Beamforming

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Beamforming

In ultrasound beamformation, we usually assume:

- Constant speed of sound (for delay calculations)
- Linear system (non-linearity can be filtered out, or imaged separately)
- Acoustic reciprocity (swapping transmit and receive is valid)
- Single scattering only (no echoes of echoes)

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Beamforming

- Say you see a lightning strike happen, but don't know where in the sky (it is cloudy).
- You hear the boom 1 second after.
- How far away was the strike? (speed of sound in air: 343 m/s)

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Beamforming

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- You hear the boom 1 second after.
- How far away was the strike? (speed of sound in air: 343 m/s)

$$d = t \cdot c \quad \Rightarrow \quad d = 1\ \text{sec} \cdot 343 \frac{\text{m}}{\text{s}} = 343\ \text{m}$$

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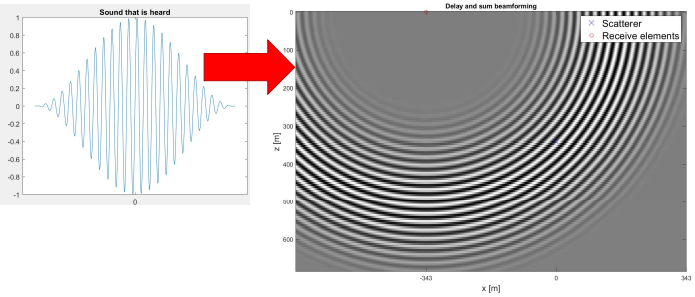
Beamforming is a back-projection

- Beamforming means projecting the received data back into space.



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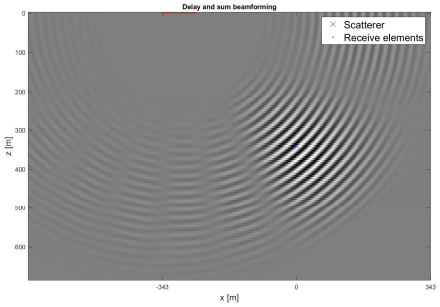
Beamforming 1: Resolution

- Beamform for 16 neighbors, and you can determine direction:



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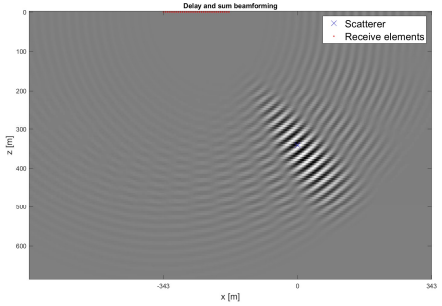
Beamforming 1: Resolution

- Beamform for 32 neighbors, and resolution is doubled



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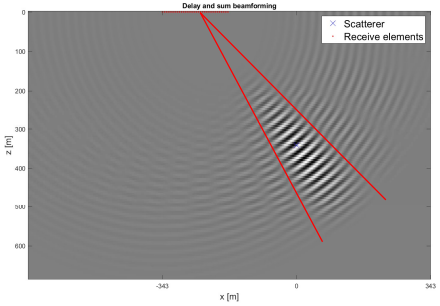
Beamforming 1: Resolution

- Resolution is proportional to the F-number: aperture width / depth



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Beamforming 1: Resolution

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- So larger aperture means better resolution.
- Can we then just increase receiver spacing to cover a larger area?

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Beamforming 1: Resolution

- Resolution is proportional to the F-number: aperture width / depth
- So larger aperture means better resolution.
- Can we then just increase receiver spacing to cover a larger area?

The answer is NO.
The recievers may not be sparsely distributed.

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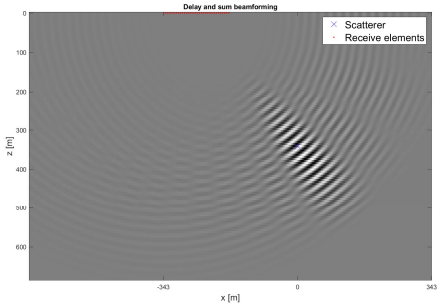
Beamforming 2: Element spacing

- If 32 neighbors are separated by lambda/4:



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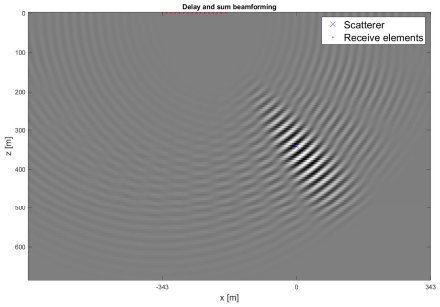
Beamforming 2: Element spacing

- If 16 neighbors are separated by lambda/2:



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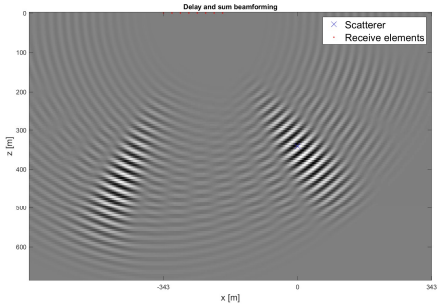
Beamforming 2: Element spacing

- If 8 neighbors are separated by lambda:



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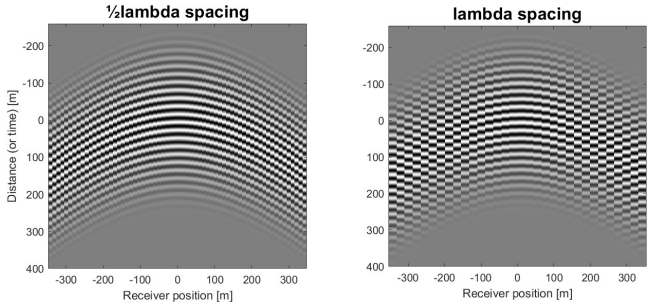
Beamforming 2: Element spacing

- A glance at the received signals show the reason for grating lobes



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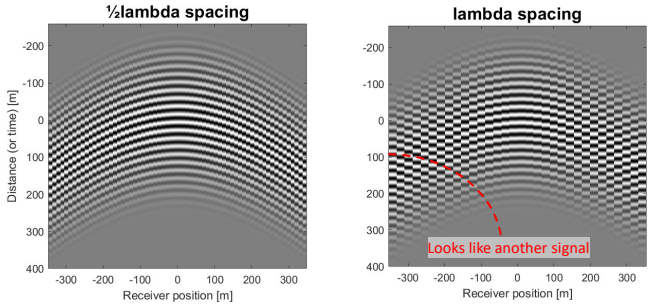

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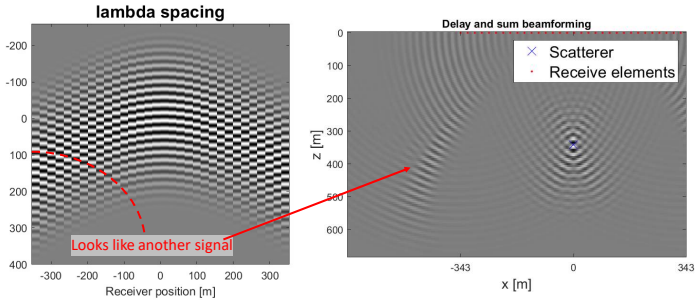
Beamforming 2: Element spacing

- Means points inside the FOV have an alias outside it, and vice versa.



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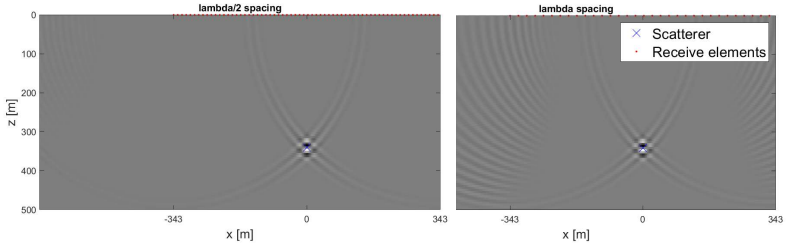
Beamforming 2: Element spacing

- In case of a shorter pulse there is less ambiguity.



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Beamforming 2: Element spacing

- Resolution is proportional to the F-number: aperture width / depth.
- Element spacing [¼ to 1 times lambda] may limit the directionality.

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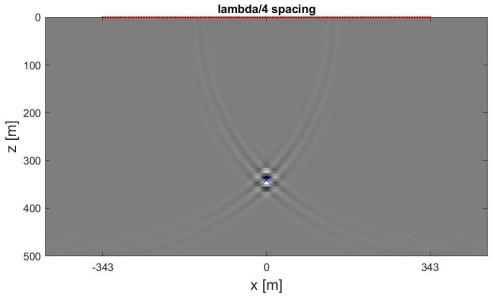
Beamforming 3: Apodization

- There is a wing-like pattern, due to the aperture stopping abruptly



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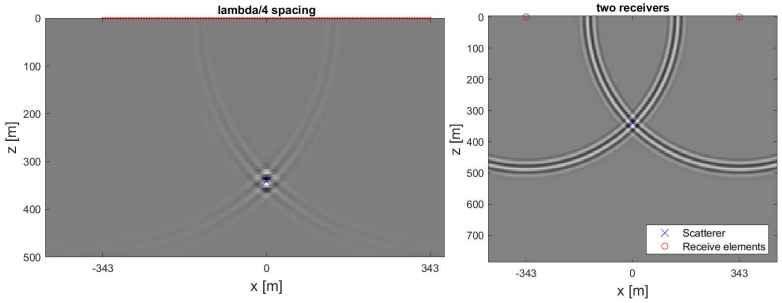

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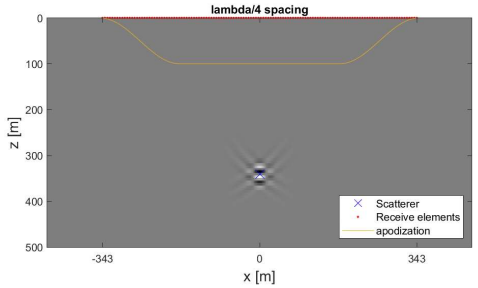
Beamforming 3: Apodization

- Use an apodization to soften the edges, reducing the edge effect.



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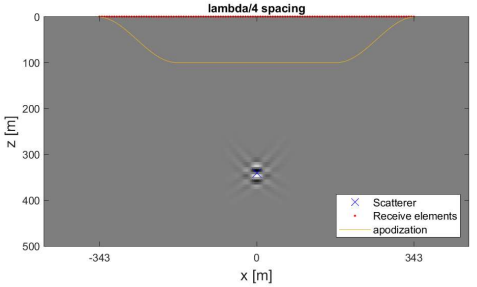
Beamforming 3: Apodization

- There is also a laterally oscillating pattern on the scatterer (diffraction).



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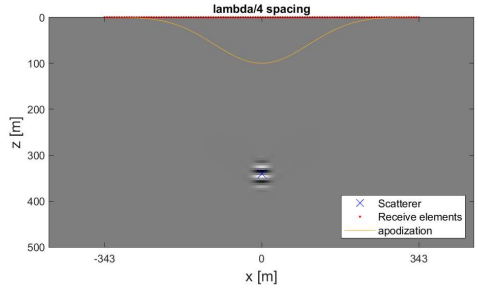
Beamforming 3: Apodization

- Diffraction can be removed with proper apodization or image-filtering.



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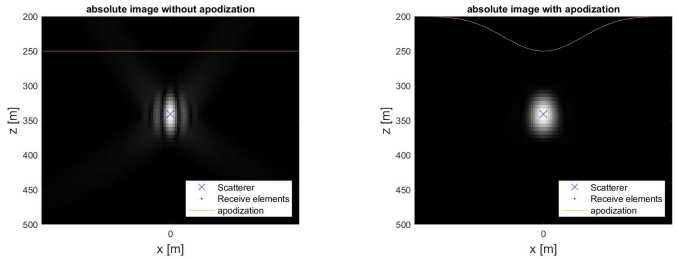
Beamforming 3: Apodization

- Resolution is slightly compromised, due to reduced aperture width.



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Beamforming 3: Apodization

- Resolution is proportional to the F-number: aperture-width/depth.
- Element spacing [¼ to 1 times lambda] limits the directionality.
- Apodization to control sidelobes at cost of resolution (a worthy trade)

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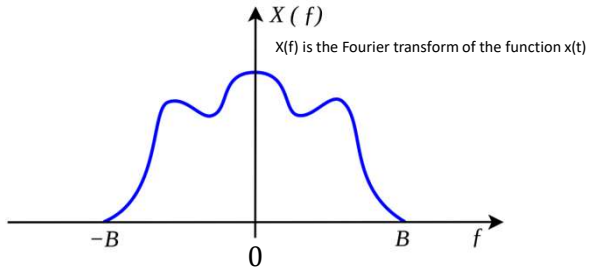
Beamforming 4: Sampling

- We assume a band-limited signal.



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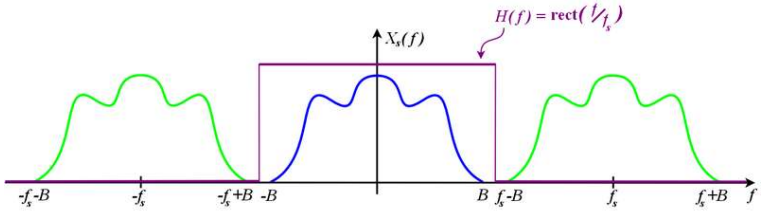
Beamforming 4: Sampling

- The theory is then that the sampled version has periodic aliases.



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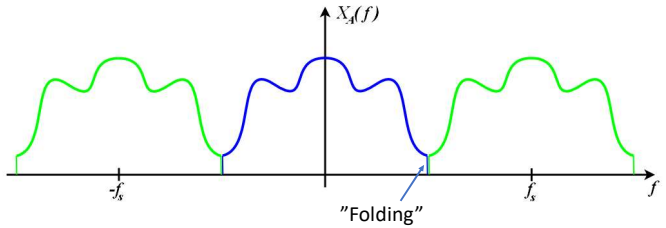
Beamforming 4: Sampling

- If you sample too sparsely, the aliases overlap, and information is lost!



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Beamforming 4: Sampling

- The RF data is sampled with an analog-to-digital converter.
- Oversampling may allow us to filter out non-linear responses, quantization errors, and noise (white noise from electronics).
- You can then filter out anything outside your signal band, as long as it has not folded on top of your signal.

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Beamforming 4: Sampling

- The beamformed image is sampled on a pixel grid.
- No benefit to oversampling this image, it only costs more time.
- Just sample at a sufficient rate, and then interpolate in-between pixels in a post-processing step.

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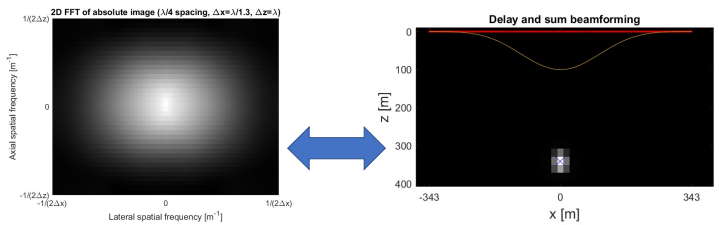
Beamforming 4: Sampling

- Absolute-value or B-mode images do not need very dense sampling.
- The min. pixel spacing is essentially proportional to the resolution.



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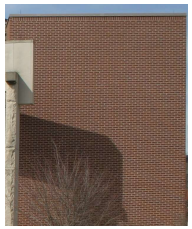

Undersampled

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Beamforming summary

- Time of flight is used to compute focusing delays.
- Resolution is proportional to the F-number: aperture-width/depth.
- Element spacing [¼ to 1 times lambda] limits the directionality.
- Apodization to control sidelobes at cost of resolution (a worthy trade)
- Be aware of sampling criteria. No information should be lost.

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Beamforming: Speed-up tricks

1. Just oversample your image slightly and use a cheap interpolation, e.g. cubic spline, to get values in-between pixels.
2. Use a GPU beamformer. Latest-gen GPUs can beamform 16.384 pixels in parallel (your multi-core CPU might do 2-16 in parallel).
3. The beamforming implementations are dominated by overhead, but you can reuse computations across frames to bring this down.
4. You will eventually be limited by memory bandwidth, therefore the RF sampling rate should be minimized, along with other tricks.

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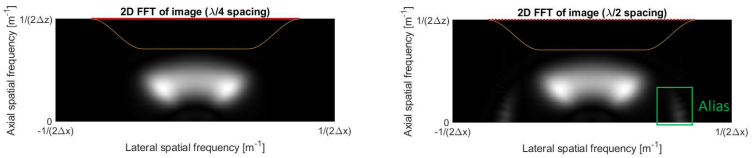
Image analysis




```
Imagesc( abs(fftshift(fft2( img ))) )
```

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Image analysis

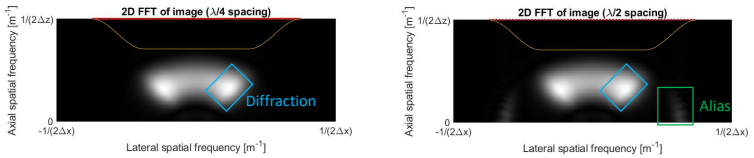

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Image analysis

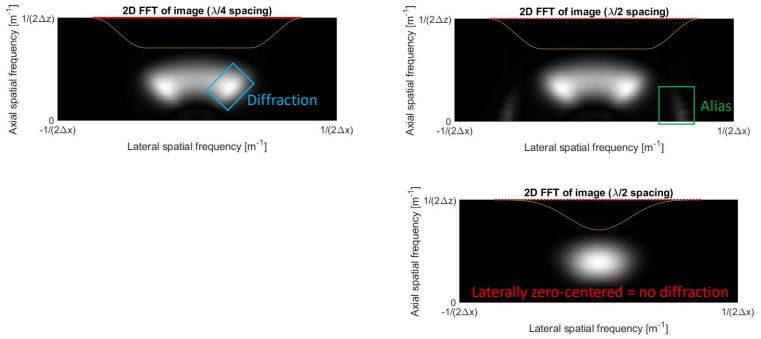

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Image analysis

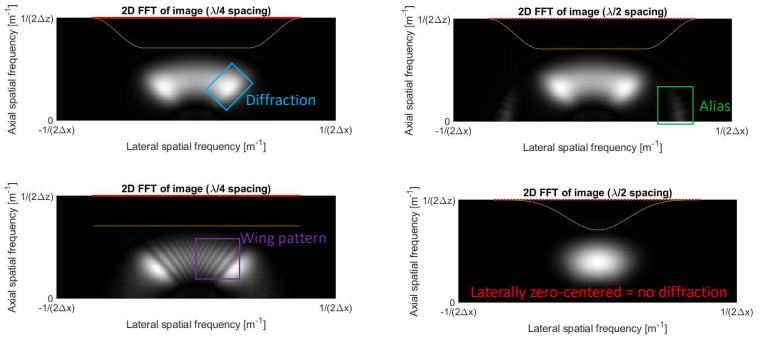

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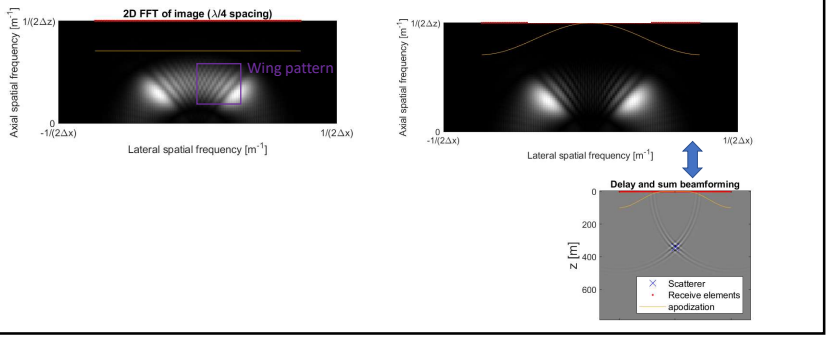
Image analysis



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