What’s the relationship between multistatic radar and MIMO radar ?

- The MIMO concept
- Systems
- Experimentation
- Future developments

MIMO telecommunication concept

- **MIMO**: **M**ultiple **I**nput, **M**ultiple **O**utput.
- Several antennas transmit and receive better than only one …
- Sparse antennas and incoherent processing of the received signals.
- Firstly developed in telecommunication systems: it dramatically increases of the capacity of the channel.

MIMO Radar concept

- **MIMO**: **M**ultiple **I**nput, **M**ultiple **O**utput.
- Several antennas transmit and receive better than only one …
- Sparse antennas and incoherent processing of the received signals.
- A subset of distributed or netted radar

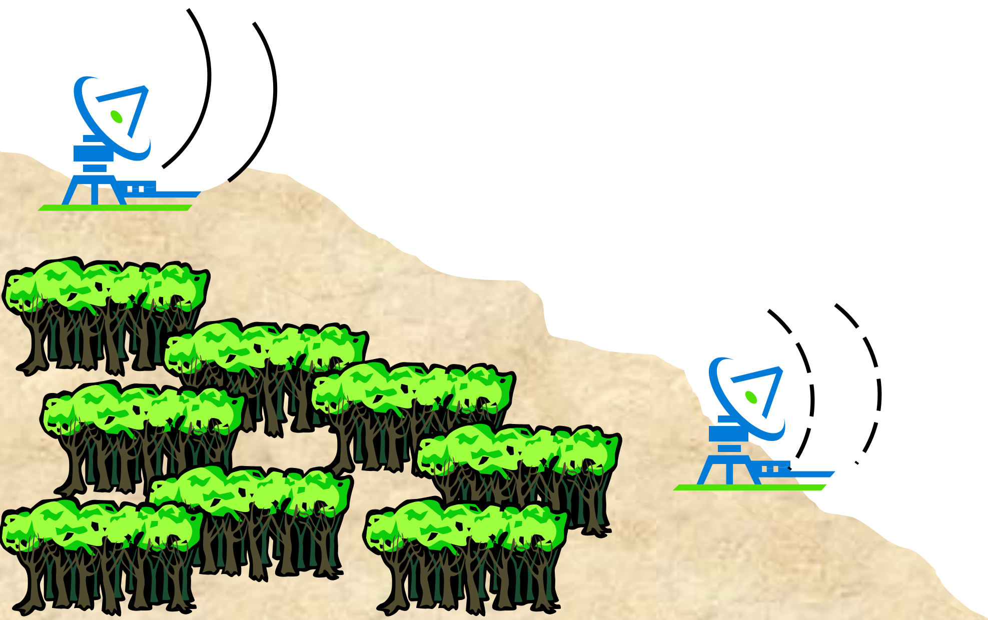
Spatial MIMO

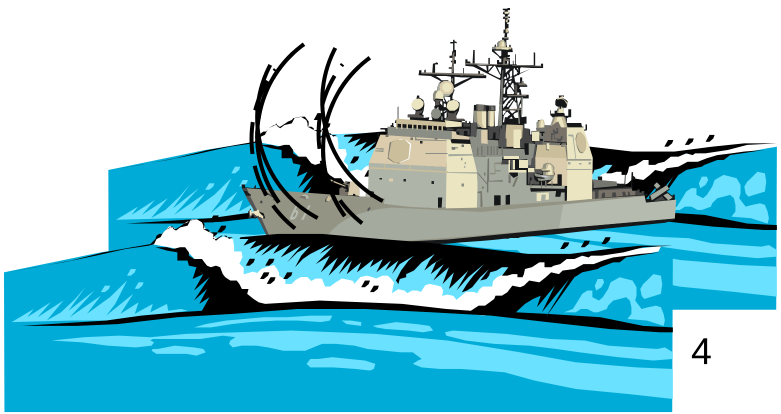
	Rx_1	Rx_2
Tx_1	s_{11}	s_{12}
Tx_2	s_{21}	s_{22}

Monostatic information

4 signals with multistatic information to be processed

Bistatic information





Distributed radar advantages ?

- Improved sensitivity, target location and tracking
- Counter stealth
- Support of new processing concepts, MIMO etc
- Reduced vulnerability to electronic and physical attack
- Improved information content

- MIMO concept
- **Systems**
  Spatial MIMO radar system
  Coherent netted radars (comparative systems)
  Frequency MIMO radar system
- Future developments
- Conclusions

Spatial MIMO radar system

Spatial MIMO

- The antennas are far away from one another: They provide more degrees of freedom but they have to be very distant from one another in order to exploit angular diversity.

- Scintillation and glint improve detection.

- Monostatic and bistatic (multistatic) configurations are achieved at the same time. Even receiving one or few bright echoes, we can detect a target, skipping possible coherent cancellations.

- We termed this system spatial MIMO as the nodes (all possible couples Tx-Rx) making the system are spatially distributed.

Spatial MIMO

- A particular type of radar network:
  - 2 or more transmitters (generally M),
  - 2 or more receivers (generally N),
  - Transmitters and receivers can be either co-located or not.
    - Possibility of silent receivers.

- In matched filtering it is possible to distinguish signals using either:
  - Time separation,
  - Frequency separation,
  - Code diversity.

Coherent netted radar systems

Coherent netted radar

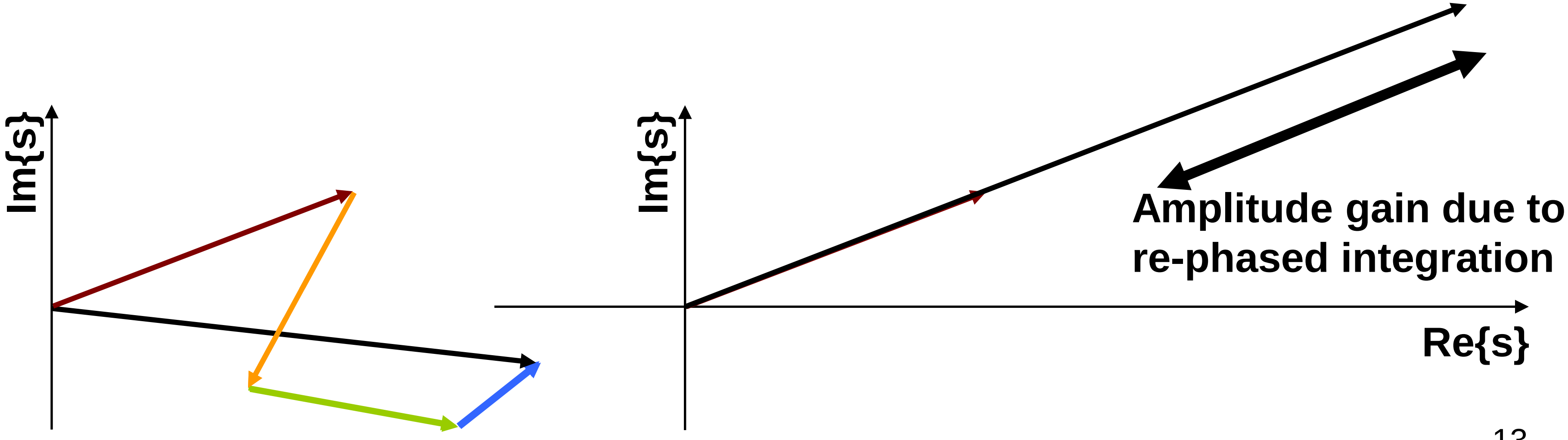
- Alternative processing to spatial MIMO radar system.
- The signals are directly summed coherently.

Re-phased coherent netted radar

- Re-phasing according to the **exact** position of the target before coherent sum.
- Total a-priori knowledge of the geometry it operates in.
- Hardly feasible, but theoretical upper bound limit for performance since it maximizes the SNR after integration.

Netted radars

- Coherent sum of the processed received signals.
- The phases of the incoming signals are strongly correlated, but unknown, since they depend on the position of the target and wrap every $\lambda/2$.
- Being possible to re-align the phases of the signals only, the highest SNR is achieved.



Processing

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_{MN} \end{bmatrix}$$ is the vector of the MN received signals after matched filtering

MIMO system
incoherent processing ➔

$$\|\mathbf{x}\|^2 = \sum_{k=1}^{MN} |x_k|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda_{MIMO}$$

Re-phased NR
coherent processing ➔

$$\left|\sum_{k=1}^{MN} x_k \exp\{-j\varphi_k\}\right|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \lambda_{NETTED}$$

Frequency MIMO radar system

Frequency MIMO

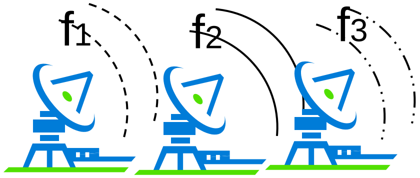
- We can still have multiple inputs and multiple outputs in a monostatic configuration trading space diversity with frequency diversity: here we exploit the response of the RCS to different carrier frequency.

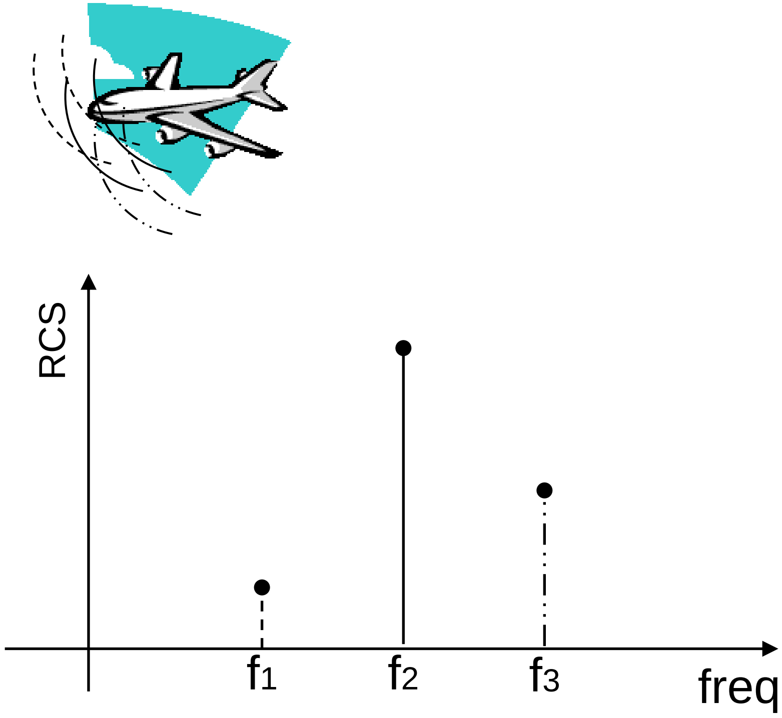
- Increased capabilities for all the frequency-based processing.

- The increased frequency occupation can be partially recovered either using “gaps” in the spectrum (if available) or in (coded) frequency sharing with other systems.

- Incoherent processing is performed as in the MIMO concept.

Frequency MIMO





Categorisation of radar networks

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Location	Fixed	Fixed	Fixed	Fixed	Fixed and moving platforms	Nodes on moving platforms
Data level	Tracks	Tracks	Detections	Detections	Raw	Raw
Coherency	Incoherent	Incoherent	Incoherent	Coherent	Coherent	Coherent
Operation mode	N Tx, N Rx monostatic	1 Tx, N Rx multi-static	1 Tx, N Rx multi-static	M Tx, 1 Rx multi-static	M Tx, 1 Rx multi-static	M Tx, N Rx multi-static
Distribution	De-centralised	De-centralised	Semi De-centralised	Centralised	Centralised	Centralised
Assessment	Straight-forward	Multiple bistatics	Challenging	Complex	Very complex	Extremely complex

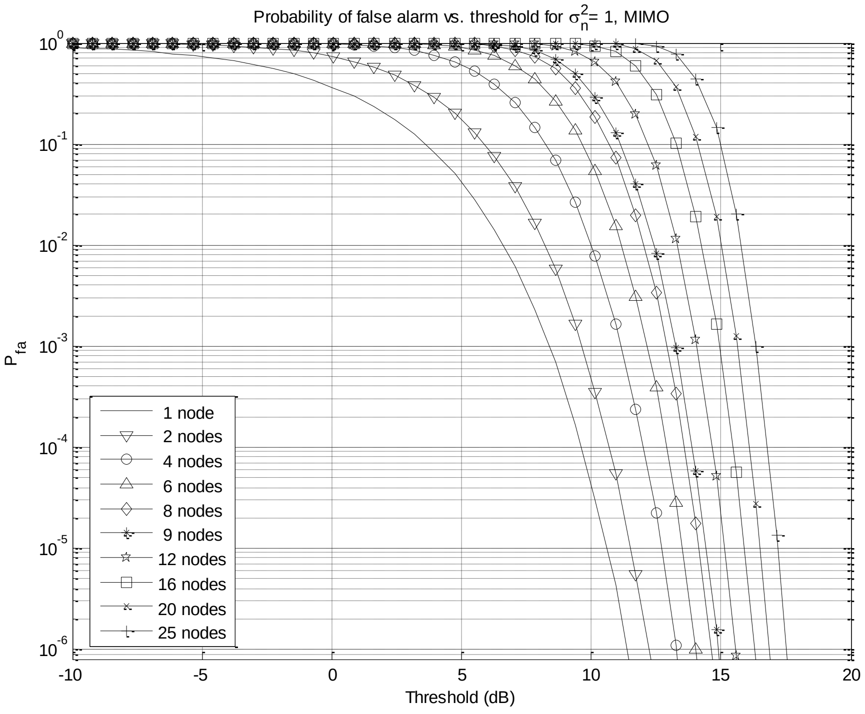
Centralized processing

False alarm rate

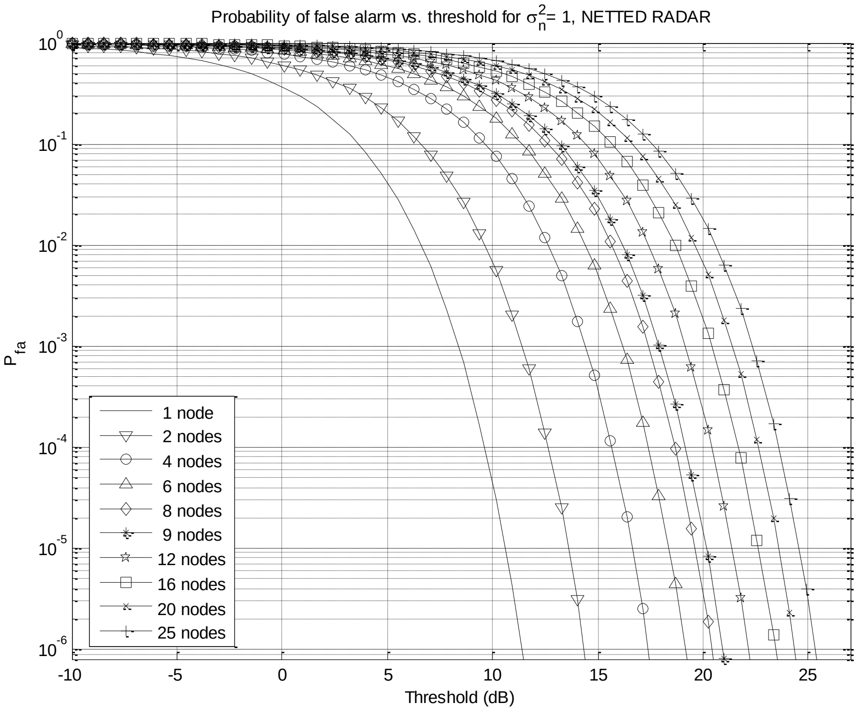
The incoherent processing modifies the noise distribution and reduces its overall power.

This allows a lower threshold to be set.

MIMO



NR

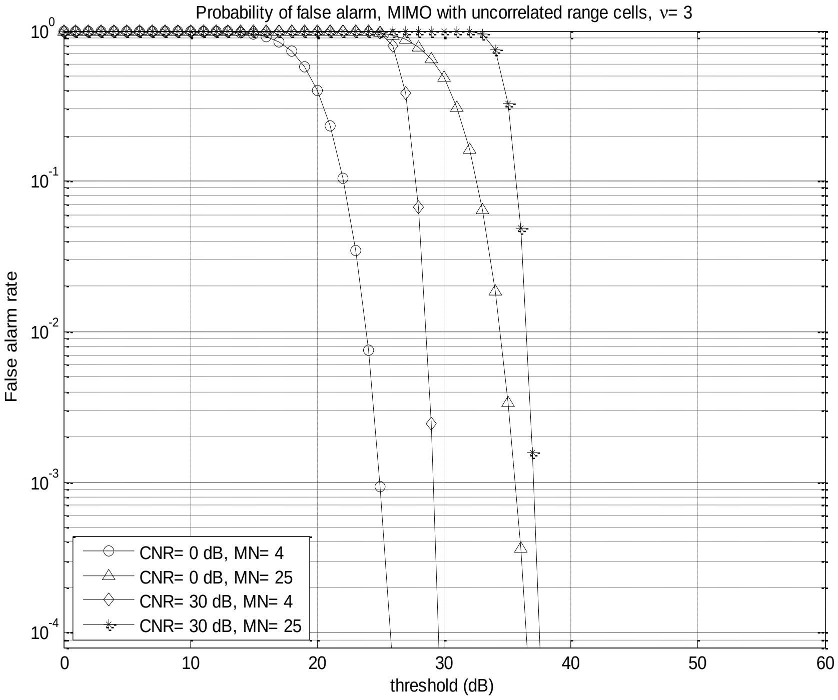


False alarm rate

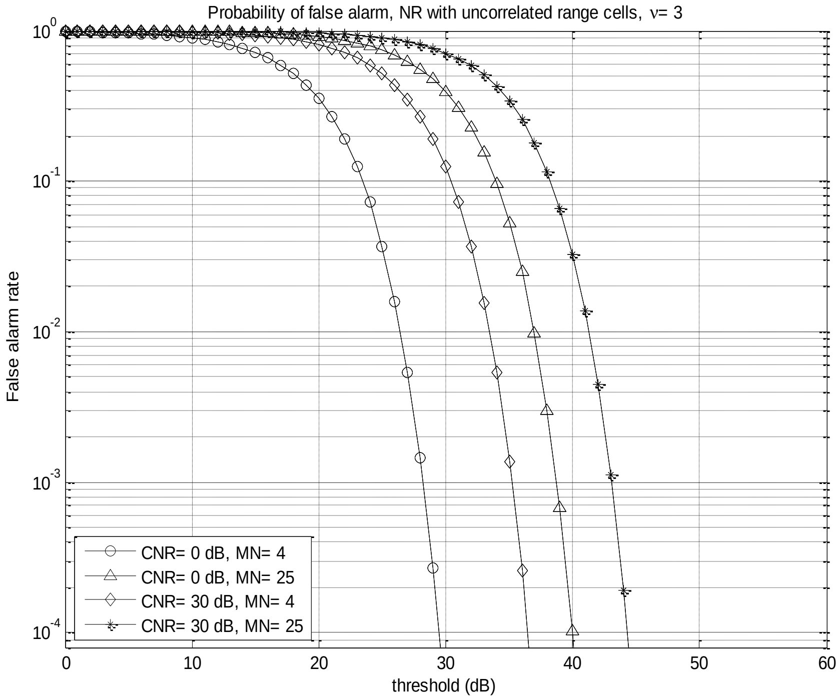
Similar performance has been obtained in clutter.

The PDF of the introduced noise is still modified by the processing. The variance of the overall noise is smaller in MIMO rather than in NR.

MIMO



NR

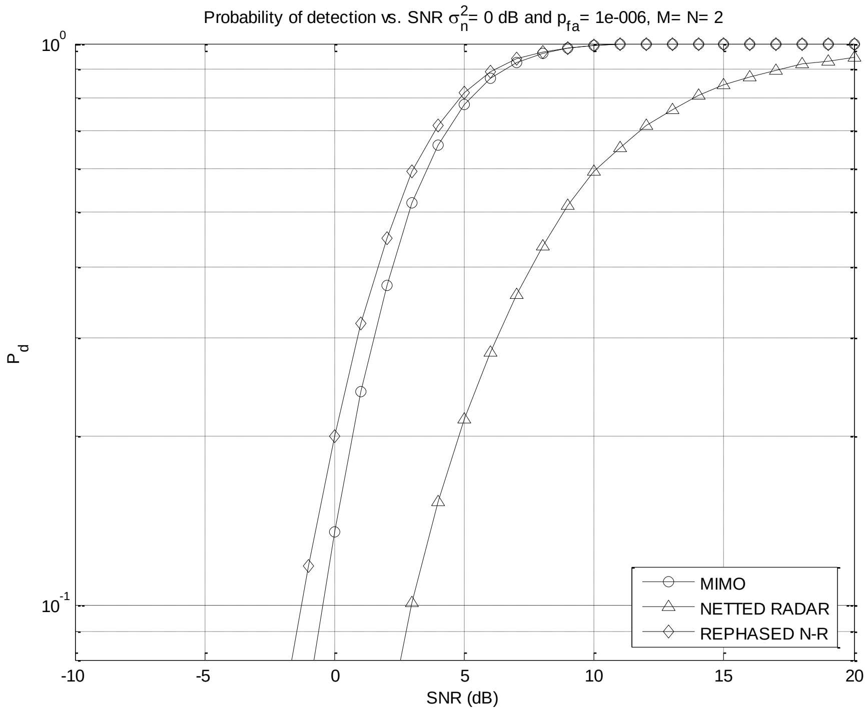


Detection – noise-like target

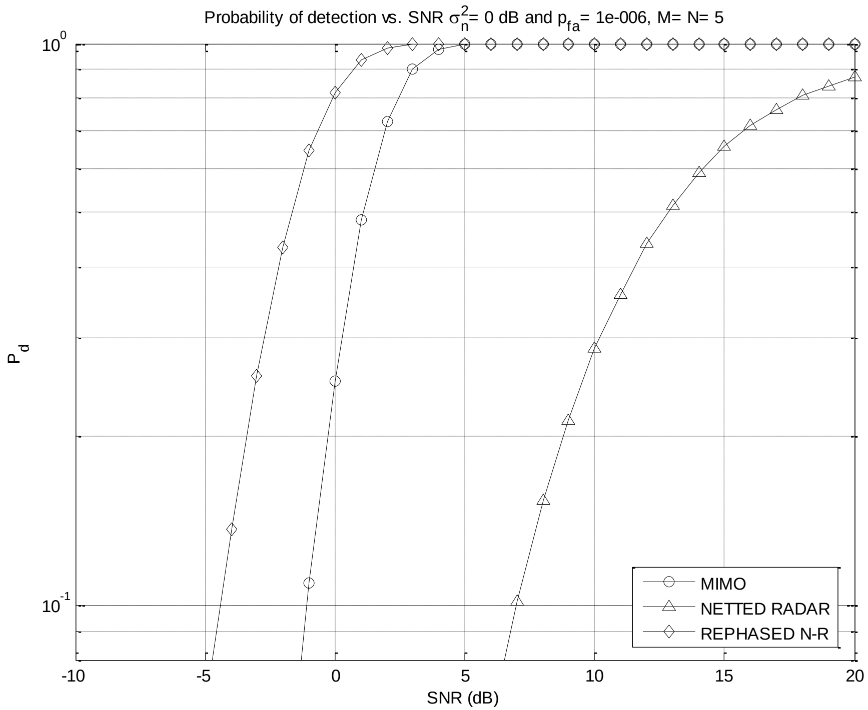
With a noise-like target MIMO performs very close to the re-phased netted radar.

Power in transmission is kept constant in all the presented results.

2 tx, 2 rx



5 tx, 5 rx

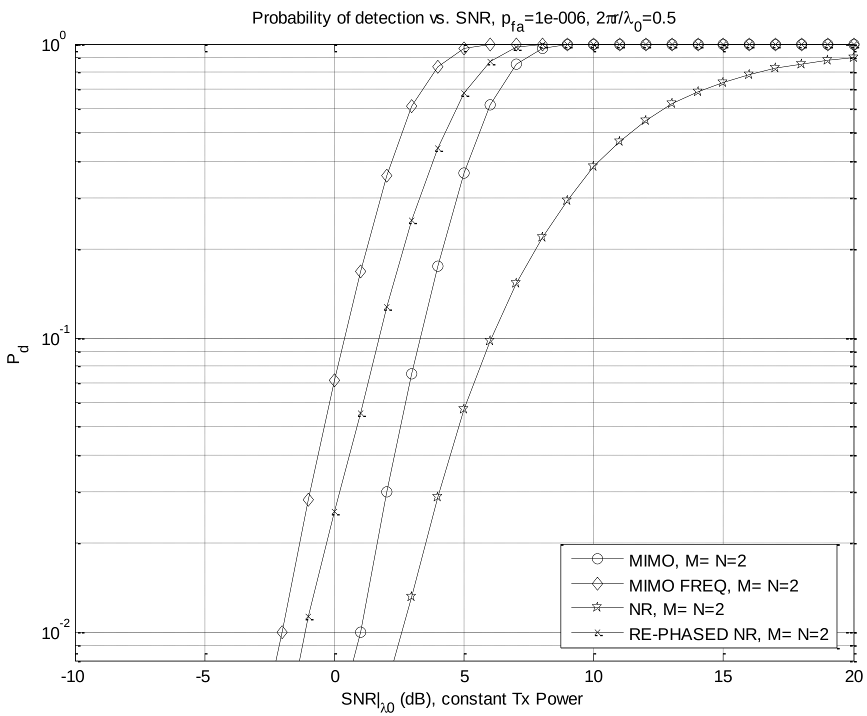


Detection – spherical target

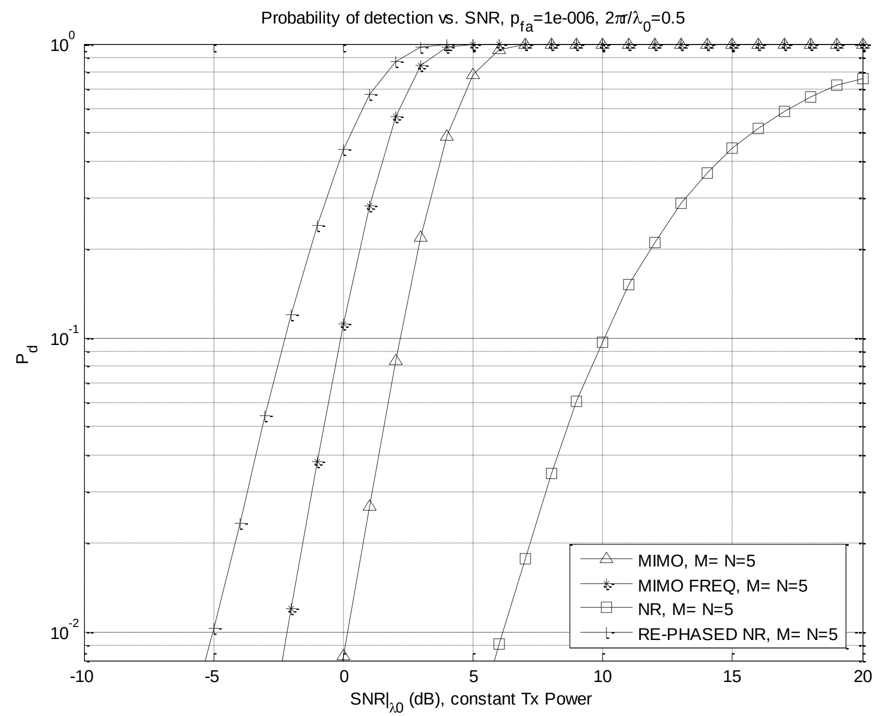
Generally, the two MIMO concept are here shown to be almost equivalent (with non-stealthy targets).

In resonance with the RCS response, frequency MIMO can outperform the re-phased NR.

2 tx, 2 rx



5 tx, 5 rx

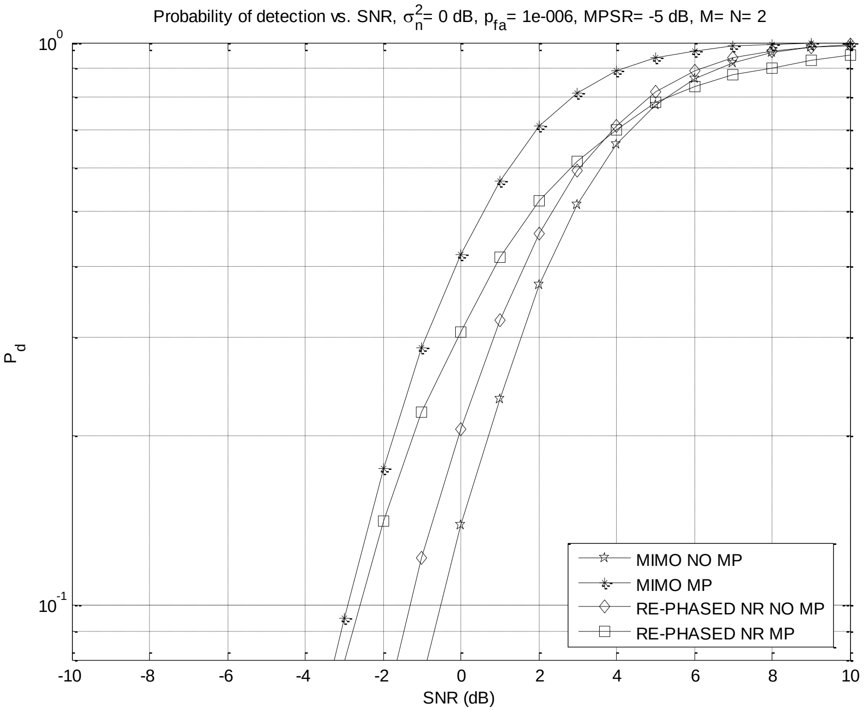


Detection - multipath

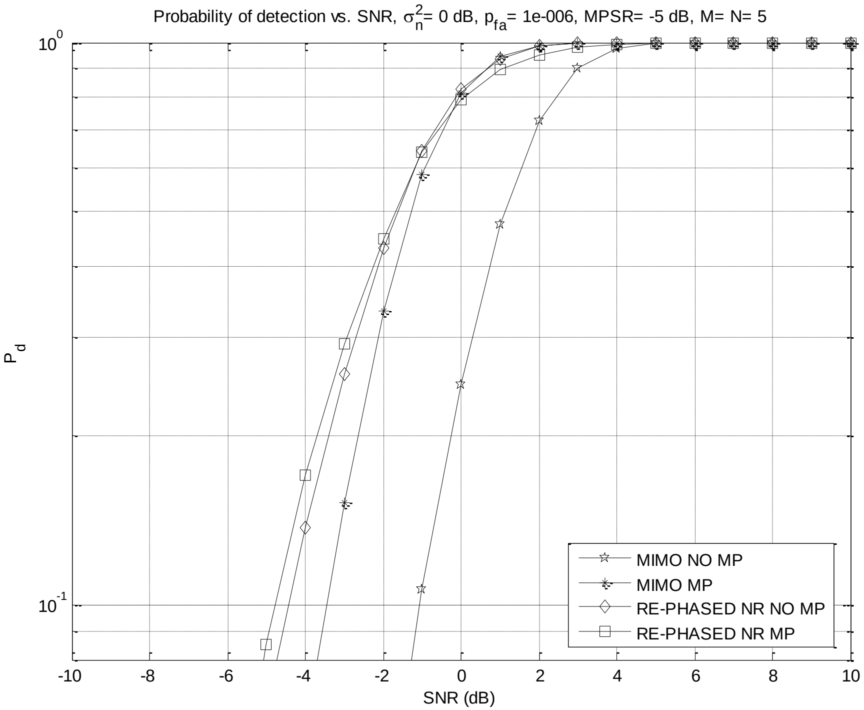
Multipath is extremely dangerous for coherent systems as may cancel signals rather than cohere and improve SNR.

As in telecommunication systems MIMO is able to exploit multipath to improve performance.

2 tx, 2 rx



5 tx, 5 rx



Decentralized processing

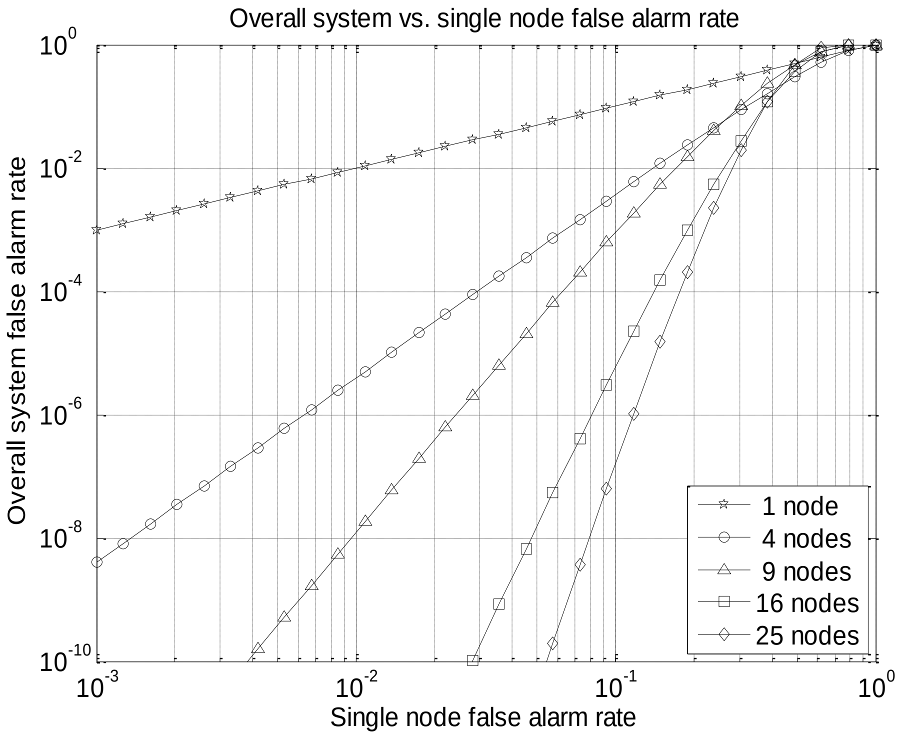
Decentralized processing

- The radar network can be considered also as made of a number of mono/bistatic systems working independently.
- Each system decides whether there is the target or not. The overall decision takes into account the number of the overall single detections.
- Double thresholding:
  - one (in power) at the end of every matched filter,
  - one (in number of single detections occurred) by a central system.
- This provides increased tolerance to jamming, but can reduce sensitivity.
- In the presented results overall detection ⇔ at least 50% single detections.

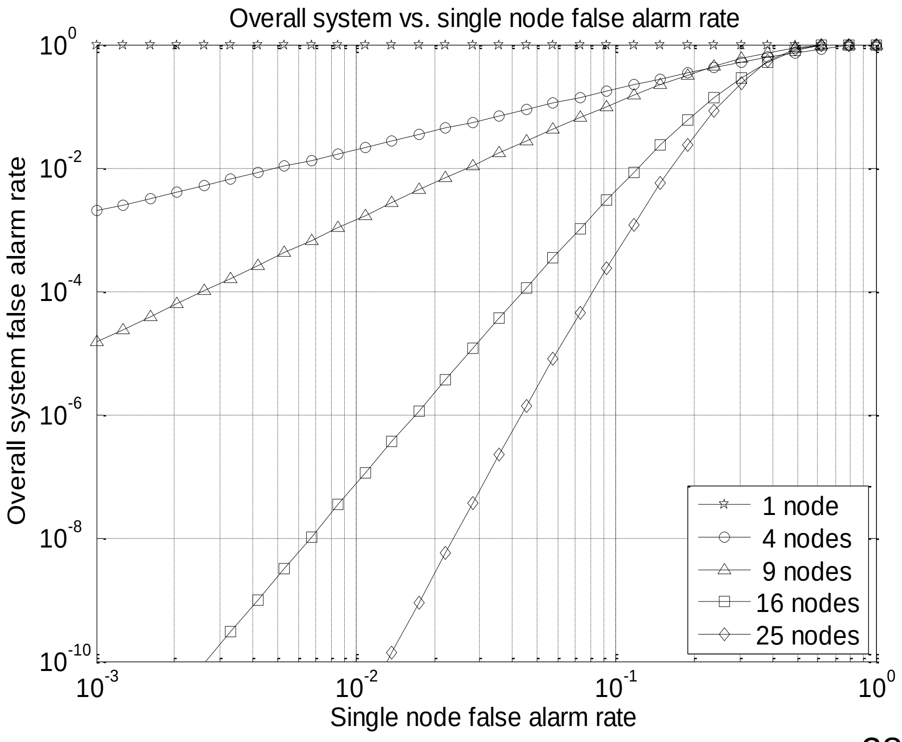
Decentralized processing - jamming

Without ECCM, when one of the receivers is fully jammed over the *M* incoming waveforms, the decentralized processing is partially able to supply to the jamming. Other common ECCM can still be applied on top of the single radars.

Without Jammer



With Jammer

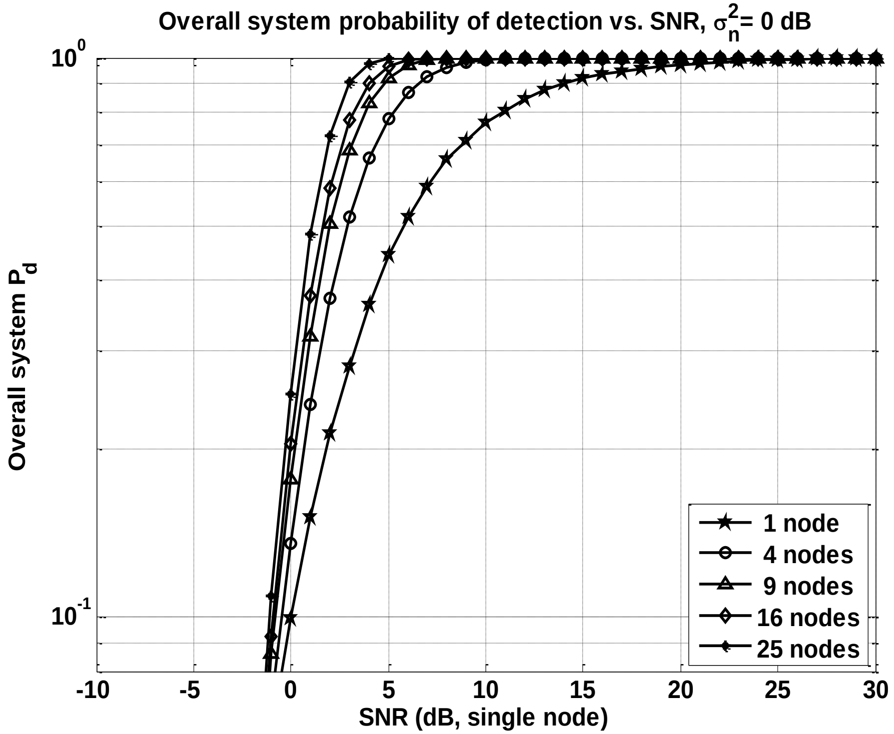


Decentralized vs centralized

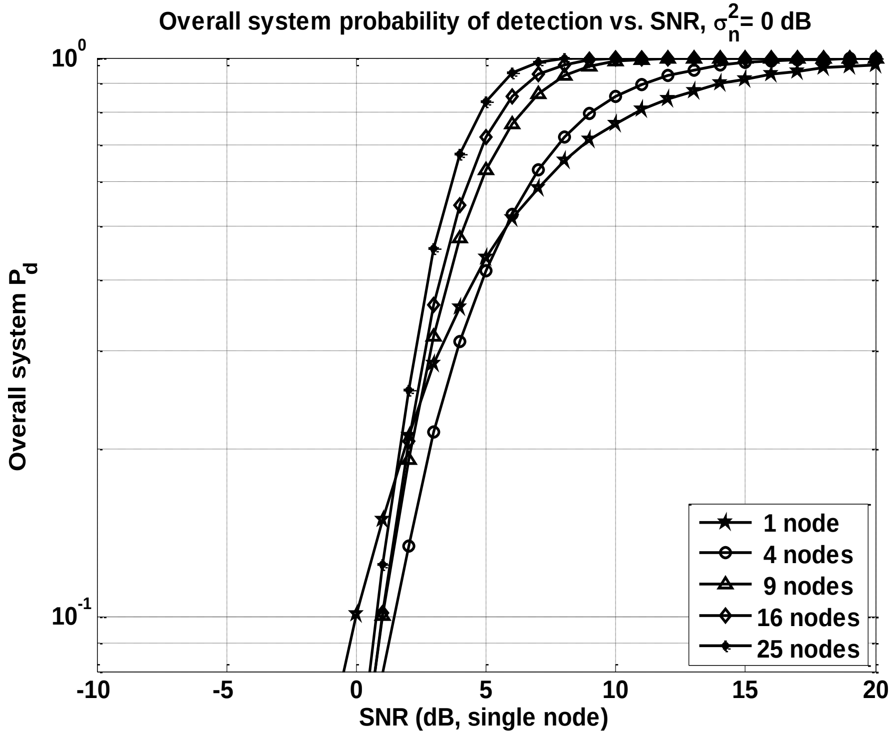
MIMO is a sub-optimal algorithm that approaches the theoretical upper bound limit for performance with a centralized processing.

Decentralized processing introduces some losses (≈ 4 dB) but has increased anti jamming capabilities.

MIMO



Decentralized



Tracking and decentralized techniques

- MIMO and NR systems can improve the single-radar resolution in locating a target.
- Tracking and initialization of the track in a MIMO system can be performed also with omni-directional antennas exploiting GPS-like algorithm for positioning rearranged for not-cooperative systems.
- When directivity is added to antennas the improvement is expected to be dramatic.
- Algorithm to joint the decentralized ECCM capabilities to the centralized increased sensitivity can be developed.
- Multi-perspective classification can be further investigated using the mono-bistatic profiles acquired.

Conclusions

- The best system between spatial and frequency MIMO radar systems is not predictable: it depends on the configuration of the nodes and on the statistical and frequency response of the RCS of the target.

- Frequency diversity results, whenever confirmed against real targets, can lead to interesting improvements in performances.

- MIMOs' performances are not so far from the theoretical upper bound limit of re-phased NR.

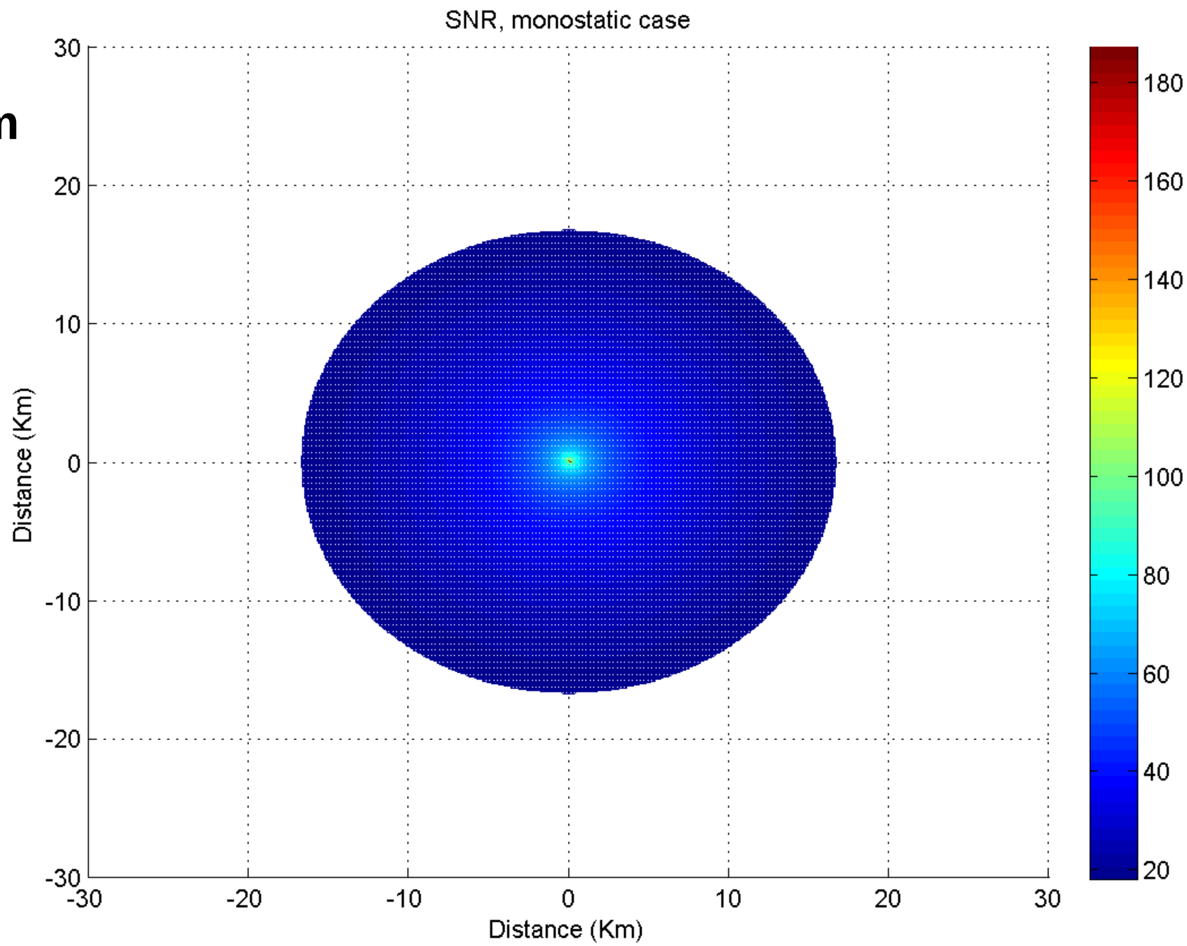
- The loss of performance of MIMO radar systems can be a fair trade off against the easier implementation of these systems.

Coverage

- The coverage of the studied systems are here compared against a monostatic system.
- Constant ERP is supplied also when the number of nodes varies. Moderate total peak power in transmission (5 kW) and RCS of 10 m^2.
- Curves are at 80% Pd for a Swerling I target.
- For multistatic systems 5 co-located tx-rx have been considered and shifted from the monostatic position of 500 m in all directions, equally spaced.

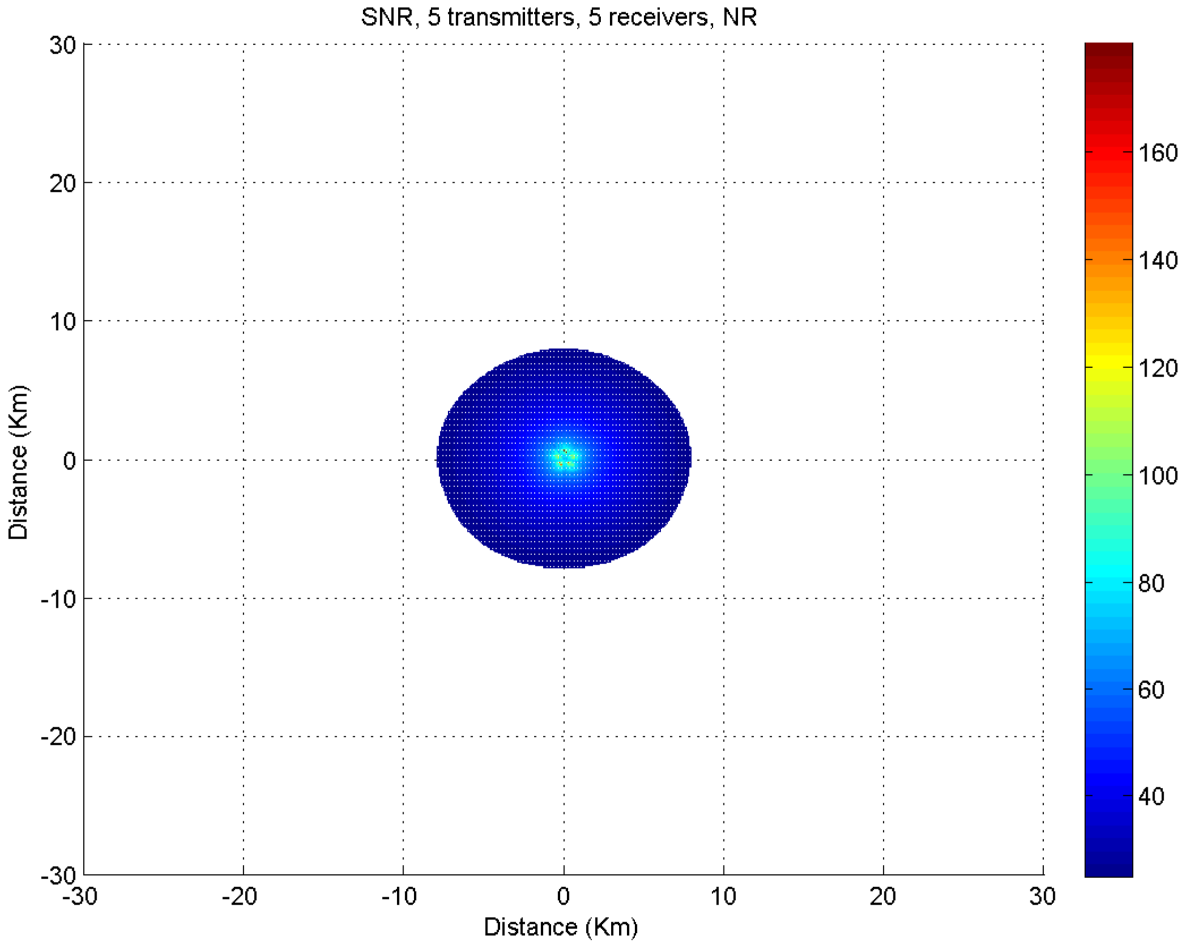
Coverage - Monostatic

- **Monostatic ≈ 16.7 km**



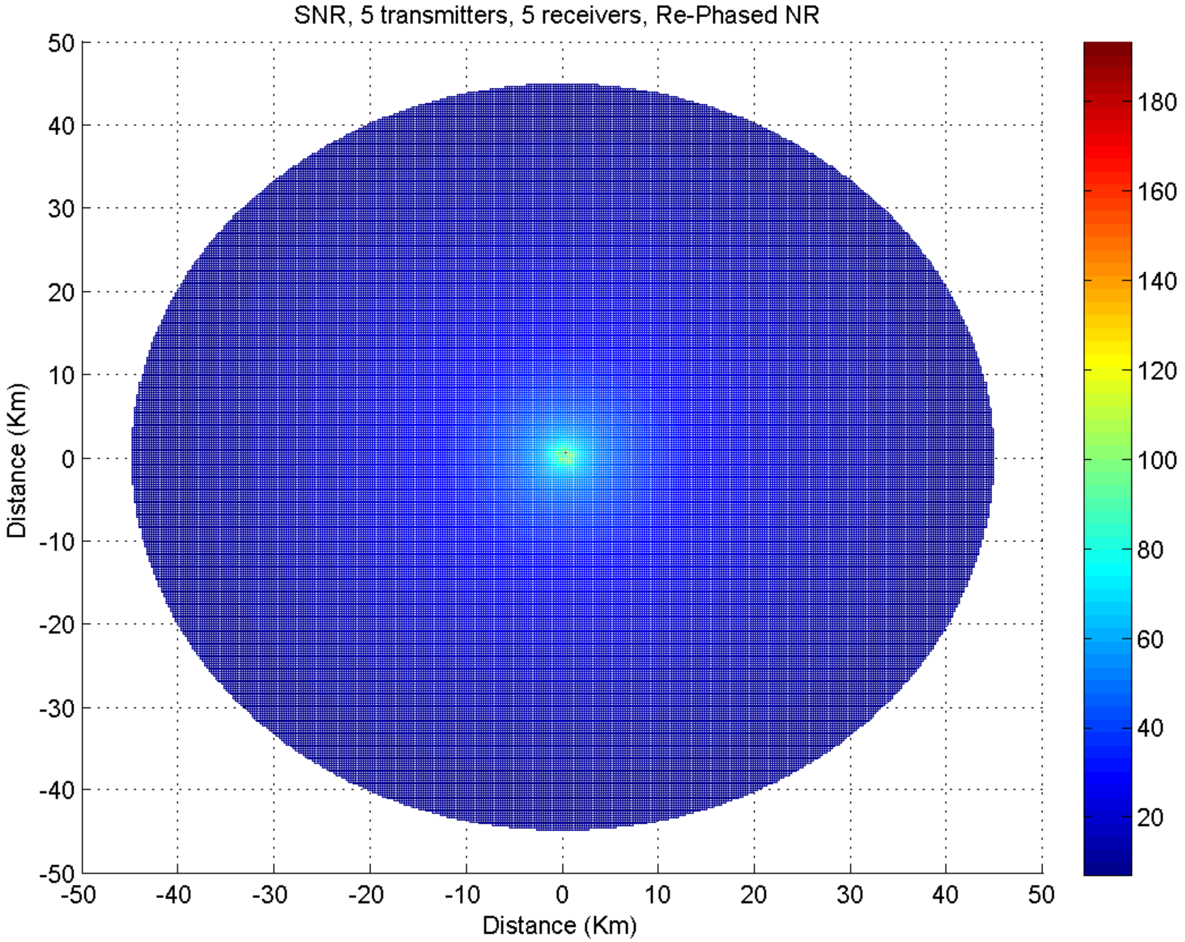
Coverage

- Monostatic ≈ 16.7 km
- **NR ≈ 7.5 km**



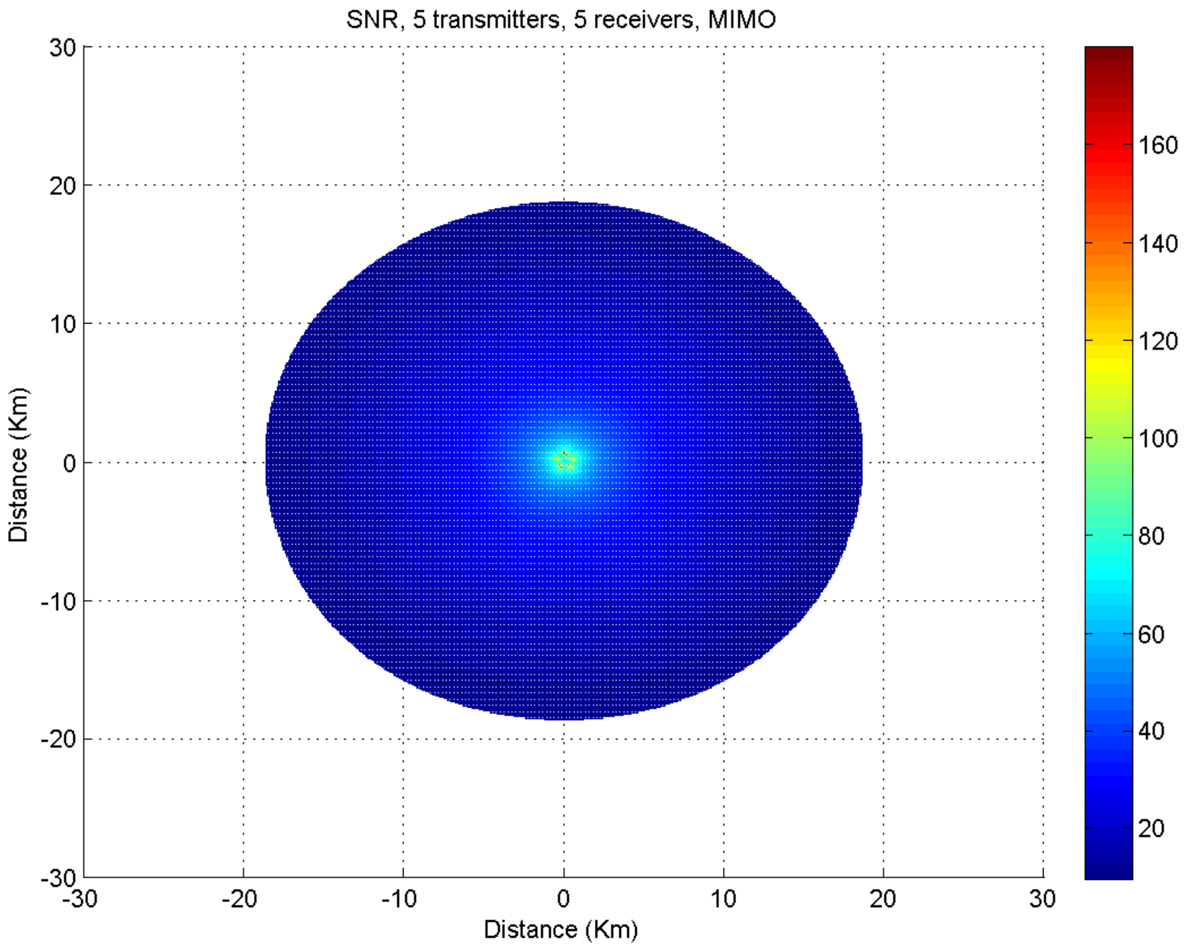
Coverage

- Monostatic ≈ 16.7 km
- NR ≈ 7.5 km
- **RPNR ≈ 45 km**



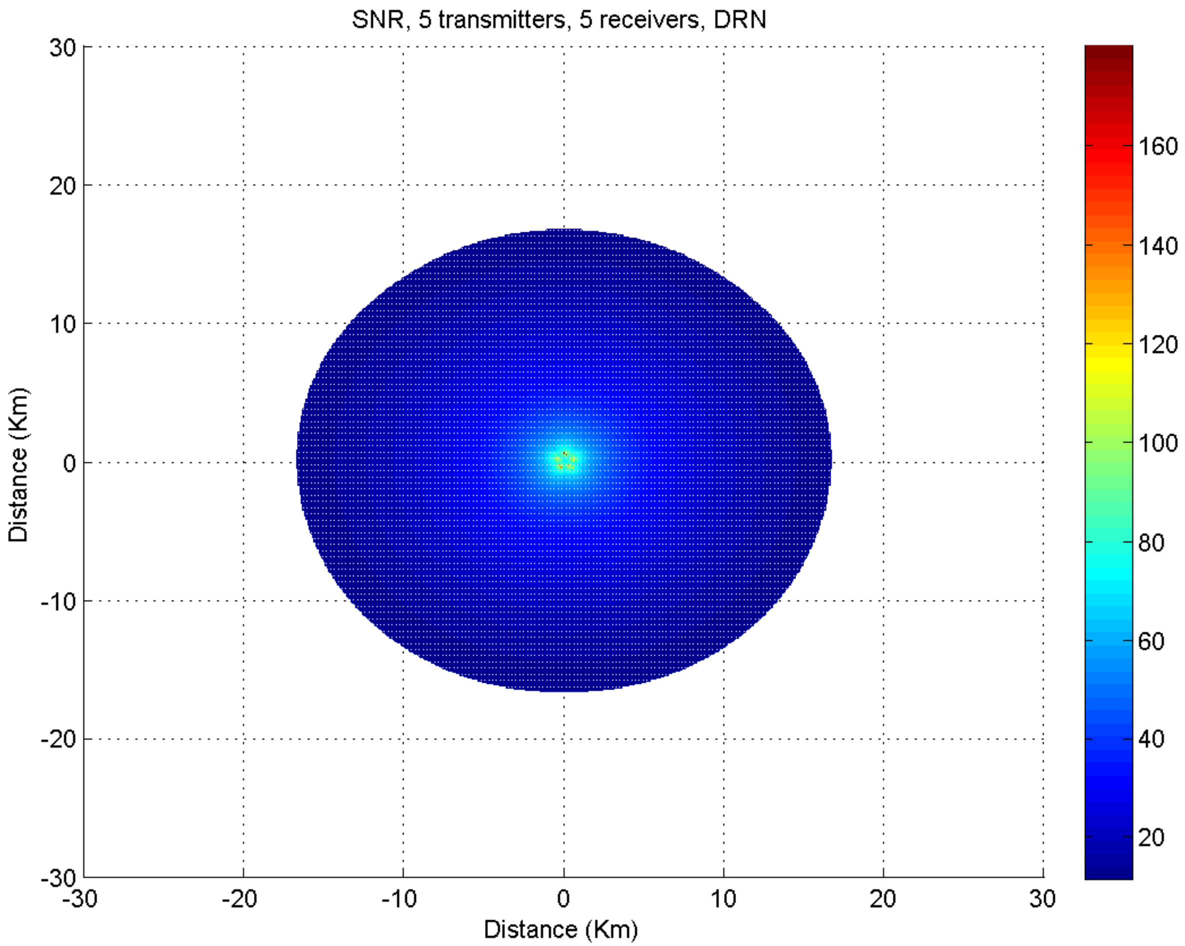
Coverage

- Monostatic ≈ 16.7 km
- NR ≈ 7.5 km
- RPNR ≈ 45 km
- **MIMO ≈ 18 km**



Coverage

- Monostatic ≈ 16.7 km
- NR ≈ 7.5 km
- RPNR ≈ 45 km
- MIMO ≈ 18 km
- **DRN ≈ 17.2 km**



Coverage

- Coverage vary according to the systems and the different thresholds set for detections.
- Also in this case the coherent approaches to processing provide the upper and lower bound for performance.
- MIMO and DRN overcome the monostatic system even under the bound of constant ERP. Further improvement may be achieved increasing the distance between devices of the same kind.

Sensitivity

Bistatic Radar

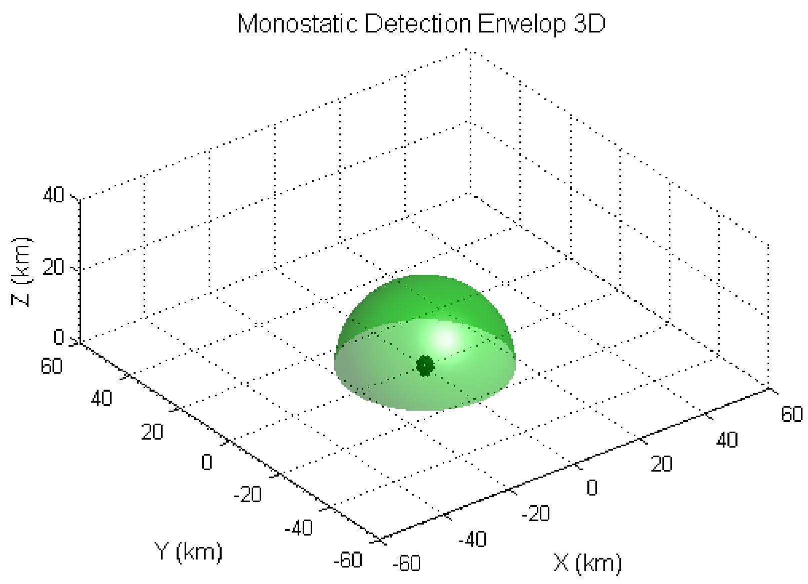
$$SNR = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 k T_s B R_t^{\ 2} R_r^2 L}$$

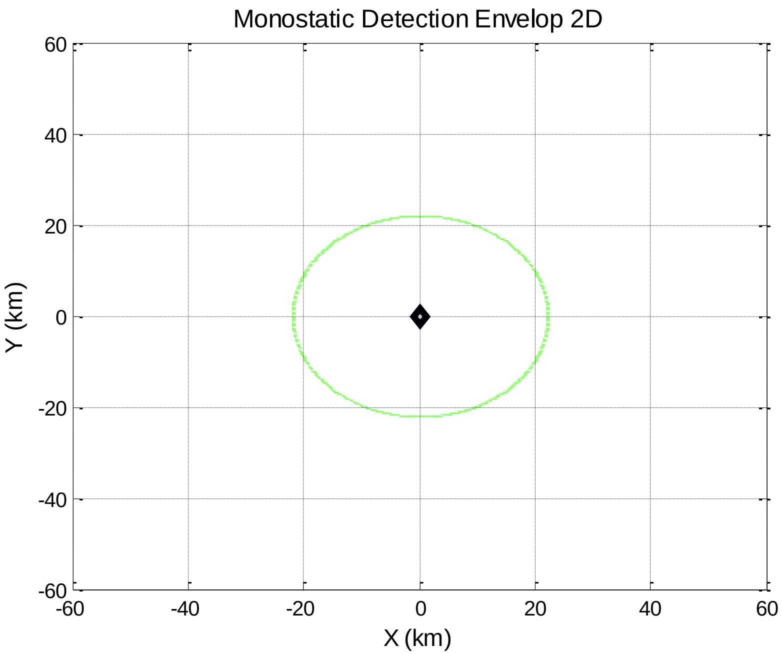
Netted Radar

- Coherent processing
- *m* transmitters & *n* receivers

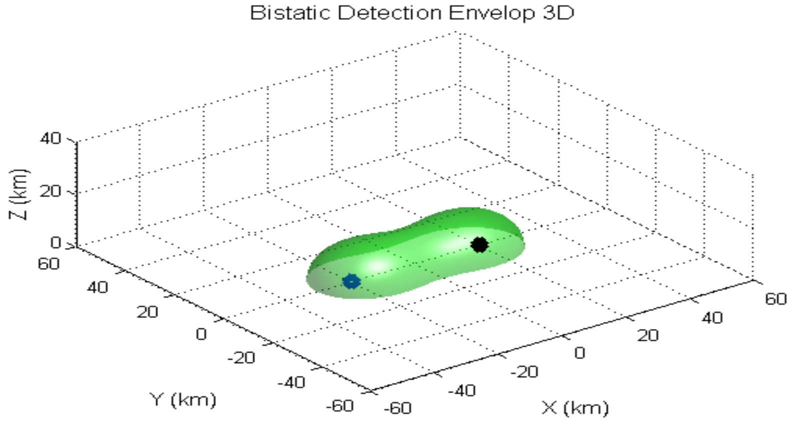
$$SNR_{netted} = \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{P_{ti} G_{ti} G_{rj} \sigma_{ij} \lambda_i^2}{(4\pi)^3 k T_s B_i R_{ti}^2 R_{rj}^2 L_{ij}}$$

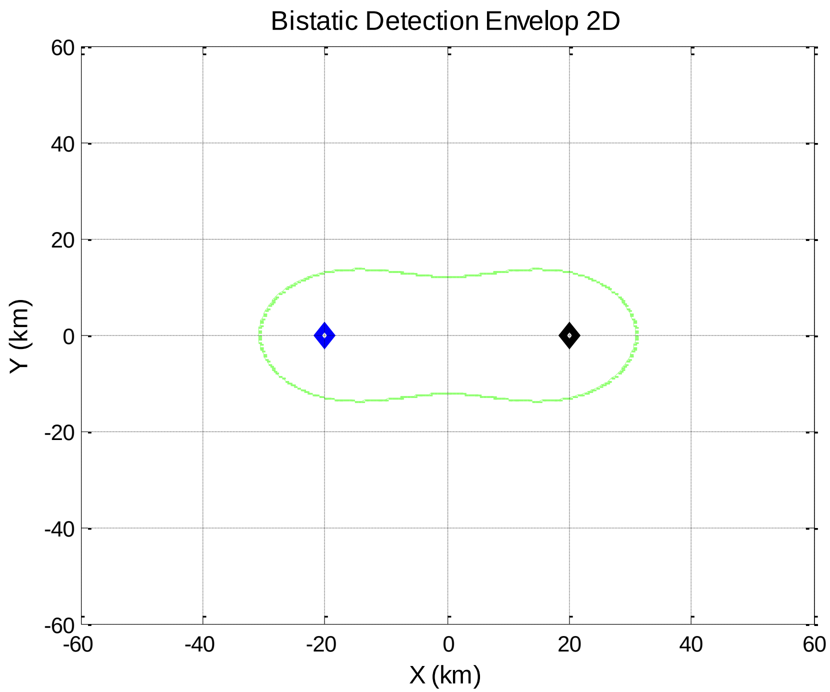
Monostatic radar sensitivity



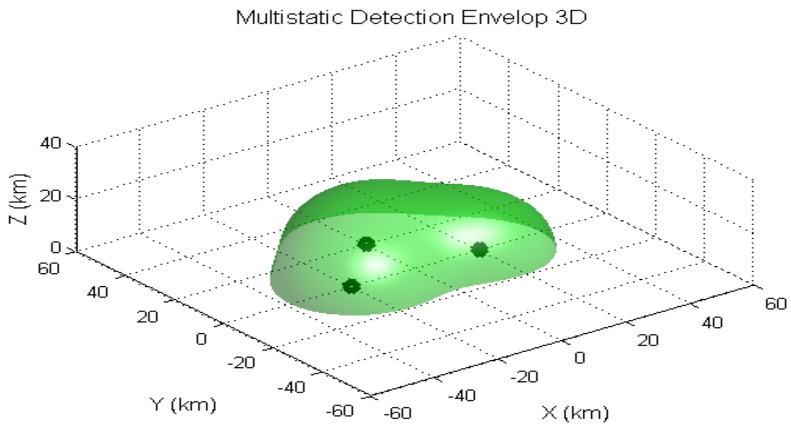


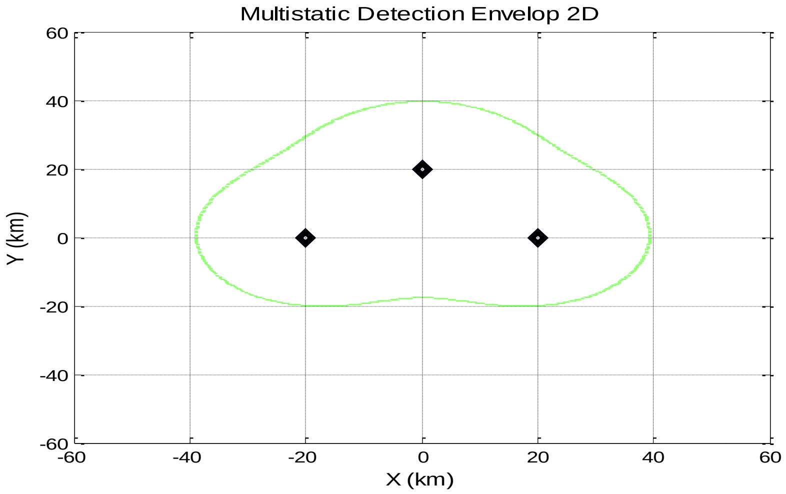
Bistatic radar sensitivity



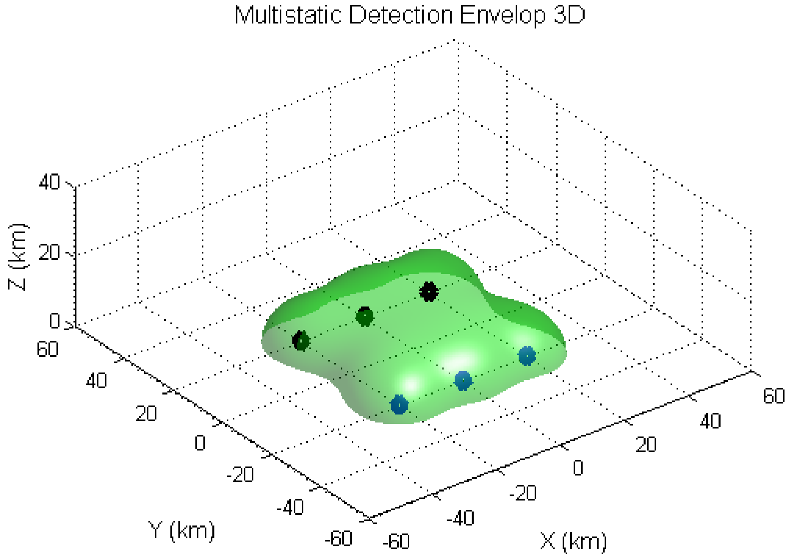


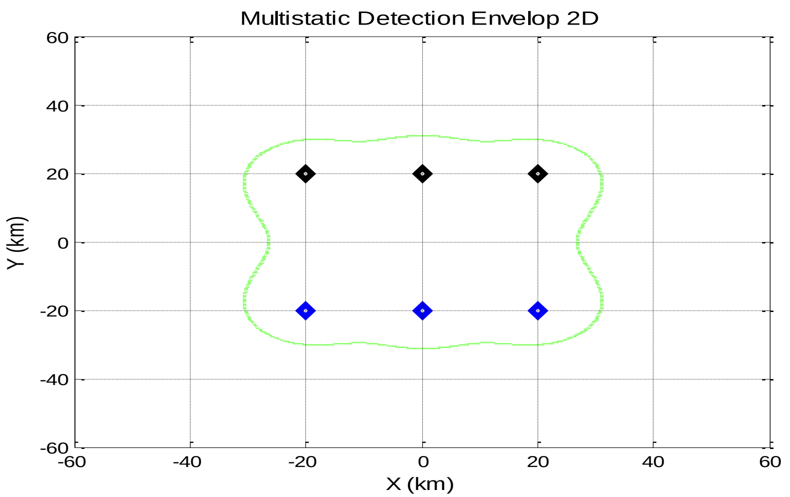
Netted radar sensitivity – dispersed transmitters & receivers





Netted radar sensitivity – fully dispersed transmitters & receivers

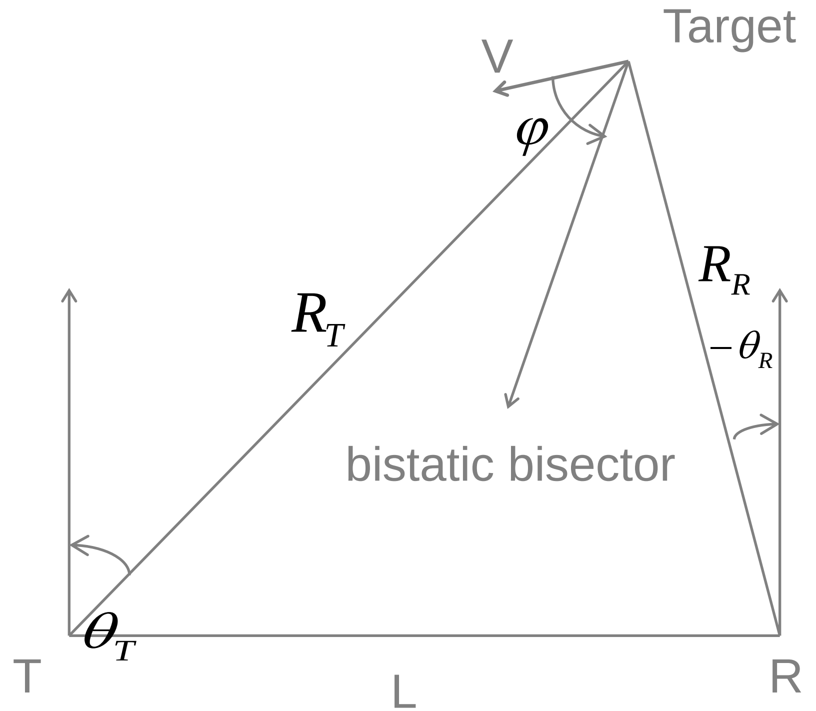




Ambiguity function – bistatic case

with $R = R_T + R_R$

- Bistatic geometry:



- Bistatic ambiguity function:

$$X(T,\omega_D) = \int_{-\infty}^{\infty} u(t)u^*(T(R,\theta_R,L)-t)\,e^{j\omega_D(R,\theta_R,L,V,\varphi)t}\,dt$$

Bistatic ambiguity function shape is affected by the transmitter – target – receiver path $\Longrightarrow$ Target location is crucial

Netted ambiguity - calculation

- Calculate bistatic ambiguity function for each transmitter - receiver pair

- Calculate weighting factor according to received signal intensity from each transmitter

$$P_{ri} = \frac{P_{ti} G_{ti} G_r \lambda^2 \sigma}{(4\pi)^3 (R_{ti} R_r)^2}, i = 1,2 \ldots N$$

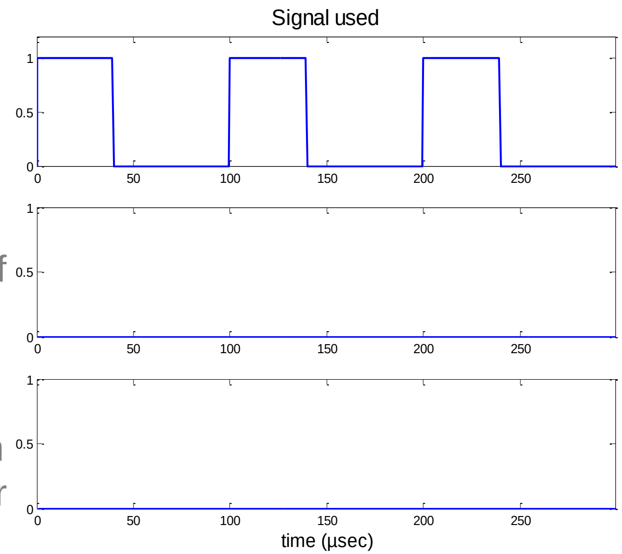
$$w_i = \frac{P_{ri}}{Max(P_{ri})}$$

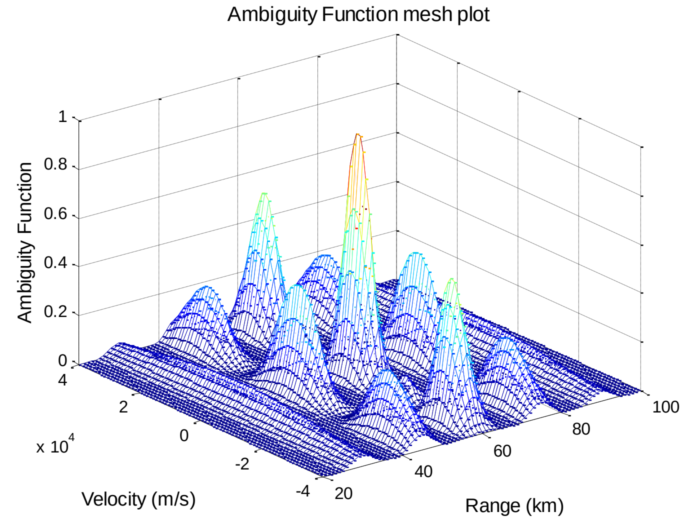
- Formulate netted radar ambiguity function using the results of previous calculations

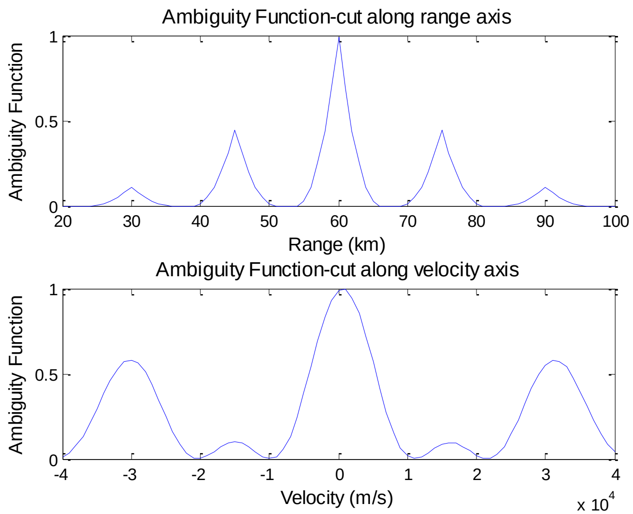
$$\chi_{netted} = \left| \sum_{i=1}^{N} w_i \chi_i \right|^2$$

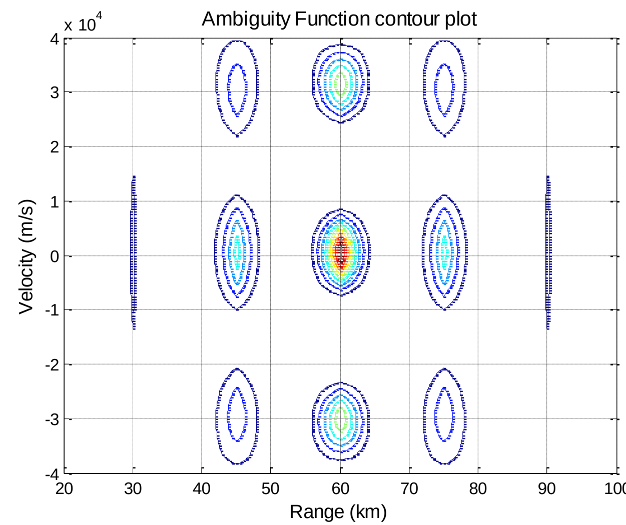
Ambiguity - monostatic

Integration of three rectangular pulses
Target 60Km from receiver with 600m/s velocity



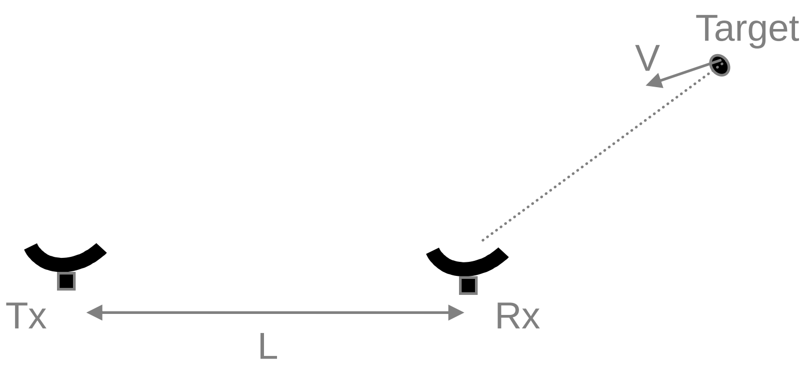


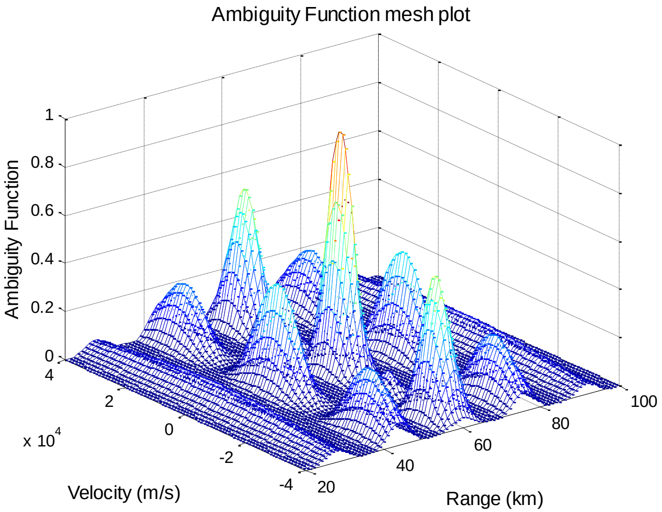


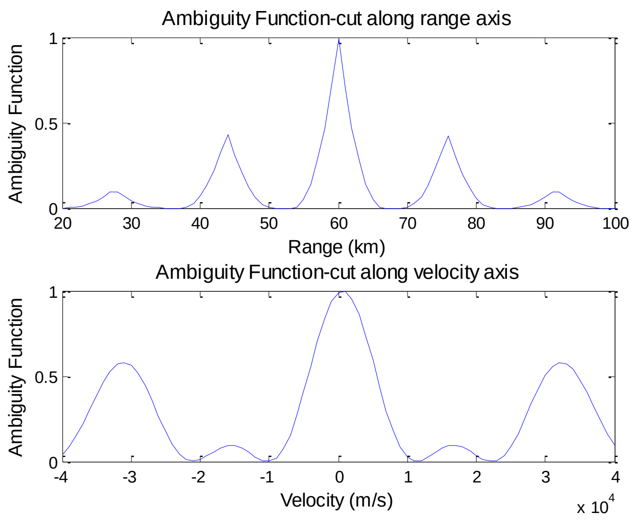


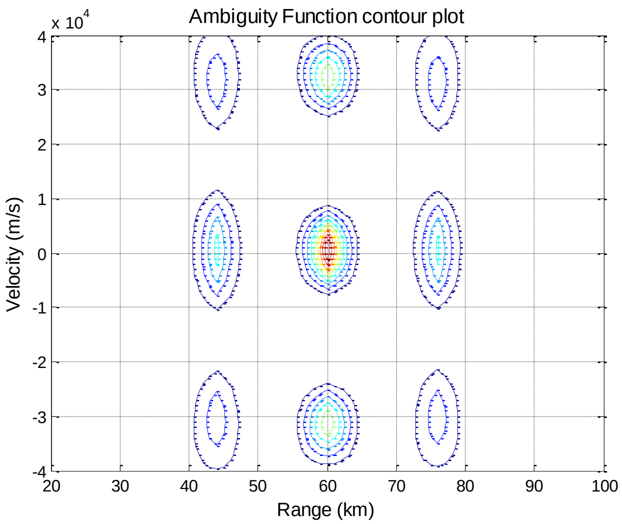
Ambiguity - Bistatic

Target far from baseline



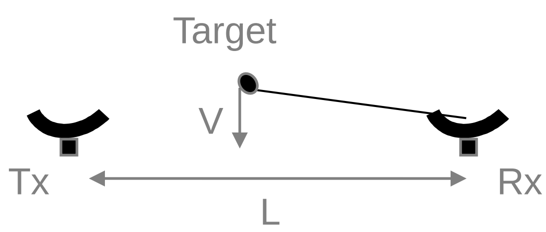


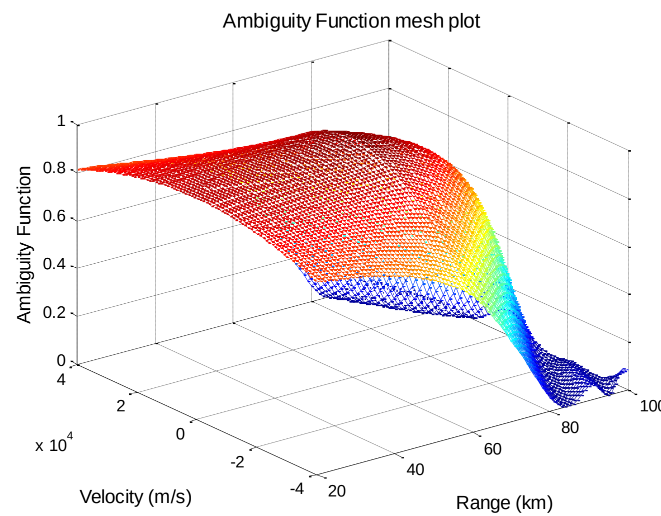


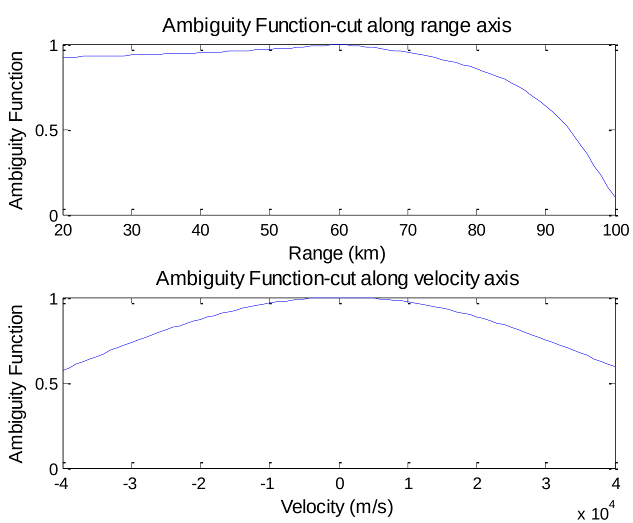


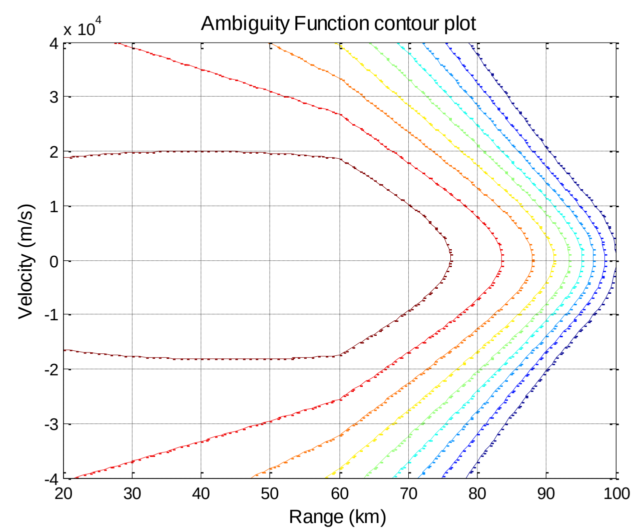
Ambiguity - Bistatic

Target close to baseline





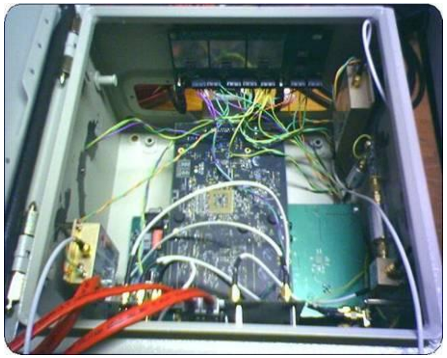




EXPERIMENTATION

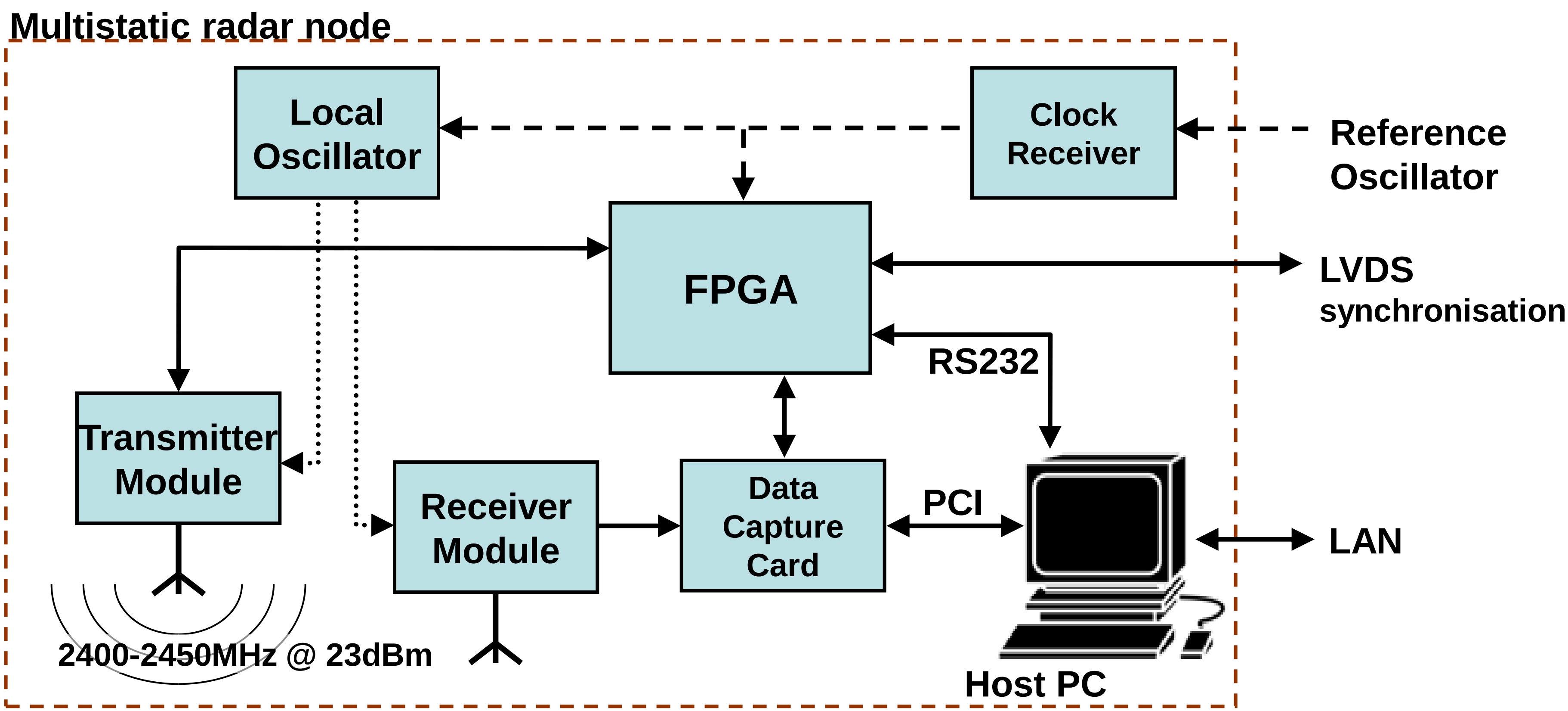
NetRAD: a multistatic radar system

Carrier frequency	**2.4 GHz**
Peak transmitted power	**23 dBm**
Maximum range over which data is recorded	**3000 m**
Antenna beamwidth	**8º × 8º**
Maximum bandwidth	**50 MHz**
Nominal range resolution	**3 m**
Pulse lengths	**0.1 – 10 µs**
Available transmissions	**Chirp, Barker code, Pulse, Polyphase / Deng codes, Passive, Continuous**
PRF	**5 0Hz – 3 kHz**
Maximum number of pulses	**1500**

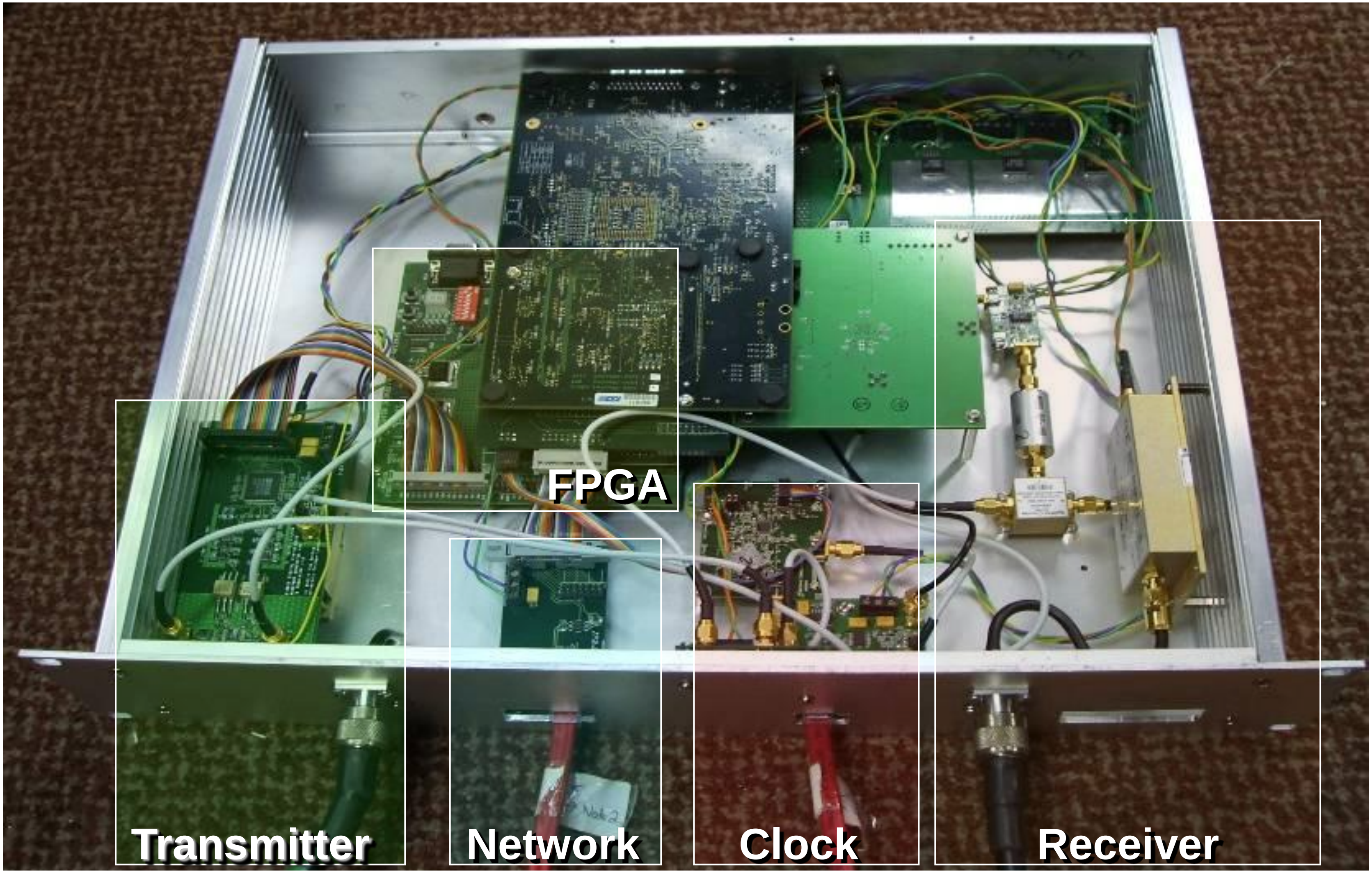


The current radar network consists of three nodes where two nodes are connected to a central node with 50 m network cables.
A 100 MHz reference oscillator is also distributed to all three nodes via three 50 m cables.
The user interface to the system is by a PC connected via parallel port to the DSP card.
When outdoors, the system is powered by 65 Ah lead-acid battery.

NetRAD: a multistatic radar system



A multistatic radar node

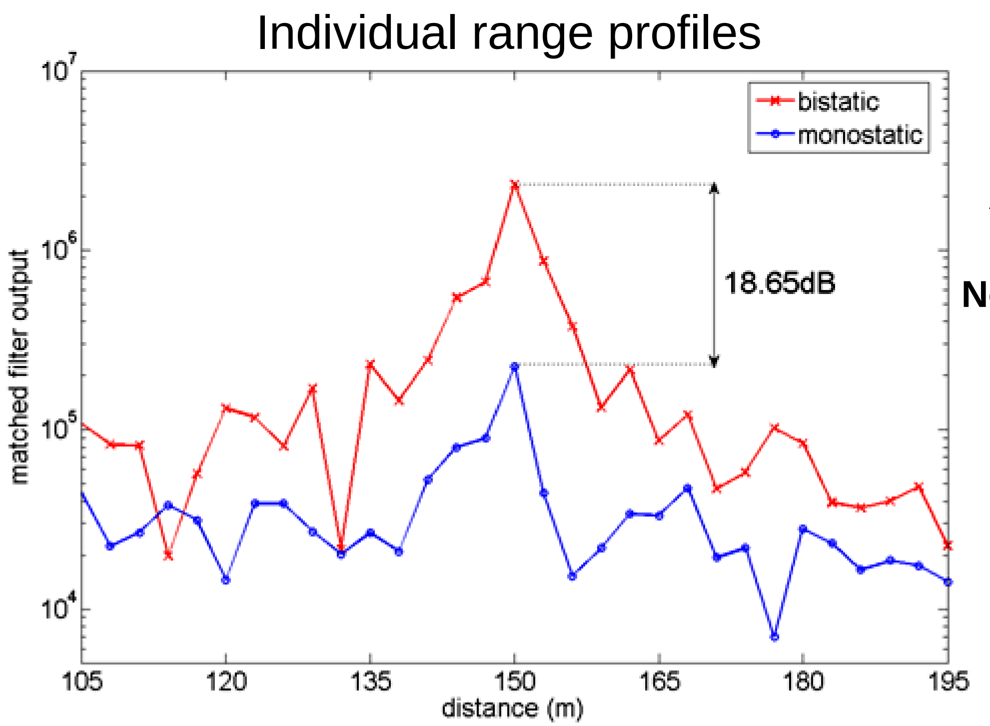


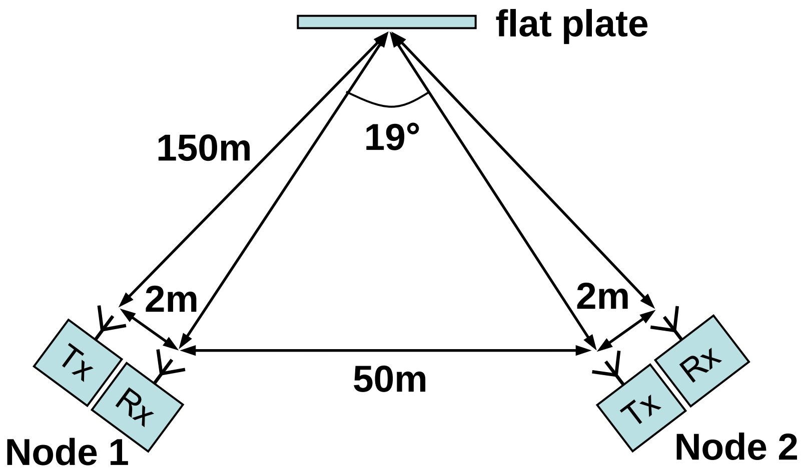
Recent experimental trials

- The system itself has been ruggedised to ease experimental trials.
- Improvements in data handling, particularly the move to a PCI capture card, allow for easier capture of moving targets.

Recent experimental trials

Looking at a flat plate

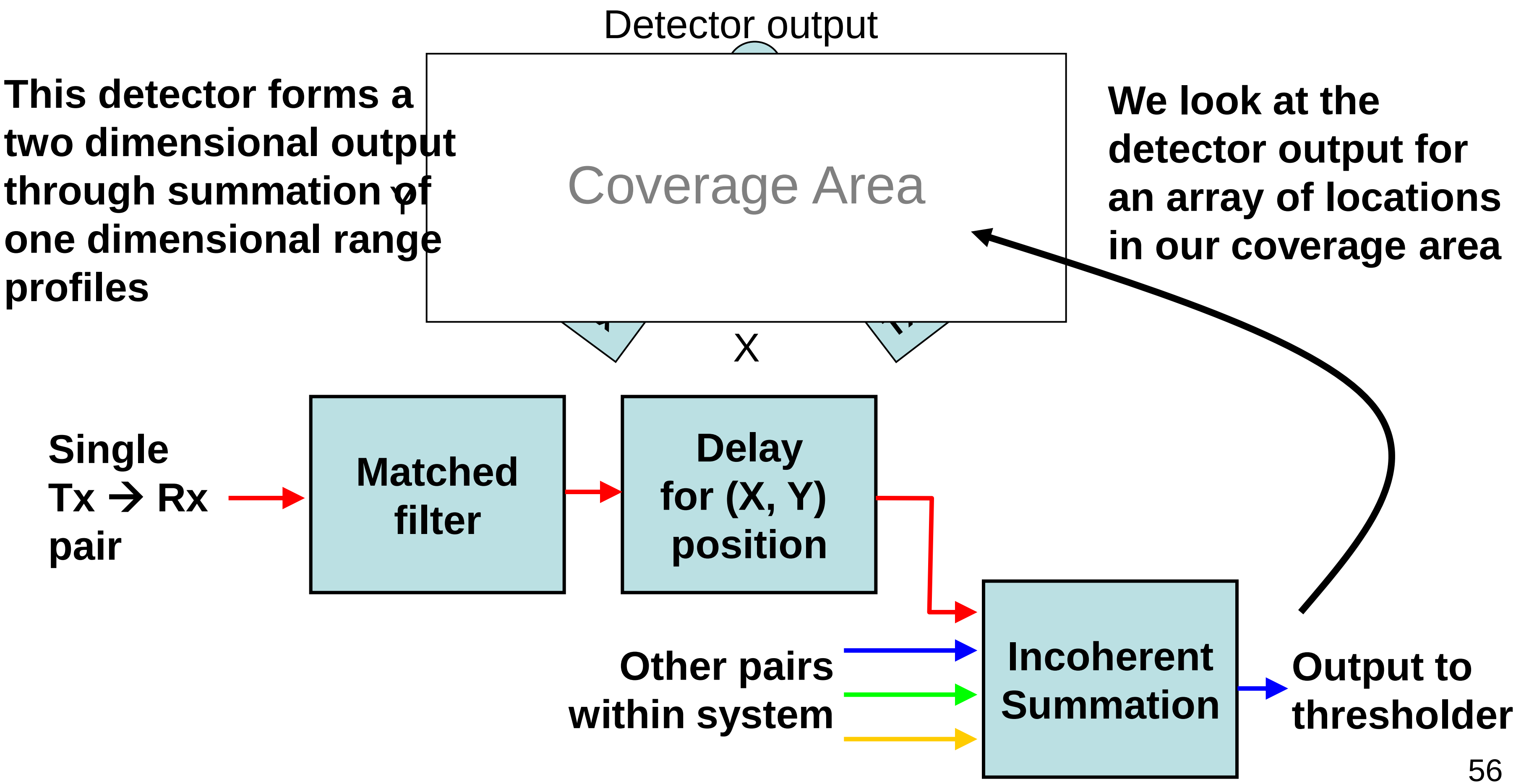




- Node separation is increased to 50m
- A much larger response is seen in the bistatic pair

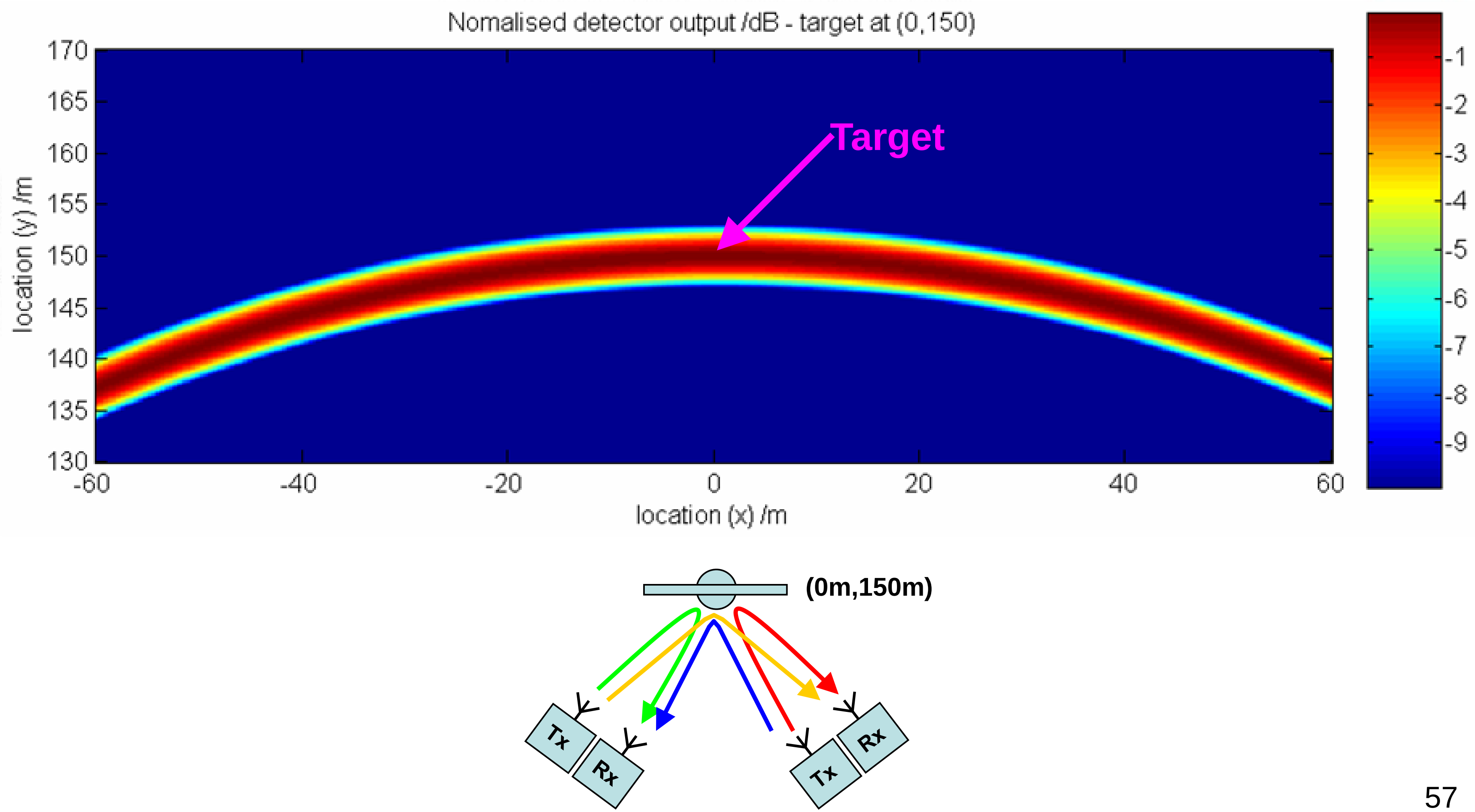
Multistatic detection

A simple centralised detector with a two dimensional output is considered:

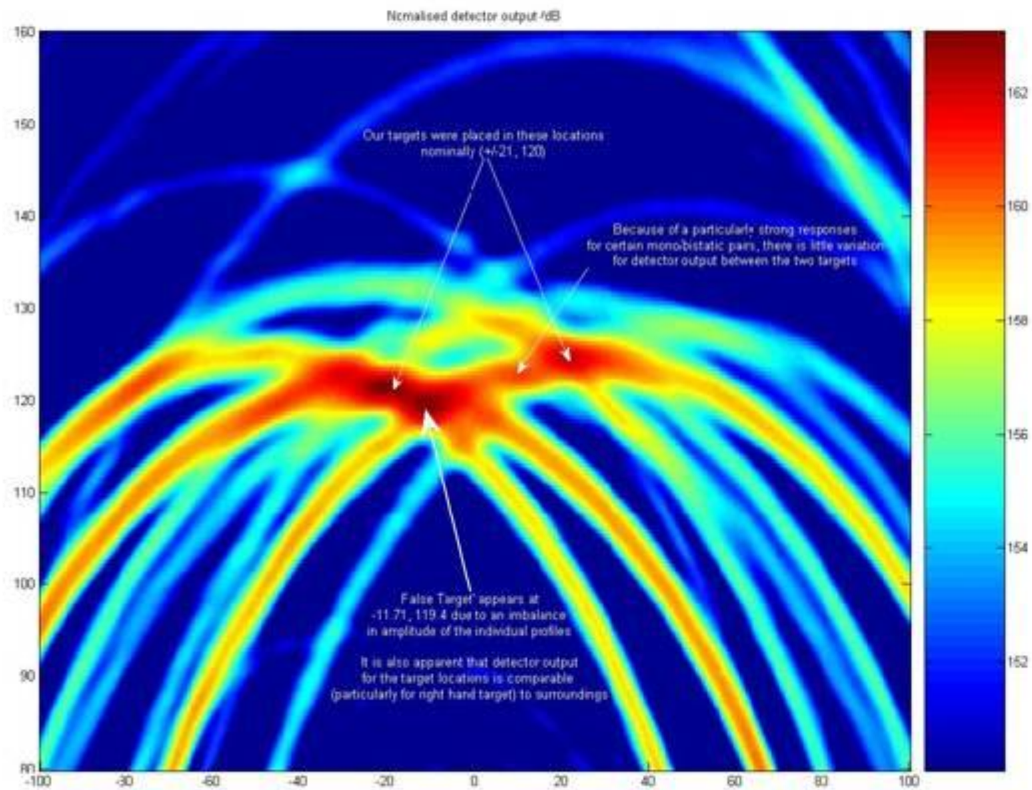


Detector output using single monostatic measurement for a cylindrical reflector

Detector output using multistatic measurement for a cylindrical reflector

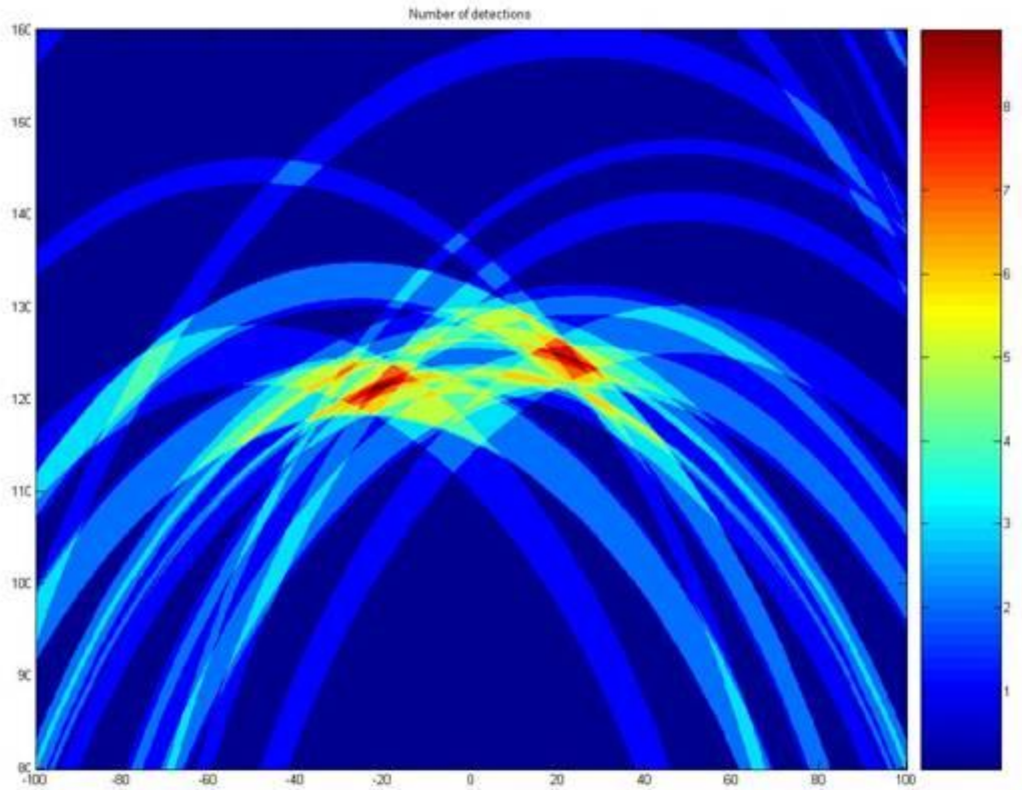


Recent experimental trials

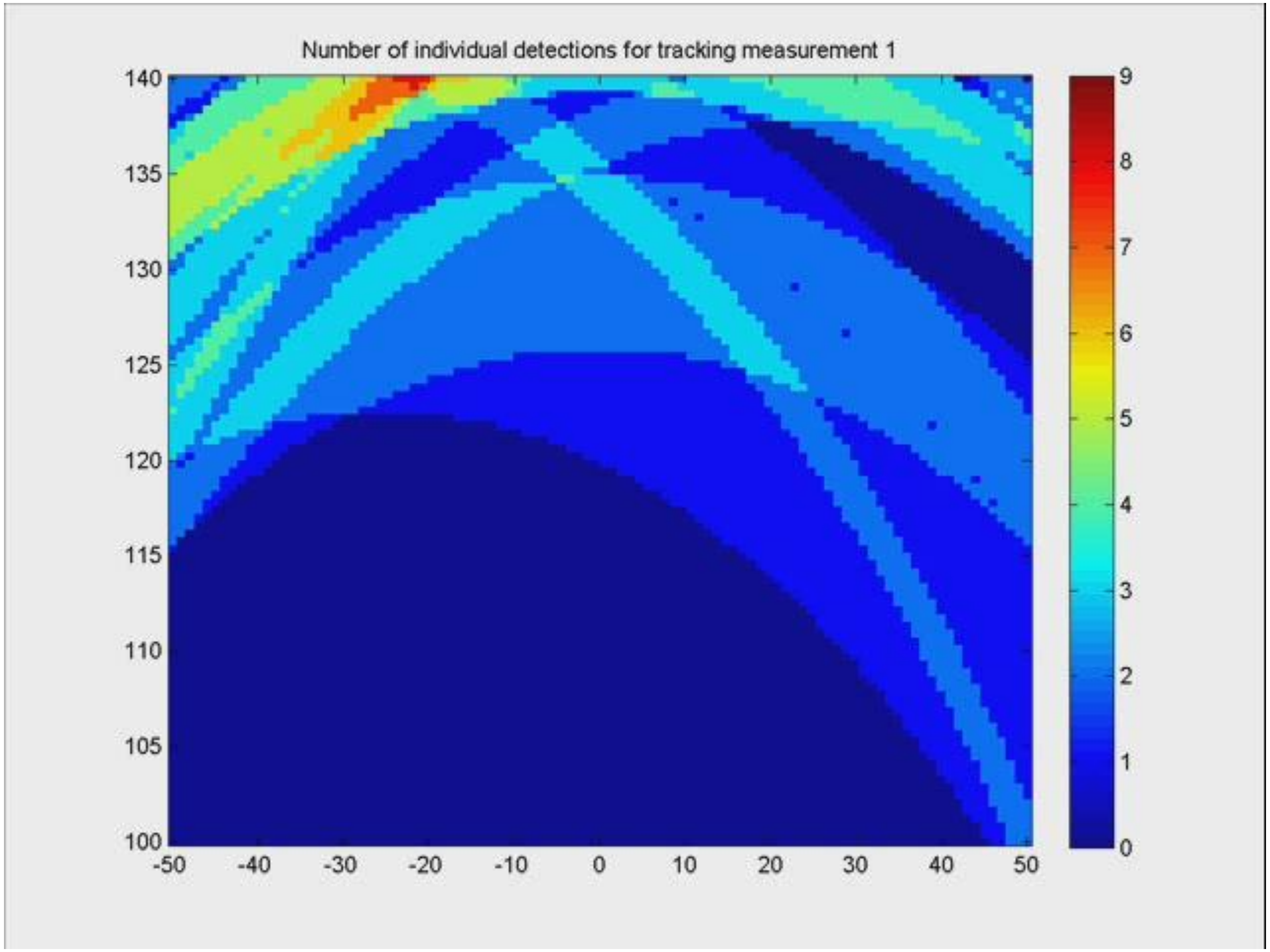


- Here we attempt to show the process of resolving two targets, through multistatic processing. In this case centralised data fusion is used.

Recent experimental trials

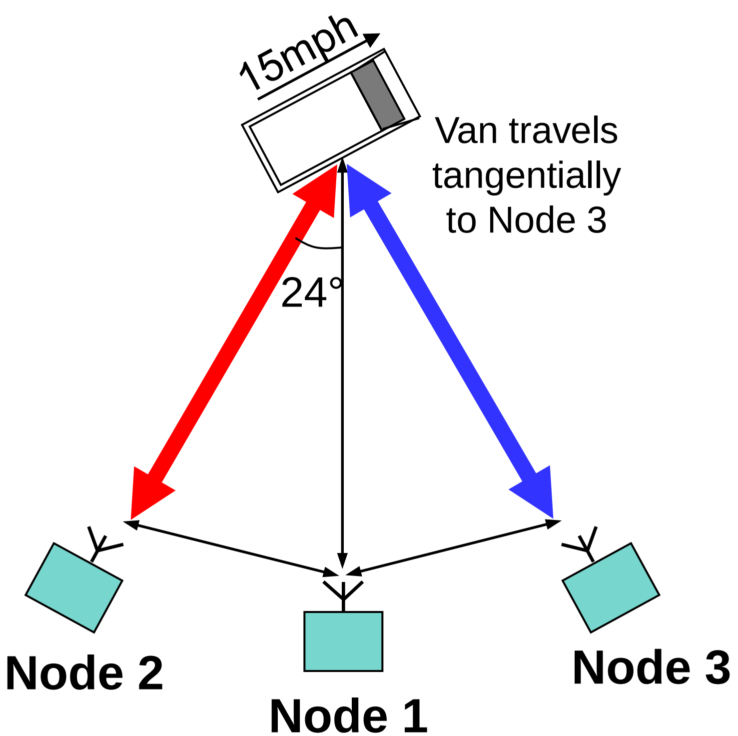


- Decentralised data fusion shows potential to avoid large responses dominating the multistatic detector, and reduce ‘false targets’.

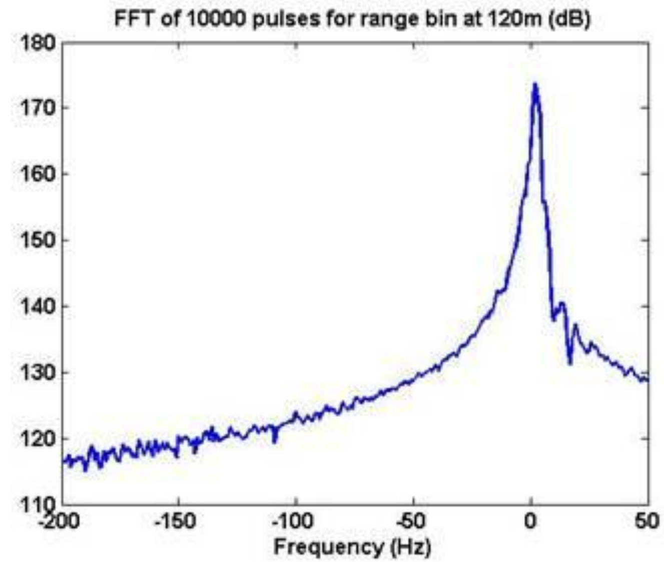


Number of individual detections for tracking measurement 1
140
135
130
125
120
115
110
105
100
-50
-40
-30
-20
-10
0
10
20
30
40
50
9
8
7
6
5
4
3
2
1
0

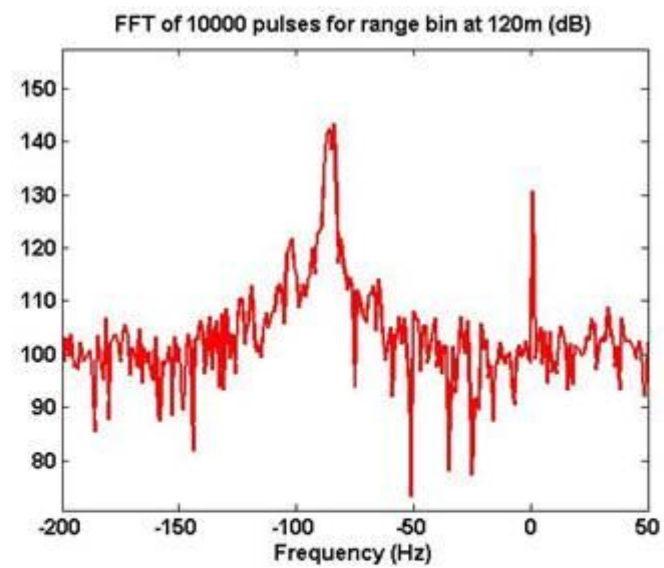
Recent experimental trials



Node 3 sees only a stationary target



Whereas Node 2, viewing from a different aspect angle enjoys a Doppler shift away from 0Hz and potential clutter

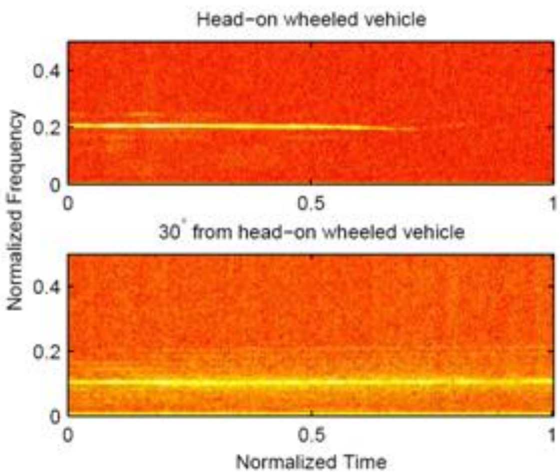


- Moving targets have also been observed using the radar system
- We can also combine individual measurements to produce a vector velocity

Multistatic Micro-Doppler Signature (μDS)

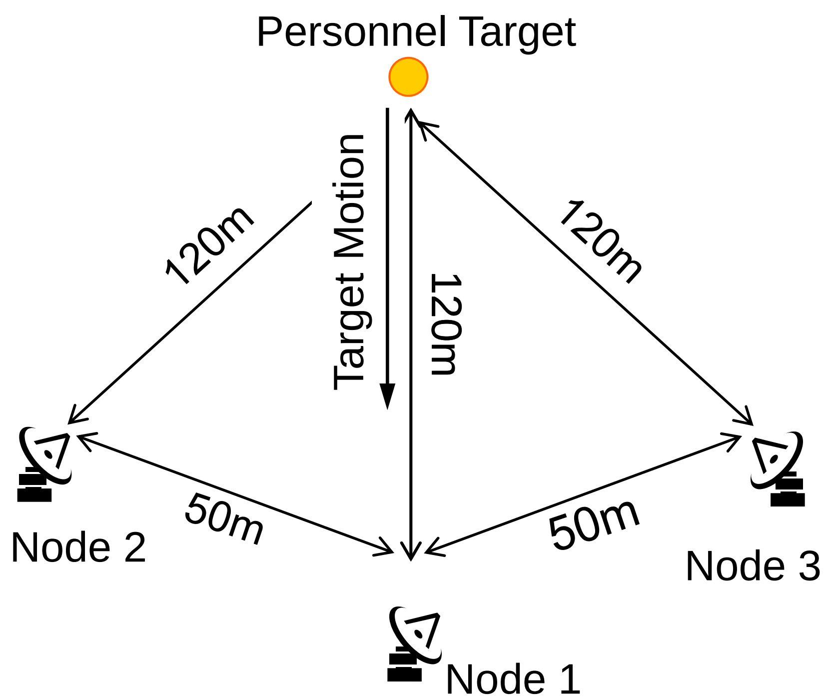
The Concept

- Monostatically the μDS is prone to problems of occlusion



- Head-on there is no μDS due to wheels being obscured
- So, move to a multistatic radar

Experimental Trials



- Use UCL's 3 node radar network
- Illuminate personnel targets
- Investigating their multistatic μDS
- 3 perspectives separated by 24°

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μDS Results For Walking Man

Range Frequency View **Time Frequency View**