Complex Analytical Challenges of Modern Radar Systems

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Introduction

- Radar systems play a key role in modern defence and civilian sensing applications.
- They are used to accomplish a wide variety of tasks which include the detection and classification of targets, the acquisition of intelligence information, imaging, autonomous navigation and collision avoidance.
- The pressing appetite for increased performance and improvements in technology are resulting in the development of intelligent radar systems that can resolve real-time complex optimisation strategies through the analysis of a large amount of digital data.
- Cutting-edge trends on industrial sponsored research looking at intelligent missile RF seekers using active phased arrays and detection and classification of drones with digital staring arrays.

Cognitive RF Seekers

- Use of novel 3D-shaped conformal phased arrays
- Exploit the ability of the seeker to diversify, select and optimise the transmitted waveform design so to optimise the measurement of target range and velocity
- Diversify the 3D phased array beam pattern characteristics on a scan to scan basis to optimise the monopulse performance and the measurement of target angle
- Development of 3D phased arrays and prioritize experimental work based on the solutions provided by the previous MCM-ITP projects
- Develop novel platform control strategies that use the radar input to maximize interception performance

The goal of the project is to design the radar seeker and the 3D phased antenna so to optimise the prosecution trajectory and target interception performance.

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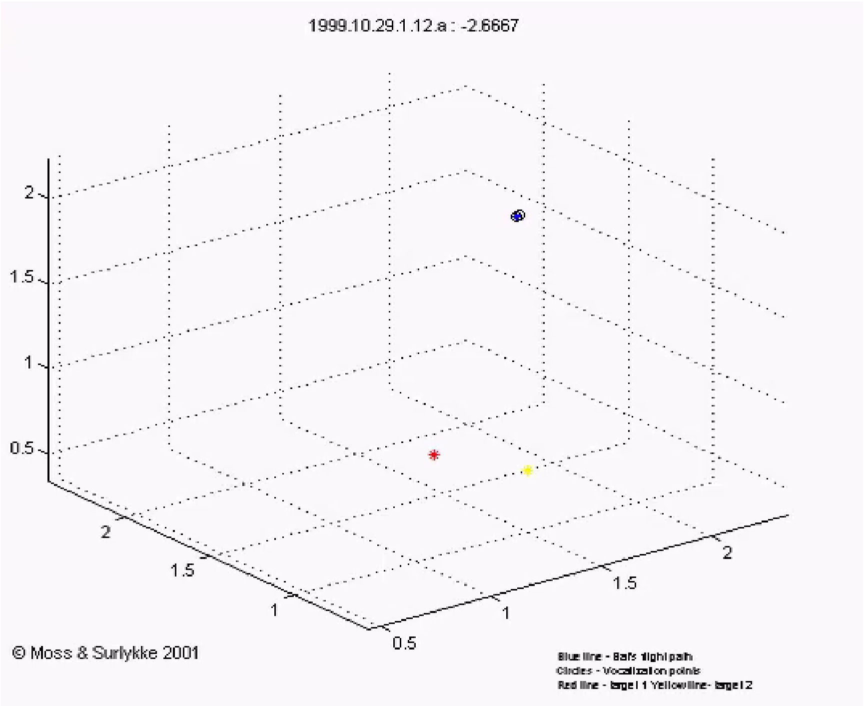
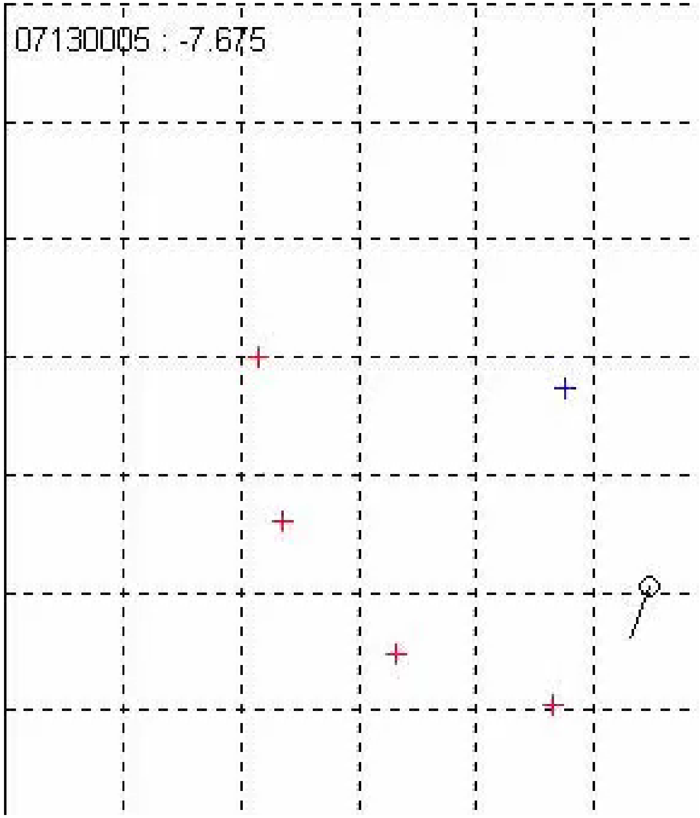
DRAGON Concept



Waveform Diversity



Beam-pattern Diversity

A fully-adaptive synthetic system capable of changing waveform and antenna pattern from pulse to pulse to maximise performance

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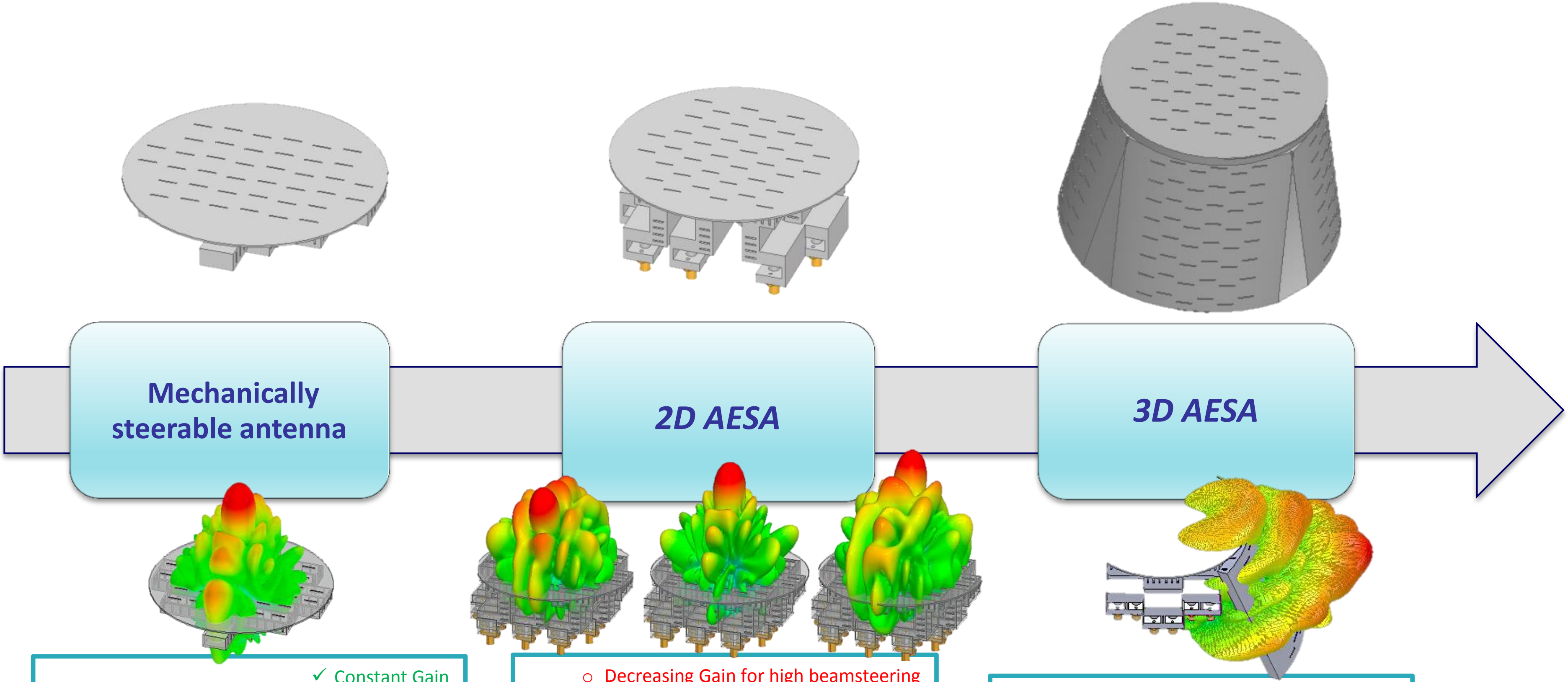
From Mechanically Steerable antennas towards 3D AESA



Mechanically steerable antenna

- ✓ Constant Gain
- ○ Narrow coverage
- ○ Bulky beam-scanning system
- ○ Slow beam-scanning
- ○ Fixed beam
- ○ One beam

2D AESA

- ○ Decreasing Gain for high beamsteering angles
- ○ Narrow coverage
- ✓ Integrated beam-scanning system
- ✓ Fast beam-scanning
- ✓ Flexible beamforming
- ✓ Multi-beam possibility

3D AESA

- ✓ Quasi-constant gain
- ✓ Wide coverage
- ✓ Integrated beam-scanning system
- ✓ Fast beam-scanning
- ✓ Flexible beamforming
- ✓ Multi-beam possibility

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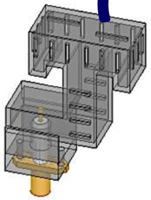
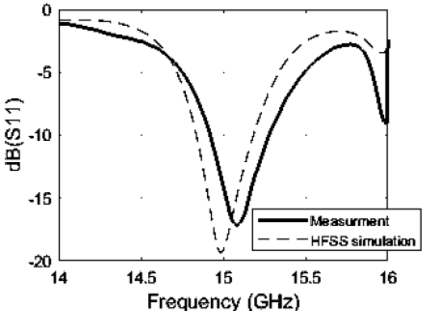
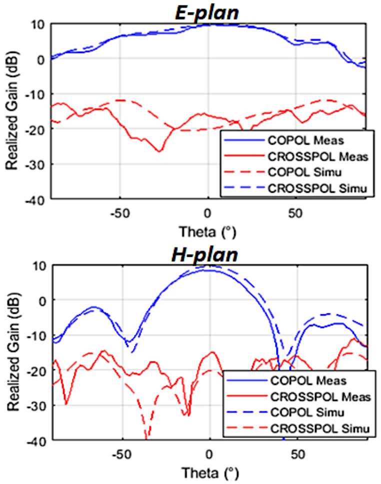
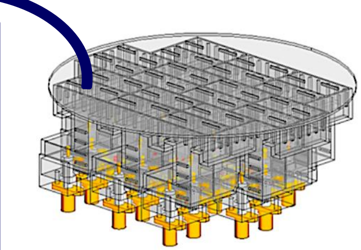
2D AESA Design

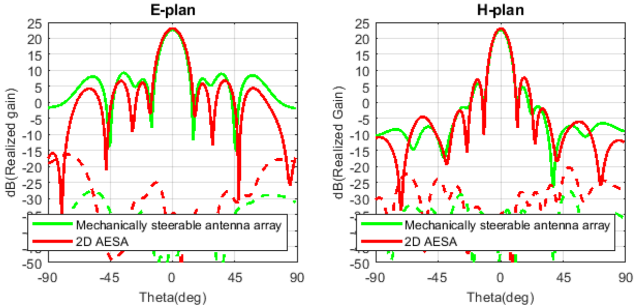
Subarray design and manufacturing

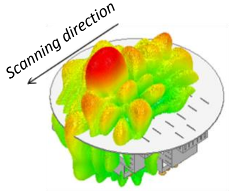


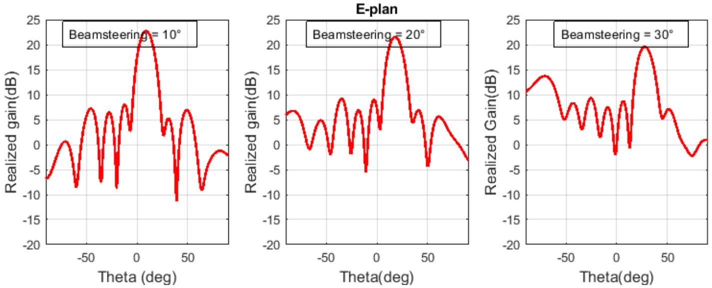


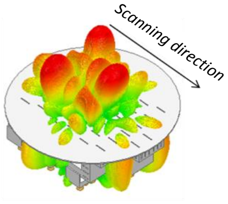


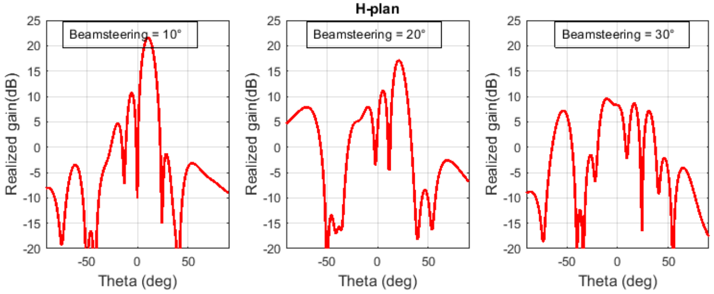




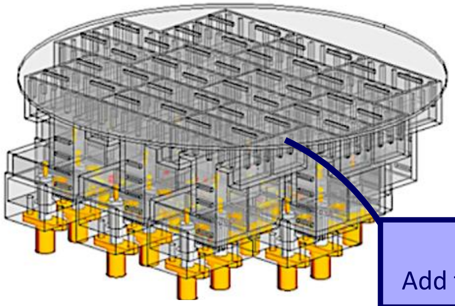




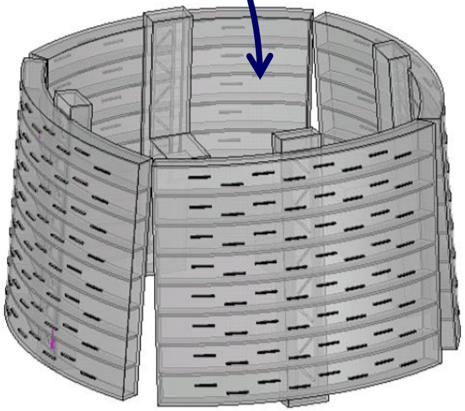




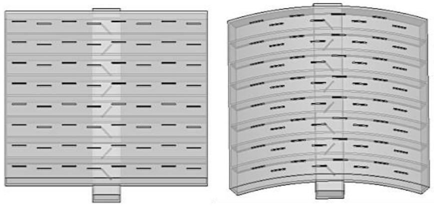
3D AESA Design

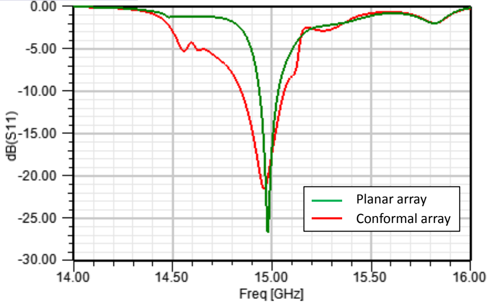


1st version
Add four conformal Lateral faces

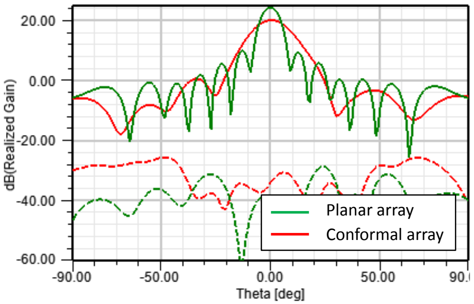


CONFORMATION

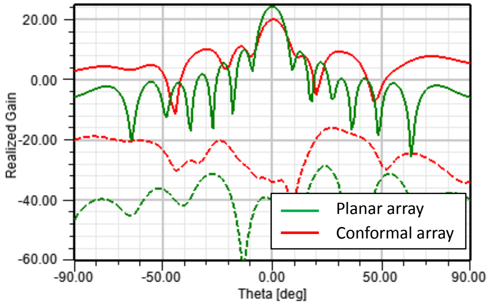




H-plan



E-plan

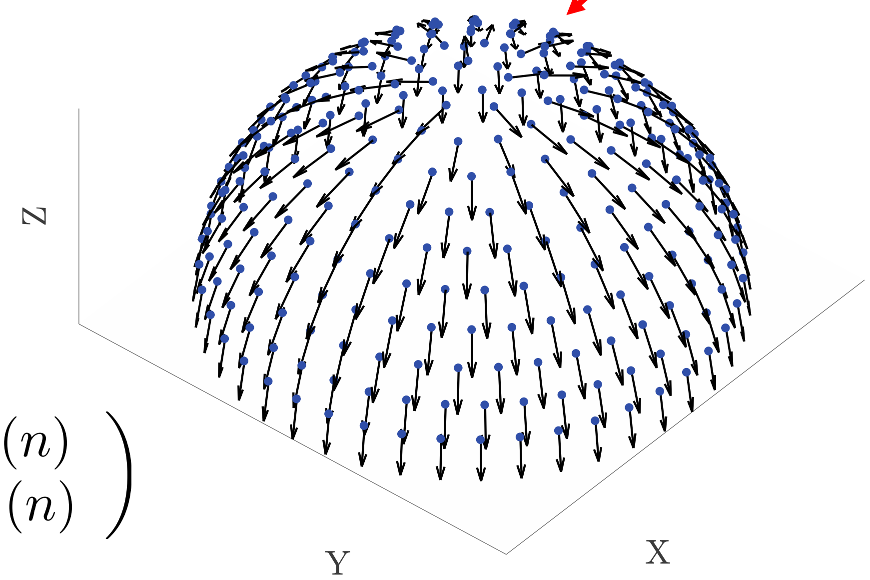


Measurement of Target Angle

- Use of directive elements
- All polarisations
- Use of 3D shapes with directive elements arranged with different orientations
- Assessment of the effects of cross-polarisation interference
- Investigate how the beampattern can be adapted to maximise overall radar performance
- Assess the performance of the proposed elements and shapes

Signal Model

$$\mathbf{E} = E_\theta \mathbf{e}_\theta + E_\varphi \mathbf{e}_\varphi$$



The co-pol and cross-pol components are extracted at each element

$$s(n) = \begin{pmatrix} \sqrt{G_c(n)} & \sqrt{G_x(n)} e^{j\phi_c(n)} \end{pmatrix} \begin{pmatrix} E_c(n) \\ E_x(n) \end{pmatrix}$$

Each element receives a delayed copy corrupted by noise

$$z(n) = \left[x_I(n) + j x_Q(n) \right] e^{j \frac{2\pi}{\lambda} \mathbf{r}(n) \cdot \mathbf{e}_r} + w(n)$$

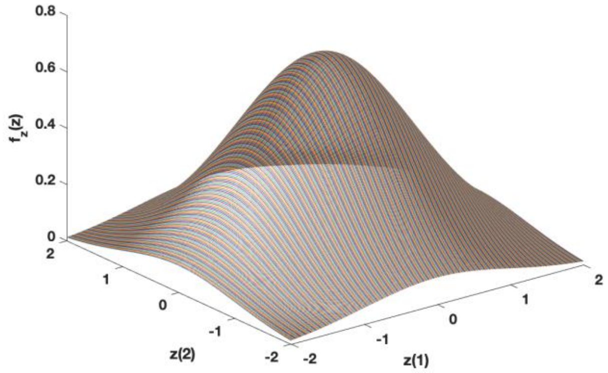
We study the performance of a snapshot (monopulse)

Optimal Performance

The best measurement accuracy performance by unbiased estimators are described by the CRLB

$$f_{\mathbf{Z}}(\mathbf{z};\theta,\varphi)=\frac{1}{(2\pi\sigma^2)^N}\times e^{\frac{-1}{2\sigma^2}\sum_{n=1}^{N}\left[\left(z_I(n)-\rho(n)\cos(\frac{2\pi}{\lambda}\mathbf{r}(n)\cdot\mathbf{e}_r+\phi(n))\right)^2\right]}$$
$$\times\, e^{\frac{-1}{2\sigma^2}\sum_{n=1}^{N}\left[\left(z_Q(n)-\rho(n)\sin(\frac{2\pi}{\lambda}\mathbf{r}(n)\cdot\mathbf{e}_r+\phi(n))\right)^2\right]}$$

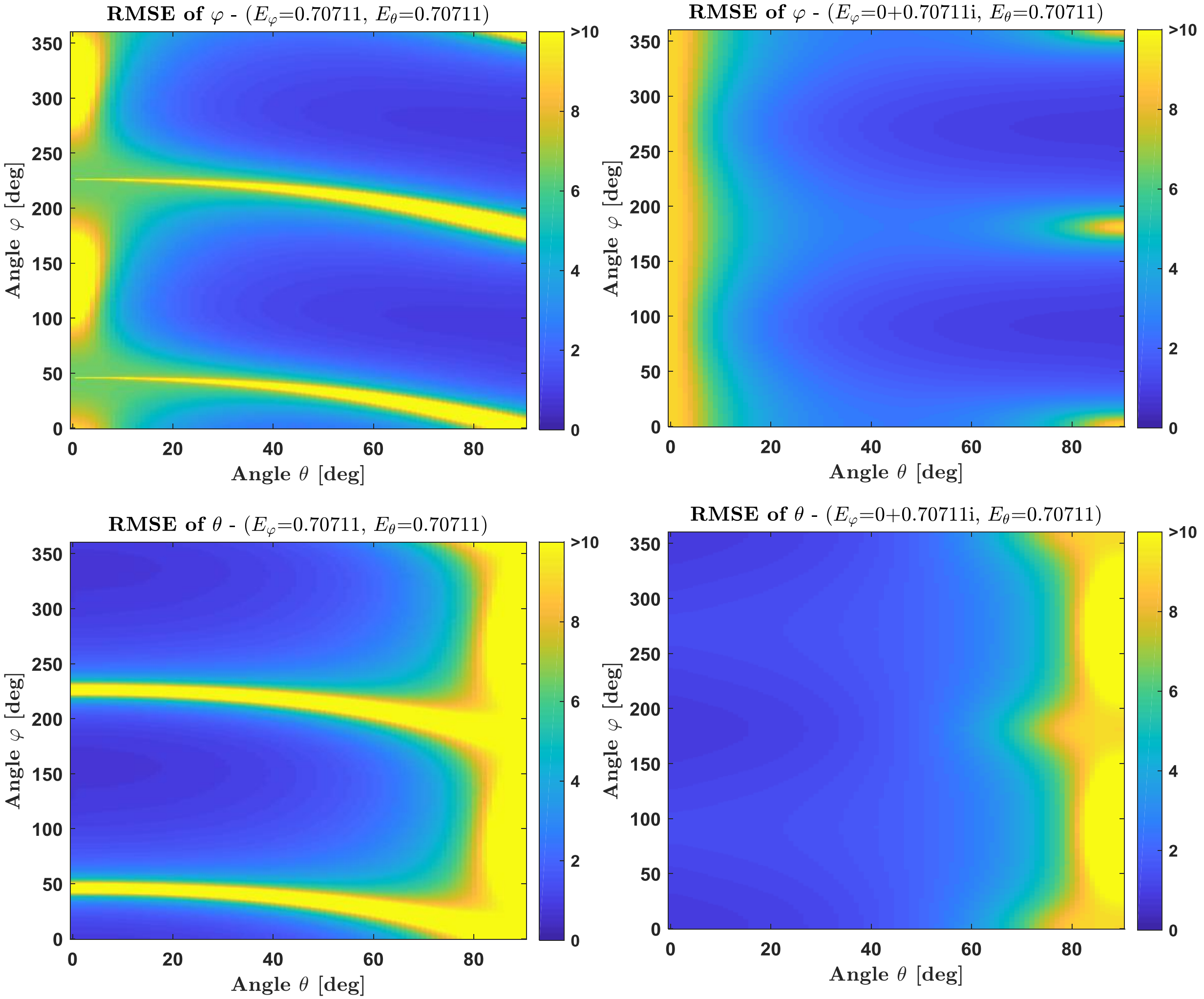
The CRLB is given by the inverse of the Fisher Information Matrix (FIM)

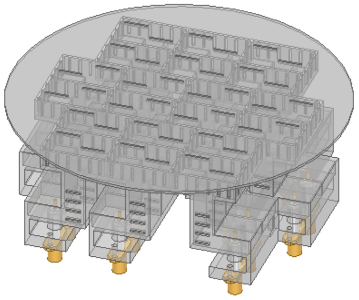


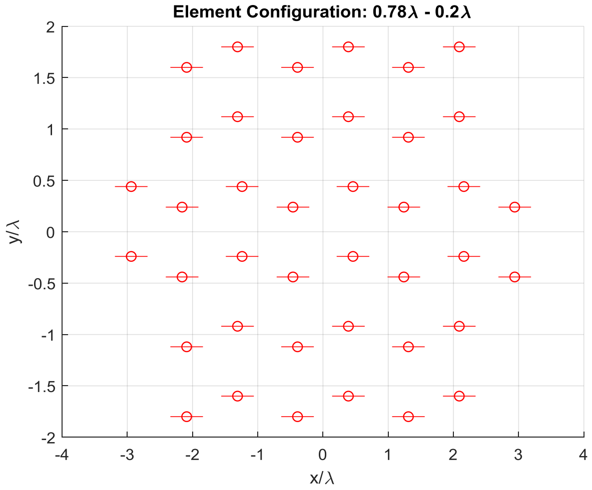
$$\mathbf{J}=\begin{pmatrix} J_{\theta\theta} & J_{\theta\varphi} \\ J_{\theta\varphi} & J_{\varphi\varphi}\end{pmatrix}$$

$$\mathbf{N}=\frac{1}{|\mathbf{J}|}\begin{pmatrix} J_{\varphi\varphi} & -J_{\theta\varphi} \\ -J_{\theta\varphi} & J_{\theta\theta}\end{pmatrix}$$

DRAGON Array Example - SNR=0 dB







Adaptive Waveform - Range and Doppler Accuracy

- The range and velocity accuracy depends on the waveform design and on the Signal to Noise Ratio (SNR)

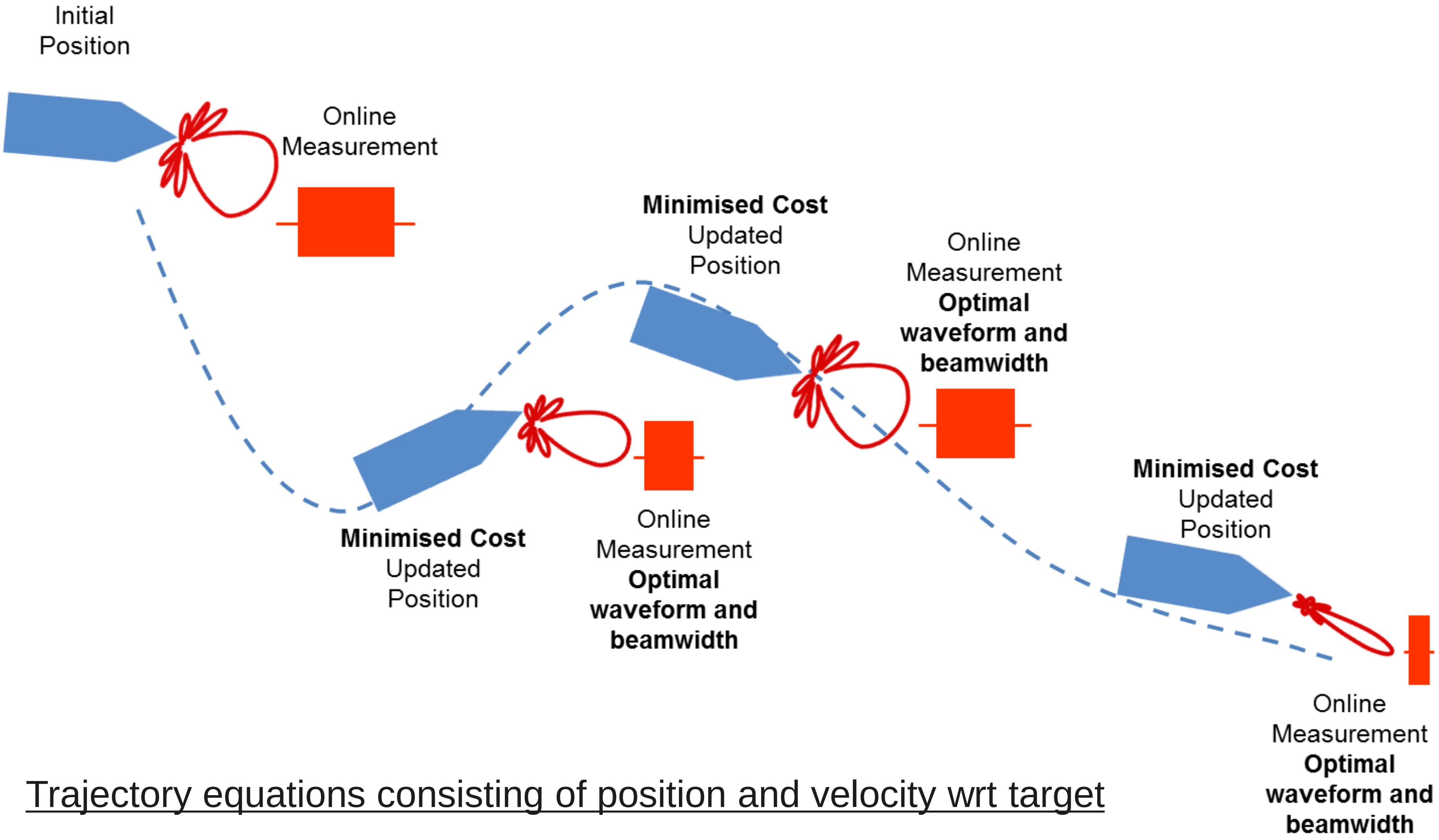
- The CRLB of the estimates $\mathbf{N}(\boldsymbol{\theta}_k)$ is the inverse of the Fisher Information Matrix (FIM) which can be expressed as,

$$\mathrm{FIM} = -\mathrm{SNR}\begin{pmatrix} \frac{4}{c^2}\frac{1}{2}\frac{\partial^2|\chi(\tau,\nu;\boldsymbol{\theta}_k)|^2}{\partial\tau^2} & \frac{4}{c\lambda}\frac{1}{2}\frac{\partial^2|\chi(\tau,\nu;\boldsymbol{\theta}_k)|^2}{\partial\tau\partial\nu} \\ \frac{4}{c\lambda}\frac{1}{2}\frac{\partial^2|\chi(\tau,\nu;\boldsymbol{\theta}_k)|^2}{\partial\nu\partial\tau} & \frac{4}{\lambda^2}\frac{1}{2}\frac{\partial^2|\chi(\tau,\nu;\boldsymbol{\theta}_k)|^2}{\partial\nu^2} \end{pmatrix}\Bigg|_{\tau,\nu=0}$$

where, $\chi(\tau,\nu;\boldsymbol{\theta}_k)$ is the Complex Ambiguity Function

$$\chi(\tau,\nu;\boldsymbol{\theta}_k) = \int_{-\infty}^{\infty} s(t;\boldsymbol{\theta}_k)s^*(t+\tau;\boldsymbol{\theta}_k)e^{j2\pi\nu t}dt$$

Control Design for Rendezvous



Trajectory equations consisting of position and velocity wrt target

$$x_{k+1} = A_k x_k + B_k u_k + v_k$$

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Control Design for Rendezvous

$$x_{k+1} = A_k x_k + B_k u_k + v_k$$

$y_k = C_k x_k + w_k$ → **Radar Measurement**

Optimal Guidance (LQG)

Linear Quadratic Regulator
(to generate control inputs according to objective)

Kalman Filter
(to optimally estimate the state from the measurement)

Waveform Design

Antenna Design

$$W_k = \mathrm{E}\{w_k {w_k}^T\} = \begin{bmatrix} \frac{c^2\lambda_G^2}{2SNR} & 0 & 0 & -\frac{c\lambda\lambda_G^2 b_G}{2\pi SNR} \\ 0 & \sigma_\theta^2 & 0 & 0 \\ 0 & 0 & \sigma_\psi^2 & 0 \\ -\frac{c\lambda\lambda_G^2 b_G}{2\pi SNR} & 0 & 0 & \frac{\lambda^2}{4\pi^2 SNR}\left(\frac{1}{2\lambda_G^2} + 2\lambda_G^2 b_G^2\right) \end{bmatrix}$$

During measurement the estimation filter is updated and the waveform design and antenna are optimized to minimize the cost

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Control Design for Rendezvous

Waveform Optimization: (2 approaches)

Fore-active Control
(minimize determinant of innovation covariance)

→ Control input and waveform/antenna are optimised independently

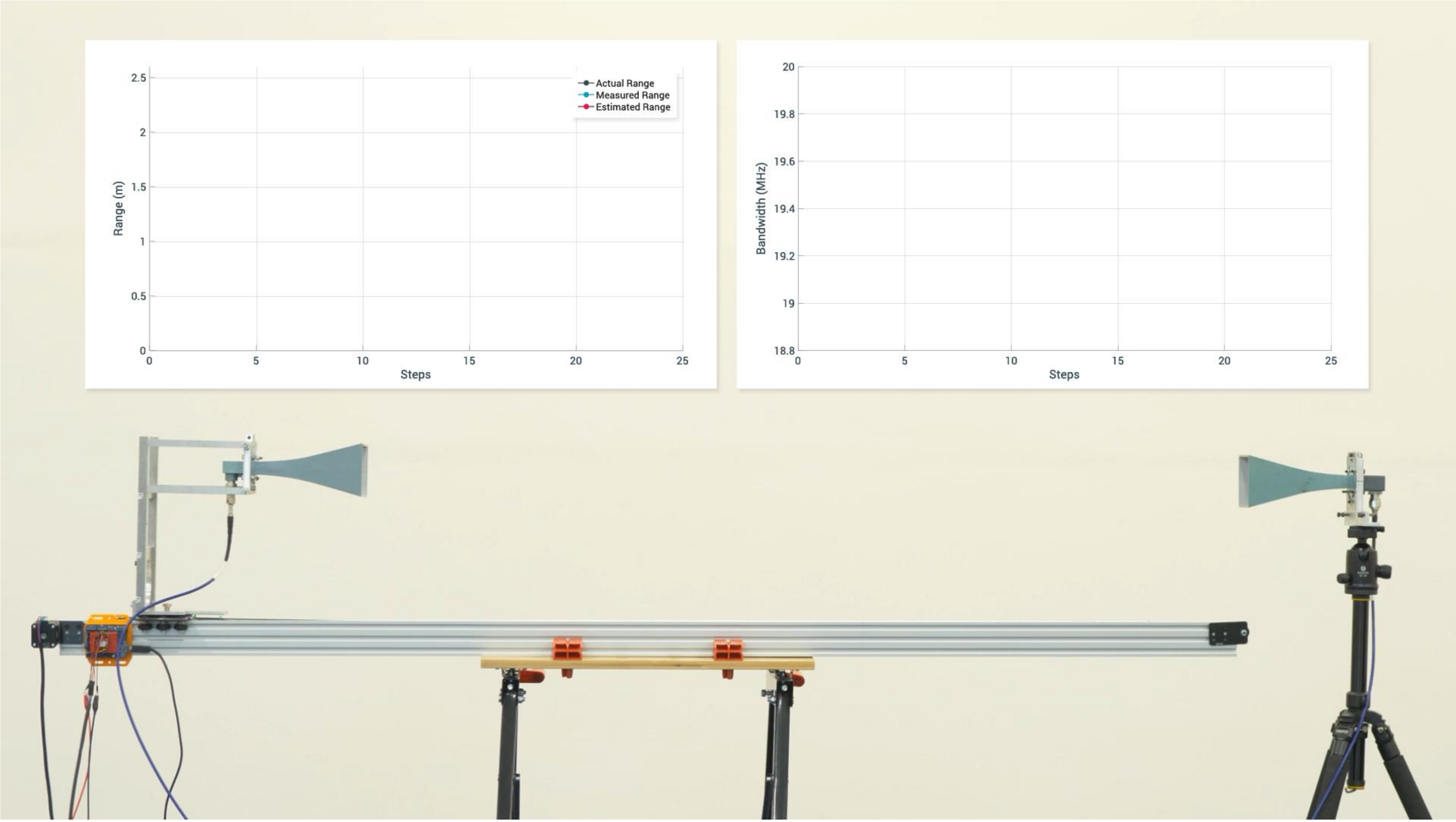
Balleri A, Farina A and Benavoli A, “Coordination of optimal guidance law and adaptive radiated waveform for interception and rendezvous problems”, *IET Radar, Sonar and Navigation*, vol. 11, no. 7, pp. 1132-1139, 2017.

JWGCO (Joint Waveform Guidance and Control Optimization)

→ Control input and waveform/antenna are optimised jointly (optimal solution)

Benavoli A, Balleri A and Farina A, “Joint waveform and guidance control optimisation for target rendezvous”, to appear in *IEEE Transactions on Signal Processing*, 2019.

Experimental Validation



Non-cooperative Surveillance

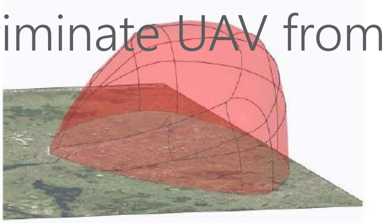
Aveillant Gamekeeper Radar Technology

- **Non-cooperative tracking**
  - Detects malicious targets
  - Detects infringement
  - Verifies cooperative data
  - Mitigates cooperative failures
  - Bridges the interoperability gap

Drone characteristics

- Small – 0.05 to 0.01 m^2
- Flying at low altitude
- Low speed & erratic flightpath

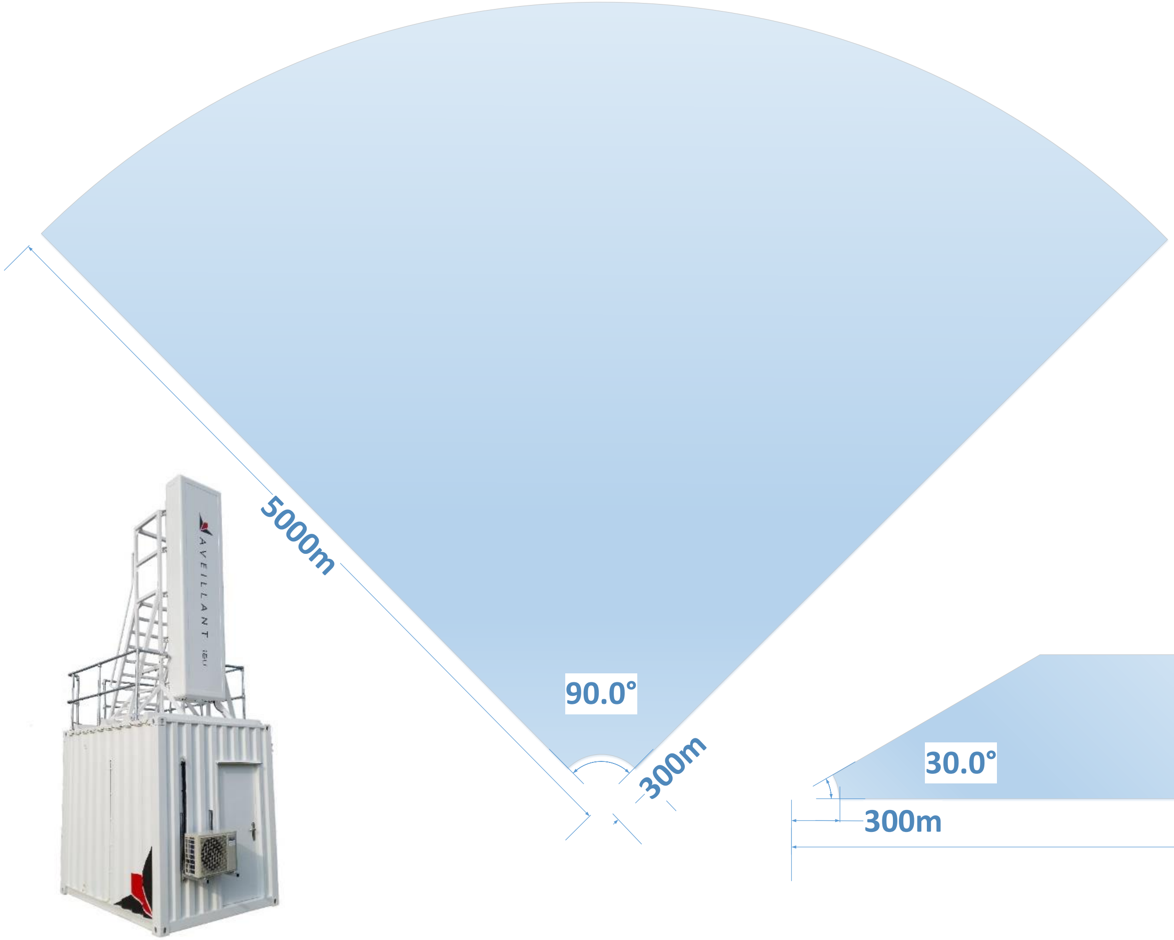
- **Gamekeeper staring Radar**
  - “Floodlights” a volume of interest on transmit
  - Forms multiple simultaneous receive beams
  - Non scanning so it can continuously monitor multiple targets.
  - Enables track creation despite erratic flightpath
  - Time on target enables system to discriminate UAV from other objects (birds...)

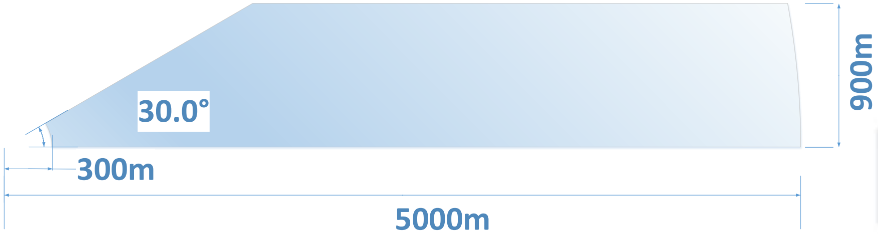


Gamekeeper 16U for C-UAS

Design parameters and approximate coverage pattern

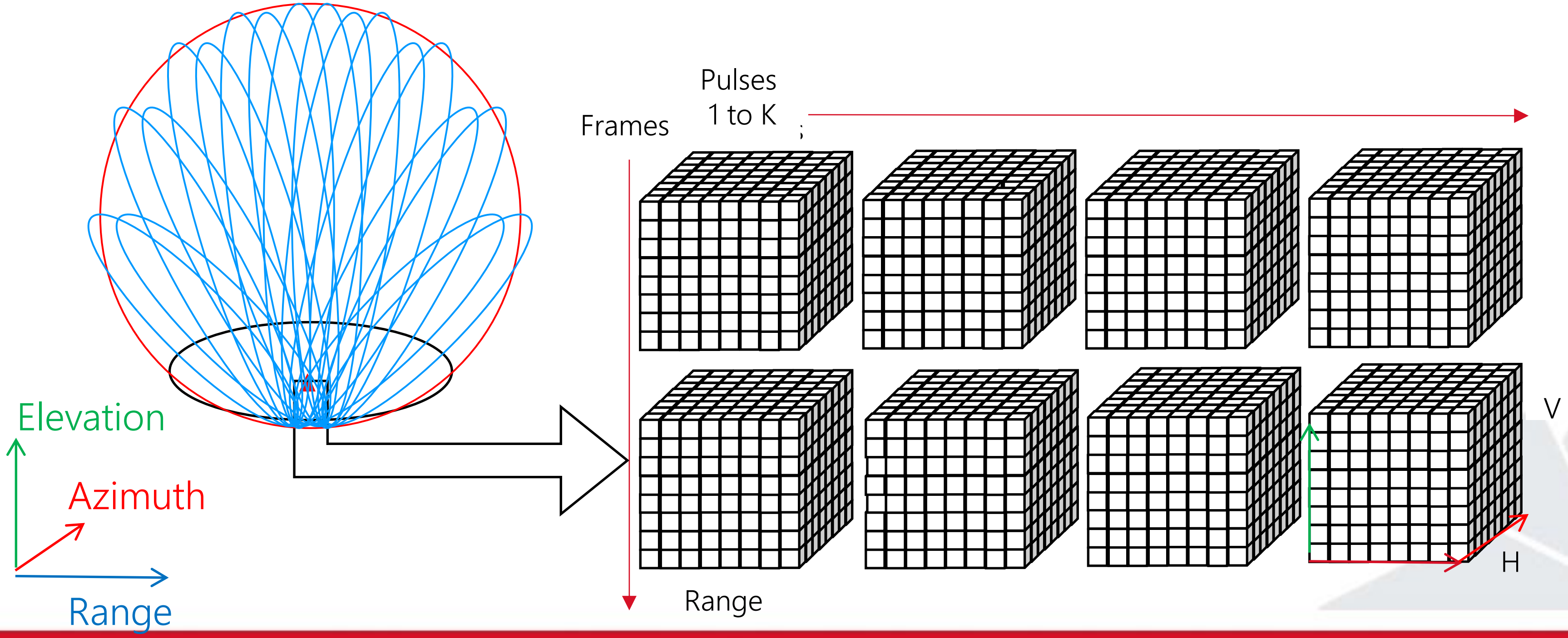
Name	Value
Maximum range	5km
Minimum range	300m
Azimuth field of view	90°
Maximum elevation angle	30°





Gamekeeper 16U – Raw Data view

- Multi-dimension Raw data space
  - Each pulse records 3-D data in range x channel horizontal x channel vertical
  - K pulses are combined to form a 4-D data matrix per frame
  - Doppler Detection is performed per frame using thresholding
  - Target association and tracking is performed using detections obtained from repeated frames



Gamekeeper 16U - Target centric view

SESAR CLASS Trials – Deenethorpe UK, Oct 2018

Heading

Height

Velocity

Acceleration

Jolt

Track Length

Understanding the environment

Geo-referencing the truth data

GPS

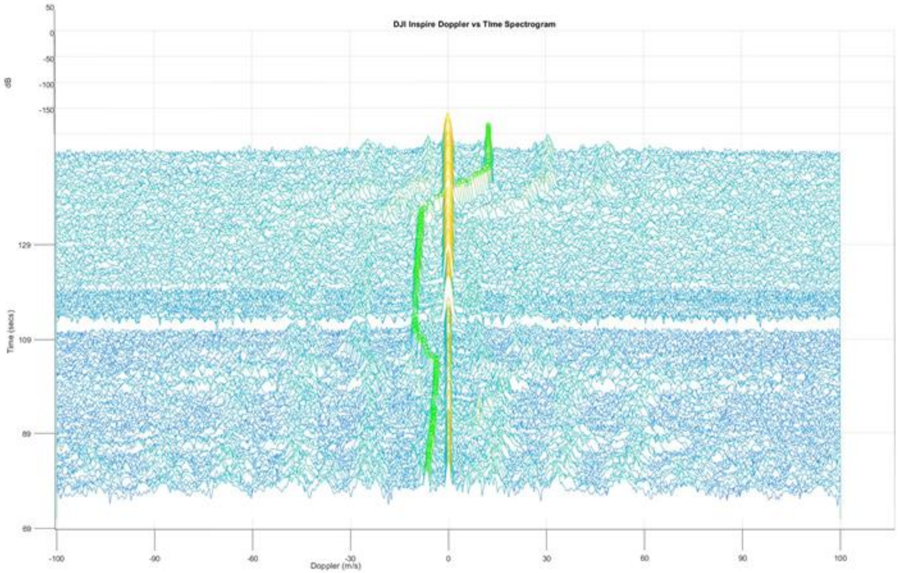
Photos

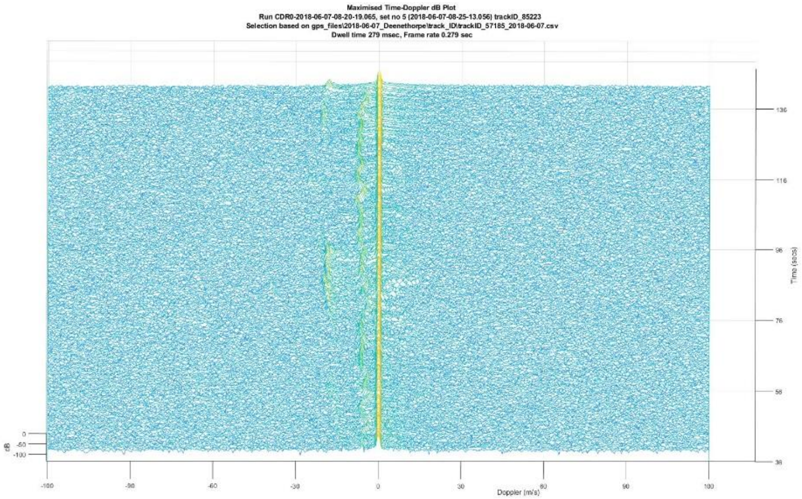
Logs

Understanding the sensor measurements

AVEILLANT
A Thales company

Micro-Doppler signatures





How to Classify ?

Supervised Learning Approach

Numerous small targets are present, placing high demand on operators.

✓ Apply a classification filter to display only targets of interest, e.g. sUAS.

Sets of salient features (micro-Doppler, height, track length, kinematics behavior, etc.) can be identified to assist differentiating between targets.

Classical classification (ML) task?

Yes, BUT

- Features are extracted from typically noisy (cluttered) raw data.
- Lack of complete tagged sets (simulated data is often not representative of real scenarios, especially impact of environmental factors).
- Features are intermittent (not available) all the time (e.g. micro-Doppler).
- Certainty requirements vary, depending on usage case.

Features

3 Classes of Features

- Position and Derivatives
- Statistical Analysis of a Feature
- Micro-Doppler and Other

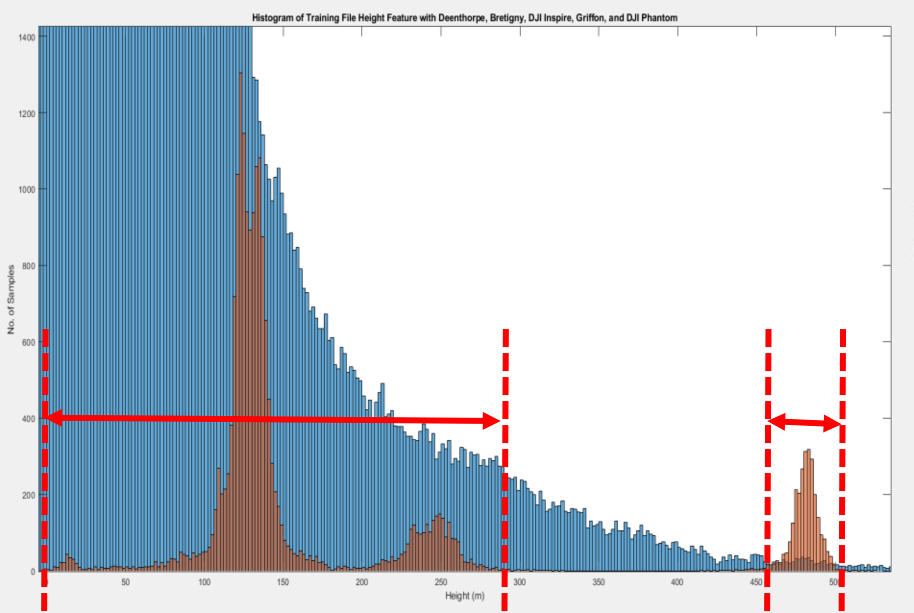
Combinations

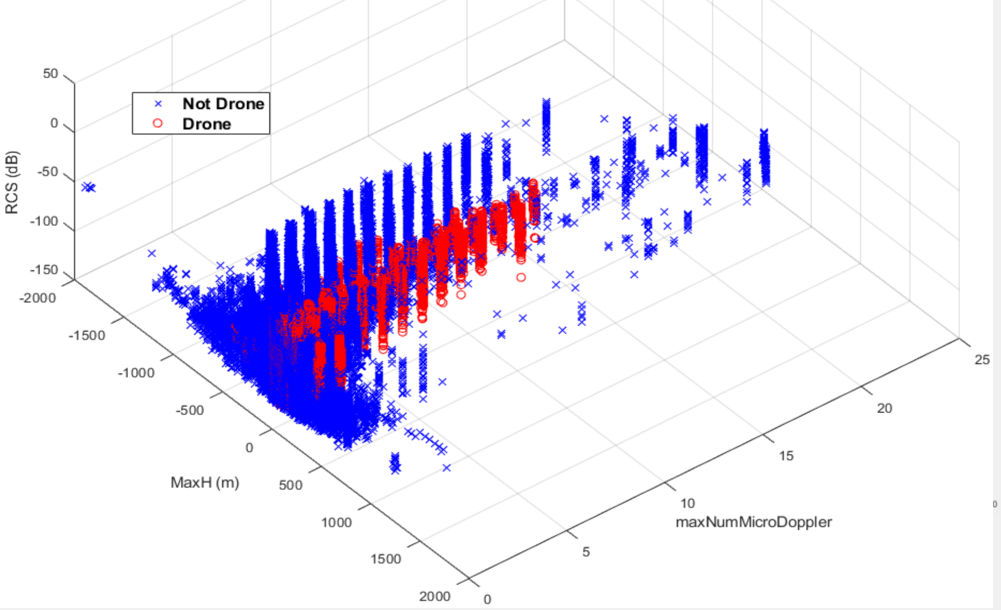
- Cases

- Z position
- Z velocity
- X-Y velocity
- X-Y-Z velocity
- Z acceleration
- X-Y acceleration
- X-Y-Z acceleration
- Z jerk
- X-Y jerk
- X-Y-Z jerk

- Max Z velocity
- Min Z velocity
- Max acceleration
- Max Heading Rate

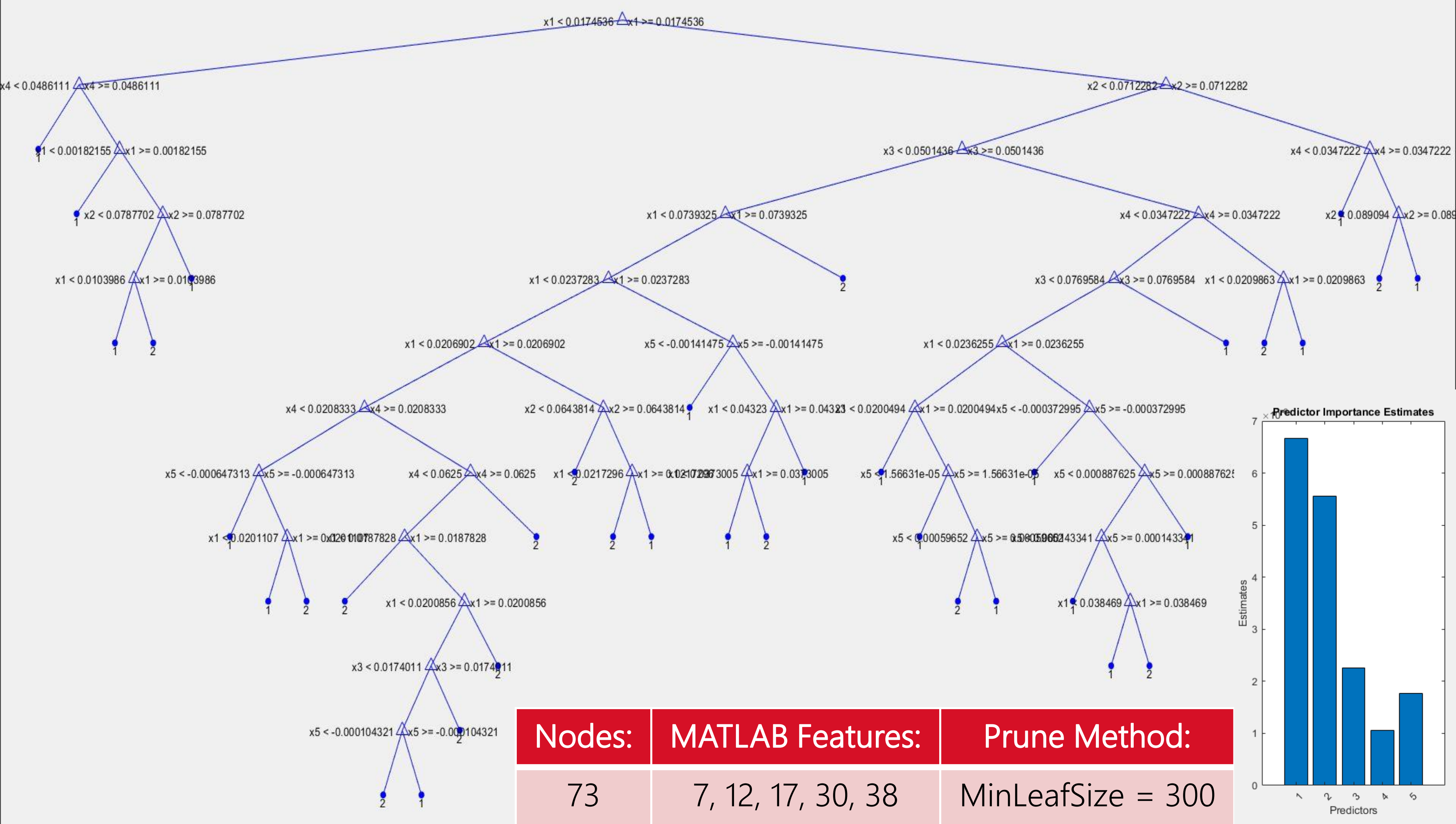
- Micro-Doppler
- Track Age
- RCS





Decision Tree Machine Learning

Trajectory and micro-Doppler features as input



Nodes:	MATLAB Features:	Prune Method:
73	7, 12, 17, 30, 38	MinLeafSize = 300

Gamekeeper – Real Data

SESAR CLASS Trials – Deenethorpe Oct 2018

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Thank you!

Questions?