Fiber optic hydrophone development for an acoustic neutrino telescope

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Neutrino signal

Understanding of the signal is of prime importance

Neutrino signal:
• Bipolar pulse
• Spectrum peaks at ~5-10 kHz, but compared to sea-states, a frequency range beyond the peak is desirable
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
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 m³. Basin should be large to avoid echoes 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

- Ringing
- Echo; Hydrophone at 3 m depth

Fiber laser hydrophone

Reference hydrophone

Signal (dB re Pa/Hz)
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**
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

\[ \frac{\Delta \lambda_B}{\Delta \varepsilon} = (1 - p_e) \lambda_B = 1.2 \left( \frac{pm}{\mu \varepsilon} \right) \]
Sensitivity @ high frequency

- Use the *sea state noise* and *interferometer noise* as input design of the transducer: \( \eta > 60 \, \text{n}\varepsilon/\text{Pa} \)
- 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.
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.

\[ \text{Emission} > \text{absorption}, \text{ so } \lambda > 1530 \text{ nm} \]
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:

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

\[ \text{Noise} \sim 10 \log \left( \frac{T}{\Delta T} \right) \]
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
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An acoustic neutrino telescope

> 100 strings,
> 1000 hydrophones,
> 100 km³
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 ‘bottlenose 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
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

\[
\begin{align*}
I_5(\text{OPD}) &= A_0 (1+V \cos \left( \frac{2\pi}{\lambda} \text{OPD} \right)). \\
I_+(\text{OPD}) &= A_0 (1+V \cos \left( \frac{2\pi}{\lambda} \text{OPD} + \frac{2\pi}{3} \right)). \\
I_-(\text{OPD}) &= A_0 (1+V \cos \left( \frac{2\pi}{\lambda} \text{OPD} - \frac{2\pi}{3} \right)). \\
\text{OPD} &= \frac{\lambda}{2\pi} \arctan \left( \sqrt{3} \frac{I_+ - I_-}{2I_s - I_+ - I_-} \right).
\end{align*}
\]