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High-resolution beamforming in ultrasound imaging

Sverre Holm

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Journal Publications

- J.-F. Synnevåg, A. Austeng, and S. Holm, "Adaptive beamforming applied to medical ultrasound imaging," IEEE UFFC (Special issue on high resolution ultrasonic imaging), Aug. 2007
- J.-F. Synnevåg, A. Austeng, and S. Holm, "Benefits of High-Resolution Beamforming in Medical Ultrasound Imaging", IEEE UFFC, Sept. 2009.
- C.-I. C. Nilsen & I. Hafizovic, Beamspace Adaptive Beamforming for Ultrasound Imaging, IEEE UFFC, Oct. 2009.
- J.-F. Synnevåg, A. Austeng, and S. Holm, A Low Complexity Data-Dependent Beamformer, to appear in IEEE UFFC, 2010.
- C.-I. C. Nilsen & S. Holm, Wiener Beamforming for Ultrasound Imaging, to appear in IEEE UFFC, June 2010

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Conference Presentations

- J. Synnevåg, A. Austeng, and S. Holm, "Minimum Variance Adaptive Beamforming Applied To Medical Ultrasound Imaging," in Proc IEEE Ultrasonics Symposium, Rotterdam, Netherlands, 2005.
 - J.-F. Synnevåg, A. Austeng, and S. Holm, "High frame-rate and high resolution medical imaging using adaptive beamforming," in Proc. IEEE Ultrasonics Symposium, Vancouver Canada, Oct 2006.
 - J.-F. Synnevåg, C. I. Nielsen, and S. Holm, "Speckle Statistics in Adaptive Beamforming", IEEE Ultrasonics Symp., NY, Oct. 2007
 - A. Austeng, T. Bjastad, J.-F. Synnevaag, S.-E. Masoy, H. Torp and S. Holm "Sensitivity of Minimum Variance Beamforming to Tissue Aberrations", IEEE Ultrasonics Symposium, Nov. 2008.
 - J.-F. Synnevåg, S. Holm and A. Austeng, "Low-Complexity Data-Dependent Beamforming", IEEE Ultrasonics Symposium, Nov. 2008.
 - K. Hølfort, A. Austeng, J.-F. Synnevåg, S. Holm, F. Gran, J. A. Jensen, "Adaptive Receive and Transmit Apodization for Synthetic Aperture Ultrasound Imaging," in Proc. IEEE Ultrasonics Symposium, Rome, Italy, Sept. 2009.
 - A. Austeng, A. F. C. Jensen, J.-F. Synnevåg, C.-I. C. Nilsen, S. Holm, "Image Amplitude Estimation with the Minimum Variance Beamformer," in Proc. IEEE Ultrasonics Symposium, Rome, Italy, 2009.
 - A. E. A. Blomberg, I. K. Hølfort, A. Austeng, J.-F. Synnevåg, S. Holm, J. A. Jensen, "APES Beamforming Applied to Medical Ultrasound Imaging" in Proc. IEEE Ultrasonics Symposium, Rome, Italy, Sept. 2009.
- Sonar:
- A. E. A. Blomberg, A. Austeng, R.E. Hansen, S. Holm, "Minimum Variance Adaptive Beamforming Applied to a Circular Sonar Array," Underwater Acoustic Measurements: Technologies & Results, Greece, June 2009.
 - S. Jetlund, A. Austeng, R.E. Hansen, S. Holm, "Minimum variance adaptive beamforming in active sonar imaging," Underwater Acoustic Measurements: Technologies & Results, Greece, June 2009.

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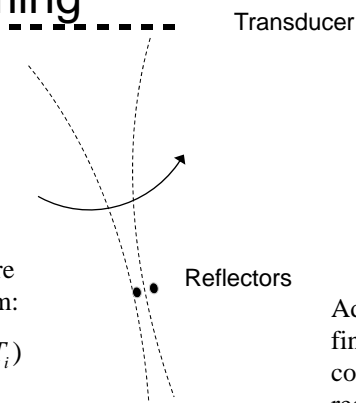


Beamforming

Delay-and-Sum, DAS:
Pre-determined aperture
shading, delay, and sum:

$$A(t) = \sum_{k=1}^M w_i x_i(t - T_i)$$

w_i : typ. rectangular or
Hamming
(real, symmetric)



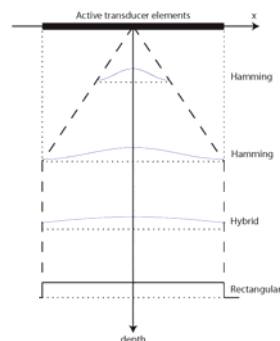
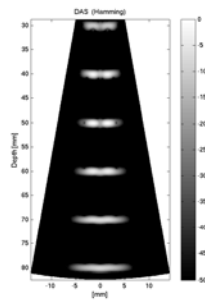
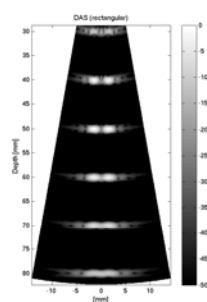
Adaptive beamformers
find w_i from spatial
correlations in the
recorded data, i.e. they
adapt to the data

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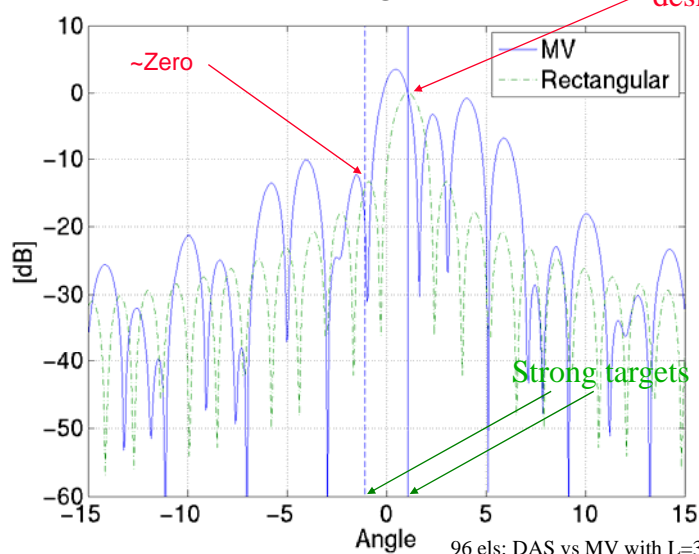
Rectangular or Hamming?



5

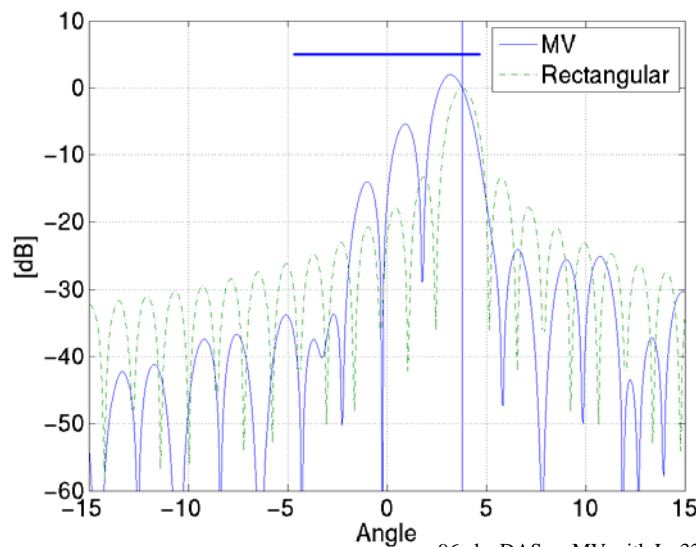


Examples of beampatterns (two wiretargets, 80 mm)





Beampatterns (cyst)



Origins

- J. Capon, "High-resolution frequency-wavenumber spectrum analysis," *Proc. IEEE*, pp. 1408–1418, 1969.
- Finn Bryn, "Optimum Signal Processing of Three-Dimensional Arrays Operating on Gaussian Signals and Noise," *Journ. Acoust. Soc. Am.*, pp. 289-297, 1962.



Terminology

- High resolution beamforming
- Minimum variance beamforming
- Capon beamforming
- Adaptive beamforming
 - But not phase aberration correction



Beamforming: Matrix formulation

- Single-frequency output of beamformer:
 $y = w'x$, where w has phase
- Power: $P_{yy} = yy' = w'x(w'x)' = w'xx'w = w'R_{xx}w$
- Signal, $x \propto e$, steering vector
- Broadband: sum over all frequencies
 \Leftrightarrow delay-and-sum beamformer:

$$y(t) = \sum_{m=0}^{M-1} w_m y_m(t - \Delta_m)$$



Steering vector

- Signal, $x \propto e$, steering vector

$$e = \begin{bmatrix} \exp(-j \cdot \vec{k}_0^0 \cdot \vec{x}_0) \\ \vdots \\ \exp(-j \cdot \vec{k}_{M-1}^0 \cdot \vec{x}_{M-1}) \end{bmatrix}$$

- Plane wave: $\vec{k}_m^0 = \vec{k}^0 = \frac{2\pi}{\lambda} \vec{\zeta}$
- Uniform Linear Array: $\vec{x}_m = m \cdot d \cdot \vec{i}_x$
- Plane wave on ULA:

$$\exp(-j \cdot \vec{k}_m^0 \cdot \vec{x}_m) = \exp(-j \frac{2\pi}{\lambda} m \cdot d \cdot \vec{\zeta} \cdot \vec{i}_x) = \exp(-j \frac{2\pi \cdot m \cdot d}{\lambda} \sin \phi)$$



Minimum variance beamforming

- Minimize output power: $\min_{\mathbf{w}} \mathbf{w}^H \mathbf{R} \mathbf{w}$
 $\mathbf{a} = \bar{\mathbf{1}}$
- subject to unity gain in desired direction: $\mathbf{w}^H \mathbf{a} = 1$
- Because of pre-steering and pre-focusing (straight ahead): $\mathbf{a} = \bar{\mathbf{1}}$



Minimum variance

- Weight:

$$w = \frac{R^{-1}e}{e^H R^{-1}e}$$

- Complex weights vary with covariance matrix, i.e. the data and direction (in e)
- Results in adaptive suppression in the direction of the largest interferers
- Result: $P_{MV} = w^H R_{xx} w = 1/(e^H R^{-1} e)$



Minimum variance beamforming

- In practice R is replaced by the sample covariance matrix
 - Only a few time-samples are available
- Averaging in space and time
 - Subaperture averaging
 - » J. E. Evans, J. R. Johnson, and D. F. Sun, "High resolution angular spectrum estimation techniques for terrain scattering analysis and angle of arrival estimation," Proc. 1st ASSP Workshop Spectral Estimation, Hamilton, Ont., Canada, pp. 134–139, 1981.
 - Diagonal loading: R is replaced by $R + \delta \cdot \text{tr}\{R\} \cdot I$
 - » J. Li, P. Stoica, and Z. Wang, "On robust Capon beamforming and diagonal loading," *IEEE Trans. Signal Processing*, vol. 51, no. 7, pp. 1702–1715, July 2003.

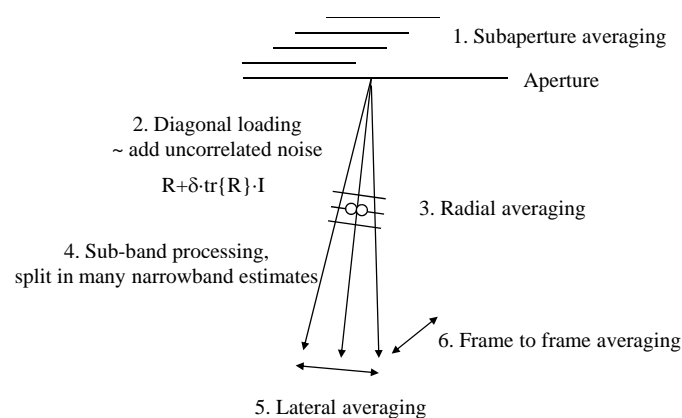


Adaptation to Medical Ultrasound

- Focused System
 - Pre-beamforming of receiver: steering and focusing
 - Adaptive beamformer only applies complex weights to model deviations
- Transmitter beam
 - Unfocused or focused beam like in medical scanners
 - Single beam, ~omnidirectional:
 - Plane wave as in acoustic streaming imaging
- From Passive to Active System
 - Coherence
 - Target cancellation
 - Illustrated in next plots

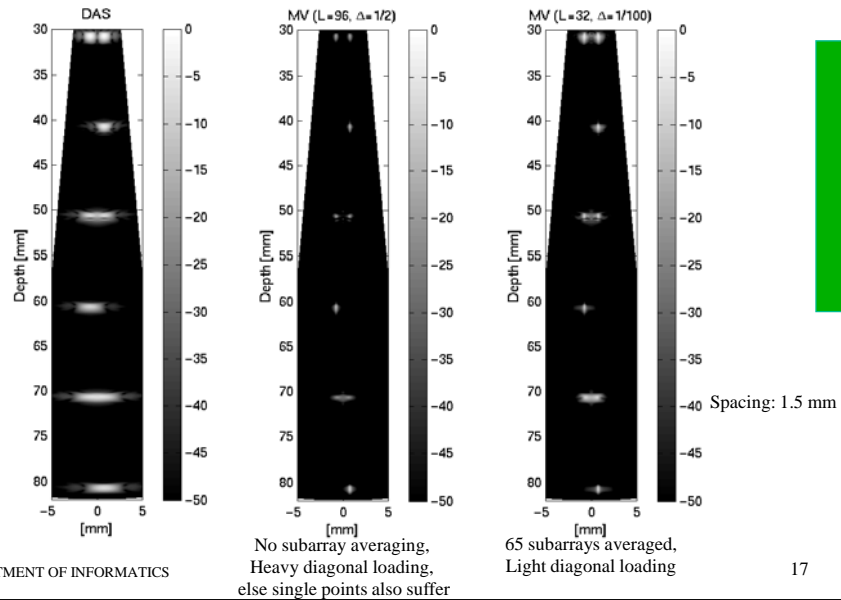


Smoothing and conditioning



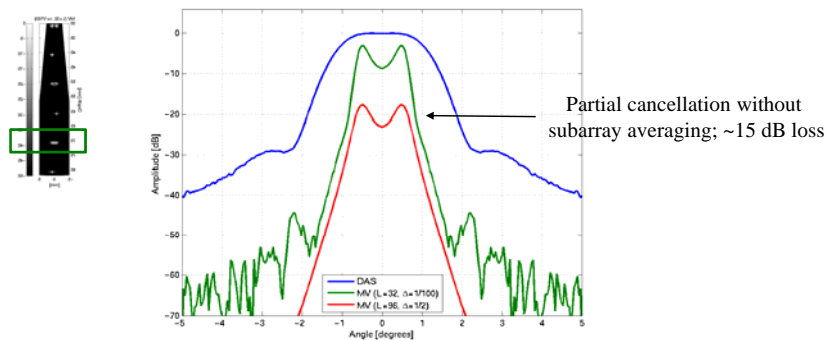


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Two targets, unresolvable by DAS

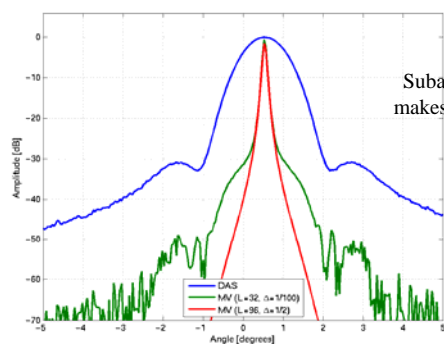


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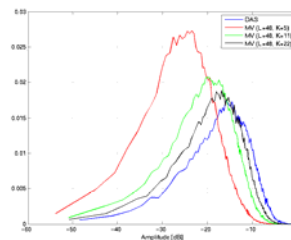
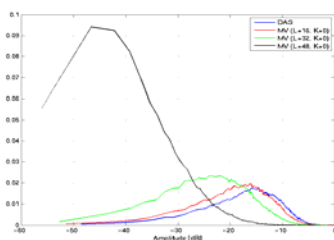
Single target



Subarray averaging
makes little difference

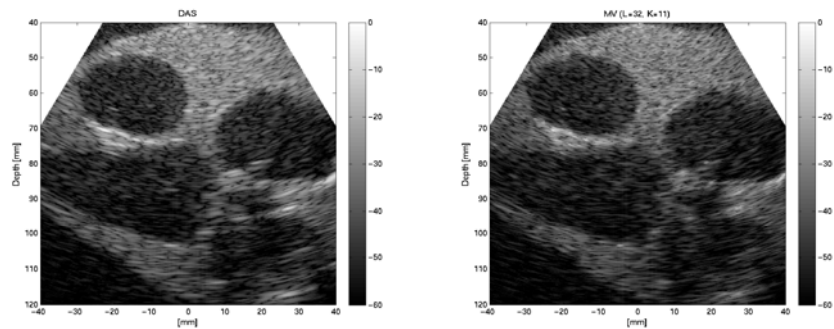


Distribution of pixel amplitudes





Heart phantom



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Preferred approach

- Subarray averaging:
 - Ensures a good covariance matrix estimate
 - Is essential to avoid cancellation due to coherence.
- Diagonal loading:
 - For robustness
- Radial averaging
 - Improved speckle
 - Only for covariance estimate, not for beamforming



Related work

- Mann and Walker, Ultrasonics 2002
 - Beamwidth reduction and sidelobe suppression
 - » No subaperture averaging, only single wire target, less coherency problems
 - Improved contrast on cyst phantom
 - Frost beamformer – Capon with FIR
- Sasso and Cohen-Bacrie (Philips), ICASSP 2005
 - Improved contrast on simulated data
 - Subaperture averaging and time averaging over neighbor beams
- Wang, Li, Wu, IEEE Trans. Med., Oct. 2005 & Synnevåg et al, Ultrasonics 2005:
 - Robustness with diagonal loading, tested on array with random element position errors
 - Only tested on single wire target and cysts, not tested handling of coherent targets
- Synnevåg et al, IEEE TUFFC, 2007
 - two very close targets, closer than the limit which can be resolved by DAS. Using this scenario, we have demonstrated that better resolution than DAS was possible even with coherent targets
 - Improved resolution and contrast on wire pairs and heart phantom
- Holfort et al. (IEEE Ultrason. Symp 2007)
 - implicit time averaging since they split the transducers bandwidth into independent bands by FFT, performed independent high resolution beamforming per band, and combined them.
 - Single transmission: very high frame rate
- Synnevåg et al, Ultrasonics 2007:
 - Time averaging over small range gate: better speckle statistics
- Vignon and Burcher (Philips), T. UFFC March 2008
 - First clinical images: in-vivo heart and abdominal images



Comments

- Fall-back to delay-and-sum:
 - Subaperture averaging as the subaperture size $\rightarrow 1$:
 - » = delay-and-sum beamforming
 - Diagonal loading as the diagonal term becomes dominant:
 - » = delay-and-sum beamforming
- Variation of a single parameter allows one to adjust the method so that it falls back to conventional delay-and-sum beamforming.
- Challenge:
 - How to do subaperture averaging on a curved transducer? (curved array or sonar array)

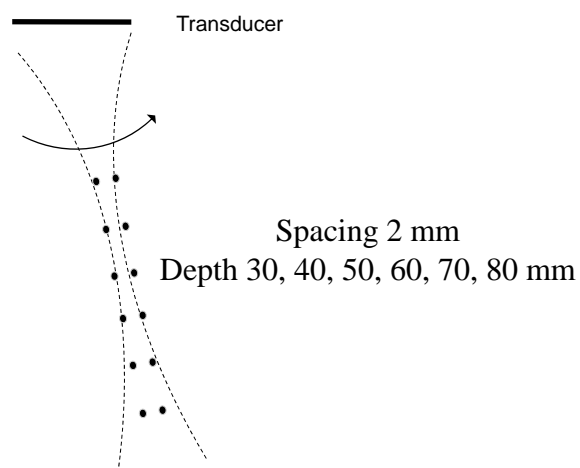


Results: simulated data

- Field II
- 96 element, 4 MHz transducer
- All transmitter / receiver combinations
- Applied full dynamic focus
- White gaussian noise added

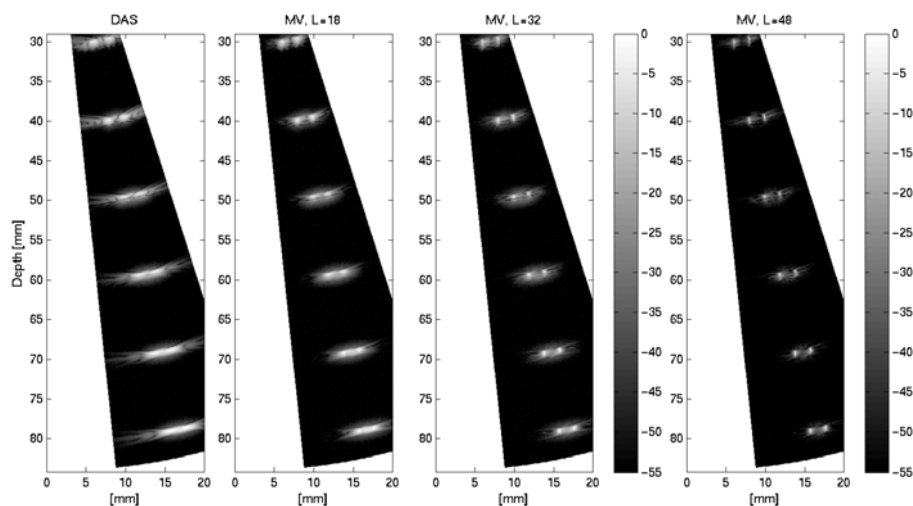


Simulated data-set





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Parameters

- Aperture: $M=96$
- Subapertures that overlap with $L-1$ elements
 - $L=48$, $96-48+1 = 49$ averages
 - $L=32$, $96-32+1 = 65$ averages
 - $L=18$, $96-18+1 = 79$ averages
- Small amount of diagonal loading
 - R is replaced by $R + \delta \cdot \text{tr}\{R\} \cdot I$
 - Ensures good conditioning of R
 - Default: $\delta=1/(100 \cdot L)$ where diagonal term is $\varepsilon = \delta \cdot \text{tr}\{R\}$
 - [Have also used up to $\delta=1/L \Leftrightarrow$ i.e. same variance for R and the added white noise]

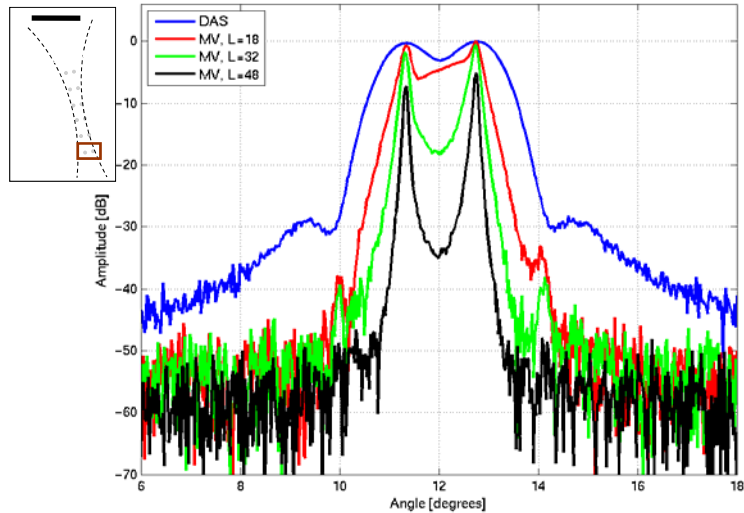
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80 mm depth



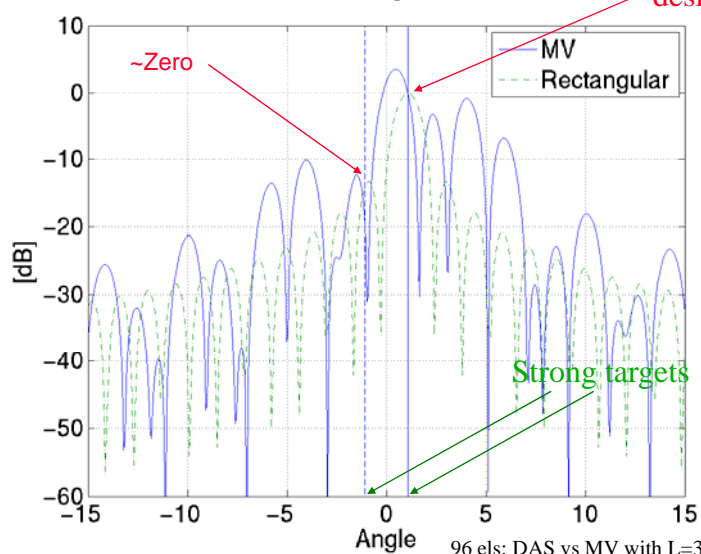
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Examples of beampatterns (two wire targets, 80 mm)



DEP

96 els: DAS vs MV with L=32 & K=0 30

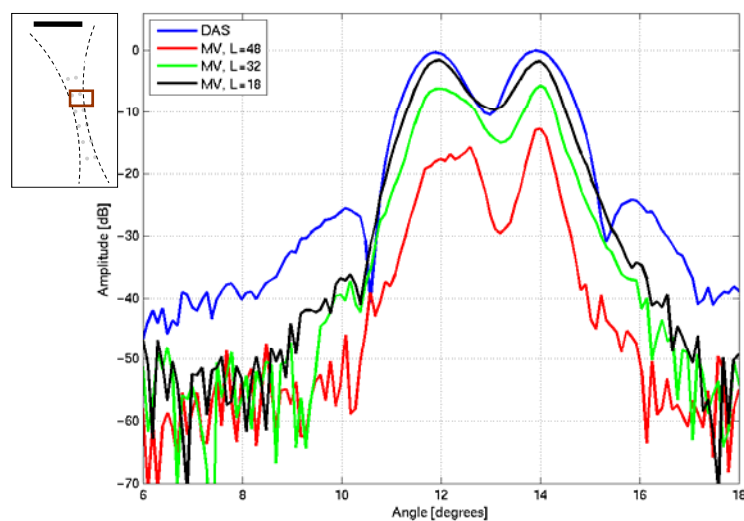


Robust adaptive beamforming

- Processed the data with 5% error in acoustic velocity
- Applied regularization:
 - Replaced \mathbf{R} with $\mathbf{R} + \epsilon \mathbf{I}$
 - Large $\epsilon \Rightarrow$ delay-and-sum



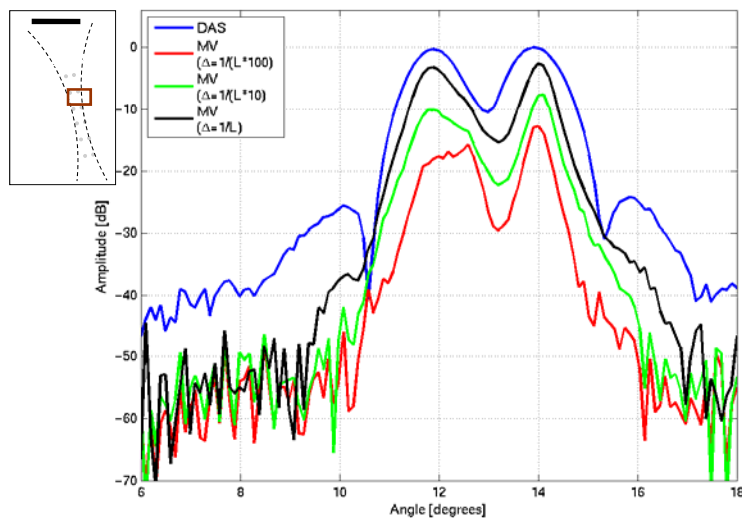
5 % error in c: Sensitivity to subarray size





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5 % error in c ($L=48$) Sensitivity to diagonal term



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Phase aberrations

- Point target at 70 mm, 2.5 MHz 64 element phased array
- 1D aberrations: time-delays as if the aberrator was on the transducer surface.
- Unweighted delay-and-sum (DAS) beamformer and a MV beamformer.
 - A. Austeng, T. Bjåstad, J.-F. Synnevaag, S.-E. Masøy, H. Torp and S. Holm "Sensitivity of Minimum Variance Beamforming to Tissue Aberrations", IEEE Ultrasonics Symposium, Nov. 2008.

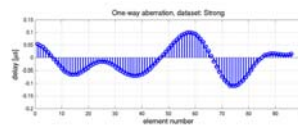
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Aberrator

- Correlation length: 2.46 mm
- Delay
 - » Weak (imaging through thorax): 21 ns rms/90 ns peak
 - » Intermediate (abdominal imaging): 35 ns rms/150 ns peak
 - » Strong (abdominal imaging): 49 ns rms/210 ns peak
 - » Very strong (breast imaging): 68 ns rms/290 ns peak



Results, phase aberration

- Main lobe of the MV beamformer was narrower or approximately equal to that of DAS
 - -6 dB lateral beamwidth being 40%, 67%, 83%, and 106% of DAS for the four cases.
- The aberrations affected the sidelobe structure producing non-symmetric patterns, but with comparable values for the maximum sidelobe levels.
 - For the weak aberrator, the MV beamformer performed better (1-5 dB) than the DAS beamformer.
- A slight reduction in sensitivity.
 - Very strong aberration: the main lobe value was decreased by 1.4 dB compared to the DAS beamformer.
 - For the other scenarios: the decrease was 0.9, 0.6, and 0.4 dB.



Phase aberrations and MV

- MV – balancing of performance and robustness.
 - Spatial smoothing, diagonal loading, time averaging over about a pulse length
- MV: substantial decrease in main lobe width without increase in sidelobe level in aberrating environments.
 - It does not degrade the beam even with very strong aberrators.
 - MV can handle realistic aberrations with a performance which is better than or equal to that of DAS.



Experimental data

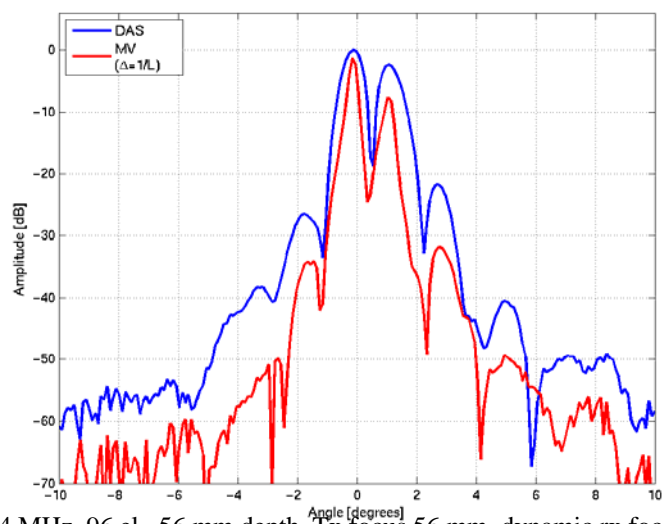
- Specially programmed GE Vingmed ultrasound scanner
 - » 96 element, 3.5 MHz transducer @ 4 MHz
 - » Specially made wire target, spacing 2 mm
- Biomedical Ultrasound Laboratory, University of Michigan
 - » 64 element, 3.5 MHz transducer
 - » heart-phantom





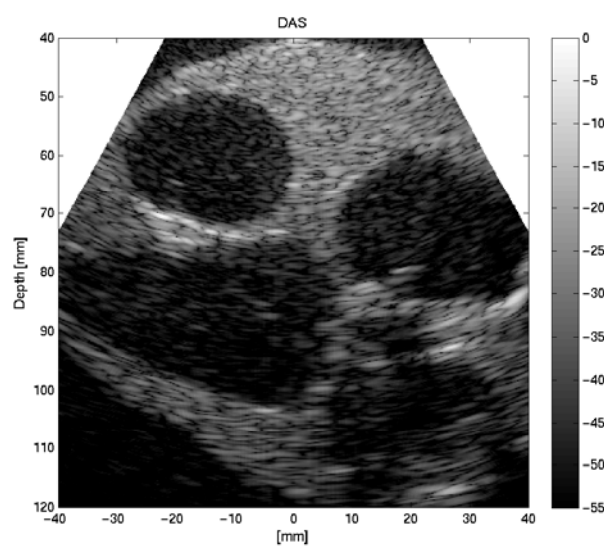
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Point targets: GEVU scanner



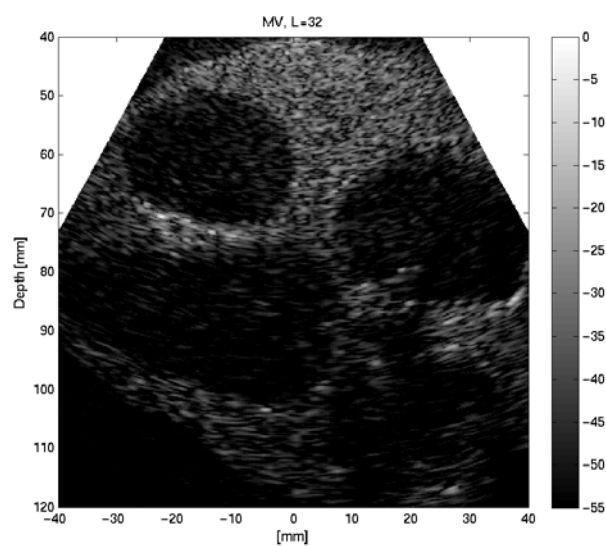
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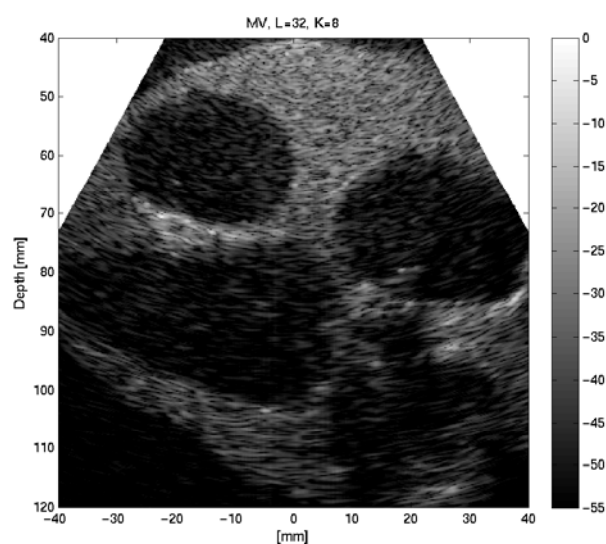
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L=32 subaperture, no time averaging, $\delta=1/(10 \cdot L)$

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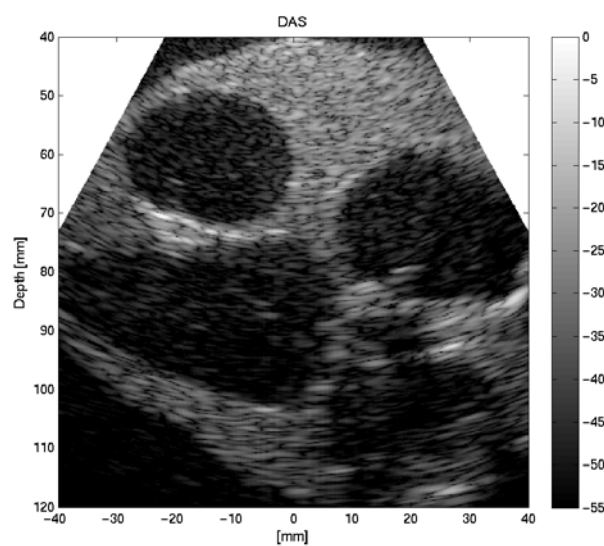
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L=32 subaperture, $2K+1=17$ time averages, $\delta=1/(10 \cdot L)$

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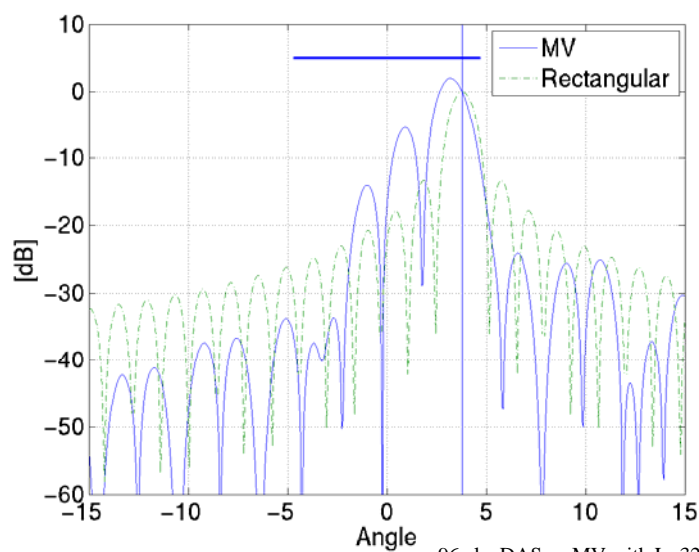
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Beampatterns (cyst)



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96 els: DAS vs MV with $L=32$ & $K=0$ 44

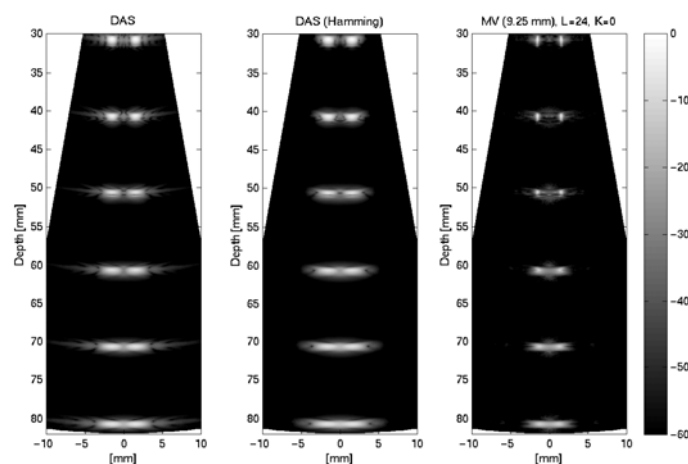


Other benefits than resolution

- Reduced transducer size
 - 18.5 mm transducer (DAS) vs 9.25 mm transducer (MV)
- Parallel receive beamforming
 - 32 Tx/rx lines (DAS) vs. 8 Tx lines (MV with 4 parallel beams)
- Increased penetration depth
 - 3.5 MHz transmission (DAS) vs. 2 MHz transmission (MV)
- Synnevåg et al "Benefits of High-Resolution Beamforming in Medical Ultrasound Imaging", IEEE UFFC, Sept. 2009.



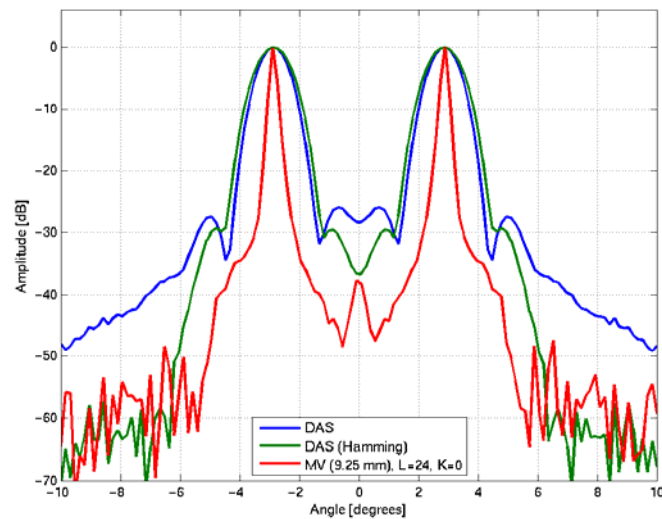
Half the transducer size





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Half the transducer size (2)



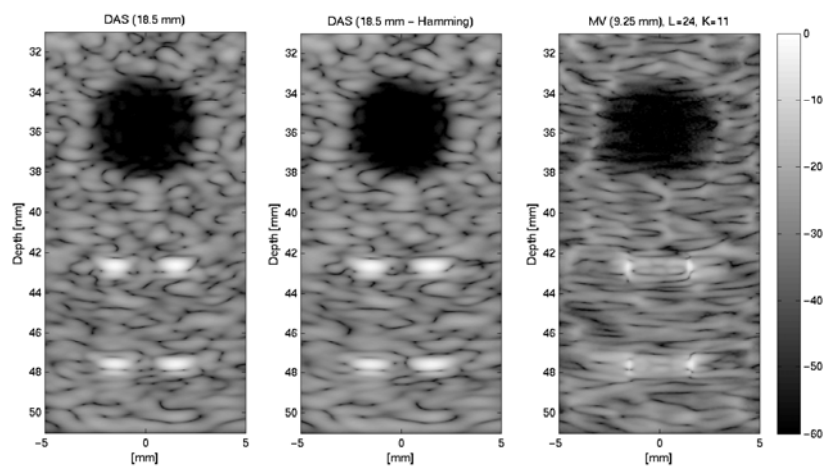
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Half the transducer size (3)



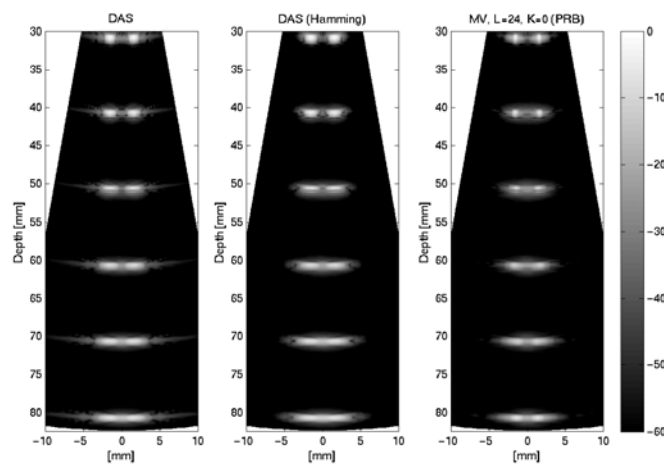
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4 times wider transmit beam
& parallel receive beams
= 4 times the frame rate



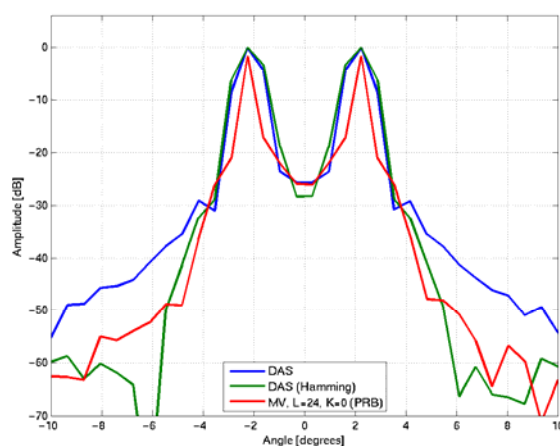
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Parallel receive beams (2)



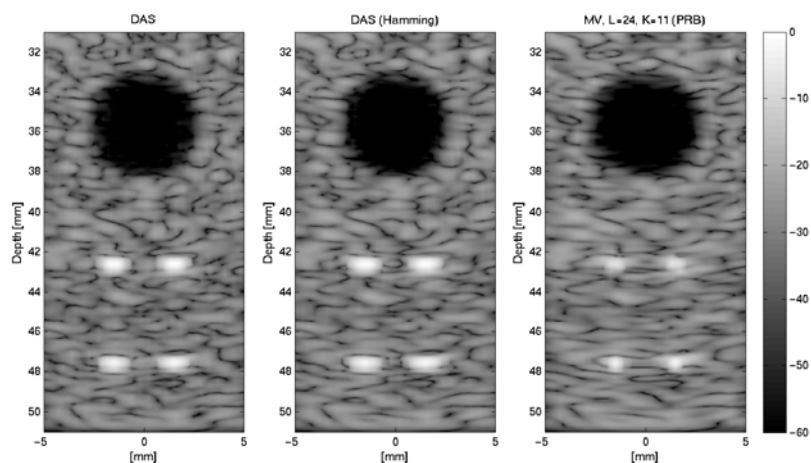
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Parallel receive beams (3)



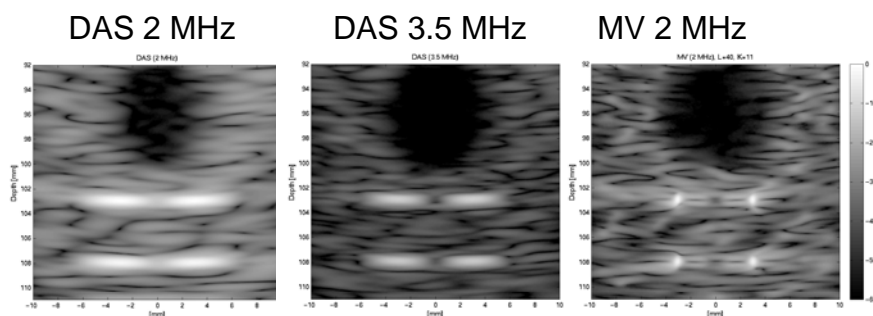
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2 MHz vs. 3 MHz transmission



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Computational cost

- M elements, L-size subarrays
- Delay is the same as for delay-and-sum
- Matrix inversion $2L^3/3$ or $O(L^3)$ + estimation of weights
 - Saves computations by using smaller subarrays, L, instead of more diagonal loading
- Application of weights (= DAS): $O(M)$



Simplified Capon

- Select the window with smallest output among $P=4-12$ pre-defined windows rather than estimate window from data
 - No matrix inversion $2L^3/3$, only $P \times$ DAS: $2P \cdot M$
 - » Ex: $M=96$, $L=32 \Rightarrow 2L^3/3 \approx 22000$ vs $P=10$: $2P \cdot M \approx 2000$
 - More robust than Capon: no possibility for signal cancellation if windows have been chosen properly
- J.-F. Synnevåg, A. Austeng, and S. Holm, A Low Complexity Data-Dependent Beamformer, to appear in IEEE UFFC, 2010.



Conclusion

- Applied MV beamformer to medical ultrasound imaging
- Balancing of performance and robustness.
 - Spatial smoothing which is important for dealing with multiple reflectors
 - Diagonal loading which helps make the method robust
 - Time averaging over about a pulse length in estimating the covariance matrix. The latter ensures that the speckle resembles that of DAS.
- Shown improvement in image quality of realistic images
- Demonstrated 3 examples where MV may be beneficial
 - Smaller aperture, higher framerate, lower frequency
- Several methods for reducing computational cost
- Needs more testing on relevant image data