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Array signal processing on distributed acoustic sensing data: directivity effects in slowness space

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Session SM2.1
Advances in fibre-optic sensing
technologies for geophysical applications

Tue, 24 May, 14:07–14:12 Room –2.16

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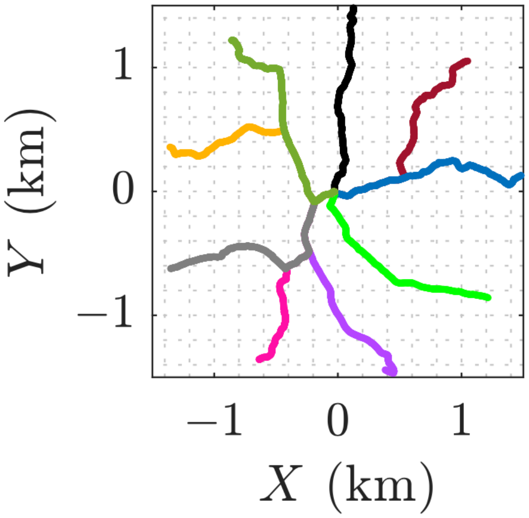
Distributed acoustic sensing (DAS) oddities

1) **Local directivity:**
   blind to broadside & fully sensitive to axial motion:

$$D_{\text{particle}}(\gamma_0) = \cos^2(\gamma_0)$$

2) **Gauge wavefield averaging** over length G

3) **Unprecedented spatial sampling opportunities**



How to incorporate 1) and 2) into array signal processing theory ?

Findings

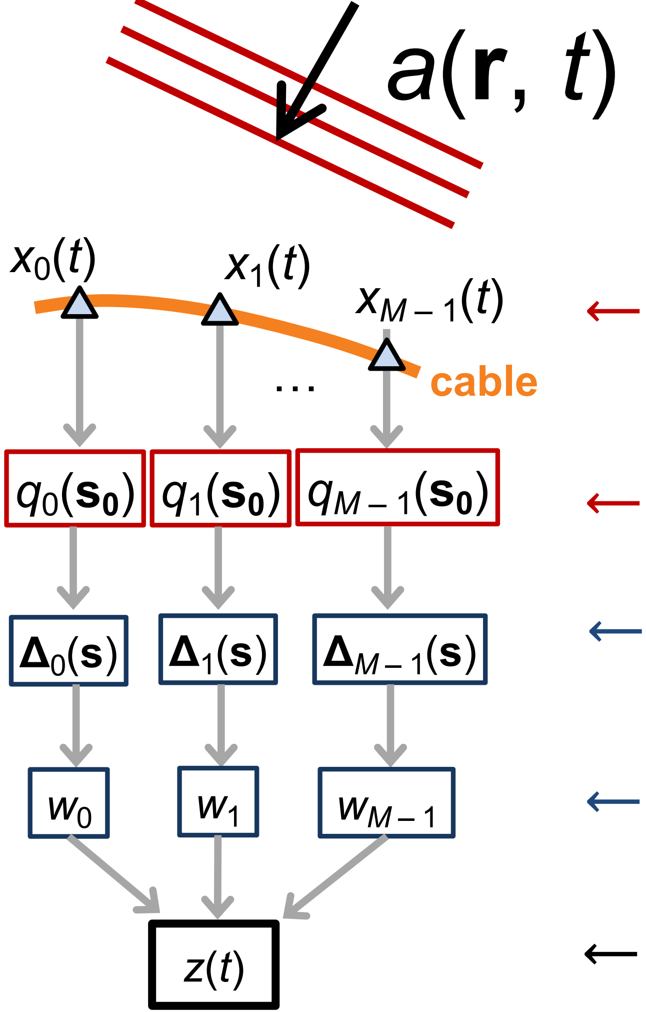
1) Gauge length averaging & cable directivity:
   Can be modelled using array signal processing theory

2) Cannot compose a classical **array response function**
   [parameterized in terms of Δ between steering & analysis slowness $(\boldsymbol{s} - \boldsymbol{s}_0)$]

   ⟹ Must consider **steered response** for the interesting directions-of-arrival

3) Processing can partly **compensate for cable directivity**

4) Paving the way for DAS array design optimization & enhanced processing



← Physical wavefield @ slowness s_0

← Sensor signals, w/o directivity

From physics
Can be adjusted

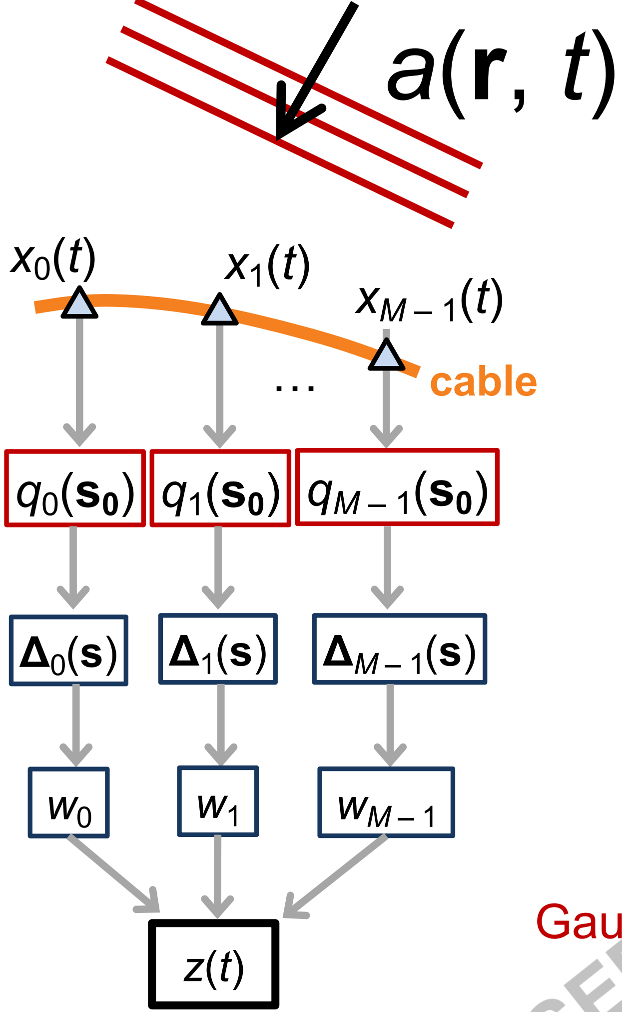
← Cable directivity factors, $\cos^2 \gamma_0$

← Moveout-compensating steering time-delays, towards slowness s

← Free weights

← Beamformer output (beam)

Also: average over gauge length



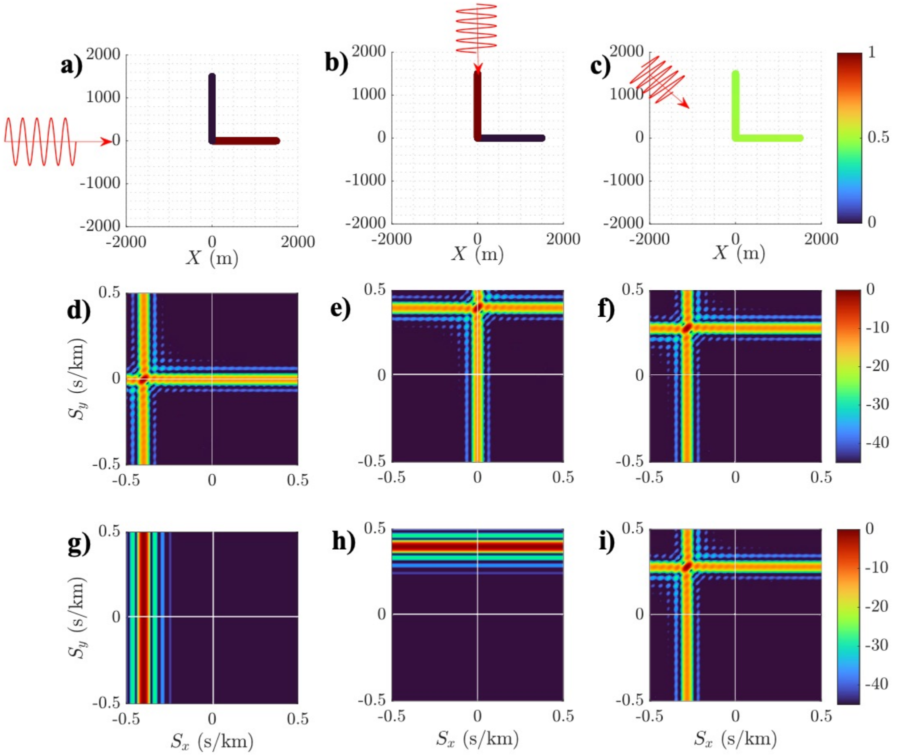
... can also be expressed as:

$$z(t) = \frac{1}{M}\sum_{m=0}^{M-1} w_m \int_{-\infty}^{\infty} \underbrace{h_m(\mathbf{r})}_{\text{gauge length region}}\, \underbrace{q(\mathbf{s}_0, \mathbf{r})}_{\text{local cable directivity } \cos^2\gamma_0} a(\mathbf{r}, t-\Delta_m) d\mathbf{r}$$

for plane-wave, single-frequency:

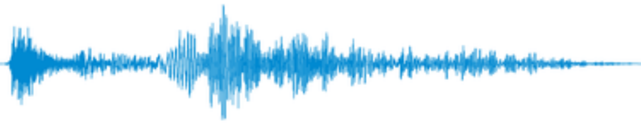
$$z(t) = \frac{e^{\omega t}}{M}\sum_{m=1}^{M} w_m \underbrace{q_m(\mathbf{s}_0) H_m(\mathbf{s}_0)}_{\text{Gauge length \& cable directivity: } \underline{\text{not}}\ (\mathbf{s}_0 - \mathbf{s})}\ e^{\underbrace{-i\omega(\mathbf{s}_0-\mathbf{s})\cdot\mathbf{r}_m}_{(\mathbf{s}_0 - \mathbf{s})}}$$

Steered response to waves from W, N, NW

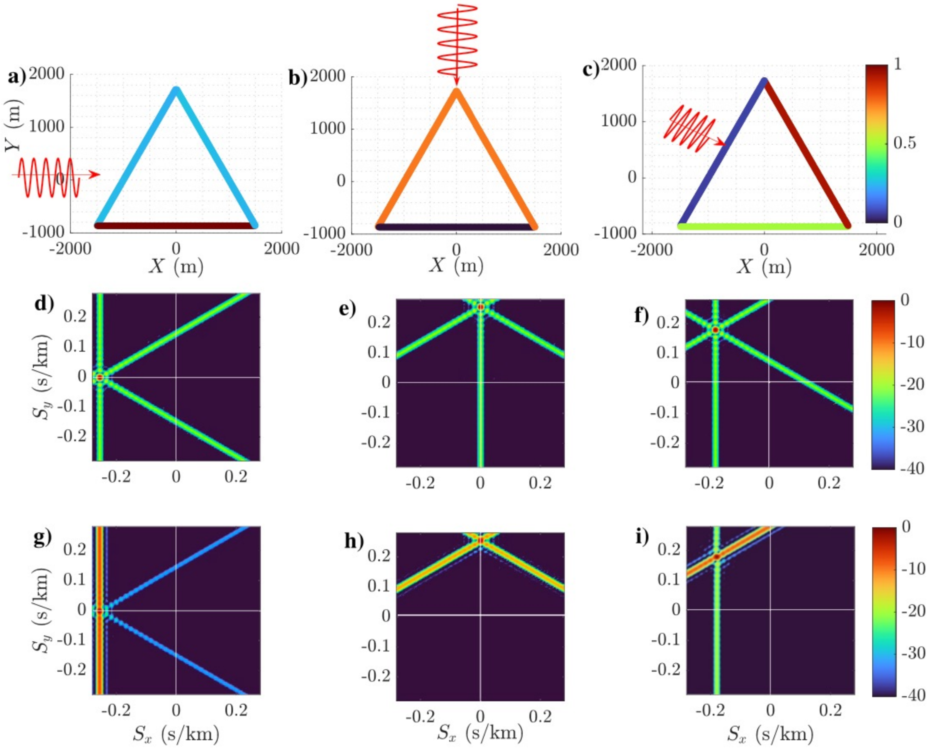


← Disregarding cable directivity

← Including cable directivity



Steered response to waves from W, N, NW



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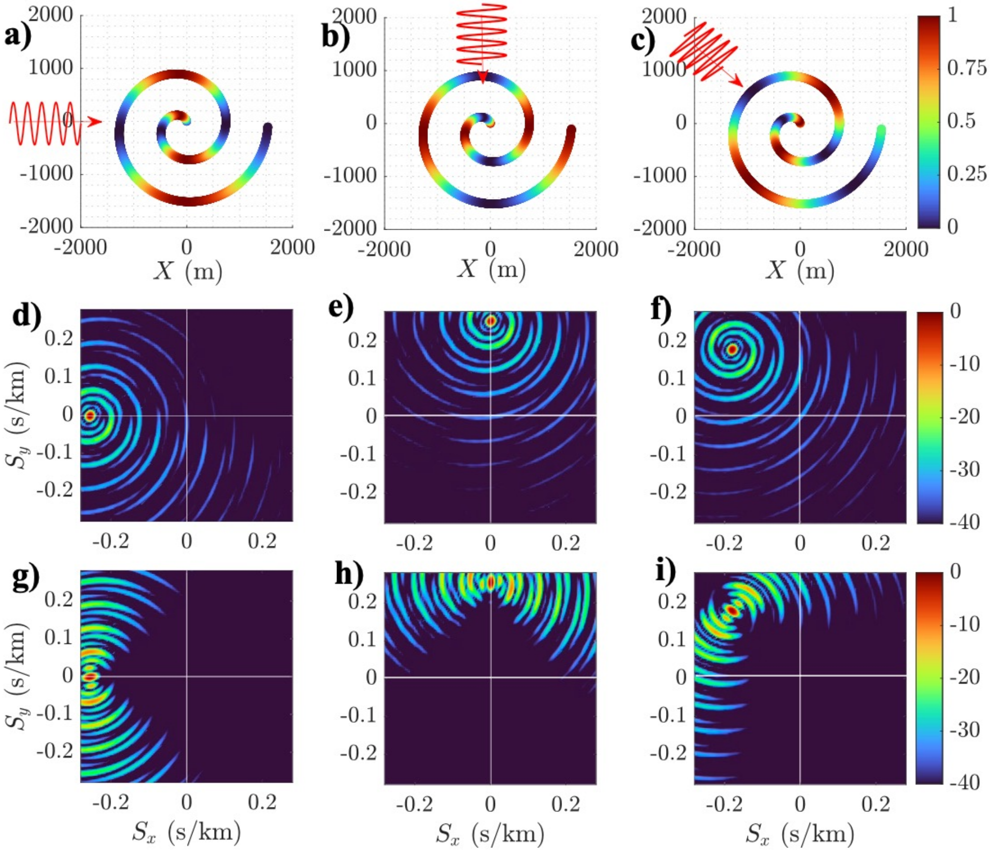


← Disregarding cable directivity

← Including cable directivity

Further reading

- Näsholm, S. P., Iranpour, K., Wuestefeld, A., Dando, B. D., Baird, A. F., & Oye, V. (2022). Array signal processing on distributed acoustic sensing data: Directivity effects in slowness space.
  Journal of Geophysical Research: Solid Earth, *127*(2), e2021JB023587
  https://doi.org/10.1029/2021JB023587 [*Source of figures in the current presentation*]

- Kennett, B. L. (2022). The seismic wavefield as seen by distributed acoustic sensing arrays: local, regional and teleseismic sources.
  Proceedings of the Royal Society A, *478*(2258), 20210812
  https://doi.org/10.1098/rspa.2021.0812

- Bowden, D. C., Klaasen, S., Martin, E., Paitz, P., & Fichtner, A. (2021). Wave-selective beamforming with distributed acoustic sensing. In *EGU General Assembly 2021*, EGU21-12216. European Geophysical Union. https://doi.org/10.5194/egusphere-egu21-12216

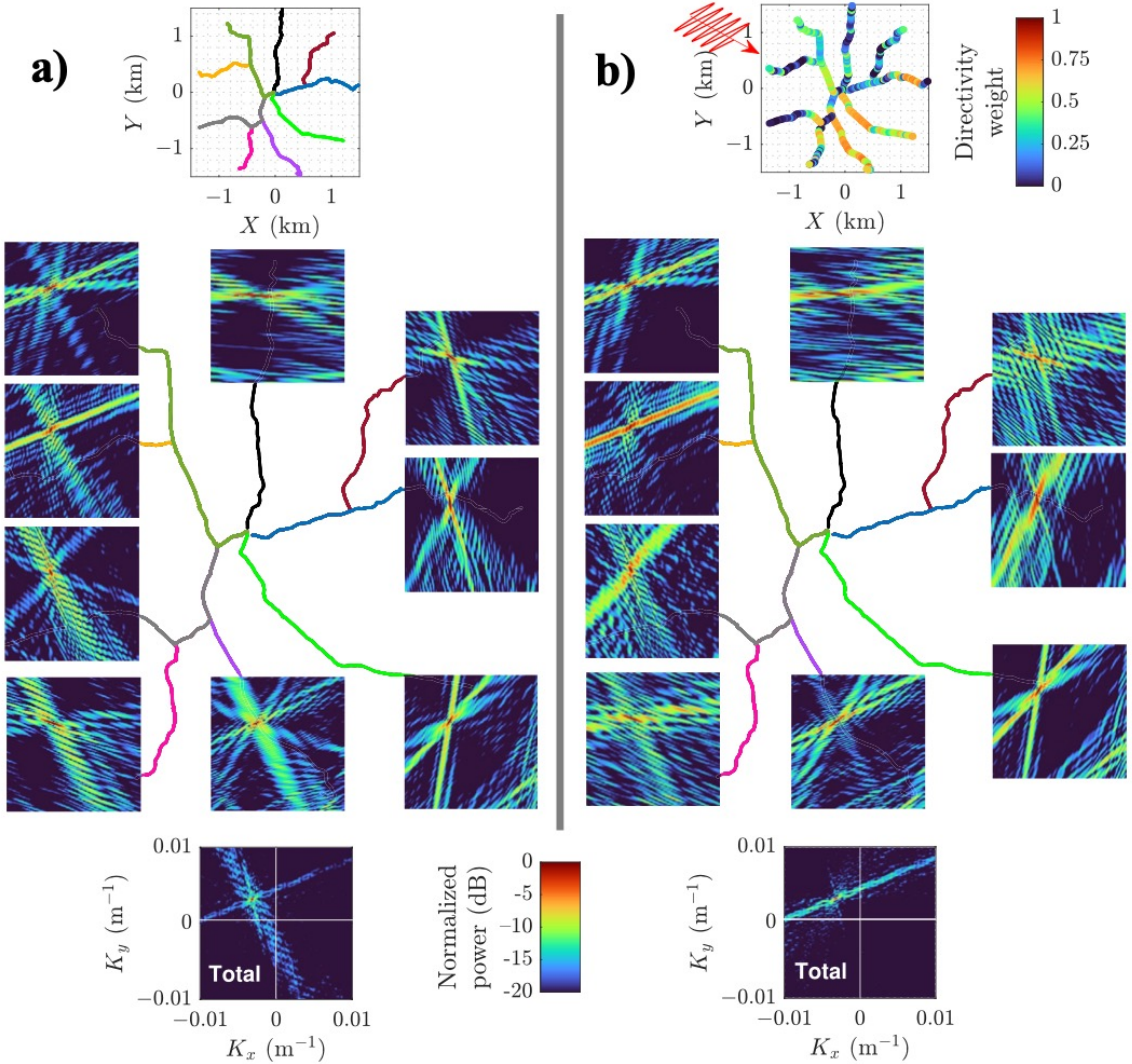
Bonus slides →

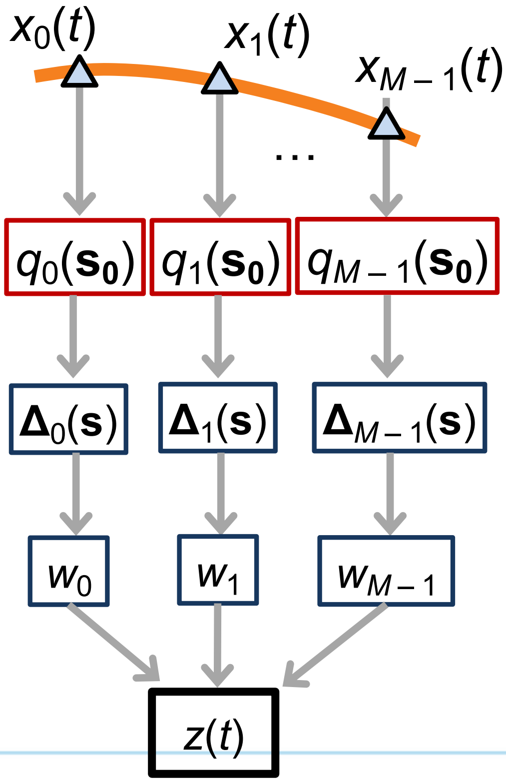
NORES field laboratory, Norway

Co-located with conventional array

a) Ignoring cable directivity

b) Cable directivity taken into account



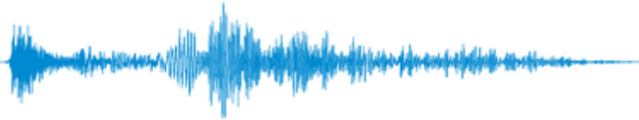


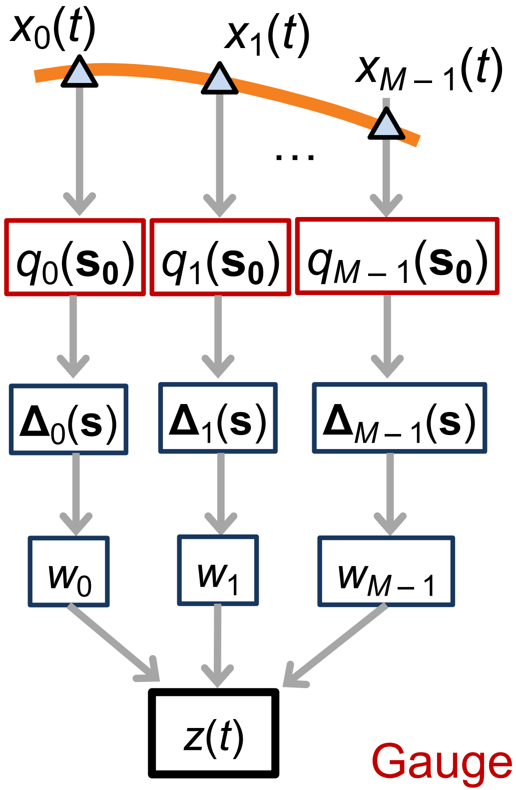
Straightforward delay-and-sum:

$$z(t) = \frac{1}{M}\sum_{m=1}^{M} w_m e^{i\omega(t-\Delta_m-\mathbf{s}_0\cdot\mathbf{r}_m)}$$

Incorporating cable & gauge averaging:

$$z(t) = \frac{1}{M}\sum_{m=0}^{M-1} w_m \int_{-\infty}^{\infty} \underbrace{h_m(\mathbf{r})}_{\text{gauge length region}}\, \underbrace{q(\mathbf{s}_0,\mathbf{r})}_{\text{local cable directivity } \cos^2\gamma_0} a(\mathbf{r}, t-\Delta_m)d\mathbf{r}$$





$x_0(t)$ $x_1(t)$ $x_{M-1}(t)$

…

$q_0(\mathbf{s_0})$ $q_1(\mathbf{s_0})$ $q_{M-1}(\mathbf{s_0})$

$\mathbf{\Delta}_0(\mathbf{s})$ $\mathbf{\Delta}_1(\mathbf{s})$ $\mathbf{\Delta}_{M-1}(\mathbf{s})$

w_0 w_1 w_{M-1}

$z(t)$

Straightforward delay-and-sum:

$$z(t) = \frac{1}{M}\sum_{m=1}^{M} w_m e^{i\omega(t-\Delta_m-\mathbf{s}_0\cdot\mathbf{r}_m)}$$

Incorporating cable & gauge averaging:

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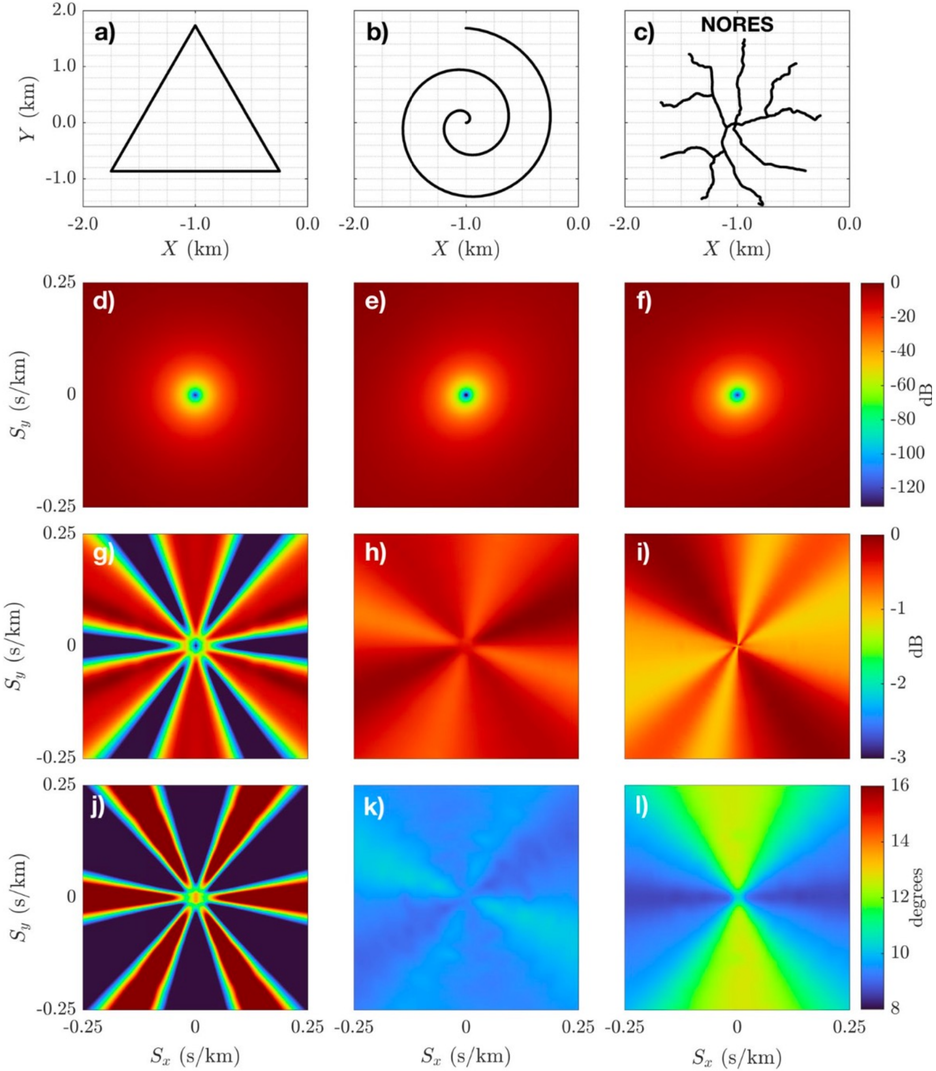
Plane wave, single frequency:

$$z(t) = \frac{e^{\omega t}}{M}\sum_{m=1}^{M} w_m \underbrace{q_m(\mathbf{s}_0) H_m(\mathbf{s}_0)}_{\text{Gauge length \& cable directivity: } \underline{\text{not}}\ (\boldsymbol{s}_0-\boldsymbol{s})}\, e^{\underbrace{-i\omega(\mathbf{s}_0-\mathbf{s})\cdot\mathbf{r}_m}_{(\boldsymbol{s}_0-\boldsymbol{s})}}$$



Consolidated steered response comparisons for an apparent velocity of 3.5 km/s, at 100 m gauge length. The virtual sources are located in the far-field. Analysis at 20 Hz.

Second row: Sensitivity distribution in terms of total steered response power as function of horizontal slowness for (d) triangular, (e) spiral, and (f) NORES DAS geometries. This is lowest when wavefront crosses the fibre array vertically and highest when the wavefront impinges horizontally.

Third row: mainlobe-to-sidelobe energy ratio (for sidelobes down to 30 dB below the maximum mainlobe level)

Fourth row: average beamwidth