Advances and Prospects in HF Surface Wave Radar Research at Helmut Schmidt University

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Projects in HF and μWave

- Distributed Shipborne Self-Configuring Over-The-Horizon-Radar
- Electrically Small HF Antennas
- Broadband HF Shipboard Antennas with Distributed Damping
- Impact of Wind Power Stations on Point-to-Point Radio Links

Outline

1. Introduction
2. Large Sparse Arrays on Sea
3. Compact Uniform Linear Array Using MIMO Beamformer
4. MIMO Beamformer Using Time-Staggered FMCW Chirp Signals
5. Outlook on Novel Concepts for Improved Ship Detection In Inhomogeneous Background
6. Summary

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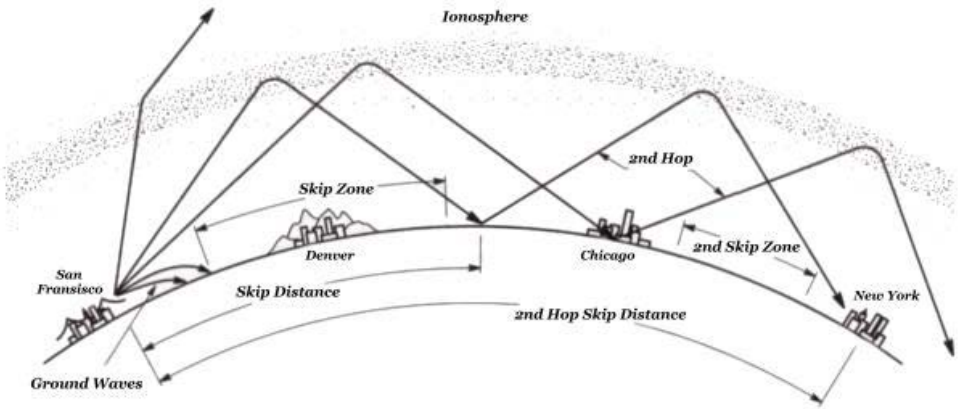
HF Band (3-30 MHz)

Sky wave

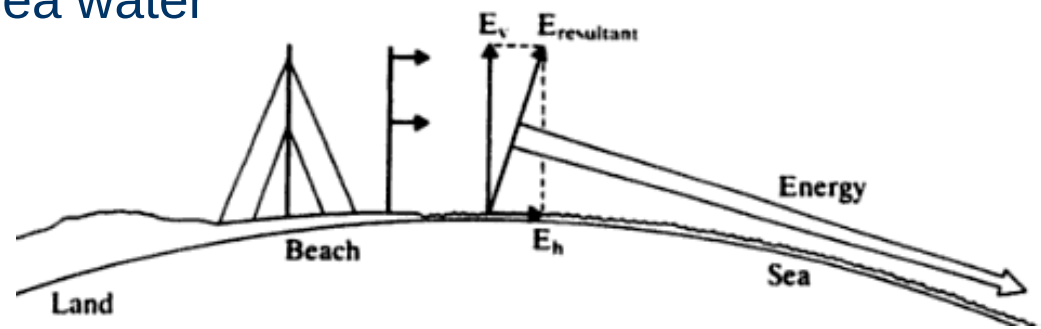
Range several thousand km



Surface wave

Propagation over conducting sea water (vertical polarization)

Range few hundred km



Simon Kingsley, Shaun Quegan, ‘Understanding Radar Systems’, Mc Graw-Hill, 1992

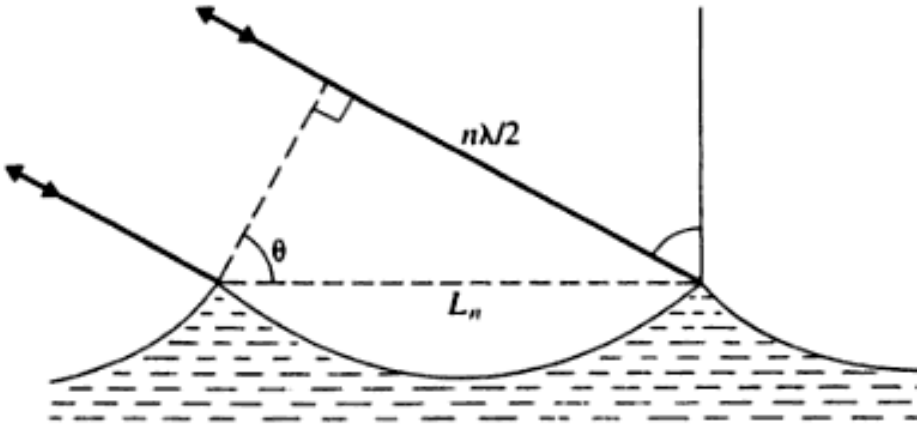
HF Radar vs. Microwave Radar

- Limitation on beam width / antenna dimension
- Limited available bandwidth (~ 10's kHz)
- ⇒ Range cell resolution of few km
- External noise limited
  ⇒ Rx antenna gain less important
- Coherent Integration time 1 – 200 sec
  ⇒ Conventional azimuthal scan mode fails
- Sea clutter: Resonant Bragg scatter
- Target RCS : in resonant range

Sea Clutter

Dominant contributor: Waves travelling in the direction of the radar beam

First order Bragg scatter: $\lambda_{water} = ½ \lambda_{radar}$



$$f_{doppler} = \pm \sqrt{\frac{g \cdot f_{radar} \cdot \sin(\Theta)}{\pi \cdot c}}$$

g = acceleration due to gravity

c = speed of light in vacuum

surface wave: $\Theta = 90°$

Note: for hard targets $f_{doppler} = \frac{2v \cdot f_{radar} \cdot \sin(\Theta)}{c}$

Sea Clutter

Dominant contributor: Waves travelling in the direction of the radar beam

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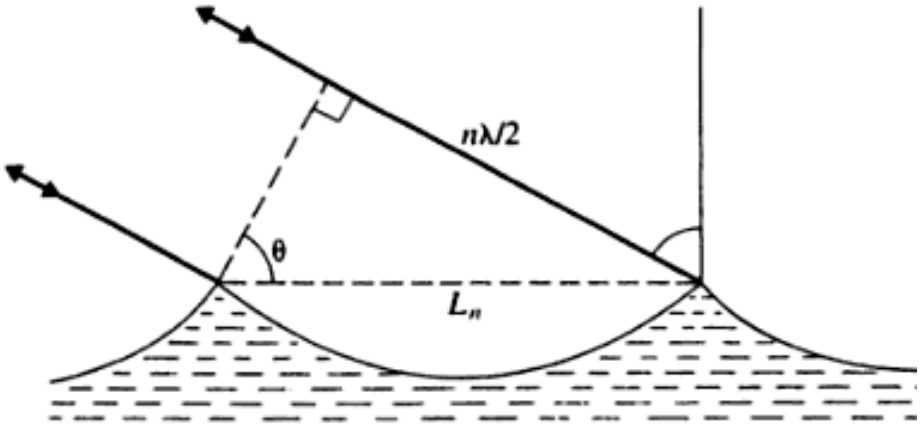


$$f_{doppler} = \pm \sqrt{\frac{g \cdot f_{radar} \cdot \sin(\Theta)}{\pi \cdot c}}$$

g = acceleration due to gravity

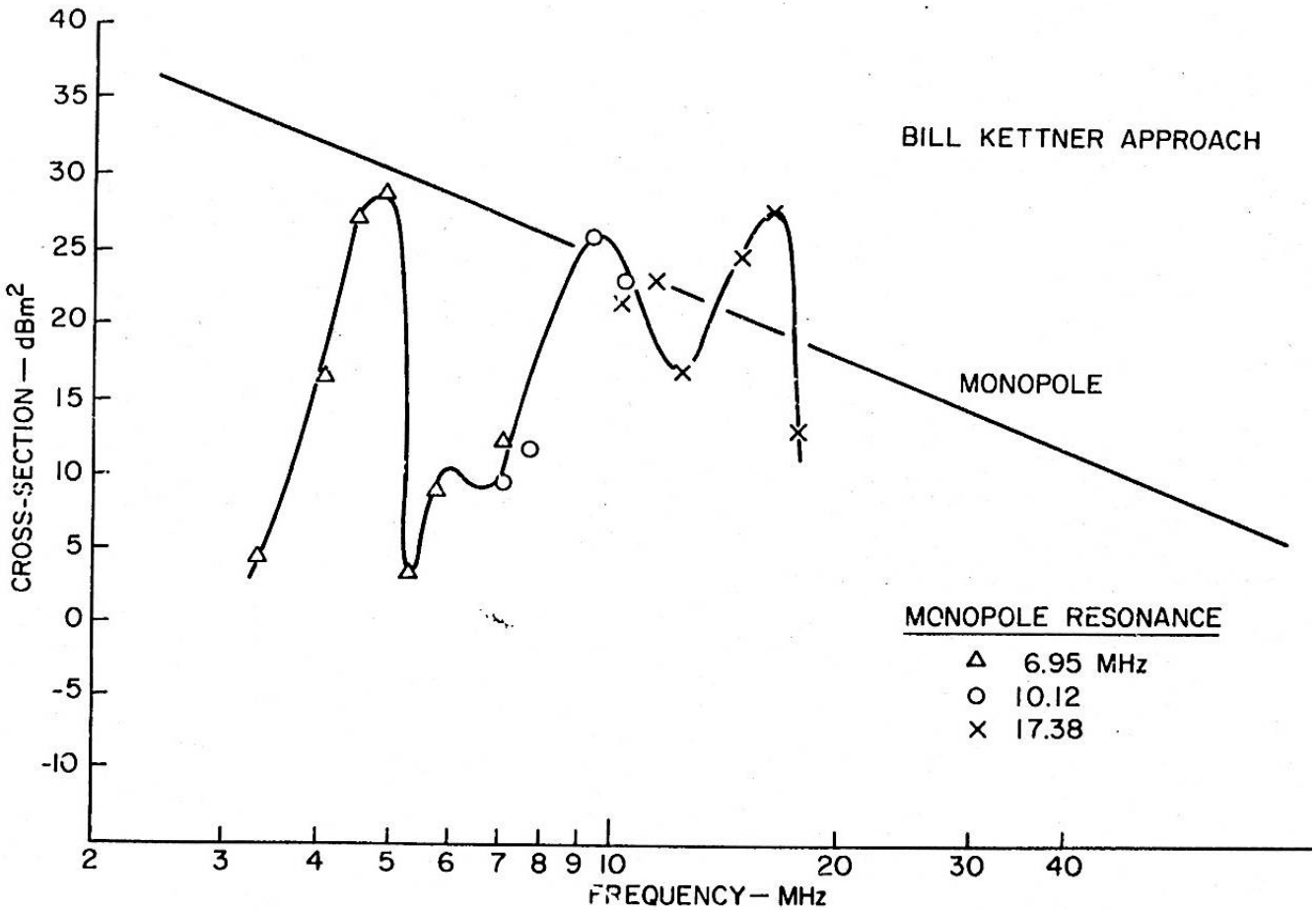
c = speed of light in vacuum

surface wave: $\Theta = 90°$

Clutter power reduces with increasing spatial resolution **!**

Note: for hard targets $f_{doppler} = \frac{2v \cdot f_{radar} \cdot \sin(\Theta)}{c}$

RCS of Fishing Boat



RCS of 65-foot fishing boat from bow-on view

Bogle, R.W., Trizna, D.B., “Small Boat HF Radar Cross Section,” Naval Research Laboratory, Washington D.C., 1976

Shore Based HF Antenna Arrays

'WERA Remote Ocean Sensing'

- Semi-compact to large
- Software beam forming
- Azimut resolution depends on wavelength / array length
- Suitable for multiple target scenario and investigation of second order clutter

Shore Based HF Antenna Arrays

'WERA Remote Ocean Sensing'

Drawbacks:

- Impact of terrain on surface wave excitation
- Land-use footprint incl. safeguarding
- Costs driven by beach property
- Visual impact
- Protection

Large HF Antenna Arrays on Sea

- Chain of Buoys
- Floating rigid platforms
- Naval formation

Large HF Antenna Arrays on Sea

- Geometrical dimensions virtually unlimited
- Element number limited for practical reasons

Cost effective solution: sparse array

Large HF Antenna Arrays on Sea

- Geometrical dimensions virtually unlimited
- Element number limited for practical reasons

Cost effective solution: sparse array

Drawback:
Distortion of array pattern by dislocation and tilting of array elements due to wind and waves

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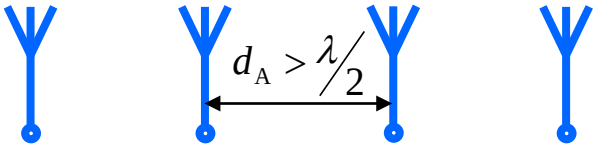
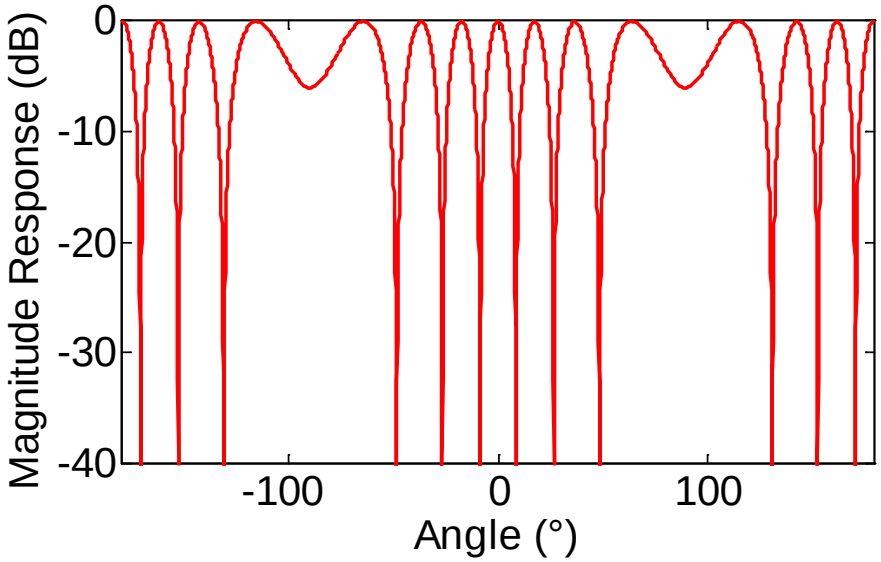
Sparse Array Beamforming

Spatial undersampling $\Rightarrow$ Gratinglobes

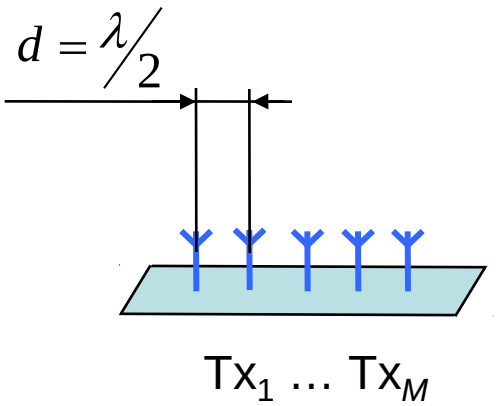


Sparse array

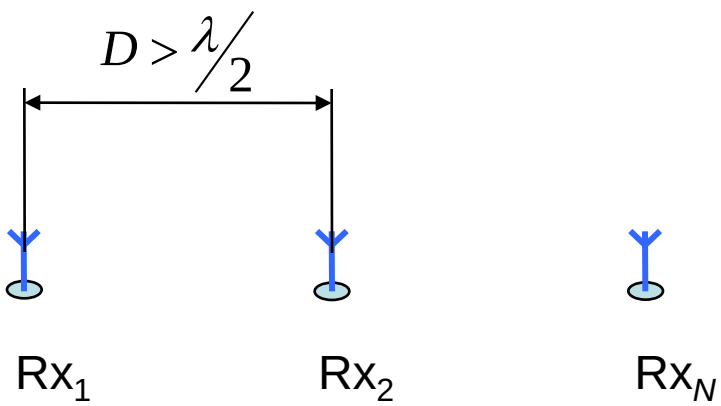


Antenna pattern

Proposed Sparse Sea Floating Array



Dense transmit array
on rigid platform

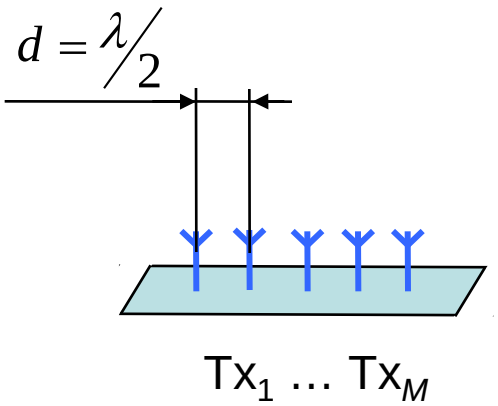


Linear sparse receive array
on individual platforms

Gratinglobes resolving by

- Concept of effective aperture
- MIMO beamforming

Proposed Sparse Sea Floating Array



Dense transmit array
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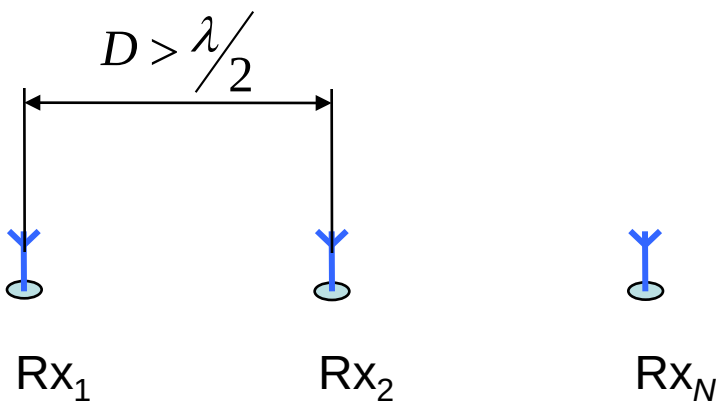


Linear sparse receive array
on individual platforms

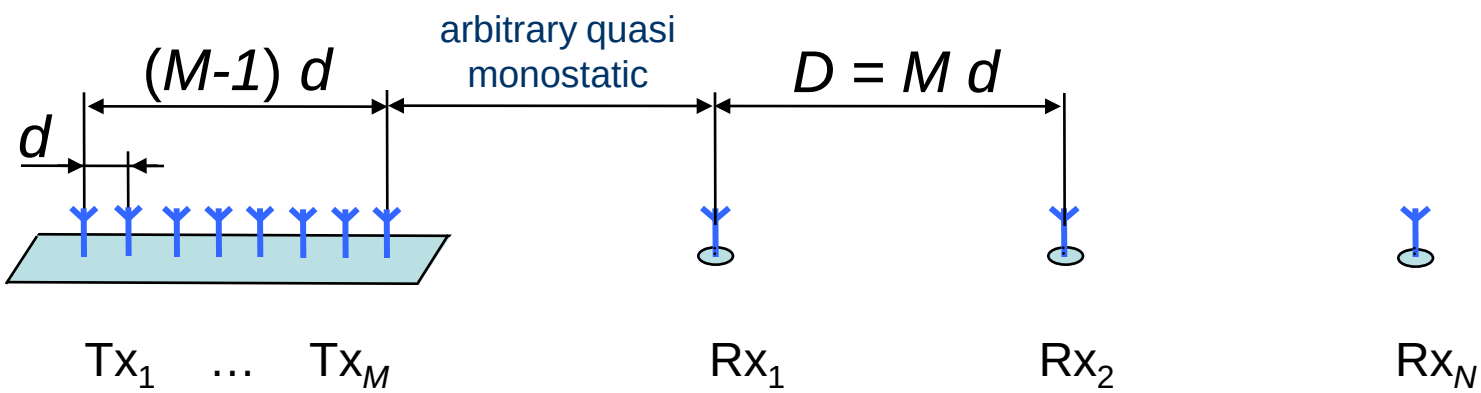
Gratinglobes resolving by

- Concept of effective aperture
- MIMO beamforming

Inter-element coupling insensitive to impact of wind and waves

Concept of Effective Aperture

The effective aperture of the combination of a transmit and a receive array is the receive aperture that would produce the same two-way radiation pattern if the transmit antenna would be a point source.



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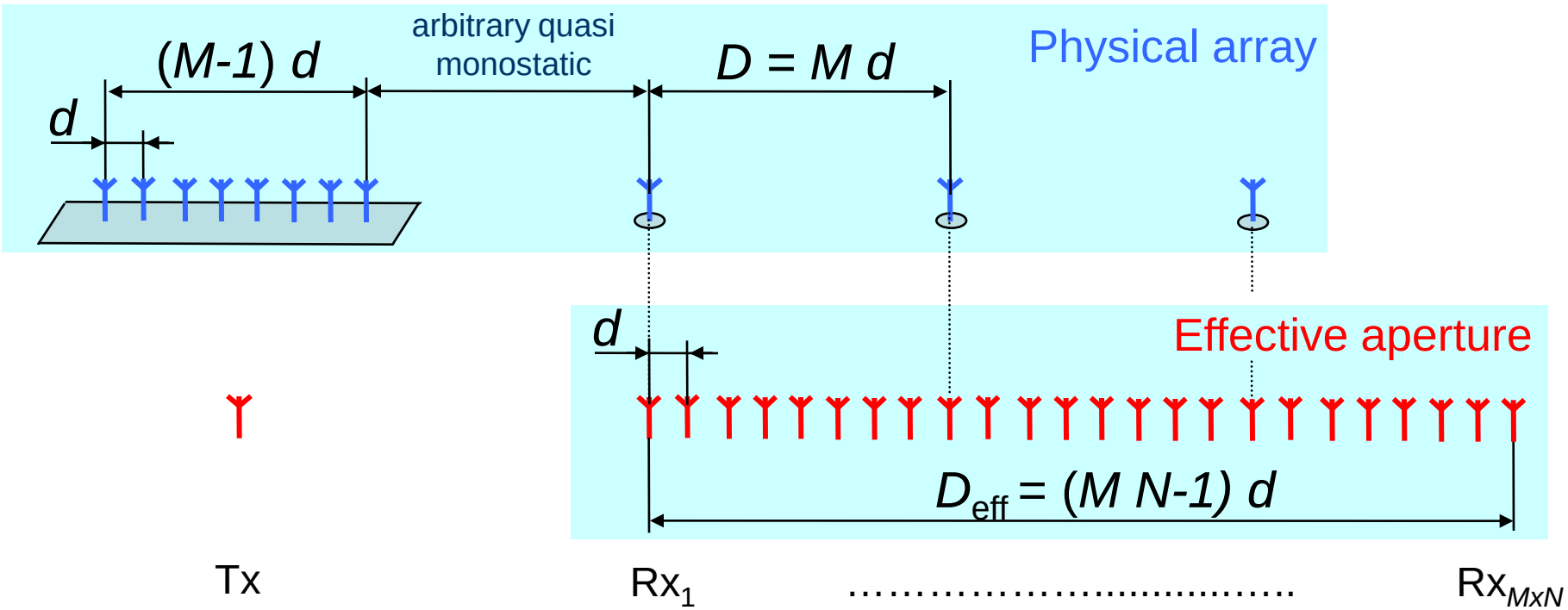
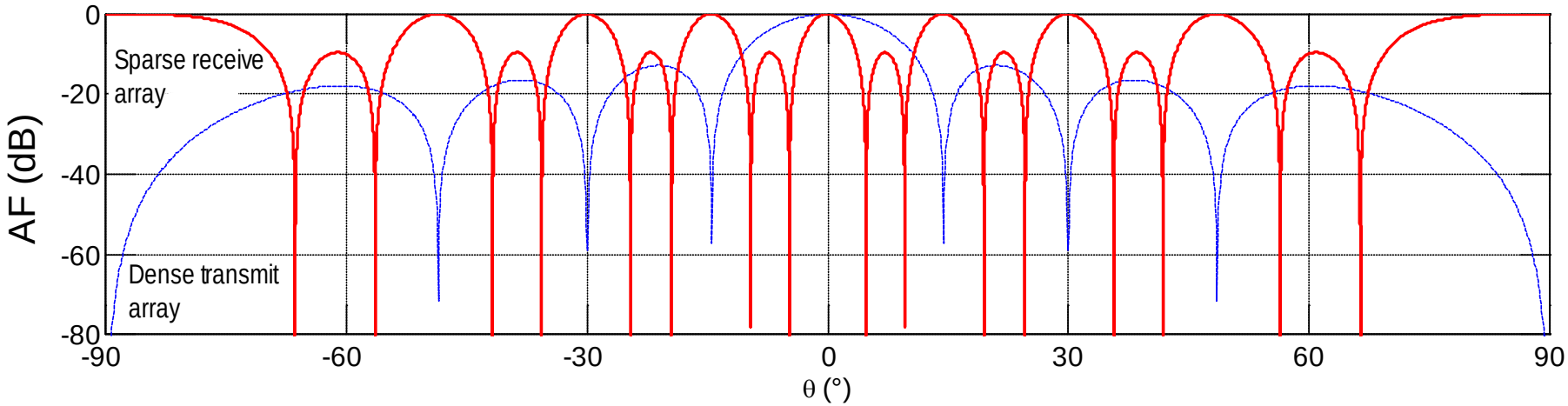
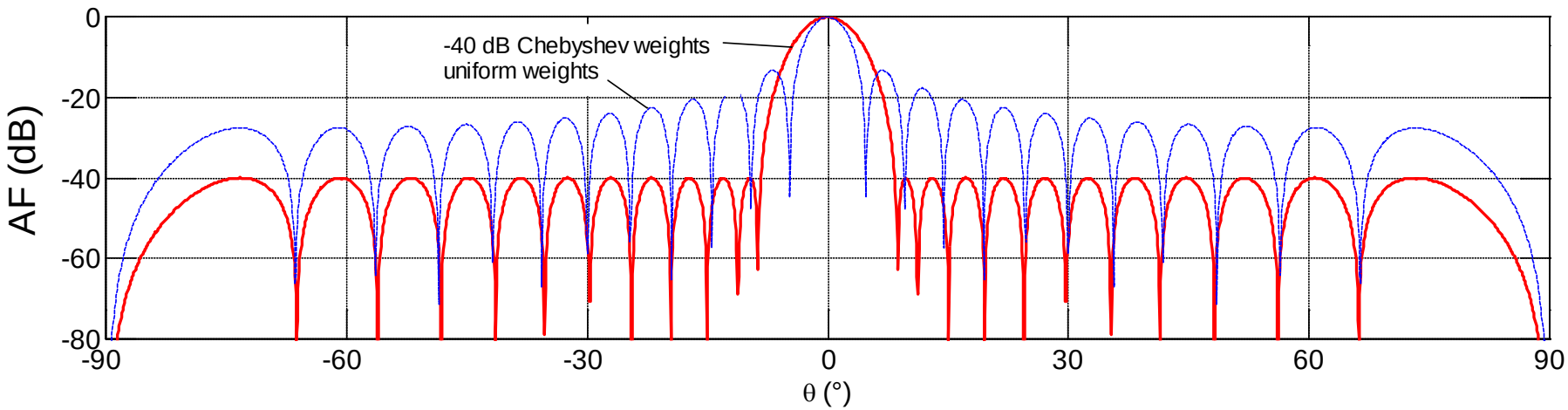


Gratinglobes Resolving

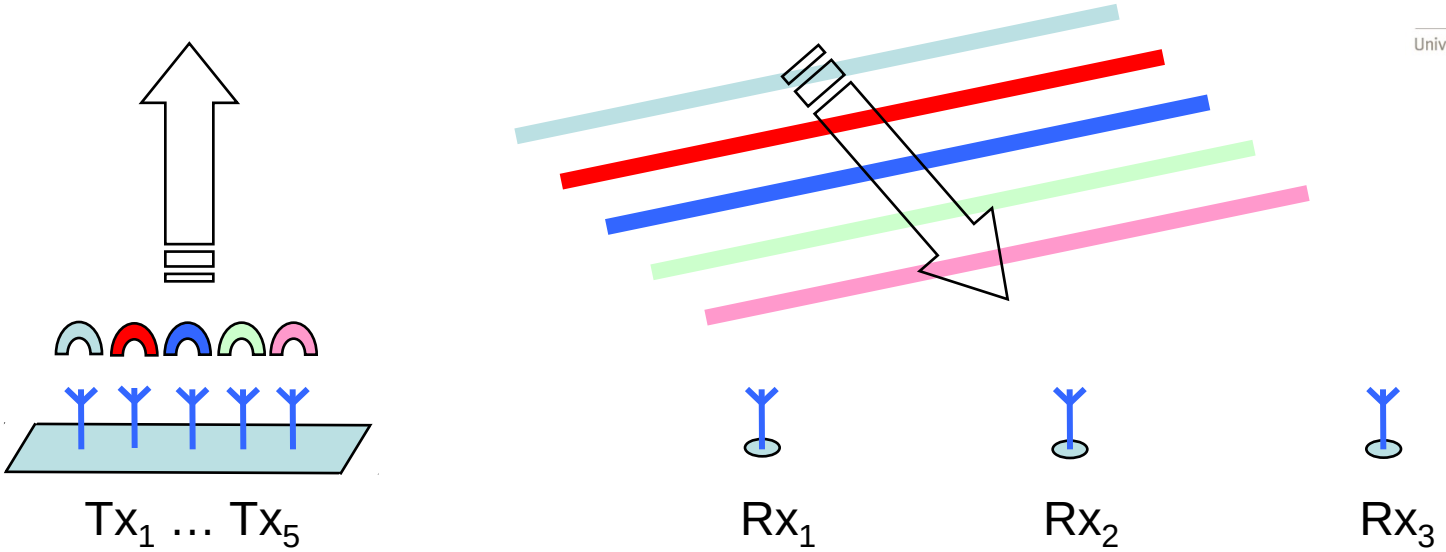


Array factor pattern of transmit and receive array with uniform amplitude weights



Convolving sparse Rx aperture with appropriate filled Tx aperture results in effective aperture with array factor pattern without gratinglobes

MIMO Beamforming

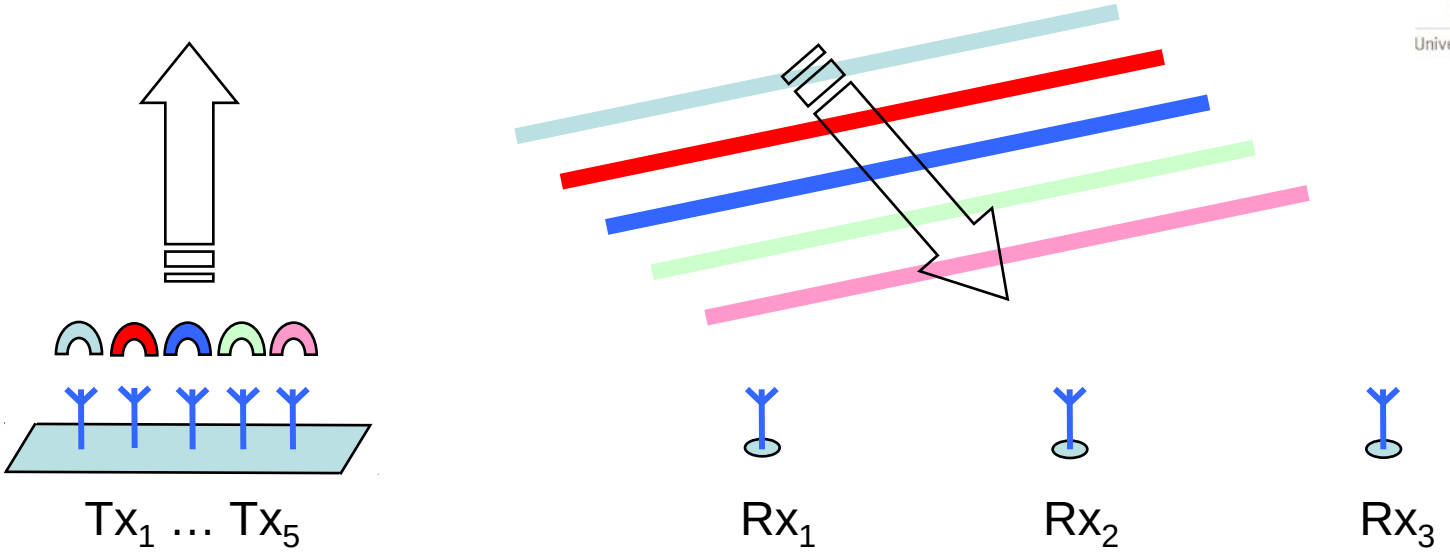


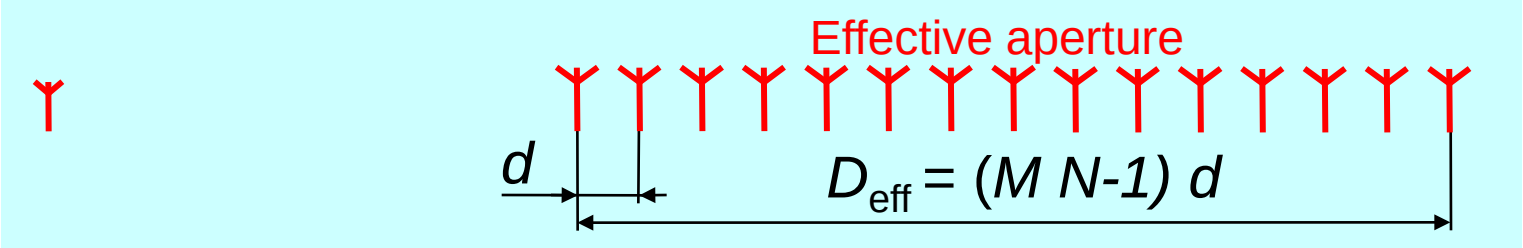
Orthogonal waveform for each transmit antenna element

Individual paths T_{xi} – R_{xj} can be processed separately

Beams simultaneously formed in software domain (baseband)

MIMO Beamforming

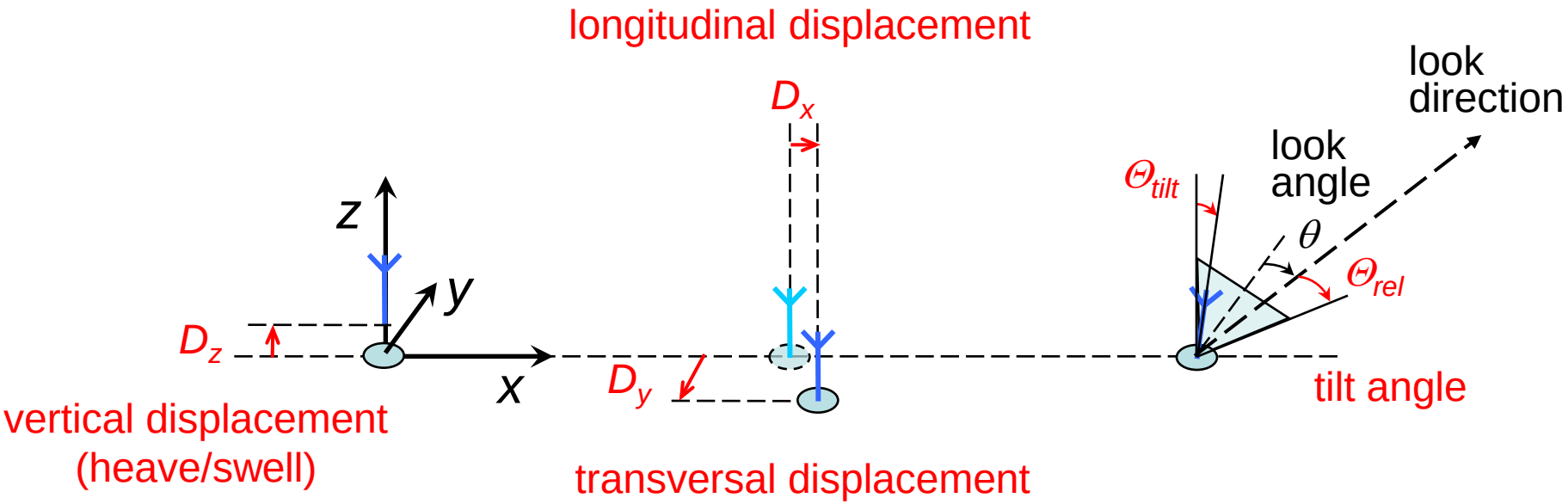




Complex weights for each element of effective aperture:
Beamforming as if effective aperture would be physical array

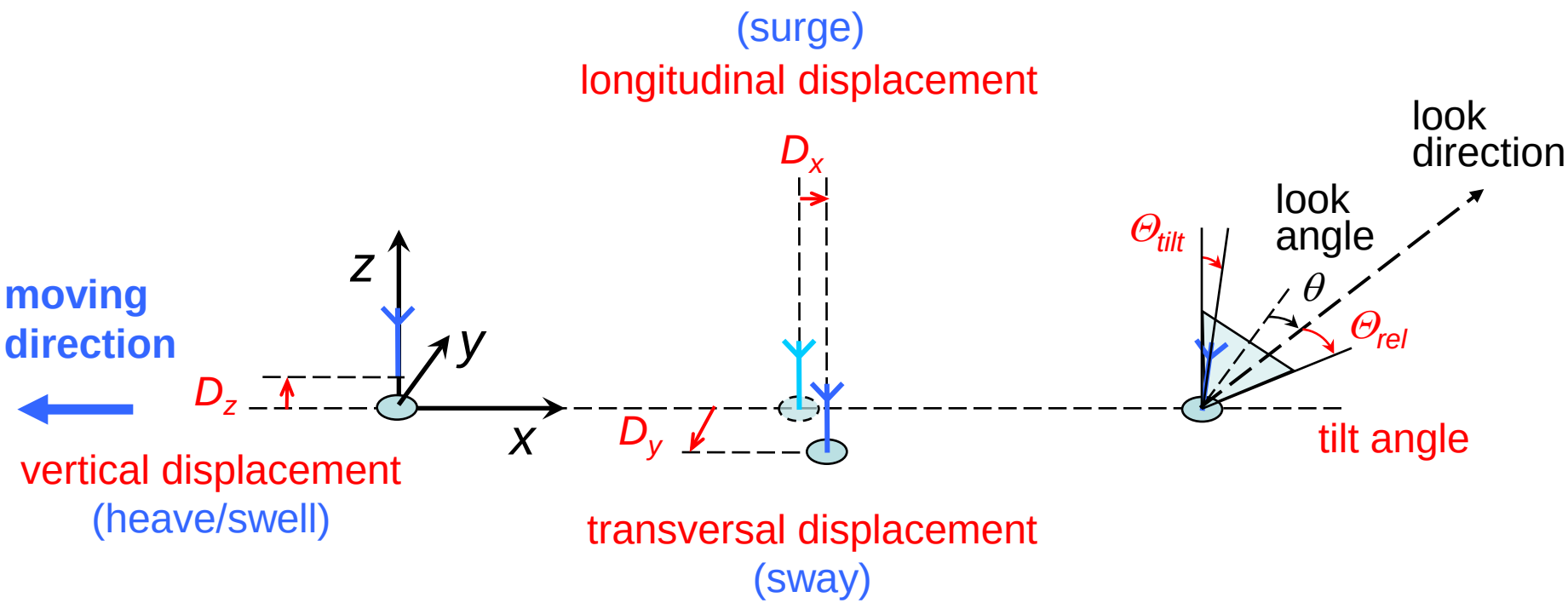
Deformation of Sea Floating Linear Array

Stationary array (moored)



Deformation of Sea Floating Linear Array

Non-stationary array (towed or propelled platforms)



Pitch	rotation along *y*-axis
Roll	rotation along *x*-axis
Yaw	rotation along *z*-axis

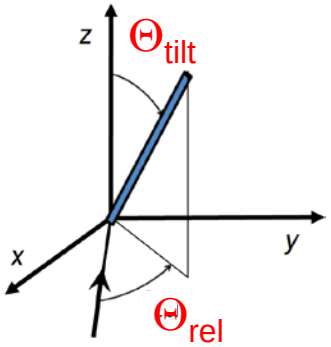
Challenges of Pattern Correction

- Individual dynamic displacement and tilt angle
- Real time compensation

Generic algorithms or particle swarm optimization provide good results but are too time consuming

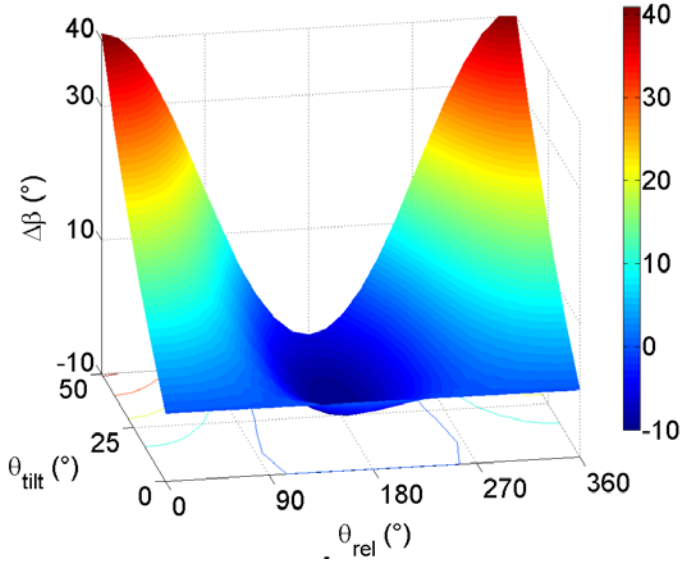
Impact of Tilt Angle

λ/4 Monopole

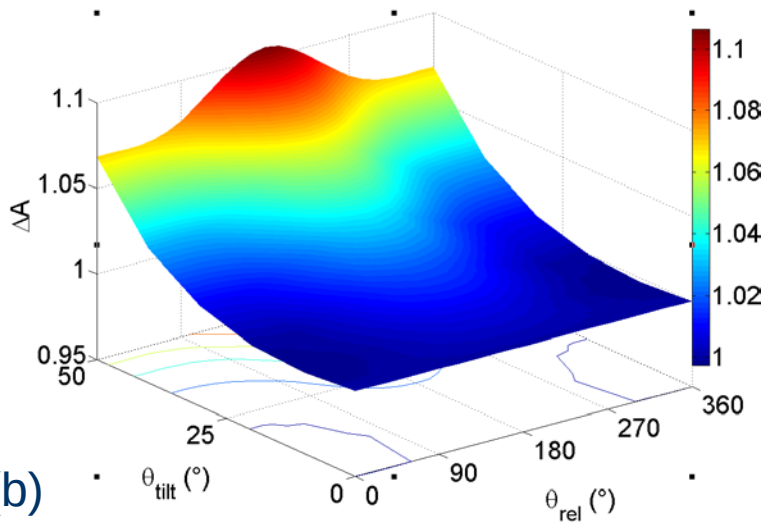


look direction

(a)

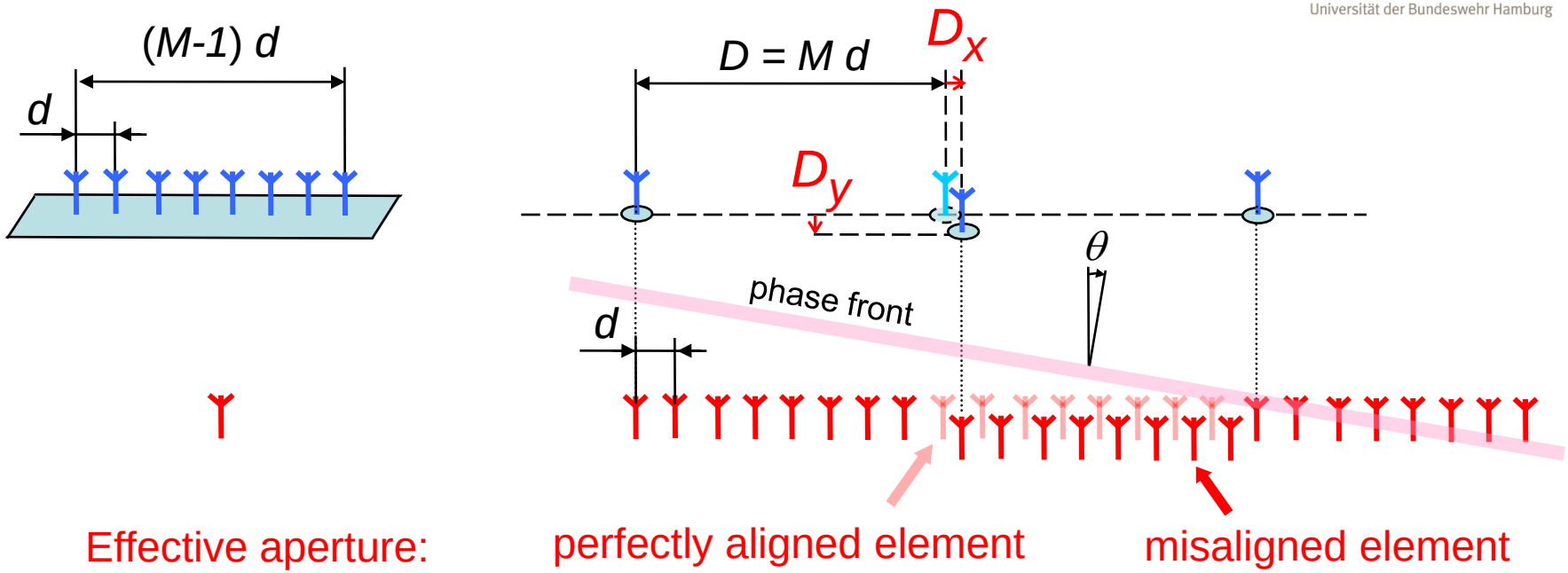


(b)



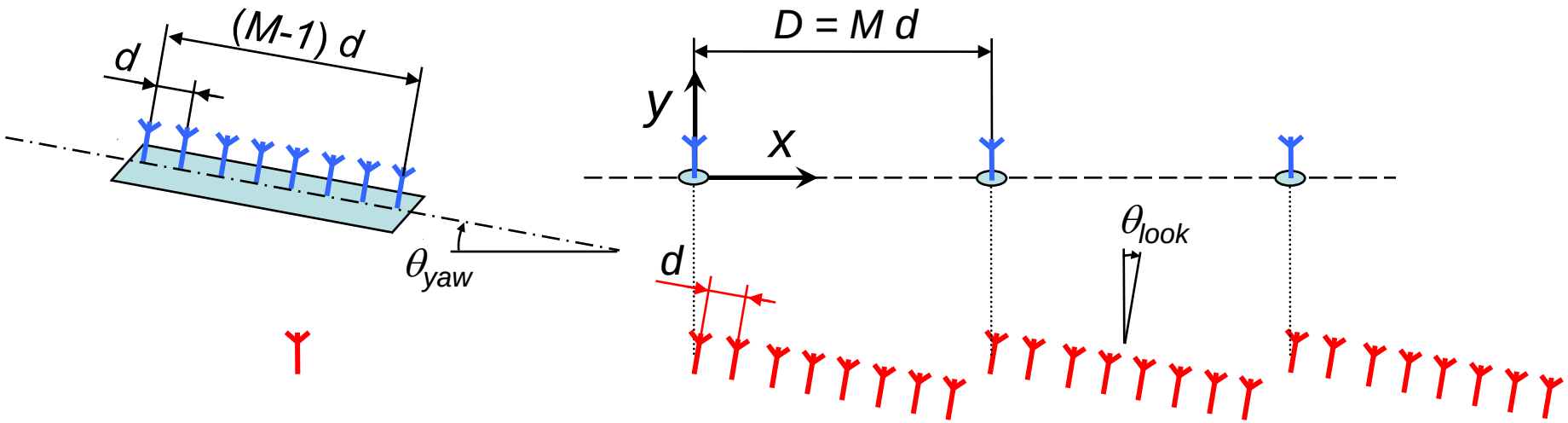
Simulation results of (a) absolute phase $\Delta\beta$ and (b) relative amplitude variation ΔA vs tilt angle Θ_{tilt} and angle Θ_{rel}

Impact of Horizontal Displacement



Impact of horizontal displacement of Rx platform on effective aperture (static approach)

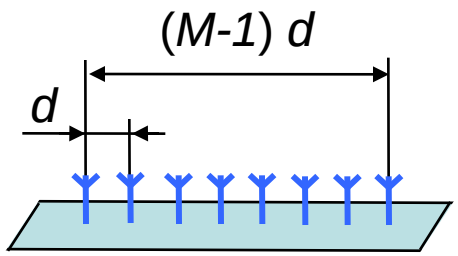
Impact of Yaw Angle

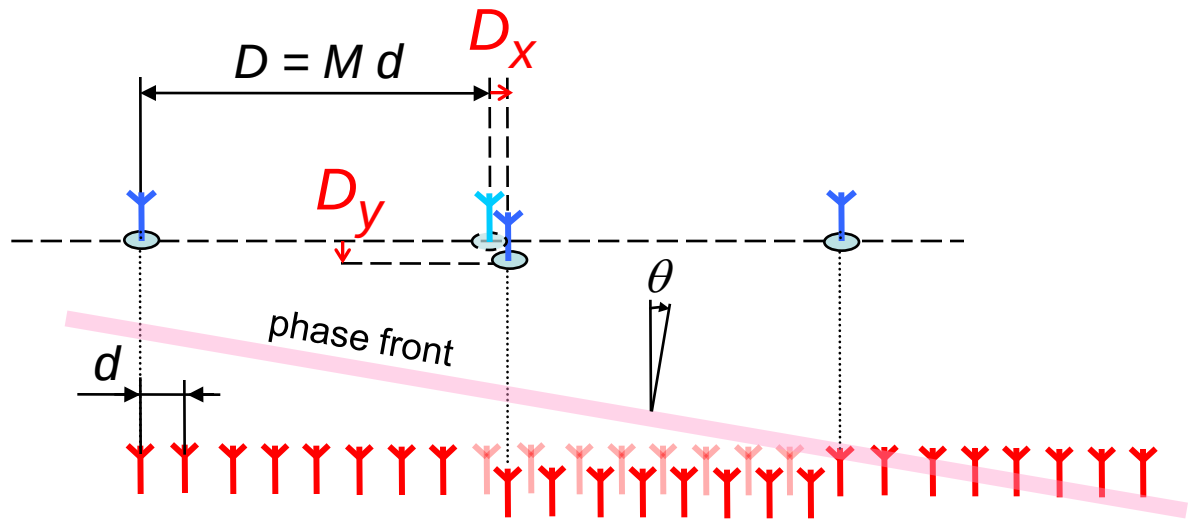


Yaw of Tx Platform

Impact of yaw angle of Tx platform on effective aperture (static approach)

Impact of Dislocation on Elementary Signal of Effective Aperture

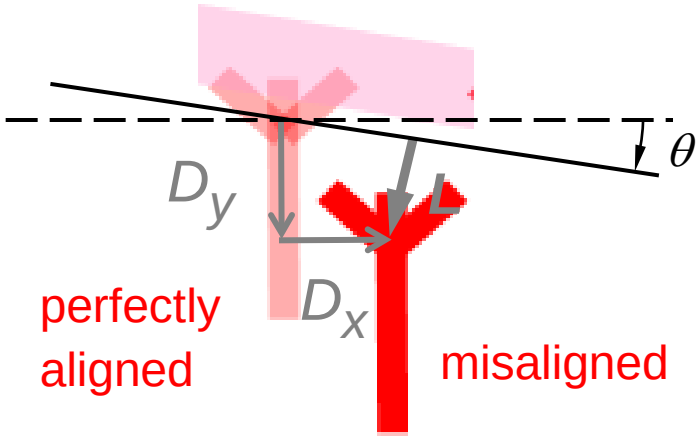




Look angle θ dependent

Additional path length L

Additional phase change $\Delta\beta = 2\pi \frac{L}{\lambda_0}$



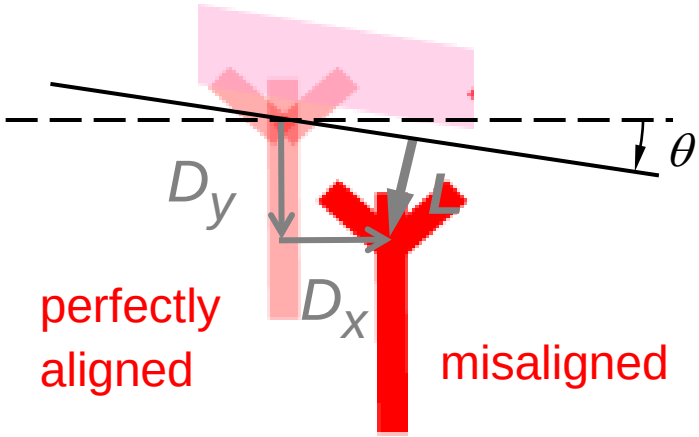
Fast Compensation Scheme

Compensate weights of misaligned elements of effective aperture for total look angle θ dependent phase shift $\Delta\beta$ and rel. amplitude variation ΔA.

Look angle θ dependent

Additional path length L

Additional phase change $\Delta\beta = 2\pi \frac{L}{\lambda_0}$

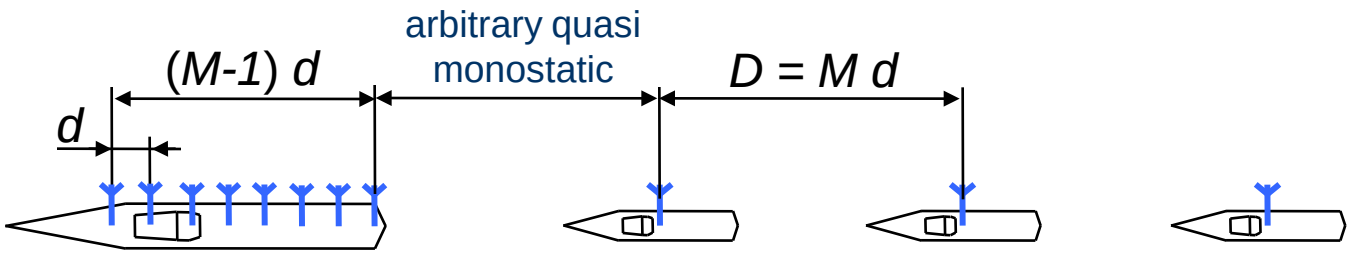


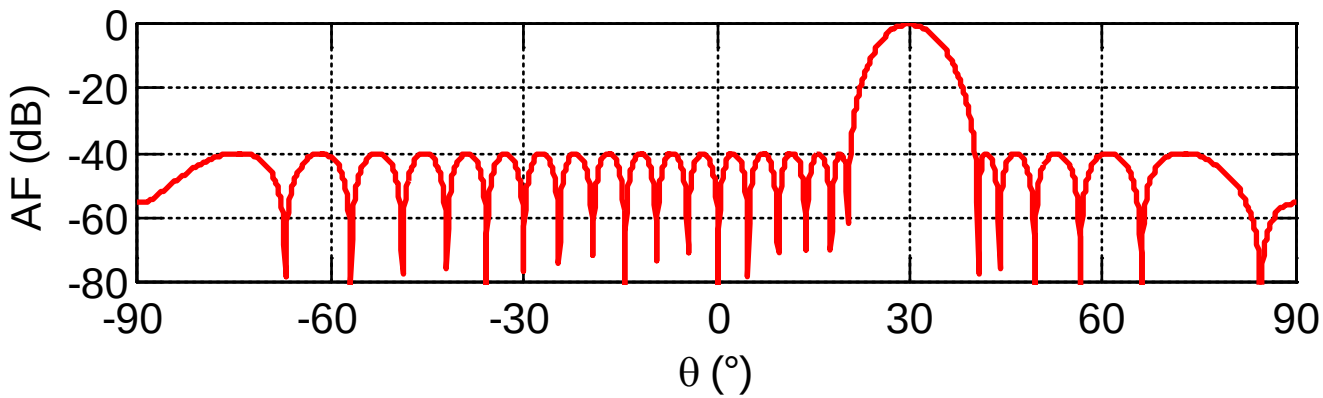
Array Factor Pattern

f = 10 MHz (λ=30m)
M = 8 Tx elements
N = 3 Rx elements

SLL = -40 dB
D_x = [0 0 0] m
D_y = [0 0 0] m

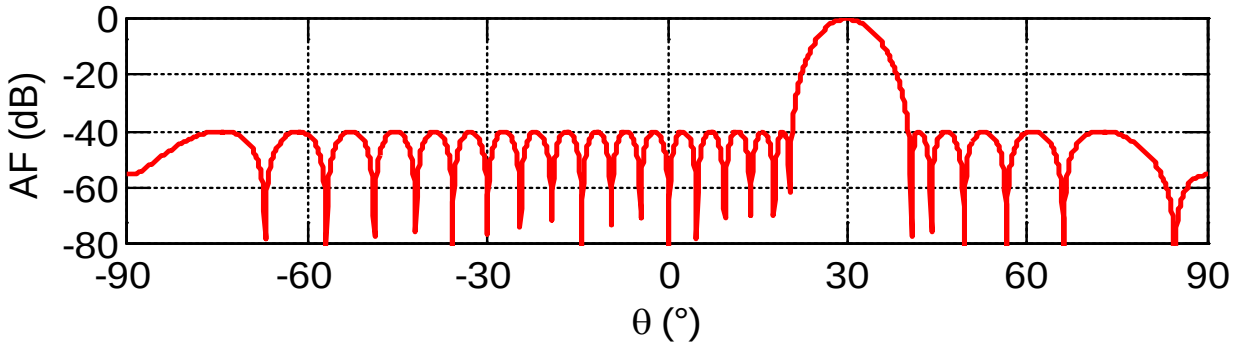
$d = \lambda/2$ = 15 m
D = 4 λ = 120 m
Effective aperture 345 m
$HPBW$ = 6° (@ θ_{look}=0°)





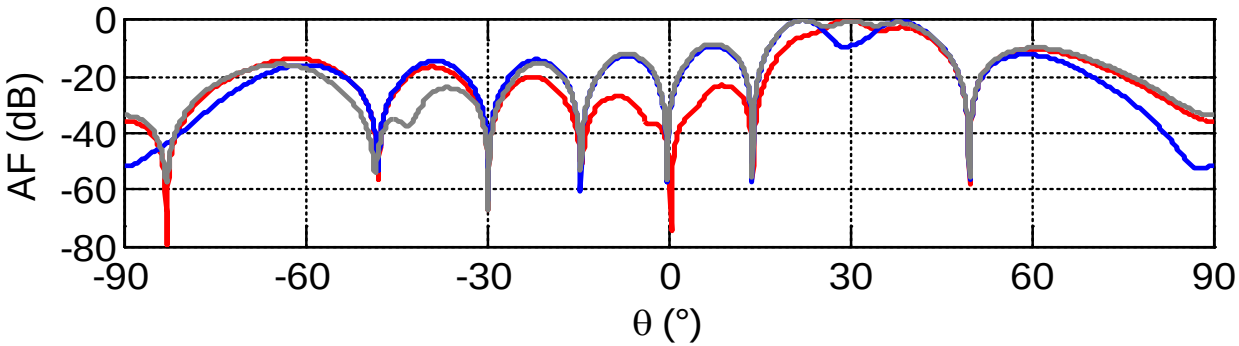
Array factor pattern for perfectly aligned inter-ship formation pattern (θ_{look} = 30°)

Look Angle Dependant Phase Corr.

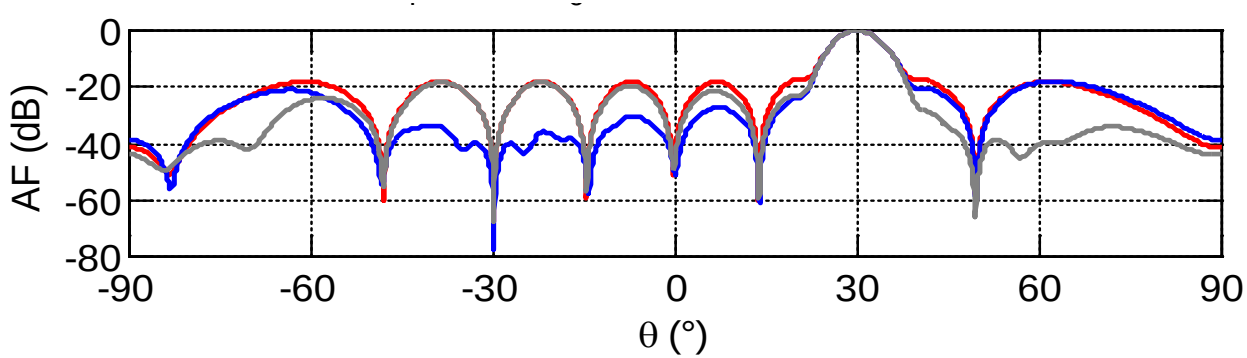


Inter-ship formation pattern

Perfectly aligned



Misaligned w/o phase corr.



Misaligned w/phase corr.

— D_x=[0 15 0]m, D_y=[0 0 0]m — D_x=[0 0 0]m, D_y=[0 15 0]m — D_x=[0 15 0]m, D_y=[0 15 0]m

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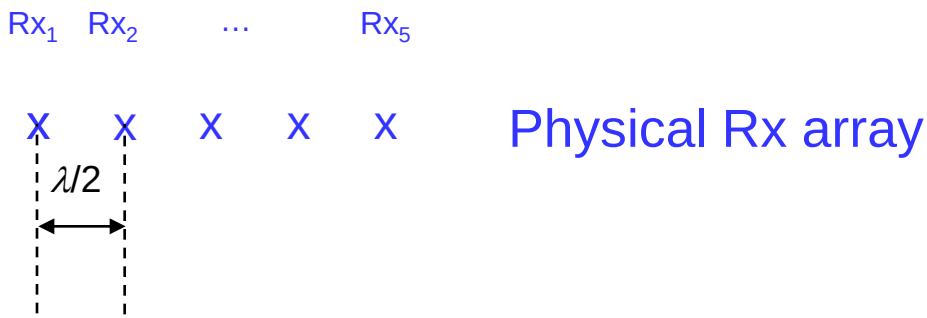
Compact Uniform Linear Array

'WERA Remote Ocean Sensing'

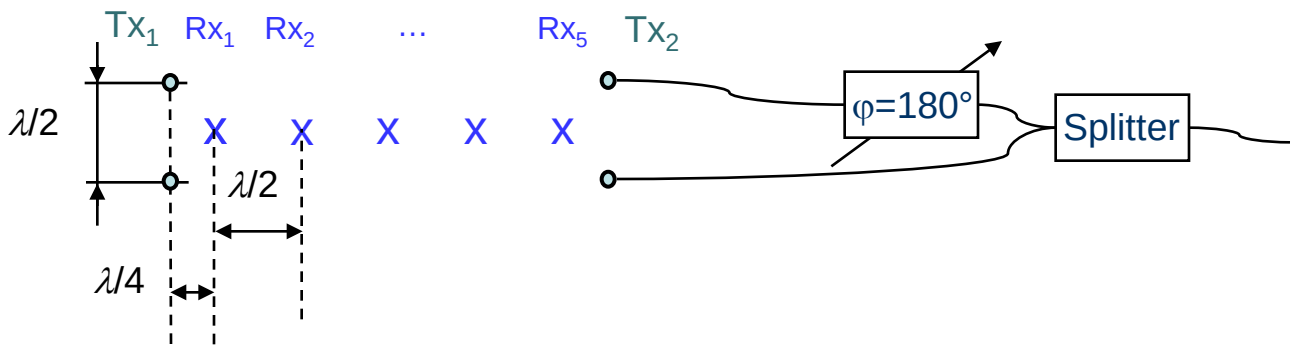
Investment for coastal HF SWR is mainly driven by the huge beach property. Shortening the array length is of higher importance than reducing hardware complexity.

With a proper array arrangement MIMO beamforming can be used to double the aperture of Rx array.

Compact Uniform Linear Array



Compact Uniform Linear Array

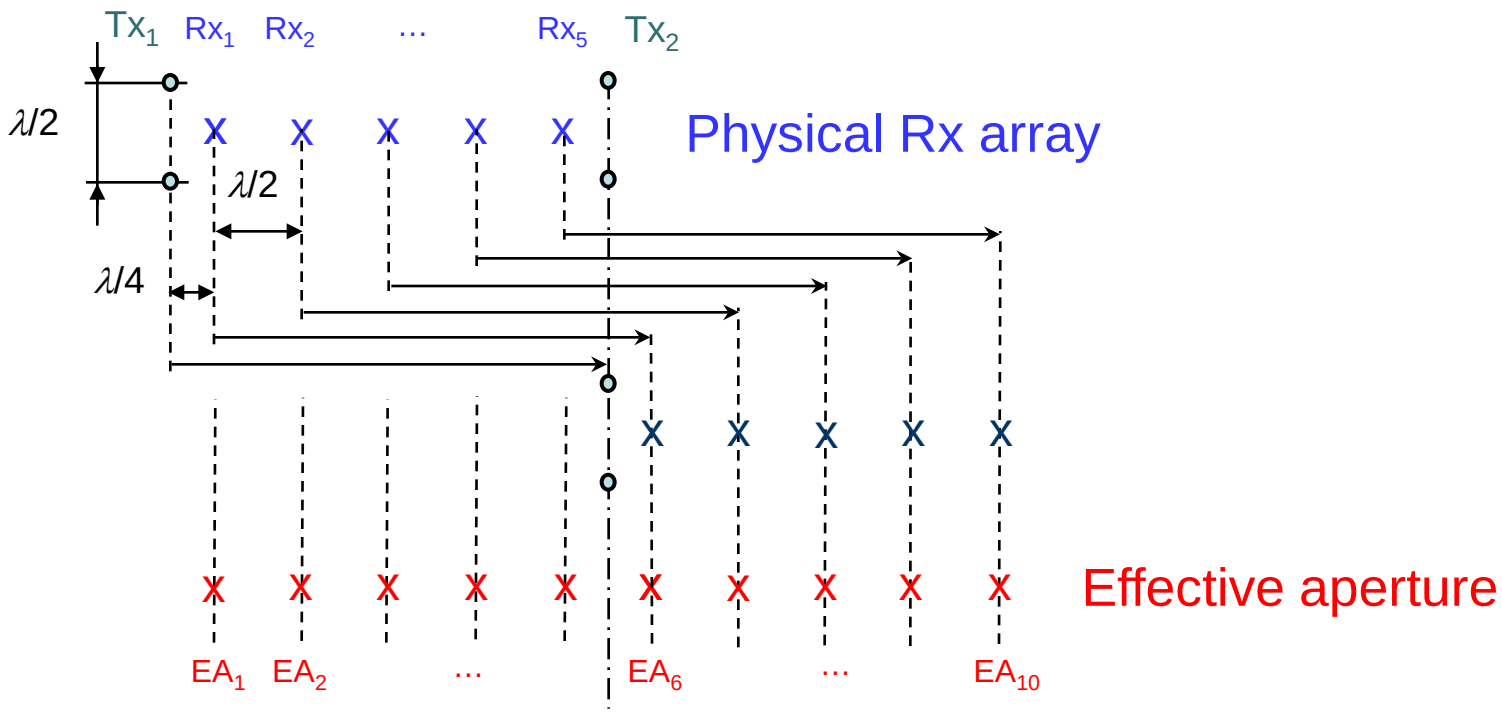


Both elements of each Tx array are driven 180° out of phase

➡ Null along Rx array

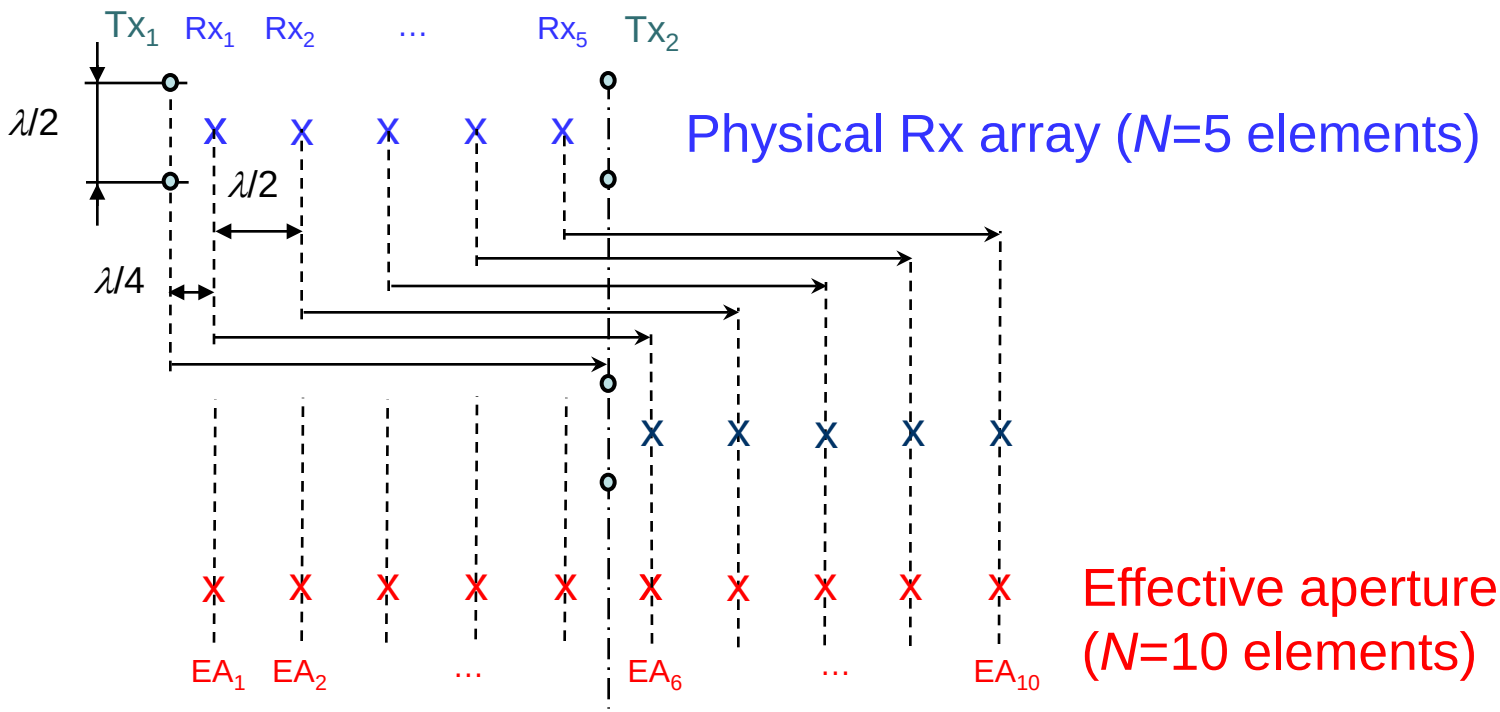
Spacing between Tx phase centers and respective neighboring Rx element is half the inter-element spacing of Rx aperture

Doubling of Rx Aperture



In conjunction with transmit array Tx_2 the elements Rx_1 … Rx_5 provide the signals of elements EA_1 … EA_5. In conjunction with transmit array Tx_1 the same elements provide the signals of elements EA_6 … EA_{10}.

Doubling of Rx Aperture



Taking into account that compared to conventional beamformer MIMO concept requires an additional Tx array, the shortening of total antenna aperture of Tx and Rx arrays is $(N+1)/(2N)$.

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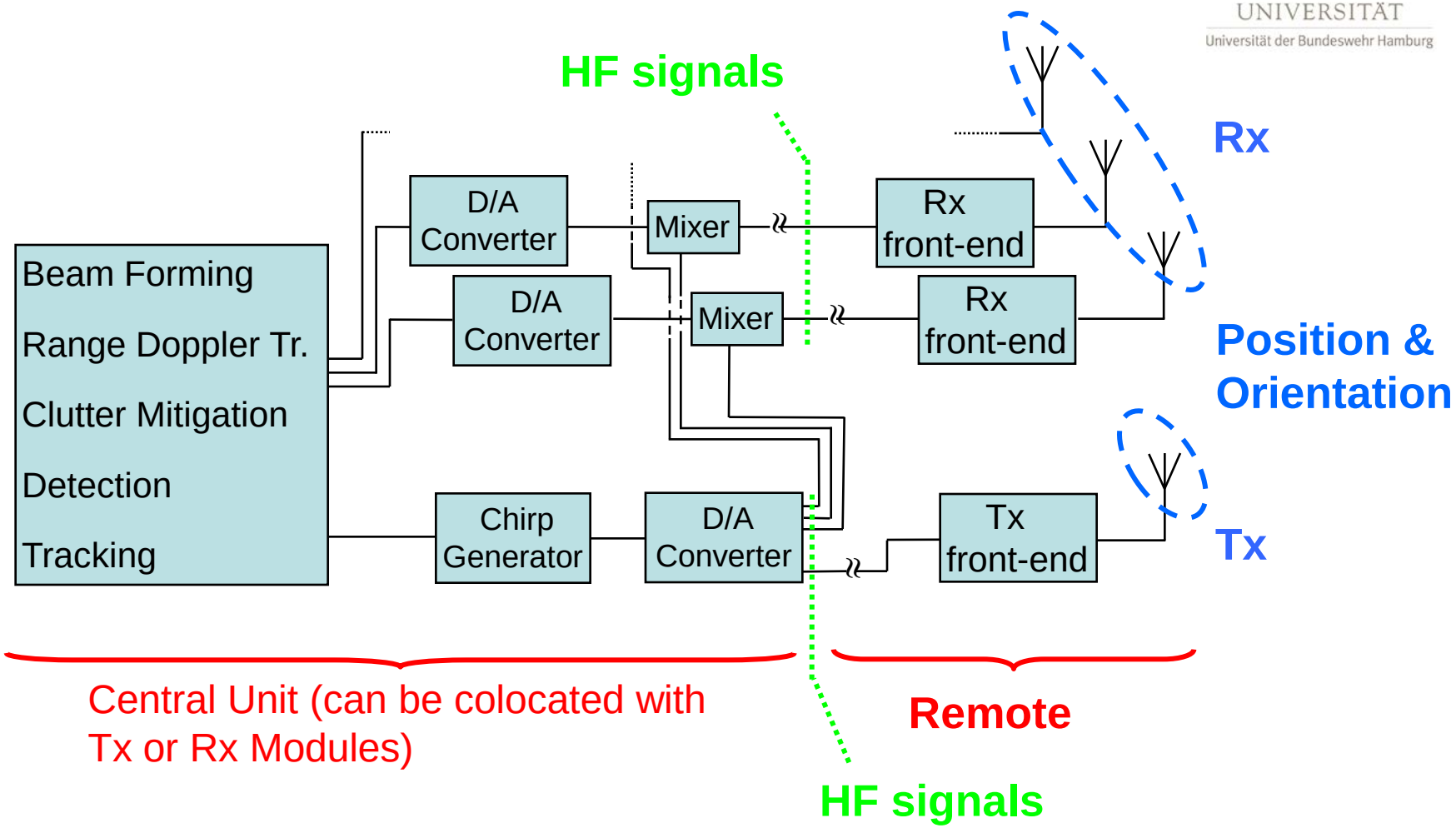
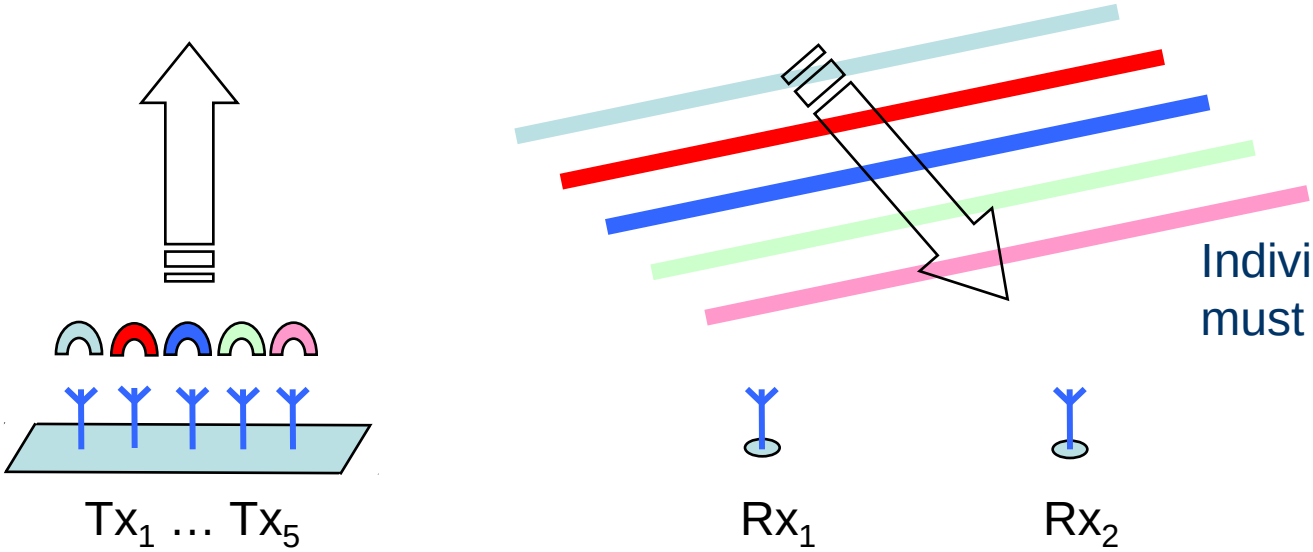
Distributed FMCW HF SWR on Sea

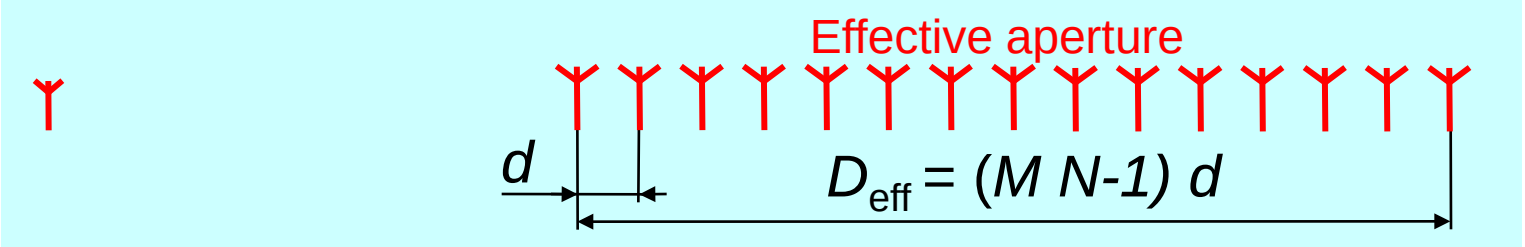


Optical or μ-Wave Interfaces for: - HF Signals
- Antenna Positions and Orientations (Pitch, Roll, etc.)

MIMO Beamforming



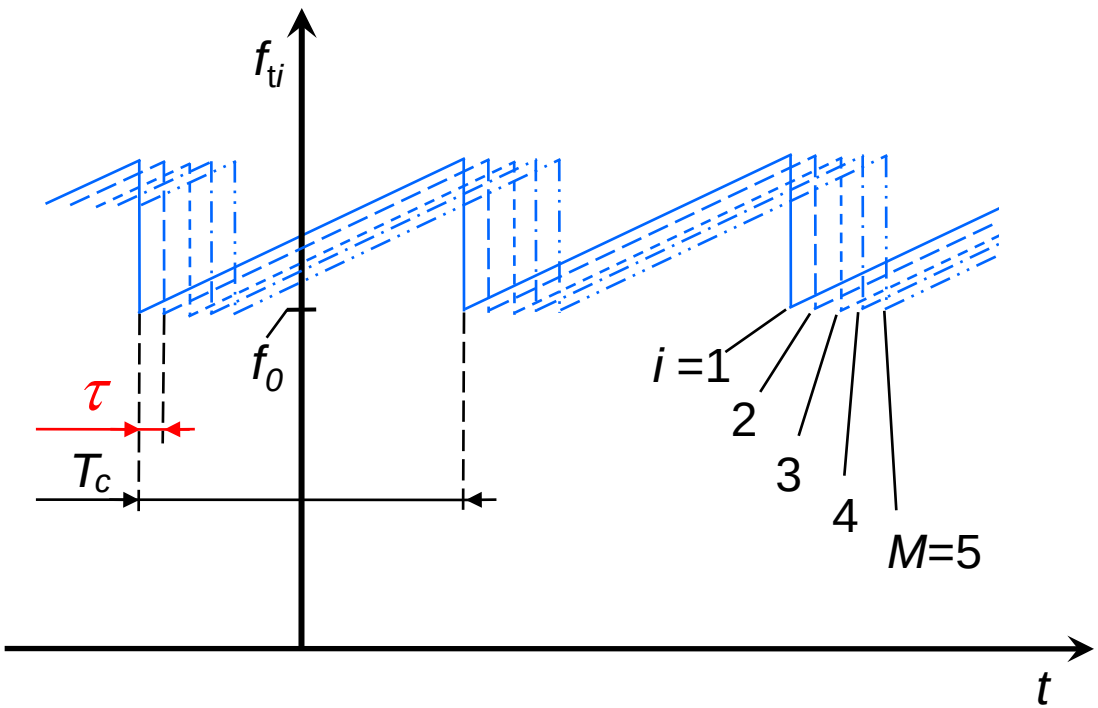
Individual paths $T_{xi} – R_{xj}$ must be discriminably



Complex weights for each element of effective aperture:
Beamforming as if effective aperture would be physical array

Time-Staggered FMCW Chip Signals

Received signals are separable in frequency domain **!**



$$f_{ti}(t) = f_0 + \alpha\left[t - (i-1)\tau\right]$$

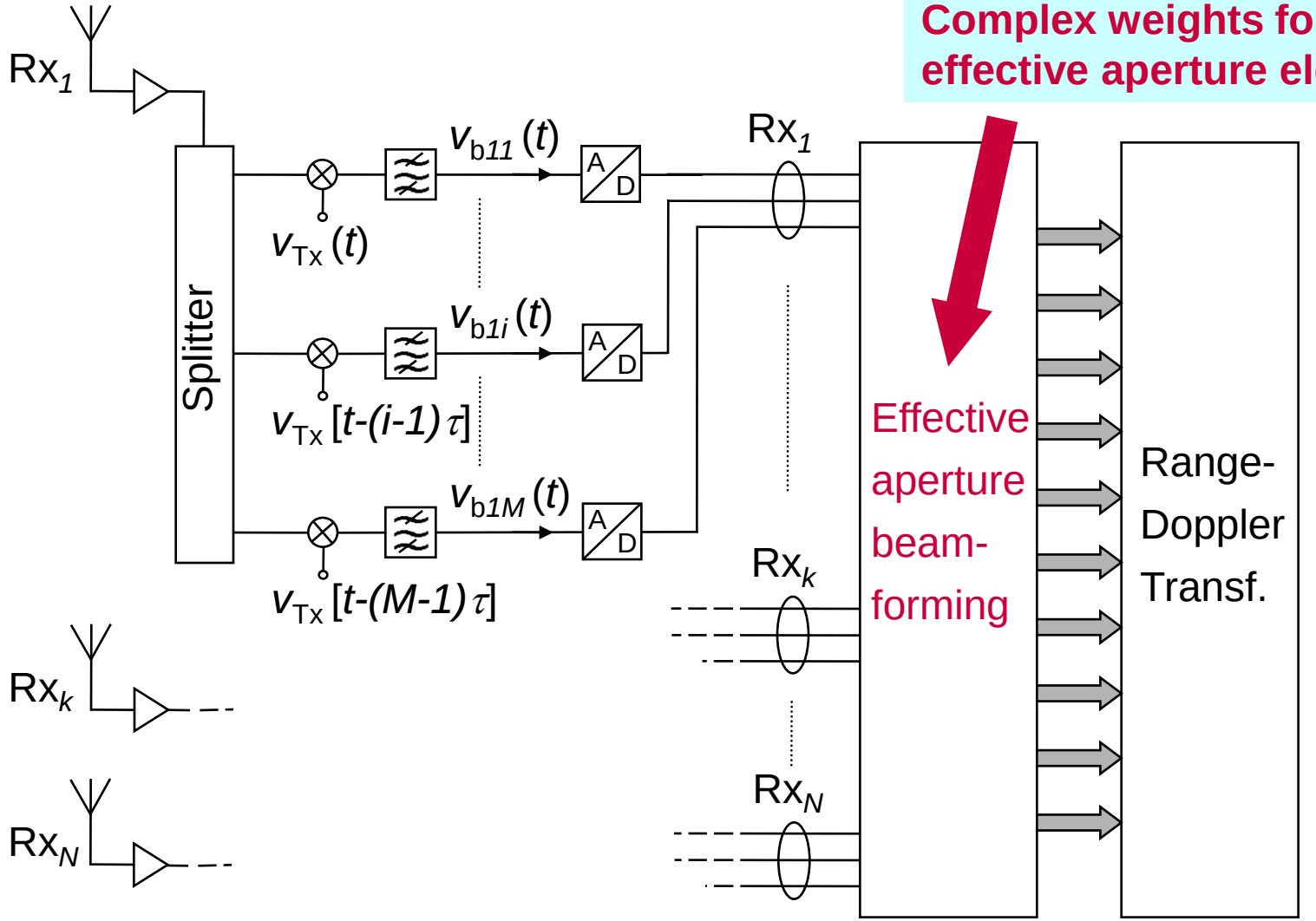
$$\frac{T_c}{M-1} > \tau > \tau_d$$

$$\tau_d = 2\frac{R_{\max}}{c}$$ Round-trip time

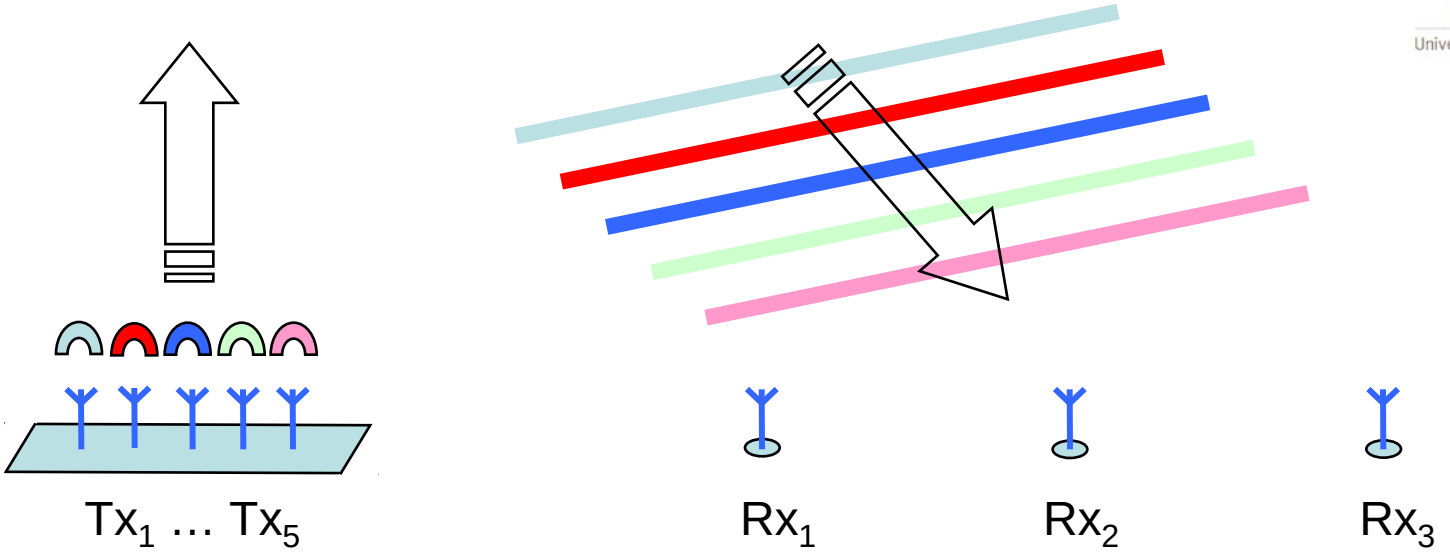
Transmit signal for individual Tx element

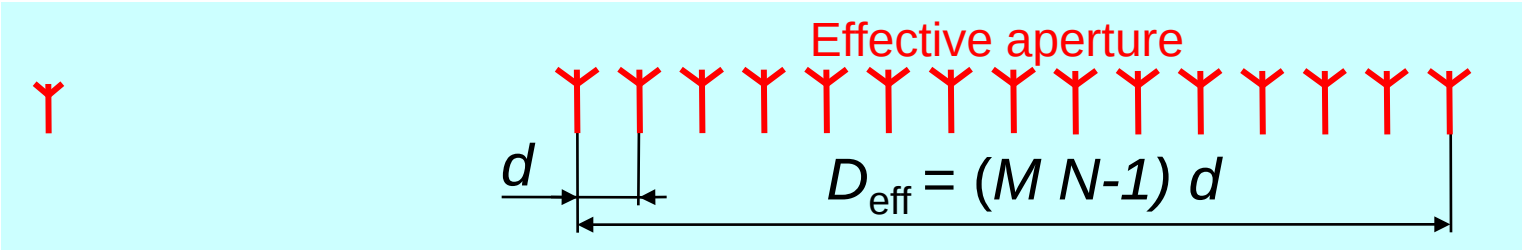
Receiver Hardware and Software Functions

MIMO approach:
Complex weights for each effective aperture element



MIMO Beamforming





Complex weights for each element of effective aperture:
Beamforming as if effective aperture would be physical array

Outline

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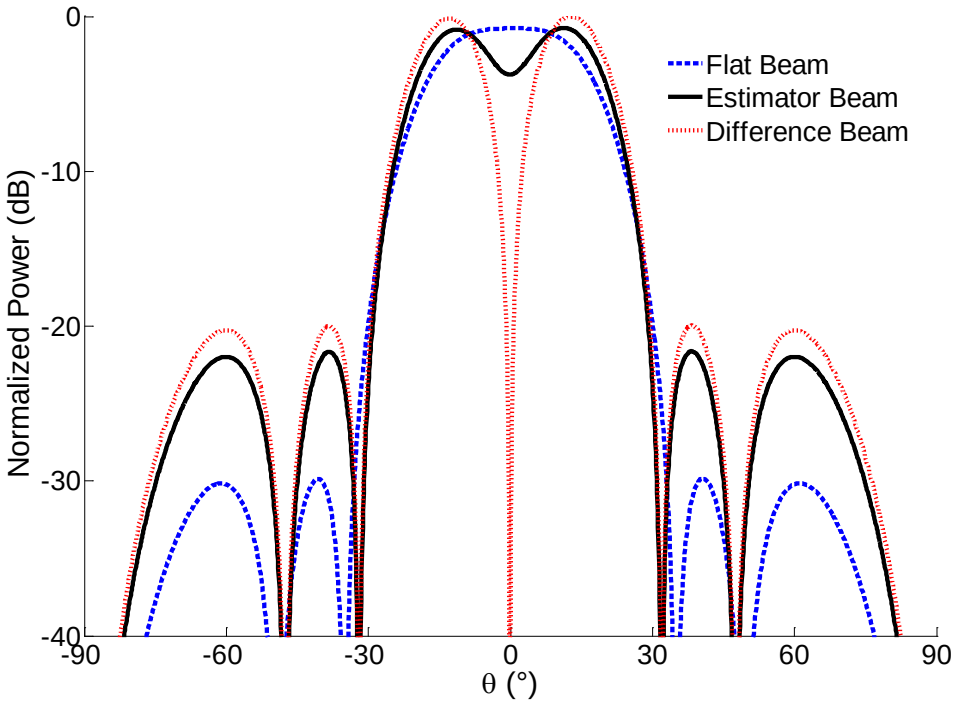
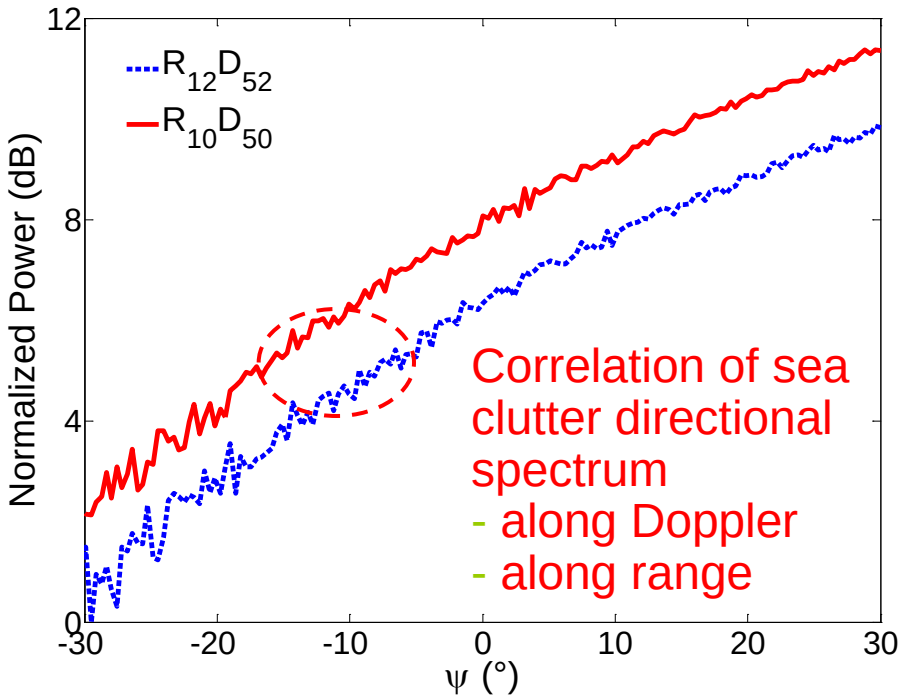
2. Large Sparse Arrays on Sea
3. Compact Uniform Linear Array Using MIMO Beamformer
4. MIMO Beamformer Using Time-Staggered FMCW Chirp Signals
5. Outlook on Novel Concepts for Improved Ship Detection In Inhomogeneous Background
6. Summary

Improving Ship Detection





Sea clutter canceller beam former using Flat Beam, Difference Beam and Estimator Beam

Correlation detector using Uni-modal Wave Directional Spectrum

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Summary

Concepts investigated:

- Large sparse array distributed on floating platforms or ship formation
- Compact uniform linear dense array on shore or on single platform
  - Challenge of beamforming solved by concept of effective aperture and MIMO approach
  - Time or frequency staggered FMCW chirp signals of MIMO beamformer are separable in the frequency domain in baseband
  - Adaptive look angle dependent phase and amplitude compensation of misaligned elements due to wind and waves successfully resolves mainlobe broadening and reduces sidelobe level
- Sea clutter canceller BF with 3 beams: effective increase in SCR
- Correlation detector using unimodal wave directional spectrum

Outlook

- System Simulation on Distributed Shipborne Self-Configuring Over-The-Horizon-Radar
- Experiments on MIMO Beam Former
- Electrically Small HF Antennas
- Broadband HF Shipboard Antennas with Distributed Damping