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Rotational motion and spatial wavefield gradient data in seismic exploration – a review

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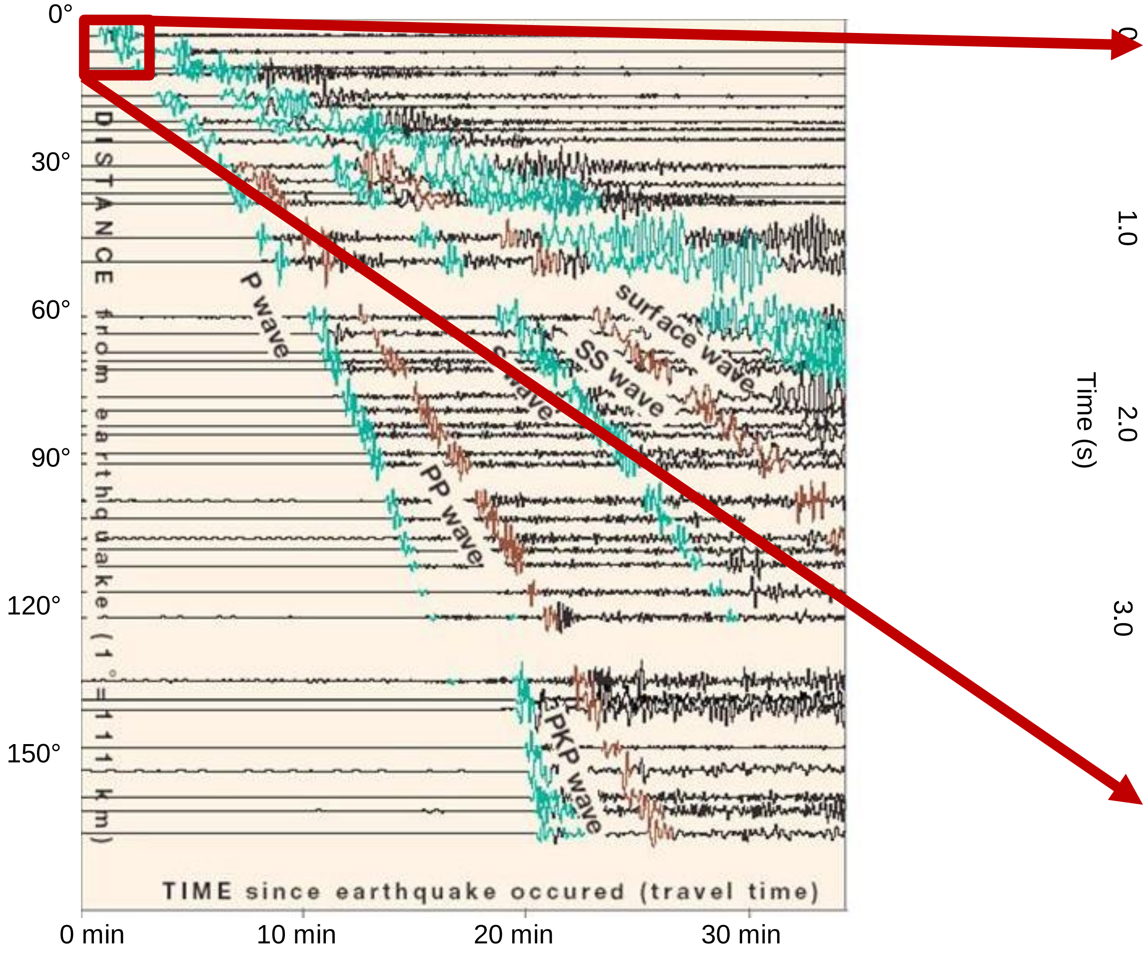
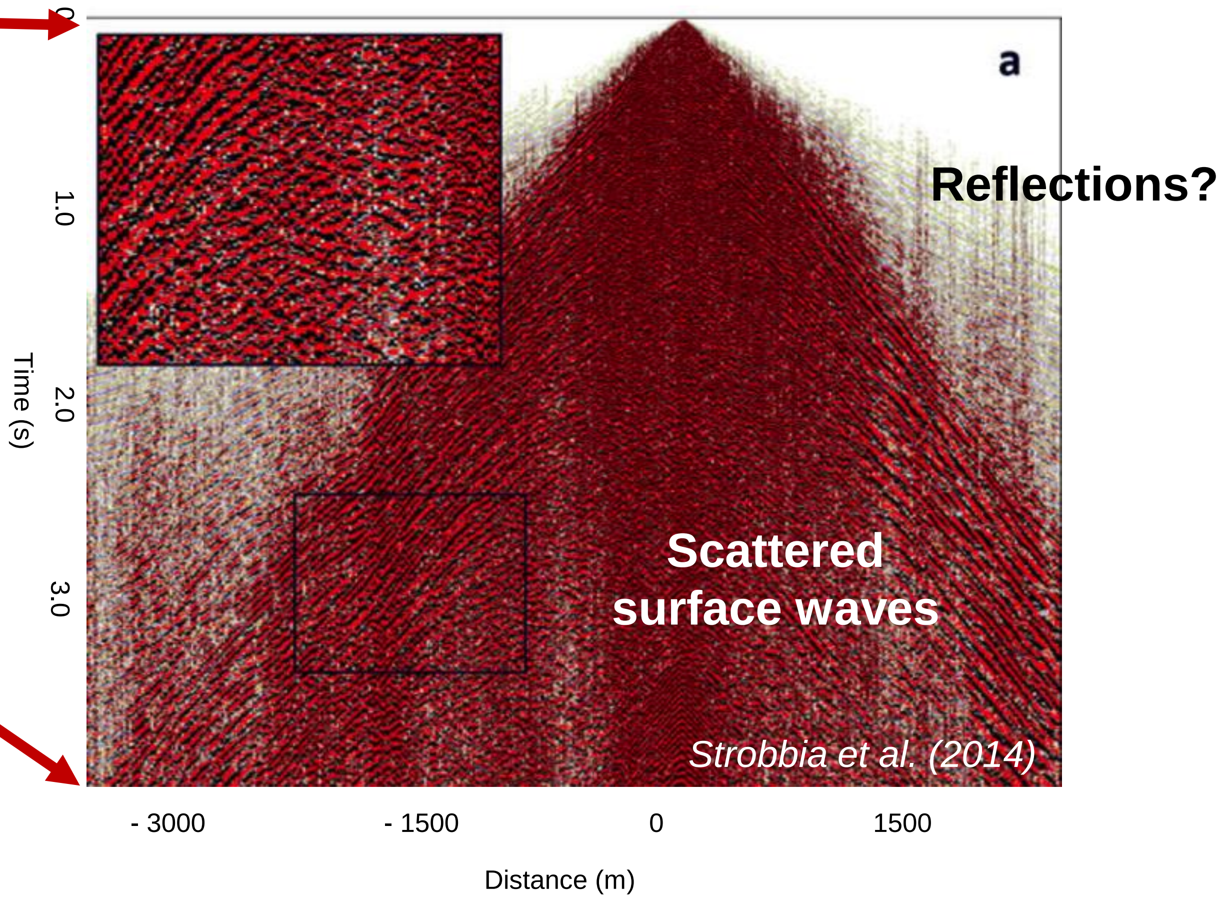
5th IWGoRS, Taiwan, 26 September 2019

A long-standing problem in exploration seismology

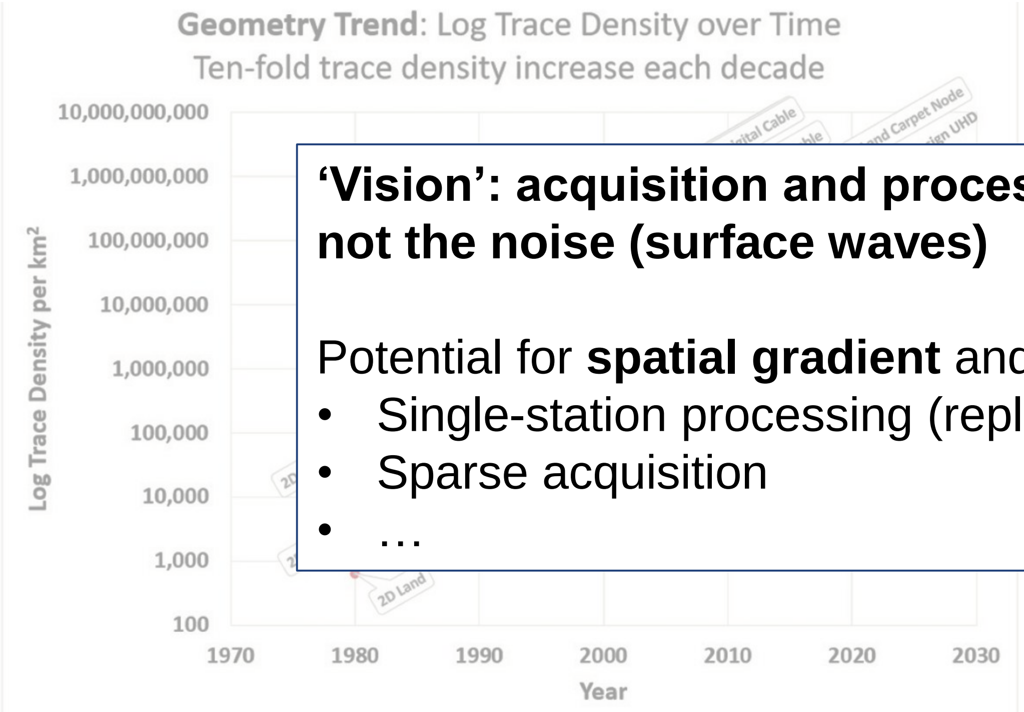
Global seismology



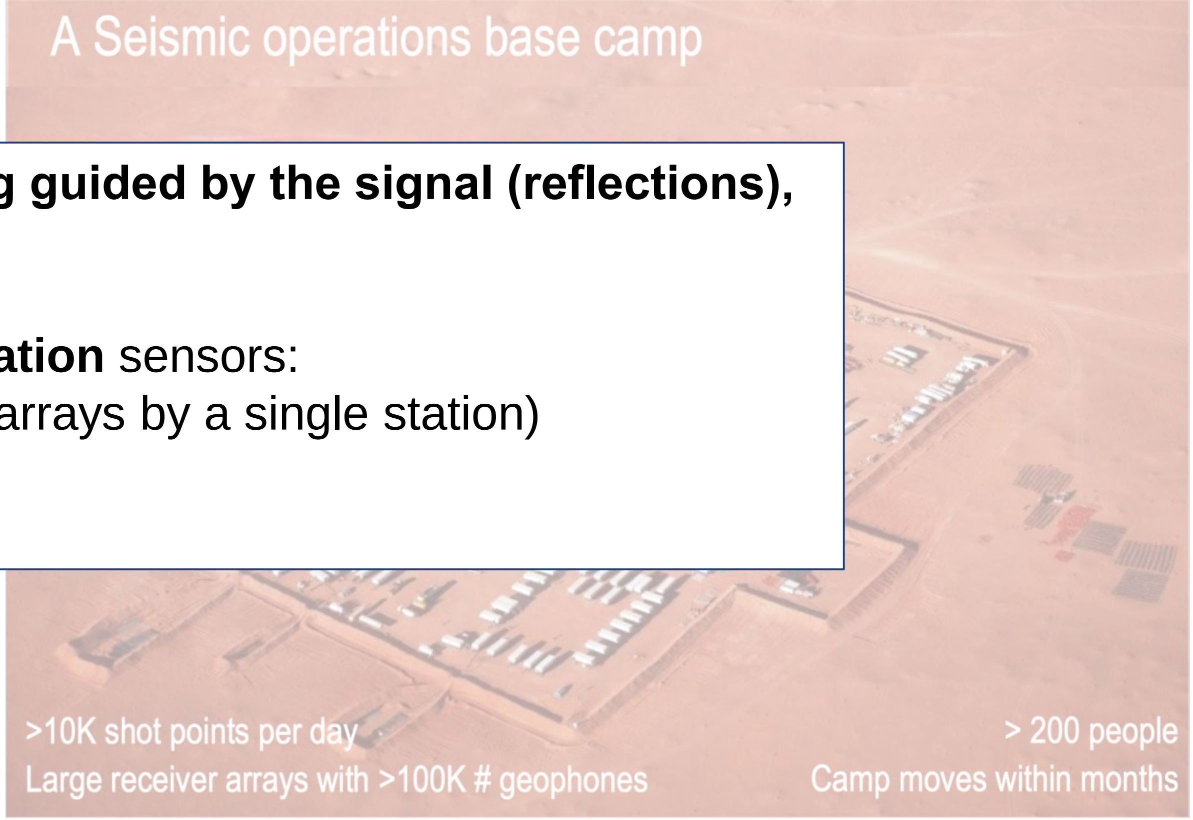
Exploration seismology



Ever rising channel (instrument) count…



Manning et al. (2019), **The nimble node — Million-channel land recording systems have arrived,** *TLE*



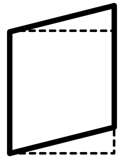
'Vision': acquisition and processing guided by the signal (reflections), not the noise (surface waves)

Potential for **spatial gradient** and **rotation** sensors:

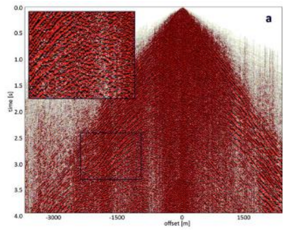
- Single-station processing (replace arrays by a single station)
- Sparse acquisition
- …

Potential of gradient and rotation data in exploration seismology

1. Link of **rotation** to S-waves and surface waves
    1. Isolate S-waves
    2. Surface-wave suppression



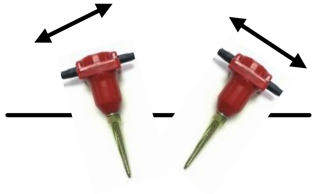
2. Spatial wavefield **gradient**
    - Local slowness
    - Wavefield separation (up-/down; P- / S- wave)
    - Wavefield reconstruction (interpolation)



3. Rotational motion as **new observable** in seismology
    - Seismic wavefield characterization & decomposition
    - Novel techniques to estimate subsurface properties (near-surface elastic properties, anisotropy, …)

$$\frac{\partial v_z}{\partial y} \approx \dot{w}_x$$

4. Correction for sensor **tilt**
    - Tilt of ocean-bottom sensors due to currents



Overview
Developments and applications of gradient data in exploration

- **Wavefield characterization & separation**
  - Plane wave and polarization analyses
  - Wave-equation based approaches

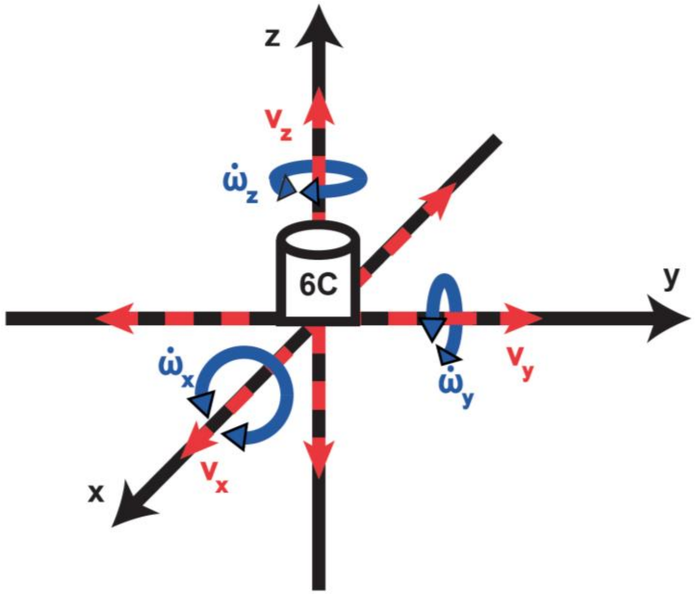
- **Wavefield reconstruction – A signal processing perspective**

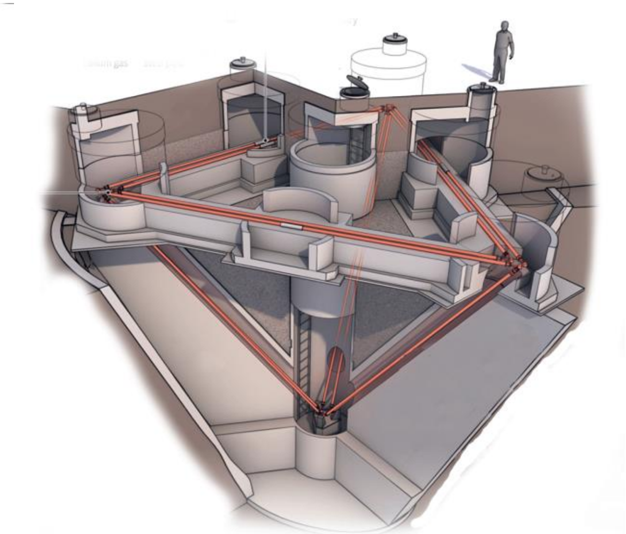
- **Hardware developments: Gradient sensors**
  - ‘Gradient-based’ rotation and divergence sensors
  - Receiver perturbation corrections

Background

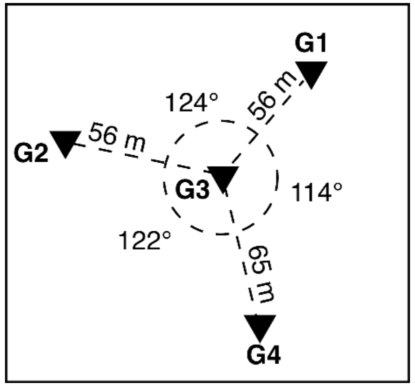
Schmelzbach et al. (2018), Geophysics.

6C measurements with a single station
3 components of translation & 3 components of rotation





Hand (2017), Science.



ROMY ring laser **BlueSeis (iXBlue)** **Arrays**

3C of translation & 3C of rotation

3C of translation & gradients

Gradients, divergence and rotation at the free-surface

Robertsson and Curtis (2002), Geophysics; Schmelzbach et al. (2018) Geophysics.

Free-surface condition: $\sigma_{iz} = 0$

$$\sigma_{ij} = (\lambda\delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}))\epsilon_{kl}$$

$$\epsilon_{ij} = \frac{1}{2}(\partial_j u_i + \partial_i u_j)$$

In medium

$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \mathbf{u} = \frac{1}{2}\begin{pmatrix} \partial_y u_z - \partial_z u_y \\ \partial_z u_x - \partial_x u_z \\ \partial_y u_y - \partial_y u_x \end{pmatrix}$$

$$\partial_z u_x = -\partial_x u_z$$

$$\partial_z u_y = -\partial_y u_z$$

$$\partial_z u_z = -\frac{\lambda}{\lambda + 2\mu}(\partial_x u_x + \partial_y u_y)$$

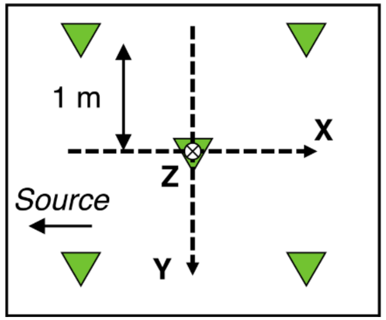
At the free-surface

$$\boldsymbol{\omega}^{\mathbf{FS}} = \begin{pmatrix} \partial_y u_z \\ -\partial_x u_z \\ \frac{1}{2}(\partial_x u_y - \partial_y u_x) \end{pmatrix}$$

$$(\nabla \cdot u)^{\mathrm{FS}} = \frac{2\mu}{\lambda + 2\mu}(\partial_x u_x + \partial_y u_y)$$

Surface-based measurements only!

Schmelzbach et al. (2018), Geophysics.

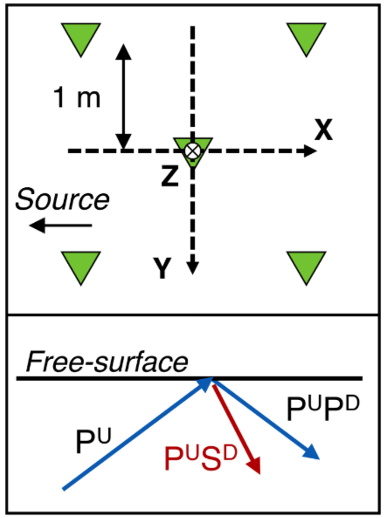


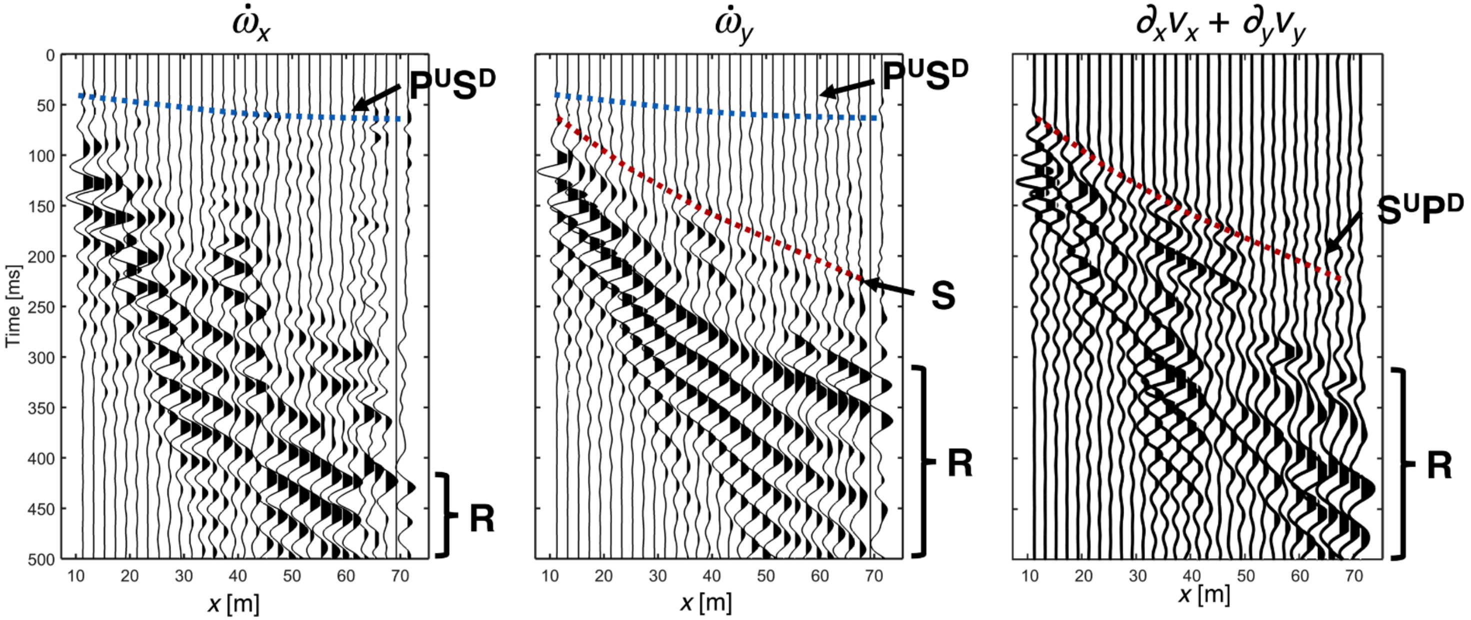
Schmelzbach et al. (2018), Geophysics.

Rotation
- P^US^D (Down-going wavefield)
- Rayleigh waves

Divergence
- S^UP^D (Down-going wavefield)
- Rayleigh waves

Coherent energy on $\dot{\omega}_x$ suggests out-of-plane arrivals





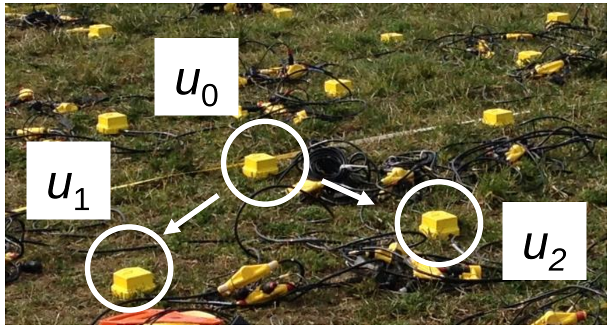
Receiver perturbation corrections

Sollberger et al. (2019), GJI.

Receiver perturbation correction
Sollberger et al. (2019), GJI.

Underlying model: Waveforms at one receiver can be predicted based on waveform measured at a reference station and the spatial gradients

$$\tilde{u}_i^{\text{pred}} = [\tilde{u}_0^{\text{obs}} + \delta x_i \partial_x \tilde{u}_0 + \delta y_i \partial_y \tilde{u}_0]$$



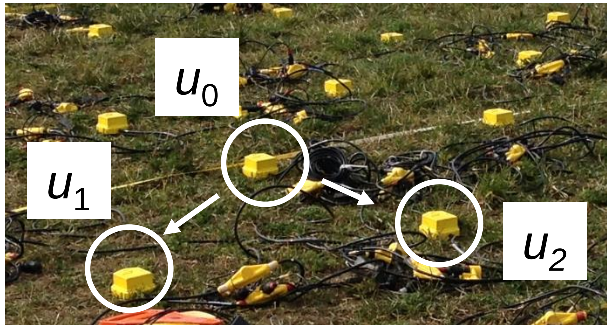
Receiver perturbation correction
Sollberger et al. (2019), GJI.

Underlying model: Waveforms at one receiver can be predicted based on waveform measured at a reference station and the spatial gradients

$$\tilde{u}_i^{\text{pred}} = \tilde{C}_i[\tilde{u}_0^{\text{obs}} + \delta x_i \partial_x \tilde{u}_0 + \delta y_i \partial_y \tilde{u}_0]$$

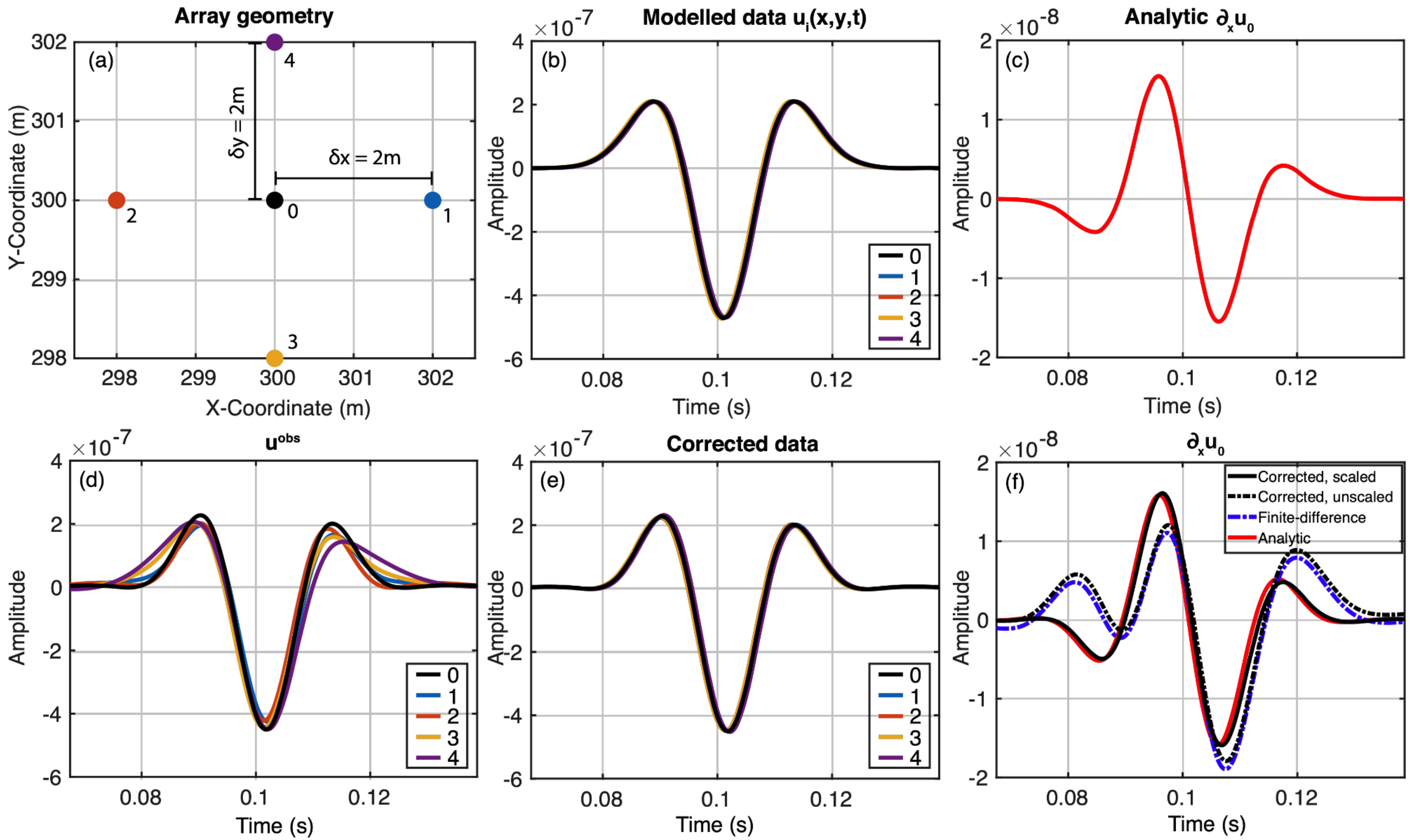
Perturbation factor

→ Jointly invert for gradients and receiver perturbation factor



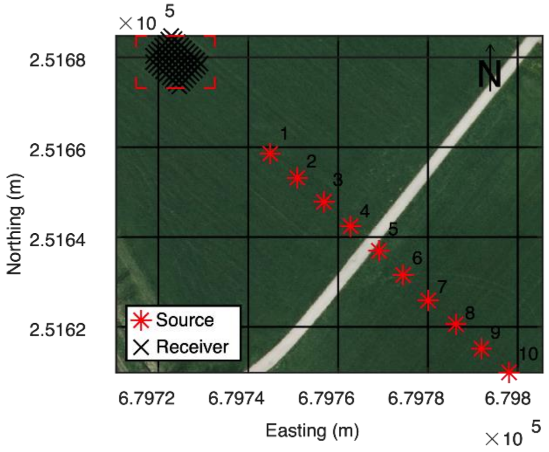
Synthetic data example

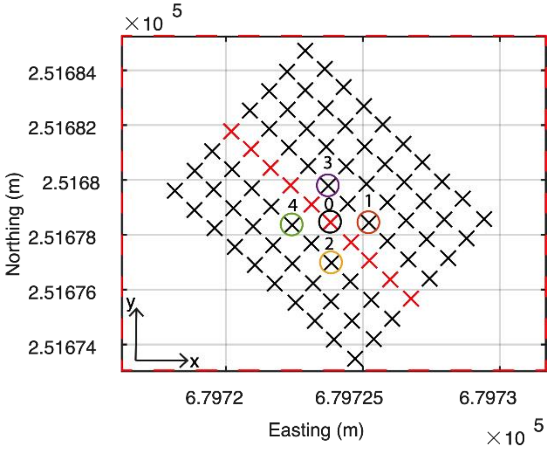
Sollberger et al. (2019), GJI.

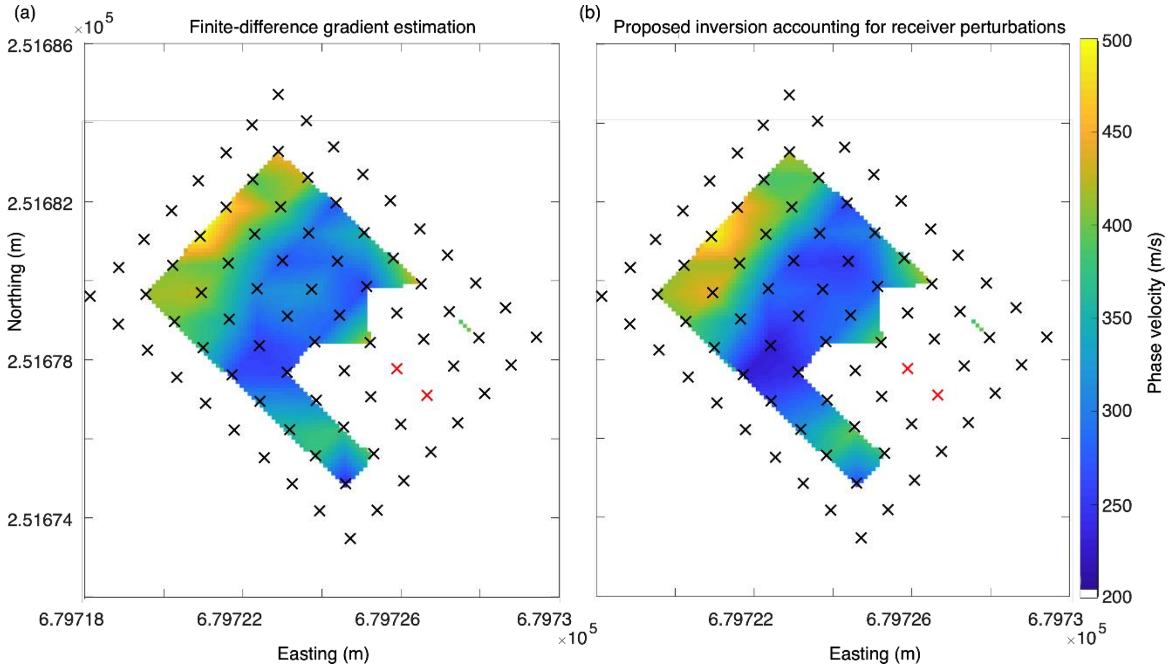


Field-data example

Sollberger et al. (2019), GJI.





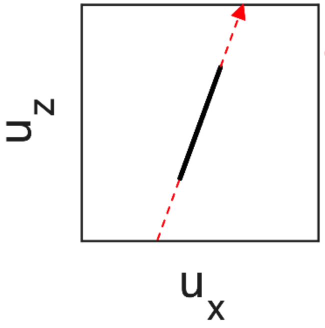


6C polarization analysis & wavefield separation

Sollberger et al. (2018), GJI.

3C polarization models – Example of a P-wave (in a medium)

3C hodograms



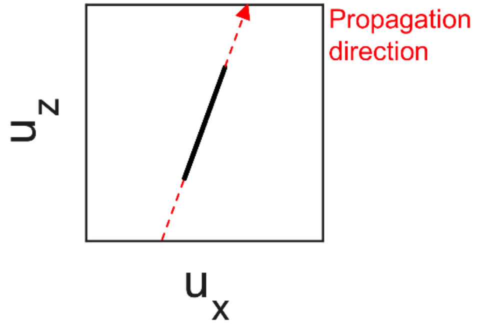
3C polarization model depends on

- Wave mode
- Azimuth & incidence angle
- Rayleigh waves: ellipticity

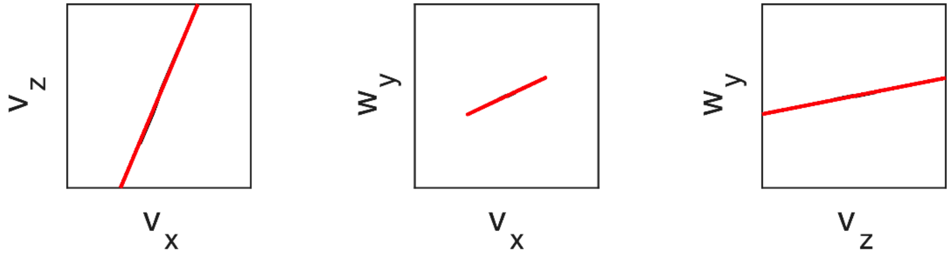
Sollberger et al. (2018), GJI.

3C versus 6C polarization models

3C hodograms



6C hodograms



v_i Particle velocity
w_i Rotation

3C polarization model depends on

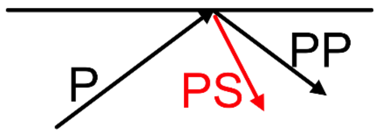
- Wave mode
- Azimuth & incidence angle
- Rayleigh waves: ellipticity

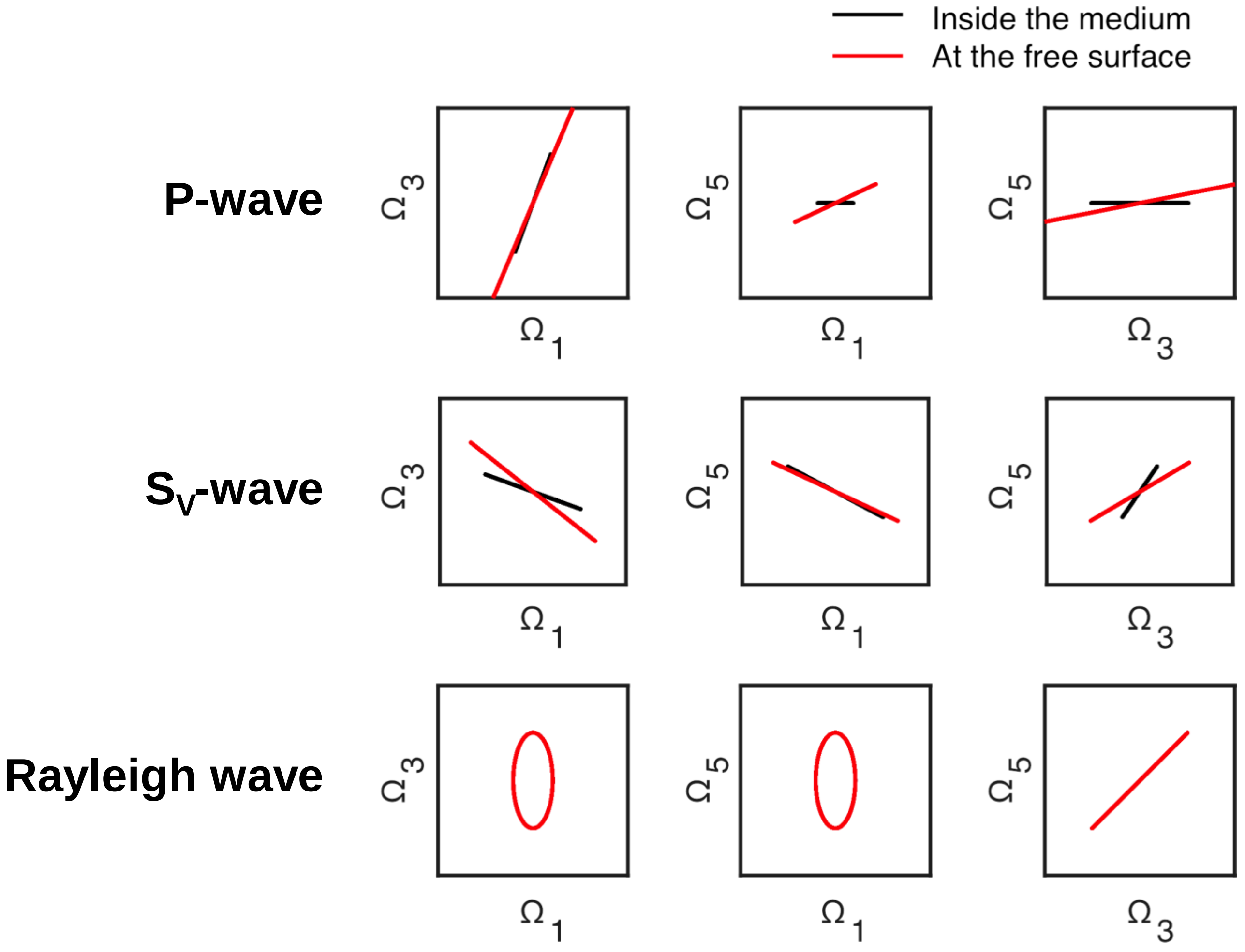
6C Polarization model depends on

- Wave mode
- Azimuth & incidence angle
- P- and S-wave velocity
- Rayleigh waves: ellipticity

Sollberger et al. (2018), GJI.

6C plane wave polarization models

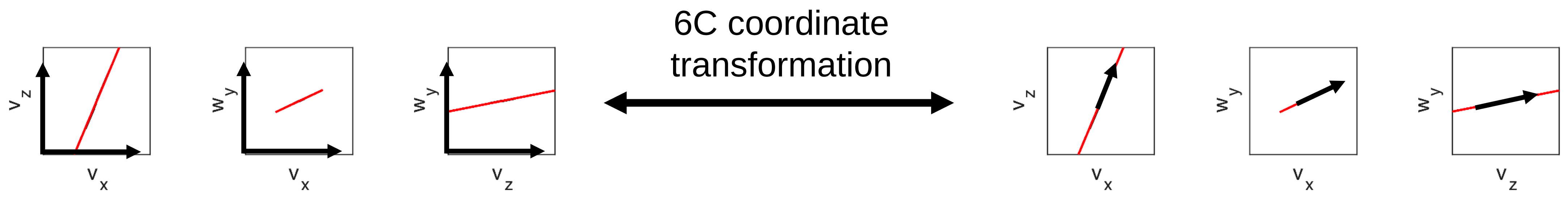




Unique for each wave type!

Sollberger et al. (2018), GJI.

6C polarization analysis



6C Polarization model depends on
- Wave mode
- Azimuth & incidence angle
- P- and S-wave velocity
- Rayleigh waves: ellipticity

Find polarization parameters by matching a 6C polarization template to the data

Sollberger et al. (2018), GJI.

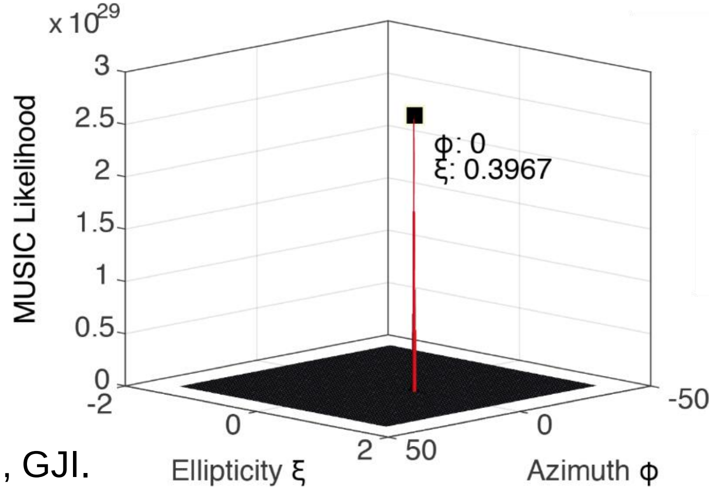
6C polarization analysis

Because the 6C polarization models are unique, we can…

- Scan the data for a polarization model
  → *Wave type identification*

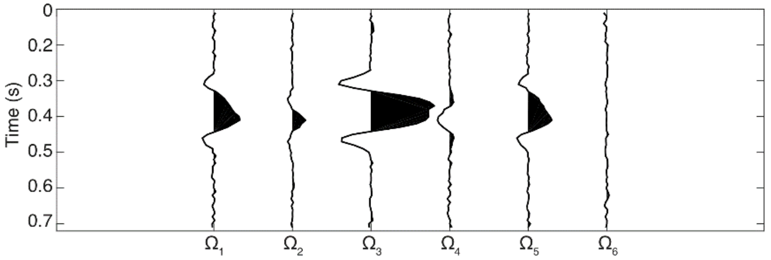
- Given a polarization model, scan for the wave parameters
  → *Azimuth, incidence angle, velocities, ellipticity*

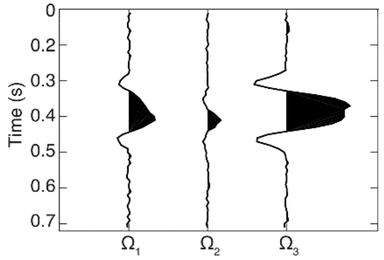
- Rotate 6C into a ‘wavetype’-specific coordinate system
  → *Wavefield separation (e.g. by wavetype, azimuth)*



Sollberger et al. (2018), GJI.

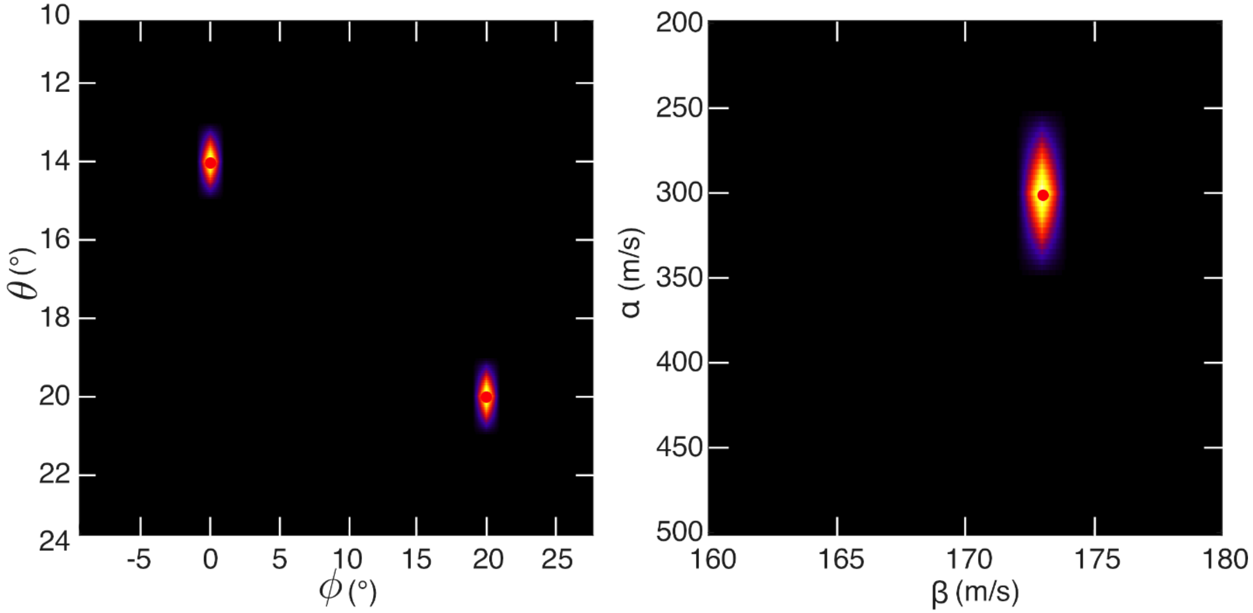
Two interfering arrivals

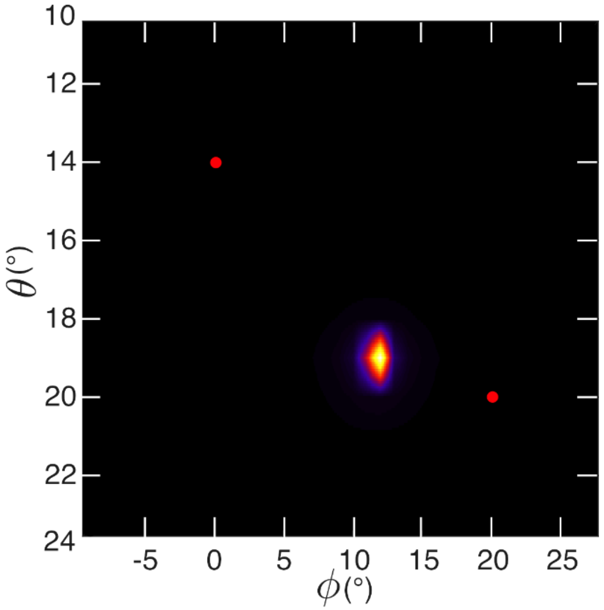




6C data

3C data

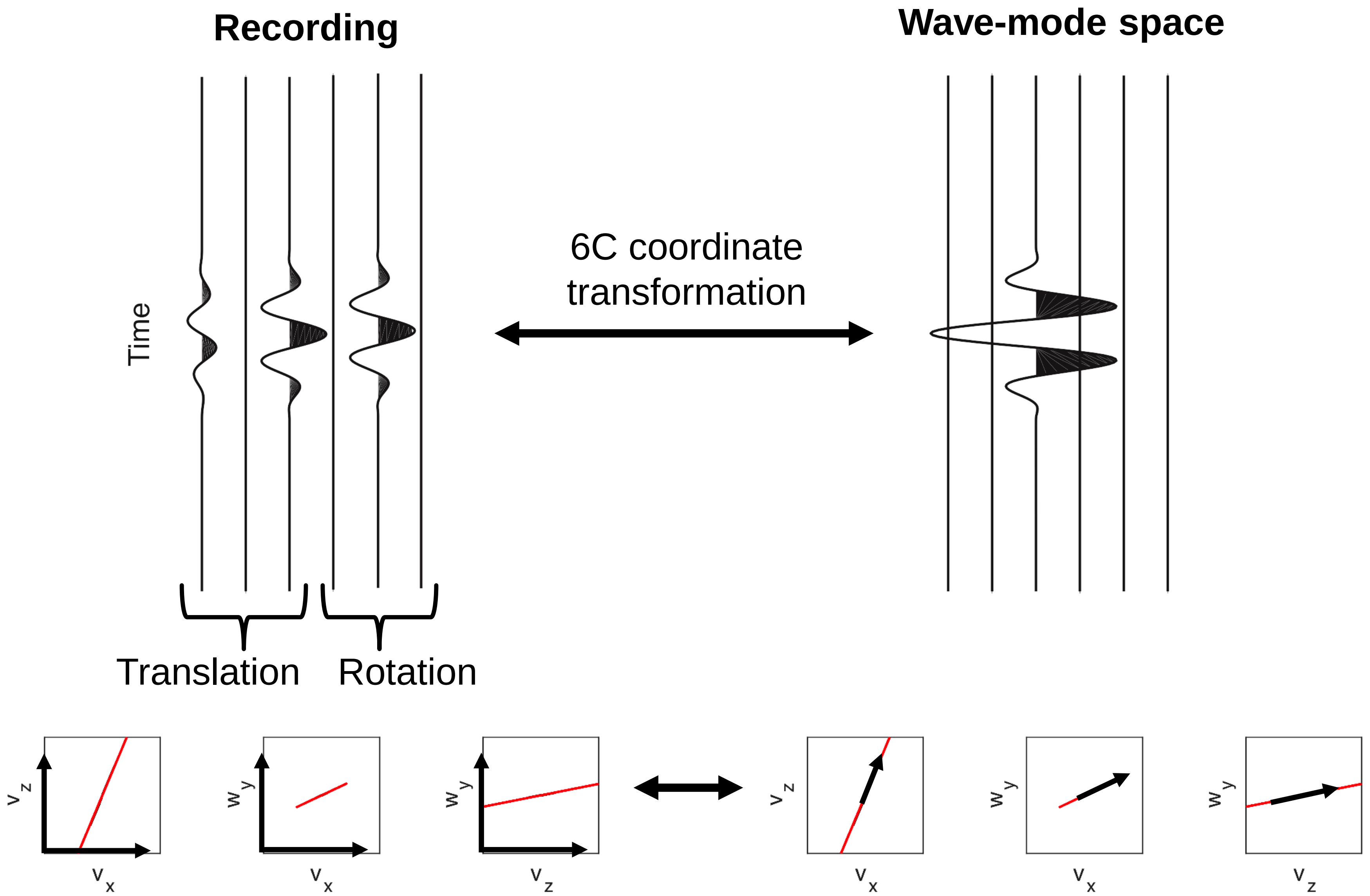




Sollberger et al. (2018), GJI.

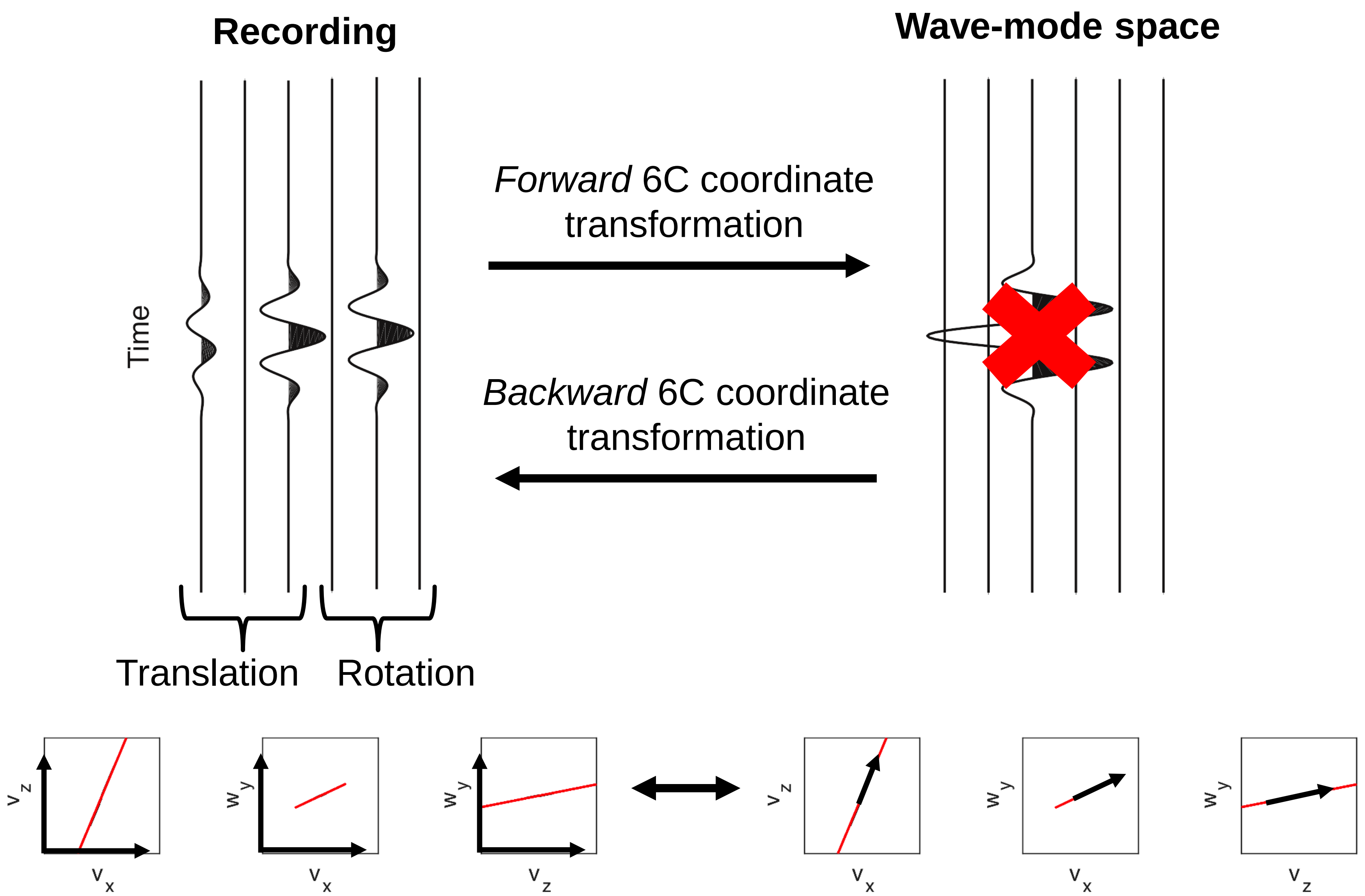
Wavefield separation

Sollberger et al. (2018), GJI.

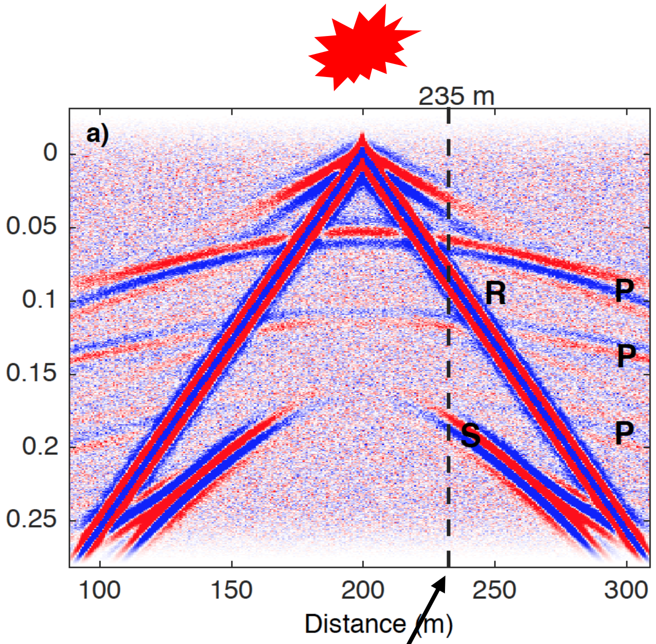


Wavefield separation

Sollberger et al. (2018), GJI.



Wavefield separation example: Rayleigh wave suppression



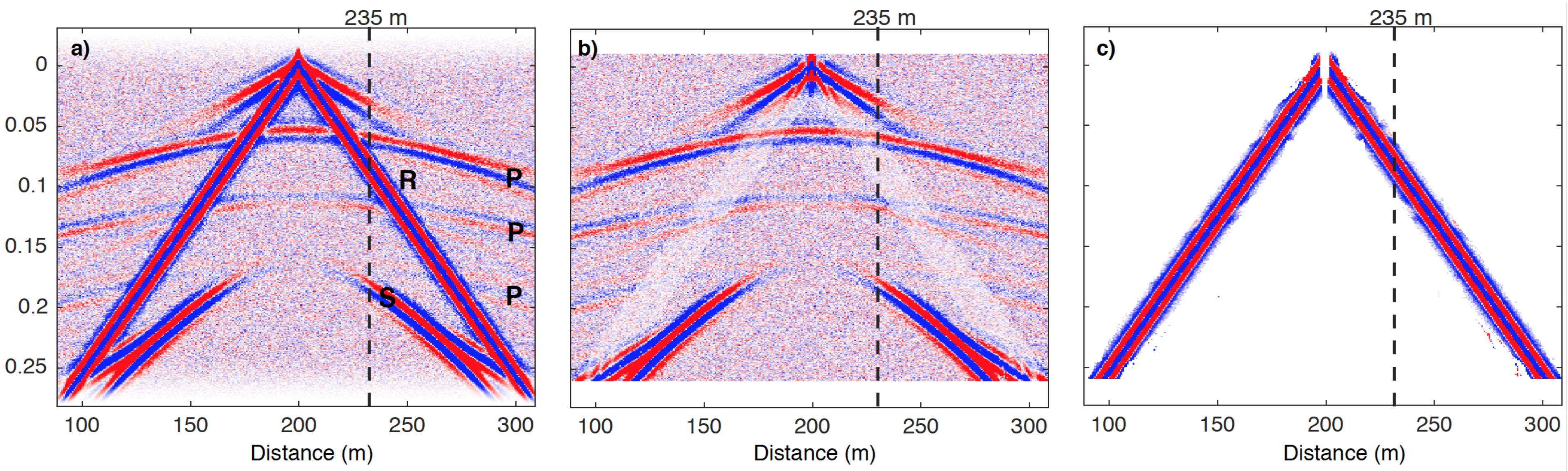
Reflection (signal)

Rayleigh wave (noise)

6C sensor

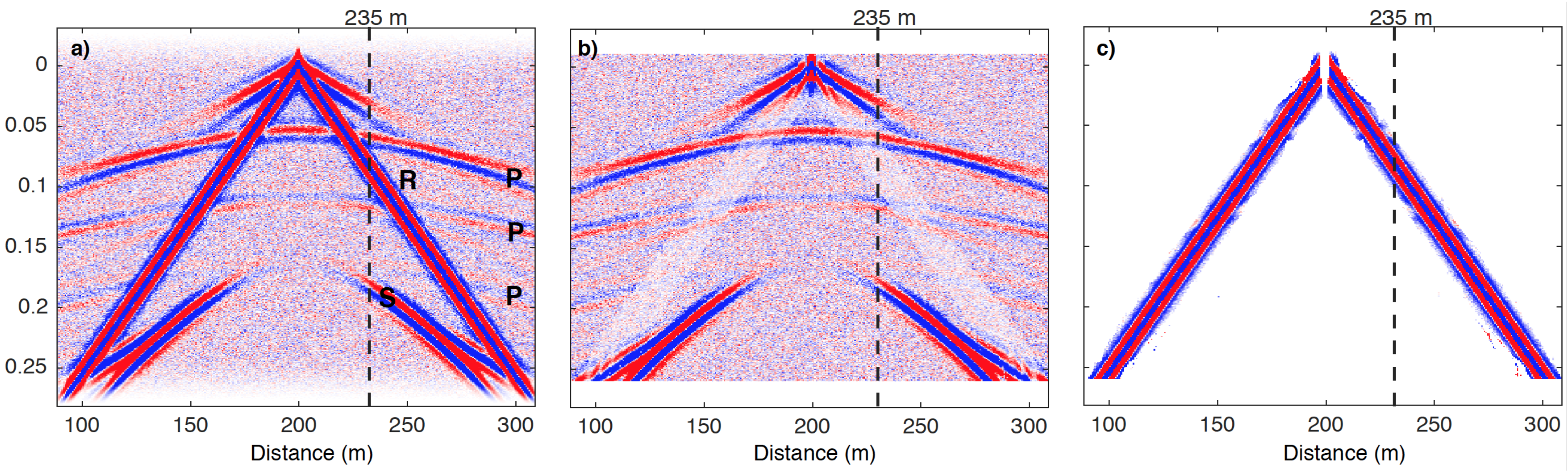
Sollberger et al. (2018), GJI.

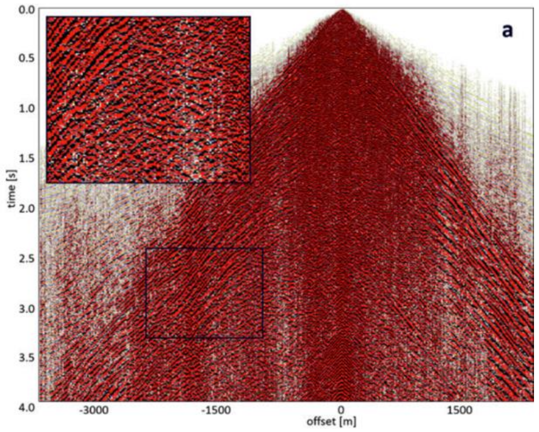
Wavefield separation example: Rayleigh wave suppression



Sollberger et al. (2018), GJI.

Wavefield separation example: Rayleigh wave suppression





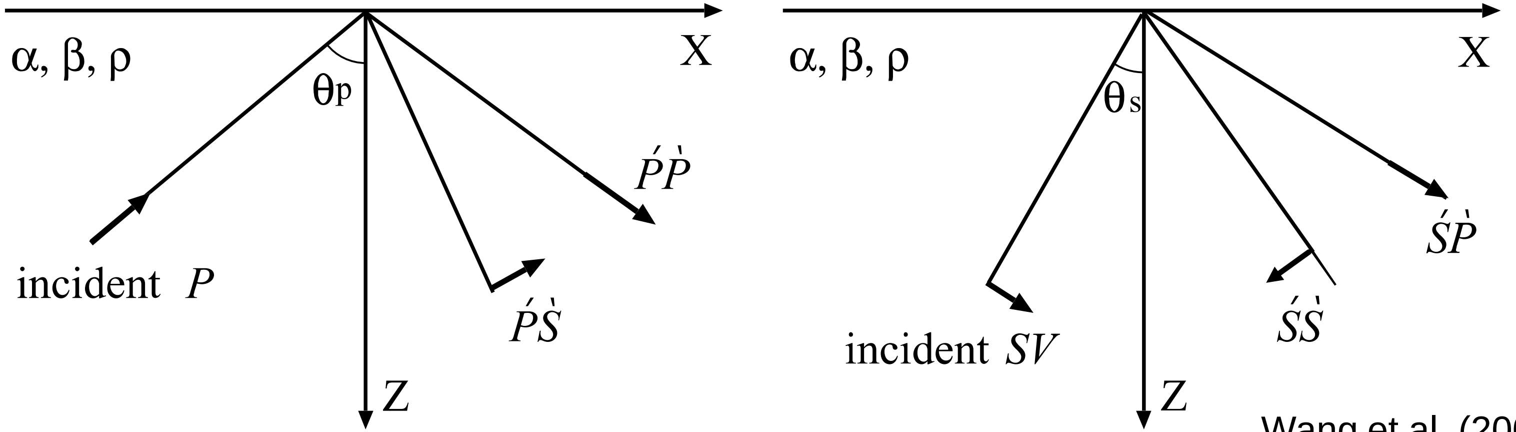
Moderate success with field data so far…
Extension to time-frequency domain under way with promising first results.

Sollberger et al. (2018), GJI.

Gradient-based wavefield separation

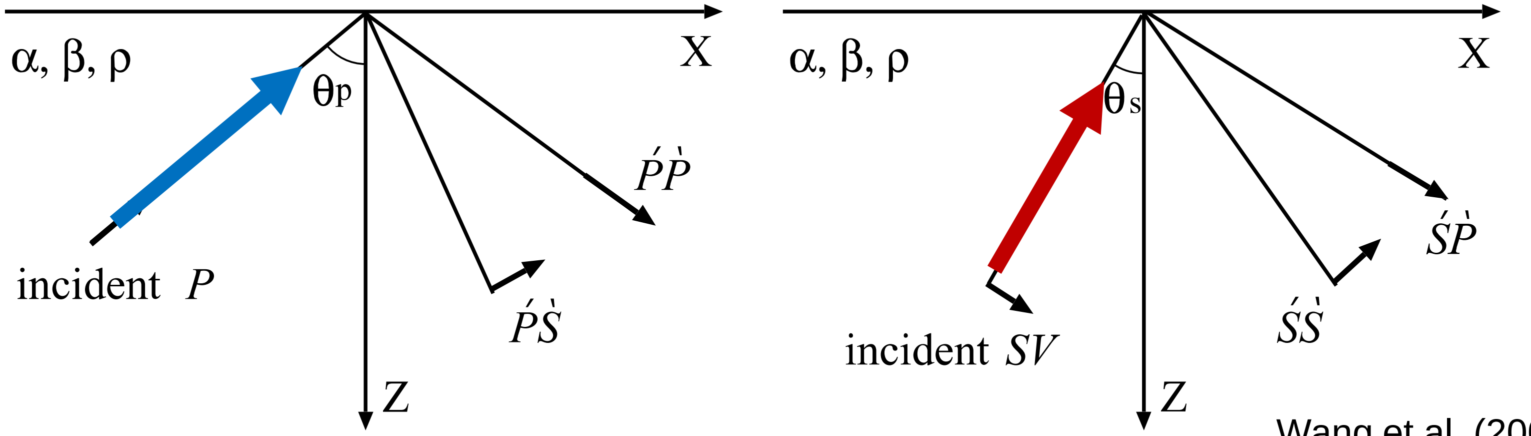
Van Renterghem et al. (2018), GJI; Van Renterghem et al. (2019a,b), Geophysics.

Seismic recordings at the free surface



Wang et al. (2002)

Motivation: "clean-up" wavefield recorded at the free surface



Wang et al. (2002)

Gradient-based filters to separate wavefield at a single station
(Robertsson and Curtis, 2002; Van Renterghem et al., 2018)

- Up-going (incident) / down-going wavefield

… and/or …

- P- / S-wavefield

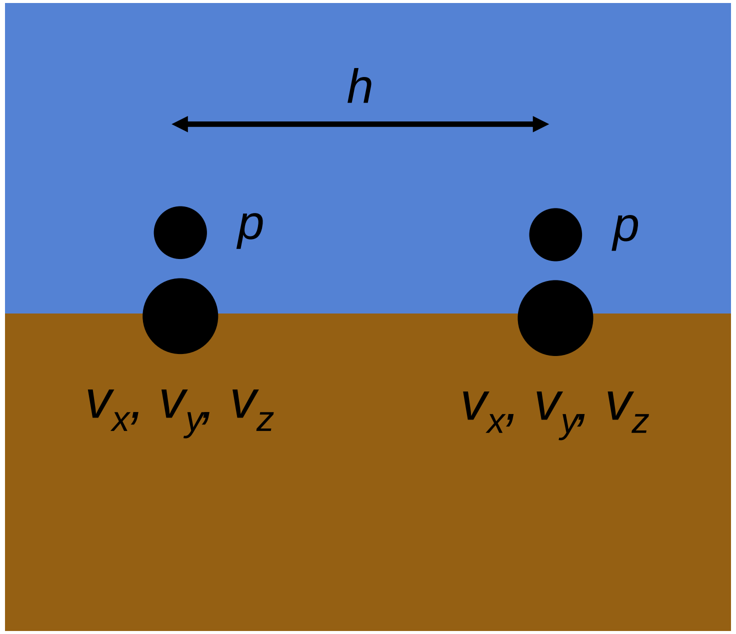
Wavefield separation of Ocean Bottom Sensor (OBS) data

- Up/down separation

$$v_h^U \approx \frac{1}{2}\left(v_h + \frac{1}{i\omega}(\alpha - 2\beta)\frac{\partial v_z}{\partial_h}\right)$$

- Up/down + P/S separation

$$v_h^{S^U} \approx \frac{1}{2}\left(v_h - \frac{1}{i\omega}2\beta\frac{\partial v_z}{\partial h} + \frac{1}{i\omega}\frac{1}{\rho}\frac{\partial p}{\partial h}\right)$$



Van Renterghem et al., submitted.

$$h = x \; or \; y$$

Wavefield separation of OBS data

rotational data

- Up/down separation

$$v_h^U \approx \frac{1}{2}\left(v_h + \frac{1}{i\omega}(\alpha - 2\beta)\frac{\partial v_z}{\partial h}\right)$$

Rotational motions

- Up/down + P/S separation

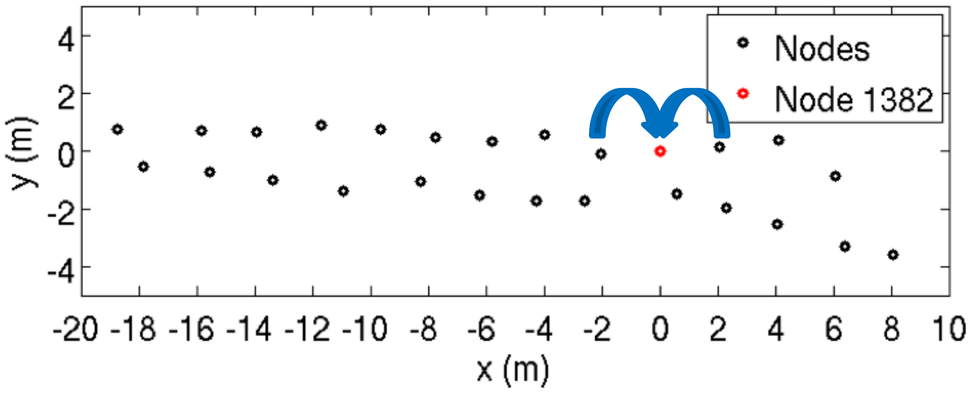
$$v_h^{S^U} \approx \frac{1}{2}\left(v_h - \frac{1}{i\omega}2\beta\frac{\partial v_z}{\partial h} + \frac{1}{i\omega}\frac{1}{\rho}\frac{\partial p}{\partial h}\right)$$

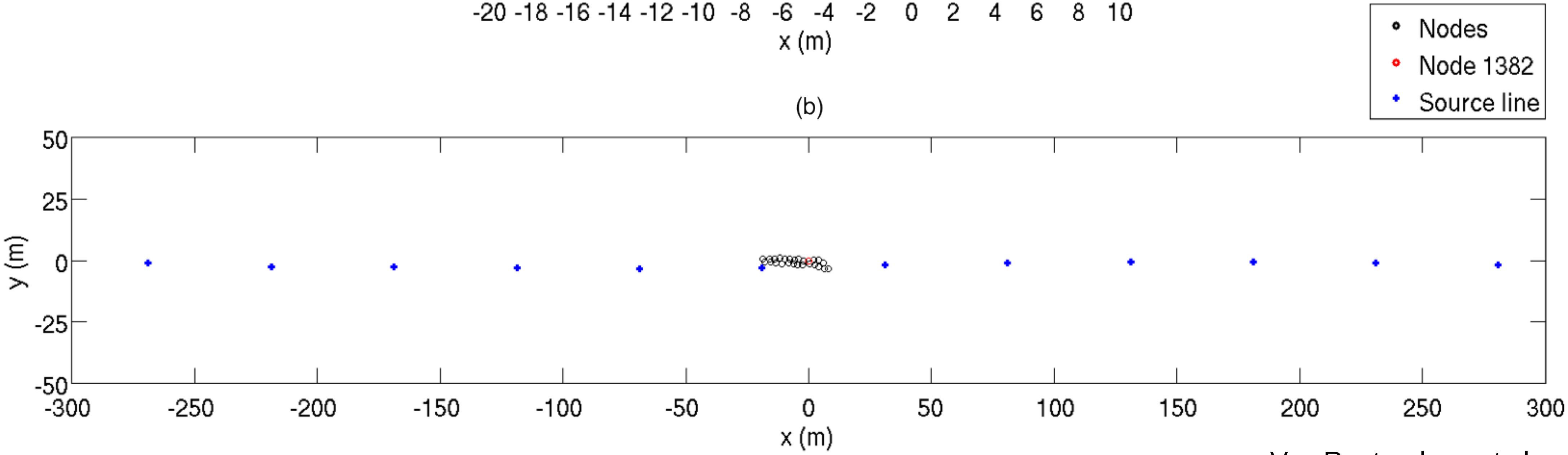
Van Renterghem et al., submitted.

$h = x \text{ or } y$

Moere Vest OBS dataset

Array-derived spatial gradients





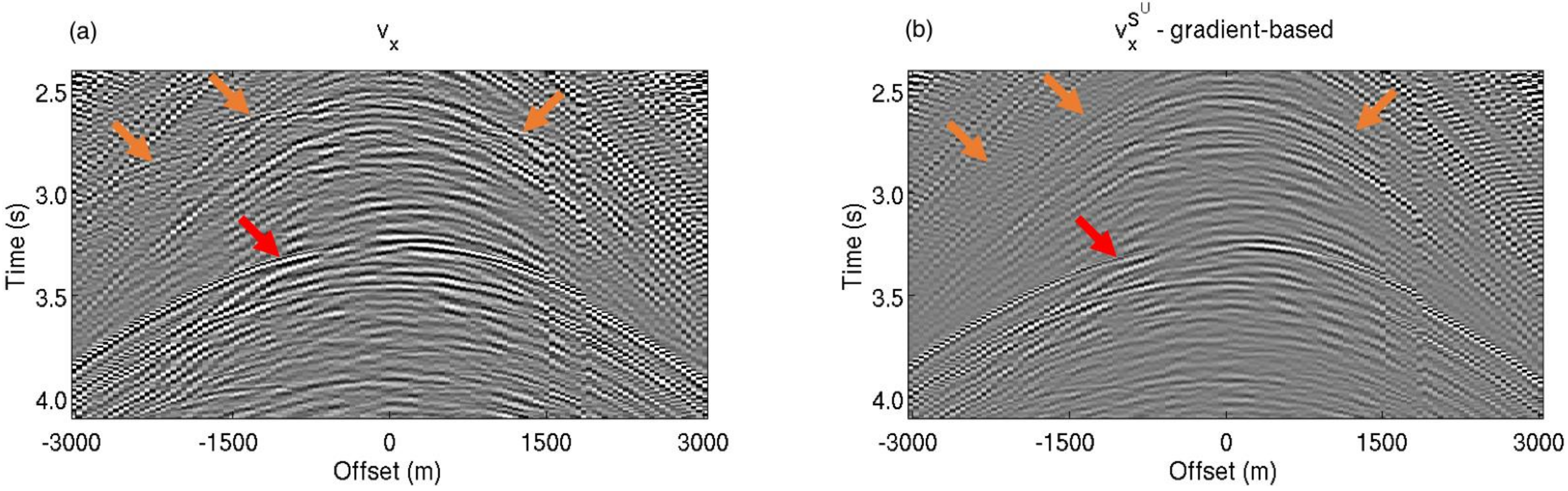
Van Renterghem et al., submitted.

Elastic wavefield decomposition

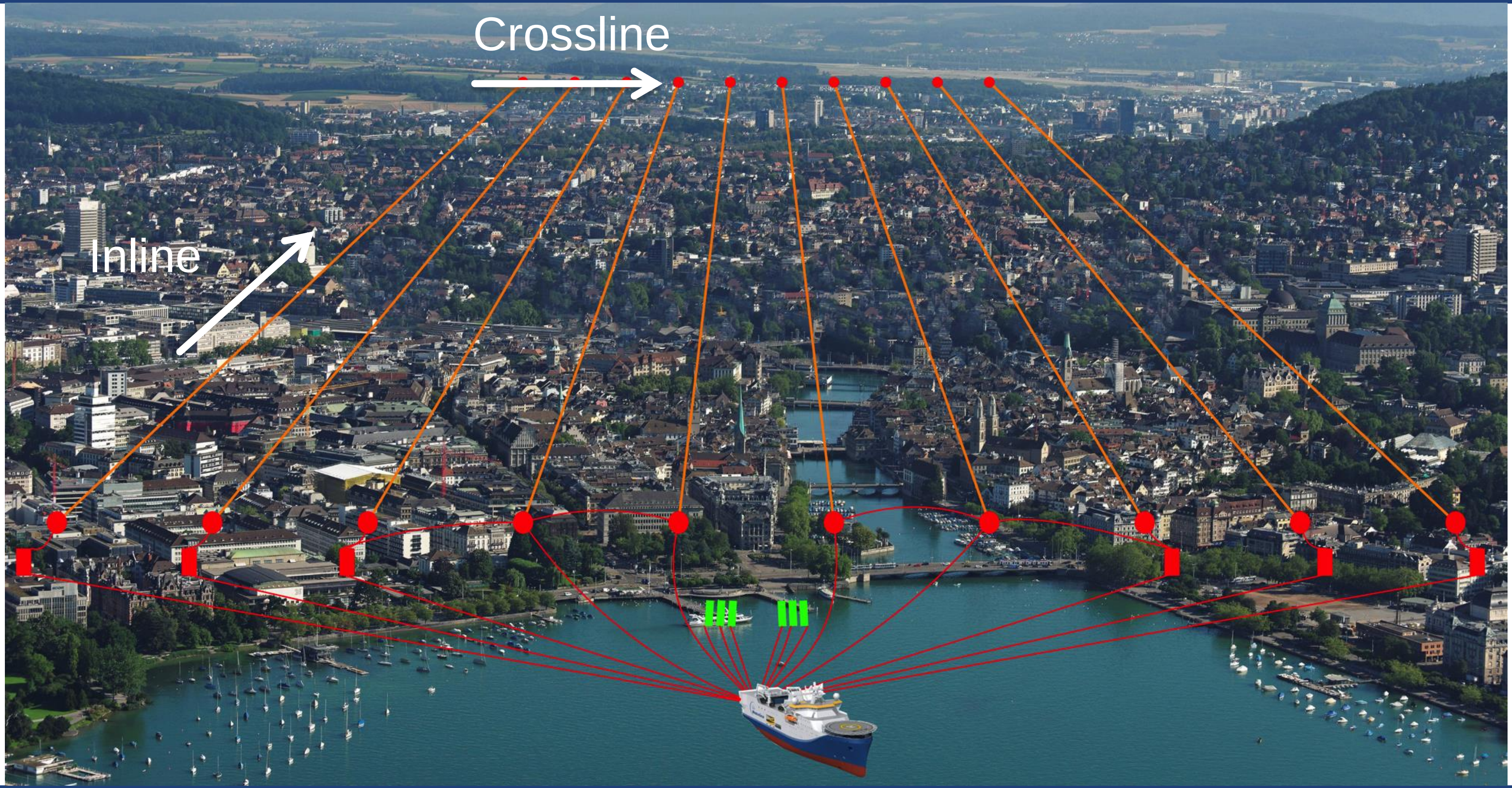
Water layer multiple

P-waves

$$v_x^{S^U} \approx \frac{1}{2}\left(v_x - \frac{1}{i\omega}2\beta\frac{\partial v_z}{\partial x} + \frac{1}{i\omega}\frac{1}{\rho}\frac{\partial p}{\partial x}\right)$$



Van Renterghem et al., submitted.

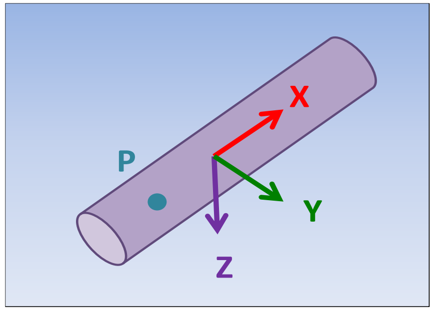


Wavefield reconstruction – A signal-processing view on gradients

Robertsson et al. (2008), Geophysics.

Wavefield reconstruction with combined pressure and pressure gradient data

Marine seismic exploration : Multicomponent streamer



- Equation of motion relates particle acceleration to pressure gradient

$$\nabla p = -\rho \dot{\vec{v}}$$

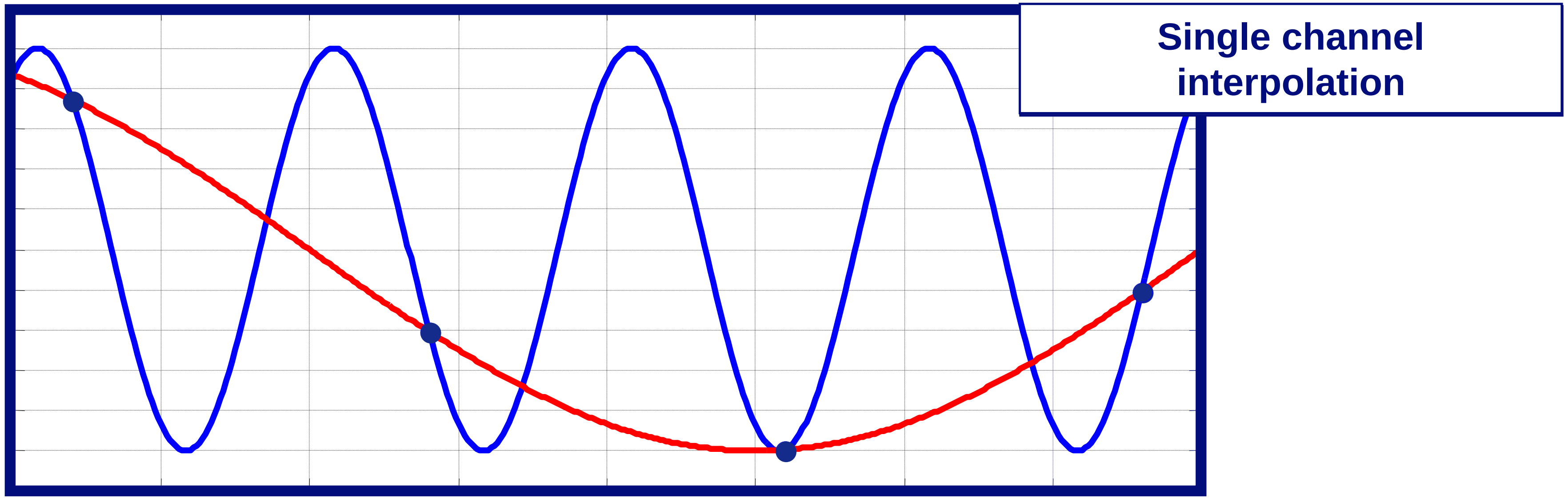
Sampling

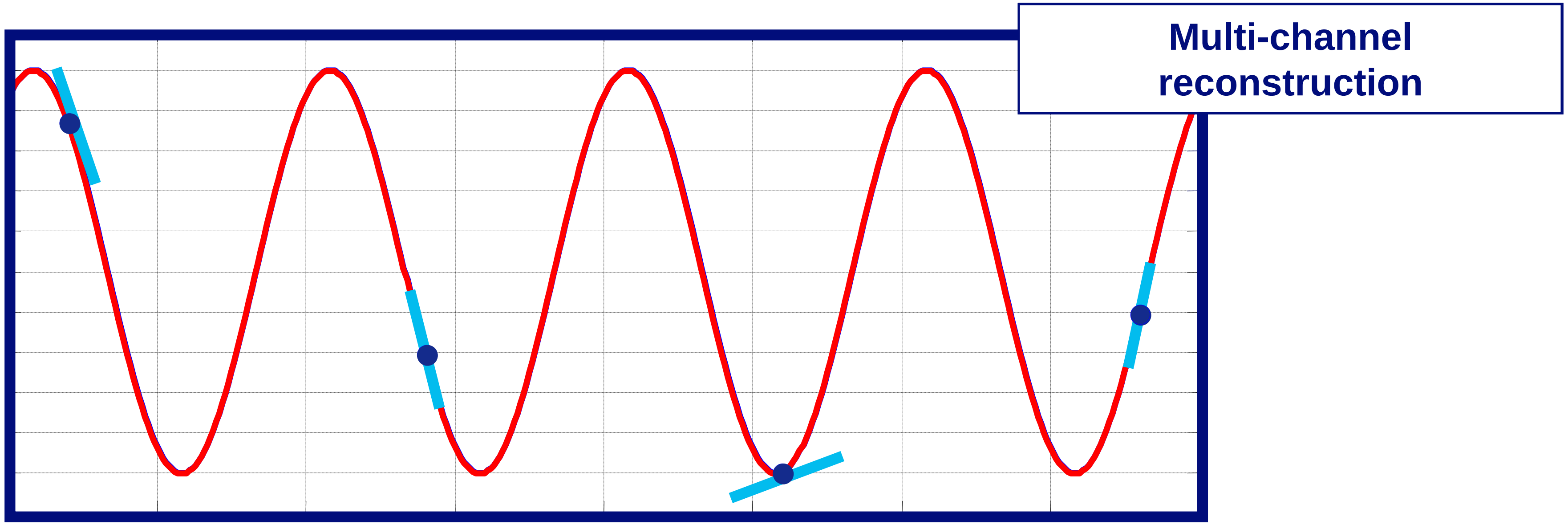
- Shannon’s (classic) sampling theorem (Shannon, 1947)
- General mutlichannel sampling theorem (Linden, 1959)
- Generalized sampling expansion (Papoulis, 1977)
  If a quantity and its derivative are available, then the Shannon-Nyquist sampling requirement can be relaxed.

Wavefield reconstruction

- Multichannel sampling theorem for a multicomponent streamer (Robertsson et al., 2008)

$$p(y_0) = \sum_{m=-\infty}^{\infty} \left\{ p\left(\frac{2m}{\sigma}\right) + i\omega\rho\left(y_0 - \frac{2m}{\sigma}\right) v_y\left(\frac{2m}{\sigma}\right) \right\} \operatorname{sinc}^2\left(\sigma \frac{y_0}{2} - m\right)$$


Single channel
interpolation


Multi-channel
reconstruction

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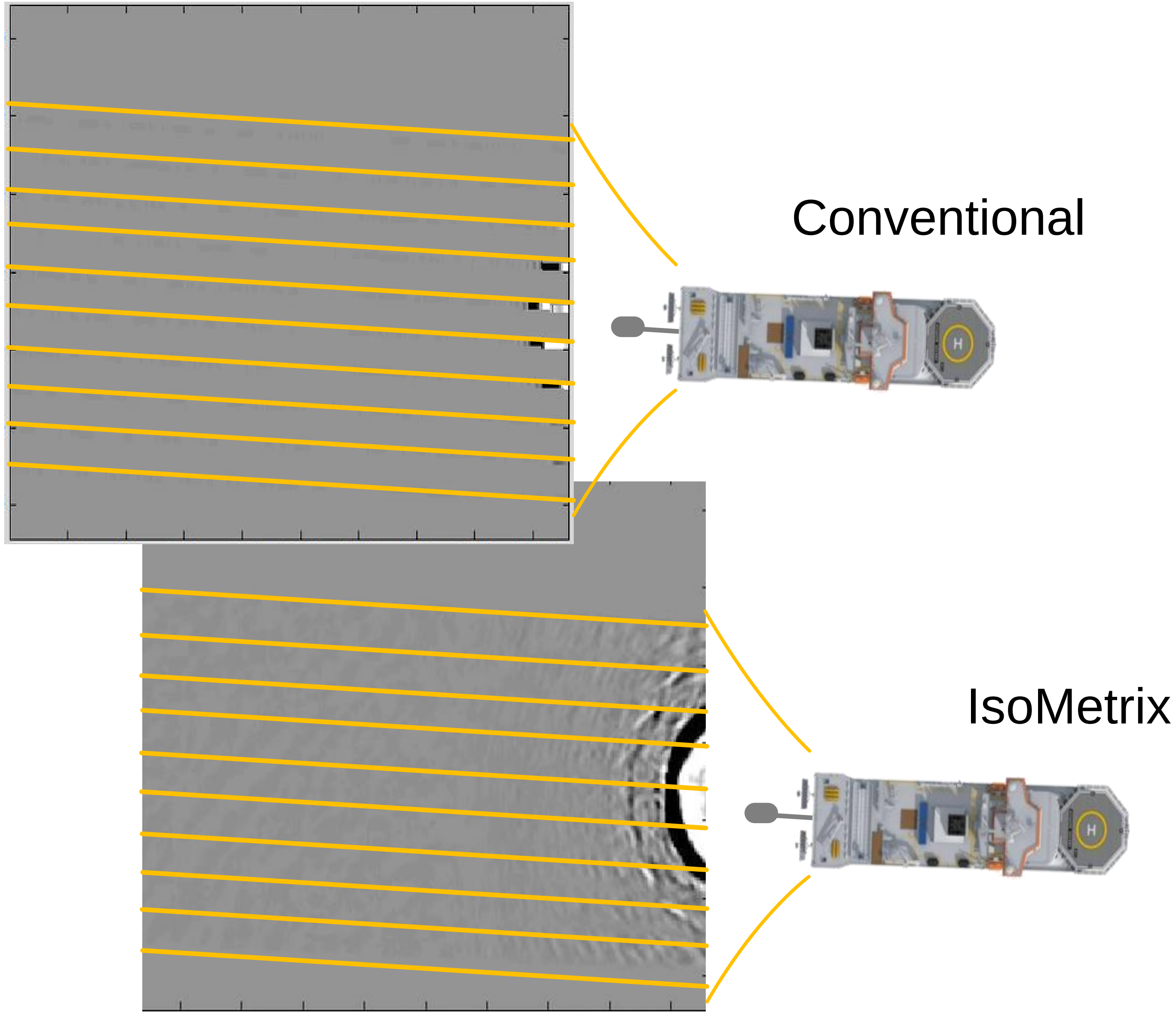
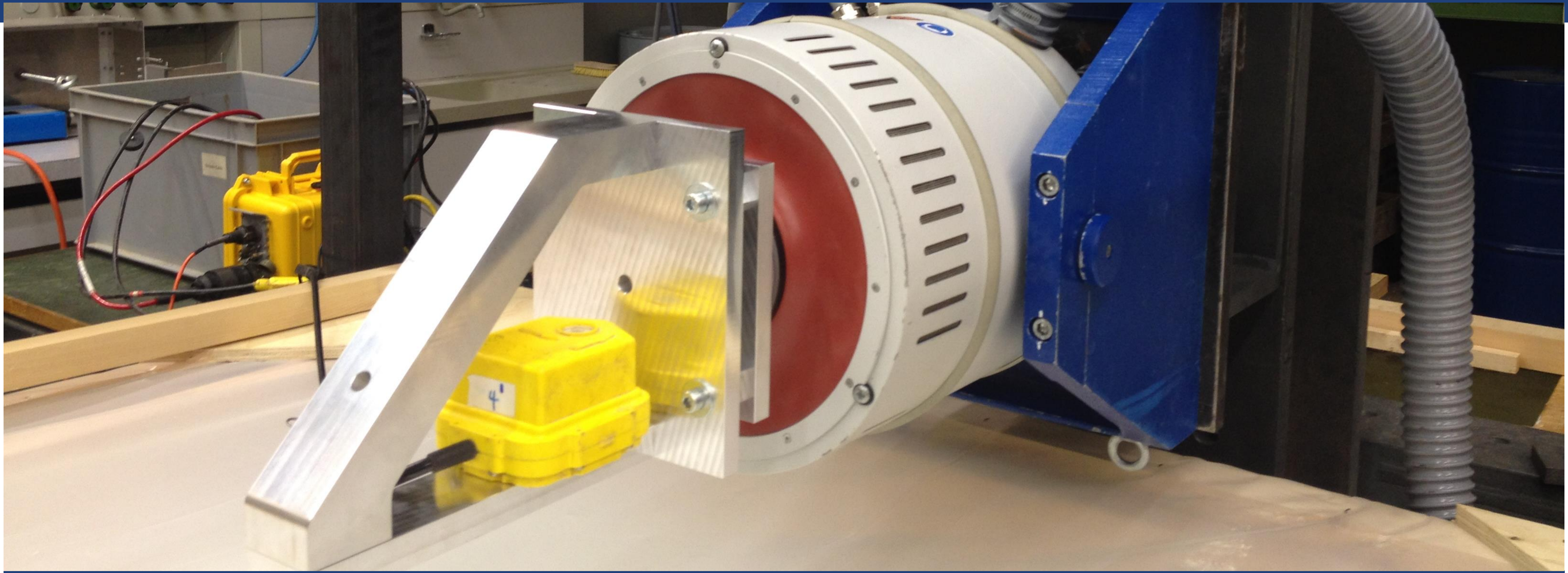
Cross-line streamer data reconstruction

(e.g. Vasallo et al., 2010, Geophysics)



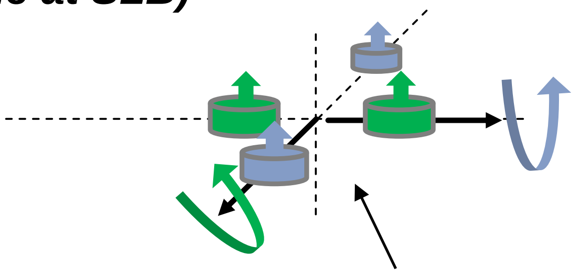


Hardware developments
Gradient and divergence sensors

Your name

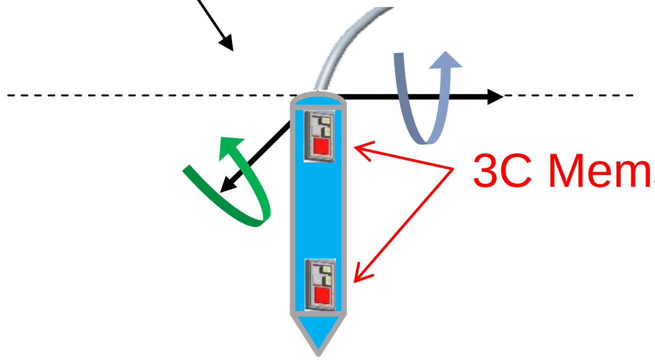
Gradient sensors *(Work by P. Edme at SLB)*

'Conventional' surface-based layout:
'horizontal' finite differences



At the free-surface $\partial_z u_x = -\partial_x u_z$

Vertical array of two 3C sensors
'Vertical' finite differences
Reduced (coupling) variations



5 components:

$V_Z = (V_{Z1} + V_{Z2})/2$
$V_X = (V_{X1} + V_{X2})/2$
$V_Y = (V_{Y1} + V_{Y2})/2$
$G_X = (V_{X1} - V_{X2})/dz$
$G_Y = (V_{Y1} - V_{Y2})/dz$


Geophysical Prospecting
EAGE EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS
Geophysical Prospecting, 2019, **67**, 97–113 doi: 10.1111/1365-2478.12716

A five component land seismic sensor for measuring lateral gradients of the wavefield

Everhard Muyzert[1]*, Nihed Allouche[1], Pascal Edme[1] and Nicolas Goujon[2]
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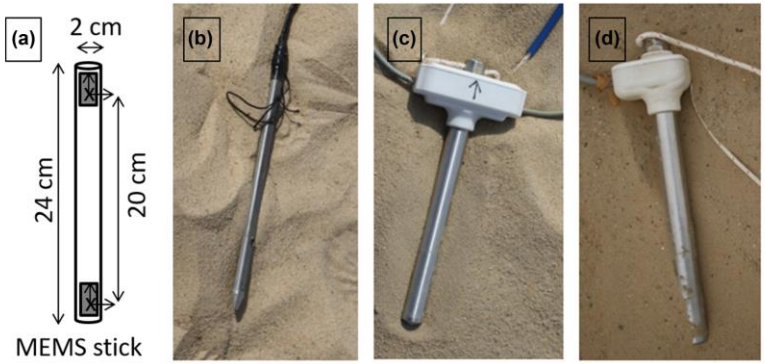
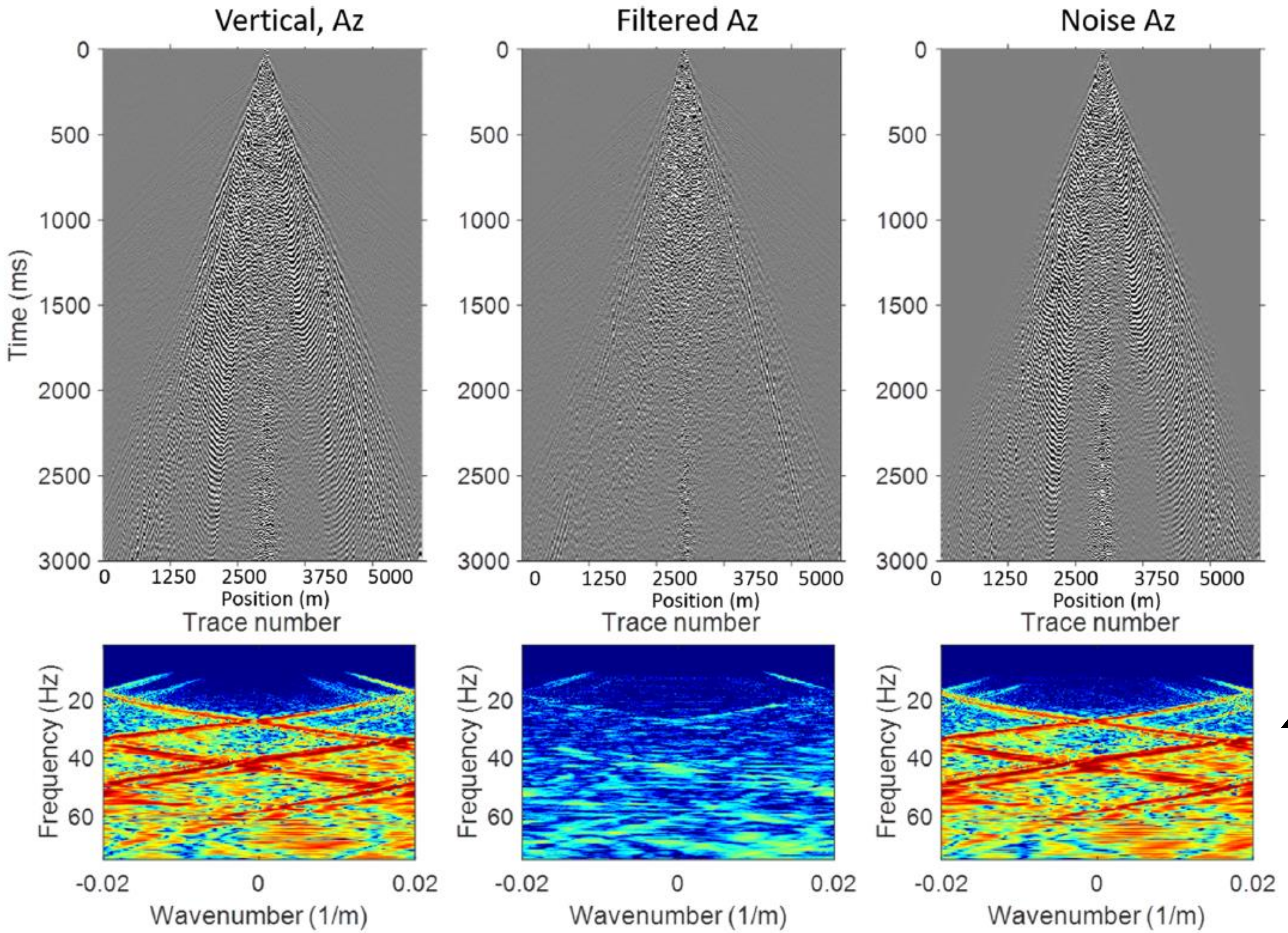
Application of the 5C sensor *(Work by P. Edme at SLB)*





Note spatially aliased noise

Divergence sensor – 'Land hydrophone' *(Work by P. Edme at SLB)*

Divergence at the free-surface

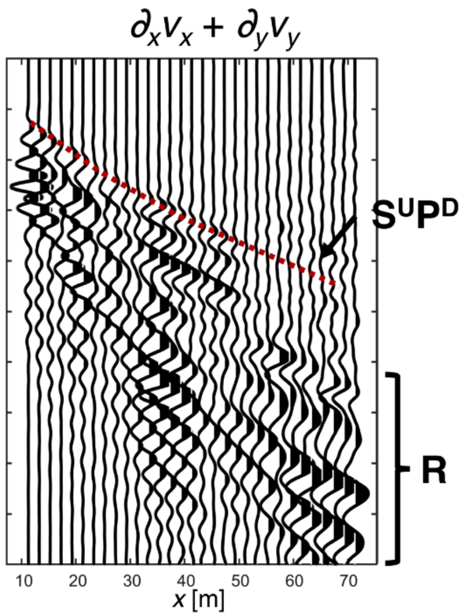
$$U_H = K_1 \cdot \frac{\partial U_Z}{\partial z} = K_2 \cdot \left(\frac{\partial U_X}{\partial x} + \frac{\partial U_Y}{\partial y} \right)$$

K_i=function of near-surface elastic properties

Local velocity filters

$$U_H = K \cdot (p_X V_X + p_Y V_Y)$$

Record mainly slowly propagating wavefield (noise) both inline and crossline simultaneously



Schmelzbach et al. (2018), Geophysics.

Divergence sensor – ‘Land hydrophone’ *(Work by P. Edme at SLB)*

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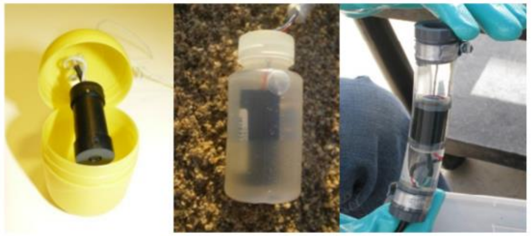


Local velocity filters

$$U_H = K \cdot (p_X V_X + p_Y V_Y)$$

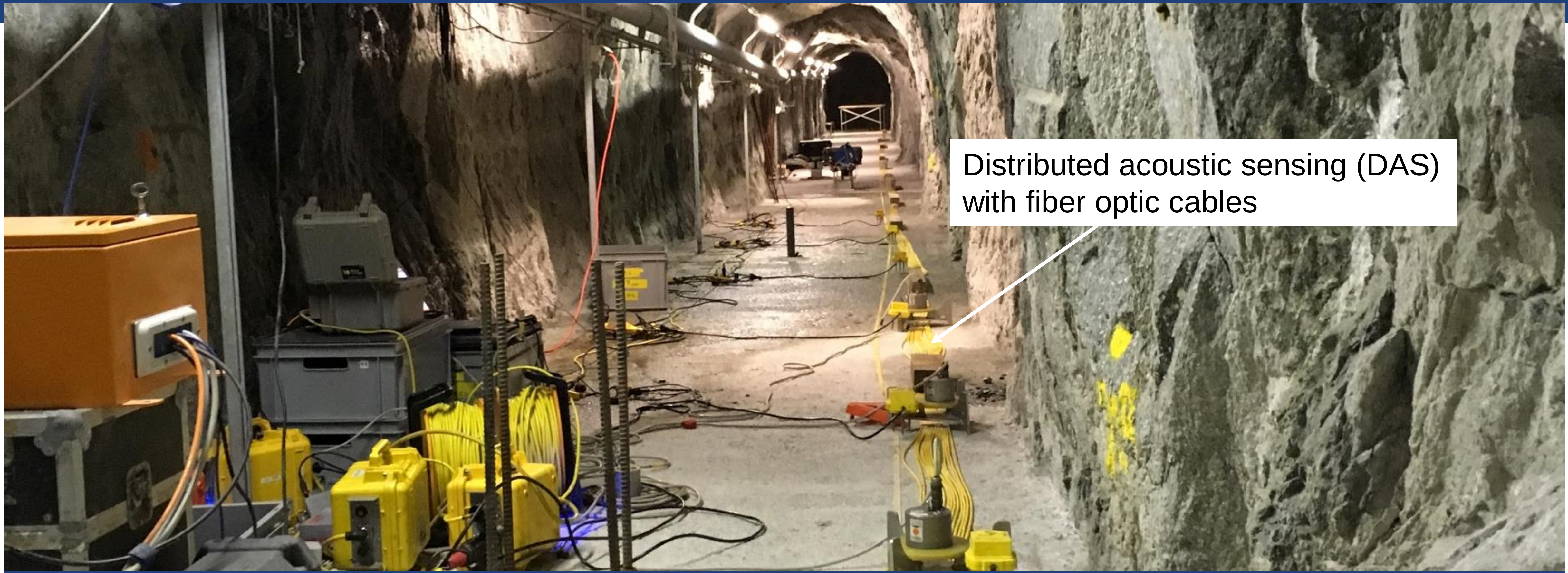
Record mainly slowly propagating wavefield (noise) both inline and crossline simultaneously

- 2 component measurement:
  - V_Z: Signal
  - U_H: Omni-directional ‘noise’ model

TECHNICAL ARTICLE fb

Seismic wavefield divergence at the free surface

Pascal Edme[1*], Everhard Muyzert[2], Nicolas Goujon[3], Nihed El Allouche[2] and Ed Kragh[2]



Summary and outlook

Summary

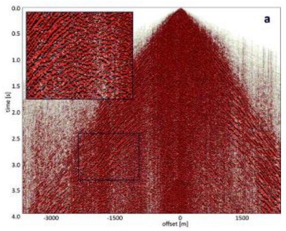
Spatial gradients at the free-surface – **Rotation**

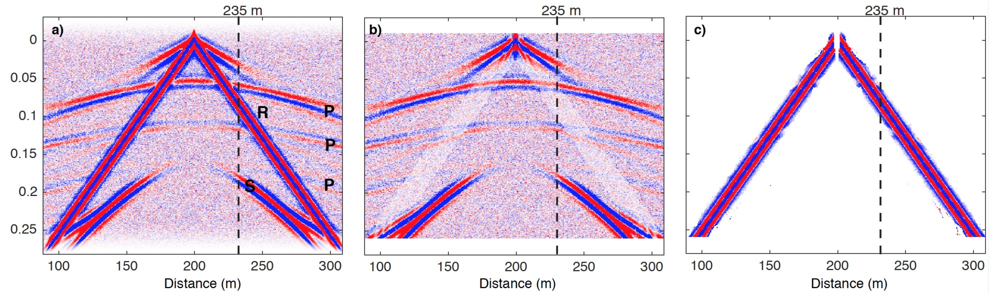
Applications groups

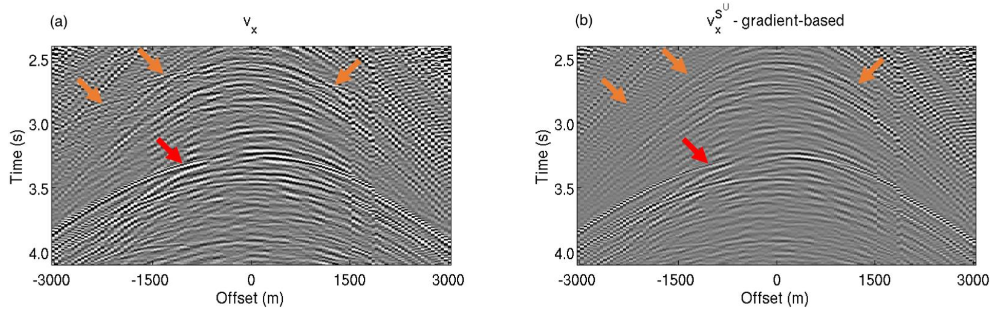
- 6C wavefield characterization
- Wavefield separation
  - 6C polarization based separation
  - Wave-equation based
  - Gradient data as noise model
- Wavefield reconstruction

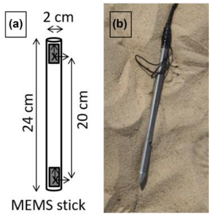
Acquisition

- Receiver coupling corrections
- Gradient sensor
- Divergence sensor









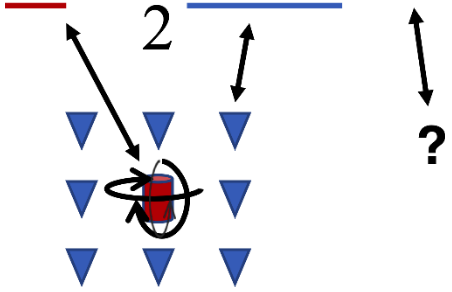
Outlook

More applications

- Space
- …

New sensing technologies (DAS, …)

$$\omega \approx \frac{1}{2}\nabla\times\mathbf{u}+\varepsilon$$



Open questions

- When do we measure the wavefield at the free-surface?
- Array-derived rotations vs. direct measurement