UiO : Department of Informatics
University of Oslo

Processing the data twice: Minimum variance as an alternative to geometry-based beamforming

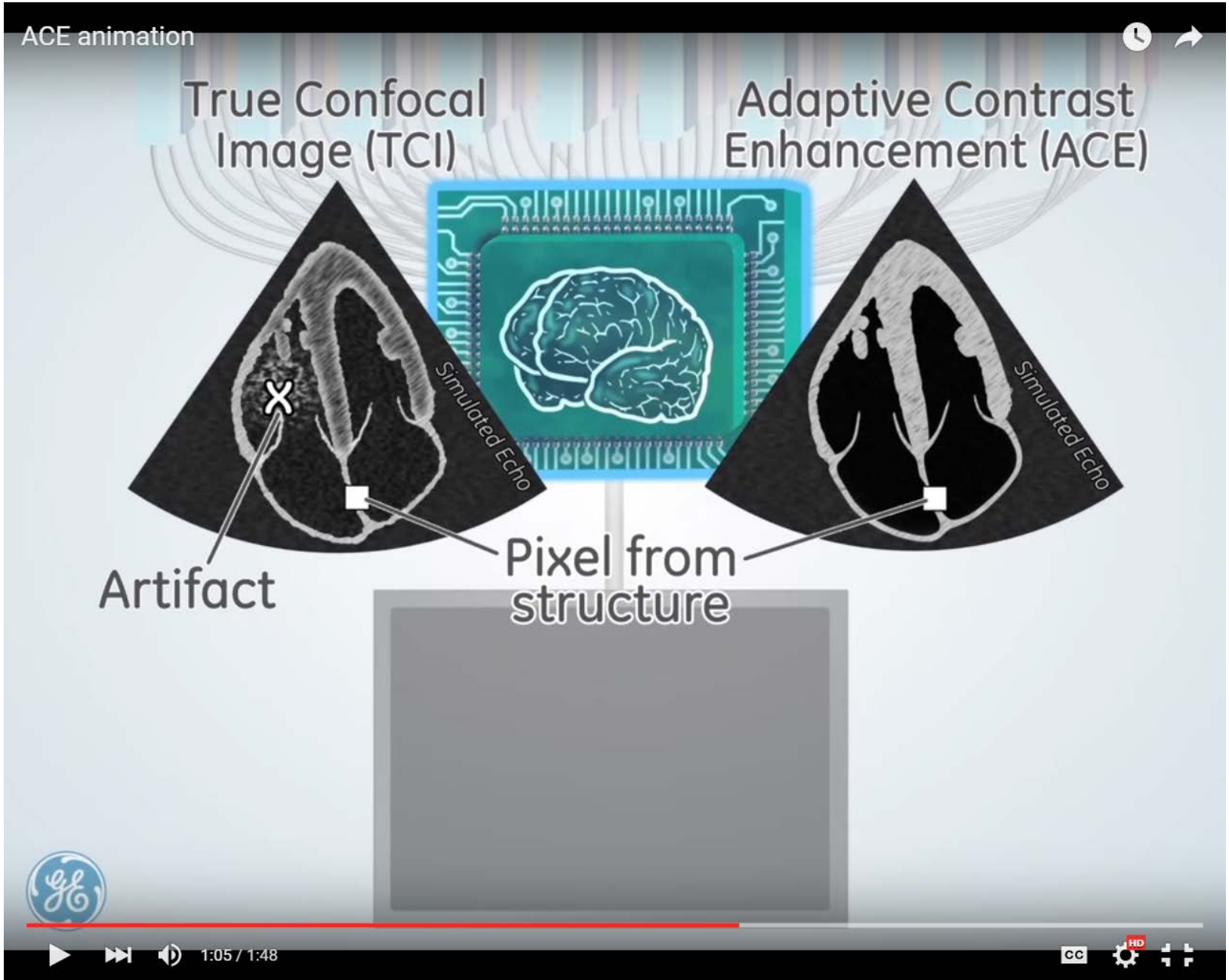
Sverre Holm

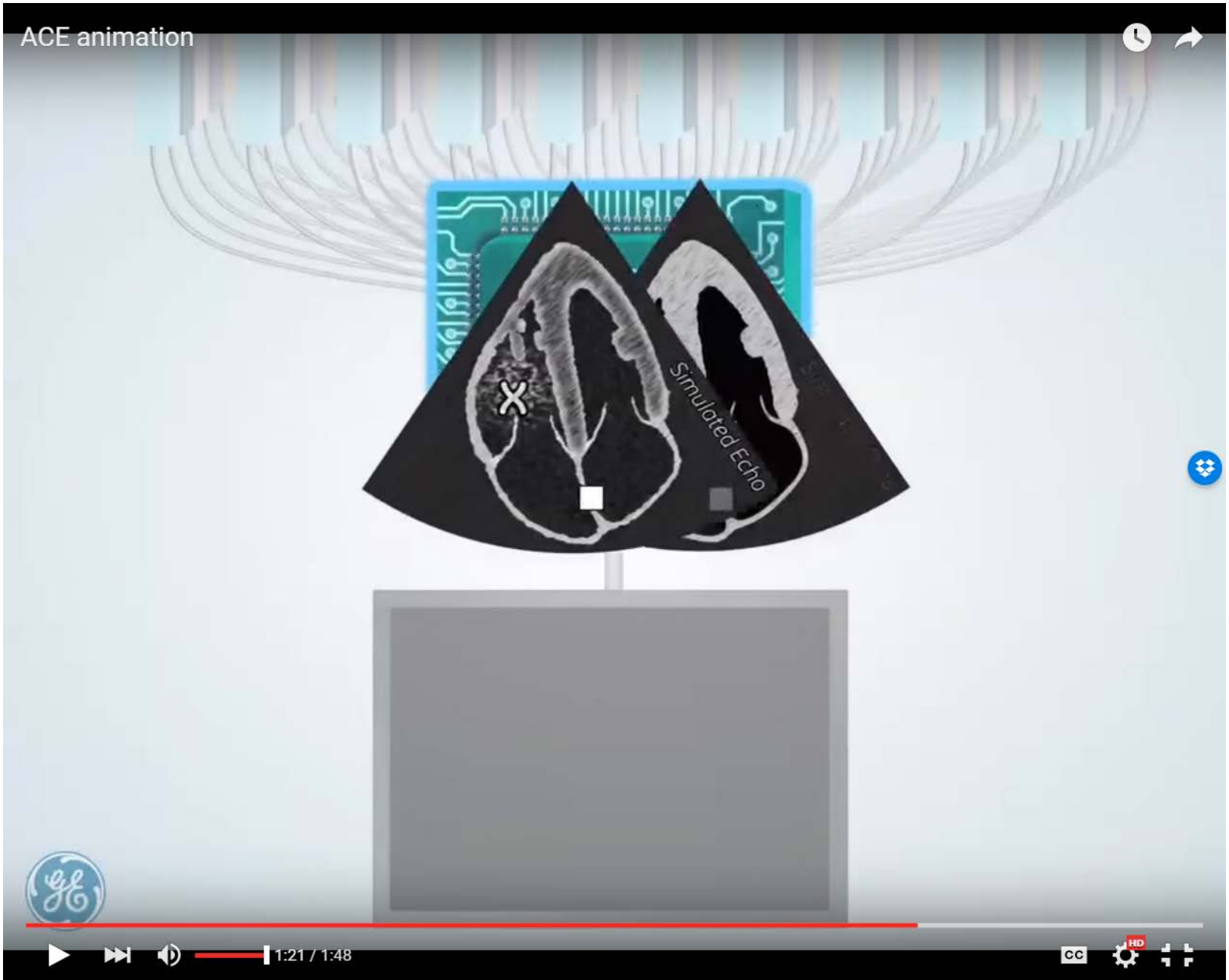
AIUM, 21 March 2016, New York

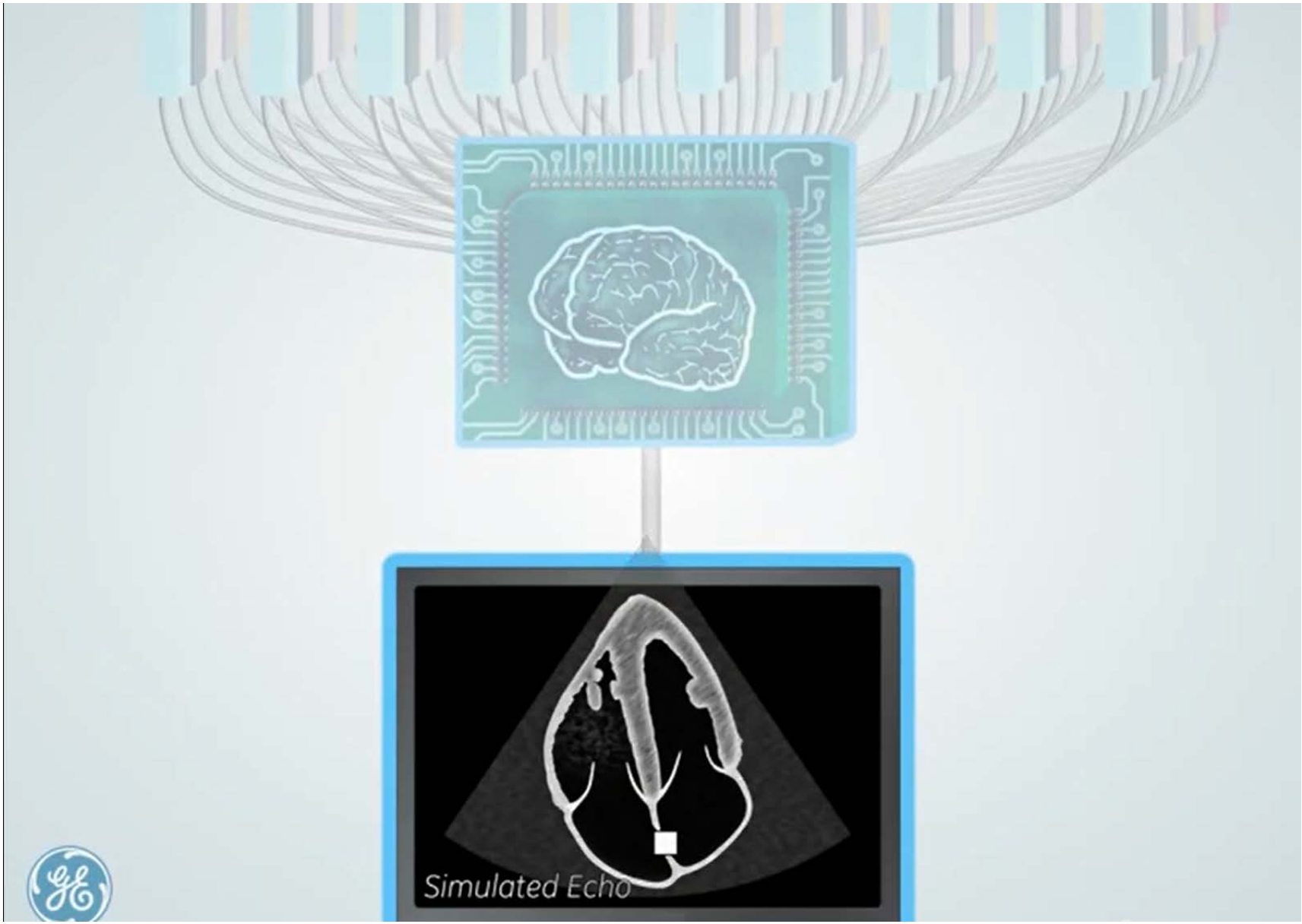
Centre for Innovative Ultrasound Solutions
For health care, maritime, and oil & gas

Now: software-beamforming

- No longer need for dedicated hardware for digital beamforming
- May consider more complex forms of beamforming than geometry-based
- Alternatives to delay-and-sum

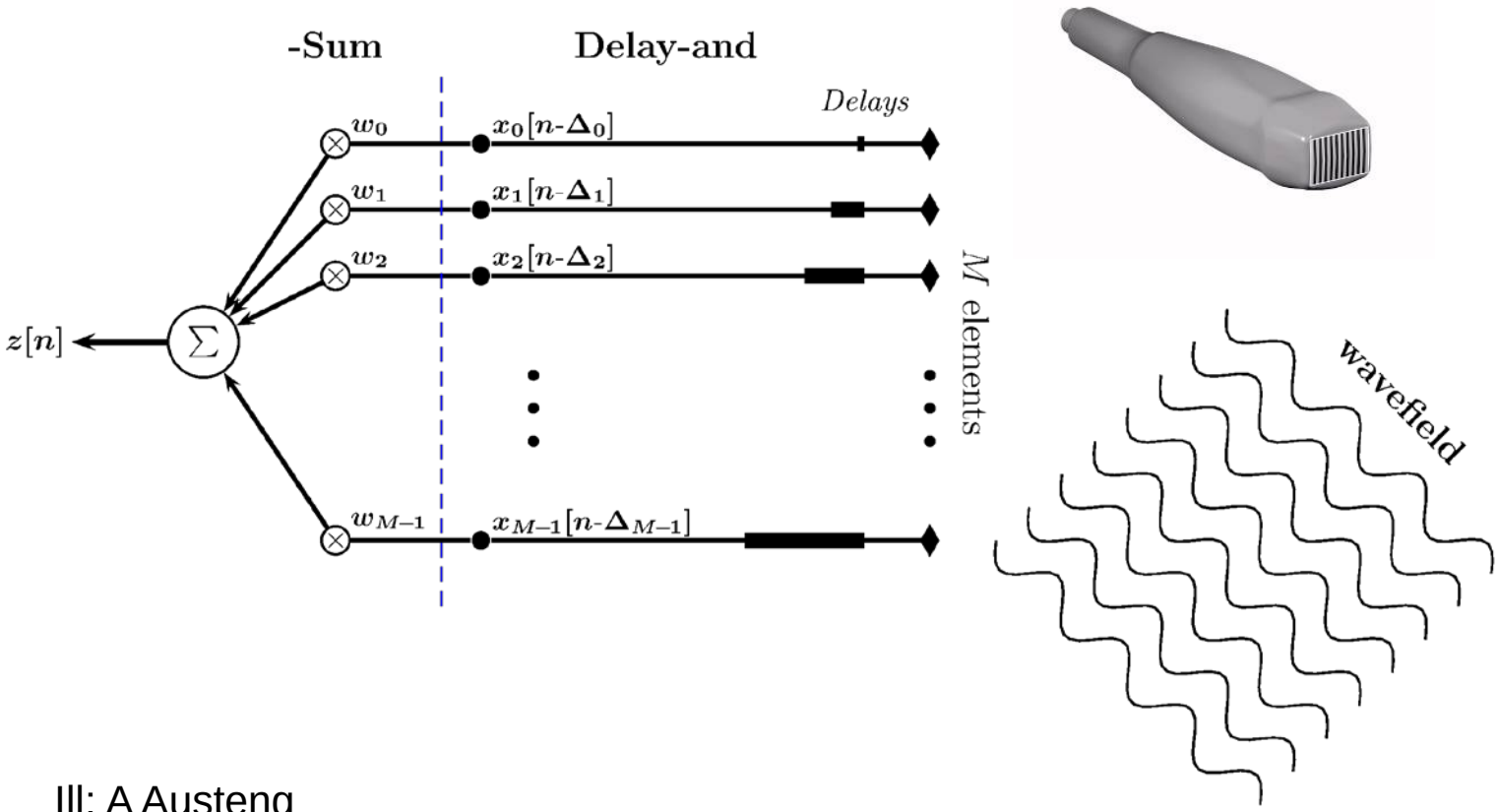

ACE animation
True Confocal Image (TCI)
Adaptive Contrast Enhancement (ACE)
Simulated Echo
Simulated Echo
Artifact
Pixel from structure
1:05 / 1:48


ACE animation
Simulated Echo
1:21 / 1:48
CC
HD


Simulated Echo

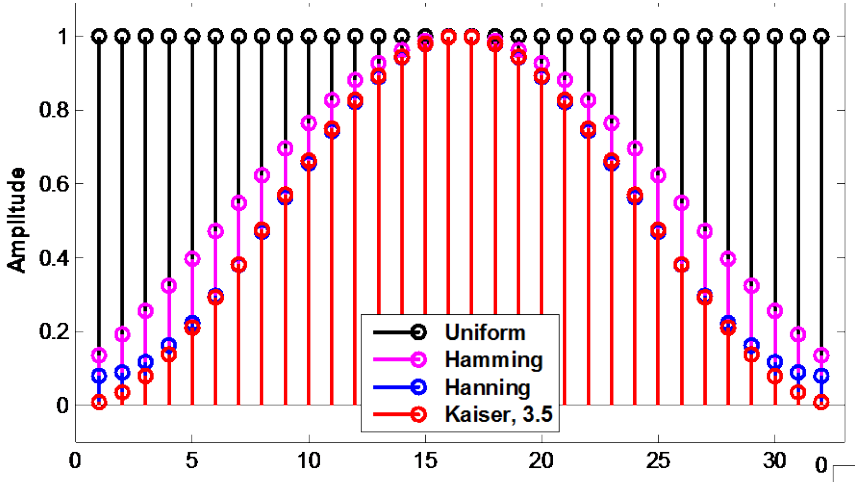
1. Processing the data twice
2. History of adaptive beamforming
3. A new look at window functions
4. More than resolution
5. Several beamformers in parallel

Delay-and-sum (DAS) beamformer

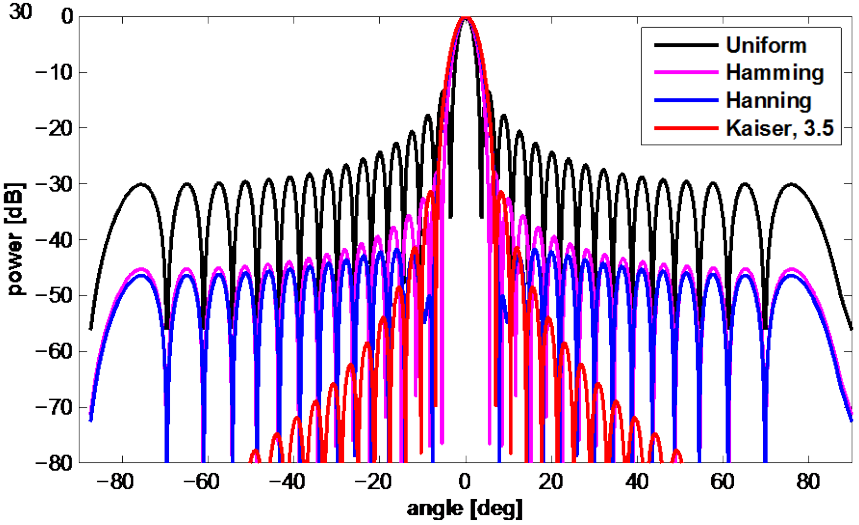


Ill: A Austeng

DAS uses predefined windows



Typical window functions



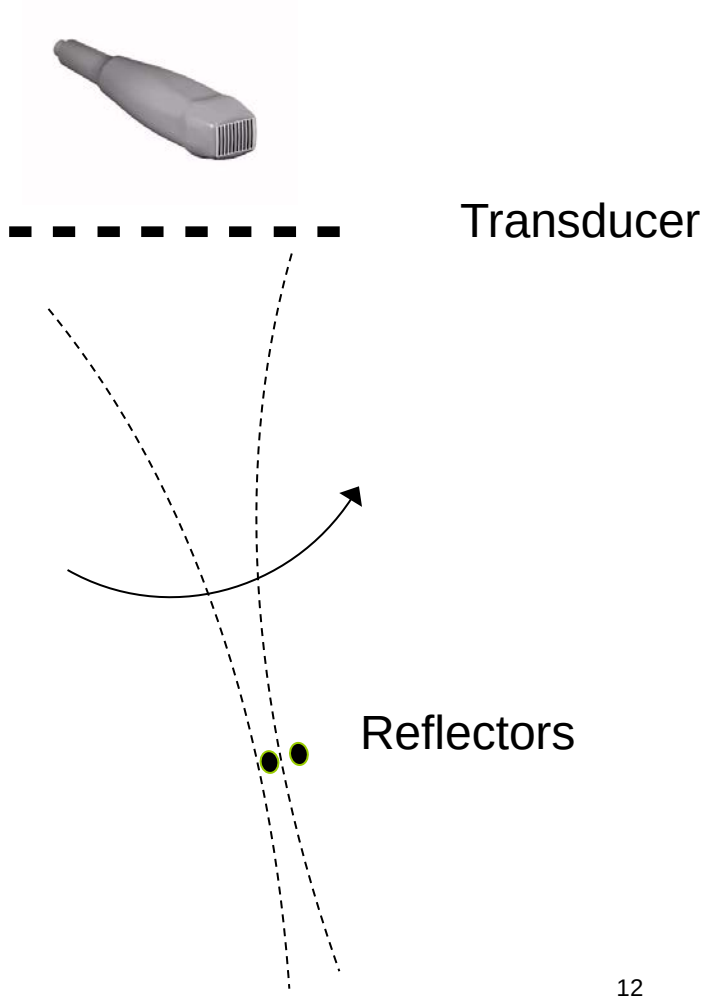
Spatial response of window functions

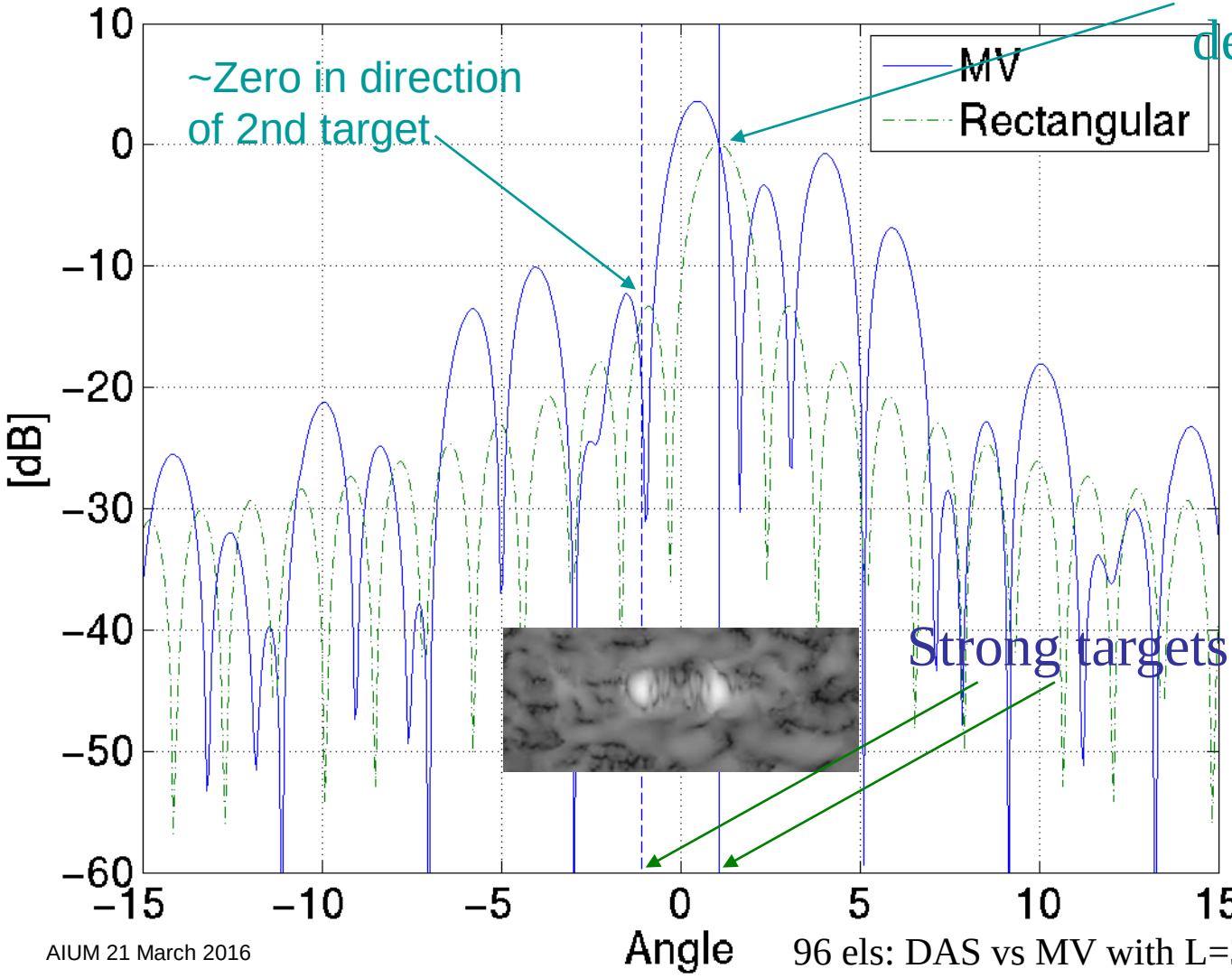
Ill: A Austeng

Image = Beamformer's response x Data

- OK with high sidelobes if there are no reflectors
- Can we take this into account and compute the weights from the data?

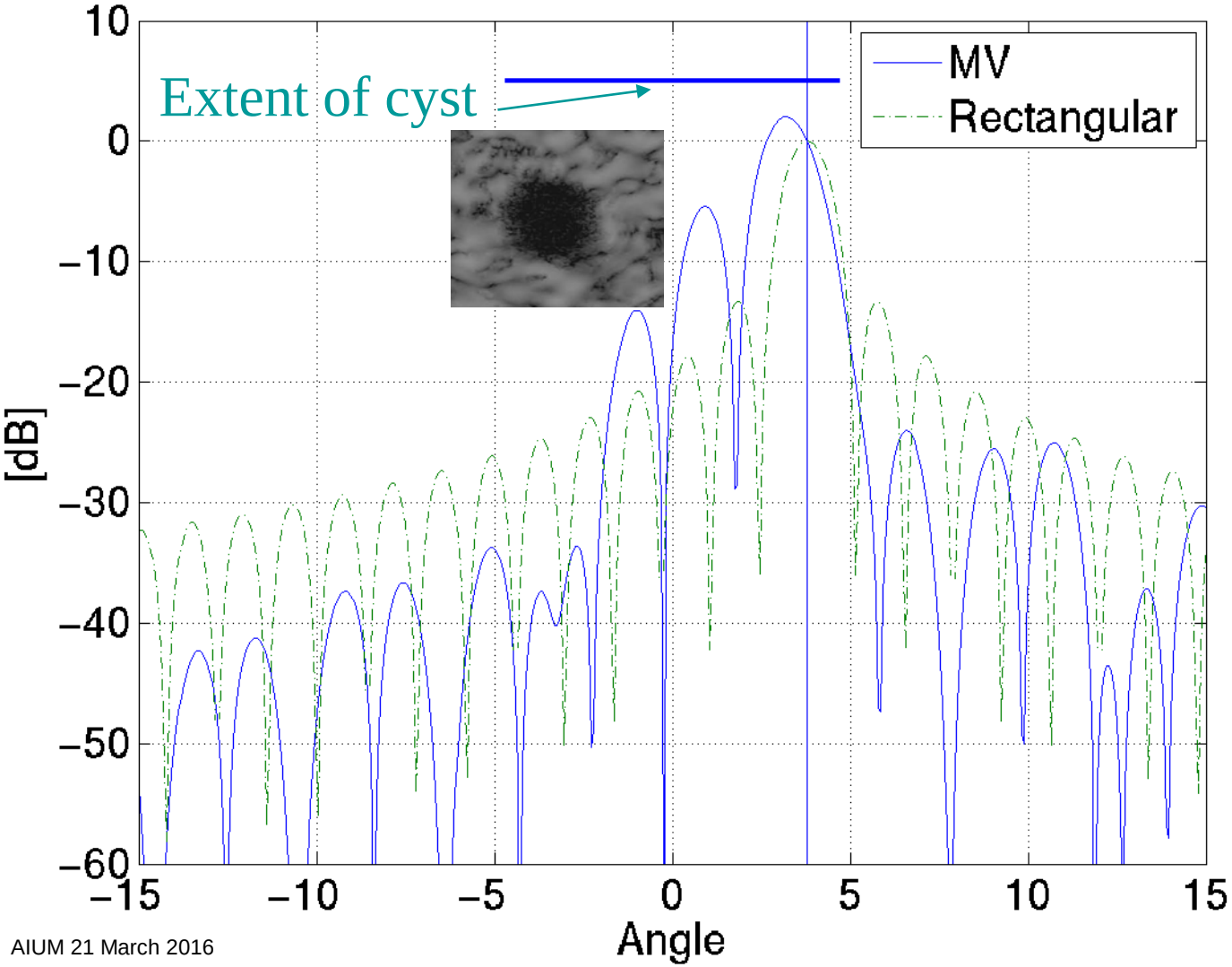
= Processing the data twice





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

Beampatterns (cyst)



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

2. History

3962 citations

1408 PROCEEDINGS OF THE IEEE, VOL. 57, NO. 8, AUGUST 1969

High-Resolution Frequency-Wavenumber Spectrum Analysis

J. CAPON, MEMBER, IEEE

$-\mathbf{x}_l)]\hat{f}_{jl}(\lambda)\}$. Thus, $P'(\lambda, \mathbf{k}_0)$ is the power output of an array processor, known as a maximum-likelihood filter, whose design is determined by the sensor data and is different for each wavenumber $\mathbf{k}_0$, which passes undistorted any monochromatic plane wave traveling at a velocity corresponding to the wavenumber $\mathbf{k}_0$ and suppresses in an optimum least-squares sense the power of those waves traveling at velocities corresponding to wavenumbers other than $\mathbf{k}_0$, cf. [3, (122)

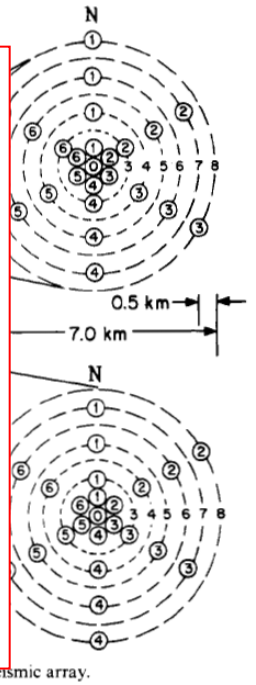


Fig. 1. General arrangement of the large aperture seismic array.

Naming

- Capon beamforming
- Minimum variance beamforming (MV)
- Minimum variance distortion-less response (MVDR)
- Adaptive beamforming
  - But not phase aberration correction
- Maximum likelihood beamformer (only early literature)

Active – not passive imaging: Early adaptation to ultrasound

- J. A. Mann and W. F. Walker. A constrained adaptive beamformer for **medical ultrasound**: Initial results. IEEE Ultrason Symp, 2002.
- M Sasso and C Cohen-Bacrie. **Medical ultrasound** imaging using the fully adaptive beamformer. IEEE Int Conf Acoust, Speech Sign Proc, 2005.
- Synnevåg JF, Austeng A, Holm S. Minimum variance adaptive beamforming applied to **medical ultrasound** imaging. Proc. IEEE Ultrason. Symp 2005
- Wang Z, Li J, Wu R. Time-delay-and time-reversal-based robust capon beamformers for **ultrasound imaging**. IEEE Trans Med Imag, 2005

Main papers from our group

- J.-F. Synnevåg, A. Austeng, and S. Holm, "Adaptive beamforming applied to medical ultrasound imaging," IEEE UFFC, Aug. 2007.
- J.-F. Synnevåg, A. Austeng, and S. Holm, ”Benefits of Minimum-Variance Beamforming in Medical Ultrasound Imaging”, IEEE UFFC, Sept. 2009.
- Nilsen, C-I C and 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", IEEE UFFC, Feb. 2011.
- J. P. Åsen, J. I. Buskenes, C.-I. Nilsen, A. Austeng, S. Holm, "Implementing Capon Beamforming on a GPU for Real-Time Cardiac Ultrasound Imaging," IEEE UFFC, Jan 2014.
- A. C. Jensen and A. Austeng, "The Iterative Adaptive Approach in Medical Ultrasound Imaging," IEEE UFFC, Oct 2014.

Implementation

1606 IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 54, NO. 8, AUGUST 2007

Adaptive Beamforming Applied to Medical Ultrasound Imaging

Johan-Fredrik Synnevåg, *Student Member, IEEE*, Andreas Austeng, *Member, IEEE*, and Sverre Holm, *Senior Member, IEEE*

Subarray averaging
Diagonal loading

+

1868 IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 56, NO. 9, SEPTEMBER 2009

Benefits of Minimum-Variance Beamforming in Medical Ultrasound Imaging

Johan-Fredrik Synnevåg, *Student Member, IEEE*, Andreas Austeng, *Member, IEEE*, and Sverre Holm, *Senior Member, IEEE*

Temporal averaging

***Abstract*—Recently, significant improvement in image resolution has been demonstrated by applying adaptive beamforming to medical ultrasound imaging. In this paper, we have used the minimum-variance beamformer to show how the low sidelobe levels and narrow beamwidth of adaptive methods can be used, not only to increase resolution, but also to enhance imaging in several ways. By using a minimum-variance beamformer instead of delay-and-sum on reception, reduced aperture, higher frame rates, or increased depth of penetration can be achieved without sacrificing image quality. We demonstrate comparable resolution on images of wire targets and a**

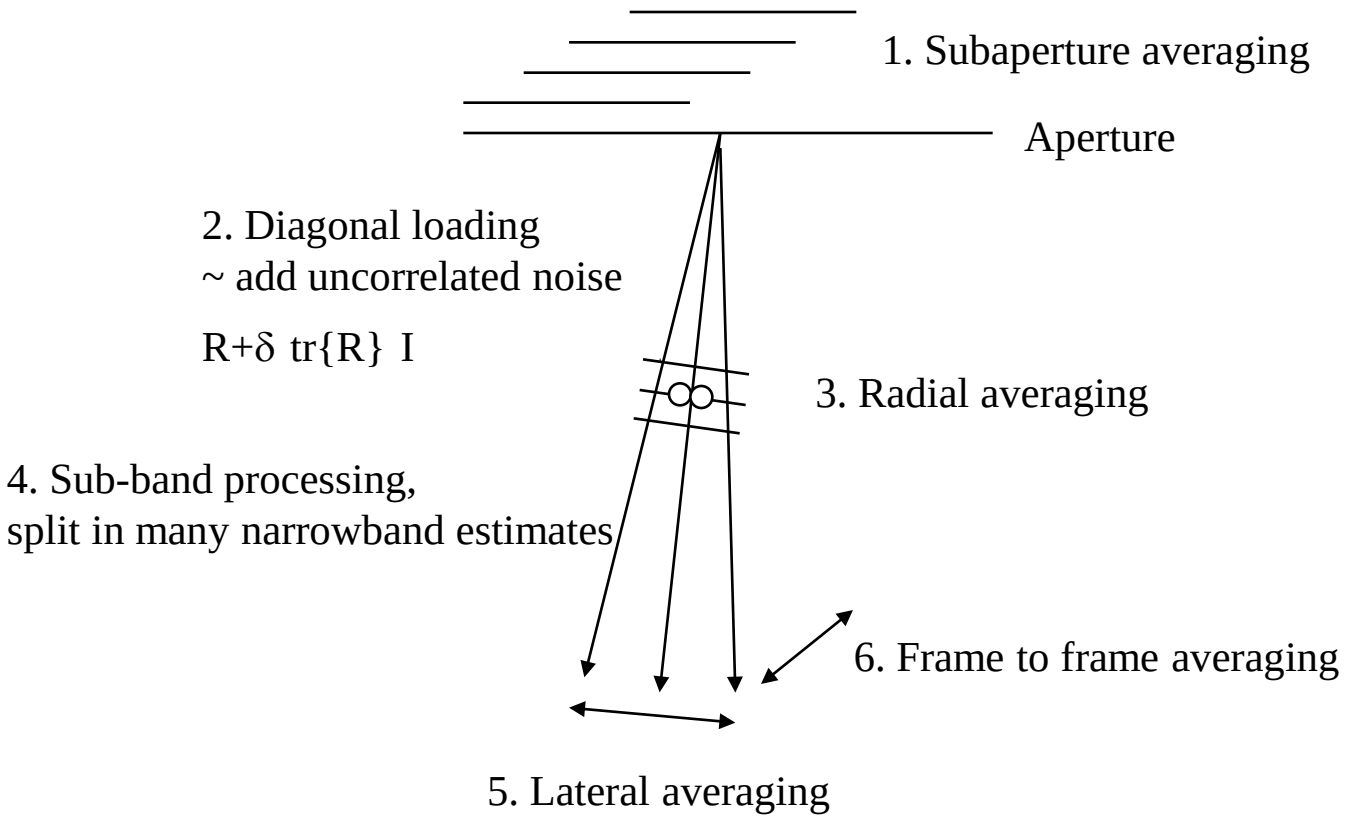
ence in the returning echoes. These measures are in the form of various forms of averaging and smoothing of the estimates.

Subaperture averaging is the main measure that has been developed for handling coherent echoes. It was first introduced by Evans *et al.* [11]. In this context, subaperture averaging means that the spatial covariance matrix is estimated by averaging the covariance matrices of different subapertures. This technique was applied to medical

Minimum variance beamforming

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

Smoothing and conditioning



Minimum variance

- Weight:

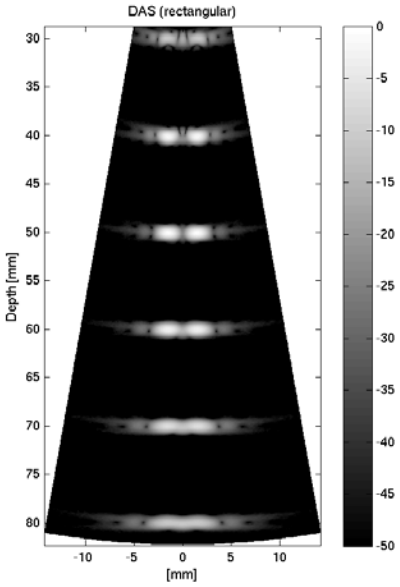
R: O(Radial-avg*SubAp-avg*SubAp-size)
R^{-1}: O(SubApp-size^3)

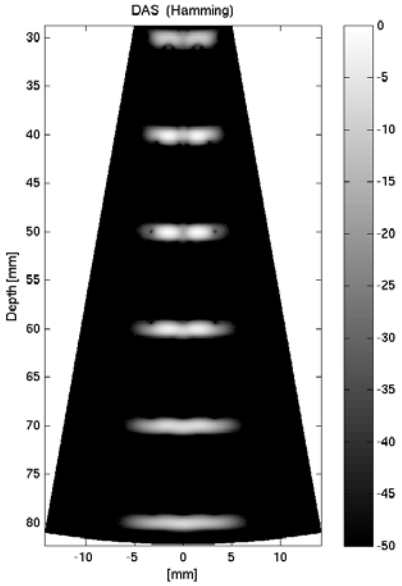
$$w = \frac{R^{-1}a}{a^H R^{-1} a}$$

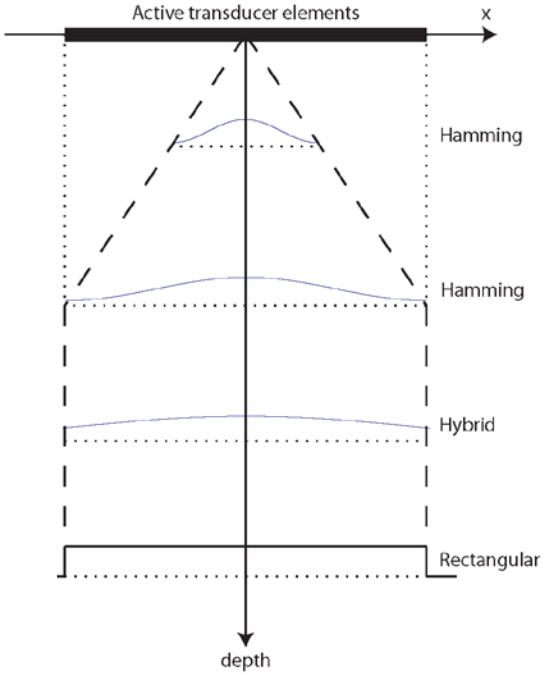
- Complex weights that vary with data

3. A new look at window functions

Rectangular or tapered?







Why must window functions be real?

- Real window ⇔ looks straight ahead

IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 57, NO. 2, FEBRUARY 2010

2011

A Low-Complexity Data-Dependent Beamformer

Johan-Fredrik Synnevåg, *Student Member, IEEE*, Andreas Austeng, *Member, IEEE*, and Sverre Holm, *Senior Member, IEEE*

***Abstract*—The classical problem of choosing apodization functions for a beamformer involves a trade-off between main lobe width and side lobe level, i.e., a trade-off between resolution and contrast. To avoid this trade-off, the application of adaptive beamforming, such as minimum variance beamforming, to medical ultrasound imaging has been suggested. This has been an active topic of research in medical ultrasound imaging in the recent years, and several authors have demonstrated significant improvements in image resolution. However, the improvement comes at a considerable cost. Where the complexity of a conventional beamformer is linear with the number of elements [$O(M)$], the complexity of a minimum variance beamformer is as high as $O(M^3)$. In this paper, we have applied a method based on an idea by Vignon and Burcher which is data-adaptive, but selects the apodization function between several predefined windows, giving linear complexity. In the proposed method, we select an apodization function for each depth along a scan line based on the optimality criterion of the minimum variance beamformer. However, unlike the minimum variance beamformer, which has an infinite solution space, we limit the number of possible outcomes to a set of predefined windows. The complexity of the method is then only P times that of the conventional method, where P is the number of predefined windows. The suggested method gives significant improvement in image resolution at a low cost. The method is robust, can handle coherent targets, and is easy to implement. It may also be used as a classifier because the selected window gives information about the object being imaged. We have applied the method to simulated data of wire targets and a cyst phantom, and to experimental RF data from a heart phantom using $P = 4$ and $P = 12$. The results show significant improvement in image resolution compared with delay-and-sum.**

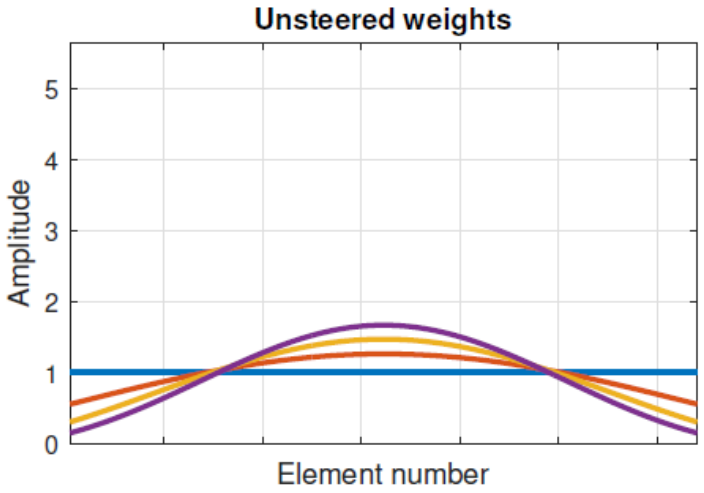
edges is often used close to the transducer to achieve low side lobes, and a rectangular window is often used at larger depths to achieve good resolution and maximum sensitivity and penetration.

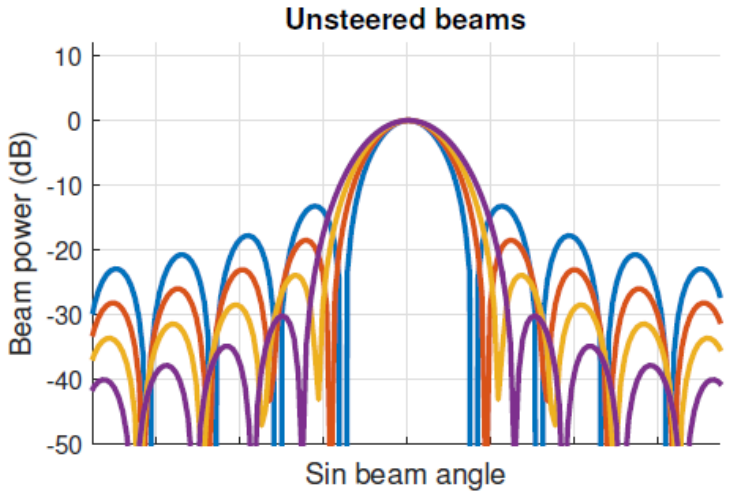
The transducer geometry, number of channels, transmit frequency, and apodization function determine the imaging capabilities of a system, characterized by the beam pattern. The ultimate goal is a beam pattern with a narrow main lobe and low side lobes, but as mentioned, these are contradictory goals. Instead, we may use adaptive beamforming, like the minimum variance (MV) beamformer, which takes the actual recorded wavefield into account to find the optimal apodization function. The key to the improved performance of the MV beamformer is that it will vary the apodization functions across the image, based on the recorded data. At a specific depth, the resulting beam patterns may contain large side lobes in regions where off-axis scattering is low and be less sensitive where off-axis scattering is present.

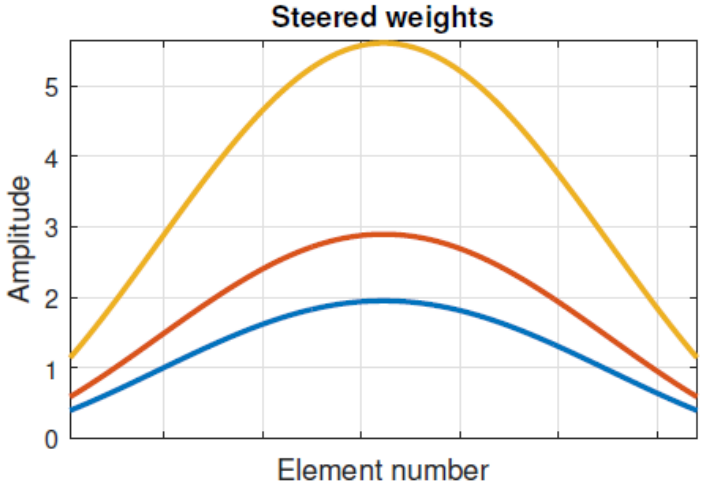
Adaptive beamforming has been an active research topic in medical ultrasound imaging in recent years, and several authors have shown significant improvement in image quality [1]–[9]. See [9] for a review of the different contributions. All authors have demonstrated improvements in image quality. However, the improvements come at a cost. The complexity of applying weights and summing in conventional delay-and-sum beamforming, is linear with the

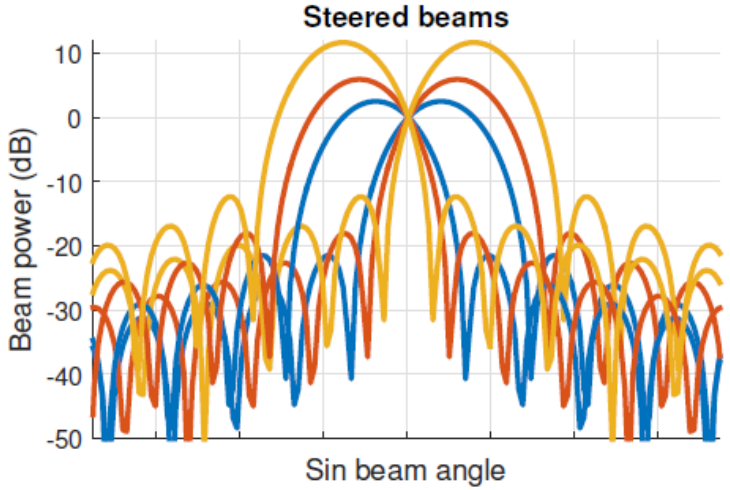
Low Complexity Adaptive Beamforming

- Determine a set of windows, typ. 6-12 windows, all with unity gain straight-ahead
  - Some conventional, looking straight-ahead
  - Some steered to either side
- Use MVDR criterion to select – per pixel – the best window
- Much faster than MVDR
  - No matrix inversion
  - 6-12 times the sum-part of a DAS beamformer

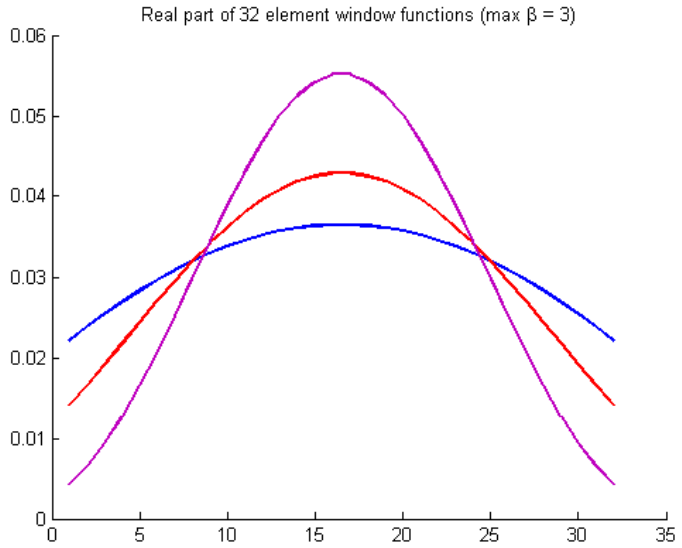

Unsteered weights
Amplitude
Element number
0
1
2
3
4
5

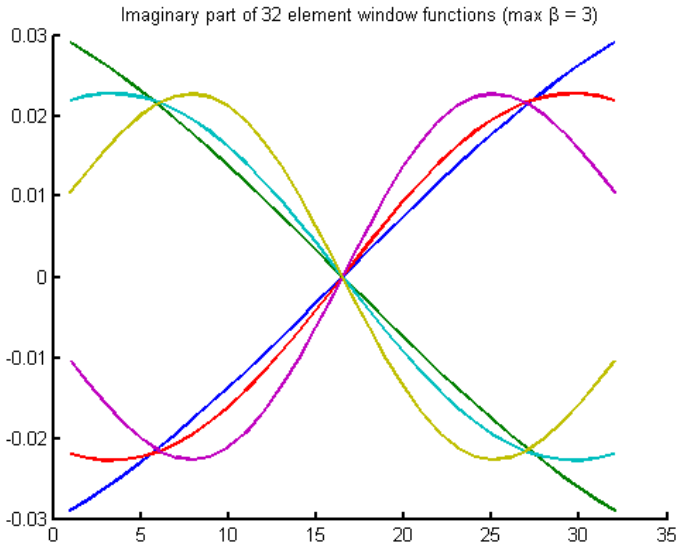

Unsteered beams
Beam power (dB)
Sin beam angle
10
0
-10
-20
-30
-40
-50


Steered weights
Amplitude
Element number
0
1
2
3
4
5

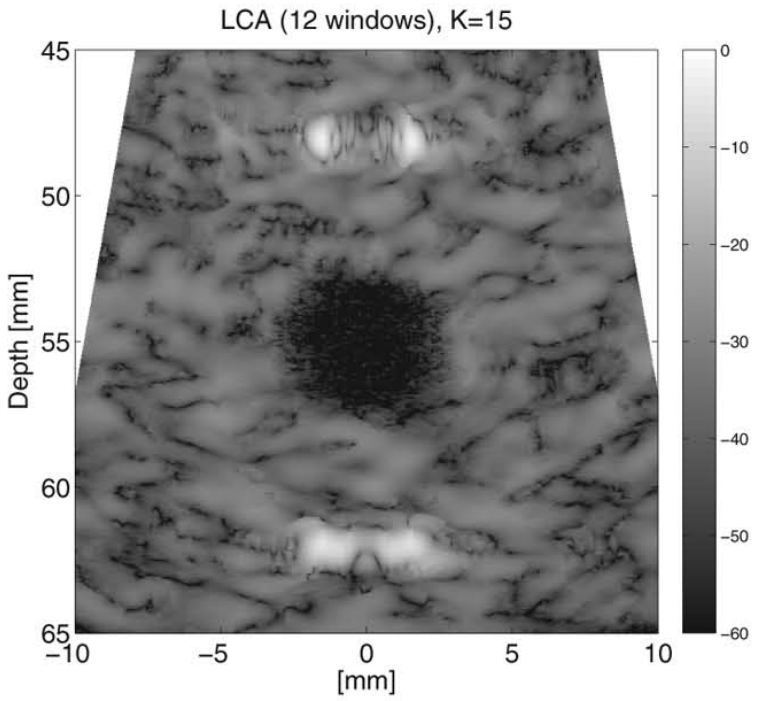

Steered beams
Beam power (dB)
Sin beam angle
10
0
-10
-20
-30
-40
-50

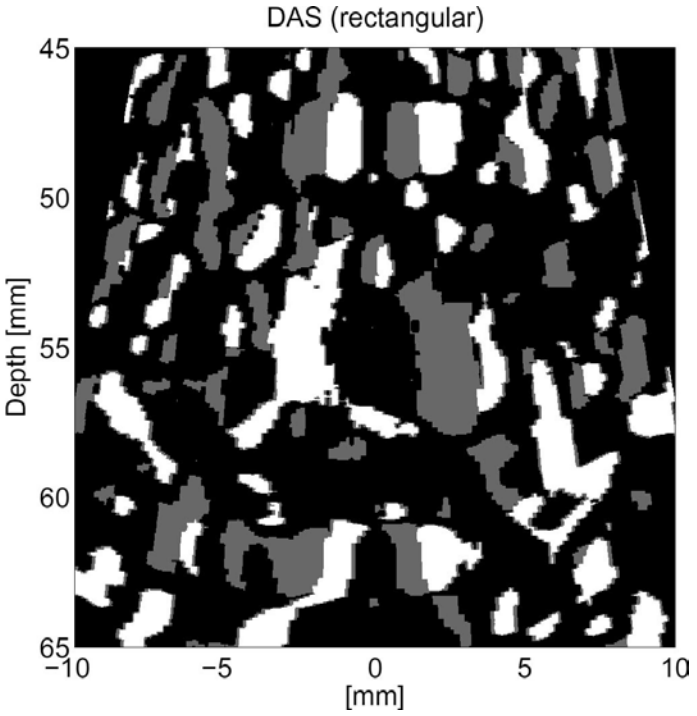
Real and imaginary parts of window





Choice of window: Black symmetric, gray/white: asymmetric





Lessons learned

Features of MVDR:

- Asymmetry in windows
- Null in direction of interference

Reasons for resolution increase:

- The asymmetry is the major feature
- Probably more important than sidelobe suppression

4. Trading resolution for other features

1868 IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 56, NO. 9, SEPTEMBER 2009

Benefits of Minimum-Variance Beamforming in Medical Ultrasound Imaging

Johan-Fredrik Synnevåg, *Student Member, IEEE*, Andreas Austeng, *Member, IEEE*, and Sverre Holm, *Senior Member, IEEE*

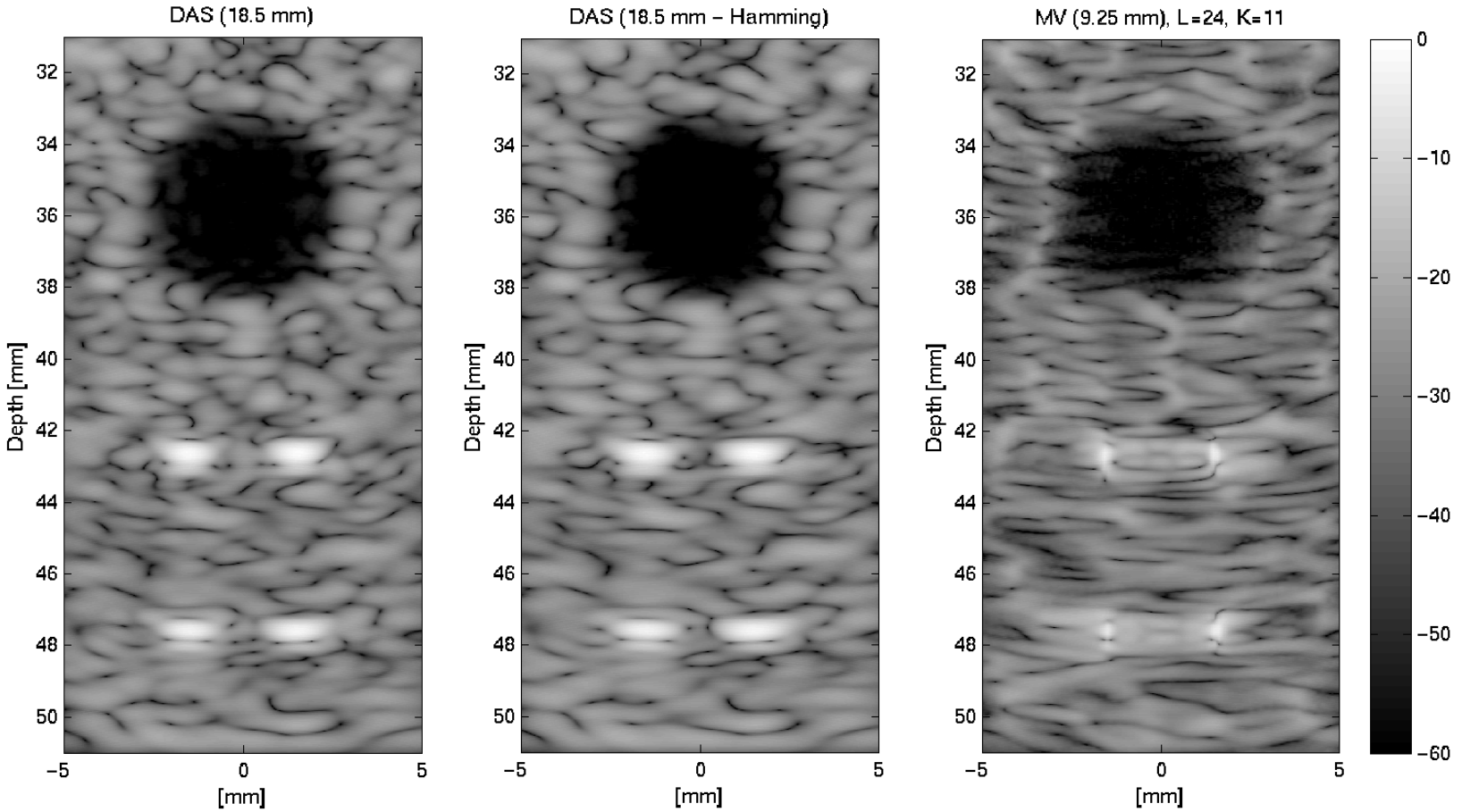
***Abstract*—Recently, significant improvement in image resolution has been demonstrated by applying adaptive beamforming to medical ultrasound imaging. In this paper, we have used the minimum-variance beamformer to show how the low sidelobe levels and narrow beamwidth of adaptive methods can be used, not only to increase resolution, but also to enhance imaging in several ways. By using a minimum-variance beamformer instead of delay-and-sum on reception, reduced aperture, higher frame rates, or increased depth of penetration can be achieved without sacrificing image quality. We demonstrate comparable resolution on images of wire targets and a cyst phantom obtained with a 96-element, 18.5-mm transducer using delay-and-sum, and a 48-element, 9.25-mm transducer using minimum variance. To increase frame rate, fewer and wider transmit beams in combination with several parallel receive beams may be used. We show comparable resolution to delay-and-sum using minimum variance, 1/4th of the number of transmit beams and 4 parallel receive beams, potentially increasing the frame rate by 4. Finally, we show that by lowering the frequency of the transmitted beam and beamforming the received data with the minimum variance beamformer, increased depth of penetration is achieved without sacrificing lateral resolution.**

ence in the returning echoes. These measures are in the form of various forms of averaging and smoothing of the estimates.

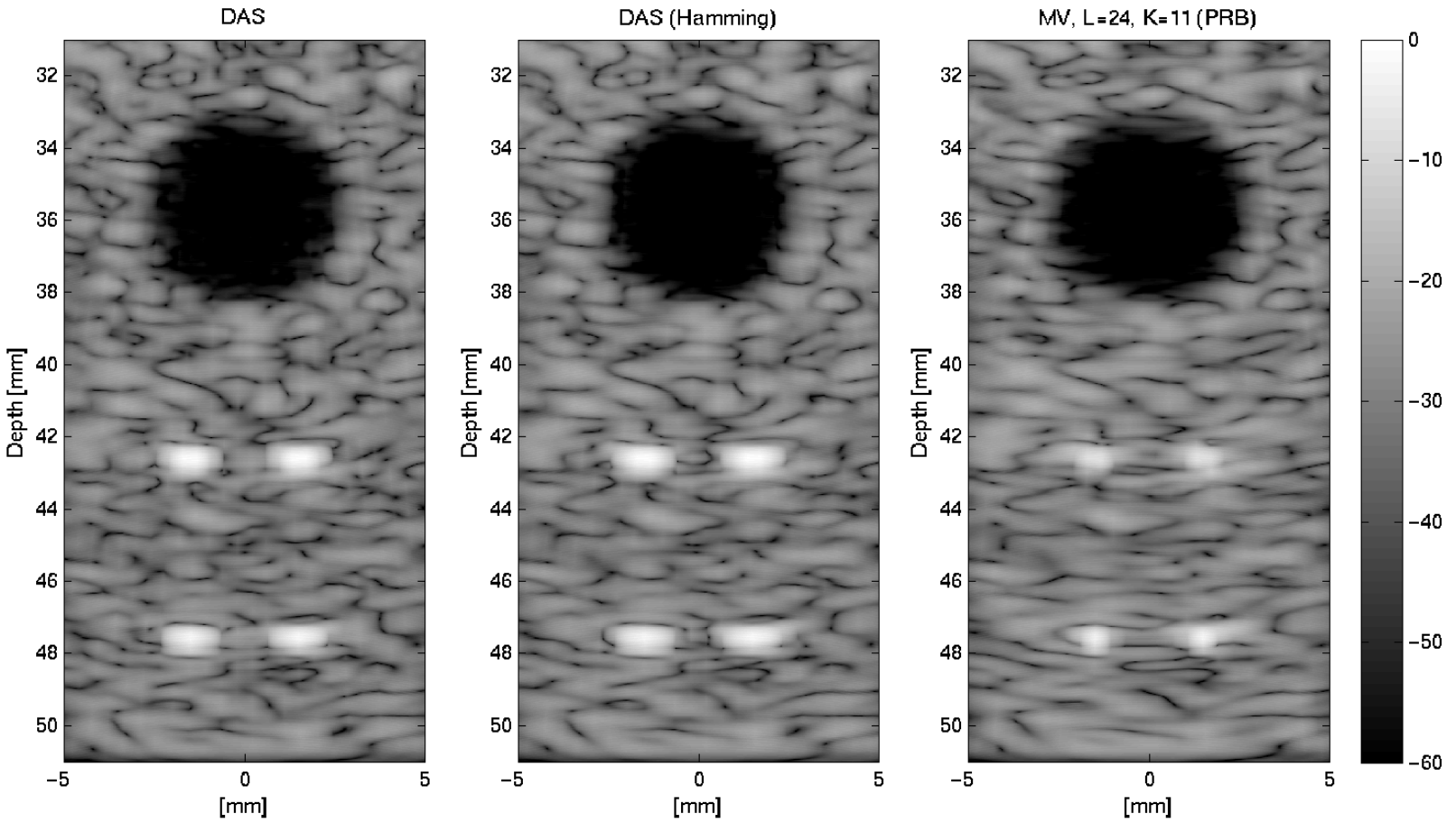
Subaperture averaging is the main measure that has been developed for handling coherent echoes. It was first introduced by Evans *et al.* [11]. In this context, subaperture averaging means that the spatial covariance matrix is estimated by averaging the covariance matrices of different subapertures. This technique was applied to medical ultrasound imaging by Sasso and Cohen-Bacrie [2], but only demonstrated on cyst images. The imaging scenario that best demonstrates the need for subaperture averaging is 2 very close targets, closer than the limit that can be resolved by DAS. Using this scenario, we have demonstrated that better resolution than DAS was possible even with coherent echoes [3].

A second measure, originally used to make high-resolution methods more robust, is *diagonal loading*. This regularization method adds a constant to the diagonal of

A. Half the transducer size



B1: 4 parallel receive beams



B2. Plane wave compounding

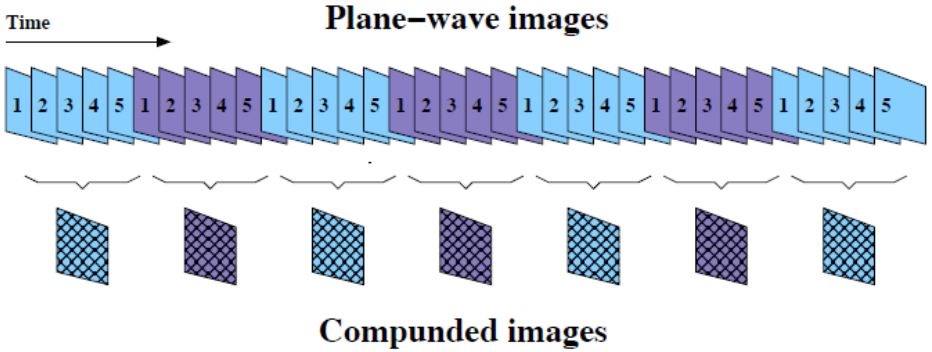
Coherent Plane-Wave Compounding and Minimum Variance Beamforming

Andreas Austeng, Carl-Inge Colombo Nilsen, Are Charles Jensen, Sven Peter Näsholm, and Sverre Holm
Department of Informatics, Universi
P. O. Box 1080
NO–0316 Oslo, Norway
E-mail: andreas.austeng@ifi.ui

70 subimages -> 22

Abstract—Achieving increased frame rate without compromising the image quality is desirable in medical ultrasound imaging. Coherent plane-wave compounding has recently been suggested as an approach to achieve this. This work proposes to generate coherent compound plane-wave images using a minimum variance adaptive beamformer. Through simulations of point scatterers and cyst phantoms, a threefold increase in frame rate is shown.

In this w
calculate th
images. We
number of
of three cor
The outli
plane-wave



PLANE WAVE MEDICAL ULTRASOUND IMAGING USING ADAPTIVE BEAMFORMING

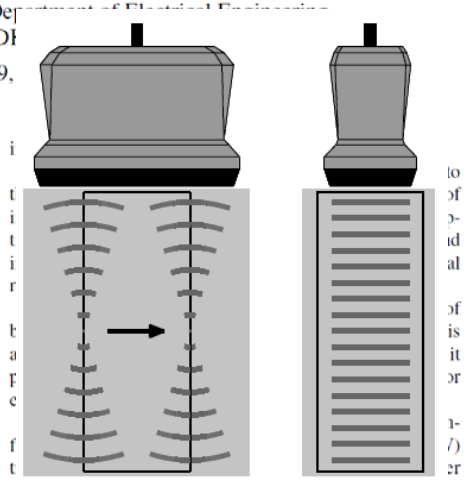
Iben Kraglund Holfort, Fredrik Gran† and Jørgen Arendt Jensen**

*Center for Fast Ultrasound Imaging, De
Technical University of Denmark, DI

†GN ReSound A/S, Lautrupbjerg 9,

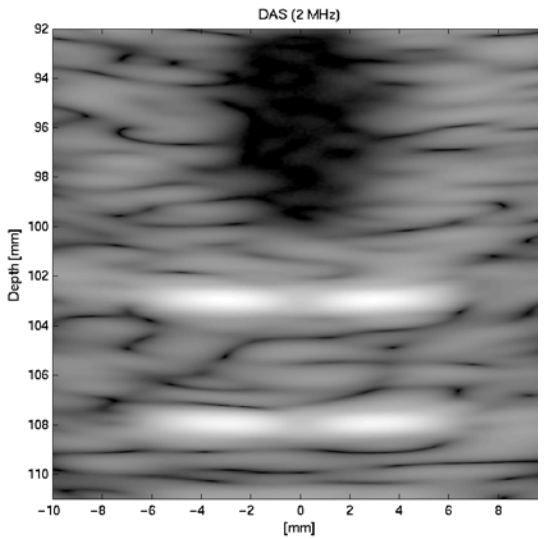
ABSTRACT

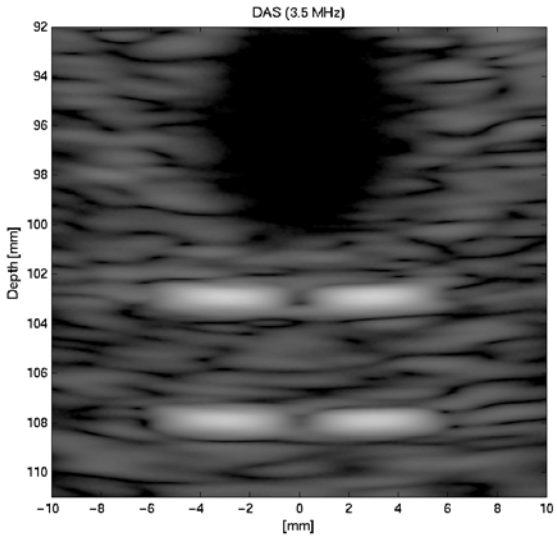
In this paper, the adaptive, minimum variance (MV) beamformer is applied to medical ultrasound imaging. The significant resolution and contrast gain provided by the adaptive, minimum variance (MV) beamformer, introduces the possibility of plane wave (PW) ultrasound imaging. Data
Field II and a 7 MHz, 128-elements, lin-
cer with $\lambda/2$-spacing. MV is compared
al delay-and-sum (DS) beamformer with
ing weights. Furthermore, the PW images
the a conventional ultrasound image, ob-
ear scan sequence. The four approaches,
S Boxcar, DS Hanning, MV}, have full
imum of {0.82, 0.71, 1.28, 0.12} mm and
els of {−40.1, −16.8, −34.4, −57.0} dB

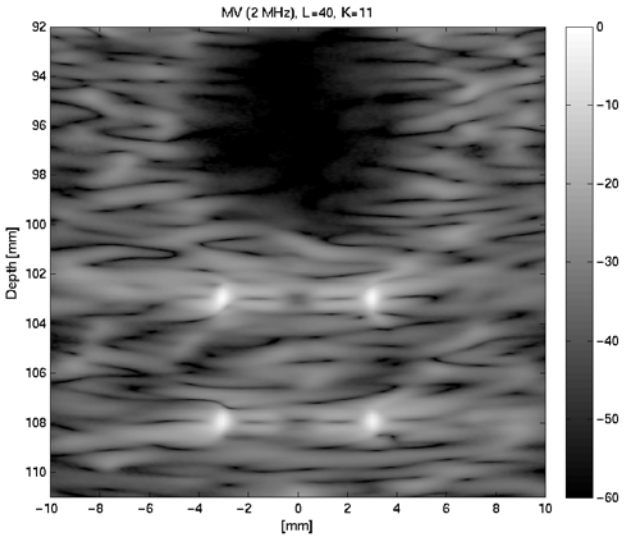


- DTU: Ultrasonics Symposium 2008
- UIO: Ultrasonics Symposium 2011

C: 2 MHz vs. 3.5 MHz







DAS 2 MHz DAS 3.5 MHz MVDR 2 MHz

D: Compressed sensing and adaptive beamforming

- Shen, Zhang, Yang, A Novel Receive Beamforming Approach of Ultrasound Signals Based on Distributed Compressed Sensing, IEEE *Instrumentation and Measurement Technology Conference (I2MTC), 2011*

Trade-off resolution

A. Smaller transducer; better access
B. Higher framerate in conventional and plane wave imaging
C. Lower frequency for deeper penetration
D. Make up for loss in compressional sensing

5. We can now afford several beamformers

- One for display
- Joint beamforming and image analysis
    - One for contours
    - One for segmentation
    - …

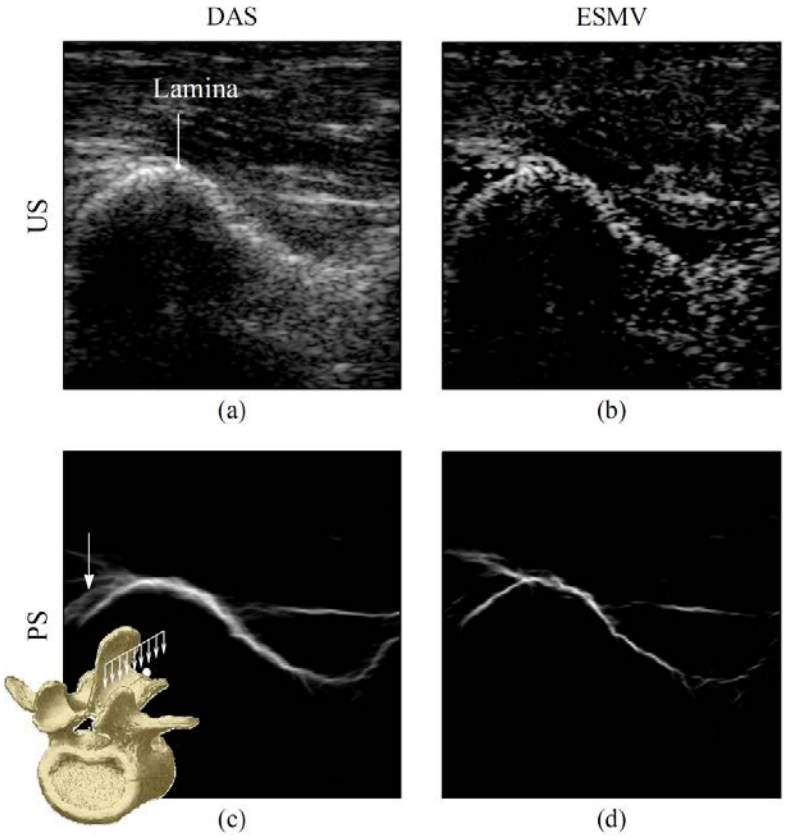
Eigenspace minimum variance vs delay and sum + phase symmetry surface detection

ESMV:

- Improved bone surface
- Thinner definition of the bone boundary

DAS:

- Left-hand side of image (arrow): unwanted features



Mehdizadeh, Austeng, Johansen, Holm. Eigenspace based minimum variance beamforming applied to ultrasound imaging of acoustically hard tissues, IEEE Trans Medical Imaging, 2012

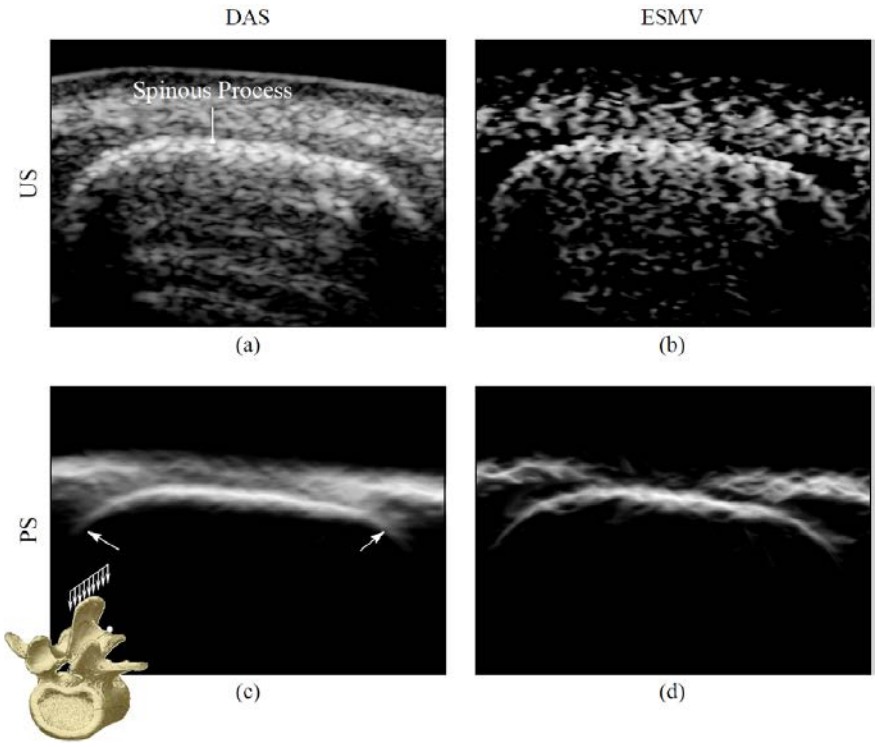
Eigenspace minimum variance vs delay and sum + phase symmetry surface detection

DAS:

- Bone surface is smeared out
- Boundaries are not well delineated
- Bone boundary, on both side of the spinous process marked with white arrows, is thick and unclear

ESMV:

- Bone surface is reasonably well isolated from the connective tissue on the top of the surface.
- Bone boundary is sharper and a prolongation of the surface is observed.



Joint Beamforming and Feature Detection

- One beamformer for display, optimized for human interpretation
- Another and totally different one for image analysis and feature extraction
  - Synnevåg, Austeng, Holm, "Adaptive beamforming applied to medical ultrasound imaging," IEEE Trans. Ultrason., Ferroelect., Freq. Contr., 2007.
  - S. Mehdizadeh, A. Austeng, T. Johansen, S. Holm, "Eigenspace Based Minimum Variance Beamforming Applied to Ultrasound Imaging of Acoustically Hard Tissues," IEEE Trans. Medical Imaging, Oct 2012.
  - J. P. Åsen, J. I. Buskenes, C.-I, C. Nilsen, A. Austeng and S. Holm, “Implementing Capon beamforming on a GPU for real-time cardiac ultrasound imaging,” IEEE Trans. Ultrason., Ferroelec. Freq. Contr., 2014

Related applications

- Vascular
  - Hoctor, Dentinger, Thomenius, Array Signal Processing for Local Arterial Pulse Wave Velocity Measurement Using Ultrasound, IEEE UFFC, 2007
  - Taki et al, High Range Resolution Ultrasonographic Vascular Imaging Using Frequency Domain Interferometry With the Capon Method, IEEE MI 2012
- Non-destructive testing (NDT)
  - Engholm, Stepinski, Adaptive Beamforming for Array Imaging of Plate Structures Using Lamb Waves, IEEE UFFC, 2010
- Sonar
  - Blomberg, Hayes, Multipath reduction for bathymetry using adaptive beamforming. IEEE OCEANS 2010, Sydney, 2010
  - Blomberg et al, Adaptive Beamforming Applied to a Cylindrical Sonar Array Using an Interpolated Array Transformation, IEEE Oceanic Eng 2012

Conclusions

- Processing the data twice
  - Window function per pixel found from data
- Asymmetrical window function
- More than resolution
  A. Smaller transducer; better access
  B. Higher framerate in conventional and plane wave imaging
  C. Lower frequency for deeper penetration
  D. Make up for loss in compressional sensing
- Parallel beamformers for display/edges