ADAPTIVE BEAMFORMING IN ACTIVE SONAR IMAGING

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Outline of this talk

Beamforming

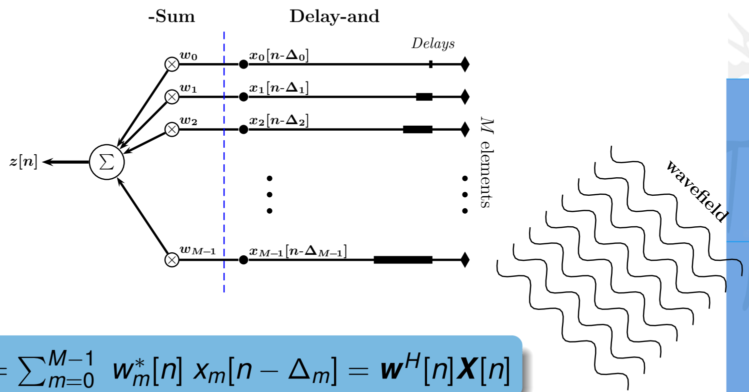
- Conventional beamforming
- Adaptive beamforming, MV and APES
- Beamspace processing

Results

- Simulated point reflectors
- Images of speckle, highlight and shadow
- Simulated point reflectors
- Experimental SSS images

Conclusion

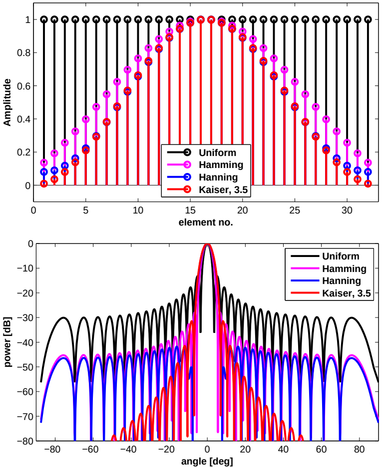
Beamforming; focus and steering of beams



$$z[n] = \sum_{m=0}^{M-1} w_m^*[n]\, x_m[n-\Delta_m] = \boldsymbol{w}^H[n]\boldsymbol{X}[n]$$

Receiving signal:
$\boldsymbol{X}[n] = A[n]\,\boldsymbol{a}(\boldsymbol{k_0}) + \boldsymbol{S}[n]$,
$A[n]$; ampl. of signal in direction $\boldsymbol{k_0}$, and $\boldsymbol{S}[n]$; noise.

Conventional beamformers uses pre-defined sensor weights

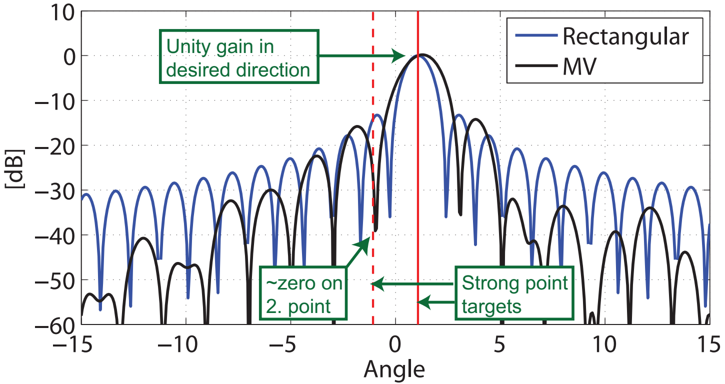


Adaptive beamformers uses the statistics of the data to estimates weights for each direction and each range

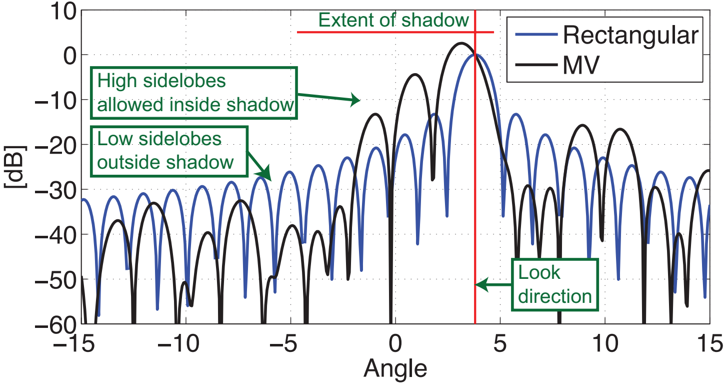
Minimum Variance (MV) beamformer

- Known by several names
  - Minimum Variance Distortionless Response (MVDR) beamformer
  - Capon method or Capon beamformer
  - (Apes beamformer)
- Problem to solve:
  - Find the weights that minimize the variance (power) of z[n] (the beamformer output) with the constraint that the signal that originates from the steering direction is passed with unity gain

MV BF passes the signal of interest with unity gain while an interferring signal is suppressed



MV BF allowes large sidelobes in regions with low energy



Minimum Variance (MV) beamformer

- Variance: $E\{|z[n]|^2\} = E\{|\boldsymbol{w}^H \boldsymbol{X}[n]|^2\} = \boldsymbol{w}^H \boldsymbol{R} \boldsymbol{w}$, where $\boldsymbol{R} = E\{\boldsymbol{X}\boldsymbol{X}^H\}$ is the spatial covariance matrix.

Problem formulation:

$$\begin{aligned} \boldsymbol{w}_{mvdr} &= \min_{\boldsymbol{w}} \; \boldsymbol{w}^H \boldsymbol{R} \boldsymbol{w} = \min_{\boldsymbol{w}} \; \boldsymbol{w}^H \left(|A|^2 \boldsymbol{a}(\boldsymbol{k_0}) \boldsymbol{a}(\boldsymbol{k_0})^H + \boldsymbol{R}_S \right) \boldsymbol{w} \\ &= \min_{\boldsymbol{w}} \boldsymbol{w}^H \boldsymbol{R}_S \boldsymbol{w} \\ \text{s.t.} \quad & \boldsymbol{w}^H \boldsymbol{a}(\boldsymbol{k_0}) = 1 \end{aligned}$$

Solution:

$$\boldsymbol{w}_{mvdr} = \frac{\boldsymbol{R}^{-1} \boldsymbol{a}(\boldsymbol{k_0})}{\boldsymbol{a}(\boldsymbol{k_0})^H \boldsymbol{R}^{-1} \boldsymbol{a}(\boldsymbol{k_0})} = \frac{\boldsymbol{R}_S^{-1} \boldsymbol{a}(\boldsymbol{k_0})}{\boldsymbol{a}(\boldsymbol{k_0})^H \boldsymbol{R}_S^{-1} \boldsymbol{a}(\boldsymbol{k_0})}$$

MV: Known problems and solutions

Known problems

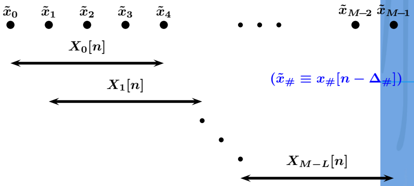
Robustness $\Longrightarrow$

- with respect to steering vector and gain differences across the array

Solutions

Diagonal loading

- Estimate $\boldsymbol{R}$ as $\tilde{\boldsymbol{R}} = \hat{\boldsymbol{R}} + \epsilon \boldsymbol{I}$



Signal cancellation $\Longrightarrow$

- cancellation of coherent signals

Sub-array averaging

- Estimate $\boldsymbol{R}$ by spatial averaging

MV (Capon) vs. Apes beamformer

- MV (Capon):
  - Minimize the spatial covariance matrix $\boldsymbol{R}$.
  - High angular resolution.
  - Known to have problems with signal cancellation and robustness.
  - Sensitive to choice of parameters.
- Apes:
  - Minimize the "interference and noise covariance matrix" $\boldsymbol{R}_S$.
  - Better amplitude estimates than MV.
  - Does not offer quite the same resolution as the MV beamformer.

Beamspace processing

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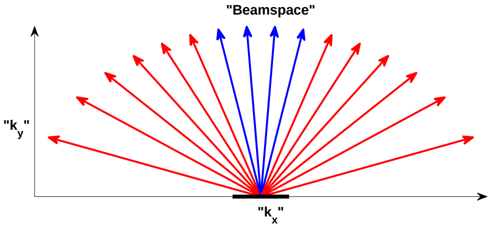
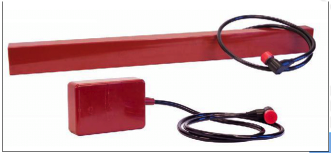
- MV/Apes: Must find $\boldsymbol{R}^{-1}$.
  - 32-els array, size of $\boldsymbol{R}$: 12×12 to 16×16.
  - Complexity: $o(12^3) = o(1728)$ to $o(16^3) = o(4096)$.
- Possibly to project our data into a subspace described by ortogonal beams; Beamspace.
  - By using 4 beams, the complexity reduces to $o(4^3) = o(64)$,
  - 64/4096 = 1/64 !!!
- Should be possible to do in real time!

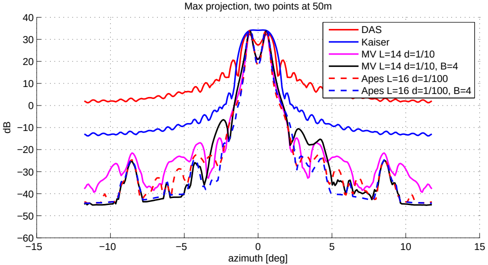


Simulated and experimental results



- HISAS 1030
  - Designed as a High Resolution Interferometric SAS system
- Used as a real aperture sonar for sector scan imaging
  - Phased-array transmitter-receiver
  - Transmitter opening angle 15 deg
  - Transmitted pulse: Chirp signal; 85-115 kHz
  - 32-element receiver, array length 120 cm
  - Receiver element opening angle 23 deg.
  - Simulated point reflectors at different depths
  - Simulated images with speckle, highlight and shadow
- and used as a side-scan sonar on experimental data

Simulated point reflectors, one meter apart, located at 50 meter and 70 meter



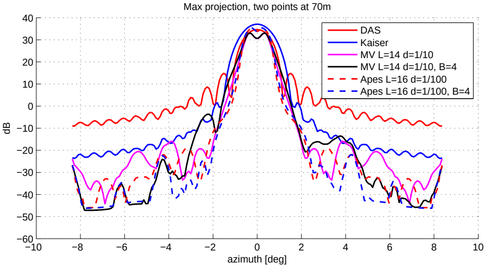


Image of speckle, highlight and shadow

A highlihgt region with diameter of 2 meter located at ≈41 meters with a constant level 15.4 dB above the average speckle region

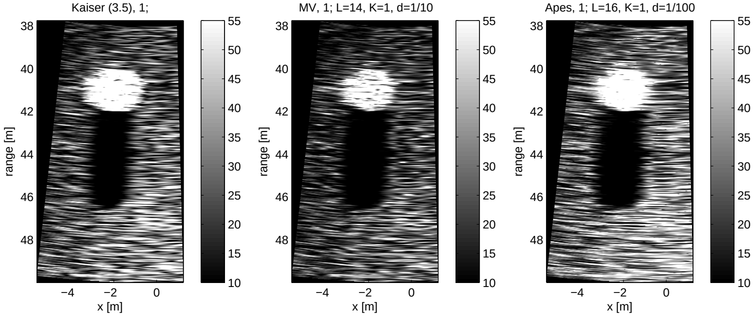


Image of speckle, highlight and shadow

Monte Carlo simulation, 100 realizations of speckle. Cut through highlight and shadow region.

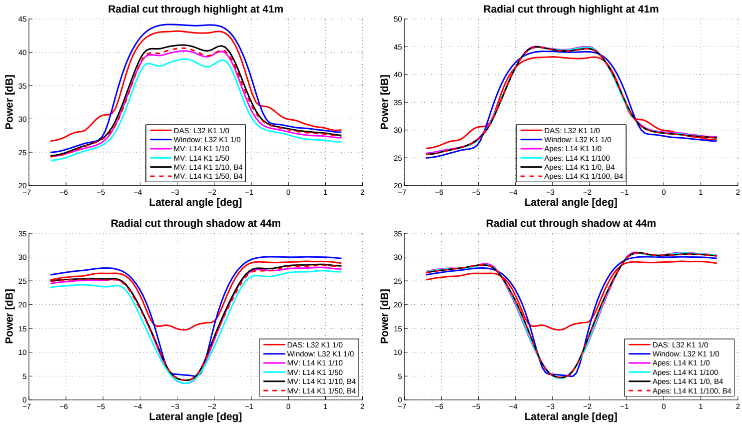
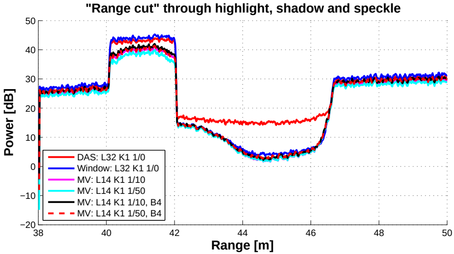
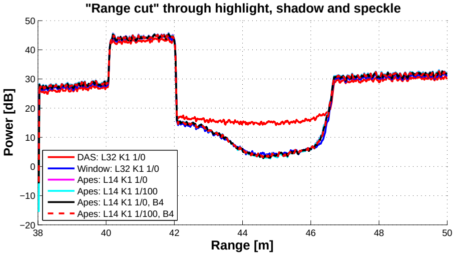


Image of speckle, highlight and shadow

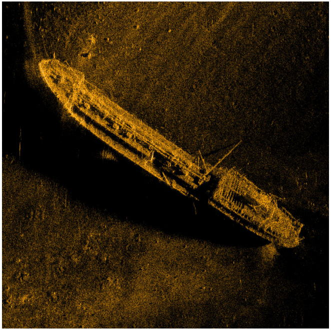
Radial through speckle, highlight and shadow regions.



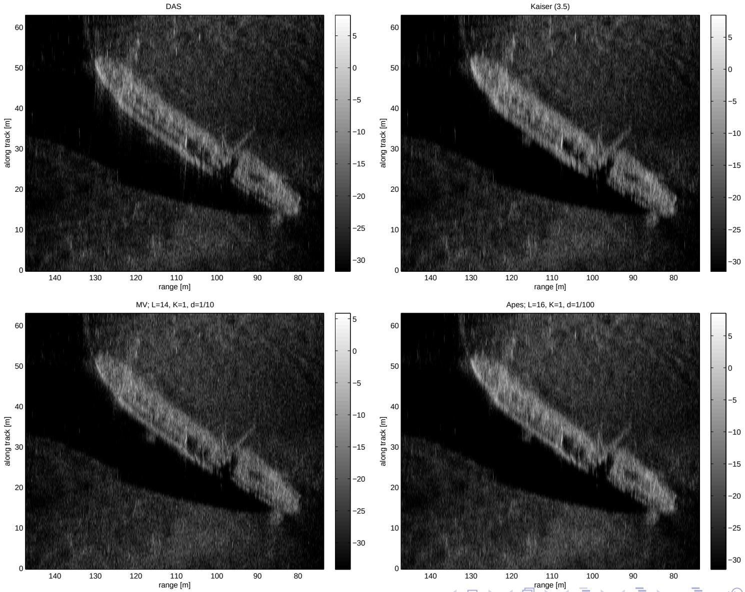


Experimental SSS images of Holmengraa

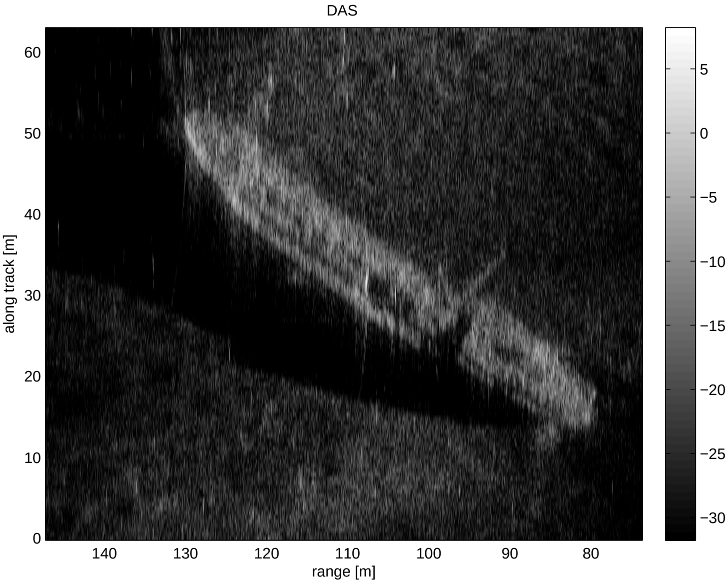
Distance to the centre of the image is about 95 m. The length of the wreck is about 68m and width about 9m. The wreck of the 1500 dwt oil tanker Holmengraa is lying on a slanted seabed at a depth of 77m.



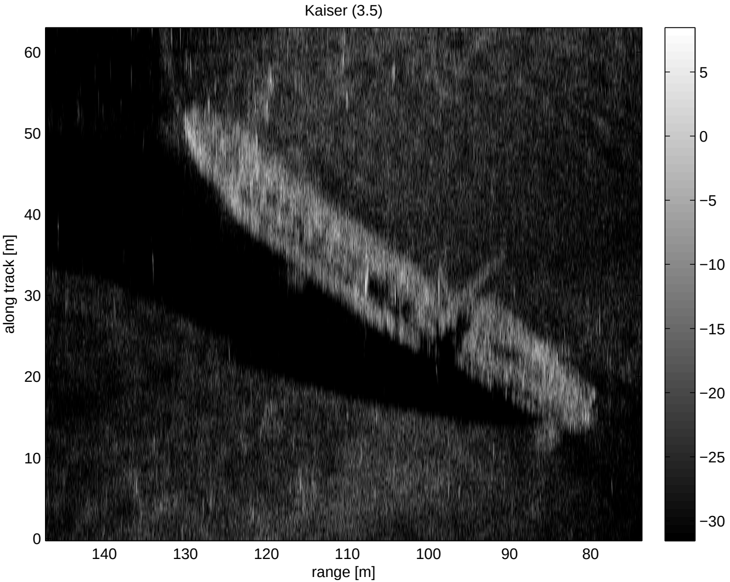
Experimental SSS images



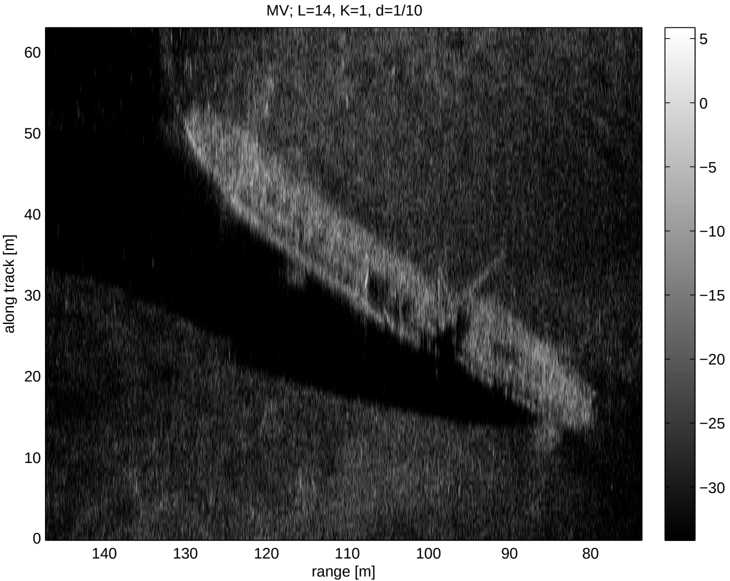
Experimental SSS images, DAS



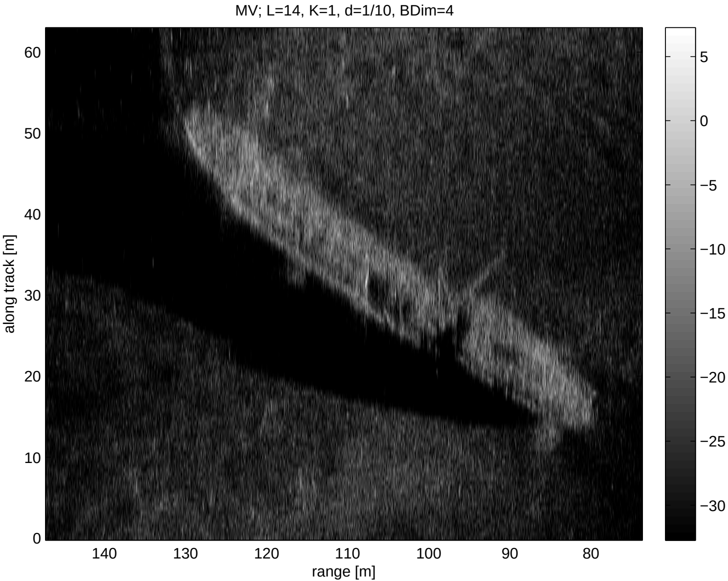
Experimental SSS images, Kaiser 3.5



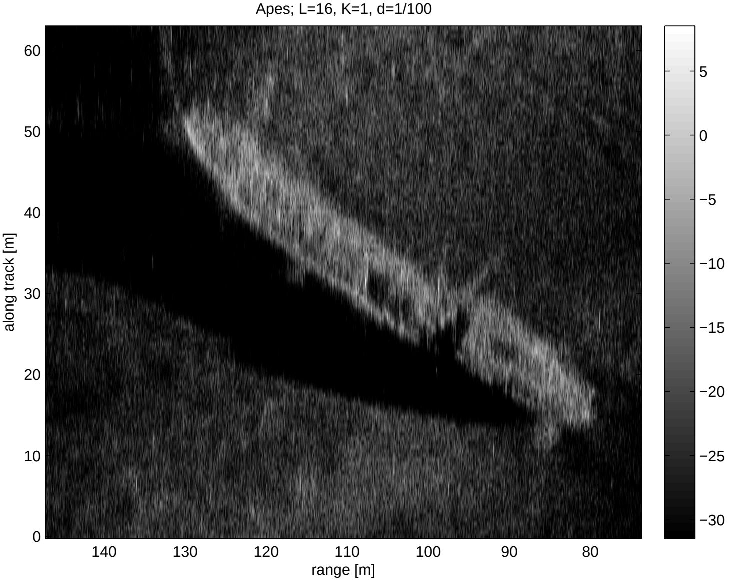
Experimental SSS images, MV



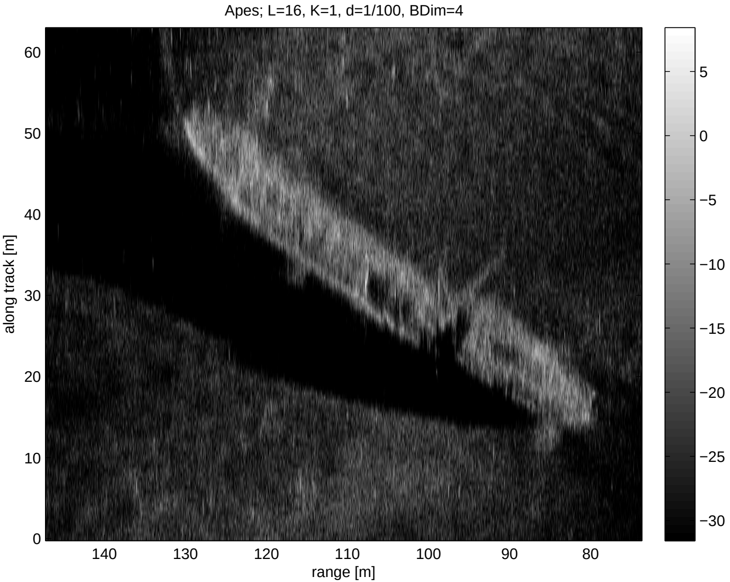
Experimental SSS images, MV, Bdim=4



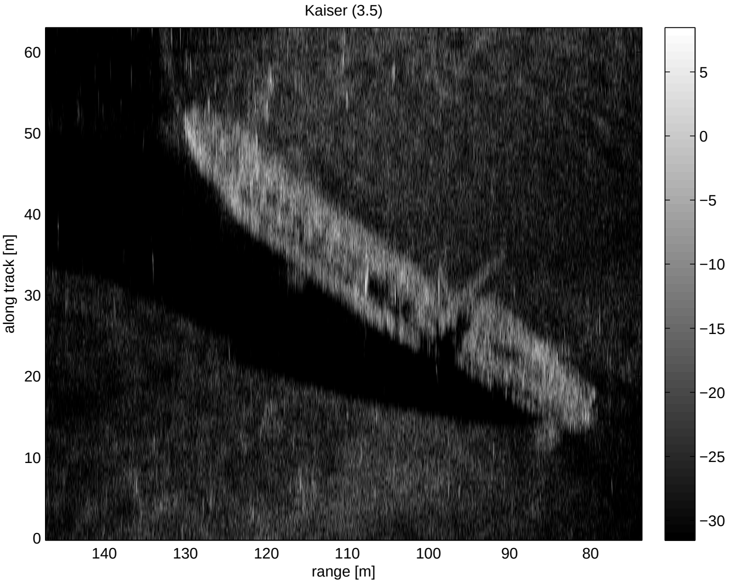
Experimental SSS images, Apes



Experimental SSS images, Apes, Bdim=4



Experimental SSS images, Kaiser 3.5



Conclusion

- Presented simulated and experimental images from conventional and adaptive beamformers
- Showed that adaptive BF produces
  - edge responses that are better or comparable with conventional BF (with or without weighting/tapering)
  - a sidelobe level or filling of shadow regions comparable to a Kaiser weighted DAS beamformer.
- Showed that beamspace processing does reduce computational complexity without degrading image quality.