Covariance Matrix Filtering for ABF with Moving Interference

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Robust ABF with Moving Ships

- ABF must estimate ship locations to null shipping noise
- Current ABF relies on time averages of the hydrophone covariance matrix
  - When ships move, the time average is not the appropriate estimator of ship locations
  - Mismatch between standard signal processing assumptions and physical reality
- Physics-based signal processing
  - A new method replaces time average with low pass filters that include ship motion

Physics-Based ABF for Moving Ships

Pressure is sum over ships and propagation modes

$$p_n = \sum_j \sum_m s_j A_{mn}(t) e^{ik_m r_{jn}(t)}$$

s_j = random spectral source noise of jth ship

A_{mn} = modal amplitude term for m^{th} mode
(including spreading and attenuation)

r_{jn} = range from j^{th} ship to n^{th} phone

Mean covariance

$$\left\langle p_{n_1} p_{n_2} {}^* \right\rangle = \sum_j \sum_{m_1} \sum_{m_2} \left\langle s_j s_j {}^* \right\rangle A_{m_1 n_1} A_{m_2 n_2} e^{i\left(k_{m_1} r_{jn_1}(t) - k_{m_2} r_{jn_2}(t)\right)}$$

(Assuming source noise is independent between ships)

The mean covariance exists, but is a function of time

Cannot be estimated simply by taking a sample mean across time

Algorithm Motivation

Expand range in Taylor series: $\quad r = r_0 + \dot{r}t + \ldots$

Mean covariance becomes:

$$\left\langle p_{n_1} p_{n_2}{}^{*}\right\rangle = \sum_{j}\sum_{m_1}\sum_{m_2} \left\langle s_j s_j{}^{*}\right\rangle A_{m_1 n_1} A_{m_2 n_2} e^{i\left(k_{m_1} r_{j n_1 0} - k_{m_2} r_{j n_2 0}\right)} e^{i\left(k_{m_1} \dot{r}_{j n_1} - k_{m_2} \dot{r}_{j n_2}\right)t}$$

- Suggests use of Fourier analysis to estimate r.v.'s from data
- From this viewpoint, the traditional mean estimator is the DC component of the Fourier analysis.
- Use of only the DC component is the ultimate low pass filter.
- Must expand low pass filter to include slowly-varying deterministic phase terms, but average rapidly varying random source terms

Covariance Filtering

Element vector time series **x**(t)

FFT

Element frequency domain epoch series **X**(w,T)

Form covariance **R=XX***

Epoch Time

Covariance Matrix
Time Samples

FFT

Covariance Matrices in
Epoch Frequency Domain
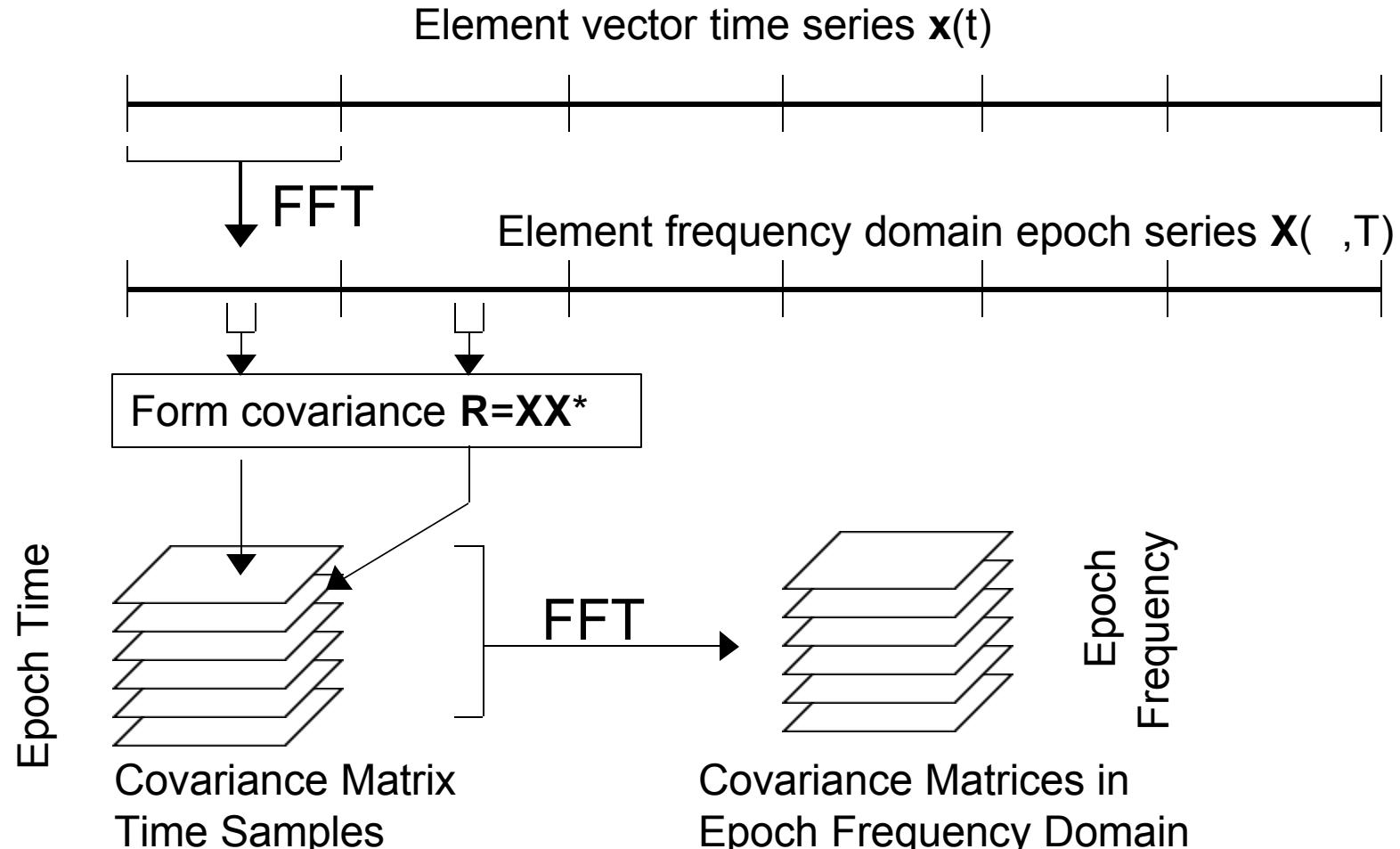
Epoch
Frequency w

Epoch frequency domain captures the slow evolution of ship motion

Covariance Spectra

Ensemble Mean Spectra

Element Separation

Epoch Frequency

Sample Spectra

Element Separation

Epoch Frequency
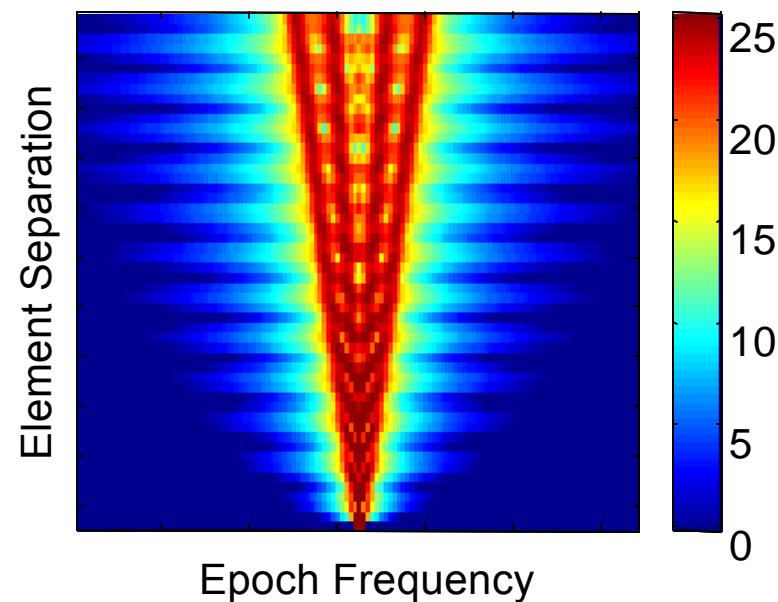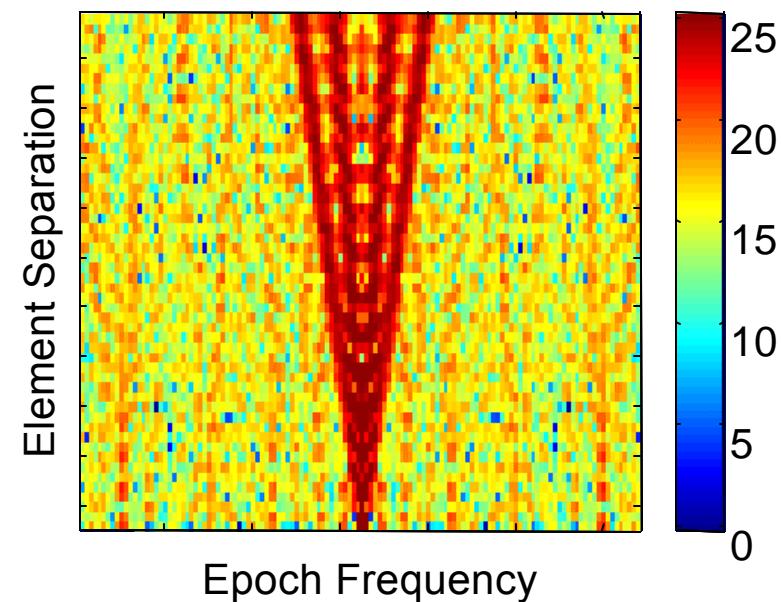
Moving ships form tracks in covariance spectra

Filtering Options

Traditional ABF Mean Estimates

### Short Time Mean

Long Time Mean
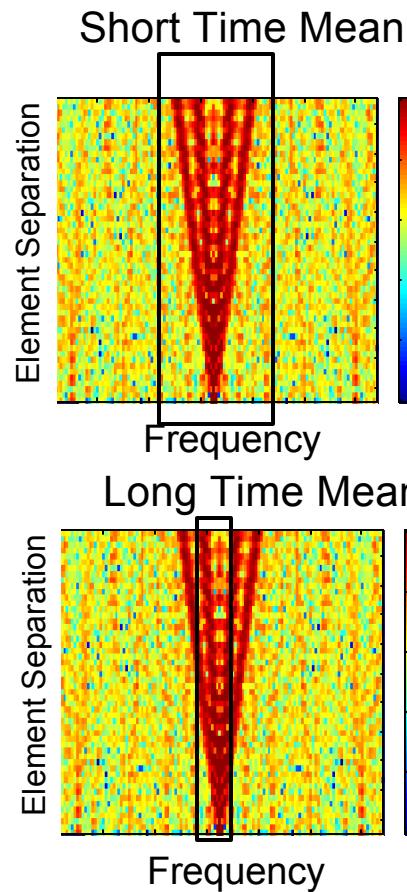
New Methods

Element Dependent Filter

### Partial *A Priori* Filters or Line Detectors to select bearing rates
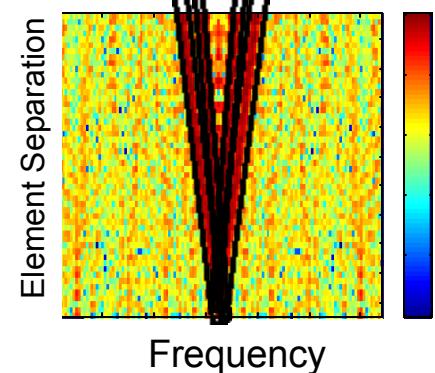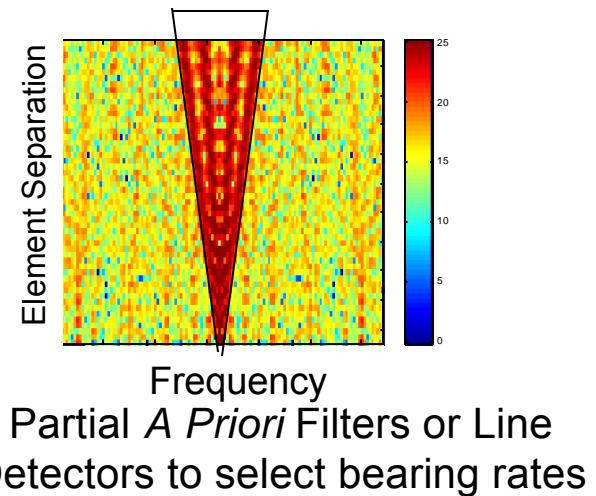
Simple Simulation

Four ships at speeds of 10-20 knots

50 Element Horizontal Line Array at 60 Hz

Ship Tracks
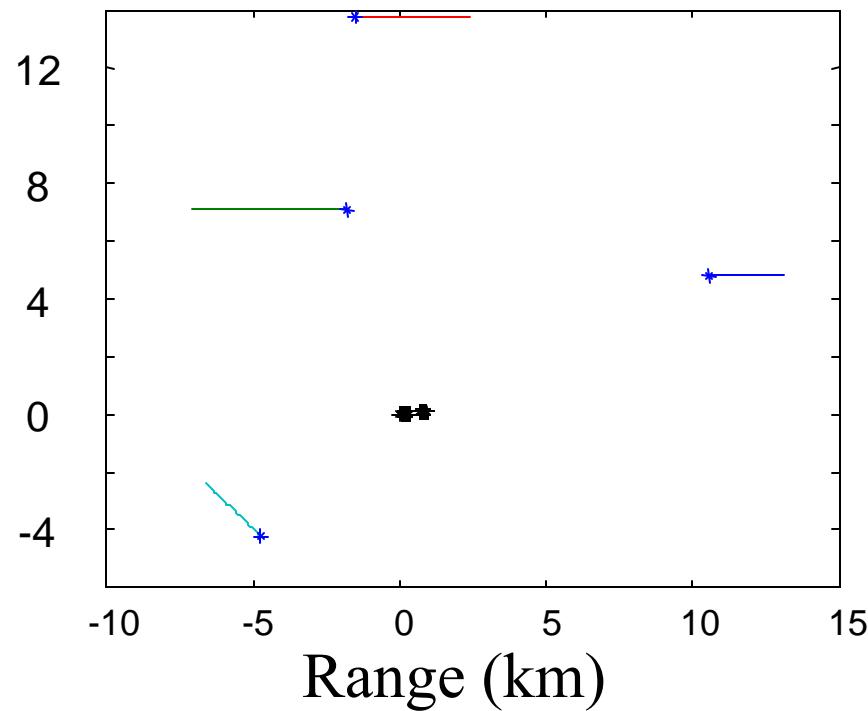
Beamforming Simulation Results

Cumulative Beam
Noise Distributions
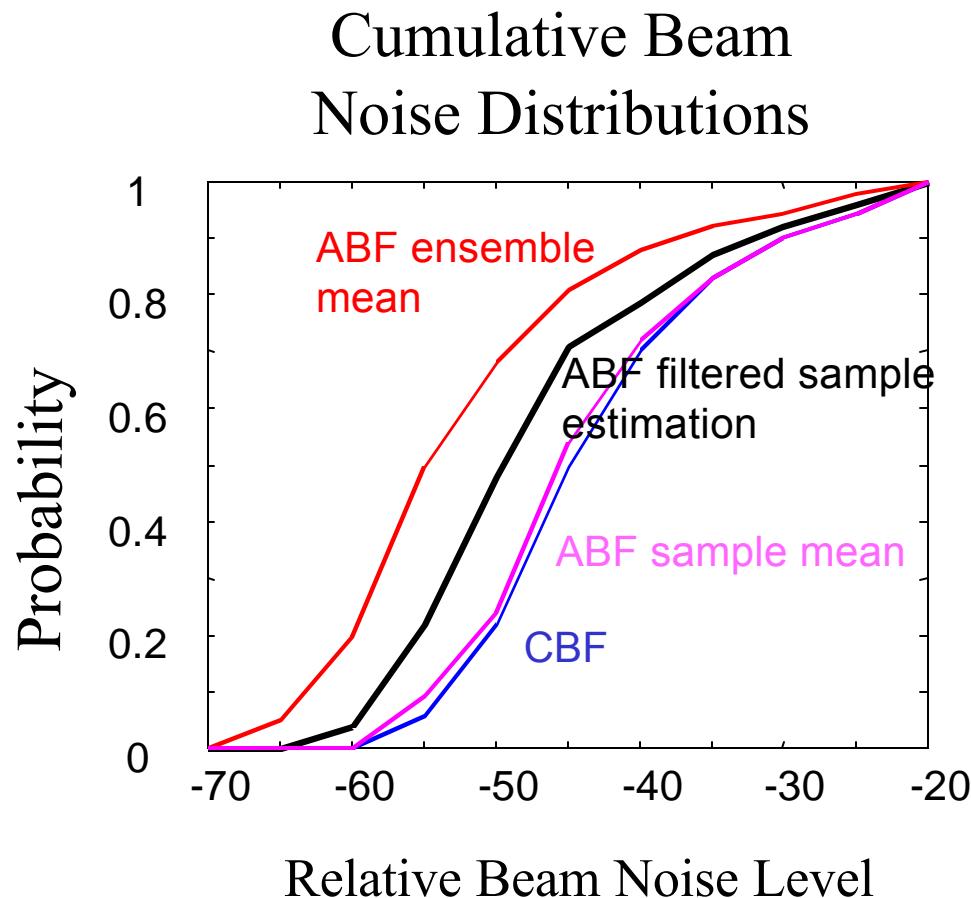
Conclusions

- Covariance filtering methods readily derived from physics of interference motion
- Physics-based simulations are useful for algorithm development
  - Known analytic mean compared to sample results
- ABF based on covariance estimate of mean from simple low pass filter may perform significantly better than current ABF based on sample mean estimate
  - Further improvement potential from better estimation techniques in epoch frequency domain, and/or a priori knowledge of bearing rates
- Two paradigms of current ABF processing may need to be abandoned
  - Sample means replaced by better estimators
  - Covariance matrix not processed as a single entity

Potential Extensions

- Algorithm Refinement
  - Improve performance by investigating alternative filters, filter settings, optimal estimation techniques
  - Investigate use of this technique augmented with spatial (toeplitz) filtering
  - Develop partial *a priori* techniques
  - Apply line detection methods (e.g. Hough or Radon transforms) in epoch frequency domain
- Extend method to MFABF on vertical and volumetric arrays