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Rotation and gradient layout for commercial land surveys

Nicolas Goujon

Outline

1. Introduction
2. Examples of published field test results
3. Solutions for rotation and spatial gradient recording
    a. Rotation sensors
    b. Gradient option 1: within a single package
    c. Gradient option 2: with standard vertical sensors
4. Proposed acquisition geometry
    a. Second spatial derivative
    b. Application for compressive sensing
5. Conclusions

Introduction

Rotation sensing and use of spatial gradients in exploration seismic have been active research topic in industry (slb Cambridge) and academia from 2000 on

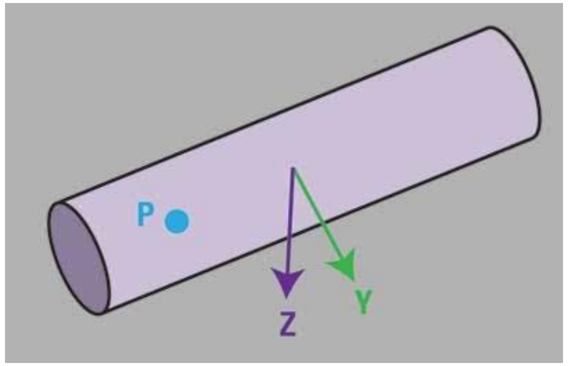
One commercial system - Isometrix marine streamer – resulted. Not a major commercial success

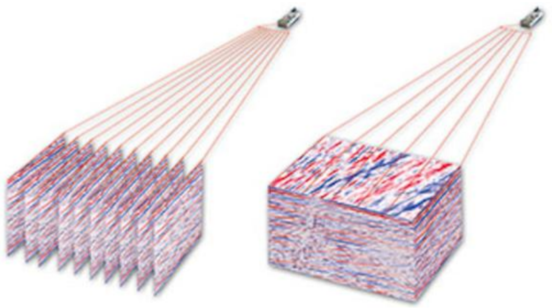
For land seismic, a 5C prototype sensor was built and successfully tested, the “StiQ”

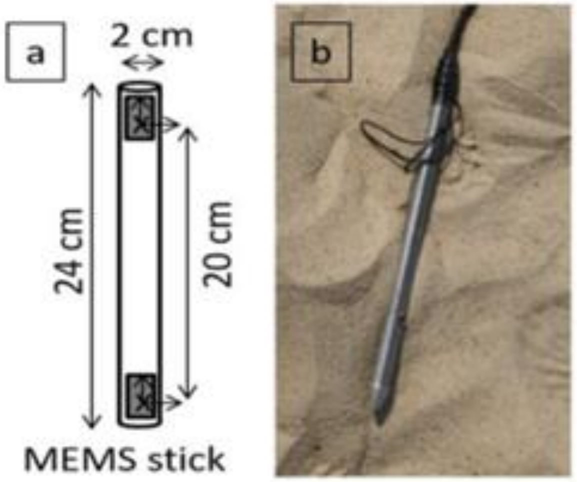
After SLB’s exit from acquisition, nobody took over in the land seismic industry

Why? Should we revisit this?

What do we need to have a commercially interesting solution for land acquisition? How long will it take?







Rotation and gradient

At the free surface, the equation of the curl of the wavefield can be simplified and becomes:

$$R_Y = \frac{\delta V_Z}{\delta x}, \qquad R_X = -\frac{\delta V_Z}{\delta y}.$$

The rotation around horizontal axes is equivalent to the spatial gradient of the vertical translational wavefield

This was shown in a number of experiments (Muyzert et al. 2012, Schmelzbach et al. 2018)

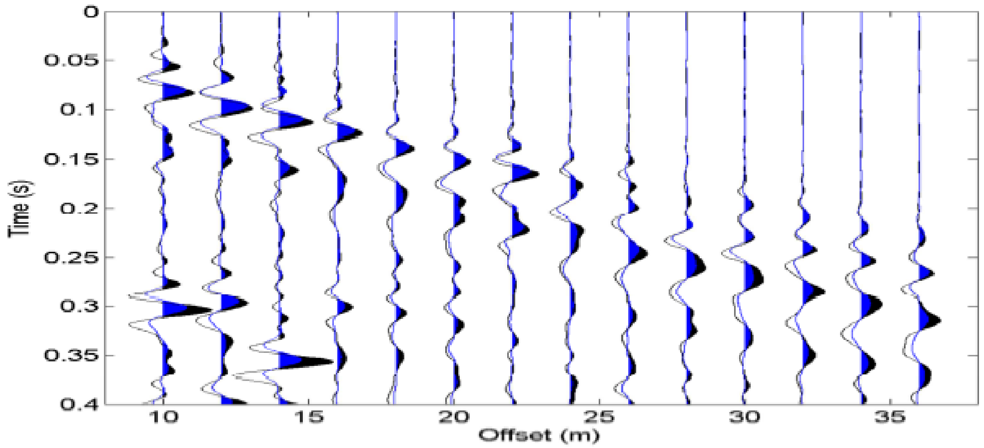
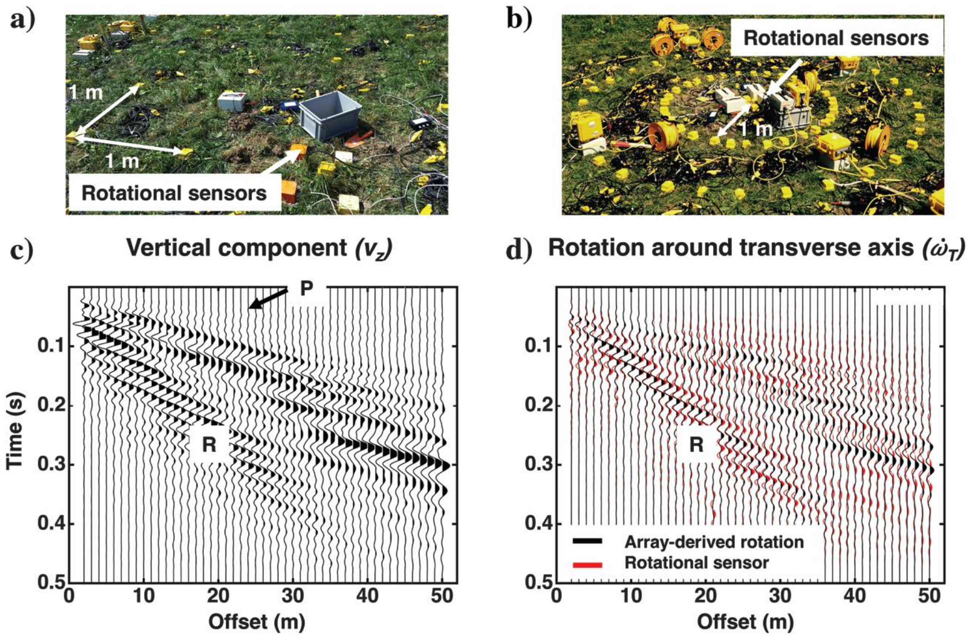


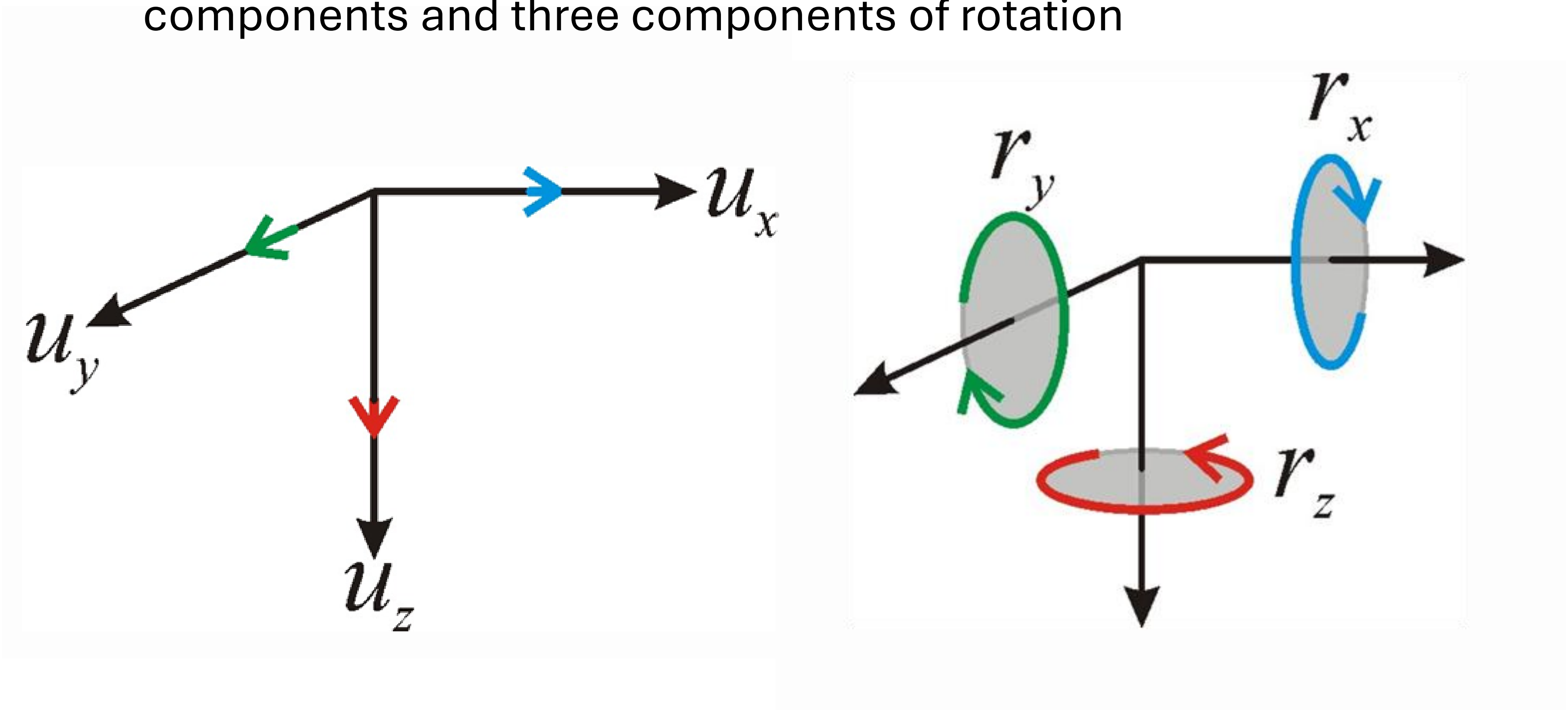
Figure 1 A rotation rate data common-receiver gather is shown in black. In blue is shown a differentiated geophone common-receiver gather acquired at the same location. A t^2 gain has been applied for visual comparison.



Robertsson, J. and Curtis, A. [2002] Wavefield separation using densely deployed three-component single-sensor groups in land surface-seismic recordings. *Geophysics* **67**, *No5, 1624-1633*.

Full Wave Seismic Recordings

The motion of a body is completely described by three translational components and three components of rotation

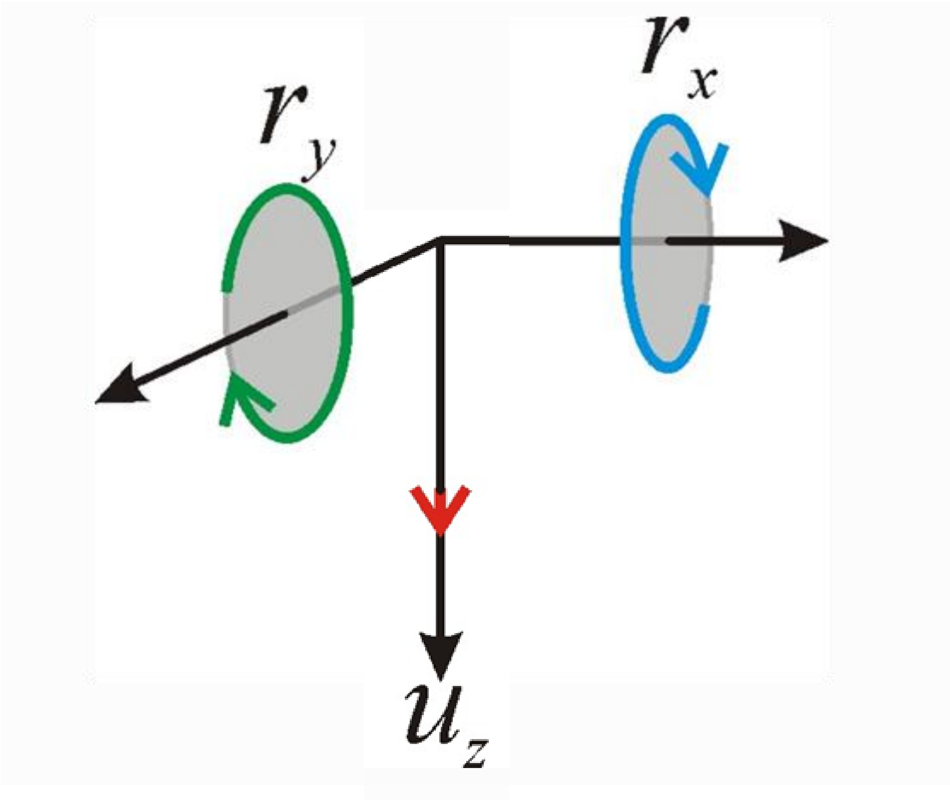


6 Degrees of Freedom (6DOF Sensor)

Compressional Wave Recording

Do we need all these 6 components?

- Not if we are only interested in P-wave imaging
  - Horizontal translational sensors record S-waves
  - Rotation around the Z vertical axis is only sensitive to SH and Love waves
- The vertical component and the two rotations around horizontal axes are of most interest
- Examples shown earlier were only using these 3 components
- We will concentrate on this configuration



Field test example 1: scattered noise attenuation

Edme P., Daly M.,Muyzert E. and Ktagh E. (2013), Side Scattered Noise Attenuation Using Rotation Data, *Conference Proceedings, 75th EAGE Conference & Exhibition incorporating SPE EUROPEC, cp-348-00855*.

Side Scattered Noise Attenuation using Rotation Data

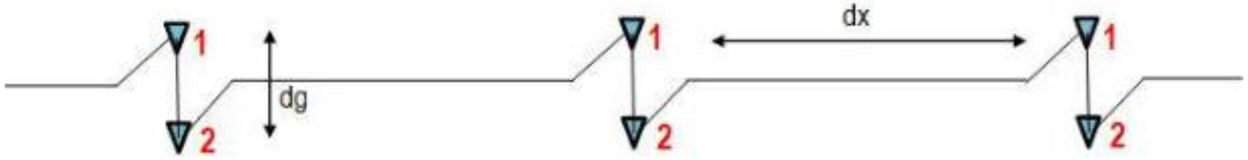


Figure 1: *Composite-point-receiver layout for acquisition of crossline rotational data.*

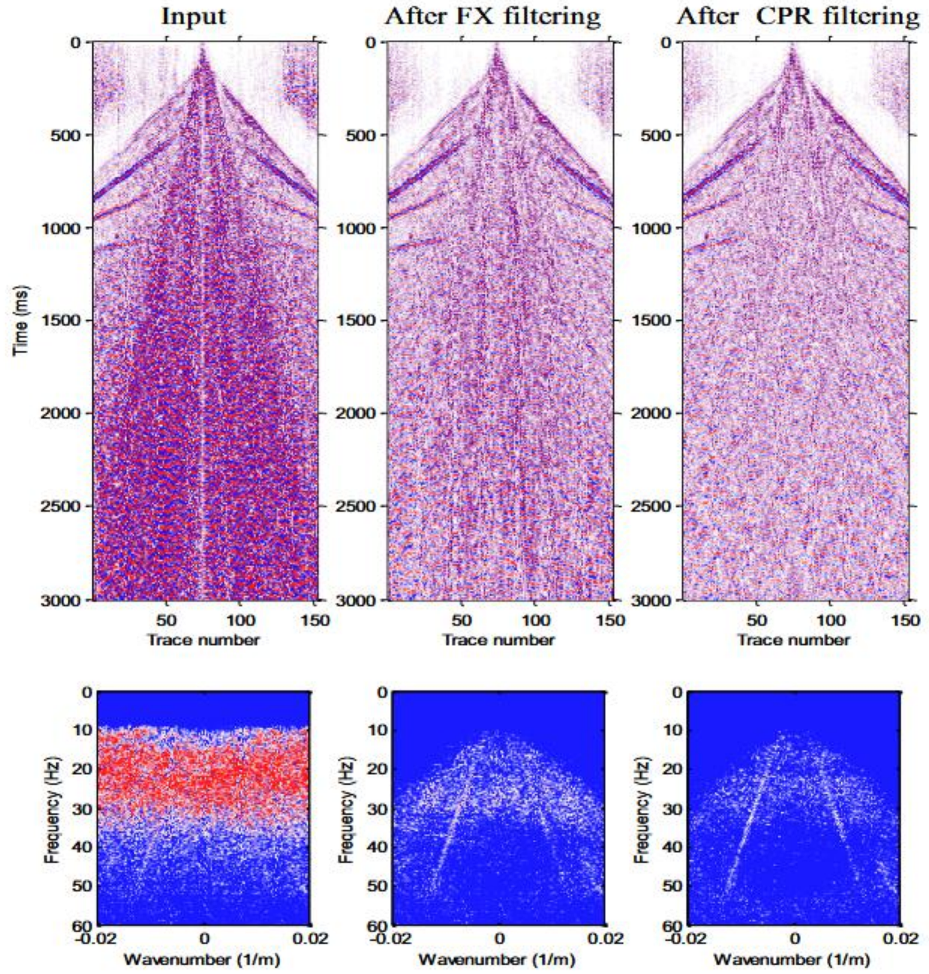
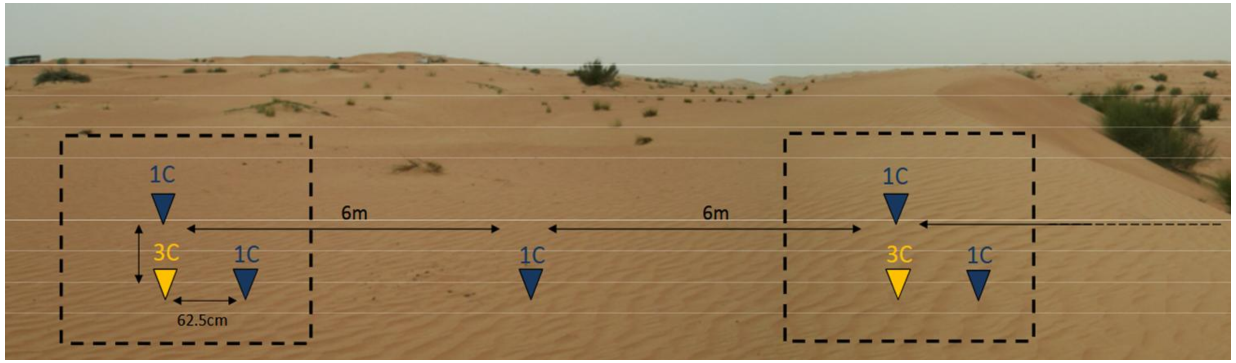


Figure 5: *Real data acquired in UAE. (Left) Input receiver gather, (centre) after FX filtering and (right) CPR filtering. Bottom row shows the data in the FK domain.*

Field test example 2: local noise attenuation

Edme P., Muyzert E. and Kragh E. (2014). Efficient land seismic acquisition sampling using rotational data. *76th EAGE Conference and Exhibition, Extended Abstracts*

Superior local ground roll attenuation using rotation as a noise model



Z | Denoise X and Y | Denoise Rx and Ry | Denoise standard

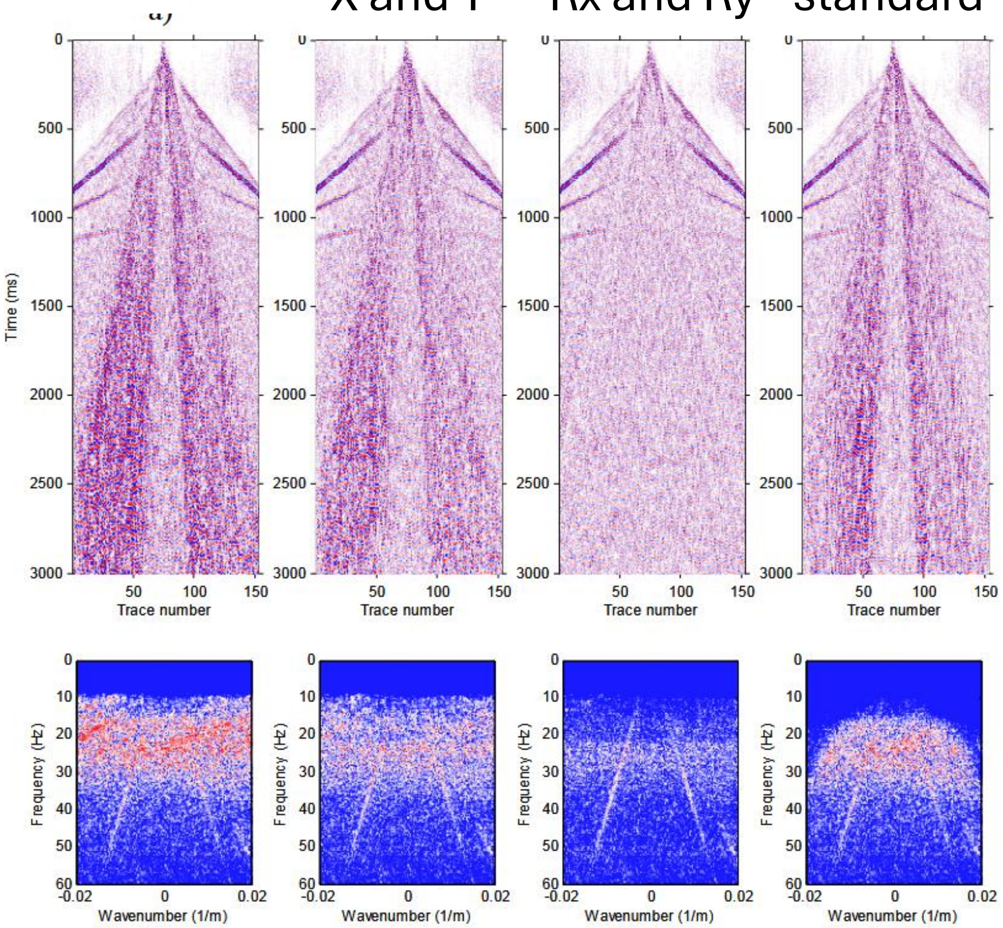


Figure 3 *Common receiver Z gather before noise attenuation (a) and after noise attenuation using b) X and Y as noise models, c) R_{XZ} and R_{YZ} as noise models, d) velocity filtering (considering a receiver and source sampling of 24m). Bottom panels show the corresponding fk spectra (with colour map ranging from 0 to20 dB). The same t-x gain is applied to all data.*

Field test example 3: wavefield reconstruction

Khatami M.I. and Ravasi M., Multichannel Wavefield Reconstruction of Land Seismic Data with Stencil-Based Spatial Gradients,
86th EAGE Annual Conference & Exhibition, Volume 2025, p.1 – 5.

Successful reconstruction of aliased signal using gradient/rotation

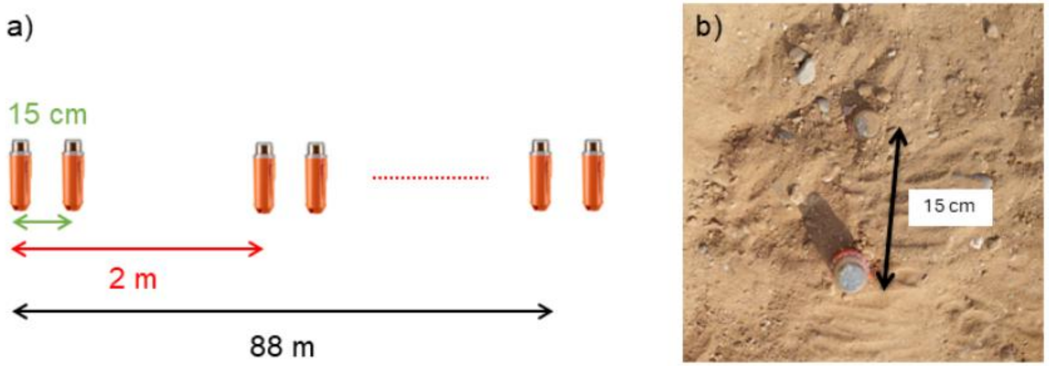
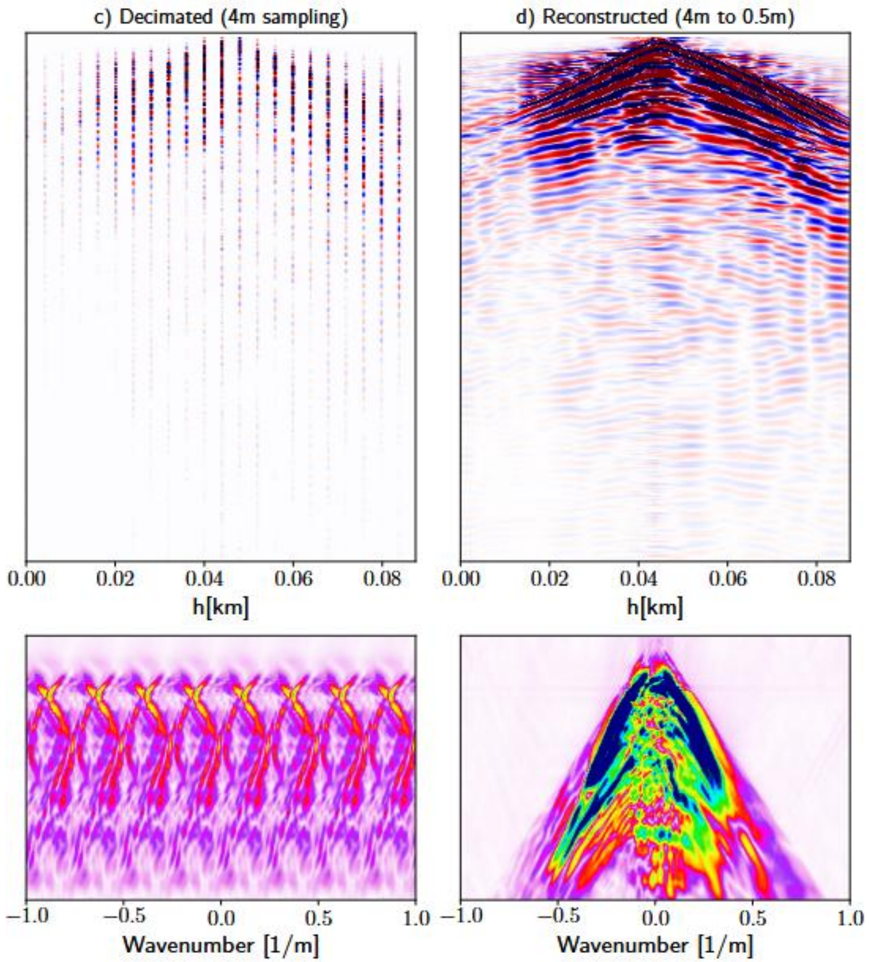


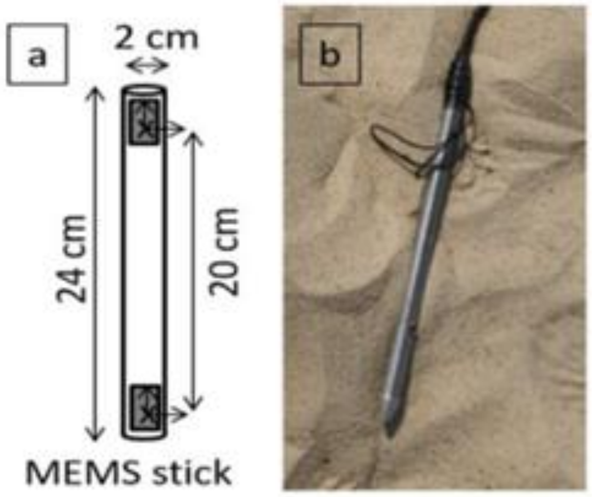
Figure 2: Field data acquisition. a) Receiver geometry, and b) aerial photo of a receiver pair.



Field test example 4: near-surface characterization

Allouche N. and Øzdemir A.K. (2019), Near-Offset Noise Characterization and Attenuation Using Orthogonal Matching Pursuit, *81st EAGE Conference and Exhibition 2019, Volume 2019, p.1 – 5*

Potential for estimating
local near-surface properties



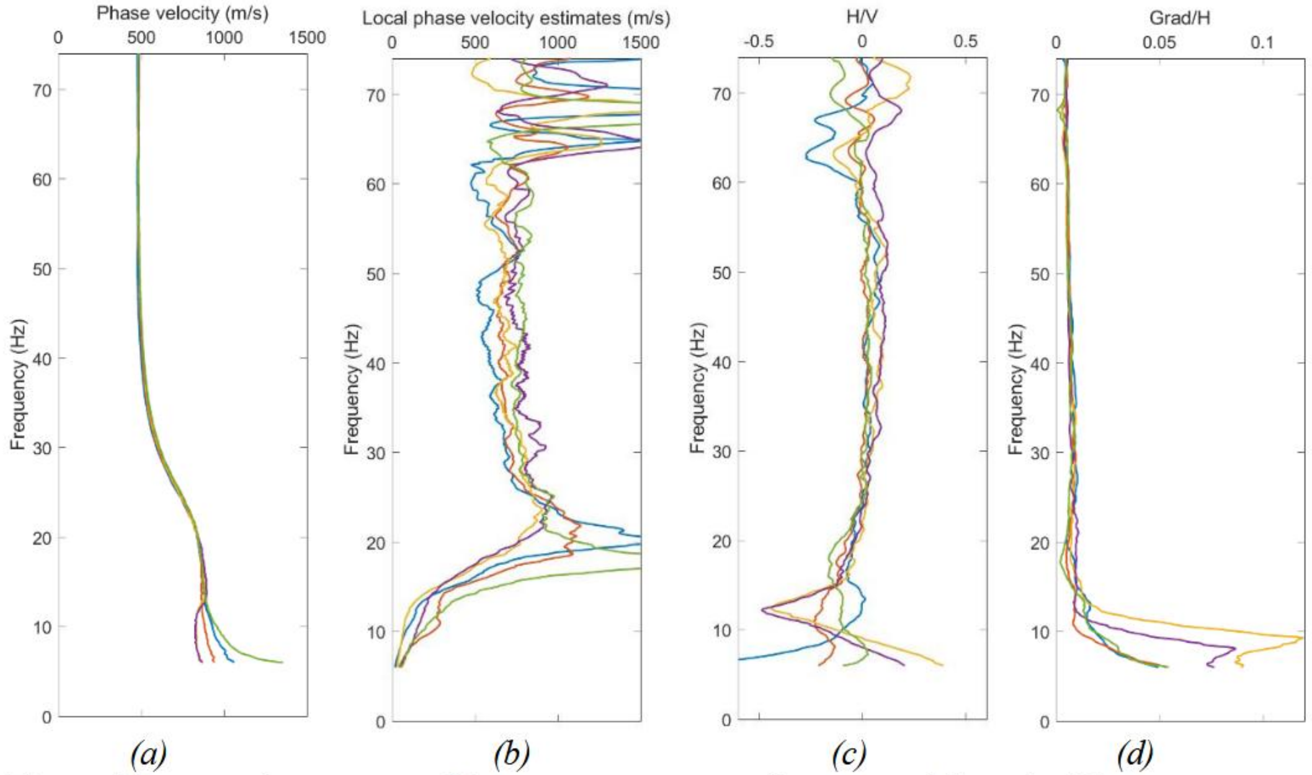


***Figure 4** Estimated properties of the energetic noise mode computed from the 5C sensor measurements for five consecutive shot gathers (different colours). a) Phase velocity estimated from dispersion curve. b) Phase velocity estimated by taking the ratio between the gradient and the vertical component. c) H/V ratio. d) Ratio of the horizontal component and its vertical gradient.*

Rotation sensing / gradient on land

Challenge 1: Noise usually much shorter wavelength than signal -> makes adequate spatial sampling difficult to achieve (cost prohibitive)

Rotation is very sensitive to short wavelength signals and is therefore very attractive for ground roll characterization and attenuation

Challenge 2: Land noise can have very short coherency lengths, and large lateral variations

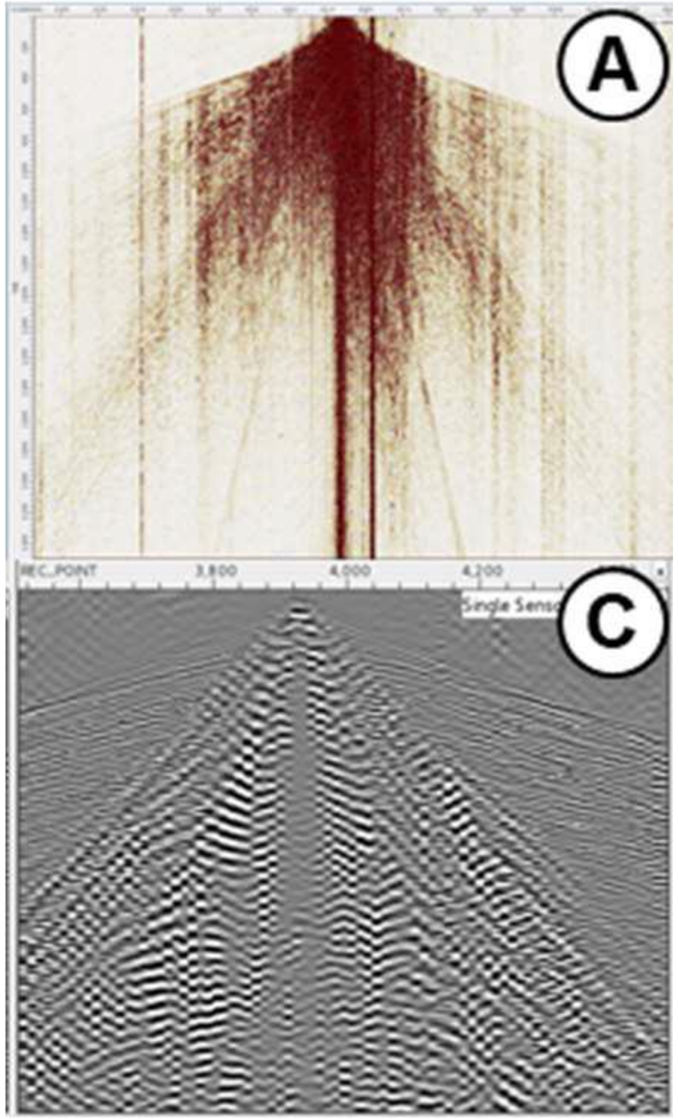
Local methods are preferable, and rotation/gradient is also a very good solution to obtain local noise models

Rotation measurements ideally suited for effective land noise attenuation, more than for marine

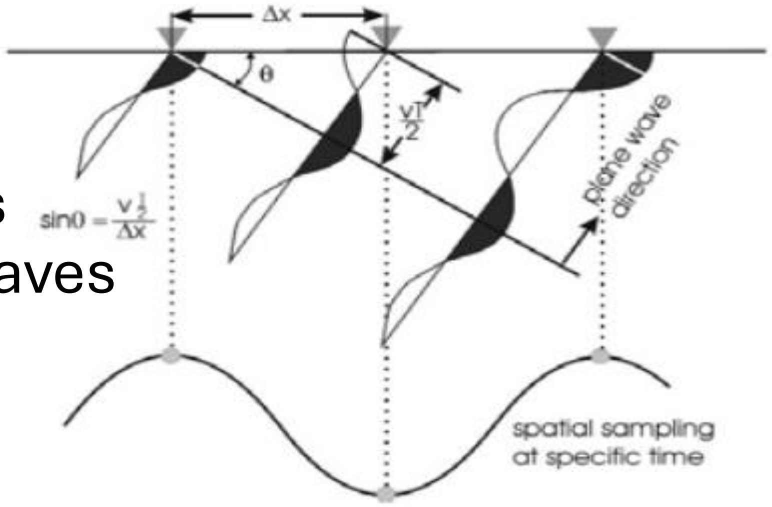
We have just shown some very promising test results

Yet, there has not been a single land commercial survey acquired with rotation

Why not? What can we do?



Apparent Wavelengths at the surface



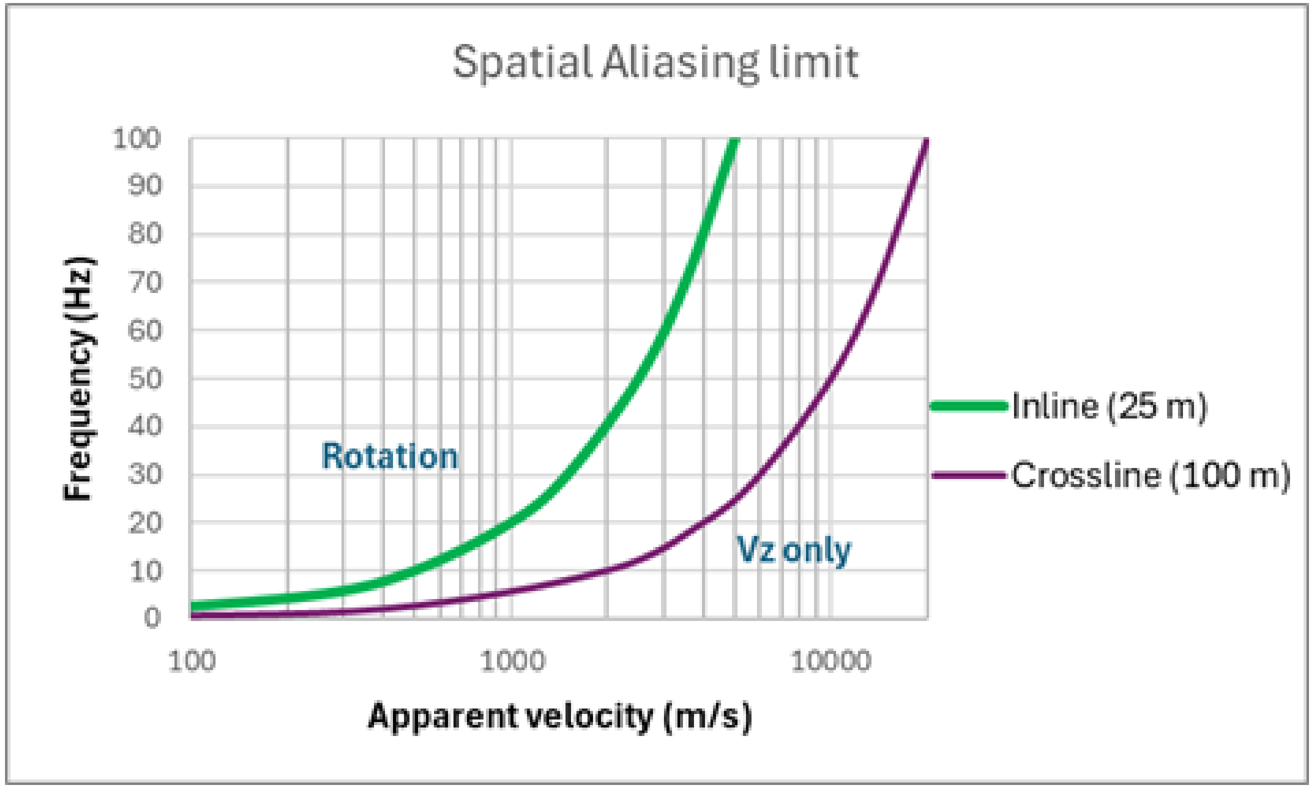
There is usually a large contrast in apparent wavelengths between horizontally propagating low velocity surface waves and faster more vertical reflections

- Equivalence between rotation and gradient means:
  - For all signals properly spatialy sampled (Nyquist criteria, apparent wavelengths larger than 50 m along a line with 25 m receiver spacing), we already can compute the gradient/rotation by calculating the spatial derivative of the Vz signal and do not need to measure it
    - Good news, as rotation for long apparent wavelength signals is very small
  - For shorter wavelengths below 2 x receiver spacing where the Vz signal is aliased, you can use a rotation sensor, or you can approximate the gradient by taking the finite difference between two closely spaced sensors

When do we need rotation or gradient?

Spatial Nyquist limit for different sensor spacings

- On the right side of the line, we are properly sampled with vertical component only
- On the left, Vz signal is aliased and we need rotation or gradient:
  - Slow apparent velocity and higher frequencies
  - Mainly surface waves, also high incidence higher frequency reflections



Rotation sensor noise specification

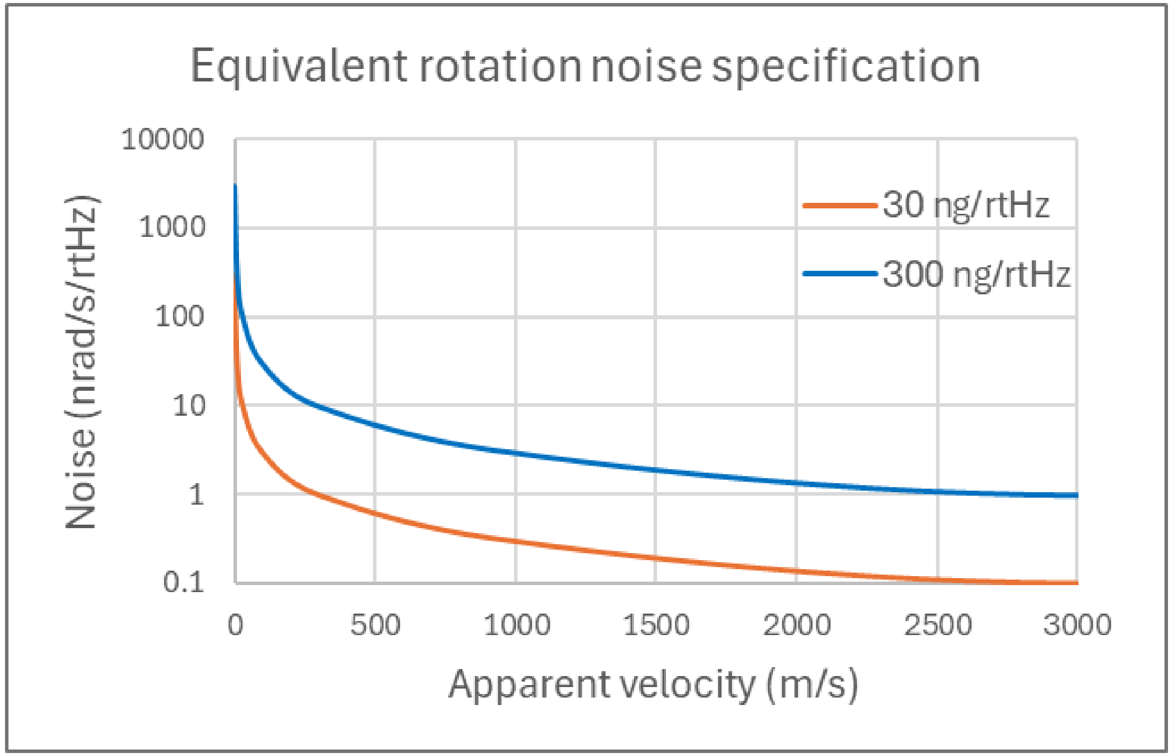
For a plane wave, rotation is acceleration scaled by slowness p:

$$R_Y = p_x \cdot A_Z, \qquad R_x = -p_Y \cdot A_z$$

Given the noise specification for an acceleration sensor, can derive an equivalent noise spec for a rotation sensor for a given apparent velocity of the signal

We do not need rotation measurements for very high apparent velocities, but would like to record them to at least 1000 m/s, preferably more

Noise specification ideally 1 nrad/s/rtHz



Rotational seismometers

Example: Blueseis 3A

- Noise 20 nrad/s/rtHZ
- Weight 20 kg
- Price > € 10K

Dimensions (L x W x H)	300 x 300 x 280 mm
Weight	20 kg

Sensor self-noise in rad/s/√Hz	10^{-3} Hz	10^{-2} Hz	10^{-1} Hz	1 Hz	10 Hz
	1.10^{-7}	2.10^{-8}	2.10^{-8}	2.10^{-8}	2.10^{-8}

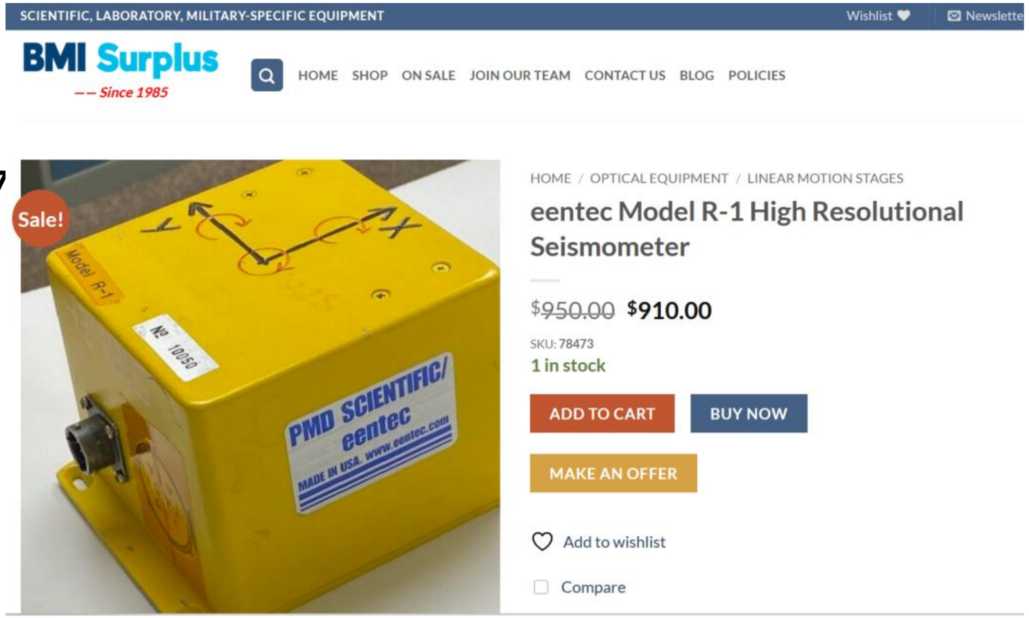
Rotation sensors for exploration seismic

Several attempts. Examples:

Eentech R1/R2

- Used in a number of tests in period 2012-2017
- Unstable sensor response
- Estimated noise level 250-500 nrad/s/rtHz
- Website still exists, no activity since 2018

One used sample currently on sale =>



K-sphere

- No noise spec available
- Target OBN nodes
  - Higher cost and size

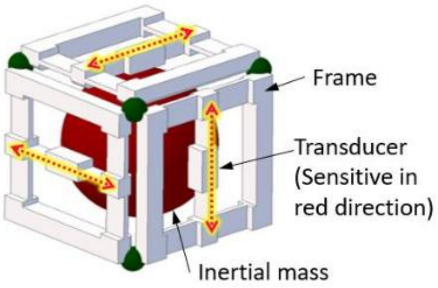


Figure 1: The new 'Ksphere' sensor

Pedersen, A.S. et. al, [2023]: Towards a next generation Ocean Bottom Node: Incorporating a 6-C motion sensor, *84th EAGE Annual Conference & Exhibition, Jun 2023, Volume 2023, p.1 – 5.*

Too expensive (and too noisy) for land seismic

Gradient within an integrated sensor package

Patent from Sercel on 6C sensor

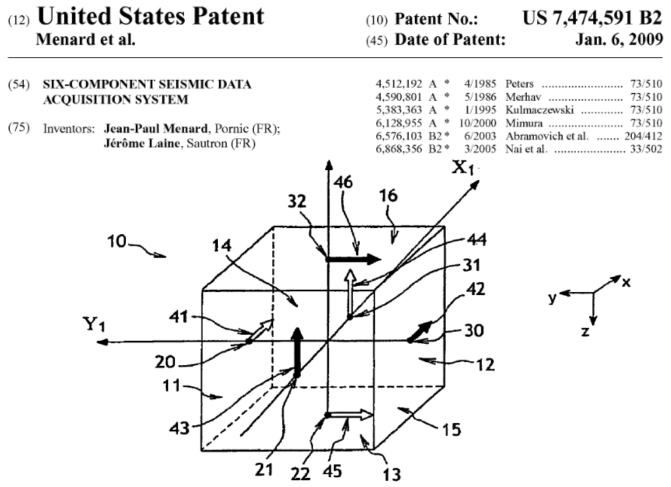
- Rotation from differentiation of pairs of translational sensors

“StiQ” from WesternGeco

- 5C sensor
- Rx and Ry from differentiating vertically separated horizontal sensors

No commercial solution:

- Small distance between sensors: sensitivity issues
- Specific hardware: high CAPEX entry barrier



(12) United States Patent
Menard et al.

(10) Patent No.: US 7,474,591 B2
(45) Date of Patent: Jan. 6, 2009

(54) SIX-COMPONENT SEISMIC DATA ACQUISITION SYSTEM

(75) Inventors: **Jean-Paul Menard**, Pornic (FR); **Jérôme Laine**, Sautron (FR)

4,512,192	A *	4/1985	Peters	....	73/510
4,590,801	A *	5/1986	Merhav	....	73/510
5,383,363	A *	1/1995	Kulmaczewski	....	73/510
6,128,955	A *	10/2000	Mimura	....	73/510
6,576,103	B2 *	6/2003	Abramovich et al.	....	204/412
6,868,356	B2 *	3/2005	Nai et al.	....	33/502

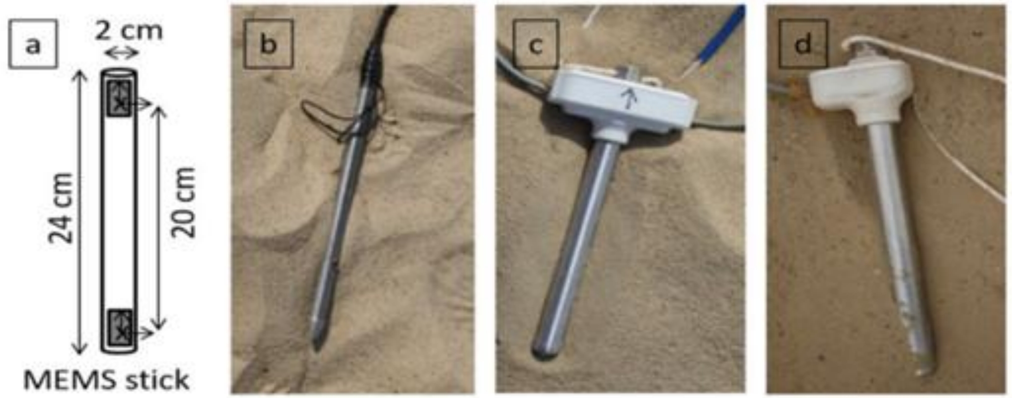


Figure 1 (a) Diagram illustrating the 5C seismic sensor with the position of the 3C MEMS accelerometers indicated in grey. (b,c,d) Three prototypes of the MEMS 5C seismic sensor.

Muyzert E., Allouche N., Edme P. and Goujon N. (2019), A five component land seismic sensor for measuring lateral gradients of the wavefield, *Geophysical Prospecting, 67*

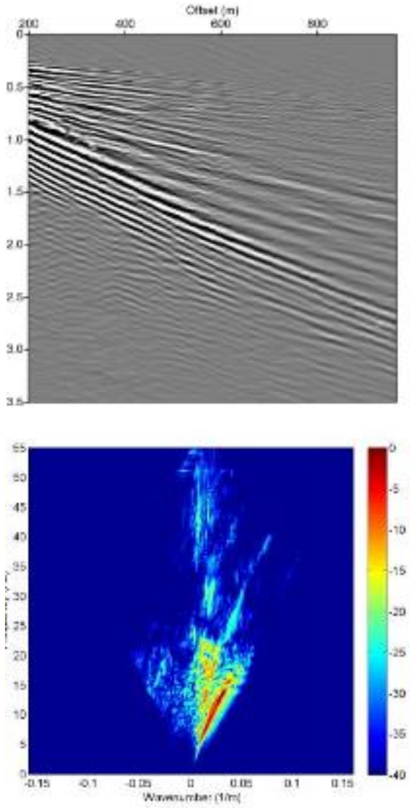
Gradient from standard vertical sensors

This can be done by differentiating the outputs of standard 1C nodes

- What distance should be used between sensors?
    - Too short: noise and sensitivity issues
    - Too long: break finite difference assumption

    Less than 1/3 of shortest wavelength of interest

- Example: 5 m between sensors
    - Gradient can be used for wavelengths from 15 m to 100 m
    - Wavelengths above 50 m already sampled inline



Reconstruction from a 3.25m separated pair of sensors every 25 m

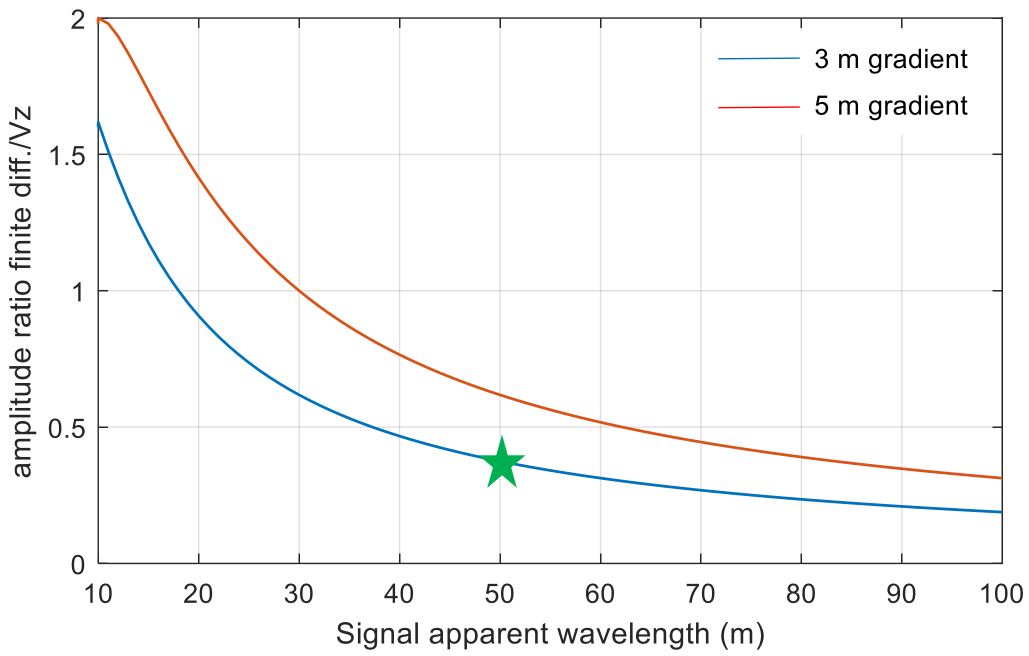
Allouche N., Ras P. and Özbek A. (2015). Aliased Ground-roll Reconstruction Using Gradients. *Proceedings of the 77th EAGE Conference and Exhibition, Extended Abstracts.*

Noise level and errors from gradients

We can calculate the amplitude of the finite difference compared to the vertical signal if we know the distance between the sensors and the apparent wavelength of the signal

If we take as an example the finite difference over 3 m of a 50 m apparent wavelength (★), the amplitude ratio is 0.37

If our vertical sensor has a noise floor of 20 ng/rtHz, using this amplitude ratio and adding 3 dB for the differentiation, we get an equivalent noise floor for th finite difference of 75 ng/rtHz, which is adequate (eq. to 1 nrad/s/rtHz for a 750 m/s apparent velocity signal)

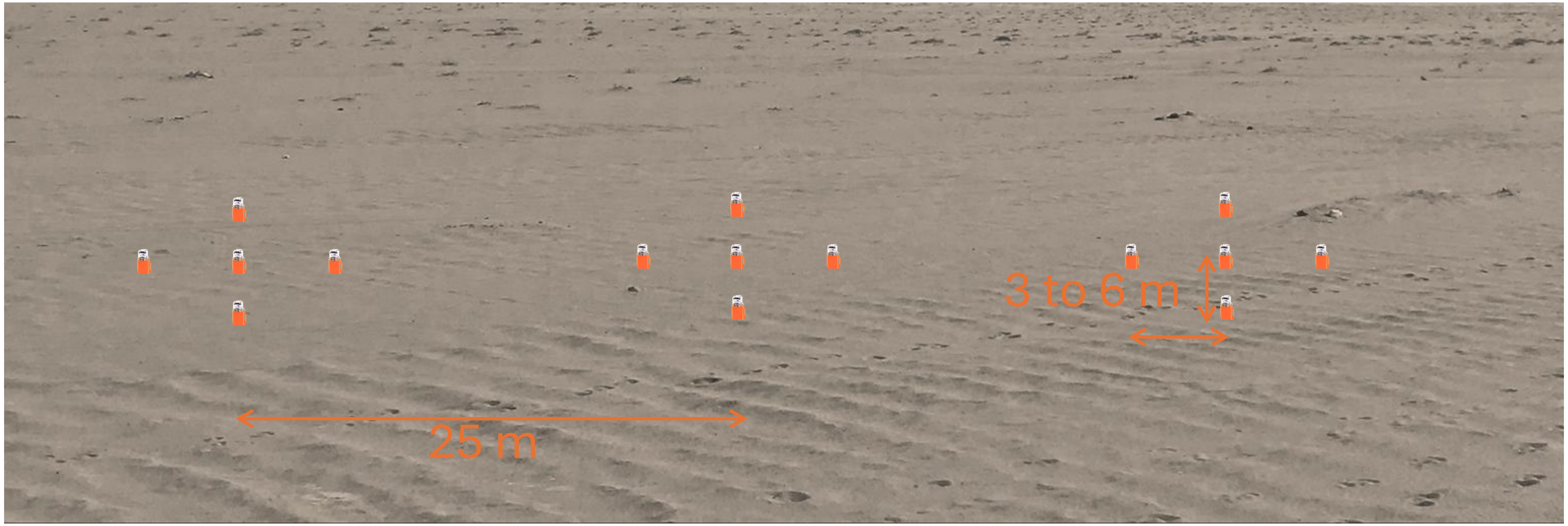


Additional noise will come from differences in coupling and sensor response, but this will also be minimized by the relatively large distance between sensors

We will get some amplitude attenuation of the finite difference compared to the theoretical gradient for the shortest wavelengths

Proposed acquisition geometry

Group of 5 single sensor nodes every 25 m



Can sum the outputs of the 5 nodes to get the equivalent of an analog array (same CAPEX)

Can compute two versions of the gradient in each direction at each group

Can compute the second spatial derivative of the wavefield by differentiating these two gradients

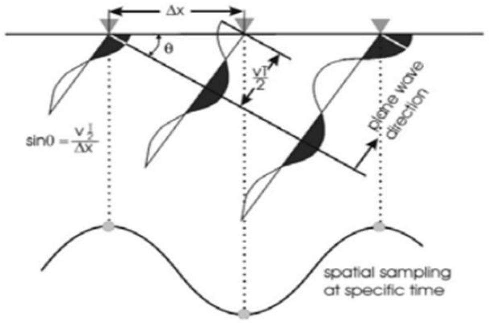
Second spatial derivative of the wavefield

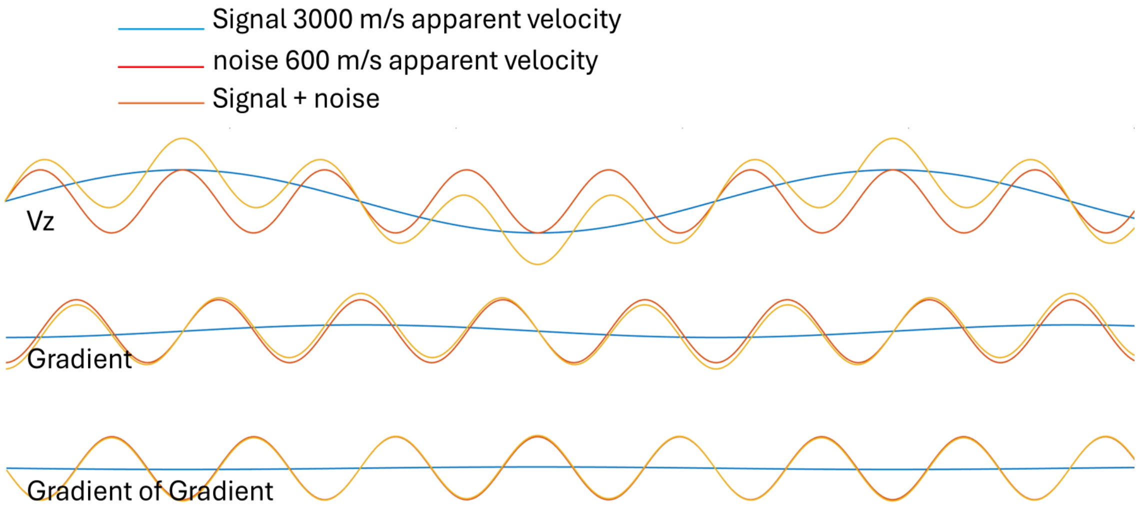
Benefits of using the second spatial derivative as a noise model:

- Wavefield scaled by the square of their slowness
  - Very high attenuation of reflection signal, better signal and noise separation
- Two derivations: two x 90 degrees phase shift = 180 degrees
  - Inverse the polarity and the second derivative is in phase with the original signal
- Second derivative output is at central location of the cross

Can be a very powerful noise model, virtually free for reflection signal

Can be integrated twice in time for correct spectral content





The second spatial derivative provides a noise model in opposition of phase

Commercial use

Data quality

- Will you always get a good and reliable gradient data?
  - This is land seismic data: of course not
- What then?
  - Use other array methods: simple or weighted sum, phase arrays…

Economics

- Use existing equipment, no investment needed for new type of receiver
- Equipment cost equivalent to a cable system with 6-geophone array
- Lower OPEX

Compressive sensing

What do we want to reconstruct? Signal or Noise?

- Land noise has often short coherency length
- Is often stronger than signal

Starting with local attenuation of the noise before reconstructing makes sense

We might also be able to use the signal gradient

Conclusions

- Rotation or gradients can be very powerful for noise attenuation and wavefield reconstruction
- Pure rotational sensors are far from being good and cheap enough for land seismic
- Rotation sensors were believed to be an interesting way to get the wavefield gradient. While that might be true in some cases (seabed for example), for land seismic it is better and easier to get the gradient from pairs of translational sensors
- A cross configuration of 5 single vertical sensors spaced 2 to 6 m presents several benefits:
    - Possibility to group-form the 5 outputs to get the equivalent of a standard geophone array for the same cost
    - In addition or instead, possibility to compute the first derivative (gradient) and the second derivative of the wavefield
    - No need to invest in new equipment, this can be done today at large scale using standard 1C nodes
    - It can be used for local noise attenuation before signal reconstruction
- The main barrier has been economic, and this approach eliminates it