Comparison and analysis of space and temporal frequency, and, spatial wavenumber and temporal frequency (e.g., P-V_z) domain approaches of Green's theorem de-ghosting techniques: Implications for 3D de-ghosting

Jing Wu

San Antonio, Texas

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Key Points

- In 3D acquisition, the data in cross-line are typically characterized with sparse sampling and narrow aperture compared to in-line direction;

- Compared to spatial wavenumber and temporal frequency domain (e.g., P-V_z) approach, Green's theorem de-ghosting method achieved in space and temporal frequency domain shows the advantages of producing effective result and boosting low frequency energy.

- Numerical comparisons

  1) Spatial sampling interval

  2) Aperture

Outline

- **Introduction and Motivation**
- **Theoretical Analysis**
- **Numerical Analysis**
  - **Spatial Sampling Interval**
  - **Aperture**
- **Conclusion**

Motivation

- Ghosts:
  - (1) Cause notches in the frequency spectrum, especially for deep water acquisition, like OBC;
  - (2) Reduce the resolution, increase the uncertainty of inversion and interpretation.
- For our group, we wish to use isolated data for each processing step in order to get a more satisfactory result.

Introduction

Weglein et al. (02), Zhang and Weglein (05, 06); Zhang (07), Mayhan(12, 13**):**

Green's theorem deghosting method

- **Space and temporal frequency** domain
- **Spatial wavenumber and temporal frequency** domain

Introduction

Weglein et al. (02), Zhang and Weglein (05, 06); Zhang (07),

Mayhan(12, 13)**):**

Green's theorem deghosting method

- **Space and temporal frequency** domain
- **Spatial wavenumber and temporal frequency** domain

So question is:

Are they equivalent except calculated in different domains ?

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  - **Aperture and Edge Effect**
- **Conclusion**

Theoretical Analysis

- **Green's Theorem de-ghosting ($x-\omega$)**
  - **No assumption**

$$P'_R(x,z,x_s,z_s,\omega)=$$

$$\int_{m.s.}(P(x',z',x_s,z_s,\omega)\nabla' G_0^d(x,z,x',z',\omega)-G_0^d(x,z,x',z',\omega)\nabla' P(x',z',x_s,z_s,\omega))\cdot n ds'$$

  - P'_R the receiver side de-ghosted data;
  - P the pressure data;
  - $\nabla' P$ the gradient of pressure data;
  - G_0^d the causal Green's function;
  - (x',z') point on measurement surface; (x,z) prediction location;
  - (x_s,z_s) source location, ω circular frequency.

Theoretical Analysis

- **Green's Theorem de-ghosting ($k_x - \omega$)**
  - Assume the acquisition geometry is **horizontal**

$$P'_R(x,z,x_s,z_s,\omega) = \frac{1}{2}[P(k_x,z,x_s,z_s,\omega) - \frac{1}{ik_z}\frac{dP}{dz}(k_x,z,x_s,z_s,\omega)]$$

  - P'_R the receiver side de-ghosted data;
  - P the pressure data;
  - $\frac{dP}{dz}$ the vertical derivative of pressure;
  - k_x horizontal wavenumber; k_z vertical wavenumber ;
  - (x, z) prediction location; (x_s, z_s) source location,
  - ω circular frequency.

If acquisition geometry is horizontal, Green's theorem de-ghosting methods in these two different domains are theoretically equivalent.

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Even though geometry is horizontal, for cross-line, because of sparse spatial sampling and narrow aperture, spatial Fourier Transform will encounter difficulties to give a precise result.

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Numerical Analysis

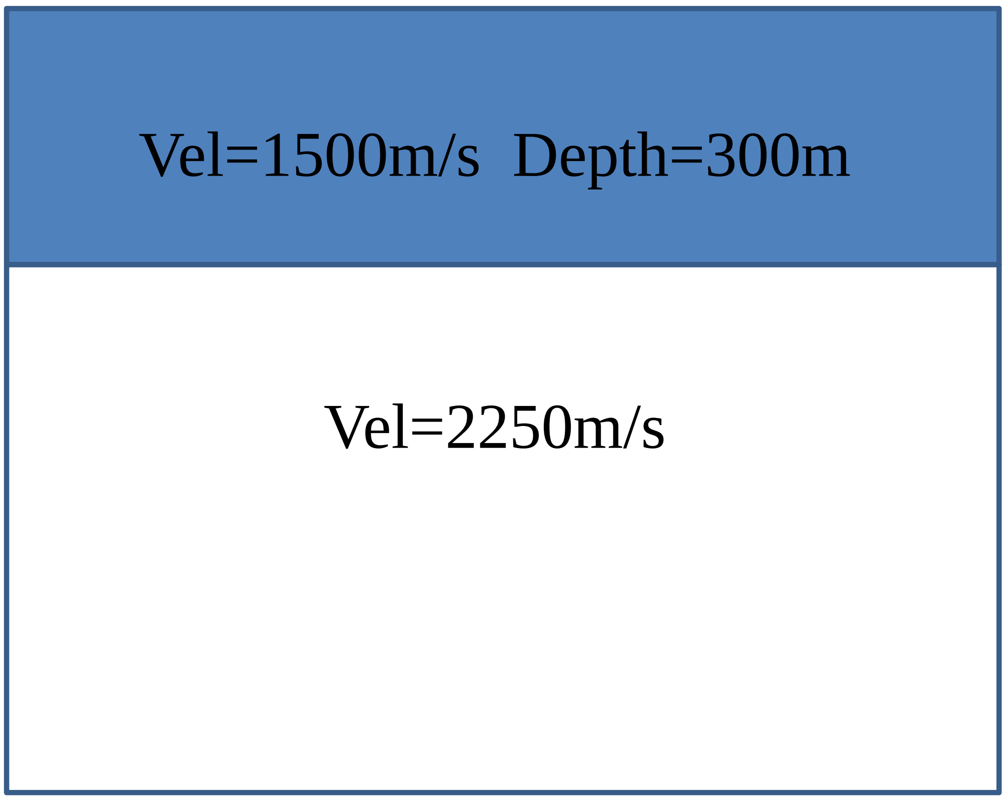
-----Spatial Sampling Interval

- In order to prevent alias, the sampling interval should satisfy

$$\Delta x \le 1/2k_{\max} \qquad \Delta t \le 1/2f_{\max}$$

- Since $$k_{\max} = f_{\max}/c$$
- Then $$\Delta x \le c/2f_{\max}$$
- If not, alias will appear in the data and contaminate the result.

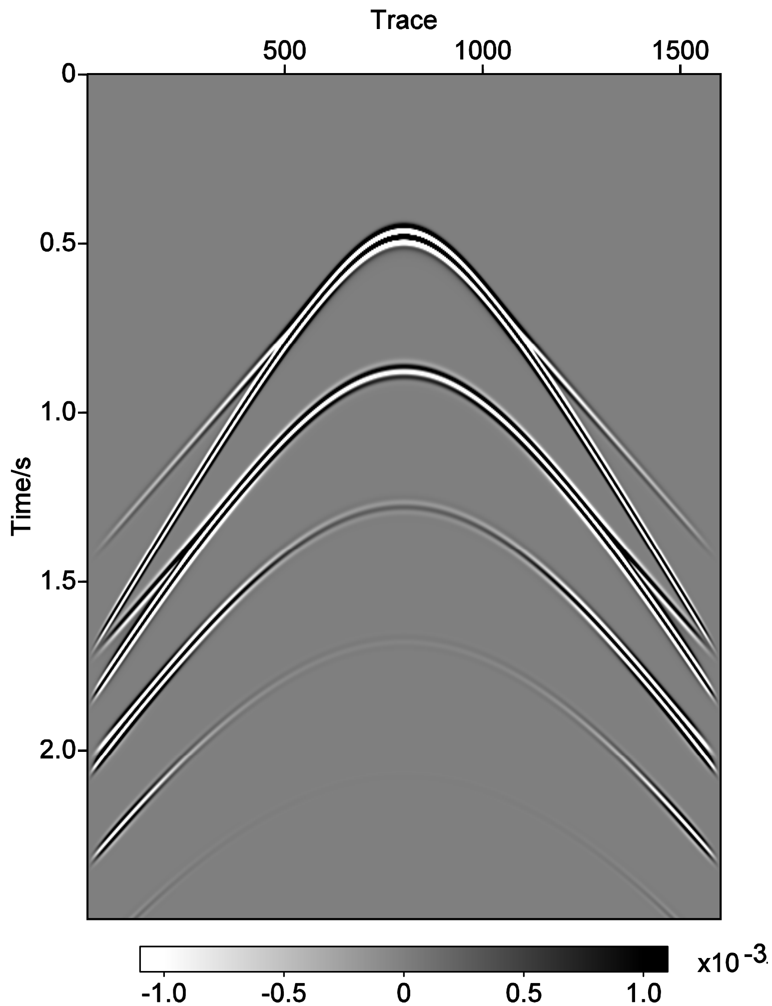
  So we need low-pass filtering before de-ghosting.



Air-water boundary

Source: **7m**
Receiver: **11m**
Sampling interval: **3m**
Aperture: **2400m**

Velocity model



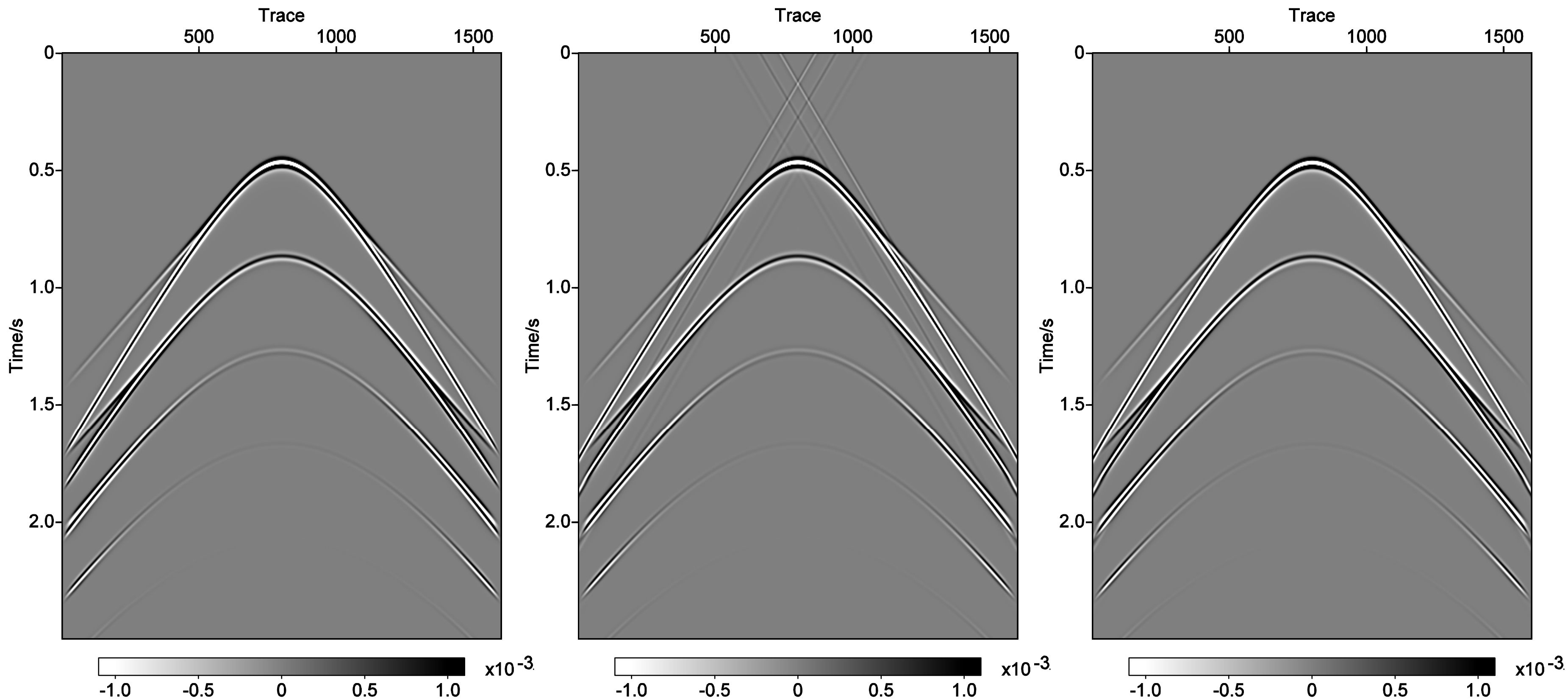
Synthetic data

Keep the aperture of 2400m

Increase spatial sampling interval gradually:
3m – 12m – 30m – 60m – 100m

To reduce the space alias, apply low pass filter before calculation.

Aperture: 2400m
Spatial sampling interval: 3m

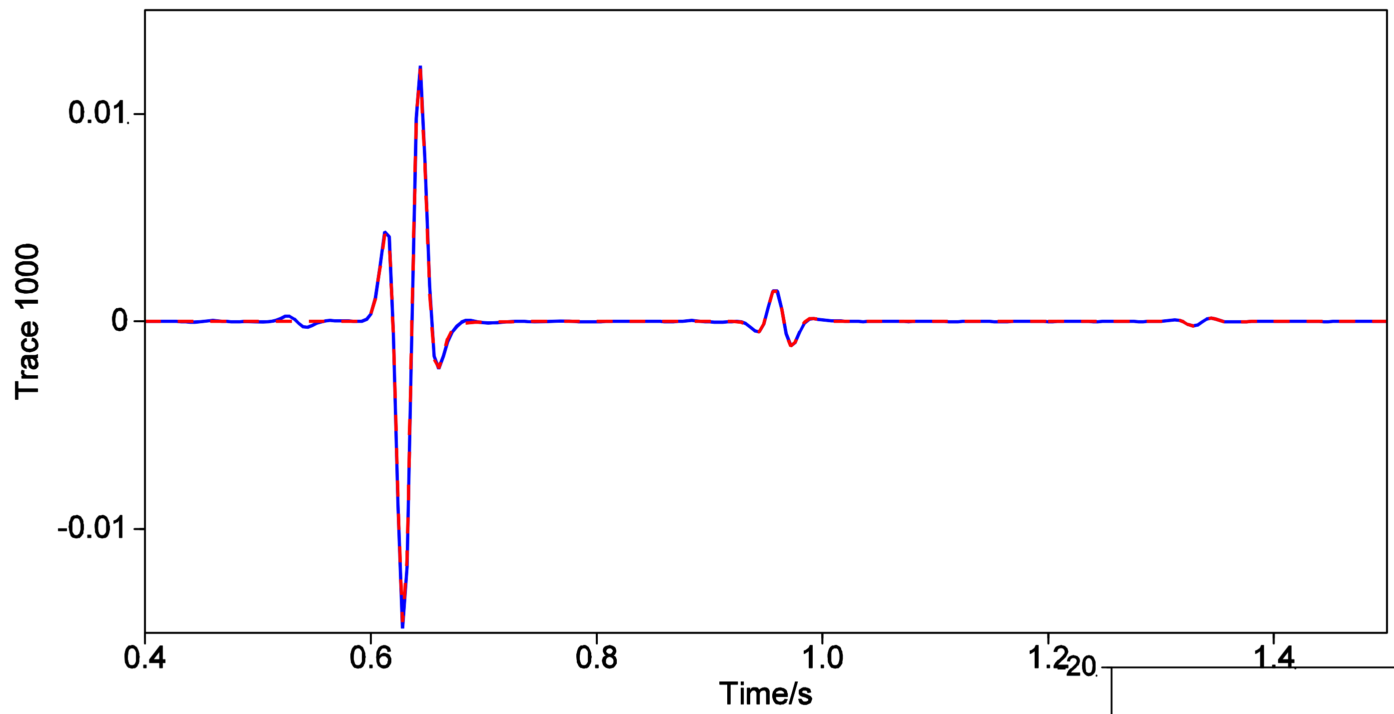


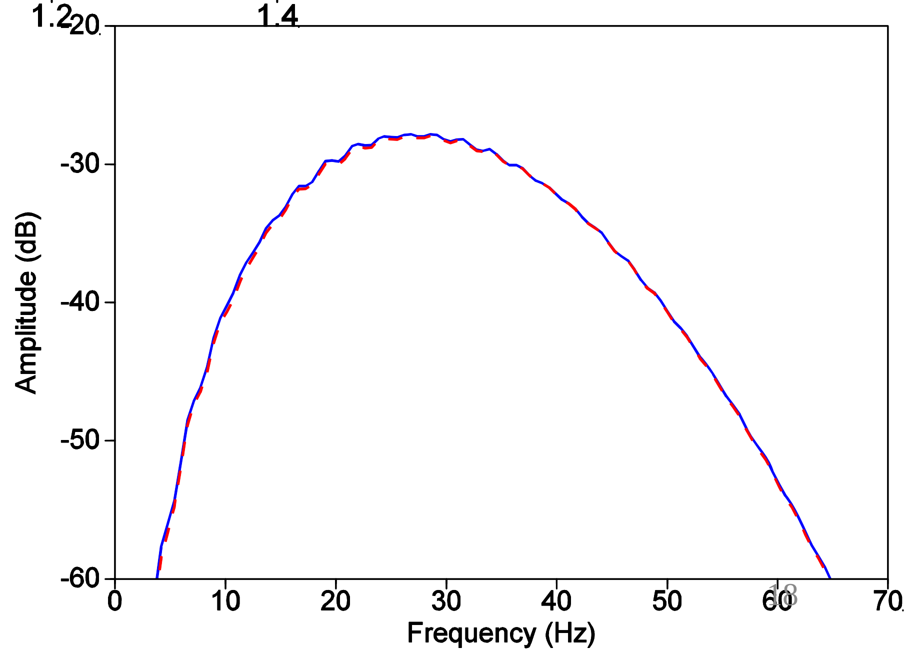
CdH upgoing wave

k_x - ω deghosted result

x - ω deghosted result

Spatial sampling interval: 3m

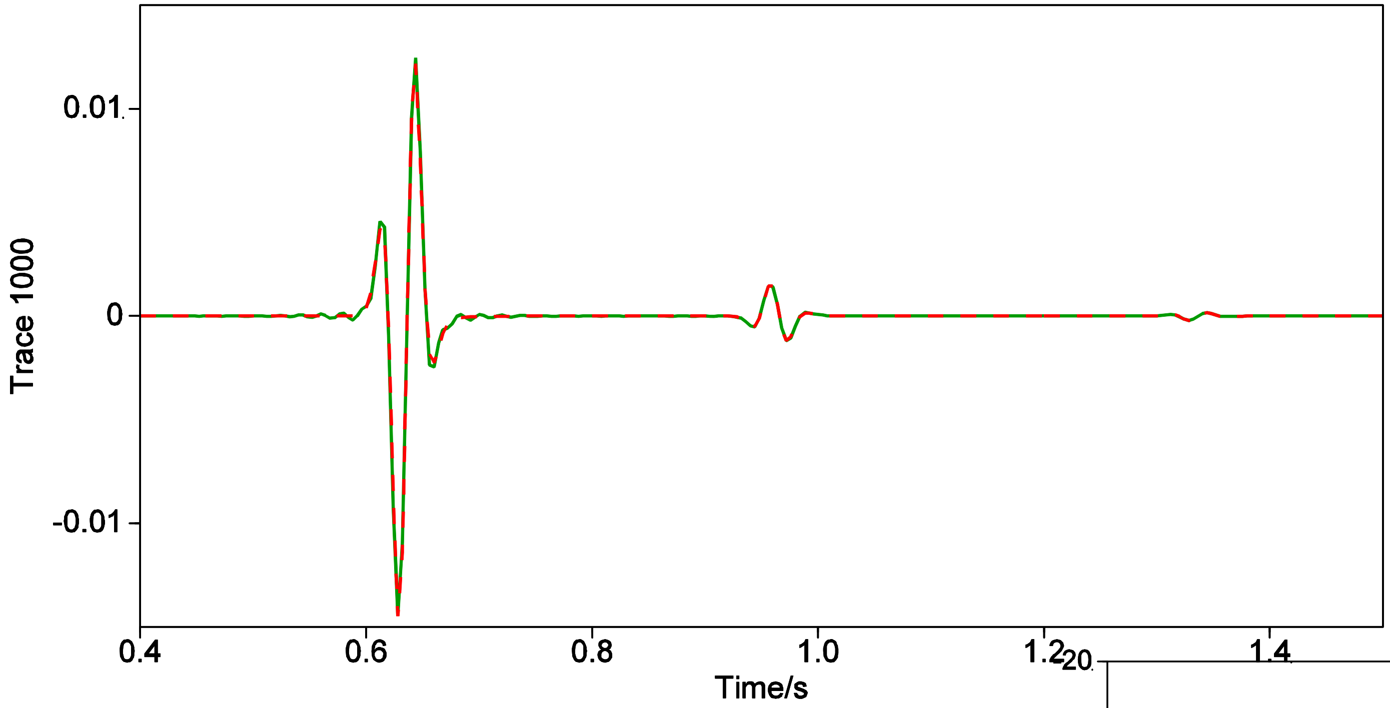


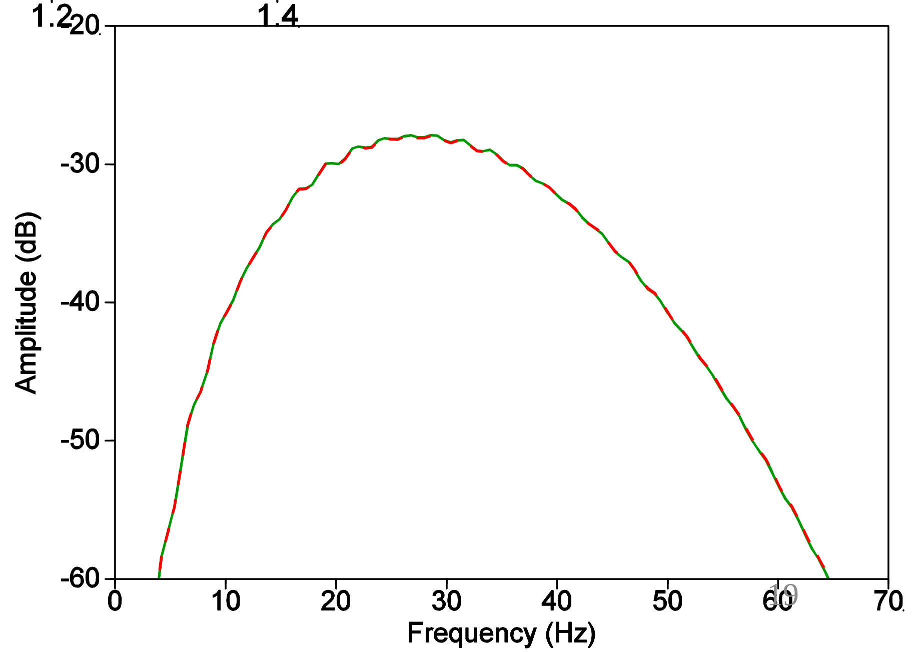


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

Spatial sampling interval: 3m

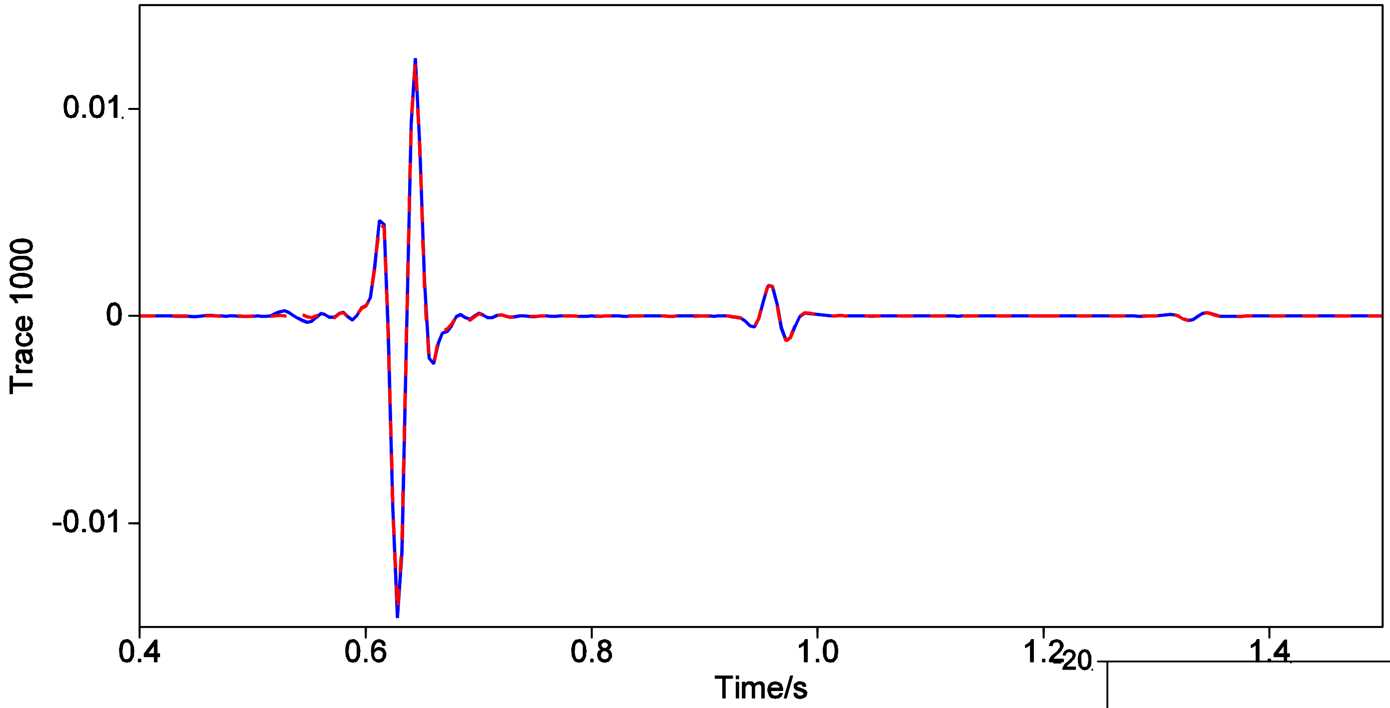


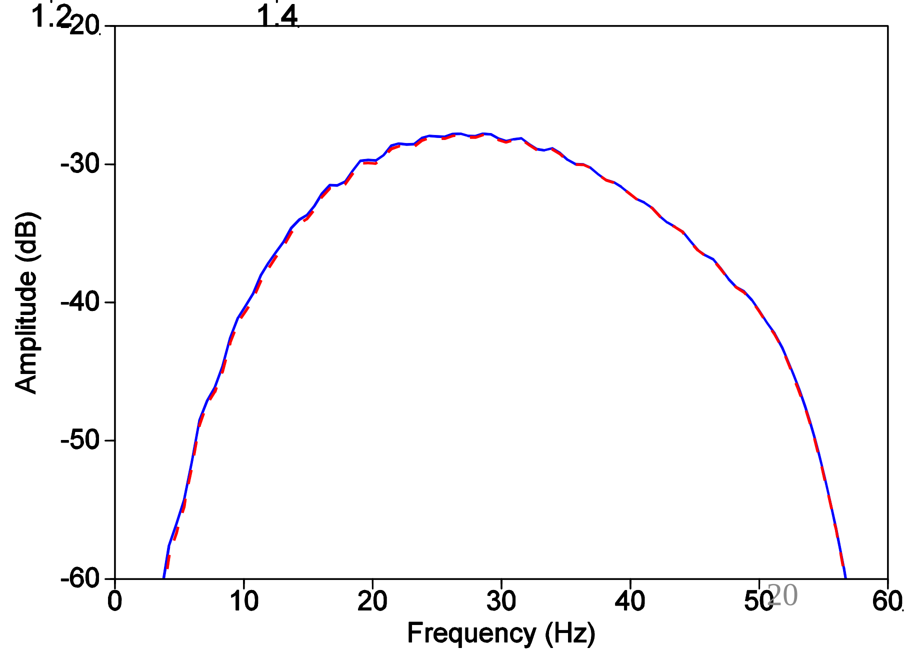


Red line: CdH upgoing wave

Green line: x - ω deghosted

Spatial sampling interval: 12m (low cut filter: 60Hz)

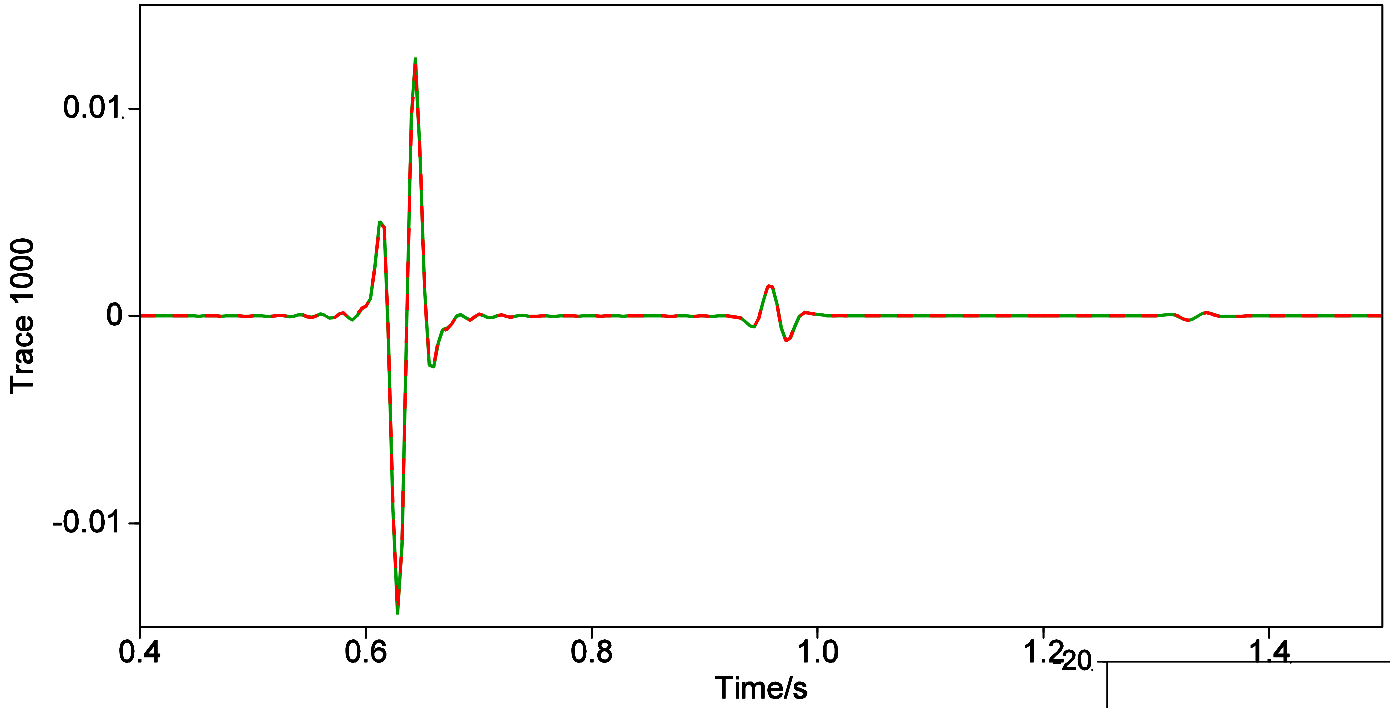


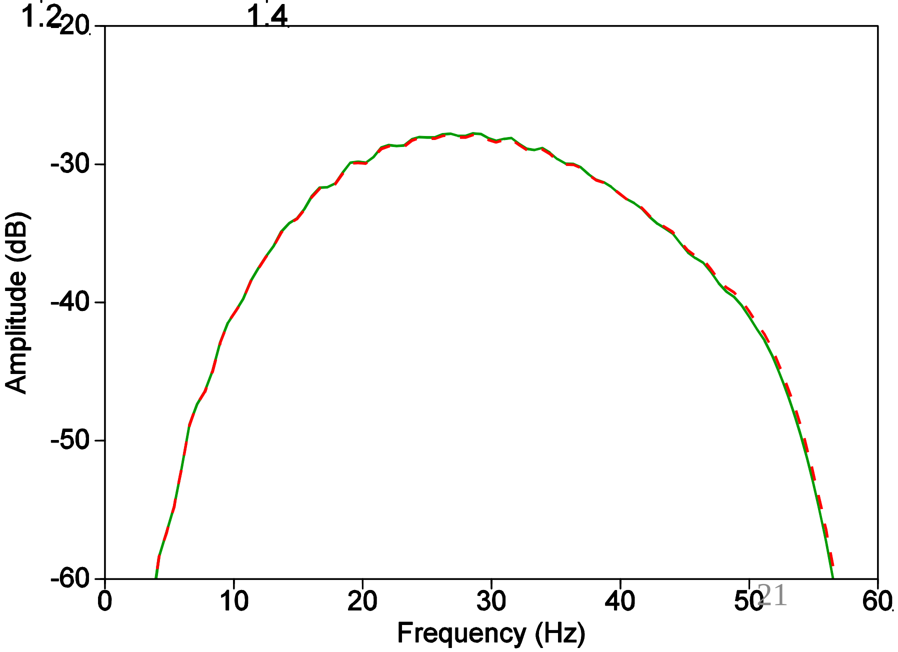


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

Spatial sampling interval: 12m (low cut filter: 60Hz)

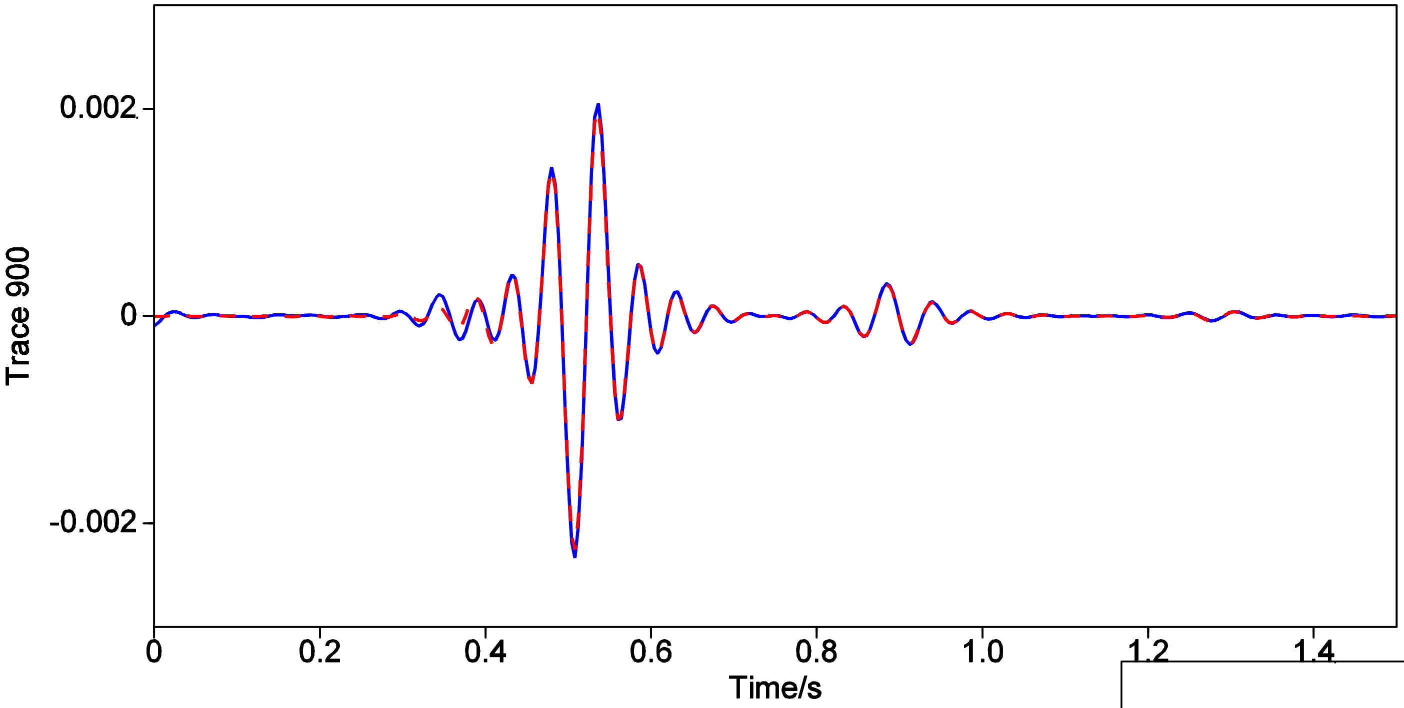


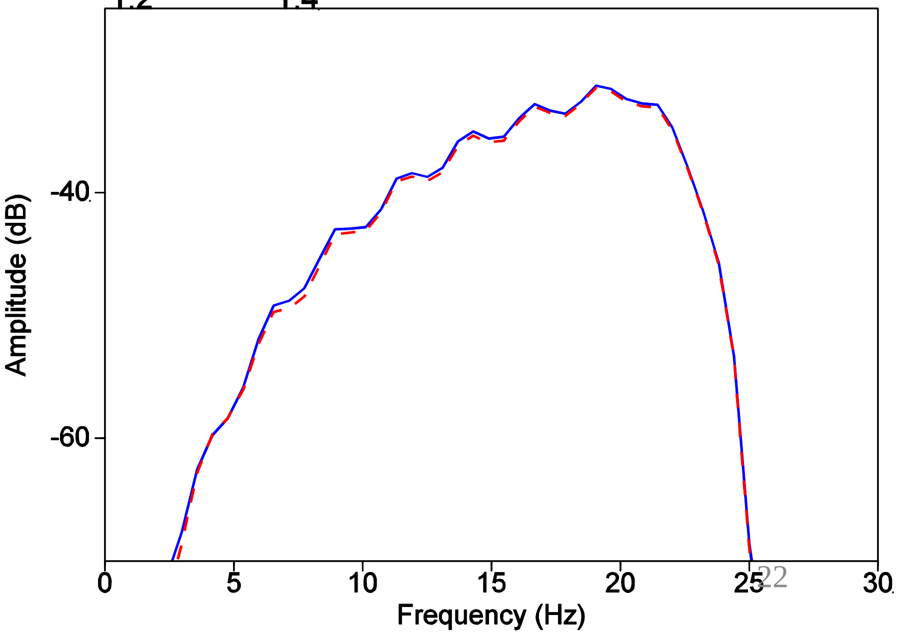


Red line: CdH upgoing wave

Green line: x - ω deghosted

Spatial sampling interval: 30m (low cut filter: 25Hz)

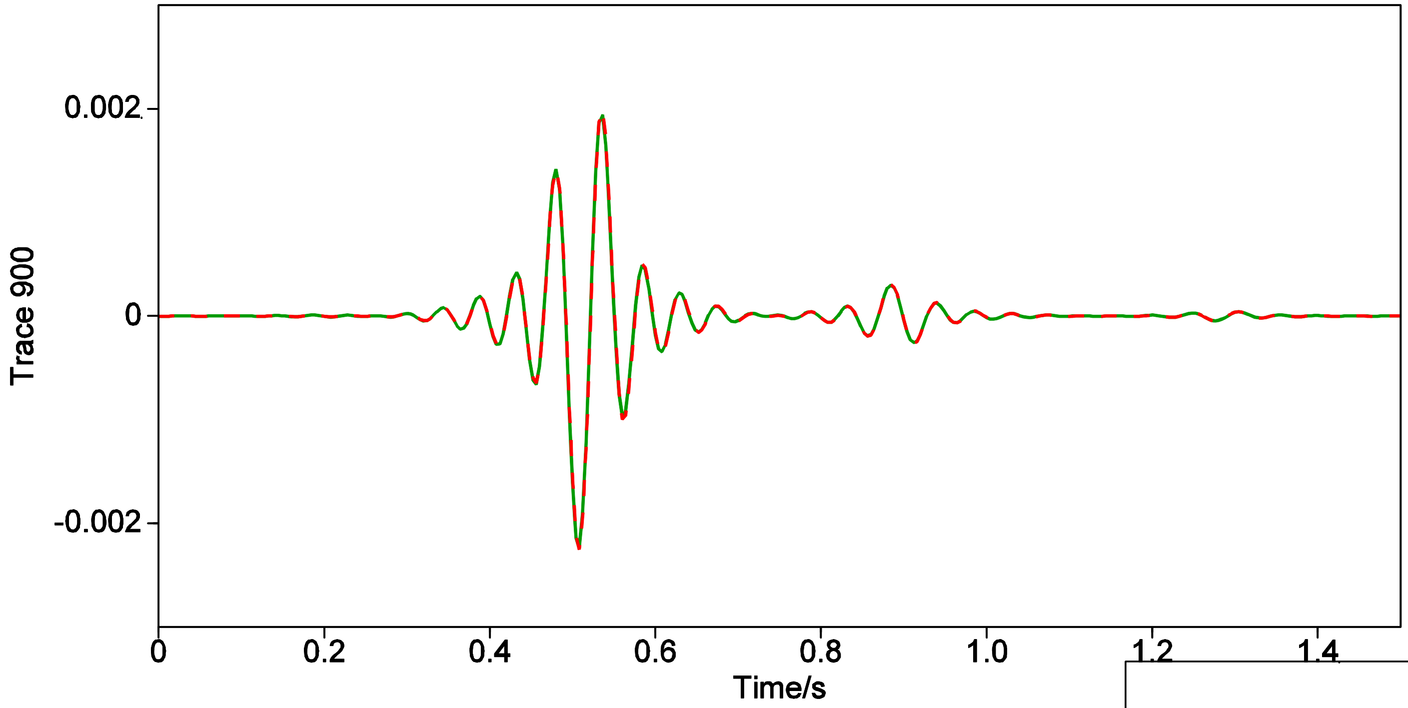


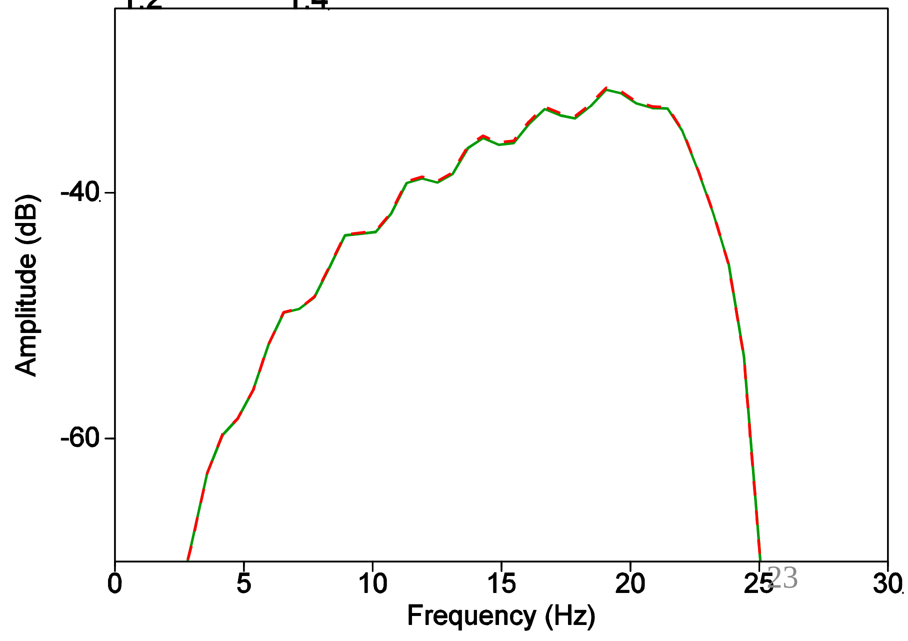


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

Spatial sampling interval: 30m (low cut filter: 25Hz)

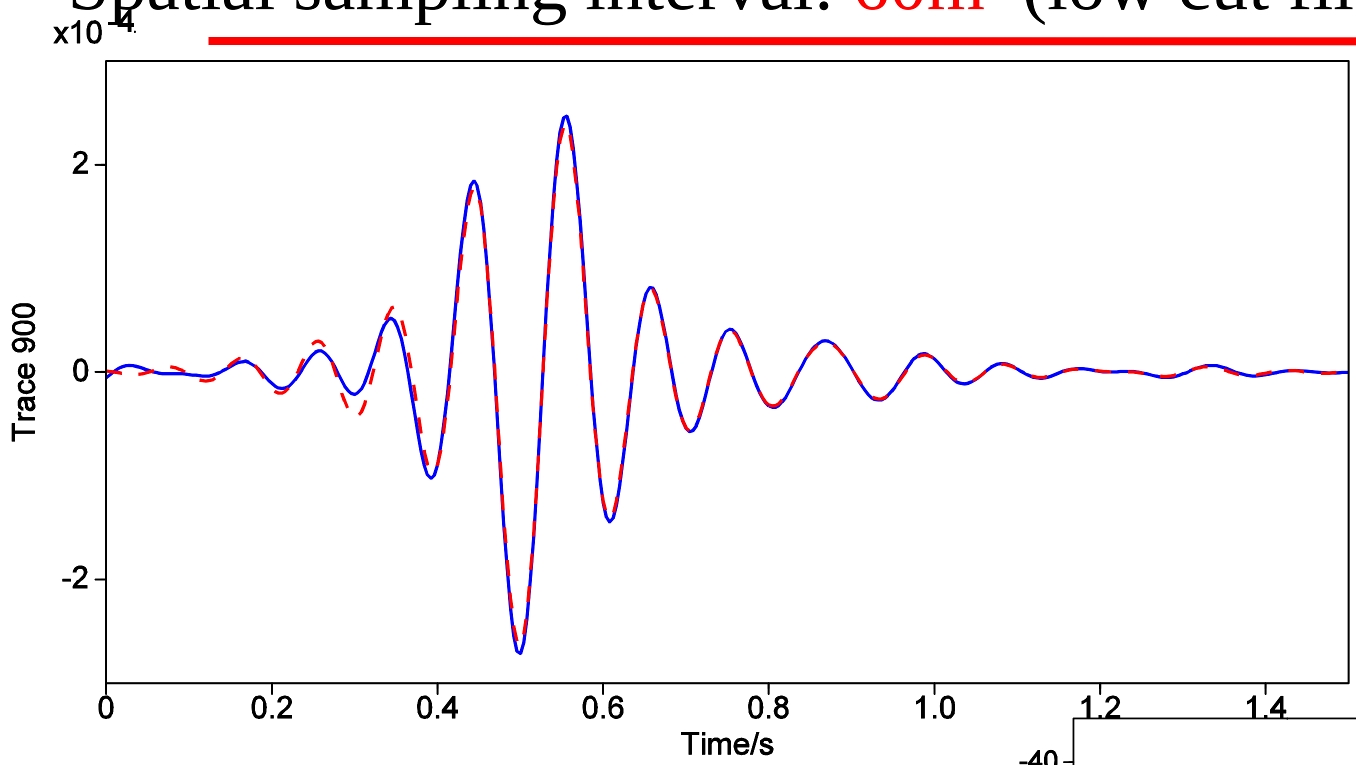


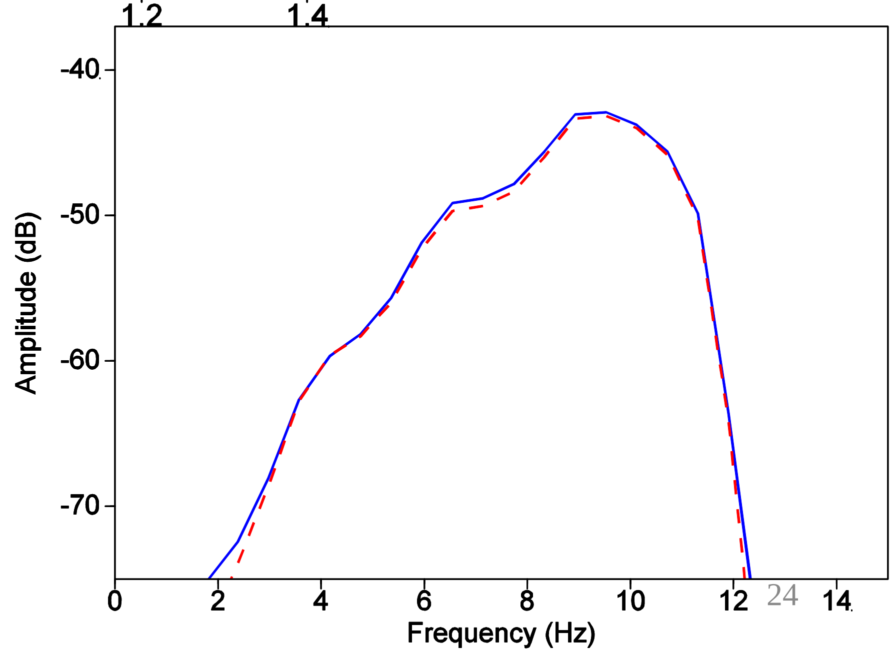


Red line: CdH upgoing wave

Green line: x - ω deghosted

Spatial sampling interval: 60m (low cut filter: 12Hz)

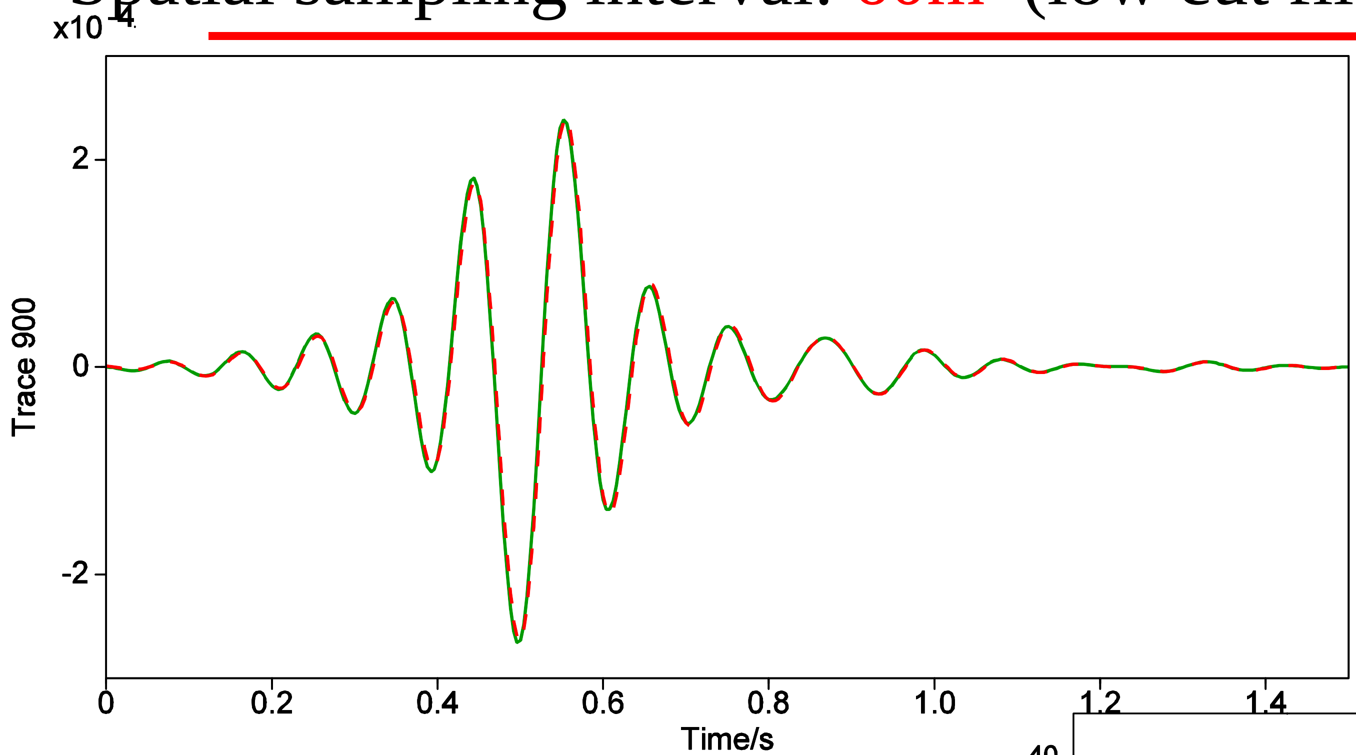


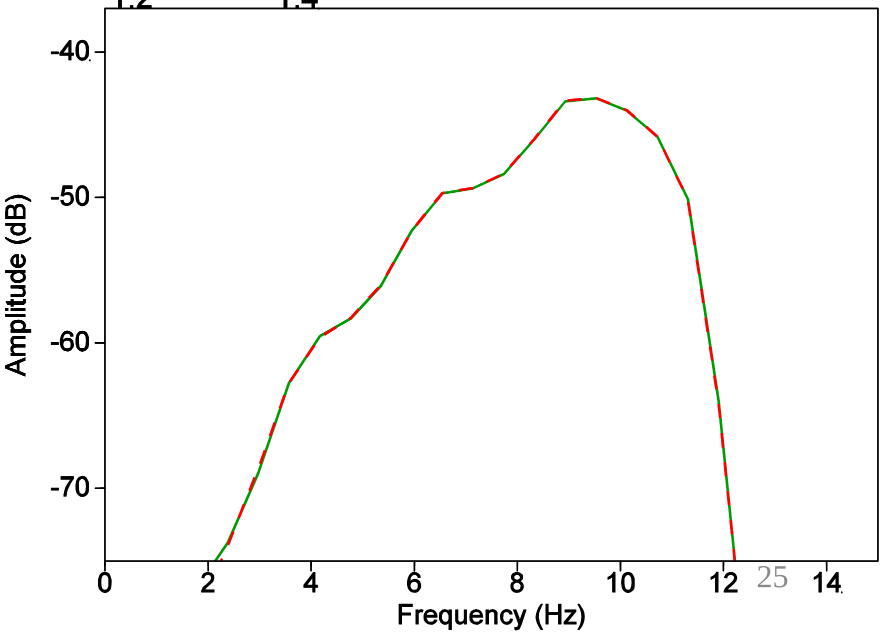


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

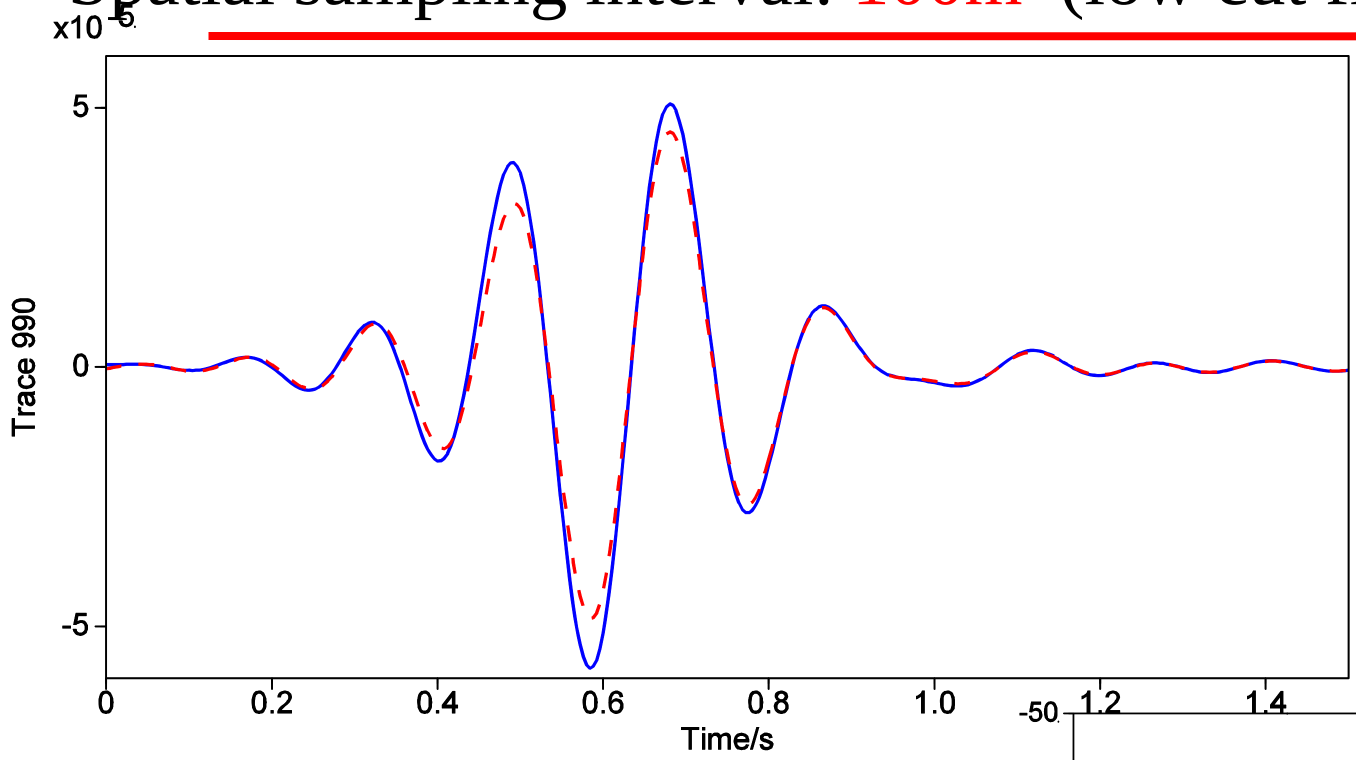
Spatial sampling interval: 60m (low cut filter: 12Hz)

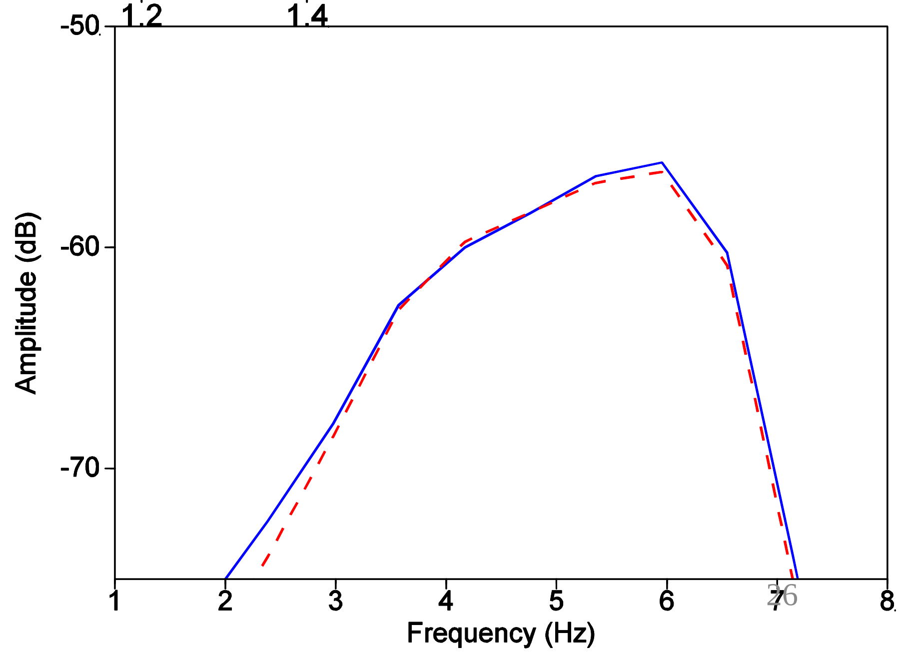




Red line: CdH upgoing wave
Green line: x - ω deghosted

Spatial sampling interval: 100m (low cut filter: 7Hz)

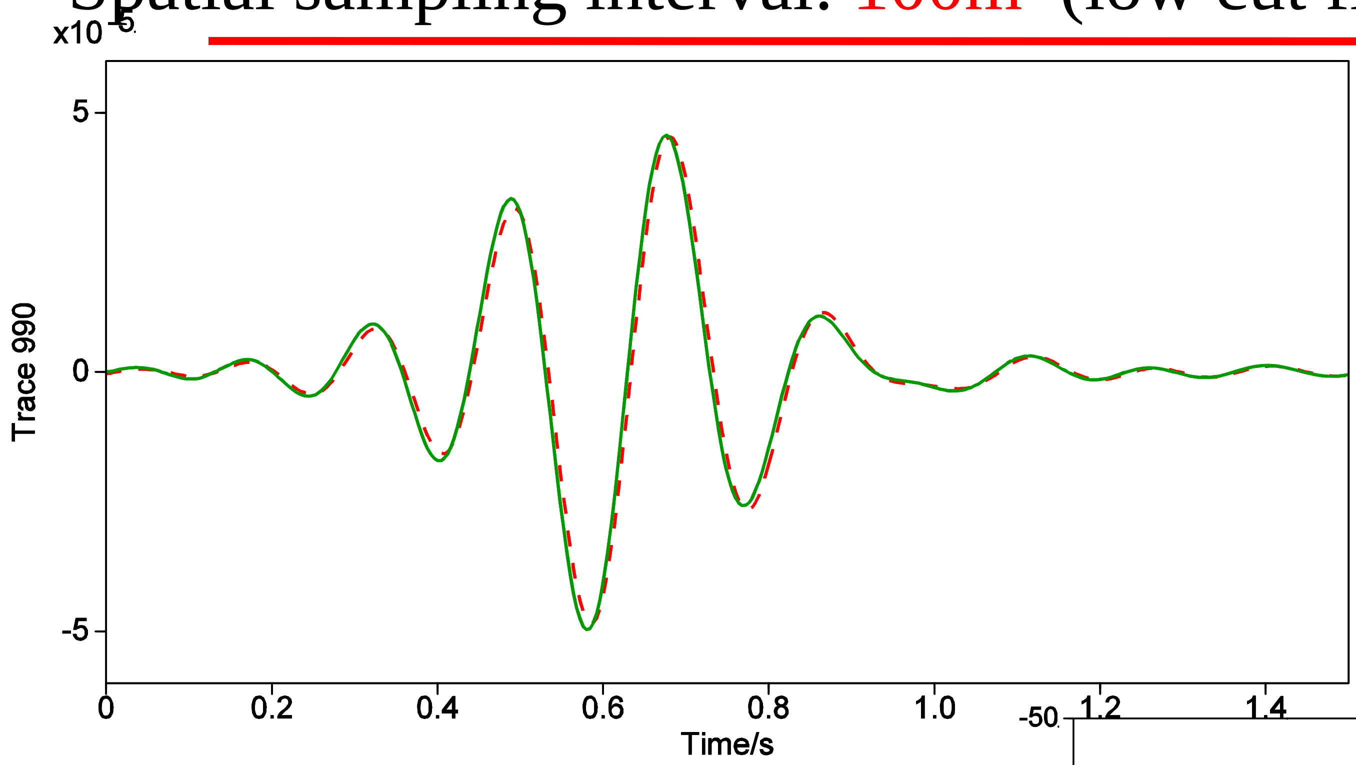


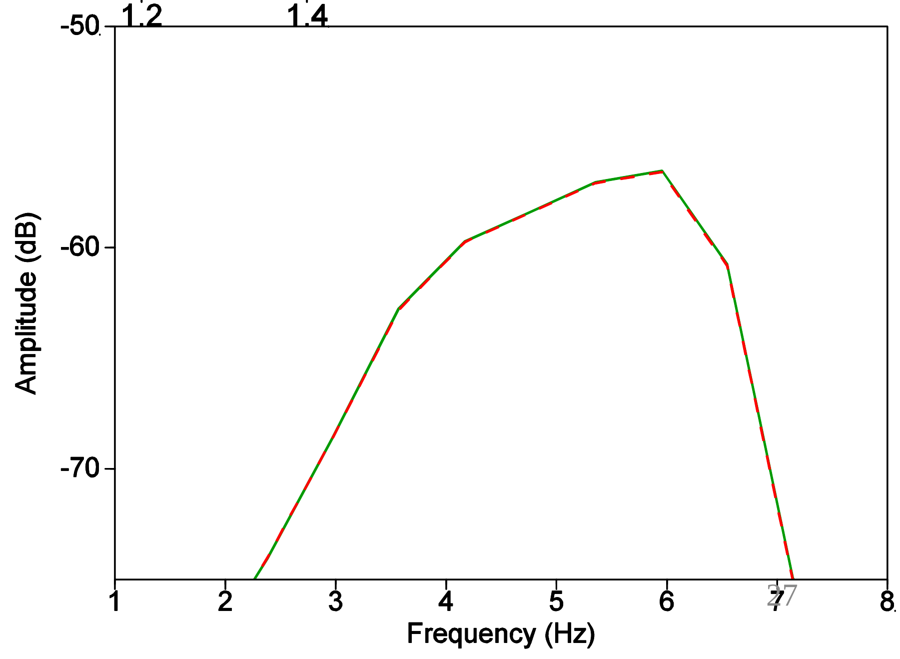


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

Spatial sampling interval: 100m (low cut filter: 7Hz)





Red line: CdH upgoing wave

Green line: x - ω deghosted

		k_x - ω domain result	x - ω domain result
Spatial Sampling	Dense (e.g. 3m,12m)	Ideal	Ideal
	Intermediate (e.g. 30m,60m)	Has residual	Satisfactory
	Sparse (100m)	Has residual Worse	Has residual Better
Frequency spectrum			Boosts low frequency energy

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Numerical Analysis

----- Aperture

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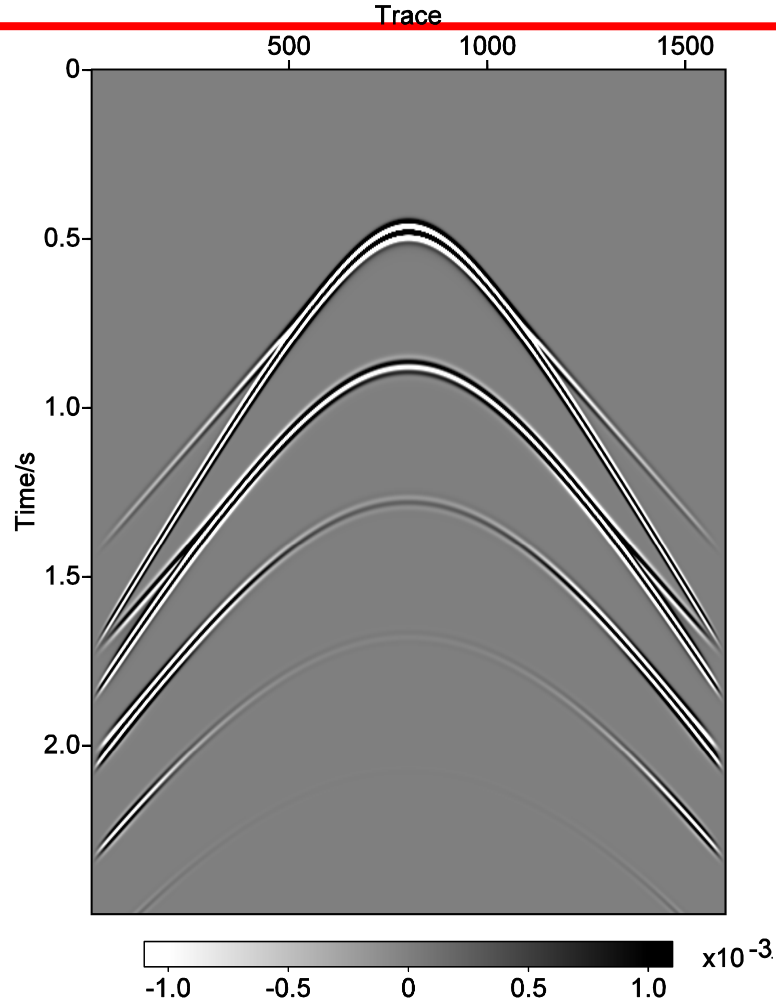


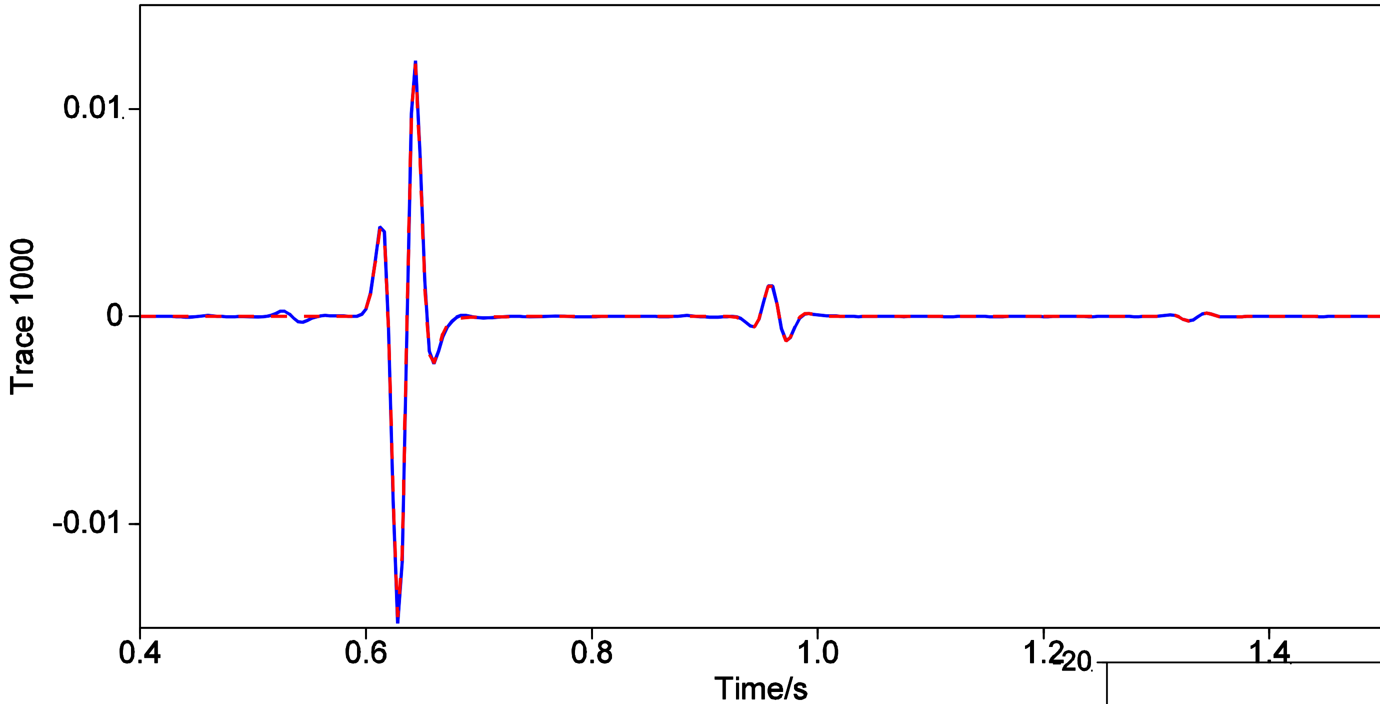
Synthetic data

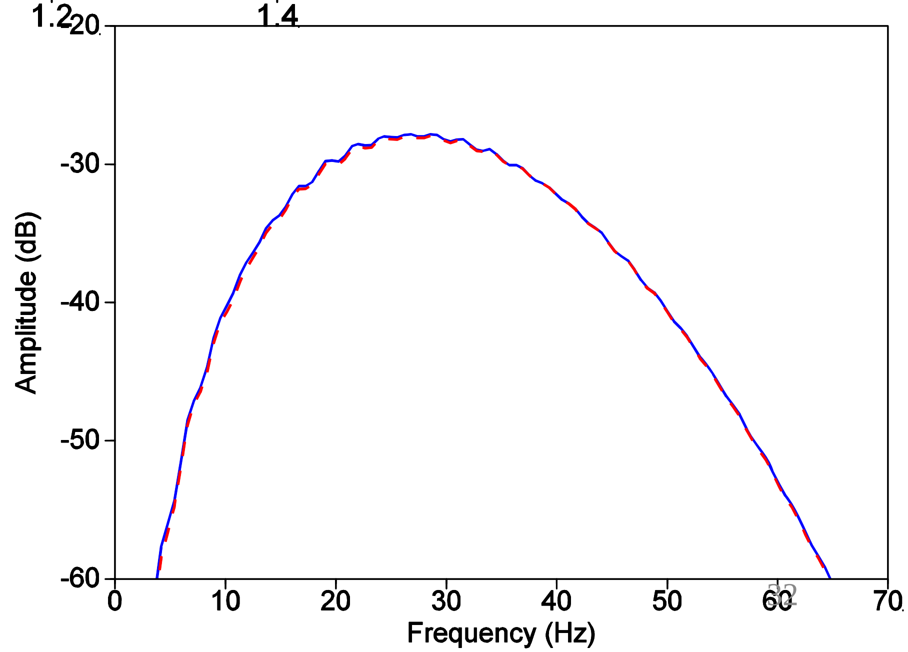
Keep the spatial sampling interval of 3m

Reduce aperture gradually:
2400m – 300m – 150m – 75m – 45m

To reduce the edge effect, apply taper at far offset before calculation.

Aperture: 2400m

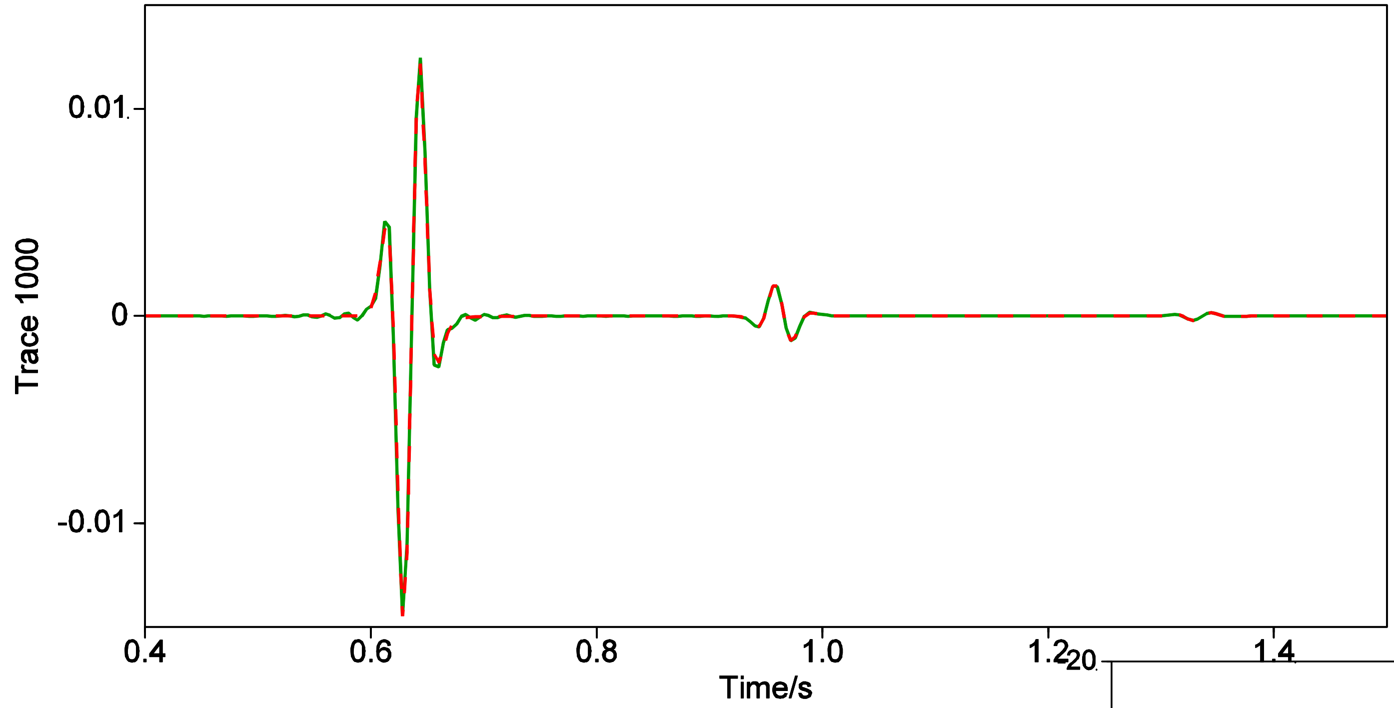


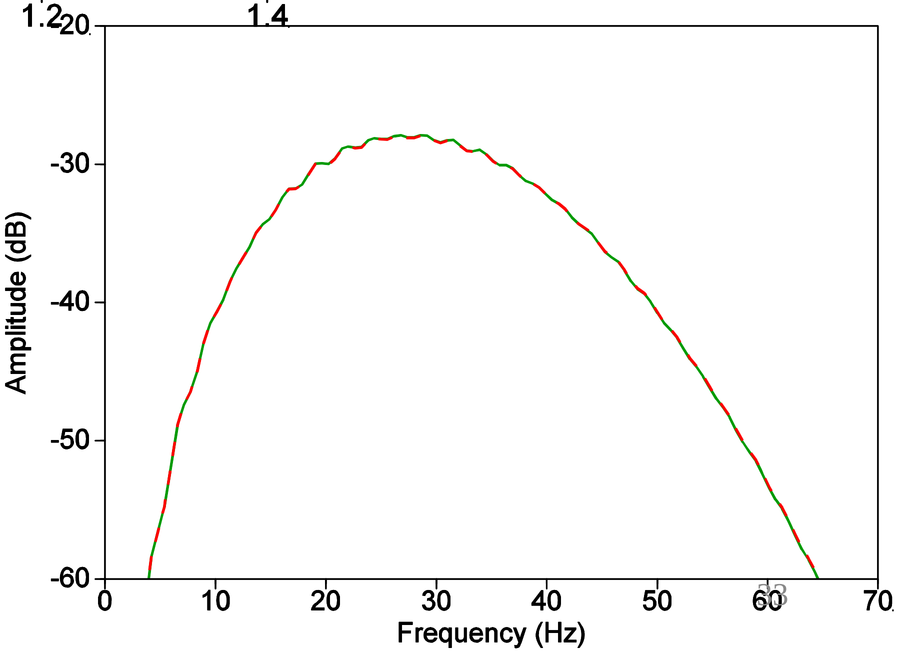


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

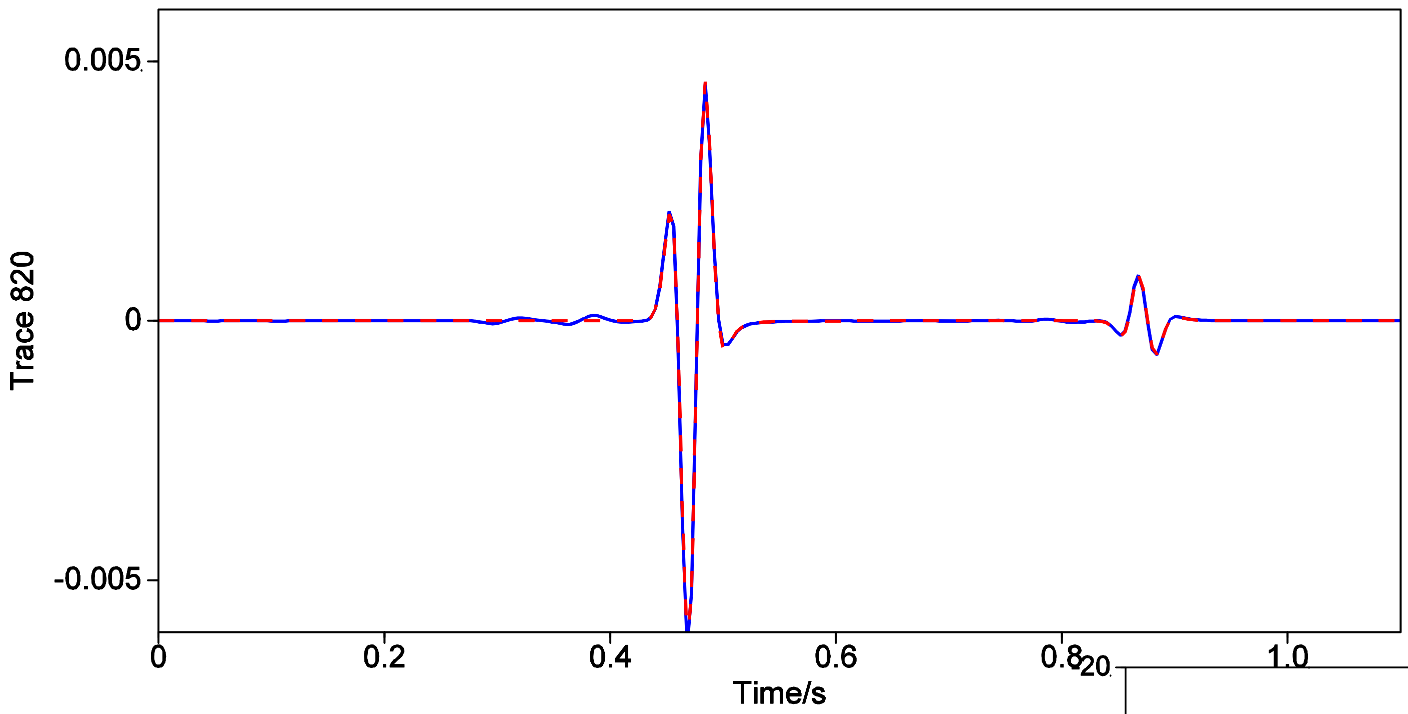
Aperture: 2400m

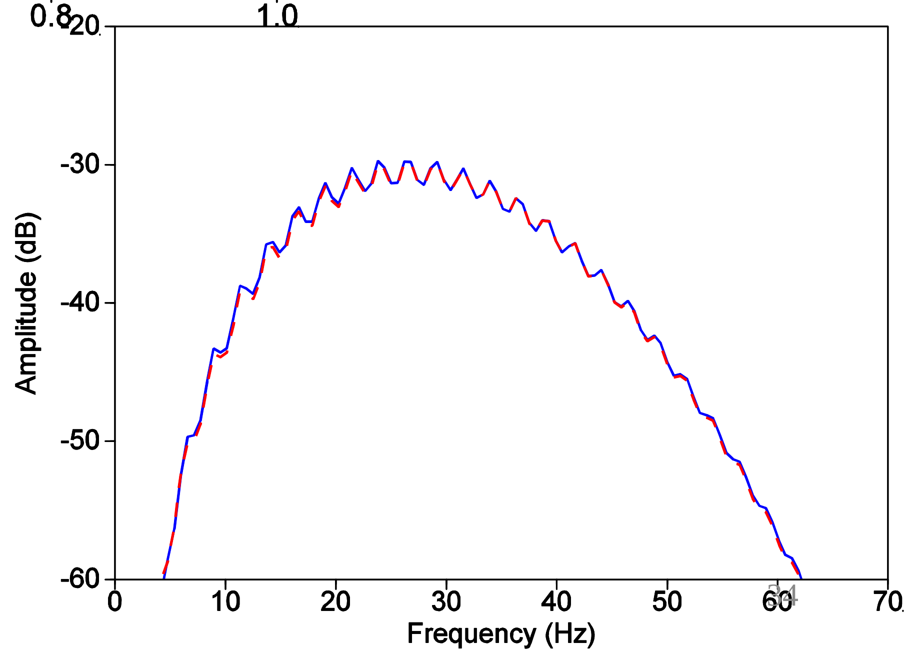




Red line: CdH upgoing wave
Green line: x - ω deghosted

Aperture: 300m

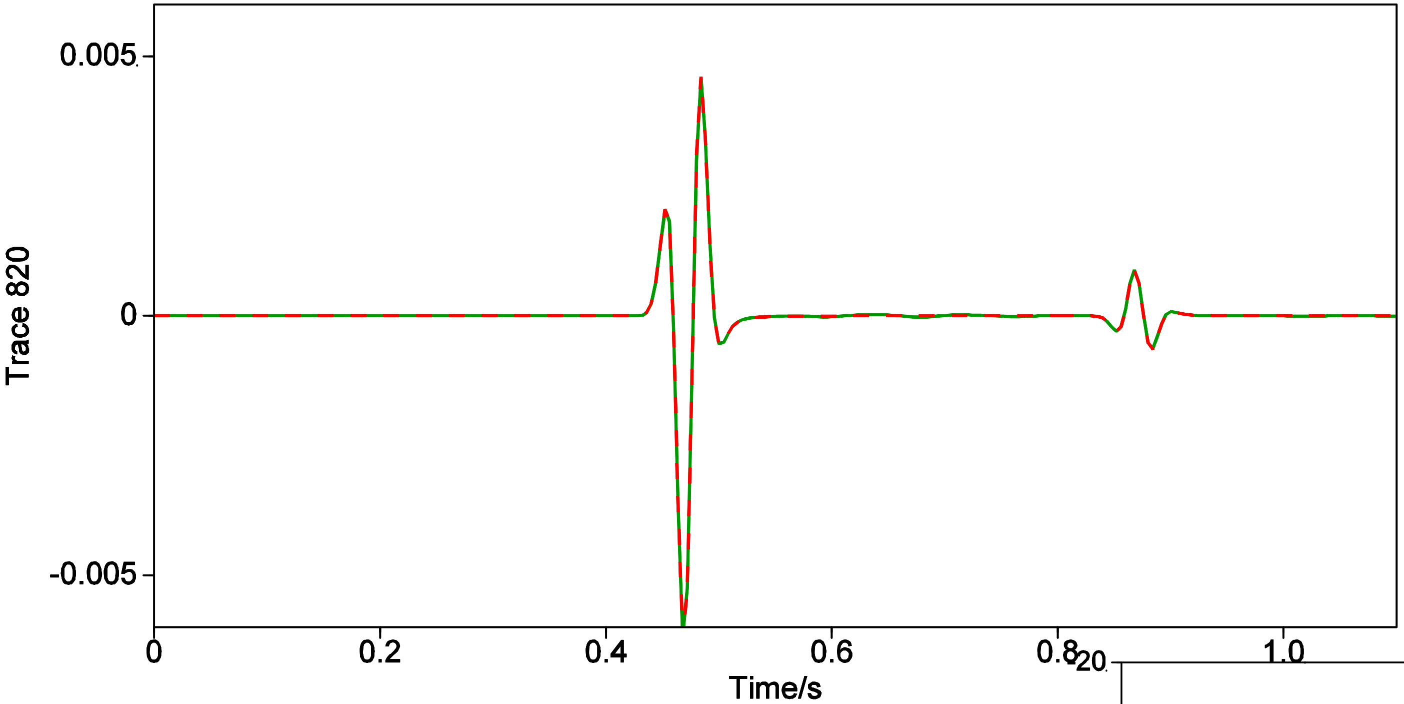


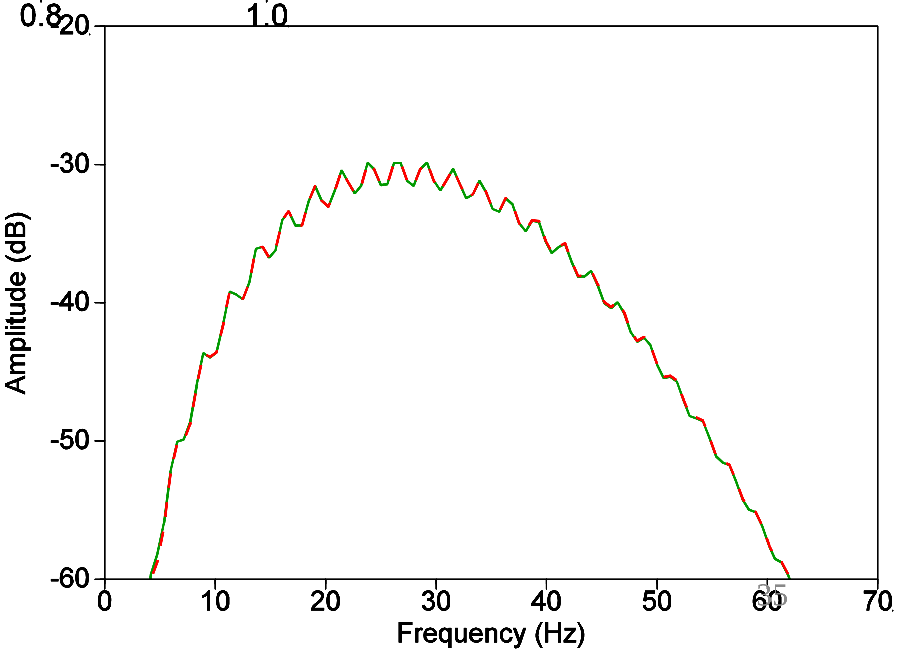


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

Aperture: 300m

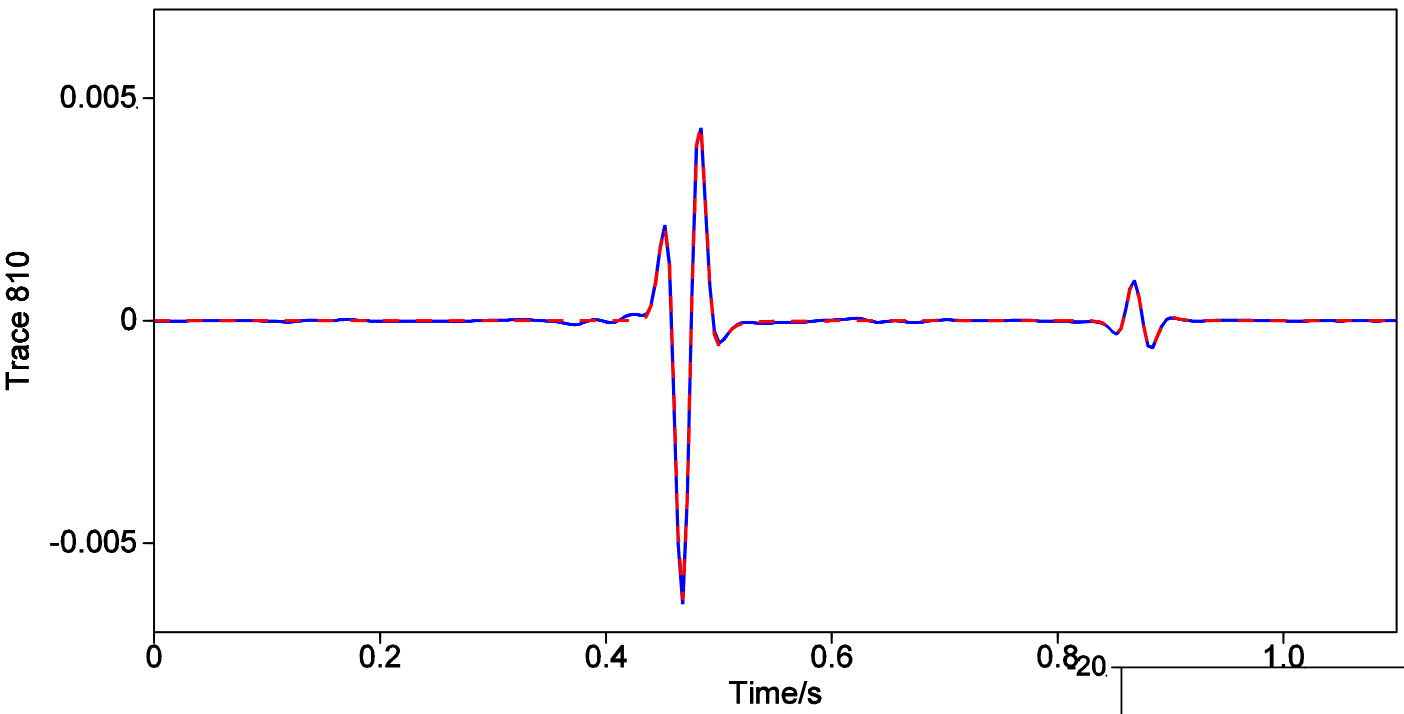


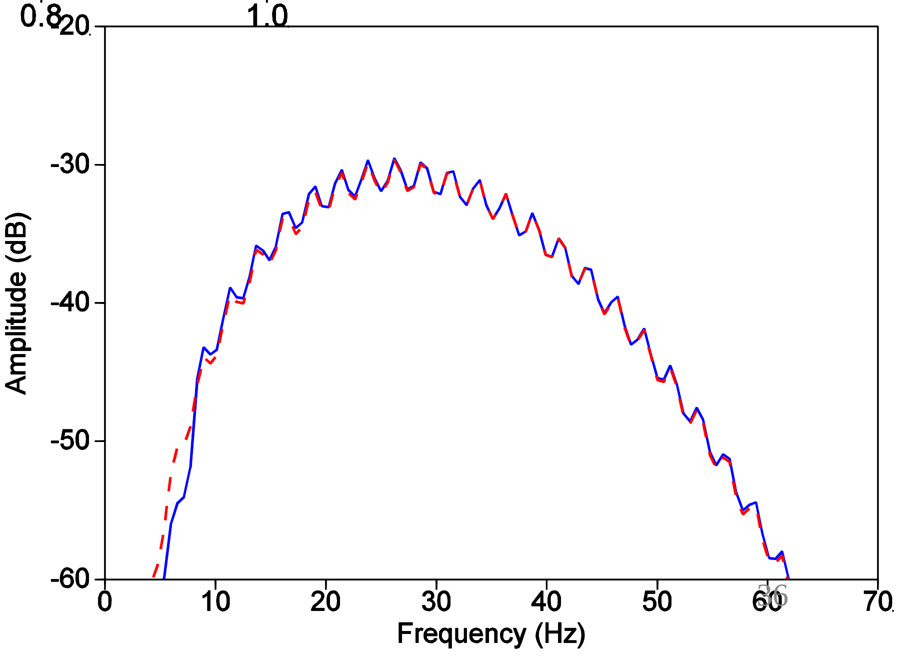


Red line: CdH upgoing wave

Green line: x - ω deghosted

Aperture: 150m

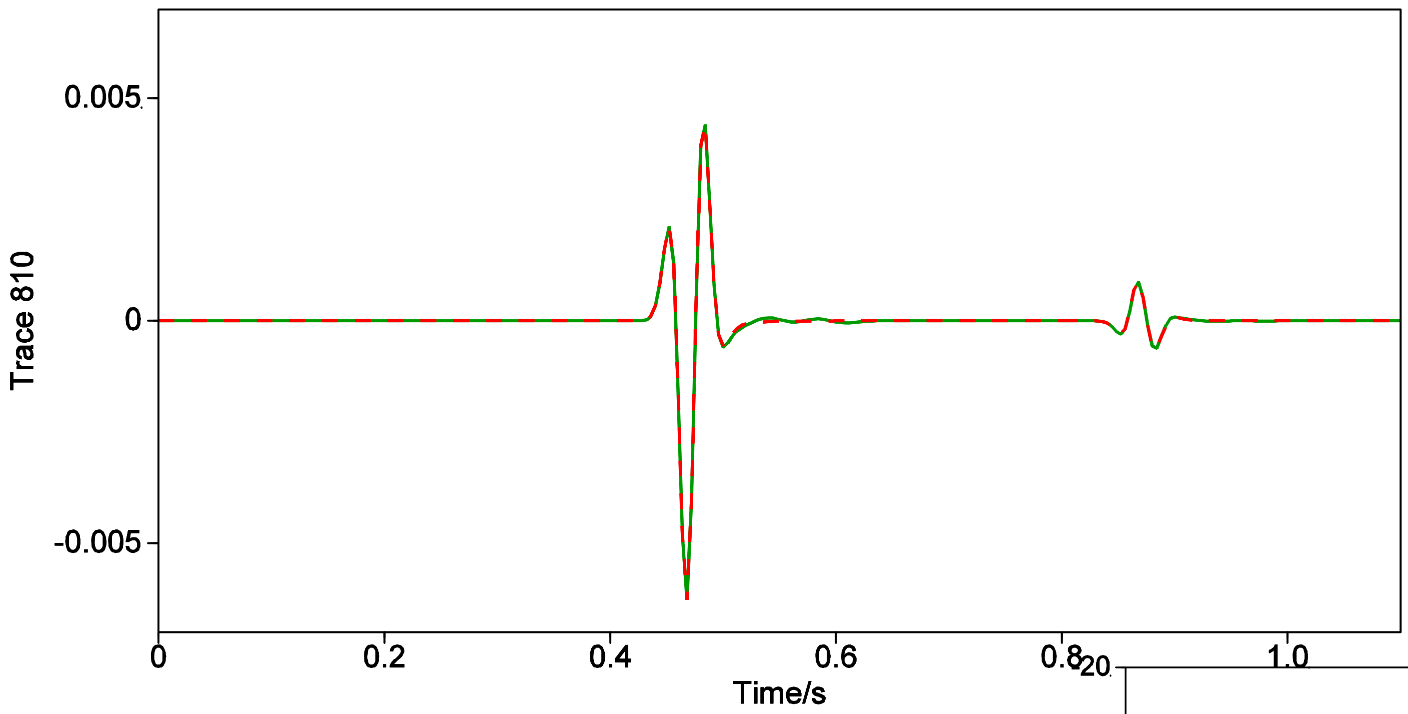


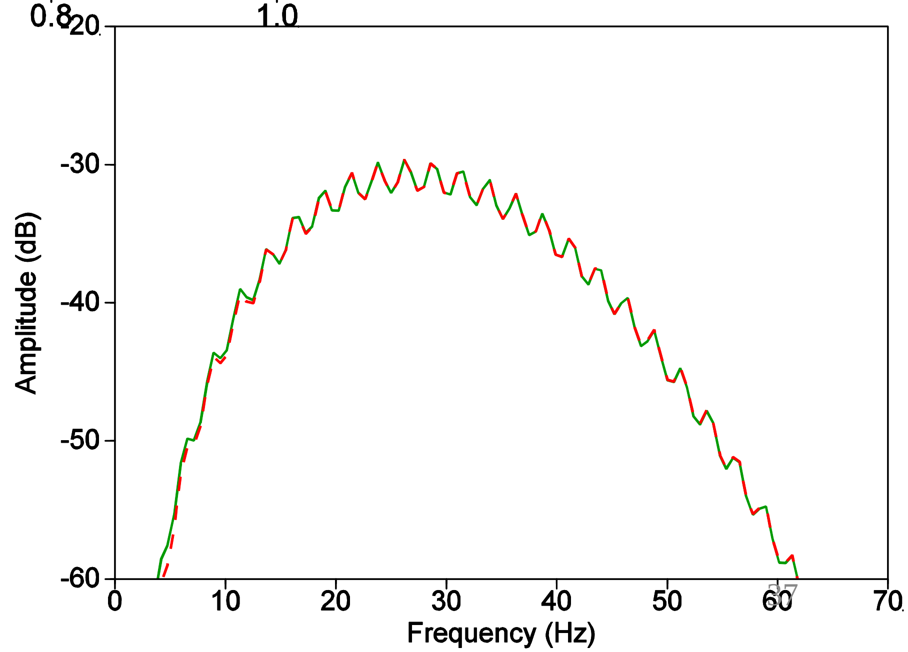


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

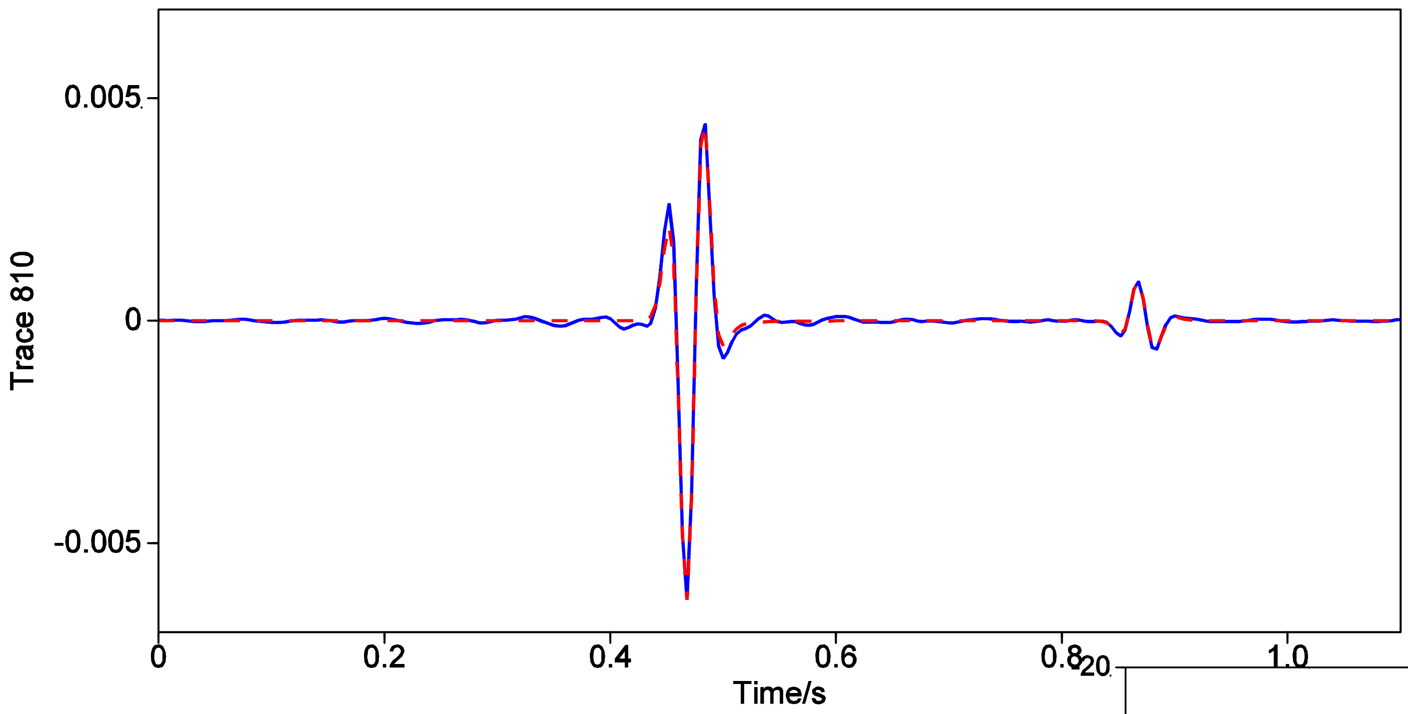
Aperture: 150m

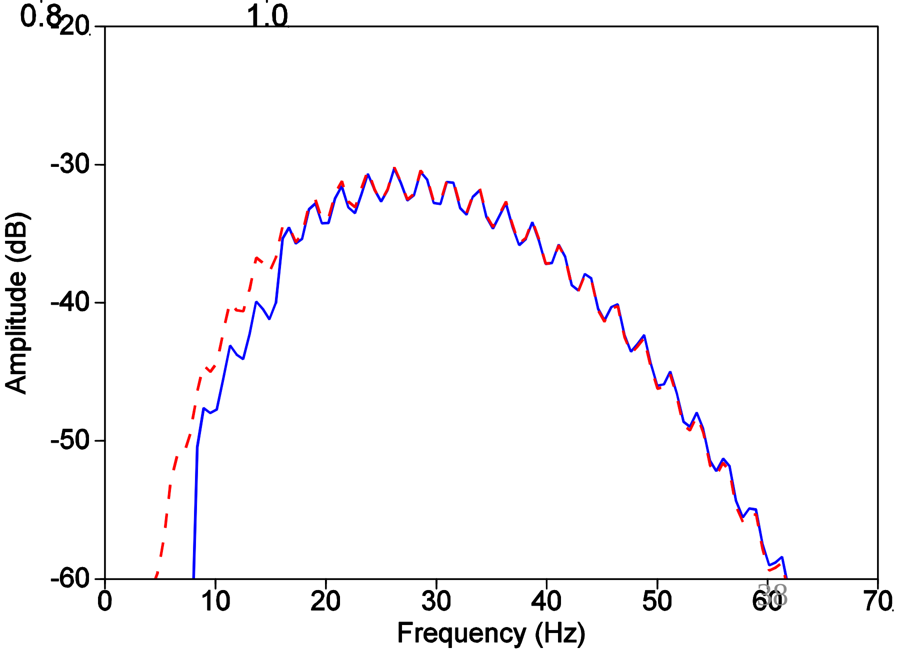




Red line: CdH upgoing wave
Green line: x - ω deghosted

Aperture: 75m

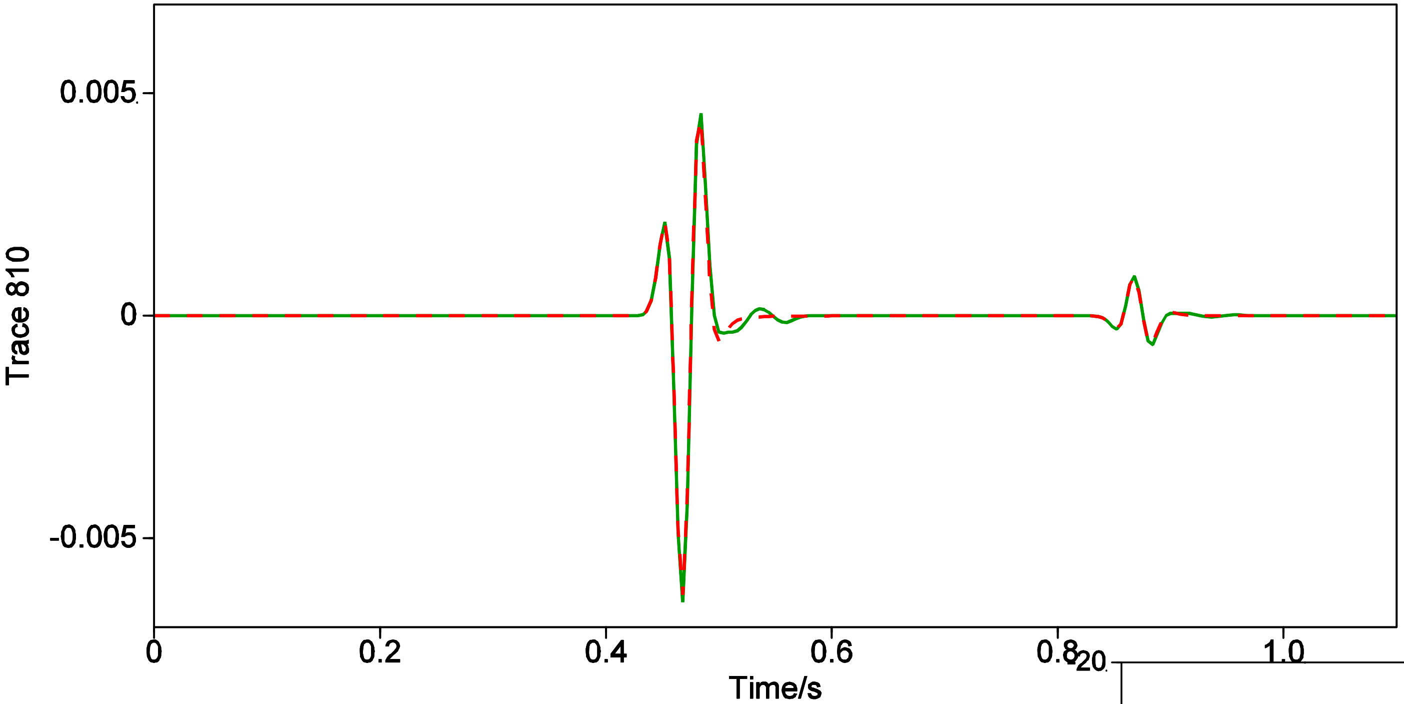


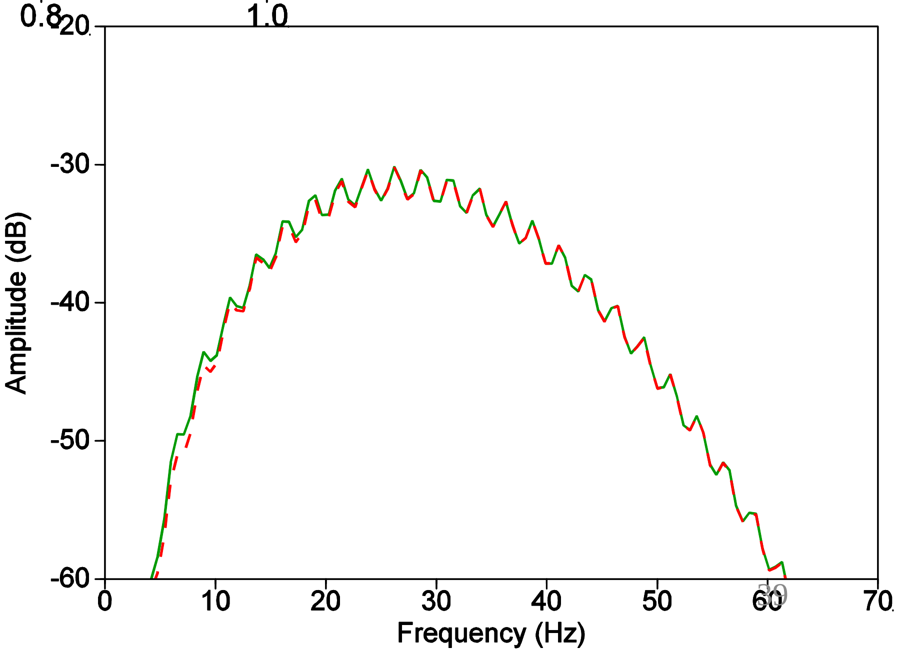


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

Aperture: 75m

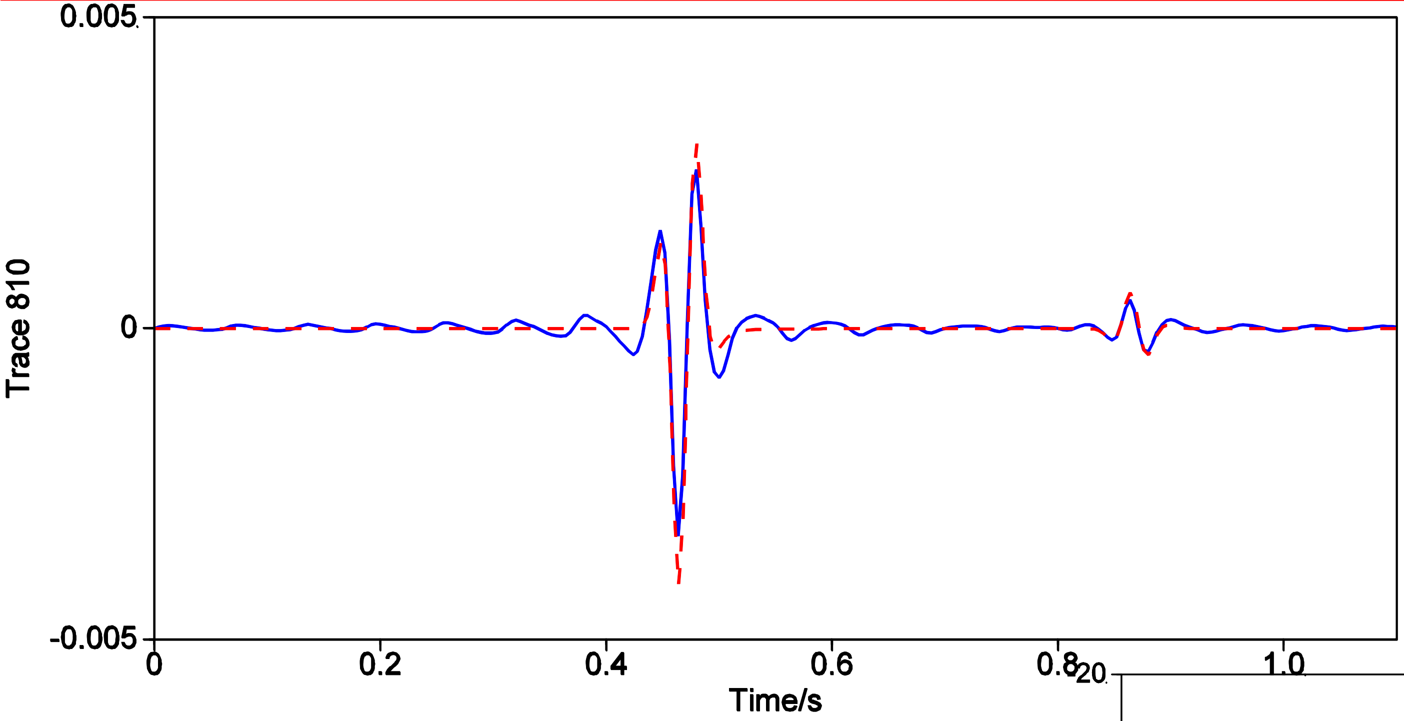


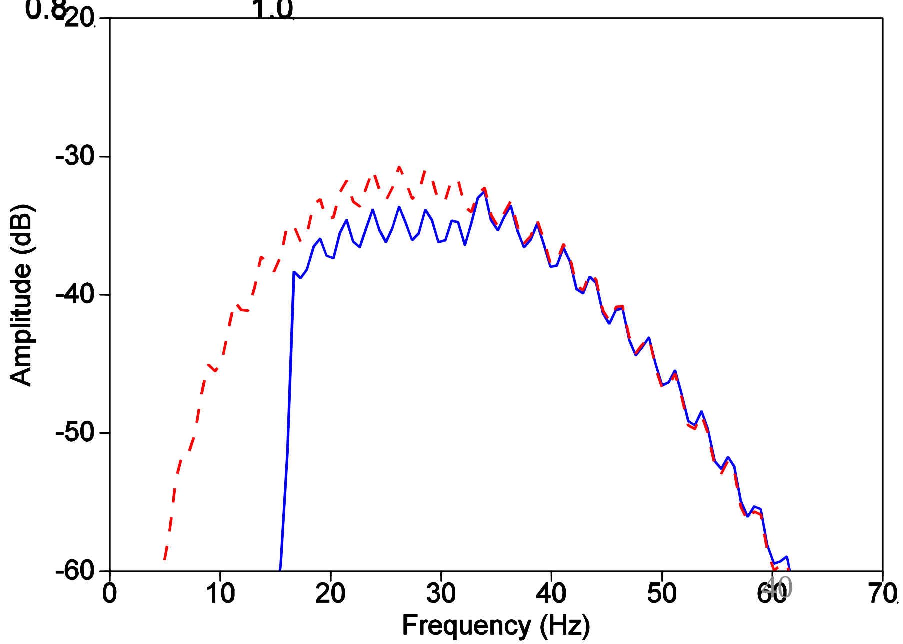


Red line: CdH upgoing wave

Green line: x - ω deghosted

Aperture: 45m

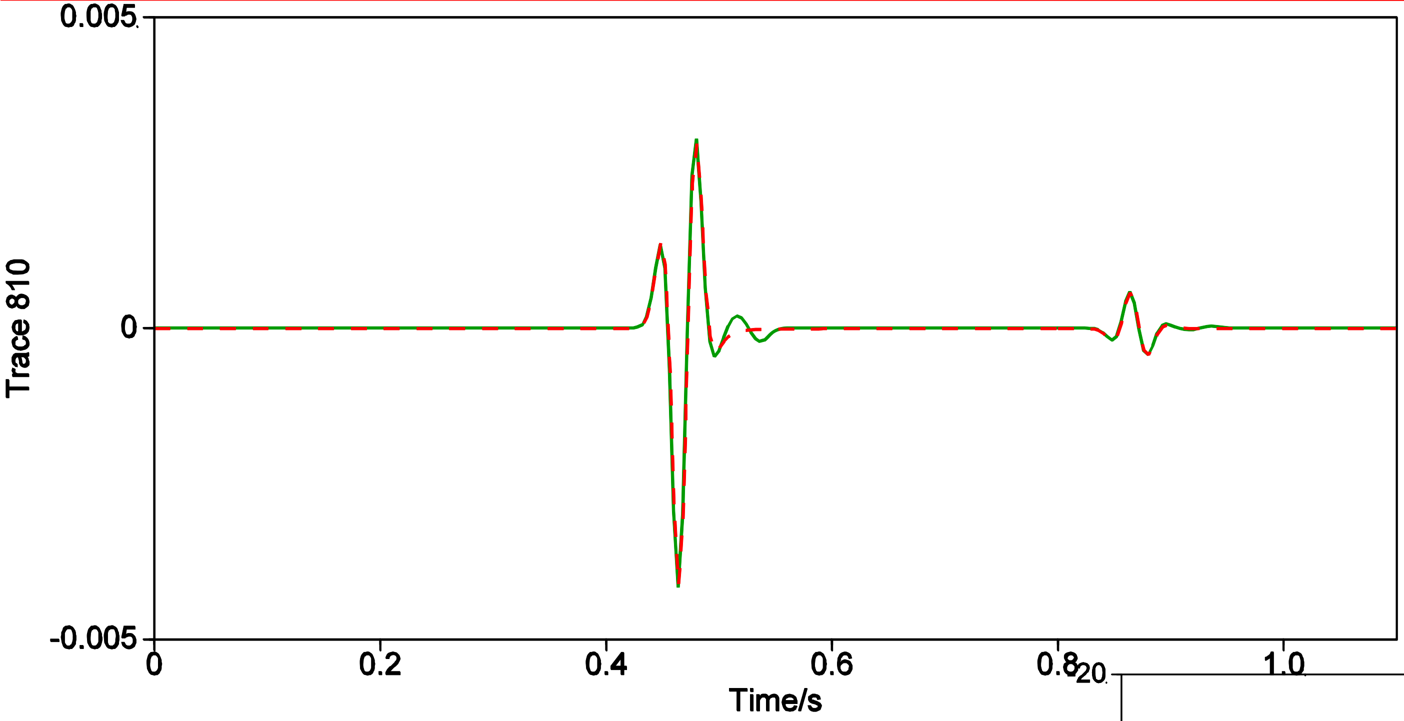


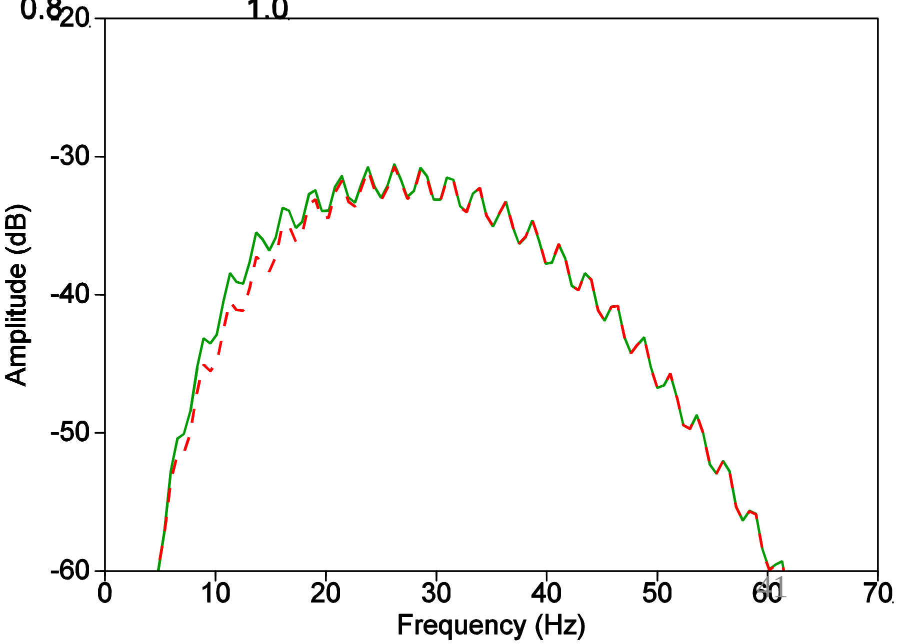


Red line: CdH upgoing wave

Blue line: k_x - ω deghosted

Aperture: 45m





Red line: CdH upgoing wave

Green line: x - ω deghosted

		k_x - ω domain result	x - ω domain result
Aperture	Wide (e.g. 2400m)	Ideal	Ideal
	Intermediate (e.g.300m,150m)	Has residual	Satisfactory
	Narrow (75m, 45m)	Has residual Worse, artifacts	Has residual Better
Frequency spectrum			Boosts low frequency energy

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Key Points and Conclusion

- For dense spatial sampling and wide aperture (e.g., in-line data), Green's theorem de-ghosting techniques in k_x - ω and x - ω domains both have ideal results;

- For sparse spatial sampling and narrow aperture (e.g., cross-line data), compared to k_x - ω domain, the approach in x - ω domain produces a better result;

- Green's theorem de-ghosting method in x - ω domain shows its advantage in boosting low frequencies.

Reference

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