SeaBird Exploration

Seismic Acquisition with Ocean Bottom Nodes

Providing full azimuth seismic images in busy oilfields

20 April 2011

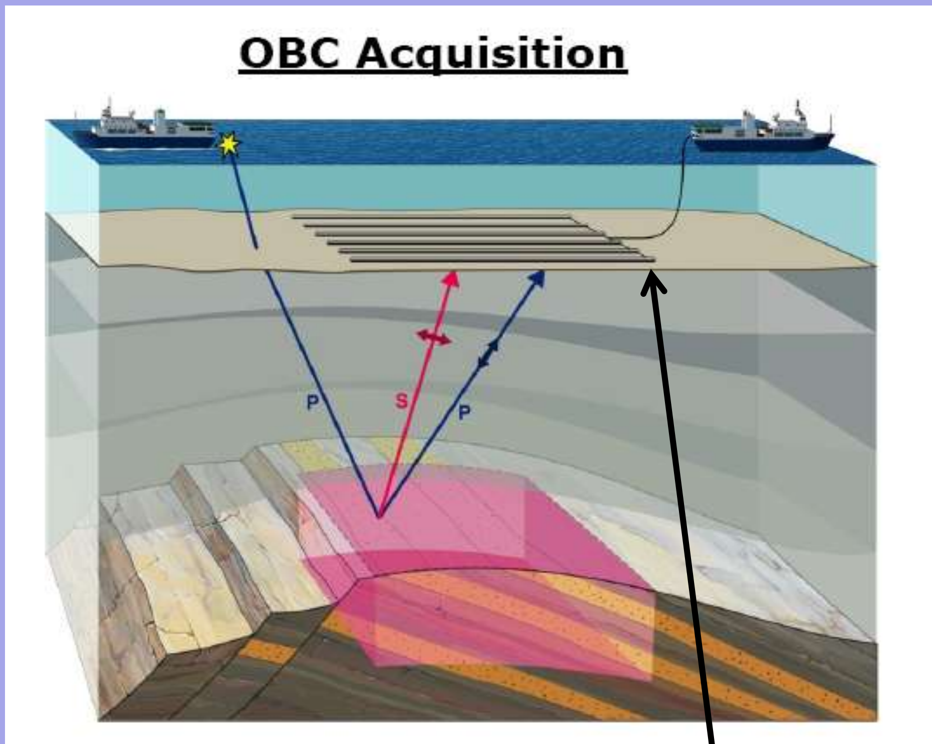
Bjorn Olofsson, Seabird Exploration

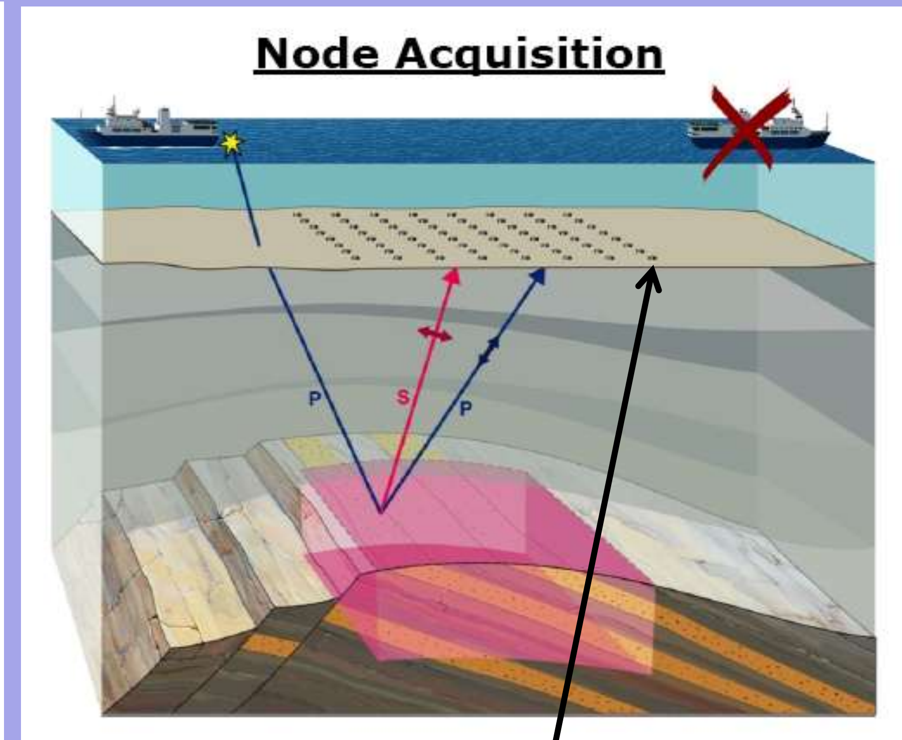
Abstract: Ocean bottom seismometers have been used by academia for several decades to study mostly the deep subsurface. But only since recently, such ocean bottom nodes (OBN) have been used in commercial seismic surveys for oil & gas exploration and development. In the 1990s the first 2D case studies using OBNs were carried out in the North Sea, and more substantial 2D & 3D pilot surveys followed in the early 2000s in the Gulf of Mexico, the North Sea, and in West Africa. The first full 3D OBN survey was carried out in 2004/2005 in the southern Gulf of Mexico, and until 2008 only one or maximum two 3D OBN survey per year were acquired world-wide. Since 2008, about 12 OBN surveys have been acquired world-wide, and demand for 2011 onwards is increasing.

Why are OBNs chosen in favor of towed streamer or ocean bottom cables?

The main driver is the full azimuth information achieved with a typical OBN survey design which enables best illumination and imaging in complex structure, for example sub-salt and sub-basalt. Another equally important driver has been the need to acquire seismic data in congested oilfields: Oilfields can be congested both on the surface, impeding towed streamer surveys, and on the seafloor, impeding the use of ocean bottom cables. Other forces driving OBN technology have been the exceptional data quality achieved by this type of acquisition, repeatability of receiver and source positions, and advances in processing full azimuth seismic data.

Ocean Bottom Node Acquisition – What is it?





4 component seismic sensor:
3 geophones (XYZ)   - also MEMS or optical for OBC
1 hydrophone

Outline

- **OBN Acquisition**
  - **Why is it done?**
  - **Equipment and Node Operation**
  - **Roll-along Operation**
  - **Survey Design**

- **Data Quality**
  - **Node Positioning**
  - **Source Signature & Sensor Responses, Low Frequency**
  - **Raw Data Analysis**
  - **Direct Arrival – First Break Analysis**
  - (Clock Drift)
  - (Sensor Orientation)

- **Data Processing**
  - **OBN Data Processing Flow**
  - **Mirror Imaging**

OBN Acquisition

Why is it done?

OBN Acquisition – Why is it done?

Complex imaging with full azimuth broad band data

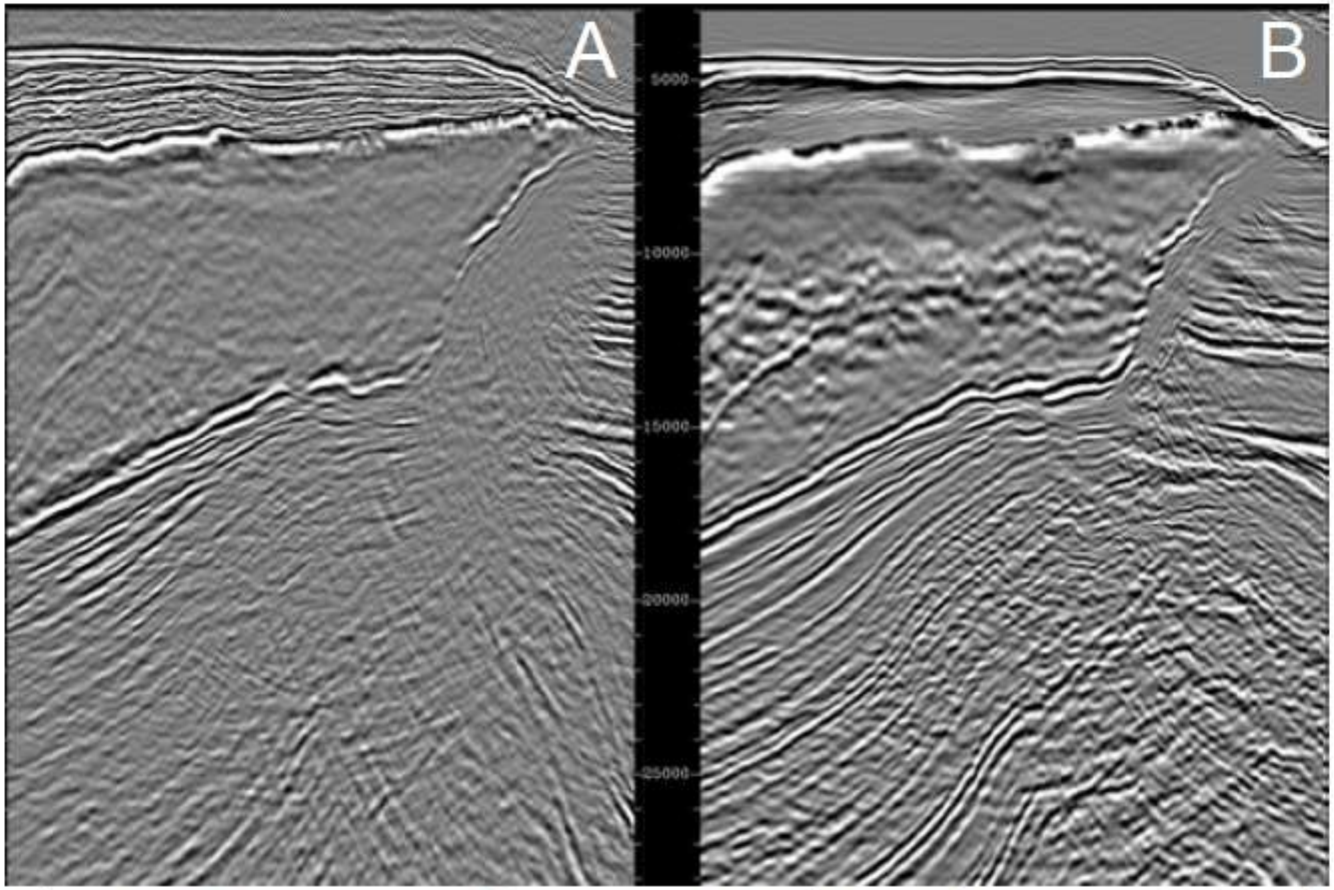


Figure 6. *Comparison of narrow-azimuth towed streamer (A), and receiver-migrated OBS node (B). The node images benefit from an improved salt model.*

Source: Atlantis, Node data acquired by Fairfield (phase 1) & Seabird (phase 2)

Beaudoin SEG 2010

OBN Acquisition – Why is it done?

High resolution both vertically and laterally

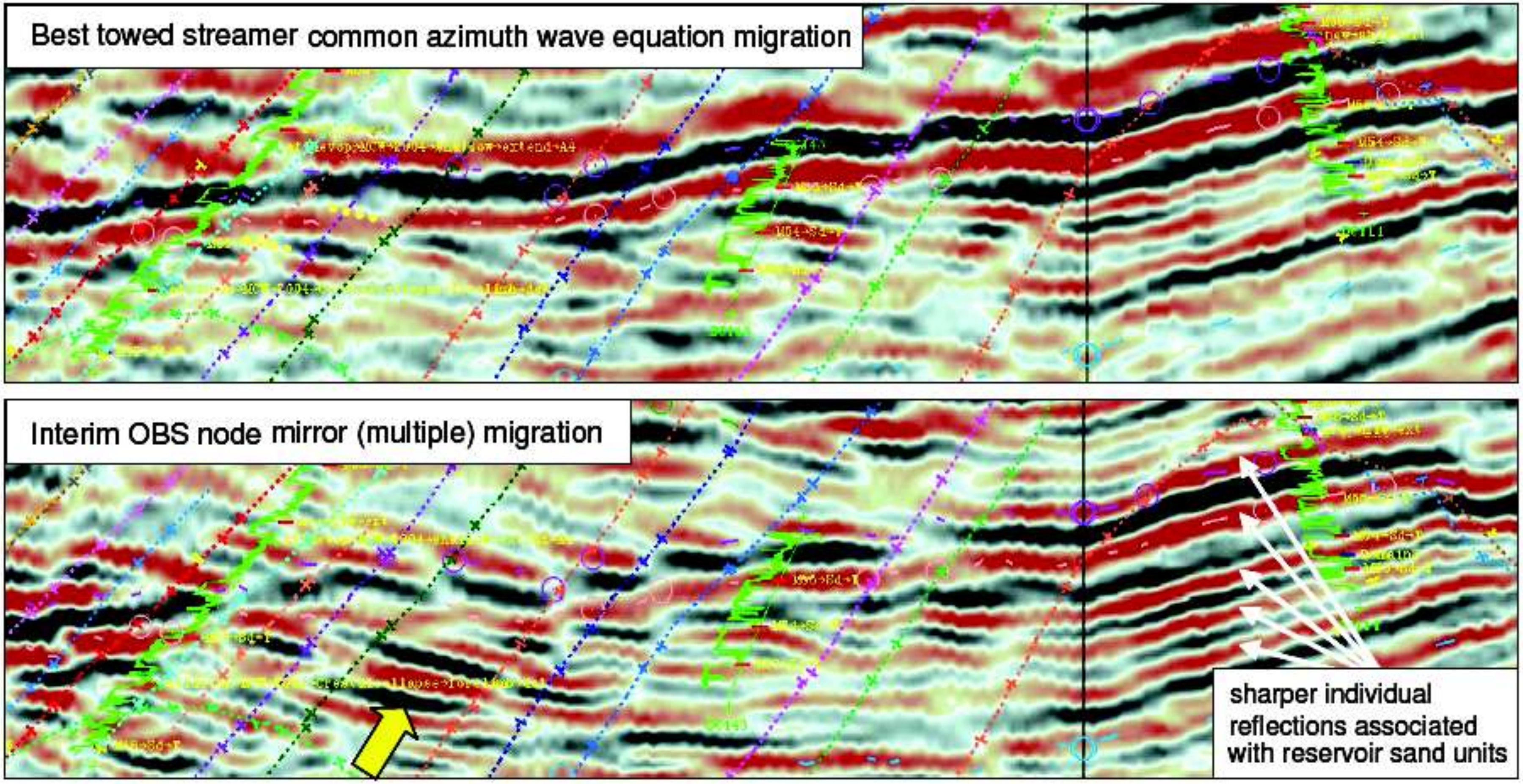


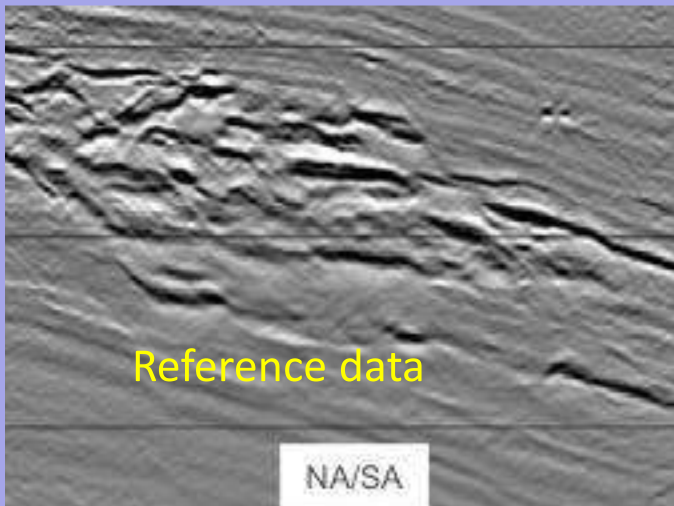
Figure 6: Comparison of extra-salt images at the Miocene level at Atlantis. Higher resolution and improved fault definition are apparent in the OBS wide-azimuth node image on the bottom compared to the narrow-azimuth towed streamer image above.

Source: Atlantis, Node data acquired by Fairfield (phase 1) & Seabird (phase 2)

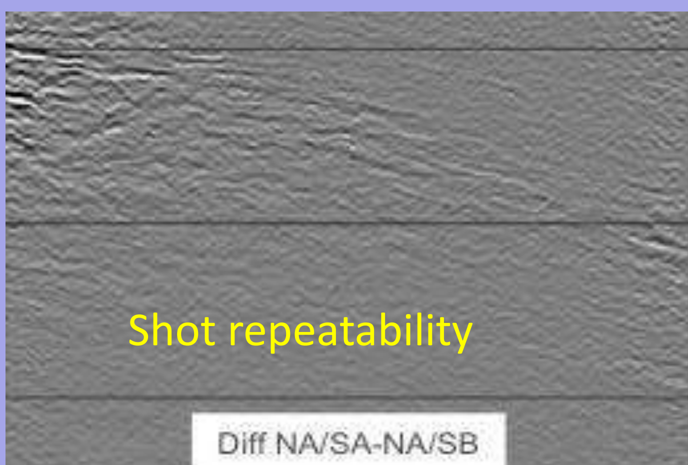
Howie et al SEG 2008

OBN Acquisition – Why is it done?

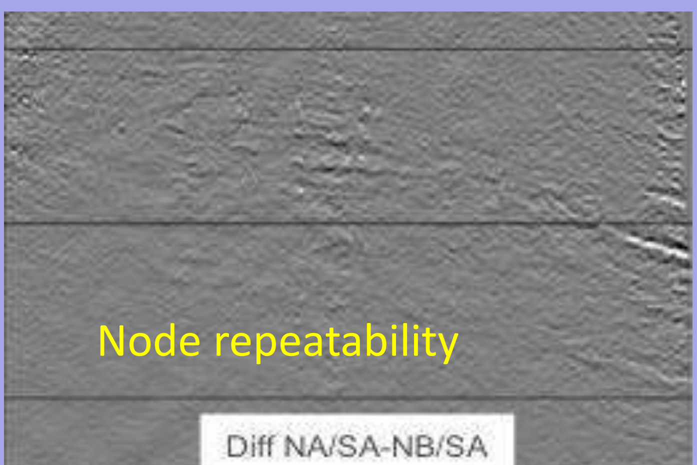
4D Repeatability



> *Comment on first node-on-node 4D survey:*
>
> *"Time-lapse noise measurements [...] are among the lowest in BP's experience even when compared to permanent installation surveys."*
>
> *Reasnor et al, SEG 2010*



Node A, Shot A and B



Node A and B, Shot A

Source: Dalia, Node data acquired by Seabird

E.Ceragioli et al, EAGE 2010

OBN Acquisition – Why is it done?

Infill under obstructions, congested oilfields

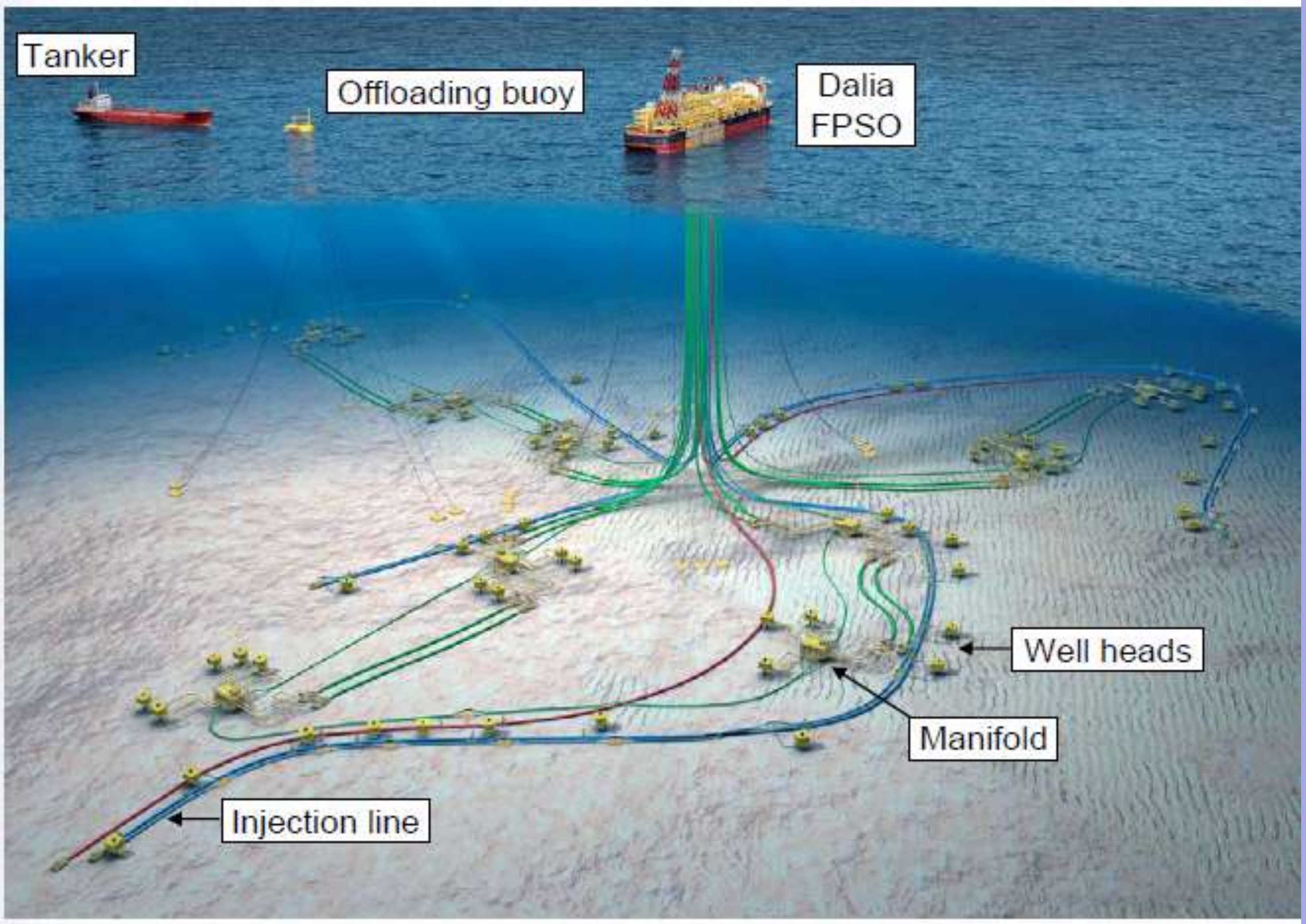
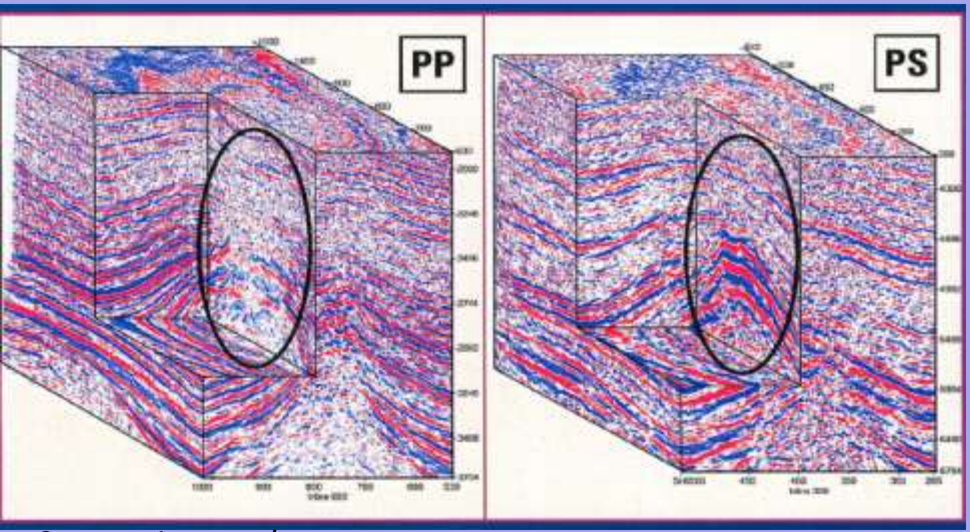
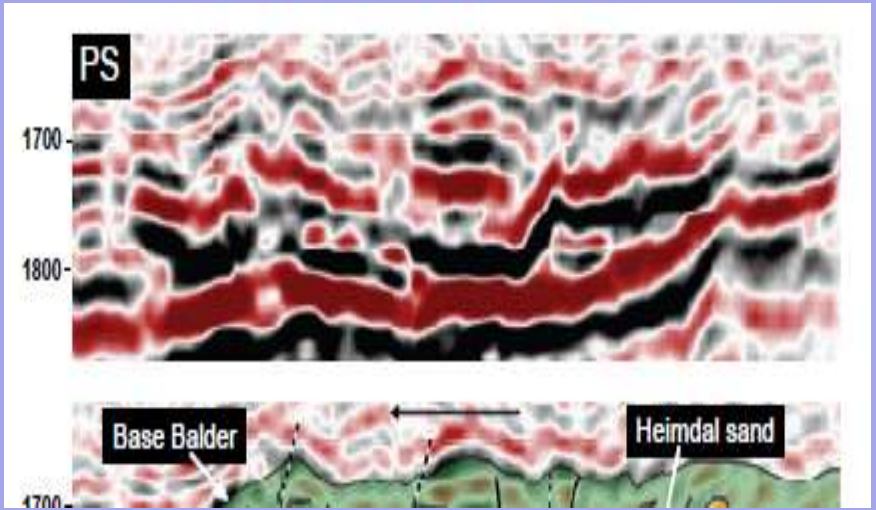


Illustration of the main surface and subsea obstructions on the Dalia field: OBN will be located on the seabed very close to obstructions.

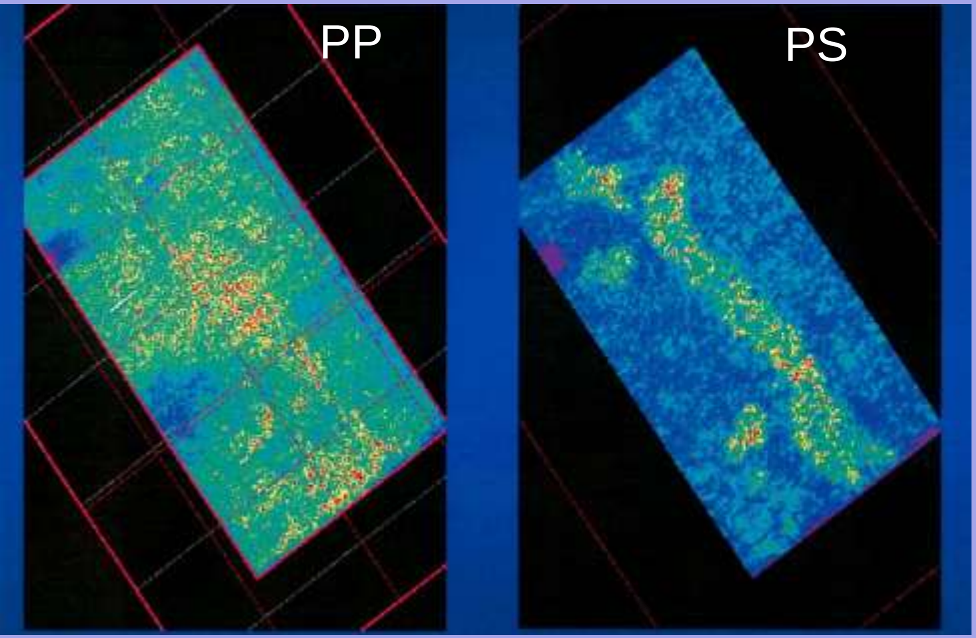
OBN Acquisition – Why is it done? ***Converted wave imaging***

Shown are classic OBC examples

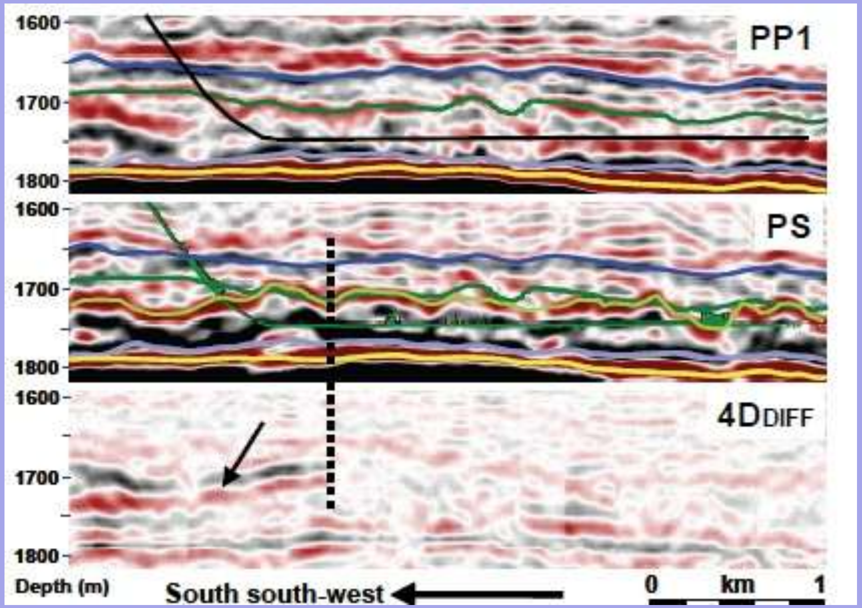




Source: Lomond



Source: Alba



Source: Grane

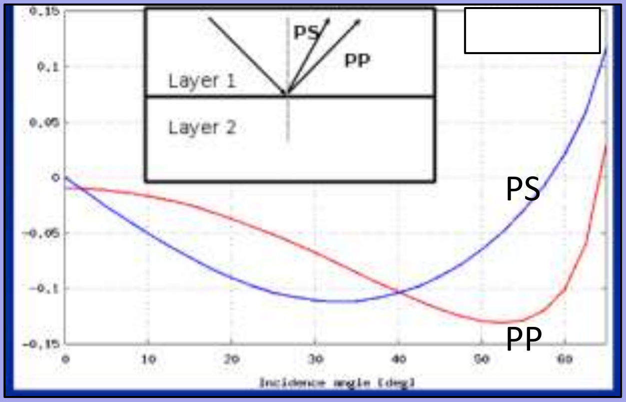
Fjellanger et al, SEG 2006

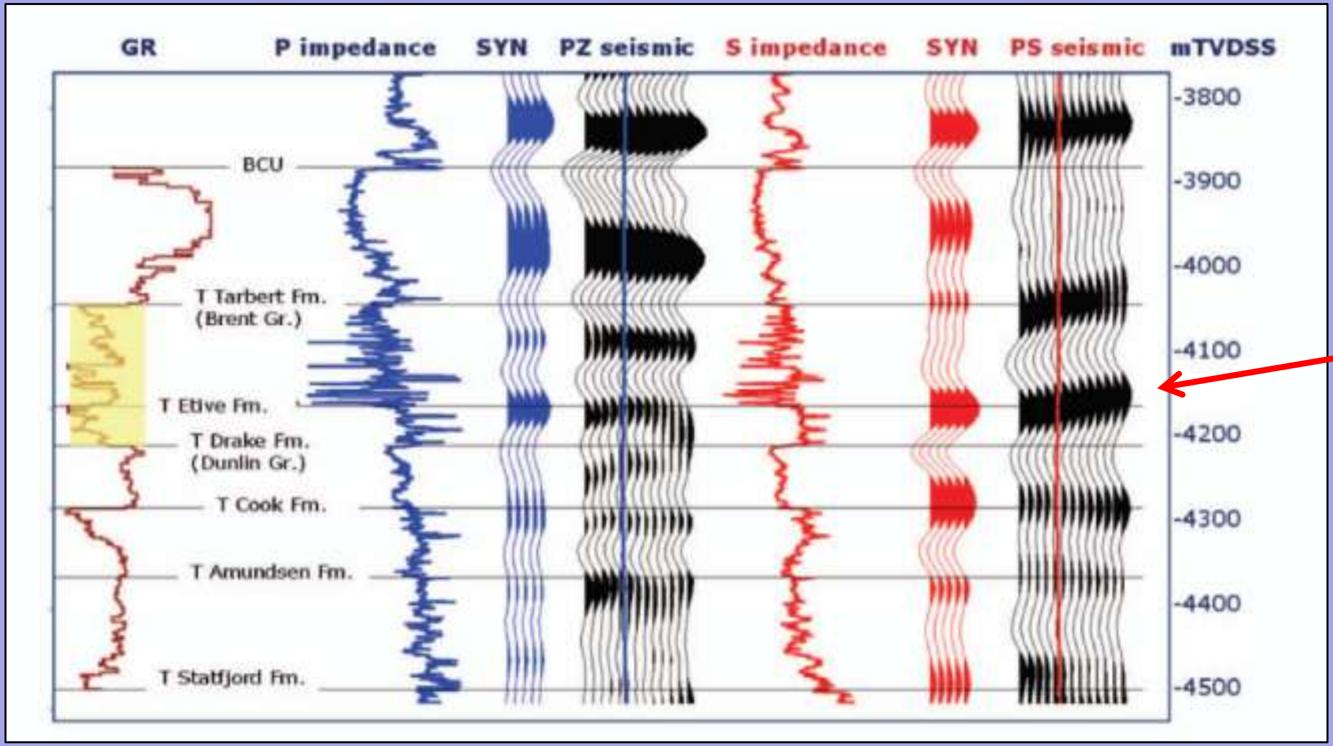
Why Converted Waves? *PP & PS = Improved reservoir characterisation*

PP AVO inversion → P impedance

PS AVO inversion → Shear impedance

..also better handle on density.





Strong shear impedance contrast from lithology change within reservoir zone.

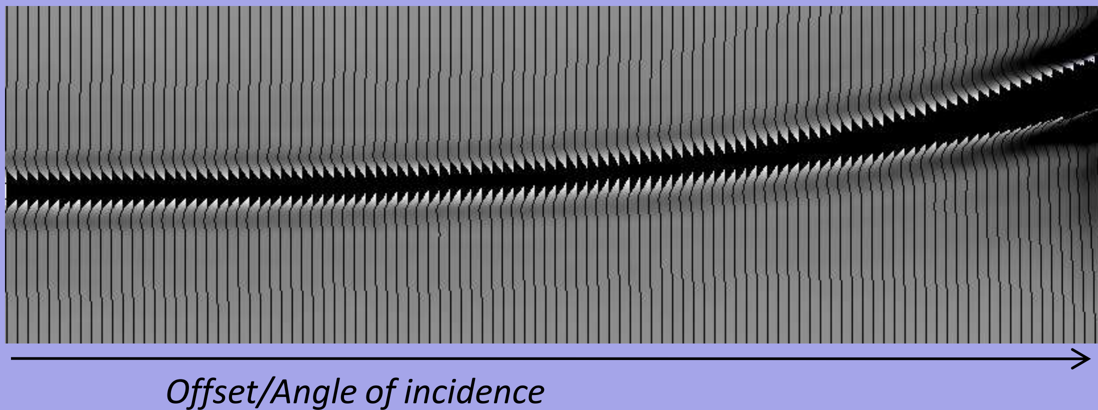
Source: Kvitebjorn

Ao & Areklett, TLE 2010

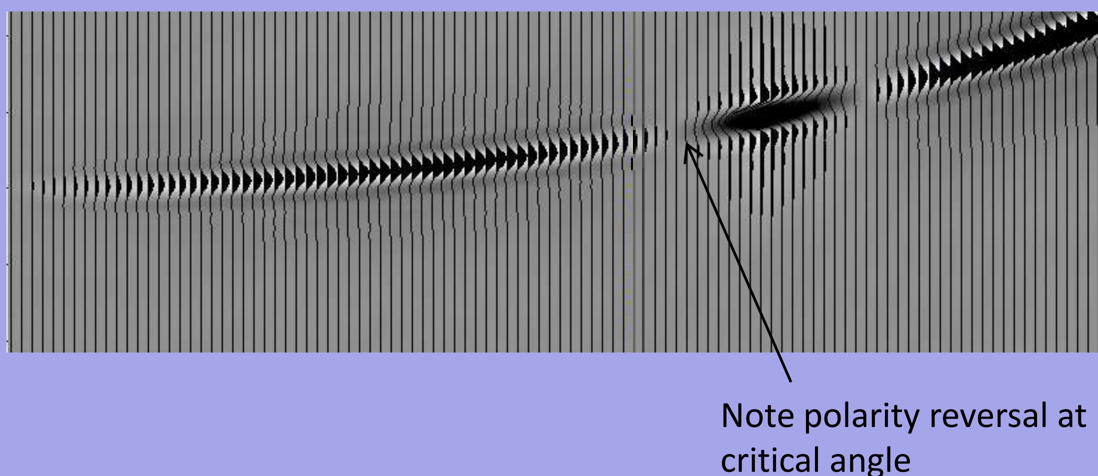
Why Converted Waves?

PP & PS = Better anisotropic velocity model building

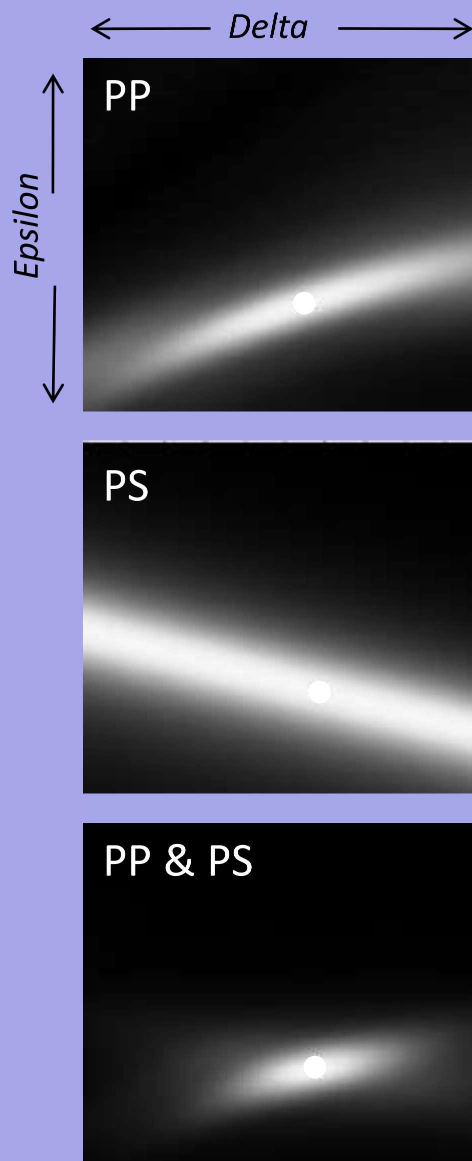
PP reflection, isotropic NMO correction



PS reflection, isotropic NMO correction



Double Scan

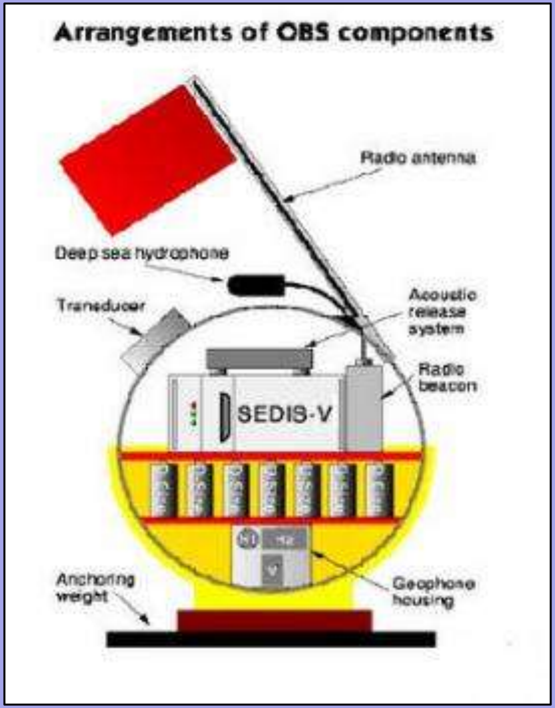


OBN Acquisition

Equipment and Node Operation

OBN Equipment – Nodes

Option 1 Throw node overboard, let it float up by itself



- Typically glass or titanium sphere
- Disposable heavy anchor
- Internal or external sensor package
- Mostly used for academic research

OBN Equipment – Nodes

Option 2 Hand-place node, pick it up manually

- Node can be custom shaped
- Recorder in cylindrical pressure vessels
- Internal or external sensor package
- Mostly used for commercial 3D surveys

OBN Equipment – Node

Node Unit/recorder:

- Microprocessor
- A/D: 24-bit
- Data Storage: 75 days @ 2 ms
- Clock: High-precision oven-controlled quartz oscillator
- QC data Link: High-speed acoustic modem
- Battery: >65 days
- Physical size: 91 x 87 x 38 cm
- Weight: 150/70 kg in air/sea
- Depth rating: 3000m

4 component (4C) sensor:

- Hydrophone
- 3 Geophones (8 Hz)
- 2 Inclinometers

OBN Equipment – Sensor technology

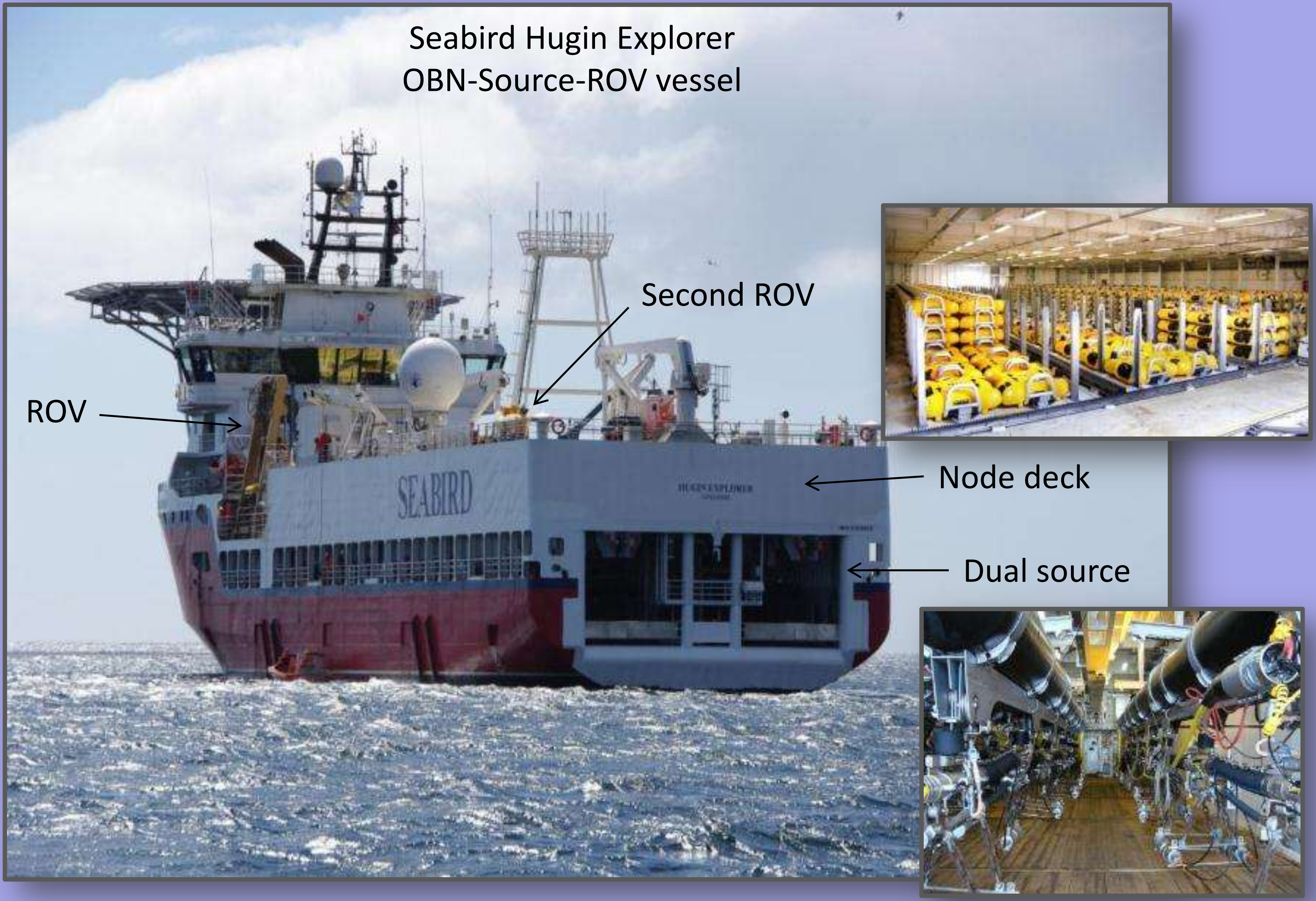
Geophone sensors

Hydrophone sensor

- ***Hydrophones*** need to be exposed to outside
- ***Geophones*** need to couple to seabed (in order to record shear waves)

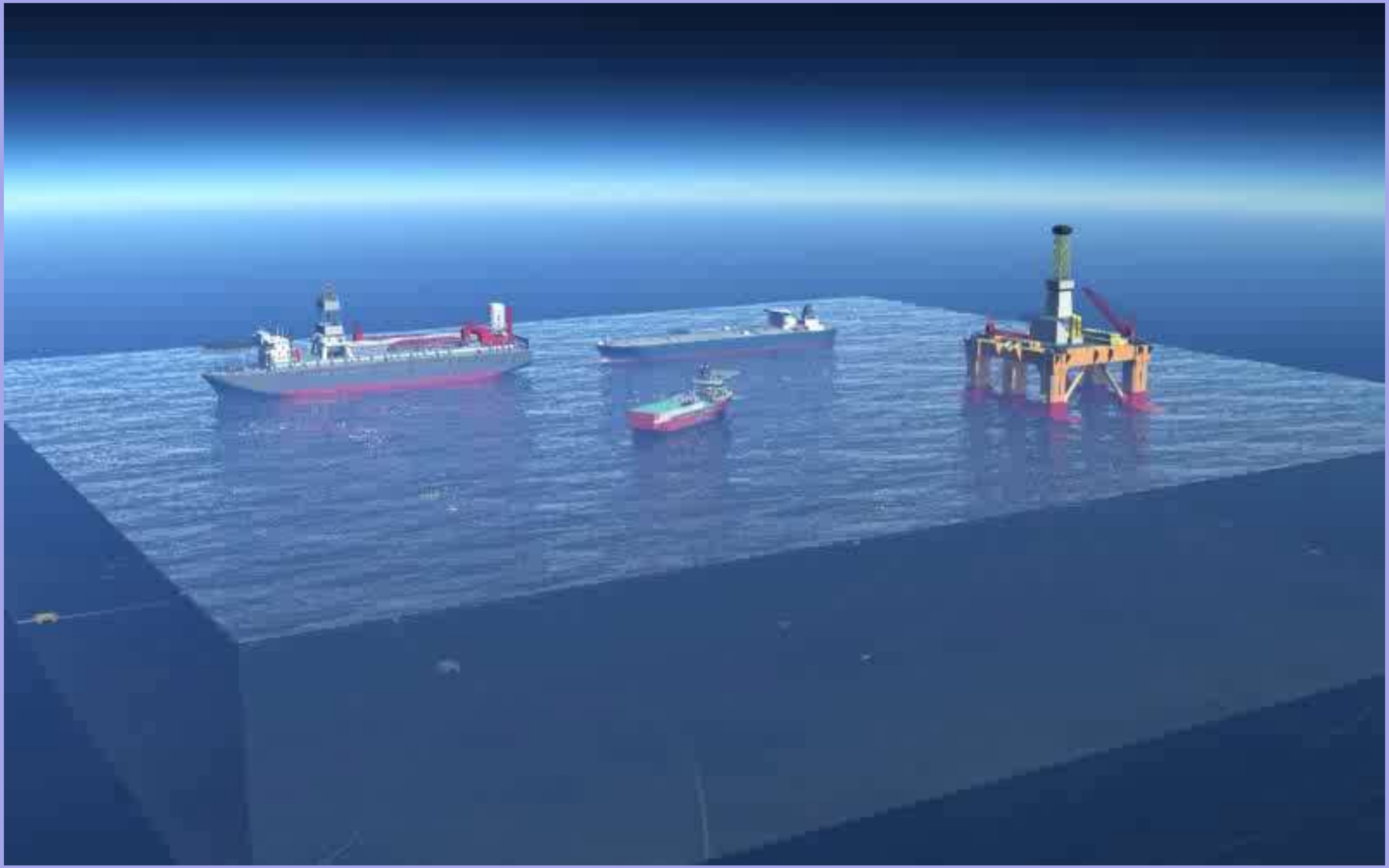
- MEMS accelerometers or optical sensors are not suitable for autonomous nodes due to high power consumption of the sensor itself or of other system components
- Others, such as piezo-electric sensors are also an option

OBN Equipment – Vessel

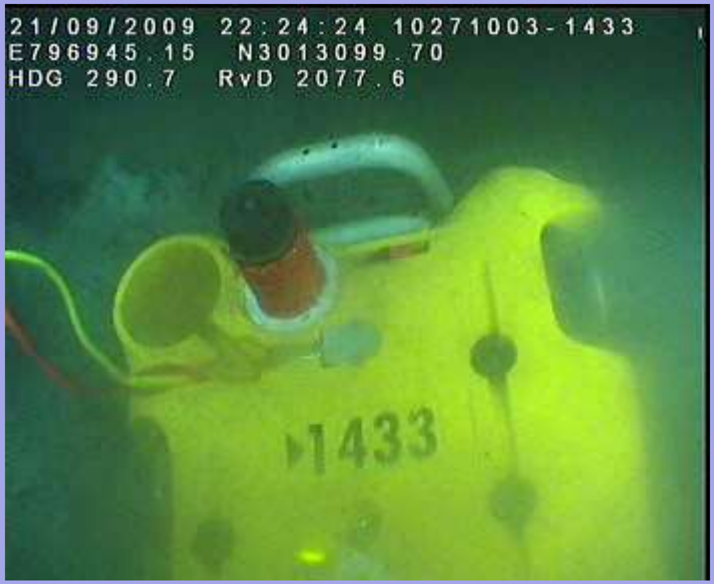


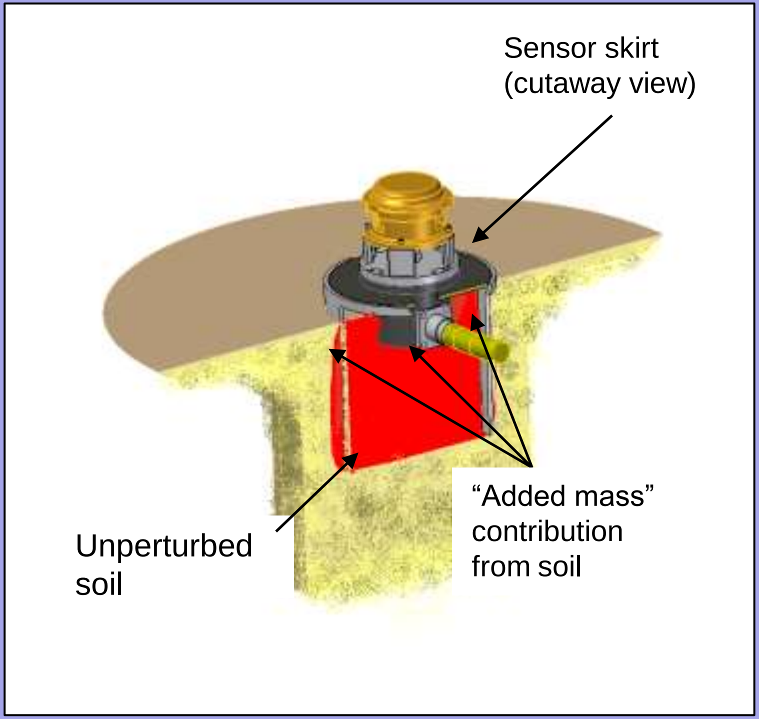
OBN Equipment – Node Handling

OBN Operation – Node Placement



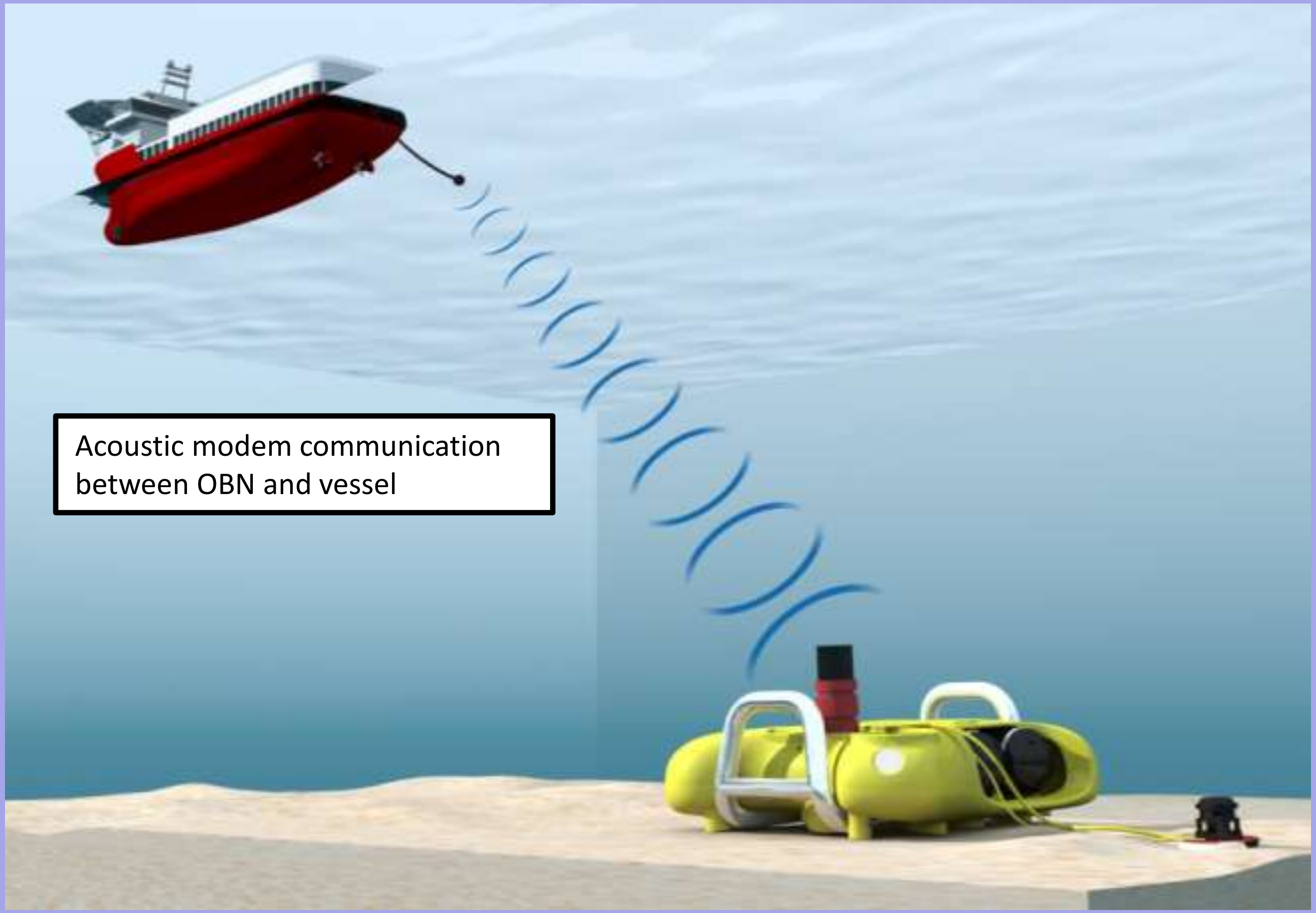
OBN Operation – Node Placement





OBN Operation – Node QC

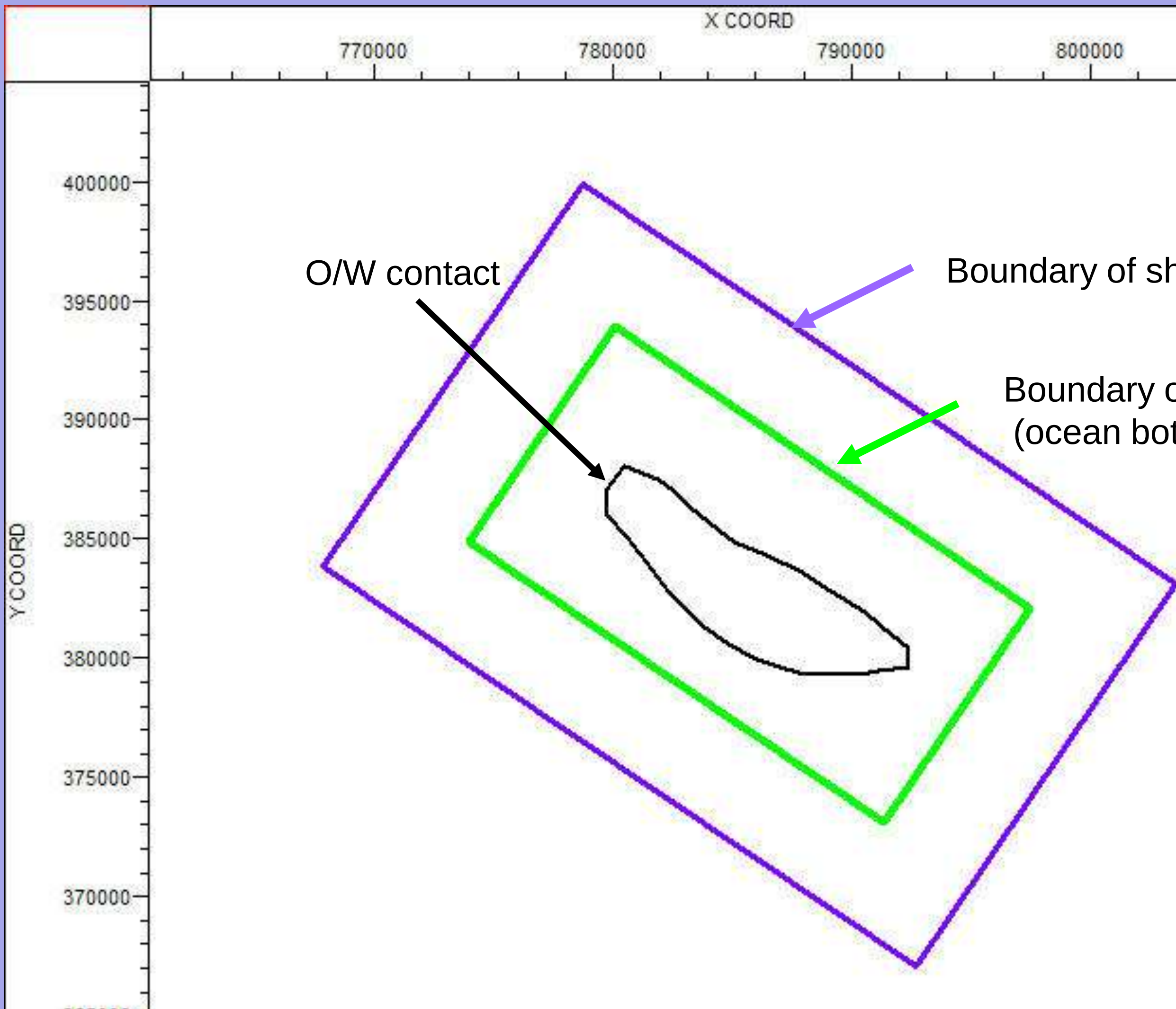
- Recorder status
- Battery status
- Hard disk status
- Power usage
- Tilt values
- Seismic data RMS amplitudes
- ...various other system information



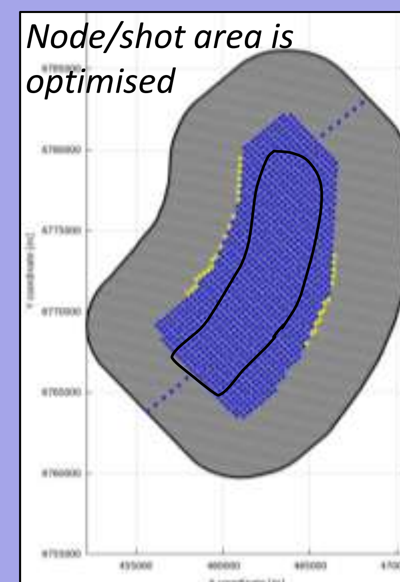
OBN Acquisition

Roll-along Operation

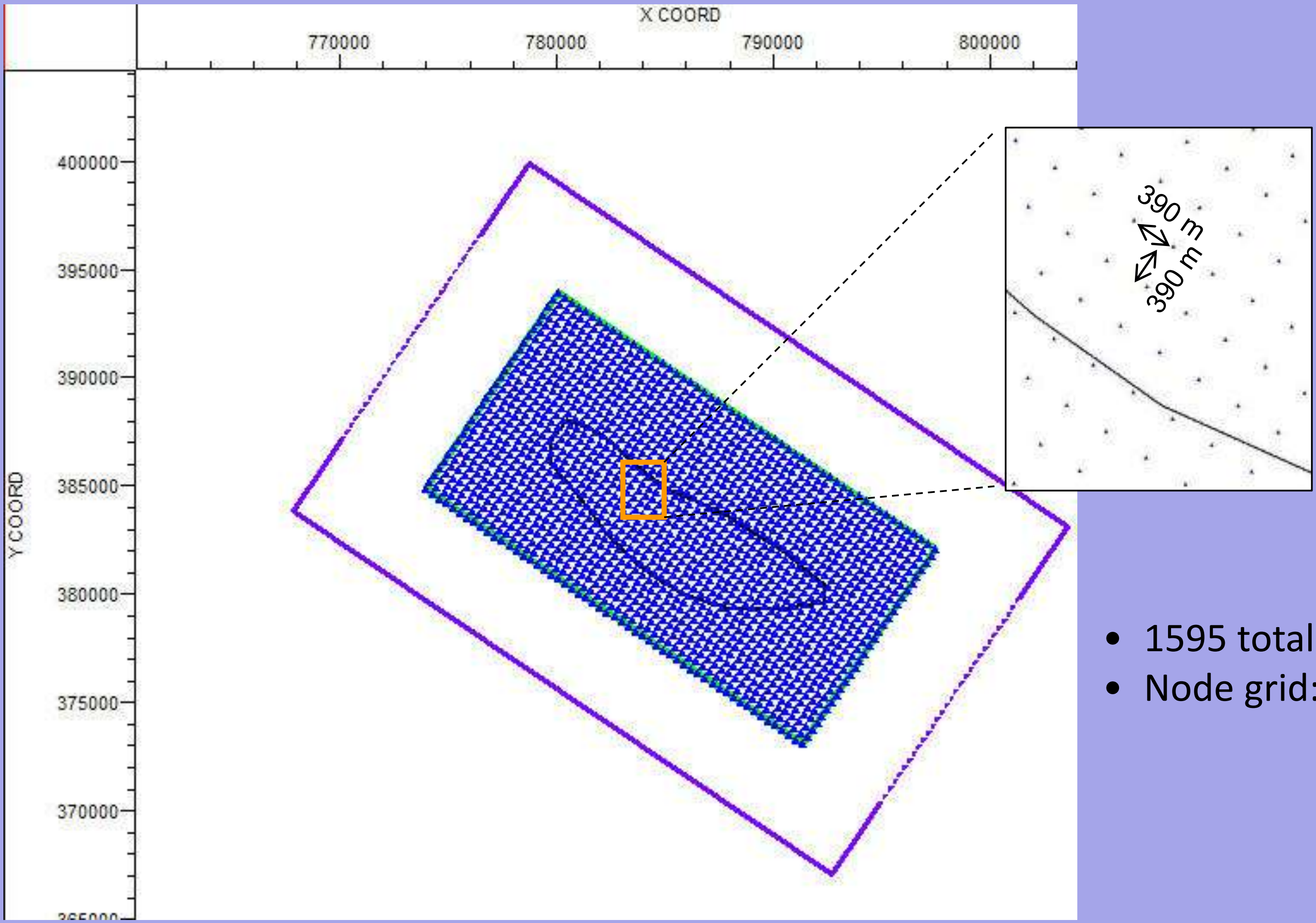
OBN Survey – Node and Source Area



Another example:

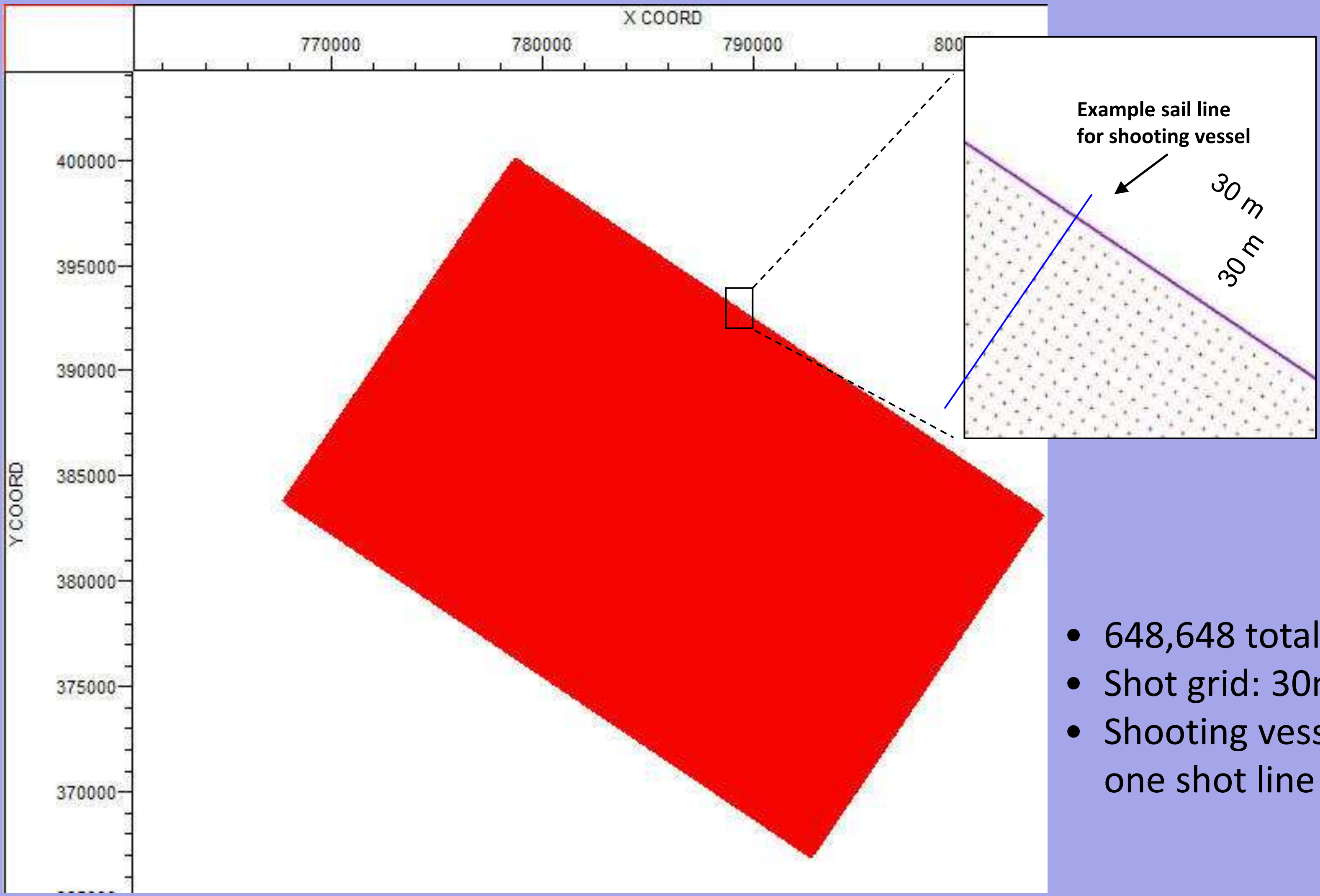


OBN Survey – Node Layout



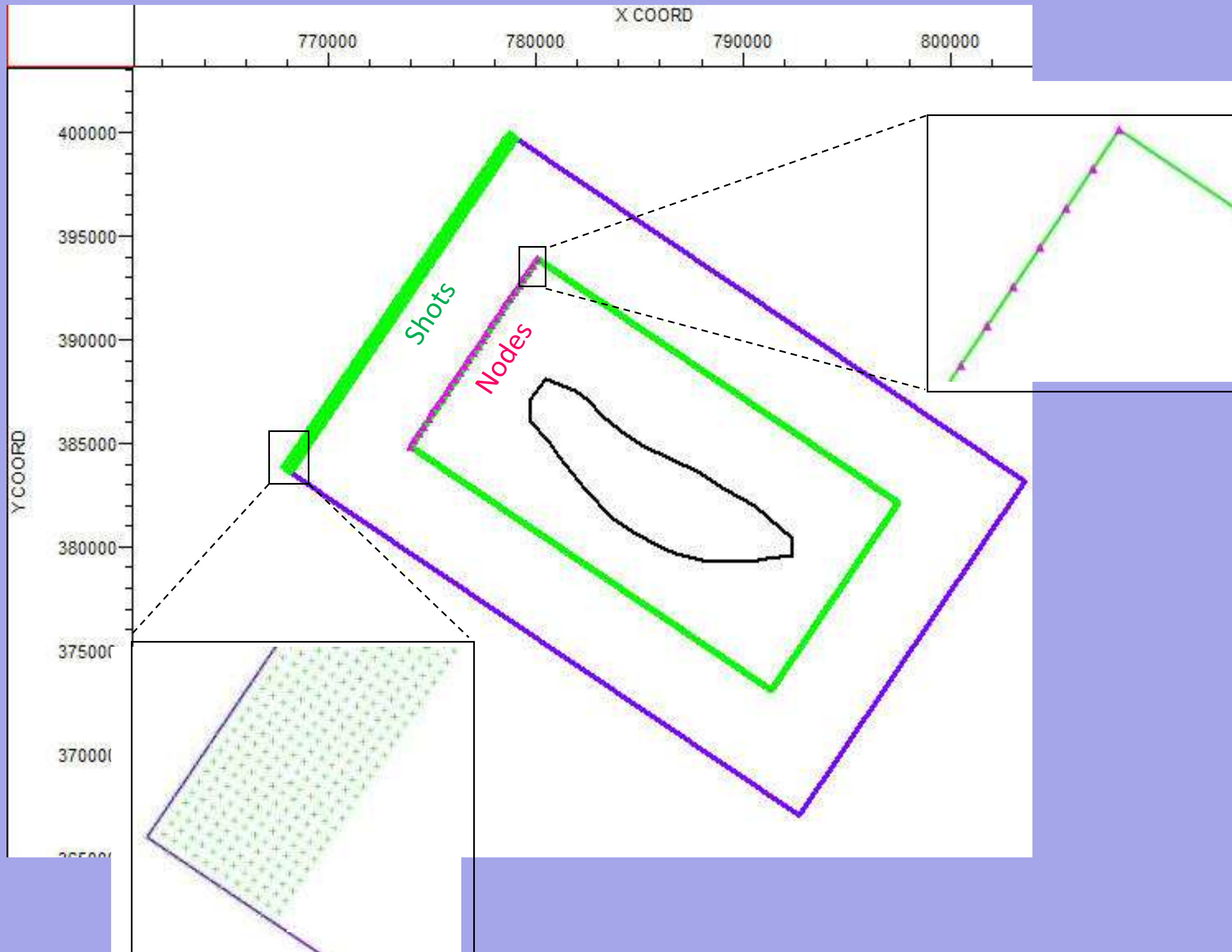
- 1595 total node positions
- Node grid: 390m x 390m

OBN Survey – Source Layout

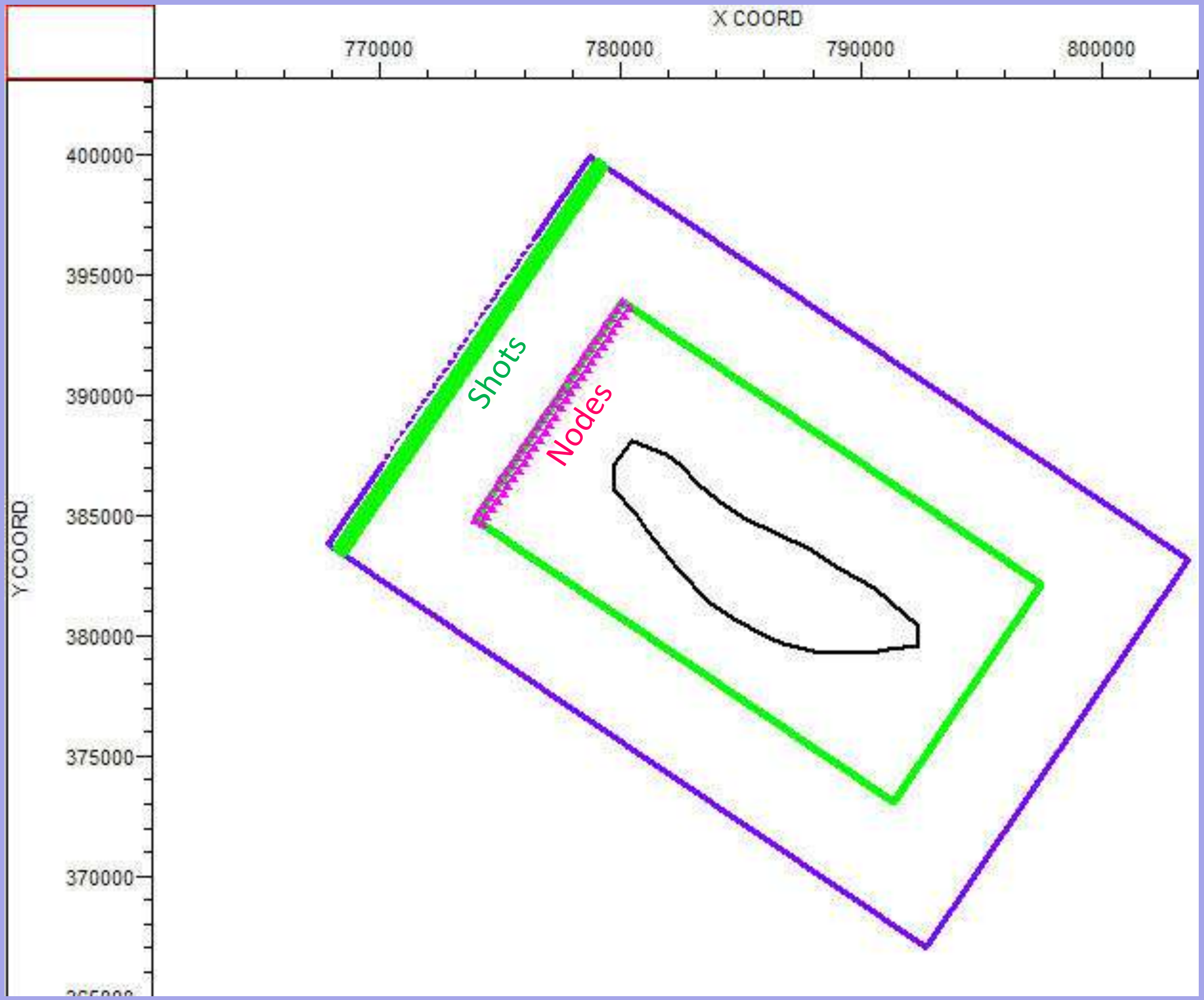


- 648,648 total shot positions
- Shot grid: 30m x 30m
- Shooting vessel acquiring one shot line at a time

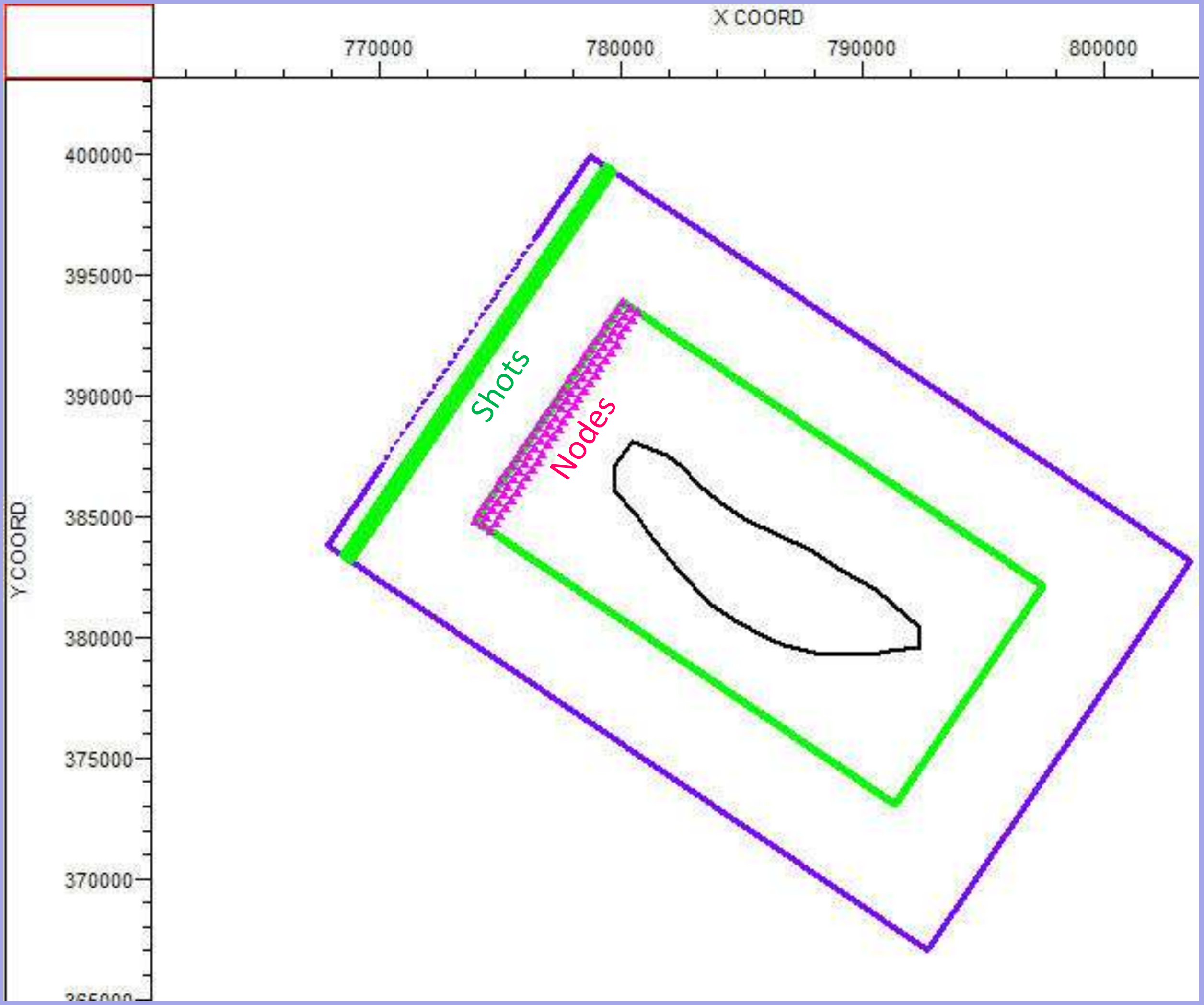
OBN Survey – Roll-along Acquisition



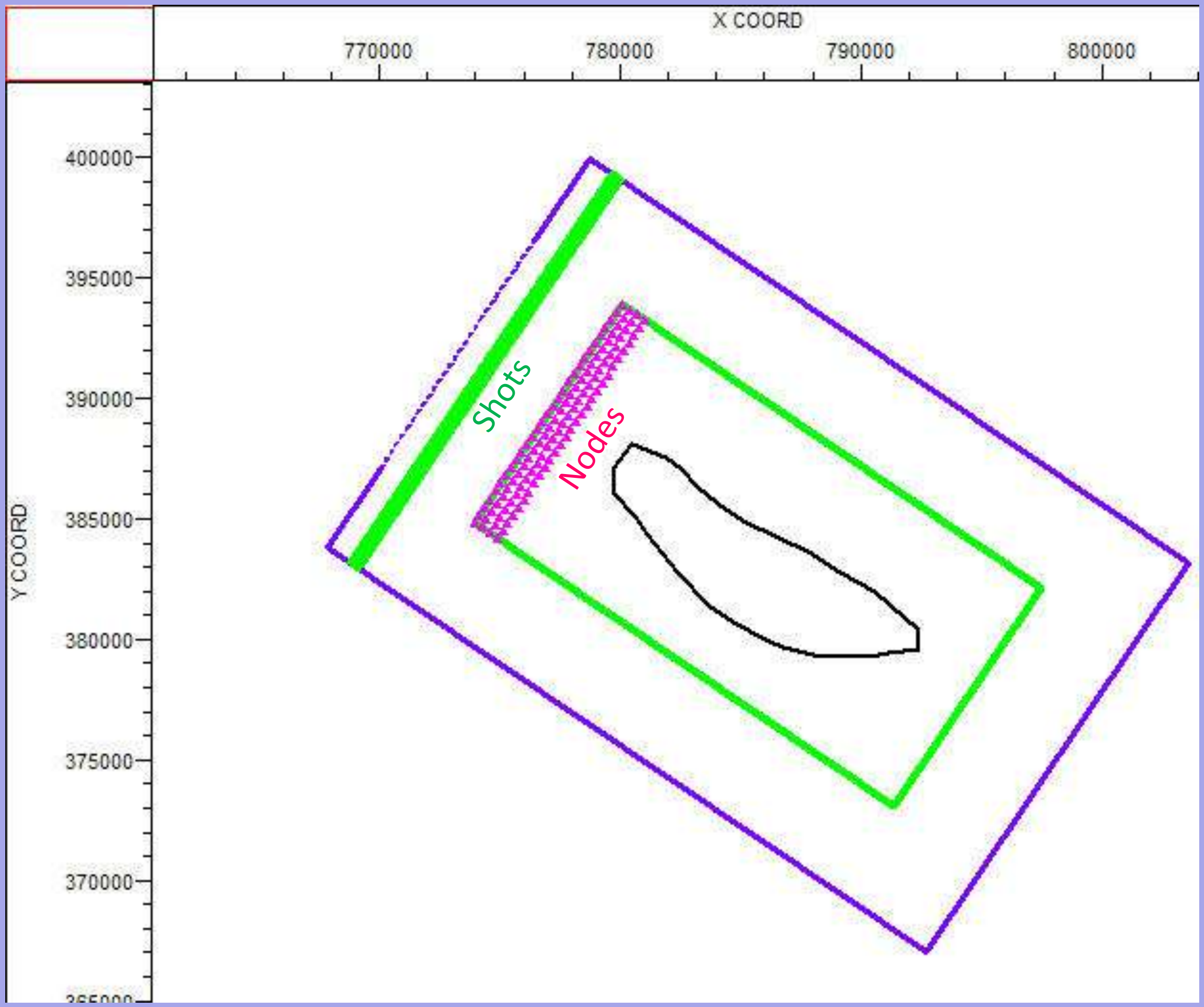
OBN Survey – Roll-along Acquisition



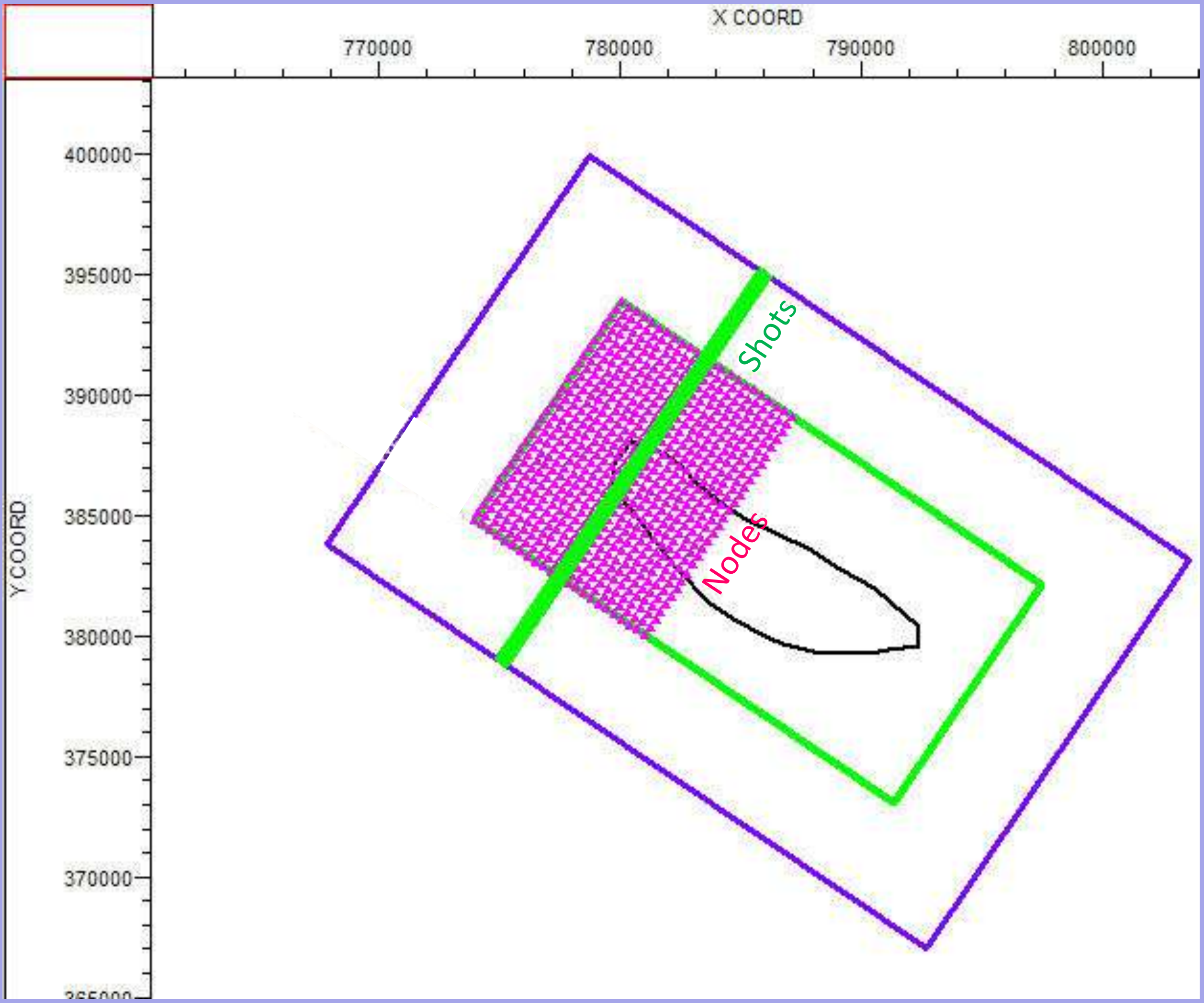
OBN Survey – Roll-along Acquisition



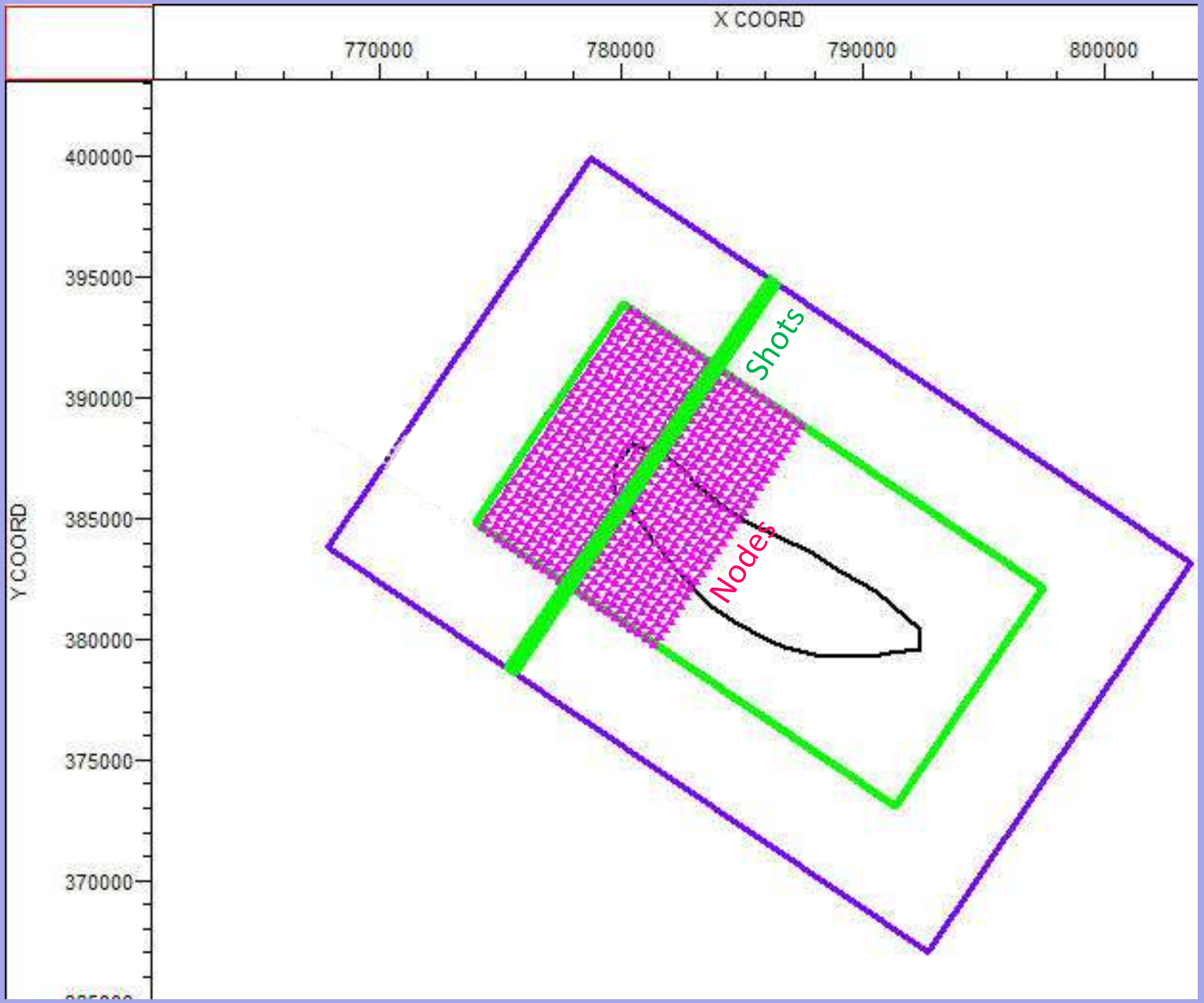
OBN Survey – Roll-along Acquisition



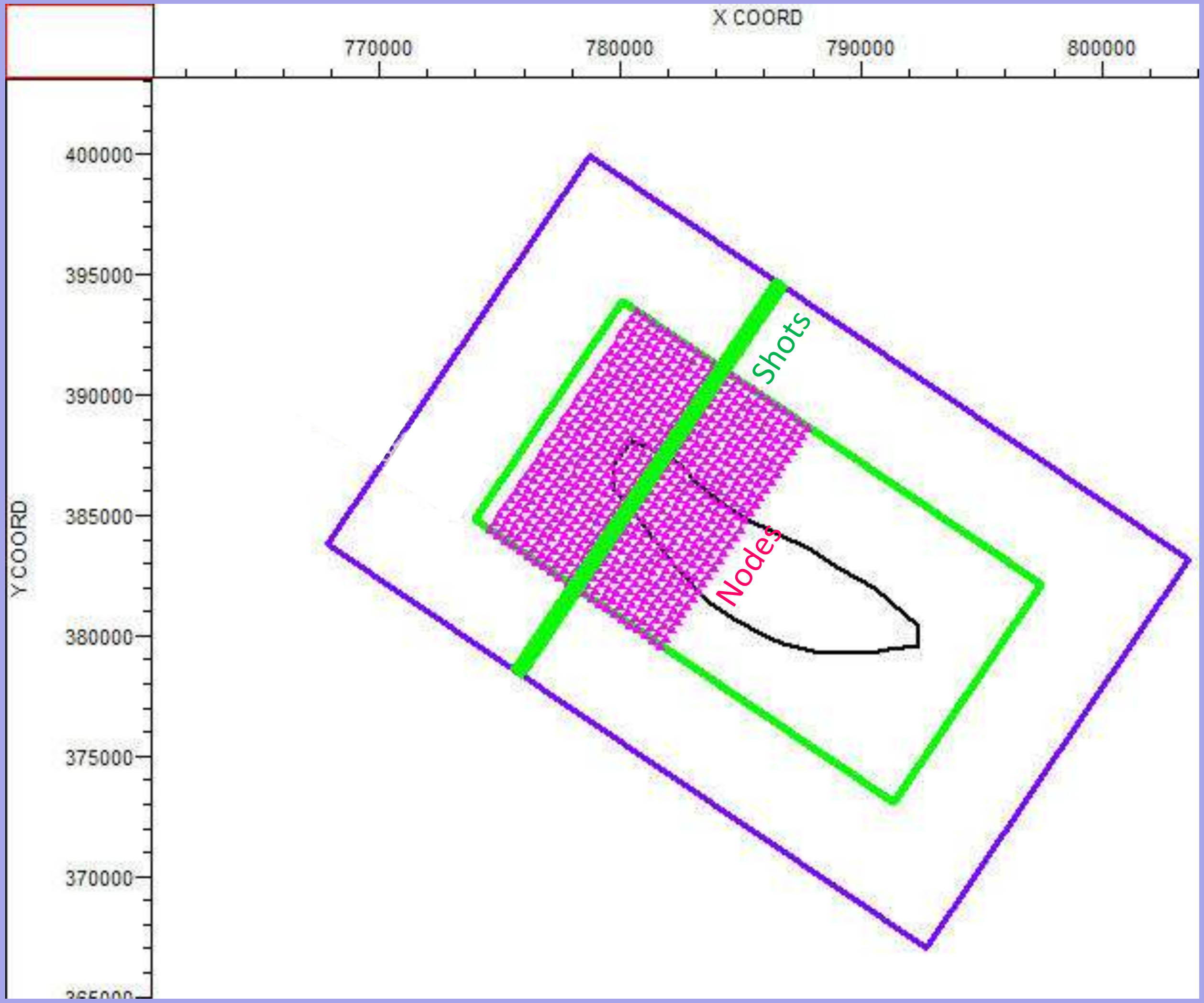
OBN Survey – Roll-along Acquisition



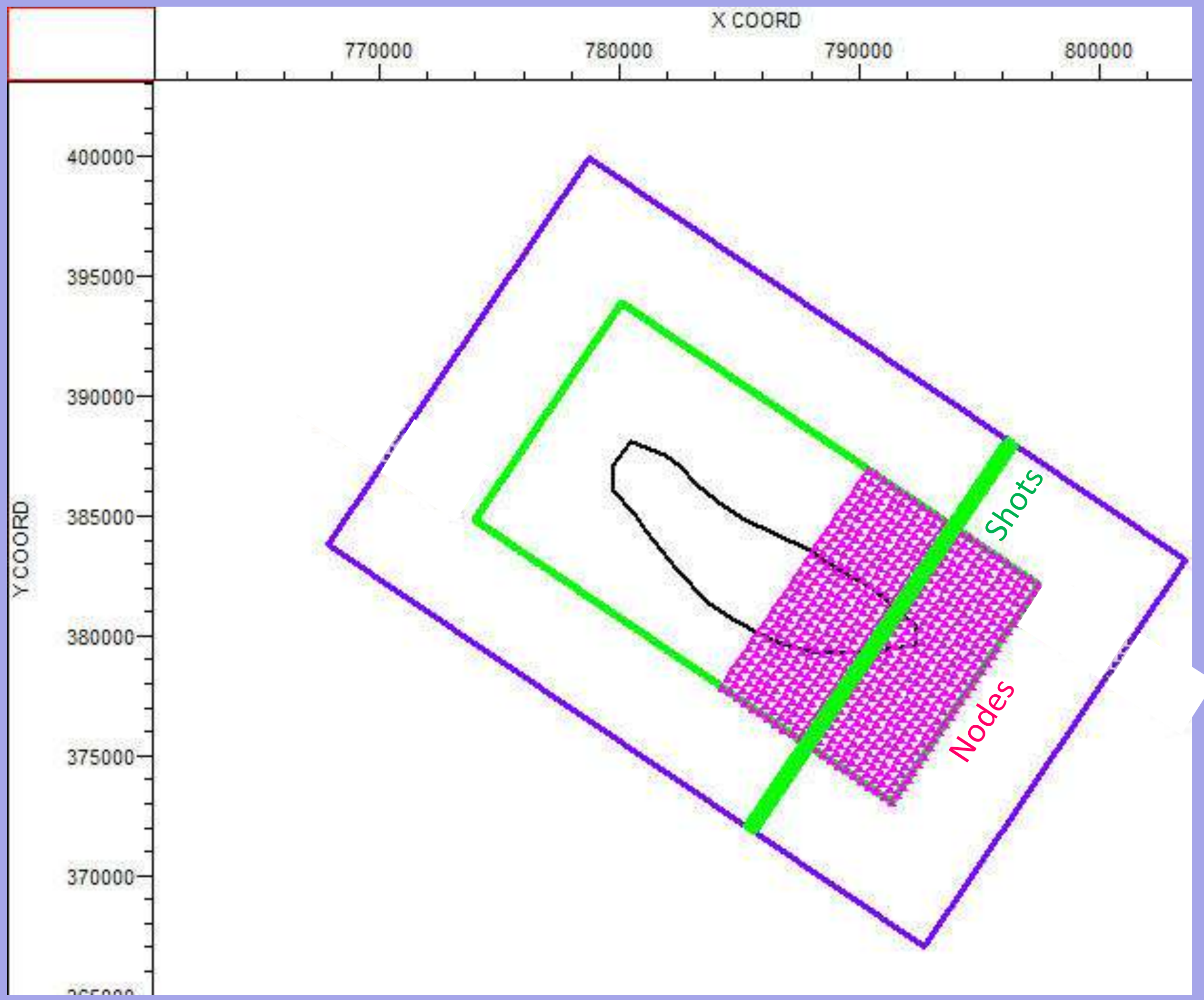
OBN Survey – Roll-along Acquisition



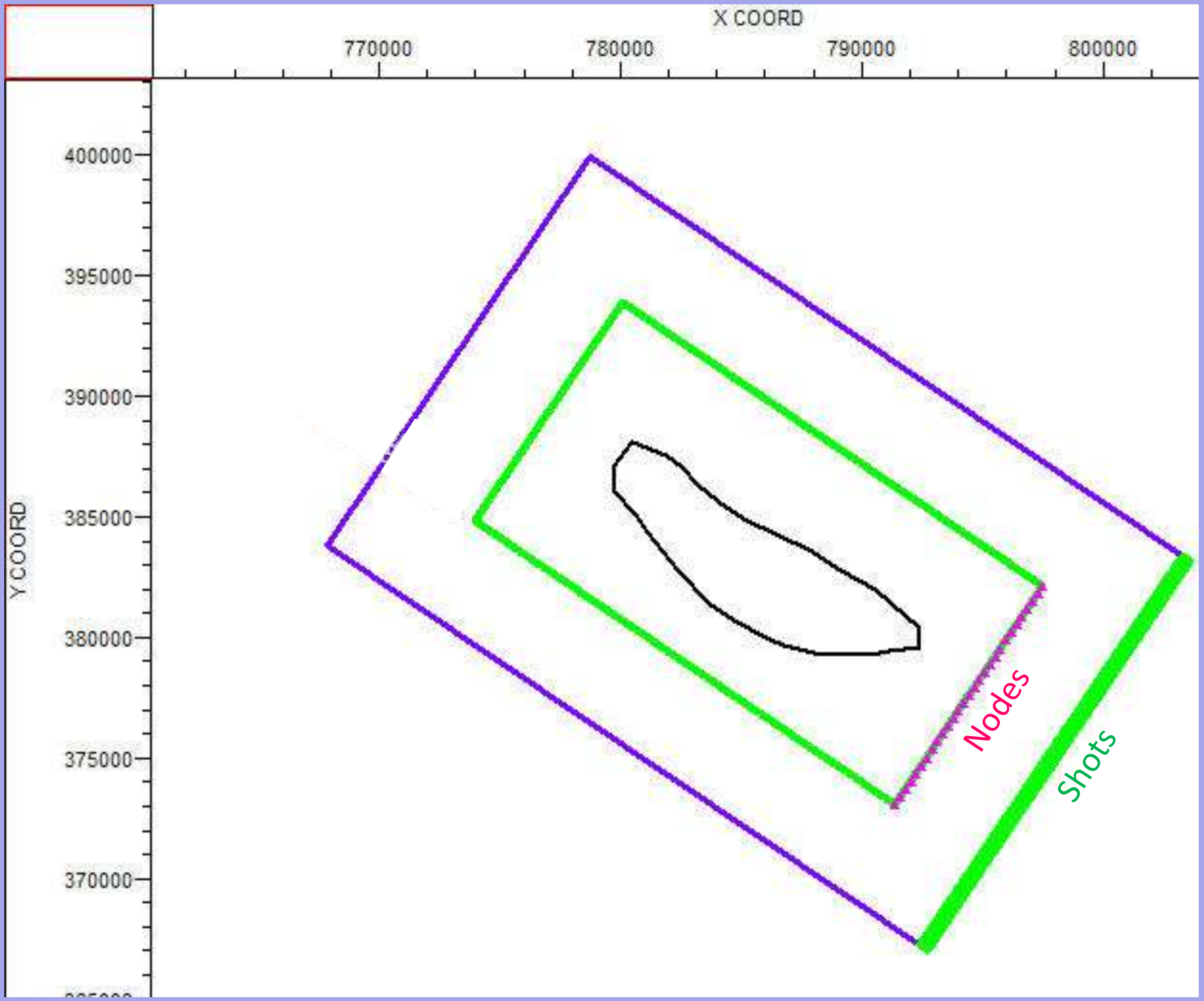
OBN Survey – Roll-along Acquisition



OBN Survey – Roll-along Acquisition



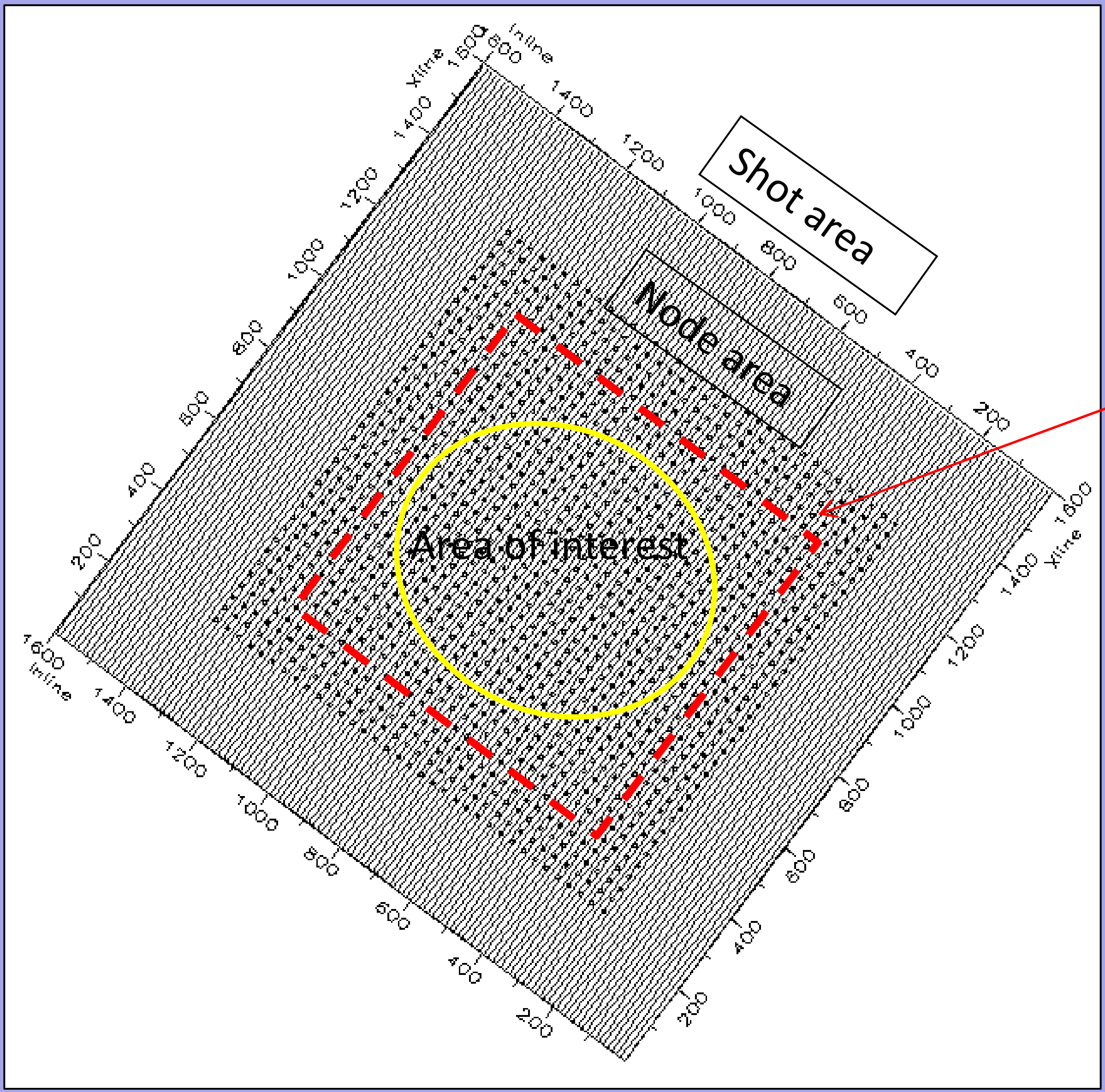
OBN Survey – Roll-along Acquisition



OBN Acquisition

Survey Design

OBN Survey Design



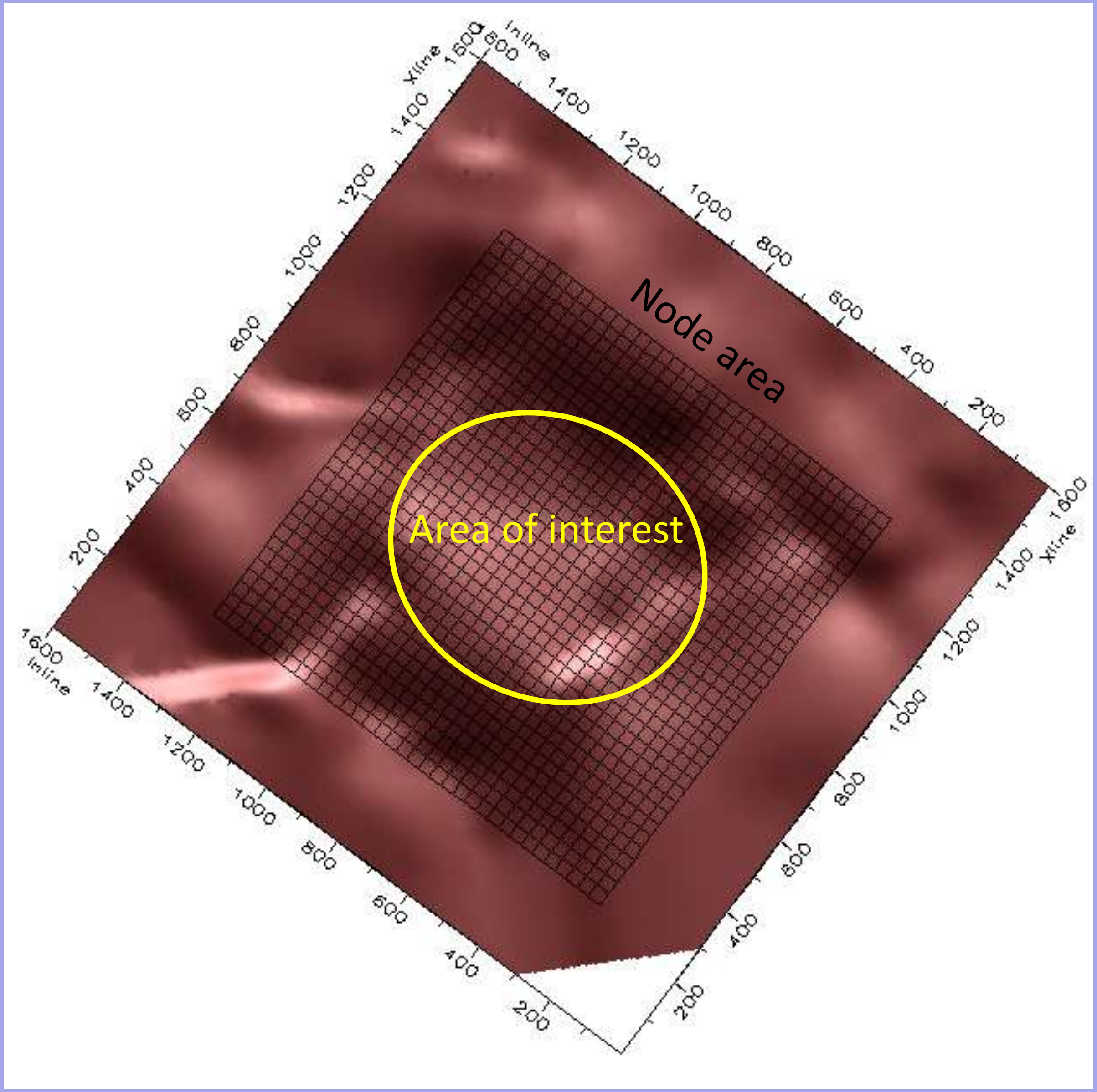
Example OBN survey layout:

Source grid: 50m x 50m

Node grid: 400m x 400m

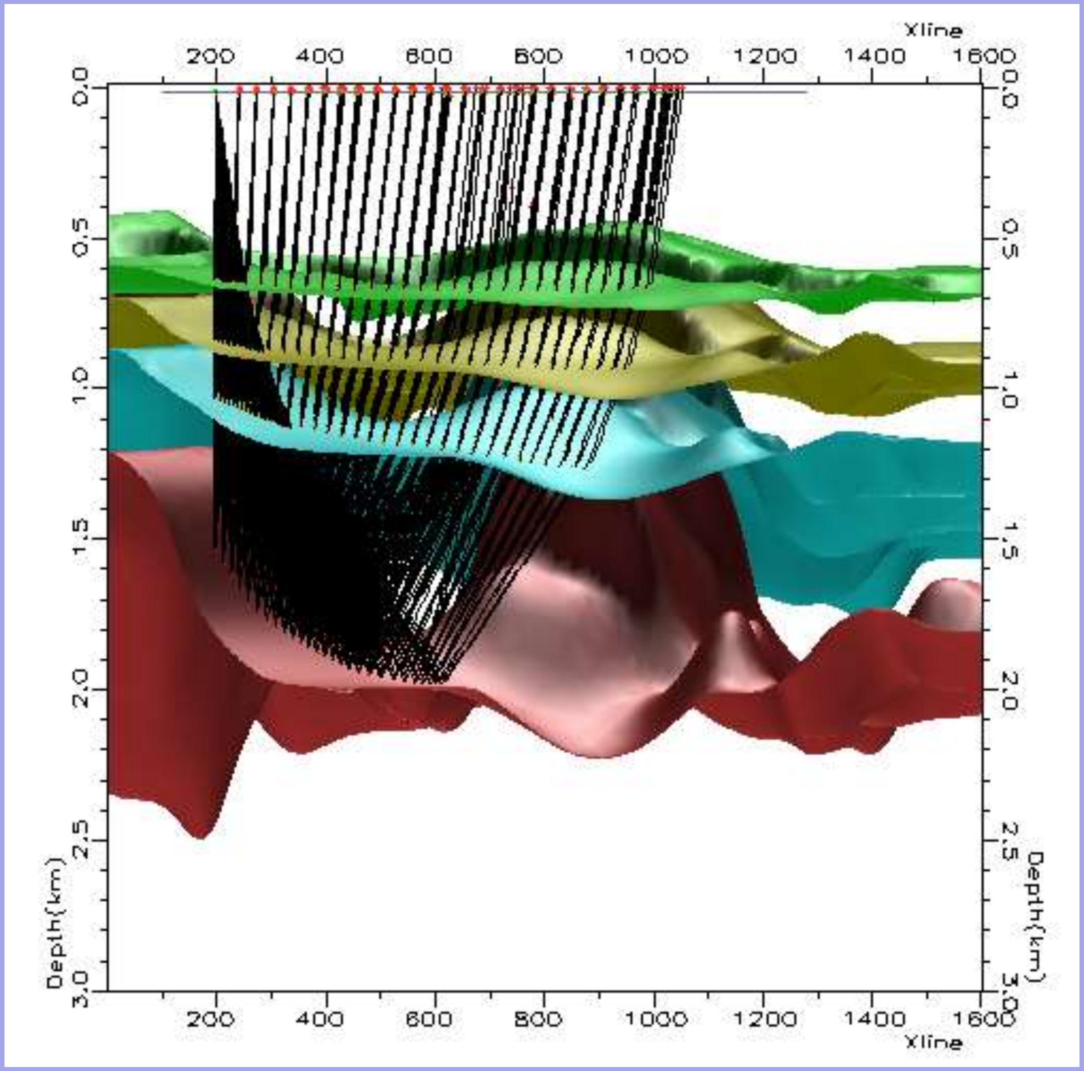
Area of full surface azimuth/ offset coverage

OBN Survey Design



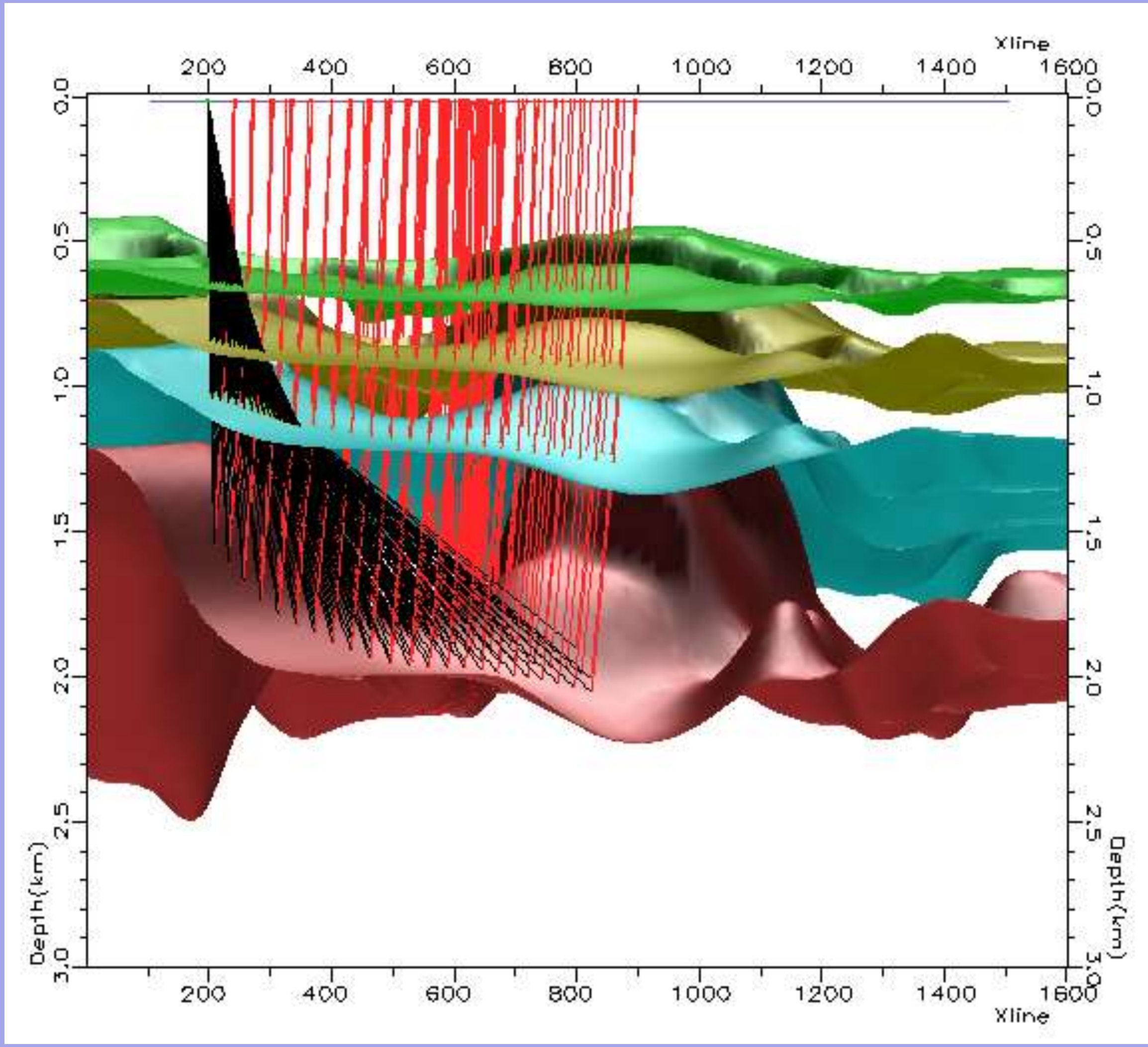
Target horizon, node area.

OBN Survey Design



Ray-tracing, PP mode

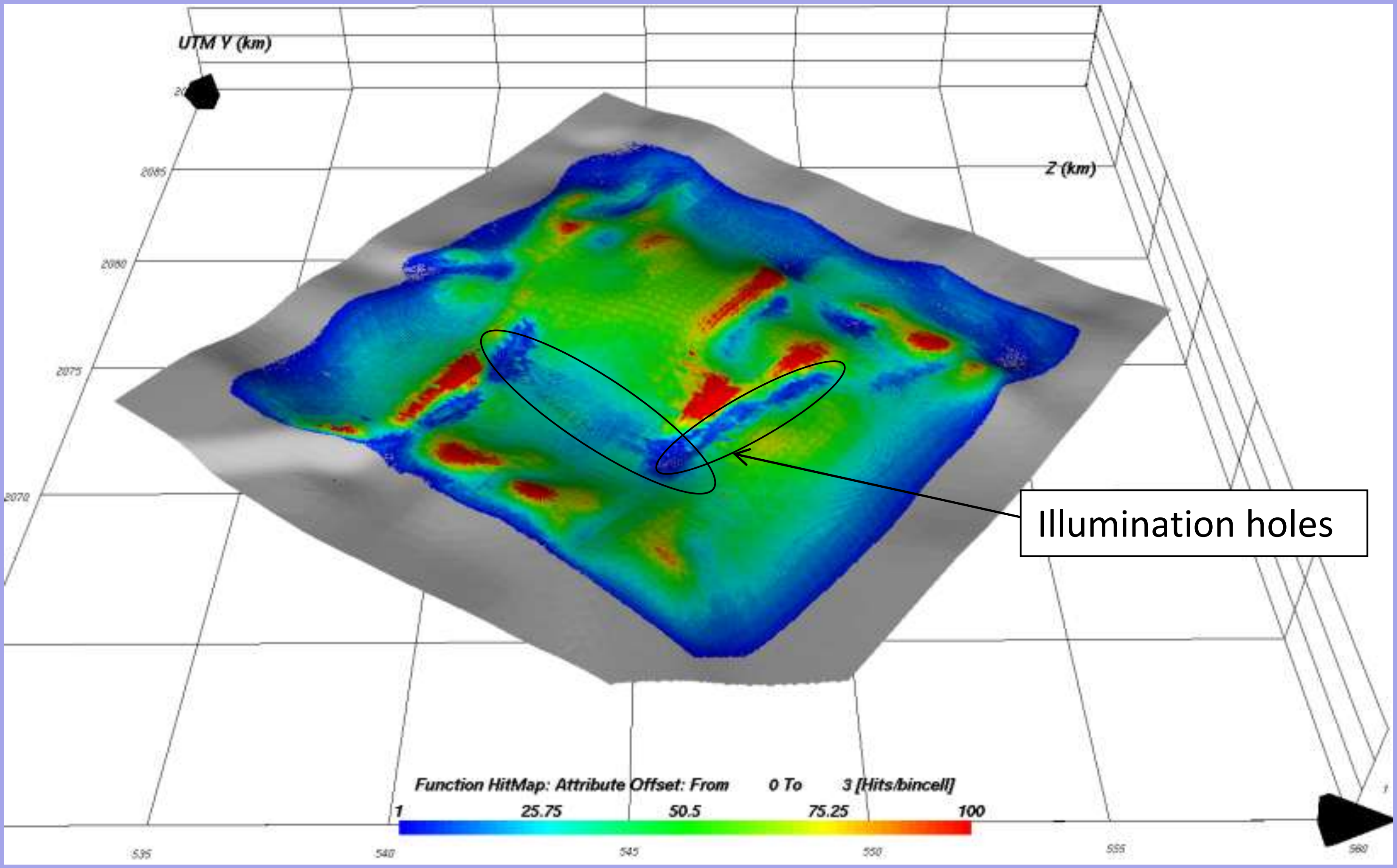
OBN Survey Design



Ray-tracing, P-to-S conversion

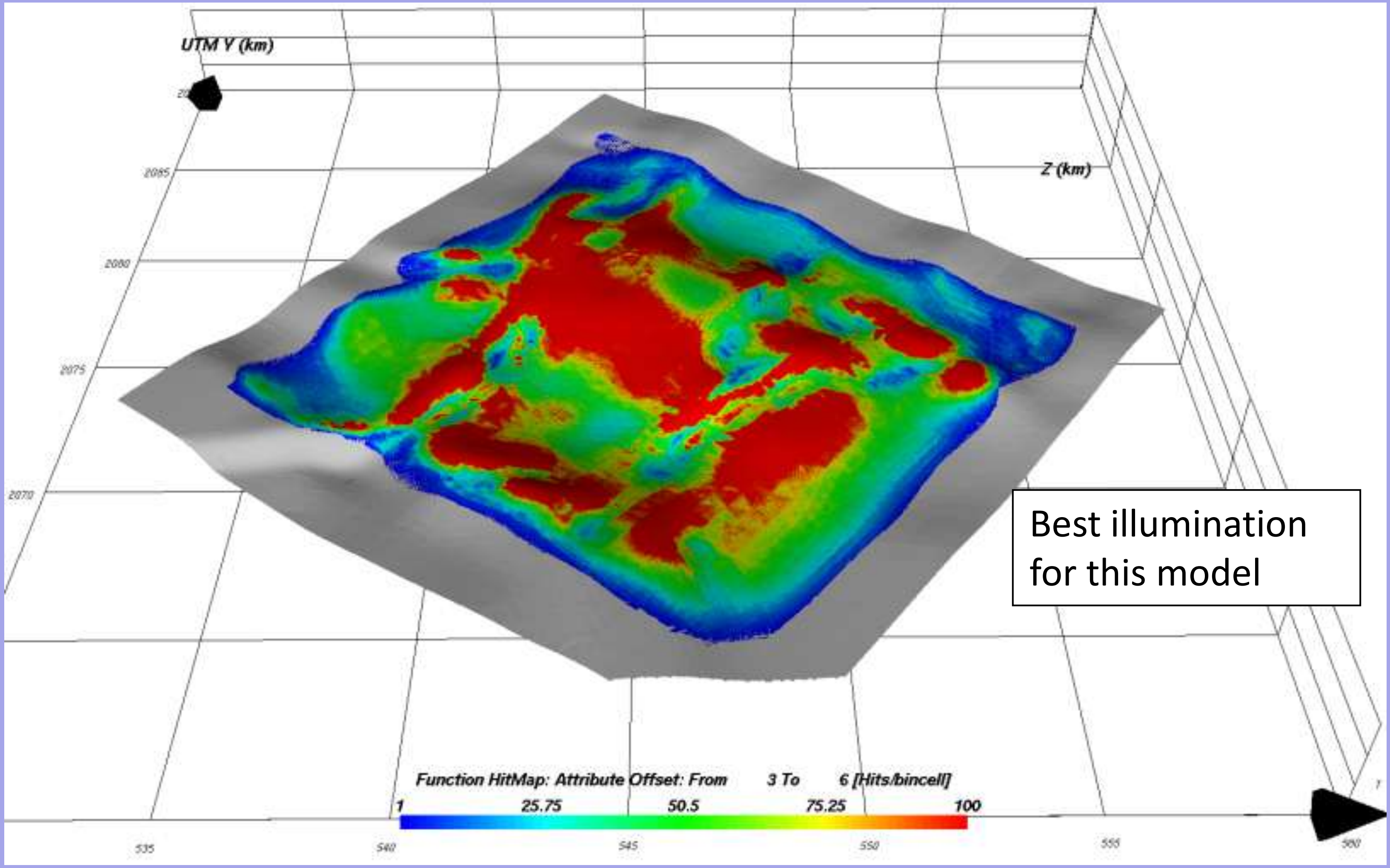
OBN Survey Design

PP illumination – **Near to mid offsets 0-3km**



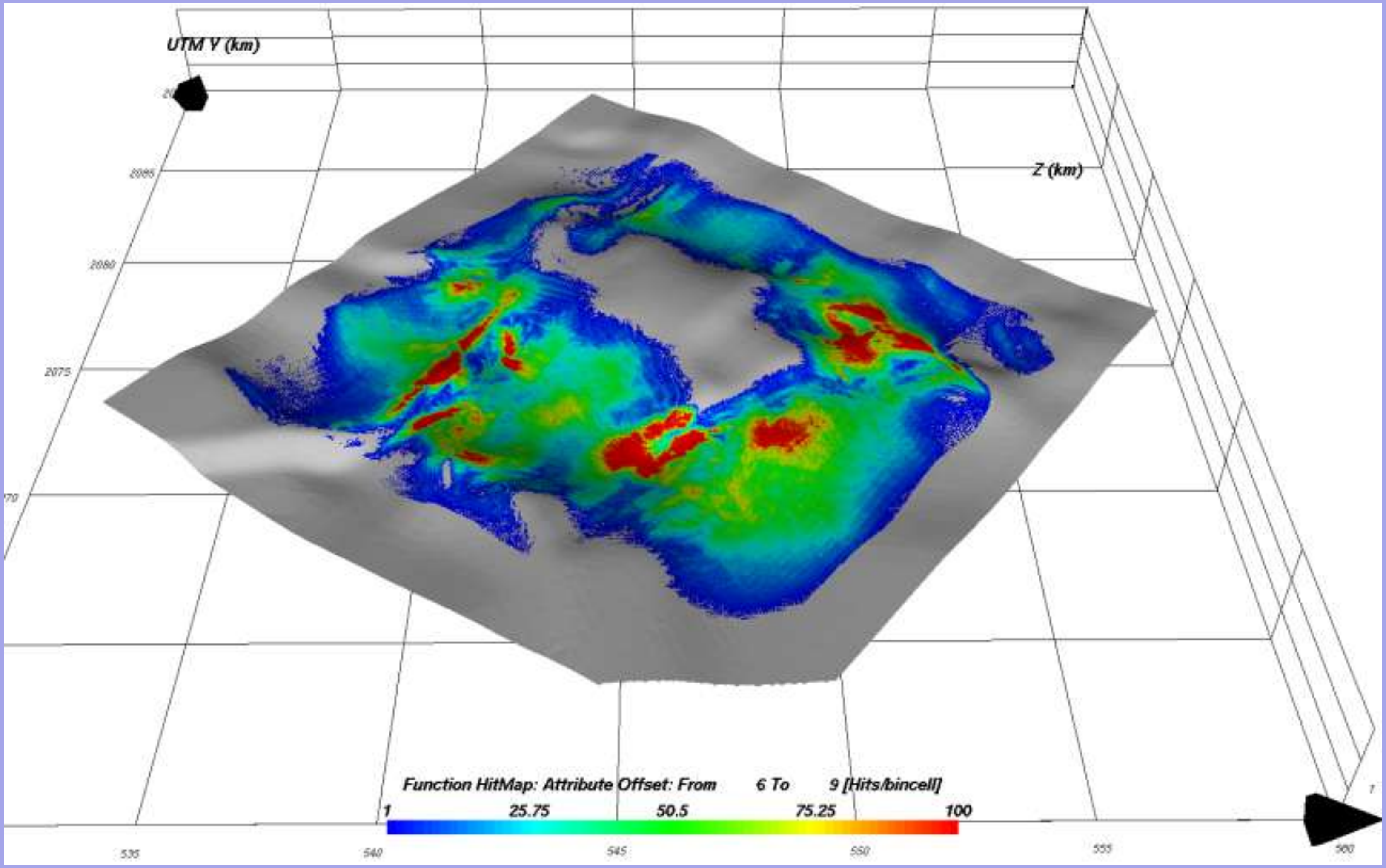
OBN Survey Design

PP illumination – **Mid to far offsets 3-6km**



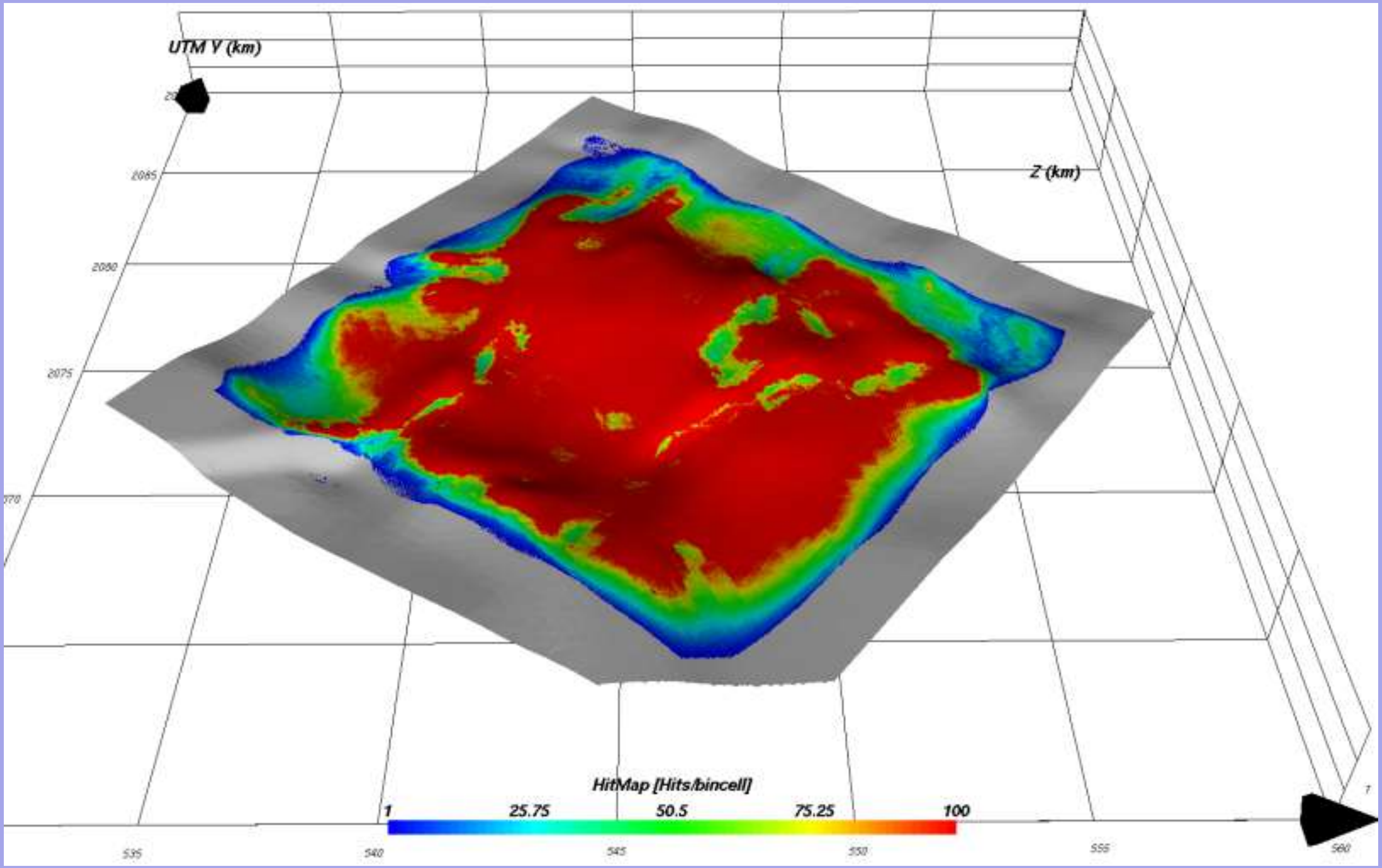
OBN Survey Design

PP illumination – **Very far offsets 6-9km**



OBN Survey Design

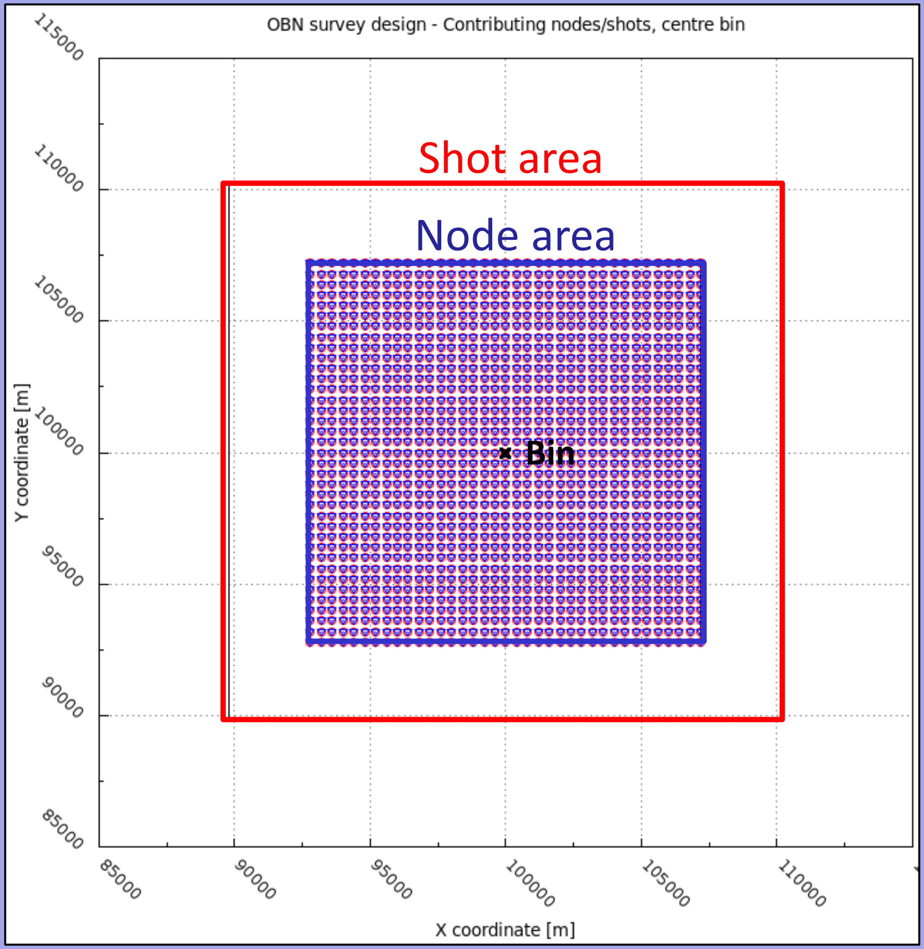
PP illumination – **All offsets (0-9km)**



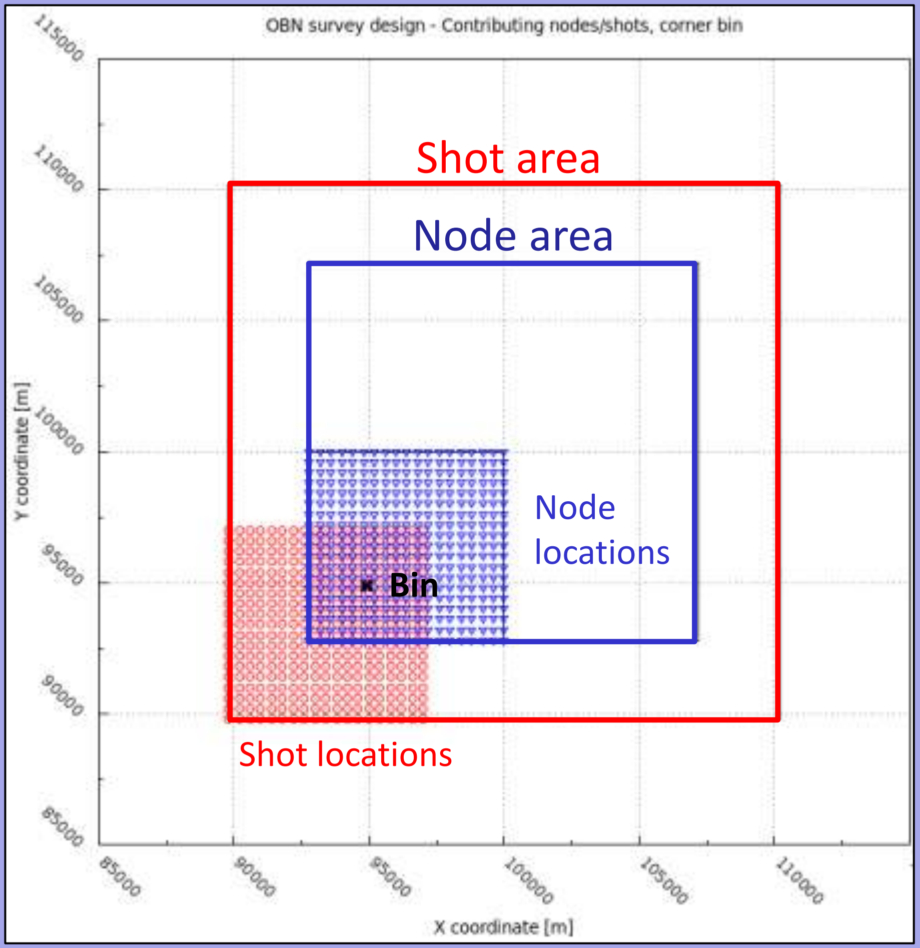
OBN Survey Design

Contributing receivers/shots for two example bins:

Centre bin



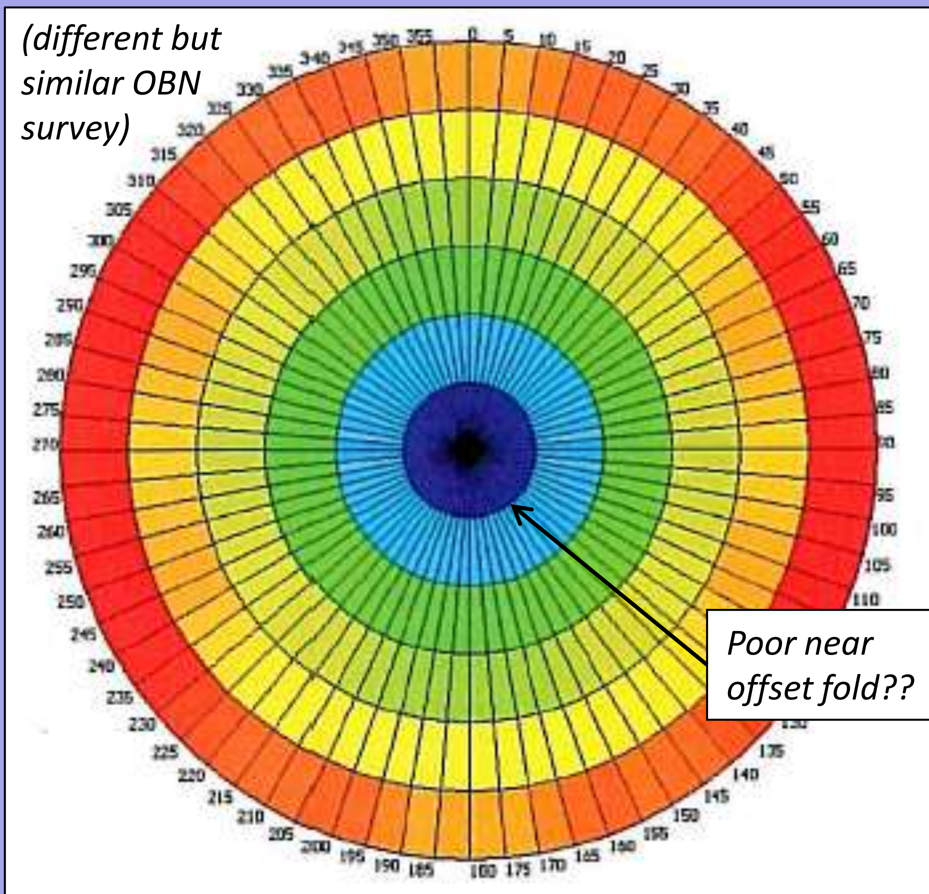
Corner bin



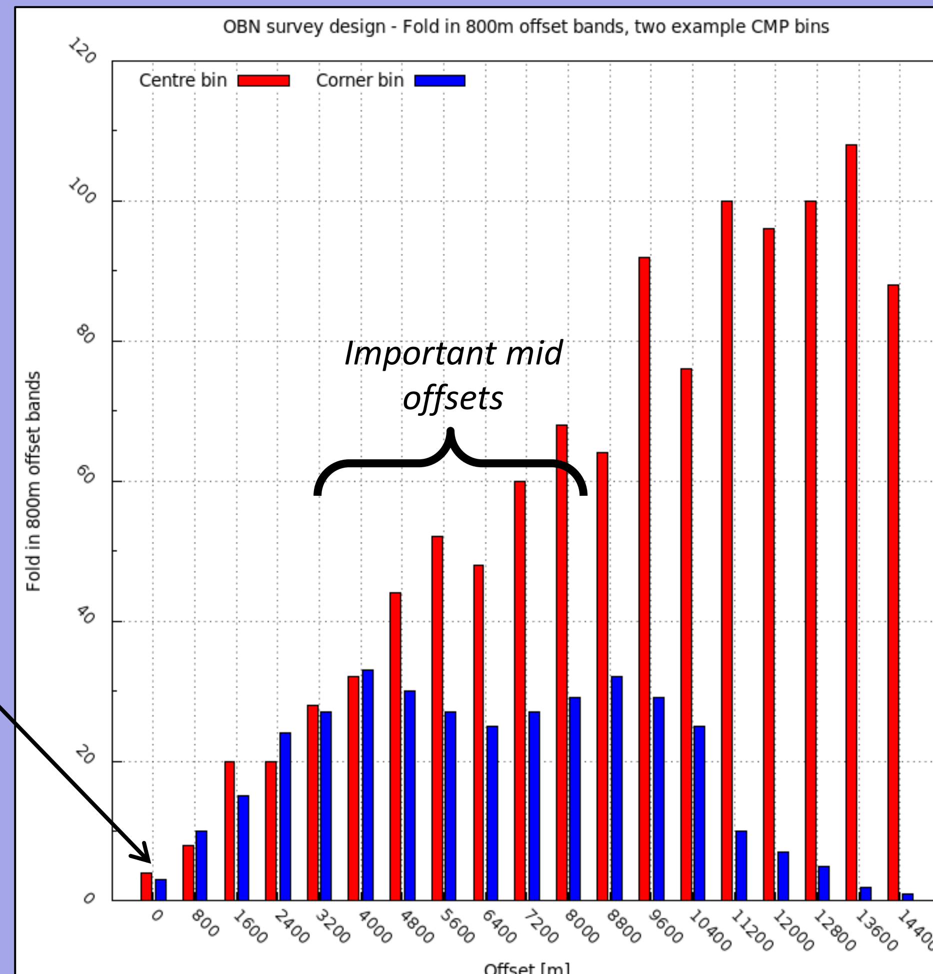
OBN Survey Design

In traditional azimuth and offset diagrams, OBN survey seems to have poor near offset fold.

Rose diagram – Azimuth-offset fold



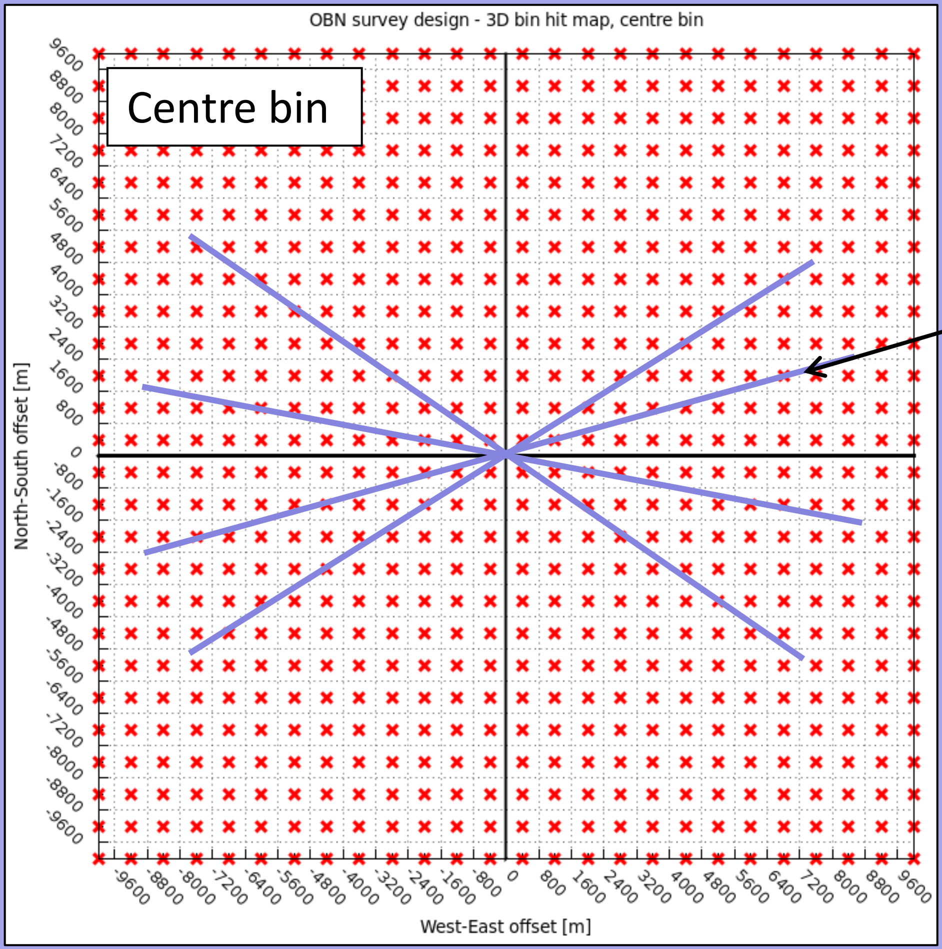
Offset fold for two example bins



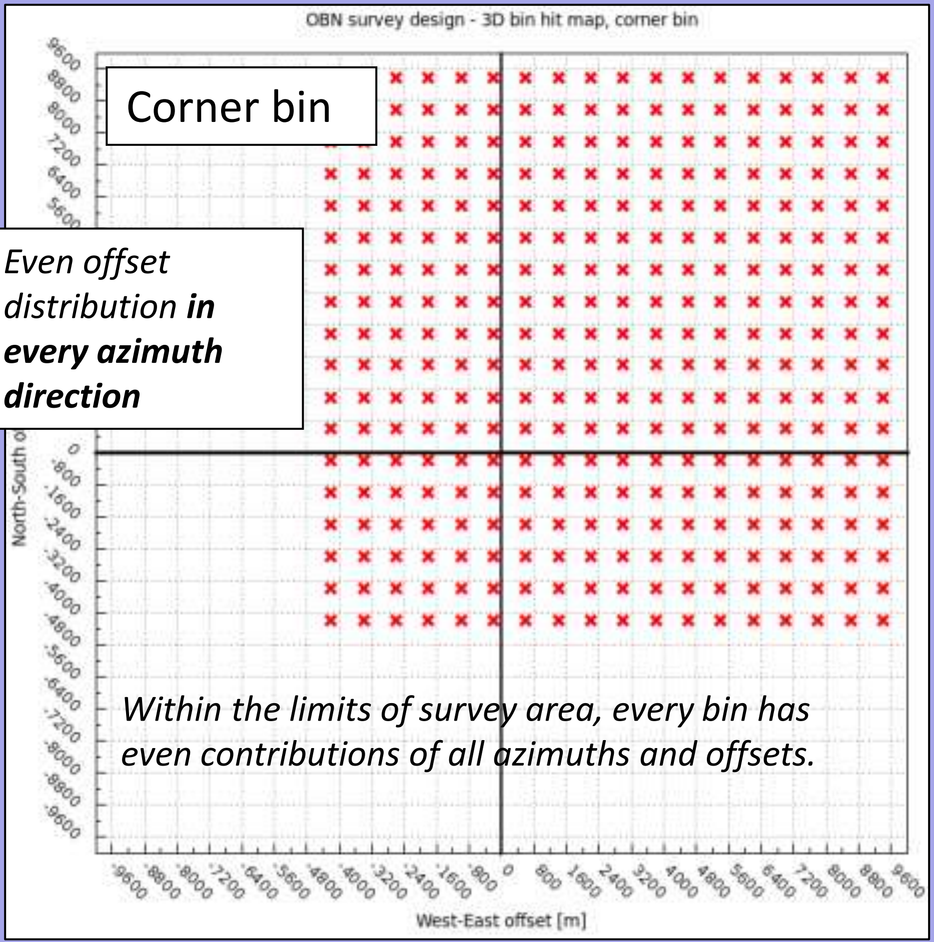
OBN Survey Design

OBN offset/azimuth fold is best viewed in so-called "common-offset vector tiles".

For any CMP bin, contributing shot-receiver pairs are evenly distributed on a regular offset/azimuth grid. → Pre-stack migration is best performed in common offset vector tiles.



Even offset distribution ***in every azimuth direction***



Within the limits of survey area, every bin has even contributions of all azimuths and offsets.

OBN Acquisition

Node Positioning

Node Positioning – Systems

Standard sub-sea positioning systems

- USBL – Ultra Short Baseline
  - Vessel based transceiver acoustically interrogates remote beacon to determine a range/bearing and computes relative position from vessel GPS. Average accuracy is a function of water depth/slant range.

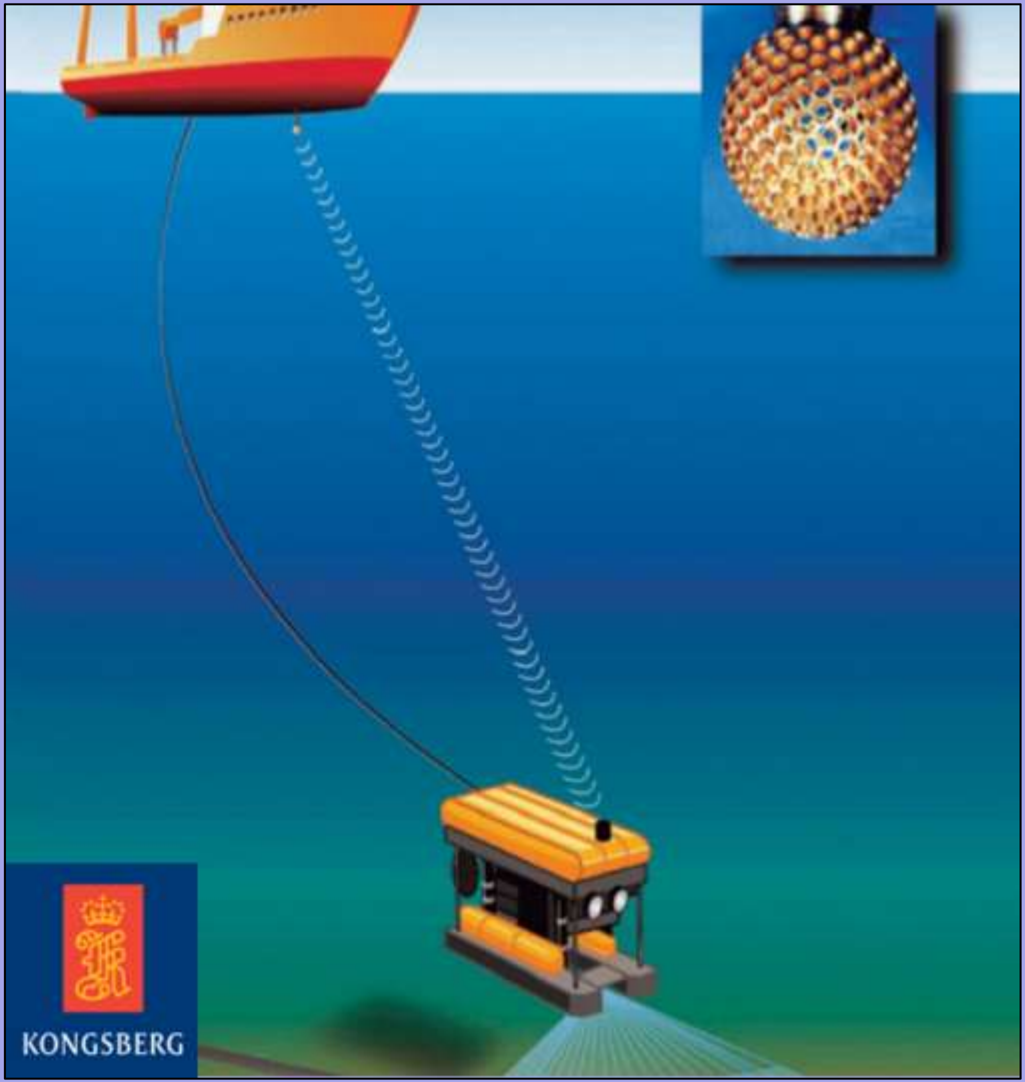
- INS – Inertial Navigation System
  - Comprised of Inertial Measurement Unit (IMU) and software Kalman filter. IMU senses motion and direction, with Kalman filter, to maintain accuracy away from control points.

- LBL – Long Baseline
  - Comprised of an array of N transponder beacons placed at the seafloor which are calibrated in a relative manner. Unambiguous fix requires at least 3 ranges. Independent of depth.
  - Costly and time consuming operation

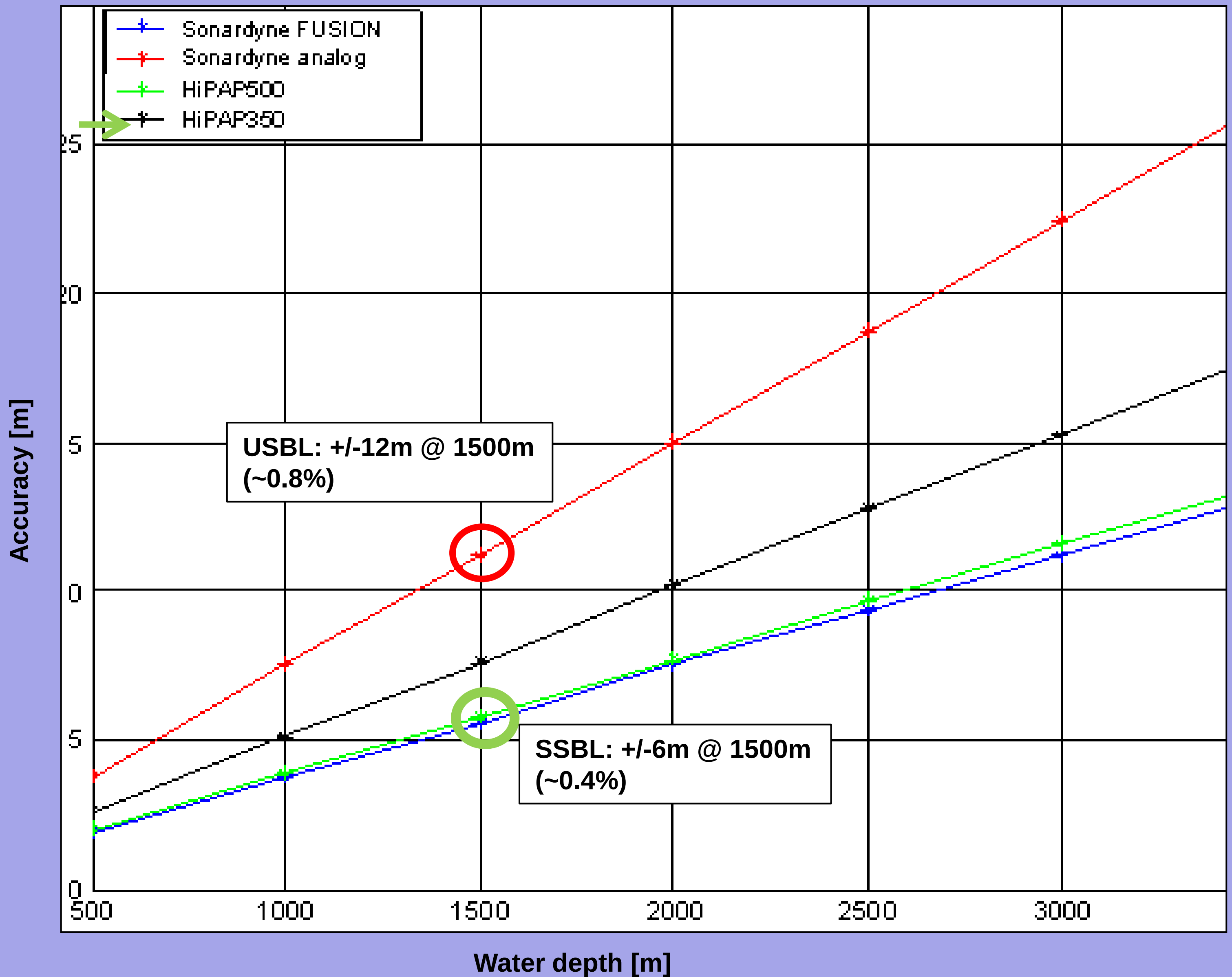
Node Positioning – Systems

High-fidelity sub-sea positioning system

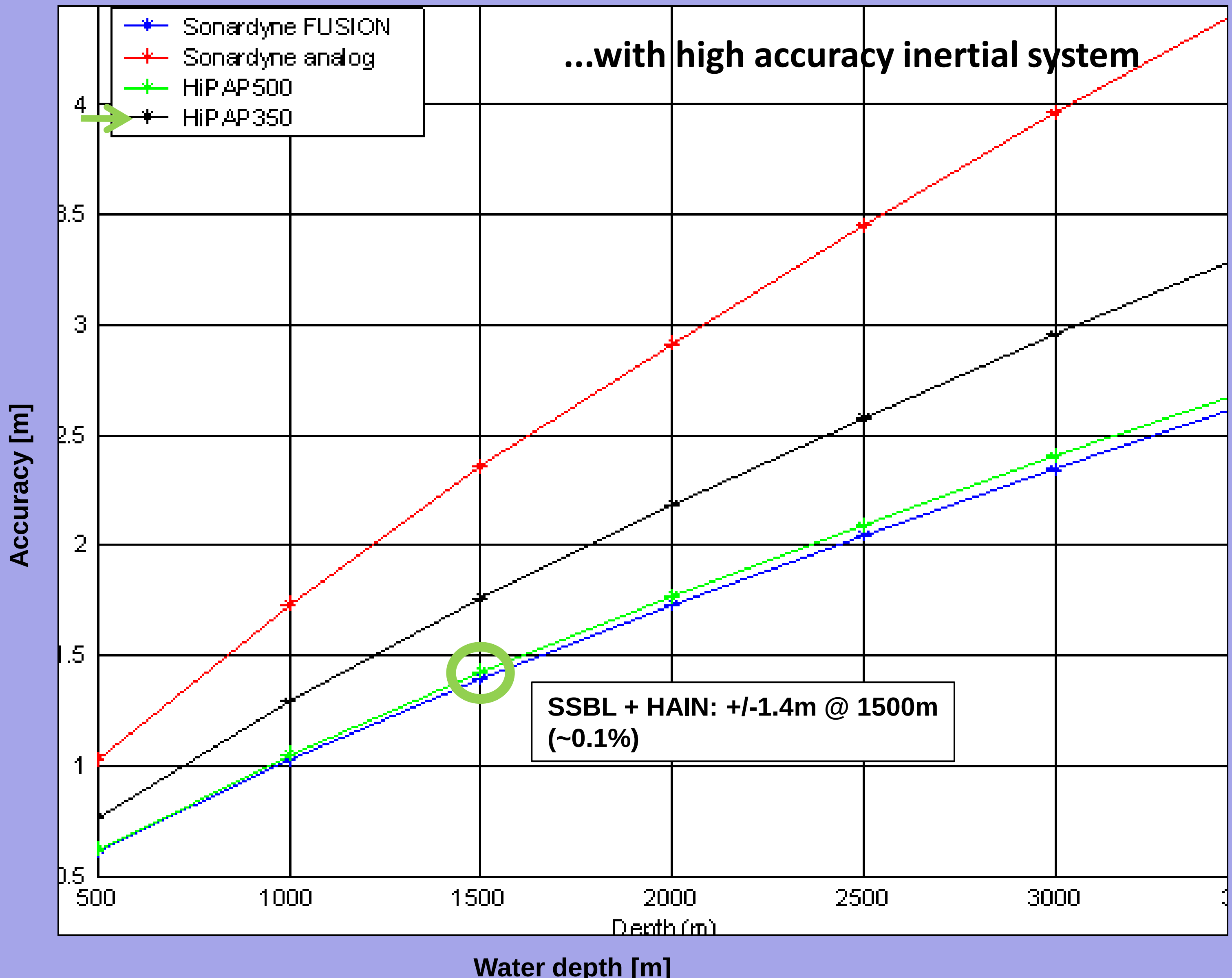
- HiPAP & SSBL
  - High Precision Acoustic Positioning using Super Short Baseline
  - Hull mounted unit & ROV transducers
- HAIN
  - Hydro-acoustic Aided Inertial Navigation System
  - Inertial Measurement Unit (3 gyro compasses & 3 accelerometers)
  - Doppler Velocity Log (ROV speed)
  - Pressure & heading sensor
  - Kalman software filter



Node Positioning – Accuracy



Node Positioning – Accuracy

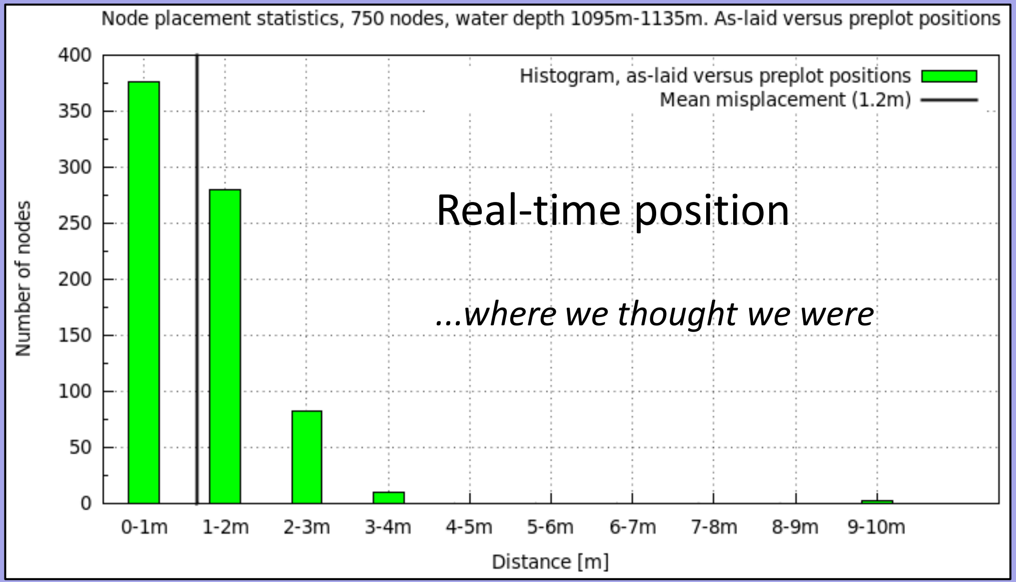


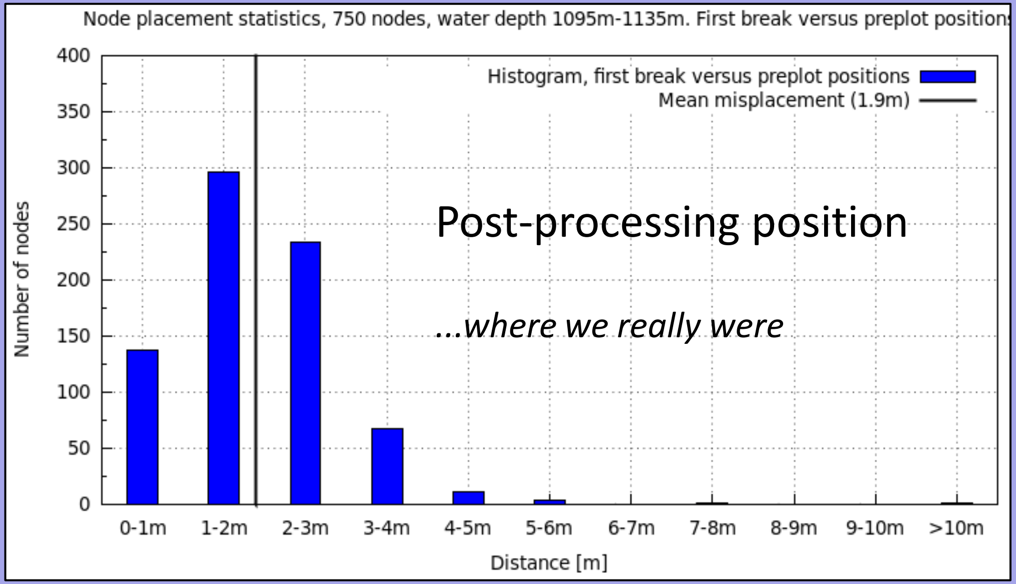
Node Positioning – Accuracy

Real OBN survey #1:

- 750 nodes
- Water depth 1095m-1135m
- Mean misplacement of
  - 1.2m (real-time)
  - 1.9m (first break solution)

- → 0.2% of water depth



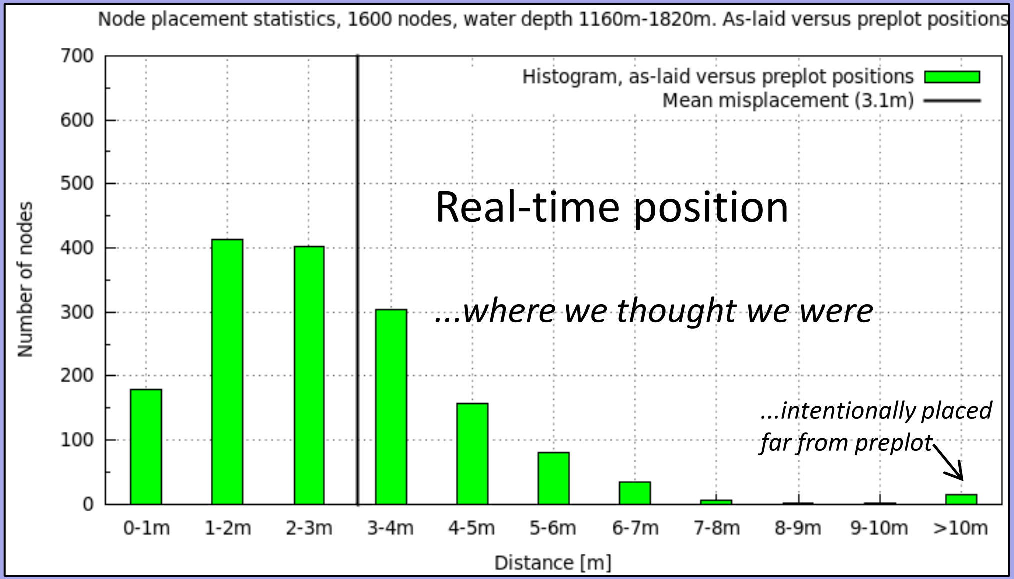


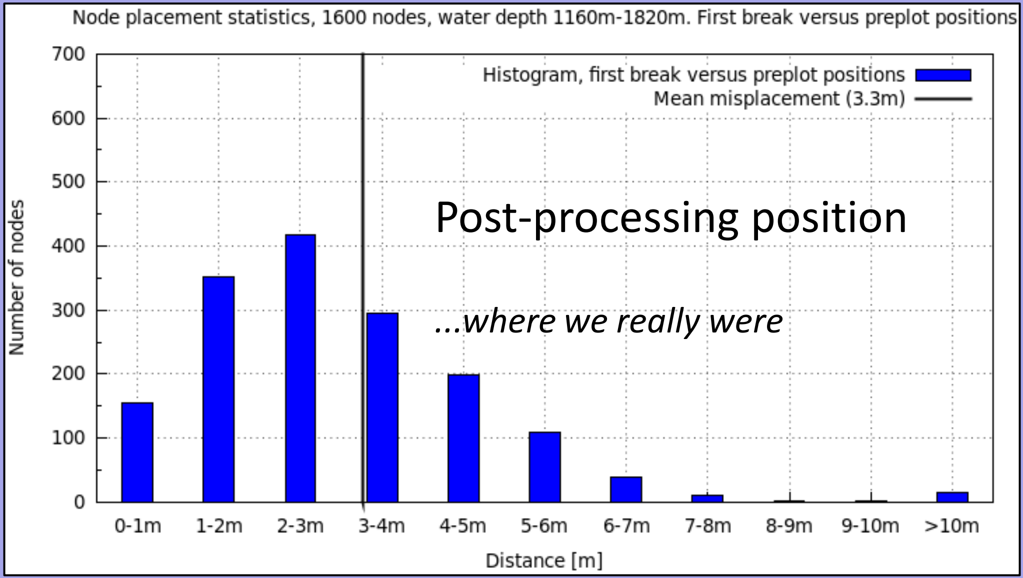
Node Positioning – Accuracy

Real OBN survey #2:

- 1600 nodes
- Water depth 1160m-1820m
- Mean misplacement of
  - 3.1m (real-time)
  - 3.3m (first break solution)

- → 0.3% of water depth



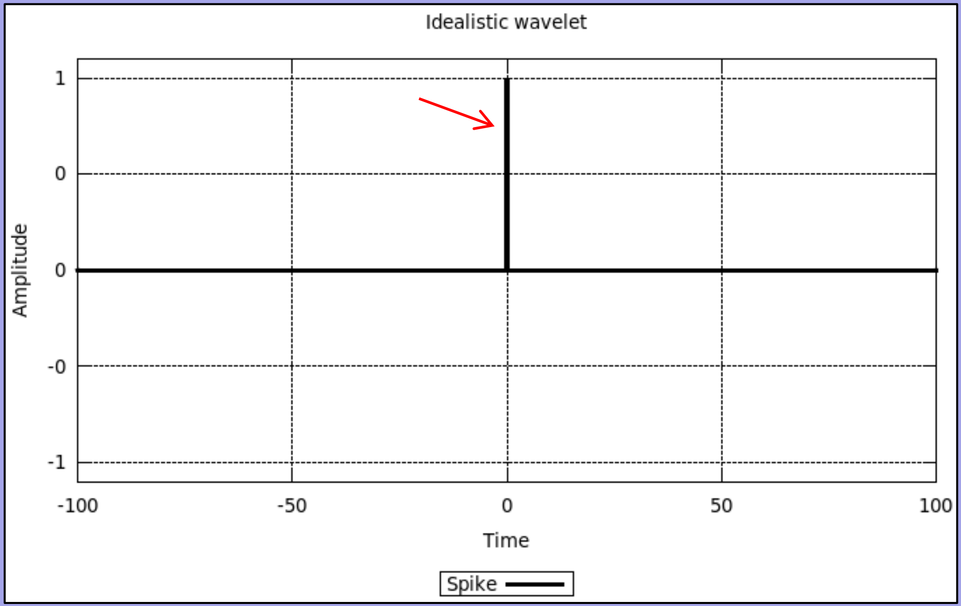


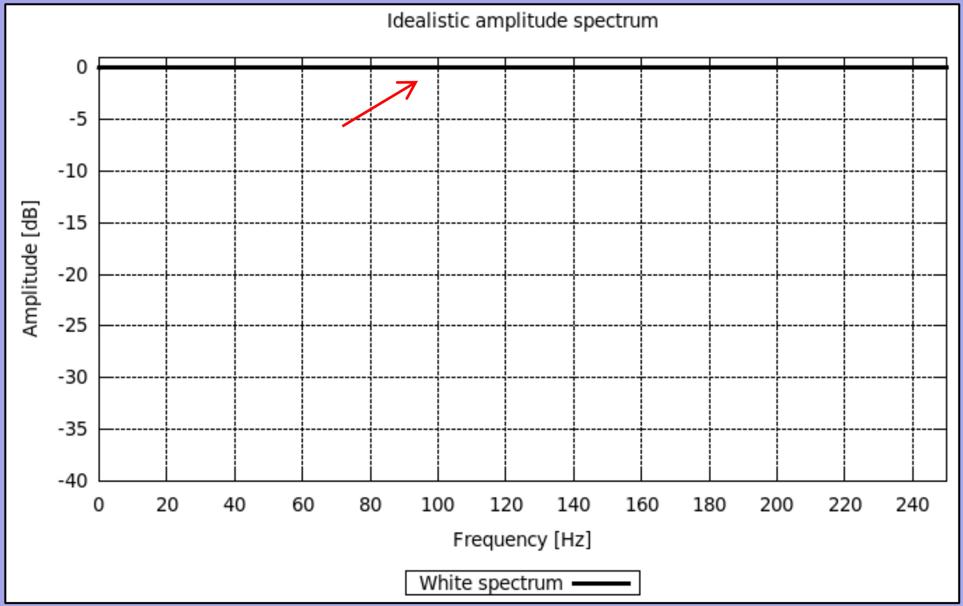
OBN Acquisition

Source Signature & Sensor Responses

- What is put into the ground and what is recorded
- How to boost low frequency energy to give broad band seismic

Ideal source wavelet & recording transfer function

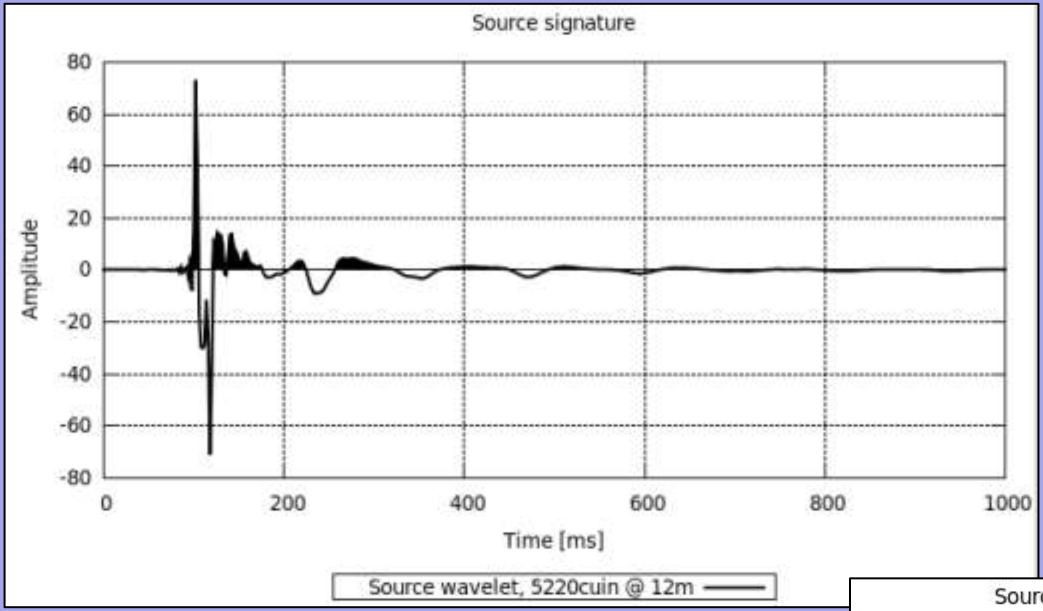




On the source side, what we really want is to generate an energy spike which is then convolved by the earth's reflectivity series.

On the receiver side, what we really want is to record the arriving wave field without distortion or filtering, i.e. with a white transfer function.

Real source signature

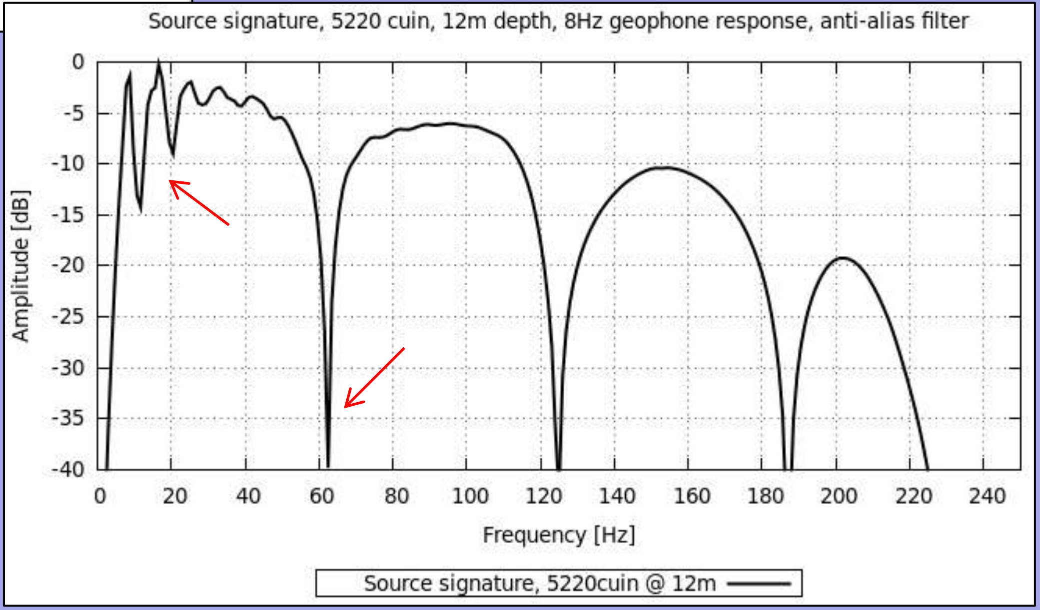


Real source wavelet

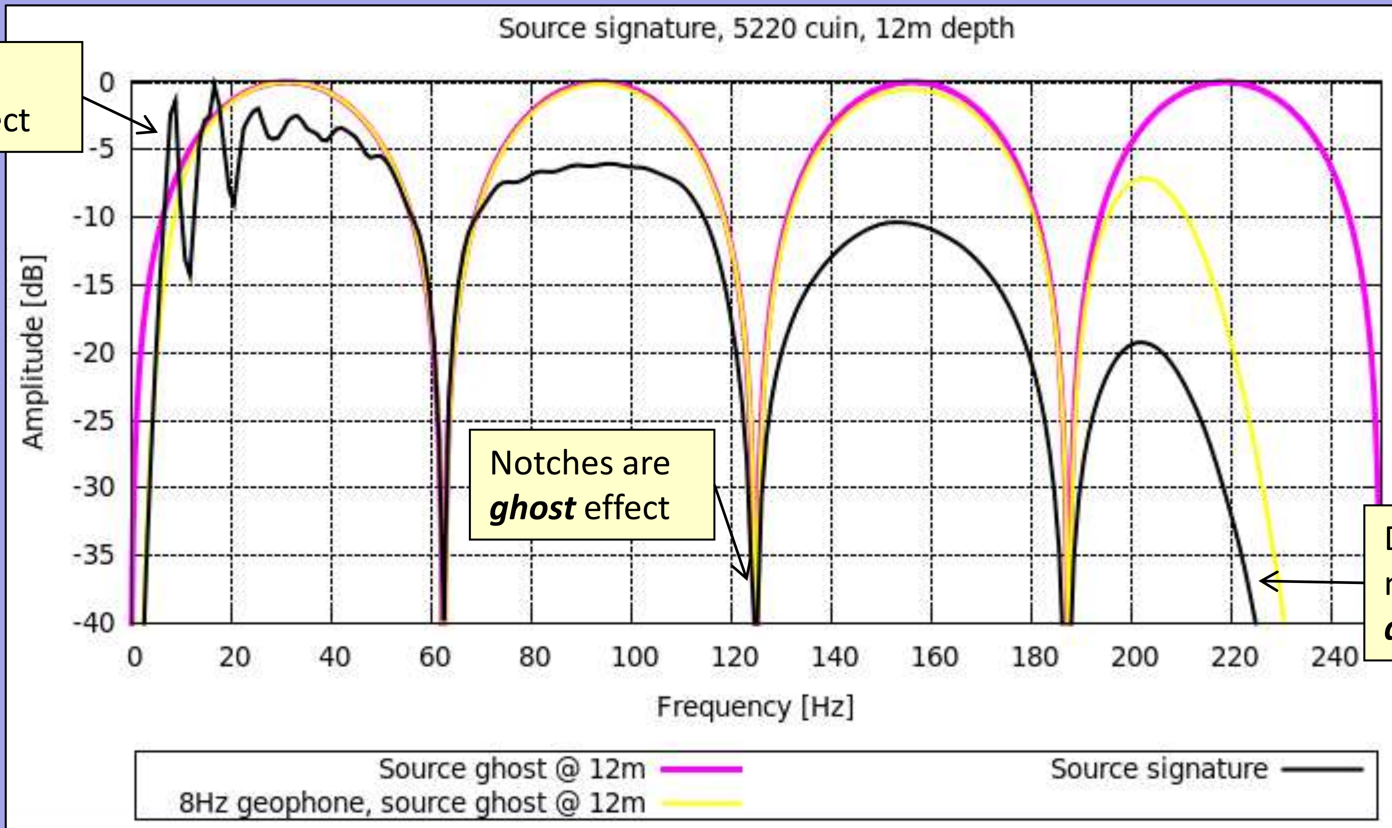
- Band limited
- Low frequency reverberations from air bubble and source ghost

Real source spectrum

- Band limited due to source output, anti-alias filter and sensor reponse
- Ripples at low end due to air bubble
- Regularly spaced notches due to surface source ghost



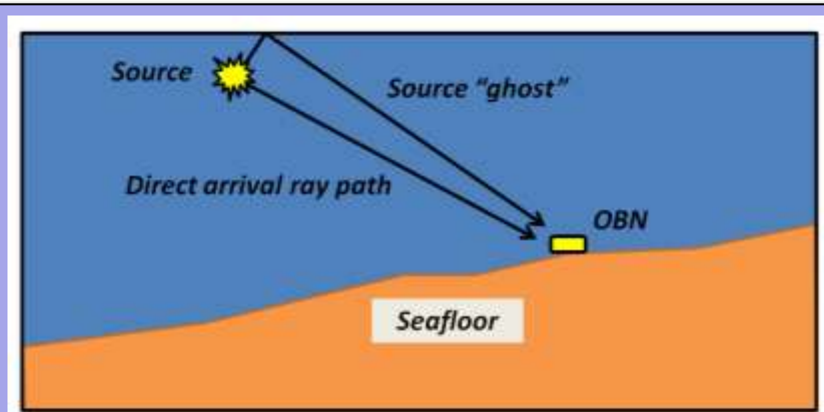
Source signature, vertical incidence



Ripples are ***bubble*** effect

Notches are ***ghost*** effect

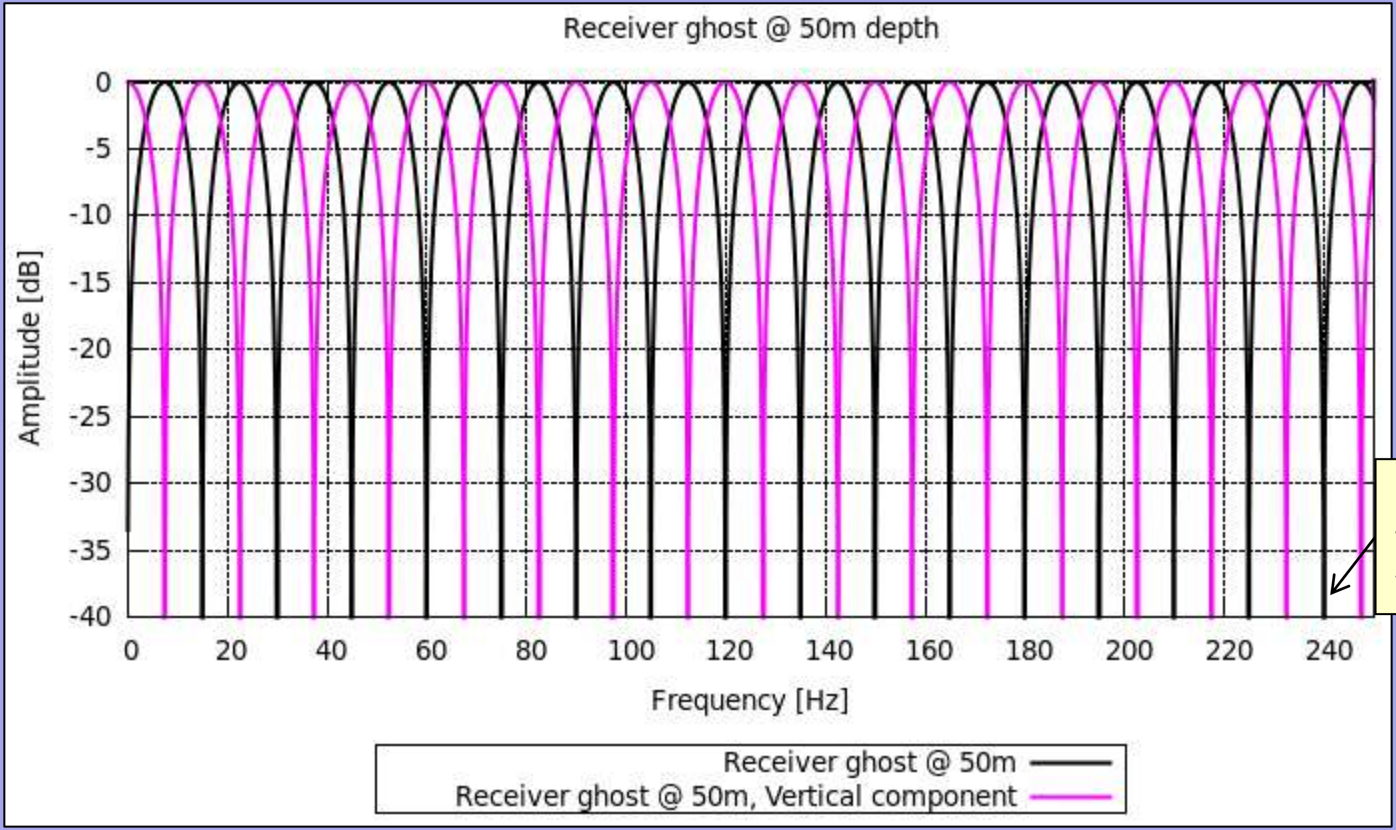
Decay is both natural and due to ***anti-alias filter***



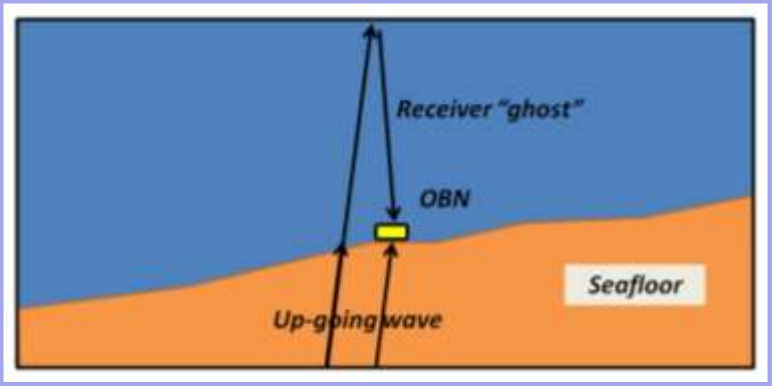
$$n \lambda_{notch} = 2 z_{source} \quad , n = 0, 1, 2 \ldots$$

$$f_{notch} = \frac{v_{water}}{\lambda_{notch}} = \frac{n v_{water}}{2 z_{source}}$$

Receiver ghost, vertical incidence



Opposite notches for pressure & vertical sensor



Vertical sensor:

$$n_v \lambda_{v,notch} = 2 z_{source} \quad , n_v = \frac{1}{2}, \frac{3}{2} \ldots$$

$$f_{v,notch} = \frac{v_{water}}{\lambda_{v,notch}} = \frac{n_v v_{water}}{2 z_{source}}$$

Sensor response/source signature wavelet

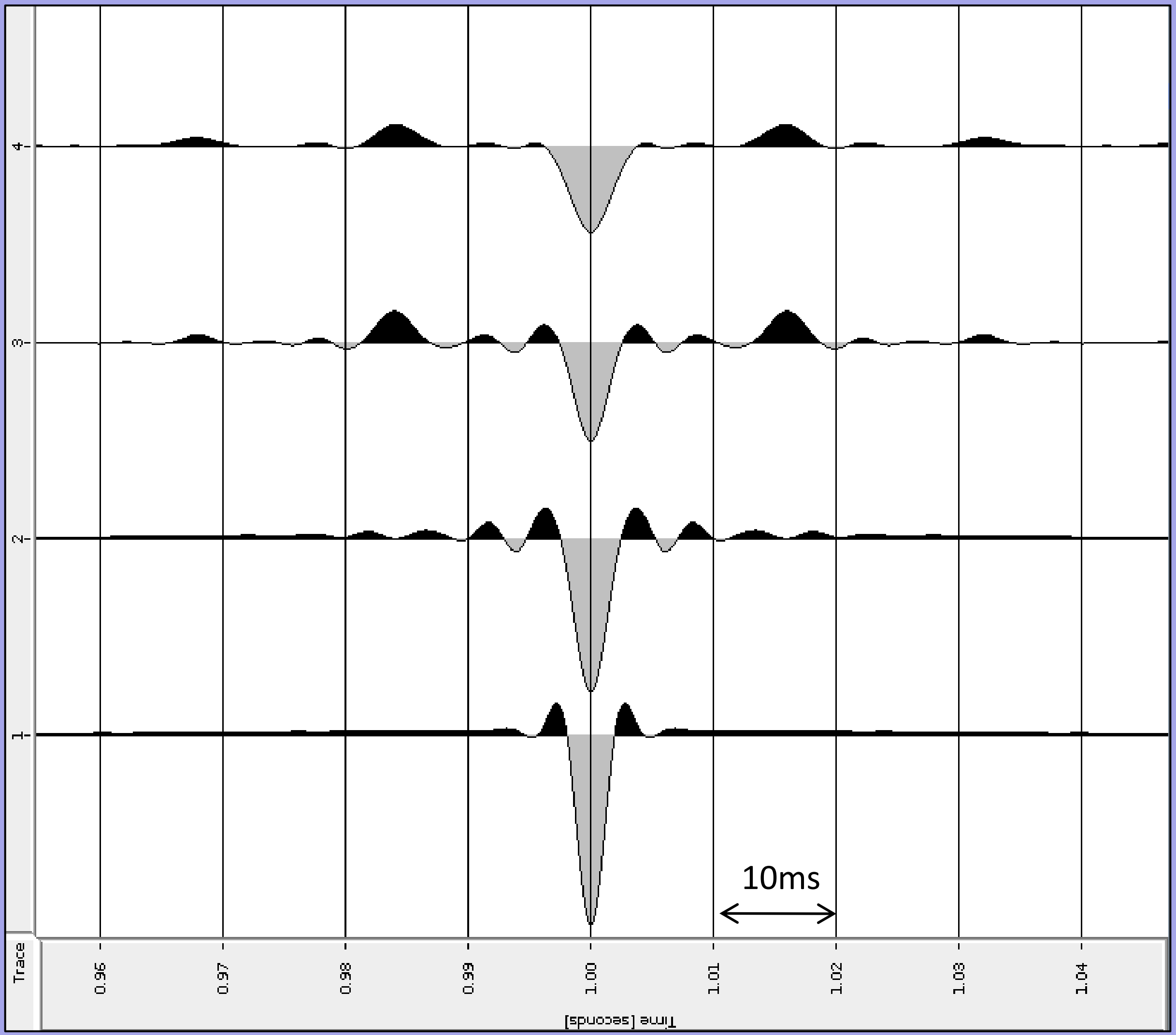
Zero-phase equivalent wavelets, vertical incidence

8Hz geoph., anti-alias, example source signature @ 12m

8Hz geophone, anti-alias, source ghost @ 12m

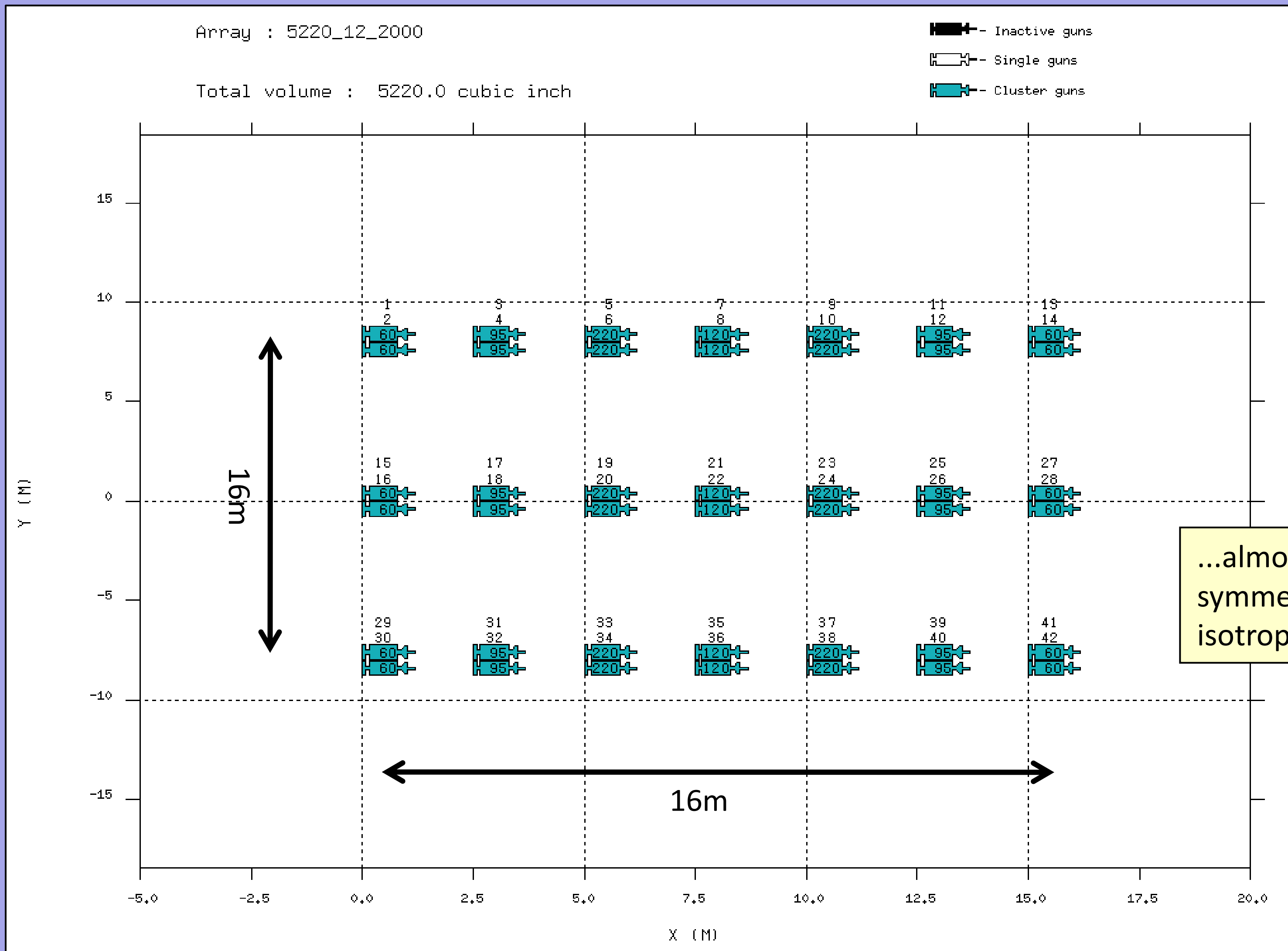
8Hz geophone, anti-alias

8Hz geophone



Seismic Airgun Source

Seismic source array layout:



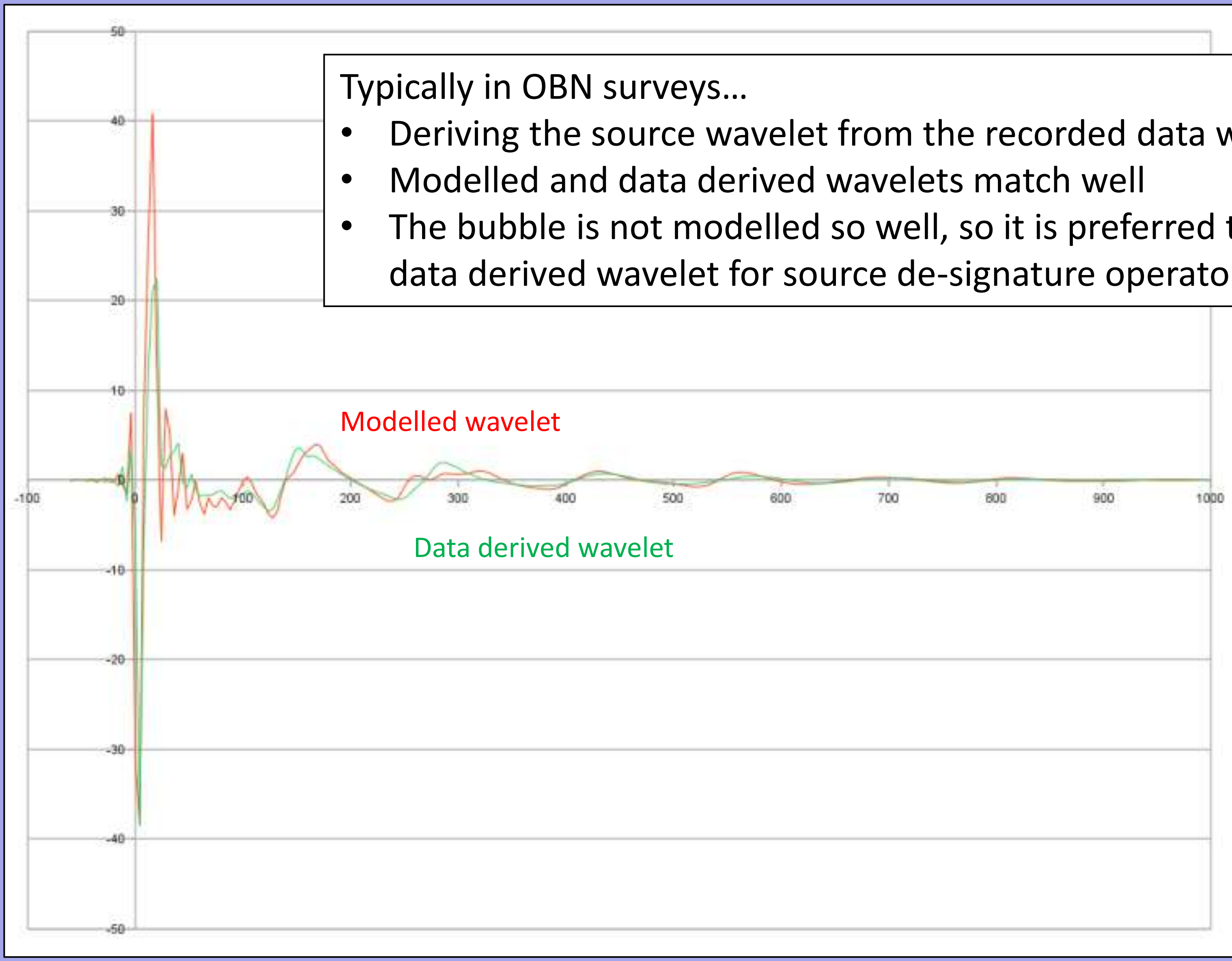
...almost fully symmetrical → isotropic response

Source Signature Processing

In data processing we will try to compress the recorded seismic wavelet as much as possible, equivalent to flattening/whitening of the spectrum.

- Care needs to be taken to avoid boosting noise in ghost notches
- De-bubble operator to remove bubble oscillations
- Full source de-signature operator
- Modelled versus data derived source signature wavelet

Source Signature Processing

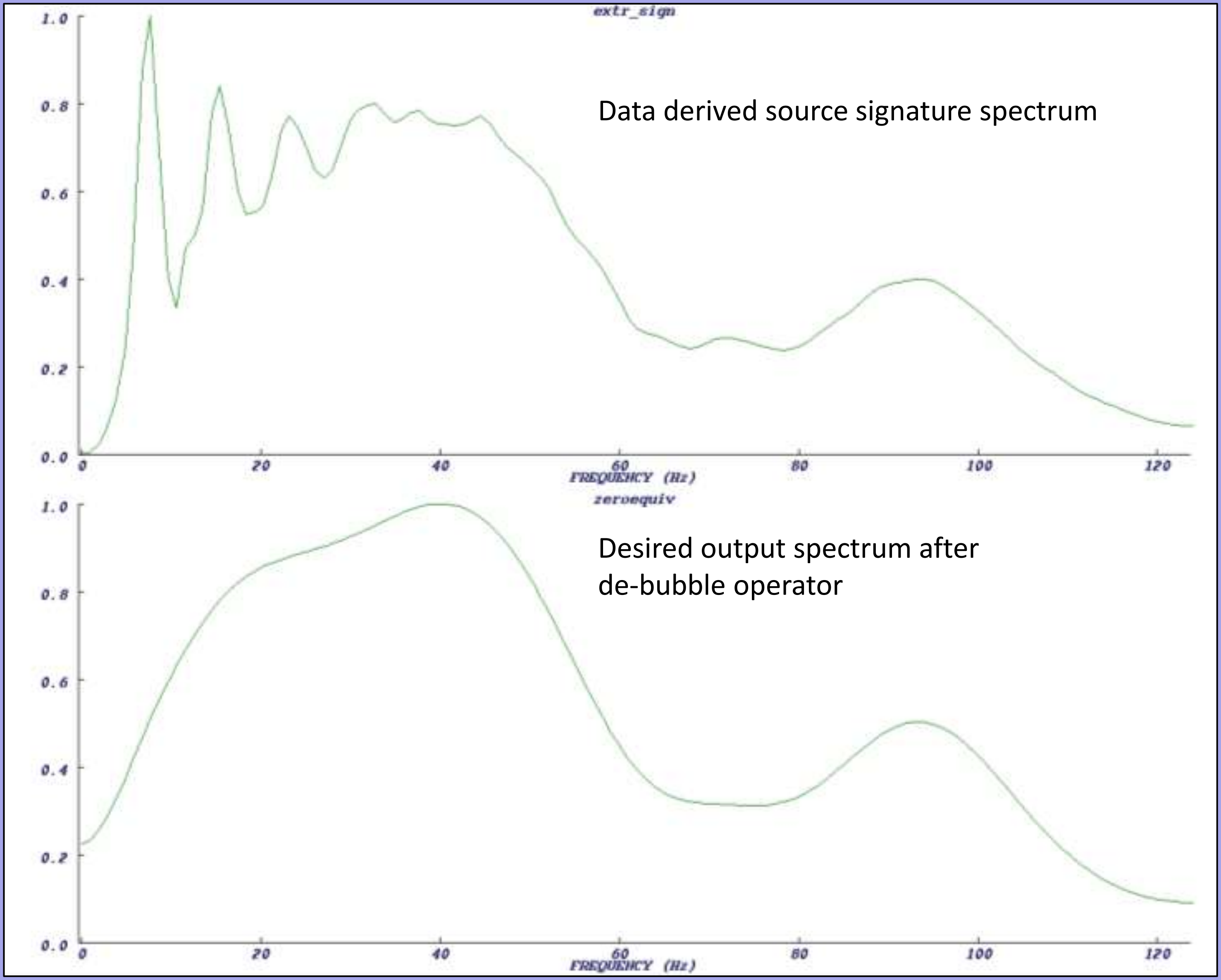


Typically in OBN surveys…

- Deriving the source wavelet from the recorded data works well
- Modelled and data derived wavelets match well
- The bubble is not modelled so well, so it is preferred to use the data derived wavelet for source de-signature operator design

Courtesy of Geokinetics

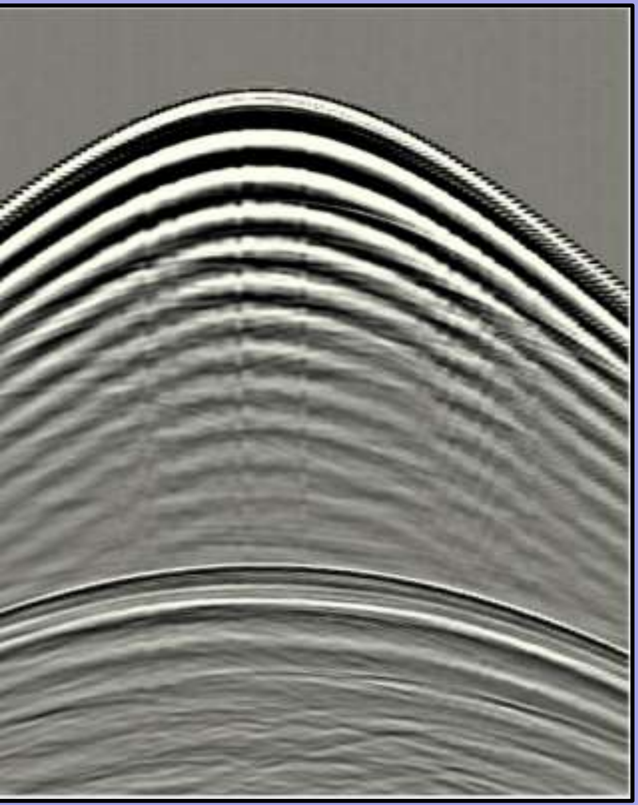
Source Signature Processing



Courtesy of Geokinetics

Source Signature Processing

Input data



De-bubble operator
Modelled signature

De-bubble operator
Data derived signature

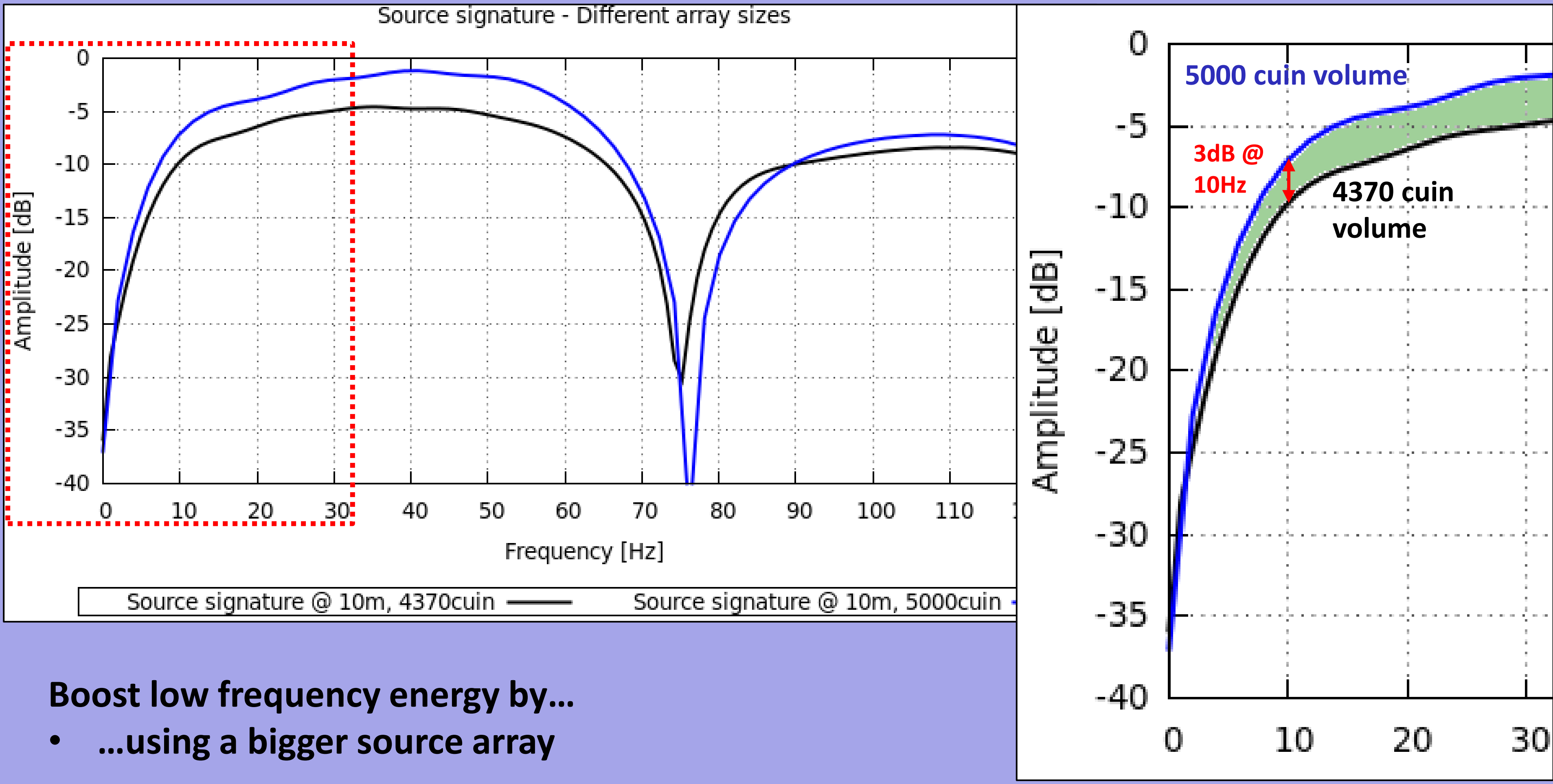
Courtesy of Geokinetics

Boosting low frequency energy

Why do we need low frequency information?

- Improved resolution from broad band seismic
- Deep, complex structural imaging, in particular:
  - Sub-salt imaging
  - Sub-basalt imaging
  - Generally, penetrating high velocity layers and rugose interfaces
- Velocity model building
- Inversion

Boosting low frequency energy (1)



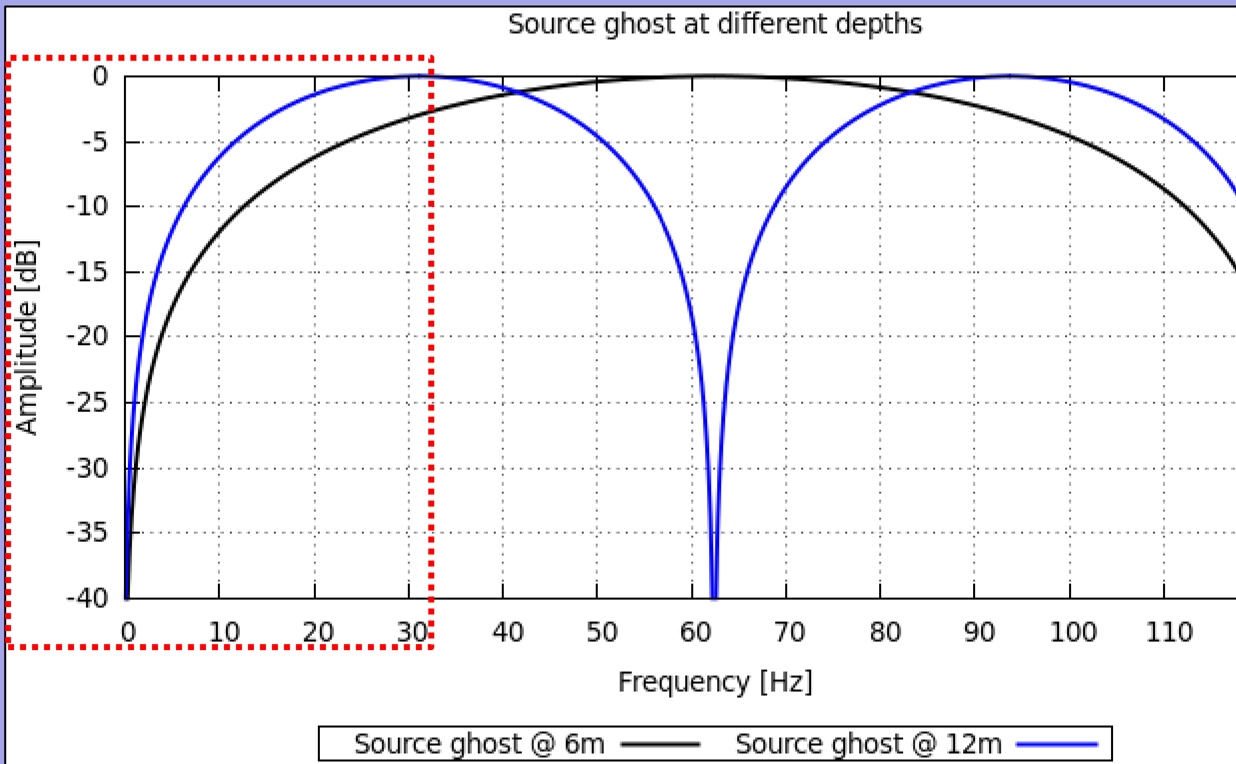
Boost low frequency energy by…

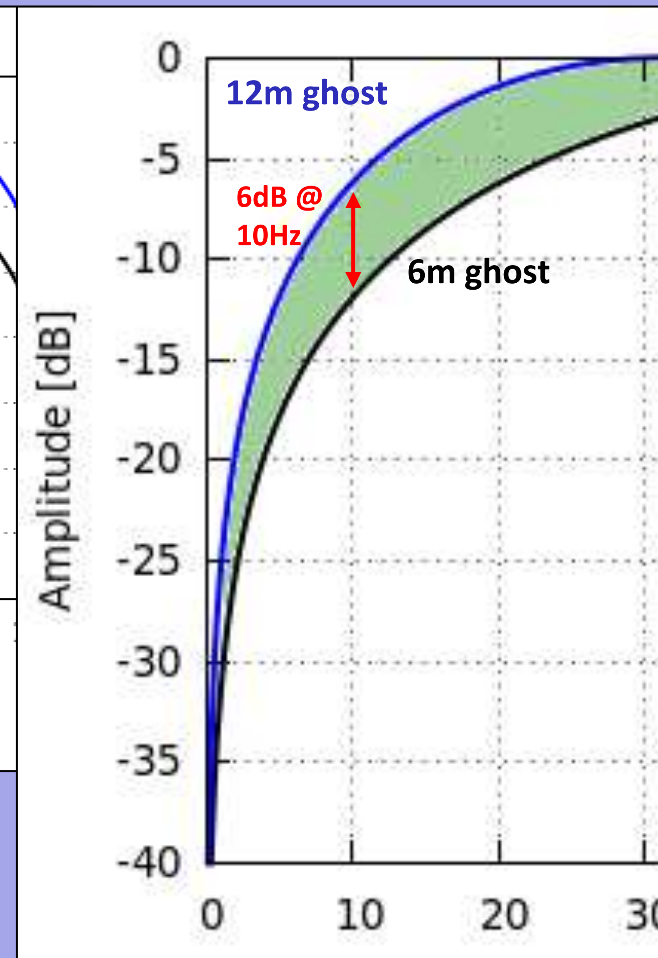
- **…using a bigger source array**

Downside

- *Limit to maximum source size, longer re-charge time, more shot generated noise*

Boosting low frequency energy (2)





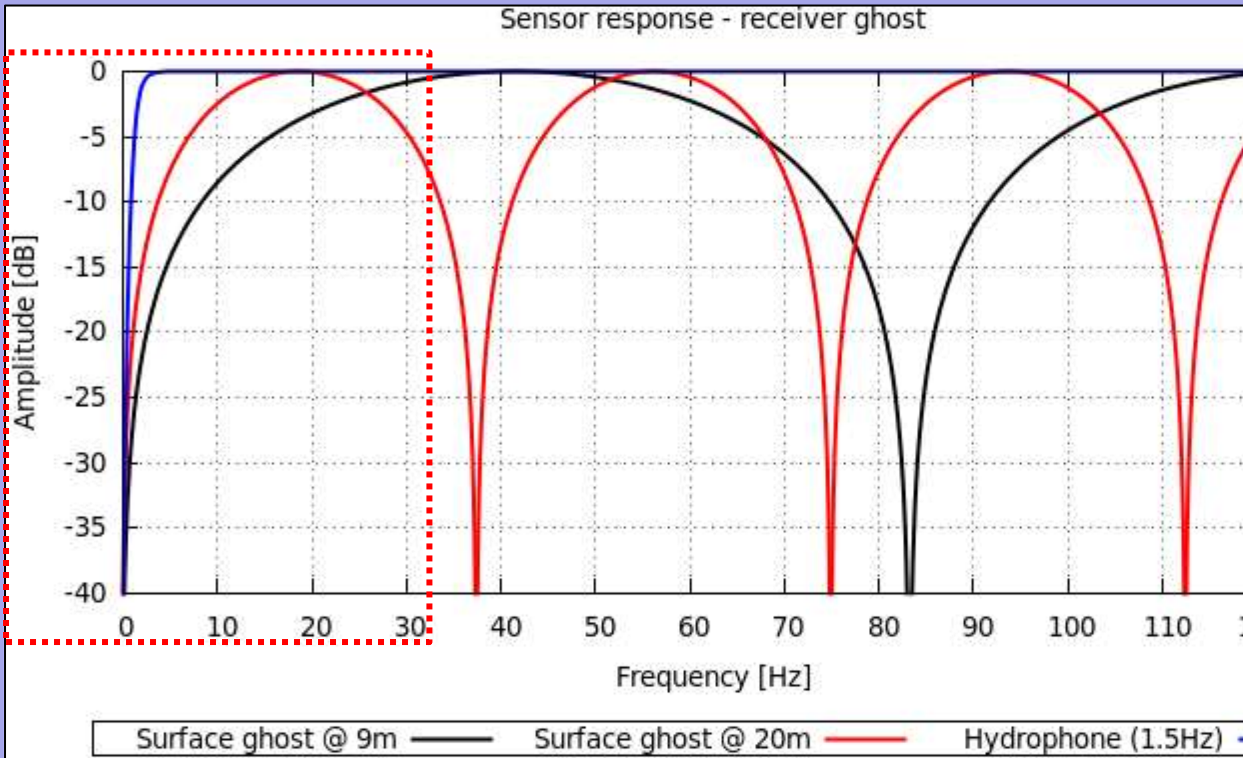
Boost low frequency energy by…

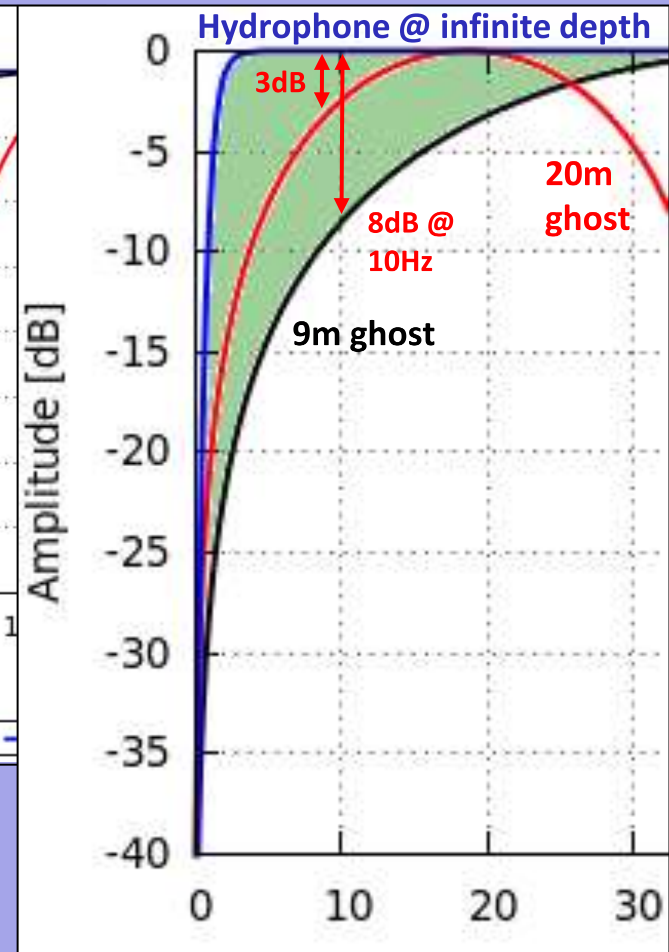
- **…towing source array deeper**

Downside

- *Introduces notch(es) within seismic signal band*

Boosting low frequency energy (3)





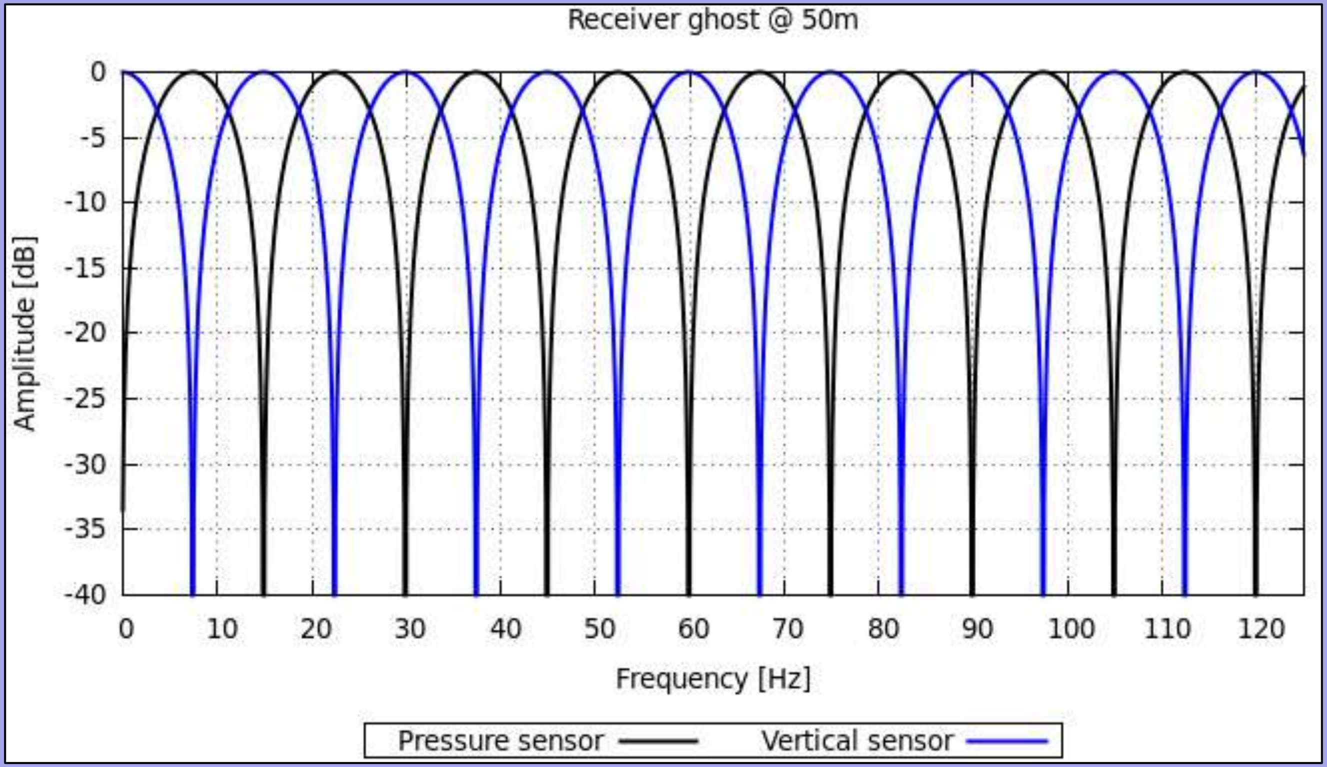
Boost low frequency energy by…

- **…placing sensors deeper, ideally at seabed**

Downside

- *Towed streamer, or OBS in very shallow water: Introduces notches within seismic signal band*

Boosting low frequency energy (4)

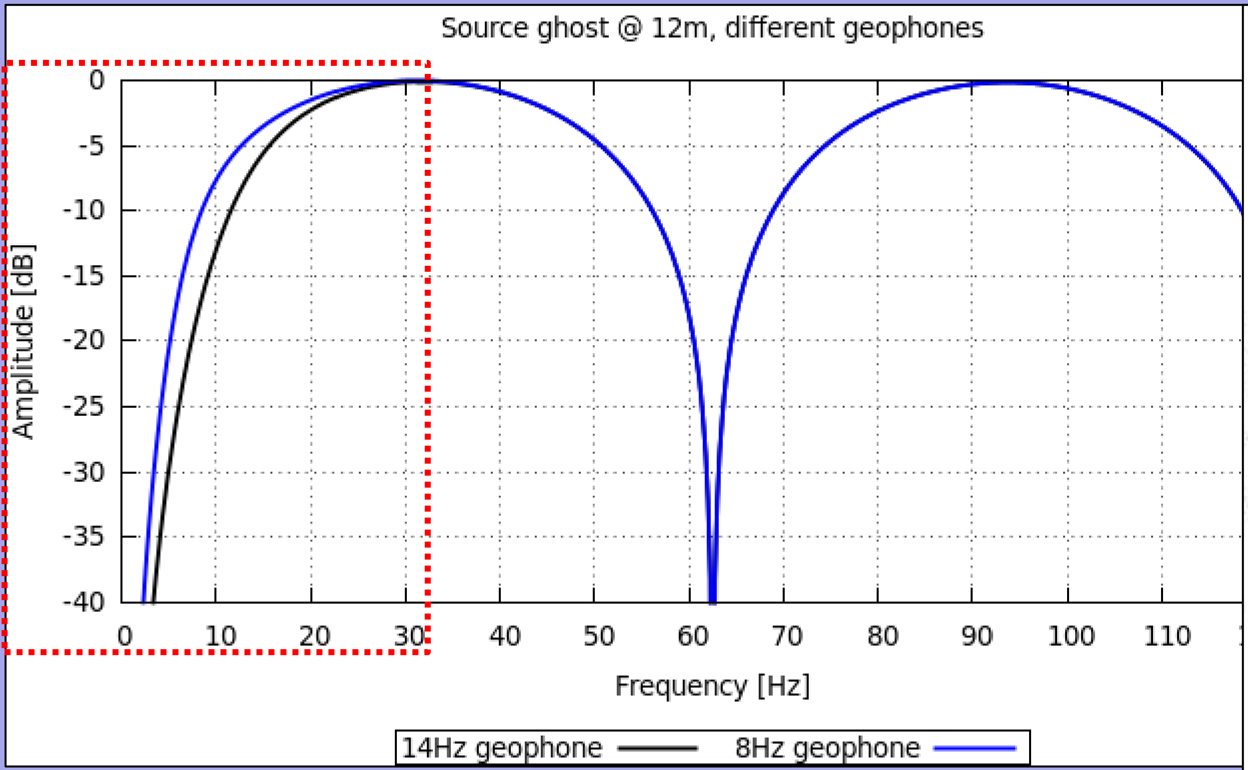


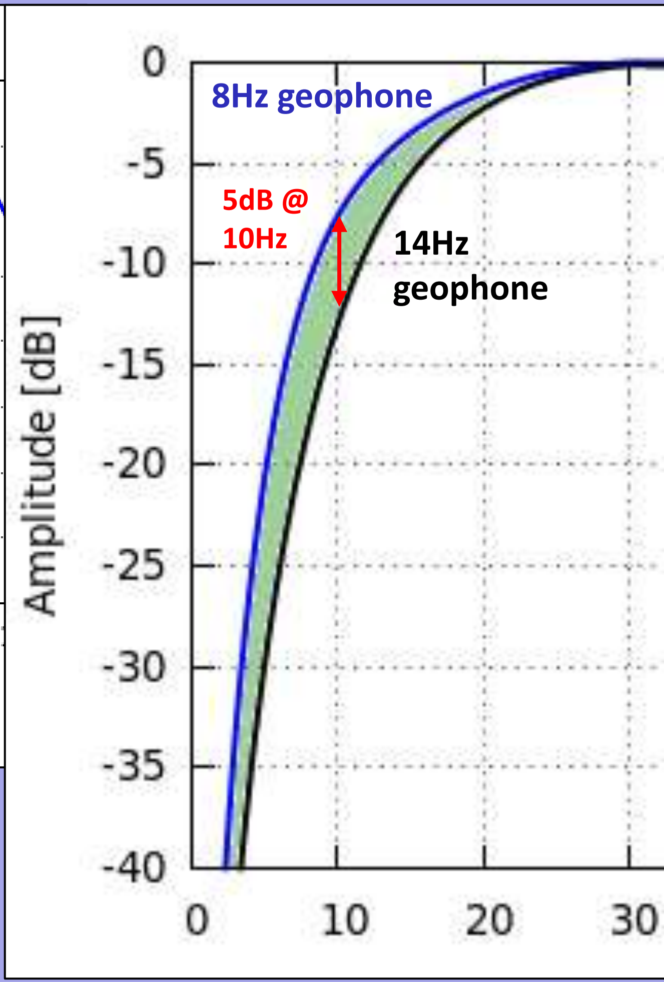
Limited at low end only by
- Sensor response
- Sensor depth

Boost low frequency energy by…
- **…performing de-ghosting / wavefield separation**

Downside
- *Requires more costly acquisition:*
  Ocean bottom seismometers, over/under streamers, or others

Boosting low frequency energy (5)





Boost low frequency energy by…

- **…using velocity sensors with high sensitivity and wide dynamic range at low end**

Downside

- *Low natural-frequency geophones are not omni-directional, i.e. they are sensitive to tilt*

Geophones versus MEMS

The figure below illustrates that MEMS accelerometers have lower effective dynamic range at low end of seismic signal spectrum:

LF events only recorded on geophone

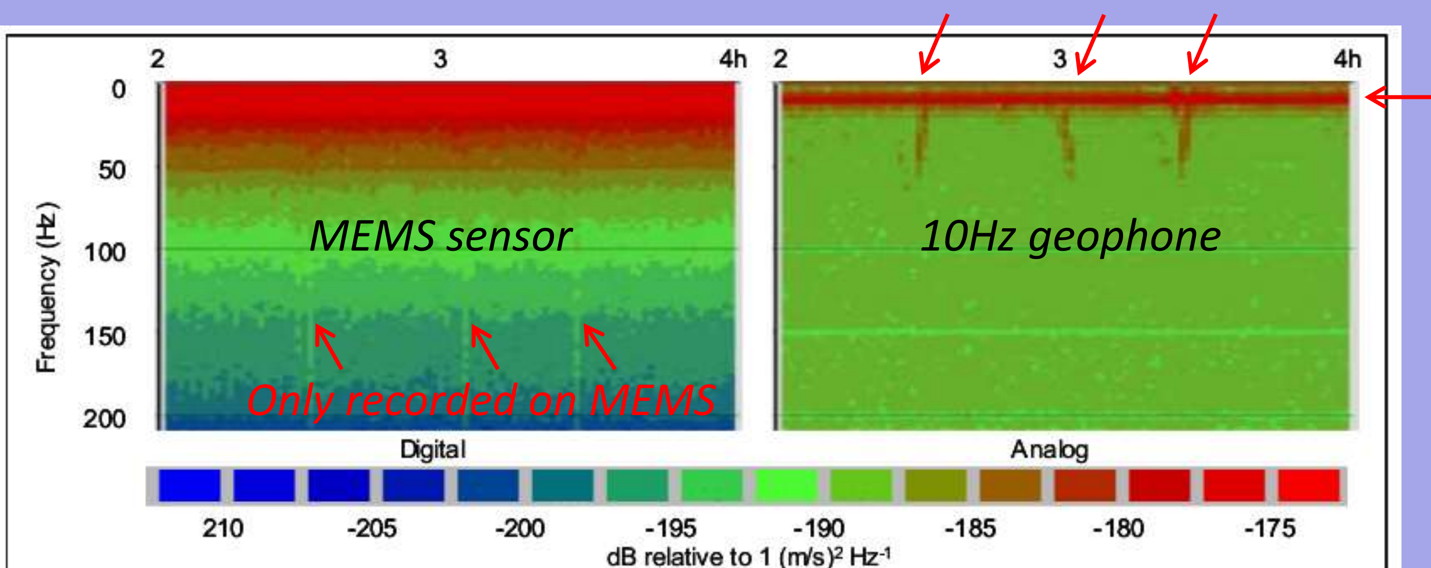


Figure 3 *spectral density of ambient noise (buried receivers, depth 200m) A notch filter is applied to analog data*

We cemented 12 digital 3-C accelerometers together with analog vertical geophones and hydrophones in a 7-inch well at depths ranging from 140 to 200 m. Figure 3 compares analog geophones and digital accelerometers. It confirms that below 50 Hz, conventional geophones are quieter than digital accelerometers and that above this frequency, the situation is the opposite: The three noise bursts recorded between 2 and 4 o'clock can be observed up to 200 Hz on the digital accelerometers. Another obvious advantage of digital sensors is their total immunity to electrical leakage. This experiment was conducted in a gas storage area close to

Meunier & Menard EAGE 2004

Boosting low frequency energy – Summary

Recorded low frequency energy can be boosted by…

1. Using a big source array

2. Towing source array deep

3. Towing streamer deep, or better: Placing sensors at seafloor

4. Using acquisition technique allowing receiver side de-ghosting / wavefield separation

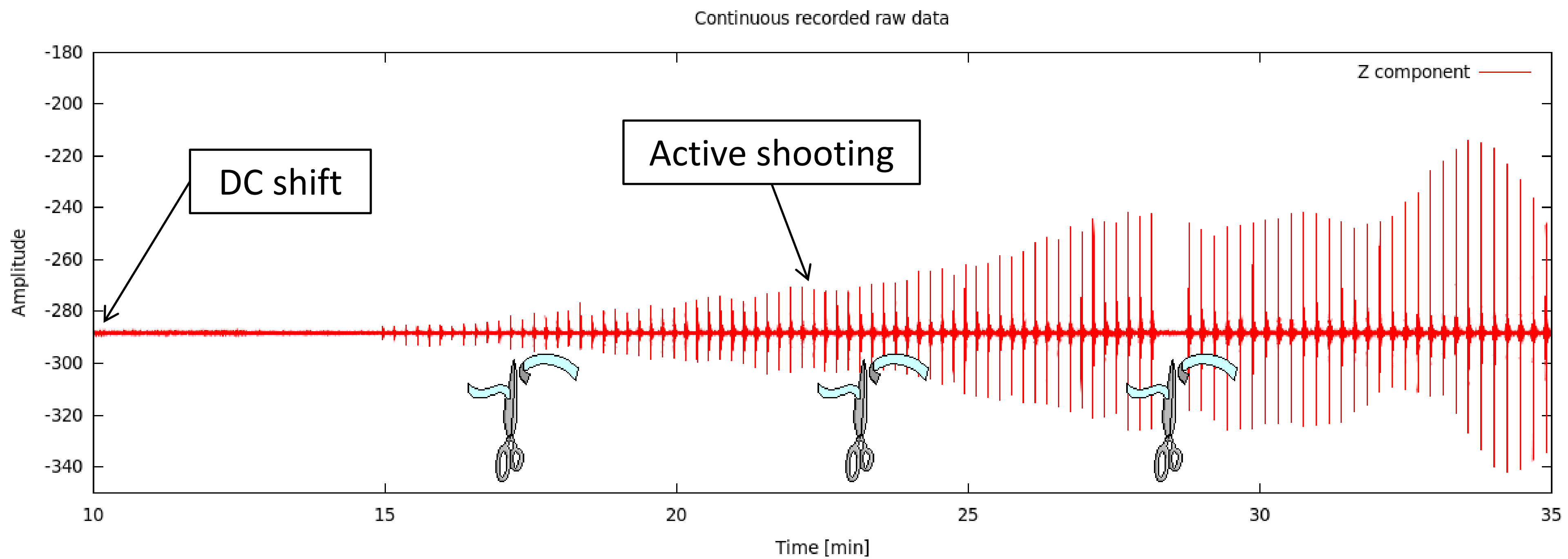
5. Using broad-band sensors that are highly sensitive at both low frequencies and high frequencies

Ocean bottom node acquisition technique is optimal with respect to all of the above.

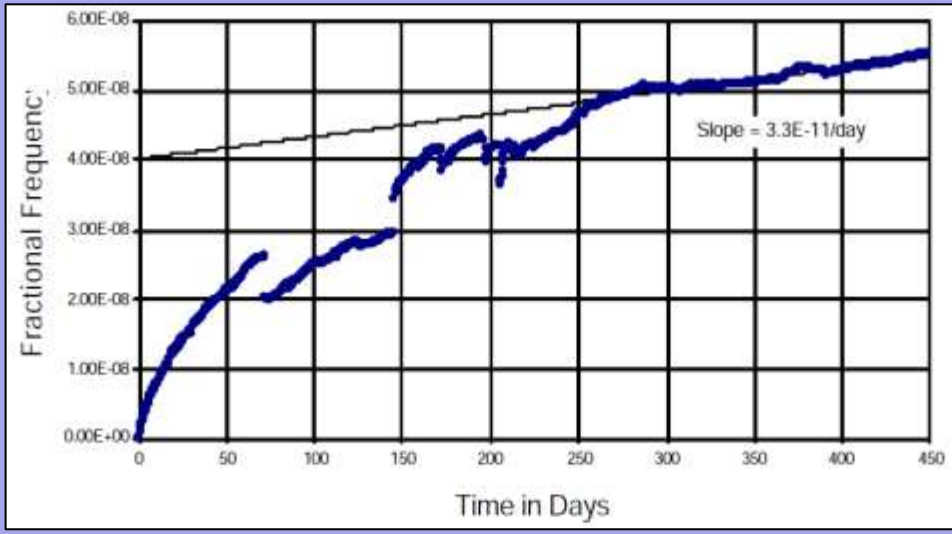
OBN Acquisition

Raw Data Analysis

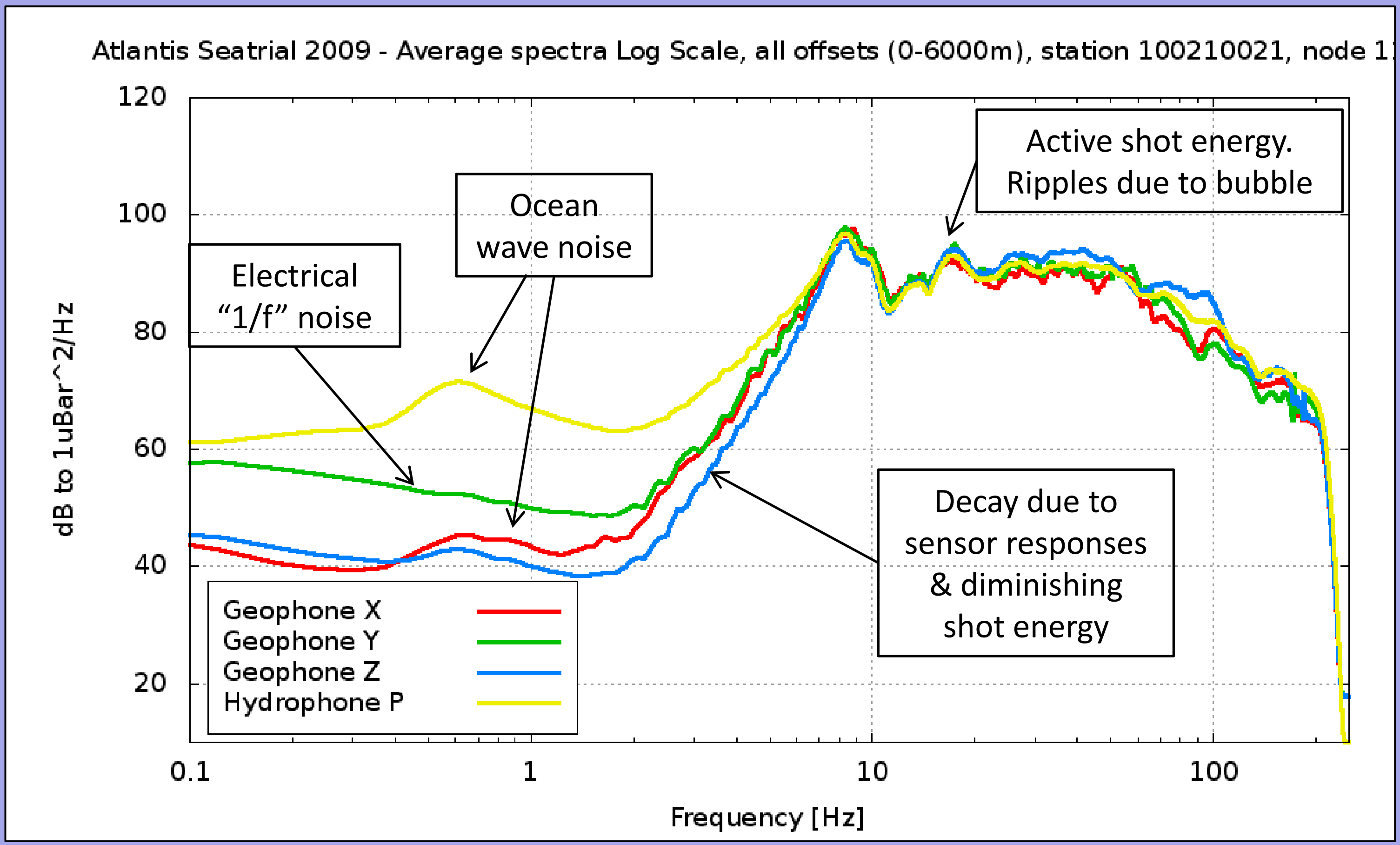
Continuous recorded data



- Active shots need to be extracted from continuous record, using shot time
- Shot time needs to be mapped to time of internal clock
- Clocks used in OBNs are very accurate, but still drift by several 10ms per month

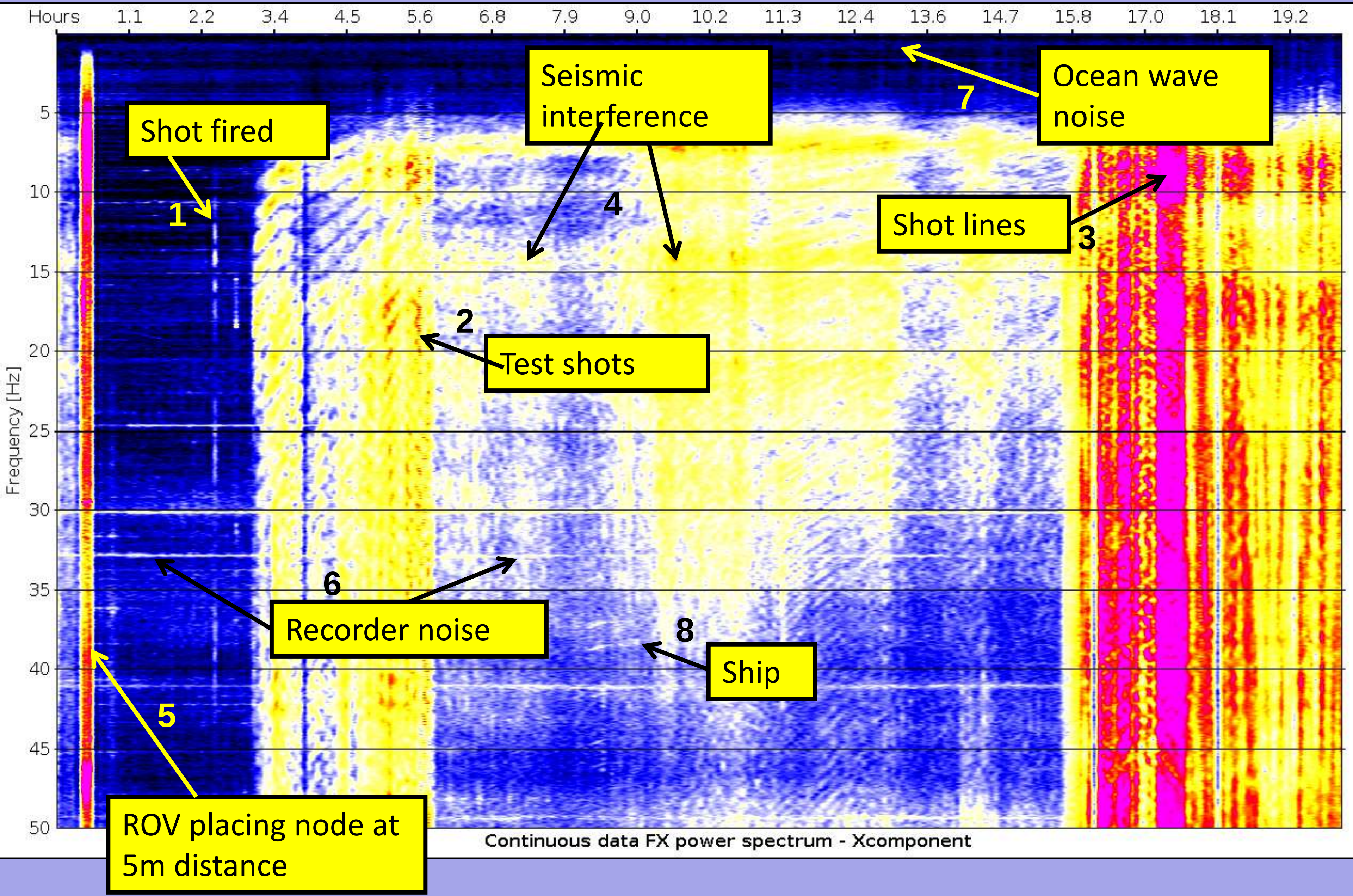


Spectral analysis



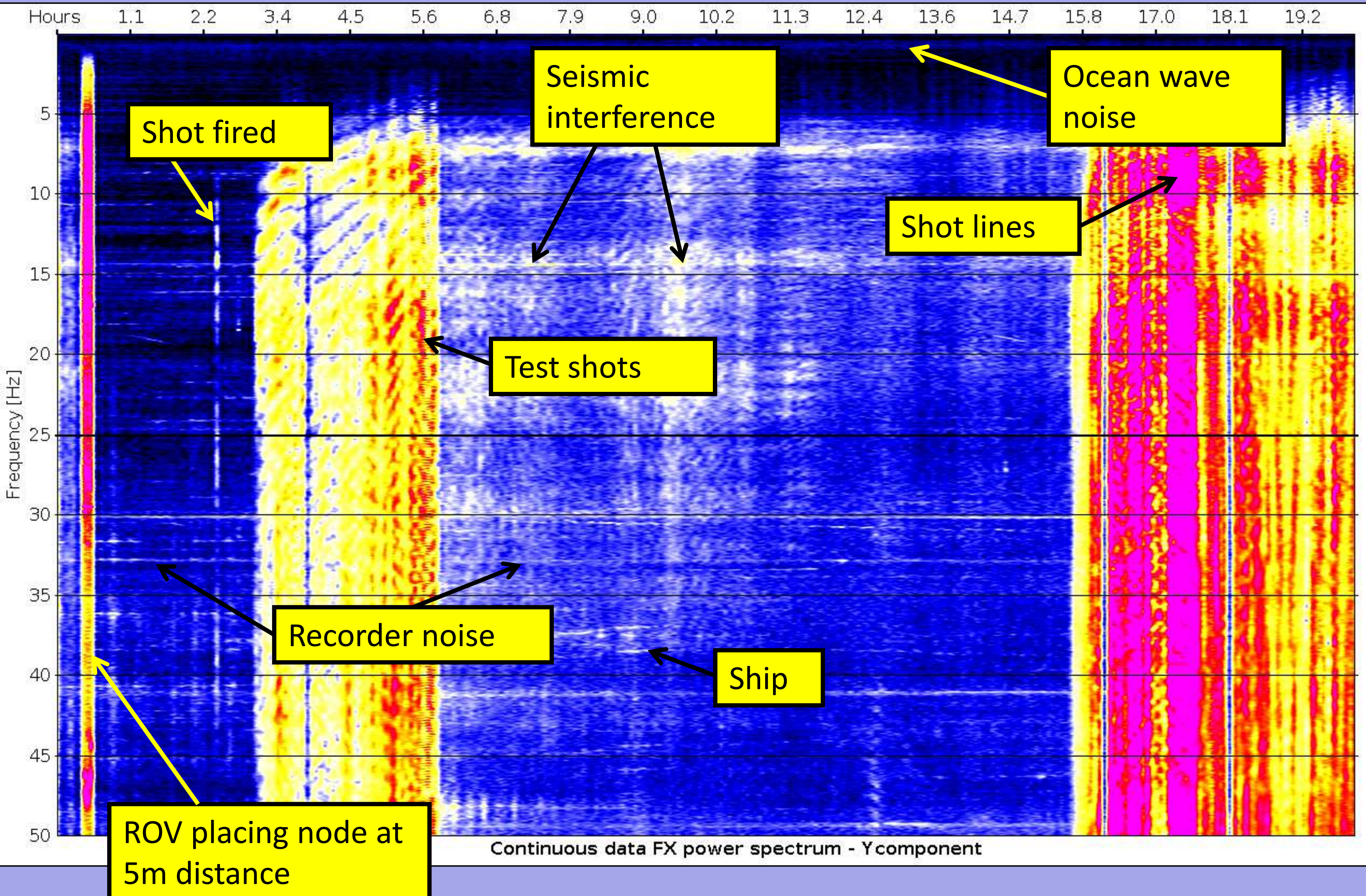
Spectral analysis

Continuous data spectra – 4 minute traces
X Component



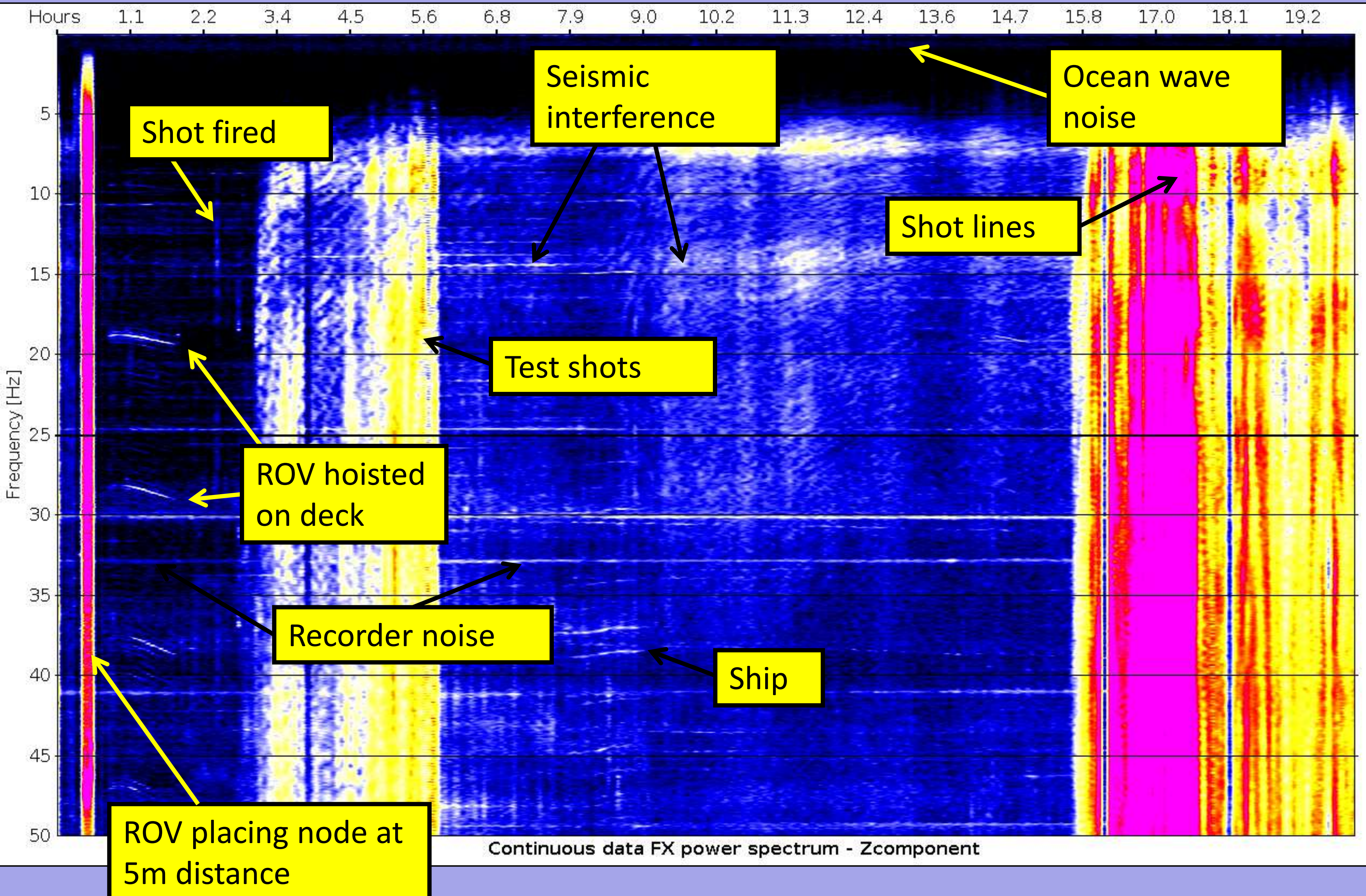
Spectral analysis

Continuous data spectra – 4 minute traces
Y Component



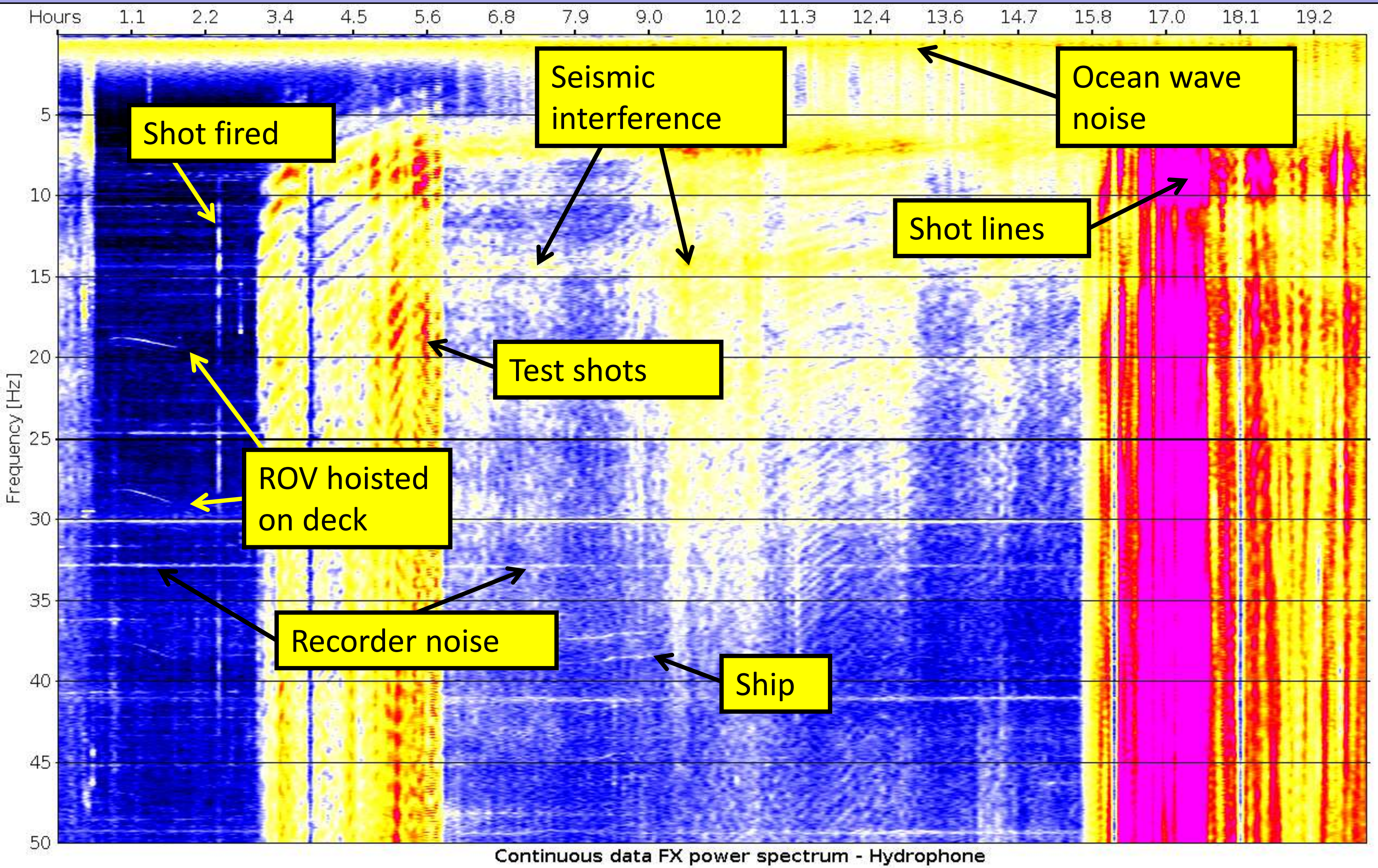
Spectral analysis

Continuous data spectra – 4 minute traces
Z Component



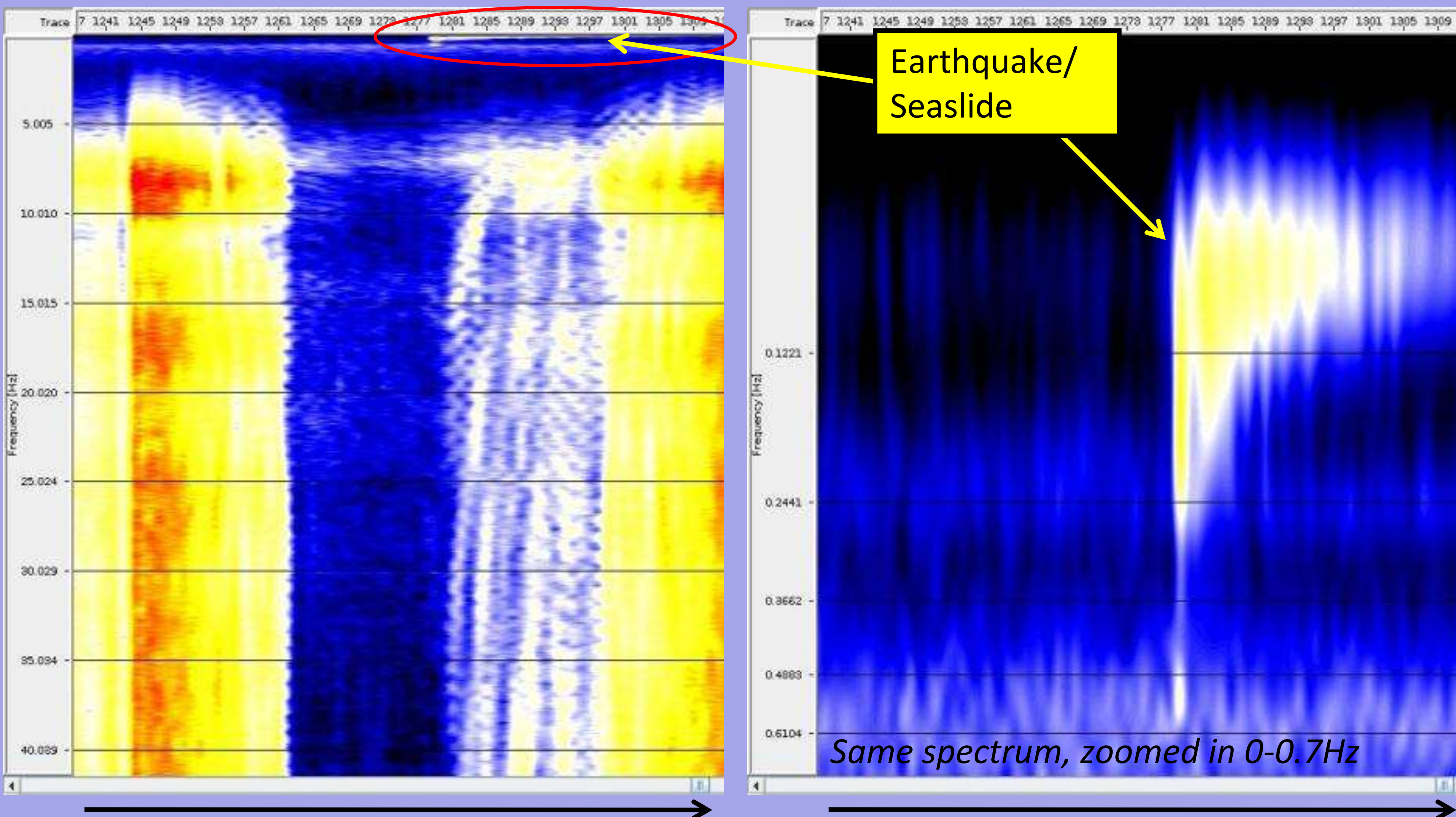
Spectral analysis

Continuous data spectra – 4 minute traces
Hydrophone



Spectral analysis

Continuous data spectra – 4 minute traces
Hydrophone

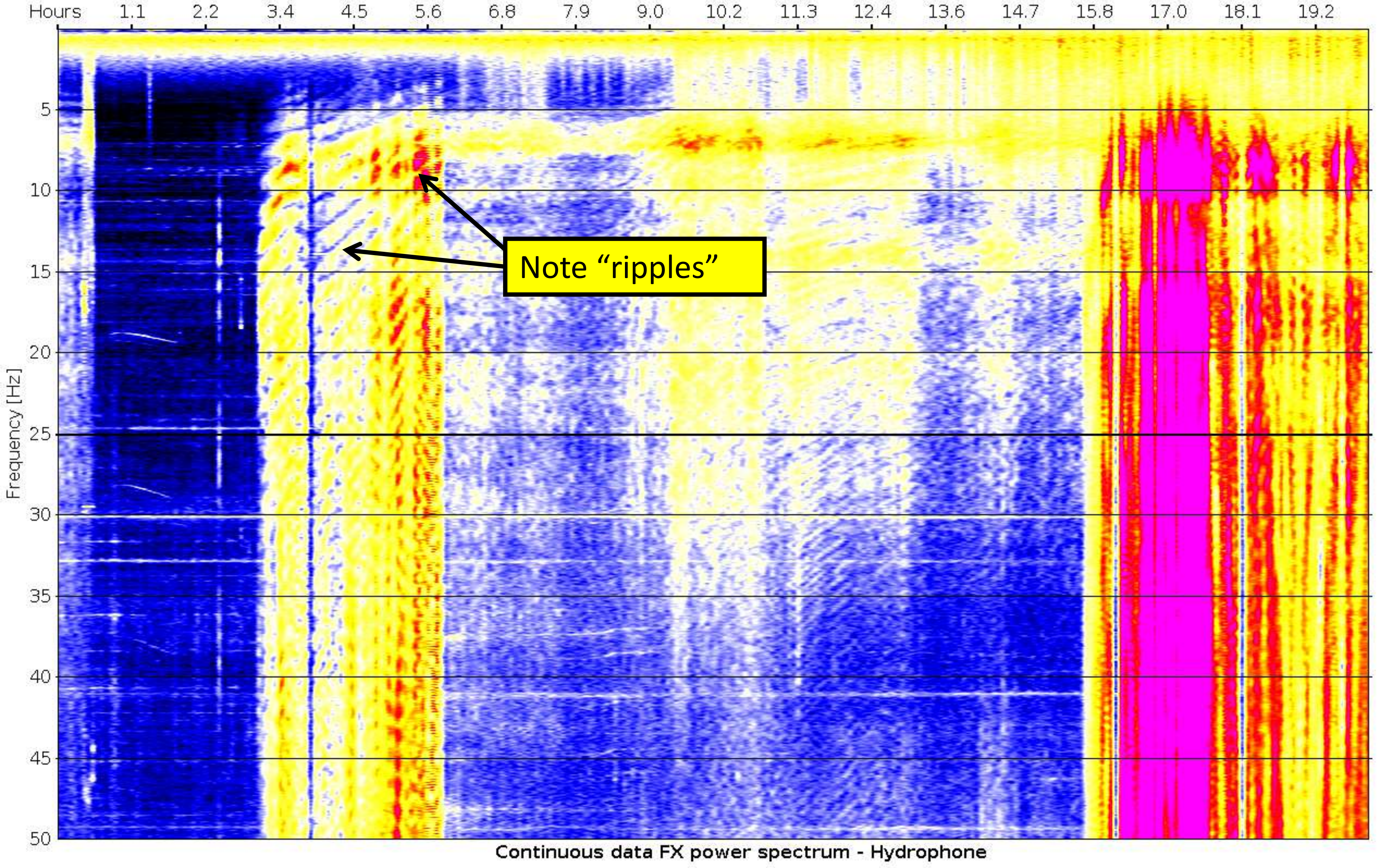


5 hours of recording

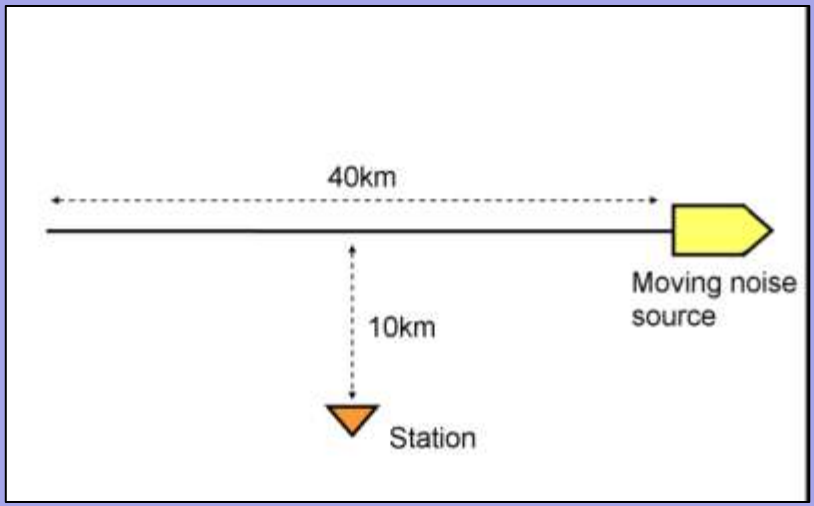
5 hours of recording

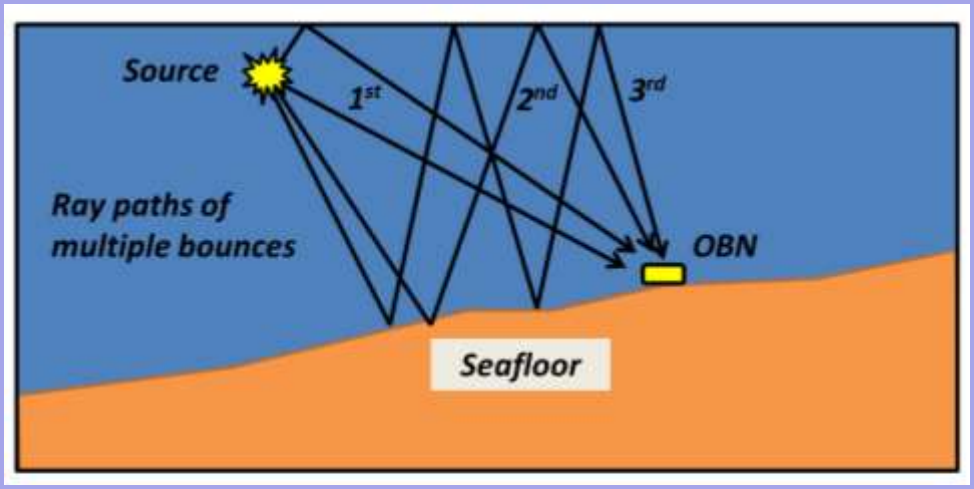
Spectral analysis

Continuous data spectra – 4 minute traces



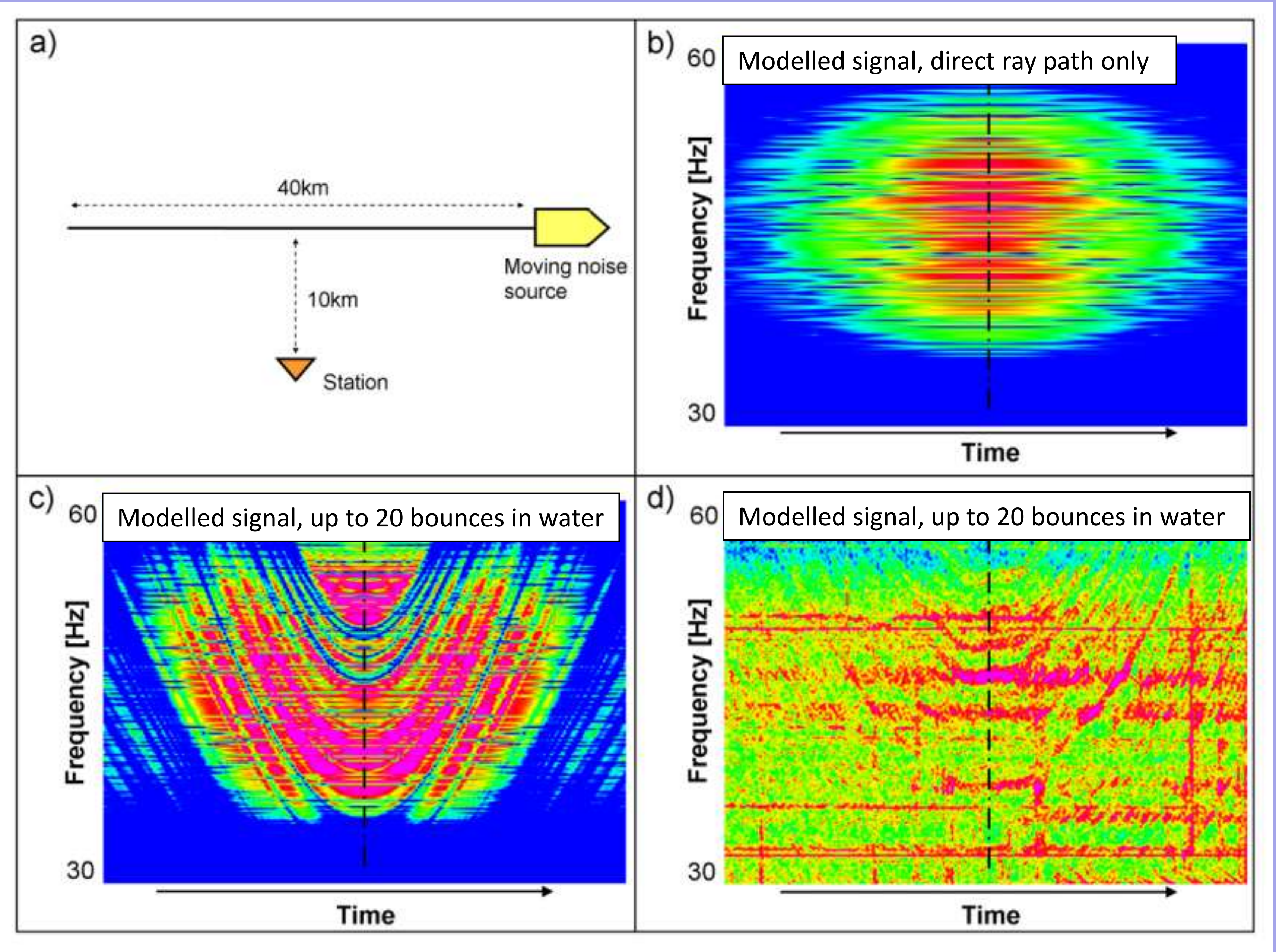
Spectral analysis – Explaining frequency ”ripples”





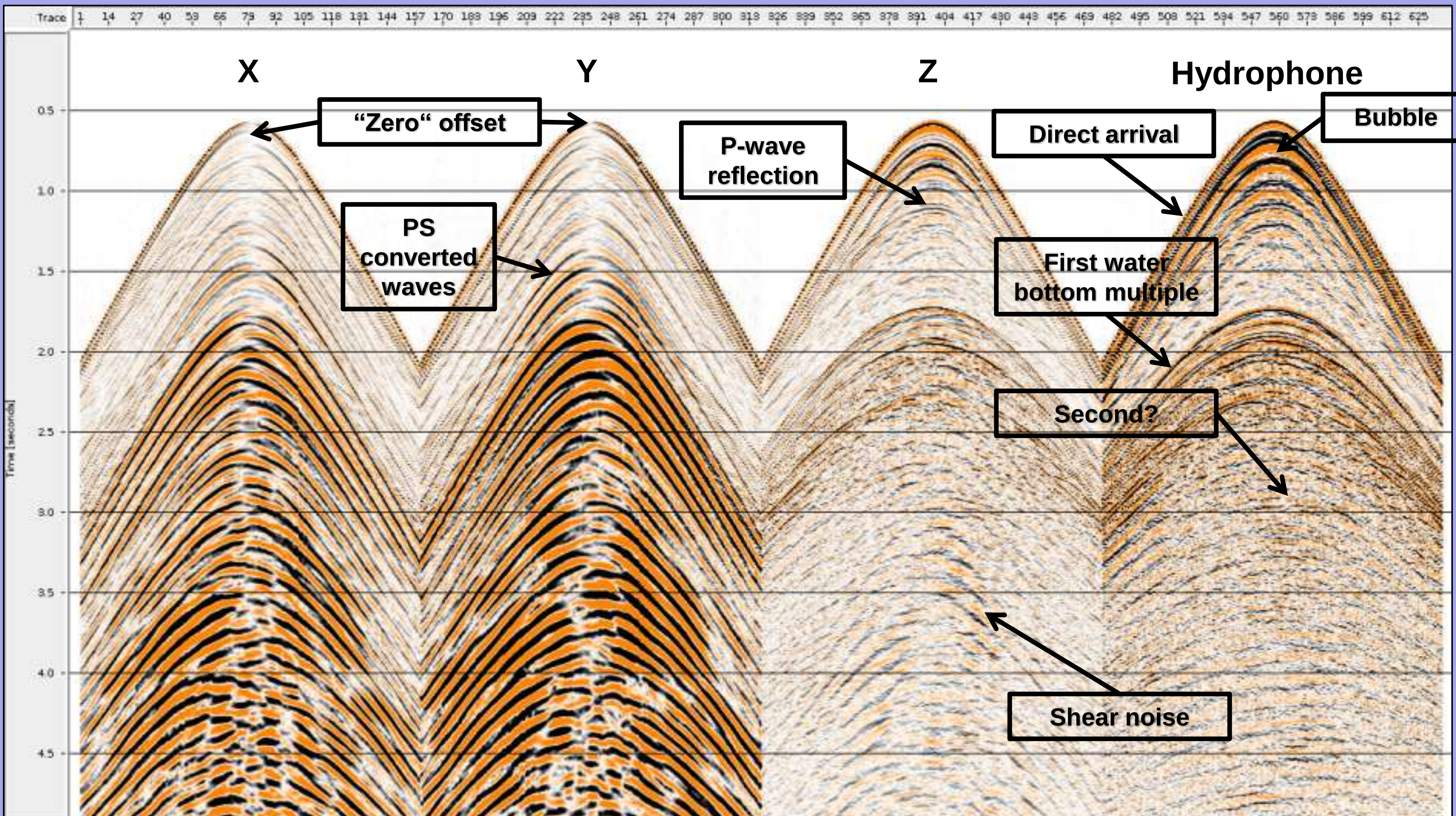
- Assume moving source close to sea surface emanating constant amplitude band limited energy with random phase
- Model all water arrivals up to 20 bounces (2D ray tracing)

Spectral analysis – Explaining frequency ”ripples”



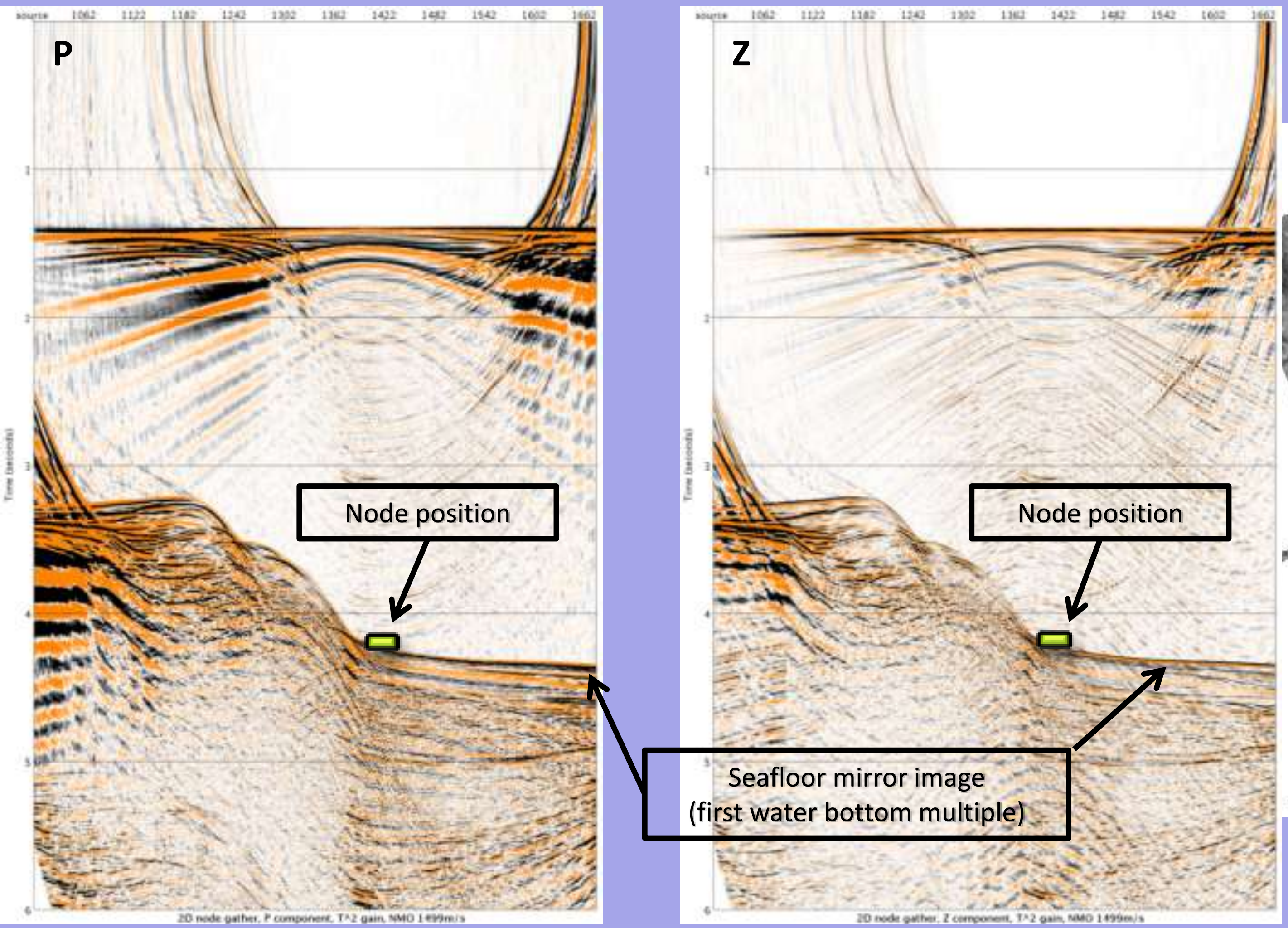
Raw data analysis

Example raw receiver gather, deep water (~1km)

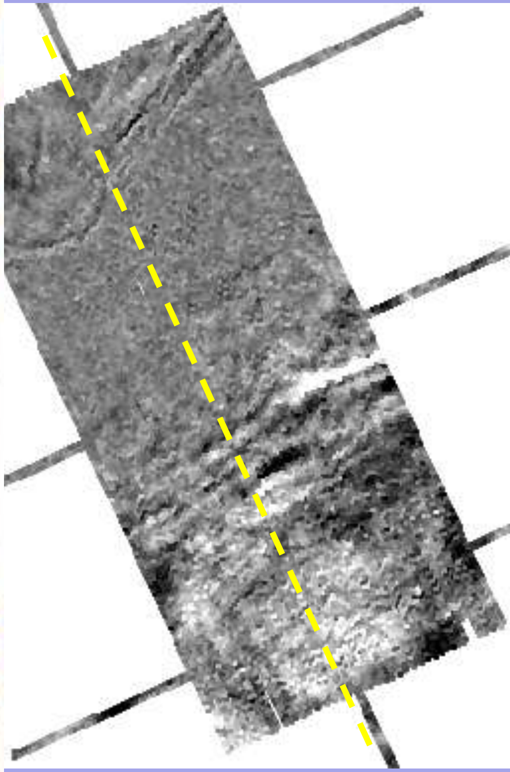


Raw data analysis

2D node gather from one shot line, displayed with true relative amplitude and constant water velocity NMO correction.



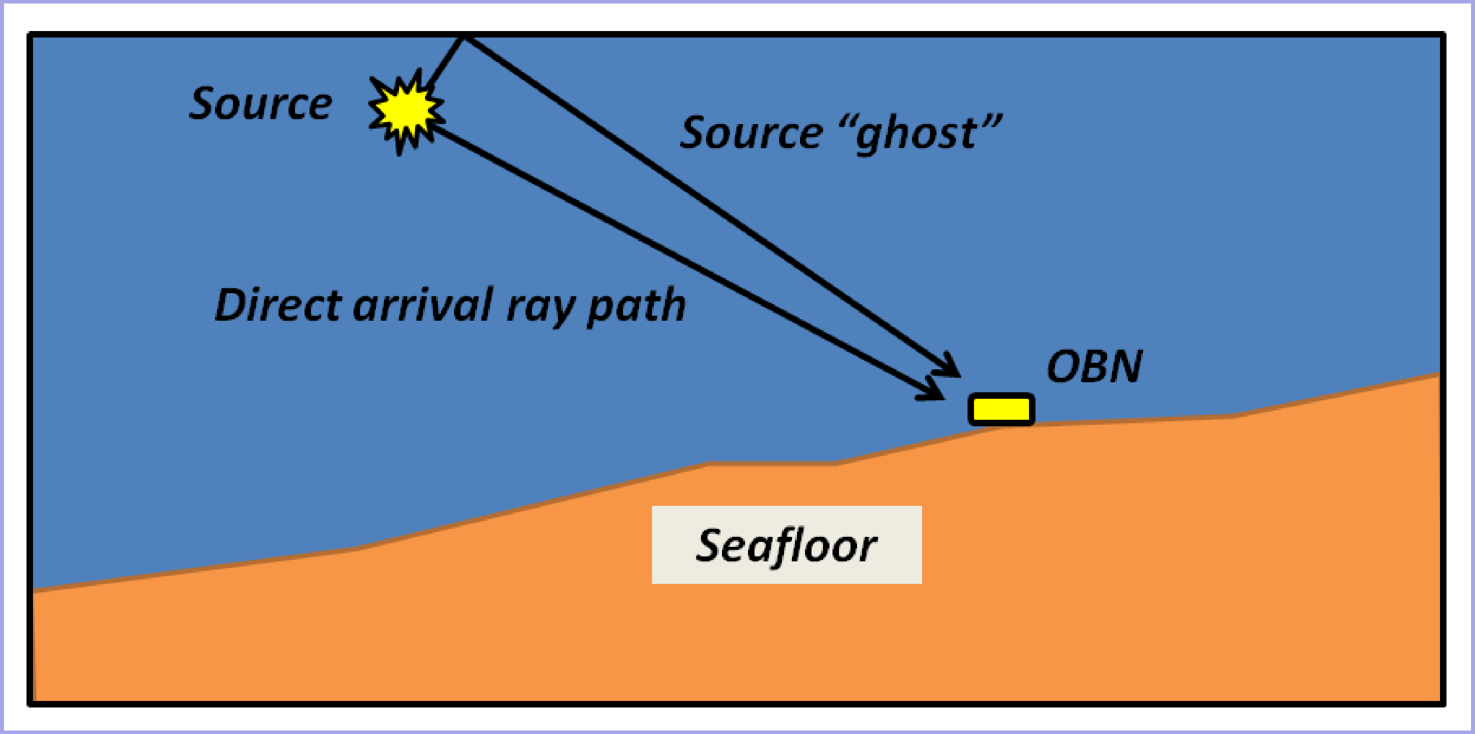
Time slice



OBN Acquisition

Direct Arrival & First Break Analysis

Direct arrival



Usages for recorded direct arrival wave = Parameters that can be derived from first break pick times:

1. Node positions
2. Source positions (to limited extent)
3. 3C sensor orientation angles
4. (Average) Water velocity

Direct arrival – First break times

Direct arrival travel time equation:

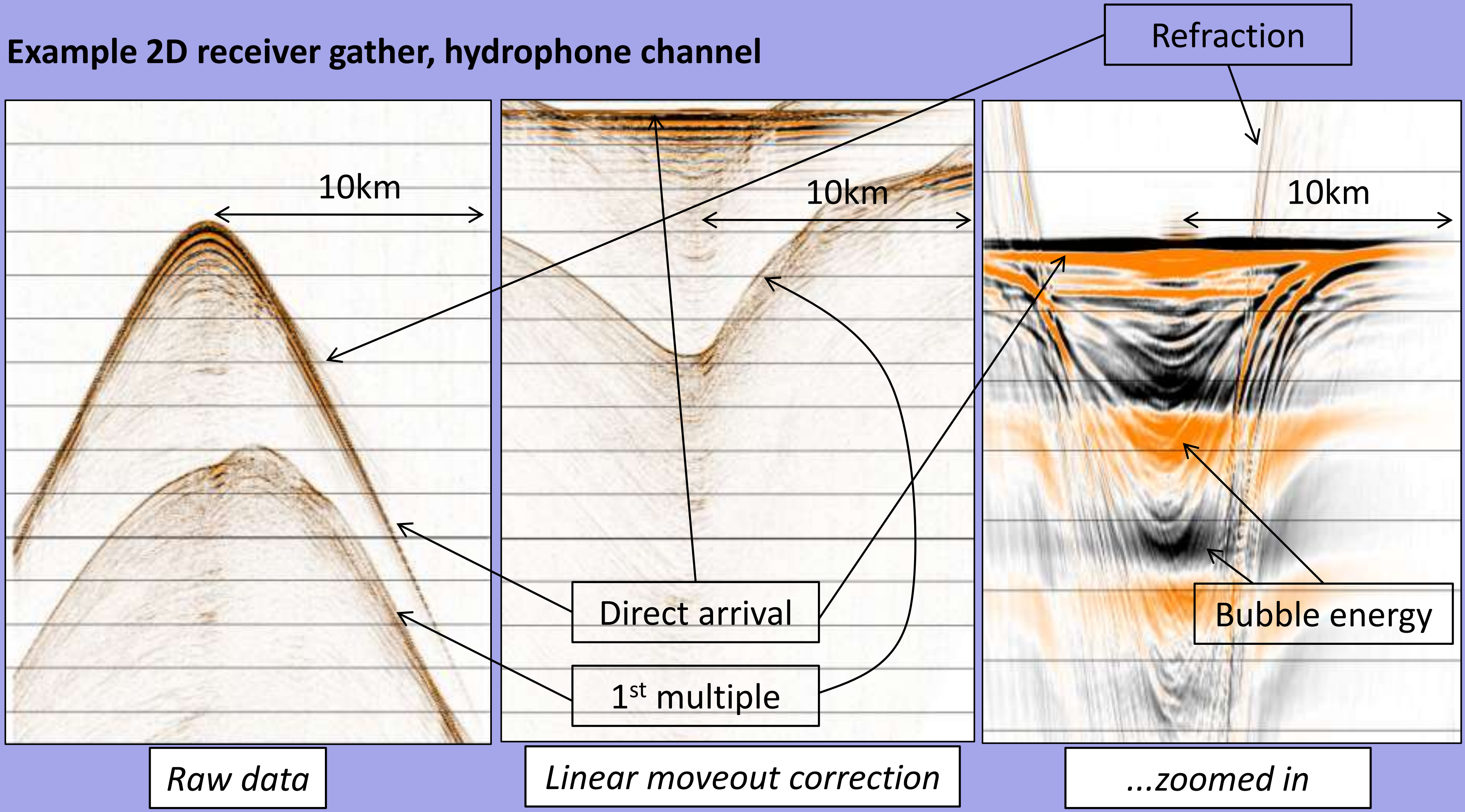
$$t = \sqrt{(x_r - x_s)(y_r - y_s)(z_r - z_s)}\,\frac{1}{v(z,t)} + t_0 + d(t)$$

x_r, y_r, z_r	:	Receiver/Node position
x_s, y_s, z_s	:	Source position
$v(z,t)$	:	Average water velocity (at best function of depth and time)
t_0	:	Residual time shift
$d(t)$	:	Clock drift (time variant)

Assumptions:
- *Straight ray path*
- *No global position biases*
- *First break pick represents true travel time*
- *...*

First Break Times

Example 2D receiver gather, hydrophone channel

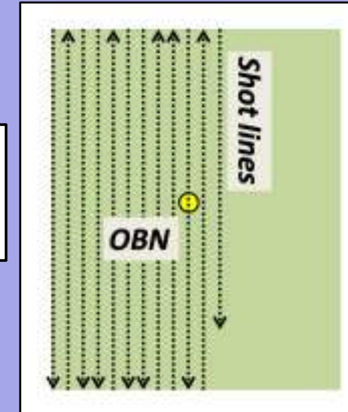


First Break Times – Sensitivity Analysis

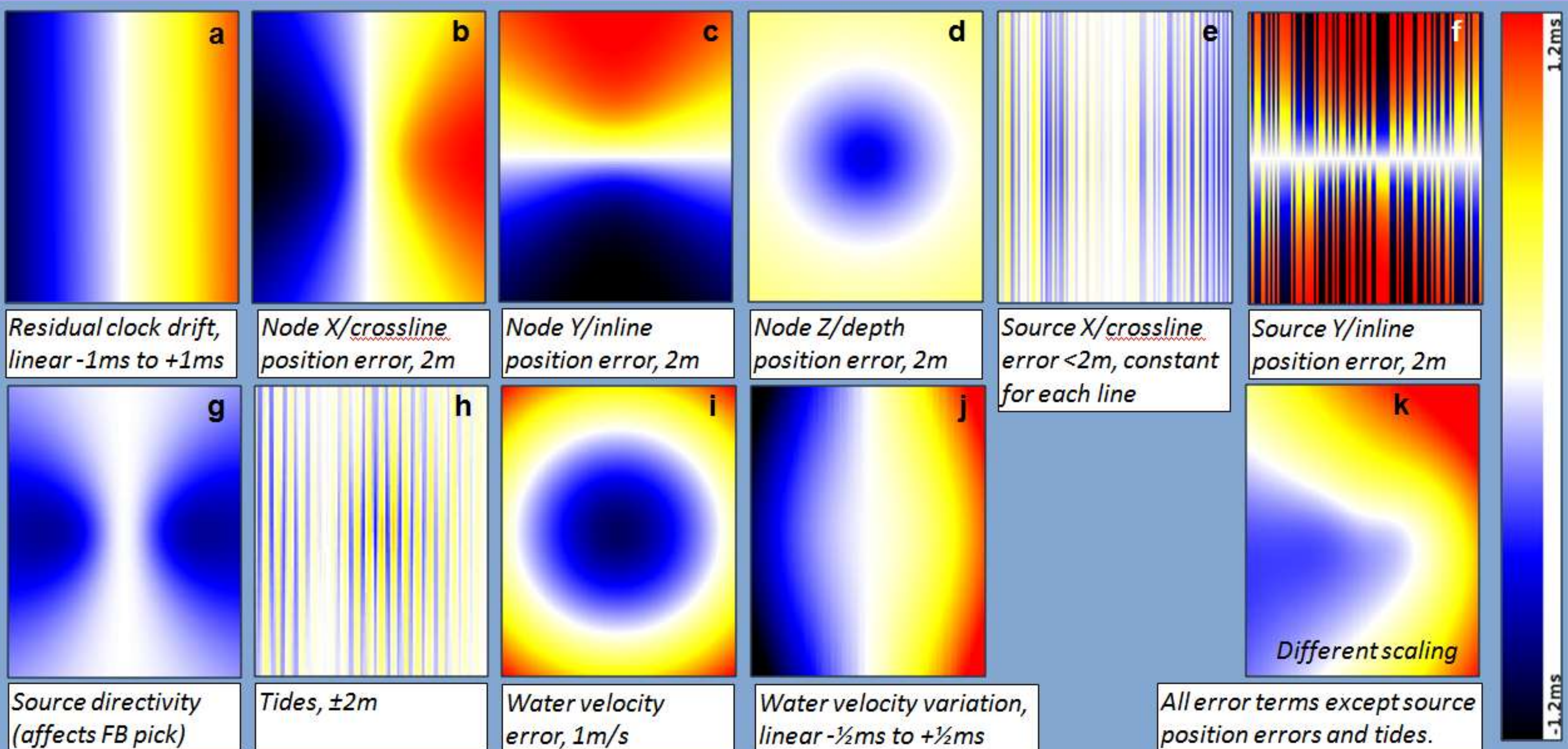
$$t = \sqrt{(x_r - x_s)(y_r - y_s)(z_r - z_s)}\,\frac{1}{v(z,t)} + t_0 + d(t)$$

b e c f d h i, j a

Fictitious node survey



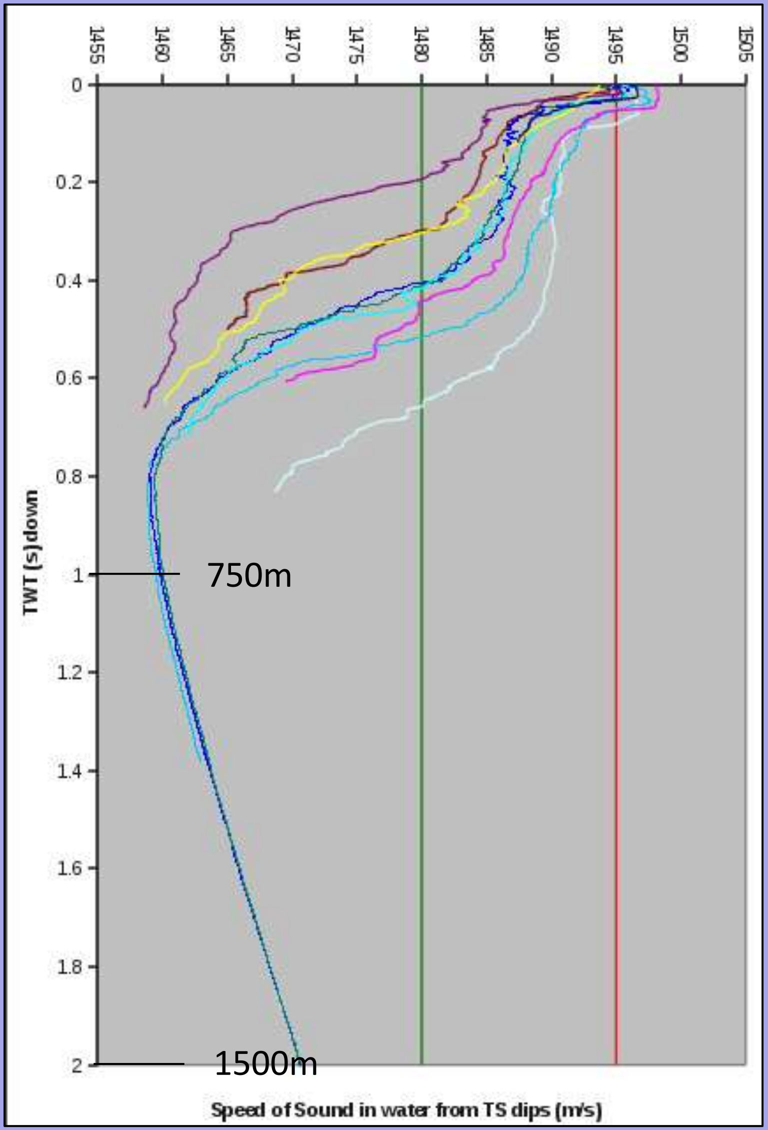
Difference between computed direct arrival travel time and first break picks:



Water velocity

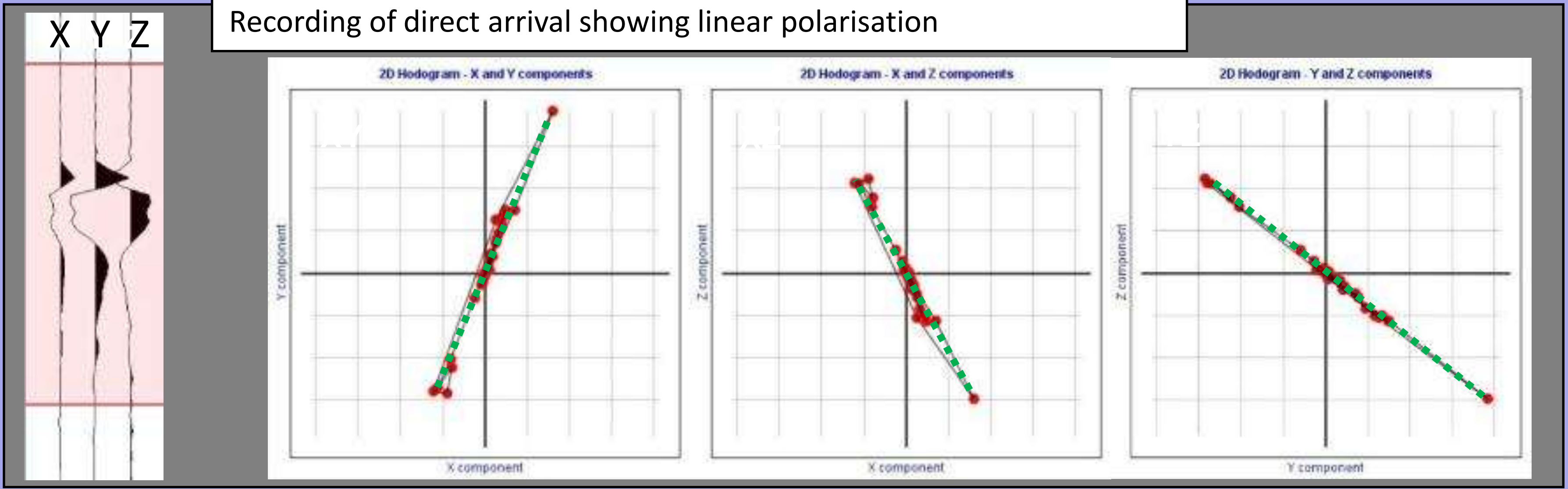
Water velocity profiles taken over the same area at different times and locations:

...illustrates that in general, water velocity is invariant neither in space nor in time.

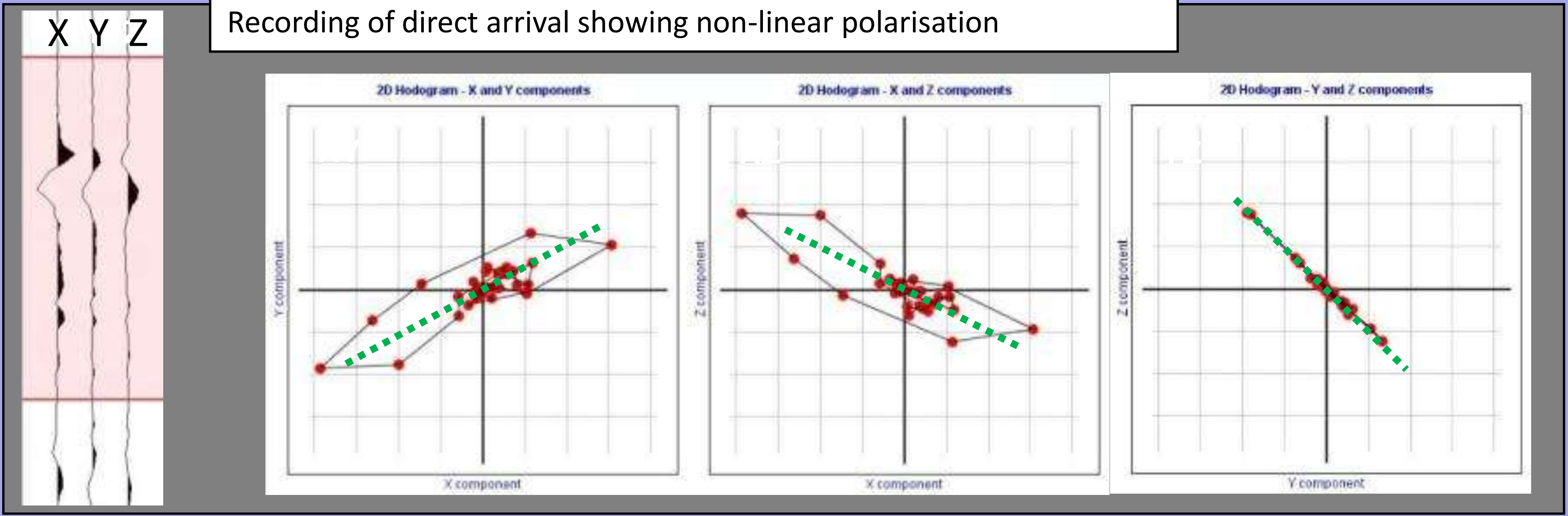


Direct Arrival Polarisation

Recording of direct arrival showing linear polarisation



Recording of direct arrival showing non-linear polarisation



Olofsson & Massacand EAGE 2007

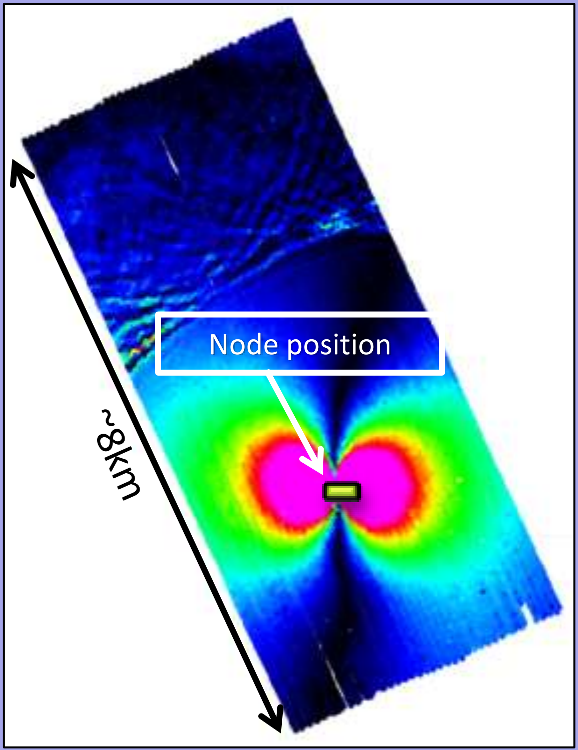
Direct Arrival Polarisation

The maps to the right show that…

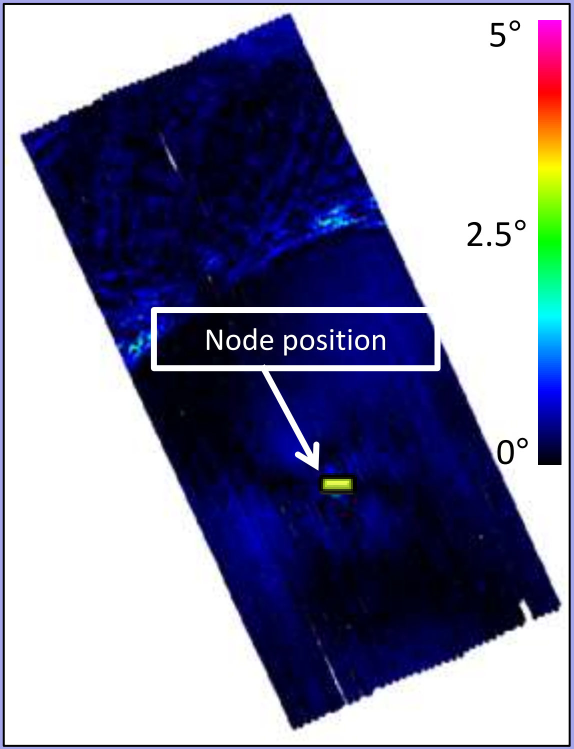
1) Direct arrival is clearly isotropic and linearly polarised → very good vector fidelity of direct arrival

2) There is very good control over sensor 3D orientation (better than 1°)

Difference between first break polarisation and source receiver azimuth, plotted at each shot position.



As-laid sensor orientation



Data derived orientation.
Corrections:

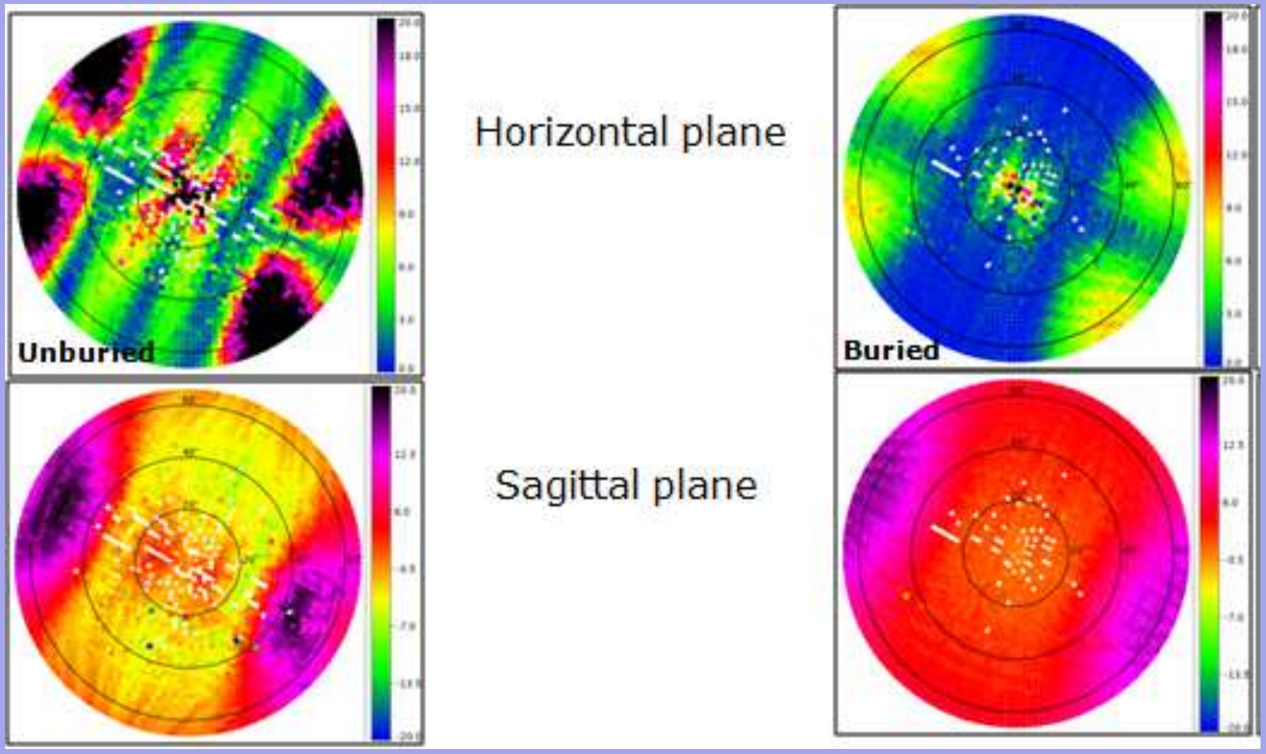
Azimuth	-0.04°
Tilt X	-0.98°
Tilt Y	-0.73°

Direct Arrival Polarisation

Polarisation error – average over many OBC sensors:

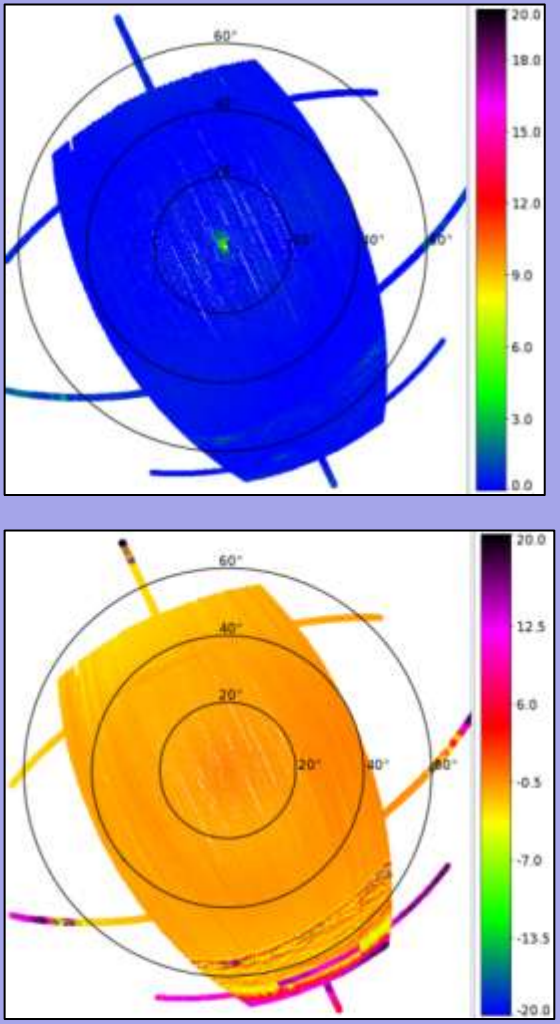
Unburied OBC

Buried OBC



Olofsson & Massacand EAGE 2007

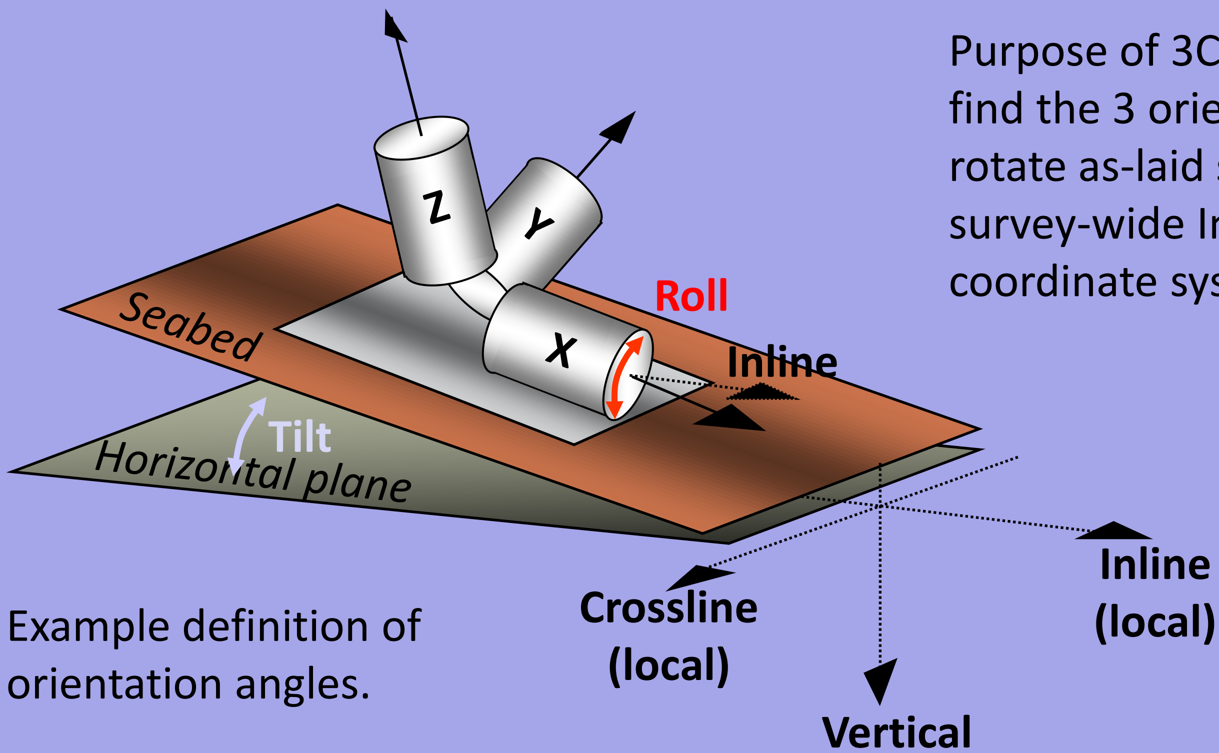
Single node, different survey, similar seabed depth & conditions:



OBN Acquisition

3C Sensor Orientation

3C Sensor Orientation



Purpose of 3C orientation analysis is to find the 3 orientation (Euler) angles that rotate as-laid sensor components to survey-wide Inline/Crossline/Vertical coordinate system.

Example definition of orientation angles.

- **Roll angle Φ** Rotation around local Inline axis
  → *makes Y component horizontal*
- **Tilt angle θ** Rotation around local Crossline axis
  → *makes X component horizontal*
- **Azimuth γ** Rotation around Vertical axis
  → *aligns X component with survey Inline (or North...)*

Olofsson et al SEG 2007

3C Sensor Orientation

Source direction vector, connecting source and receiver…

$$\vec{e}_b = R_\gamma R_\theta R_\phi \vec{e}_a$$

…equals recorded polarisation vector of the direct arrival, rotated by azimuth, tilt and roll angle.

$$R_\gamma \equiv \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} R_\theta \equiv \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}, R_\phi \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sin\phi & -\cos\phi \\ 0 & \cos\phi & \sin\phi \end{pmatrix}$$

$$\vec{e}_b = R_\gamma \begin{pmatrix} \cos\theta & \sin\theta\cos\phi & \sin\theta\sin\phi \\ 0 & \sin\phi & -\cos\phi \\ -\sin\theta & \cos\theta\cos\phi & \cos\theta\sin\phi \end{pmatrix} \vec{e}_a$$

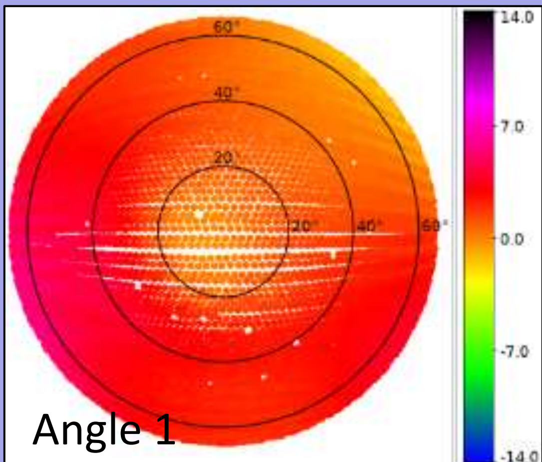
This equation can be solved analytically for roll and tilt angle, assuming the azimuth is known.

There are two independent solutions for the roll and tilt angle, which depend on the mode of acquisition:
One solution applies if sources are located *above* the receivers (typical seabed survey), the other one if sources are located *below* the receivers (land/transition zone survey).

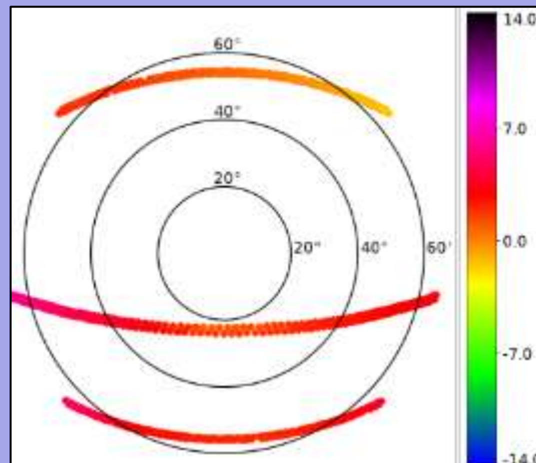
Olofsson et al SEG 2007

3C Sensor Orientation

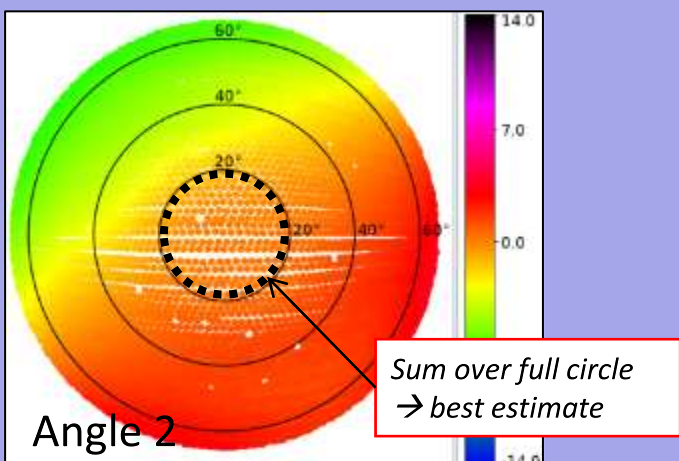
OBN sensor orientation

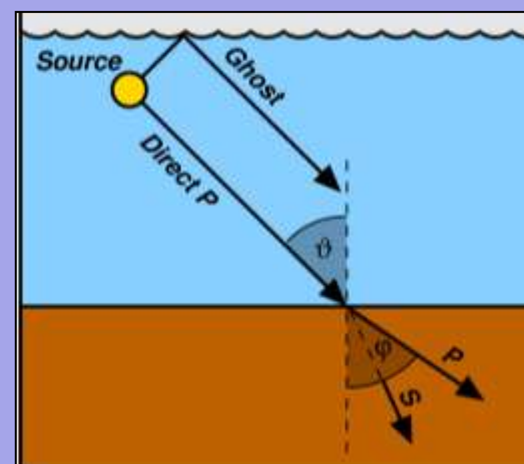


Three source lines only:



Estimated orientation angles mapped by source-receiver azimuth and incidence angle at seabed.

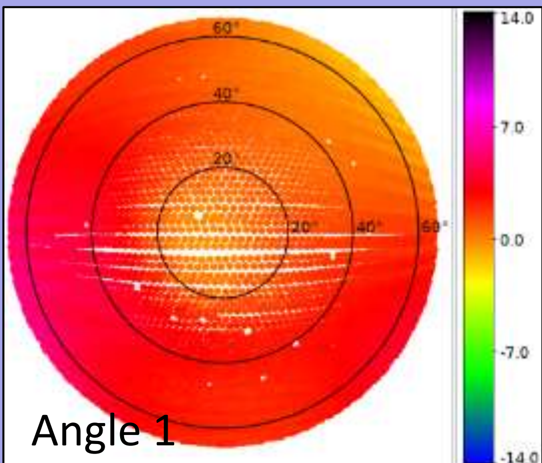




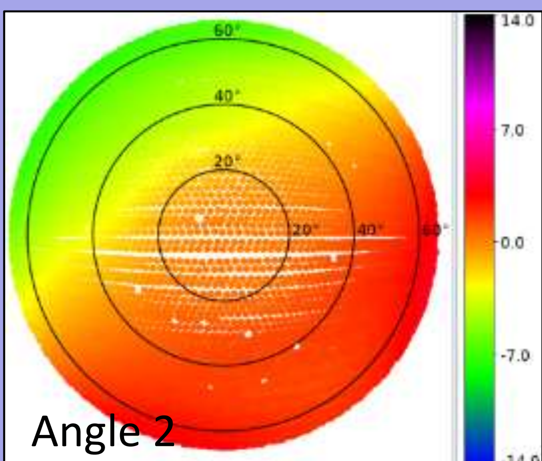
3C Sensor Orientation

...in comparison, OBC:

OBN sensor orientation

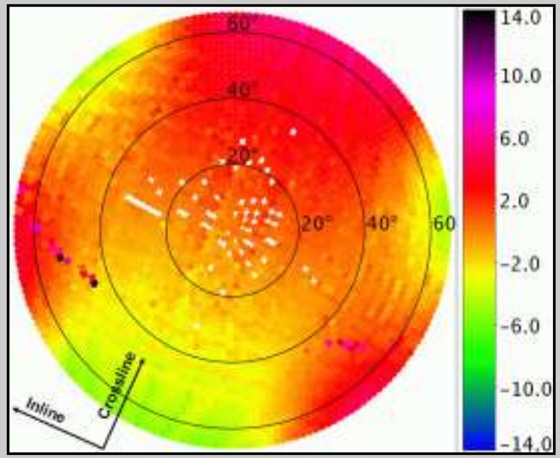


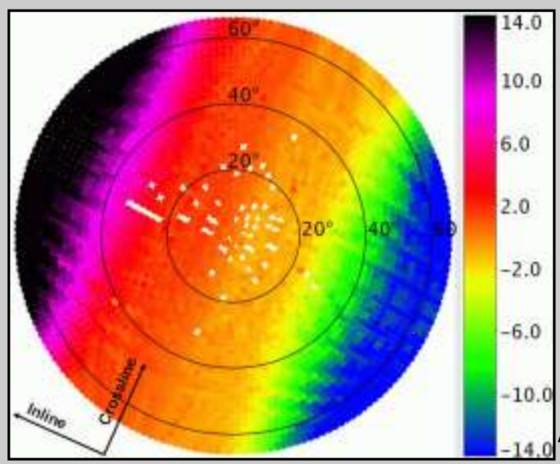
Angle 1



Angle 2

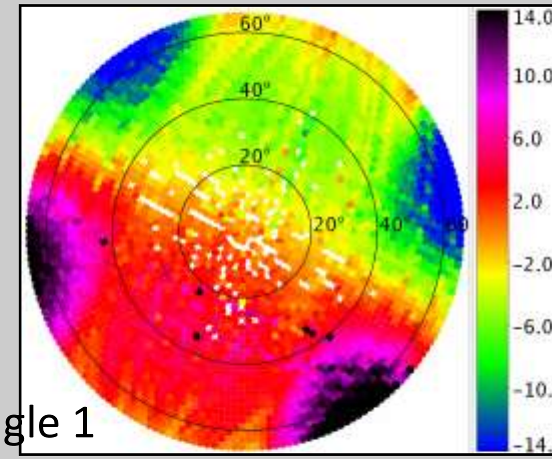
Buried OBC



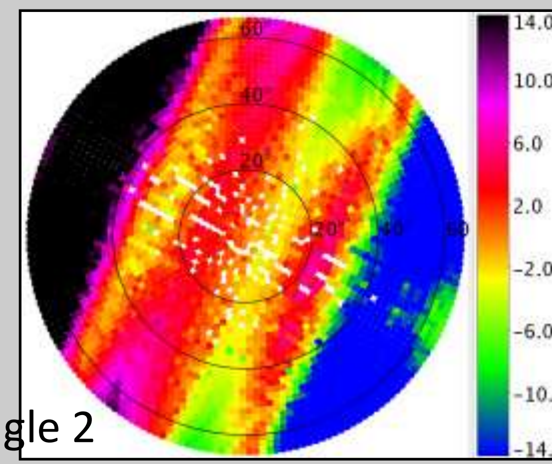


Unburied OBC

Angle 1



Angle 2

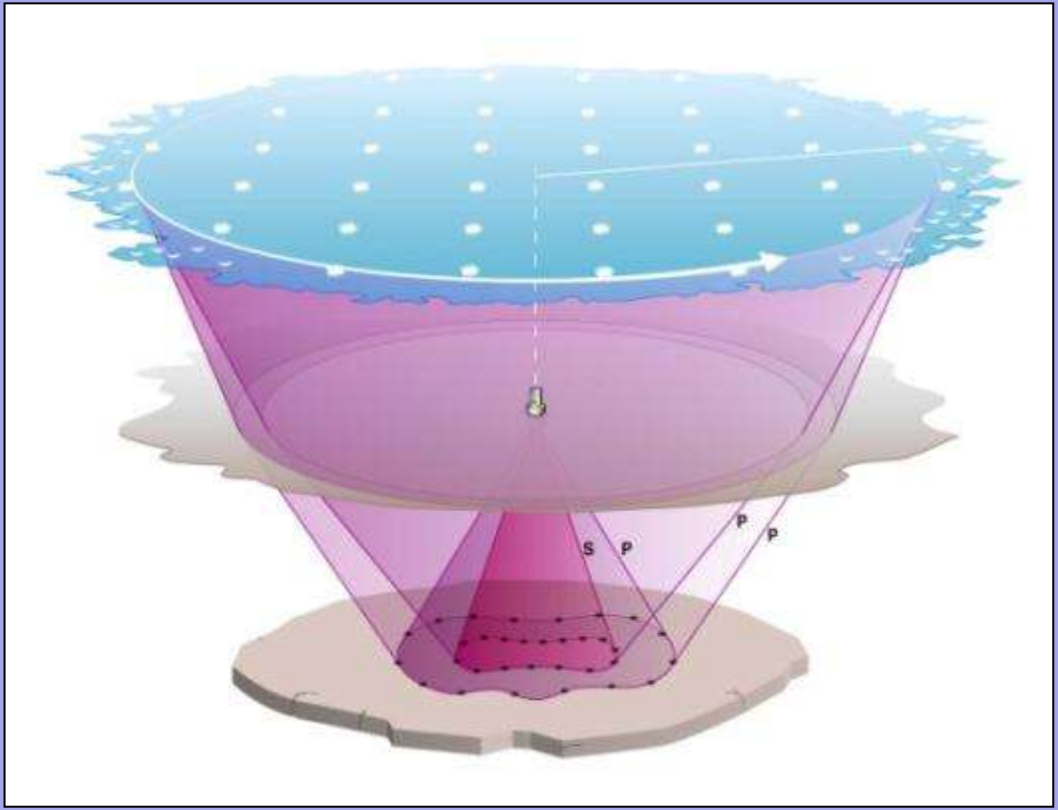


Olofsson et al SEG 2007

OBN Data Processing

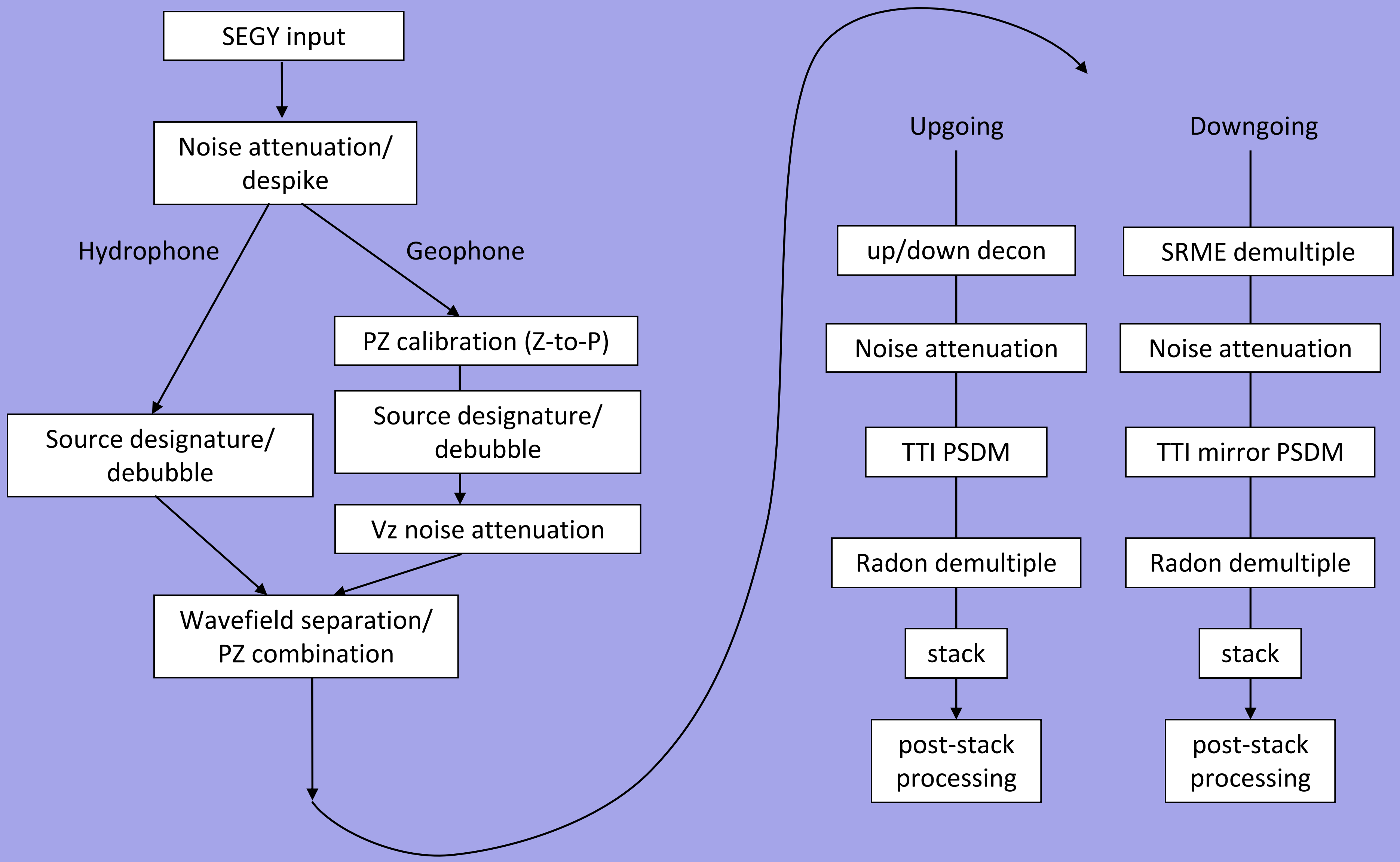
OBN Data Processing

Raypath geometry for a node gather:

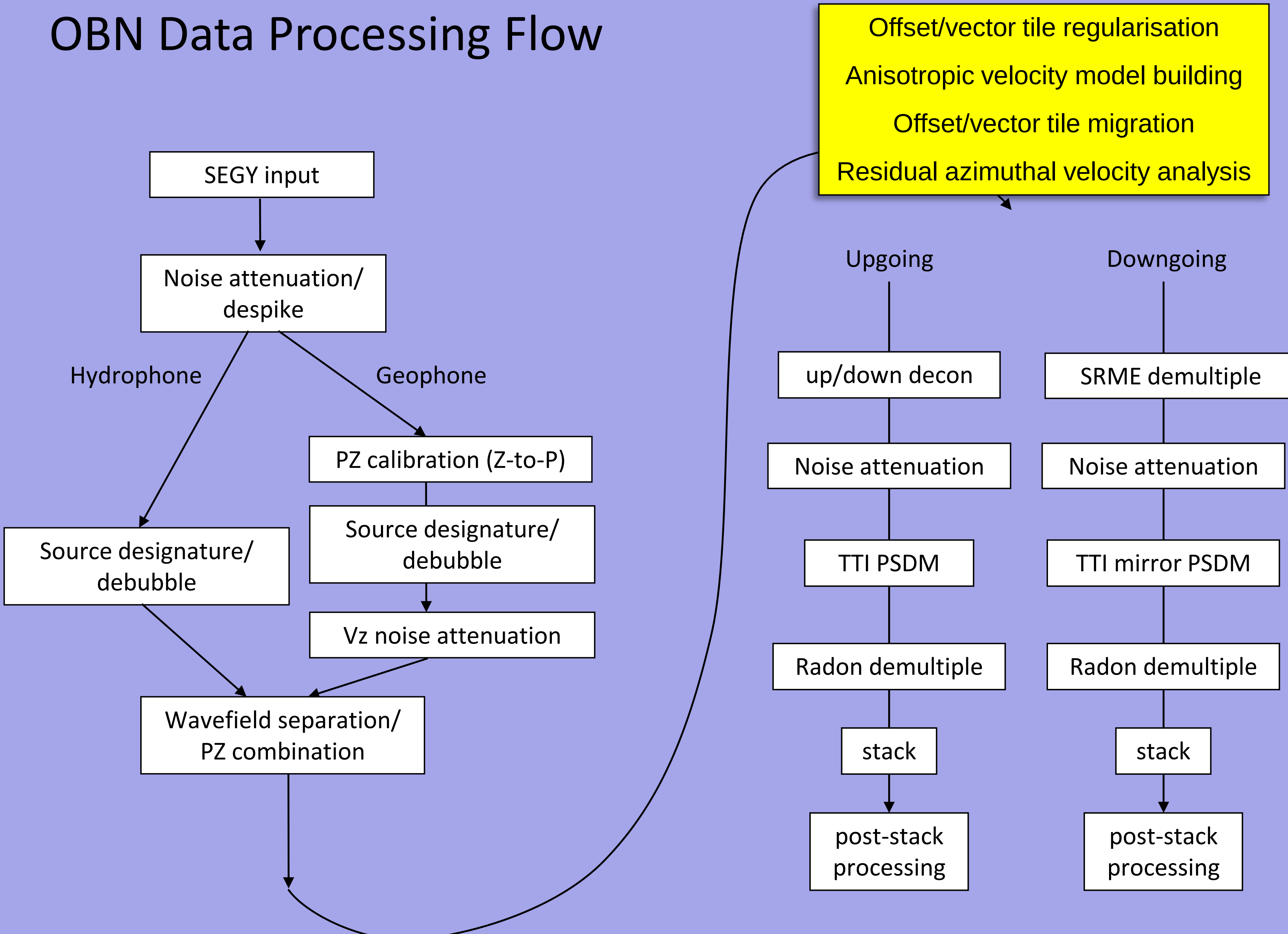


Pre-processing is done mostly in 3D receiver gather domain.

OBN Data Processing Flow

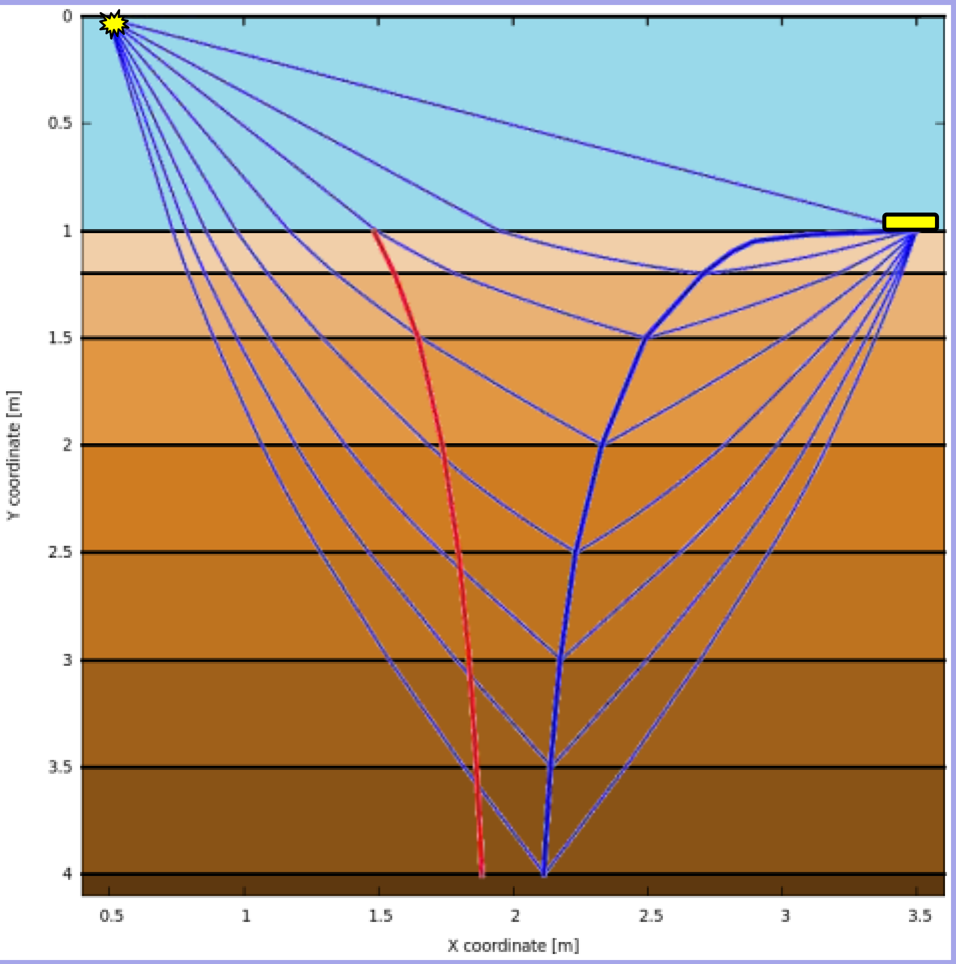


OBN Data Processing Flow

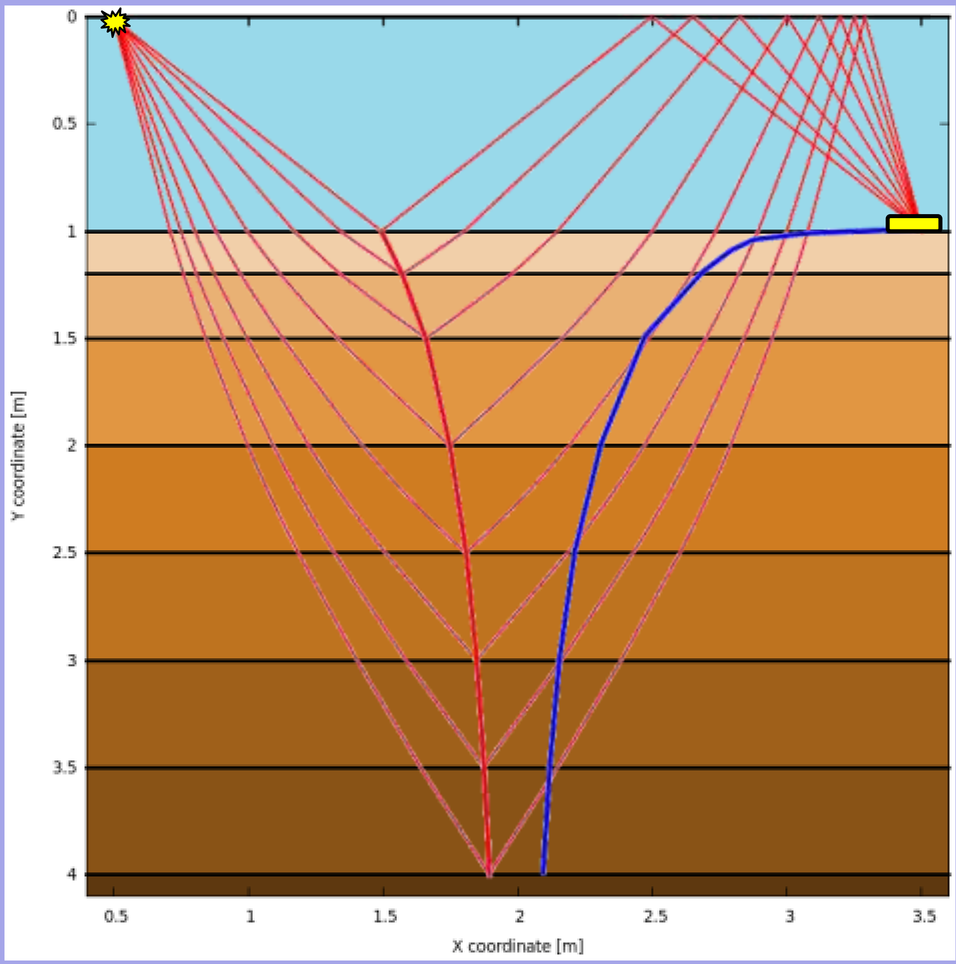


Mirror imaging

“Conventional” imaging
Primary reflections, up-going wavefield

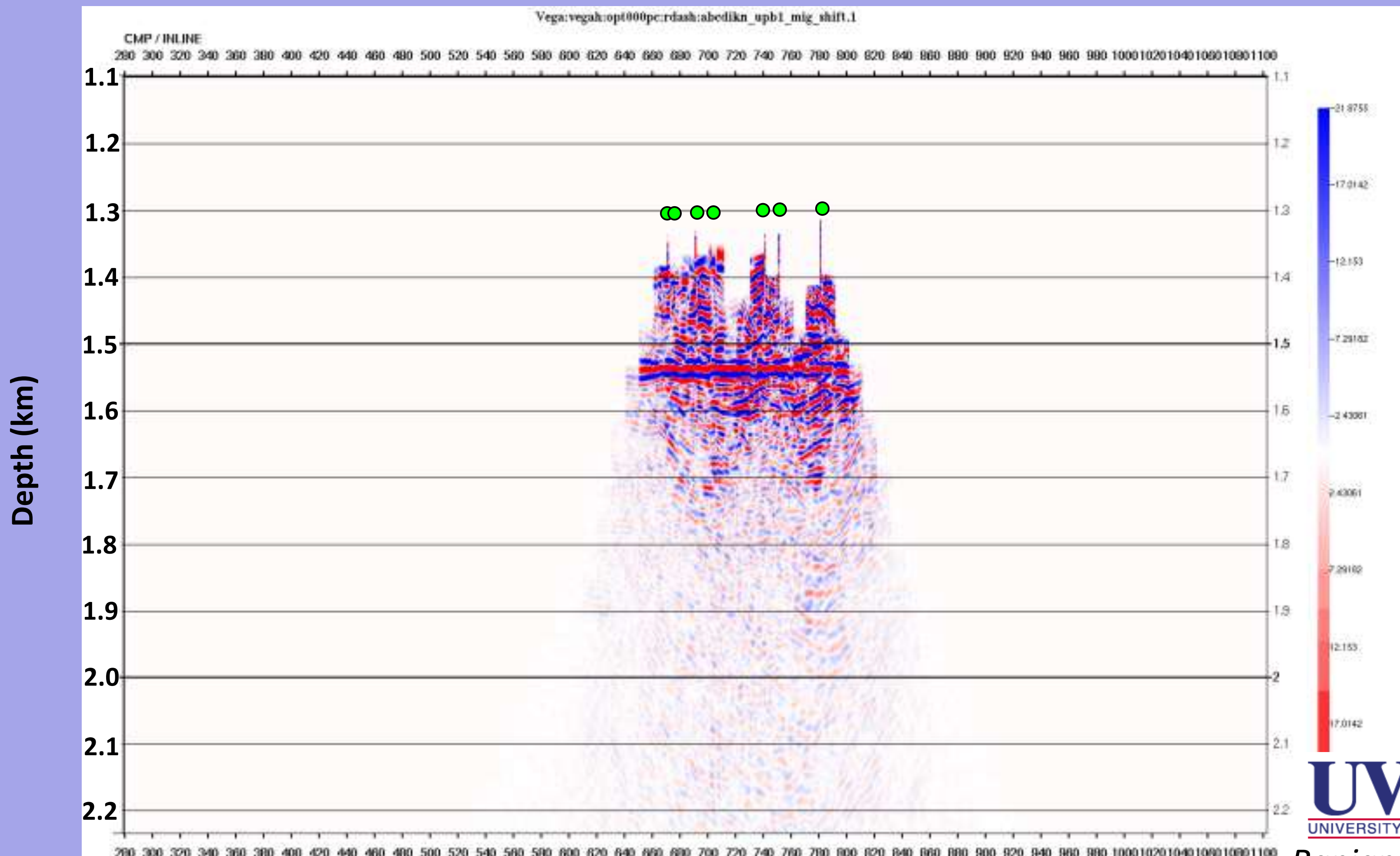


“Mirror” imaging
Receiver side multiple, down-going wavefield



Mirror imaging

Upgoing (conventional) Image



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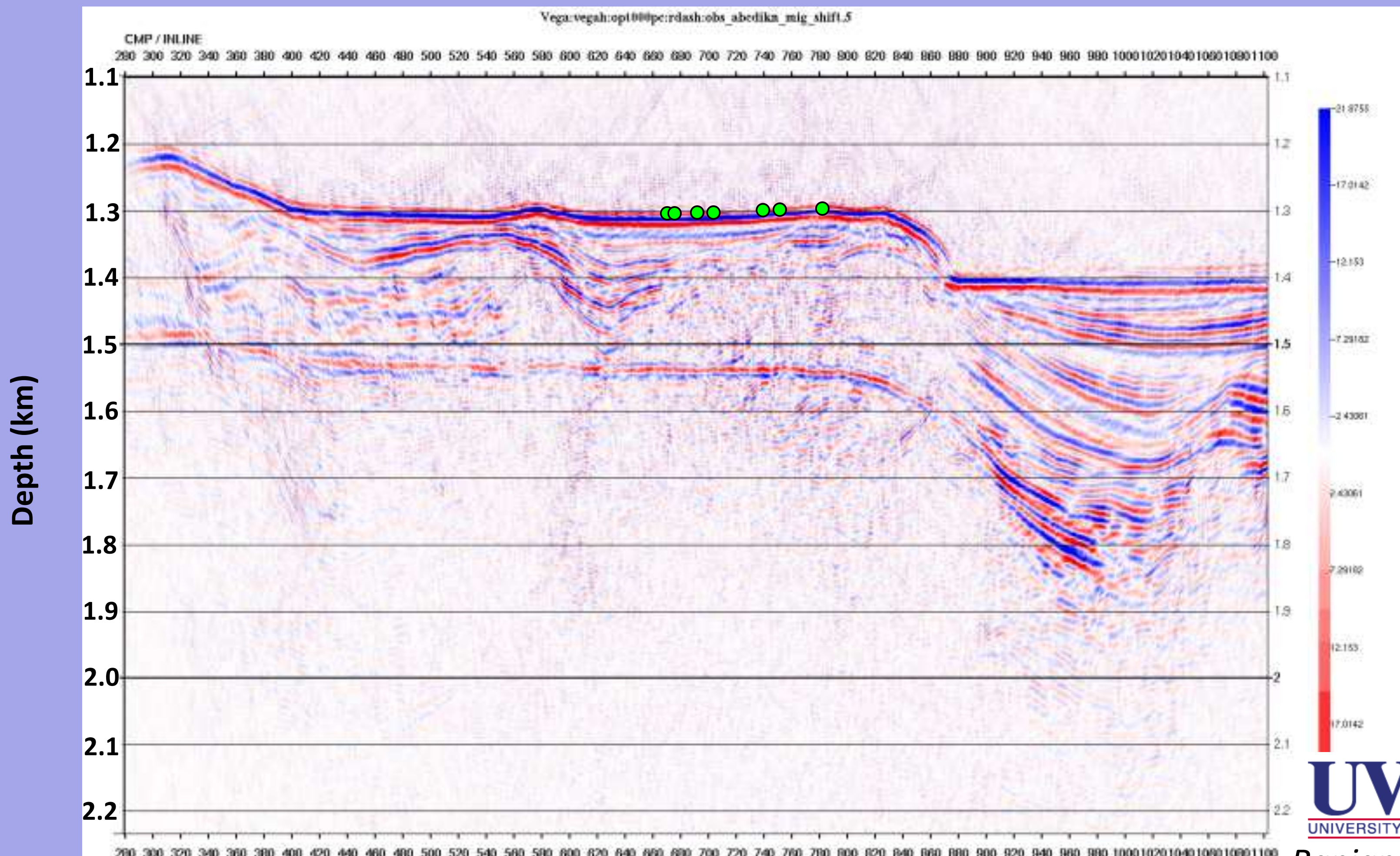
Ranjan Dash

Mirror imaging

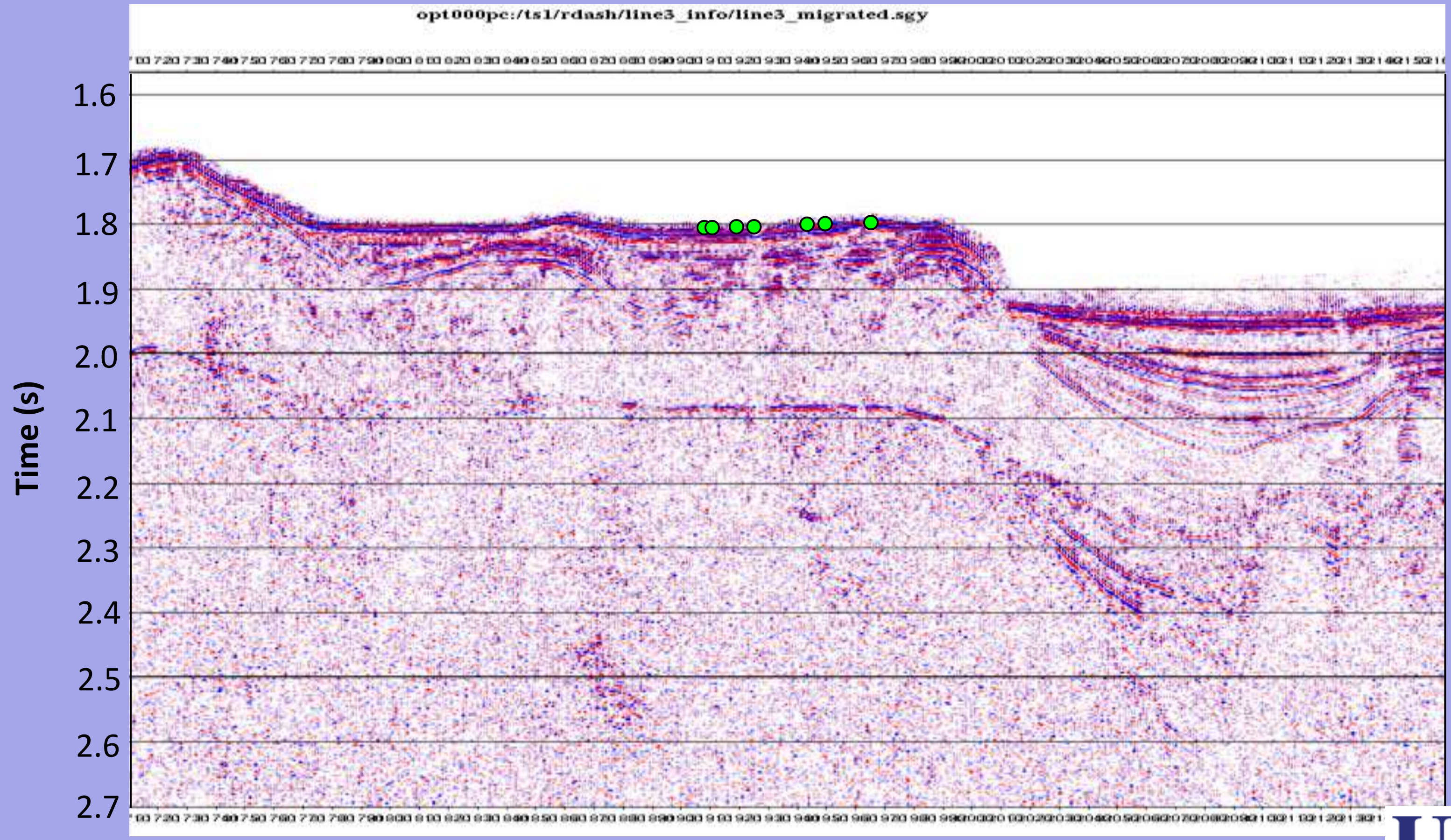
Downgoing (mirror) Image



Ranjan Dash

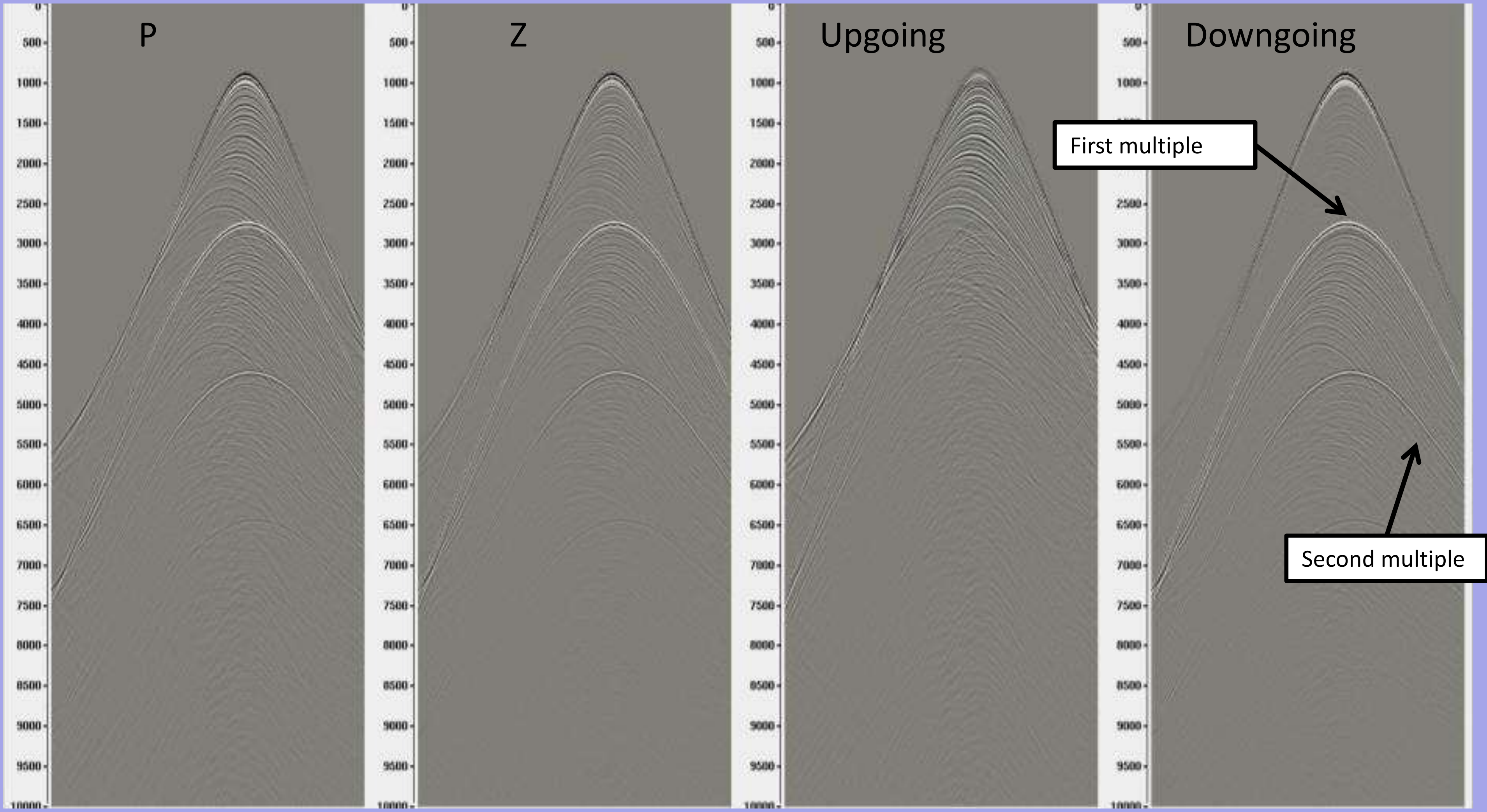
Mirror imaging

Short Streamer data



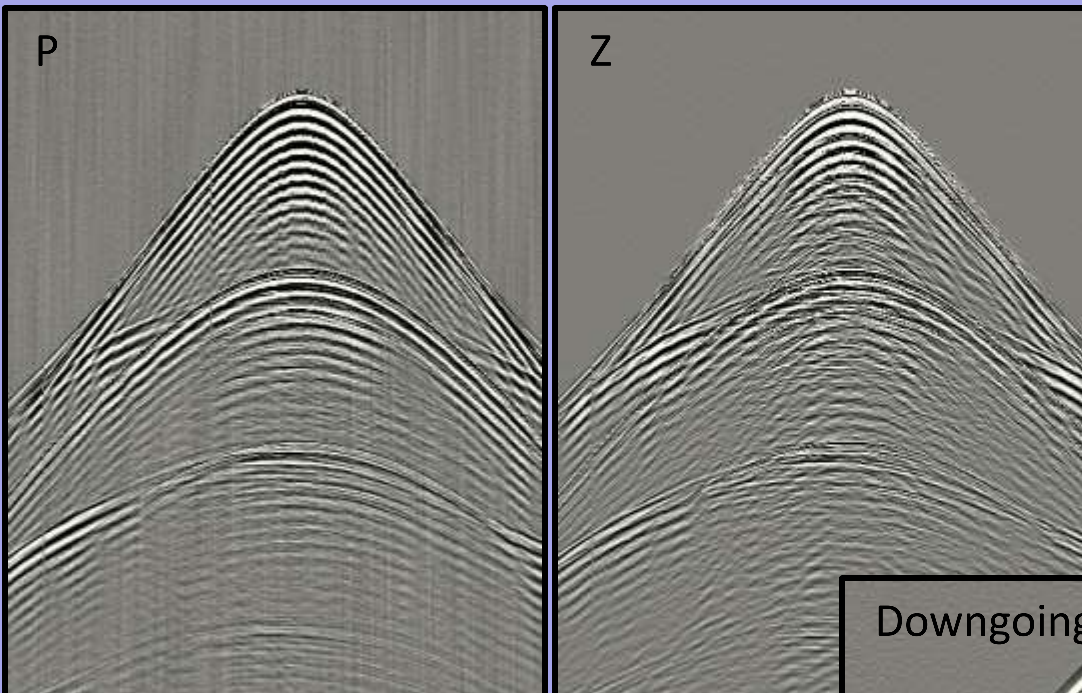
Ranjan Dash

Mirror imaging

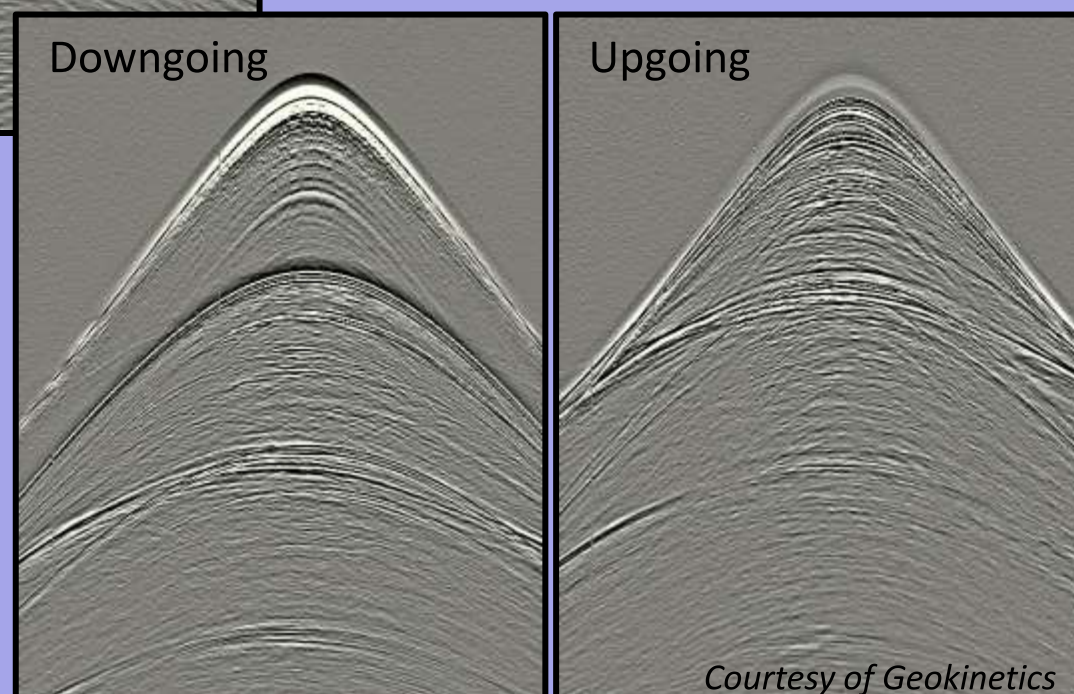


Courtesy of Geokinetics

Mirror imaging



Example – Raw input data



After PZ calibration, debubble operator, Vz noise attenuation and PZ combination.

Summary

Upsides

- Operationally, OBN acquisition is very efficient in presence of
  - Surface obstructions (impeding use of towed streamer)
  - Seabed obstructions, rugged seafloor (impeding use of ocean bottom cables/OBC)

- Ocean bottom nodes provide an ideal data set
  - Full & even surface azimuth/offset distribution
  - Low ambient noise environment
  - Ideal sensor coupling
  - Full waveform recording: P-wave and S-wave arrivals
  - Naturally rich in low frequencies, no compromise at high end

Downsides

- Autonomous recording
  - Requires elaborate clock drift correction
  - Node reliability

- Sparse receivers, limiting shallow illumination
  - Can be resolved by multiple (mirror) imaging
  - Problematic for converted wave imaging

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