Log-validated FWI with wavelet phase & amplitude updating applied on Hussar dataset

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Motivation

Margrave introduced a variant of FWI using reflections, one way operators and well-logs.

We propose a methodology to correct the amplitude and phase of the modelled data, and with this information, update the wavelet in each iteration.

The unknown wavelet represents a challenge that may prevent the successful application of FWI on real seismic data.

Velocity perturbation

$$\delta v(x,z) = \lambda \int \sum_{s,r} \omega^2 \hat{\Psi}_s(x,z,\omega) \delta \hat{\Psi}^*_{r(s),k}(x,z,\omega) d\omega$$

Data residuals

$$\delta\Psi = \Psi - \Psi_k(m,w)$$

Velocity perturbation when PSPI is used instead of RTM

$$\delta v = \lambda \, Imp(\delta R)$$

PSPI migration of data residuals with a deconvolution imaging condition

$$\delta R = \int \sum_{s,r} \frac{\delta U_r(x,z,\omega) D_s^*(x,z,\omega)}{D_s(x,z,\omega) D_s^*(x,z,\omega) + \mu I_{max}(z)} d\omega$$

Separating observed and modelled reflectivity

$$\delta R = R_{o,z} - R_{m,z}$$

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depth to time

$$R_{o,t} \qquad R_{m,t}$$

Cost function

$$\varepsilon_R = \sum [R_{o,t} - R_{m,t}(A, \phi)]^2$$

$$A, \phi$$

Methodology

$$A, \phi$$

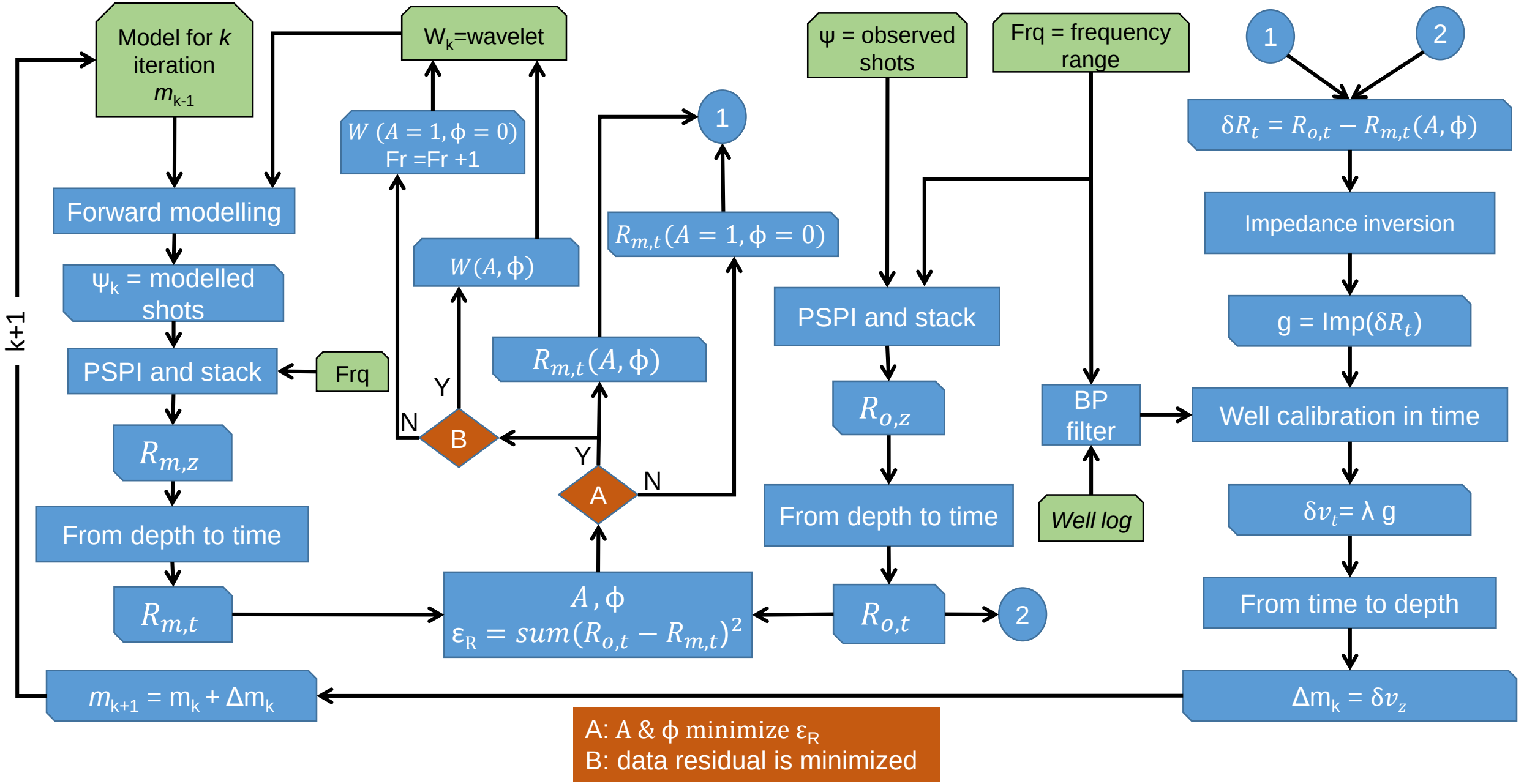
$$\delta v_t = \lambda \, Imp\left(R_{o,t} - R_{m,t}(A, \phi)\right)$$

$$w(A, \phi)$$

time to depth

$$\delta v_z$$

Workflow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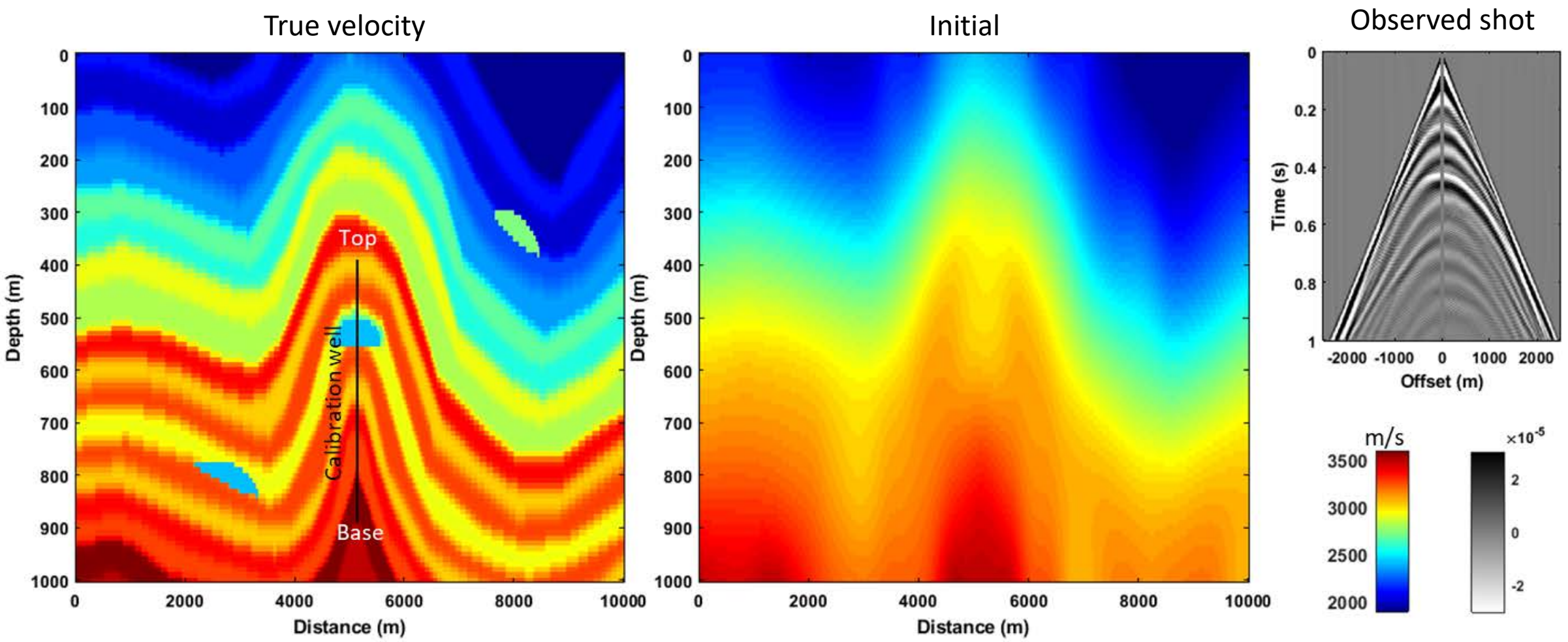
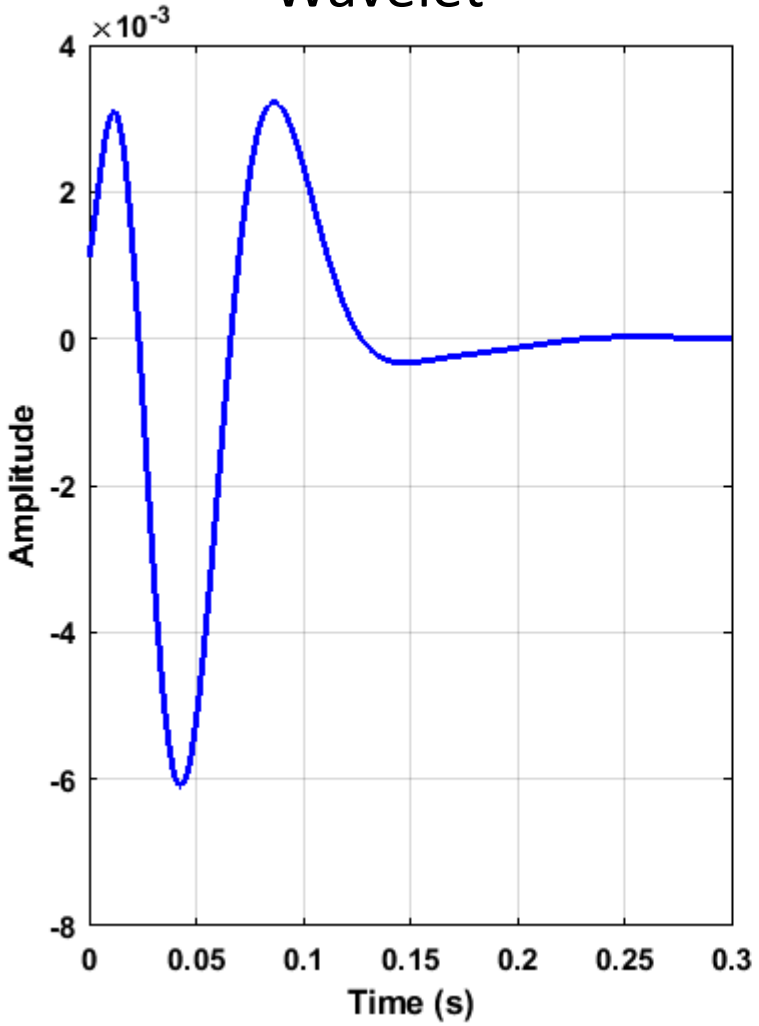
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

Illustrating the workflow

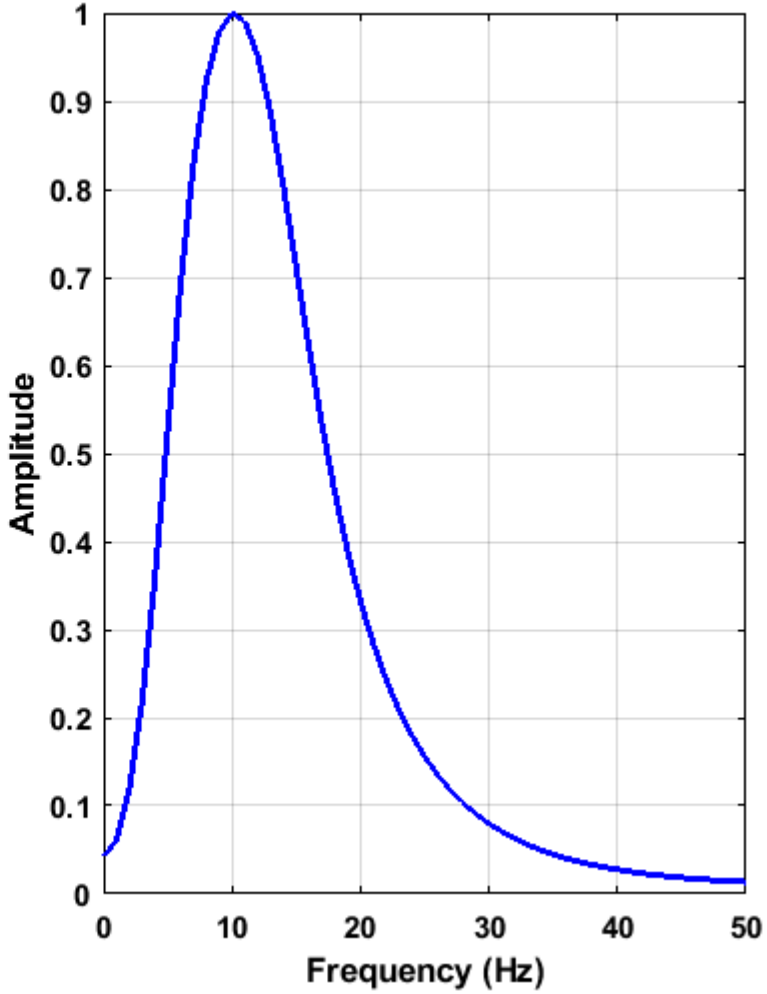


True wavelet

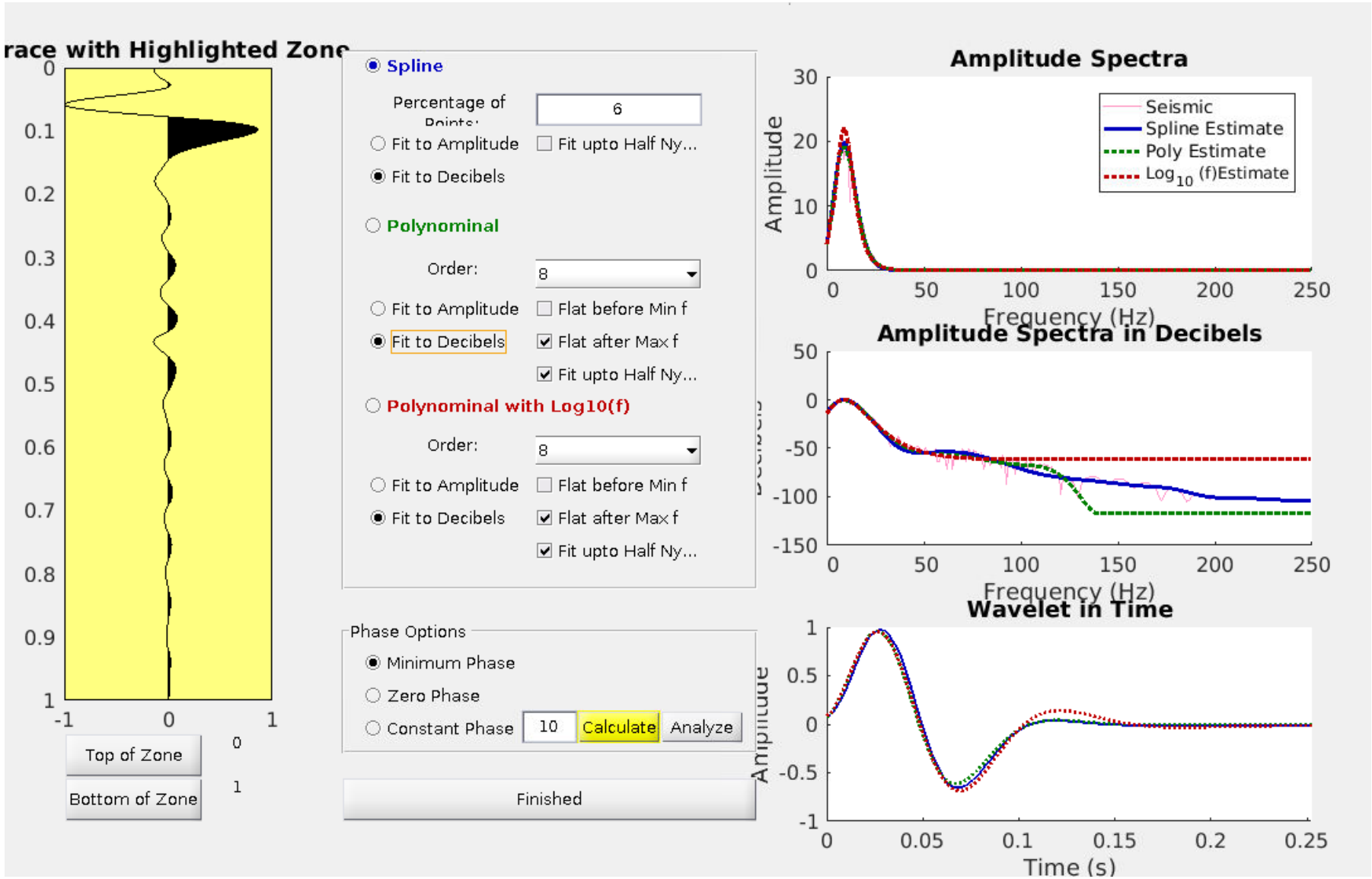
Wavelet



Amplitude spectrum

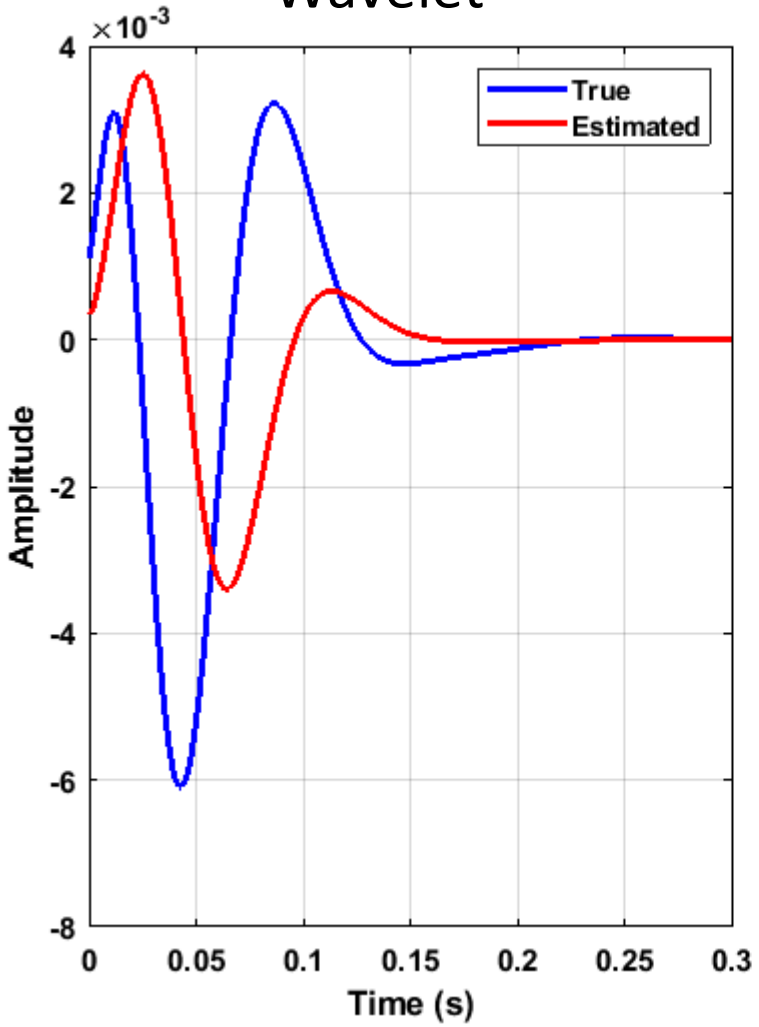


Estimating wavelet from the seismic



True and initial wavelet

Wavelet



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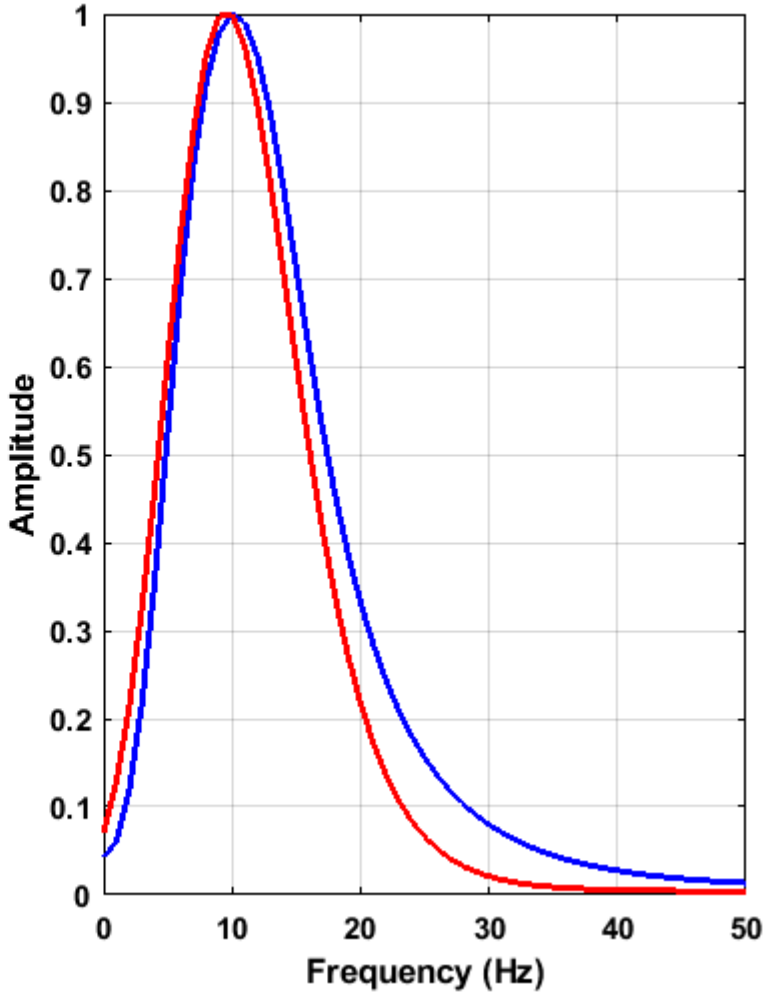
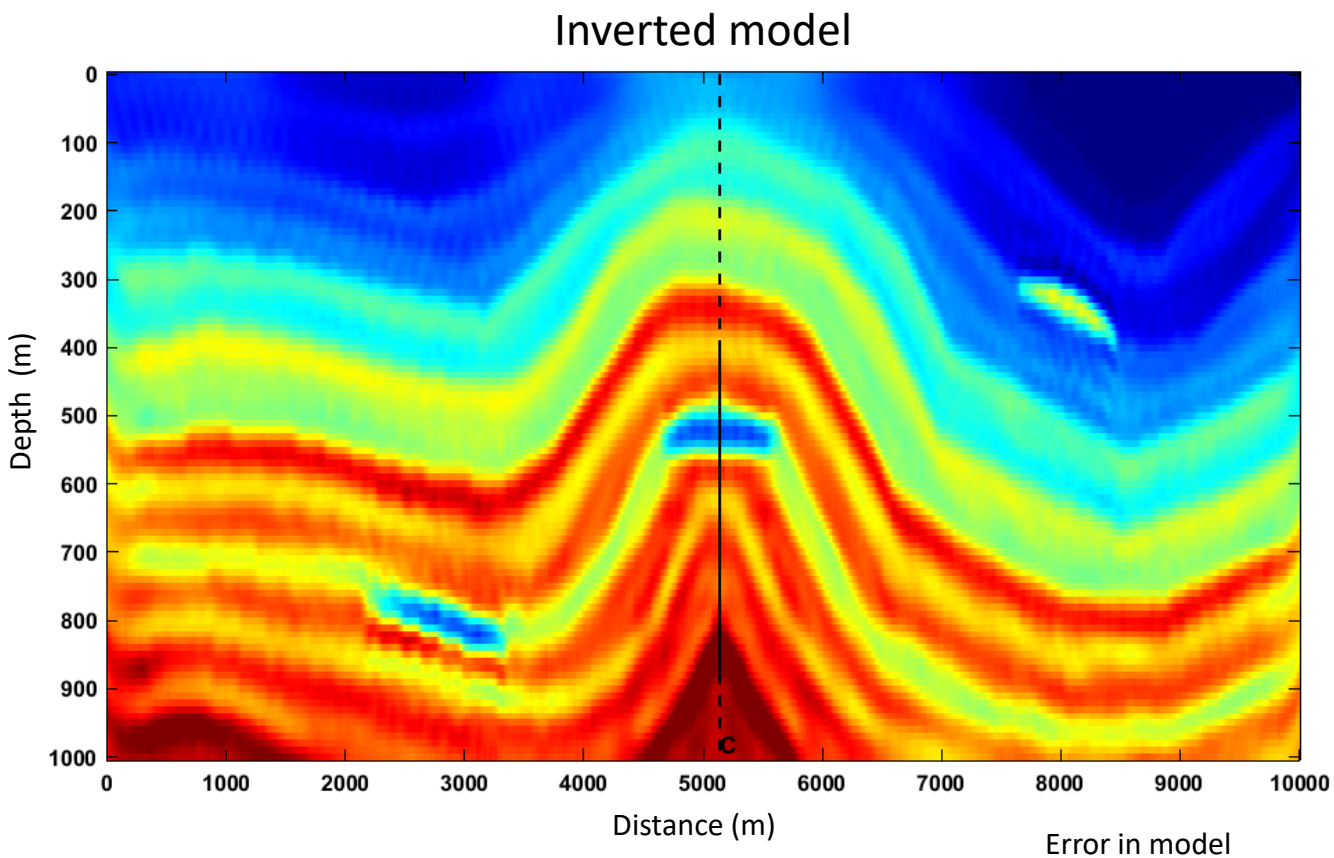
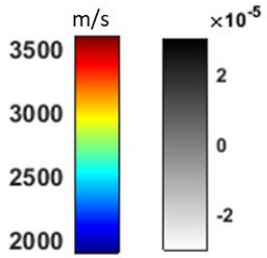
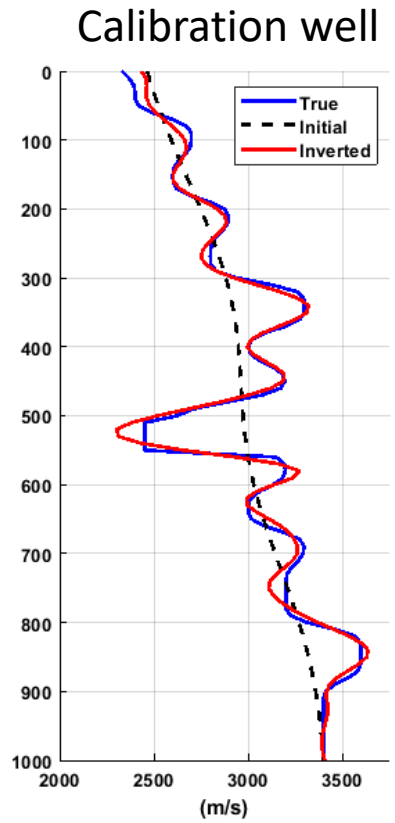
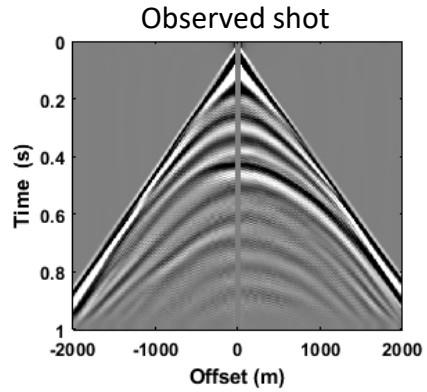


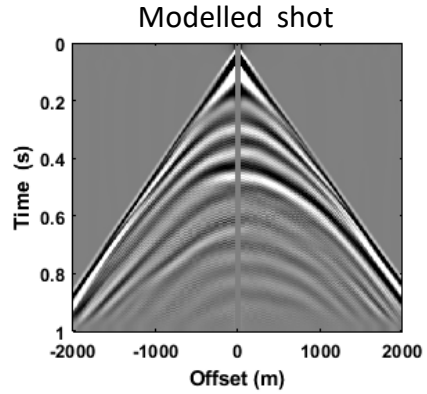
Inversion with true wavelet

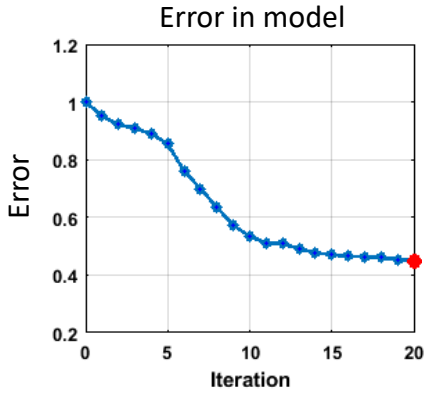


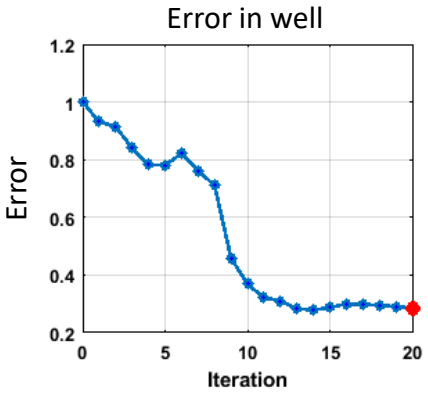


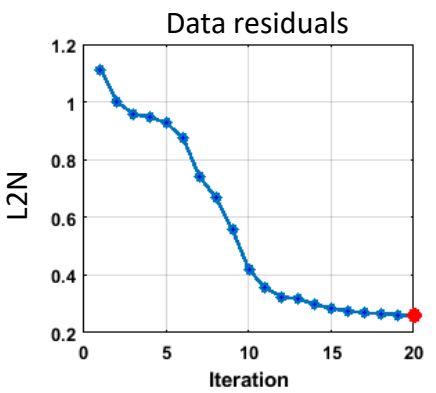




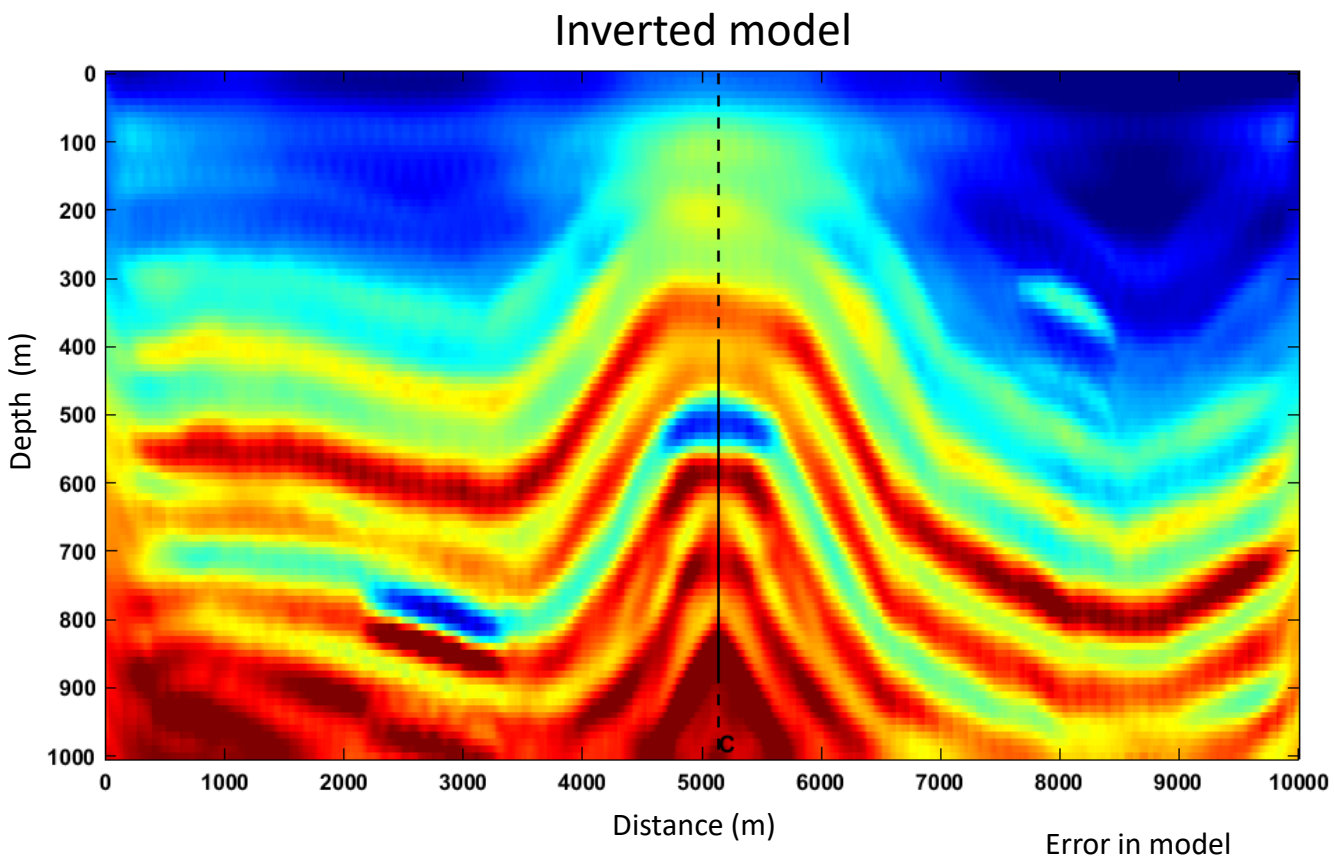


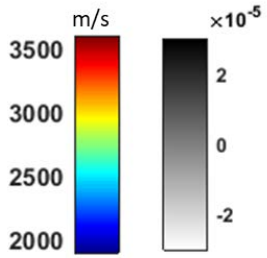


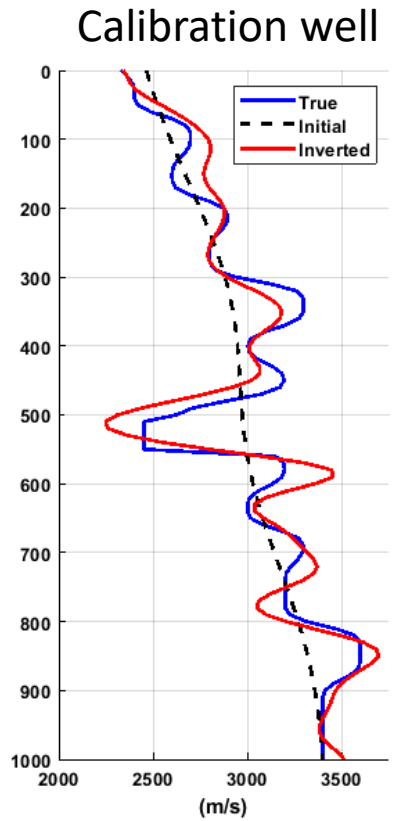


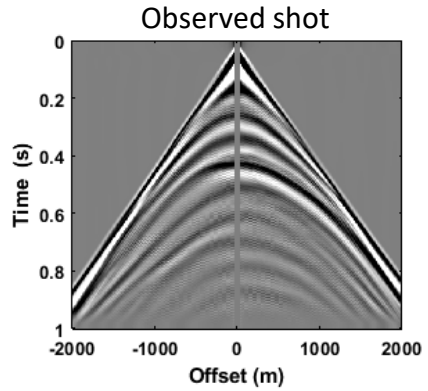


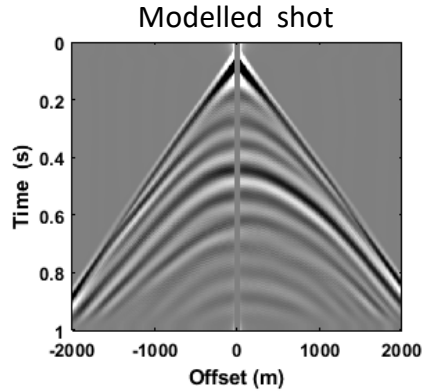
Inversion with wrong wavelet

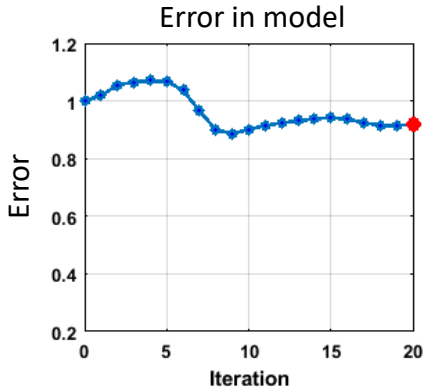


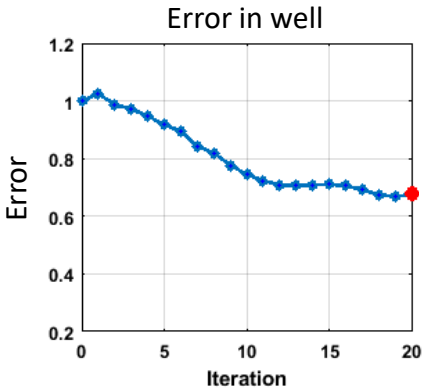


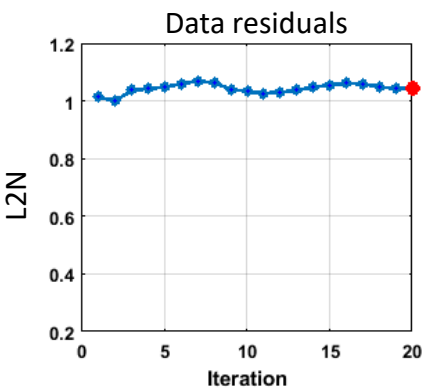




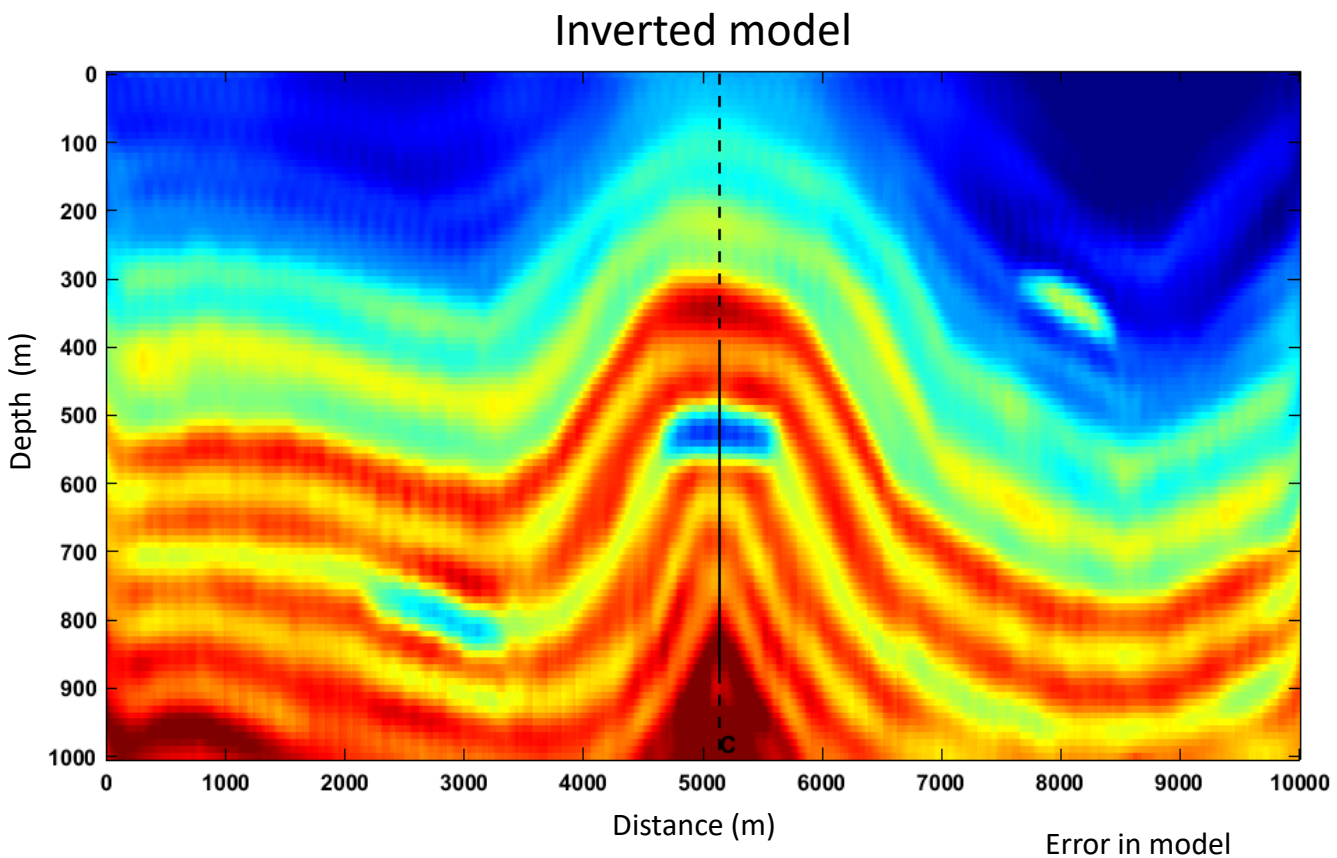


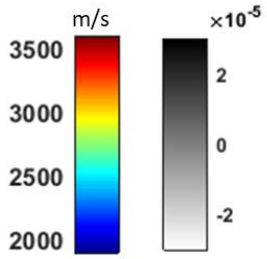


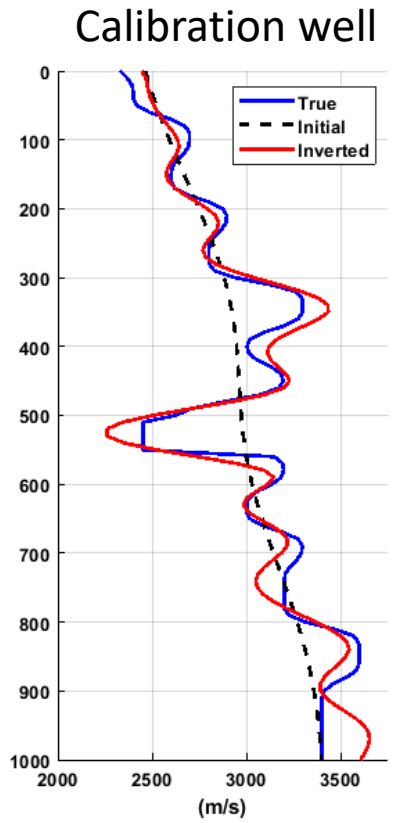


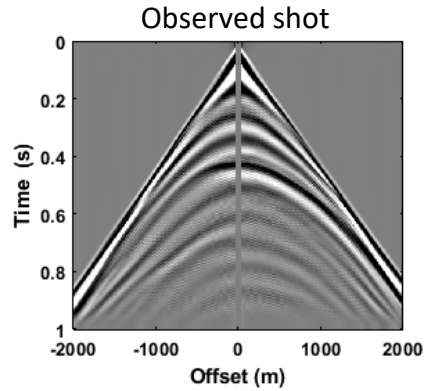


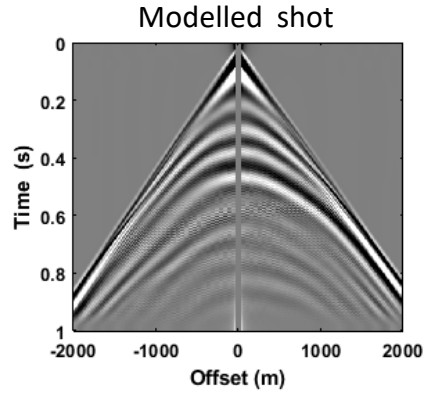
Inversion with wrong wavelet and applying amplitude and phase updating

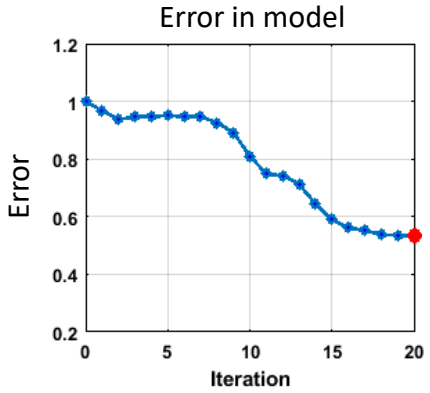


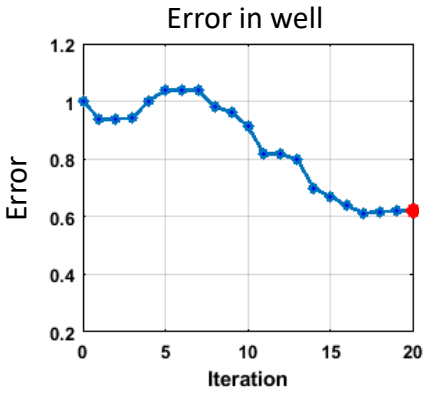


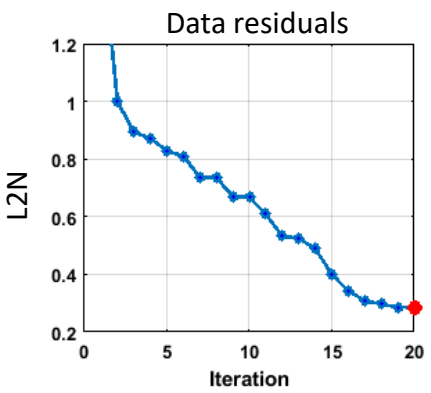




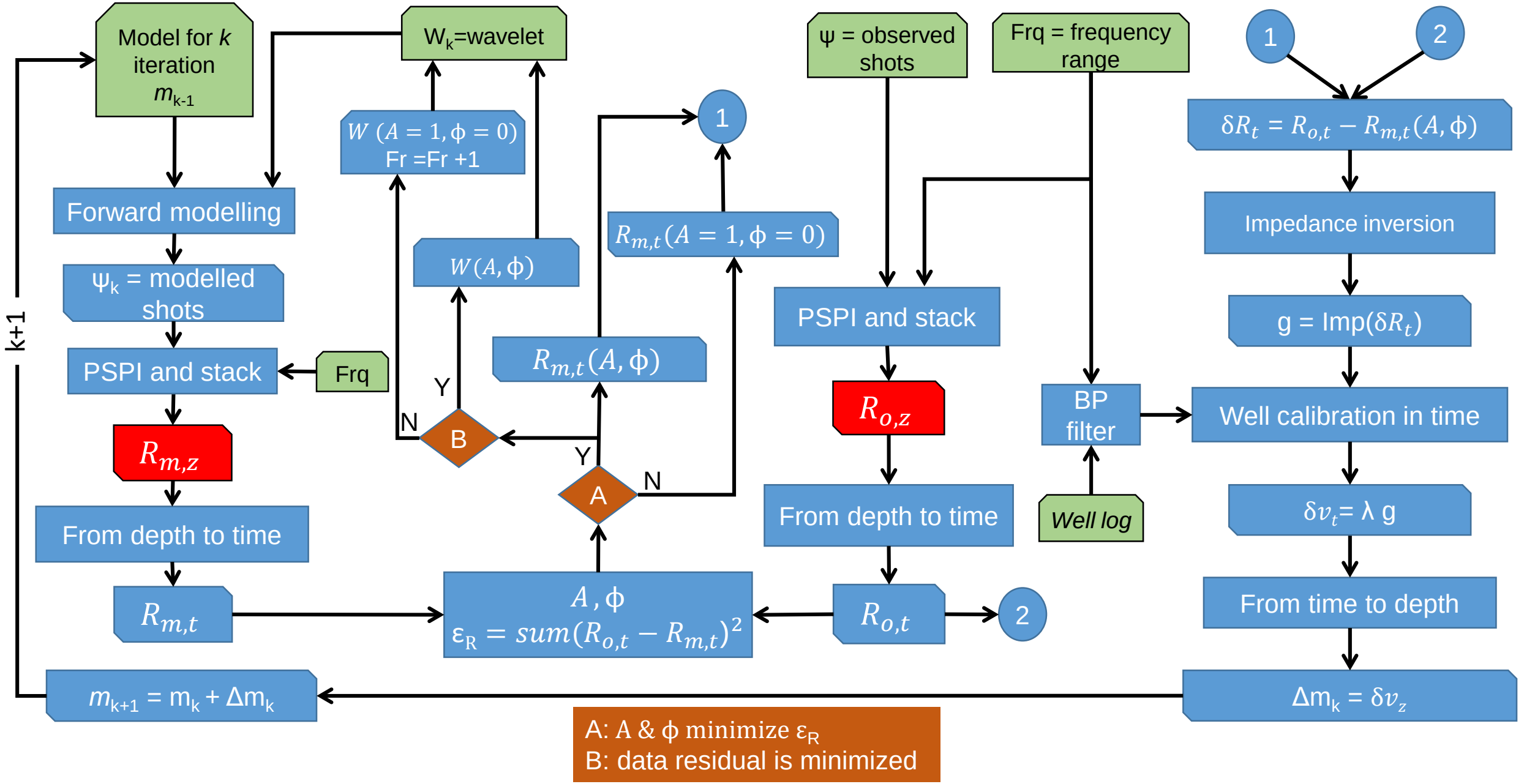








Workflow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A: A & ϕ minimize ε_R
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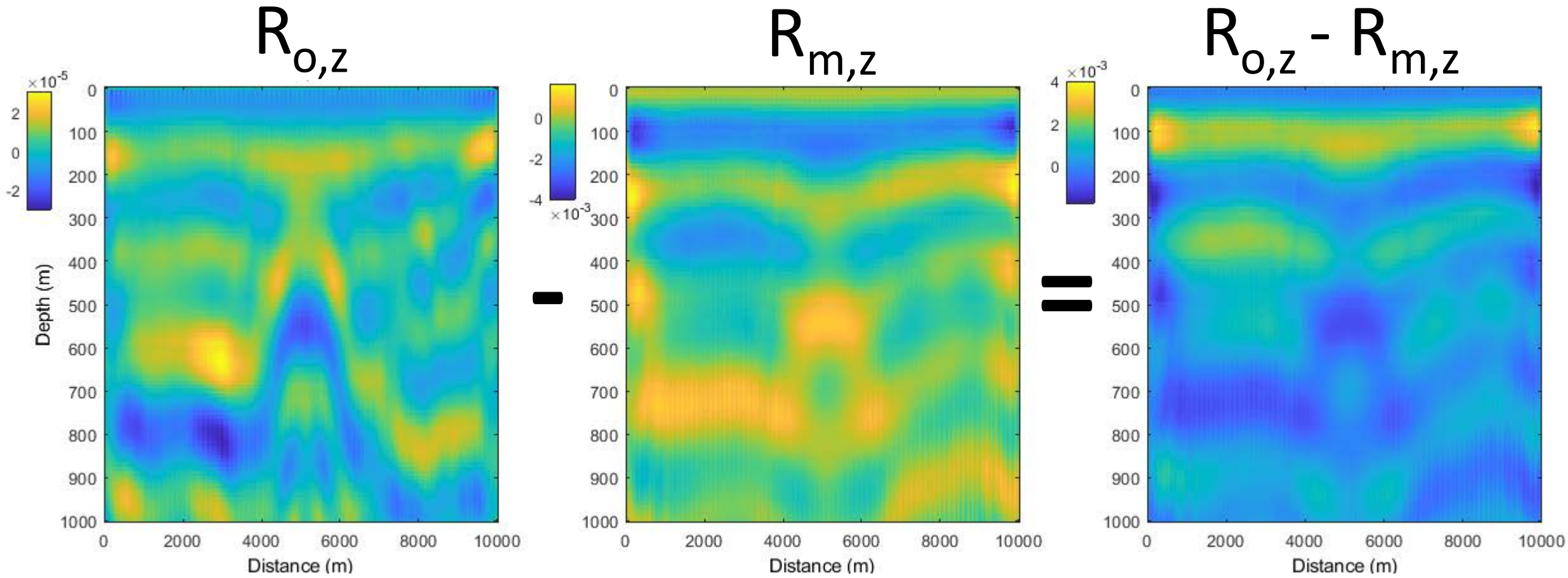
Process flow



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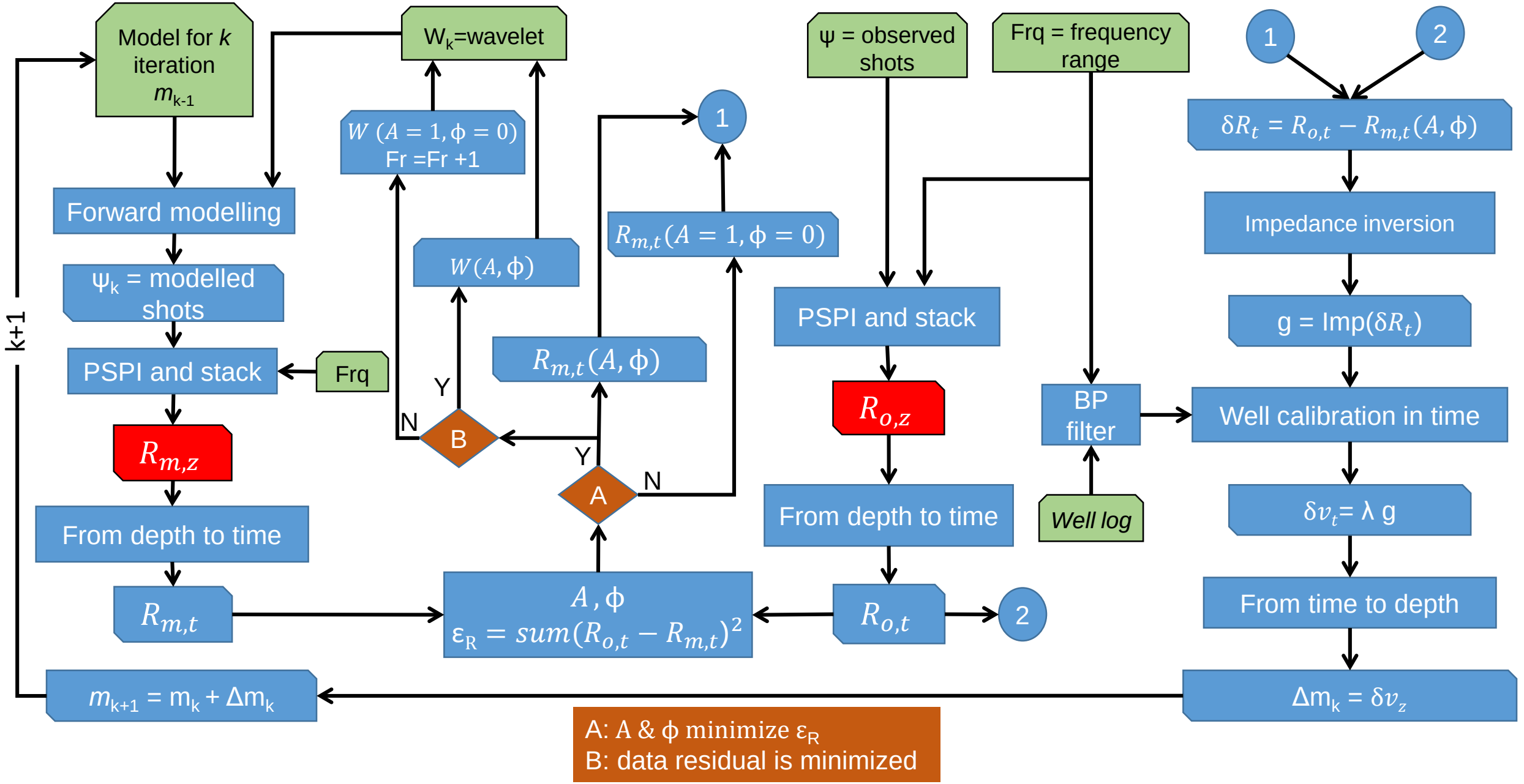
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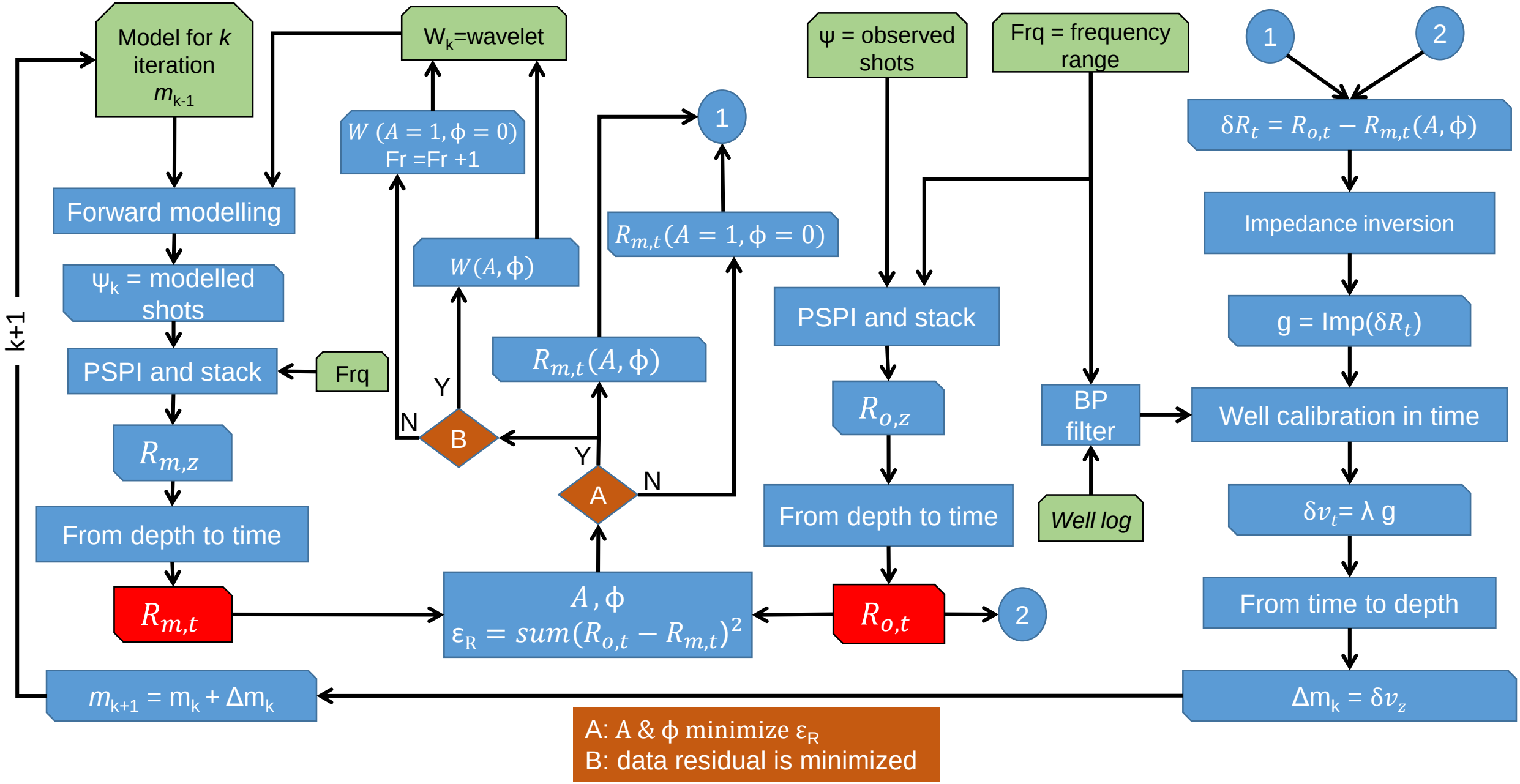
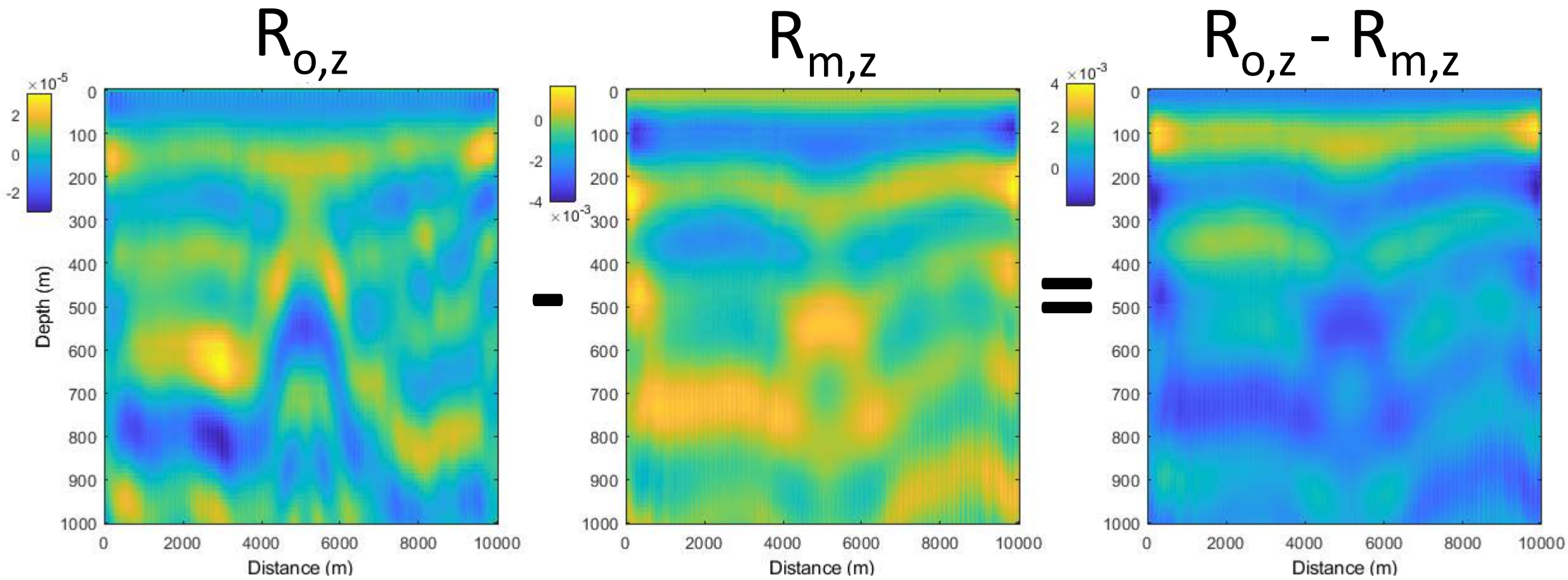


Amplitude and phase updating



Amplitude and phase updating

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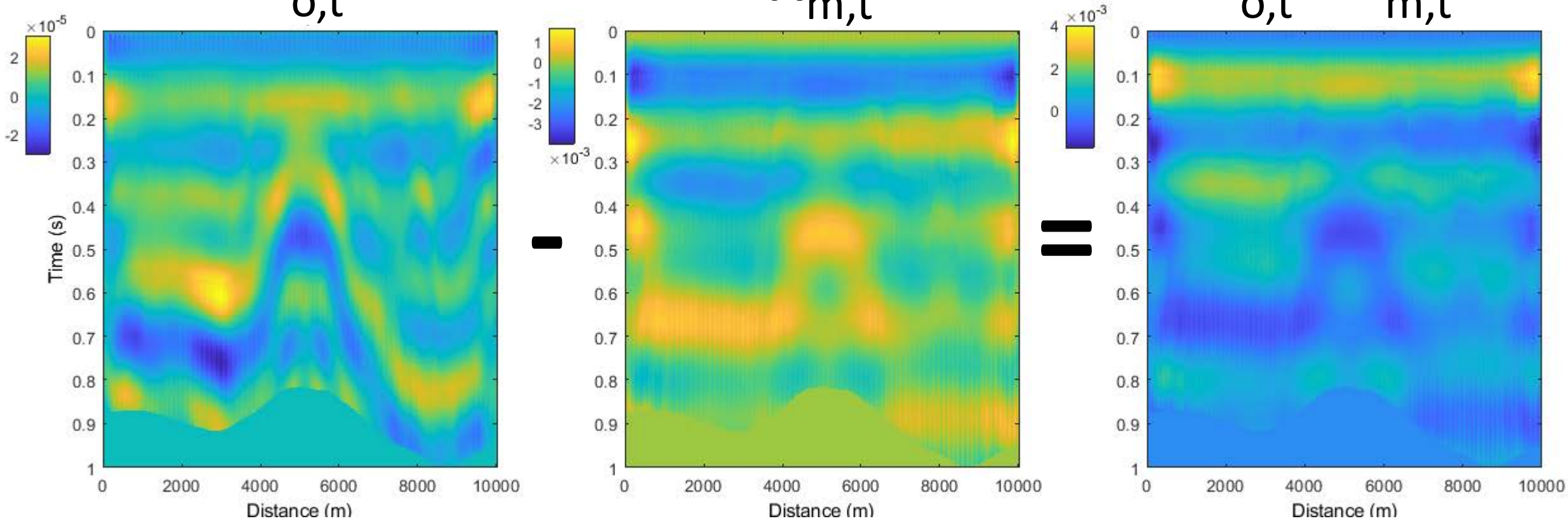

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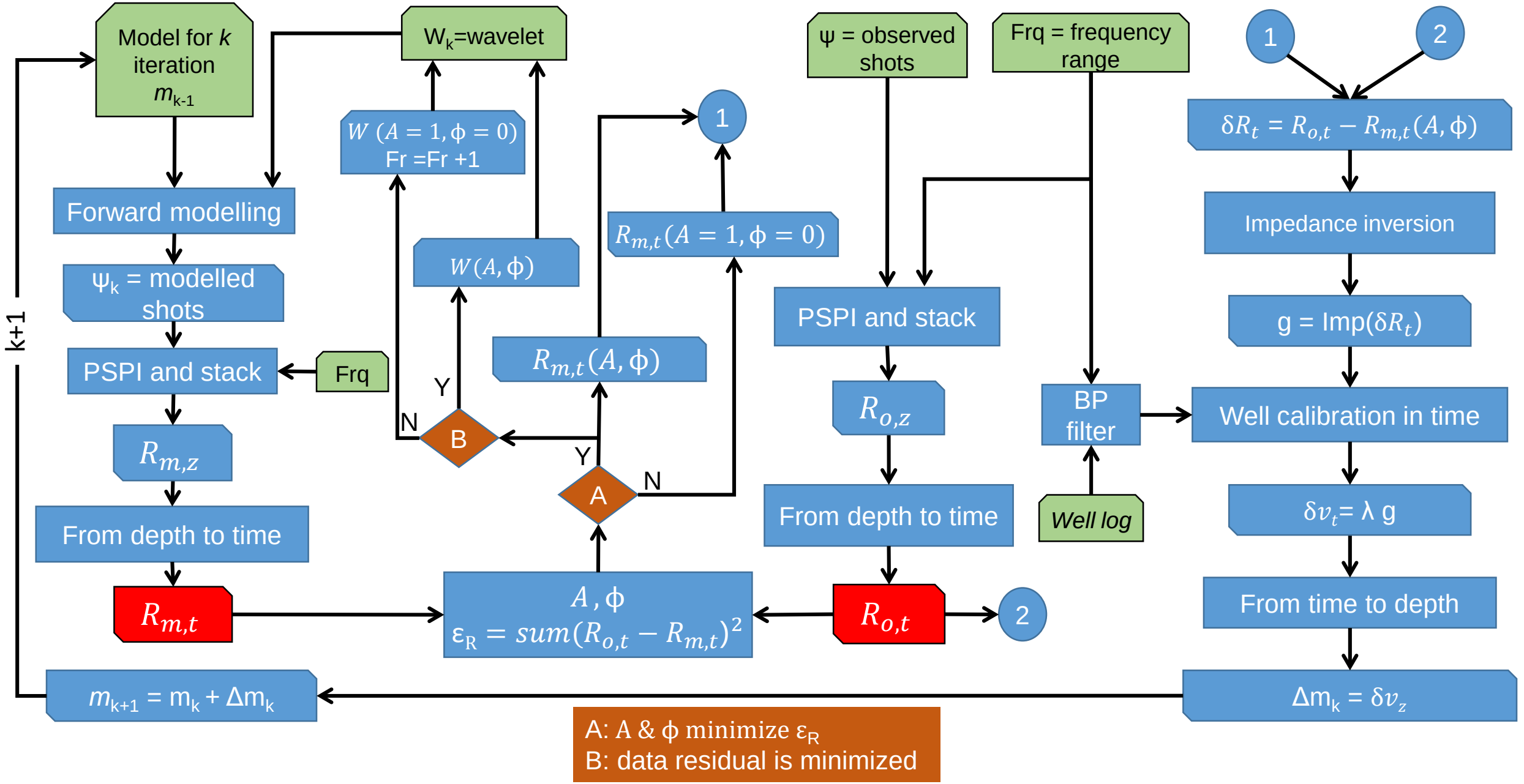
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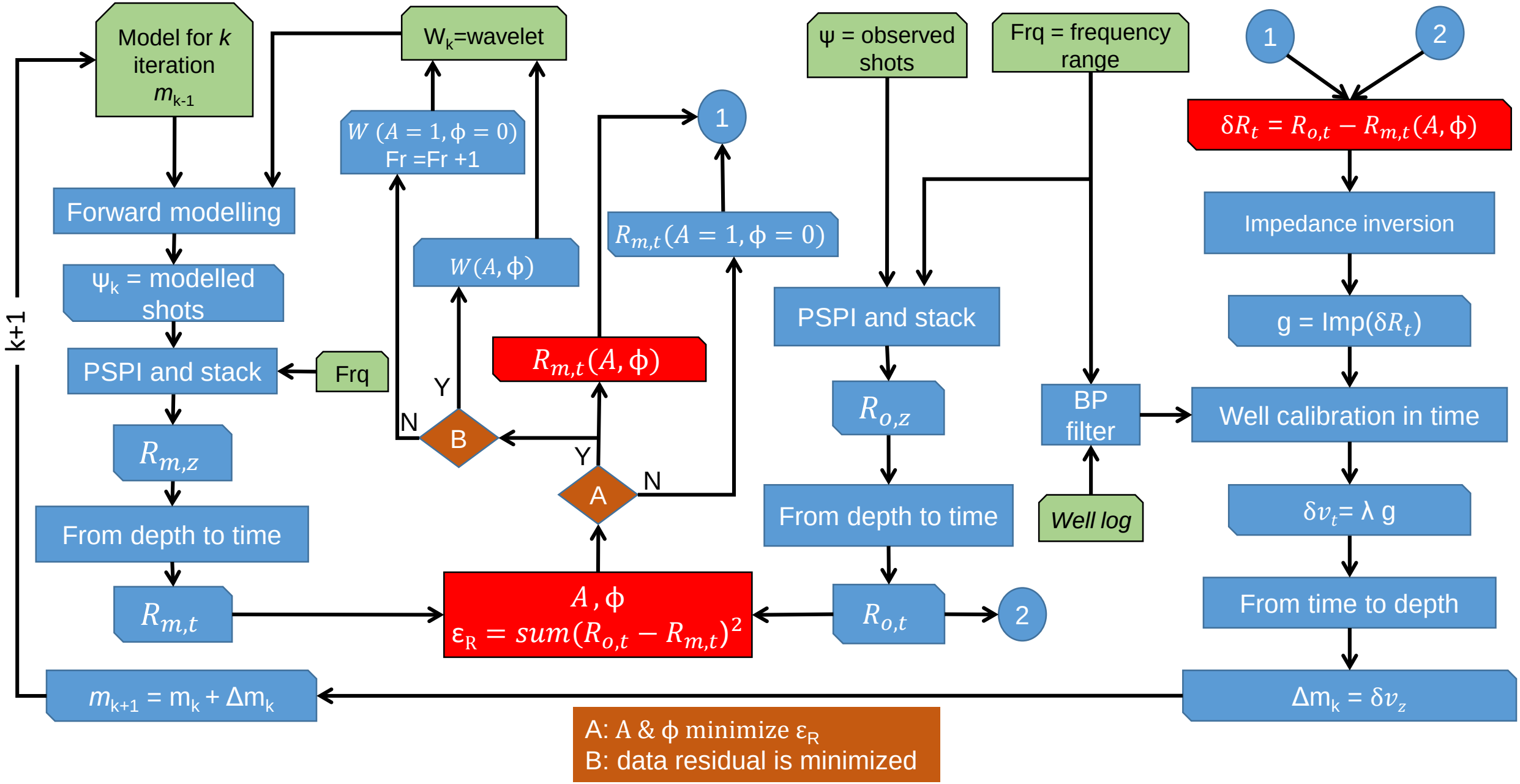
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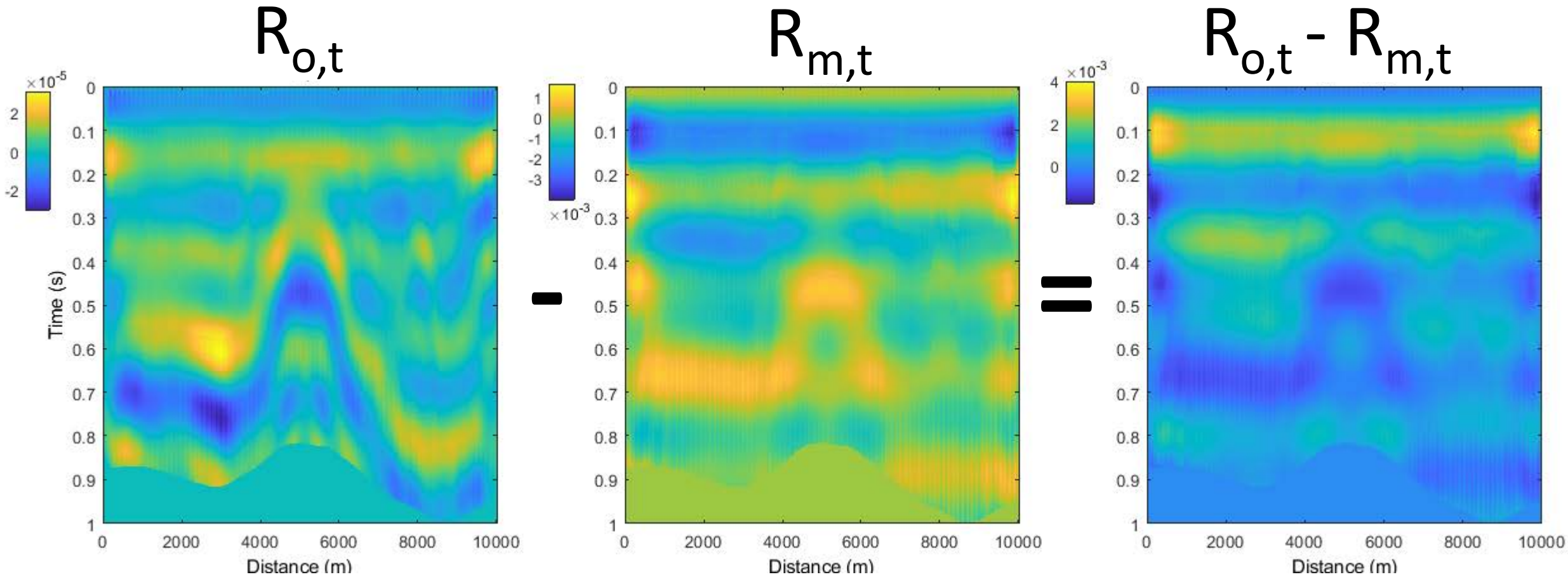

Amplitude and phase updating

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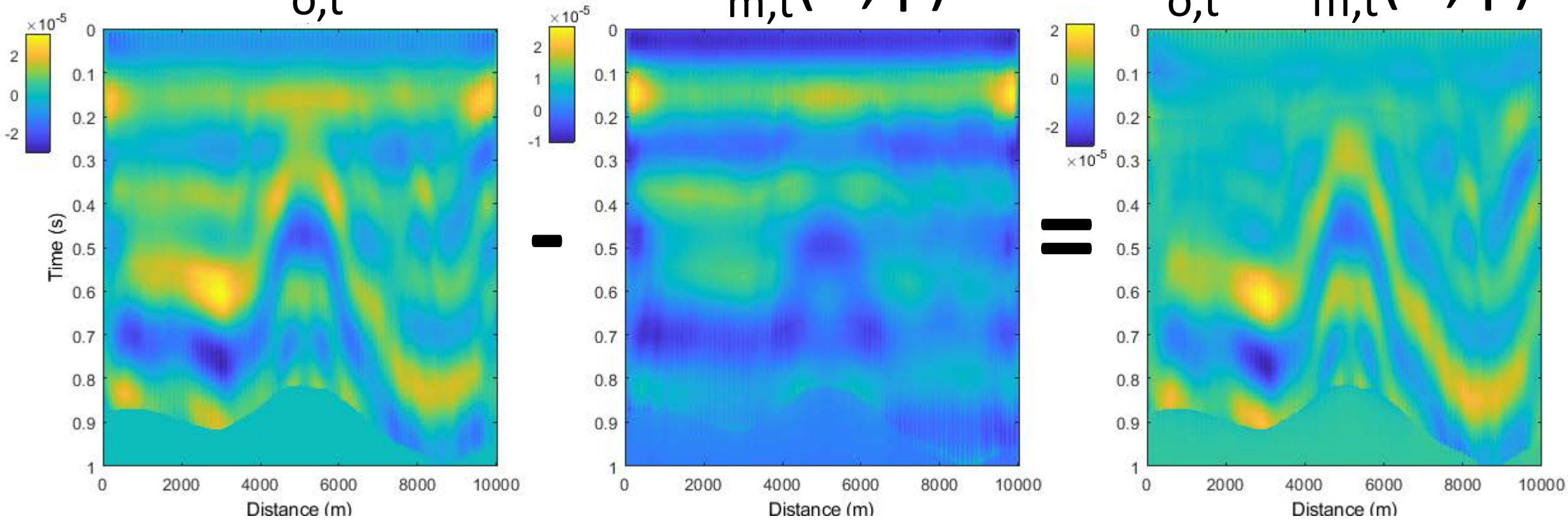

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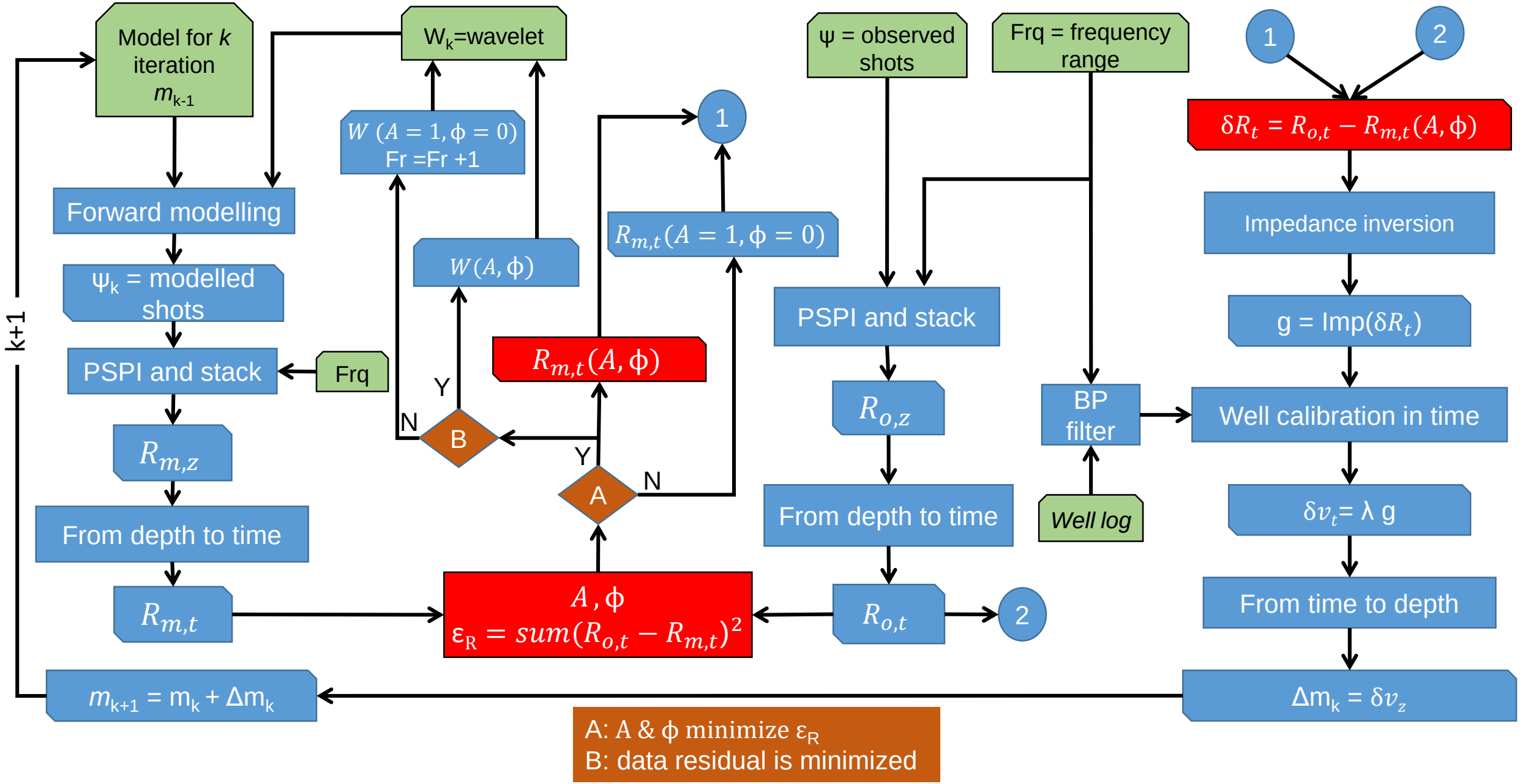
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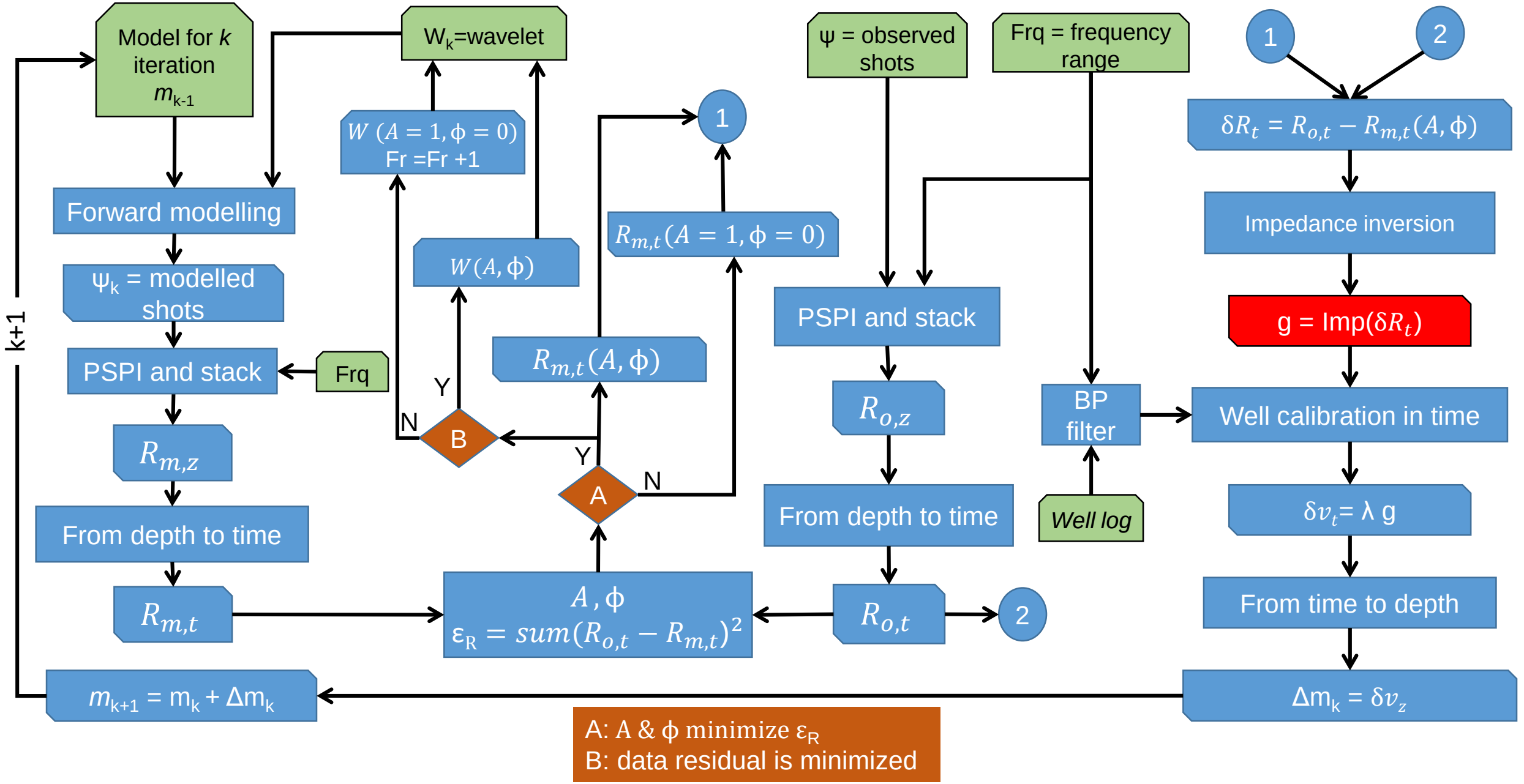
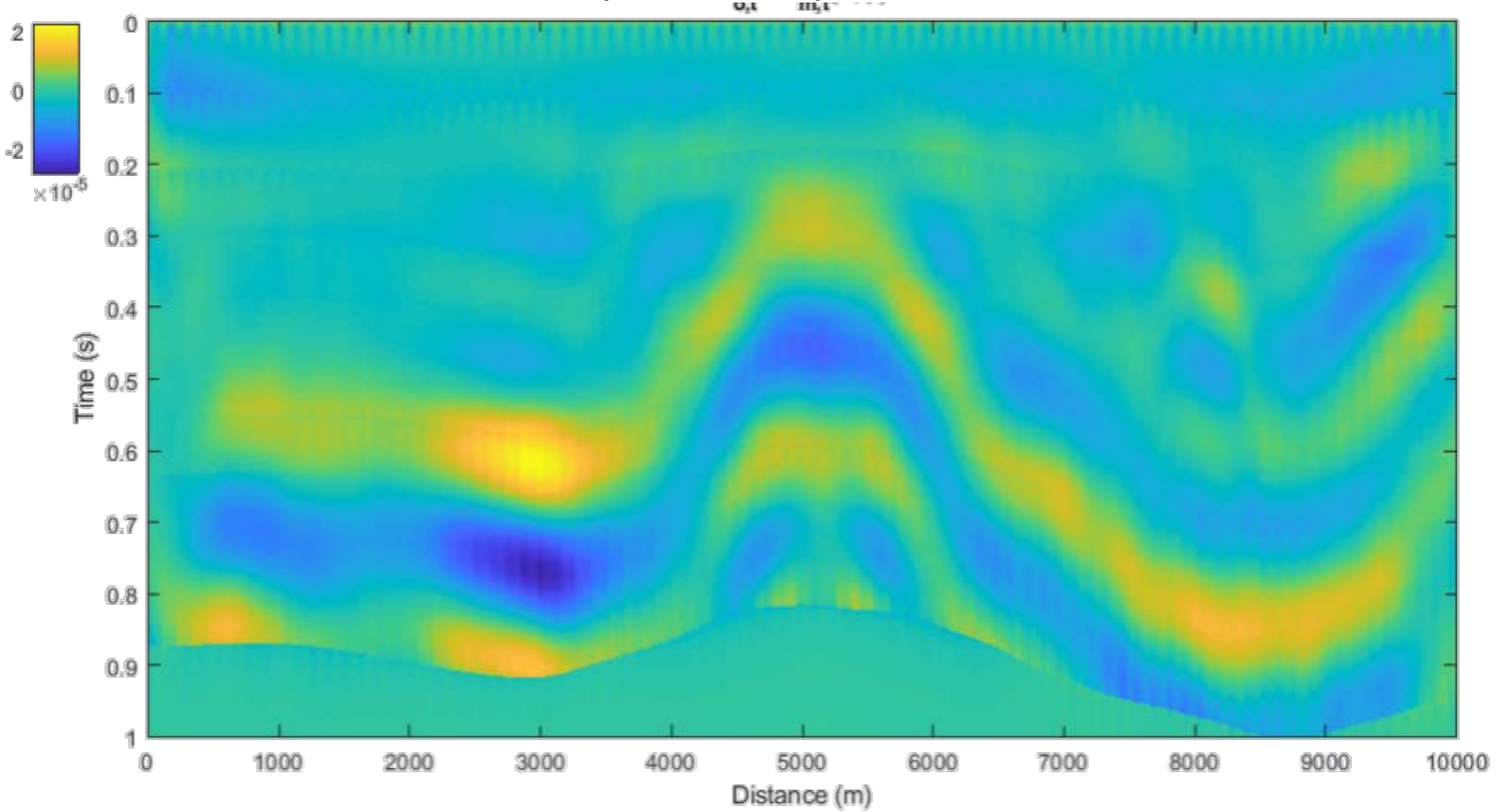
PSPI and stack
$R_{o,z}$
From depth to time
$R_{o,t}$
2
BP filter
Well log
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A,\phi)$
Impedance inversion
g = Imp(δR_t)
Well calibration in time
δv_t= λ g
From time to depth
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

Workflow


Model for k iteration m_{k-1}
W_k=wavelet
ψ = observed shots
Frq = frequency range
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A, \phi)$
$W\ (A = 1, \phi = 0)$ Fr =Fr +1
1
Forward modelling
$R_{m,t}(A = 1, \phi = 0)$
Impedance inversion
$W(A, \phi)$
PSPI and stack
g = Imp(δR_t)
ψ_k = modelled shots
$R_{m,t}(A, \phi)$
PSPI and stack
Frq
$R_{o,z}$
BP filter
Well calibration in time
k+1
$R_{m,z}$
Y
N
B
Y
N
A
From depth to time
Well log
$\delta v_t = \lambda$ g
From depth to time
$R_{m,t}$
A, ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
$R_{o,t}$
2
From time to depth
$m_{k+1} = m_k + \Delta m_k$
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

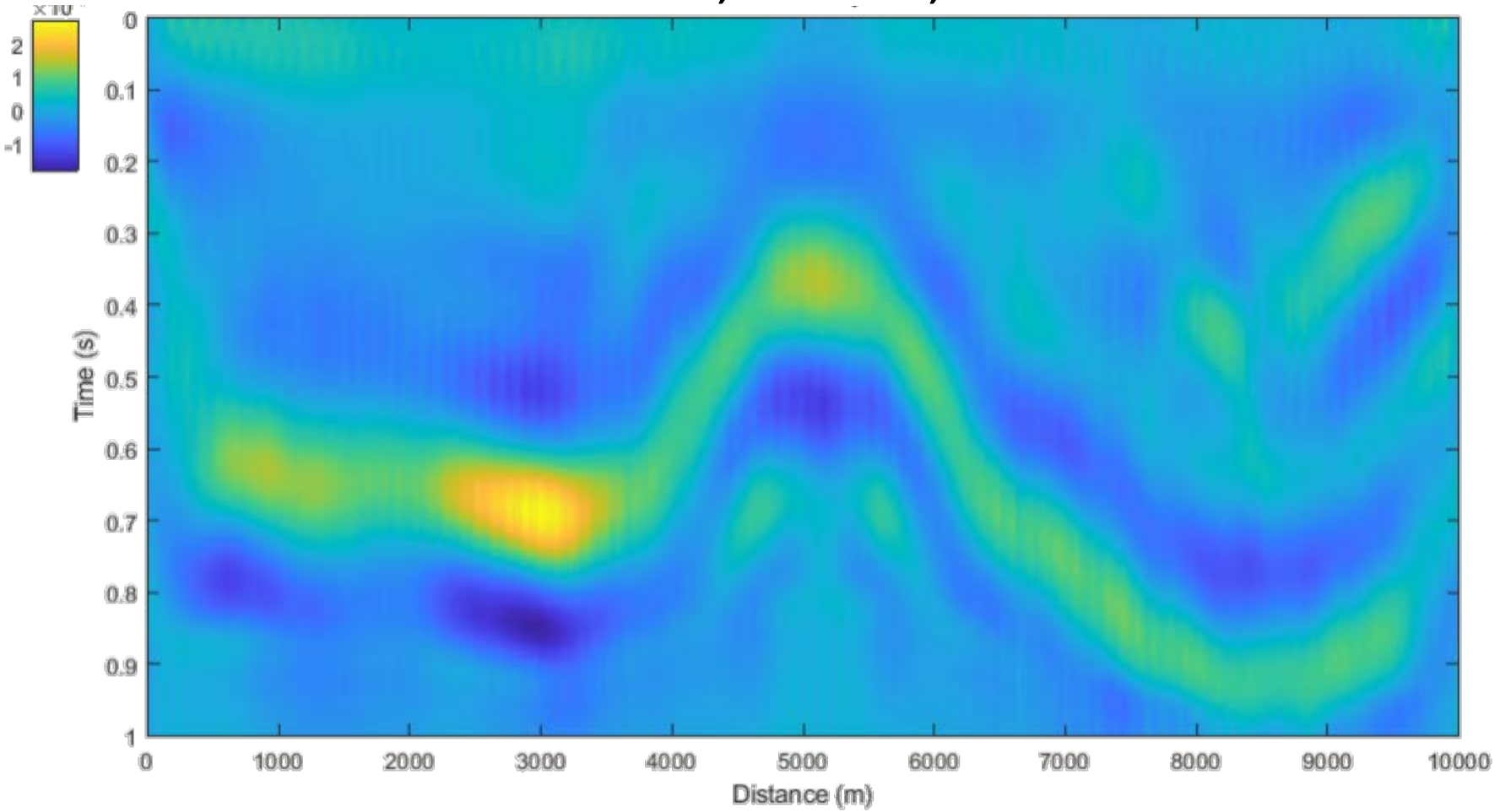
Amplitude and phase updating

$$R_{o,t} - R_{m,t}(A,\phi)$$

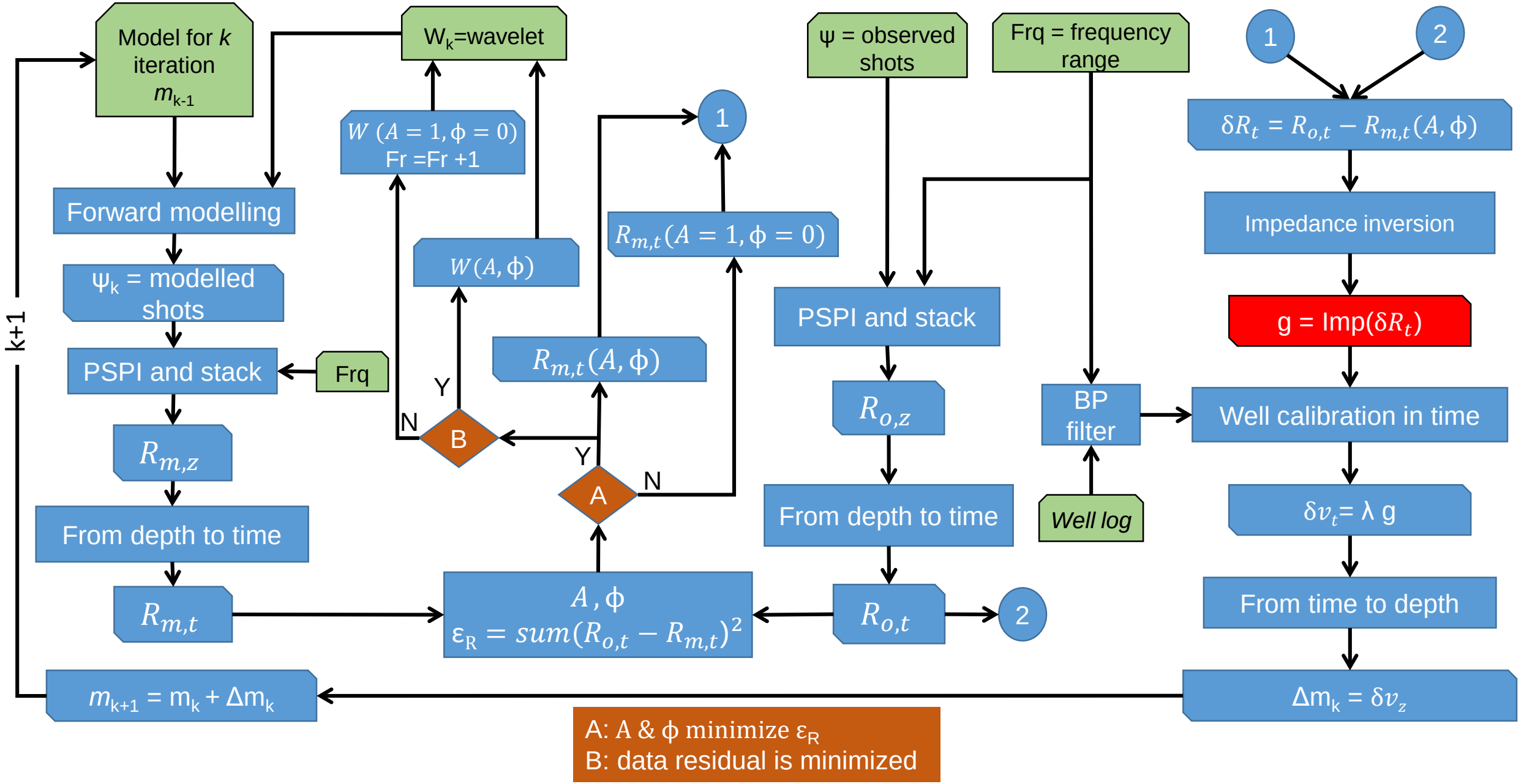


Amplitude and phase updating

$$g = Imp[R_{o,t} - R_{m,t}(A,\phi)]$$



Workflow


Model for k iteration m_{k-1}
W_k=wavelet
ψ = observed shots
Frq = frequency range
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A, \phi)$
$W\ (A = 1, \phi = 0)$ Fr =Fr +1
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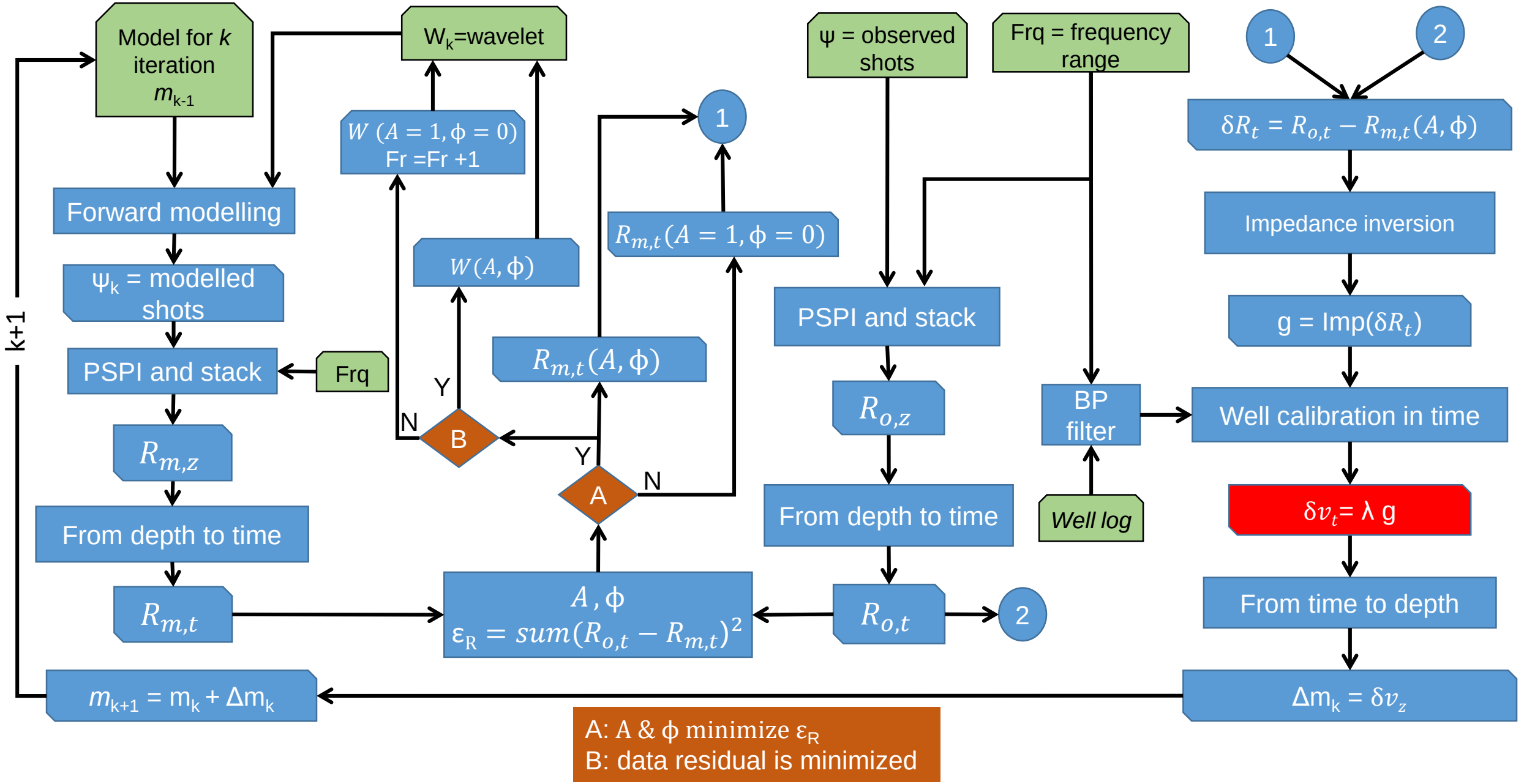
Forward modelling
$R_{m,t}(A = 1, \phi = 0)$
Impedance inversion
$W(A, \phi)$
PSPI and stack
g = Imp(δR_t)
ψ_k = modelled shots
$R_{m,t}(A, \phi)$
PSPI and stack
Frq
$R_{o,z}$
BP filter
Well calibration in time
k+1
$R_{m,z}$
Y
N
B
Y
N
A
From depth to time
Well log
$\delta v_t = \lambda$ g
From depth to time
$R_{m,t}$
A, ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
$R_{o,t}$
2
From time to depth
$m_{k+1} = m_k + \Delta m_k$
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

Workflow


Model for k iteration m_{k-1}
W_k=wavelet
ψ = observed shots
Frq = frequency range
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A, \phi)$
$W\ (A = 1, \phi = 0)$ Fr =Fr +1
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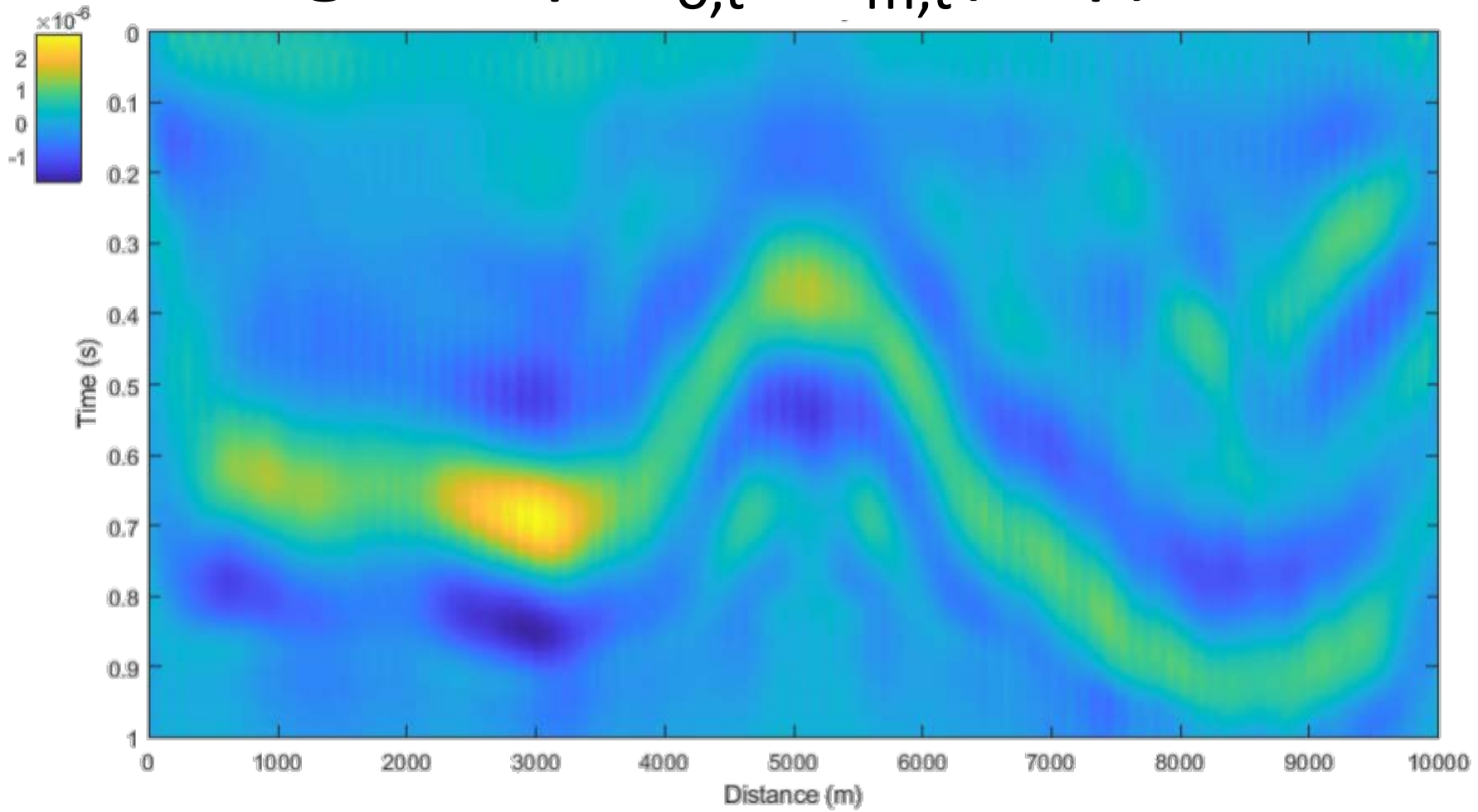
Forward modelling
$R_{m,t}(A = 1, \phi = 0)$
Impedance inversion
$W(A, \phi)$
ψ_k = modelled shots
PSPI and stack
g = Imp(δR_t)
$R_{m,t}(A, \phi)$
PSPI and stack
Frq
Y
N
B
Y
N
A
$R_{m,z}$
$R_{o,z}$
BP filter
Well calibration in time
From depth to time
From depth to time
Well log
δv_t= λ g
$R_{m,t}$
A, ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
$R_{o,t}$
2
From time to depth
k+1
$m_{k+1} = m_k + \Delta m_k$
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

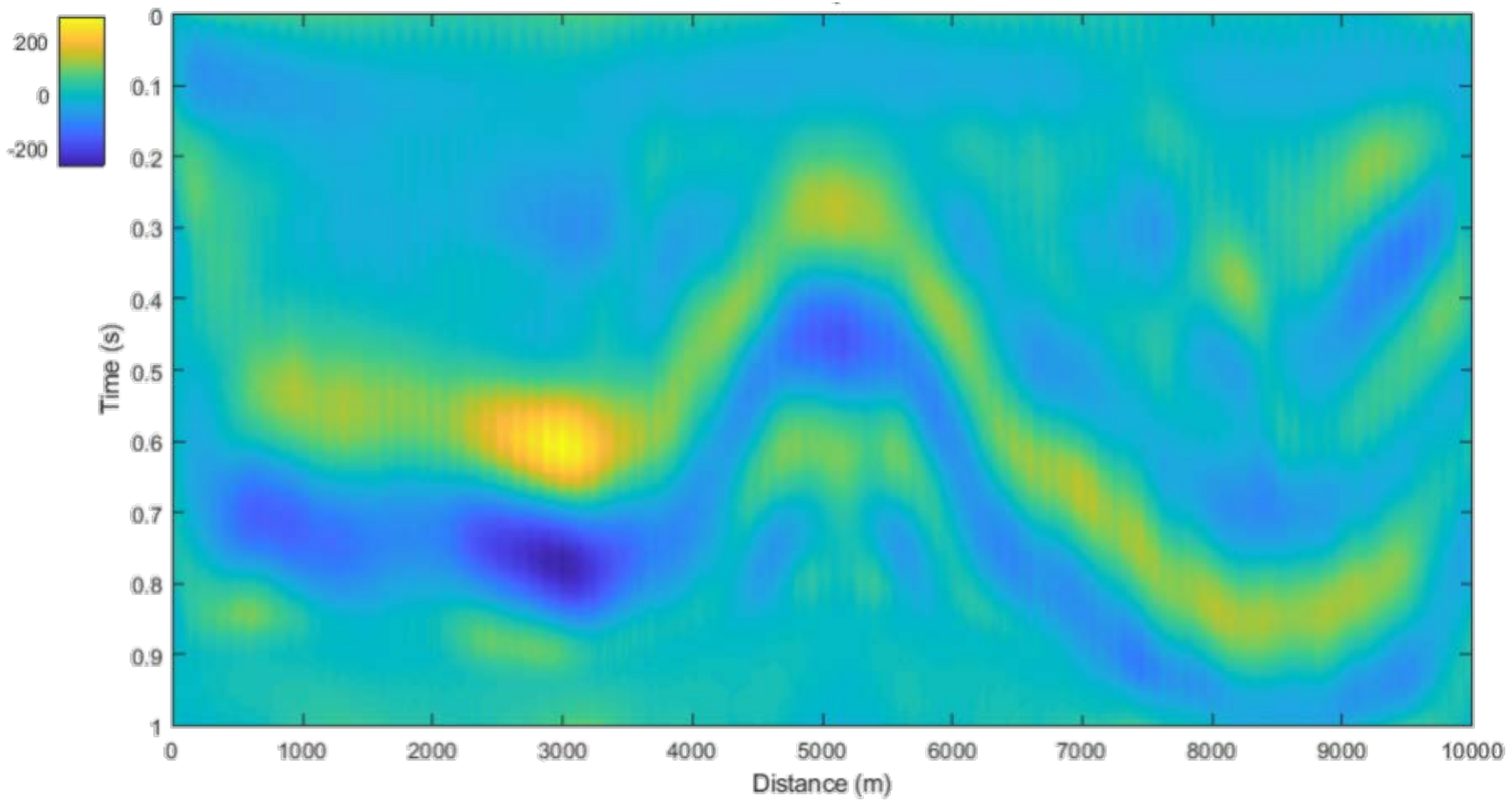
Amplitude and phase updating

$$g = Imp[R_{o,t} - R_{m,t}(A,\phi)]$$

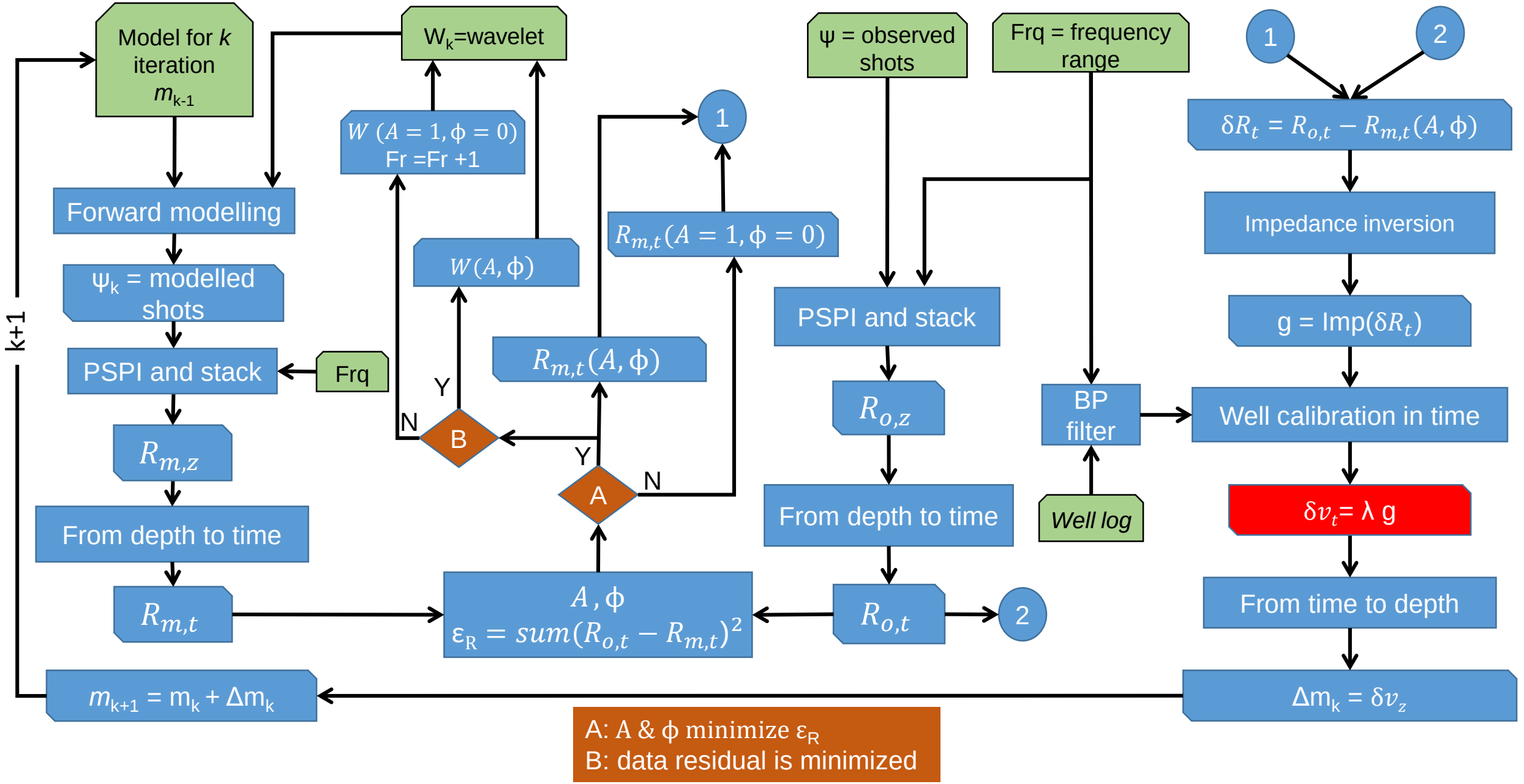


Amplitude and phase updating

$$\delta v_t = \lambda \mathrm{g}$$



Workflow


Model for k iteration m_{k-1}
W_k=wavelet
ψ = observed shots
Frq = frequency range
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A, \phi)$
$W\ (A = 1, \phi = 0)$ Fr =Fr +1
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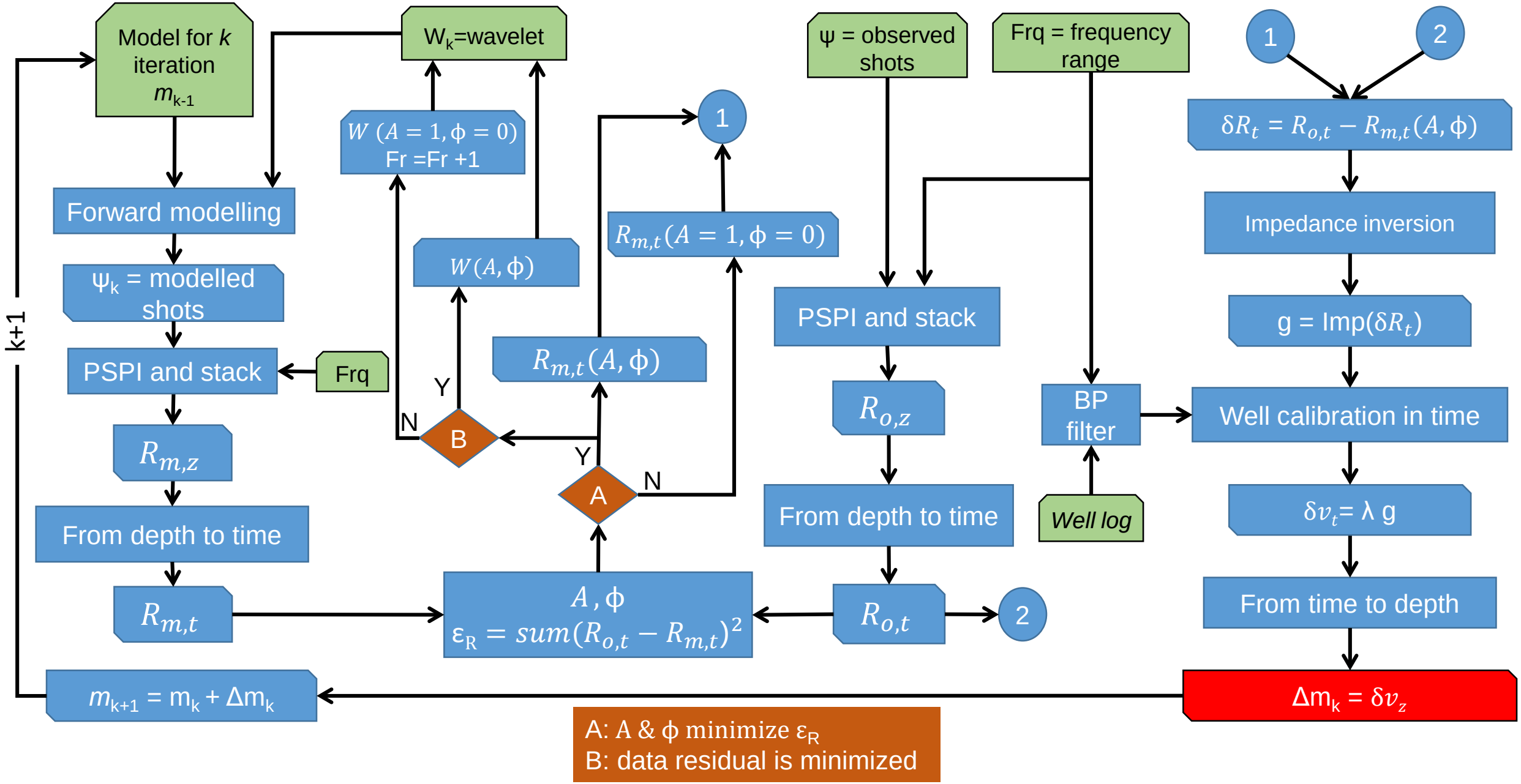
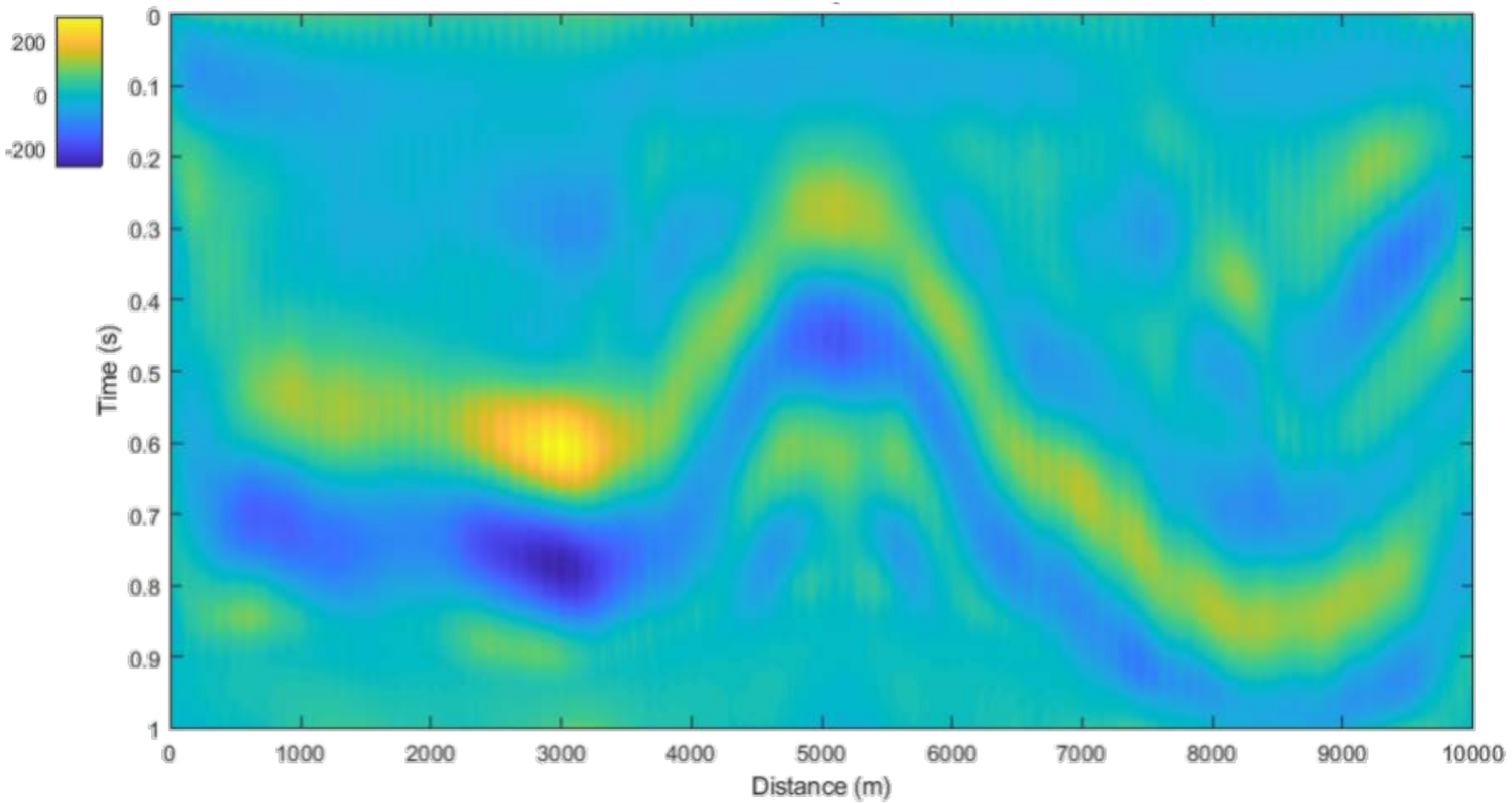
Forward modelling
$R_{m,t}(A = 1, \phi = 0)$
Impedance inversion
$W(A, \phi)$
ψ_k = modelled shots
PSPI and stack
g = Imp(δR_t)
$R_{m,t}(A, \phi)$
PSPI and stack
Frq
Y
N
B
Y
N
A
$R_{m,z}$
$R_{o,z}$
BP filter
Well calibration in time
From depth to time
From depth to time
Well log
δv_t= λ g
$R_{m,t}$
A, ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
$R_{o,t}$
2
From time to depth
k+1
$m_{k+1} = m_k + \Delta m_k$
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

Workflow

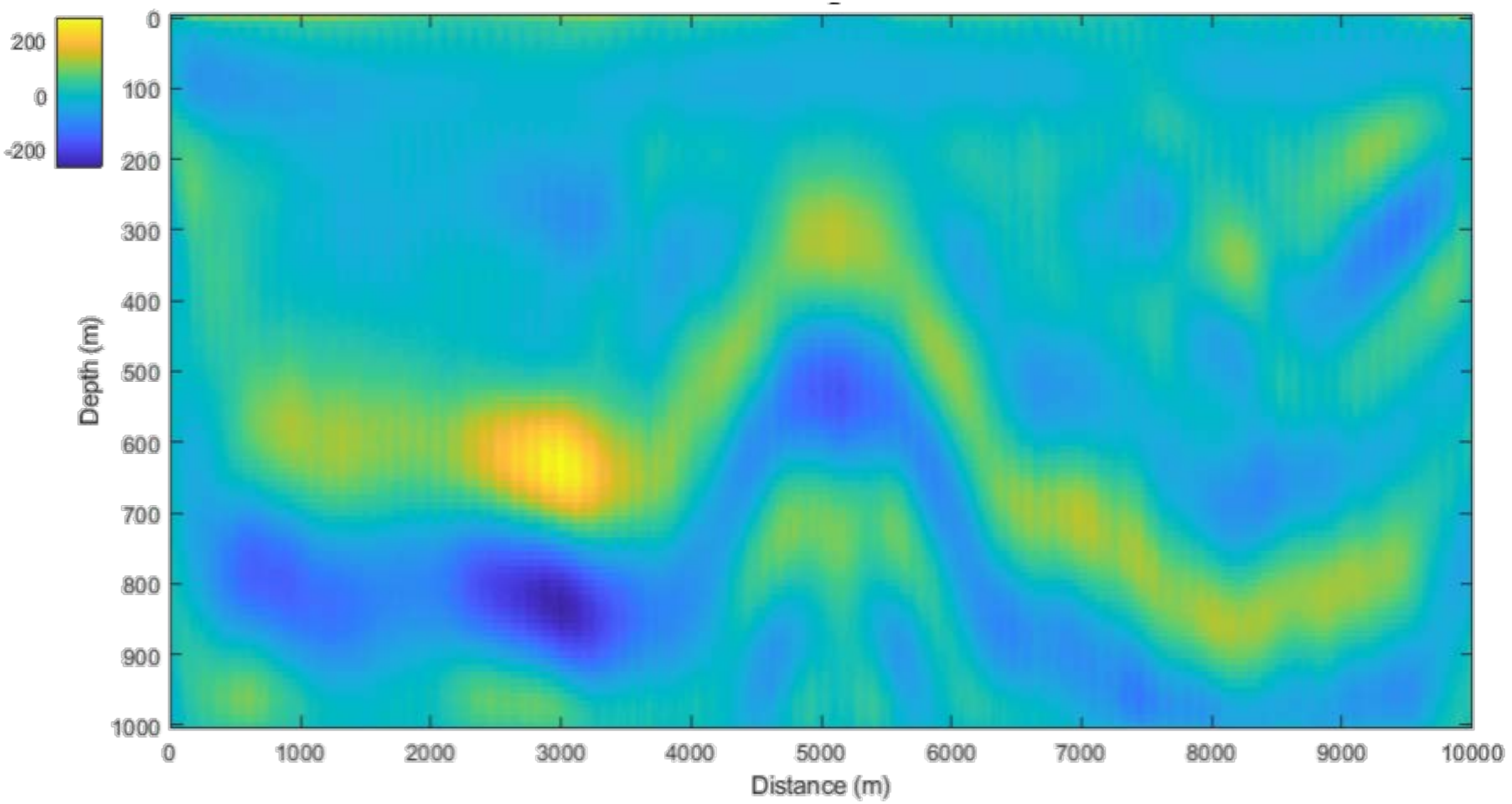

Model for k iteration m_{k-1}
W_k=wavelet
ψ = observed shots
Frq = frequency range
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A, \phi)$
$W\ (A = 1, \phi = 0)$ Fr =Fr +1
Forward modelling
Impedance inversion
$R_{m,t}(A = 1, \phi = 0)$
1
$W(A, \phi)$
ψ_k = modelled shots
PSPI and stack
g = Imp(δR_t)
k+1
PSPI and stack
Frq
$R_{m,t}(A, \phi)$
$R_{o,z}$
BP filter
Well calibration in time
Y
N
B
Y
N
A
$R_{m,z}$
From depth to time
Well log
δv_t= λ g
From depth to time
From time to depth
$R_{m,t}$
A, ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
$R_{o,t}$
2
$m_{k+1} = m_k + \Delta m_k$
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

Amplitude and phase updating

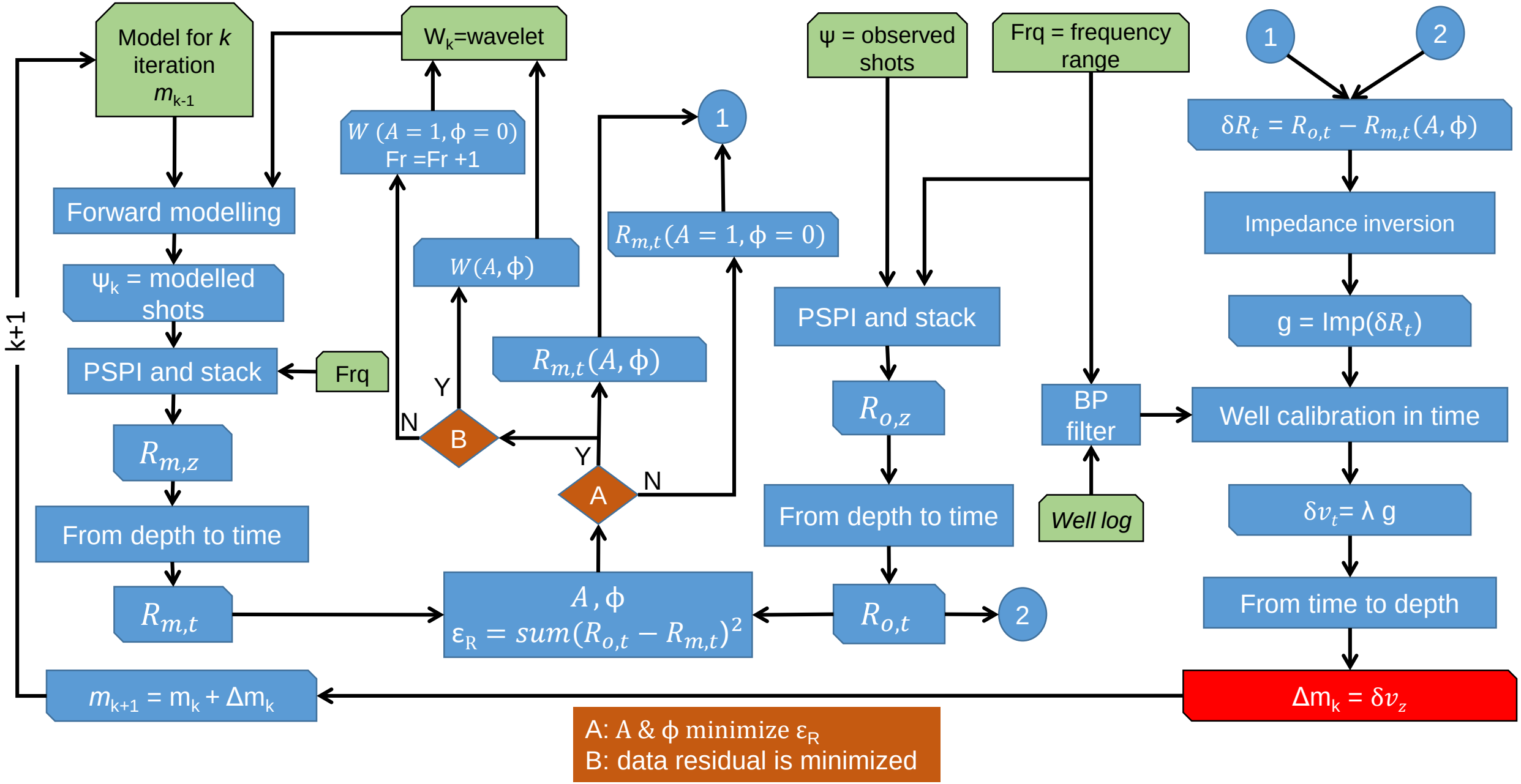
$$\delta v_t$$



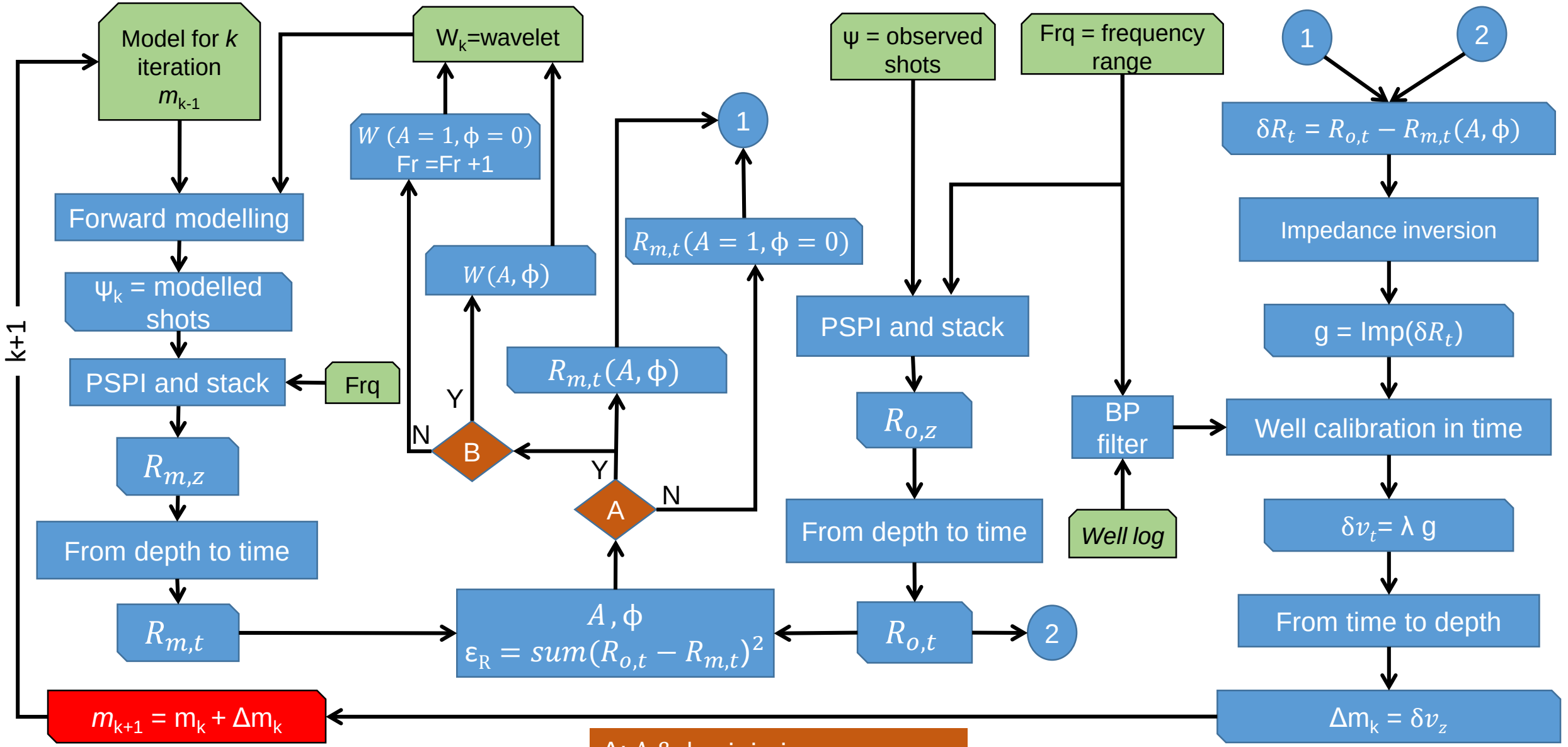
δv_z

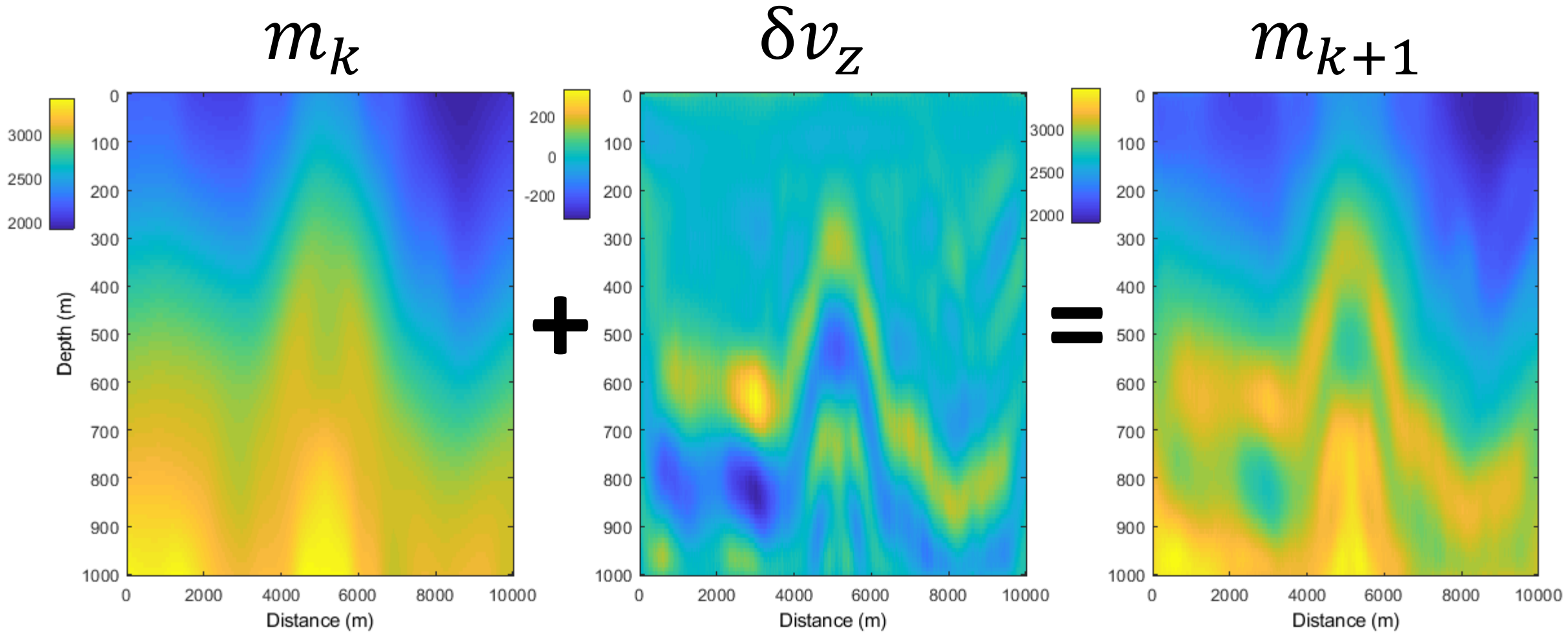

200
0
-200
Depth (m)
0
100
200
300
400
500
600
700
800
900
1000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Distance (m)

Workflow

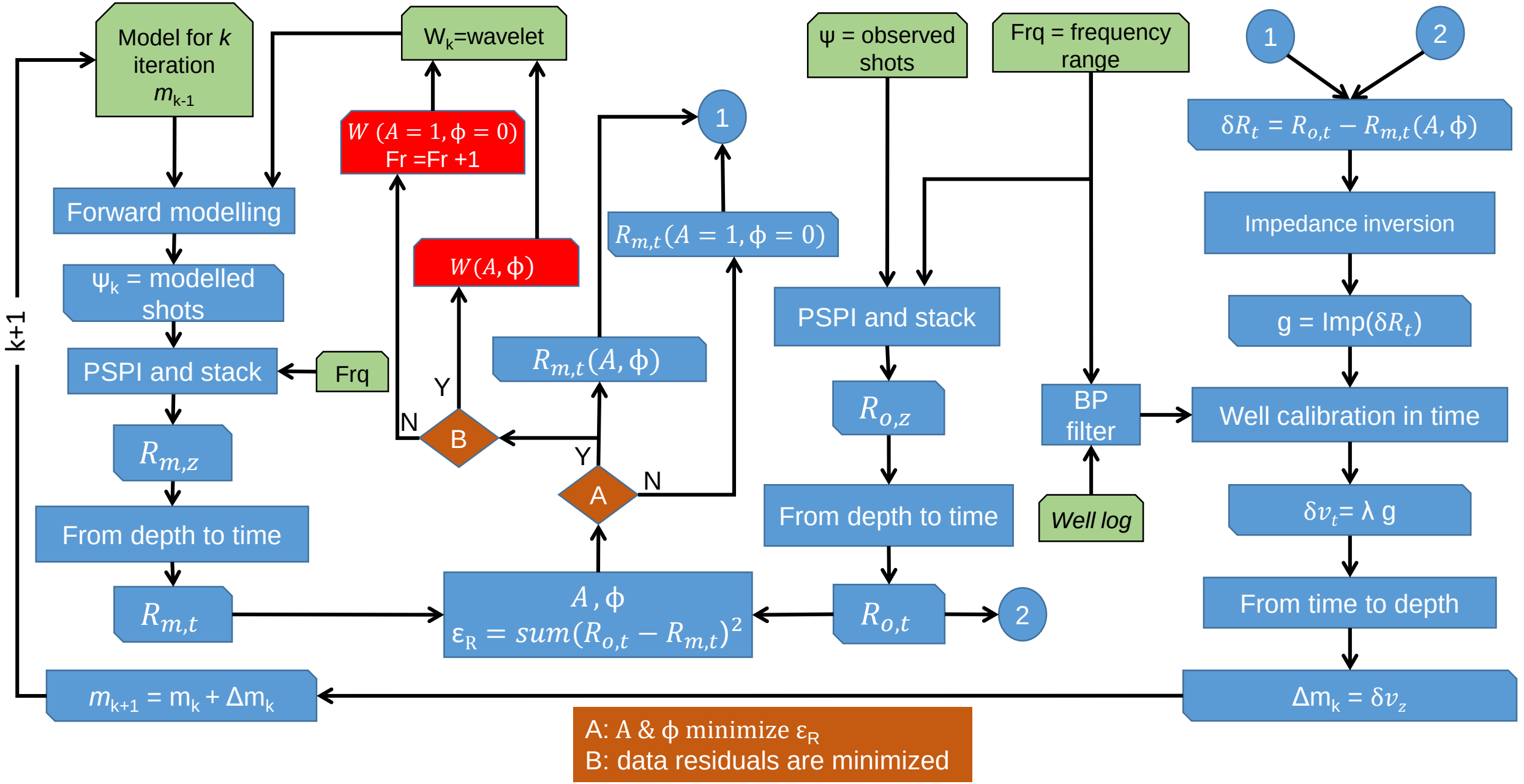

Model for k iteration m_{k-1}
W_k=wavelet
ψ = observed shots
Frq = frequency range
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A, \phi)$
$W\ (A = 1, \phi = 0)$ Fr =Fr +1
Forward modelling
Impedance inversion
$R_{m,t}(A = 1, \phi = 0)$
1
$W(A, \phi)$
ψ_k = modelled shots
PSPI and stack
g = Imp(δR_t)
k+1
PSPI and stack
Frq
$R_{m,t}(A, \phi)$
$R_{o,z}$
BP filter
Well calibration in time
Y
N
B
Y
N
A
$R_{m,z}$
From depth to time
Well log
δv_t= λ g
From depth to time
From time to depth
$R_{m,t}$
A, ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
$R_{o,t}$
2
$m_{k+1} = m_k + \Delta m_k$
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

Workflow


Model for k iteration m_{k-1}
W_k=wavelet
ψ = observed shots
Frq = frequency range
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A, \phi)$
$W\ (A = 1, \phi = 0)$ Fr =Fr +1
Forward modelling
Impedance inversion
$R_{m,t}(A = 1, \phi = 0)$
1
$W(A, \phi)$
ψ_k = modelled shots
PSPI and stack
g = Imp(δR_t)
k+1
PSPI and stack
Frq
$R_{m,t}(A, \phi)$
$R_{o,z}$
BP filter
Well calibration in time
Y
N
B
Y
N
A
$R_{m,z}$
From depth to time
Well log
δv_t= λ g
From depth to time
From time to depth
$R_{m,t}$
A, ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
$R_{o,t}$
2
$m_{k+1} = m_k + \Delta m_k$
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

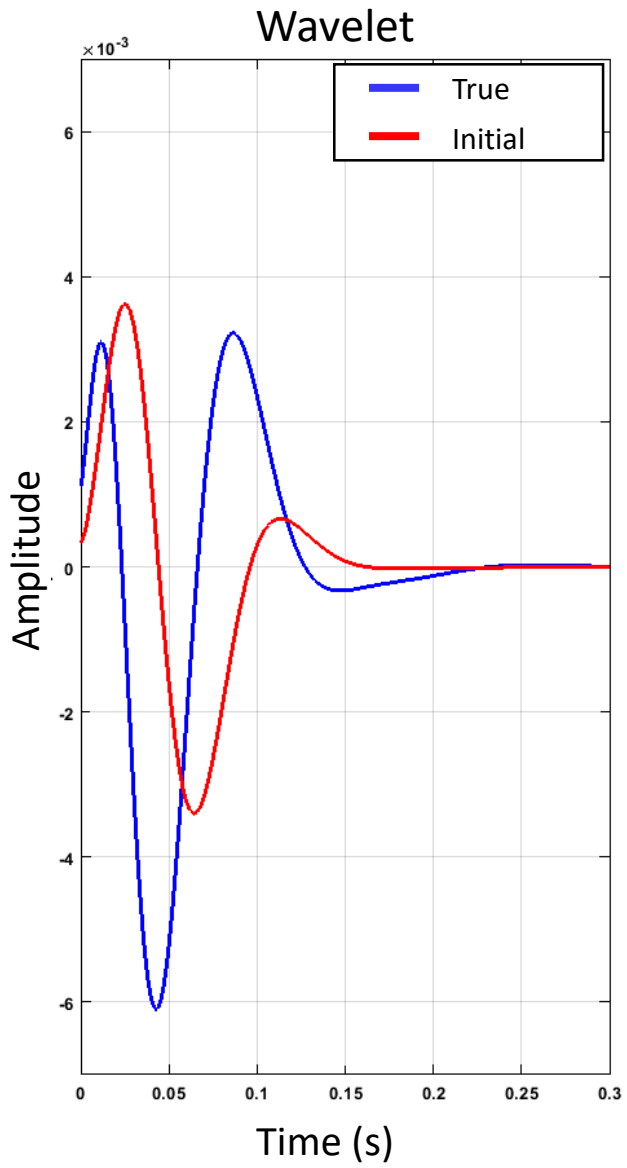

m_k
δv_z
m_{k+1}
Depth (m)
Distance (m)
Distance (m)
Distance (m)

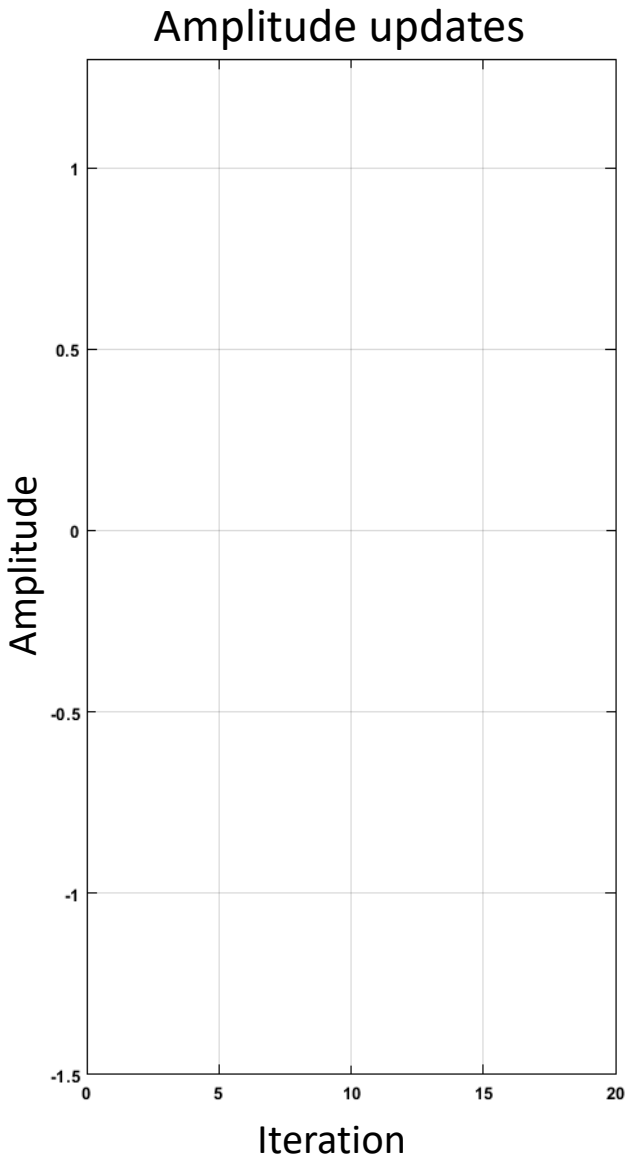
Workflow

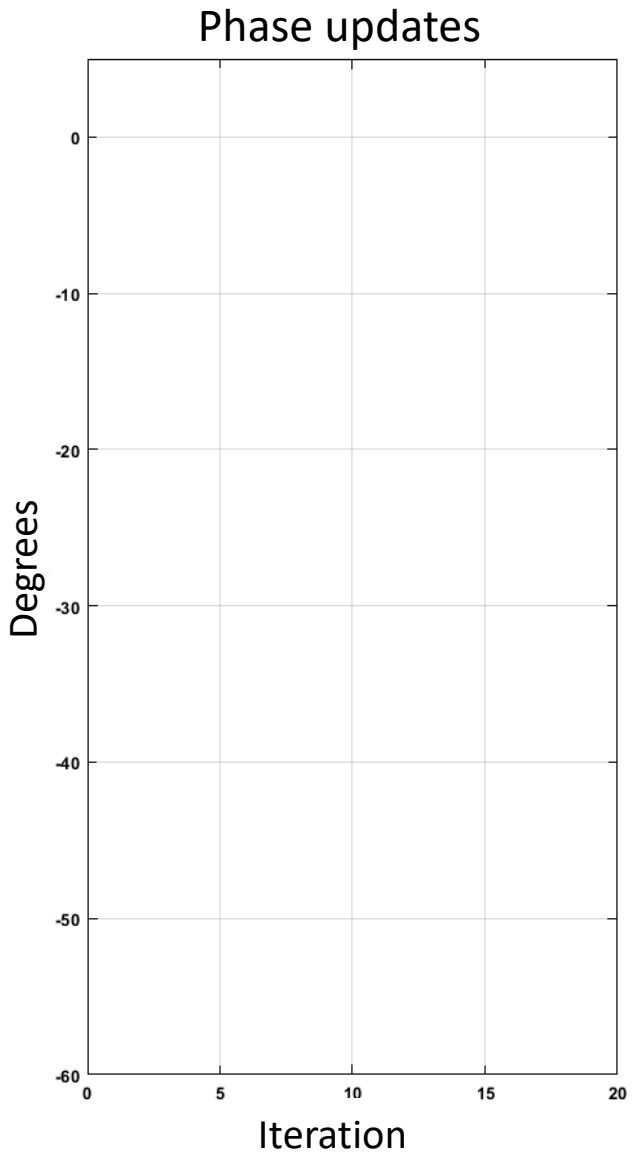

Model for k iteration m_{k-1}
W_k=wavelet
$W\ (A=1,\phi=0)$ Fr =Fr +1
$W(A,\phi)$
Forward modelling
ψ_k = modelled shots
PSPI and stack
Frq
$R_{m,z}$
From depth to time
$R_{m,t}$
$R_{m,t}(A=1,\phi=0)$
$R_{m,t}(A,\phi)$
B
A
Y
N
1
A,ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
ψ = observed shots
Frq = frequency range
PSPI and stack
$R_{o,z}$
From depth to time
$R_{o,t}$
2
BP filter
Well log
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A,\phi)$
Impedance inversion
g = Imp(δR_t)
Well calibration in time
δv_t= λ g
From time to depth
$\Delta m_k = \delta v_z$
$m_{k+1} = m_k + \Delta m_k$
k+1
A: A & ϕ minimize ε_R
B: data residuals are minimized

Evolution of the wavelet

It = 1

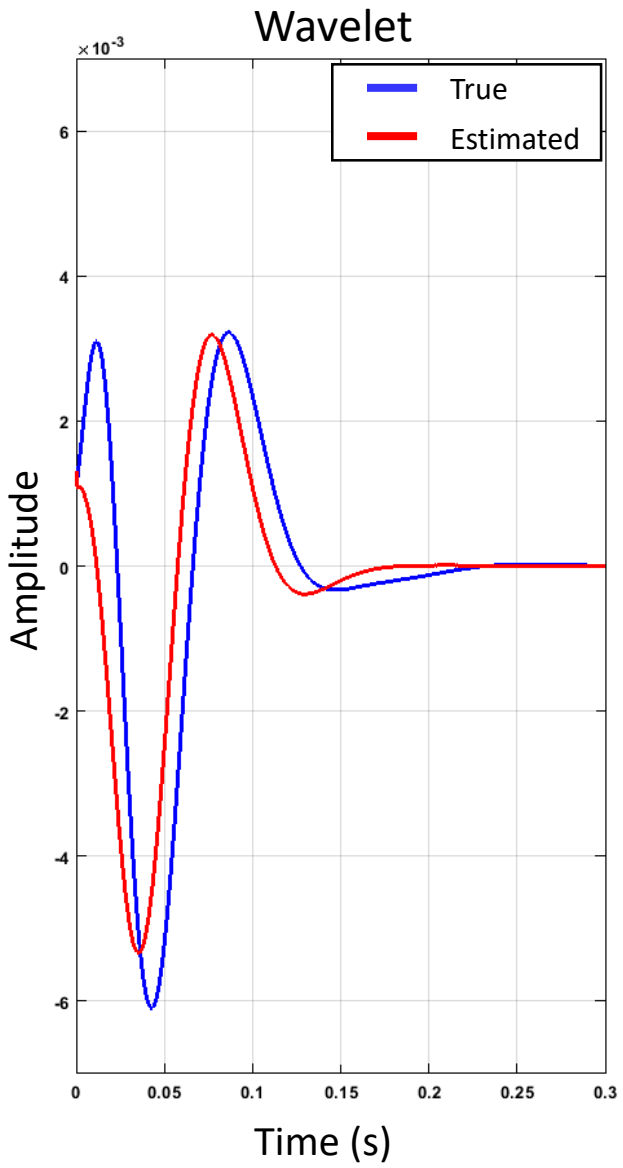


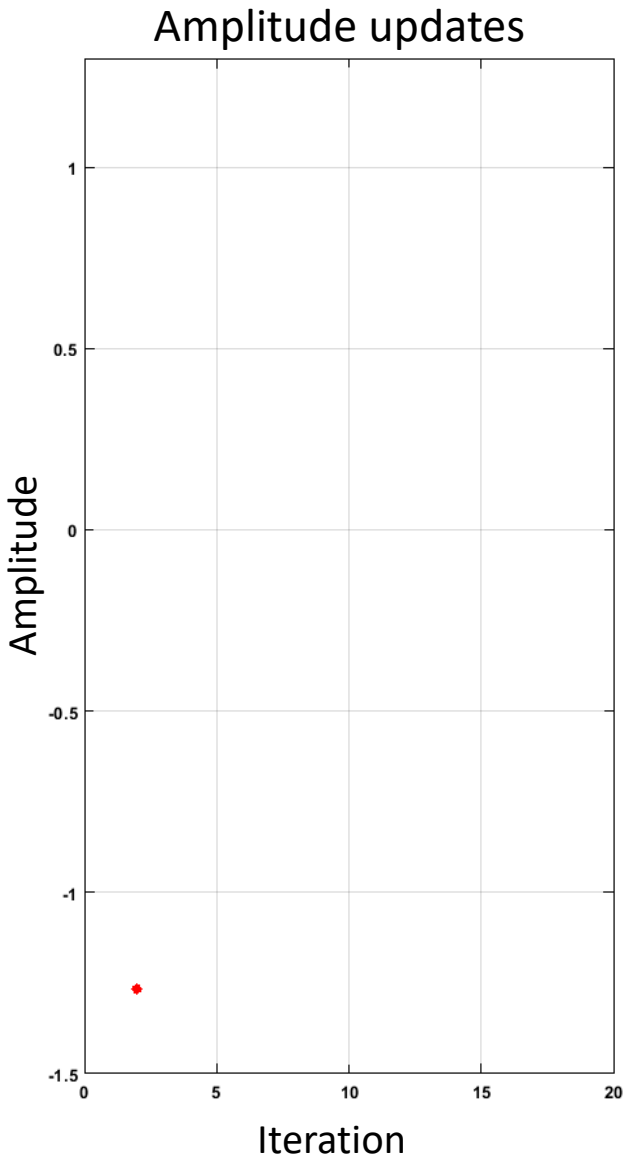


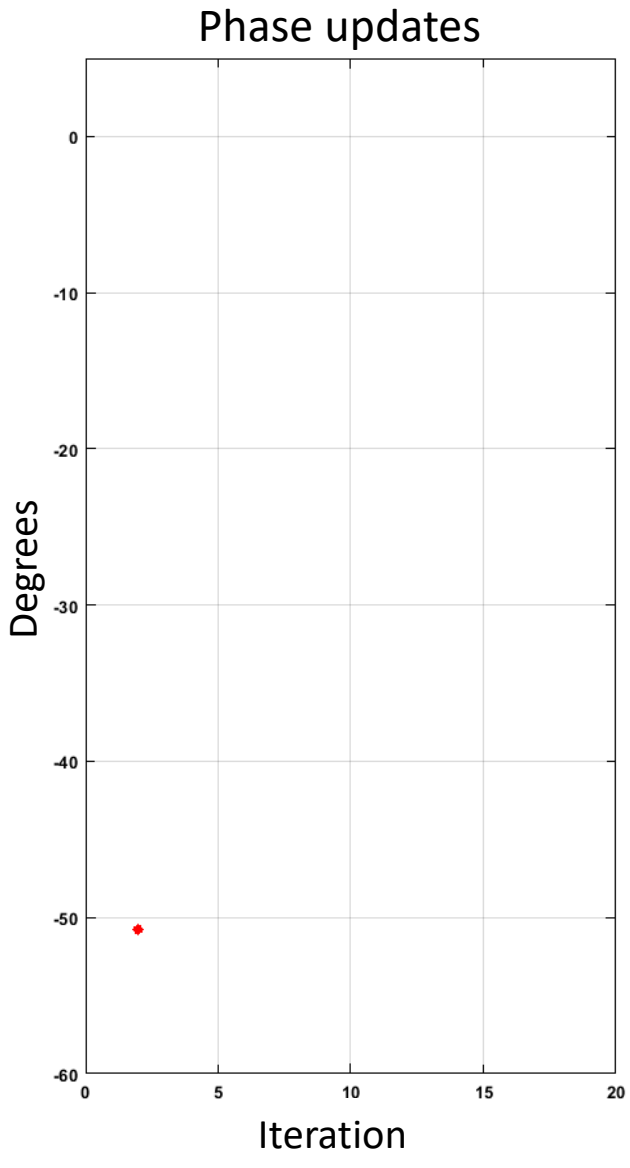


Evolution of the wavelet

It = 2

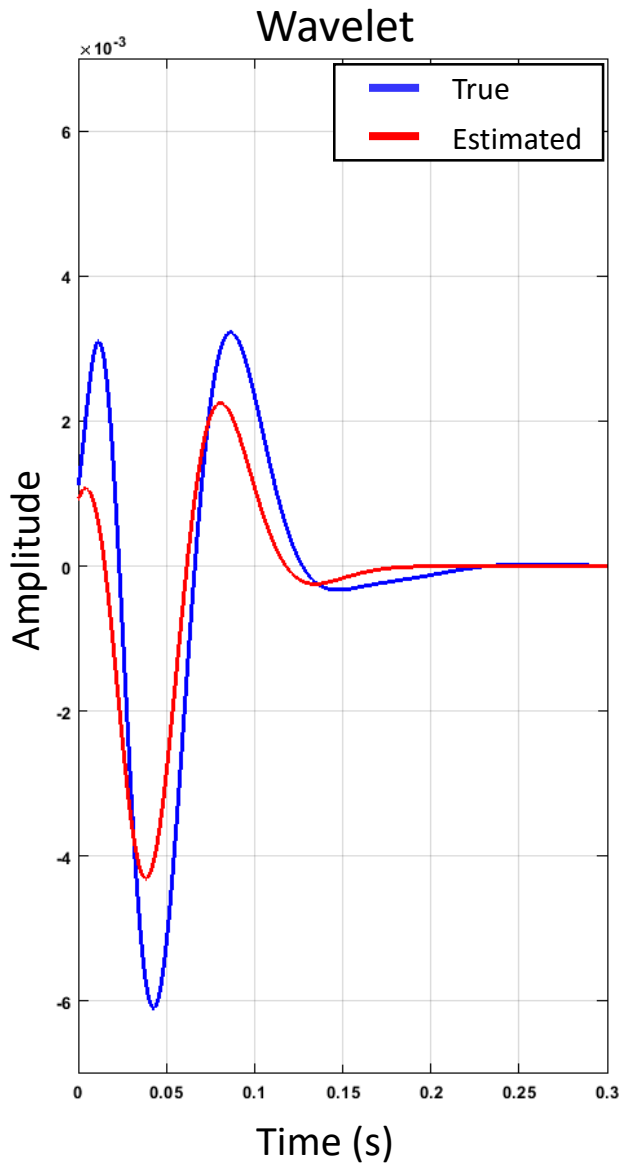


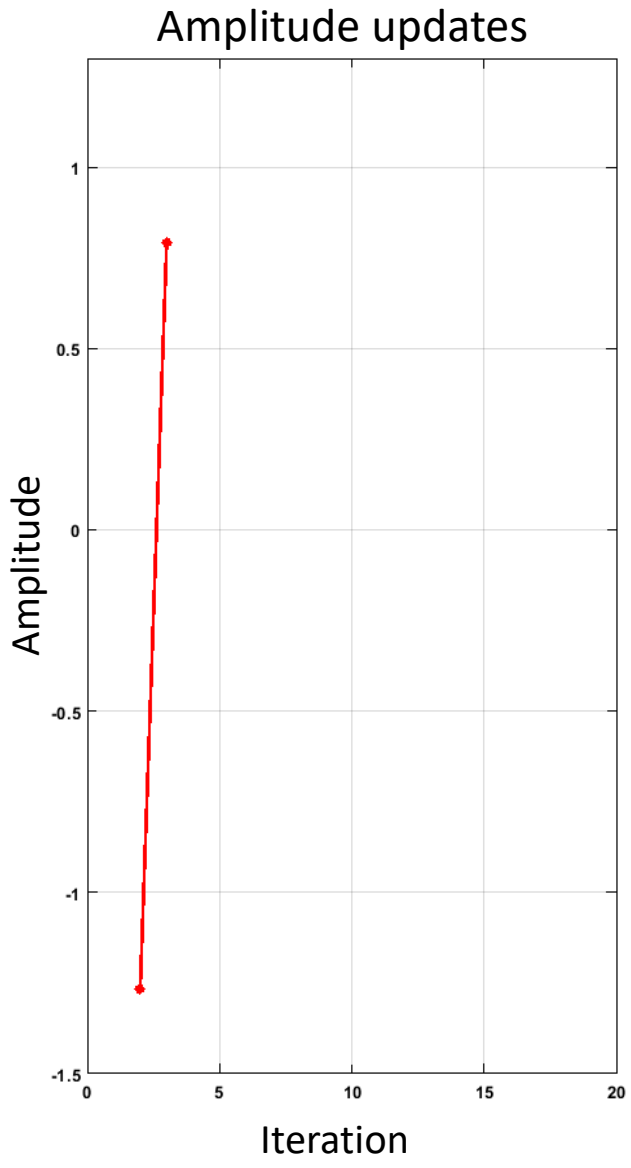


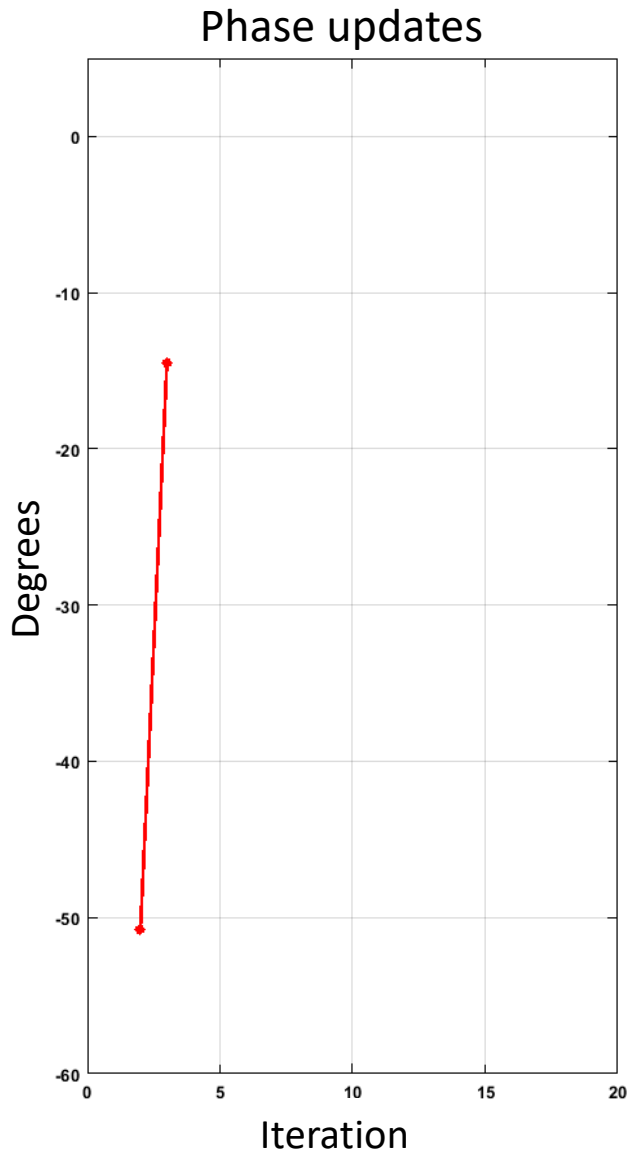


Evolution of the wavelet

It = 3

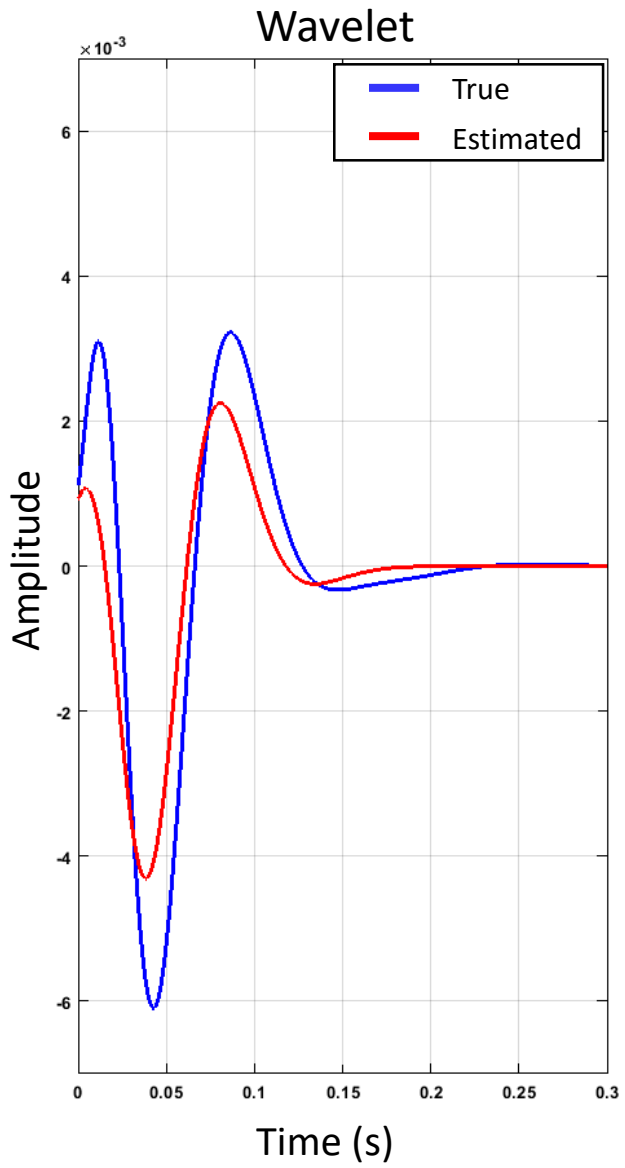


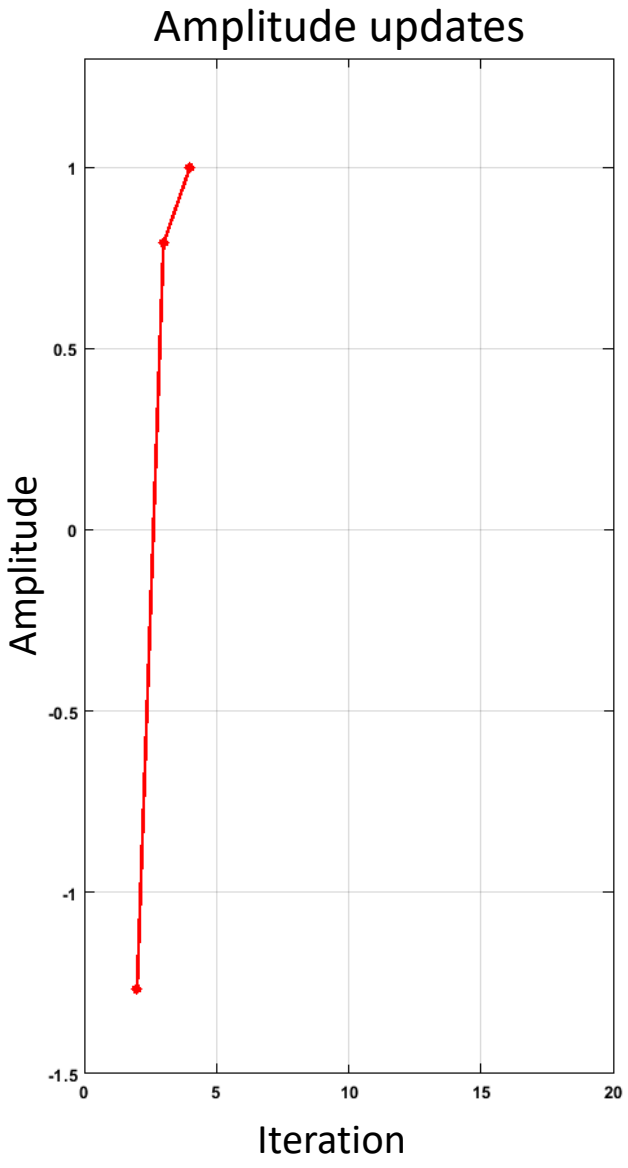


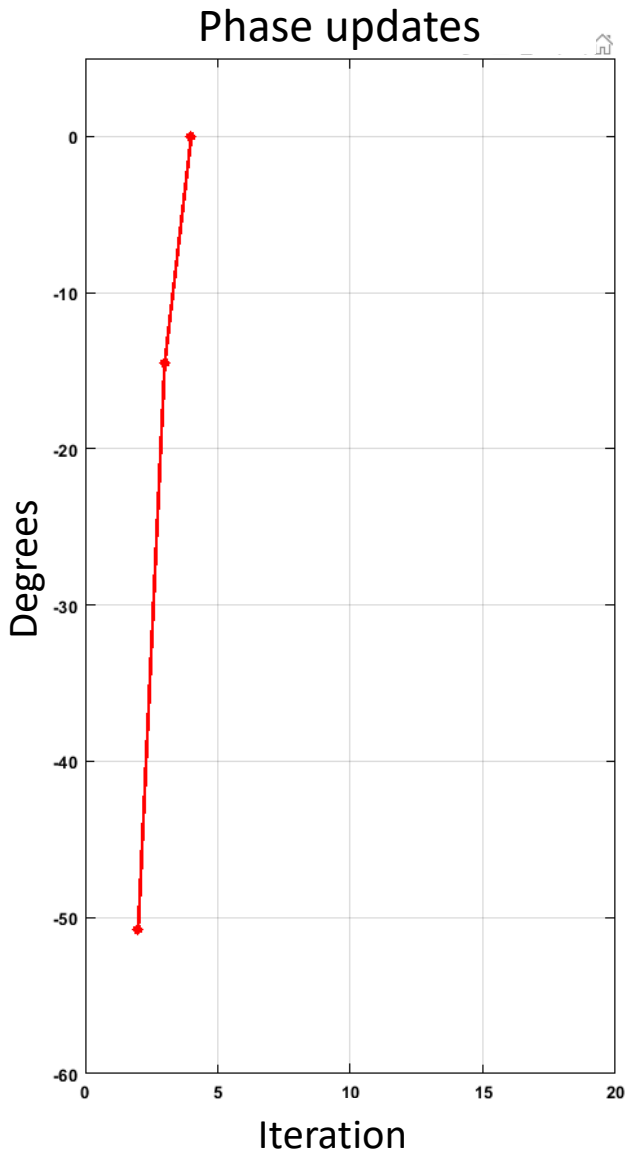


Evolution of the wavelet

It = 4

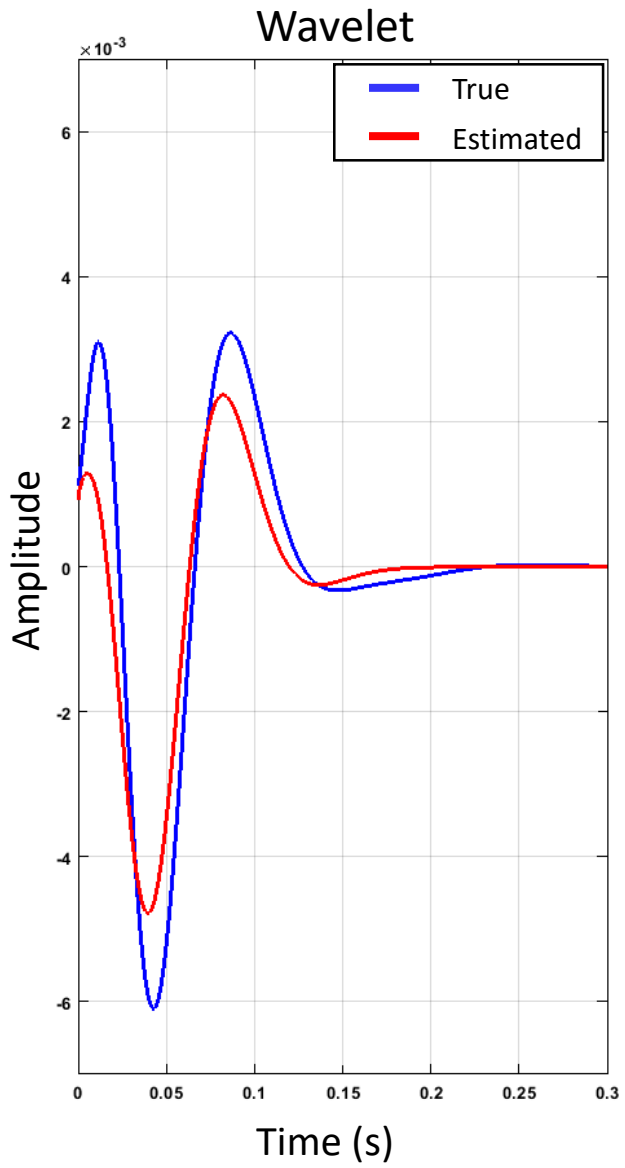


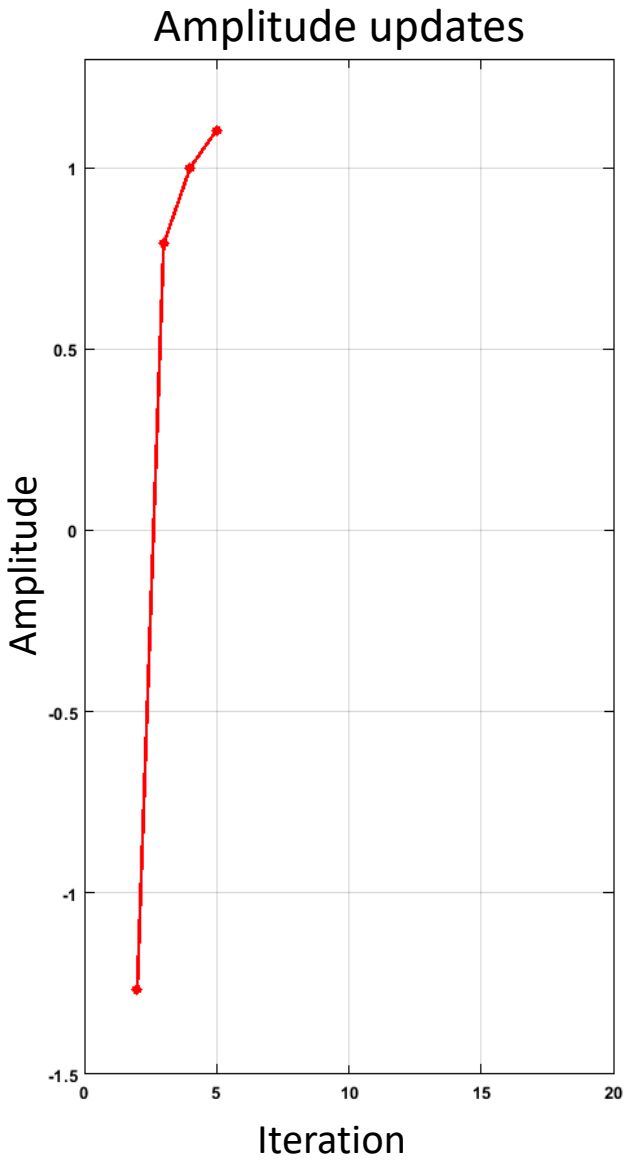


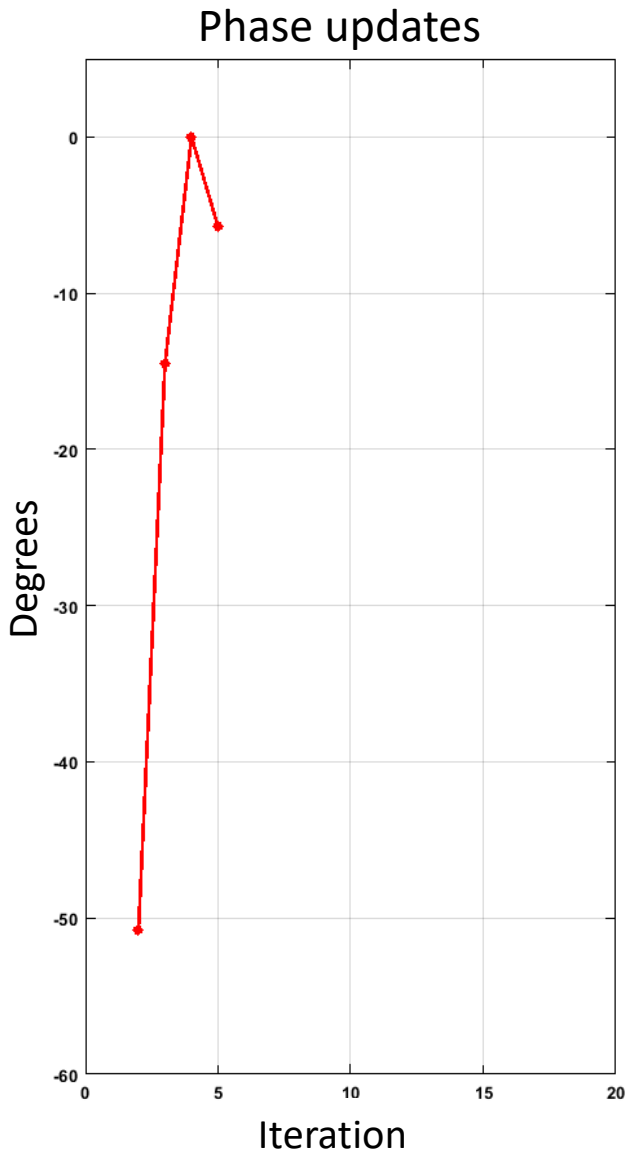


Evolution of the wavelet

It = 5

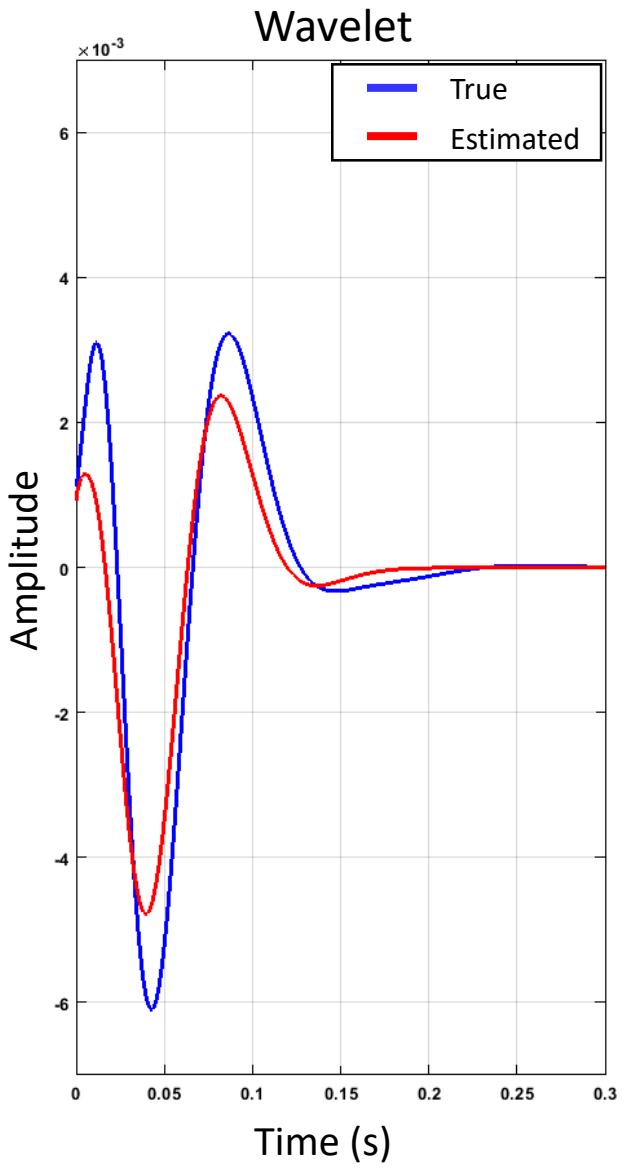


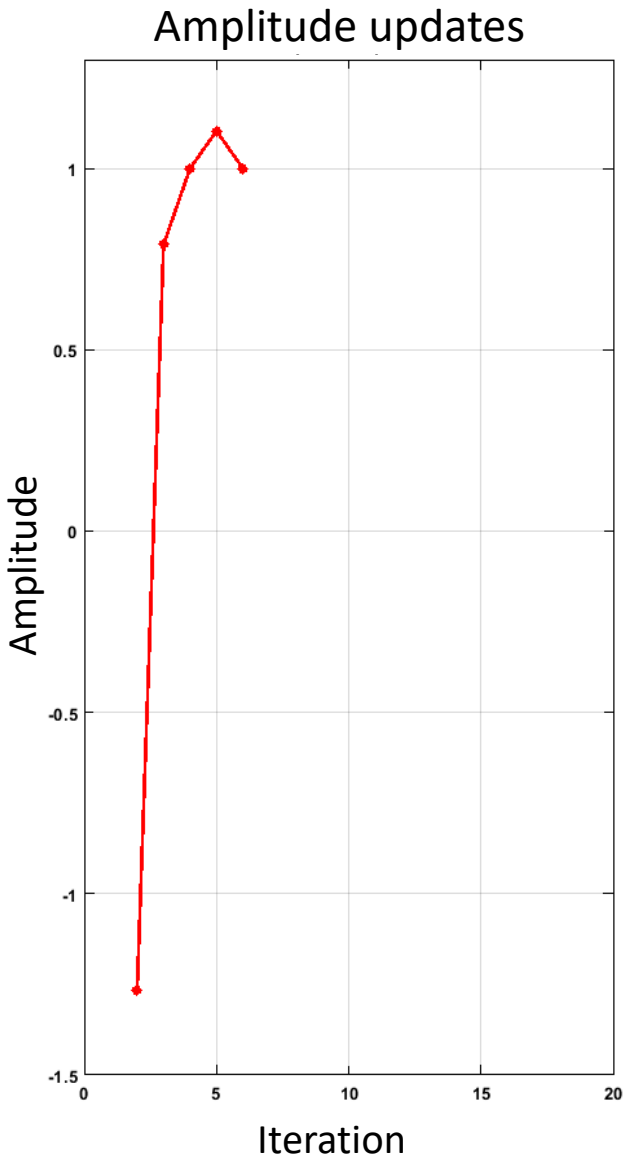


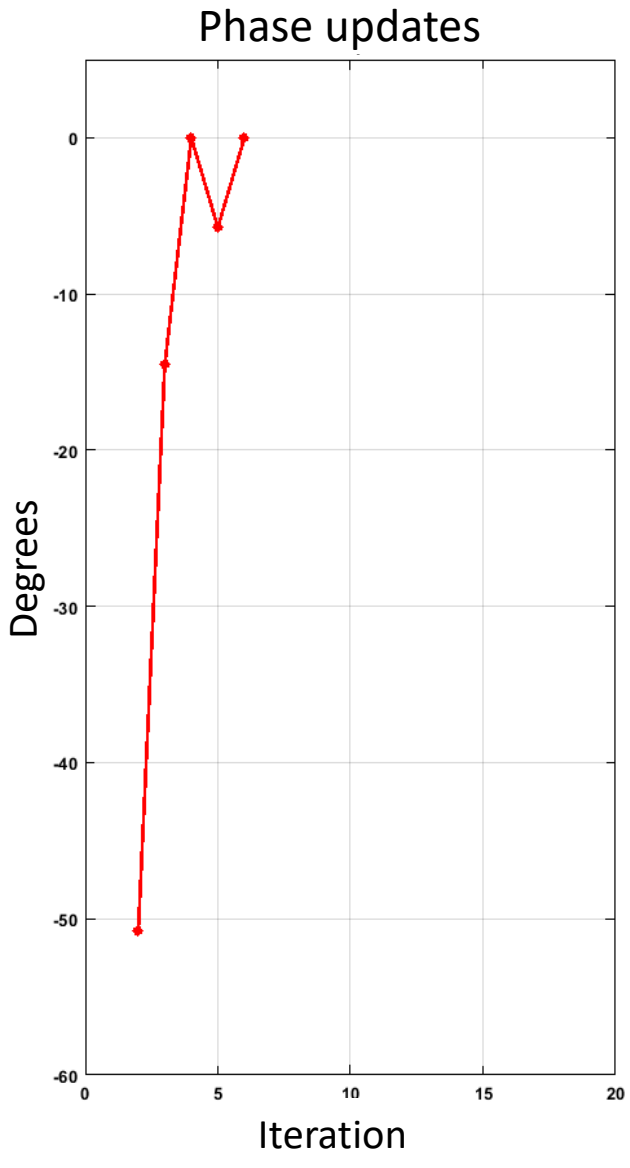


Evolution of the wavelet

It = 6

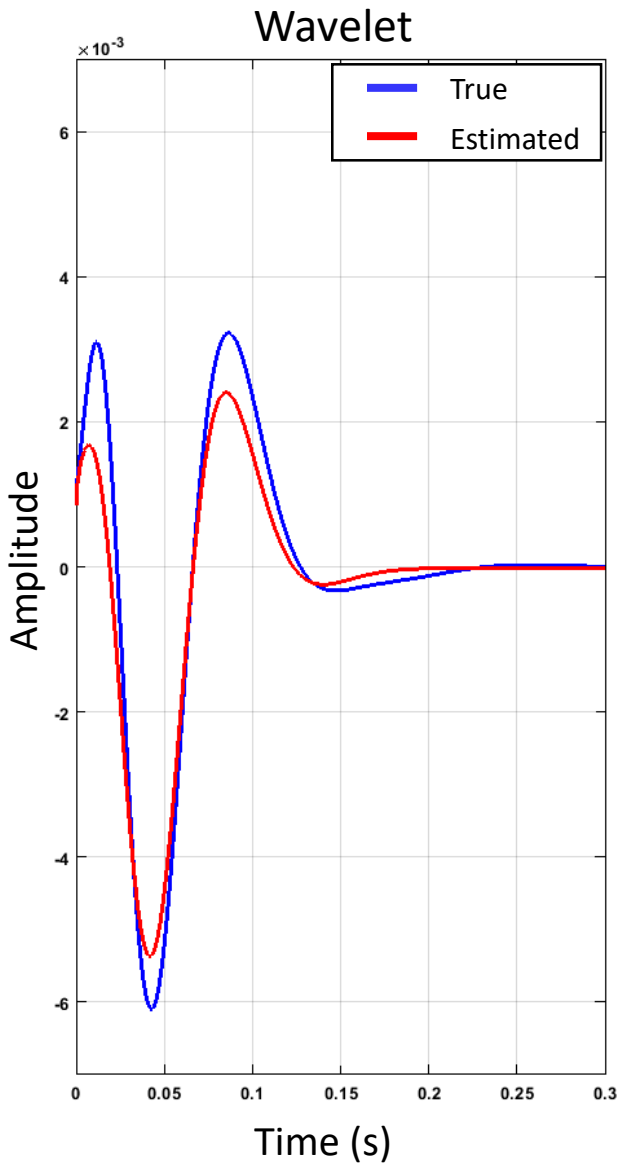


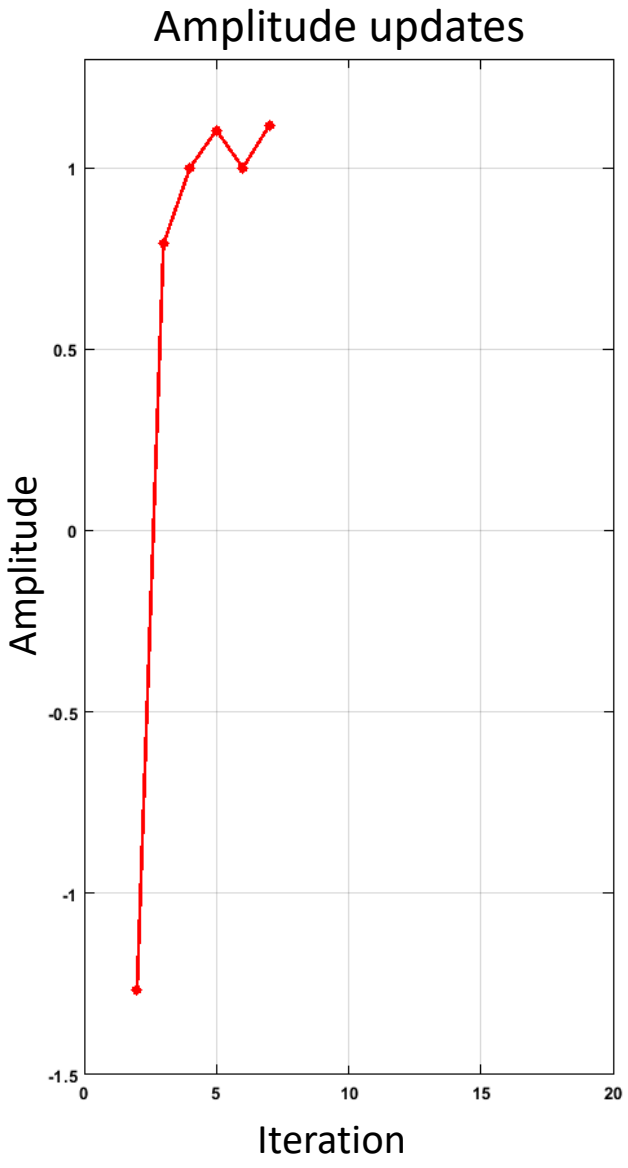


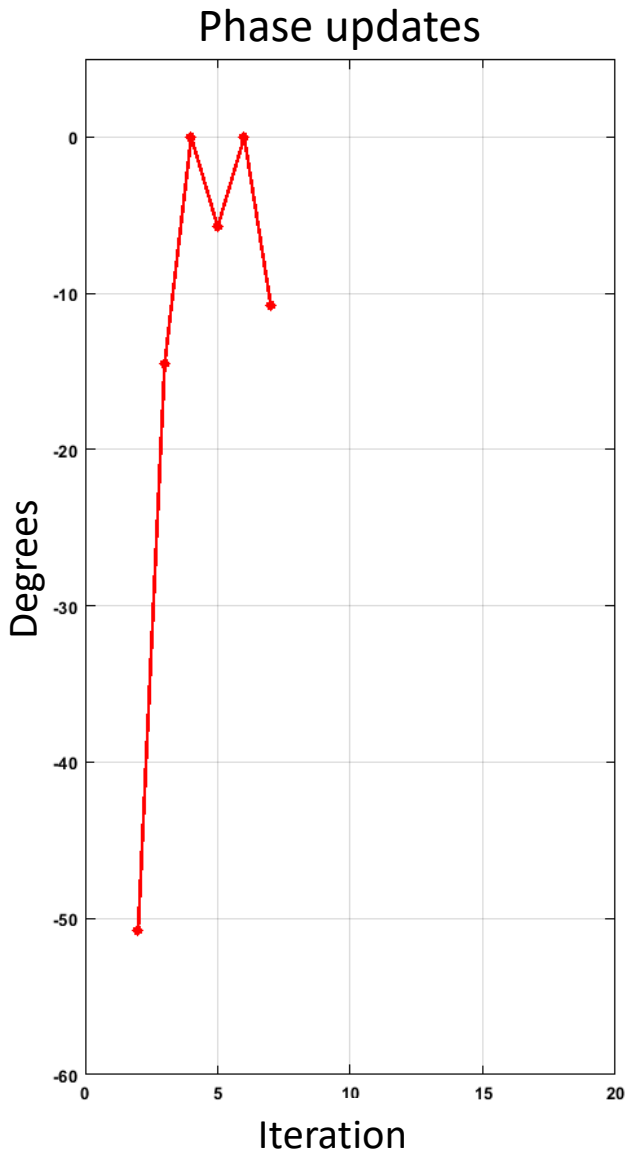


Evolution of the wavelet

It = 7

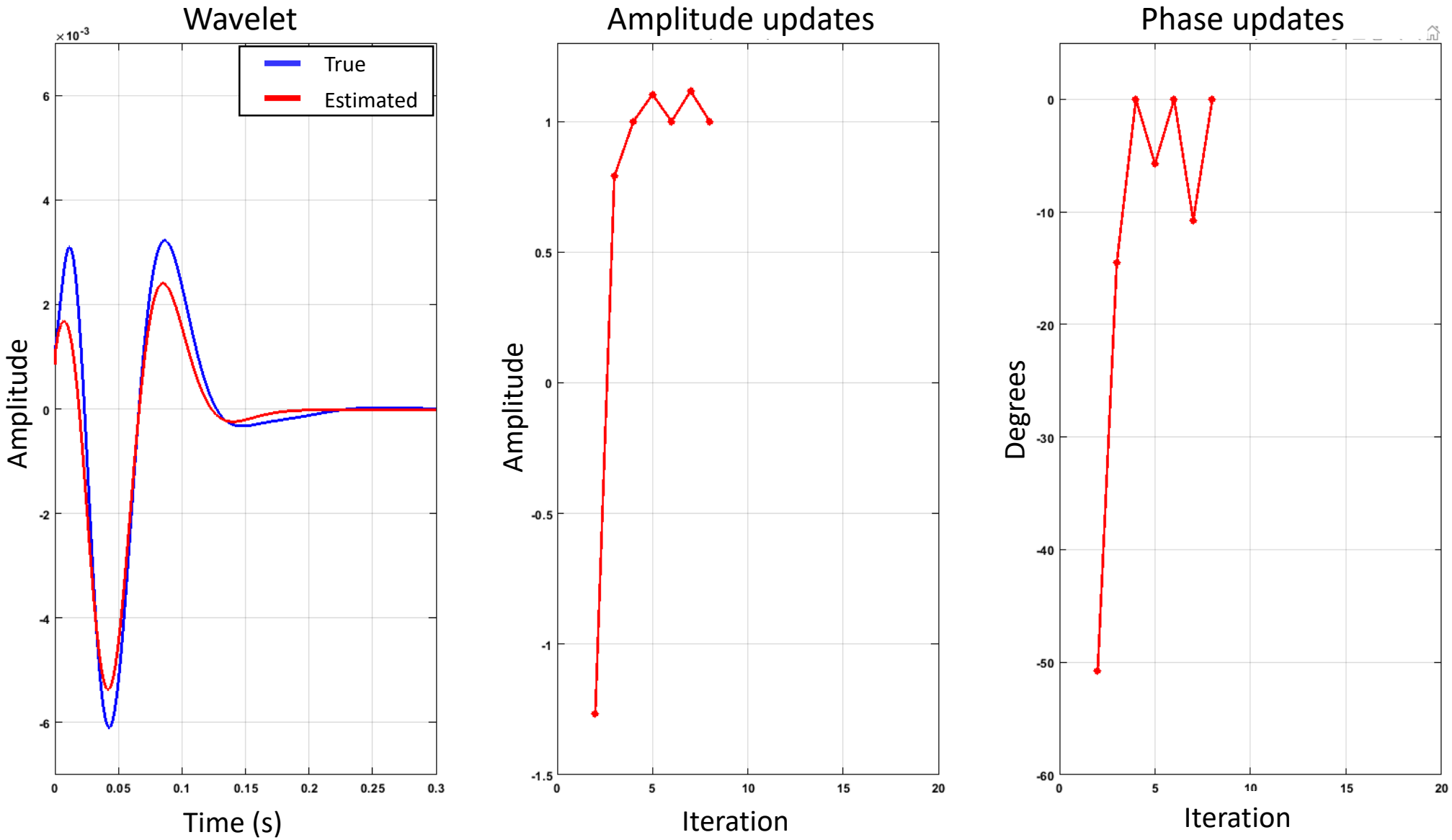






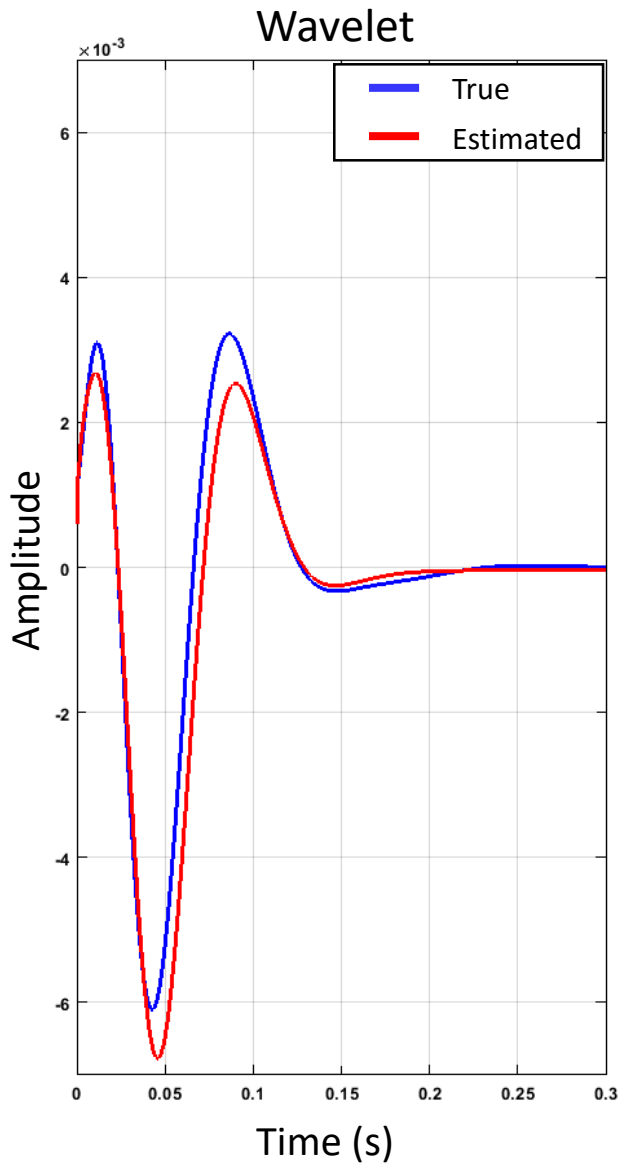
Evolution of the wavelet

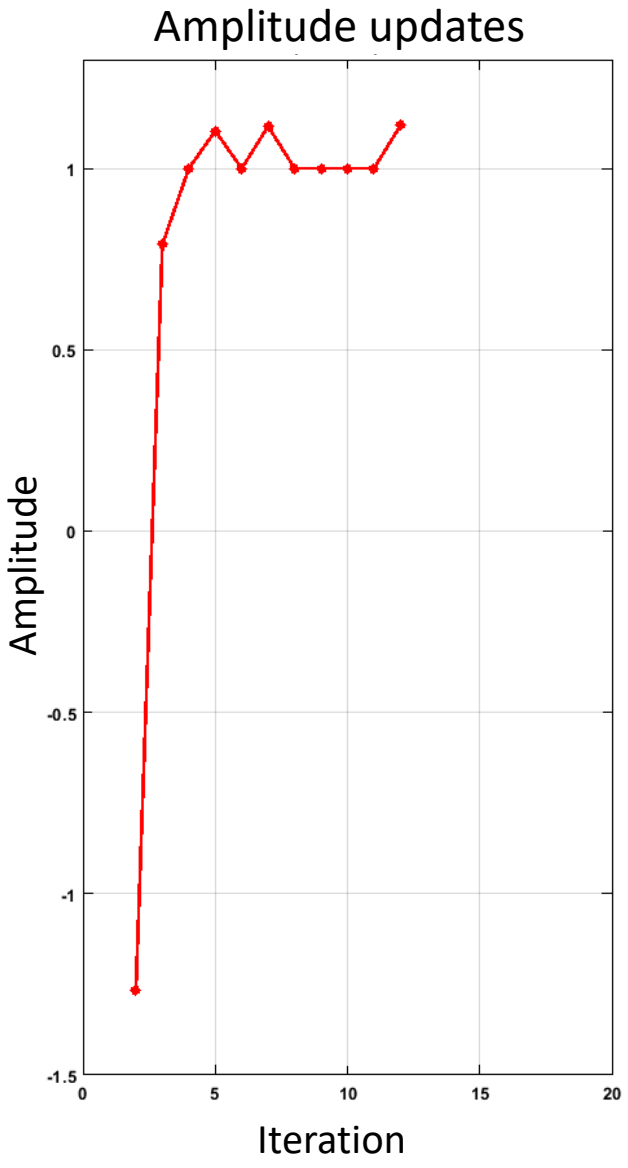
It = 8

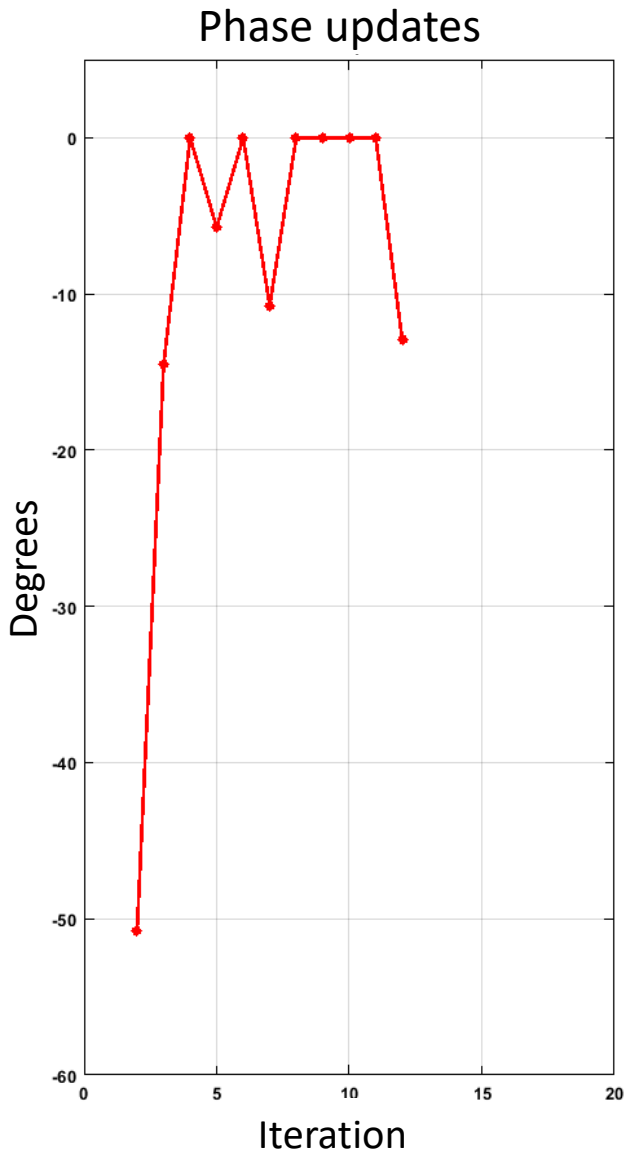


Evolution of the wavelet

It = 12

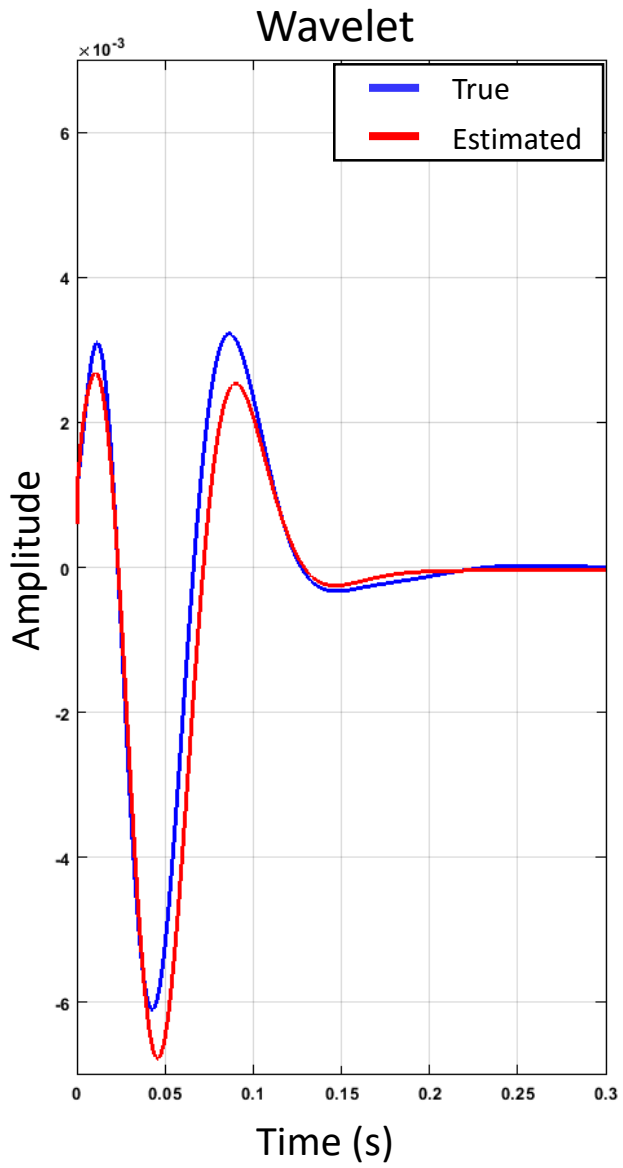


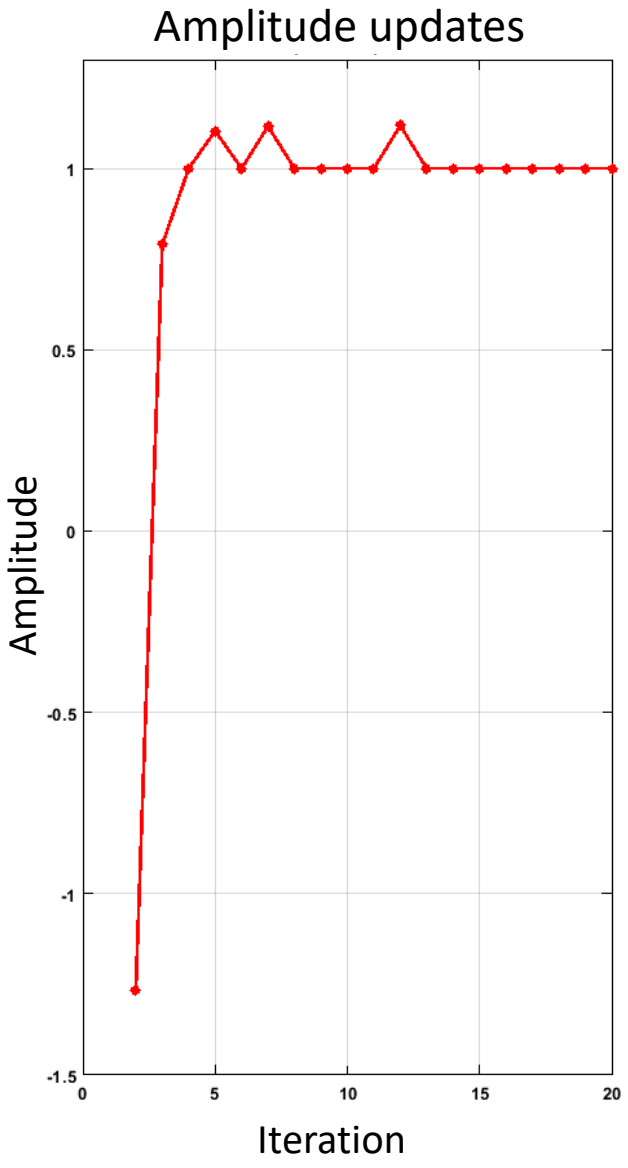


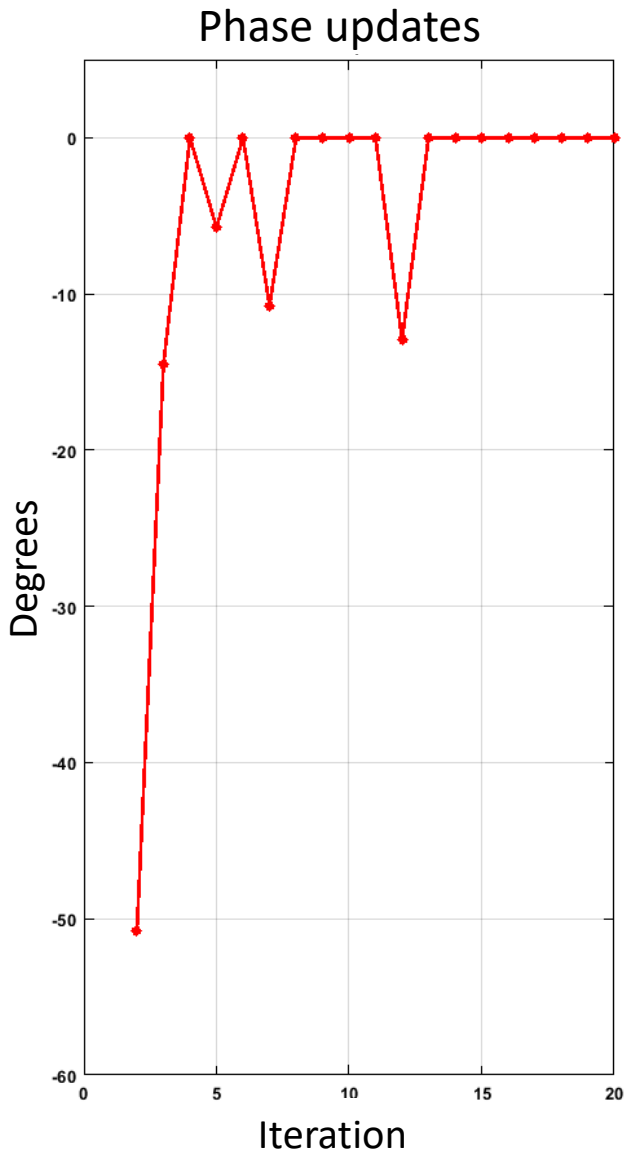


Evolution of the wavelet

It = 20

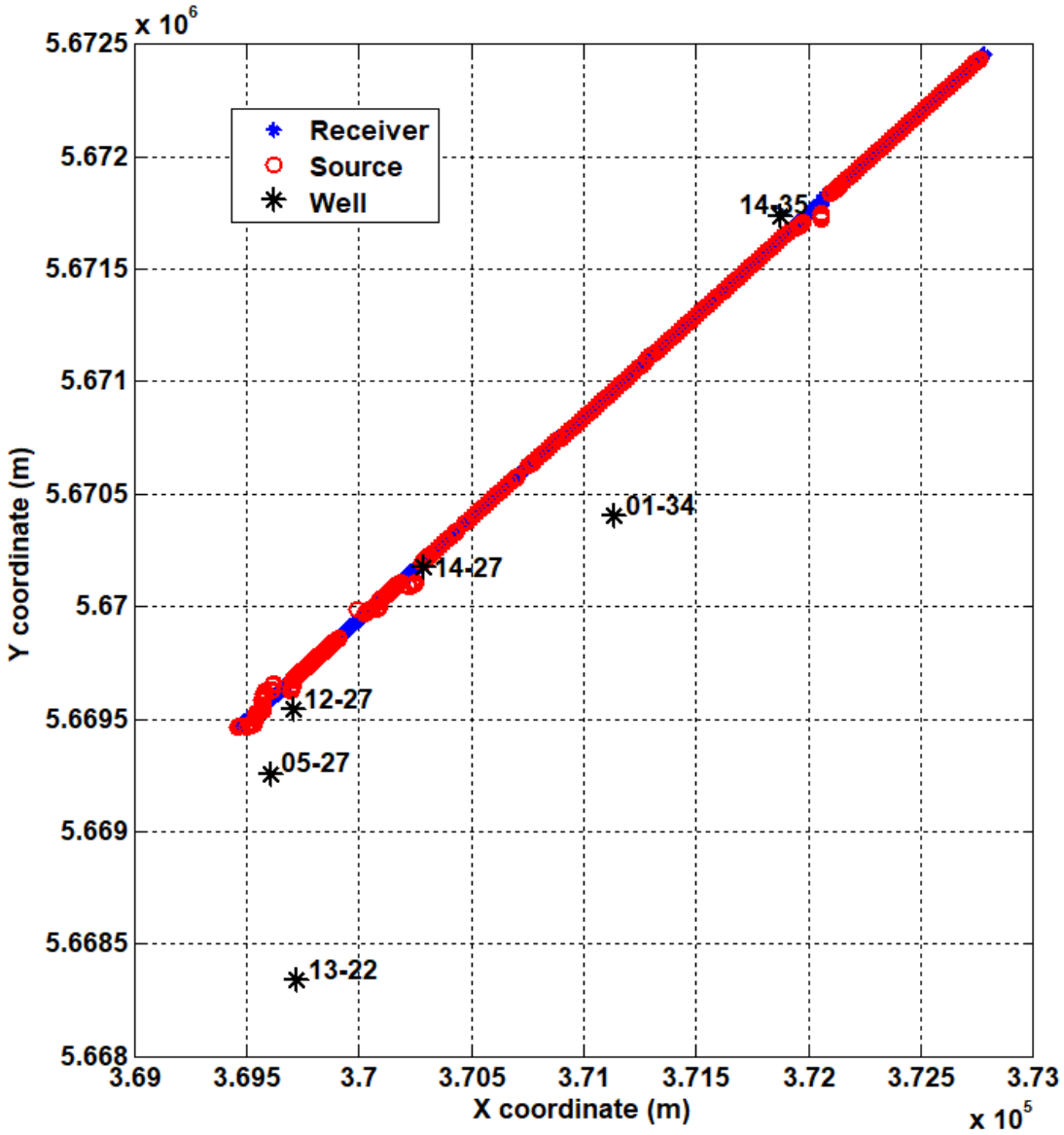






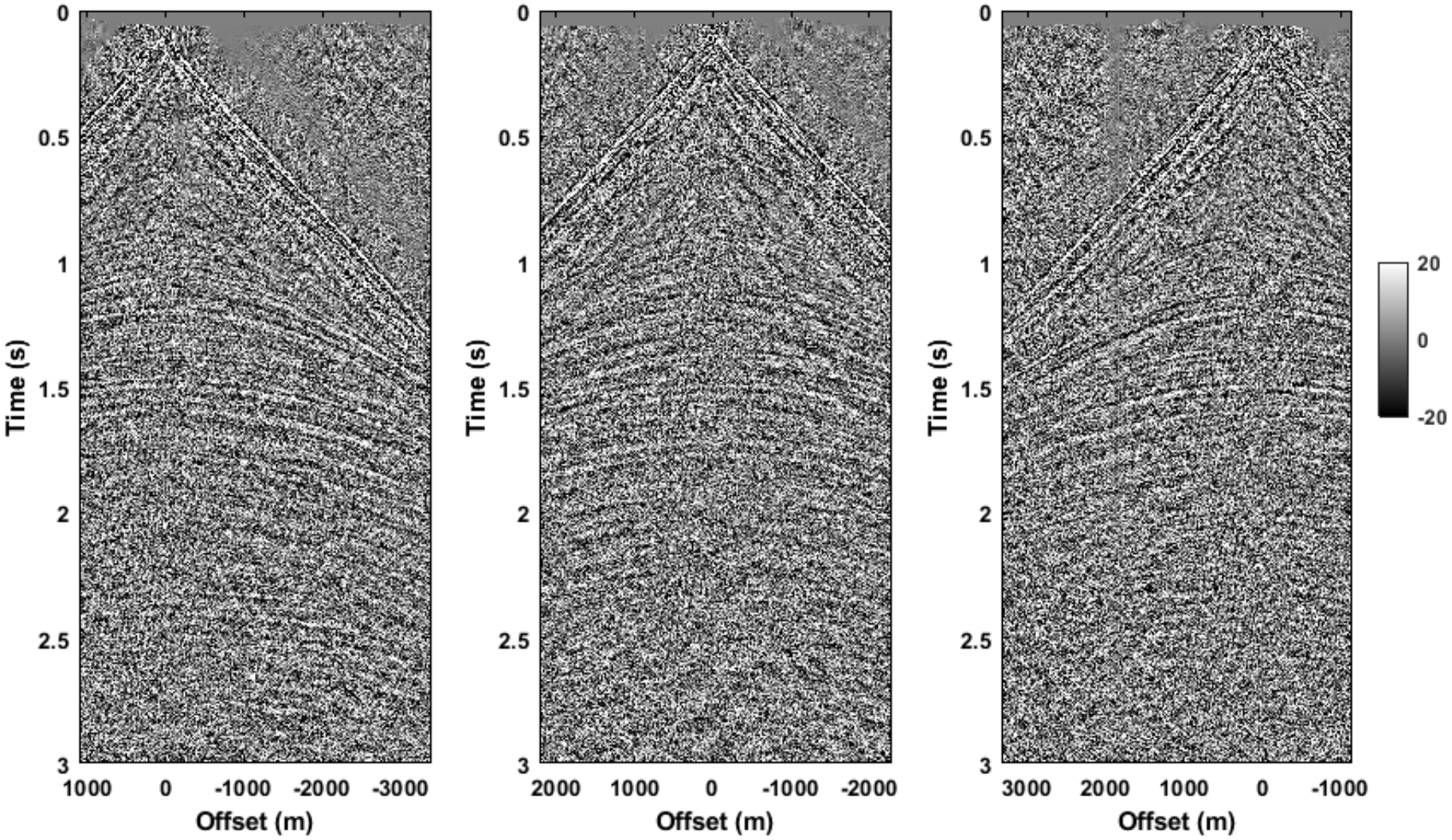
Hussar dataset

Seismic survey

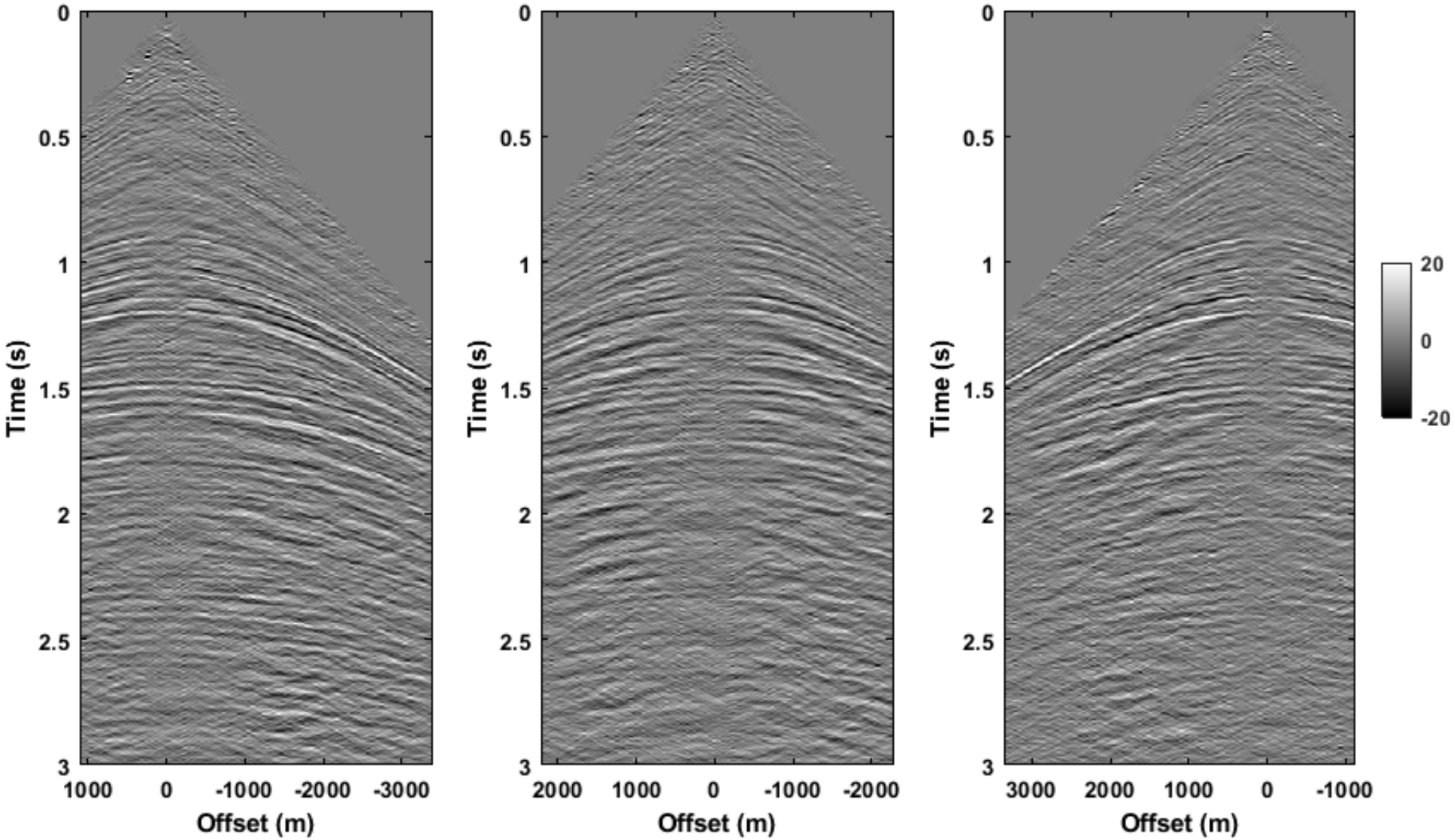


Seismic shots with radial filtering and Gabor deconvolution

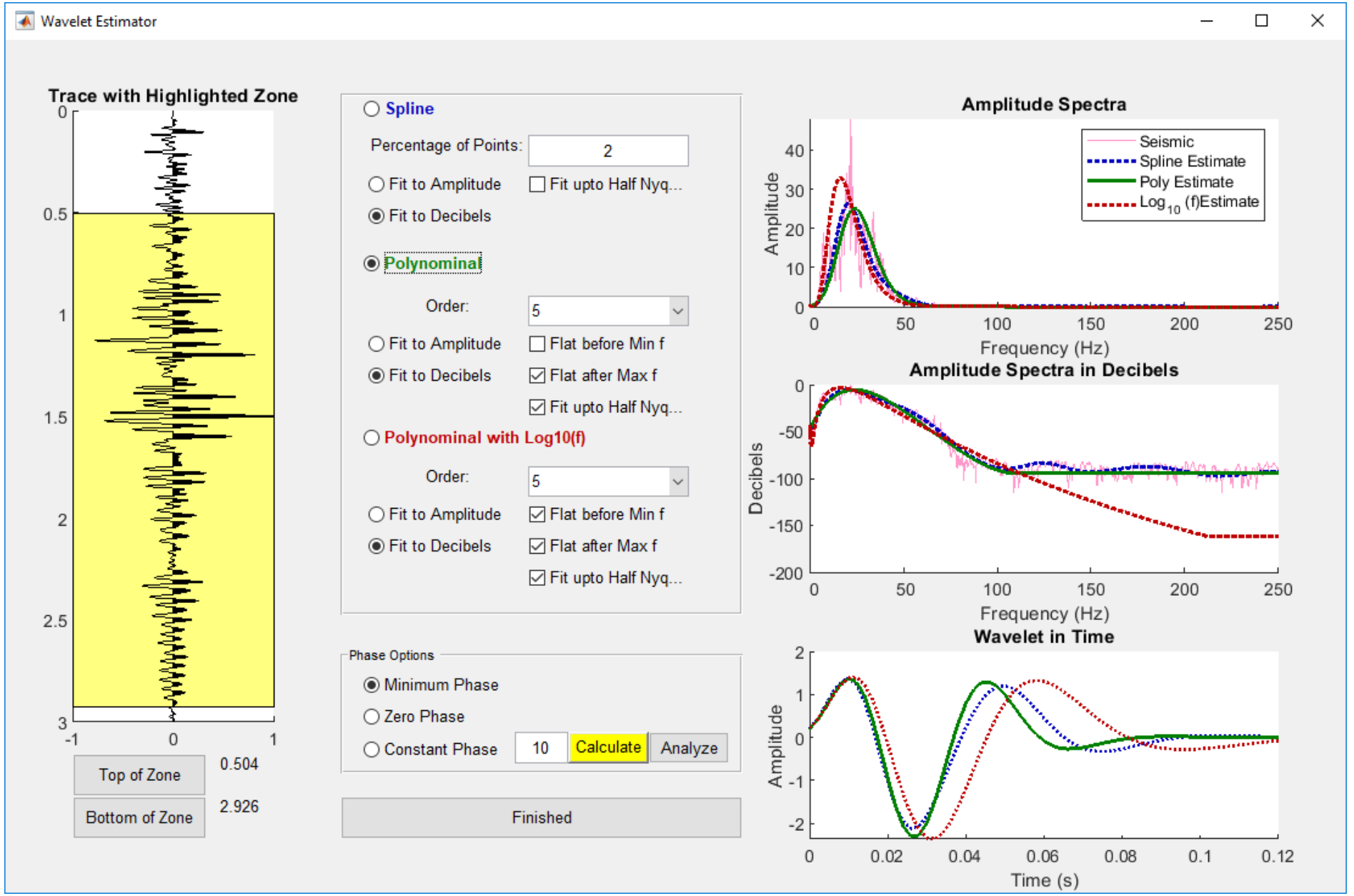
Isaac and Margrave (2011)



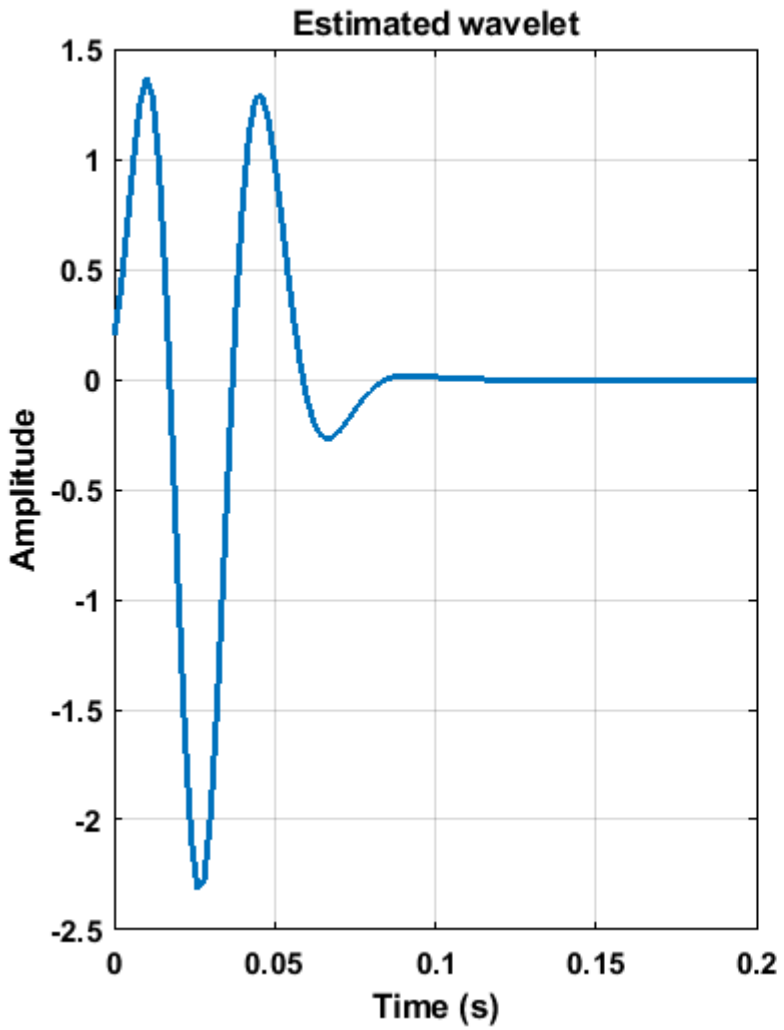
Seismic shots + LPF + FK filter

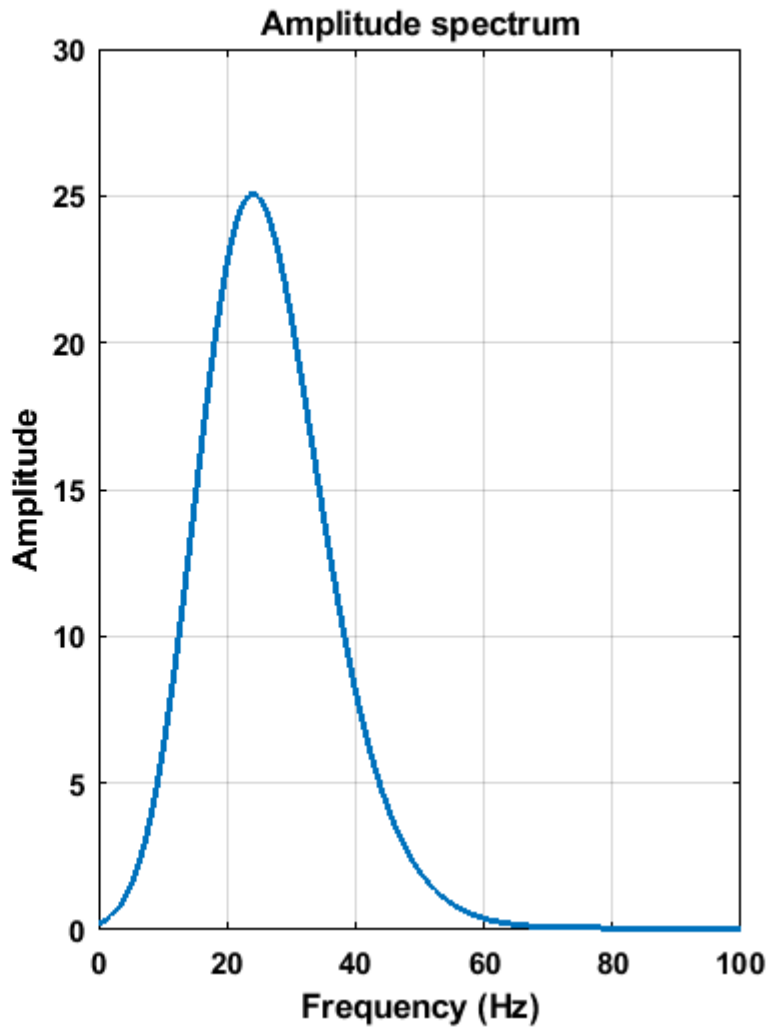


Wavelet estimation

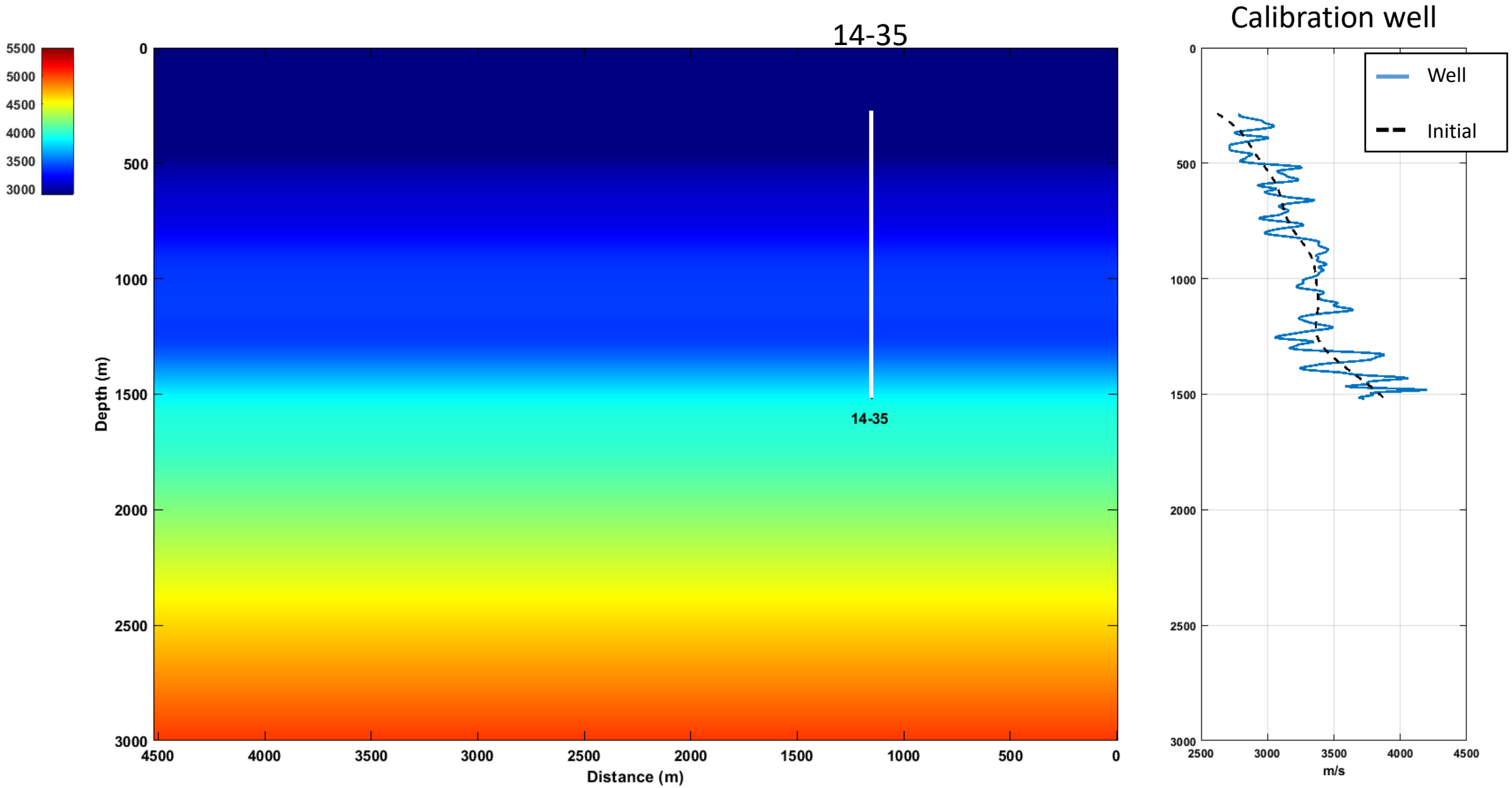


Estimated wavelet



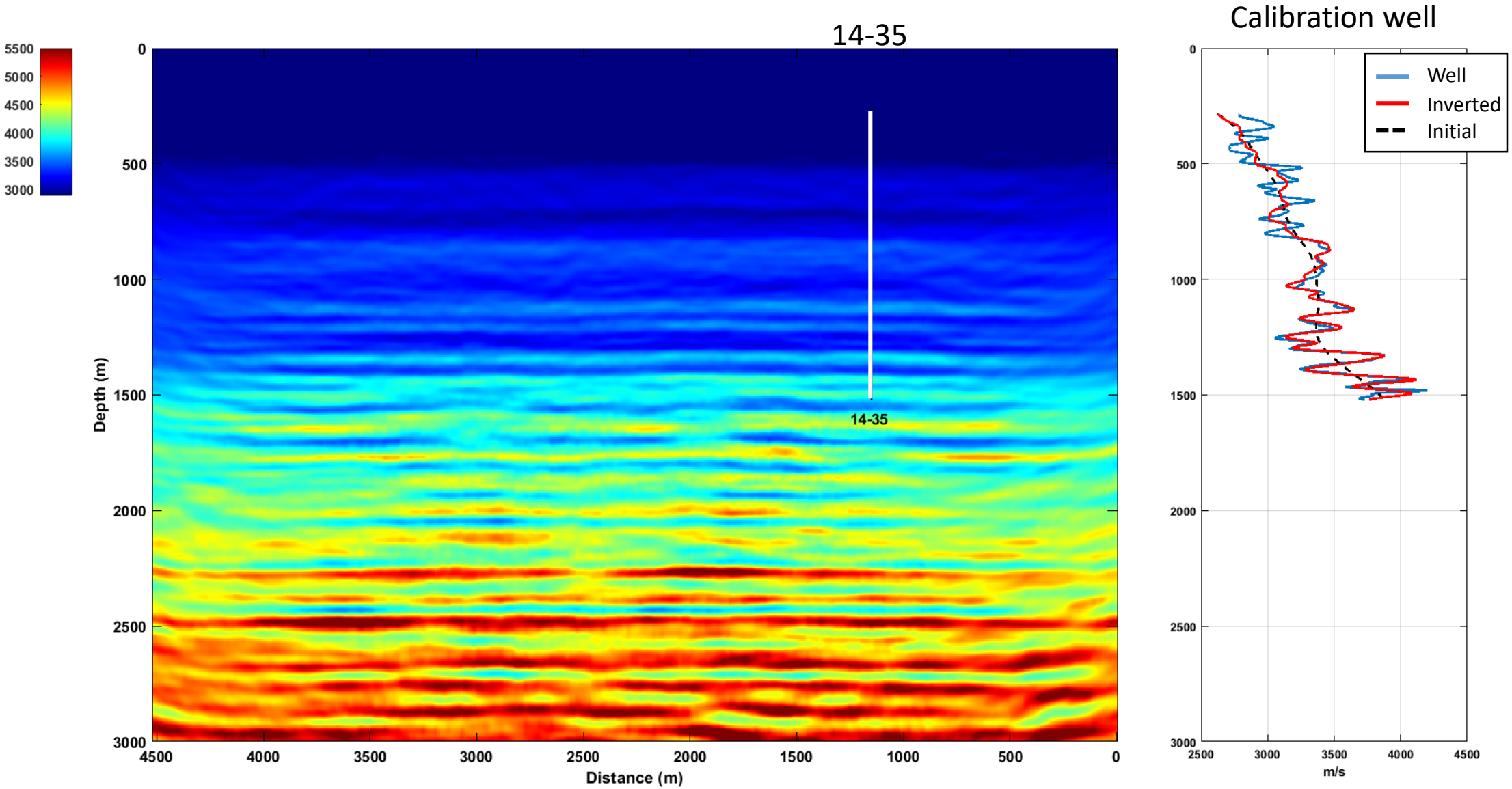


Initial model using well 14-35

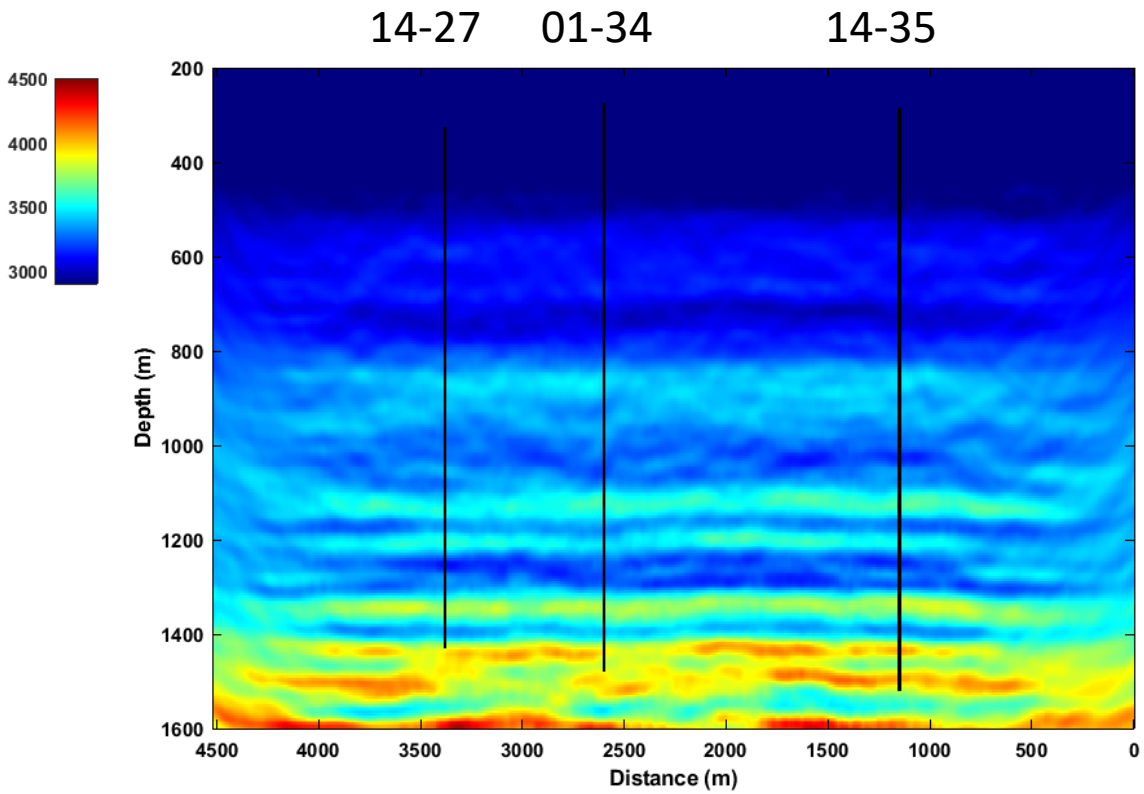


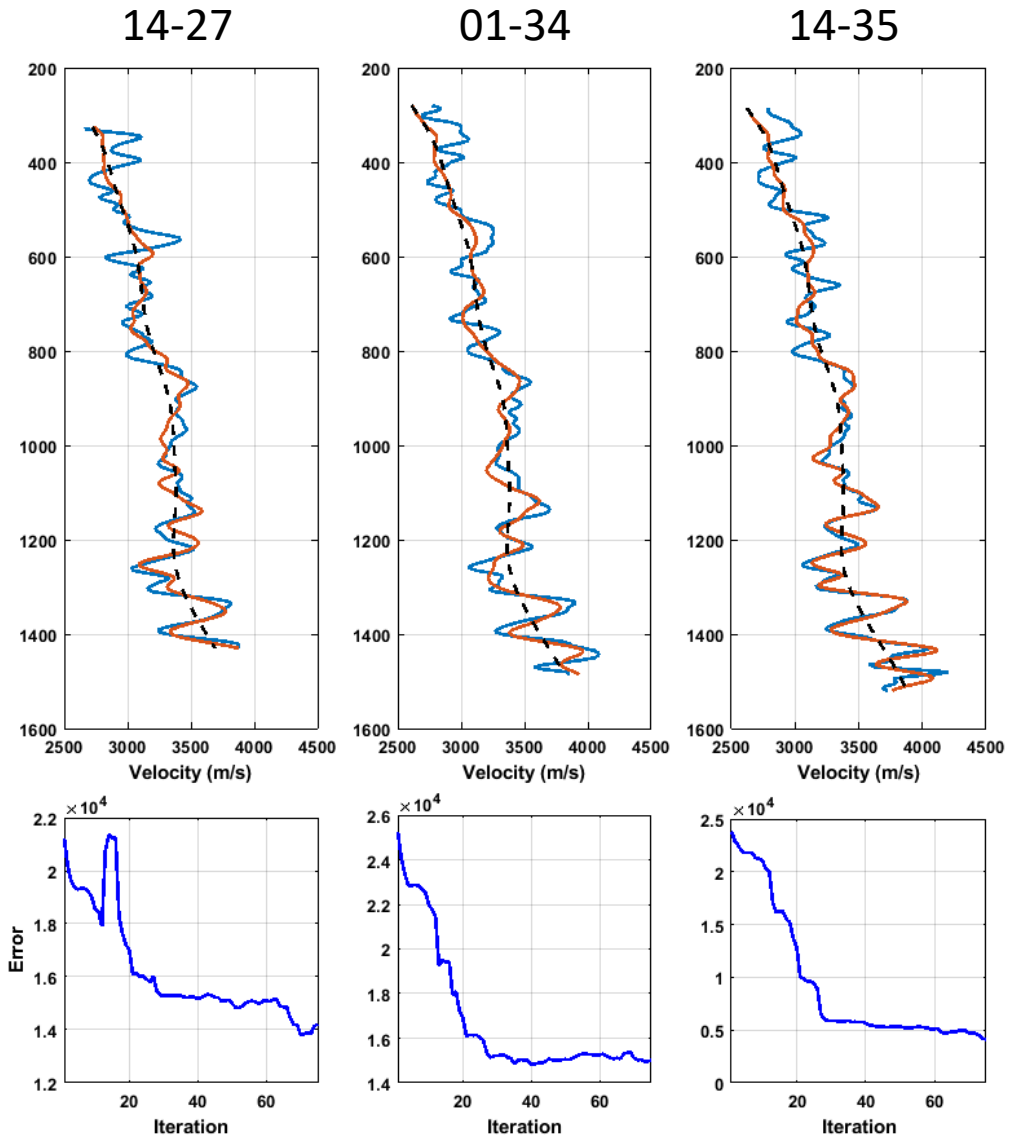
Calibration well

Inverted model



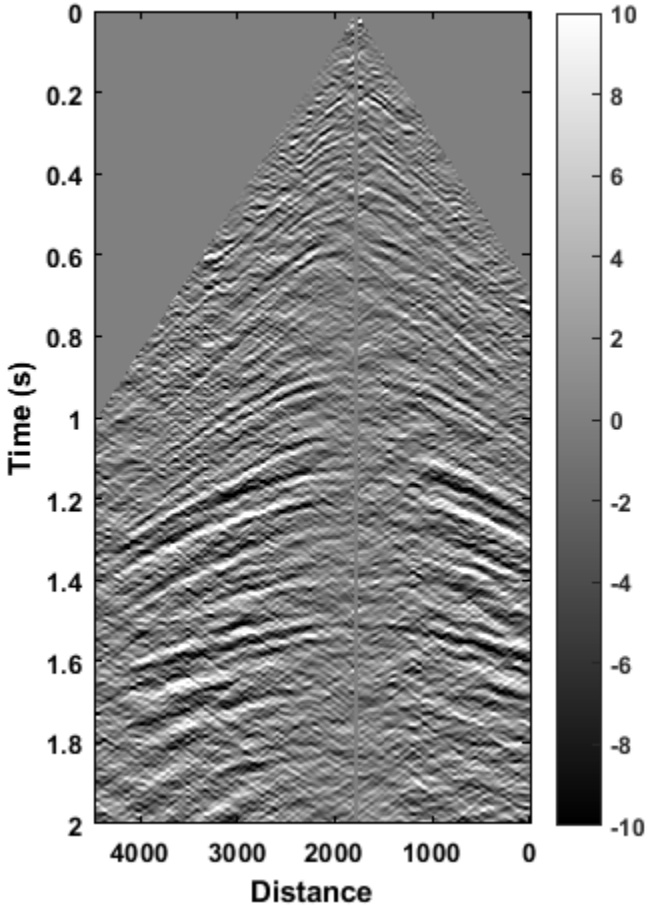
Verification at other wells



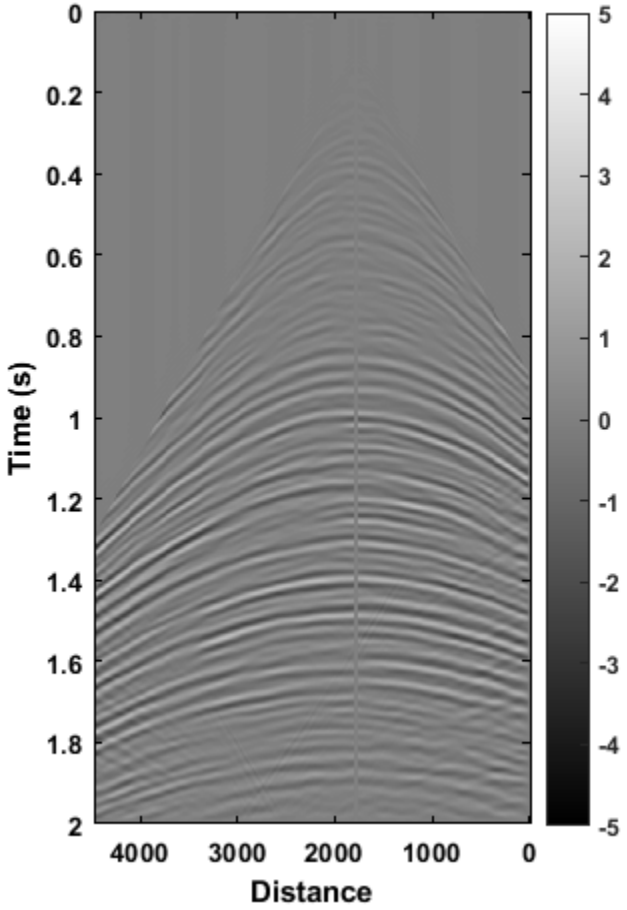


Observed and modelled shots

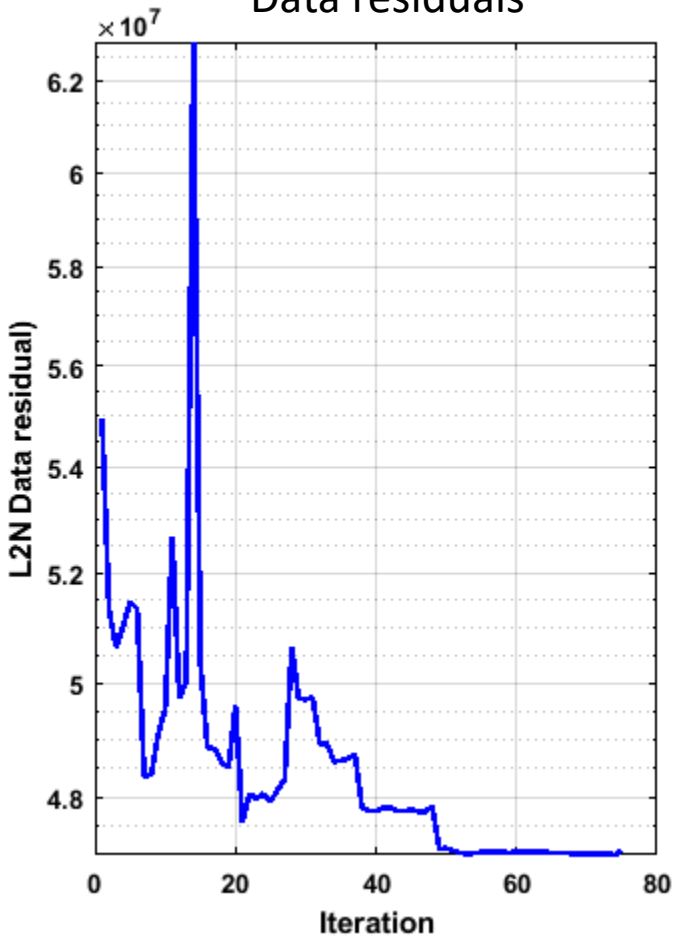
Observed shot



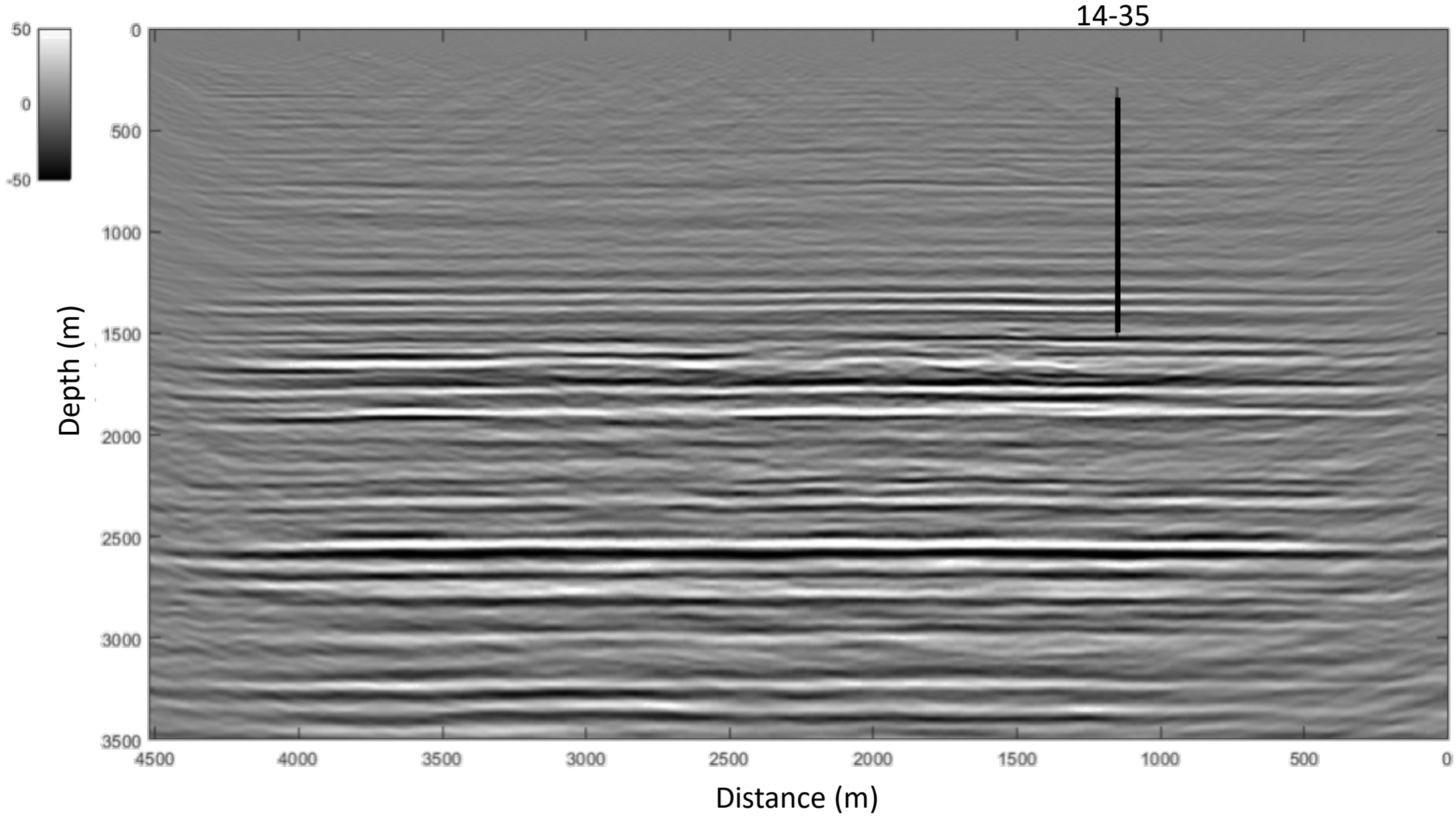
Modelled shot



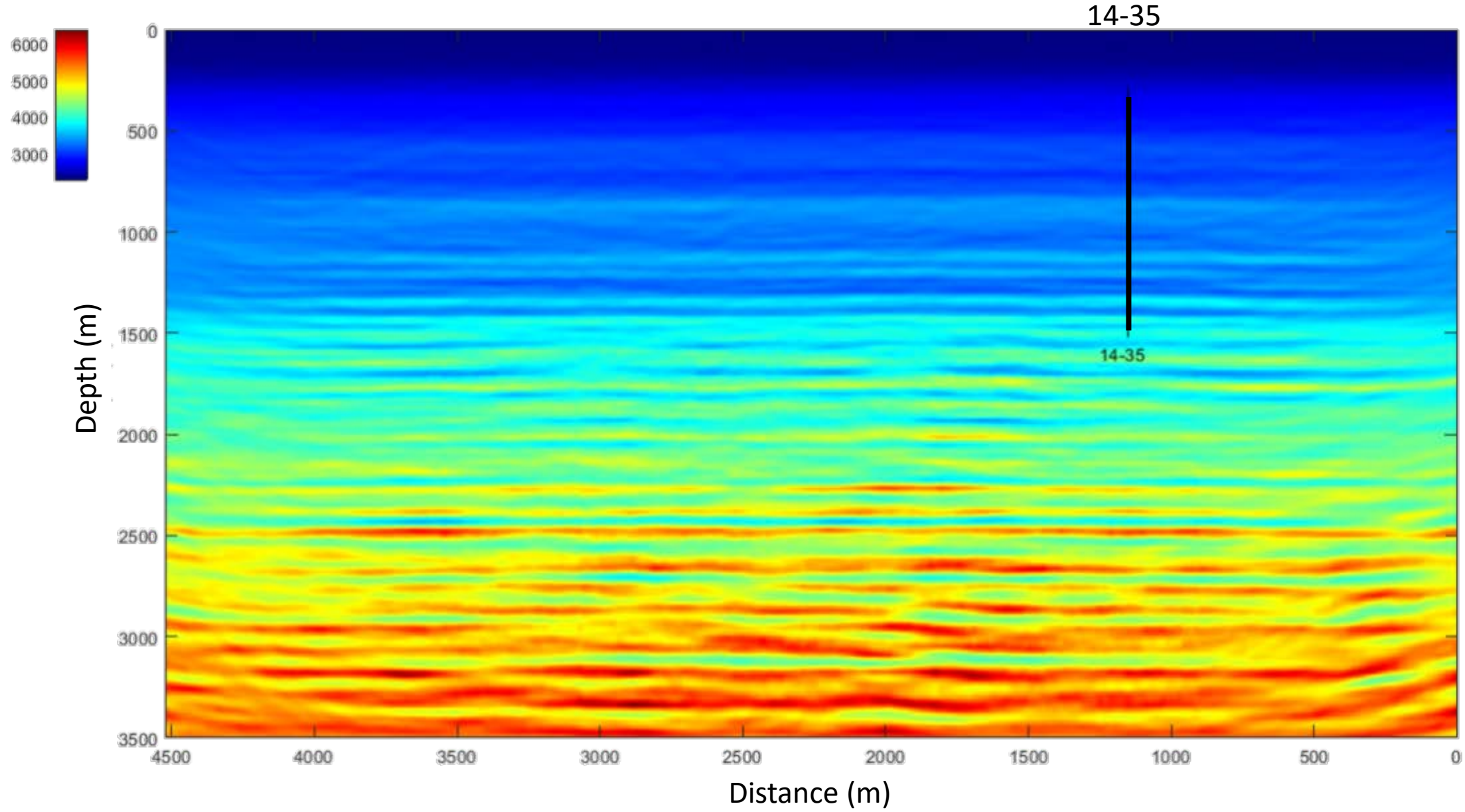
Data residuals



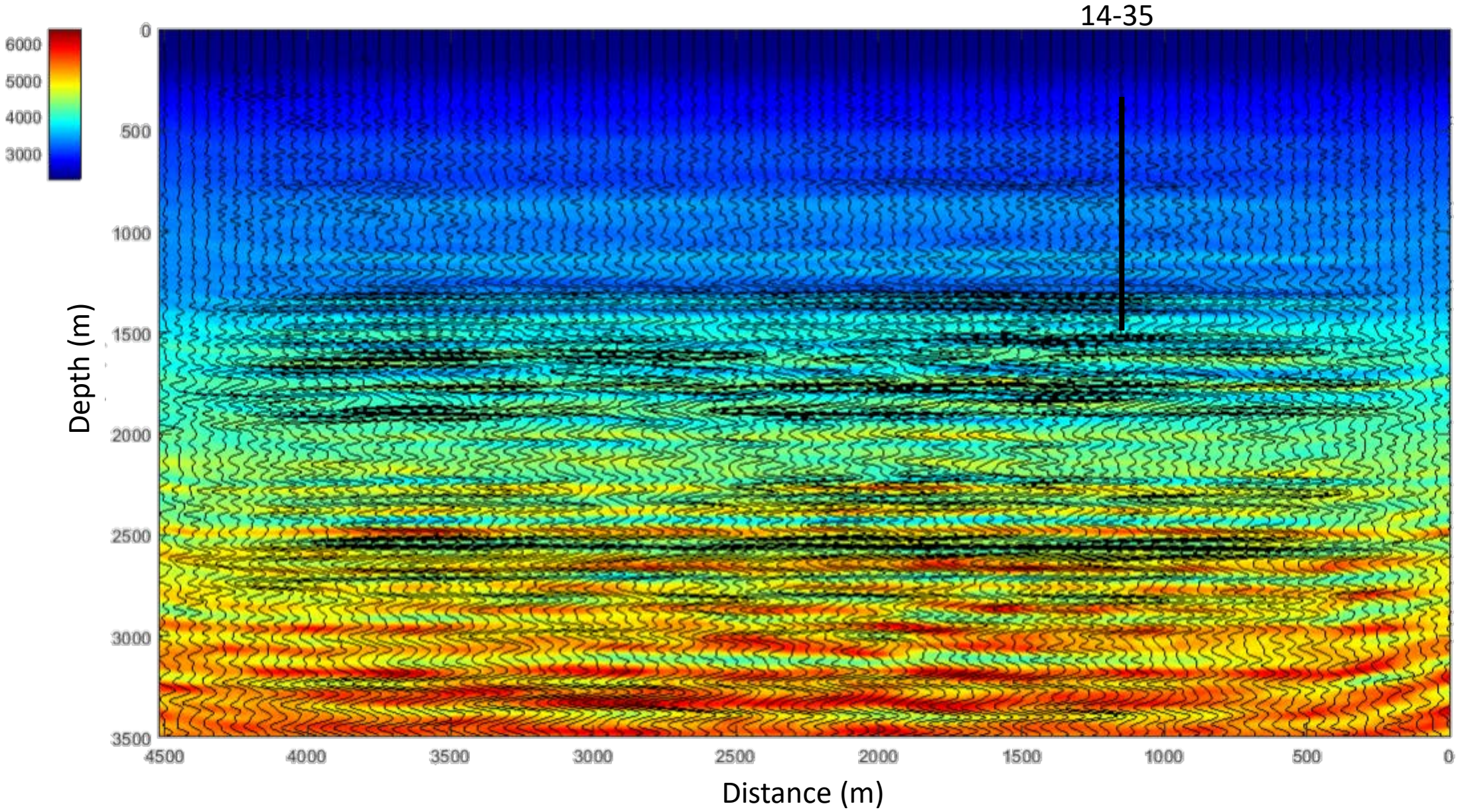
Migrated section



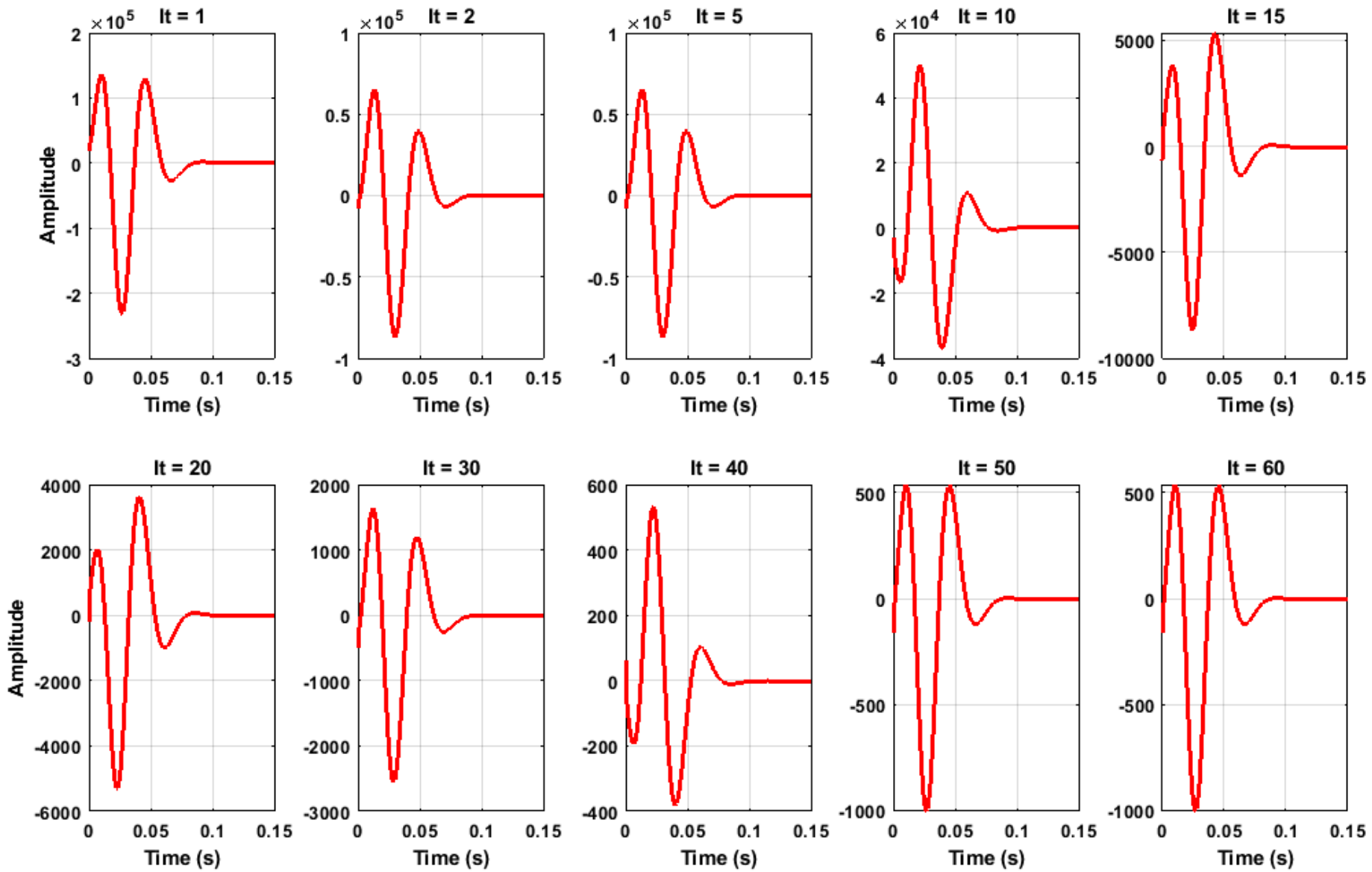
Inverted model



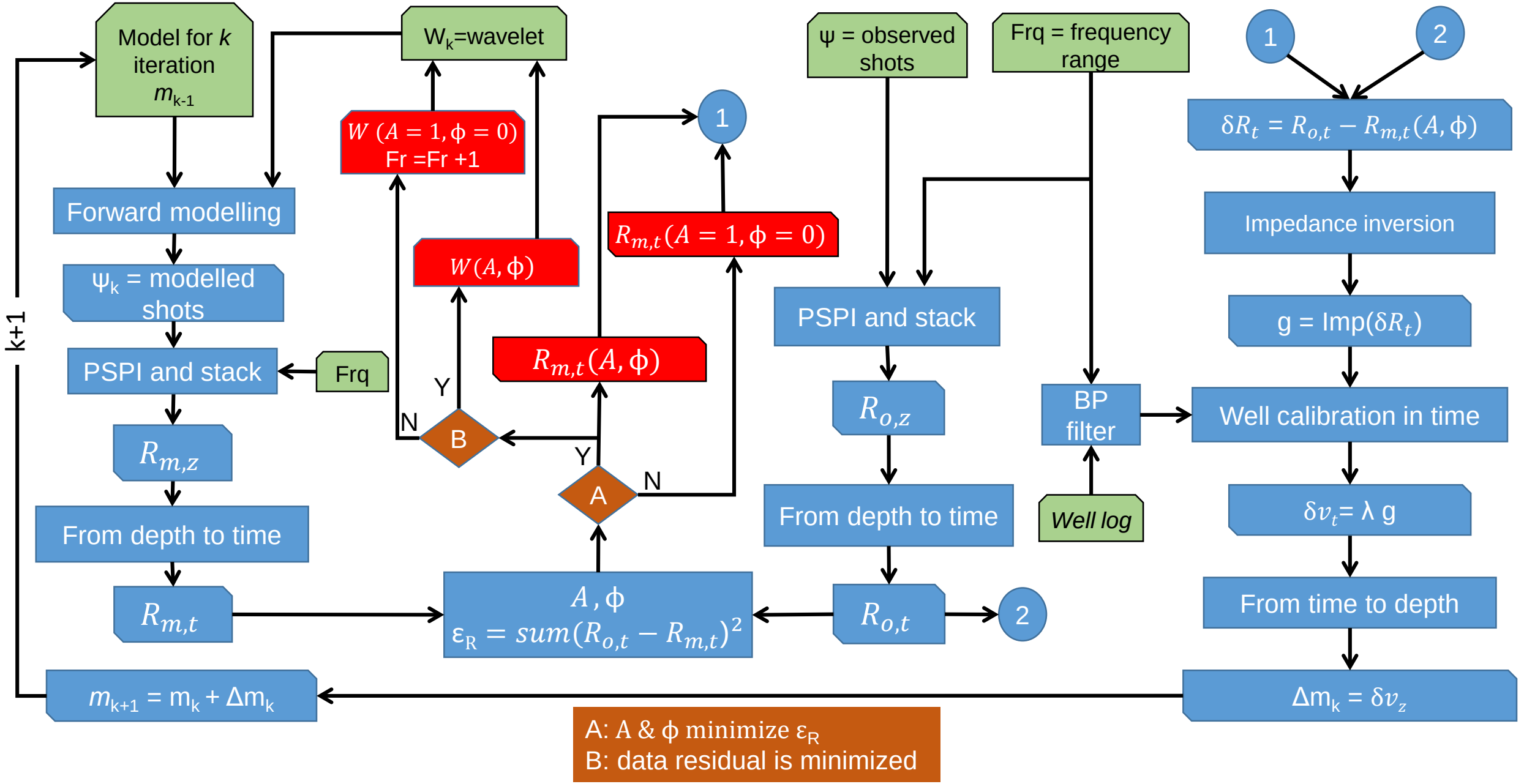
Inverted model + migrated seismic data



Evolution of the wavelet



Workflow


Model for k iteration m_{k-1}
W_k=wavelet
ψ = observed shots
Frq = frequency range
1
2
$\delta R_t = R_{o,t} - R_{m,t}(A, \phi)$
Forward modelling
$W\ (A = 1, \phi = 0)$ Fr =Fr +1
1
$R_{m,t}(A = 1, \phi = 0)$
Impedance inversion
ψ_k = modelled shots
$W(A, \phi)$
PSPI and stack
$R_{o,z}$
BP filter
g = Imp(δR_t)
PSPI and stack
Frq
$R_{m,t}(A, \phi)$
Y
N
B
Y
N
A
Well calibration in time
$R_{m,z}$
From depth to time
Well log
δv_t= λ g
From depth to time
$R_{m,t}$
A, ϕ
$\varepsilon_R = sum(R_{o,t} - R_{m,t})^2$
$R_{o,t}$
2
From time to depth
k+1
$m_{k+1} = m_k + \Delta m_k$
$\Delta m_k = \delta v_z$
A: A & ϕ minimize ε_R
B: data residual is minimized

Conclusions

- Methodology to update the amplitude and phase of the modelled data for well-log validated FWI
- Separate the migration of the observed and modelled data before constructing the gradient
- Synthetic analysis suggests that the scheme is stable
- Applied to the Hussar dataset obtaining encouraging results
- The variability of the wavelet suggests that it is absorbing errors, both due to the actual wavelet and the reflectivity, and that the success of the inversion relies on the matching process of the observed and modelled reflectivity
- Future: continue to address the instability of the updated wavelet

Acknowledgments

Sponsors of CREWES for their support

NSERC through the grant CRDPJ 461179-13

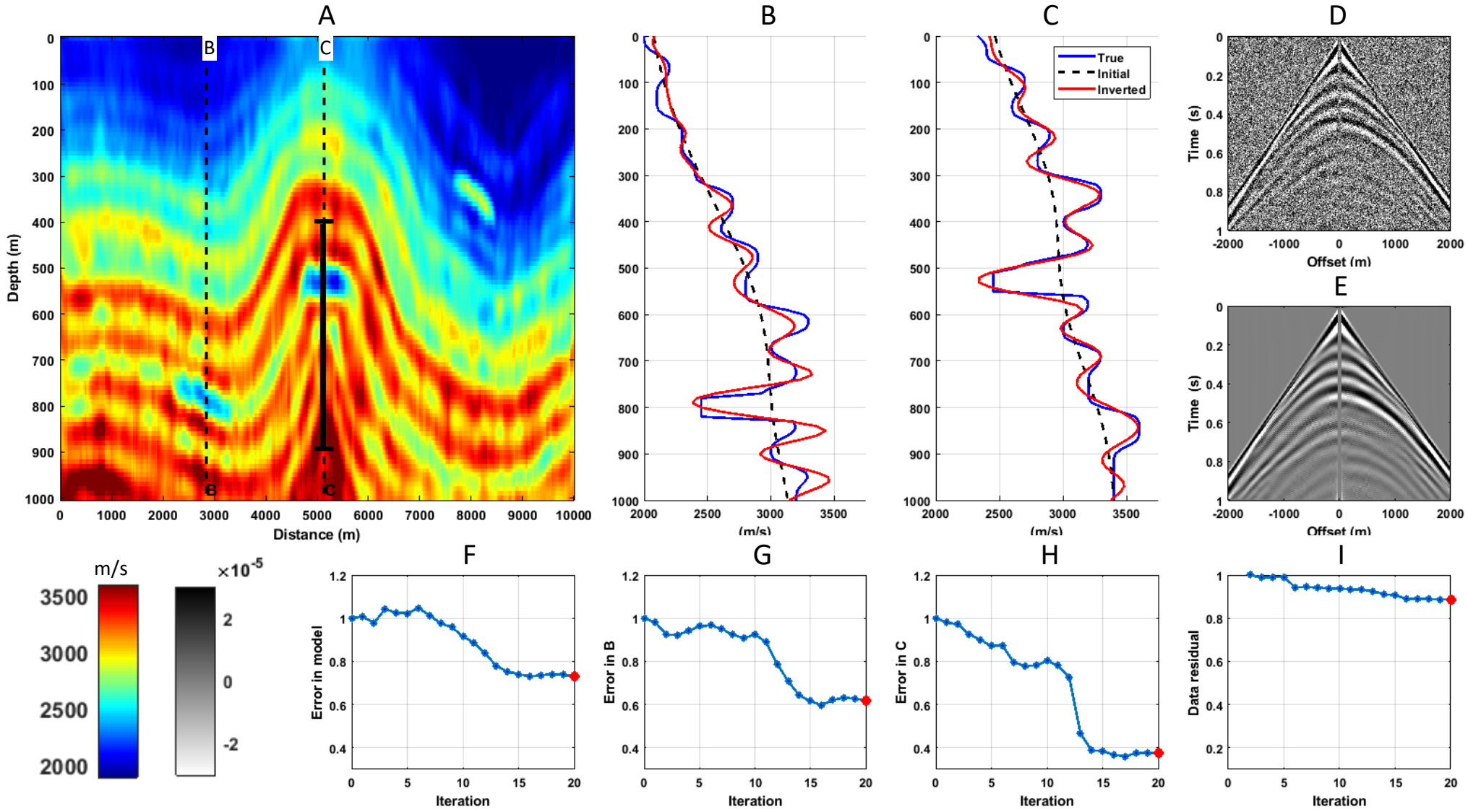
PEMEX and the government of Mexico for funding this research

Thank you!

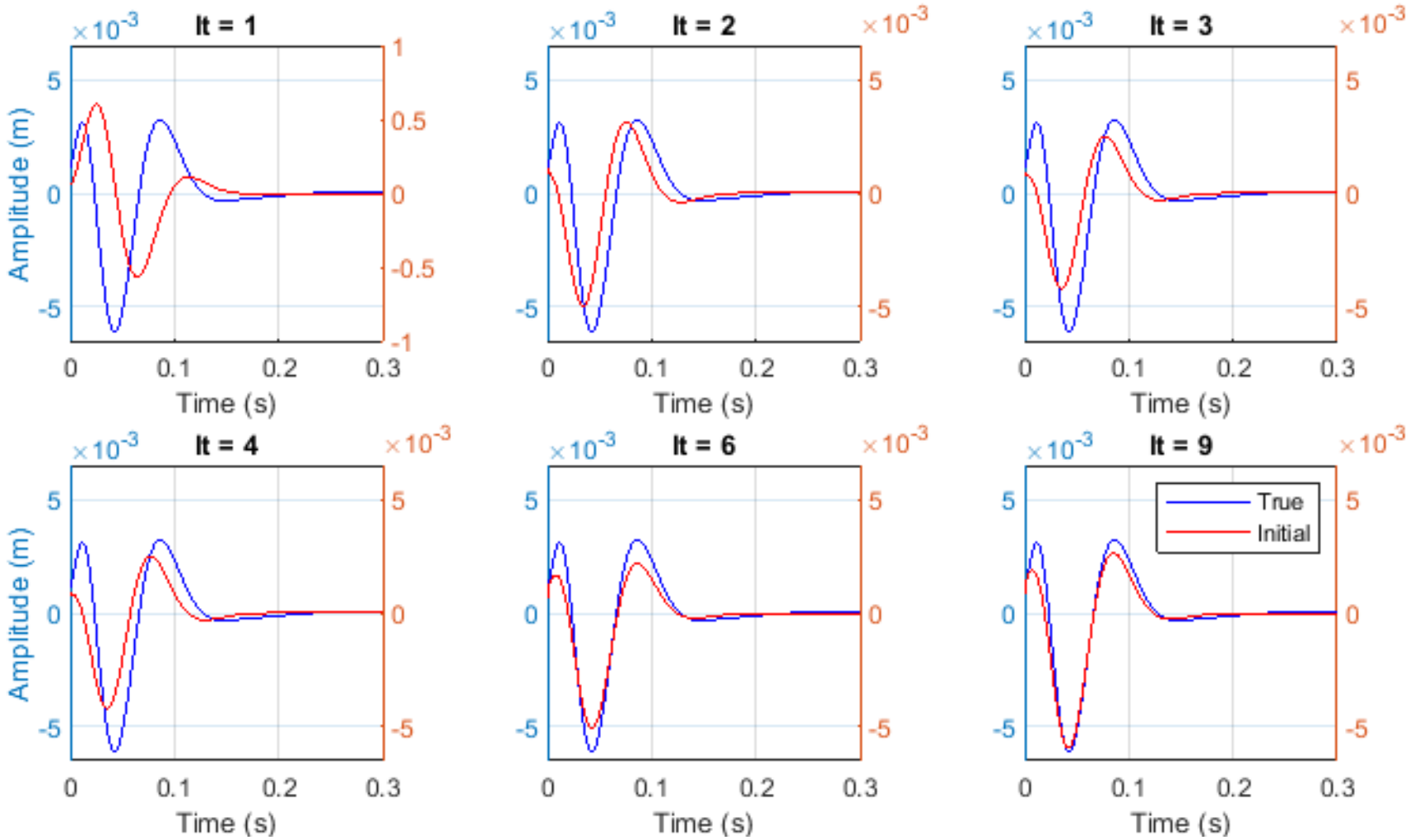
Annex 1
Synthetic example

Random noise

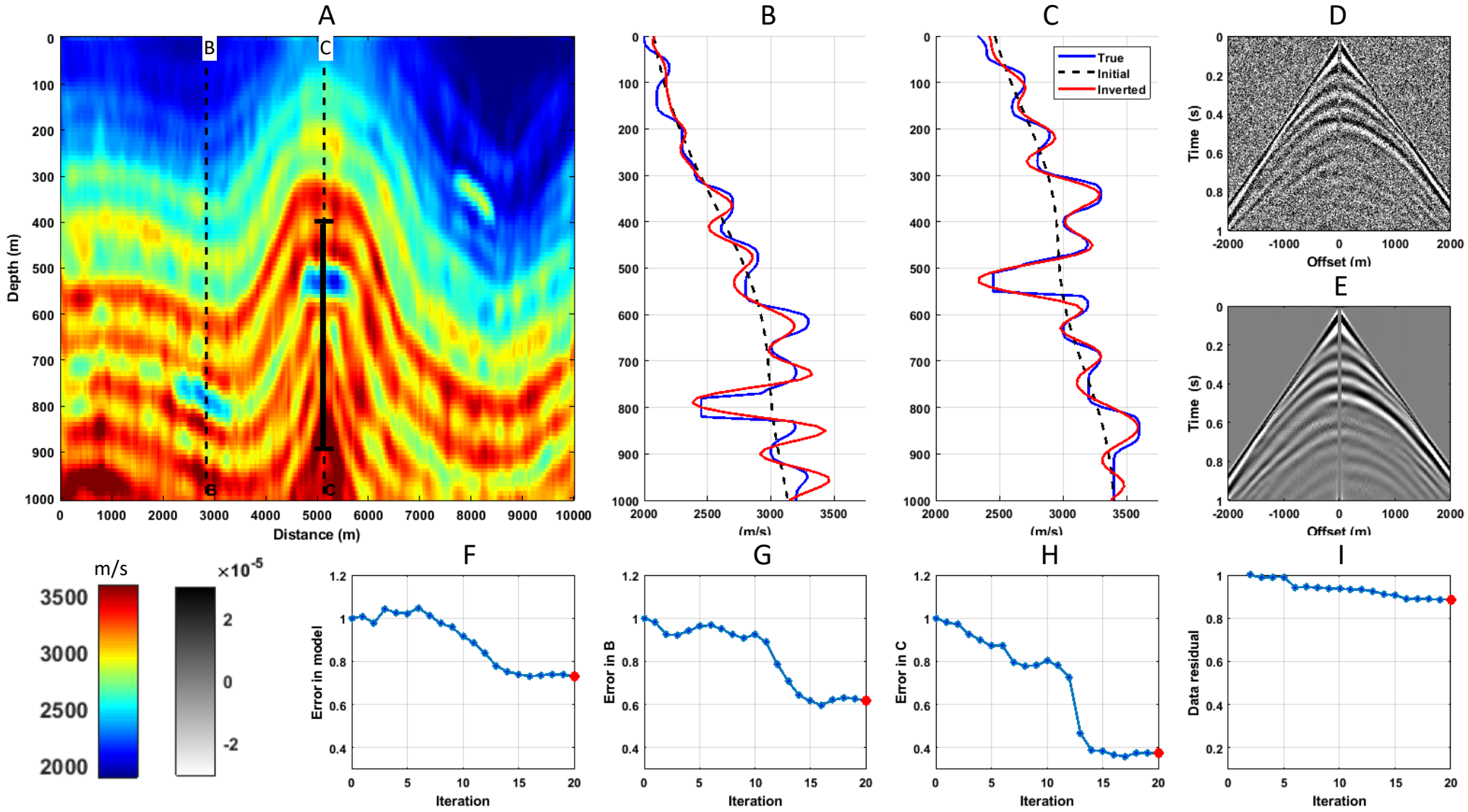
Inversion with amplitude and phase updating



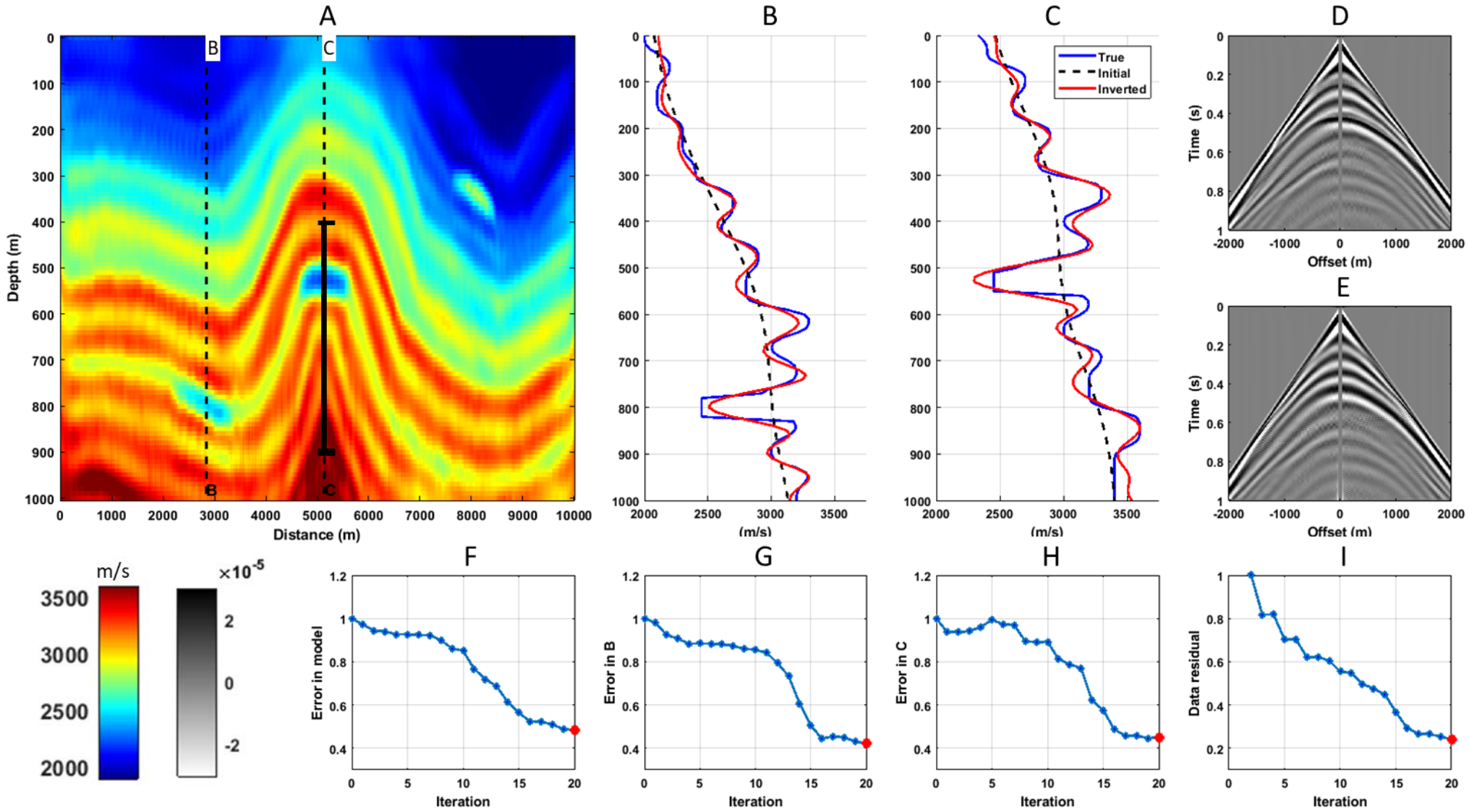
Evolution of the wavelet with iterations



Inversion with amplitude and phase updating



Inversion with amplitude and phase updating

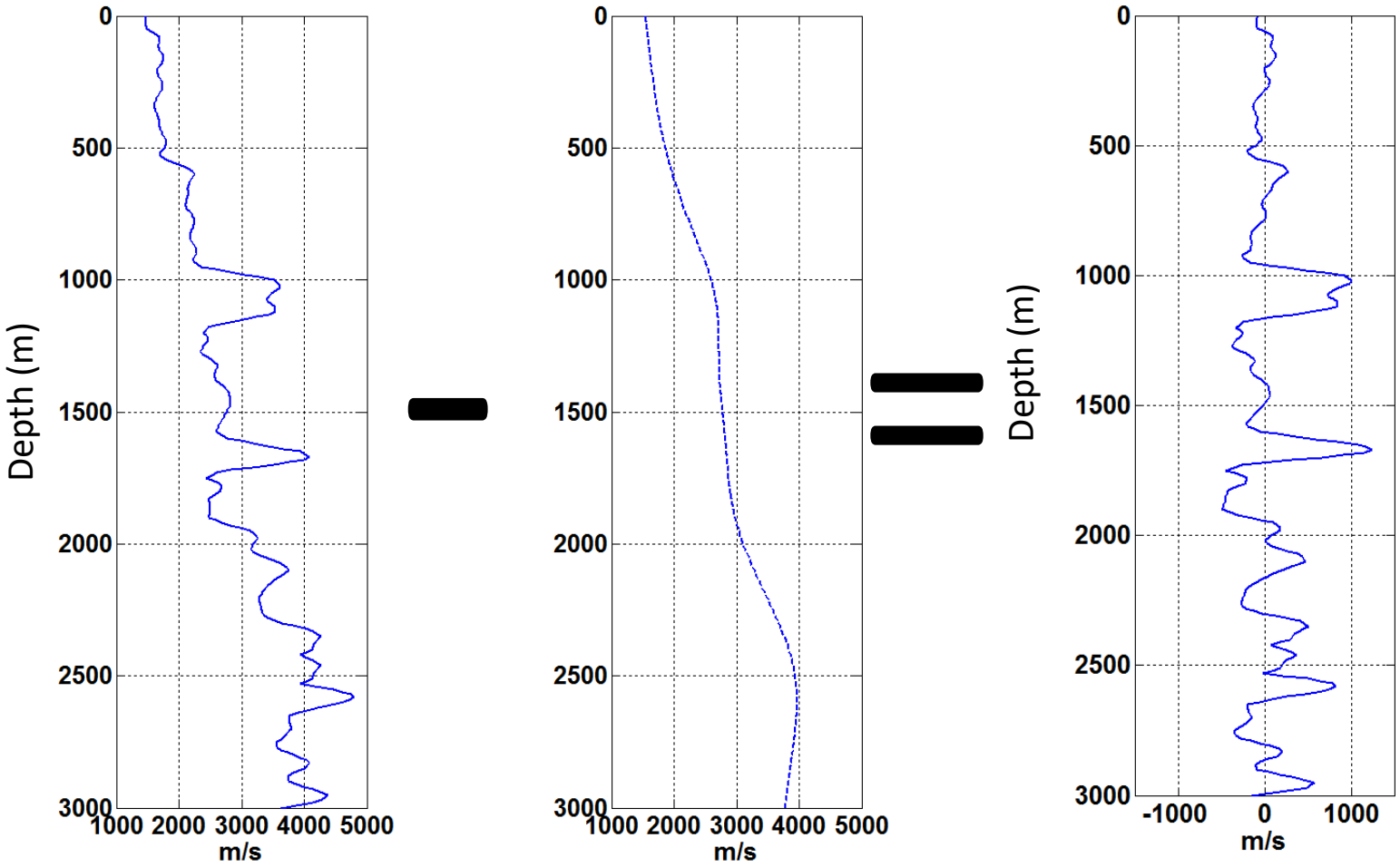


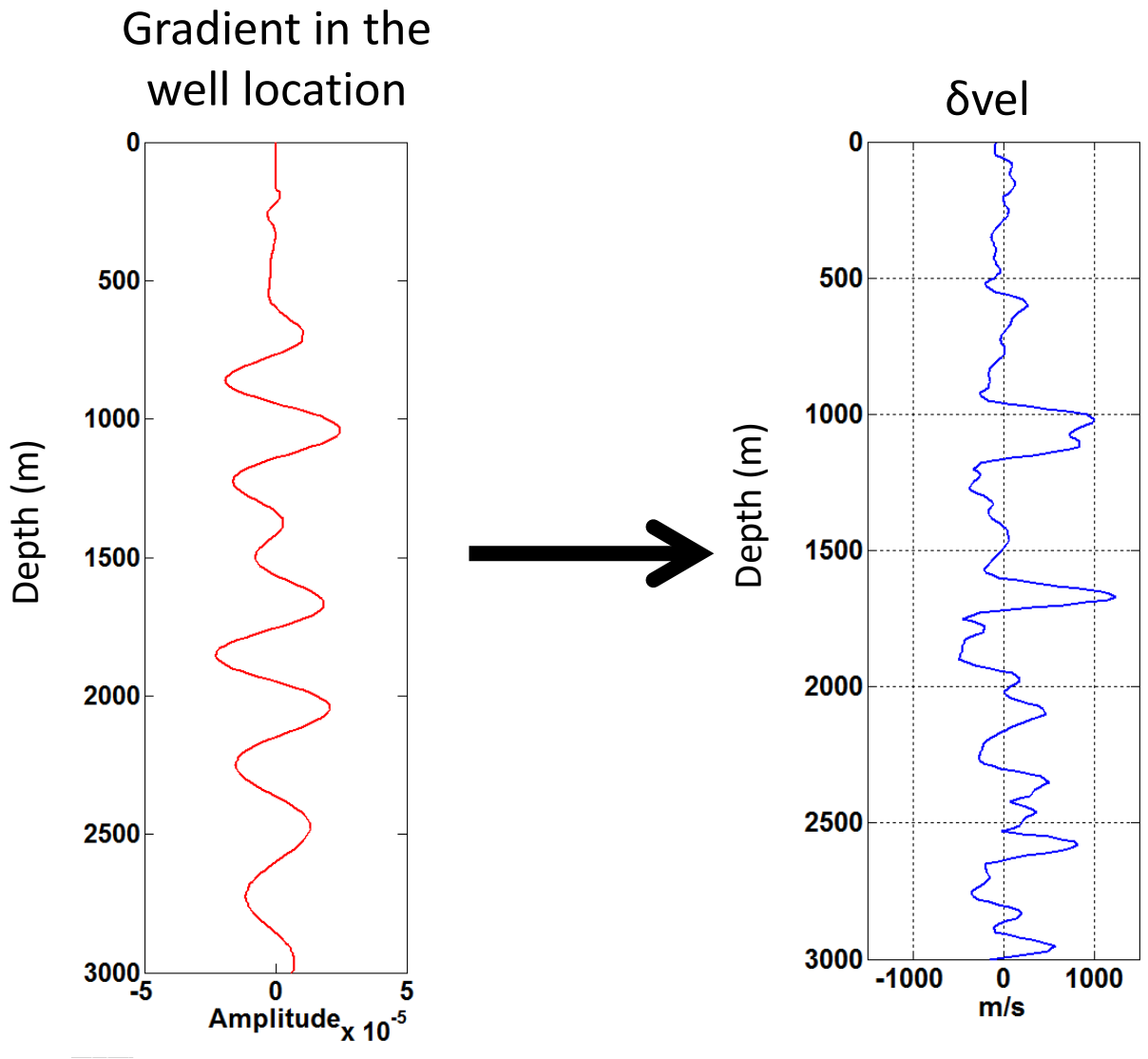
Annex 2
Well validation

Velocity in well C

Initial velocity in well C

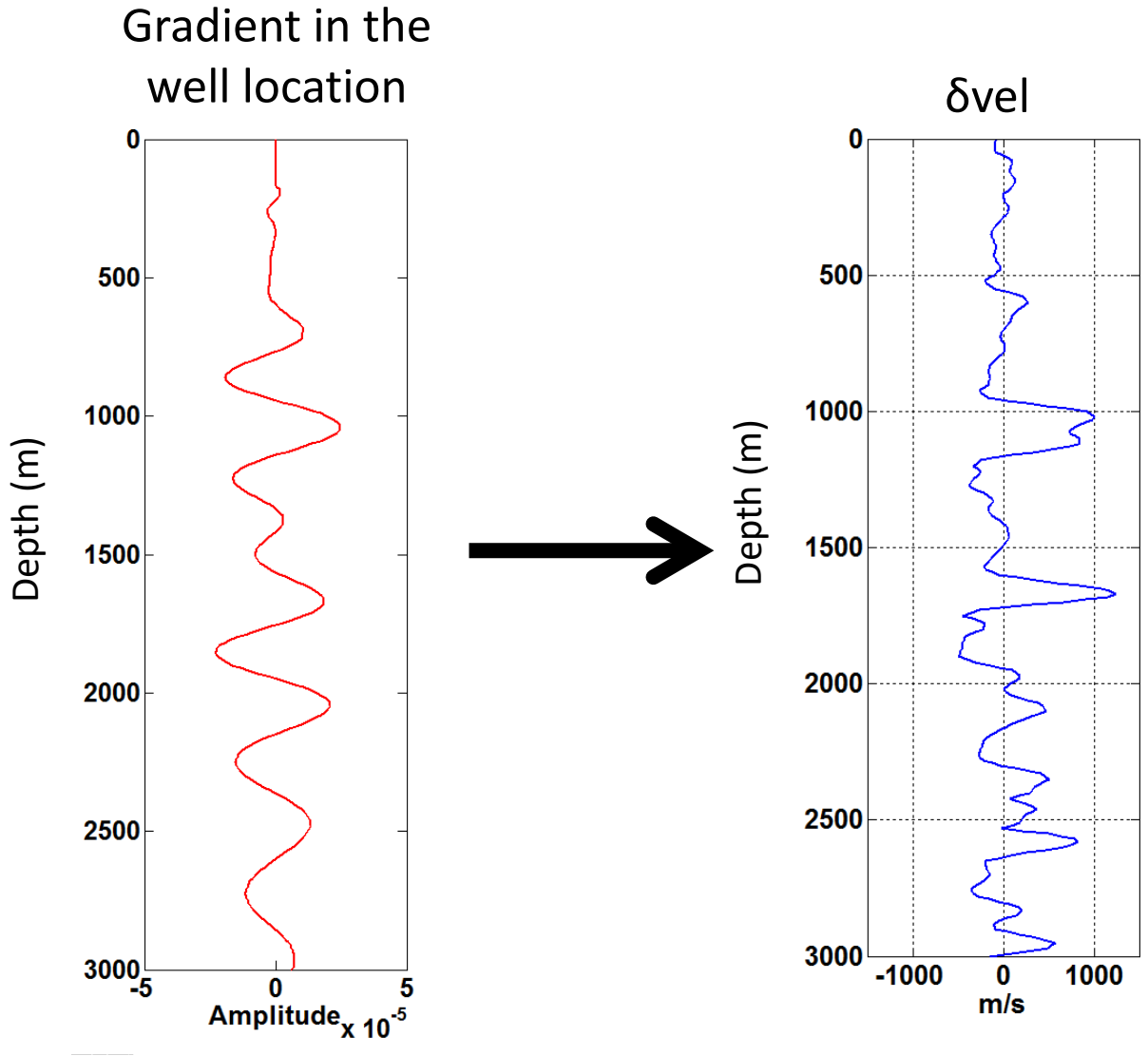
δvel



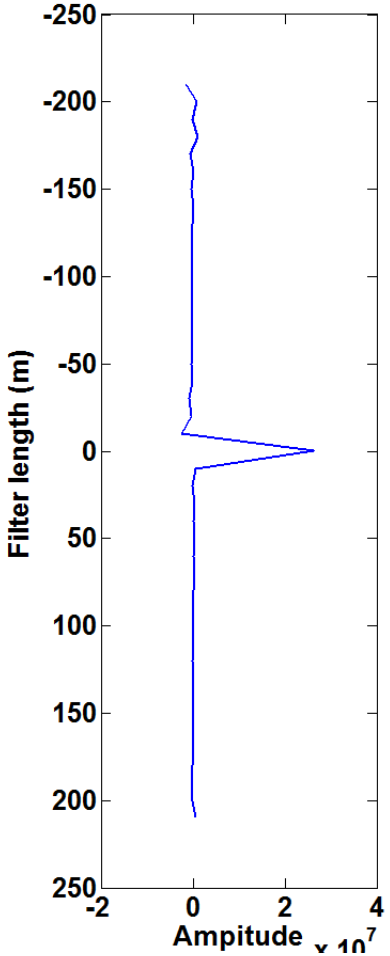

Gradient in the well location
δvel
Depth (m)
0
500
1000
1500
2000
2500
3000
-5
0
5
Amplitude
x 10^-5
Depth (m)
0
500
1000
1500
2000
2500
3000
-1000
0
1000
m/s

An amplitude scalar **a** so that **δvel – ag** is mimimized by least squares

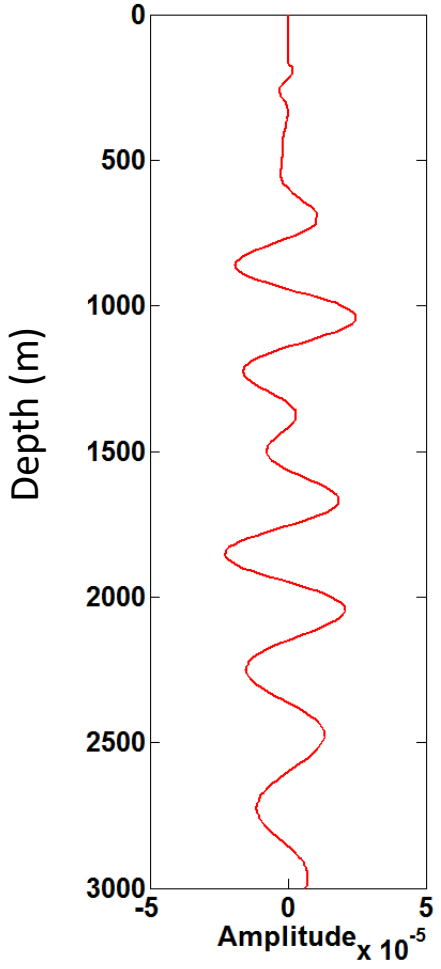
A phase rotation angle **ϒ**, so that, δvel and the calibrated gradient have similar phase



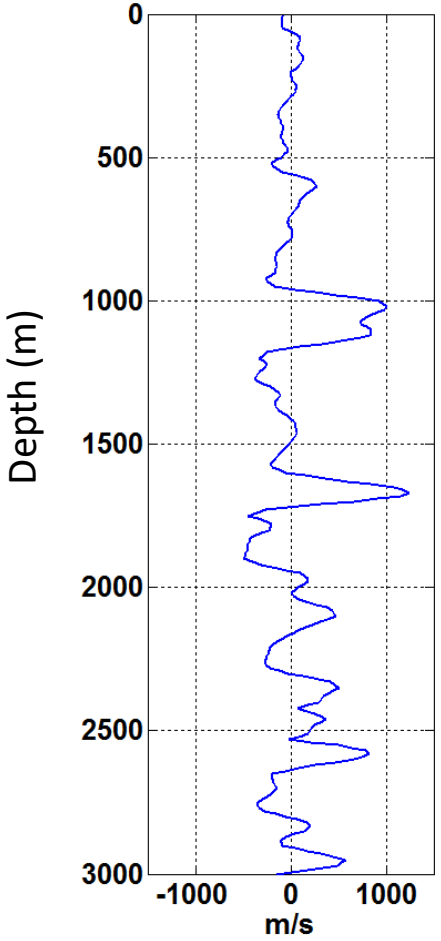
Match filter



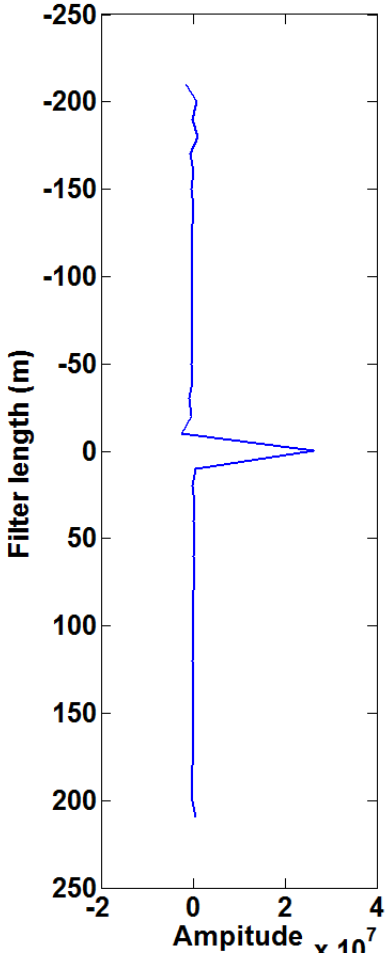
Gradient in the well location



δvel

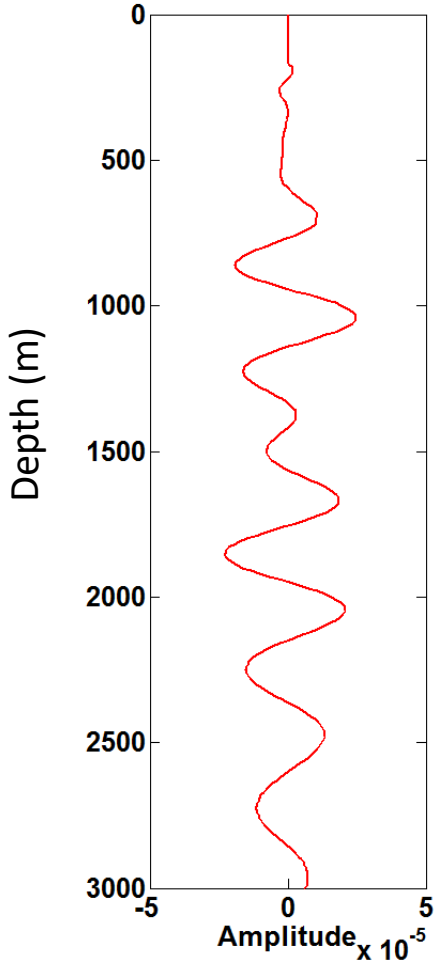


Match filter



*

Gradient in the well location



→

δvel and calibrated gradient