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Lincoln Laboratory ASAP-2003 Workshop

Array Shape Tracking Using Active Sonar Reverberation

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Supported by the ONR 321US 6.1 Program



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Array Shape Tracking from Active Sonar Clutter

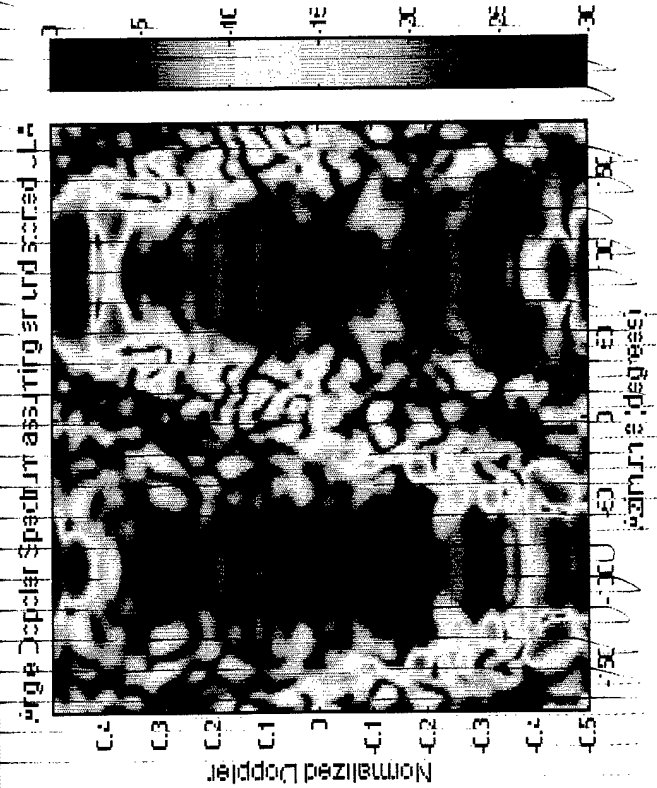
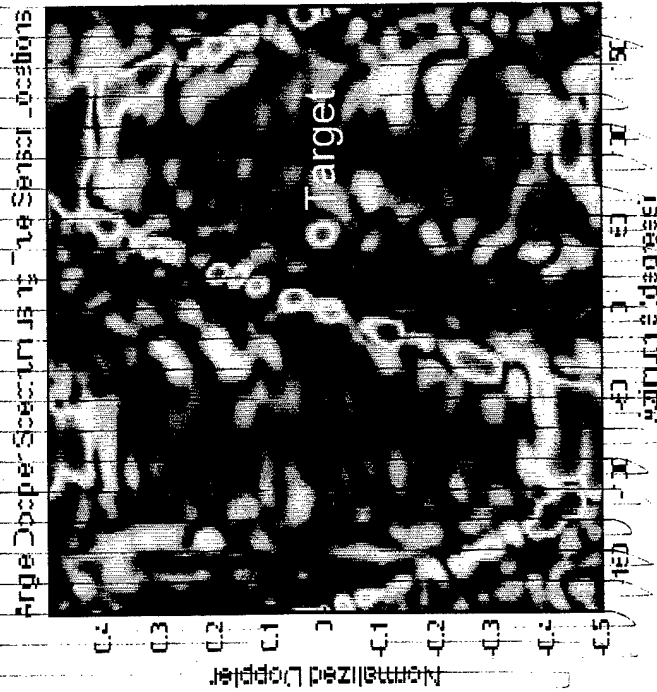
OBJECTIVE: To estimate and track the shape of a towed distorted-linear array using reverberation from active sonar pings as a distributed source of opportunity.

BACKGROUND:

- Array shape estimation using heading and depth sensors has been previously developed, e.g. Gray *et al.* (1993), by applying Kalman filtering with a state equation derived from spatio-temporal discretization of the simplified Poldosiss equation (water-pulley model) for array motion.
- Acoustic sources of opportunity have been employed for array shape estimation by fitting transverse element displacements to measuring inter-element phase differences e.g. Owsley (1980).
- For mid-frequency active sonar arrays the above methods may be precluded since it may be infeasible to instrument the array with a sufficient number of heading sensors and strong point sources of opportunity may not always be available in the presence of strong reverberation.
- Clutter has previously been used for element gain and phase calibration of a uniform linear airborne radar array (Robey, Fuhrmann, and Krisch, 1994) but not for array shape estimation.
- We propose constrained maximum likelihood array shape estimation from clutter (ASEC) which uses an array shape-dependent model of spatially-distributed, Doppler-spread reverberation.
- Array shape parameters are tracked within and across pings by using ML ASEC heading estimates as input to a Kalman filter whose state equation incorporates a dynamical model for array motion.

Motivation for Array Shape Estimation

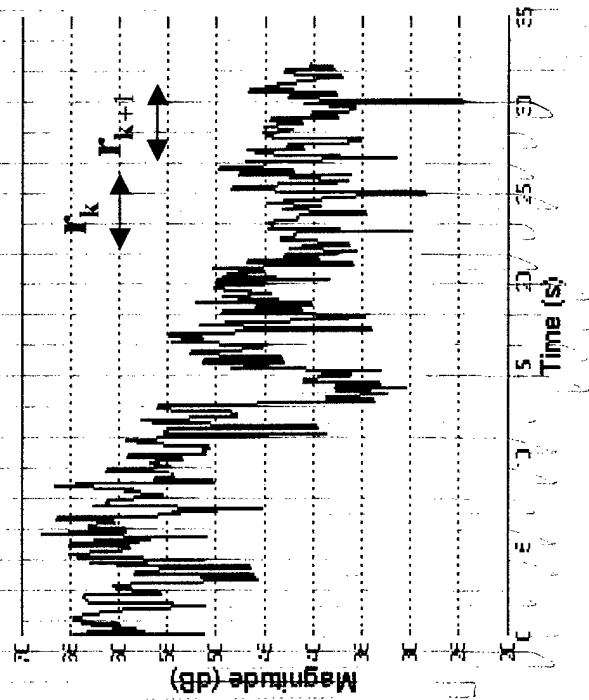
- Detection of slowly-moving targets with Doppler-sensitive waveforms is limited by beamformer sidelobes.
- Uncompensated array distortion causes increased clutter rank and target masking.
- Simulation example angle-Doppler spectrum from *perfectly compensated* array (left) vs. uncompensated *distorted* array (right). Note target masked by reverberation due to beamformer sidelobes of uncompensated array



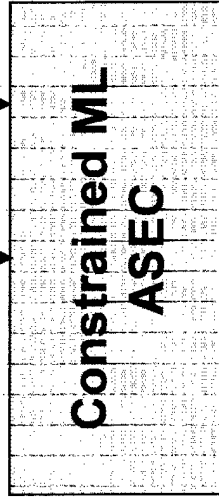
Array Shape Estimation from Clutter Concept

- Constrained ML ASEEC assimilates clutter data with a few heading sensor outputs to obtain array shape parameters from each sub-pulse length space-time snapshot.
- Kalman tracker filters sub-CPI shape coefficients using a model for array dynamics.

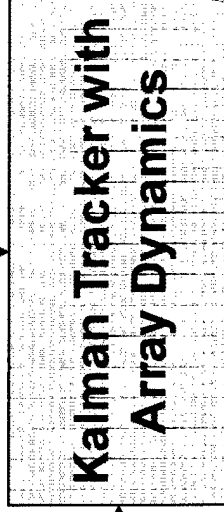
Example SWAC-3 Reverberation Return



Sub-CPI space-time clutter snapshots \mathbf{r}_k Heading sensors \mathbf{g}_k



Tow-cable Excitation μ_k



Filtered array shape



Reverberation Received at a Distorted Array

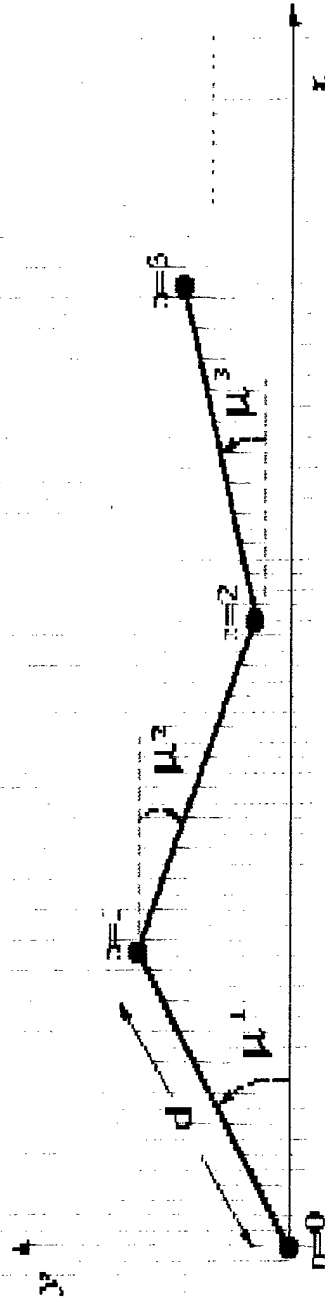
The clutter data from the n^{th} sensor located at (x_n, y_n) at time $t_m = \tau + mT_r$ for a distorted array moving with velocity v_a along the x direction is modeled as:

$$r_{nm} = \sum_{\theta_k, \phi_l} \alpha(\theta_k, \phi_l) e^{j \frac{2\pi}{\lambda} (\sin \theta_k \cos \phi_l \cdot x_n + \cos \theta_k \cos \phi_l \cdot y_n) + j 2\pi \frac{v_a}{\lambda} \sin \theta_k \cos \phi_l \cdot mT_r}$$

where $\alpha(\theta_k, \phi_l)$ is the complex Gaussian scatter amplitude from clutter at azimuth, θ_k , and multipath elevation, ϕ_l .

Sensor coordinates can be expressed in terms of heading μ and inter-element spacing d

$$\text{as } x_n = d \sum_{i=1}^n \cos(\mu_i), \quad y_n = d \sum_{i=1}^n \sin(\mu_i), \quad 0 \leq n \leq N-1, \quad (x_0, y_0) = (0, 0).$$



Space-Time Reverberation Model

The space-time data snapshot at time t_k consisting of clutter from all azimuths

$\theta_i \in [-\pi, \pi)$, $1 \leq i \leq N_\theta$ and elevation angles $|\phi_j| \leq \phi_{\max}$, $1 \leq j \leq N_\phi$, can be written as

$$\mathbf{r}_k = \mathbf{V}(\boldsymbol{\mu}_k) \boldsymbol{\eta}_k + \boldsymbol{\varepsilon}_k$$

where $\boldsymbol{\mu}_k = [\mu_k^1 \ \dots \ \mu_k^{N_\theta-1}]^T$, $\mathbf{V}(\boldsymbol{\mu}_k) = [\mathbf{v}(\theta_1, \phi_1, \boldsymbol{\mu}_k) \ \dots \ \mathbf{v}(\theta_{N_\theta}, \phi_{N_\theta}, \boldsymbol{\mu}_k)]$ is the clutter steering matrix, $\boldsymbol{\eta}_k$ represents unknown scattering, and noise $\boldsymbol{\varepsilon}_k \in \mathbb{C}^{MN \times 1}$ has covariance $\sigma_\varepsilon^2 \mathbf{I}_{MN}$.

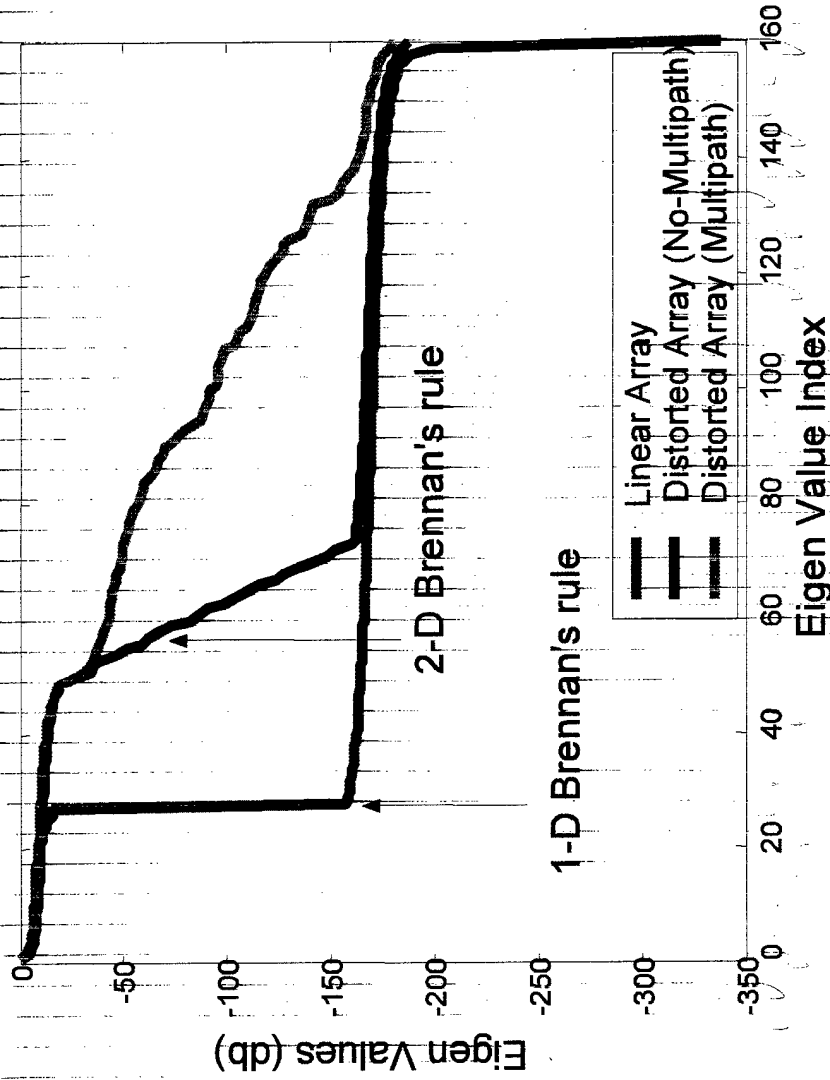
The $((i-1)N_\theta + j)^{\text{th}}$ column of $\mathbf{V}(\boldsymbol{\mu}_k)$ is $\mathbf{v}(\theta_i, \phi_j, \boldsymbol{\mu}_k) = \mathbf{b}(\varphi_{ij}) \otimes \mathbf{a}(\theta_i, \phi_j, \boldsymbol{\mu}_k)$ which represents the return from a single clutter patch at location (θ_i, ϕ_j) .

Array shape parameters $\boldsymbol{\mu}_k$ are assumed constant over the sub-CPI.

Array shape parameters $\boldsymbol{\mu}_k$ estimated by fitting the low rank ($< MN$) clutter subspace of $\mathbf{V}(\boldsymbol{\mu}_k)$ to the observed received space-time snapshot, \mathbf{r}_k .

Clutter Eigenvalues for a Distorted Linear Array

Eigenvalues of the asymptotic space-time covariance matrix for a modestly distorted array versus ideal uniform linear array for $N=32$ and $M=5$. Observe that rank inflation with 0 dB backlobes agrees with 2-D Brennan's rule [Varadarajan and Krolik, 2002].



Maximum Likelihood Array Shape Estimation

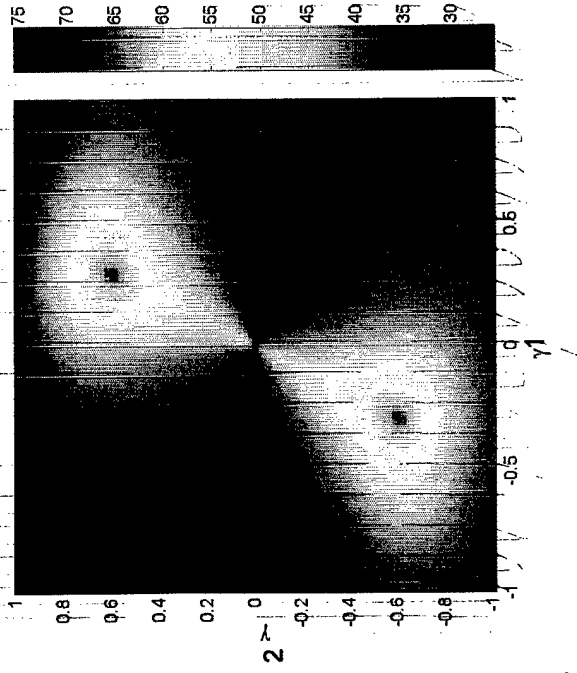
The $N - 1$ array shape headings can be parameterized by a low dimensional subspace using $(N - 1) \times (L - N)$ arbitrary but known shape basis as $\mathbf{\mu}_k = \mathbf{\Psi}\boldsymbol{\gamma}_k$.

The likelihood function for $\boldsymbol{\gamma}_k$ for the model reduces to minimizing the projection:

$$\hat{\boldsymbol{\gamma}}_k = \arg \min_{\boldsymbol{\gamma}_k} f(\boldsymbol{\gamma}_k) = \|\mathbf{P}(\boldsymbol{\gamma}_k)\mathbf{r}_k\|^2$$

where $\mathbf{P}(\boldsymbol{\gamma}_k) = \mathbf{I} - \mathbf{V}(\boldsymbol{\gamma}_k)(\mathbf{V}(\boldsymbol{\gamma}_k)^H \mathbf{V}(\boldsymbol{\gamma}_k))^{-1} \mathbf{V}^H(\boldsymbol{\gamma}_k)$ is the projection matrix onto the orthogonal complement of the clutter subspace.

Evaluation of $\log(f(\boldsymbol{\gamma}))$ (right) for $L = 2$ demonstrates left-right ambiguity in shape estimate corresponding to mirrored solutions about the array axis.



Constrained ML ASEC Algorithm

The left-right shape ambiguity can be resolved with knowledge of the position or heading of a single off-axis sensor which can be expressed as a linear constraint on the shape basis coefficients as

$$\mathbf{c}^T \boldsymbol{\gamma}_k = g.$$

The ML ASEC estimate can be obtained iteratively using a gradient projection approach (e.g. Frost (1972)):

$$\hat{\boldsymbol{\gamma}}_k^{j+1} = \boldsymbol{\gamma}_c + \mathbf{P}_c^\perp \left(\hat{\boldsymbol{\gamma}}_k^j - \xi \mathbf{f}^j \right)$$

where $\boldsymbol{\gamma}_c = \mathbf{P}_c \hat{\boldsymbol{\gamma}}_k^j = \mathbf{c}(\mathbf{c}^T \mathbf{c})^{-1} g$ is the projection of the current solution (j^{th} iteration) onto the constraint subspace, $\mathbf{P}_c^\perp = \mathbf{I} - \mathbf{P}_c$, $\left[\mathbf{f}^j \right]_i = \left[\frac{\partial f(\boldsymbol{\gamma})}{\partial [\boldsymbol{\gamma}_k]_i} \right]_{\boldsymbol{\gamma}=\hat{\boldsymbol{\gamma}}_k^j} = -2\Re \left\{ \mathbf{r}_k^H \mathbf{P}(\boldsymbol{\gamma}_k) \mathbf{V}_i(\boldsymbol{\gamma}_k) \left(\mathbf{V}(\boldsymbol{\gamma}_k)^H \mathbf{V}(\boldsymbol{\gamma}_k) \right)^{-1} \mathbf{V}(\boldsymbol{\gamma}_k)^H \mathbf{r}_k \right\}$, $0 < \xi < 1$.

The matrix $\mathbf{V}_i(\boldsymbol{\gamma}_k) = \frac{\partial \mathbf{V}(\boldsymbol{\gamma}_k)}{\partial [\boldsymbol{\gamma}_k]_i}$ can be computed analytically by assuming the temporal component of the steering matrix is independent of array shape distortion over a sub-CPI, and an analytic form for $\mathbf{V}(\boldsymbol{\gamma}_k)$ obtained by judicious sampling of the clutter wavenumber spectrum.

The rank of $\mathbf{V}(\boldsymbol{\gamma}_k)$ is assumed constant and can be chosen so that it does not change over the set of possible array distortions.

Incorporating Array Dynamics into ASEC

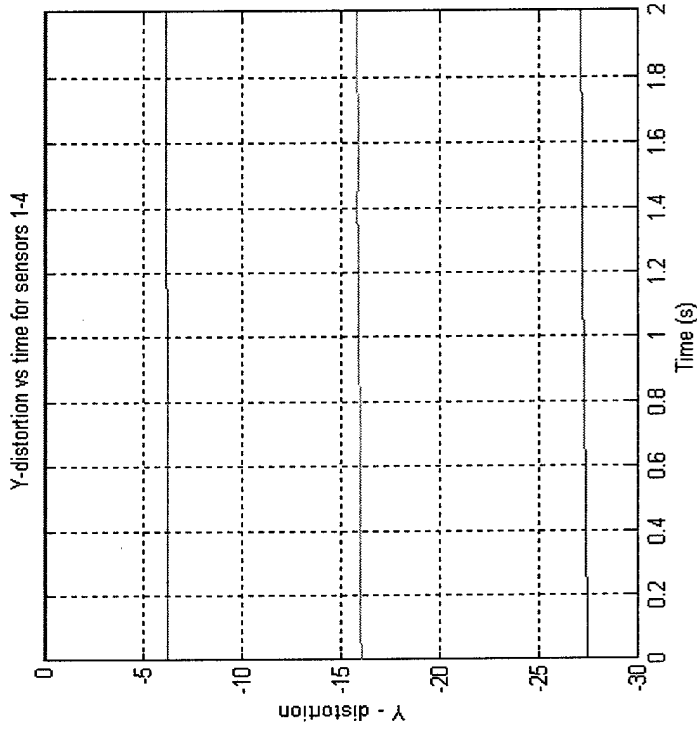
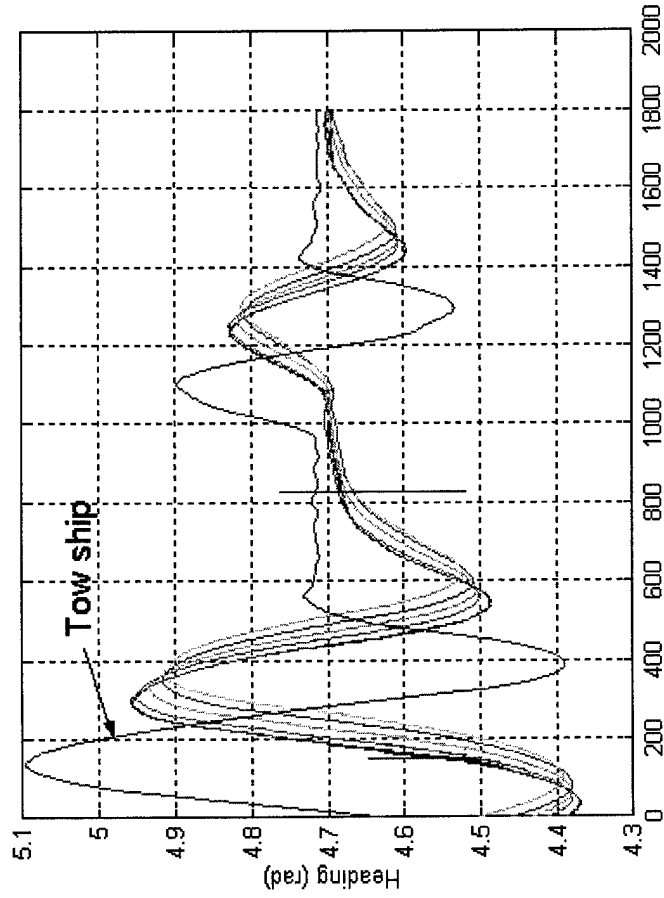
- A Kalman filter can be used to track the array shape coefficients across multiple sub-CPI intervals during a ping.
- The state vector $\mathbf{\mu}_{k+1}$ can be related to $\mathbf{\mu}_k$ using the water-pulley model:

$$\mathbf{\mu}_{k+1} = \mathbf{F}\mathbf{\mu}_k + \mathbf{u}_k + \mathbf{v}_{1k}$$
 where $\mathbf{F} = (1 - \rho)\mathbf{I} + \rho\mathbf{L}$ is the state transition matrix, $\mathbf{\mu}_k = [\mu_k \mathbf{0}_{1 \times N-2}]^H$ is the tow-cable driving term, \mathbf{v}_{1k} and represents white state noise with $\sigma_{v_1}^2 \mathbf{I}$. It can be shown that the displacement velocity along the array is determined by $\rho = \tilde{\rho} \beta / 2$.
- An observation equation can be defined using the MLE $\mathbf{z}_k = \hat{\mathbf{\mu}}_k$ from each sub-CPI:

$$\mathbf{z}_k = \mathbf{\mu}_k + \mathbf{v}_{2k}$$
 where \mathbf{v}_{2k} is the measurement noise with covariance $\sigma_{v_2}^2 \mathbf{I}$.
- The predicted MMSE array shape is used to initialize the next ASEC MLE search.

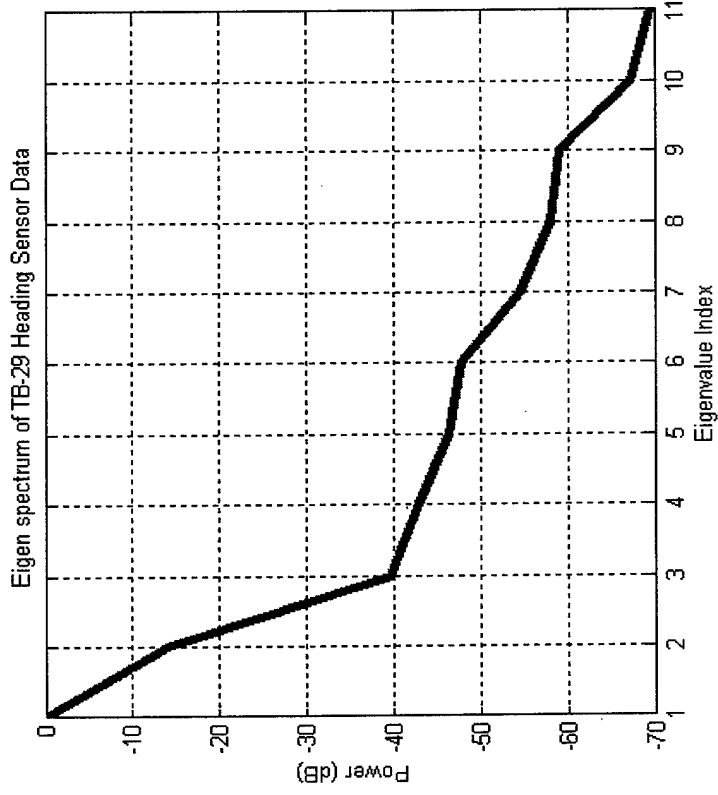
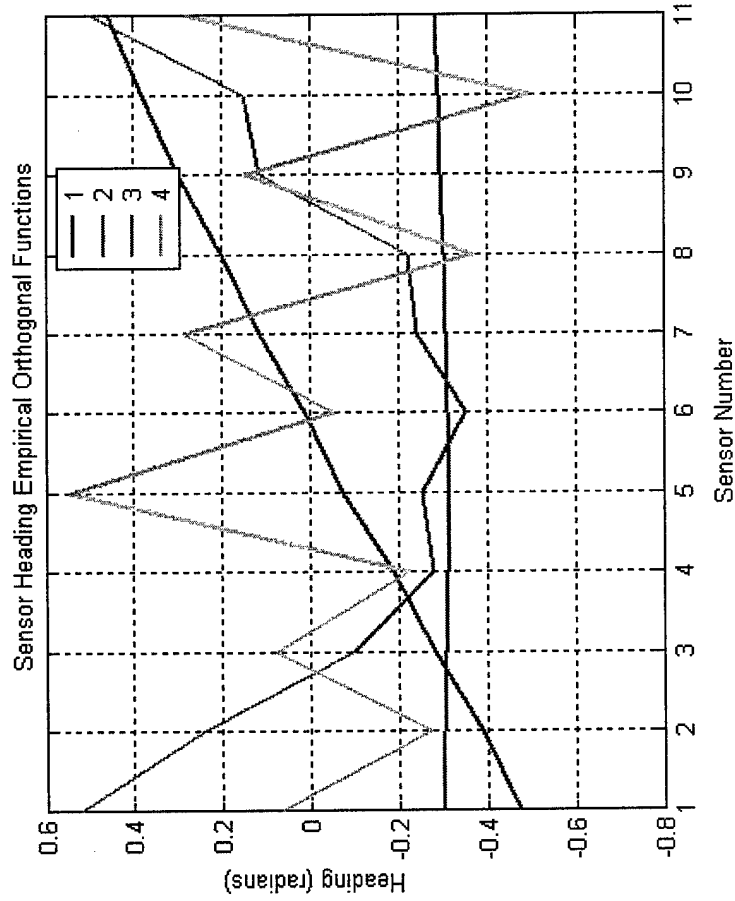
Array Dynamical Model Validation Using TB-29 Data

- Real heading sensor data from a TB-29 array (left) vs. time (sec), courtesy of Bruce Newhall at APL/JHU, indicates water pulley model valid for mild maneuvers.
- Transverse distortion over CPI (right) validates assumption of rigid short-time motion.



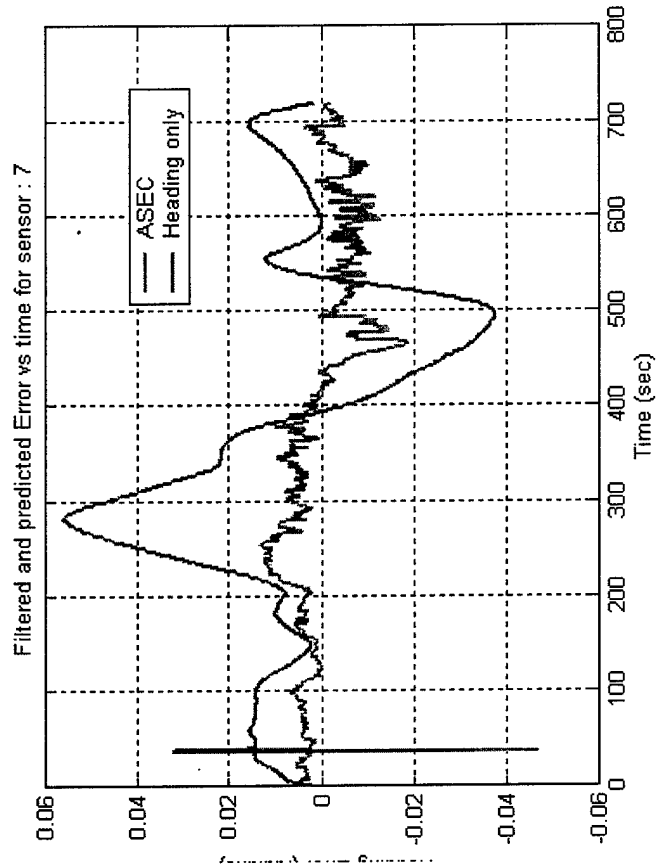
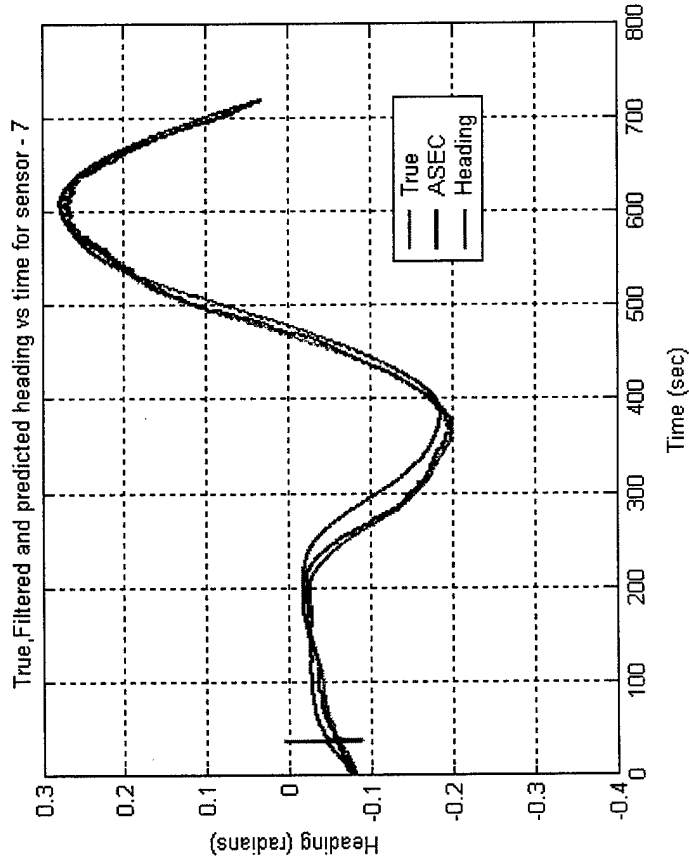
TB-29 Heading Sensor Eigenbasis

- Empirical orthogonal basis vectors (left) for headings derived from 6 heading sensor TB-29 data (interpolated to 11 sensors) demonstrate characteristic behavior.
- TB-29 heading sensor eigen-spectrum (right) indicates most of the variation captured by less than 4 modes.



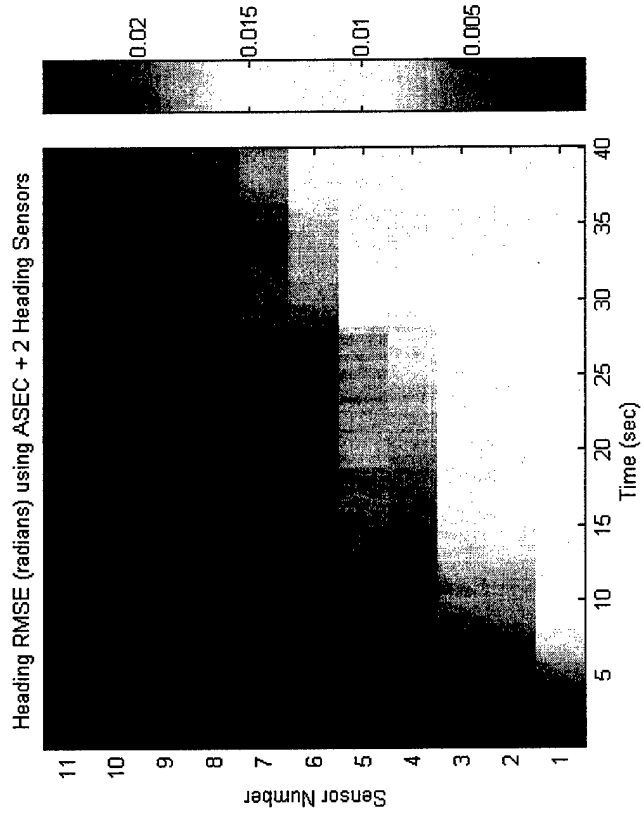
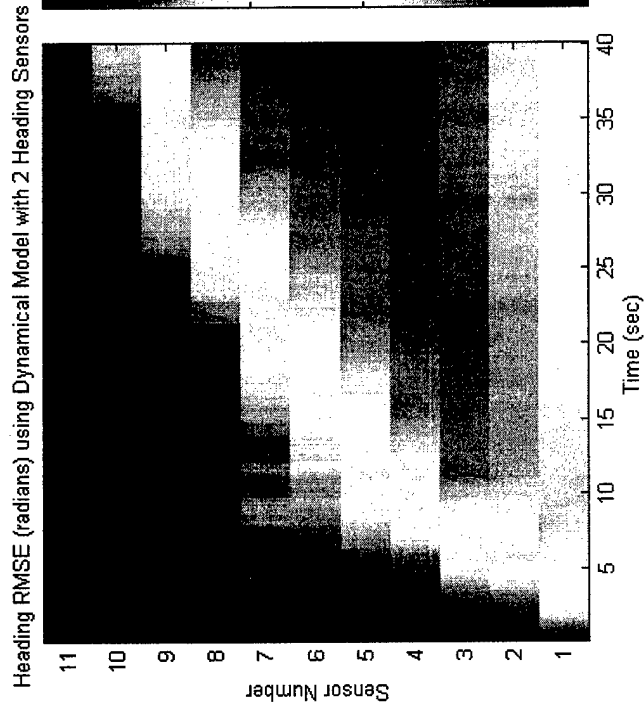
ASEC versus Heading Only Shape Estimation

- Illustrative simulation comparison of ASEC versus headings only tracking of a mild maneuver as seen in the middle of the array based on TB-29 heading data (left).
- Simulation assumes ASEC with 1.2 s. moving window sub-CPI, 4 EOF basis, space-time snapshot dimension 144 and clutter rank of 55.
- Heading (left) and error (right) for ASEC and 2 heading-sensor tracking as in MFTA.



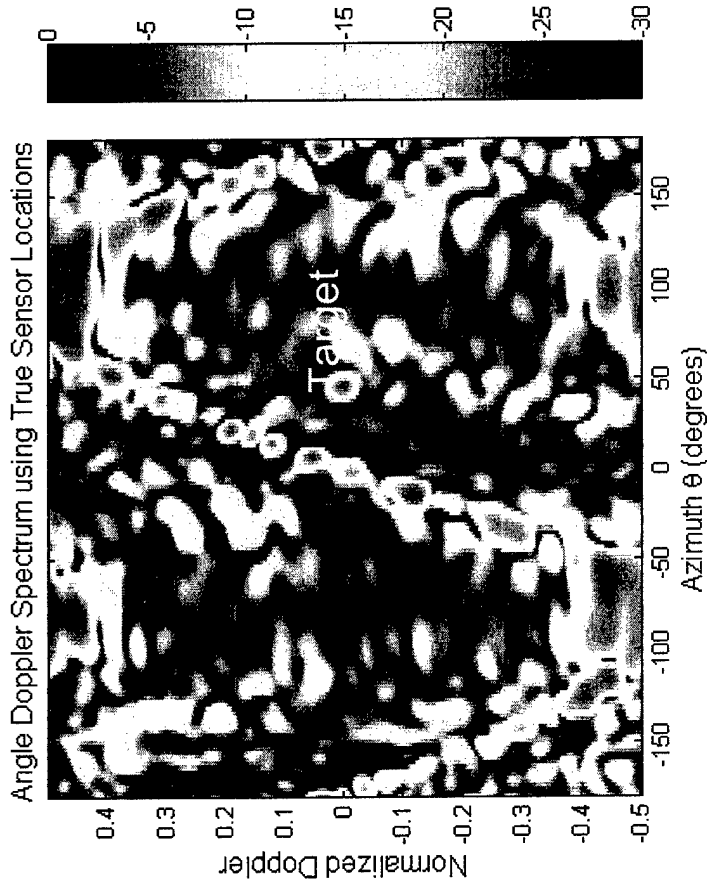
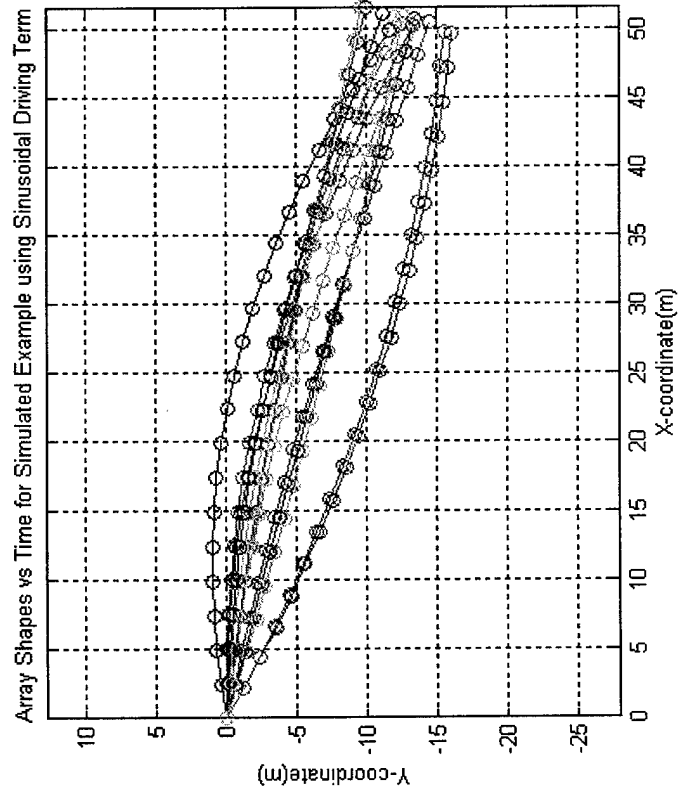
RMS Heading Error along the Array versus Time

- Simulated RMSE for 2-sensor headings-only tracking error (left) and ASEC (right) over 40 second ping along the array, ensemble averaged over initial condition perturbations and clutter realizations.
- Observe propagation of error down the array with time using water-pulley model (left). Error largest in the middle of the array since headings known at the end and at tow-point offset from first sensor.



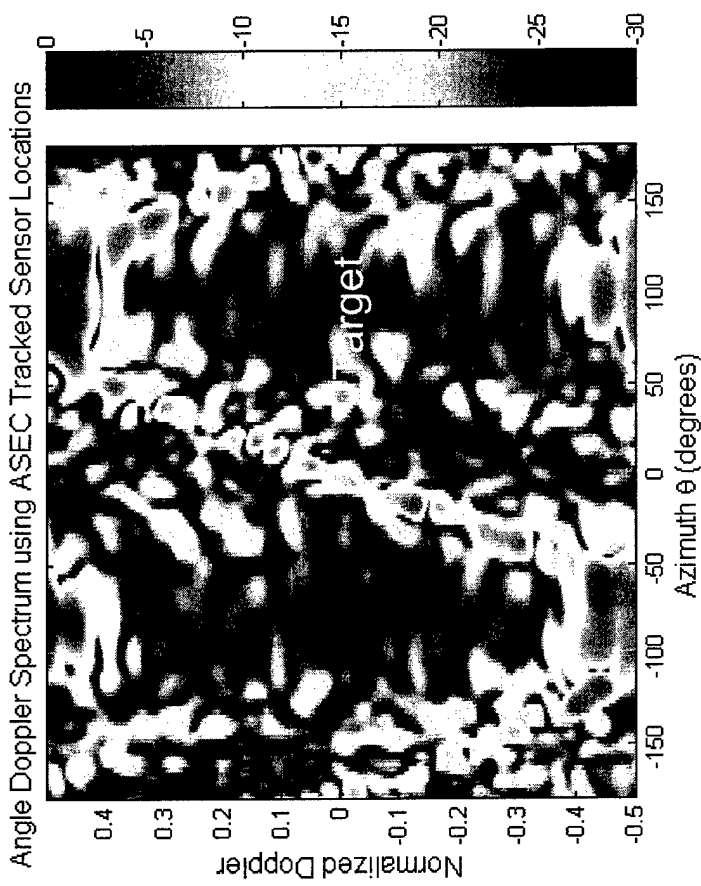
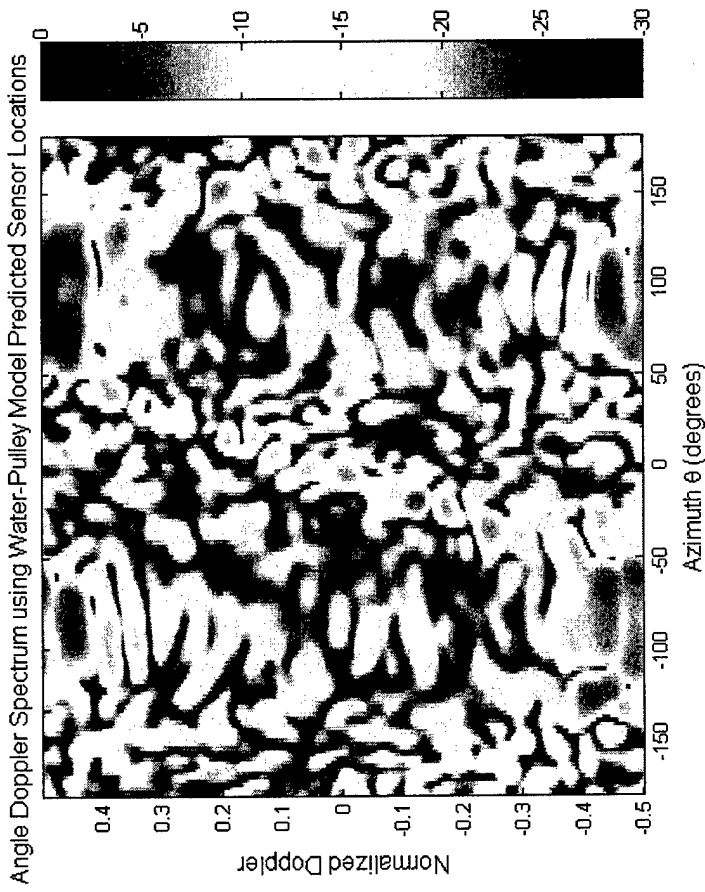
Angle-Doppler Spectrum for Distorted Array

- Impact of ASEC tracking on sonar performance illustrated by conventional beamforming-Doppler spectra outputs simulated for continuous array motion.
- Time-evolving simulated array shapes based on scaled TB-29 motion model (left). Angle-Doppler spectrum with 10 dB target for perfect array compensation (right).



ASEC vs. Headings-only Tracking Angle-Doppler Spectra

- Spectrum for conventional array tracking for WP model with 2 heading sensors (left).
- Spectrum for ASEC tracking with 4 basis functions, 1.2 s. sub-CPI sliding window, and CNR = 30 dB (right). Target visible at zero-Doppler and 45 degree bearing.



ASEC Summary and Future Work

- Distortion of nominally linear arrays will often result in a substantial increase in spatial sidelobe levels which can mask slowly-moving targets.
- ML estimation of array shape is facilitated by fitting a reduced-rank reverberation model to a sliding window of sub-CPI space-time snapshots over the extent of each sonar return.
- Shape ambiguities can be resolved by efficiently maximizing likelihood subject to a constraint which incorporates measurements from at least a single heading sensor.
- Constrained ML ASEC heading estimates are used as inputs to a Kalman tracker incorporating an array dynamical model and driven by a tow-cable heading sensor output.
- Simulations using array motion scaled from real TB-29 heading data suggests that ASEC tracking can facilitate improved array compensation compared to headings-only tracking.
- Future work will include ASEC performance evaluation with real 53C/MFTA data.