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This project has received funding from The European Union's Horizon 2020 research and innovation programme under grant agreement No. 646804-ERC-COG-BNYQ
646804 – BNYQ

ieee IUS 2016 International Ultrasonics Symposium
september 18-21, Tours, France

Efficient Coded Ultrasound Imaging Based on Frequency Domain Processing

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Motivation

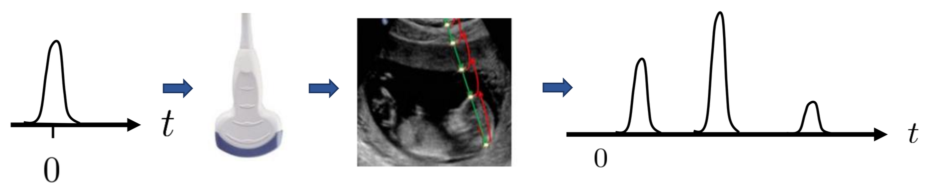
- Coded excitation (CE) and pulse compression increase the Tx energy and keep the same axial resolution
- Improved SNR and imaging depth
- Crucial for synthetic aperture and plane-wave based imaging modalities

Bottleneck – application to imaging with an array of elements due to increased computational complexity

Our approach is to introduce the pulse compression to computationally efficient frequency domain beamforming (FDBF)

Conventional Transmission

- In the standard approach transducer transmits a Gaussian pulse

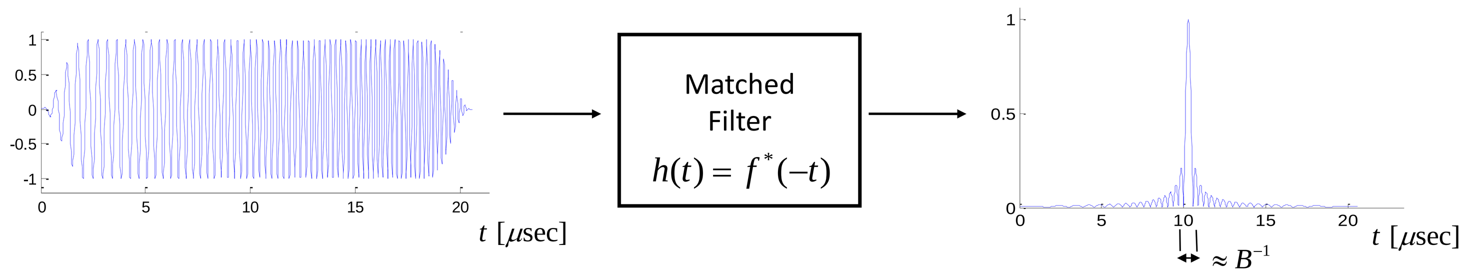


- Axial resolution is proportional to the pulse duration
- SNR and imaging depth are defined by the transmitted energy

Transmitting more energy with the same pulse duration (resolution) requires higher intensity peak, which is limited by the FDA

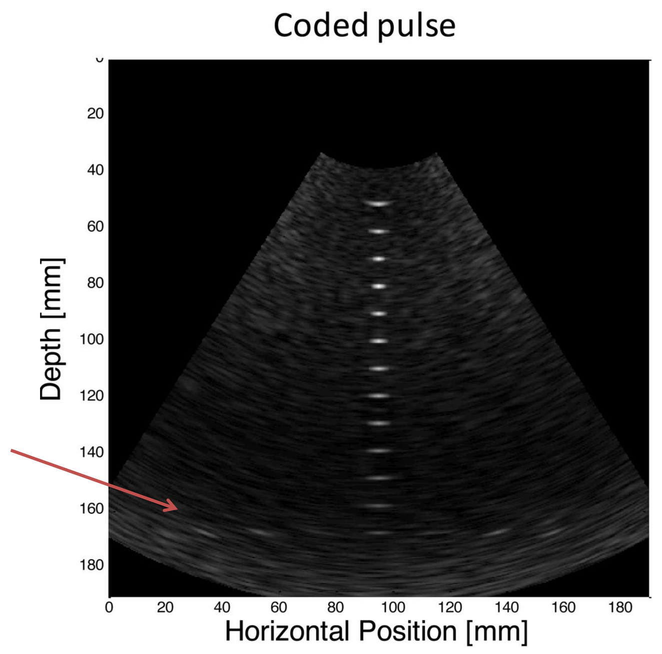
Coded Excitation Approach

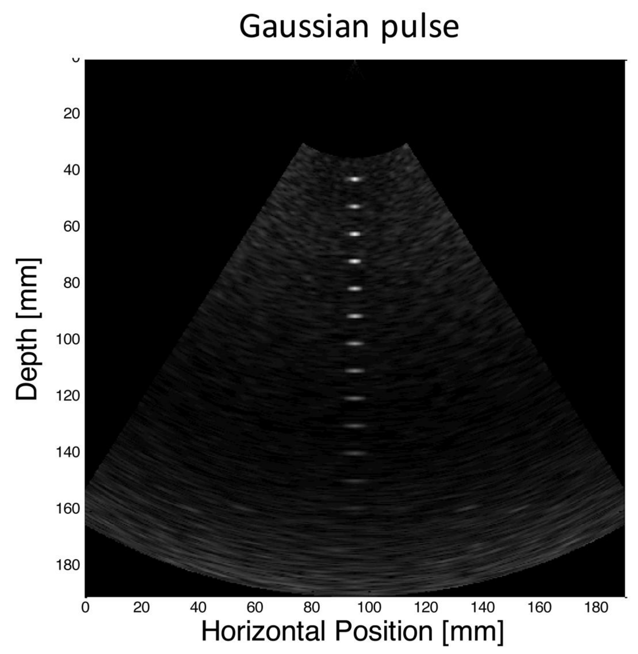
- Coded signals are transmitted and compressed upon reception
- An image line is comprised of pulse's autocorrelations
- Linear frequency modulated (FM) signal:



- The resolution is inversely proportional to B, the available system bandwidth determined by the transducer properties

CE breaks the link between axial resolution and the transmitted energy

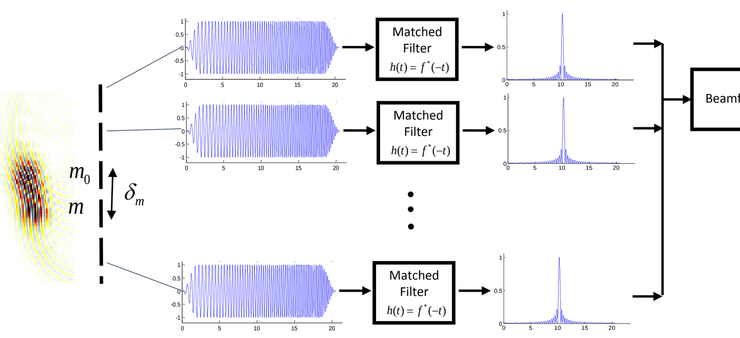




Scatterers in the high depth can not be seen when using the Gaussian pulse

Beamforming (BF) and Pulse Compression

- Optimal processing requires compressing every channel prior to BF



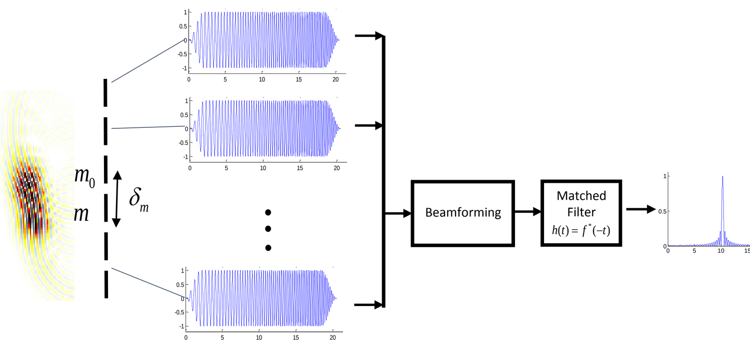
$$\Phi_{CE} = \frac{1}{M}\sum_{m=1}^{M}\{\varphi_m * h\}(\tau_m(t;\theta))$$

$$\tau_m(t;\theta) = \frac{1}{2}\left(t + \sqrt{t^2 - 4(\delta_m/c)t\sin\theta + 4(\delta_m/c)}\right)$$

The computational complexity is vastly increased by filtering each detected signal **restricting the use of CE in array imaging**

- An obvious solution – beamforming before pulse compression
- Saving $(N_e - 1)\left(\frac{3}{2}(N_s+N_h)\log(N_s+N_h) + N_s + N_h\right)$

elements, samples, filter coefficients



Non-linear time dependent delays distort the phases of the coded signals

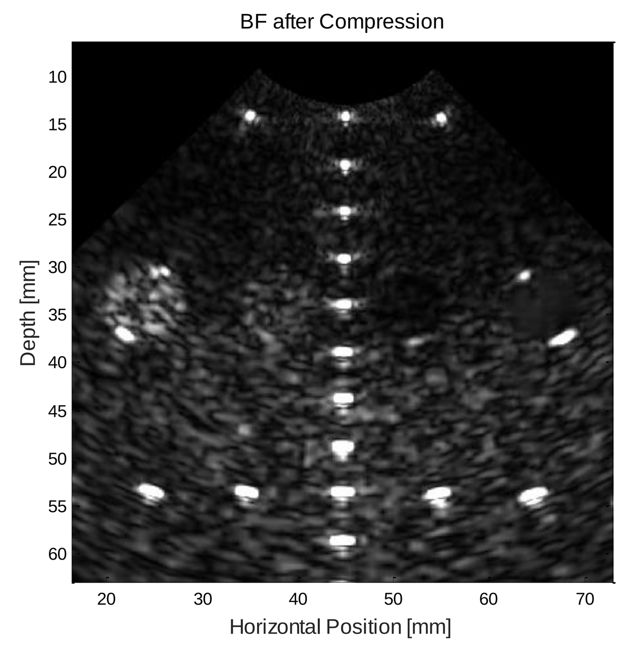
$$\Phi_{CE_{pre}} = \left\{\frac{1}{M}\sum_{m=1}^{M}\varphi_m(\tau_m(t;\theta))\right\} * h(t)$$

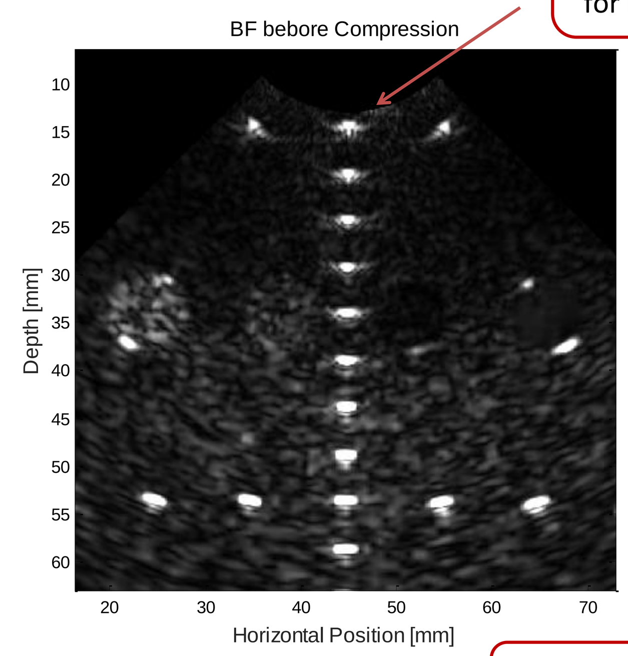
Image Degradation due to Compression Error

- Non-linear phase distortion affects the properties of the compressed output and degrades the image quality

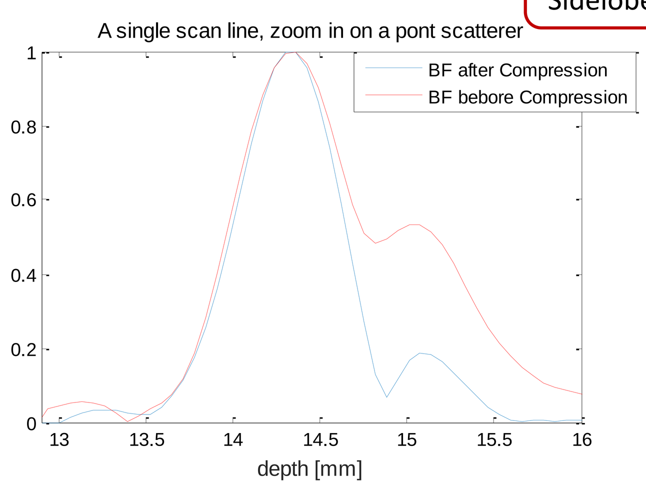
$$\Phi_{CE} = \frac{1}{M}\sum_{m=1}^{M}\{\varphi_m * h\}(\tau_m(t;\theta)) \neq \Phi_{CE_{pre}}\left\{\frac{1}{M}\sum_{m=1}^{M}\varphi_m(\tau_m(t;\theta))\right\} * h(t)$$

The errors are more prominent for low depth





Main lobe ~13% wider
Sidelobe ~9 dB higher

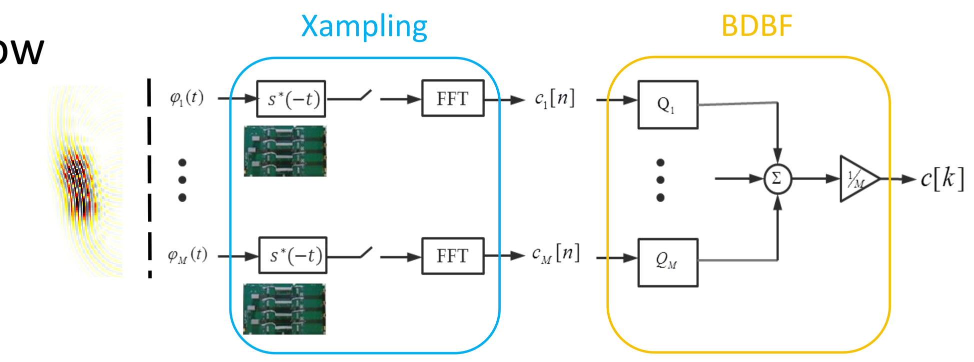


Other existing solutions

- Limiting the coded signal duration ($T < 64/f_0$)
  Drawback – limited SNR improvement
- Imaging several zones with different codes
  Drawback – reduced frame rate

Frequency Domain Beamforming and Pulse Compression

- Each channel is sampled at a low rate using Xampling approach
- Beamforming is performed directly in frequency



Standard Imaging

$$\Phi(t;\theta) = \frac{1}{M}\sum_{m=1}^{M}\varphi_m(\tau_m(t;\theta))$$

$$c[k] = \frac{1}{M}\sum_{m=1}^{M}\sum_{n=-N_1}^{N_2} c_m[k-n]Q_{k,m;\theta}[n]$$

$$\varphi_m^{CE}(t) = \{\varphi_m * h\}(t)$$
$$\to c_m^{CE}[k] = c_m[k]h[k]$$

Coded Imaging

$$\Phi_{CE}(t;\theta) = \frac{1}{M}\sum_{m=1}^{M}\{\varphi_m * h\}(\tau_m(t;\theta))$$

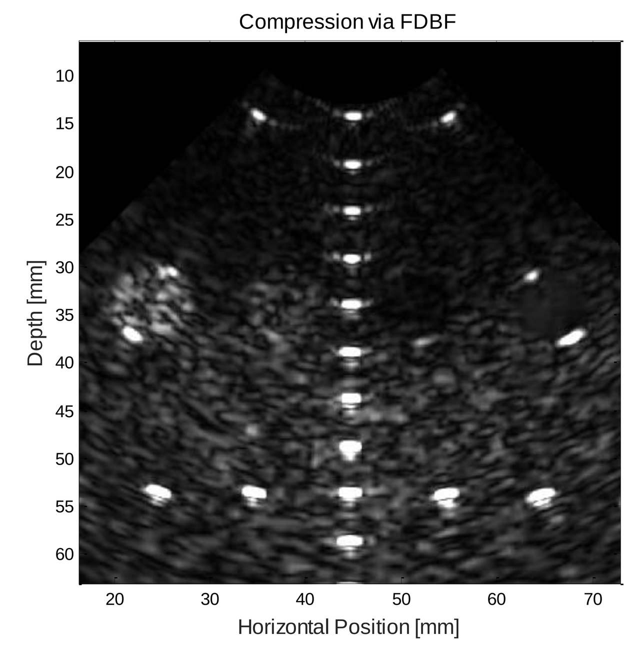
$$c_{CE}[k] = \frac{1}{M}\sum_{m=1}^{M}\sum_{n=-N_1}^{N_2} c_m[k-n]h[k-n]Q_{k,m;\theta}[n]$$

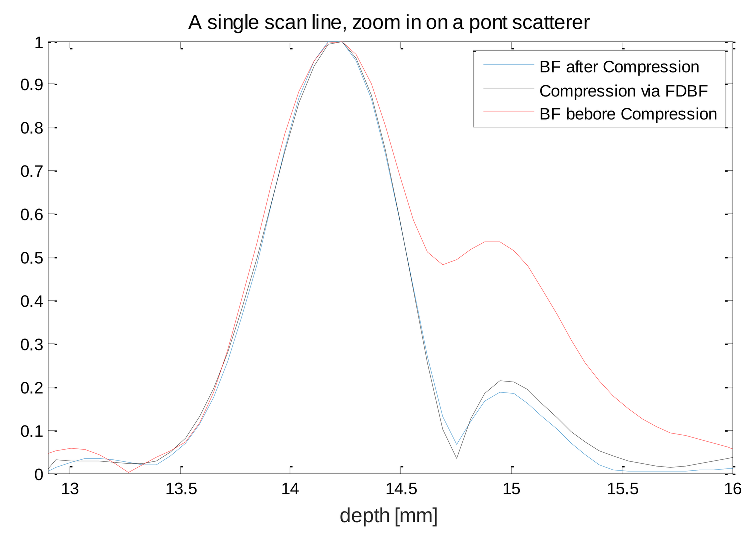
$$= \frac{1}{M}\sum_{m=1}^{M}\sum_{n=-N_1}^{N_2} c_m[k-n]Q_{k,m;\theta}^{CE}[n]$$

- The set $\{Q_{k,m;\theta}^{CE}[n]\}$ includes the Fourier series coefficients of the matched filter
- Performs beamforming and pulse compression simultaneously in the frequency domain

Pulse compression is performed in frequency together with beamforming and does not require any additional computational load

Experimental Results





Verasonics Vantage 256
64 element probe, $f_0 = 2.98MHz$
$f_s = 11.9MHz$

Computational complexity

- Time domain processing $N_{time} = MN_s + M\left(\frac{3(N_s+N_h)}{2}\log(N_s+N_h) + N_s + N_h\right)$
- Frequency domain processing $N_{frequency} = MKN_Q + \frac{N_s}{2}\log N_s$

16 fold reduction in the number of multiplications