SYNTHETIC APERTURE GEOACOUSTIC INVERSION IN THE PRESENCE OF RADIAL VELOCITY AND ACCELERATION DYNAMICS

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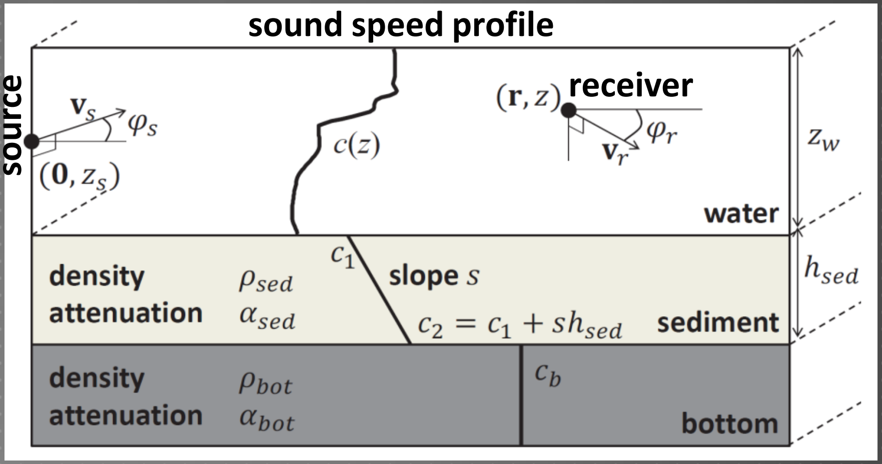
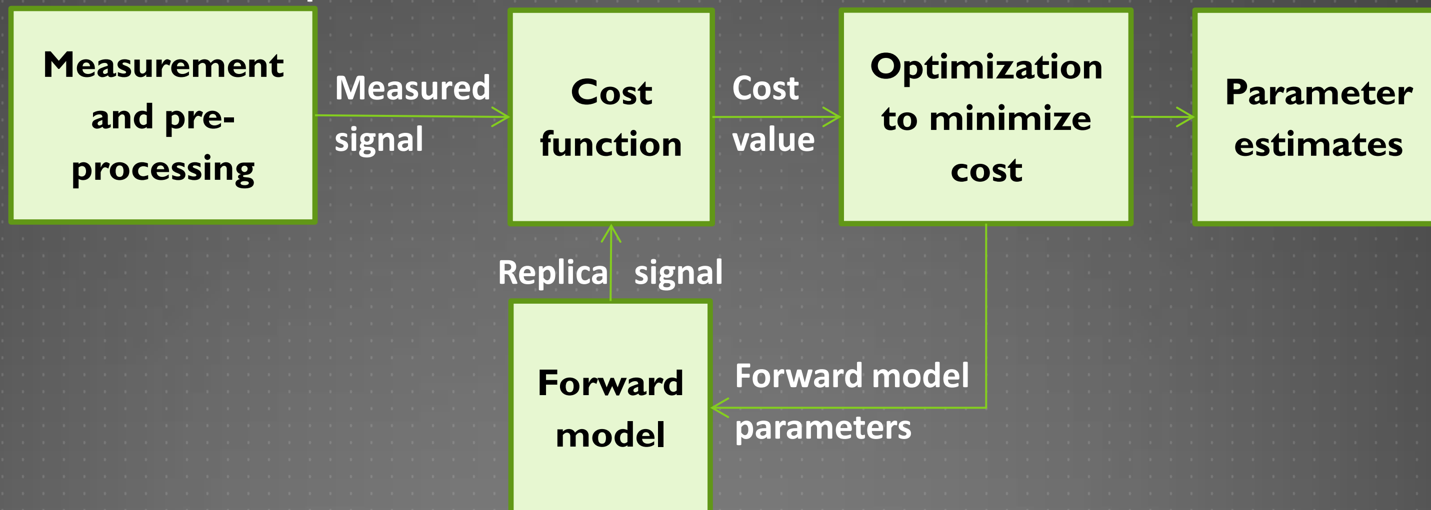
- Mobile single source and receiver matched field inversion method for low SNR
- Long observation time of P LFM chirps
- Requires waveguide Doppler
- Constant radial velocity constraint
- Extension to acceleration

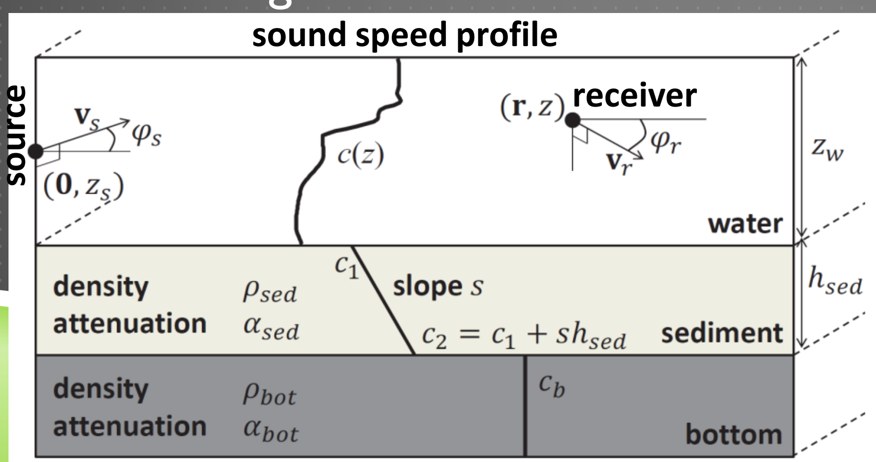


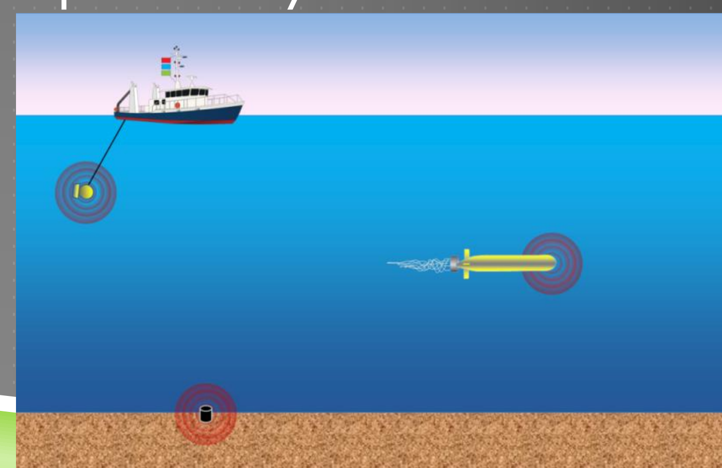
BACKGROUND / MOTIVATION

- Generic inversion process



- Mobile single source/receiver method – operationally attractive





MOTIVATION

- Low SNR / source power
  - Most methods works on the basis of high SNR/source power
  - Concern for disturbance of marine mammals (Gervaise 2012)
  - Development of expendable/low powered acoustic sources for AUV based survey (Massa) (source level restrictions, rapid environment assessment by AUV)
- Existing single source/receiver methods
  - Modal dispersion curve analysis (Bonnel, Gervaise)
  - Matched impulse response method (Josso, Le Gac, Jesus, Hursky, Hermand)
  - Matched field processing method (Siderius, Tan)
  - Synthetic aperture modal inverse method (Frisk, Rajan)

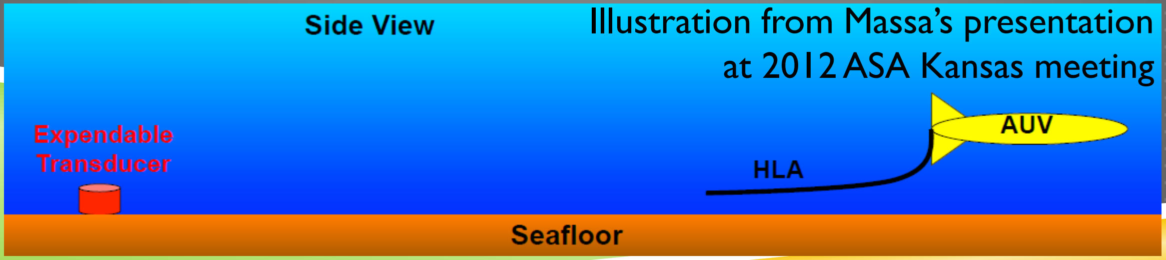
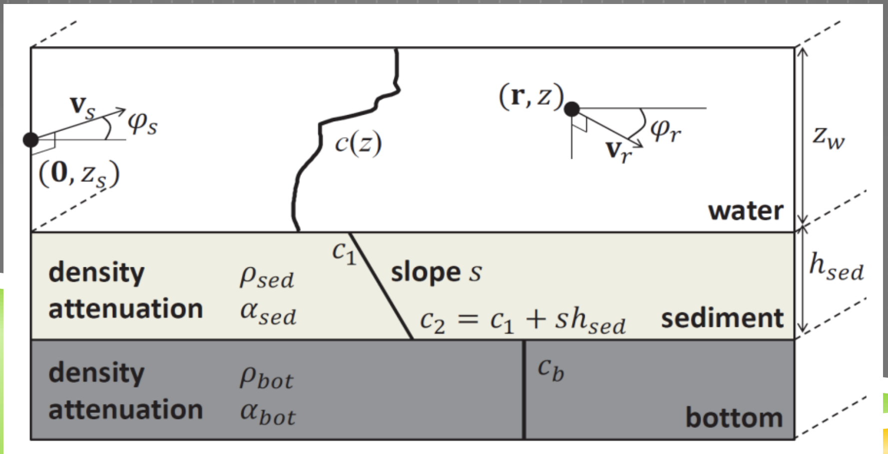


Illustration from Massa's presentation at 2012 ASA Kansas meeting

PREVIOUS WORK

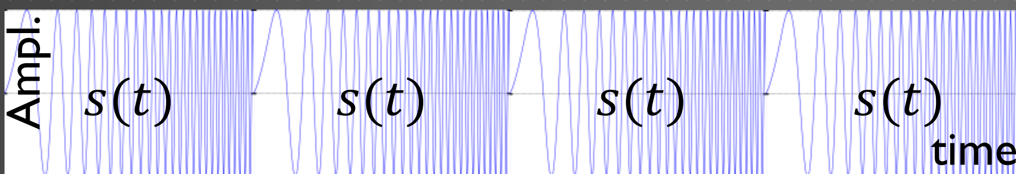
- **Tan et al, "Broadband synthetic aperture geoacoustic inversion", JASA, 2013.**
  - Mobile single source and receiver method for low SNR
  - Lost of spatial diversity and array gain (w.r.t to VLA)
  - Broadband frequency coherent method (100-900 Hz)
  - Long observation time (64 s) of P LFM chirps (1 s)
  - But method becomes Doppler/motion intolerant., requires waveguide Doppler model
  - Assume constant horizontal source/receiver radial velocities



COHERENTLY EXPLOITING MULTIPLE LFMS

- P LFMs
- 100–900 Hz T=1 s T_r =1 s
- Periodic peaks at $1/T_r$ Hz

- Peak samplings and doubling P
  - Signal peak increases 6 dB
  - Noise level increase 3 dB
  - 6 – 3 = 3 dB gain
  - Increasingly Doppler intolerant



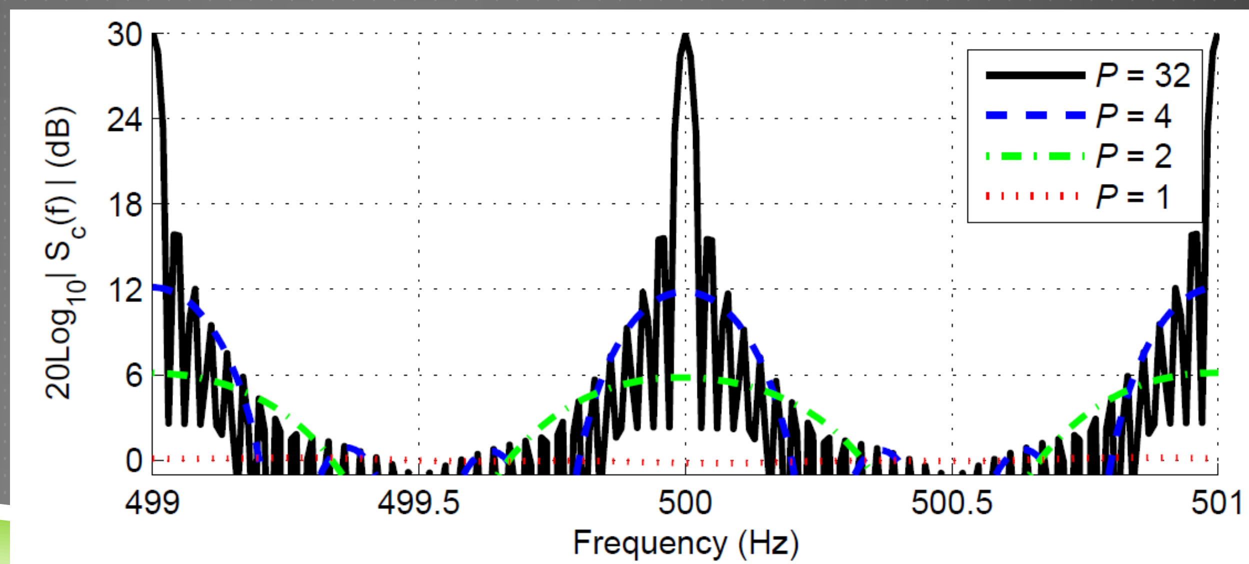
FT ⇔

$$S_c(f) = \sum_{p=0}^{P-1} \exp(i2\pi f p T_r) S(f)$$

$$\{S(t) * \sum \delta(t - nT_r)\} \times \text{rect}\left\{\frac{t - PT_r/2}{PT_r}\right\}$$

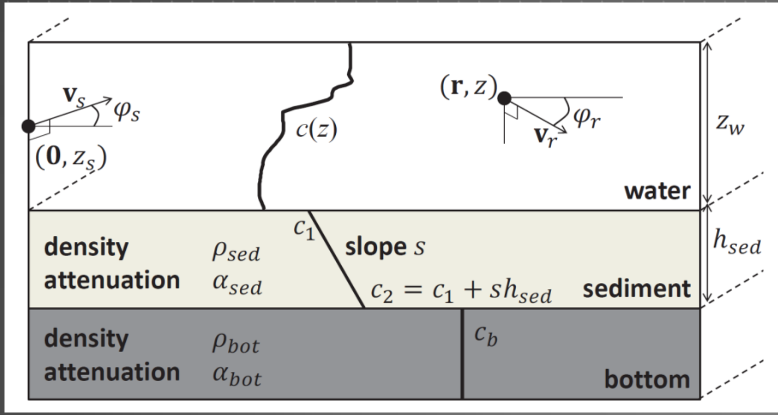
⇕ FT

$$\{S(f) \times \sum \delta(f - j/T_r)\} * PT_r \text{sinc}\{fPT_r\}$$



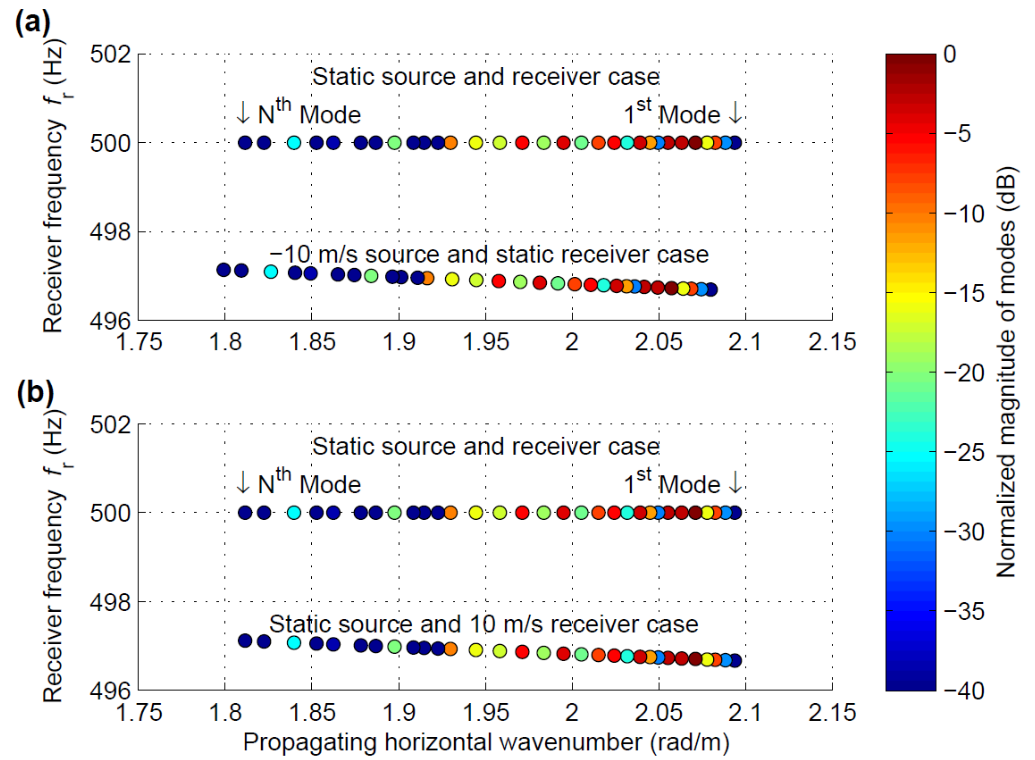
WAVEGUIDE DOPPLER

- 1994 Schmidt and Kuperman
  - Spectral/**Modal** Solution
  - Non-reciprocity
  - Frequency domain



- Each mode has a different Doppler

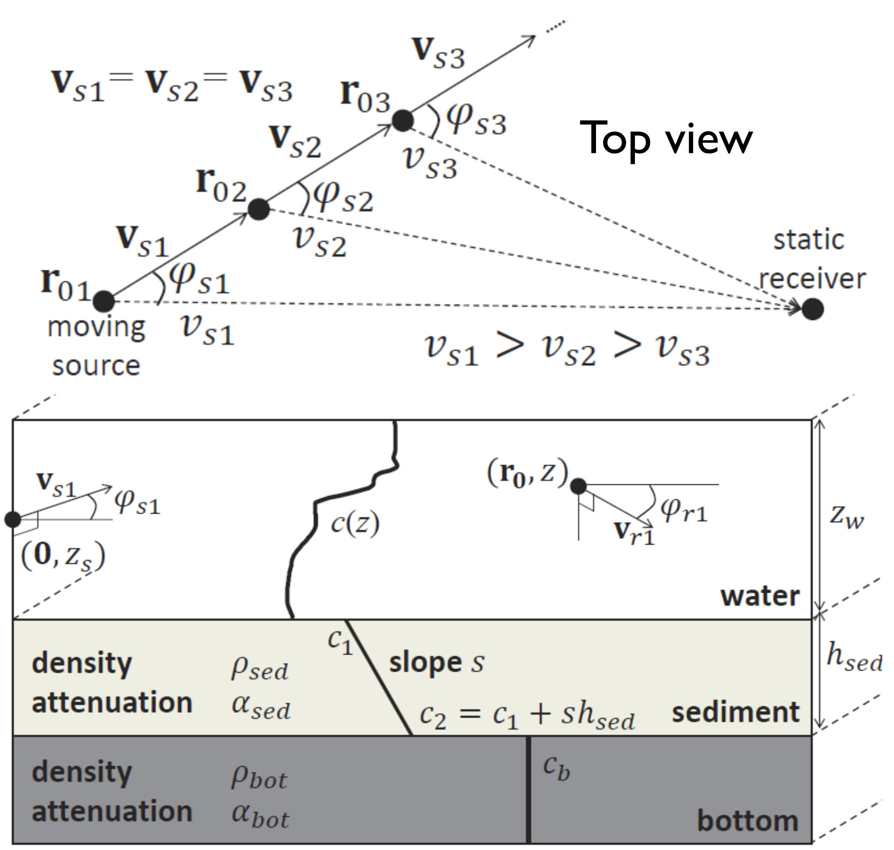
Example: 500 Hz harmonic source (KRAKEN)

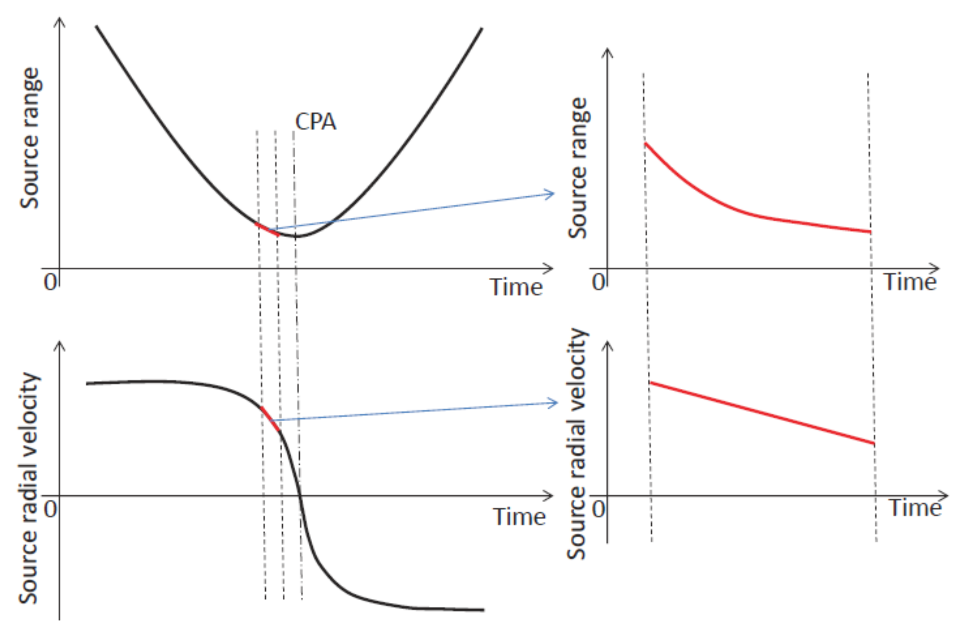


Source	Propagation	Receiver
$\omega_s^{(k_n)} = \omega_r - k_n(v_s - v_r)$	$\omega = \omega_r + k_n v_r$	ω_r
ω_s	$\omega = \omega_s + k_n v_s$	$\omega_r^{(k_n)} = \omega_s + k_n(v_s - v_r)$

FOR THIS OCEANS PAPER…

- Extend previous method to more practical scenarios such as near CPA or when radial velocity changes.
- Allow pulse dependent changes in source/receiver radial velocities





COMPUTE $\psi(\mathbf{r}, z, \omega_r)$

Source	Propagation	Receiver
$\omega_s^{(k_{np})} = \omega_r - k_{np}(v_{sp} - v_{rp})$	$\omega = \omega_r + k_{np}v_{rp}$	ω_r
ω_s	$\omega = \omega_s + k_{np}v_{sp}$	$\omega_r{}^{(k_{np})} = \omega_s + k_{np}(v_{sp} - v_{rp})$

- However, modeling acceleration is non-trivial
- Time varying modal wavenumbers and functions (Walker 2007)
- Circumvent by approximating acceleration
- Assume radial velocities are piece-wise constant for each pulse
- But radial velocities are linearly changing pulse to pulse

Compute normal modes (normalized) as per static case $\{\Psi_n(z_s), \Psi_n(z), k_{rn}, u_{rn}\}$ @ ω_r

↓

For each pulse, assume $\{v_{s1}, v_{r1}, p, a_s, a_r\}$ known. Compute the propagation horizontal wave number k_{np}

↓

Extract the source spectrum $S(\omega_r - k_{np}(v_{sp} - v_{rp}))$ and coherently combine all pulses to give $\psi(\mathbf{r}, z, \omega_r)$

COMPUTE $\psi(\mathbf{r_0}, z, \omega_r)$

Source	Propagation	Receiver
$\omega_s^{(k_{np})} = \omega_r - k_{np}(v_{sp} - v_{rp})$	$\omega = \omega_r + k_{np} v_{rp}$	ω_r
ω_s	$\omega = \omega_s + k_{np} v_{sp}$	$\omega_r^{(k_{np})} = \omega_s + k_{np}(v_{sp} - v_{rp})$

- $\psi(\mathbf{r}, z, \omega_r) \approx \frac{i e^{-i\frac{\pi}{4}}}{\sqrt{8\pi}\rho(z_s)} \sum_p \exp(i\omega_r (p-1) T_r) \sum_n S\big(\omega_r - k_{np}(v_{sp} - v_{rp})\big) \Psi_n(z_s; \omega_r) \Psi_n(z; \omega_r) \frac{e^{i k_{np} r_{0p}}}{\sqrt{k_{np} r_{0p}}}$
- *where* $k_{np} \approx \frac{k_{rn}}{\left(1 - \frac{v_{rp}}{u_{rn}}\right)} \approx \frac{k_{sn}}{\left(1 - \frac{v_{sp}}{u_{sn}}\right)}$ is the mode and pulse dependent propagating wavenumber and for any arbitrary ω_r or ω_s
- $v_{sp} = v_{s1} + (p-1) T_r a_s$ and $v_{rp} = v_{r1} + (p-1) T_r a_r$

Compute normal modes (normalized) as per static case $\{\Psi_n(z_s), \Psi_n(z), k_{rn}, u_{rn}\}$ @ ω_r

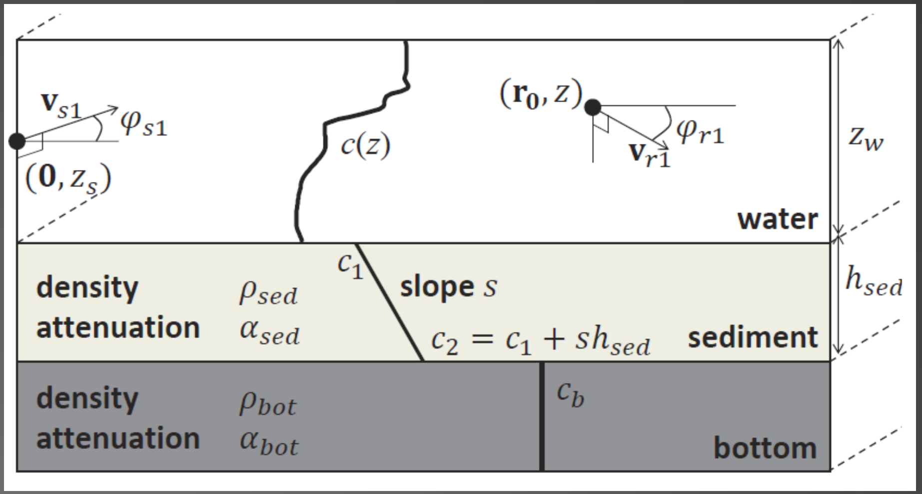
For each pulse, assume $\{v_{s1}, v_{r1}, p, a_s, a_r\}$ known. Compute the propagation horizontal wave number k_{np}

Extract the source spectrum $S\big(\omega_r - k_{np}(v_{sp} - v_{rp})\big)$ and coherently combine all pulses to give $\psi(\mathbf{r}, z, \omega_r)$

SW06 SIMULATION

LFM 100–900 Hz T=1 s T_r =1 s

- Moving source & static receiver
  - Coherently exploit P=64 LFMs
- Source initial radial vel. 1.9 m/s
- Source acceleration -0.006 m/s^2
- Source depth 30 m
- Receiver depth 45 m
- Source range at t = 0, r_0=600 m
- SNR = 0 dB
- Sampling interval Δf=5 Hz



GA

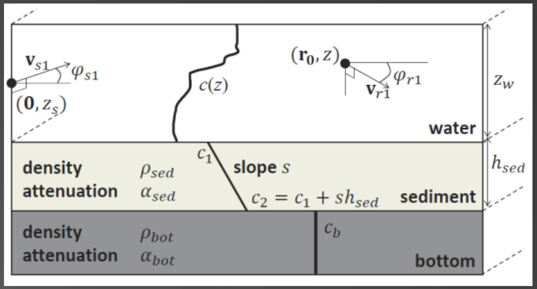
$$\{\xi, \mathbf{x}\}_{ML} = \arg\max_{\xi,\mathbf{x}} \left[\ln L(\xi, \mathbf{x}) \right]$$

$$= \arg\min_{\xi,\mathbf{x}} \left[10 \ \log_{10} \Phi(\xi, \mathbf{x}) \right]$$

where the cost function

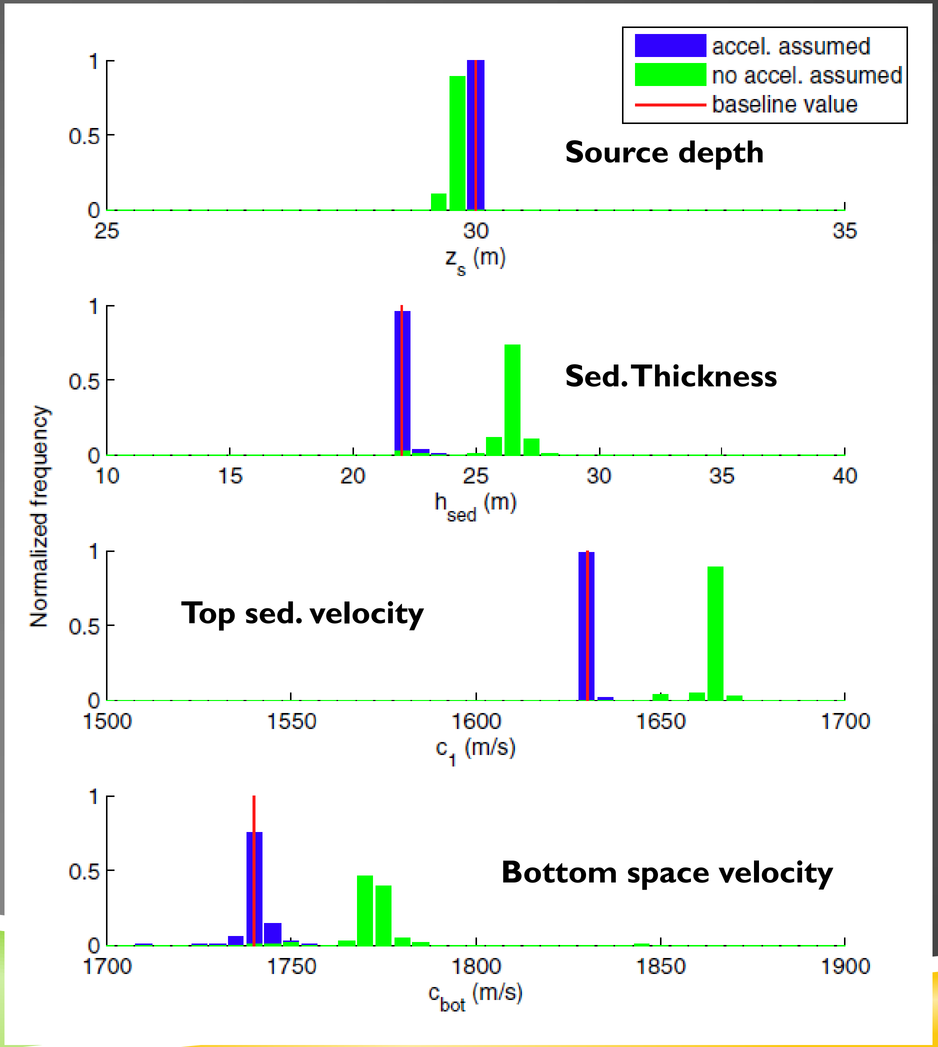
$$\Phi(\xi, \mathbf{x}) = 1 - \frac{|\mathbf{y}^{\mathrm{H}} \tilde{\mathbf{C}}_{\mathrm{w}}^{-1} \mathbf{b}|^2}{\mathbf{y}^{\mathrm{H}} \tilde{\mathbf{C}}_{\mathrm{w}}^{-1} \mathbf{y} \mathbf{b}^{\mathrm{H}} \tilde{\mathbf{C}}_{\mathrm{w}}^{-1} \mathbf{b}}$$

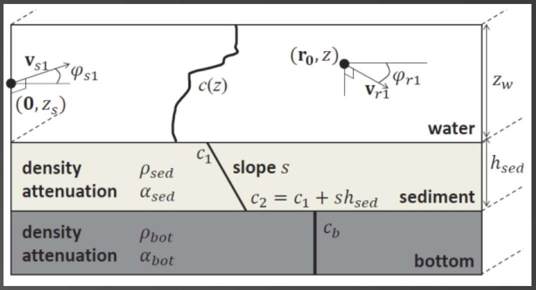
MOVING SOURCE & STATIC RECEIVER



Monte Carlo inversion *P* = 64

- 200 noise realizations
- SNR = 0 dB
- Executed twice
  - Forward model include acceleration (Blue)
  - Forward model assumes no acceleration (Green)





SW06 EXPERIMENT

- JD238 2040 UTC
- Source: J-15, 30 m, LFM 100–900 Hz T=1 s T_r =1 s,
- Receiver: Hydrophone 8 of VLA, 44.6 m
- Source – receiver range ~600m
- Initial radial velocity ~1.6 m/s with acceleration ~ -0.006 m/s^2 SNR ~ 0 dB

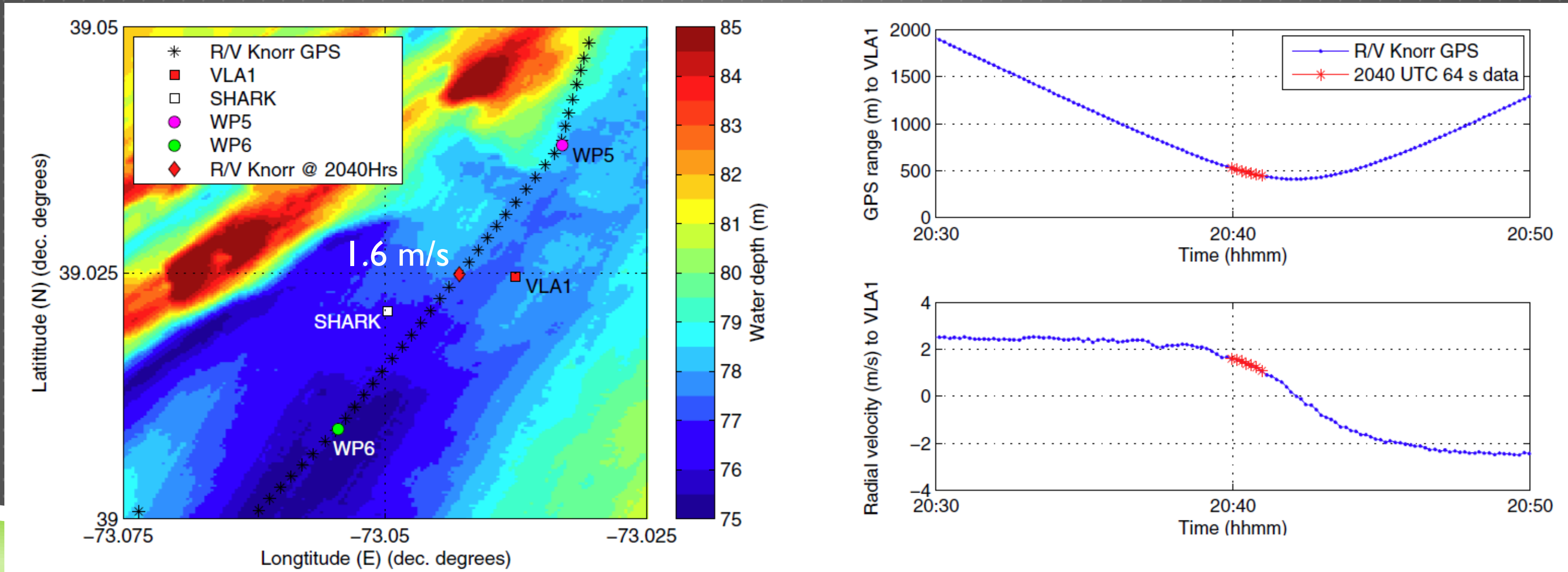
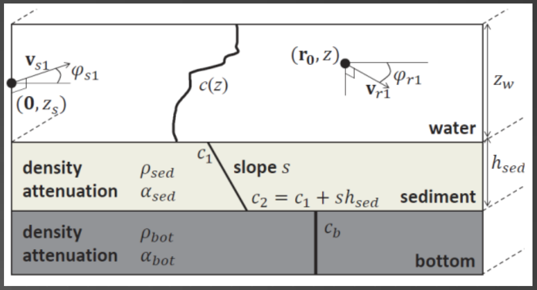
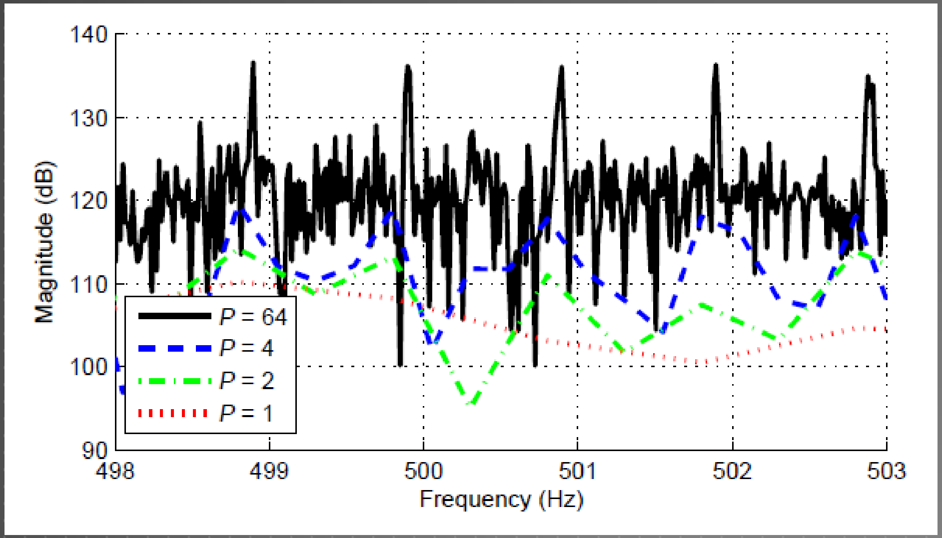


Fig. 7. R/V Knorr Telemetry

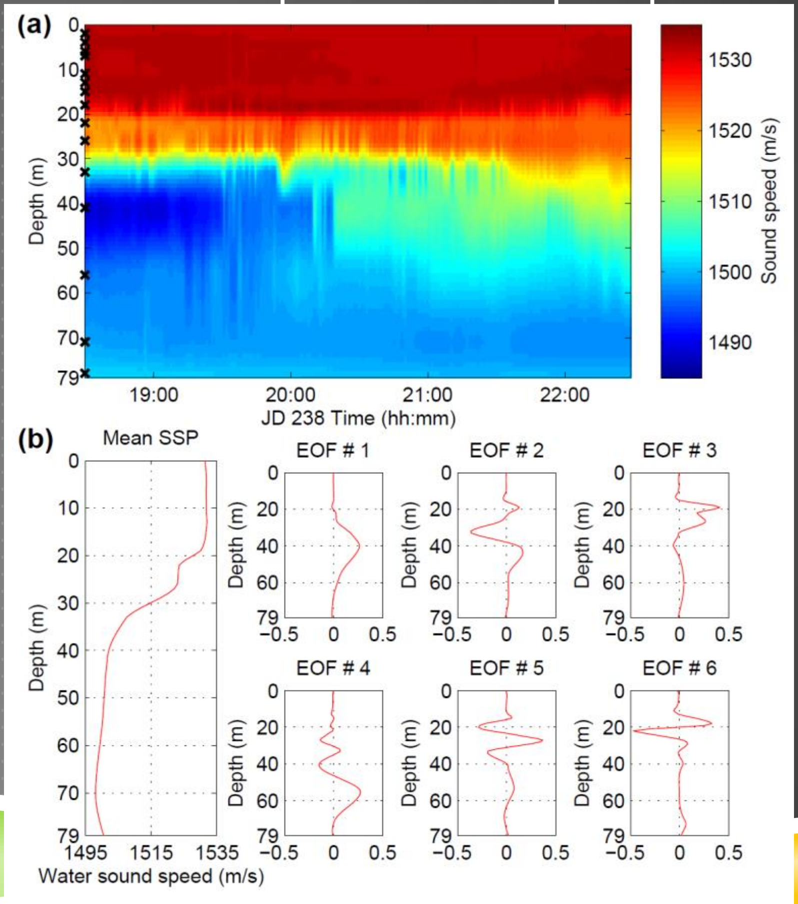
SW06 RECEIVED SPECTRUM AND EOFS



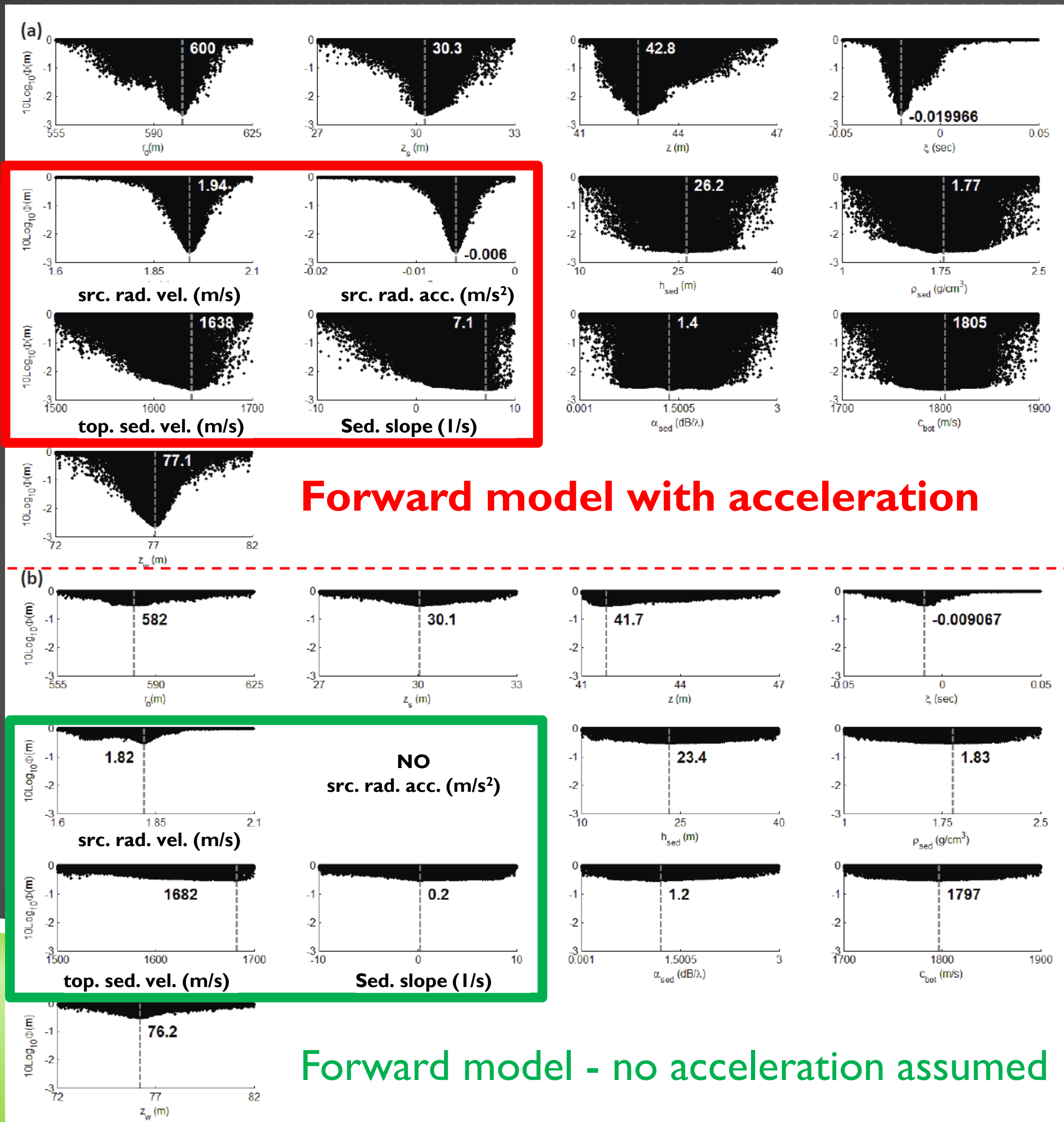
- Section of SW06 received signal spectrum with LFM pulses P = [1, 2, 4, 64]

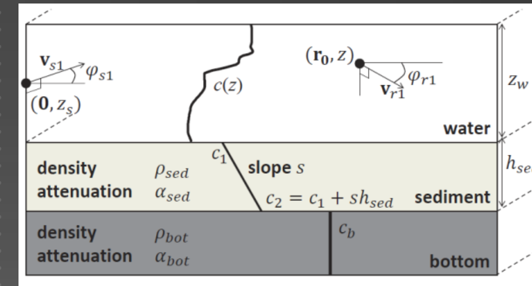


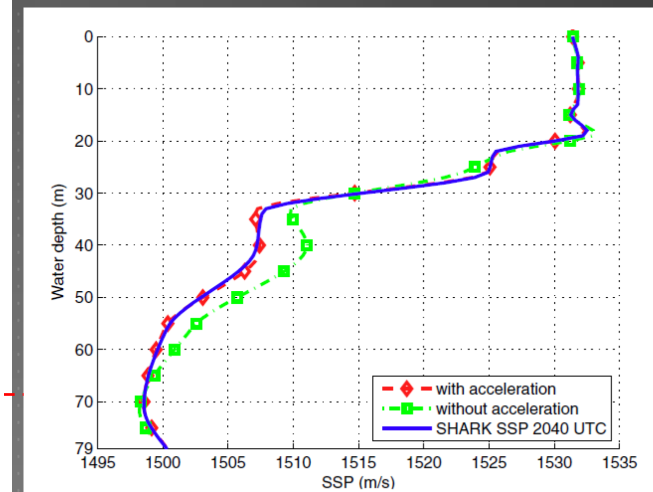
SHARK interpolated sound speed profile



INVERSION RESULTS P=64







- Sediment velocity profile estimate adversely affected
- Relatively lower sensitivities = higher estimation uncertainties

CONCLUSIONS

Discussions…

Questions and answers…

- Extends broadband synthetic aperture geoacoustic inversion to cases where radial velocities change.
- Well-suited for horizontally accelerated source/receiver.
- Demonstrated in simulation/real data that modeling **radial** acceleration is critical for correct inversion

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