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Leveraging physics-based simulations for Operational Analysis:

Task Group Air Defence Case Study

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NOTICE

(U) This document has been reviewed and DOES NOT CONTAIN controlled goods.

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Canada

Background: OA tasking to study Task Group Air Defence

- Late 2017 the Canadian Forces Maritime Warfare Centre (CFMWC) received an Operational Analysis (OA) tasking to study naval Task Group (TG) Air Defence (AD)

- CFMWC stakeholders:
  - Above Water Battlespace (AWB): expertise in Anti-Air Warfare (AAW) weapon systems, tactics and doctrine
  - Modelling and Simulation (M&S): provision of computing infrastructure and M&S expertise supporting the CFMWC battlespaces
  - Operational Research Team (ORT): 3 defence scientists supporting AWB, Underwater Battlespace (UWB) and Joint Technology and Innovation Battlespace (JITB)

- This presentations provides an overview of how physics-based simulations employed by M&S to support AWB are being used to underpin the TG AD OA study

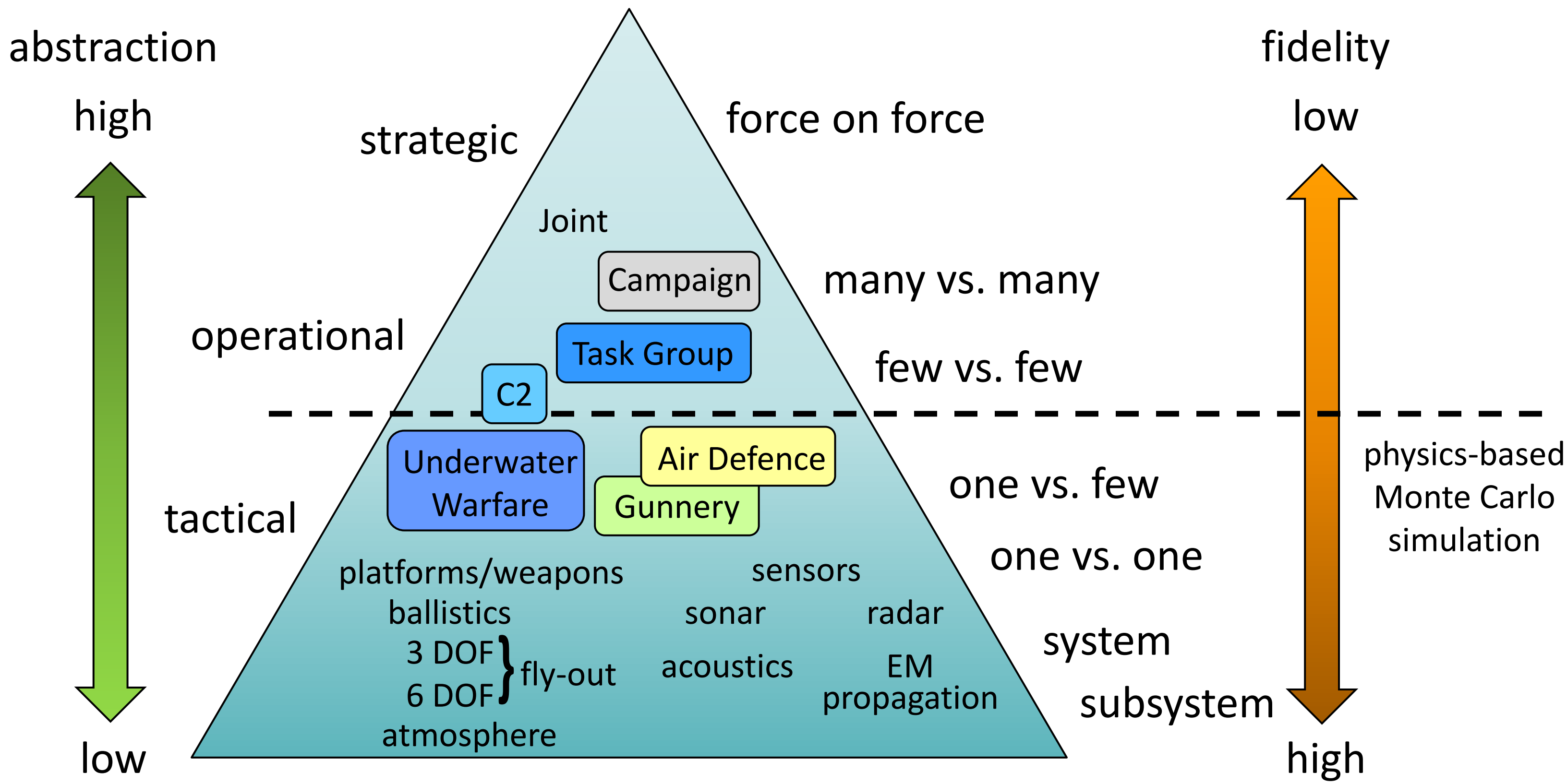
Acknowledgements to the officers and staff of CFMWC AWB,
M&S and ORT for their contributions through the TG AD study

Presentation Overview

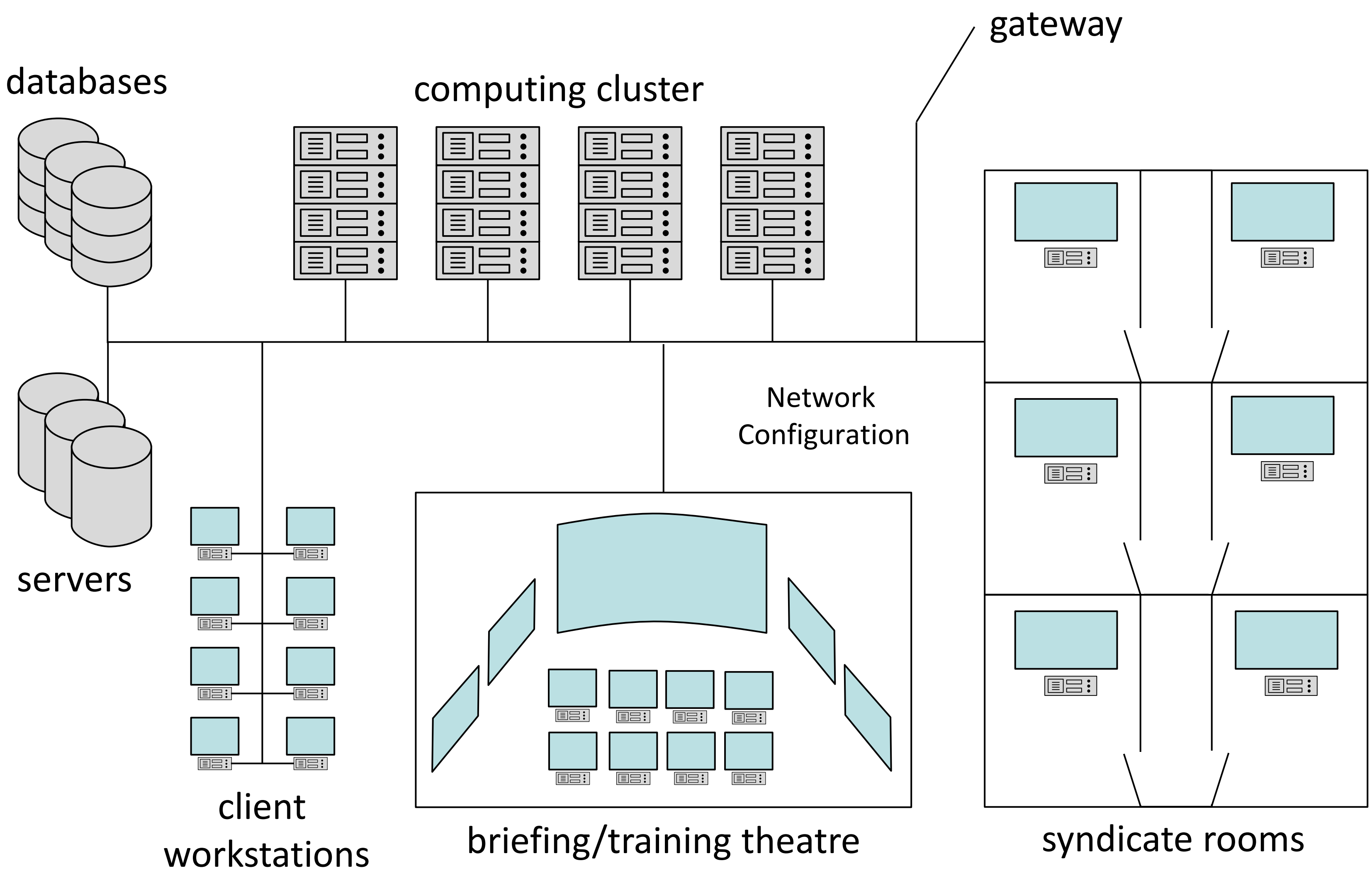
- Overview of CFMWC modelling and simulation capability
  - Modelling capability
  - Computing infrastructure
- Case Study: Task Group Air Defence
  - Study design considerations
  - Analysis approach
  - MEZ construction using physics-based simulations
  - Ship stationing analysis with illustrative results
- Summary with observations
- Concluding remarks

All data and examples shown are for illustrative purposes only and do not reflect actual systems.

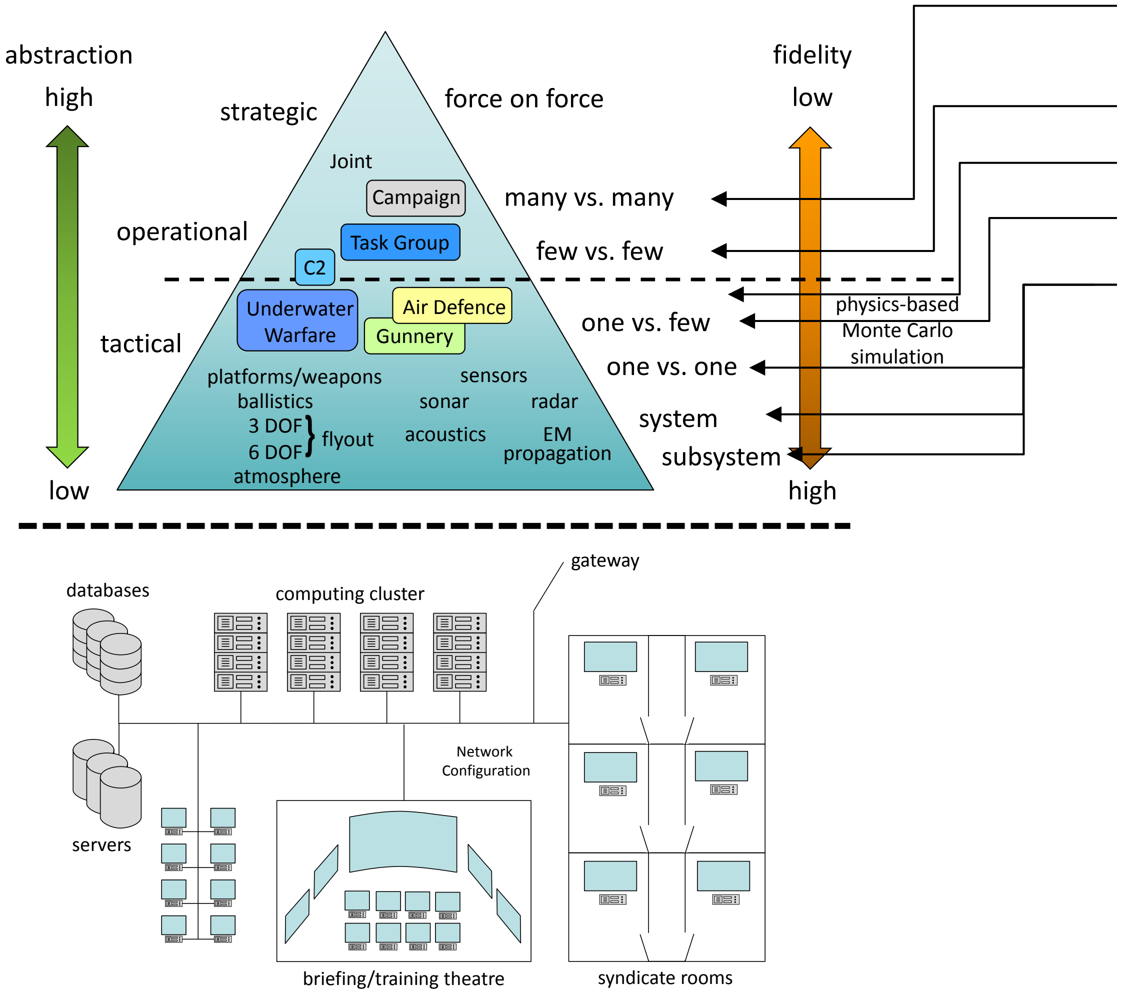
CFMWC modelling and simulation capability



CFMWC computing infrastructure



Industrialised M&S supporting the Royal Canadian Navy



- Applications:
  - Concept Development & Experimentation (CD&E)
  - Training
  - Tactics development
  - Doctrine development
  - Operational Test & Evaluation (OT&E)
    - Planning
    - Post-trial reconstruction and analysis
  - Requirements development & verification
  - *Operational Analysis*

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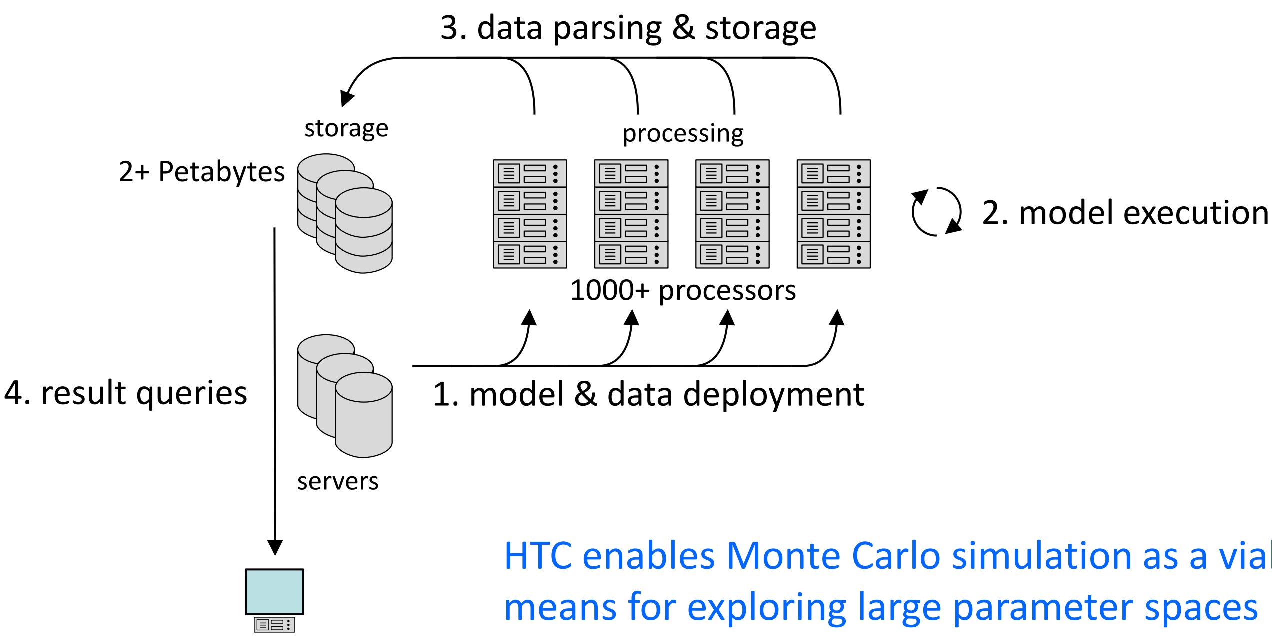
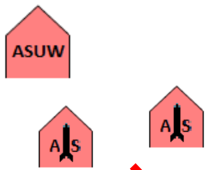
High Throughput Computing (HTC) for M&S



HTC enables Monte Carlo simulation as a viable means for exploring large parameter spaces using high fidelity models

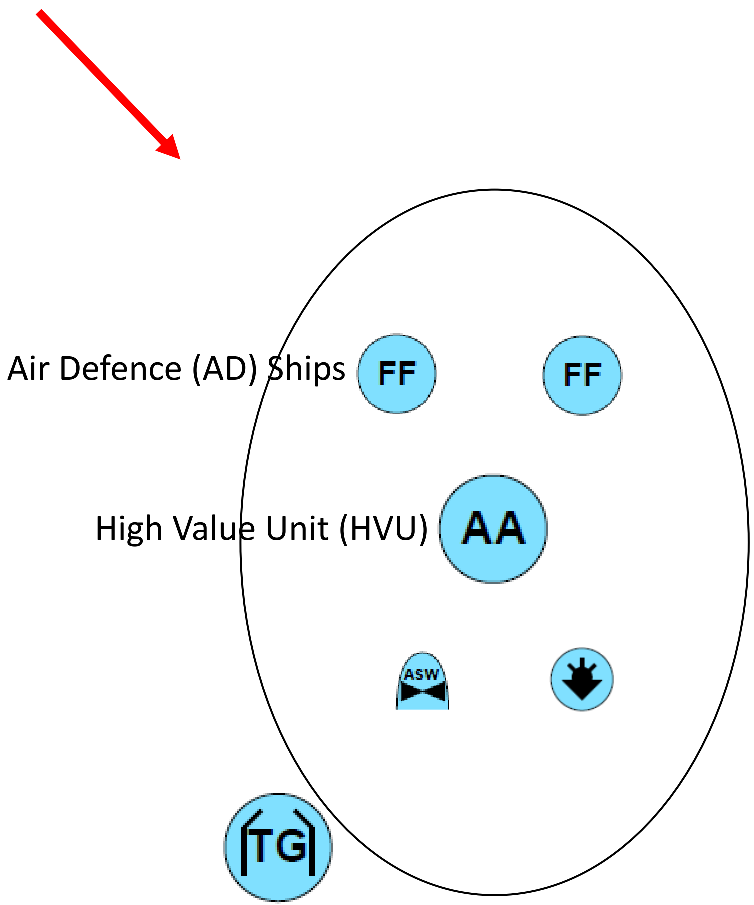
Parameter space dimensionality, run-time speeds and data management still provide limitations

Case Study: Naval Task Group Air Defence



Air threat

- Fighter Bomber
- Anti-Ship Missile (ASM)



Air Defences

- Long Range (LR) Surface-to Air Missile (SAM)
- Short Range (SR) SAM
- *Naval Gun*

Study design considerations

System /subsystem aspects

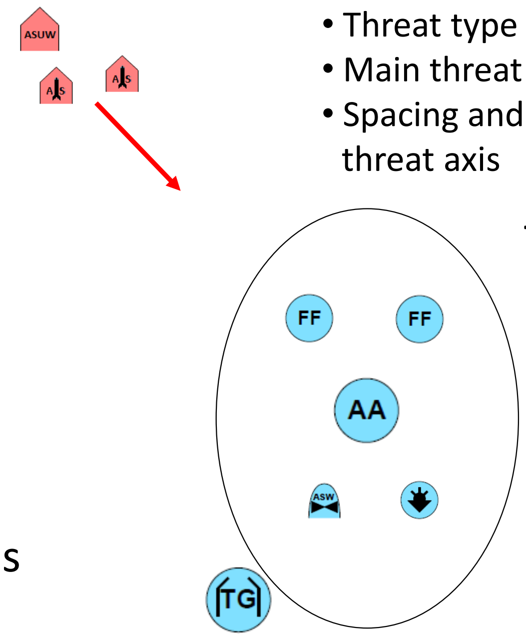
Threat
- Seeker
- Flight dynamics
- Signature
- Vulnerability

AD Ship
- Search radar
- Tracking radar
- SAM
  - Seeker
  - Propulsion
  - Flight dynamics
  - Warhead

Atmospheric conditions
- Temperature/Pressure
- Ducting
- Wind
- Water surface

Scenario / study aspects

Threat presentation
- Threat type and number
- Main threat axis
- Spacing and timing about threat axis



Task Group
- Numbers and types of ships
- AD ship capabilities
- C3I systems
- Mission
- Threat assessment
- Firing policies
- Ship stationing

Key metric: SAM expenditure to counter the threat raid (expressed as cost)

Use physics-based simulations to perform engagement assessments

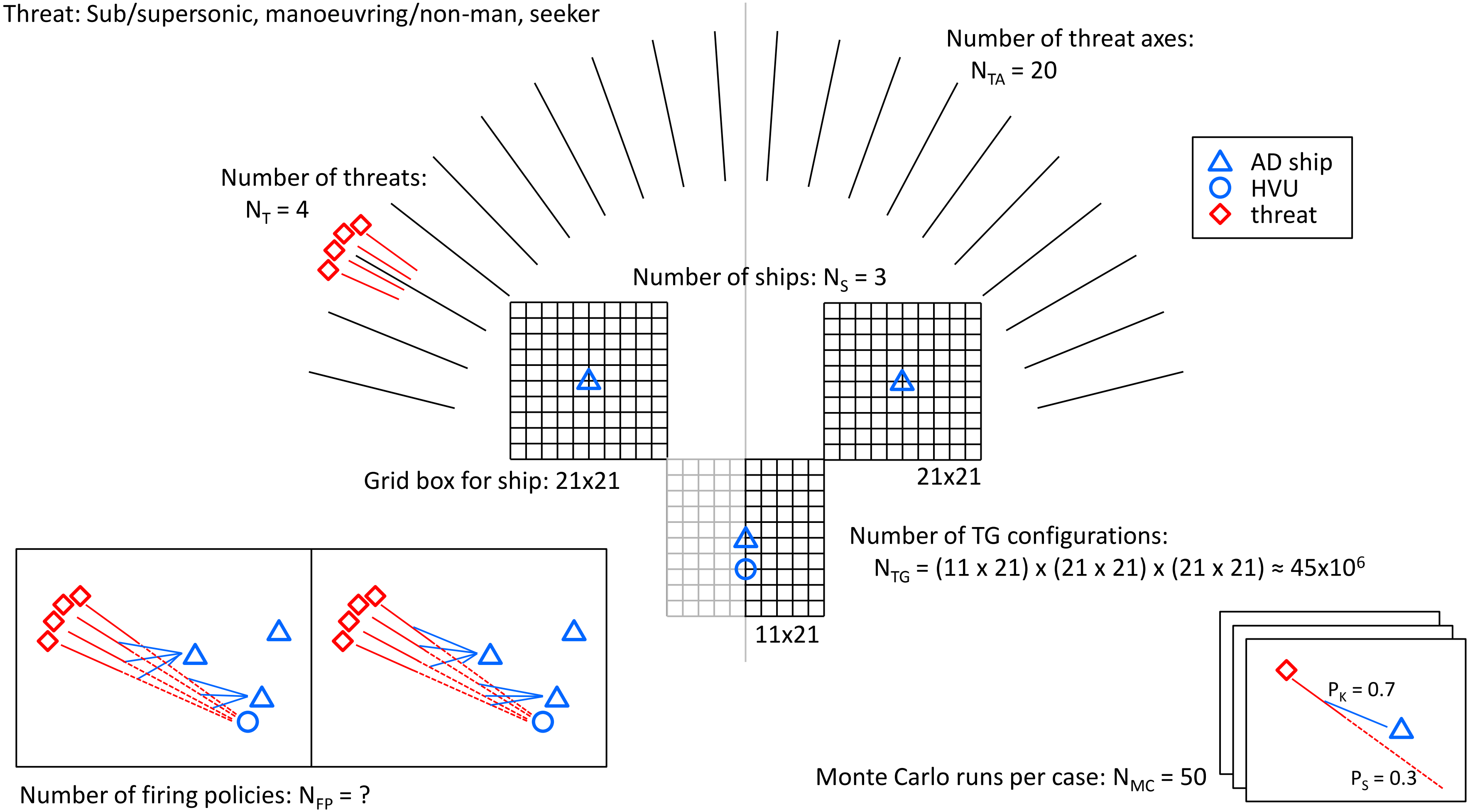
Use high level "OA" approach to analyse TG configurations

fidelity high

abstraction high

Problem parameter space

AD Ship configuration: radar, C3, LR SAM, SR SAM
Threat: Sub/supersonic, manoeuvring/non-man, seeker



Number of cases: $N_C = N_{TG} \times N_{TA} \approx 9 \times 10^8$

Number of runs: $N_R = N_C \times N_{MC} \approx 45 \times 10^9$

Number of engagements: $N_E = N_T \times N_R \approx 18 \times 10^{10}$

Excessive, even with HTC

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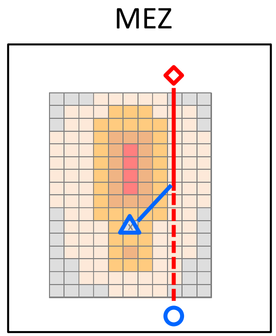
Analysis approach

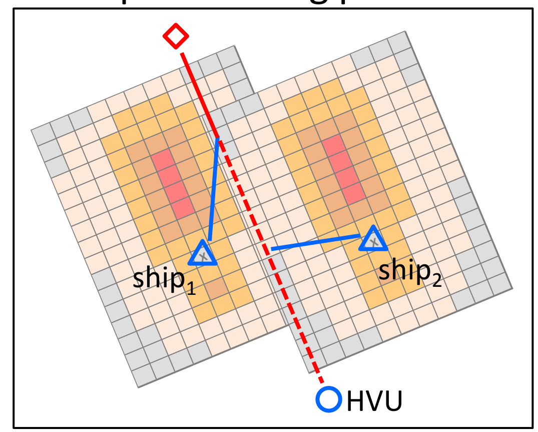
1. Use high fidelity simulations to construct Missile Engagement Zones (MEZs)

Air Defence Model
└── 6 DOF Missile Model

Commercial Monte Carlo simulation with integrated high fidelity models from DRDC and Allied partners

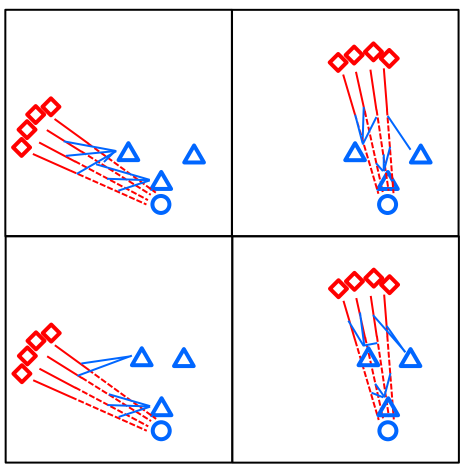


2.a Employ MEZs in a lookup manner to determine optimal firing policies

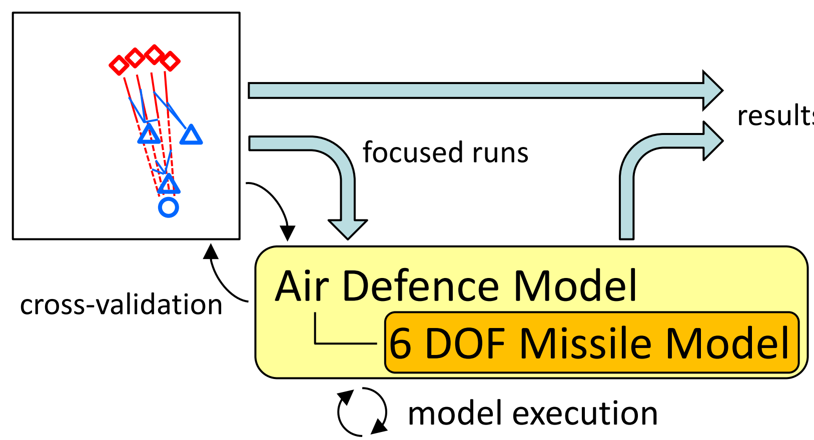


Coordinated AD: shoot$_1$ – look –shoot$_2$

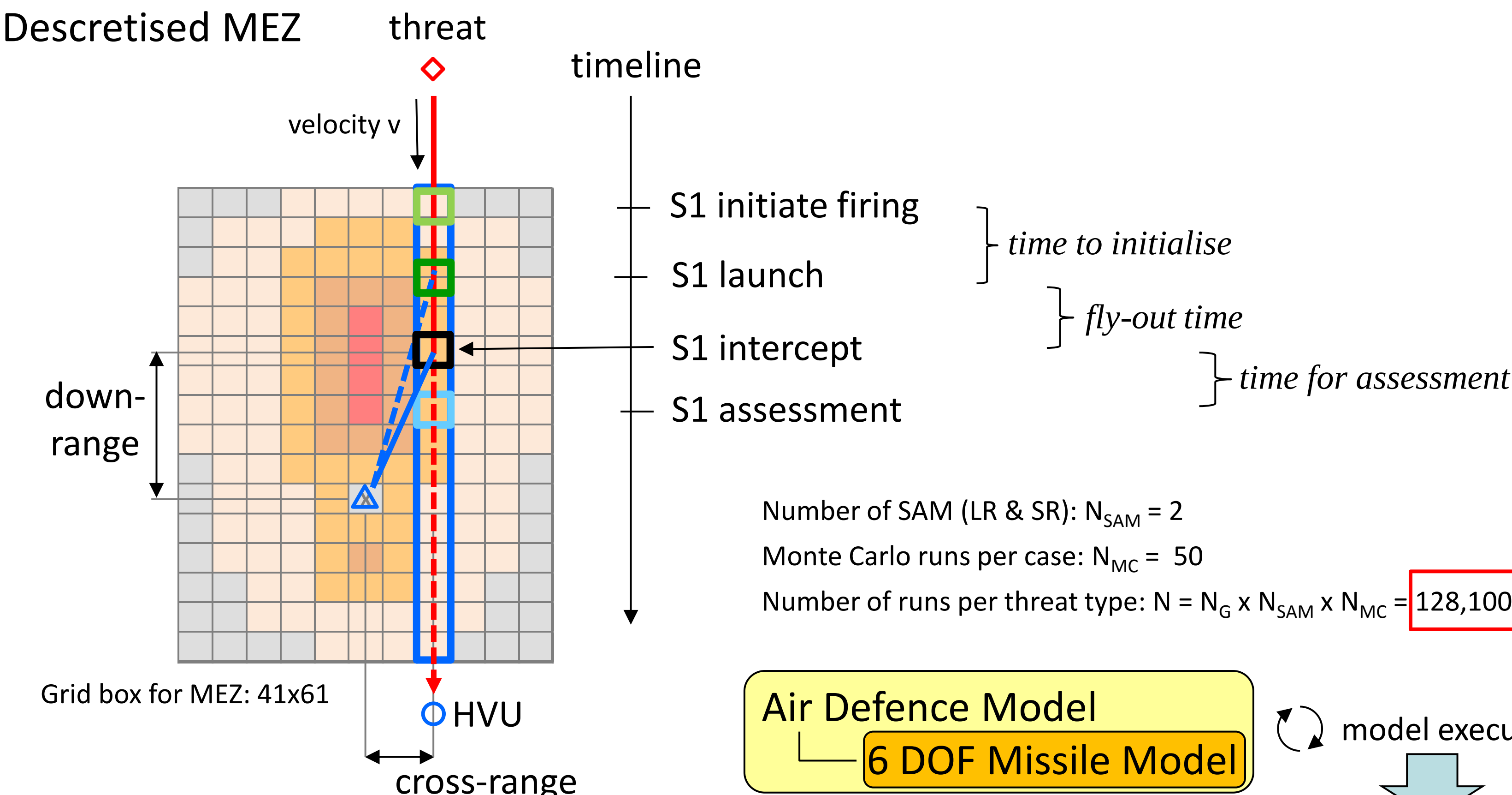
2.b Conduct ship stationing analysis



3. Cross-validate results with and perform focused runs using high fidelity simulations



Step 1. MEZ construction using physics-based simulation

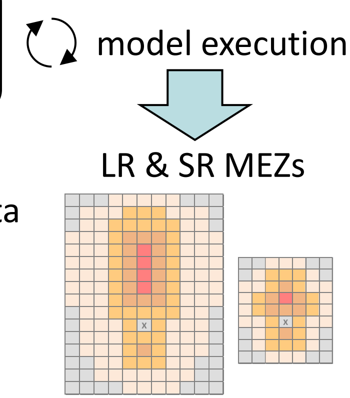


Number of SAM (LR & SR): $N_{SAM} = 2$

Monte Carlo runs per case: $N_{MC} = 50$

Number of runs per threat type: $N = N_G \times N_{SAM} \times N_{MC} =$ 128,100 *

Air Defence Model
└── **6 DOF Missile Model**



- 1 to 2 days for model execution
- 1 week turn-around, including data parsing and post-analysis

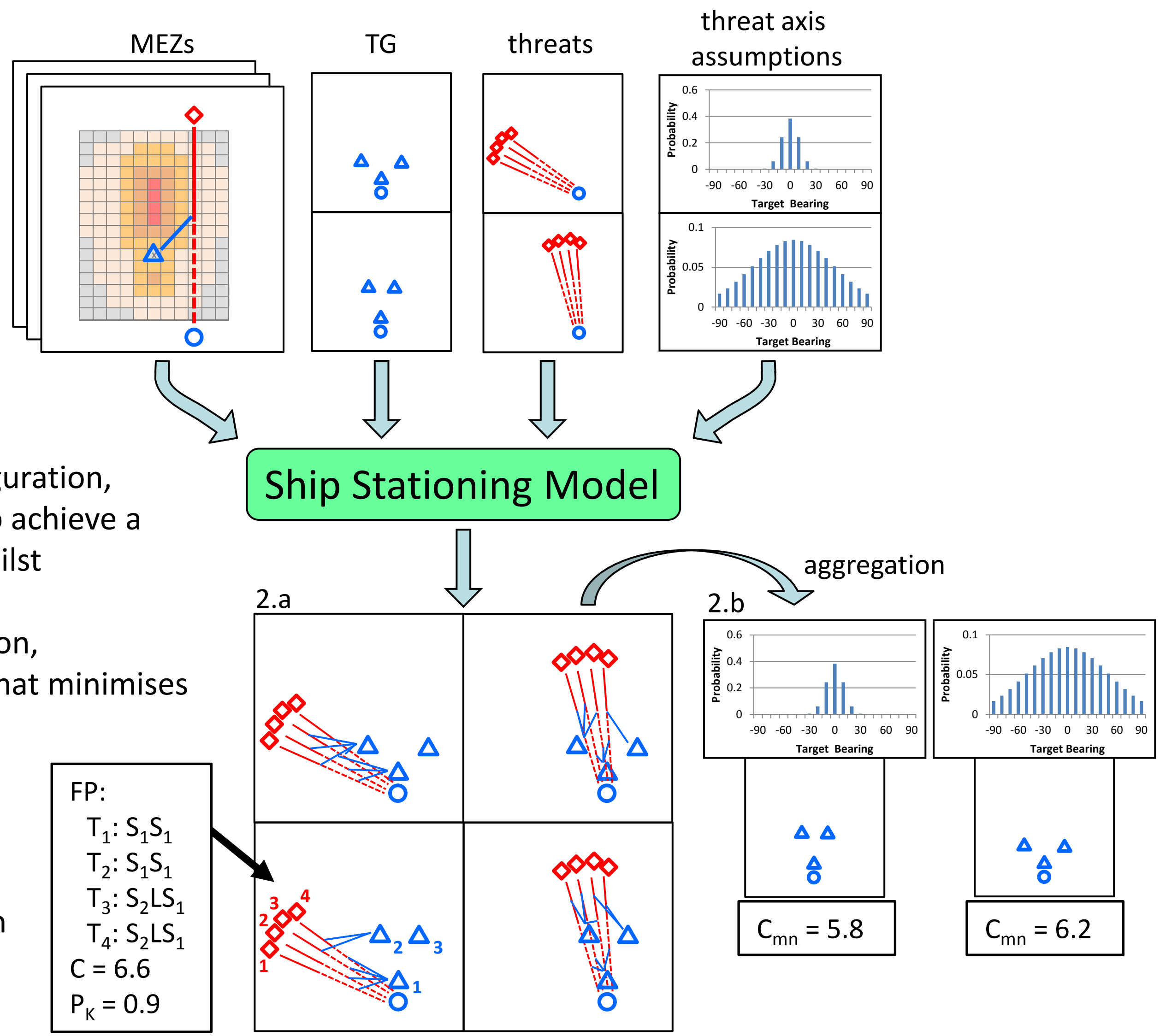
* Plus other factors: e.g. threat flight profile and ducting height

Step 2. Ship stationing analysis

Inputs
- SAM – threat MEZs
- Number of AD ships
- Number of threats
- Range of TG configurations
- Range of threat axes
- Threat axis assumptions
- Firing doctrine constraints
- AD coordination

Functionality
- 2.a For each threat axis/TG configuration, determine optimal firing policy to achieve a desired P_K against each threat whilst minimising SAM expenditure
- 2.b For each threat axis assumption, determine the TG configuration that minimises mean missile expenditure

Outputs
- Optimal firing policy for each threat axis/TG configuration
- Optimal TG configuration for each threat axis assumption



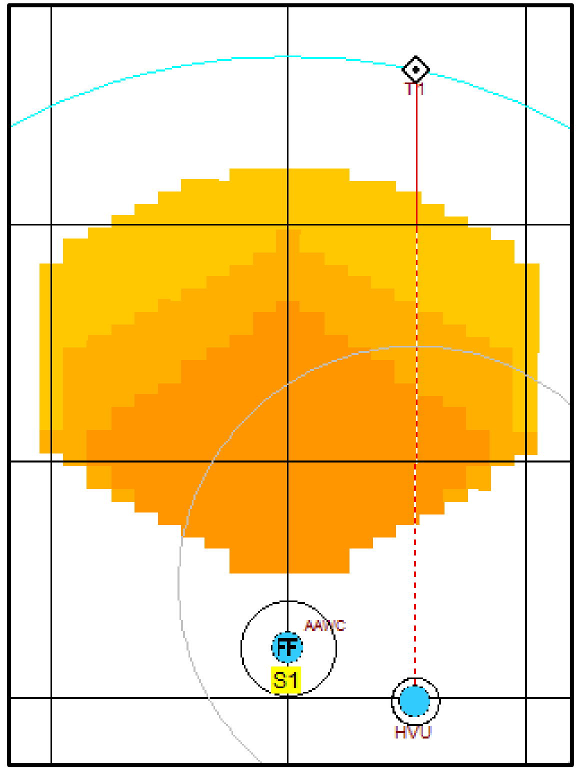
SSM showing illustrative MEZ for a crossing target

MEZ captures key aspects of a complete single shooter – single target engagement

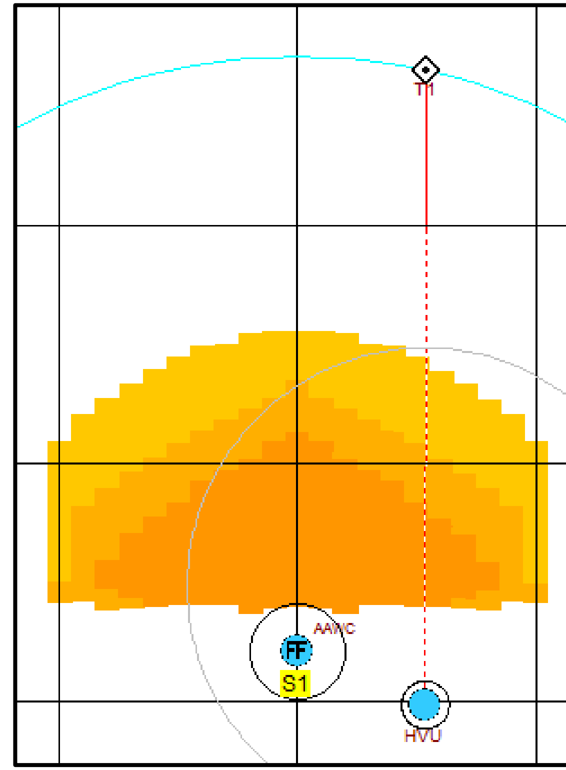
- Detection by a search radar
- Tracking by a fire control radar
- Launch and fly-out of the SAM with associated fly-out time
- Intercept of the SAM with the target with resultant single-shot P_K

MEZ dependencies

- Target type and flight profile (height & velocity)
- Search and tracking radar performance
- SAM guidance and flight capabilities
- SAM warhead effectiveness against the target
- Environment conditions (duct height, atmosphere)

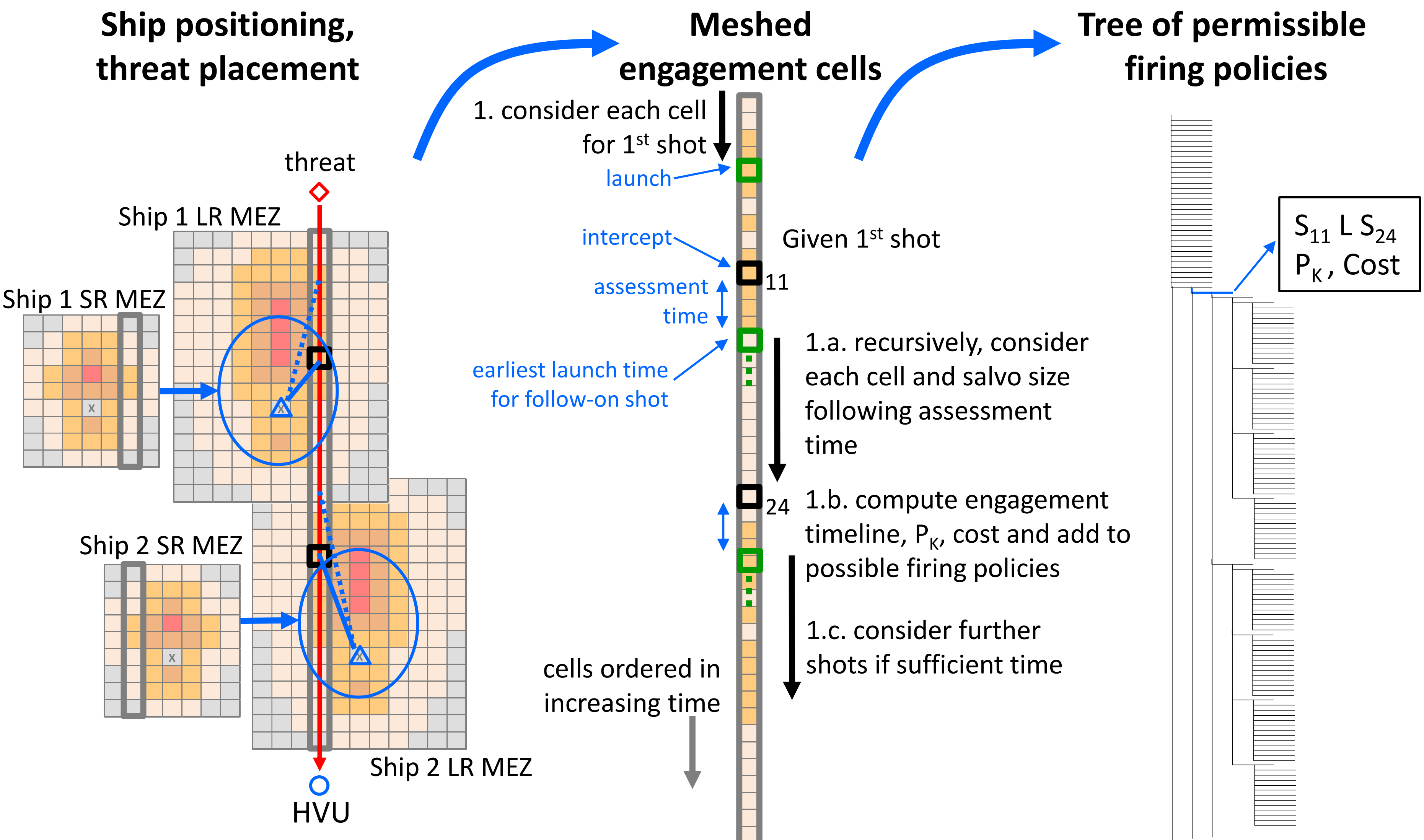


Launch points



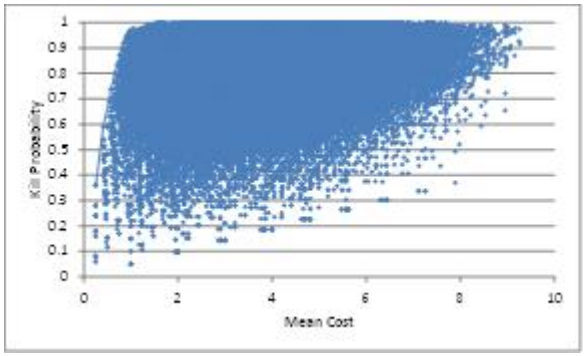
Intercept points

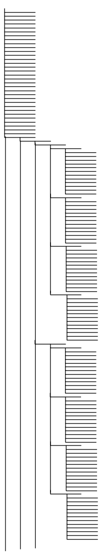
2.a Determination of optimal firing policies



Evaluation of firing policy tree to determine the Pareto Efficient Boundary (PEB) for PK vs. Cost

Complete tree

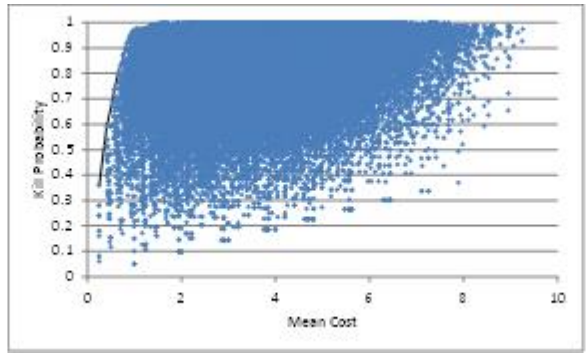




PEB determined after construction of complete tree

232876 nodes (firing policies)

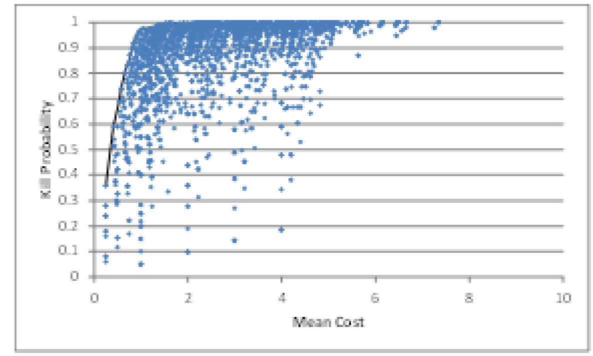
Leaf pruning

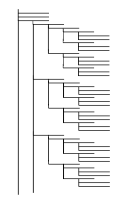


Pareto dominance condition applied during tree construction to prune leaf nodes

138027 nodes

Local pruning





Pareto dominance condition applied locally during tree construction to prune branch nodes

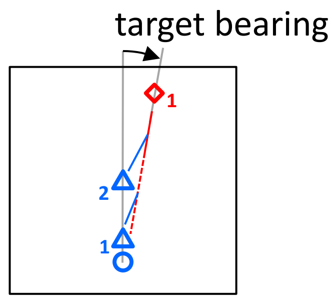
2792 nodes

Methodology

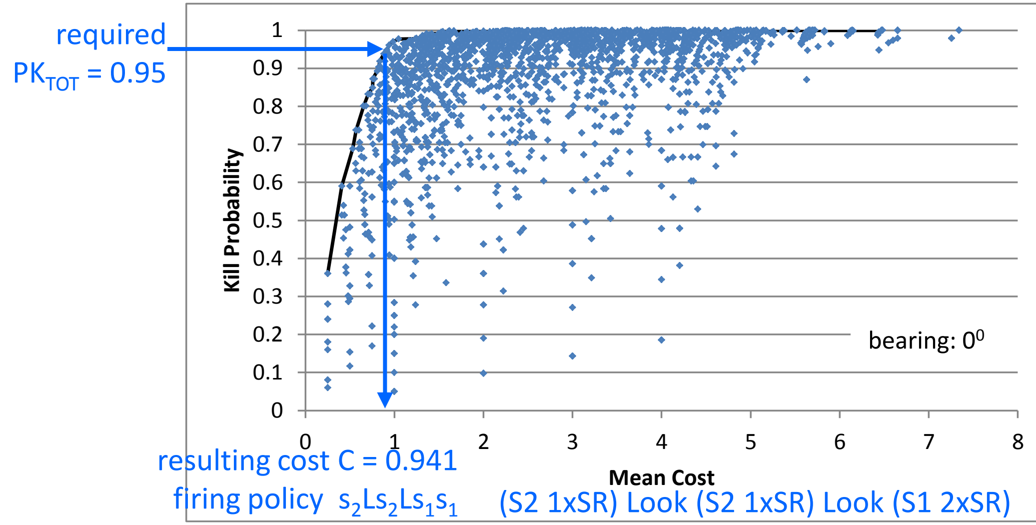
- Construct firing policy tree
  - Apply Pareto dominance condition at local branch level to confine tree growth
- Parse tree to determine PEB
  - Recursive algorithm to identify dominant firing policies

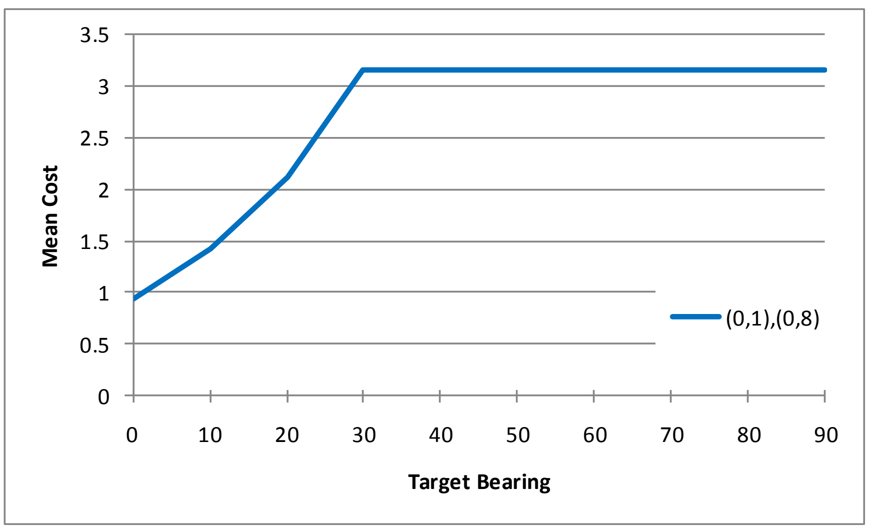
Graphs show Pareto Efficient Boundaries (PEB) for illustrative results, where solution points below and to the right are dominated by solutions on the boundary

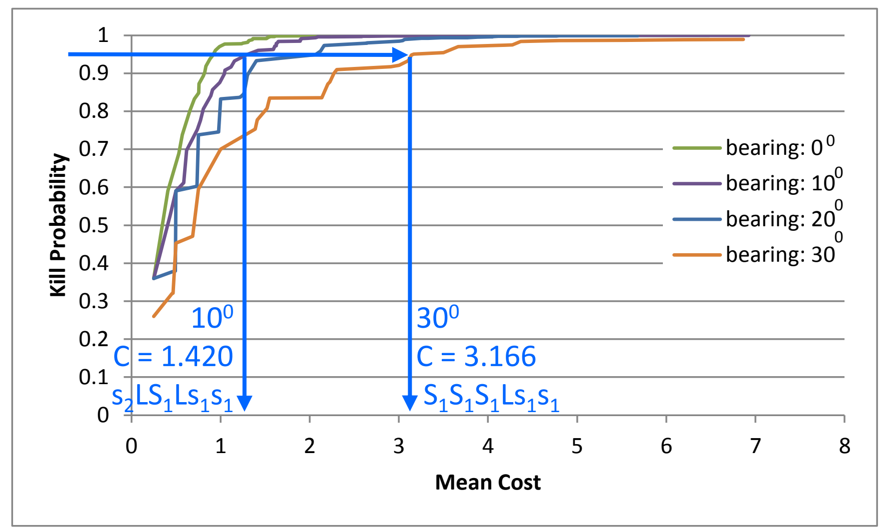
Optimal firing policy to achieve a desired PK : Solution for TG configuration 1



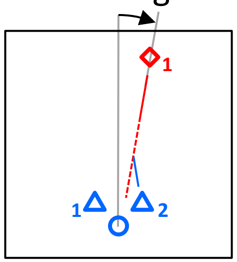
TG configuration 1
S1: (0,1), S2: (0,8)





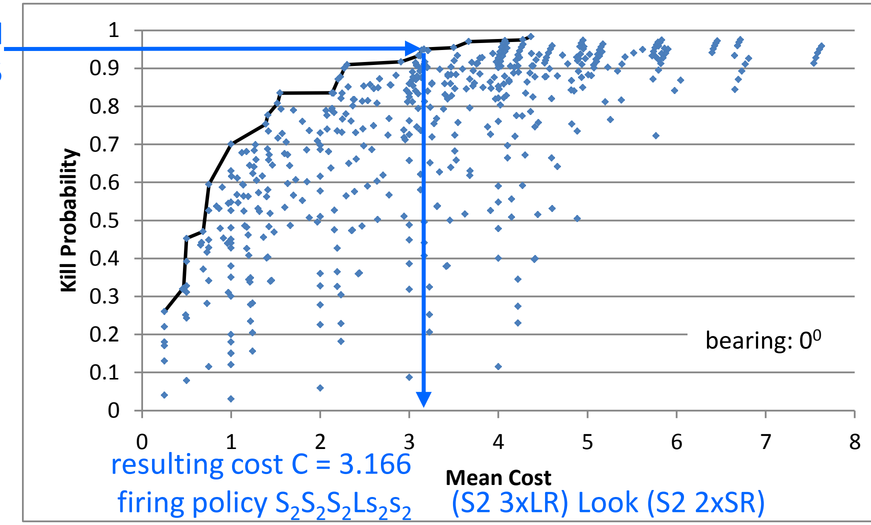


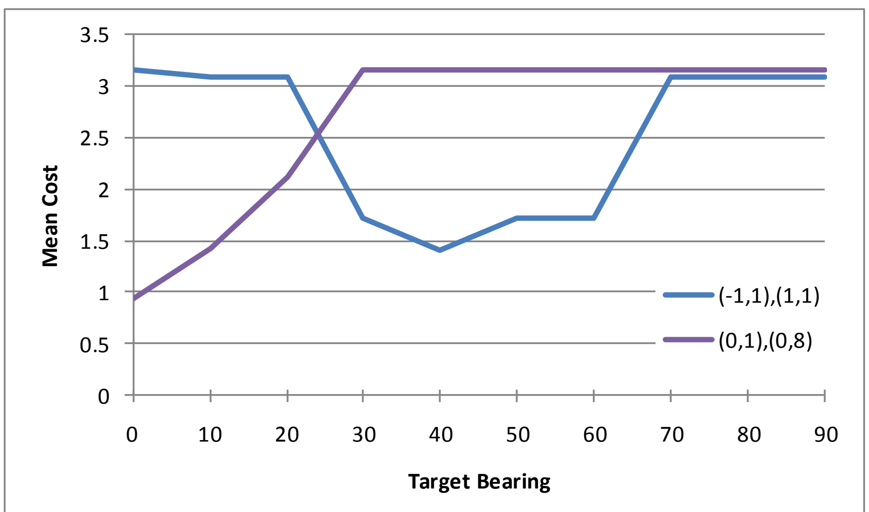
Optimal firing policy to achieve a desired PK: Solution for TG configuration 2

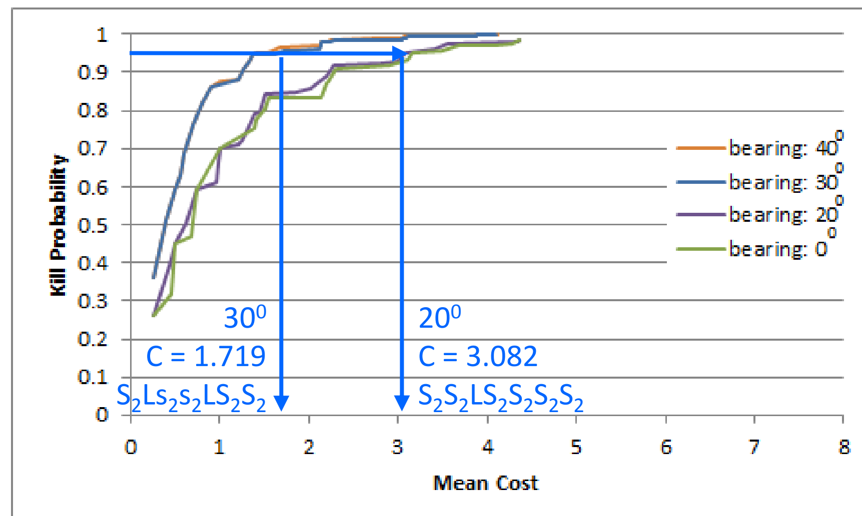


TG configuration 2
S1: (-1,1), S2: (1,1)

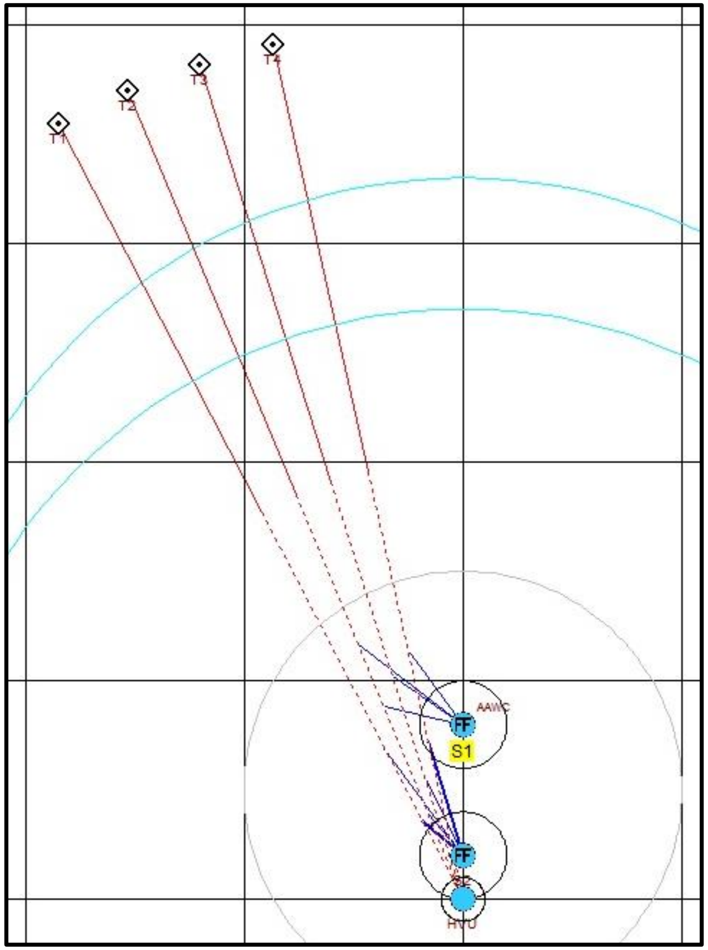
required
PK_{TOT} = 0.95



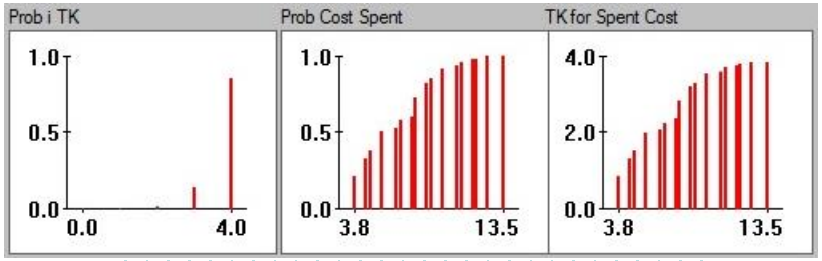




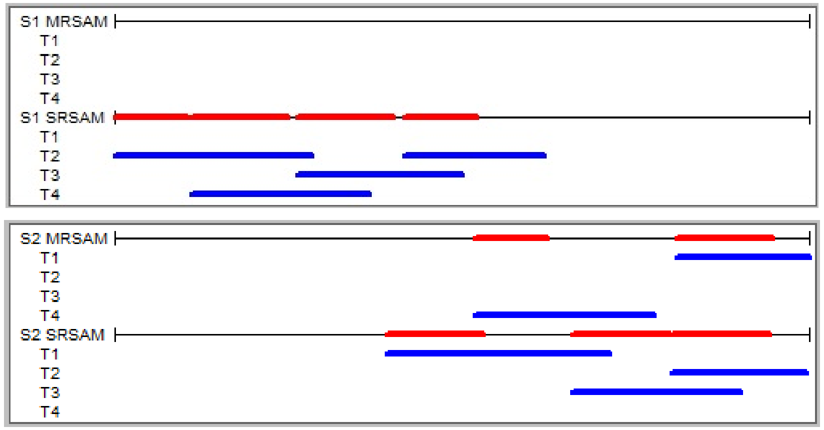
SSM showing illustrative threat raid engagement



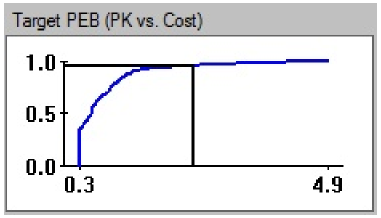
SSM can rapidly assess a single raid presentation (approx. 0.3 s for this scenario)



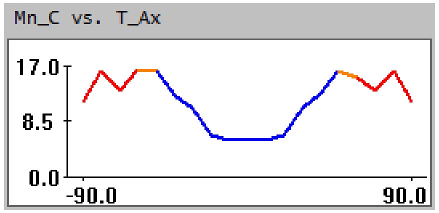
Metrics for main threat axis of -20^0



Launch and missile support schedule



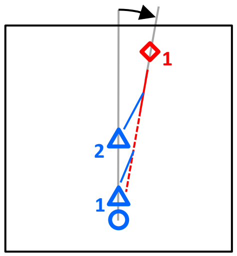
PEB for T1



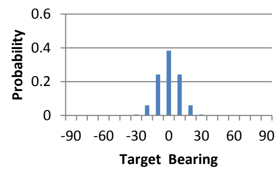
Cost as function of main threat axis angle

2.b Assessing TG configurations

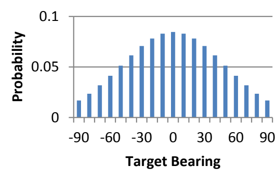
threat axis assumptions



TG conf. 1

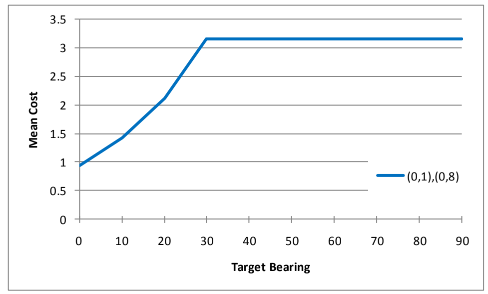


“narrow”



“wide”

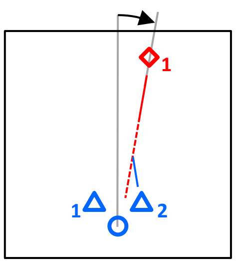
cost – target bearing results



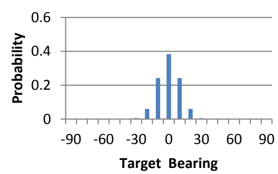
weighted mean cost

- **narrow: C_{narrow} = 1.34**
- wide: C_{wide} = 2.53

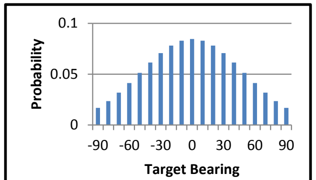
preferred TG configuration given threat axis assumption



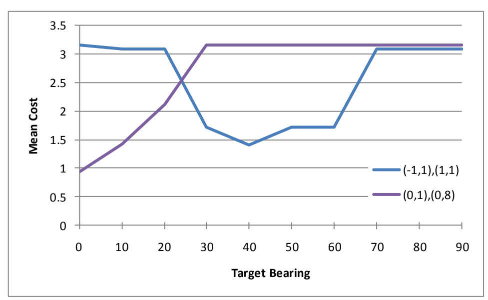
TG conf. 2



“narrow”



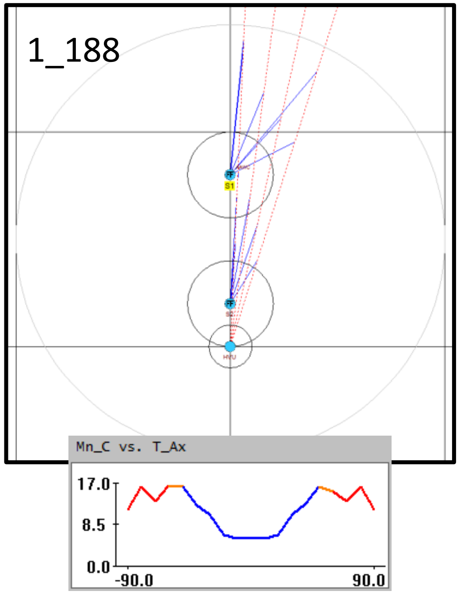
“wide”

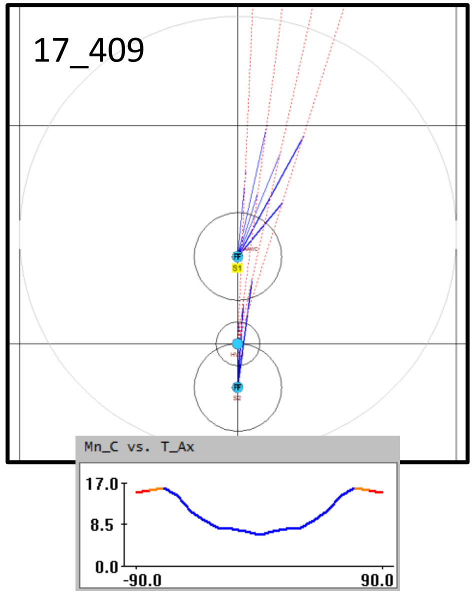


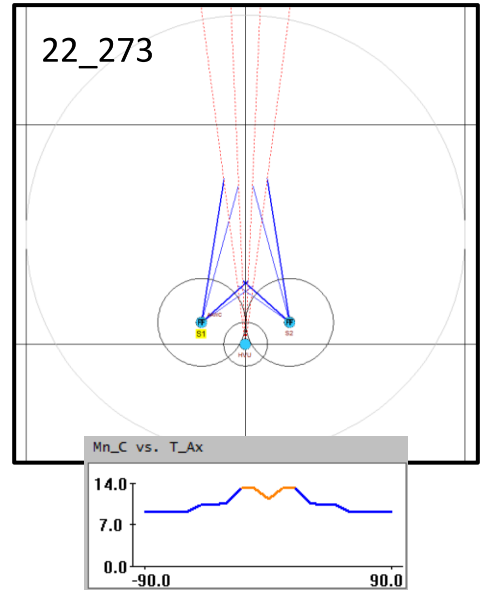
weighted mean cost

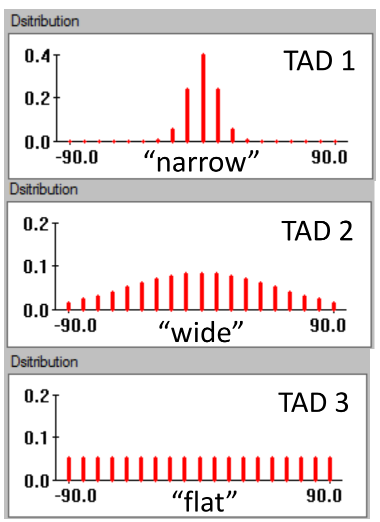
- narrow: C_{narrow} = 3.10
- **wide: C_{wide} = 2.44**

Illustrative SSM results for 3 TG configurations









Threat Axis Distributions (TAD)

RS Batch Mn_C aggregation over Threat Axis Distribution

BATCH_RUN	TAD	P_ARA	Mn_PK	Mn_C	Mn_TK
1_188	1	0.845	0.959	5.735	3.835
1_188	2	0.813	0.949	10.472	3.797
1_188	3	0.780	0.939	11.762	3.757
17_409	1	0.840	0.957	6.893	3.830
17_409	2	0.831	0.955	9.778	3.818
17_409	3	0.817	0.951	11.320	3.802
22_273	1	0.813	0.950	12.512	3.798
22_273	2	0.829	0.954	11.174	3.817
22_273	3	0.832	0.955	10.577	3.820

RS Batch Mn_C aggregation over Threat Axis Distribution

BATCH_RUN	TAD 1	TAD 2	TAD 3
1_188	5.735	10.472	11.762
17_409	6.893	9.778	11.320
22_273	12.512	11.174	10.577

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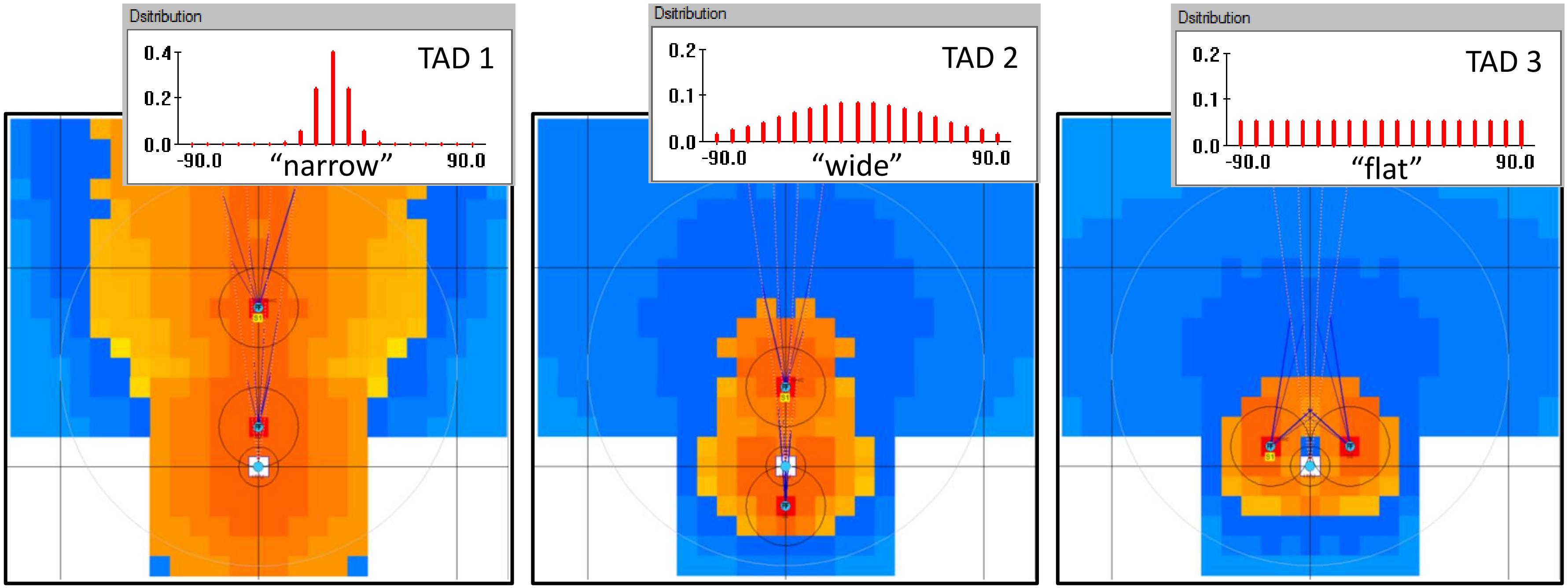
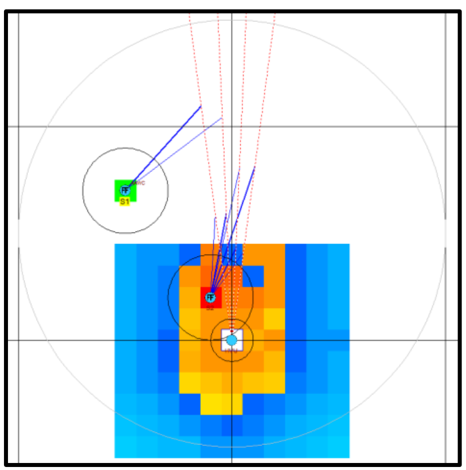
2.b Determining the optimal TG configuration to minimise missile expenditure

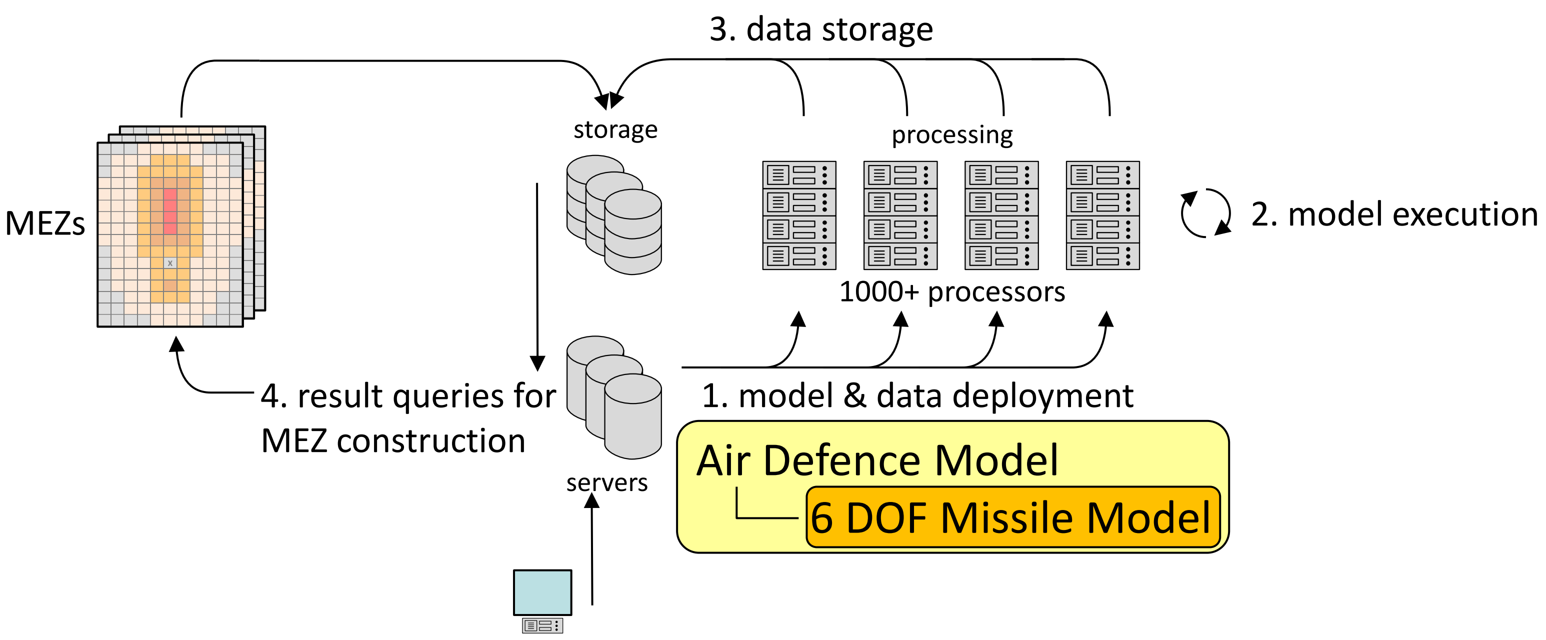


- Heat maps used to identify optimal ship locations given assumptions on the main threat axis
- Permits what-if analysis, e.g. if one ship’s location is fixed
- Production requires extensive number of TG configurations to be considered



What-if analysis: Revised heat map given S1‘s location fixed, TAD 1

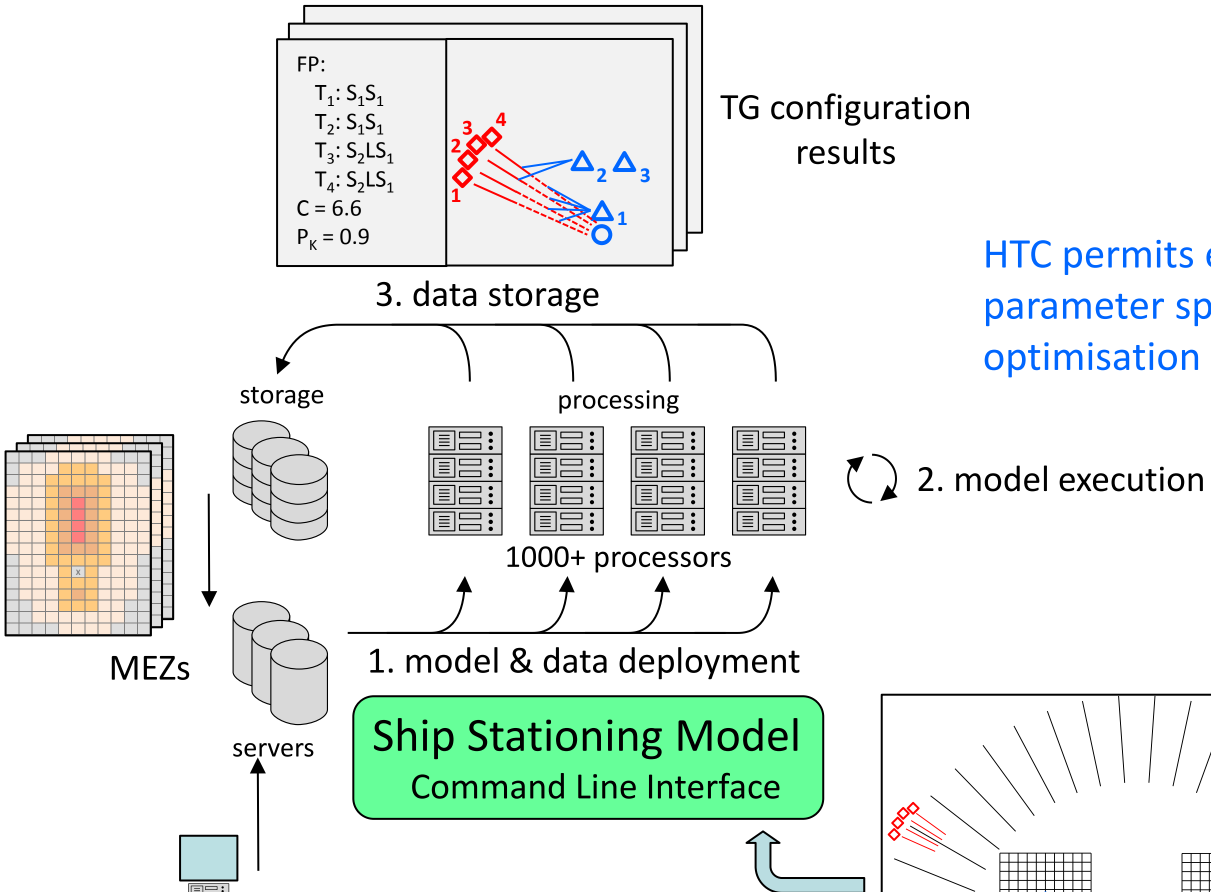
Summary: TG AD study
1. MEZ construction using physics-based simulations



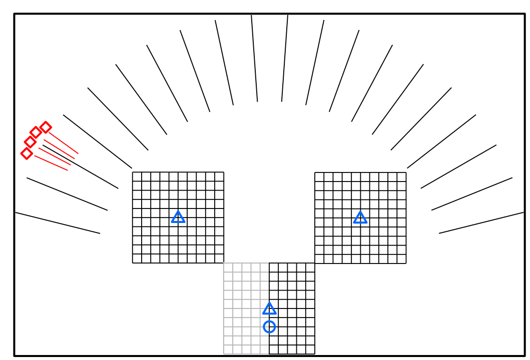
Each MEZ captures radar detection, tracking, SAM fly-out, intercept and endgame aspects of an engagement as represented in the physics-based simulations

- 1 to 2 days for HTC model execution
- 1 week turn-around, including data parsing and post-analysis

Summary: TG AD study
2. TG ship stationing analysis using MEZs



HTC permits extensive search of parameter spaces to support optimisation problems



Number of TG configurations:
N_{TG} = (11 x 21) x (21 x 21) x (21 x 21) ≈ 45x10^6

- 1 hour for HTC model execution of 10^5 configurations
- 1 day turn-around for data storage and post-analysis

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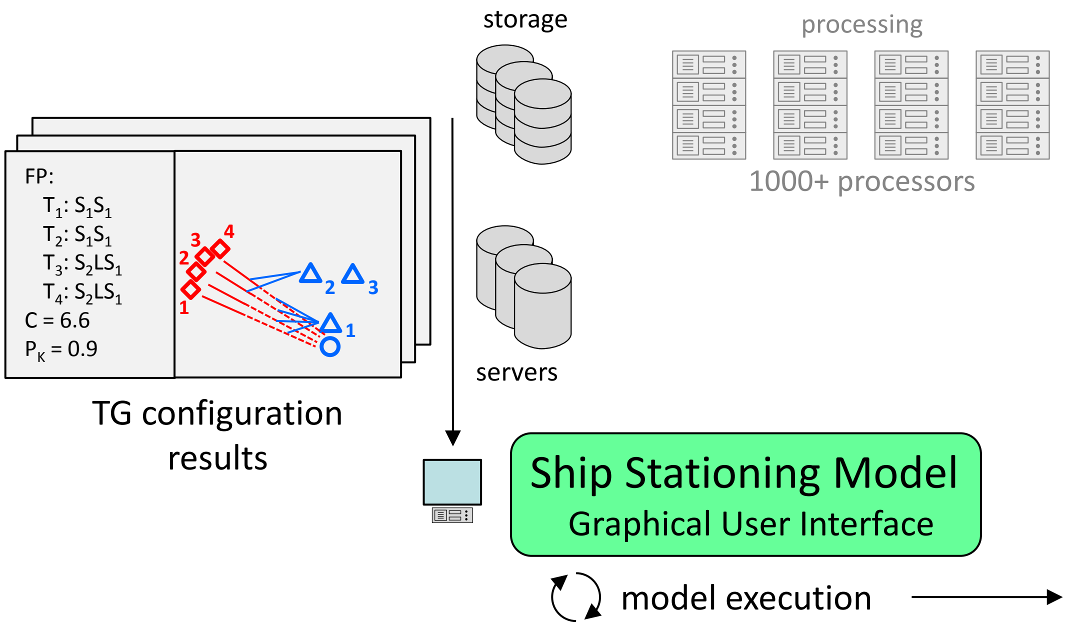
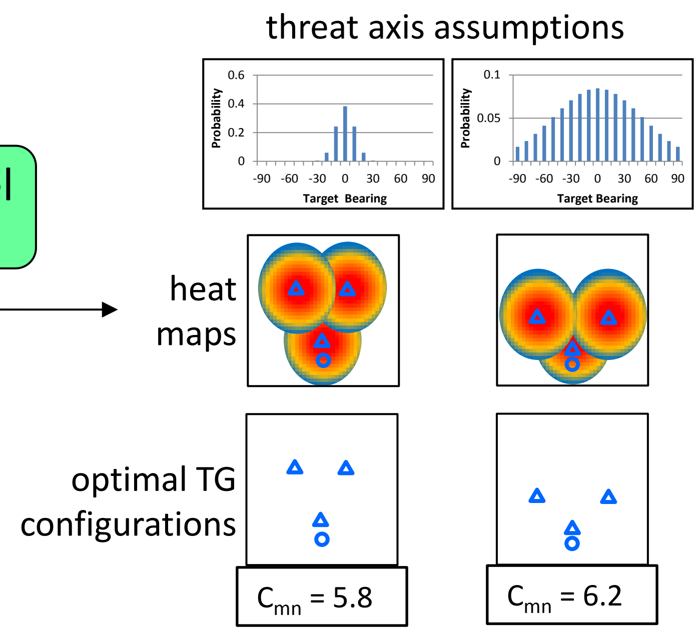
Summary: TG AD study
3. TG aggregated results





A simplified model, layered over and underpinned by physics-based simulations, can extend analysis to larger parameter spaces

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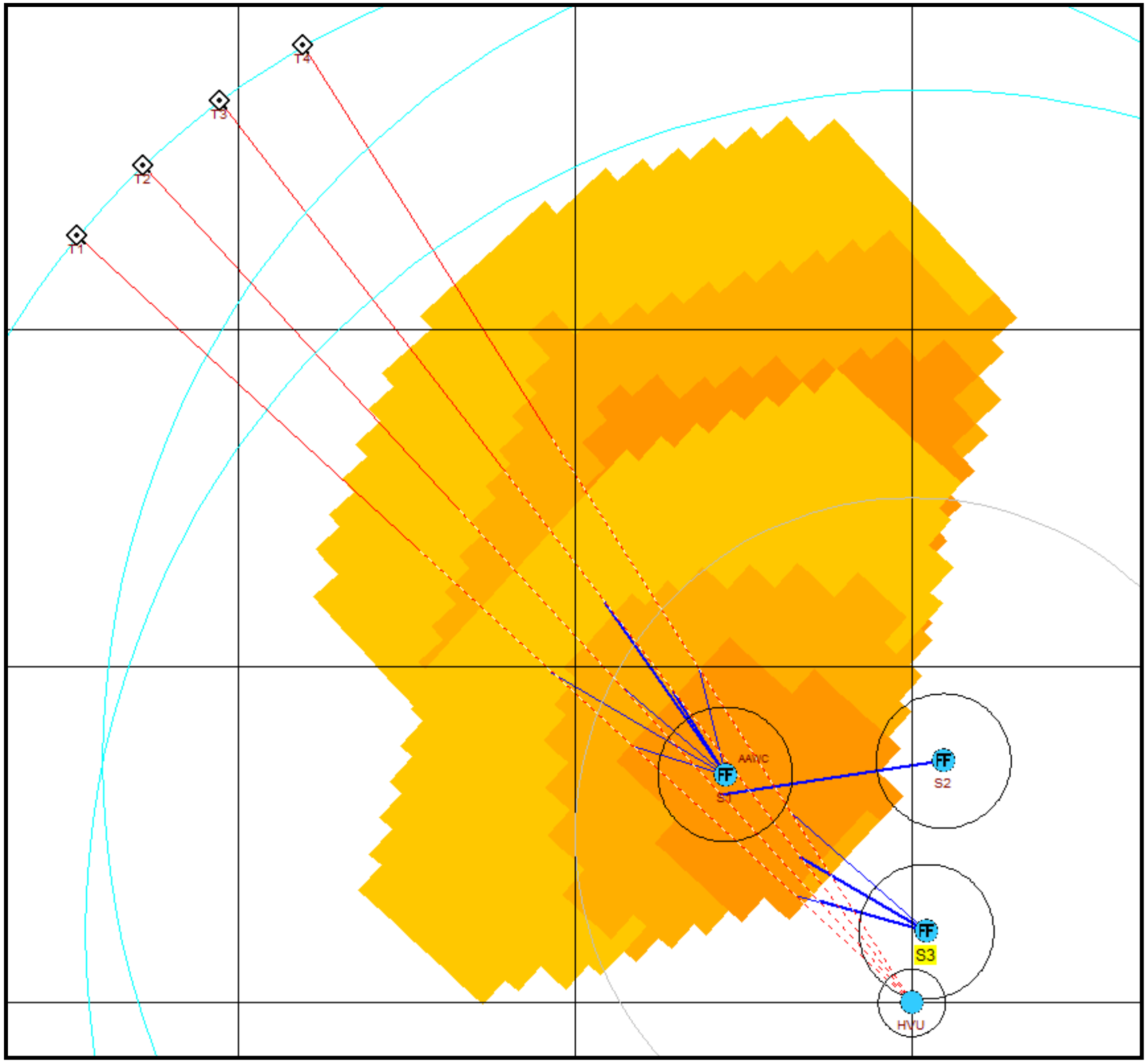
Concluding remarks (1 of 2)

- Two layered approach, OA model underpinned by physics-based simulations, permits exploration of a large parameter space in a structured manner
- Analysis benefits being realised through HTC
  - Permits high fidelity Monte Carlo simulations to be used in a wider context
  - Permits brute-force extensive search of large parameter spaces, but parameter space increases can still outgrow HTC capacity
  - Data management challenges arise from the vast amounts of data that can be rapidly generated
- M&S fully embraced the approach to construct MEZs
  - Gives firm basis and credibility to the ship stationing analysis
  - Approach adopted to support planning for an upcoming trial
  - Exploring feasibility of peeling back the layers in a MEZ to separate out detection, tracking and SAM fly-out

Concluding remarks (2 of 2)

- OA model observations and benefits
  - In-house development responsive to evolving requirements
  - Fast running thereby permitting large number of cases to be quickly considered
  - Push to increase functionality:
    - Visualisation of MEZs from the physics-based simulations
    - Command Line Interface to utilise HTC, Graphical User Interface to visualise results
    - Data output control to minimise amount of data produced – better to quickly run large number of cases with minimal data recording and then rerun the cases of interest
    - Heat maps for visualising TG ship stationing results
- Further work:
    - Validation and focused runs using physics-based simulations
    - Increase complexity of engagements represented
    - Explore exploitation of the engagement planner
    - Explore exploitation of the heat maps to support tactical planning

Questions ?



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