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DIRECTION OF ARRIVAL ESTIMATION USING A CLUSTER OF BEAMS IN A CONE-SHAPED DIGITAL ARRAY RADAR

DEPARTMENT OF
INFORMATION ENGINEERING,
ELECTRONICS AND TELECOMMUNICATIONS

SAPIENZA
UNIVERSITÀ DI ROMA

RRSN Group
Radar Remote Sensing & Navigation

SEASTEMA
MARINE AUTOMATION SOLUTIONS

FINCANTIERI
The sea ahead

Sensor Signal Processing for Defence SSPD Conference 2015

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Outline

- System description and potentialities
- PAR vs DAR with conical array
- Aim of the study
- Proposed direction of arrival estimation technique
- Cramer Rao lower Bound derivation for elevation direction of arrival estimation
- Cramer Rao lower Bound comparison
- Beam cluster tilt
- Conclusions

System description (1/2)

- Innovative architecture for masts to be mounted on ships "d.Mast", which is being studied and demonstrated by Fincantieri S.p.A. and Seastema S.p.A.
- N available resources
- Conical geometry
- Shared services

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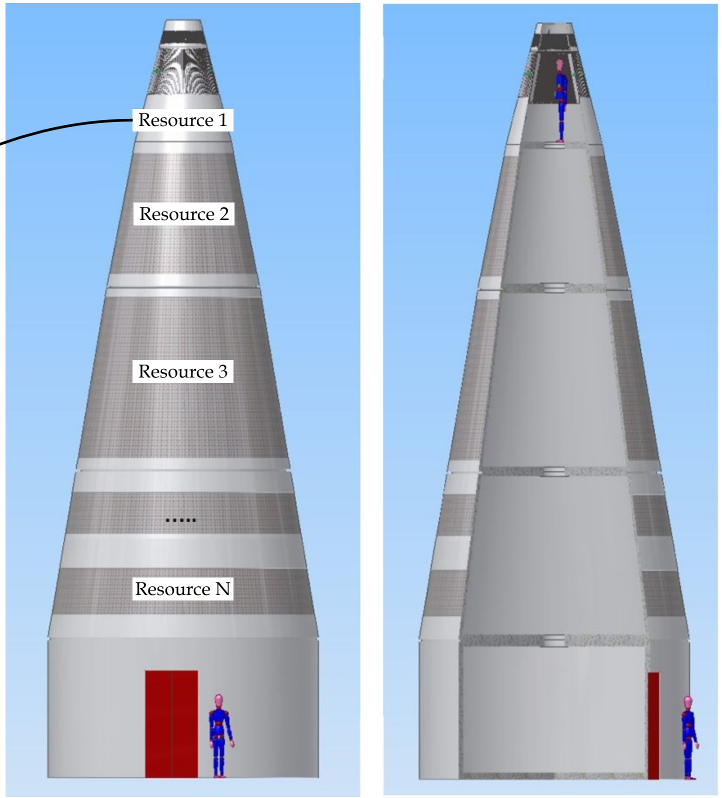
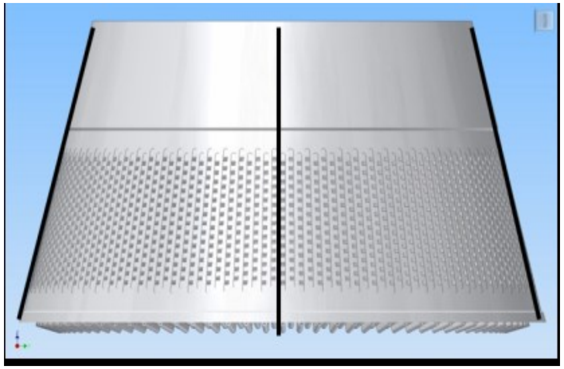
Technological breakthrough

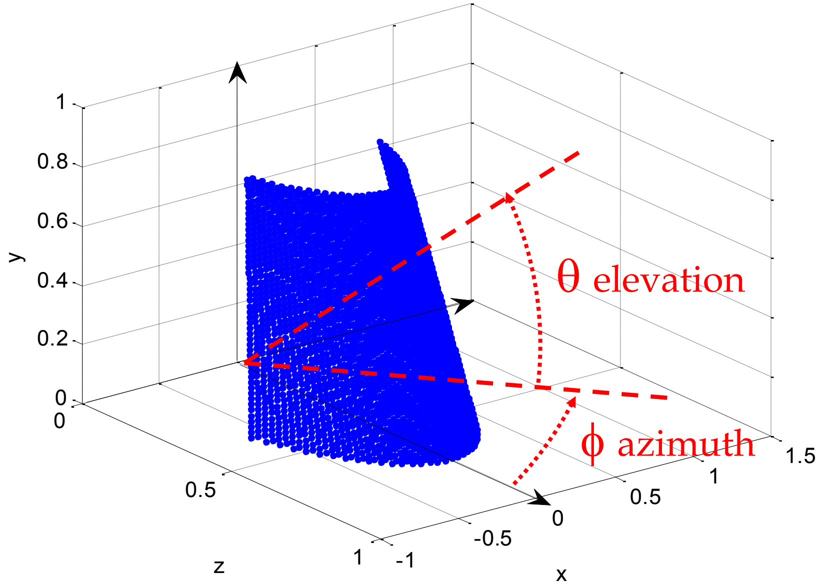
X-band Radar is one of the available resources



System description (2/2)

- The RX array is modelled as the “d.Radar”
- Conical array whose horizontal sections have the same number of radiating elements.
- Approximate dimensions
  - Larger diameter less than 1,5 m
  - Height less than 1 m
- AD conversion at element level.





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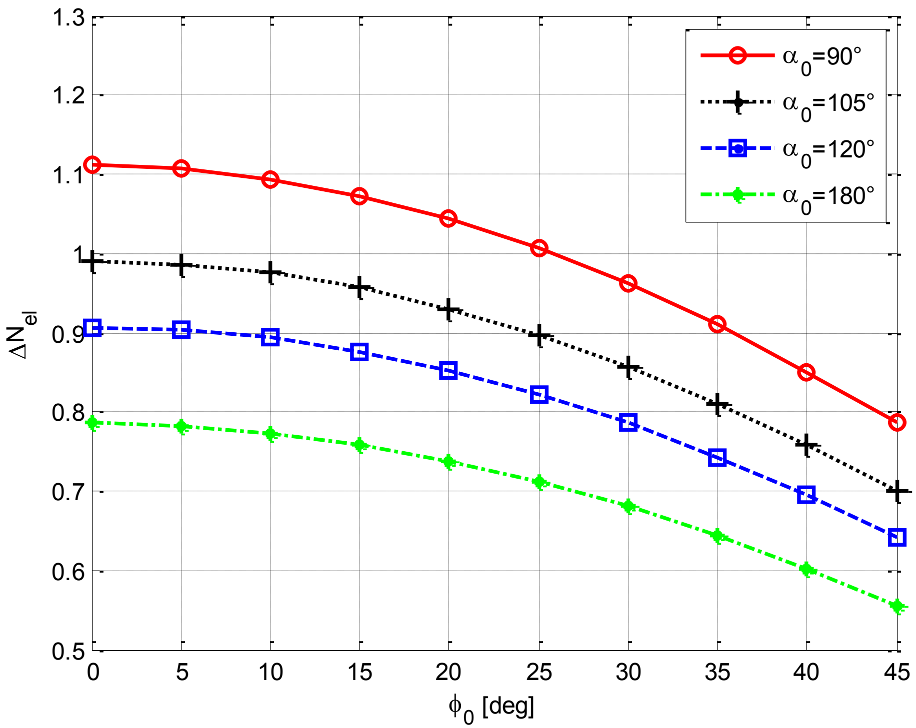
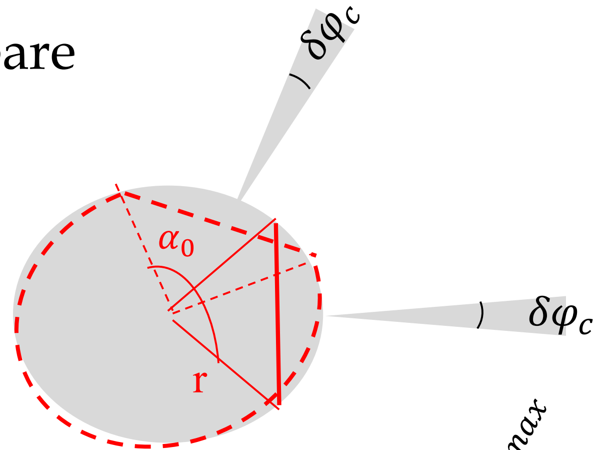
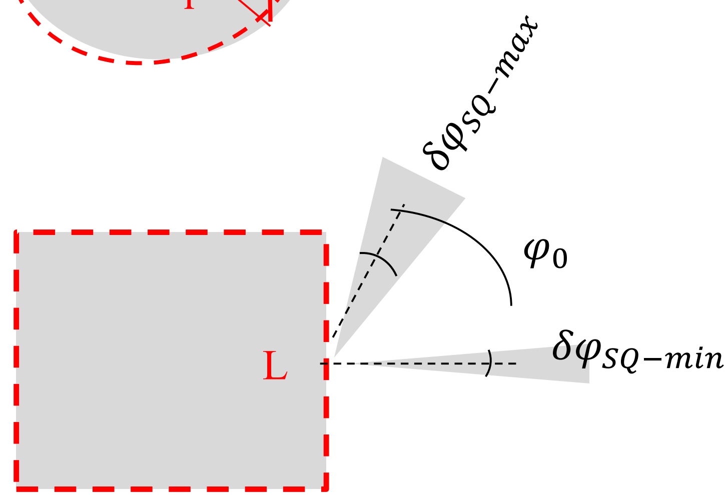
Circular array & number of radiating elements

- The circular shape of the array allows to spare radiating element
- Rule of thumb

$$\Delta N_{el} = \frac{N_{el}(circ)}{N_{el}(square)} = \frac{2\pi r}{4L} = \frac{\pi\cos(\varphi_0)}{4\sin(\alpha_0/2)}$$







Compare performance of the different array configurations in the worst case ($\delta\varphi_{SQ\text{-}max}$)

Circular array & 3D angular scan/coverage

- 360^{o} azimuth beamforming without beamscanning, only shifting of the sector of active elements

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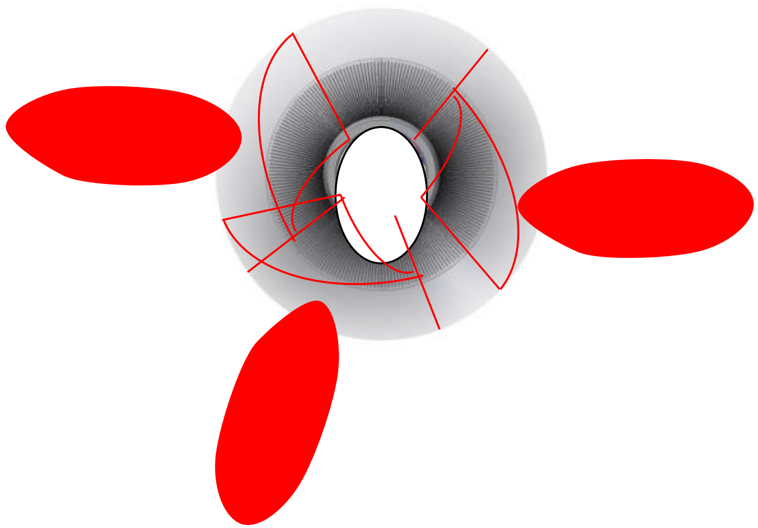
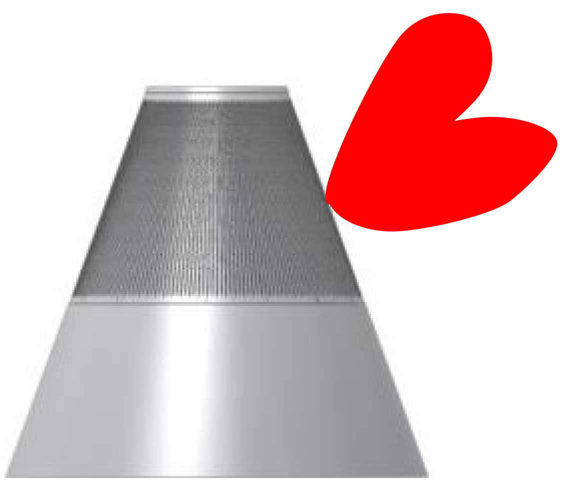
Beams have the same width in azimuth whichever the steering direction is!

- Coverage in elevation with traditional beamforming.





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PAR vs DAR for circular-based array

Array of radiating elements to form multiple beams with different characteristics and functionalities

- Phased Array Radar (PAR)

  Analog BeamForming (ABF) through beamforming networks

  - fixed number of beams
  - pre-determined beam characteristics

- Digital Array Radar (DAR)

  Early analog to digital (AD) conversion at and recording of all the amount of data for successive centralized processing

  - "Ubiquitous radar"
  - reduction of the dynamic range and isolation requirements
  - **Natural solution with circular array**

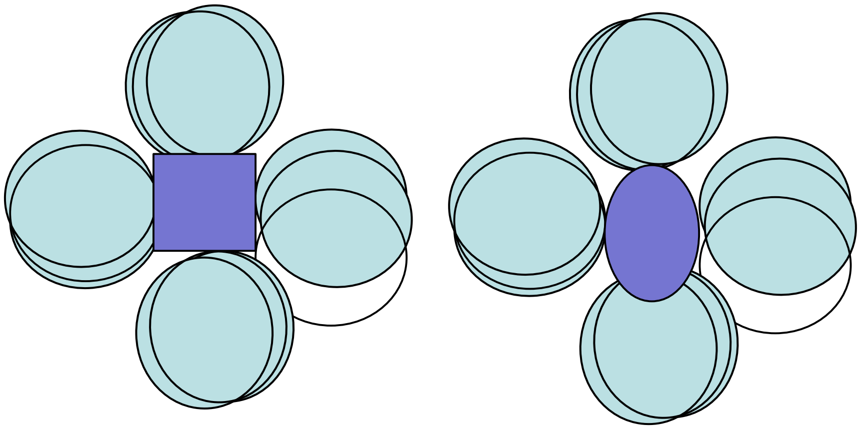
DAR provides flexibility at the expense of increased computational load and data transfer rate

advanced processing schemes are required to improve efficiency

Digital vs Phased Array Radar (I)

Phased Array

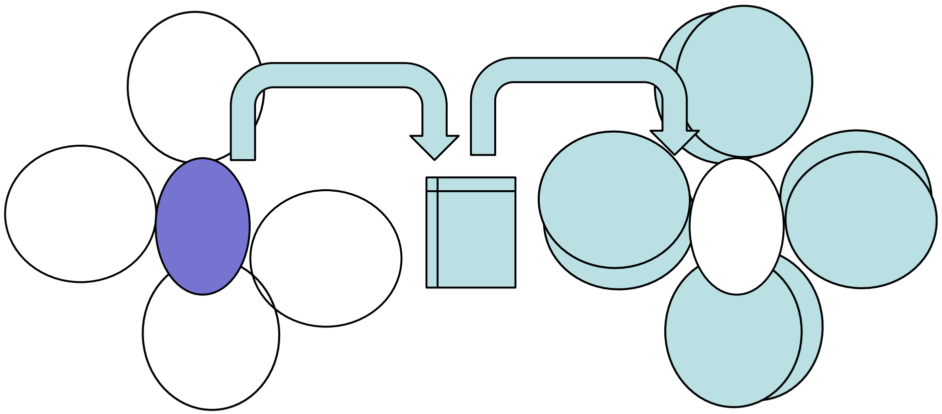
- Fixed number of beams (BFN)
- Beam shape is fixed at design time



- RX beam are necessarily always present for:
  - Detection
  - DoA estimation (otherwise DoA of detection must be illuminated again)

Digital Array

- Fixed number of beams givem by the maximum available computational load
- It is possible to synthesize virtually any desired beam by storing the data collected at the element level



- It is possible to modify beams adaptively depending on data content
- Δ monopulse beams can be evaluated only for the «range cells» where a target has been detected

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Digital vs Phased Array Radar (II)

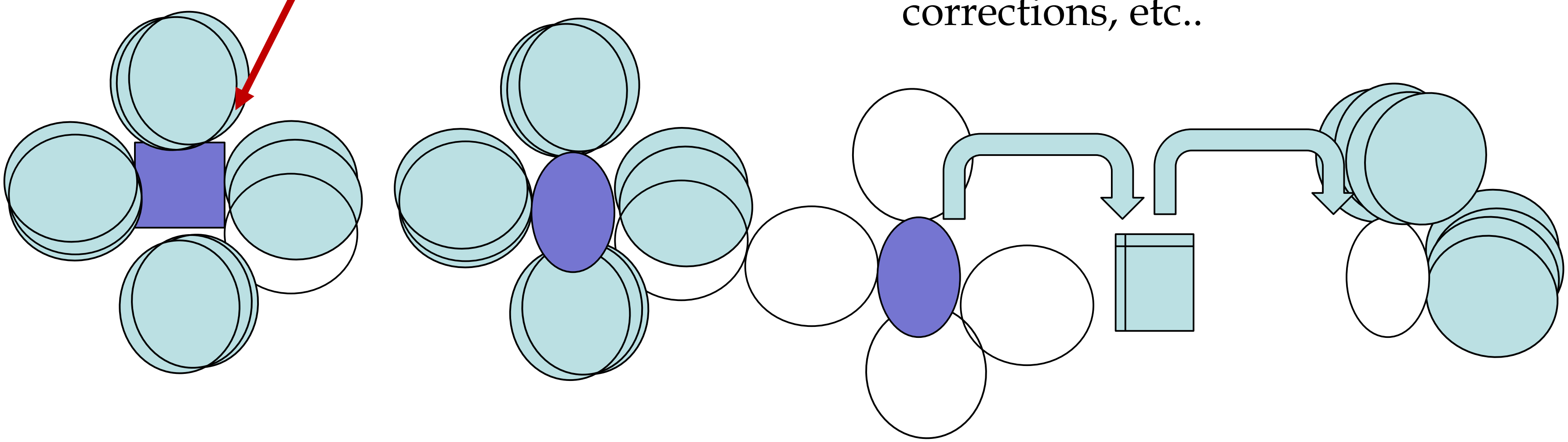
Flexibility in the use of multiple beams

Phased Array

- Beam cluster with preassigned shape

Digital Array

- Few beams are used for the search
- It is possible to add bemas in «critical» regions, use multiple tilts to handle clutter, etc…
- A lot of computation capability is left for accurate DoA estimation, corrections, etc..



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Digital vs Phased Array Radar (III)

Stima DOA interferenti CW (i.e. standoff jammer)

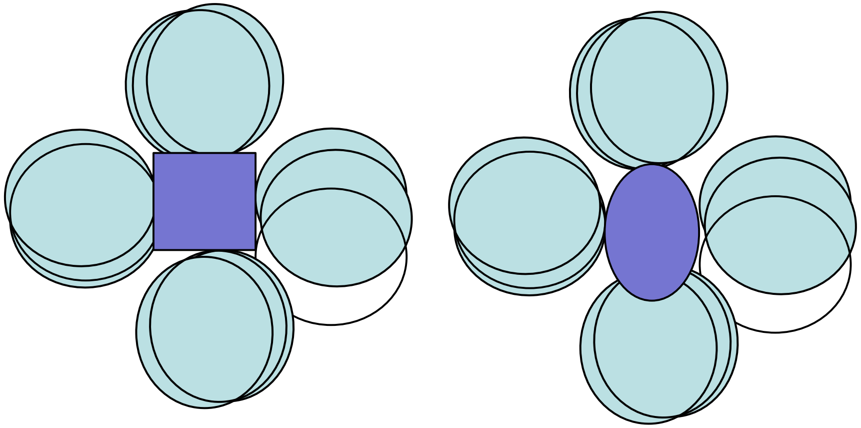
- Inhibit TX for a some PRTs and collect responses
- How many times TX must be inhibited to know the whole intereference scenario?

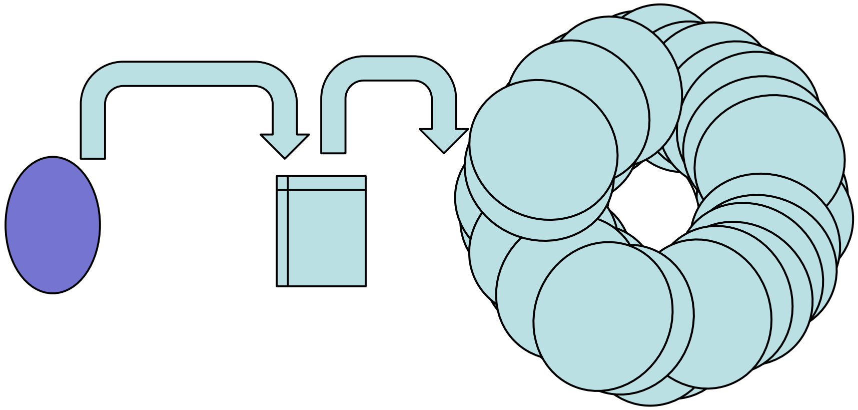
Phased Array

- For each inhibited TX, a few DoAs are suveryed, covered by the avaibalble RX beam cluster
- Many inhibited PRTs are necessary to cover all angles

Digital Array

- With a single inhibited PRT data rom all DoAs are collected
- Then beams in all directions can be synthesized in background





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Digital vs Phased Array Radar (IV)

CW interference nulling (i.e. standoff jammer)

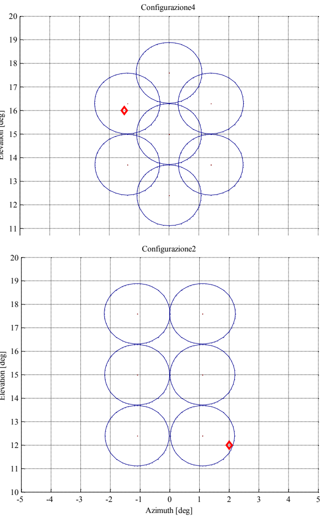
- Beam cluster use

Phased Array

- Performance depends on the used beam cluster
- Beam cluster optimisation to cancel MB jammer and estimate target DoA

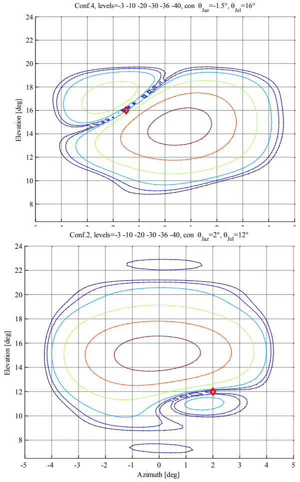
Digital Array

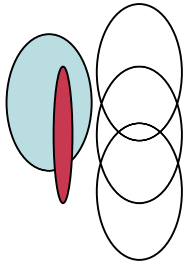
- After jammer DoA estimation, it is possible to build a beam steered to it
- Close-to-ideal performanca achievable
- Use of single auxiliary beam to calcel jammer – reduced adaptivity losses

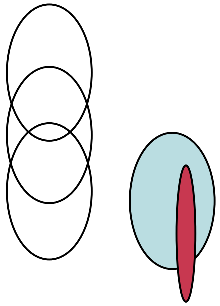


7 Fasci Σ con puntamenti (θaz,θel)= (0, 13.4) (-1.4, 14.7); (1.4, 14.7); (0, 15) (-1.4, 16.3); (1.4, 16.3) (0, 17.6)

6 Fasci Σ con puntamenti (θ_{az},θ_{el})= (-1.1, 13.4); (1.1, 13.4) (-1.1, 17.6); (1.1, 17.6) (-1.1, 15); (1.1, 15)







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Aim of the study

Starting point: innovative conformal DAR system

?

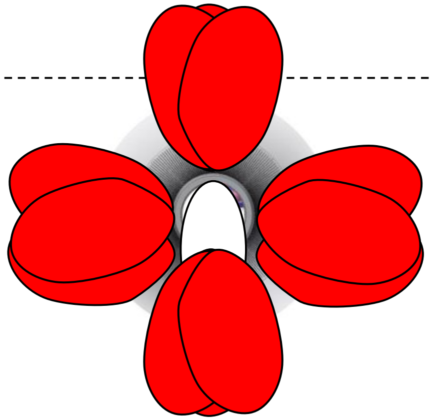
Numerous potentialities

Analysis of an approach for
Direction of Arrival (DoA) estimation based on a properly designed crowded cluster of RX beams and comparison with traditional monopulse approach

PAR vs DAR multiple beam forming

- Typical cluster of beams in PAR:
  - ❑ for each azimuthal direction and range

    N_Σ sum beams, N_Δ difference beams
    + 1 omnidirectional beam.



PAR approach

- Possible strategies in DAR:

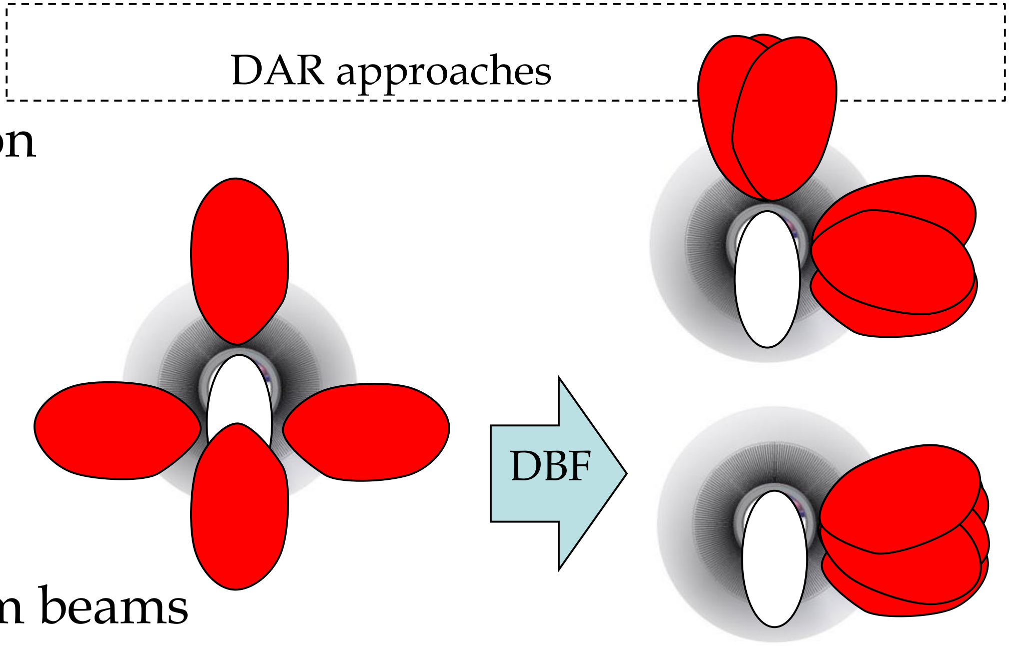
Detection:

- ❑ for each azimuthal direction

  N_Σ sum beams.

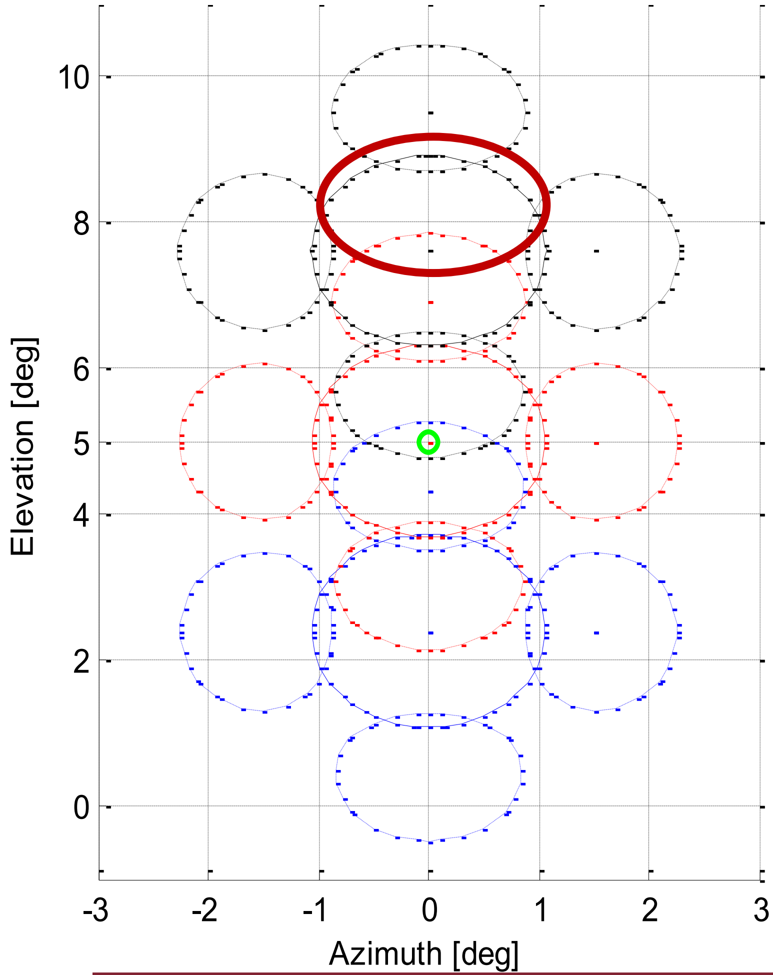
DoA estimation:

- ❑ only at DoA and ranges where detections occurred
  - N_Δ difference beams.
  - Cluster of crowded sum beams



Detection Beam Cluster for DAR

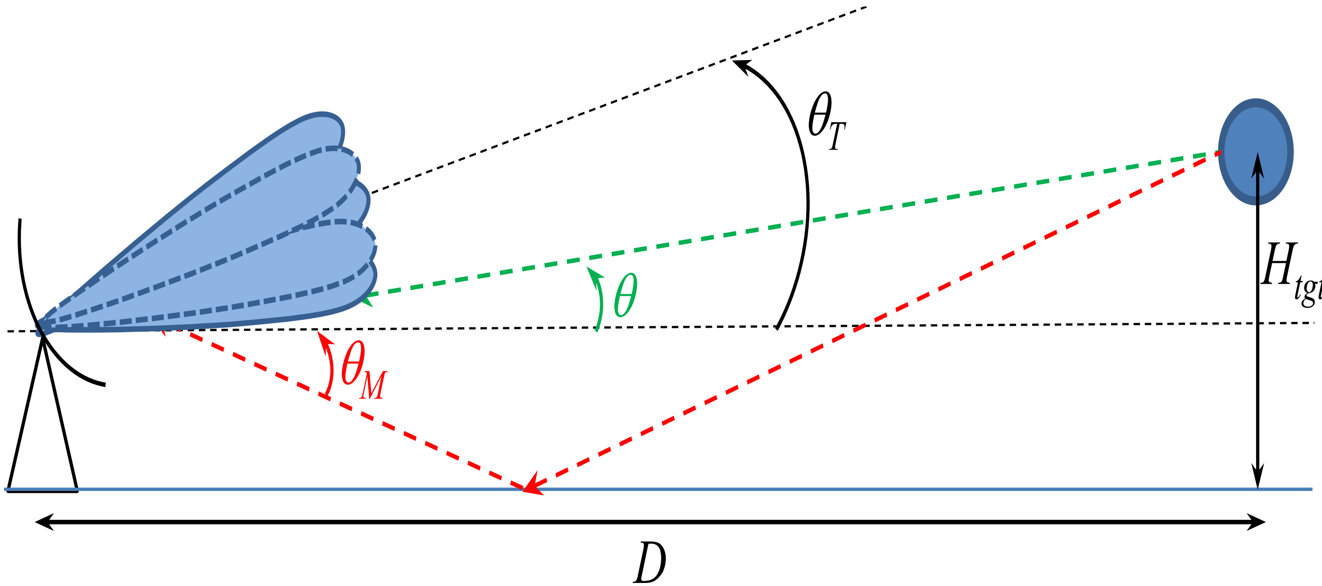
- Beam cluster configuration for radar operating in search mode with low steering direction in elevation (5°).



- Solid lines: sum beams with a width of 2,6° in elevation and 2° in azimuth to cover an aperture of nearly 8° in the elevation dimension.
- Dashed lines: difference beams for DoA estimation

Low elevation angles problem (I)

Operational scenario → signals from a low altitude target are received through a direct and a specular reflected path in the flat earth model.



Low elevation angles problem (II)

Lower Sum and especially Difference beams in the cluster may suffer from multipath arising from low-height target.

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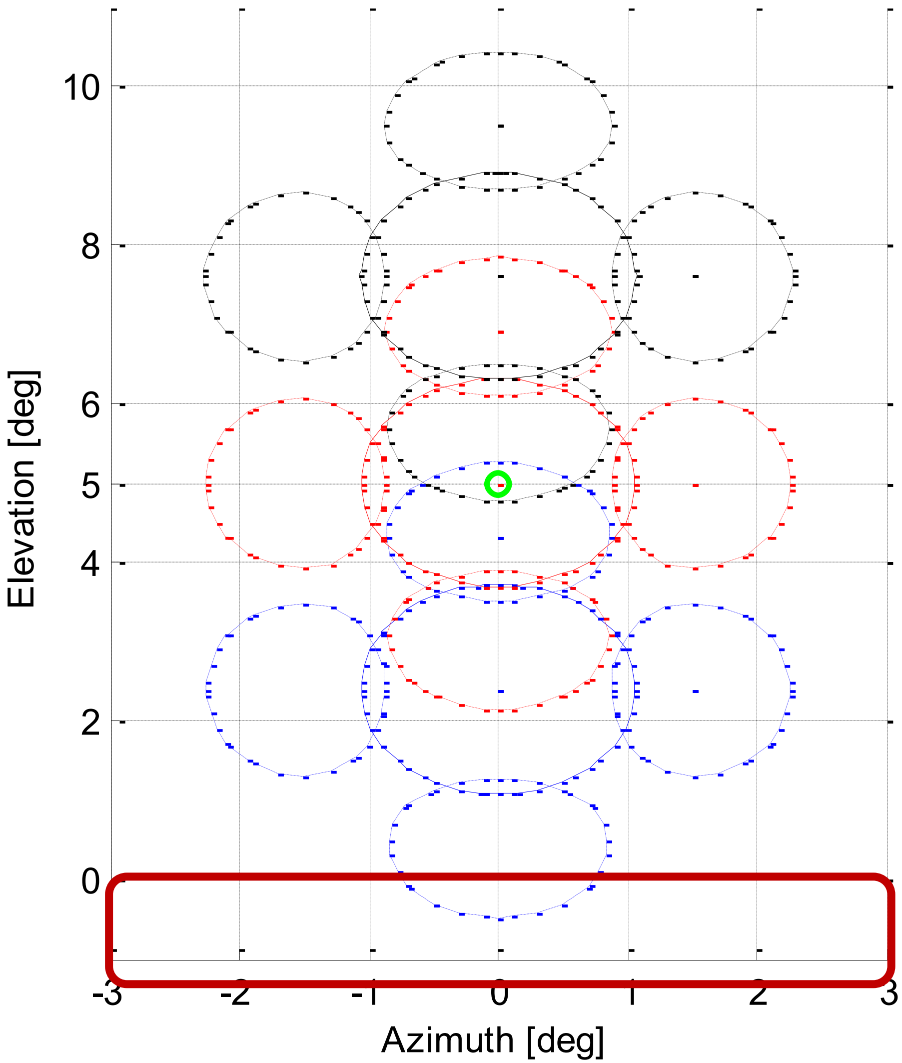
Possibility of using a different approach for DoA estimation, in particular for the elevation angle.



Presented DoA estimation for DAR

- Data acquired by all elements are available at a central processing unit before beamforming.
- Identification of the beams and resolution cells detections occurred.

Only for those detections a crowded clusters of sum beams properly displaced in the angular area of interest must be formed for accurate angle estimation.

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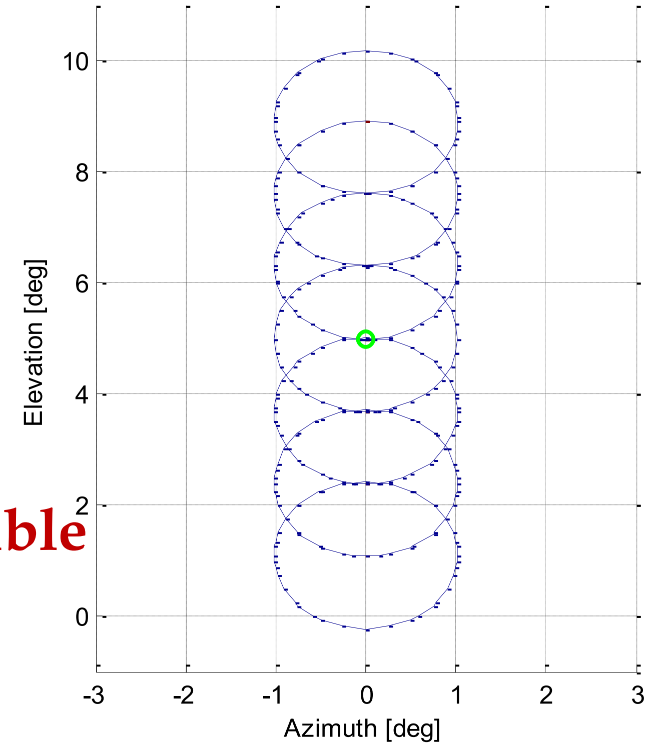
- Use of a wide beam cluster

even a high number of beams is possible for the few detected targets

Computational cost is certainly low



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CRLB derivation for elevation DoA estimation

- Received signal

$$\mathbf{x}(\theta)=A_0 G_{TX}(\theta,\theta_0)G_E(\theta)\mathbf{T}\mathbf{s}(\theta)+\mathbf{T}\mathbf{n}$$

Steering vector at element level

Transformation matrix from element to cluster of beams

Noise at element level

Element gain

Transmitting gain

- Probability density function

$$f[\mathbf{x}]=\frac{1}{2\pi\cdot\det(\mathbf{M})}\exp\left\{-[\mathbf{x}-A_0\mathbf{v}]^H\mathbf{M}^{-1}[\mathbf{x}-A_0\mathbf{v}]\right\}$$

Expected value vector

$$\mathbf{M}=\sigma_n^2\mathbf{T}\mathbf{T}^H$$

Covariance noise matrix at cluster level

- Elevation DoA estimation accuracy

$$\sigma_\theta^2=2\frac{|A_0|^2}{\sigma_n^2}\dot{\mathbf{v}}^H\left[\mathbf{M}^{-1}-\frac{\mathbf{M}^{-1}\mathbf{v}\mathbf{v}^H\mathbf{M}^{-1}}{\mathbf{v}^H\mathbf{M}^{-1}\mathbf{v}}\right]\dot{\mathbf{v}}$$

Derived expected value vector

Signal to noise ratio at element level

CRLB comparison (I)

- Comparison between the accuracies of monopulse (3Σ+3Δ) and estimation of elevation DoA through a cluster of K beams equally spaced in an aperture of 8°.

- **Sum beams**

modified Taylor windows both in azimuth PSLR of 42 dB and elevation PSLR of 36 dB.

- **Difference beams (elevation)**

Bayliss taper with same PSLR

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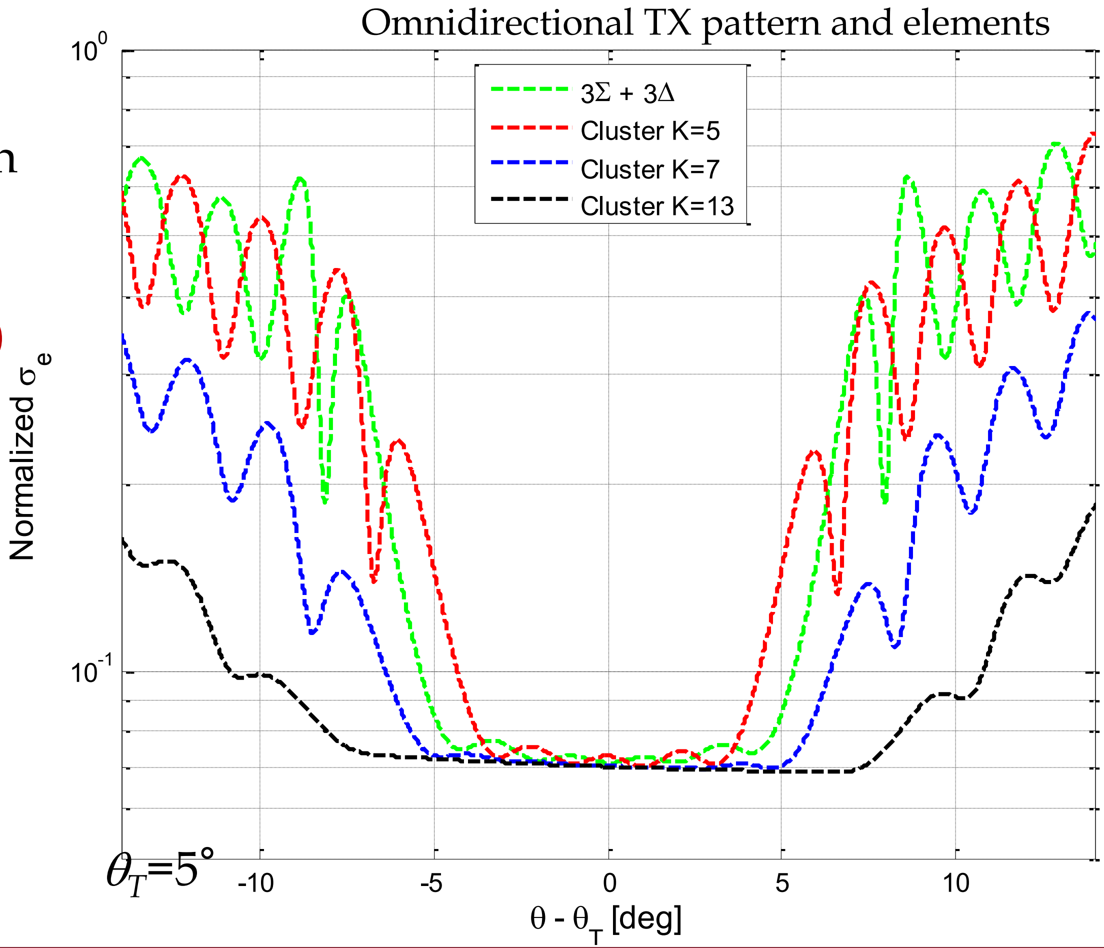
- SNR_{el} =-20 dB

→peak SNR on the central beam of nearly 13 dB.

Performance equivalence, especially in the interval [-4°, 4°]



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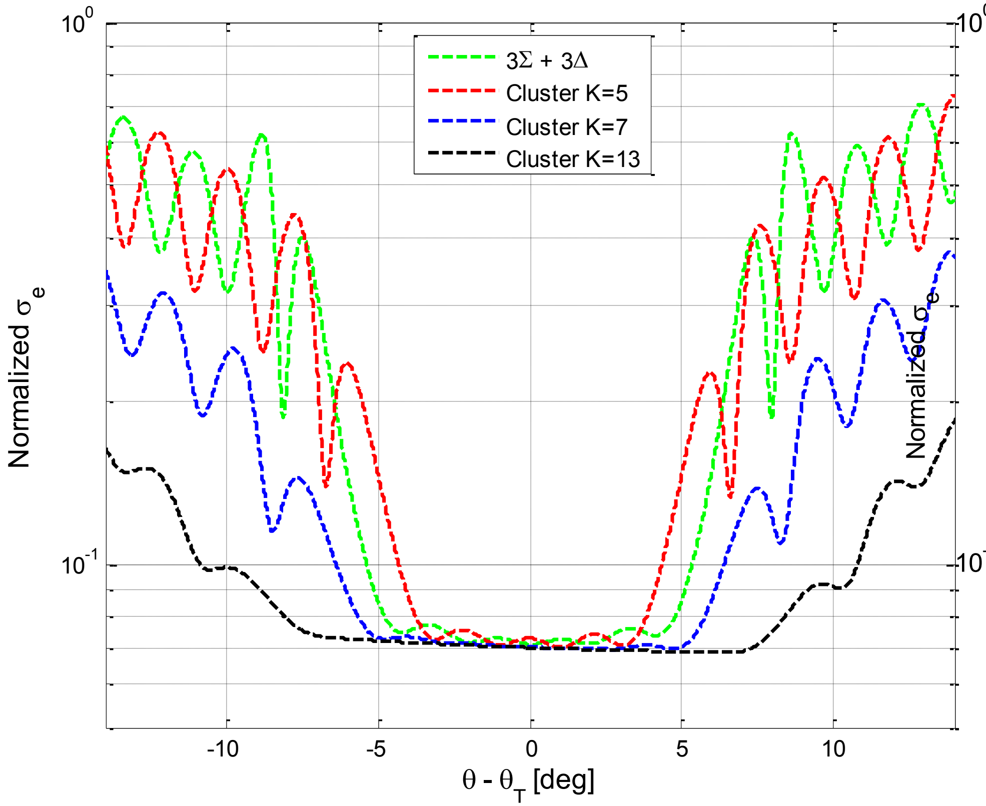
CRLB comparison (II)

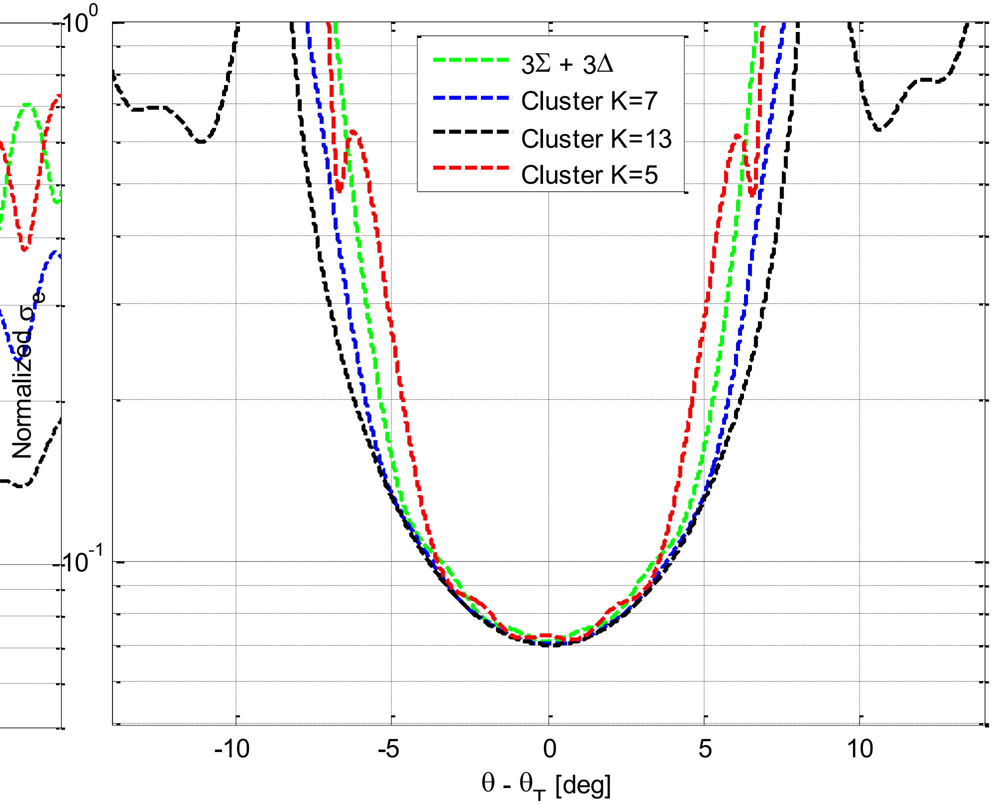
- **Impact of transmit pattern**

θ_T=5°

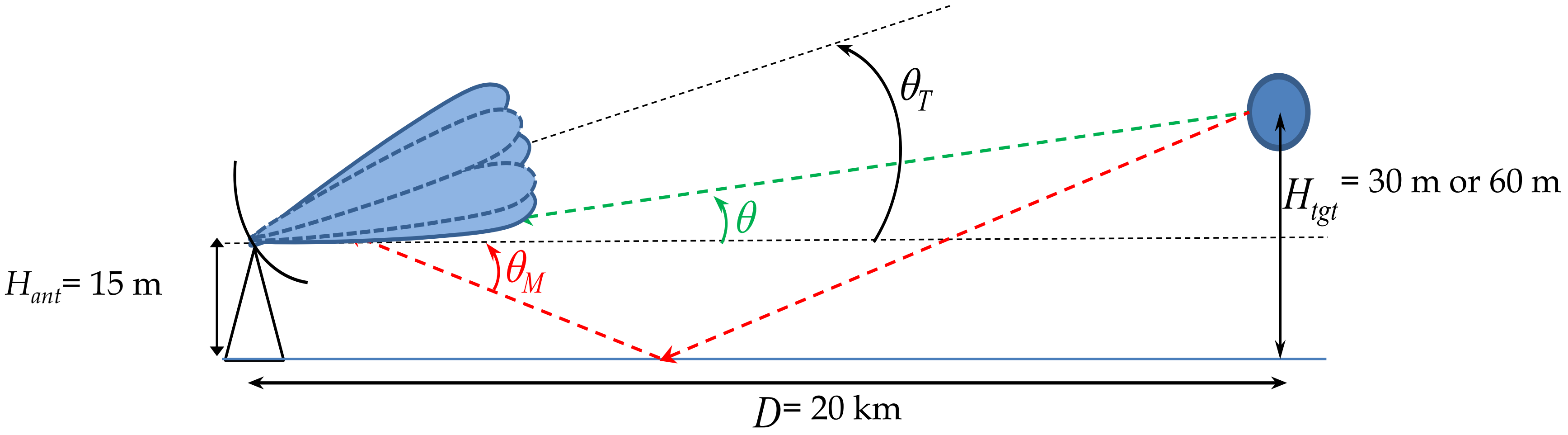
Omnidirectional TX pattern and elements



Directive TX pattern and omnidirectional elements



Beam cluster tilt(1/3)



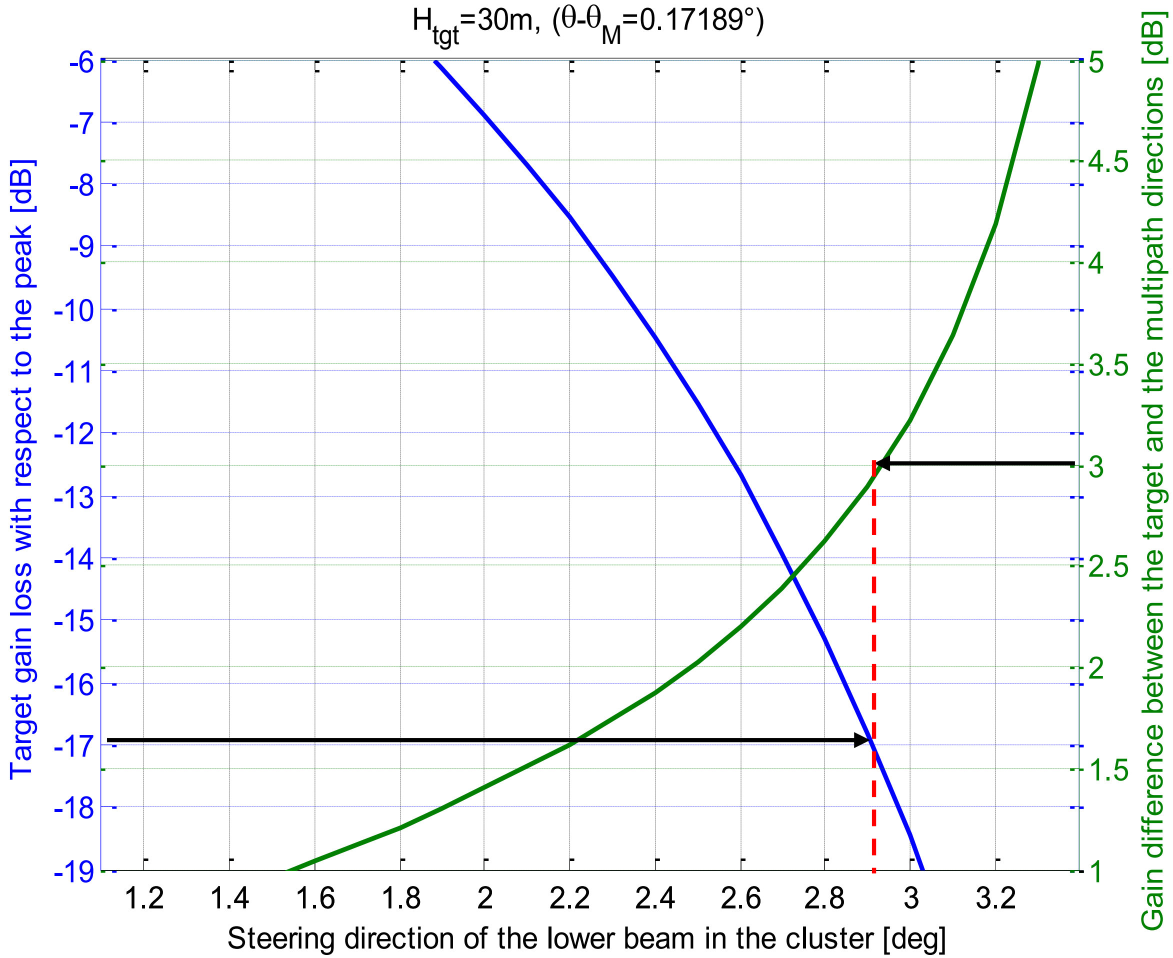
- The steering direction of the lower beam in the cluster is selected
- The steering direction of the remaining beams in the cluster follow it, to uniformly cover the 8° angular aperture.

- AIM: provide a gain of at least X dB to the direct signal from θ with respect to the multipath signal received from θ_M

 under worst condition of operation (minimum target height)

Beam cluster tilt (2/3)

Example: provide a gain of at least 3 dB to the direct signal from θ with respect to the multipath signal received from θ_M



loss of -17 dB in the target direction for H_{tgt}=30 m

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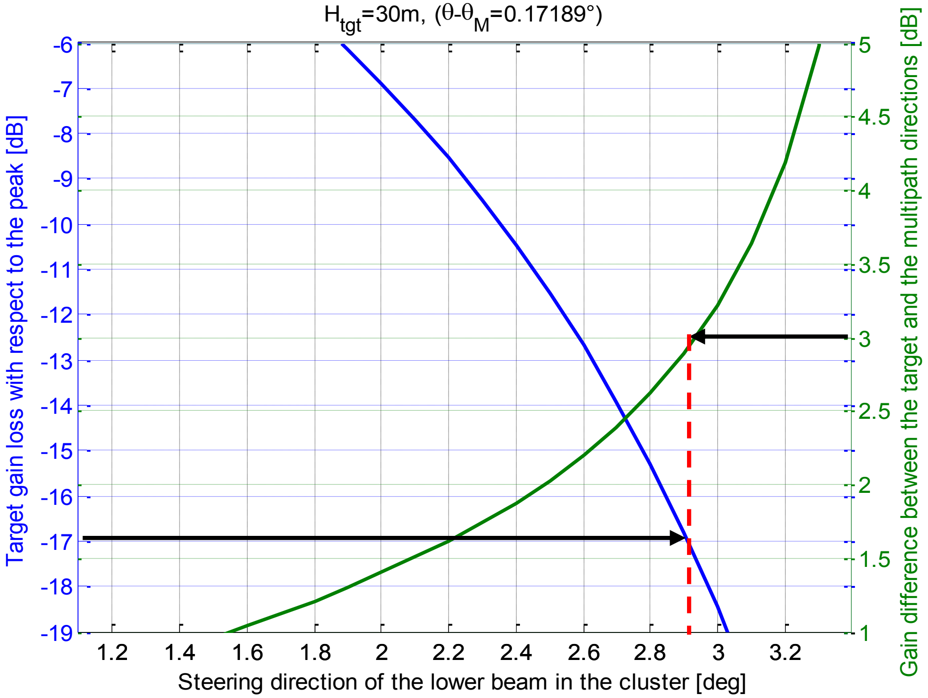
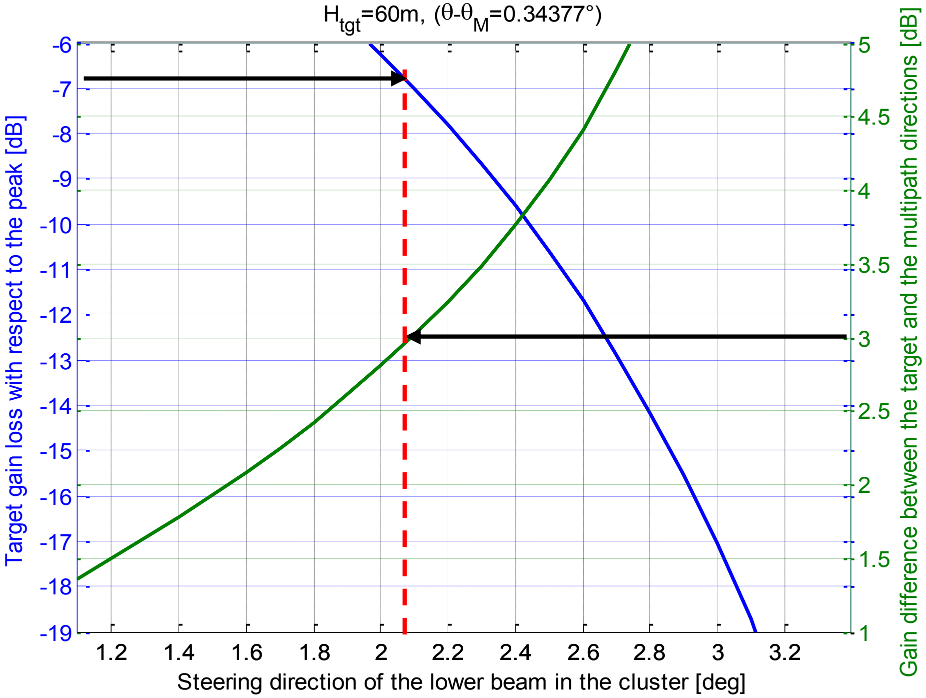
Beam cluster tilt (3/3)

- The design becomes less demanding as the target height increases with a loss of -7 dB in the target direction for H_{tgt}=60 m and -17 dB for H_{tgt}=30 m.





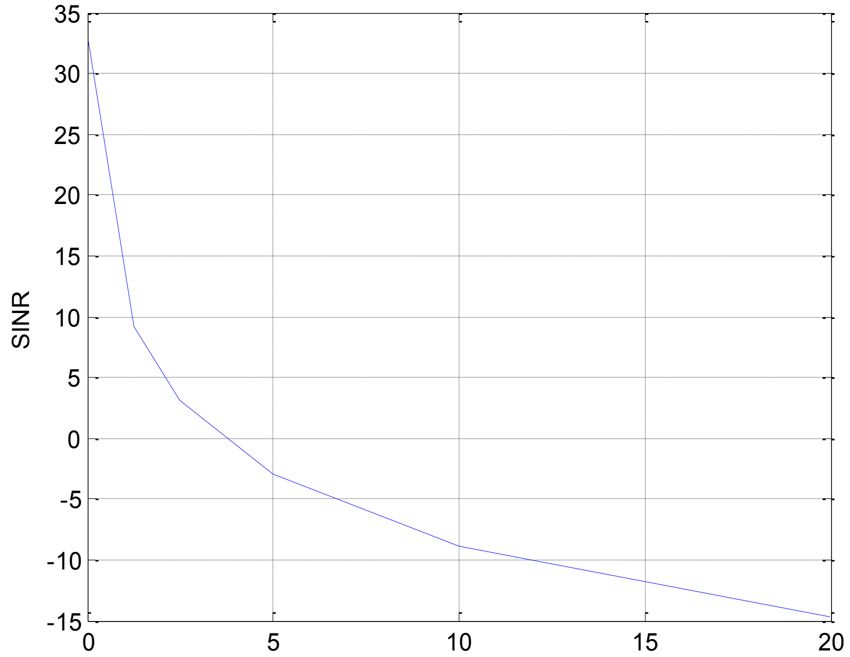
Conclusions

- An innovative conformal DAR has been presented (conical shape factor) with its potentialities and some comparison to more usual PAR
- We derived the theoretical expression of the CRLB for elevation angle estimation using a cluster of beams.
- We analysed the limit performance of DoA estimation achievable with monopulse to those achievable with a RX beam cluster solution that is shown to be more attractive for DAR.
- Performance of both techniques resulted to be comparable, making the second particularly interesting for those situations where monopulse is known to experience performance degradation, as low elevation angle estimation.
- In this latter case an example of the design of the cluster of beams in presence of specular multipath has been provided.

System potentialities: DAR ECCM strategies (1/3)

Approximate knowledge of the jammer DoA

- Antenna nulling without fast time adaptivity
  - The beam pattern if formed with a null in the known jammer direction without estimating and inverting the disturbance covariance matrix.
  - The accuracy of the knowledge of the jammer DoA has an impact on the achievable Signal to Interference and Noise Ratio (SINR)
  - In the proposed example the beam Steering direction is set to (15°, 0°) in elevation and azimuth and the jammer DoA is (17,5°, 0°) and the Jammer to Noise Ratio (JNR) is set to 30 dB
  - The cancellation performance rapidly degrades as the jammer DoA inaccuracy increases



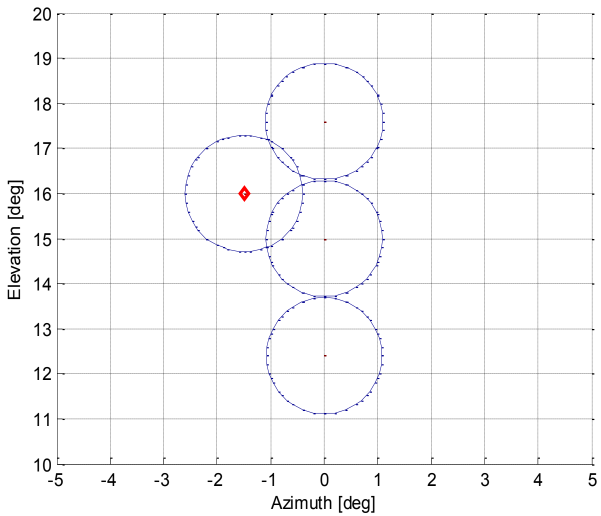
Error: percentage of the elevation beamwidth

System potentialities: DAR ECCM strategies (2/3)

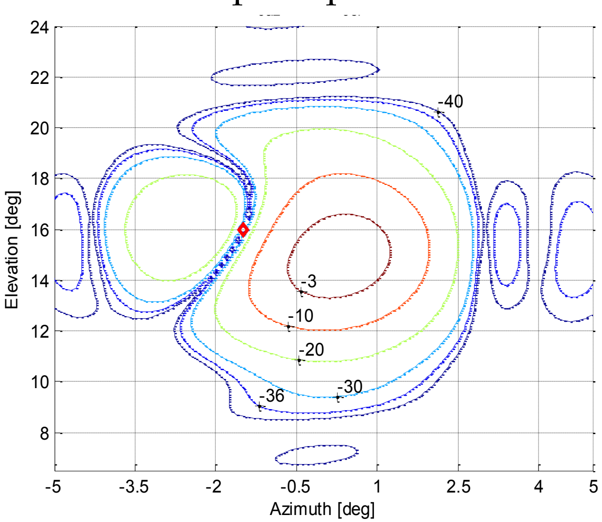
Approximate knowledge of the jammer DoA

- Antenna nulling with fast time adaptivity at beam level
  - The adaptive beam pattern if formed from a cluster of beams: $N_{\Sigma} + 1$ steered in the estimated jammer direction.
  - The covariance matrix to be estimated at beam level has a reduced dimension, still allowing to recover a near ideal performance
  - Steering direction is set to (15º, 0º) in elevation and azimuth and the jammer DoA is (16º, -1,5º)

Cluster



Adaptive pattern



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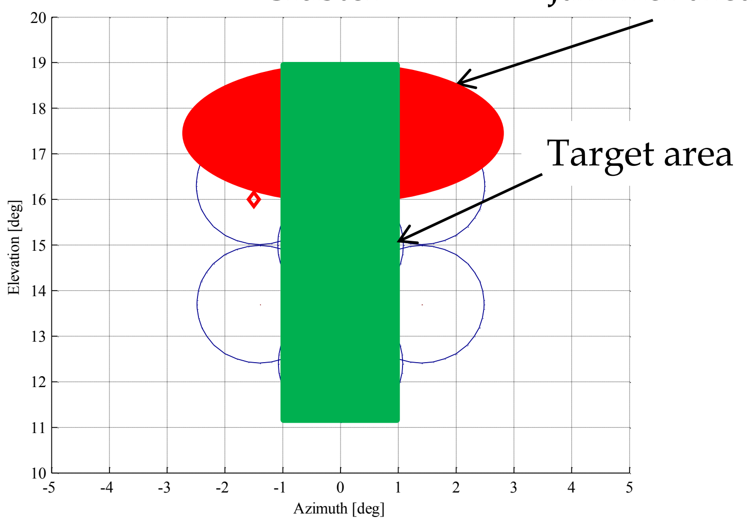
System potentialities: DAR ECCM strategies (3/3)

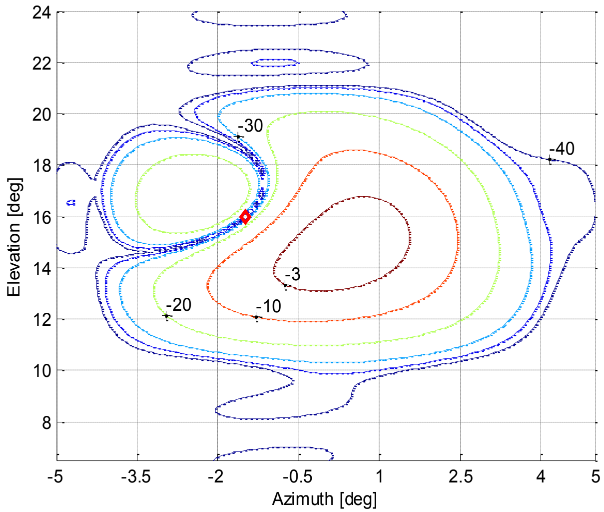
Jammer DoA not known

- Antenna nulling with fast time adaptivity at beam level
  - The adaptive beam pattern if formed from a cluster of sufficient number beams to cover the target and jammer area.
  - The covariance matrix to be estimated at beam level has a higher dimension
  - Steering direction is set to (15º, 0º) in elevation and azimuth and the jammer DoA is (16º, -1,5º)

Cluster



Adaptive pattern



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