Multi-static Active Target Tracking using an Invariance Constraint

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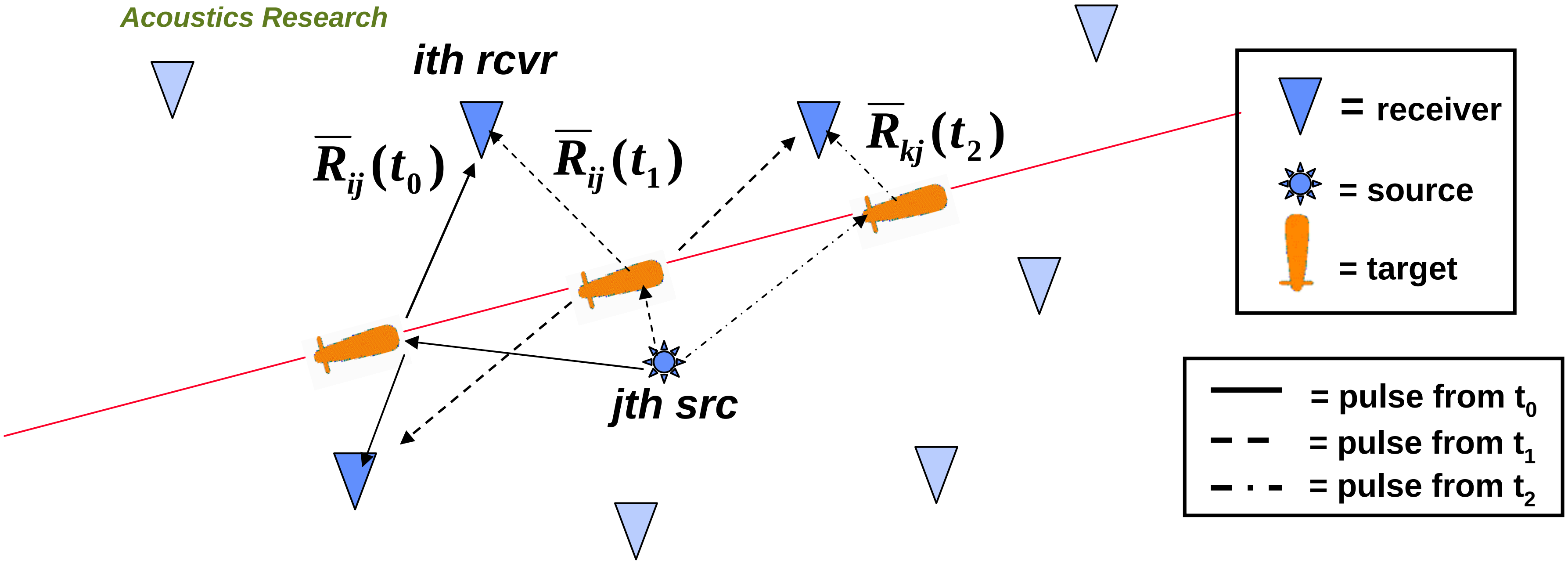
A significant challenge in tracking targets in multi-static active geometries is the large dimensionality and inherent uncertainty of the track hypothesis space. Traditional tracking approaches (such as Bayesian state estimators) rely on prescribed target kinematics to describe track evolution, but cannot easily incorporate the effects of shallow water multipath. The objective of the proposed research is to improve the capability and robustness of tracking algorithms for Navy multi-static active sonar systems with a physics-based processing technique that relies on the invariance principle and is incorporated into the tracker framework.

Although the invariance principle is approximately invariant to details of the ocean environment, it still provides a useful relationship between source frequency, frequency offset, target range, and target range rate. For a broadband waveform, the invariance principle suggests a method to constrain the track-hypothesis space by relating the frequency dependent signal characteristics to physically realizable target range rates. This effort is a three year effort (2005-2008).

Multi-static Sonar Systems



- **Sensor network of underwater acoustic sources and receivers**
  - **Acoustic pulses illuminate and scatter from underwater targets**
  - **Received pulses provide information on time dependent range and Doppler**
- **Objective: Determine target track (location vs. time) from observations**
- **Challenges**
  - **Underwater propagation physics and bottom reverberation**
  - **Multi-dimensional solution space**

Active Sonar Signal Contributions

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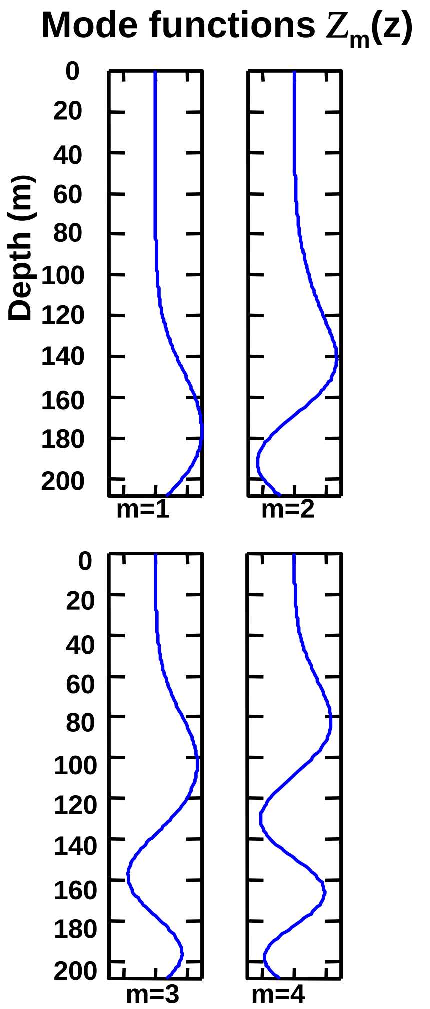

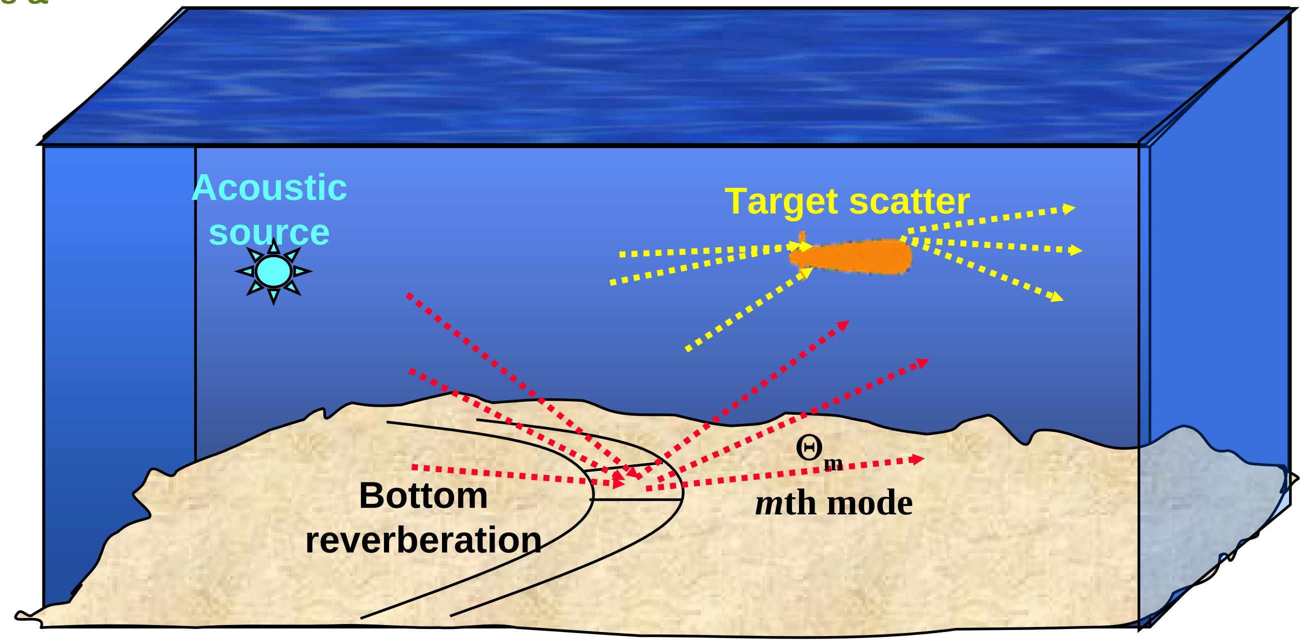

- Acoustic waves travel via discrete modes
  - Environment-dependent propagation paths and velocity (hence multiple arrival times and angles)
- Reverberation from (rough) ocean bottom
  - Dominant source of noise for active sonar

Hypothesis: Moving target time-frequency structure can be separated from reverberation using its invariant structure

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Time-Frequency Intensity Variation Invariance Principle

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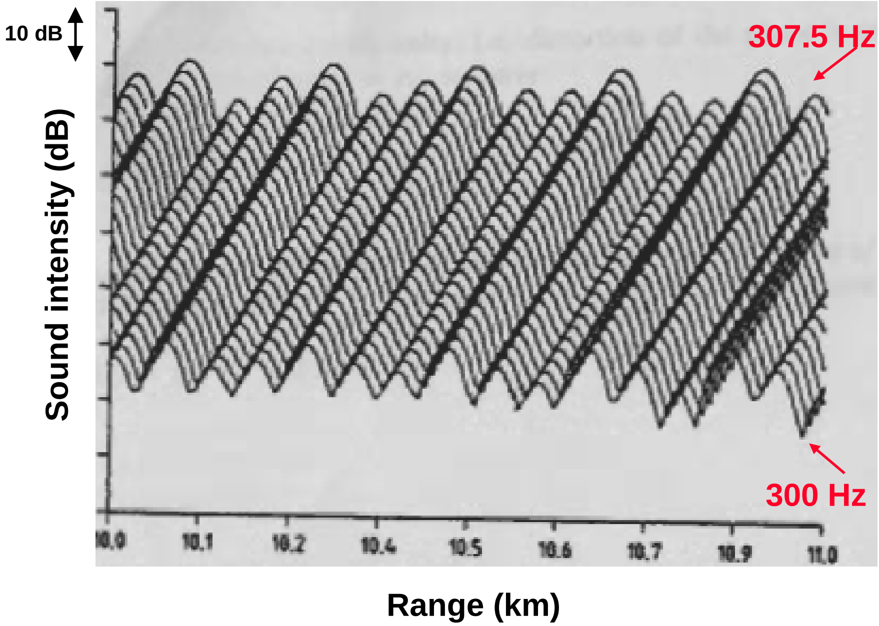
Sound intensity versus range (from Brehkovskikh & Lysanov)



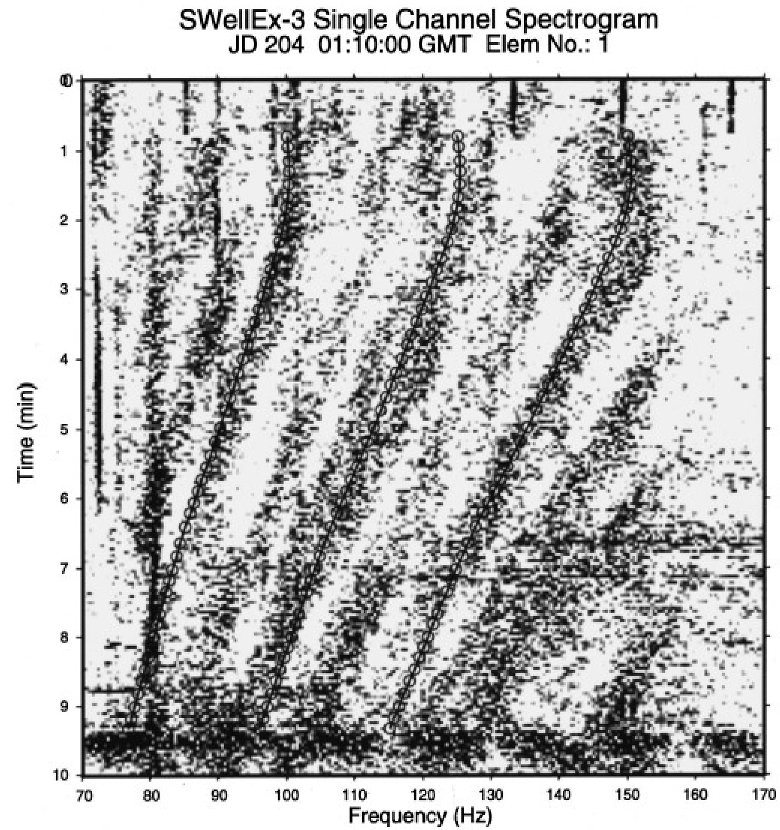
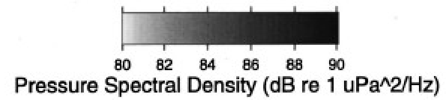


Figure from D'Spain & Kuperman, 1999



Invariant time-frequency structure described by Brekhovskikh in terms of normal mode interference

- **Invariance parameter β approximately unity**
- **Principle applied to interpretation of lofargrams**

Question: is there an invariant structure in active (bi-static) sonar? Can it be exploited?

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Shallow Water Active Classification (SWAC)
Characterization & Reduction of Active False Tracks*

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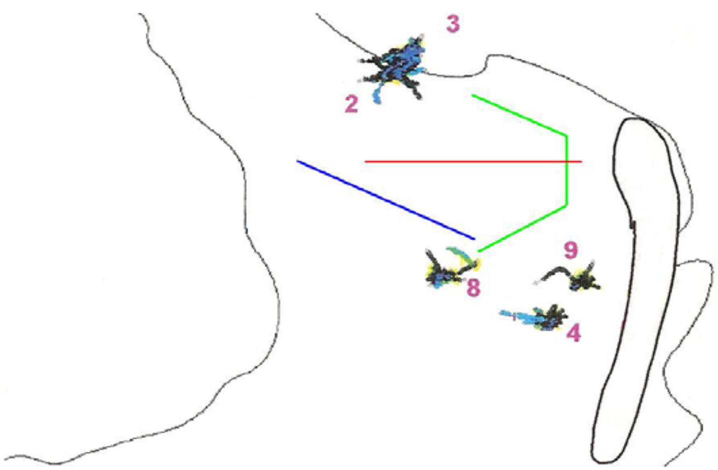
Geographic Details



Contacts
2=Oil rig
3=Moored tanker
4=Wreck 1
8=Wreck 2
9=Wreck 3

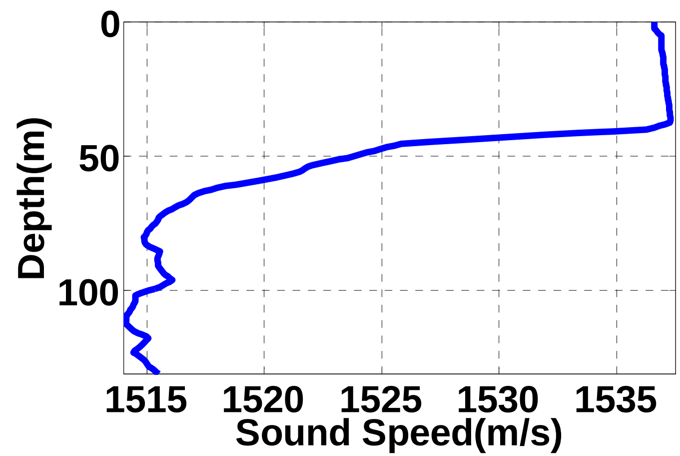
Tracks
Red=East/West
Blue=Diagonal
Green=Ridge geometry

Experiment specifications

	Variable	Value
Signal processing	Sampling rate	222 to 666 S/s
	Pulse length	1.2 to 2 s
Broadband source	Bandwidth	70 to 400 Hz
	Center frequency	495 to 600 Hz
Kinematics	Receiver depth	66.5 m
	Ship's speed	4.9 knots

Channel specifications(135 m depth)

Sound speed profile of the channel



*NUWC-NPT Tech Memo 04-054, 2004; Comeau & Petersen

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Active Spectrograms from Malta Plateau

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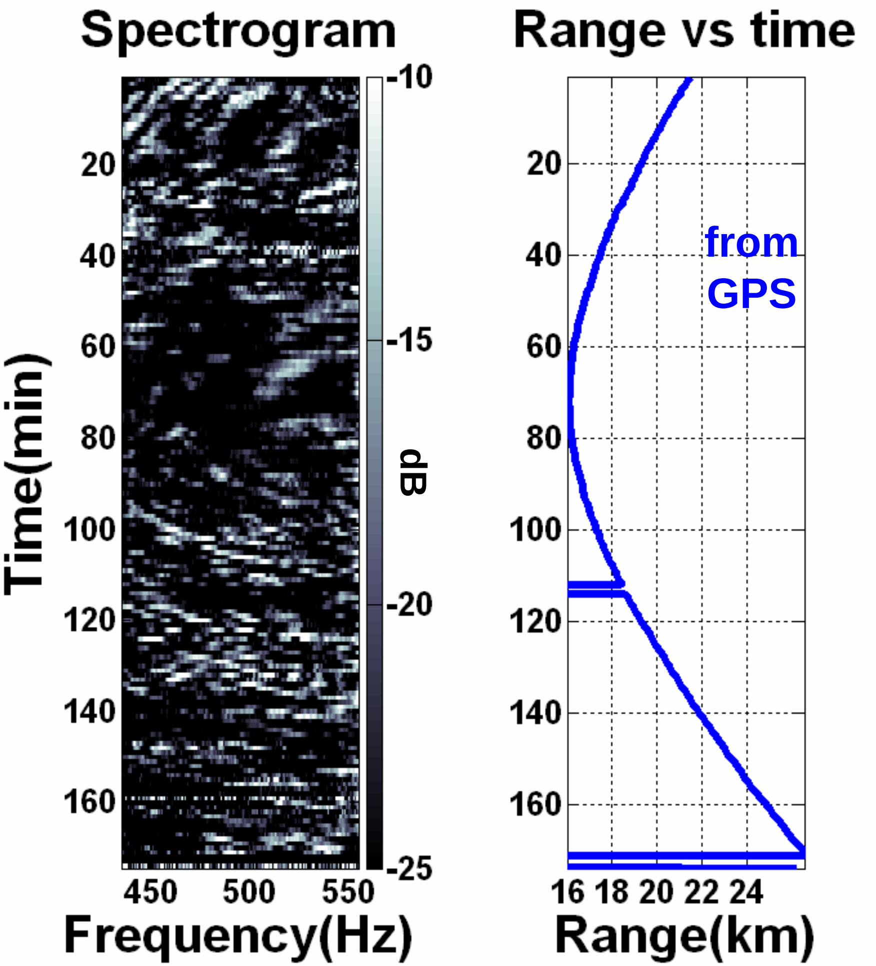
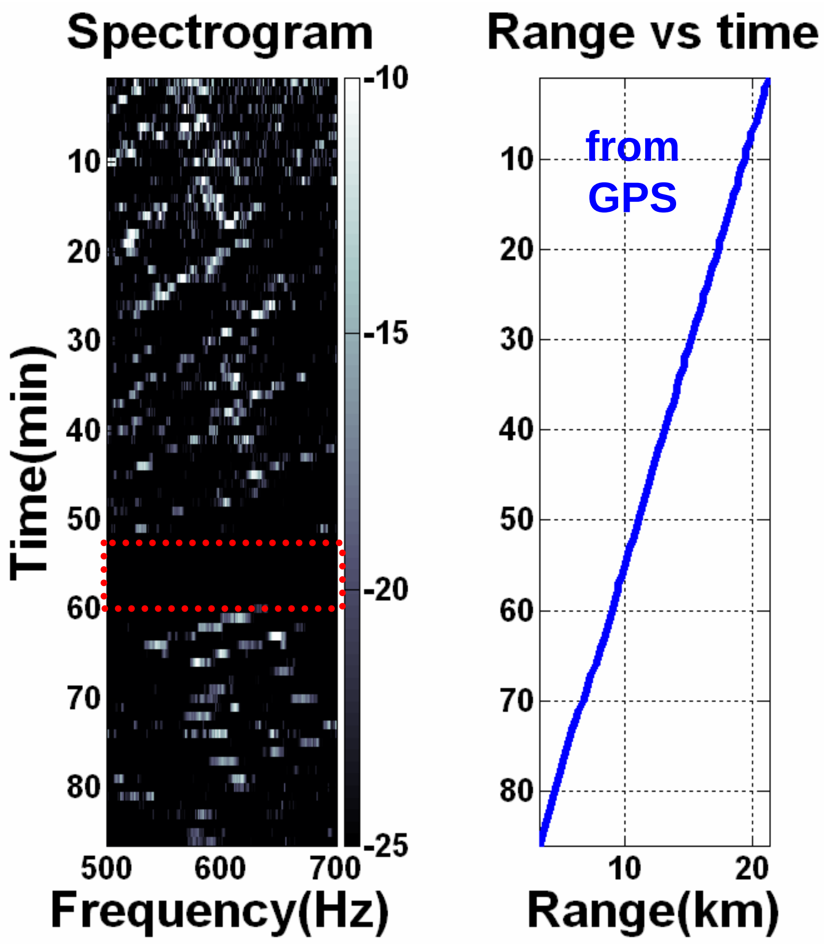
Bathtub



Contact 03/track 56: moored tank

Linear



Contact 09/track 03:Wreck

=missing data

Note appearance of striation patterns indicative of target track

Active Sonar Simulation

- **Received (bi-static) pressure:**

Source to target — Target to receiver

$$p(r,z,w) = C\sum_m \sum_n \left\{ \psi_m(z_s,w)\psi_m(z_t,w)\frac{e^{ik_m r_1}}{\sqrt{k_m r_1}} G_{mn}\psi_n(z_t,w)\psi_n(z_r,w)\frac{e^{ik_n r_2}}{\sqrt{k_n r_2}} \right\}$$

where:
$\psi_m(z,w) =$ mth mode function in the water column.
$k_m =$ horizontal wavenumber of mth mode
$r_1, r_2 =$ Source/target and target/receiver ranges
$G_{mn} =$ Scattering matrix defined by the target
$C =$ Normalizing constant
$p(r,z,w) =$ Pressure due to a point source of frequency ω

- **Environment values (bathymetry, sound speed, etc.) from NUWC**
  - **Mode functions computed with KRAKEN**

- **Scattering matrix: assume no mode coupling (diagonal matrix)**

Measured versus Simulated Spectrograms for Contact 3 (Moored Tank)

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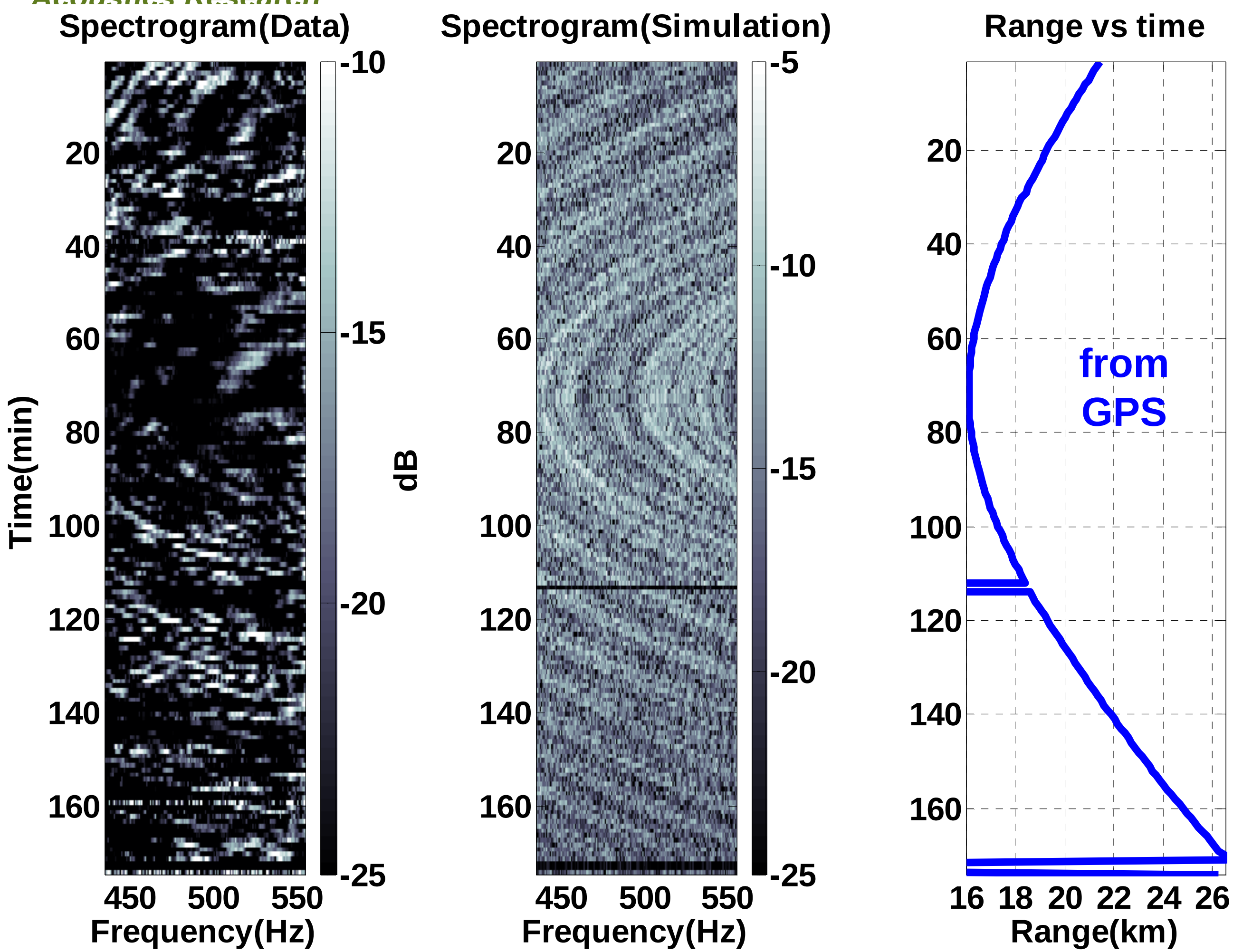

Simple scattering matrix: no inter-mode coupling

m

n					
	1	0	0	0	···
	0	1	0	0	···
	0	0	1	0	···
	0	0	0	1	···
	⋮	⋮	⋮	⋮	⋮

Contact 03/track 56: moored tank

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Measured versus Simulated Spectrograms for Contact 8 (Wreck)

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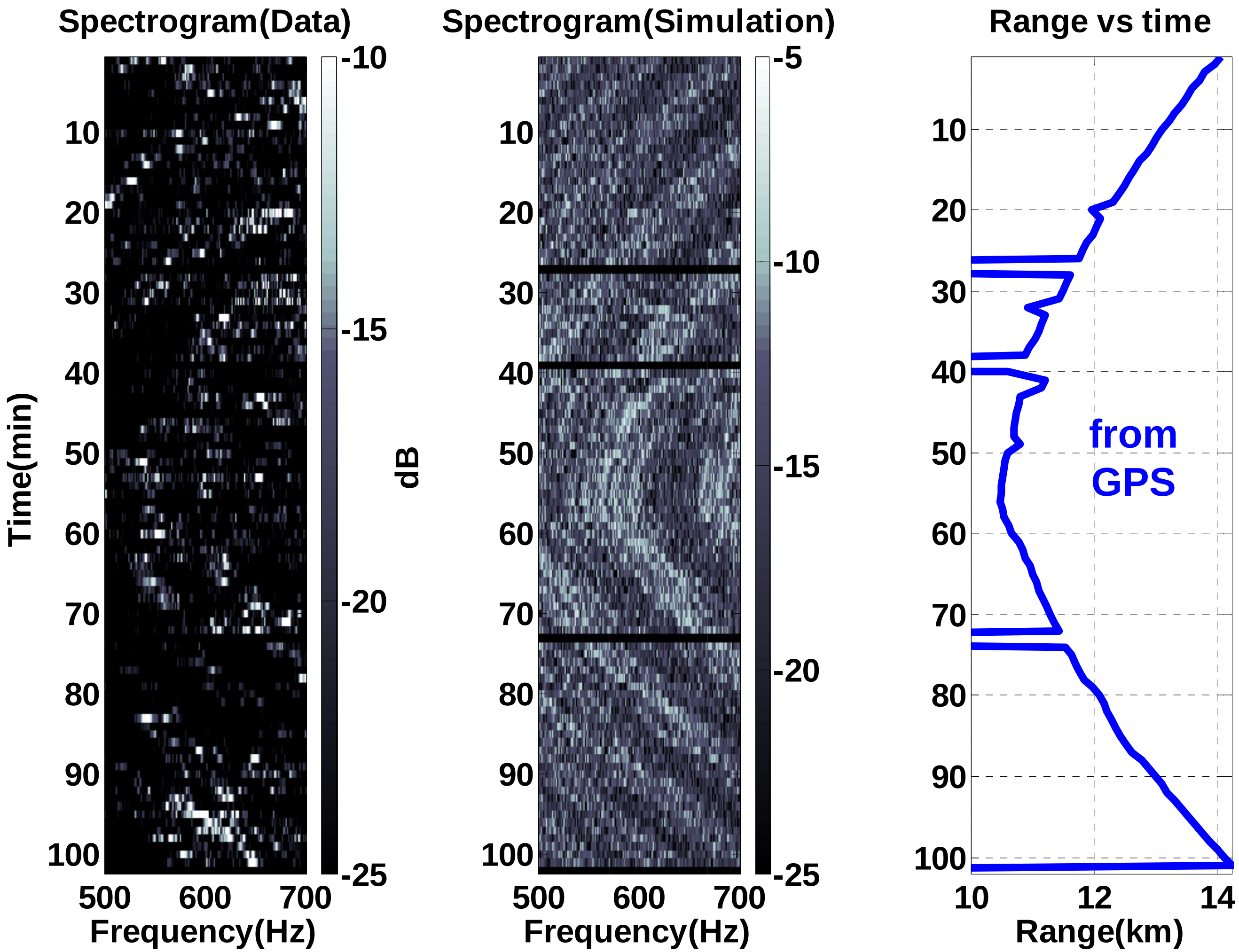

Simple scattering matrix: no inter-mode coupling

n \ m				
1	0	0	0	···
0	1	0	0	···
0	0	1	0	···
0	0	0	1	···
⋮	⋮	⋮	⋮	⋮

Contact 08/track 23:wreck

Tracking using the Invariance Features

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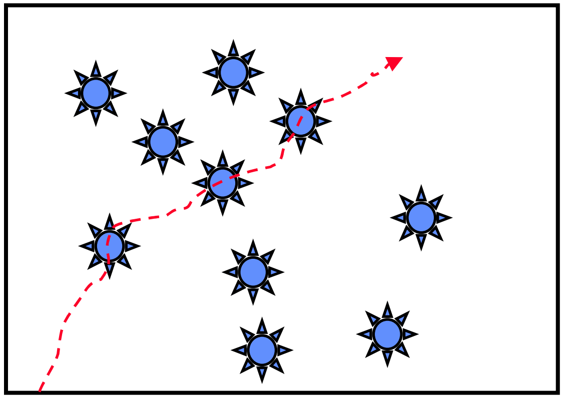
Standard Kalman Filter (SKF): Tracking based only on kinetics

State vector

$$X_{state} = \begin{bmatrix} x_t \\ v_t \end{bmatrix}$$

Observations vector

$$V = \begin{bmatrix} range_t \\ bearing_t \end{bmatrix} + \begin{bmatrix} n_{rt} \\ n_{bt} \end{bmatrix}$$



= detection

Target track

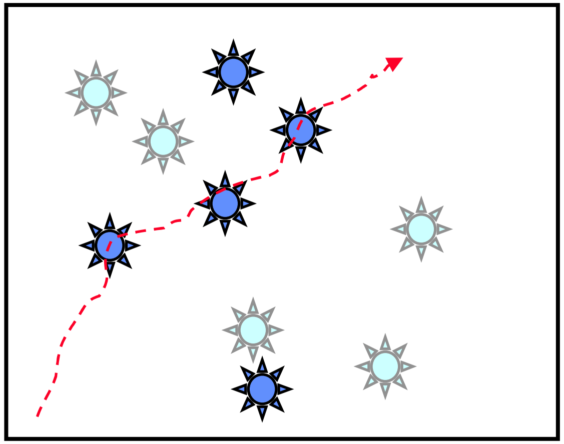
Physics-based Invariance with KF: Additional time-frequency constraint imposed to decrease allowable detections

Def. Invariant:

$$\frac{\Delta f}{f_{t-1}} = \frac{[\Delta r]}{r_{t-1}}\gamma \quad \longrightarrow \quad f_m(T) = \gamma \frac{f_m(T-1)v_{t-1}T}{r_{t-1}} + 1$$

New set of equations:

$$X_{inv} = \begin{bmatrix} x_t \\ v_t \\ f_m(T) \end{bmatrix} \qquad V_{inv} = \begin{bmatrix} range_t \\ bearing_t \\ f_m(T) \end{bmatrix} + \begin{bmatrix} n_{rt} \\ n_{bt} \\ n_{ft} \end{bmatrix}$$



$r_t = r_{1t} + r_{2t}$ $\qquad f_m(t) =$ Frequency of striation

Conventional Extended Kalman Filter (CEKF) for Bistatic Geometries

- **State vector (position & velocity)**

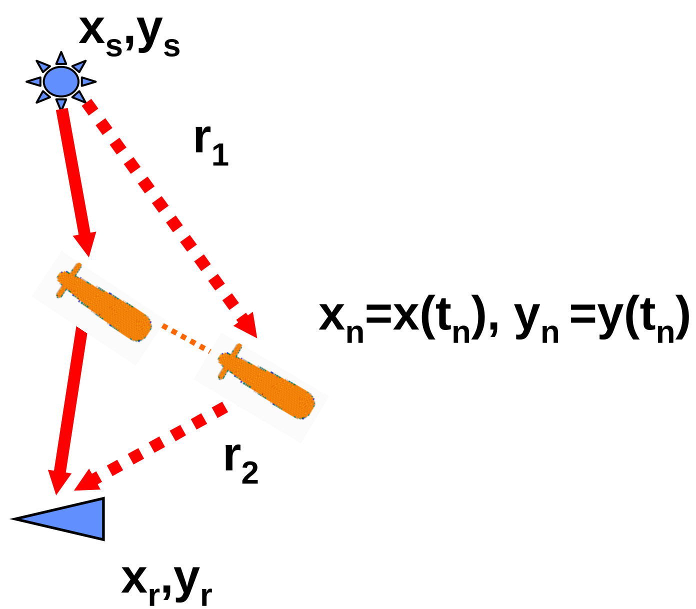
$$X_n = \begin{bmatrix} x_n & y_n & \dot{x}_n & \dot{y}_n \end{bmatrix}^T$$

- **Nearly constant velocity (NCV) dynamics model**

$$X_{n+1} = \mathrm{F}\, X_n + w_n,$$

$$\mathrm{F} = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \Delta t = t_{n+1} - t_n$$

Bistatic geometry:



F = state transition matrix; w_n = zero mean, white Gaussian noise

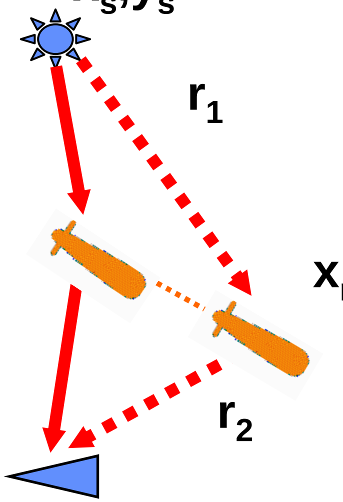
CEKF Observations and Measurement Model

- **System measures bistatic range, r, and bearing angle w.r.t. receiver:**

Measurement: $$Z_n = [r_n \quad \phi_n]^T$$

$$r_n = r_1(t_n) + r_2(t_n)$$
$$= \sqrt{(x_n - x_s)^2 + (y_n - y_s)^2} + \sqrt{(x_n - x_r)^2 + (y_n - y_r)^2},$$

Bistatic geometry:



- **Measurement model:**

$$Z_n = h(X_n) + m_n$$

$$h(X_n) = \begin{bmatrix} r_n \\ \tan^{-1} \dfrac{y_n - y_r}{x_n - x_r} \end{bmatrix},$$

Measurement noise:

$$m_n = [m_r(t_n), m_\phi(t_n)]^T,$$

Invariance EKF (IEKF) State Transition

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- **State space vector includes time dependent frequency**

$$\boldsymbol{X}_n = [\boldsymbol{x}_n \quad \boldsymbol{y}_n \quad \dot{\boldsymbol{x}}_n \quad \dot{\boldsymbol{y}}_n \quad \boldsymbol{f}_n]^T \qquad X_{n+1} = \mathrm{F}(X_n) + w_n,$$

Determine state transition, F, from definition of invariance

$$\frac{\Delta f}{f(T-1)} = \frac{\Delta r}{r(T-1)}\gamma$$

Invariance relation

$$\mathrm{F}(X_n) = \begin{bmatrix} x_n + \Delta t\, \dot{x}_n \\ y_n + \Delta t\, \dot{y}_n \\ \dot{x}_n \\ \dot{y}_n \\ f_n\left[1 + \frac{(\dot{x}_n + \dot{y}_n)\Delta t}{r_n}\right] \end{bmatrix}$$

Relates new frequency to previous value using invariance

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IEKF Observations & Measurements

- **System measures frequency for each pulse**
  - **For now, assume single value representing the maximum frequency**
  - **Add to measurement vector**

$$Z_n = \begin{bmatrix} r_n & \phi_n & f_n \end{bmatrix}^T$$

Measurement noise:

$$m_n = \left[m_r(t_n), m_\phi(t_n), m_f(t_n) \right]^T,$$

- **Measurement model becomes:**

$$h(X_n) = \begin{bmatrix} r_n \\ \tan^{-1} \dfrac{y_n - y_r}{x_n - x_r} \\ f_n \end{bmatrix}$$

- **Proceed with Kalman prediction and update as before**

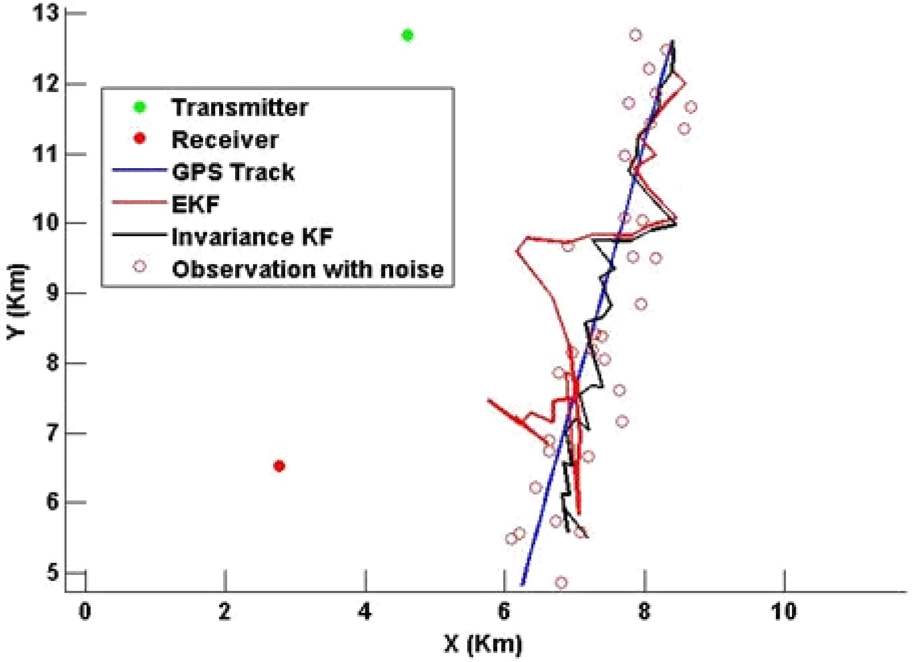
Tracker Logic

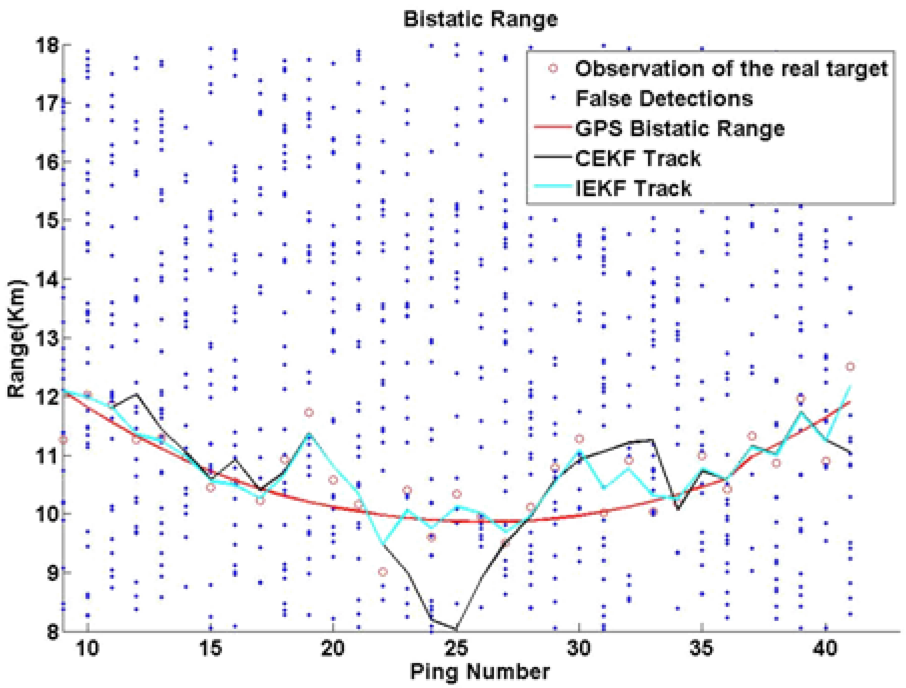
- **Confirm: If M contacts are associated**
- **Discarded: If less than M contacts are associated with N scans**
- **Terminated: If it's confirmed and after K consecutive missed detections**
- **Validated contacts are those that satisfy the following threshold condition**

$$\left(Z_{ij} - c(i)X(i|i-1)\right)' \left(C(i)P(i|i-1)C'(i) + R_i\right)^{-1} \left(Z_{ij} - C(i)X(i|i-1)\right) < \chi^2$$

Where the χ^2 parameter is the association gate parameter

Tracker Performance





- Addition of invariance constraint improves tracker performance
  - Eliminates false detections using frequency (in addition to kinetics)
  - Average range error decreases 34% to 117 m (averaged over 100 realizations)

Future Work

- **Extend frequency measurement to spectral information**
  - **Use family of frequencies representing striations**
  - **Need transition relationship and estimation (Hough? Radon?)**
  - **Add uncertainty due to gamma**
- **Improve tracker formulation**
  - **Multiple tracks, increased tracker logic (track initiation, confirmation, and elimination**
  - **More realistic reverberation environment**
- **Apply to real data**

Publications

- J. Quijano, L. M. Zurk, D. Rouseff, Demonstration of the invariance principle for monostatic active sonar, Journal of the Acoustical Society of America, May 2007, submitted for publication
- L.M. Zurk and C. He, *Active target tracking using the bistatic invariance principle*, invited for presentation Acoustical Society of America, Salt Lake City, Utah, June 2007
- L. M. Zurk, J. Quijano, and M. Velankar, D. Rouseff, *Bistatic invariance for active sonar systems*, Acoustical Society of America, Vol. 120, No. 5, p. 3221. November 2006
- J. Quijano, L. M. Zurk, D. Rouseff, *Use of the invariance principle for target tracking in active sonar geometries*, IEEE Oceans Conference, Boston, MA, September 2006
- L.M. Zurk, J. Quijano, D. Rouseff, *Bistatic Invariance Principle for Multi-Static Active Geometries*, Acoustical Society of America, Providence, RI, June 2006
- L. M. Zurk, D.Rouseff, J. Quijano, G. Greenwood, *Bistatic Invariance Principle for Active Sonar Geometries*, European Conference on Underwater Acousics (ECUA), Carvoviero, Portugal, June 2006