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Sparsity-driven Passive Tracking-
of Underwater Accoustic Sources

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Sparsity-Driven Passive Tracking of Underwater Acoustic Sources

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IEEE/MTS OCEANS '15
Genova, Italy
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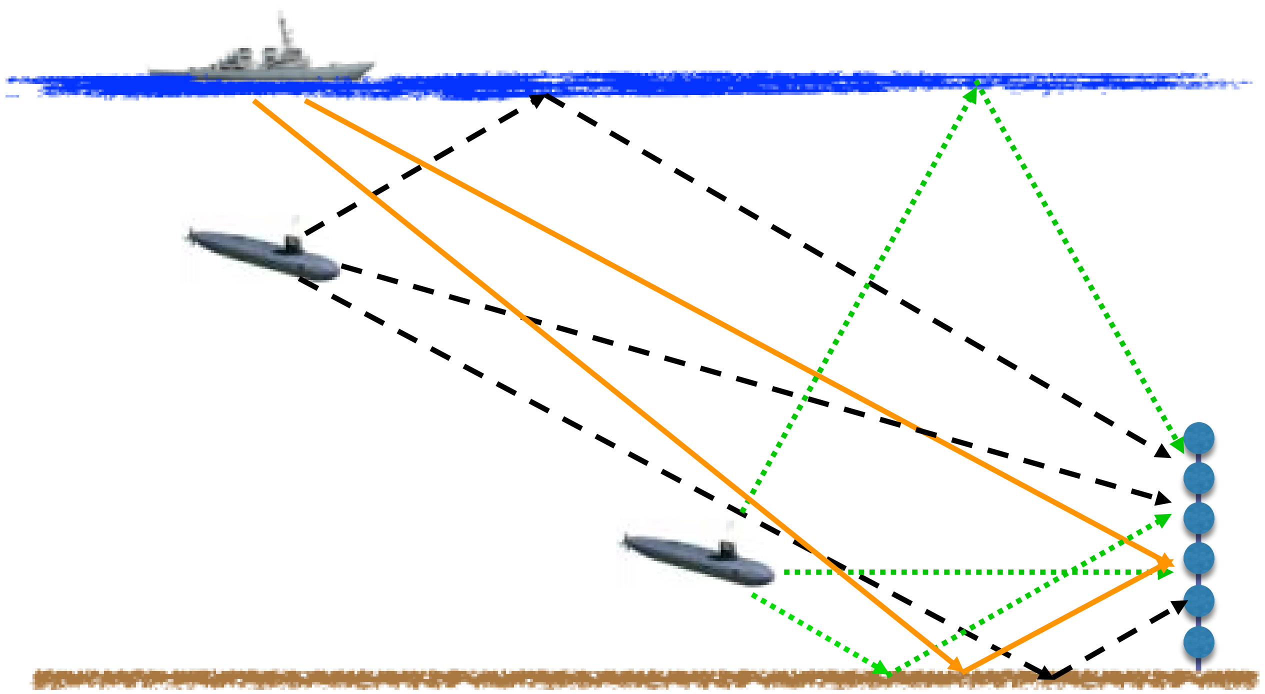
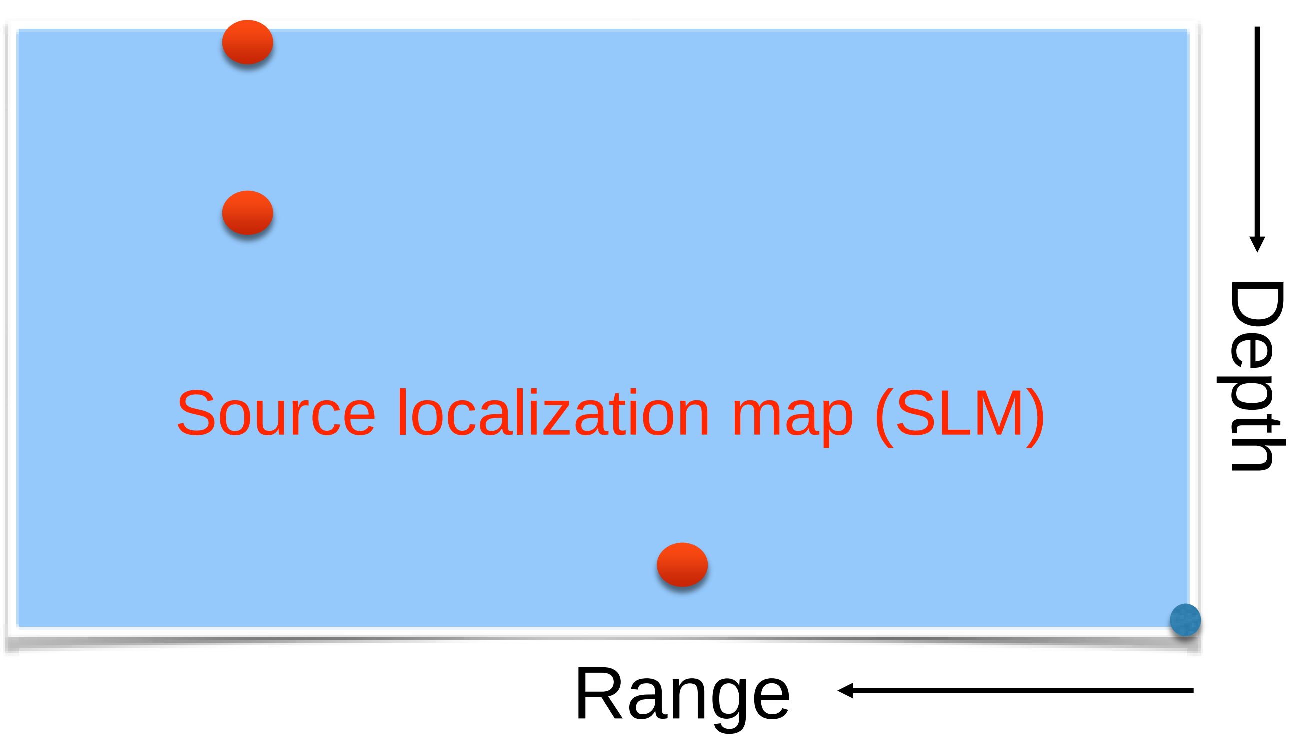
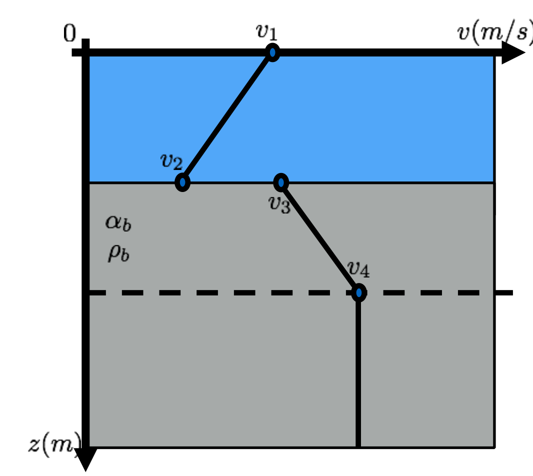
Motivation





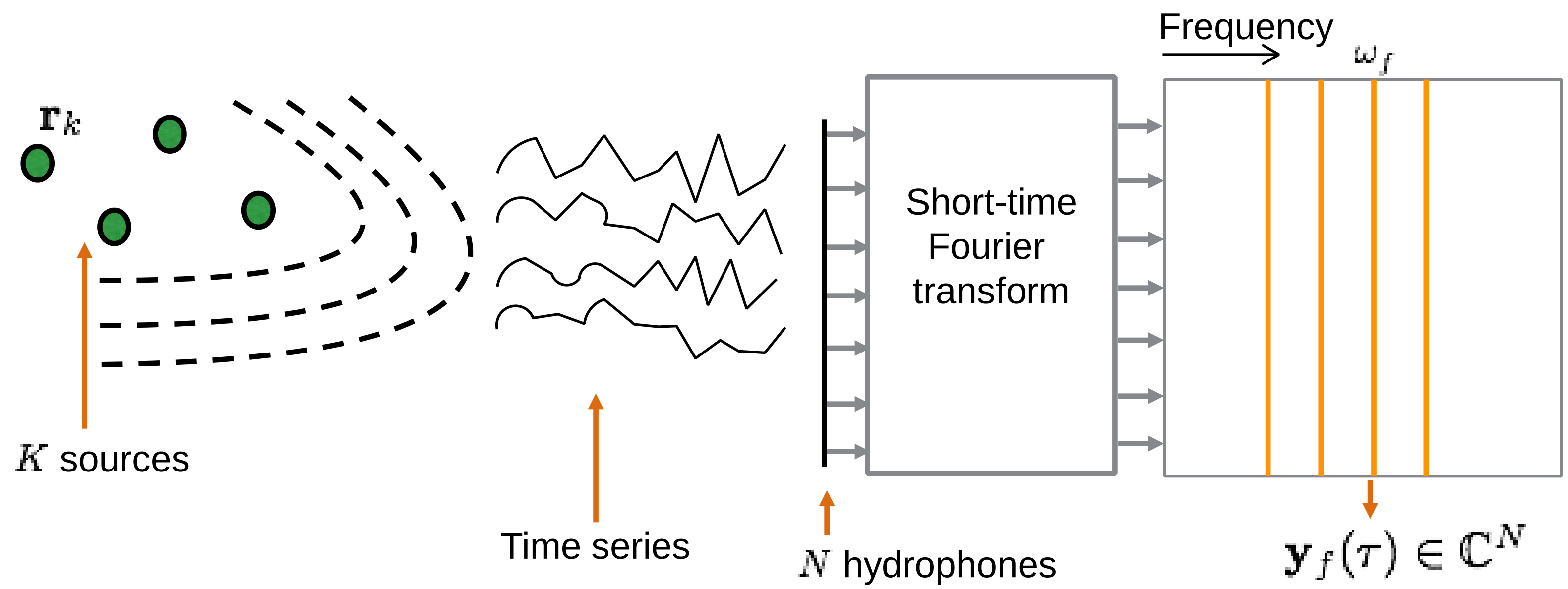
- Localization of acoustic sources using passive sonar
- Fundamental task for monitoring and surveillance systems
- Difficult due to complexities of the propagation environment
  - Ocean behaves as an acoustic waveguide
  - Varying sound-speed causes acoustic signals to bend
    - Temperature, pressure and salinity

Shallow water sound-speed profile



Modeling Preliminaries

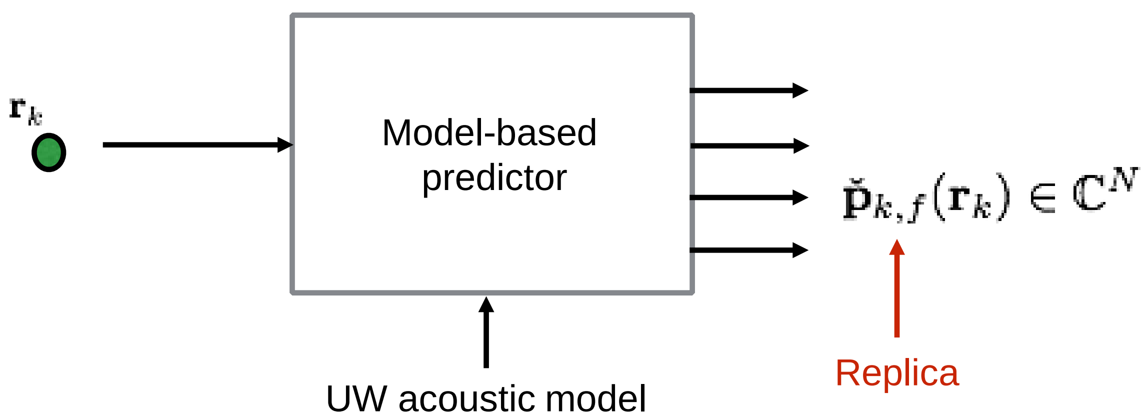
Measurements



Our data:

$$\{\mathbf{y}_f(\tau) \in \mathbb{C}^N, \forall f\}_{\tau=1}^{t}$$

Acoustic model



Problem statement

Given $\{\mathbf{y}_f(\tau) \in \mathbb{C}^N, \forall f\}_{\tau=1}^{t}$ an UW acoustic model and K, estimate the source locations $\{\mathbf{r}_k(t)\}_{k=1}^{K}$ while being robust to model uncertainty.

Related Works

Matched-field processing (MFP) [Baggeroer '88], [Csenzak '97], [Debever' 07], [Mantzel '12], [Forero '13]

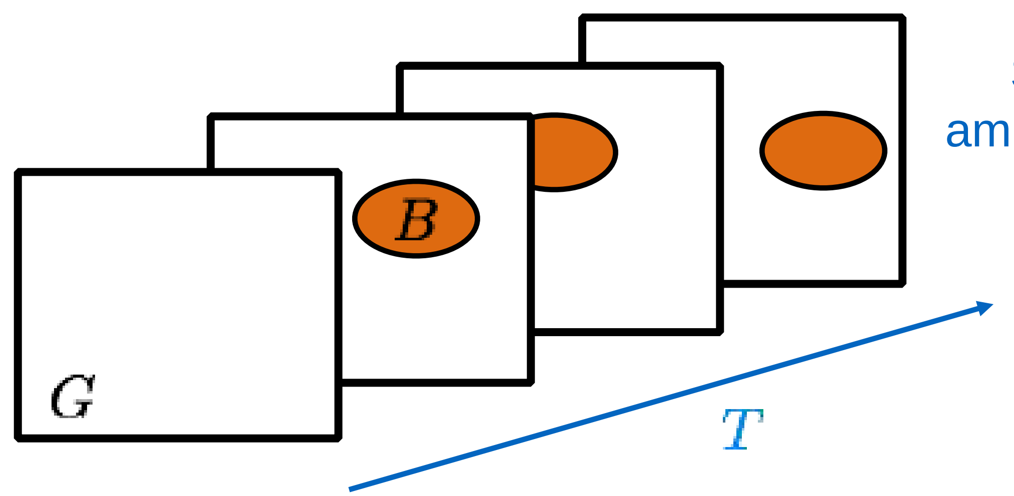
- Measurements $\mathbf{y}_f(t)$ and UW acoustic model
- Grid of tentative locations $\mathcal{G} := \{\mathbf{r}_g\}_{g=1}^{G}$
- Use UW acoustic model to generate replicas $\mathbf{P}_f := [\mathbf{p}_{1,f}(\mathbf{r}_1), \ldots, \mathbf{p}_{G,f}(\mathbf{r}_G)]$
- "Match" measurements and replicas to construct ambiguity surface $\longrightarrow$ Acoustic power estimates

Matched-field tracking (MFT) [Bucker '94], [Wilmut '98], [Fialkowsky '01]

Score all possible tracks across ambiguity surfaces

Unconstrained: G^T

Constrained: $G \cdot B^{T-1}$



Sequence of ambiguity surfaces

Caveats:
- Computationally taxing due to batch processing
- Temporal information is not used when constructing ambiguity surfaces
- Multiple sources

A Nonlinear Model for the Measurements

Data model:

$$\mathbf{y}_f(t) = \sum_{k=1}^{K} s_{k,f}(t)\left[\check{\mathbf{p}}_{k,f}(\mathbf{r}_k) + \check{\mathbf{v}}_{k,f}(t,\mathbf{r}_k)\right] + \boldsymbol{\epsilon}_f(t),\ \forall f$$

Acoustic gain
Fourier coefficient
for k-th source at ω_f

Perturbation

Goal: find estimates for $\{\mathbf{r}_k(t)\}_{k=1}^{K}$ sequentially

Caveats:
- Mapping $h : \mathbf{r}_k \to \check{\mathbf{p}}_{k,f}(\mathbf{r}_k)$ is not available in closed form
- Perturbations $\{\mathbf{v}_{k,f}(t,\mathbf{r}_k)\}$ and acoustic gains $\{s_{k,f}(t)\}$ are unknown
- How to summarize the history $\{\mathbf{y}_f(\tau) \in \mathbb{C}^N, \forall f\}_{\tau=1}^{t-1}$?

Challenges Faced by Kalman-Based Trackers

Assumption: $\check{\mathbf{v}}_{k,f}(t,\mathbf{r}_k) = \mathbf{0},\ \forall t, \mathbf{r}_k$

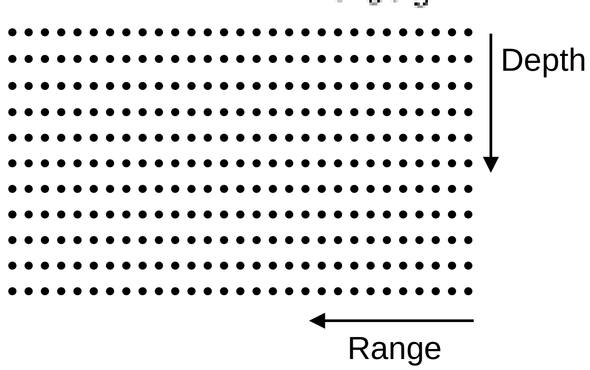
Problematic!

Measurement equation: $$\mathbf{y}_f(t) = \sum_{k=1}^{K} s_{k,f}(t)\check{\mathbf{p}}_{k,f}(\mathbf{r}_k) + \boldsymbol{\epsilon}_f(t),\ \forall f$$

State equation: $\mathbf{x}(t) = \mathbf{A}\mathbf{x}(t-1) + \boldsymbol{\zeta}(t)$ → Acoustic gains, source location, kinematics

Sparsity-based methods: [Maliutov '05], [Edelman '11], [Fannjiang '10], [Mantzel '12], [Liu '12], [Forero '13,'15]

Grid: $\mathcal{G} := \{\mathbf{r}_g\}_{g=1}^{G}$



New model: $$\mathbf{y}_f(t) = \sum_{g=1}^{G} s_{g,f}(t)\mathbf{p}_{g,f} + \boldsymbol{\epsilon}_f(t),\ \forall f$$

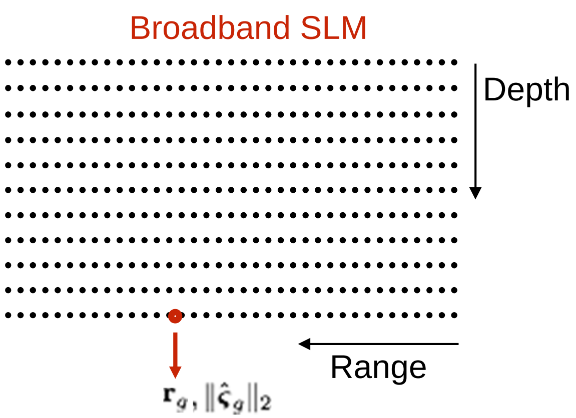
Large dimensionality can be problematic → $\mathbf{s}_f(t) = \mathbf{A}\mathbf{s}_f(t-1) + \boldsymbol{\zeta}(t),\ \forall f$

↓

Sparse

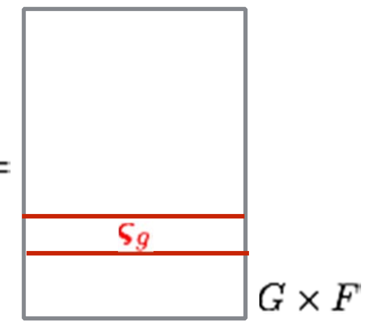
Sparse Kalman trackers [Filos '13], [Farahmand '14] → Performs covariance matrix updates

Coherent Broadband Source Localization



New model: $$\mathbf{y}_f(t) = \sum_{g=1}^{G} s_{g,f}(t)\mathbf{p}_{g,f} + \boldsymbol{\epsilon}_f(t), \ \forall f$$

$\mathbf{S} :=$



Coherence: Common support across $\boldsymbol{\varsigma}_g$ ‘s

$$\hat{\mathbf{S}}(t) = \arg\min_{\mathbf{S} \in \mathbb{C}^{G \times F}} \frac{1}{2} \sum_{f=1}^{F} \|\mathbf{y}_f(t) - \mathbf{P}_f \mathbf{s}_f\|_2^2 + \frac{\lambda}{2} \sum_{f=1}^{F} \|\mathbf{s}_f - \hat{\mathbf{s}}_f(t-1)\|_2^2 + \mu \sum_{g=1}^{G} \|\boldsymbol{\varsigma}_g\|_2$$

Summary term for $\{\mathbf{y}_f(\tau) \in \mathbb{C}^N, \forall f\}_{\tau=1}^{t-1}$

Remark: Perturbations can be captured in this estimator as in [Forero ‘15]

Equivalent Problem and Proximal Gradient

Real-valued problem:

$$\check{\mathbf{S}}(t) = \arg\min_{\check{\mathbf{S}} \in \mathbb{R}^{2G\times F}} \frac{1}{2}\sum_{f=1}^{F} \|\check{\mathbf{y}}_f(t) - \check{\mathbf{P}}_f \check{\mathbf{s}}_f\|_2^2 + \frac{\lambda}{2}\sum_{g=1}^{G} \|\check{\mathbf{v}}_g - \check{\mathbf{v}}_g(t-1)\|_2^2 + \mu \sum_{g=1}^{G} \|\check{\mathbf{v}}_g\|_2$$

$$\check{\mathbf{v}}_g := [\check{\boldsymbol{\varsigma}}'_g, \check{\boldsymbol{\varsigma}}'_{g+G}]' \in \mathbb{R}^{2F}$$

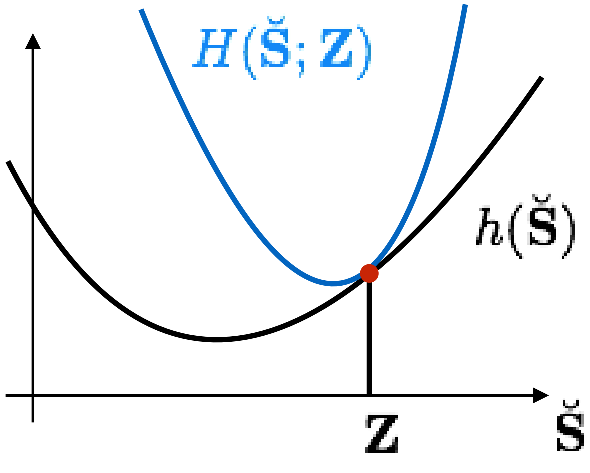
Proximal Gradient (PG) method: A form of majorization-minimization

Differentiable part of the cost

$$\min_{\check{\mathbf{S}}} \; h(\check{\mathbf{S}}) + \mu \sum_{g=1}^{G} \|\check{\mathbf{v}}_g\|_2$$

Majorizer: function H is a majorizer for h iff

$$H(\check{\mathbf{S}};\mathbf{Z}) \geq h(\check{\mathbf{S}})$$
$$H(\mathbf{Z};\mathbf{Z}) = h(\mathbf{Z})$$



Lipschitz constant for $\nabla h(\check{\mathbf{S}})$

PG uses: $H(\check{\mathbf{S}};\mathbf{Z}) := h(\mathbf{Z}) + \sum_{f=1}^{F} \nabla h_f(\mathbf{z}_f)'(\check{\mathbf{s}}_f - \mathbf{z}_f) + \frac{L_h}{2}\|\check{\mathbf{S}} - \mathbf{Z}\|_F^2$

PG Solvers

For each t, iteratively solve

$$\check{\mathbf{S}}^{[i]}(t) = \arg\min_{\check{\mathbf{S}}} \left[H(\check{\mathbf{S}}; \check{\mathbf{S}}^{[i-1]}(t)) + \mu \sum_{g=1}^{G} \|\check{\mathbf{v}}_g\|_2 \right]$$

Equivalent to

$$\check{\mathbf{S}}^{[i]}(t) = \arg\min_{\check{\mathbf{S}}} \sum_{g=1}^{G} \left(\frac{L_h}{2} \left\| \check{\mathbf{v}}_g - \mathbf{w}_g^{[i-1]}(t) \right\|_2^2 + \mu \|\check{\mathbf{v}}_g\|_2 \right) \longrightarrow$$

Decomposable across g

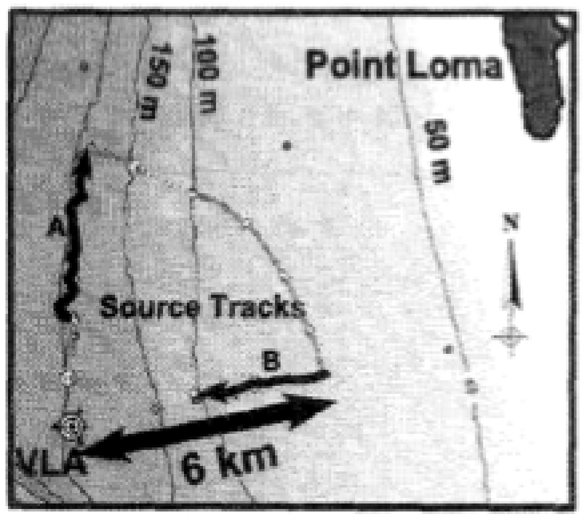
Closed for solutions per $\check{\mathbf{v}}_g^{[i]}(t)$

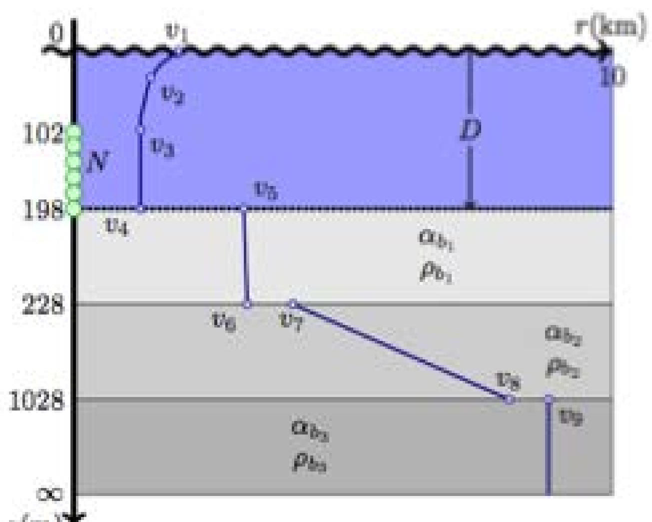
$$\check{\mathbf{v}}_g^{[i]}(t) = \mathbf{w}_g^{[i-1]}(t) \left(1 - \frac{\mu}{L_h \|\mathbf{w}_g^{[i-1]}(t)\|_2} \right)_+$$

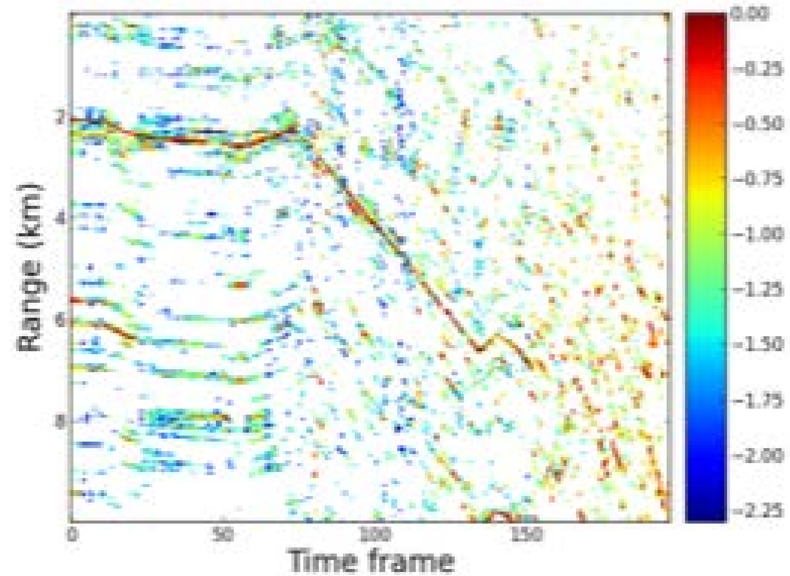
Convergence: For any $\mu > 0$, the sequence $\{\check{\mathbf{S}}^{[i]}(t)\}_{i \geq 0}$ converges to $\check{\mathbf{S}}(t)$ as $i \to \infty$, featuring worst-case convergence rate $O(1/i)$.

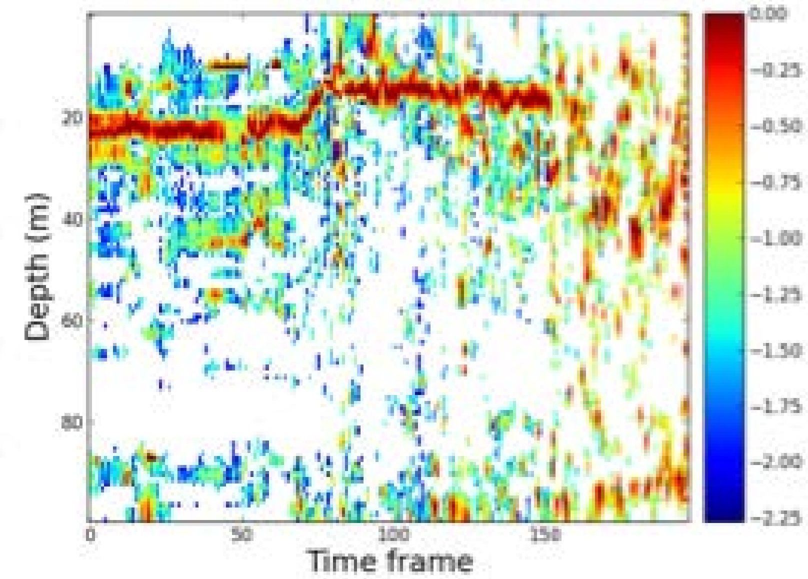
Proof: Follows from [Beck '09]

SWellEX-3 Dataset: MFP



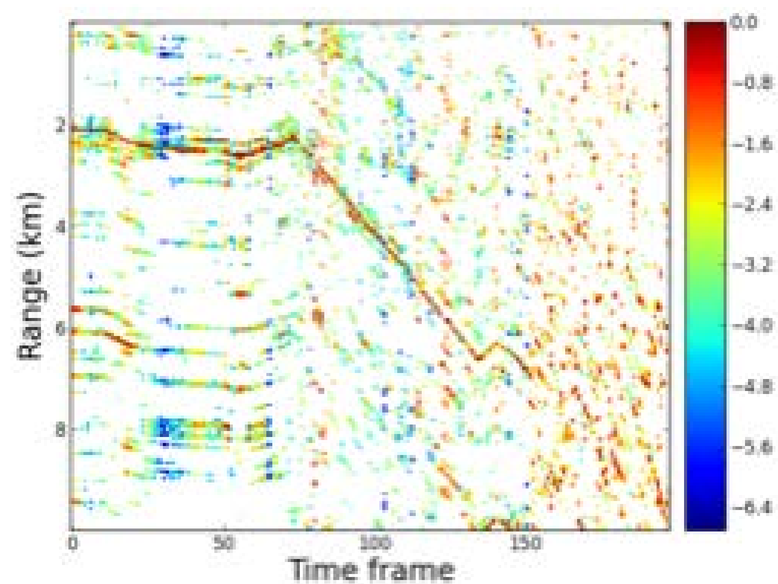


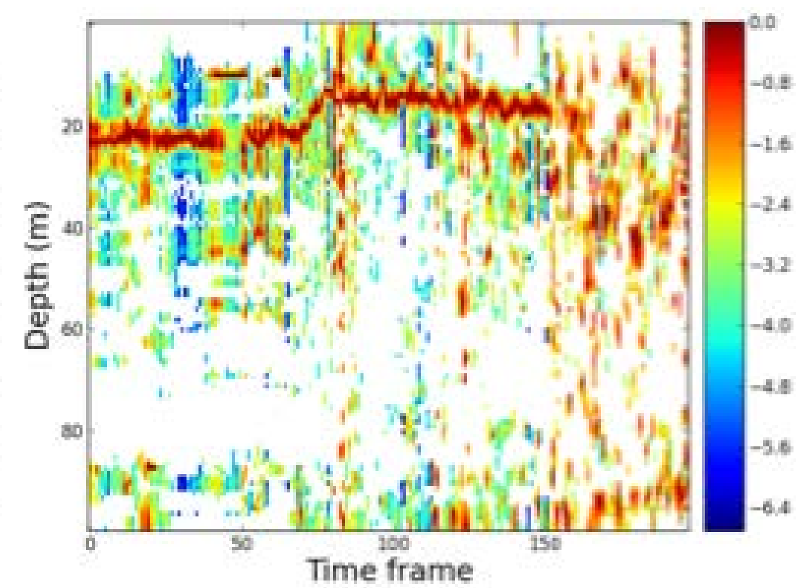




Barlett

Many ambiguities



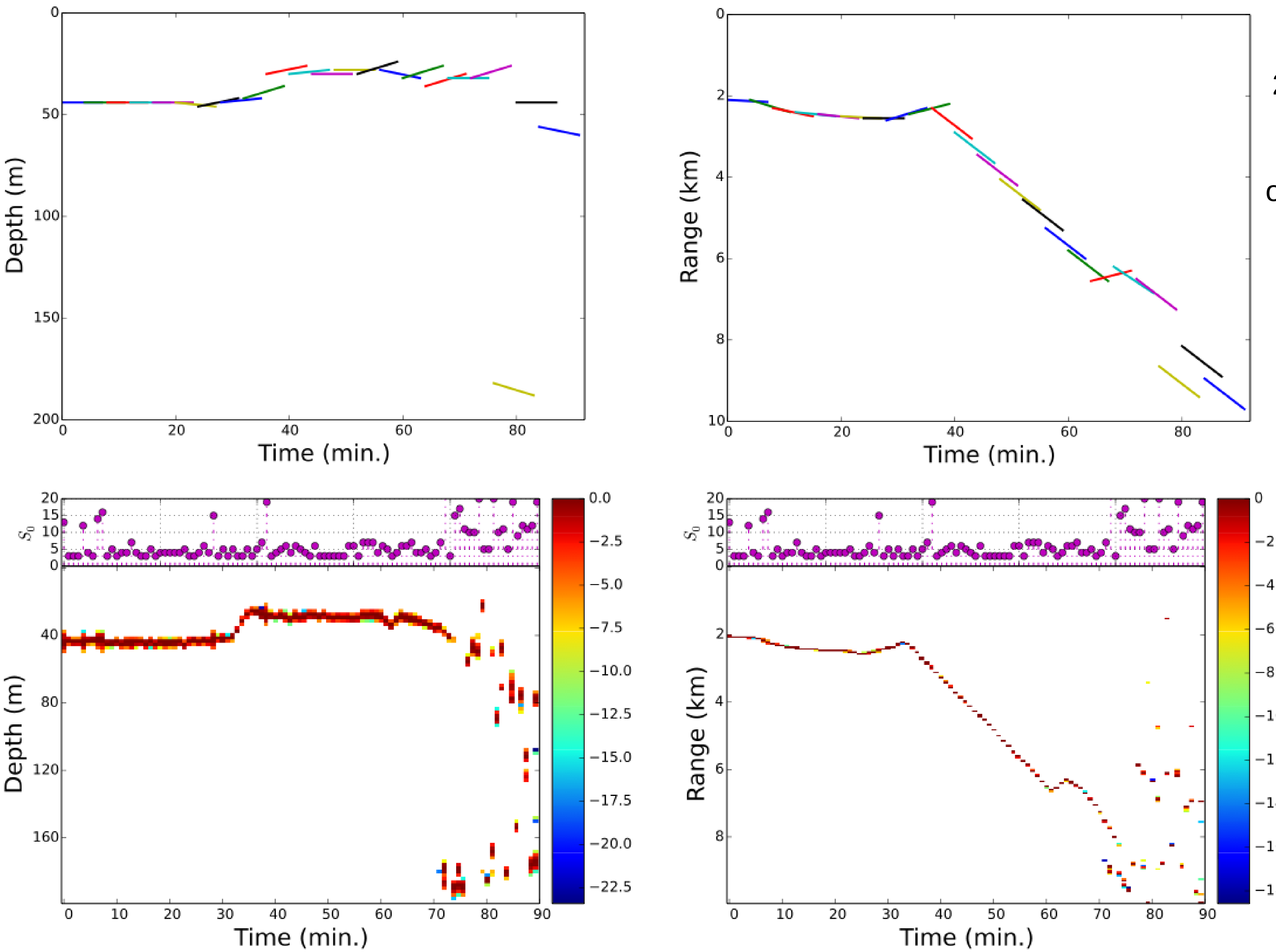


Capon

- 10 frequencies between 53 Hz and 197 Hz
- $N = 9$ and $G = 20,000$ (100 depths and 200 ranges)
- $M = 1$ for SLM and $M = 10$ for all others
- Per time frame, plot 100 largest peaks

Single frequency 149 Hz

SWellEX-3 Dataset: Broadband SLM Tracks



Constraint region:
22 depths by 5 ranges

Scores averaged
over all 10 frequencies

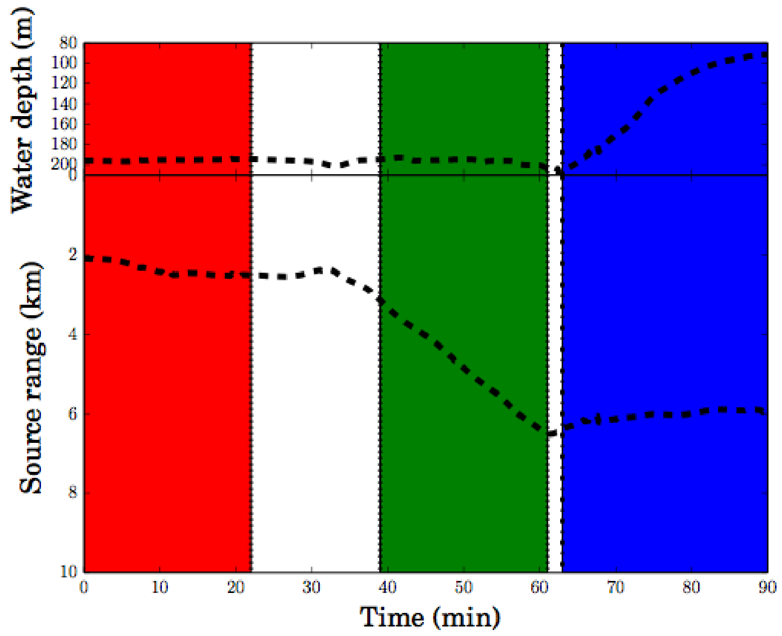
High computational
Complexity

Roughly 77 min
per tracklet (8 min)

Few nonzero
entries per SLM

Few seconds
to obtain each SLM

SWellEX-3 Dataset: Multiple Sources

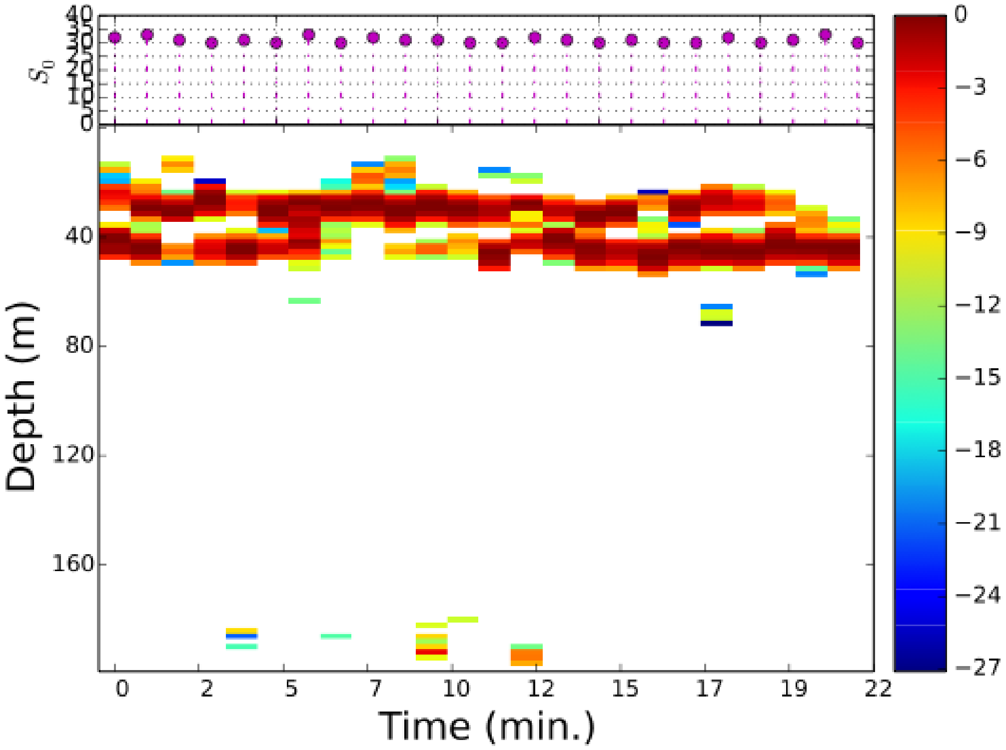


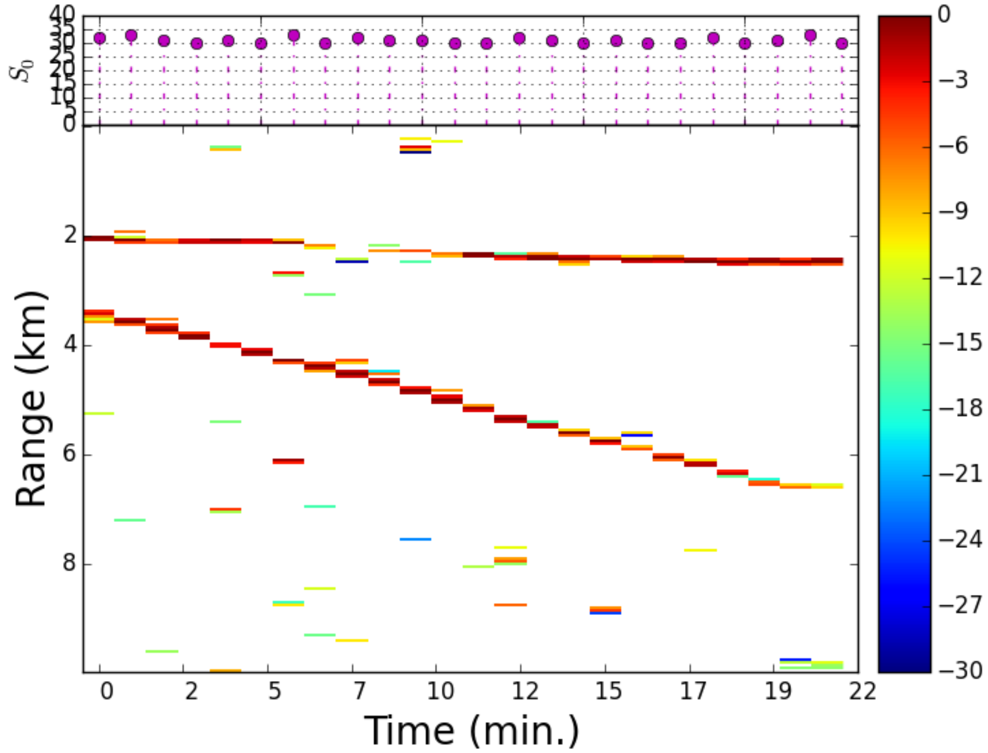
Data set was artificially modified to emulate two sources

MFT: Challenging to identify two different tracks due to width of the beams in the ambiguity surfaces

Tuning parameters: grid search over μ

$$\mu_{\max} = \max_{g} \| [|\mathbf{p}_{g,1}^{\dagger} \mathbf{y}_1(t) + \mu \hat{s}_{g,1}(t-1)|, \ldots, |\mathbf{p}_{g,F}^{\dagger} \mathbf{y}_F(t) + \mu \hat{s}_{g,F}(t-1)|] \|_2$$



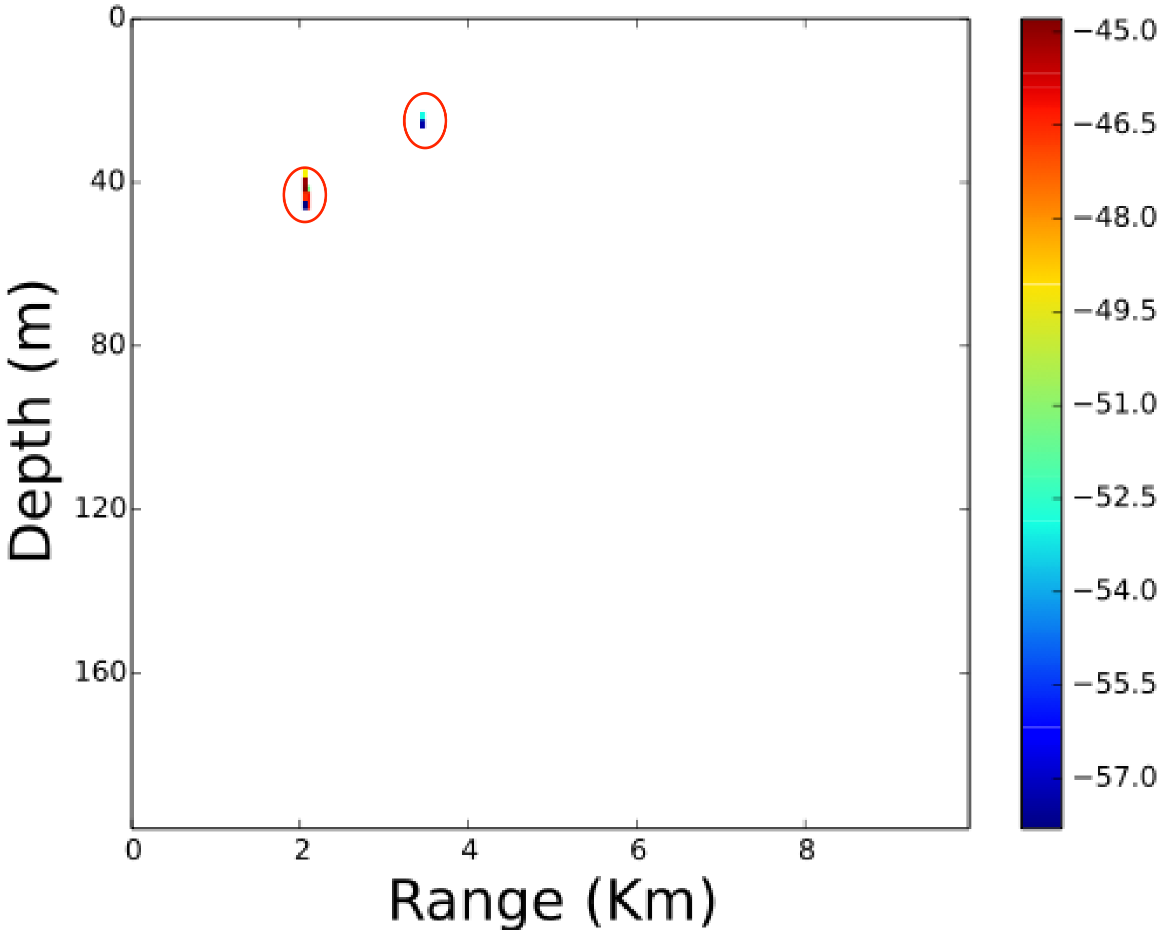


Can identify the two sources

Selection of tuning parameter λ

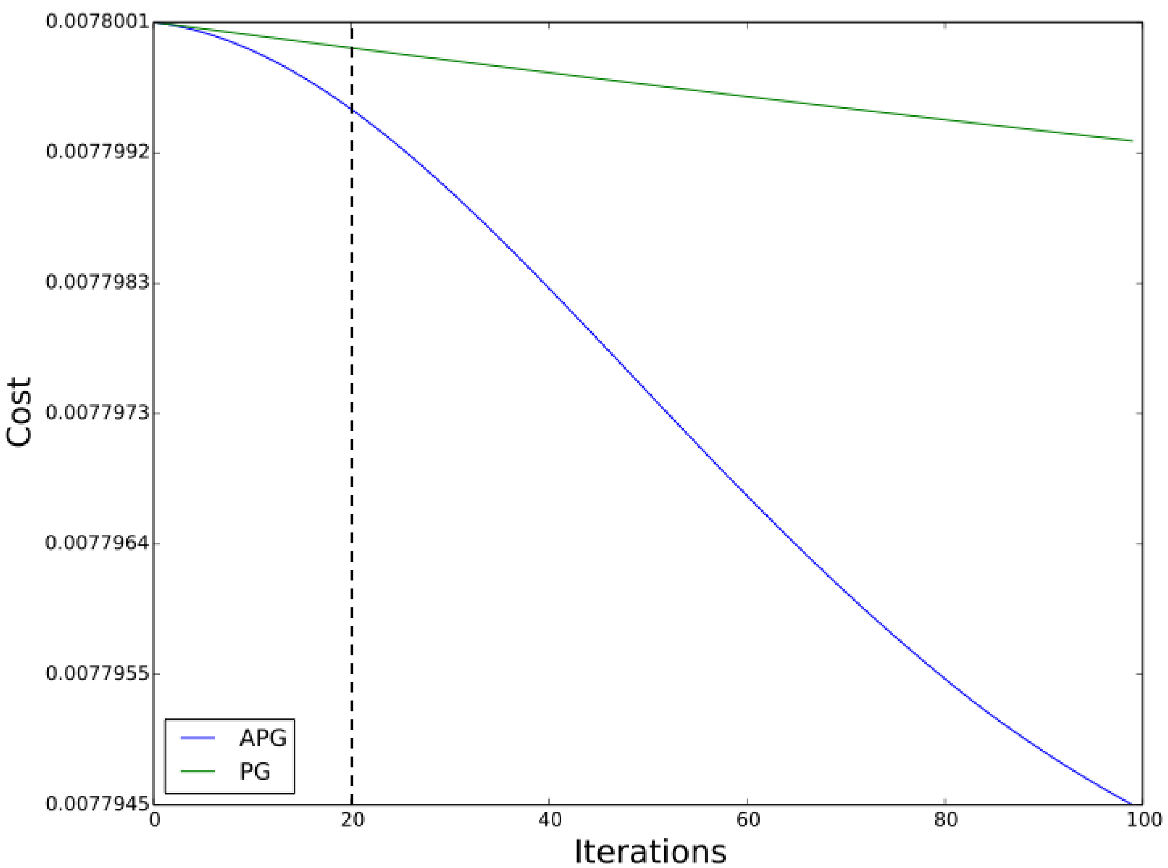
SWellEX-3 Dataset: SLMs and Algorithm

Two-source case at
initial position (time = 0)



SLM obtained after 20
APG iterations

APG solver converges much
faster than PG solver



In practice, few iterations are
needed to identify the support of
the SLM

Summary

- Sparsity enables underwater source tracking of multiple sources
- Possible to coherently process broadband data for improved tracking
- Fast PG and accelerated proximal gradient (APG) algorithms for constructing SLMs and source tracks
- Reduced computational complexity via screening of predictors
- Tuning parameter selection is challenging

Current work:

- Validation of results with other datasets
- Rules for selection of tuning parameters

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