* with fixed phase difference in output branches.
- Standard commercial components

Interferometer



- 3x3 interferometer: *coupler* with fixed phase difference in output branches.
- Need 3 photo diodes per interrogator
- Normalize each output

$$I_S(OPD) = A_0(1+V\cos(\frac{2\pi}{\lambda}OPD)).$$

$$I_+(OPD) = A_0(1+V\cos(\frac{2\pi}{\lambda}OPD+\frac{2\pi}{3})).$$

$$I_-(OPD) = A_0(1+V\cos(\frac{2\pi}{\lambda}OPD-\frac{2\pi}{3})).$$

$$OPD = \frac{\lambda}{2\pi}\arctan\left(\sqrt{3}\frac{I_+ - I_-}{2I_s - I_+ - I_-}\right).$$