# Module 5: BroadBand Seismic and Beyond

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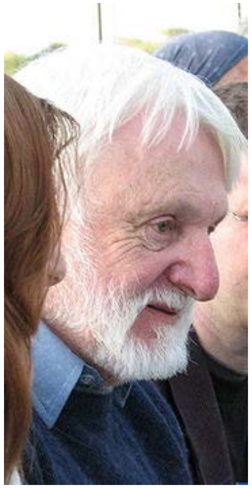
April 25, 2013

*“Technology presumes there’s just one right way to do things and there never is.“*
Robert M. Pirsig (1928–), American writer and philosopher



Each of the vendor’s BroadBand seismic solutions has unique capabilities. There is not one right way to do things.



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# CONTENTS

- Definitions: Octave, Bandwidth, Resolution
- The benefits of the low frequencies
- Processing technologies
- Acquisition technologies
- …

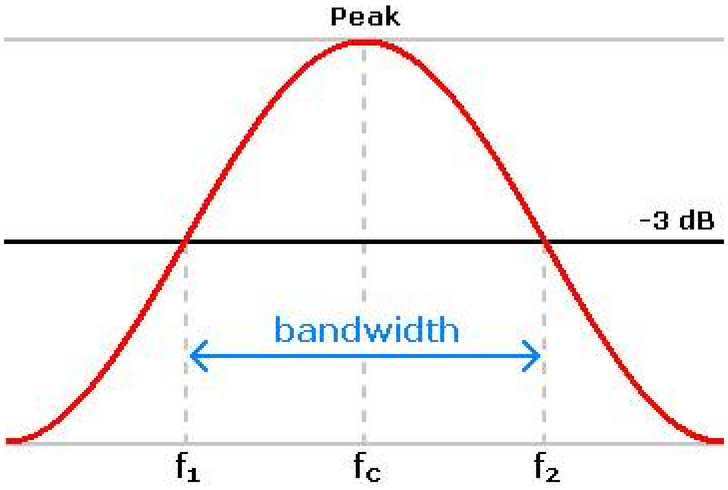
# OCTAVE

- An octave refers to the interval between one frequency and its double or its half
- There is one octave band between frequencies 10 Hz and 20 Hz
- There is another one octave band between 10 Hz and 5 Hz
- The audio spectrum from ~ 20 *Hz* to ~ 20 *KHz* can be divided up into ~ 11 octave bands: 20-40, 40-80, 80-160, 160-320, 320-640, 640-1280, 1280-2560, ….
- f1 to f2 > f1 represents one octave if f2 = 2 f1
- f1 to f0 < f1 represents one octave if f0 = f1/2

# BANDWIDTH VS RESOLUTION

- Improving bandwidth and resolution has been a priority since the early days of the seismic method – to see thinner beds, to image smaller faults, and to detect lateral changes in lithology
- Sometimes used synonymously, but represent different concepts
- There is no single universal precise definition of bandwidth, but it is vaguely understood to be a measure of how wide a function is in the frequency domain

- *Bandwidth describes simply the breadth of frequencies comprising a spectrum. This is often expressed in terms of octaves.*





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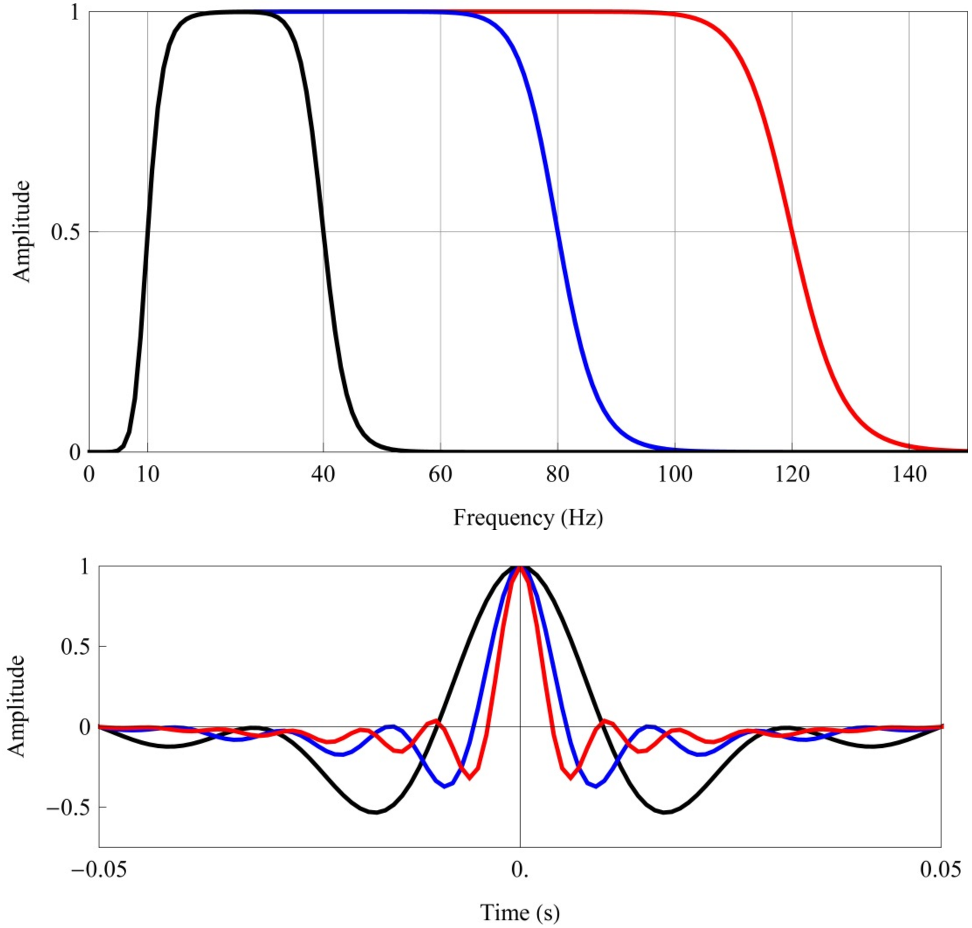
# RESOLUTION

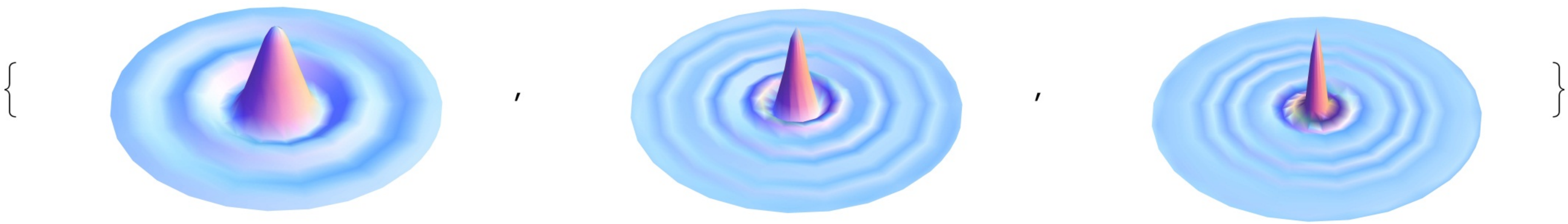
- The classic definition of resolution is the ability to distinguish two features from one another
- The seismic method is limited in its ability to resolve or separate small features that are very close together in the subsurface
- The definition of ‘small’ is governed generally by the *seismic wavelength*, $\lambda = v/f$
- Geophysicists can do little about a rock’s velocity, but they can change the wavelength by working hard to change the frequency
- Reducing the wavelength by increasing the frequency helps to improve both temporal/vertical and spatial/horizontal resolution

# TEMPORAL RESOLUTION




*TR = 1 ⁄ (1.5 FMAX)*

# SPATIAL RESOLUTION
## (Post-stack migration of point diffractor response)



10-40 Hz | 10-80 Hz | 10-120 Hz

# TEMPORAL RESOLUTION

- In a classic empirical study, Kallweit and Wood (1982) found a useful relationship between bandwidth and resolution. For a zero-phase wavelet with *at least* two octaves of bandwidth, they showed that the temporal resolution *TR* in the noise-free case could be expressed as

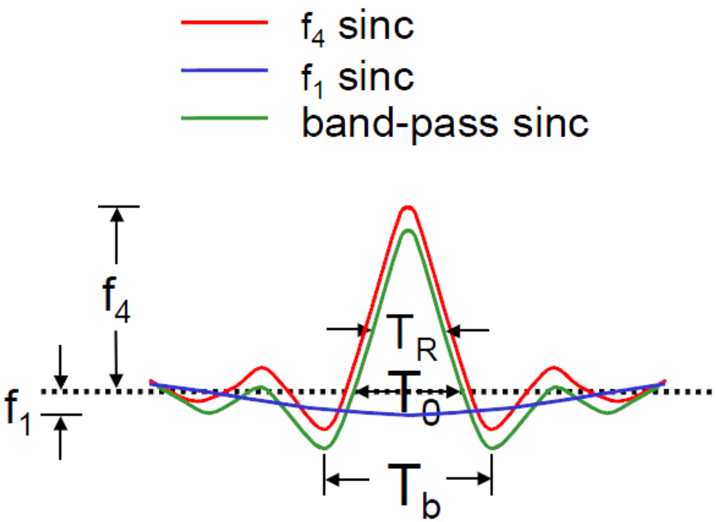
  $$TR = 1/(1.5\ FMAX)$$

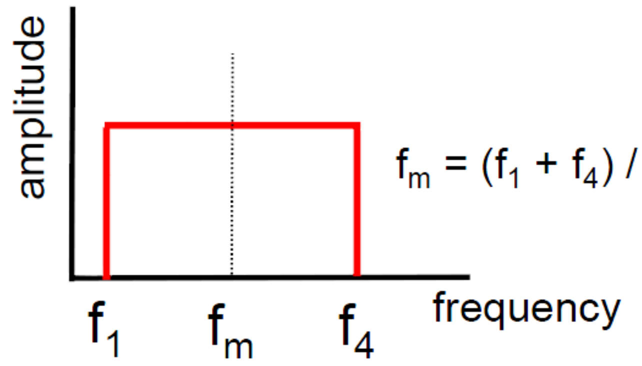
  where *FMAX* is the maximum frequency in the wavelet

- Other definitions are possible, but for two octaves or more of bandwidth the clue is that one can approximately relate temporal resolution to the highest, and only the highest, frequency of a wavelet. This leads to some very useful and quite accurate predictions

# Temporal Resolution ($T_R$) of the Bandpass Sinc Wavelet

$$K_t = \frac{2 f_4 \sin(2\pi f_4 t)}{(2\pi f_4 t)} - \frac{2 f_1 \sin(2\pi f_1 t)}{(2\pi f_1 t)}$$




| | | | |
|---|---|---|---|
| temporal resolution: | $T_R$ | $= 1 / (1.5) f_4$ | ; 2 octaves (where $f_4 / f_1$ .ge. 4) |
| wavelet breadth: | $T_b$ | $= 1 / (0.7) f_4$ | ; 2 octaves (where $f_4 / f_1$ .ge. 4) |
| peak-to-trough: | $T_b / 2$ | $= 1 / (1.4) f_4$ | ; 2 octaves (where $f_4 / f_1$ .ge. 4) |
| 1st zero crossings: | $T_0$ | $= 1 / (2 f_m)$ | ; all octaves |
| relationship of $T_b$ to $T_R$: | $T_R$ | $= 0.47 T_b = 0.93 T_b / 2$ | ; for sincs .ge. 2 octaves |

$T_R$ of sinc and Ricker wavelets are equal when $f_1$ (peak frequency Ricker) = $f_4$ (sinc) / 2

*Seismic Resolution of Zero-Phase Wavelets, R. S. Kallweit and L. C. Wood, Amoco Houston Division DGTS, January 12, 1977*

*G. Partyka (Oct 06)*



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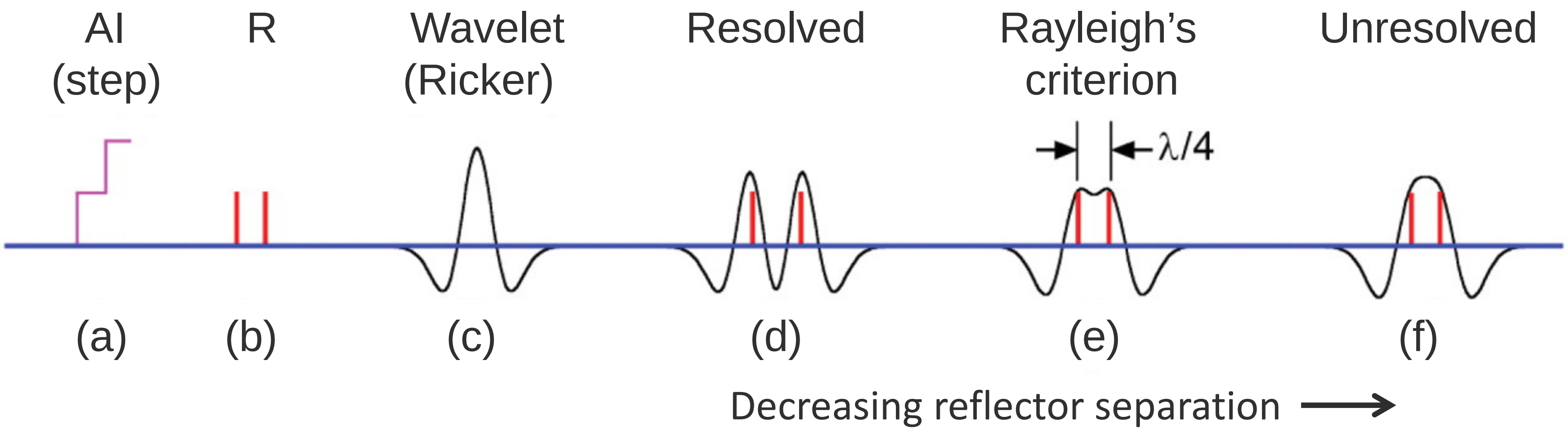


*Different limits of vertical resolution (d-f, after Kallweit and Wood, 1982; Zeng, 2009) for a step-wise acoustic impedance (AI) profile (a) giving rise to two reflection events R of same polarity (b). Resolution can be increased by increasing the high-frequency content of the seismic wavelet.*
*Rayleigh criterion occurs when a distinct peak-trough-peak character becomes perceptible*

# THE BENEFITS OF LOW FREQUENCIES

- Better resolution
  - low frequencies reduce sidelobes

- Deeper penetration
  - low frequencies scatter less and suffer less from absorption

- Waveform and impedance inversion
  - low frequencies reduce number of local minima
  - low frequencies reduce the need for well-derived velocities to fill the traditional band-gap in impedance inversion



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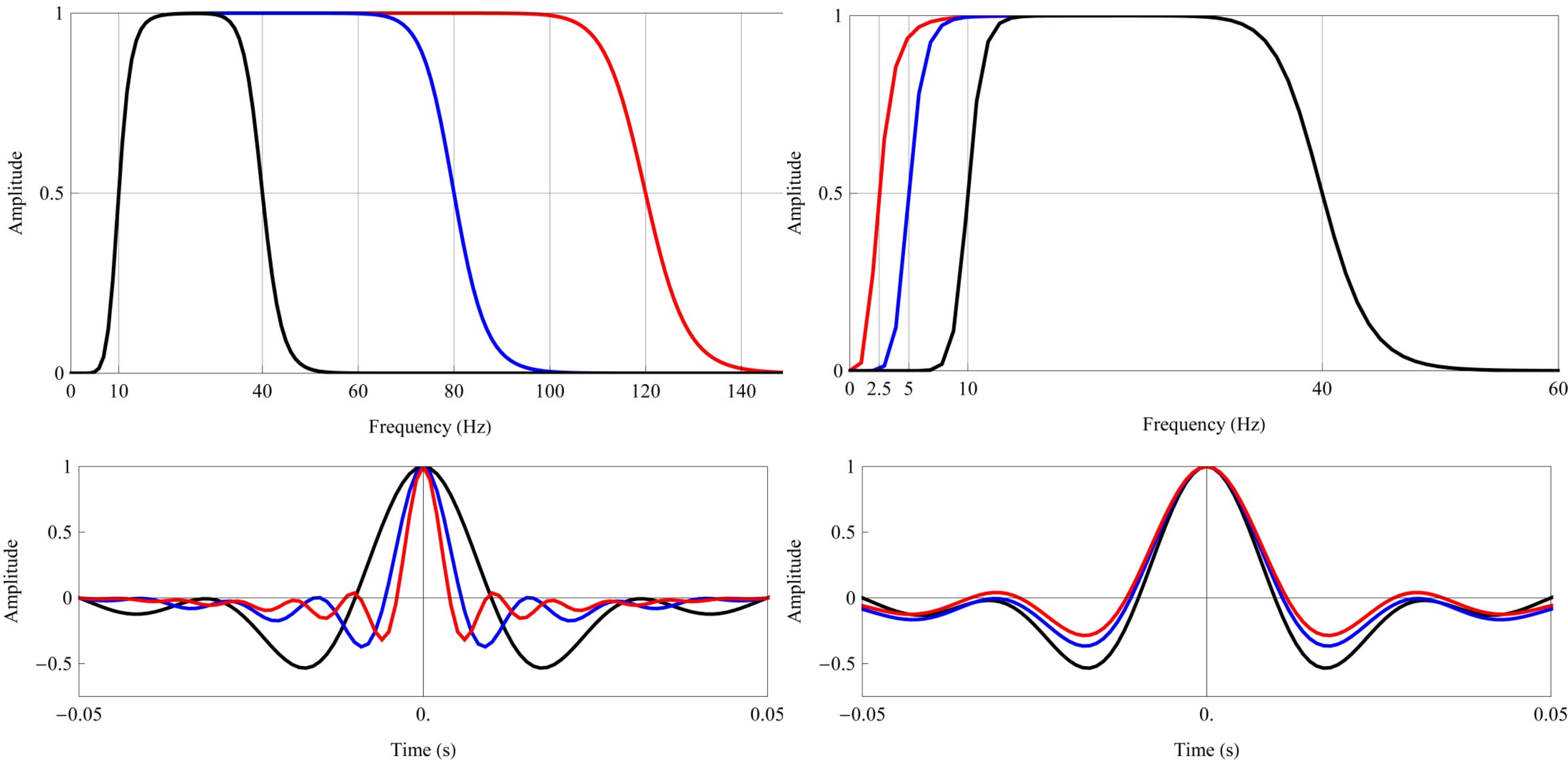
# Low frequencies reduce side lobes

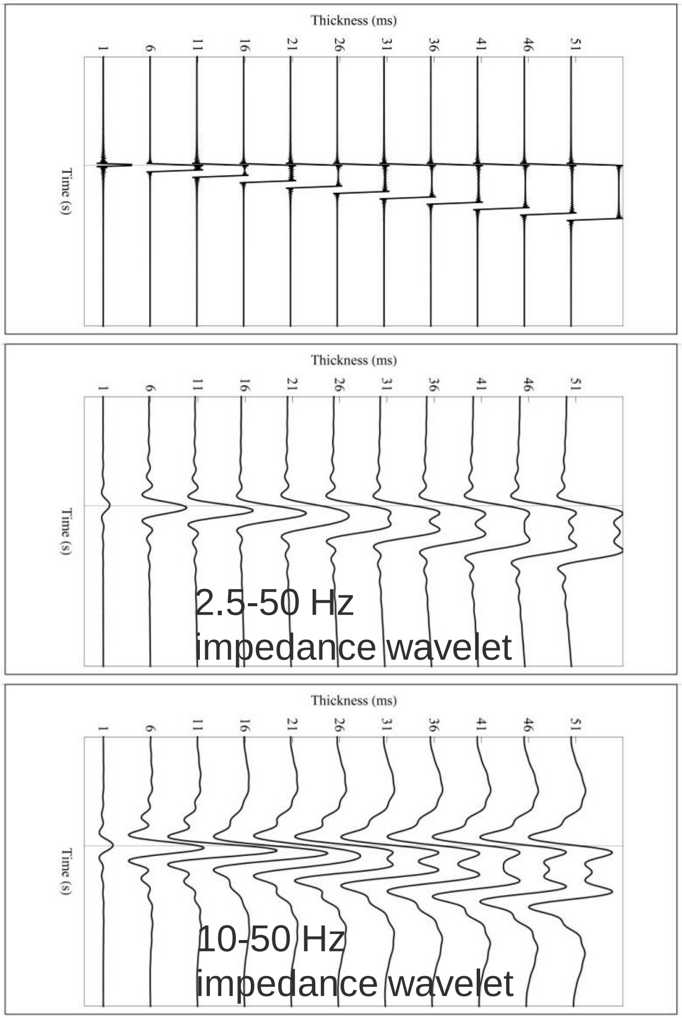



More high-frequencies → better resolution

More low-frequencies → less side-lobes

# WEDGE MODEL AND ITS RESOLUTION

- Wedge model gives interference of a positive and equal strength negative reflection at various time intervals
- Time integration of reflection spikes gives impedance
- Time integration of reflection wavelets
- = **relative impedance inversion** depends on frequency content
- Sidelobes are significantly reduced when low frequencies are put into wavelet

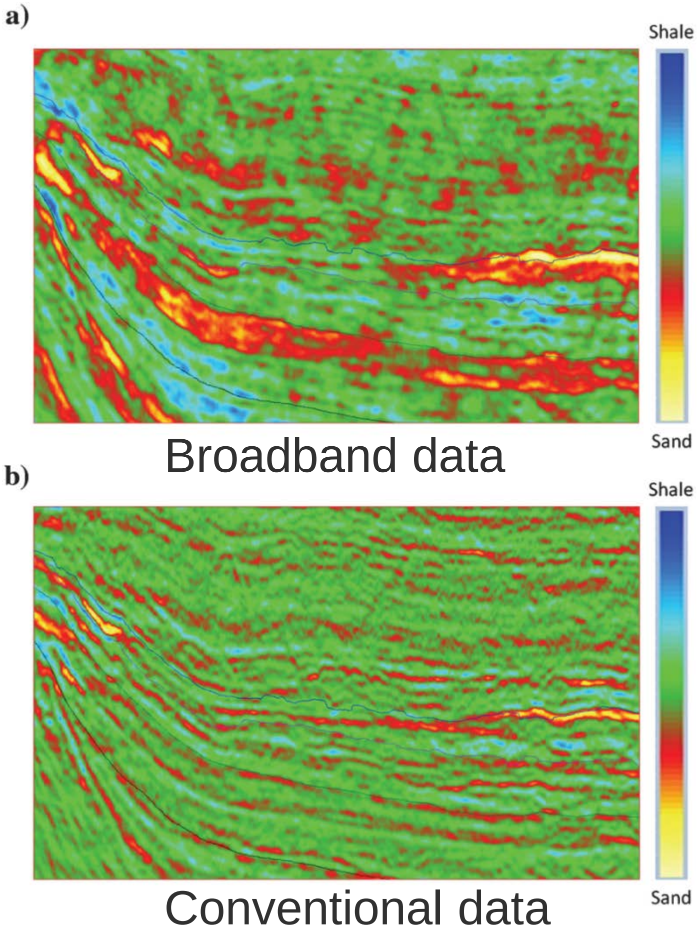


# IMPEDANCE INVERSION WITHOUT ADDING WELL INFORMATION

GEOPHYSICS, VOL. 78, NO. 2 (MARCH-APRIL 2013); P. WA3–WA14
Broadband seismic data — The importance of low frequencies
Fons ten Kroode, Steffen Bergler, Cees Corsten, Jan Willem de Maag, Floris Strijbos and Henk Tijhof

Often conventional seismic lack low frequencies so that a low frequency model must be included in the inversion process to recover absolute impedance values. Typically, low frequency models are obtained from low-pass filtered impedance logs.

Broadband seismic are better suited for inversion as they provide directly the missing low frequencies, hence removing the need to build low frequency models from well data.




Broadband data

Conventional data

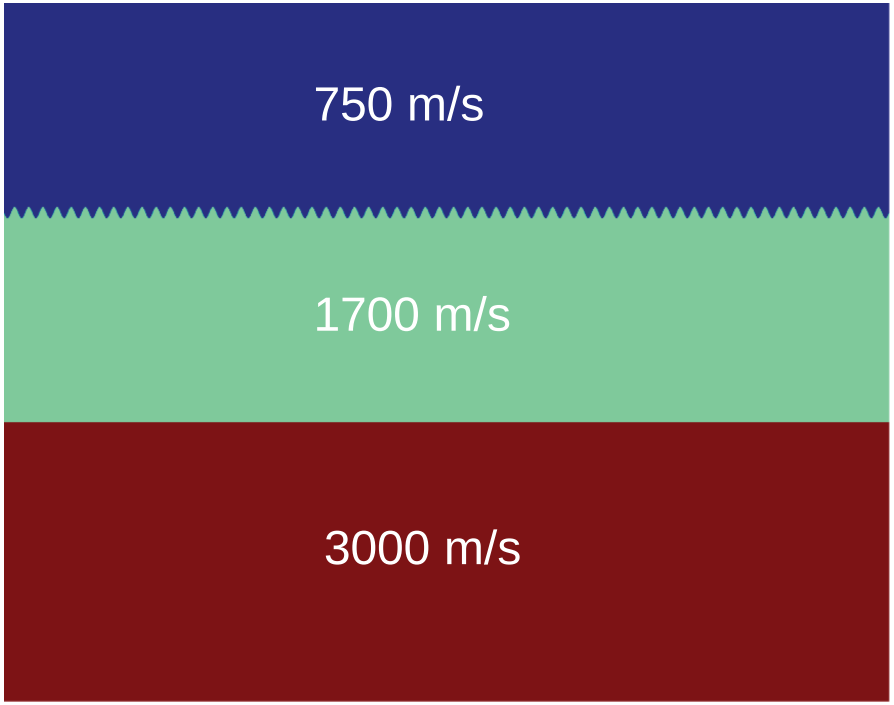
Thick sands (yellow-red) are visible on the broadband data. Shales (blue-green).

# LOW FREQUENCIES SCATTER LESS

- P scattered ~ frequency squared × contrast × incident wavefield
- For low frequencies, or long wavelengths, the scattered wave is negligible to the incident wavefield
- As a consequence, the low-frequency part of the wavefield is influenced  little by small scale inhomogeneities and propagates as if they were not present

# VELOCITY MODEL RUGOSE LAYER

- Wavelength 15 m
- Amplitude 7.5 m
- Incident wave velocity 750 m/s
- Low-frequency source 10-15 Hz
  - Wavelength 50-75 m
- High-frequency source
  - Wavelength 10-15 m

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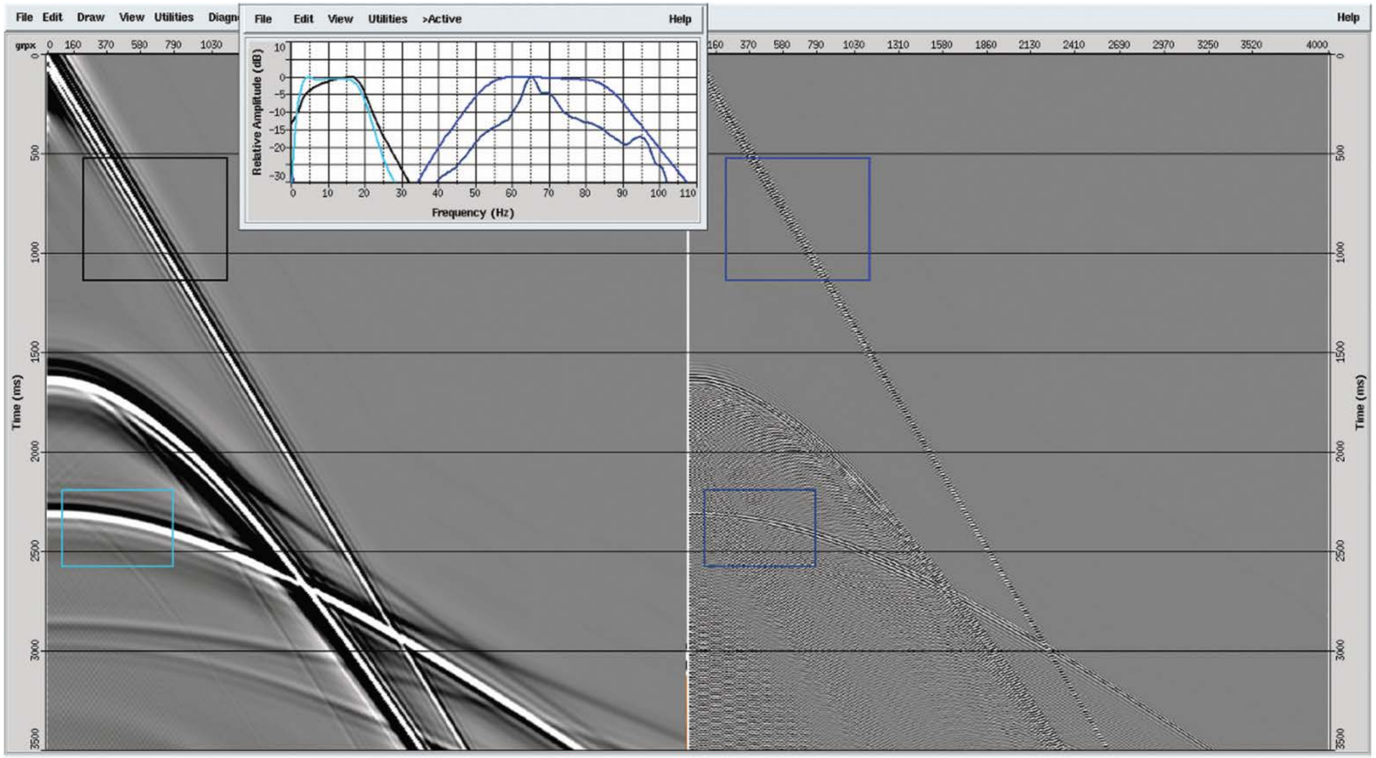
# DATA

Wavelet 10–15 Hz

Wavelet 50–80 Hz

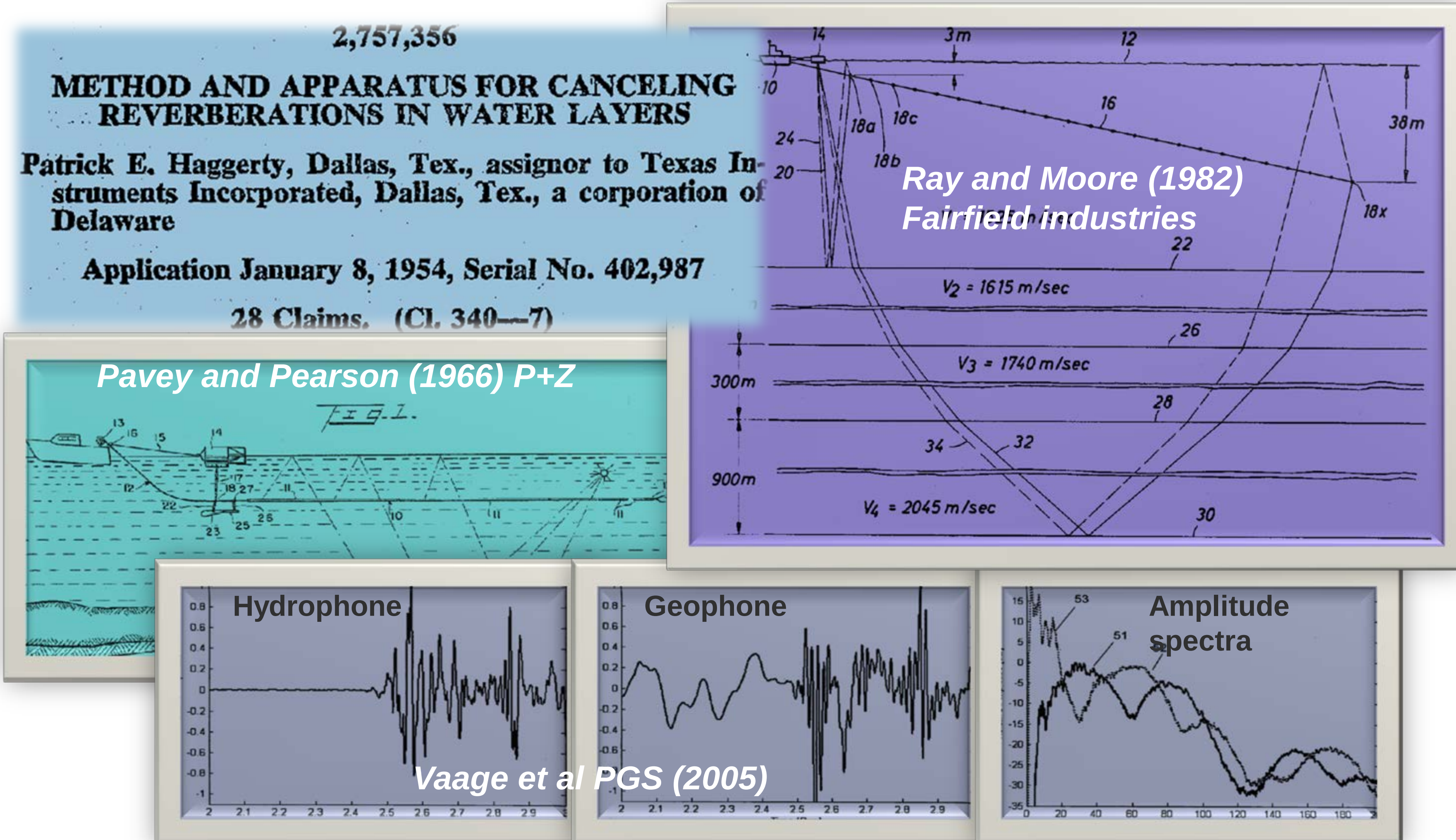



Low-frequency signal reflected and recorded virtually undisturbed by the rugose interface, as if it was not present, whereas the high frequency signal is heavily affected by it.
Note: decibel-amplitude-versus-frequency display.

# ACQUISITION

- Conventional streamer acquisition @ 7.5 m is limited in terms of low frequencies
- Reason: S/N is insufficient
  - Signal low because of receiver ghost
  - Noise too high due to sea surface action
- Deep towing increases S/N
  - Price: second notch limits high frequencies
- Solutions?
  - Over-under streamers
  - Dual-sensor (PZ) streamers
    - Limit to tow depth due to high level of noise on Z for f<20 Hz?
  - Slant streamers
  - ObliQ
  - Multicomponent streamer
  - Data processing

# 1954, 1966, 1982, …, 2005



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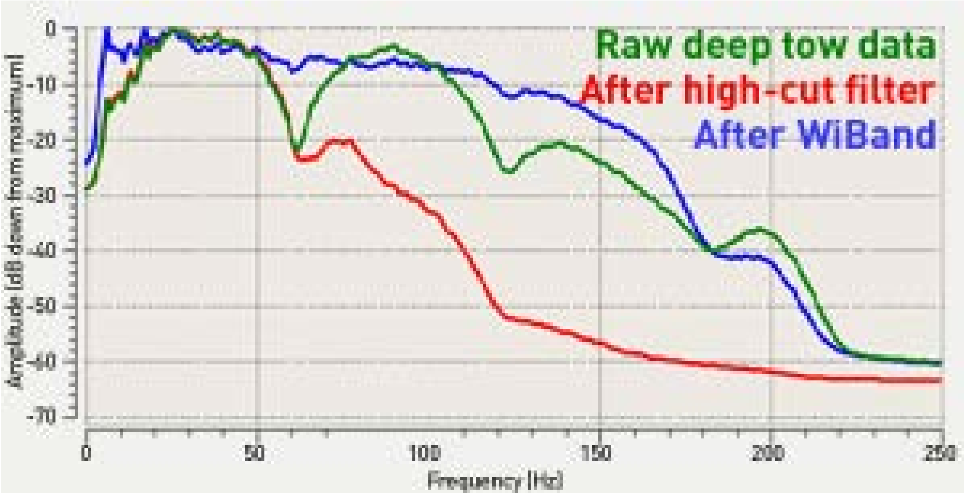
# WiBand (ION) Broad Bandwidth Answer for Conventional Streamer Data

"ION GXT's WiBand data processing technology can remove most of the ghost effects from conventional streamer data. This methodology, a combination of algorithms and workflows, uniquely tackles both the source and receiver ghosts to recover the full spectrum in data acquired using conventional towed streamers, delivering superior broadband images."

Zhou, Z., M. Cvetkovic, B. Xu, and P. Fontana, 2012, Analysis of a broadband processing technology applicable to conventional streamer data: First Break, 30, 77-82.

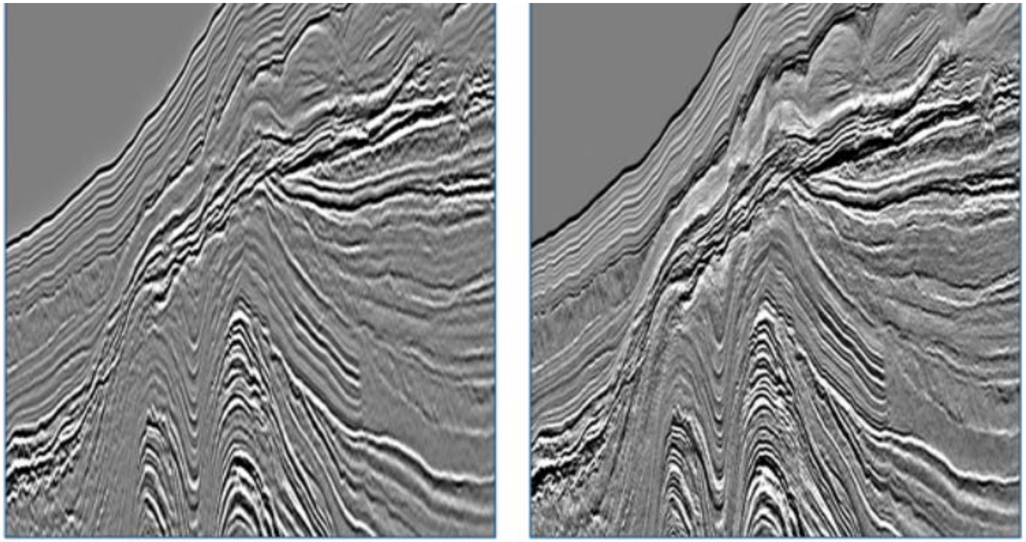



http://www.iongeo.com/Products_Services/Data_Processing/PreProcessing/WiBand/

# Clari-Fi (TGS), a Technique to Provide Broadband Seismic Data from Conventional Acquisition

"Clari-Fi imaging enhances low and high frequencies and effectively solves for the earth's attenuation, resulting in images that are broadband and focused, thus improving the resolution of the data.
This technique works with conventional streamer acquisition and so enables reprocessing of legacy data."

Deghosting is run in T-p domain.



Data is from a joint TGS/Dolphin Geophysical project

http://www.tgs.com/Subpage.aspx?id=7022&terms=clari-fi

# GeoStreamer (PGS)

"GeoStreamer uses the proprietary buoyant void filler (BVF) technology to provide a low-noise environment for both pressure sensors (hydrophones) and particle velocity sensors (geosensors), collocated at dense intervals along the streamer. Injected into the streamer section as a dense gel, the BVF cures into a material with the physical properties of a solid, and that is environmentally stable even if exposed to water for prolonged periods (for example, in the case of a shark bite)."

www.pgs.com

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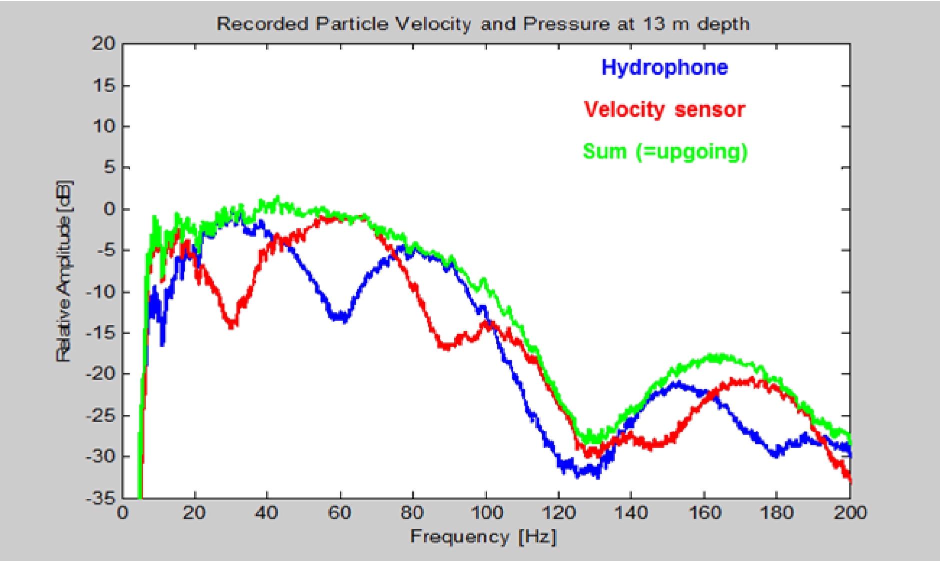
# GeoStreamer (PGS)

- Combines P and Vz into deghosted, up-going wavefield
- Below ~20Hz, Vz predicted from P
- Mostly 2D deghosting, cross-line variation neglected
- Need interpolation or other tricks for 3D deghosting




GEOPHYSICS, VOL. 78, NO. 2 (MARCH-APRIL 2013); P. WA55–WA70
**Wavefield-separation methods for dual-sensor towed-streamer data**
Anthony Day[1], Tilman Klüver[1], Walter Söllner[1], Hocine Tabti[1], and David Carlson[2]

www.pgs.com

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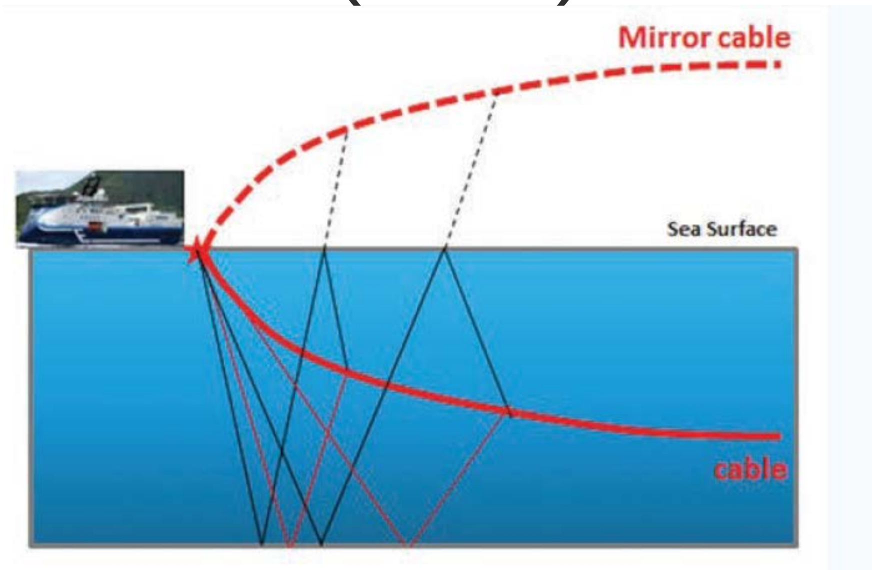
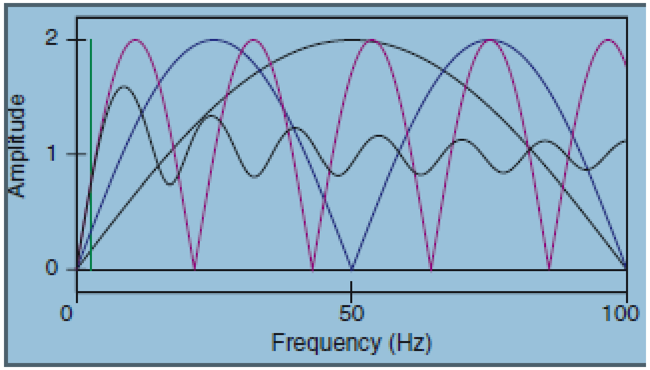
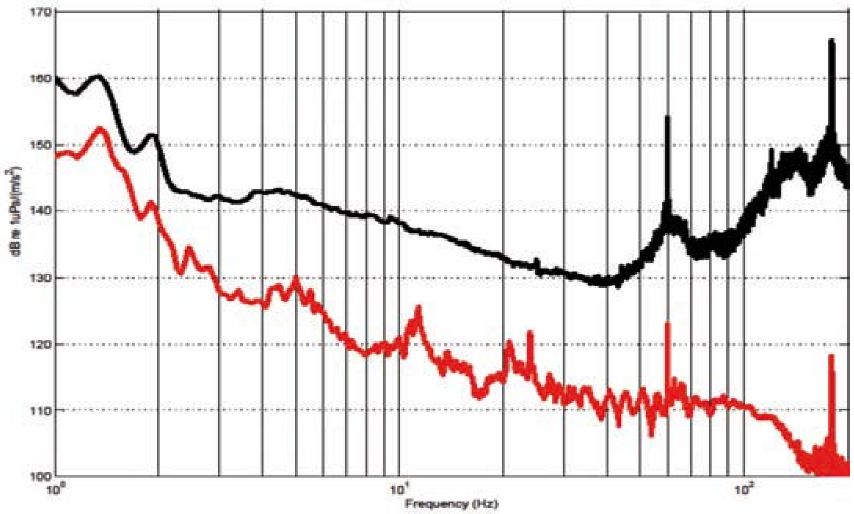
# BroadSeis (CGG)




*Receiver ghost amplitude spectrum for different streamer depths: red: 7.5 m, blue: 15 m, purple: 35 m, black: variable-depth 7.5 to 50 m with an average of 35 m. The low-frequency slope of VDS is the same as the purple curve. This is a very high slope, with significant energy at 2.5 Hz (green line).*

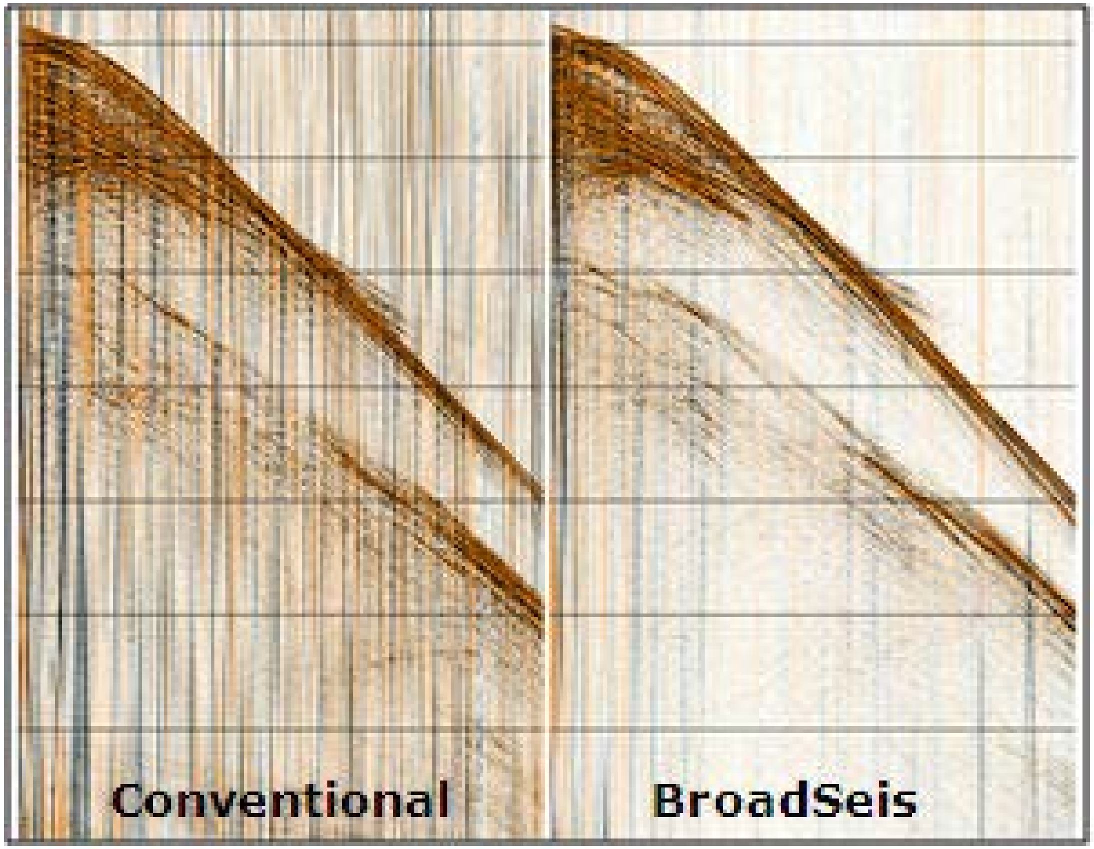
"Builds on the advantages of the Sentinel solid streamer with its extremely low noise characteristics and precise low-frequency response to give the highest S/N ratio available" [www.cgg.com](www.cgg.com)




*Noise performance of a Sentinel solid streamer compared with a gel-filled streamer in a vibration tank test.*


GEOPHYSICS, VOL. 78, NO. 2 (MARCH-APRIL 2013); P. WA27–WA39
**Variable-depth streamer acquisition: Broadband data for imaging and inversion**
Robert Soubaras and Yves Lafet

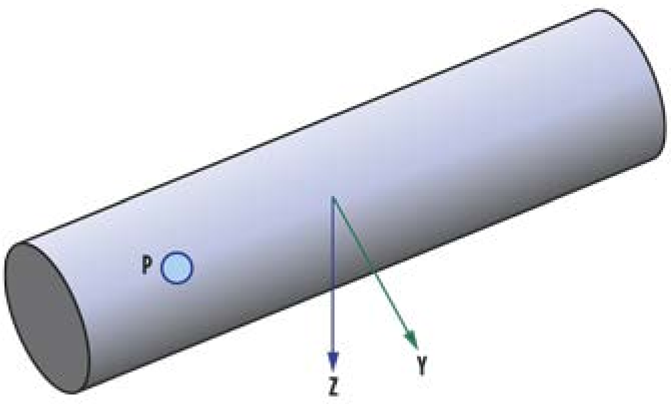
# BroadSeis (CGG)



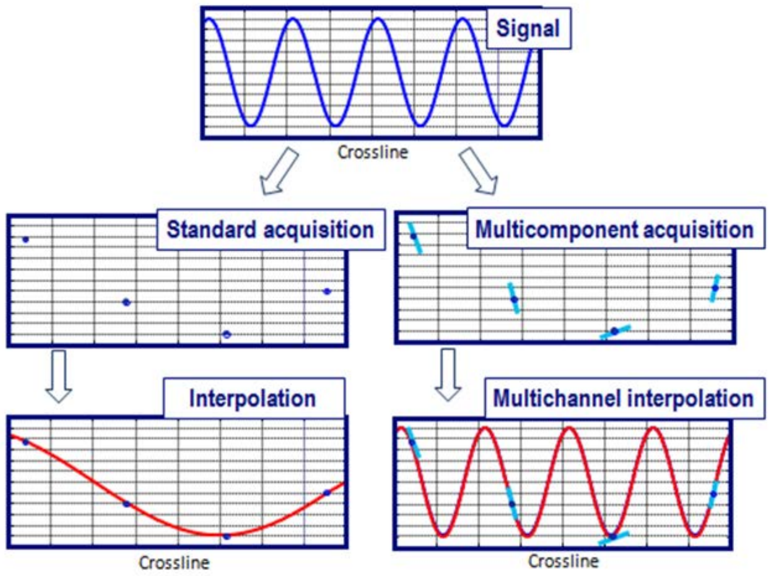

“Shot gathers, acquired in marginal weather, show how BroadSeis' deep tow reduces weather-related noise and so extends the weather window”

www.cgg.com

# IsoMetrix (WesternGeco)




Nessie-6 streamers deliver point-receiver sampling of pressure (hydrophone) and MEMS-based measurements of acceleration that provide Vy and Vz datasets for wavefield reconstruction




“Measurement of Vy enables unaliased reconstruction of the wavefield between streamers.”

Blue signal is the actual signal, and the red signal shows the reconstructed signal. The figures contrast reconstructed signal with P-only measurements, as recorded in conventional surveys (top) versus P + Vy as recorded in IsoMetrix surveys (bottom).

www.westerngeco.com



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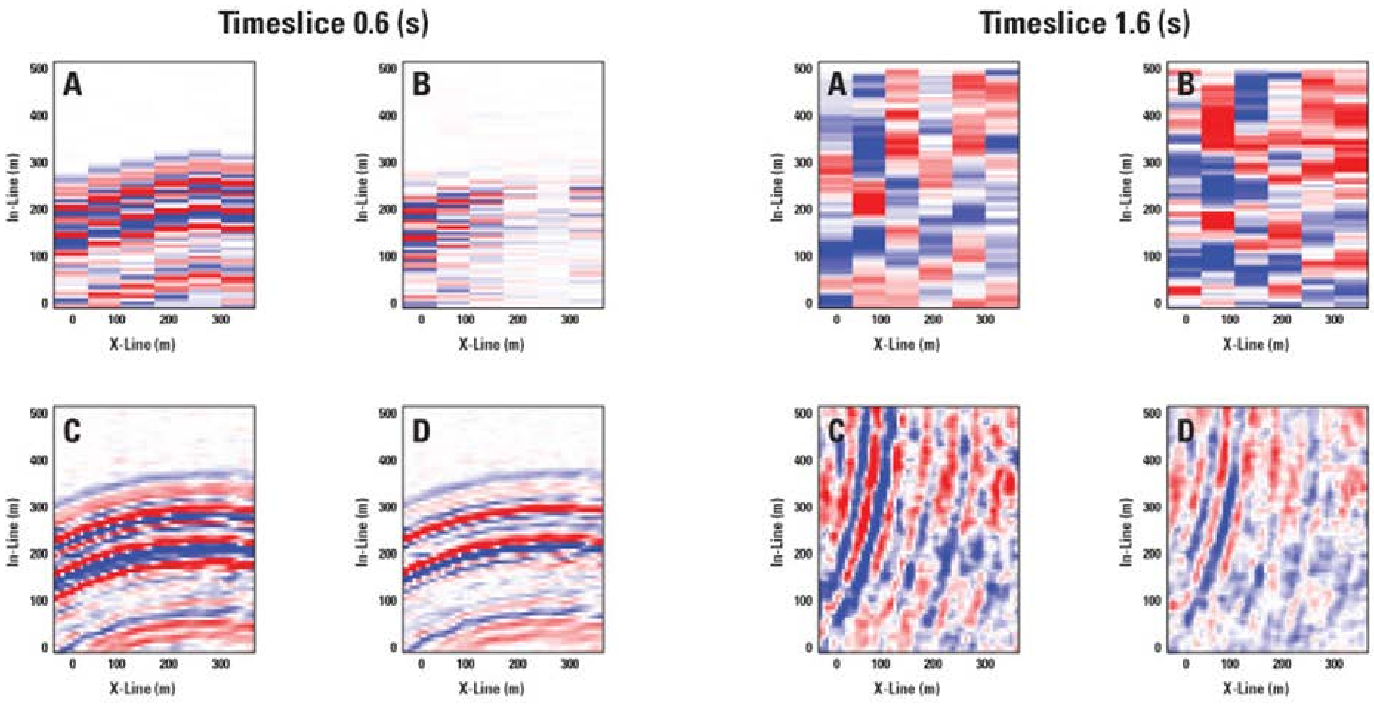
# Data examples (IsoMetrix)




Data examples from a: A) Input P, 6.25 m (inline) x 75 m (crossline) sampling; B) Input Vy, 6.25 m (inline) x 75 m (crossline) sampling; C) Reconstructed P, on a 6.25 m x 6.25 m grid; D) Deghosted P, on a 6.25 m x 6.25 m grid (Özbek et al 2013).

# Why so difficult to make low frequency?

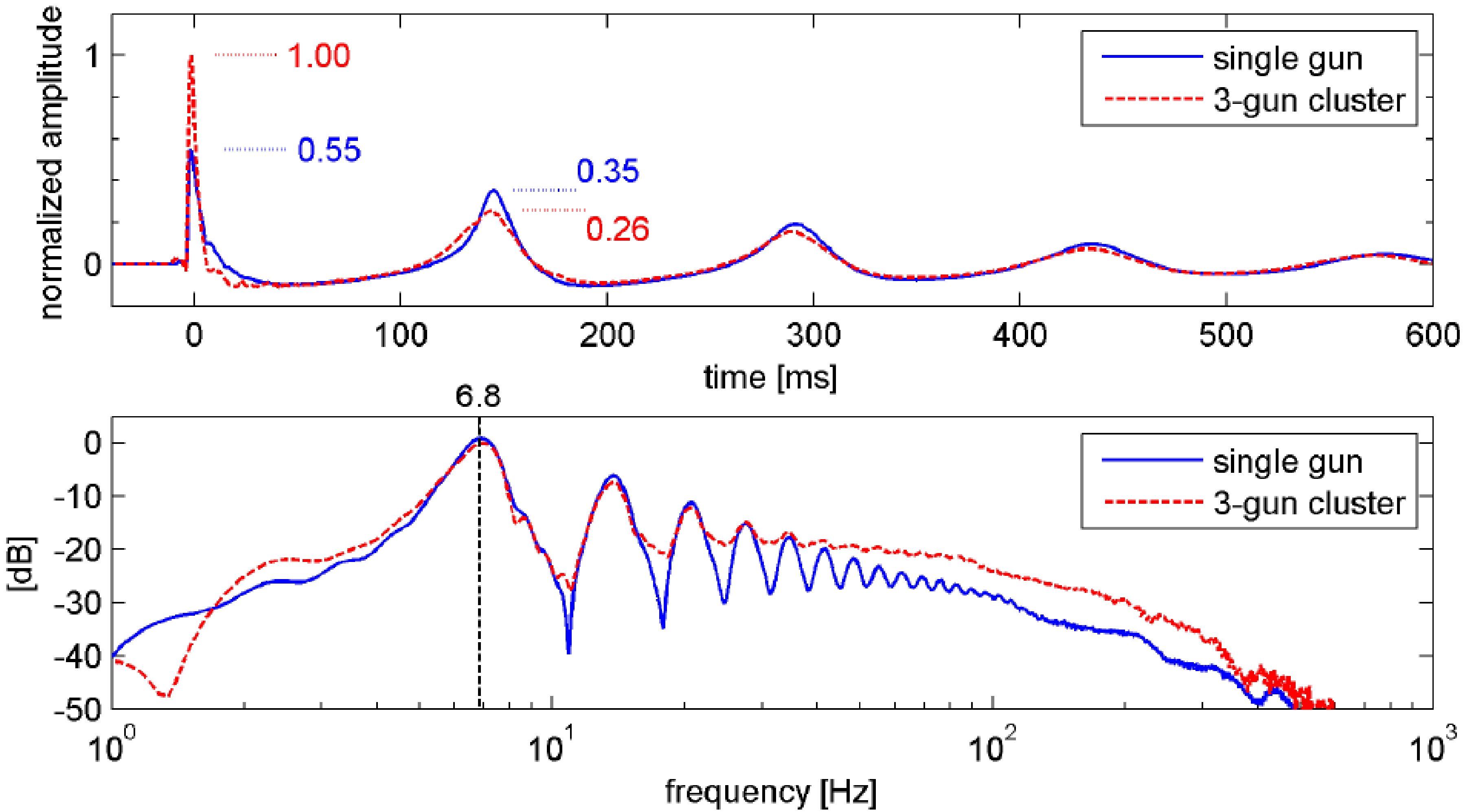
- Free surface effect – strong for low frequency

- Limit on volume and pressure:

$$T \propto \frac{P^{1/3} V^{1/3}}{P_h^{5/6}}$$

- Vibrators will be big as well

# 600 cubic inch (both), 6 m depth *Hopperstad et al. EAGE 2012*




Near field measurements – note that 3-gun cluster gives slightly more energy around 2-4 Hz

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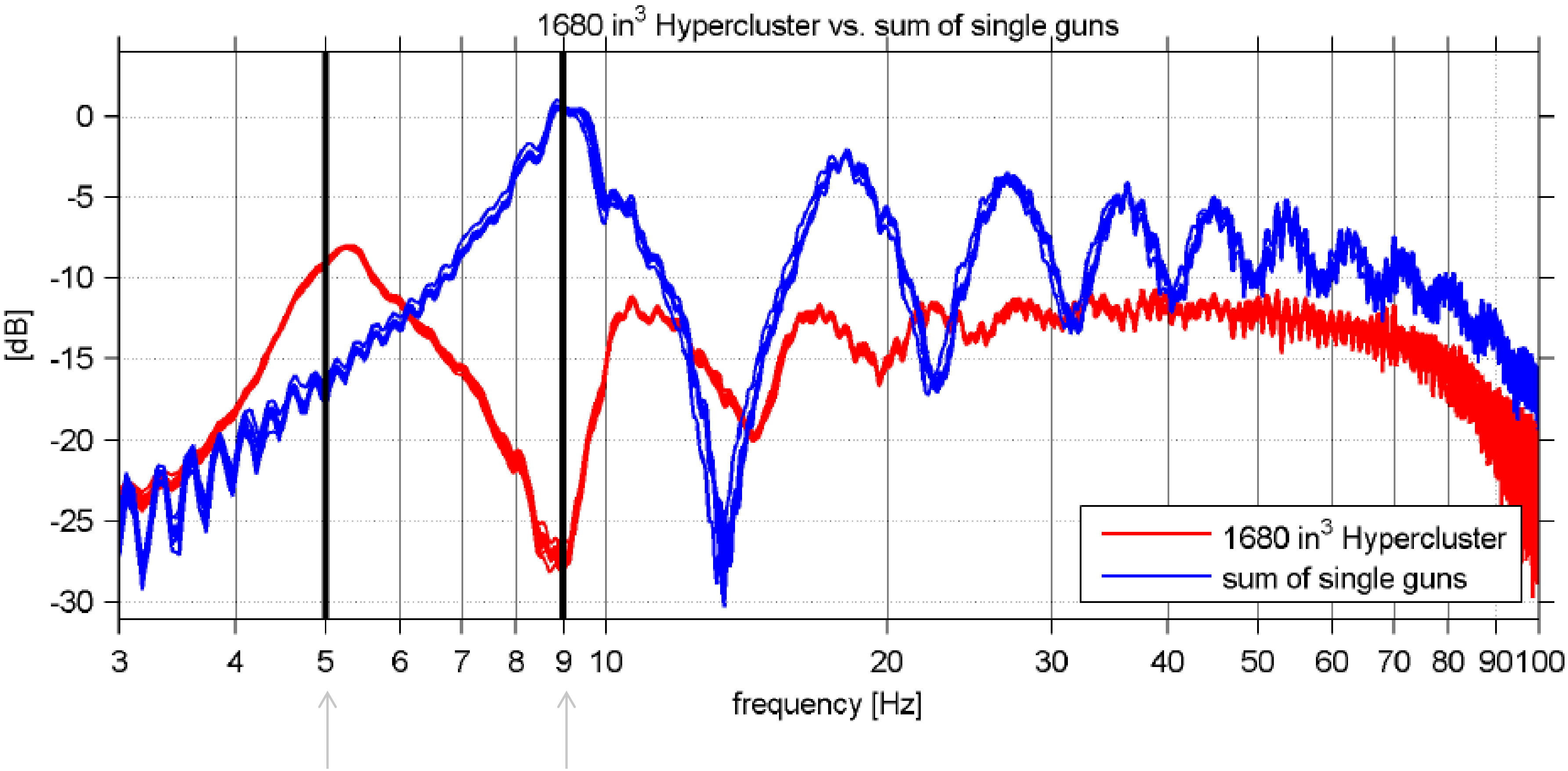
# Airgun hyperclusters *Hopperstad et al. EAGE 2012*




Theoretical bubble frequecies fit nicely with measured data

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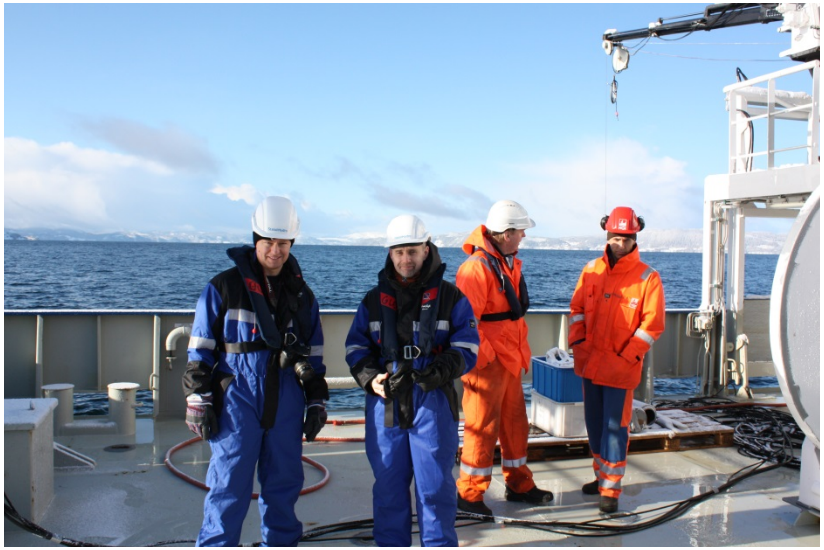
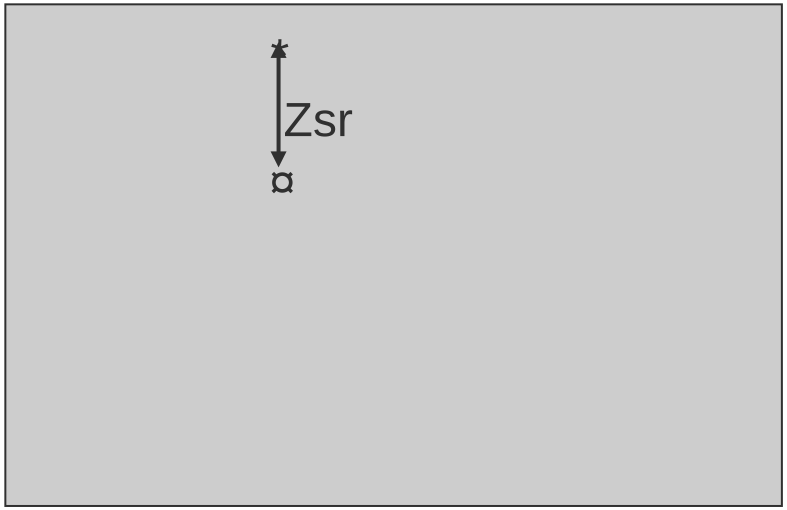
# Gunnerus test – Feb 2009 Trondheimsfjorden






The source depth is varied from 3 to 40 m, and the distance between the source and the hydrophone is kept constant: Zsr = 20m. Water depth is ~300 m .

Source volume: 600 cubic inch Bolt
Firing pressure: 2000 psi

- TC4047 hydrophone

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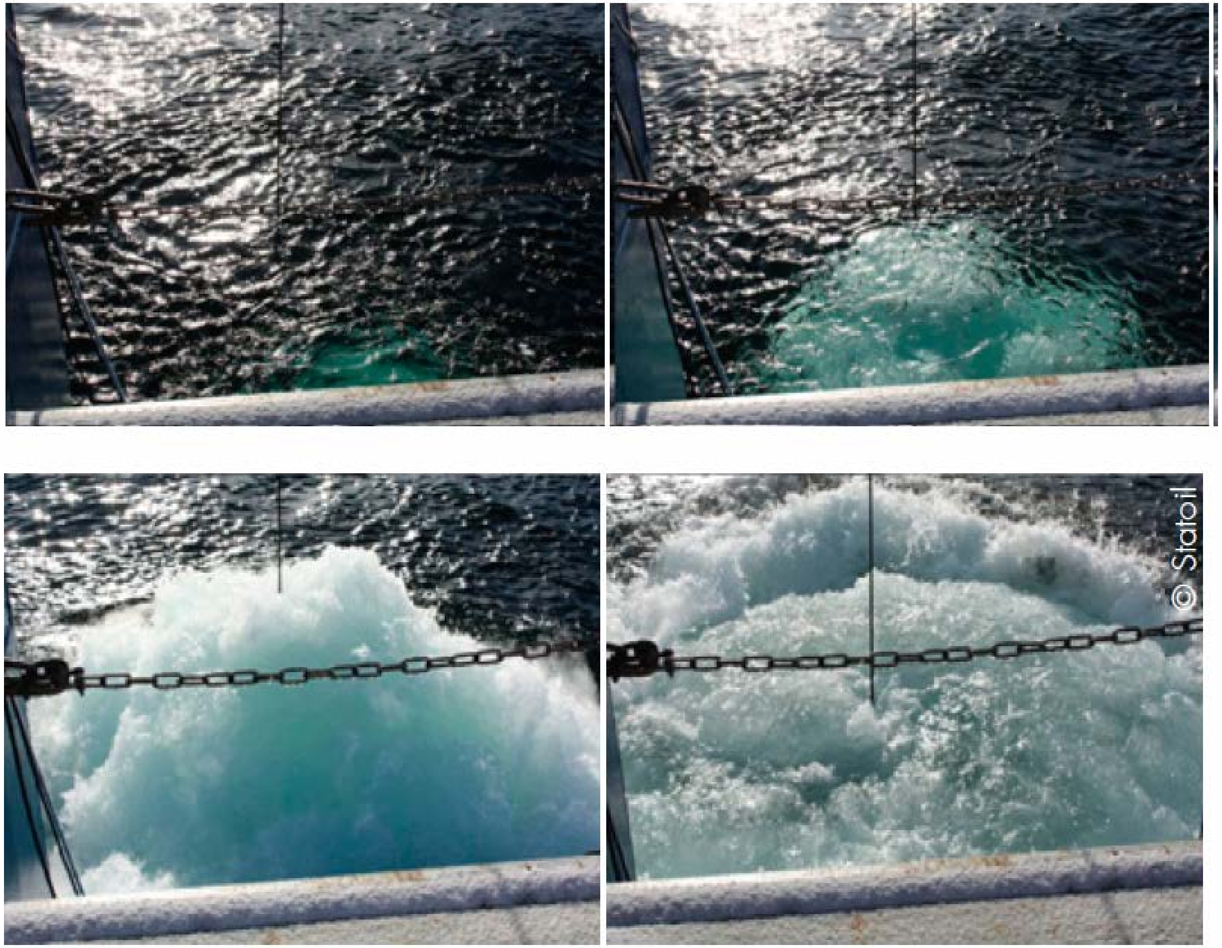
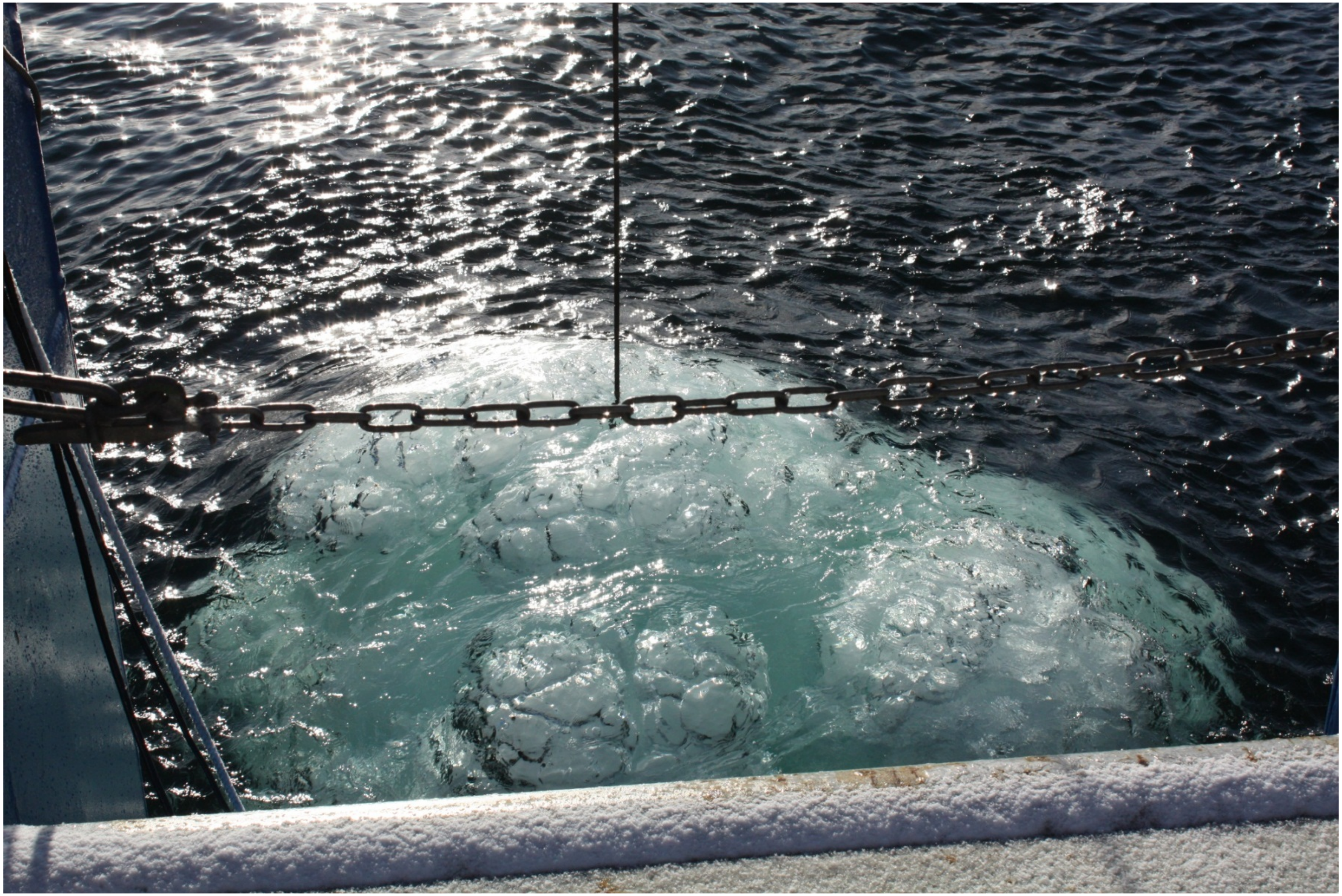
# Firing a 600 cubic inch air gun creates a big bubble



# Bubble is not perfectly sperical



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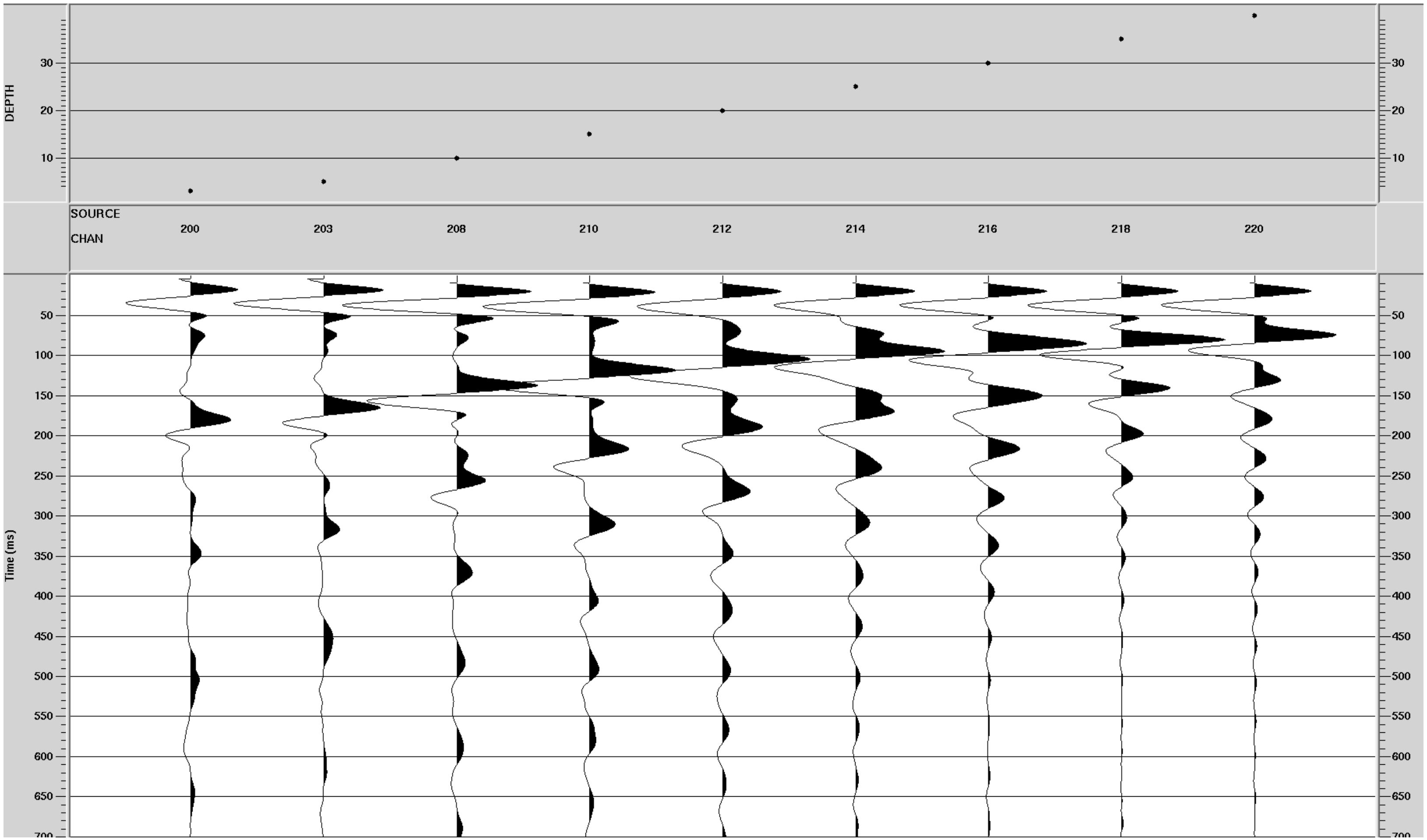
# Band pass filtered (0-2-30-50 Hz) signatures

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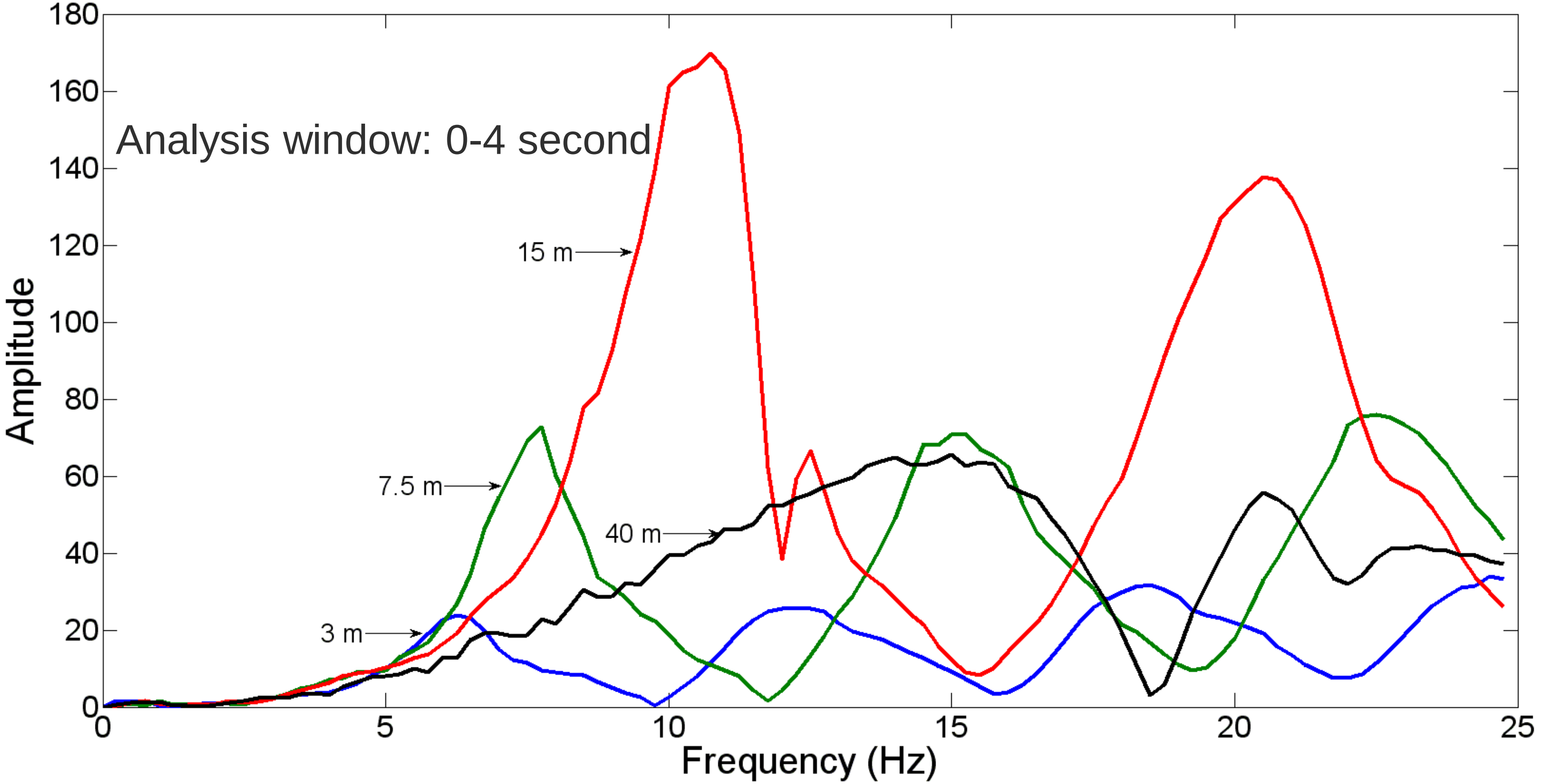
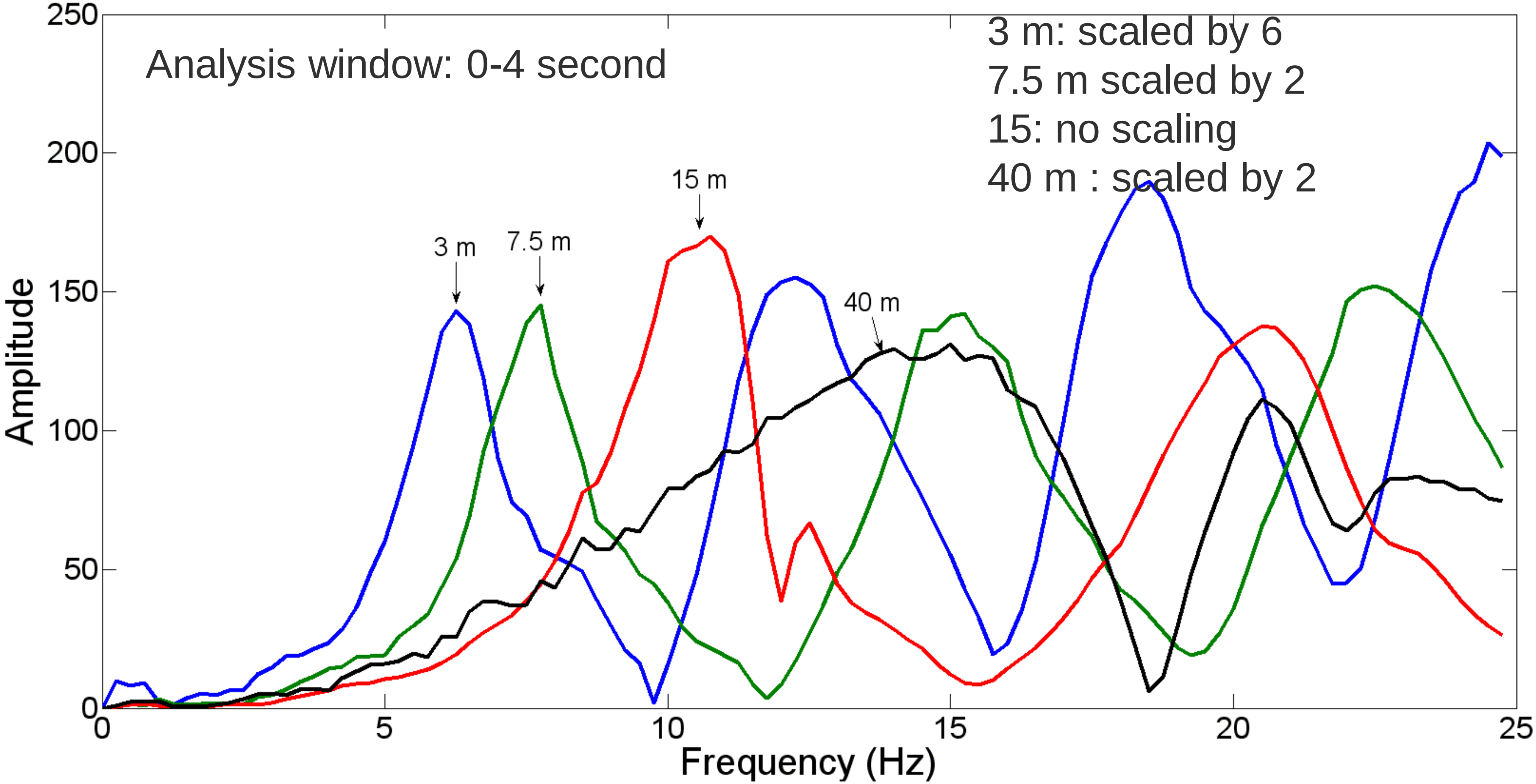
# Farfield spectra for various source depths




The data has been deghosted and THEN ghosted to estimate the farfield signature

# Scaled farfield spectra for various source depths

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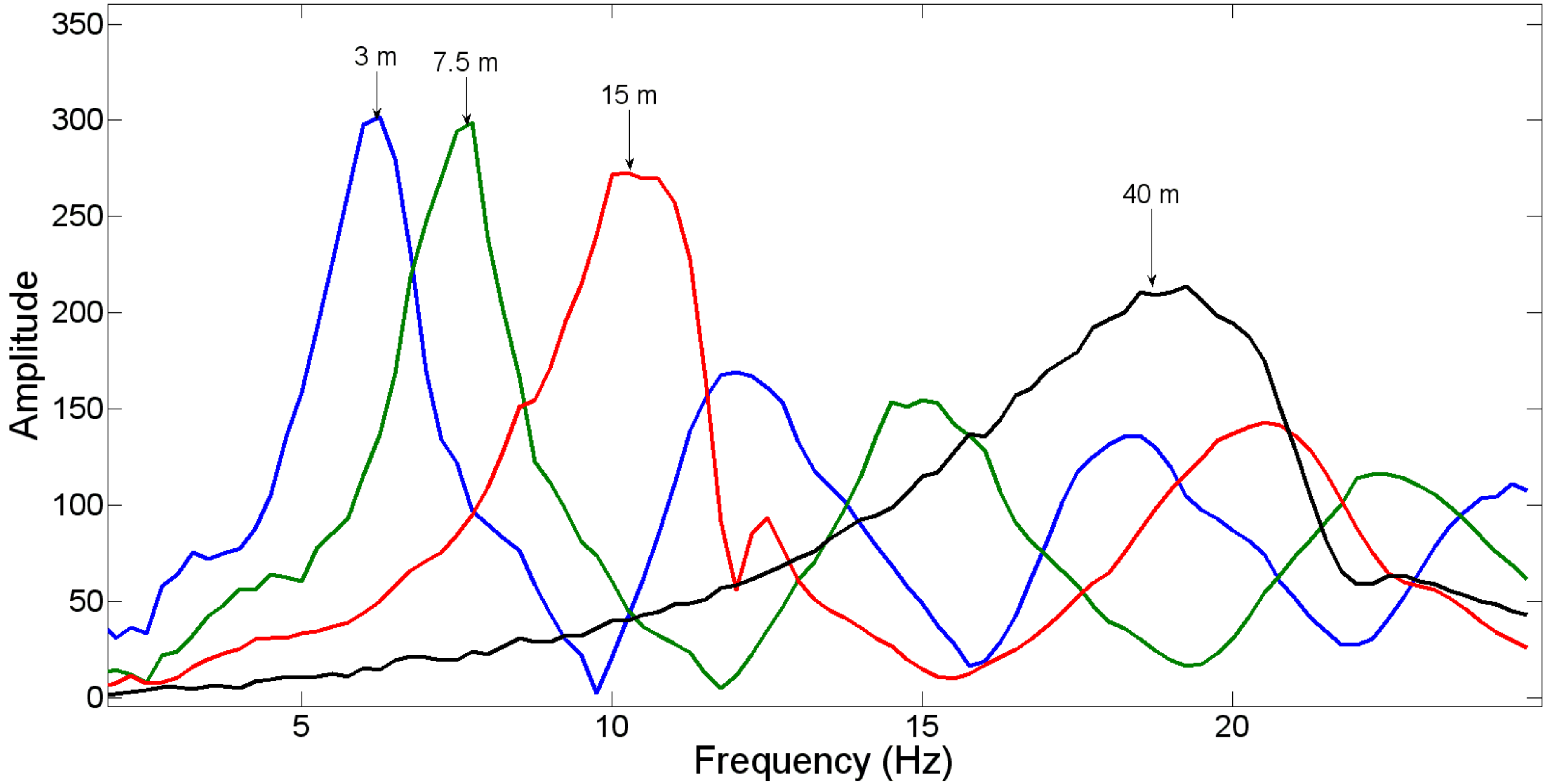
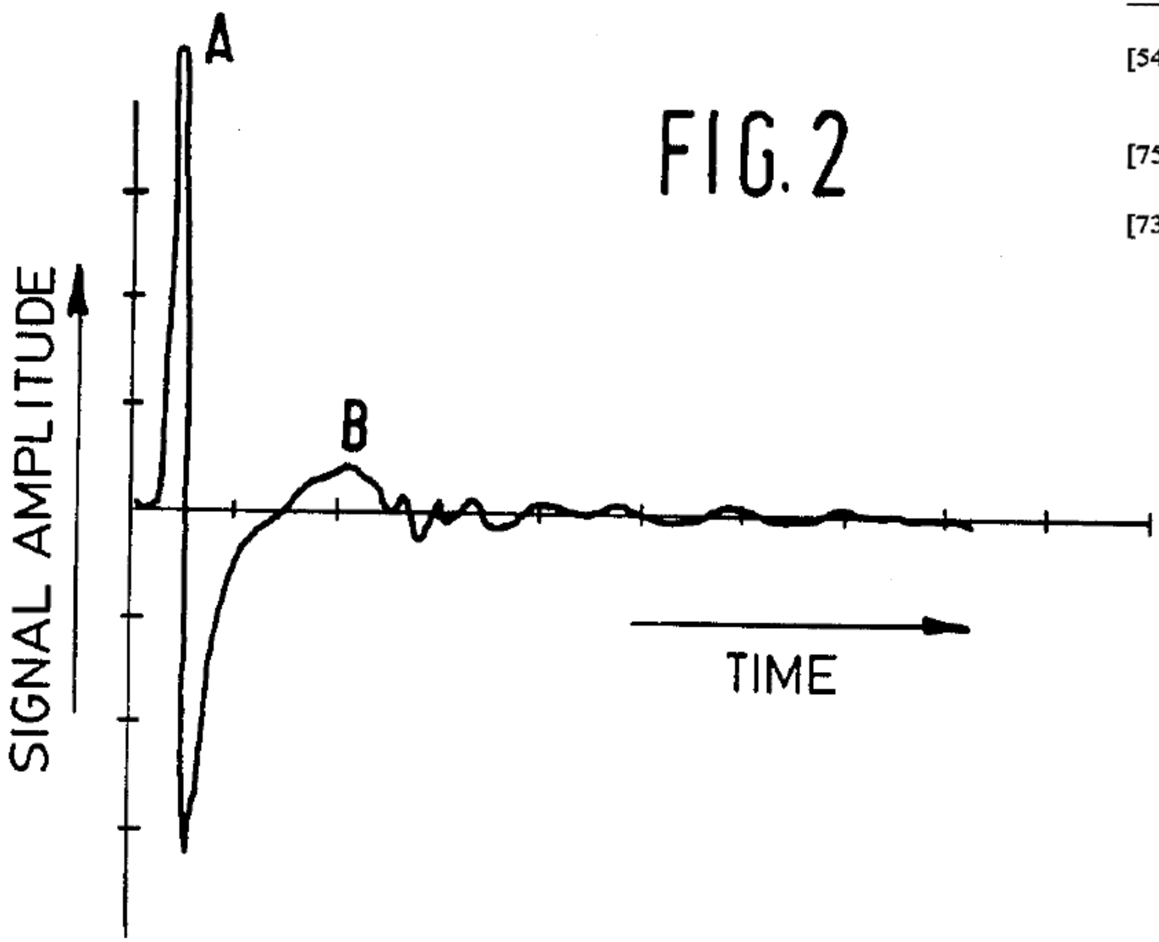
# Estimated notional source spectra for various source depths (0-4 s)



# Sources at different depths




**United States Patent** [19]

**Huizer**

[54] **METHOD AND APPARATUS FOR SIGNAL IMPROVEMENT IN MARINE SEISMIC EXPLORATION**

[75] Inventor: **Willem Huizer**, Rijswijk, Netherlands

[73] Assignee: **Shell Oil Company**, Houston, Tex.

By towing one subarray at 7.5 m depth and the other at 5 m depth, and using firing time delays, the P/B –ratio was improved from 5.6 to 9.5.

# On the generation of low frequencies with modern seismic vibrators

GEOPHYSICS, VOL. 78, NO. 2 (MARCH-APRIL 2013); P. WA91–WA97, 6 FIGS.
10.1190/GEO2012-0342.1

Zhouhong Wei[1] and Thomas F. Phillips[1]

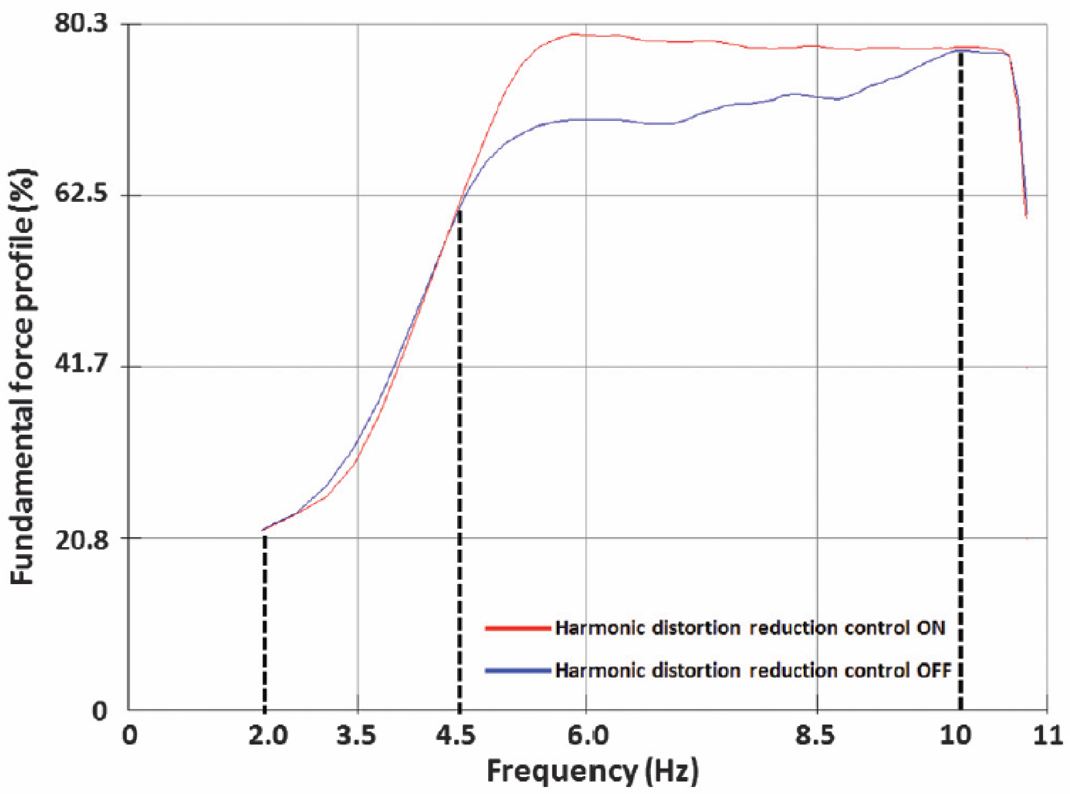
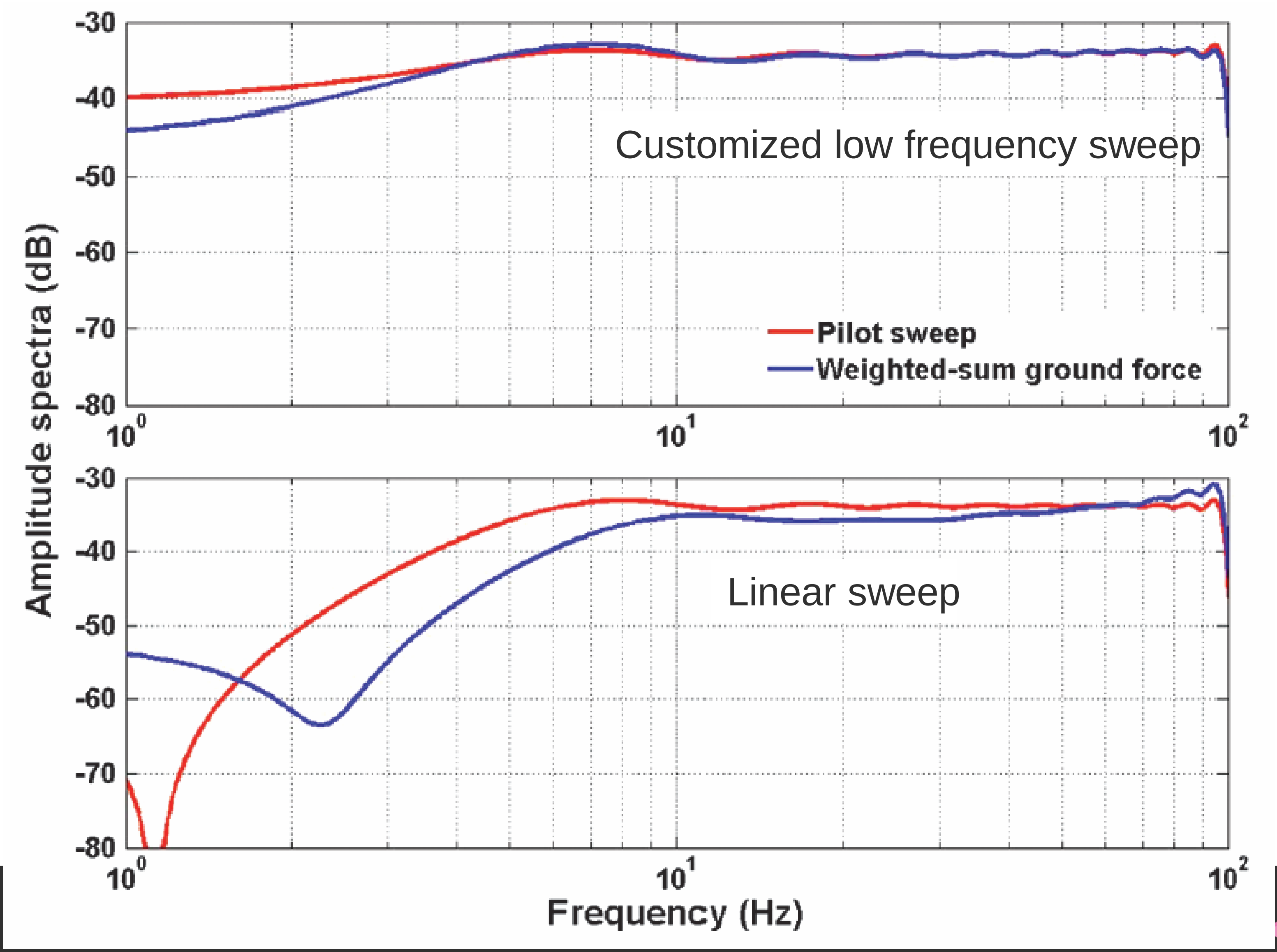



Figure 2. Fundamental force profiles of a 266,880-N or 60,000-lbf peak-force vibrator.

# Customized low frequency sweep, Wei et al., 2013

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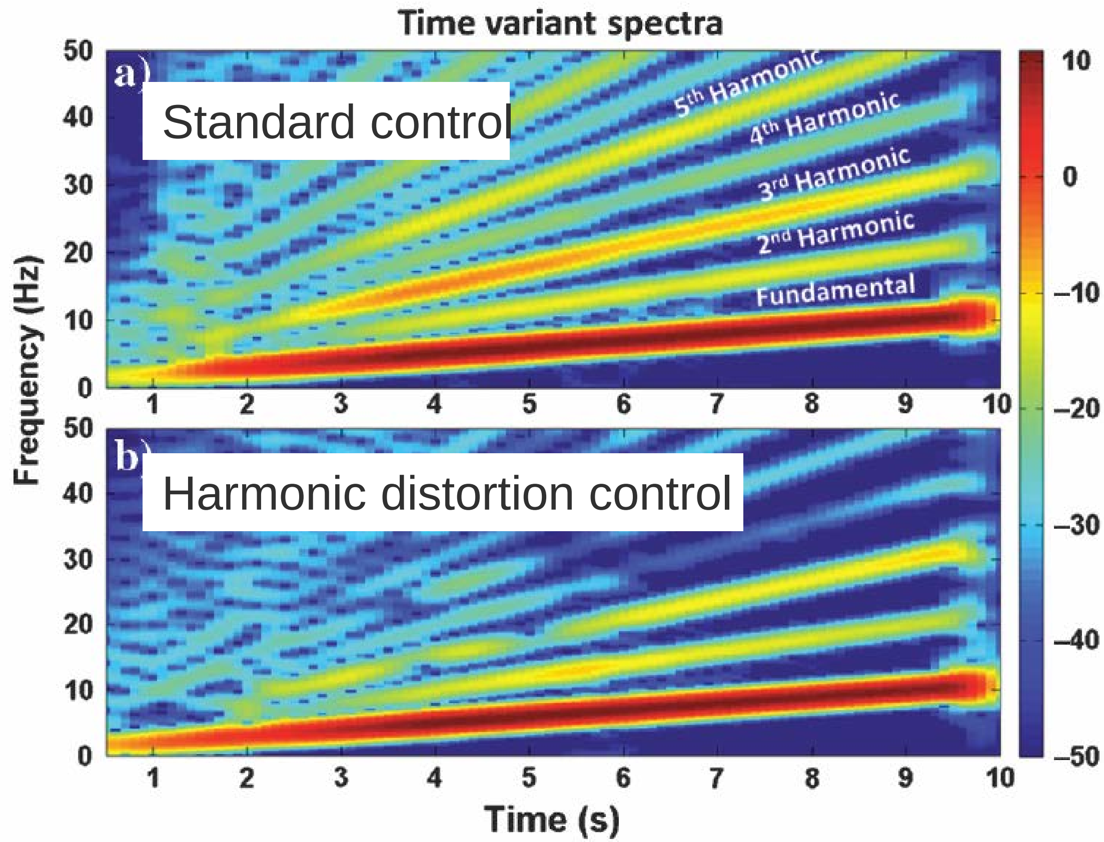
# Customized low frequency sweep, Wei et al., 2013

more force energy at low frequencies. With the knowledge of these limits, customized low-frequency sweeps can be built. Experimental results show that, through customized low-frequency sweeps, vibrators can generate much more ground-force energy at low frequencies. Furthermore, harmonic distortion reduction at low fre-



# CONCLUSIONS

- Two of the main limiting factors in seismic resolution for marine towed-streamer acquisition are
  - the ghost effect
  - sparse crossline sampling of the streamers
- New streamer technologies have been introduced to address these factors
  - deployed at larger depths
  - improve low-frequency content, signal-to-noise ratio due to reduced swell noise
  - improve acquisition efficiency
- The low frequencies are extremely important for broadband seismic imaging, inversion and interpretation
- The very high frequencies are attenuated by the earth
- Need marine sources with more low frequencies