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A Survivability Assessment Method for Surface-to-Air Missile Threat Evasion Based on Probability-of-Kill Analysis Using a Wargaming Tool

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Physics Based Analysis 2005

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UAV Episode-1 2012

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Wargaming Overview — Experimenting with War Without Combat

Definition

A structured method in which two opposing sides (Blue/Red) interact under agreed rules, data, and adjudication—without actual combat - to explore how operations and strategies unfold and what outcomes result.

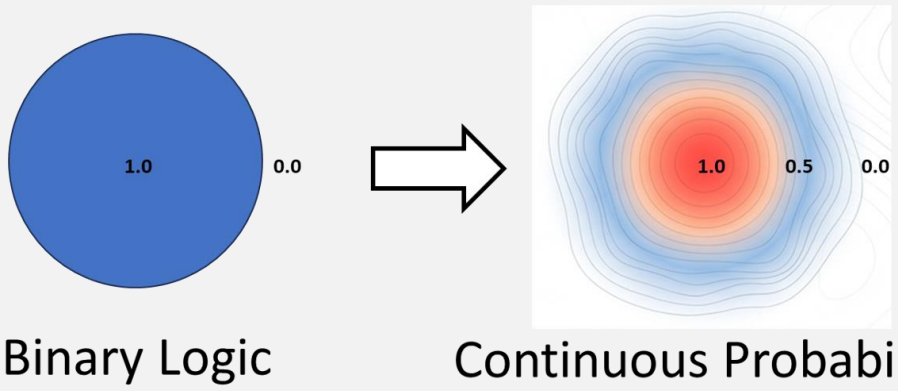
- Enables repeated "***what-if***" exploration **at low cost and low risk**, combining quantitative ***M&S effectiveness analysis*** with qualitative insight.
- ***Making decisions*** that are hard to test ***in reality*** be experimented with ***beforehand***.

> *"**A wargame** is not a tool for predicting war, but a laboratory for **training** and **validating thought and decision**."*

Why binary threat zones are not enough

- Threats are rarely isolated - interlocking SAM and AAA coverage leaves few gaps to fly around
- Standard planners model the engagement envelope as a solid, static obstacle - 1 or 0
- The resulting outer detours burn fuel and prolong time in hostile airspace
- Worse, a blind detour can push the aircraft into a secondary, unobserved threat

From Binary to Gradient



Consequence

➔ A binary envelope forces a decision the data does not support.
➔ Every point inside is equally lethal
➔ Every point outside is equally safe.

Toward risk-aware path planning

The P_k map is not the end product → it is the input data layer for the planner.

1

Grid sweep

Straight-line transit paths across a bearing and offset grid around the threat

2

Endgame extraction

Per-engagement kill probability and hit / miss outcome from the native report

3

Polar P_k map

Outcomes binned and aggregated by aircraft nose bearing

4

Hit map

Spatial risk layer supplied to risk-aware hybrid path planning

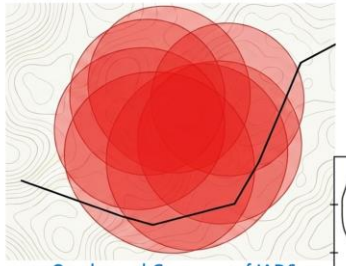
Path Planning with Risk-awareness

Hybrid Risk-Aware Path Planning for Survivability Against Integrated Air Defense System(IADS), DAFMSAS, 2026

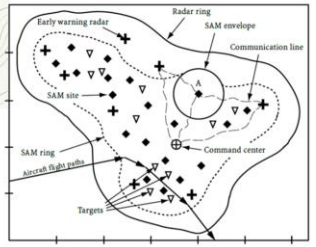
Why This? Problem Matters: The Operational Context – Saturated Environments

- **Overlapping Threat Zones**
  Modern IADS deploy continuous, Interlocking anti-aircraft domes (SAMs, AAA).
- **The Cost of Detours**
  Wide outer detours burn critical fuel and dangerously prolong time-in-hostile-airspace.
- **The Tactical Reality**
  Threats are rarely isolated; Survival requires navigating through the layers, not just around them.

SAM: Surface-to-Air Missile
AAA: Anti-Aircraft Atillery
IADS: Integrated Air Defense System



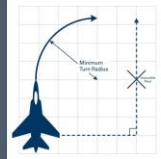
Overlapped Coverage of IADS



General Layout of IADS

2

Technical Challenges / Roadblocks



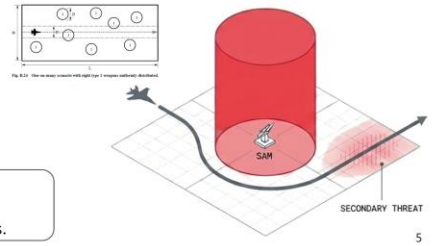
- Traditional path Finding ignores the aerodynamics.
- Minimum turn radius and maximum pitch limits.
- Paths must be continuously flyable.

- Conflict between Safety and Performance
- Flight paths must actively account for the lethal ranges of proximity-fuze engagements.

Kinematics Solved, Threats Failed
Standard Dubins-RRT* perfectly models flight physics but uses 1-dimensional threat assessment.

The Concrete Wall Fallacy
Threats probabilistic missile engagement zones as solid, static obstacles.

The Consequence
Forces the aircraft into massive outer detours, pushing it blindly into secondary, unseen threats.



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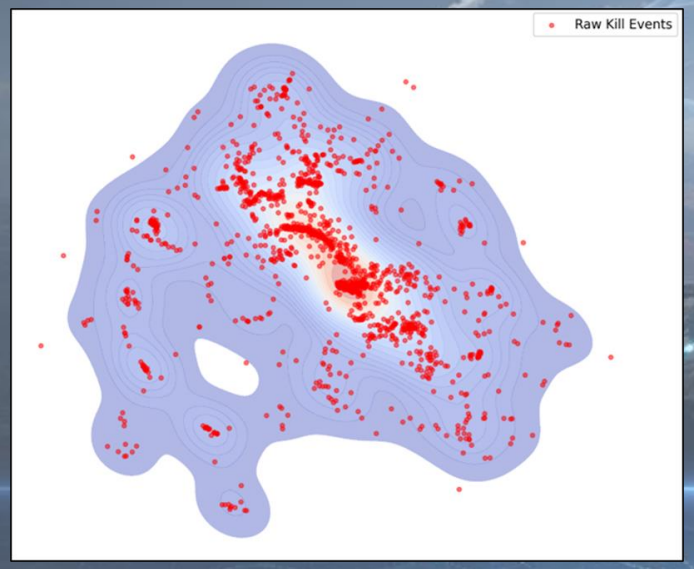
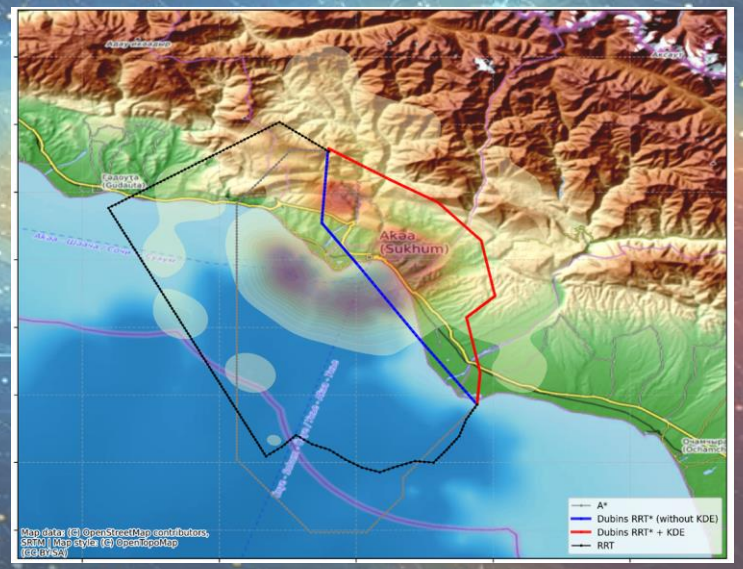


Risk Map with Raw Points
Spatial Distribution of Aircraft Kill Events
Scenario Execution Results

Georeferenced Path Planning Algorithm Comparison Over Realistic Terrain



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Research question

How does probability of kill vary with aircraft nose bearing, and can that variation be produced with a COTS wargaming tool?

Q1 Feasibility

Can engagement outcomes be instrumented from a COTS tool at a volume sufficient for statistical treatment?

Q2 Phenomenon

Does the kill probability show a systematic, reproducible dependence on the aircraft nose bearing?

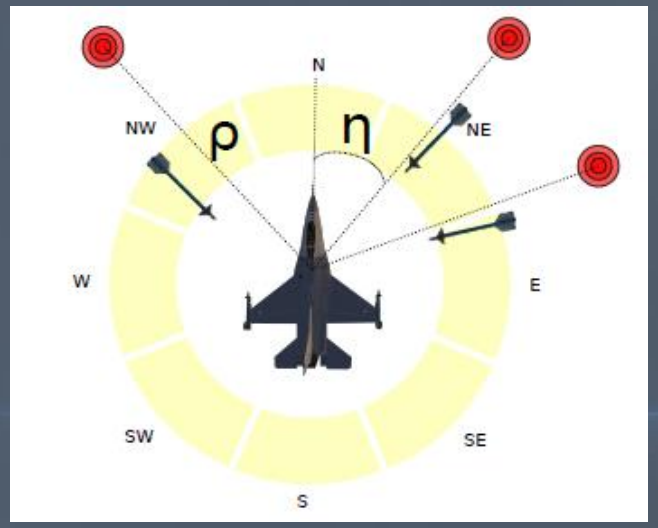
Q3 Utility

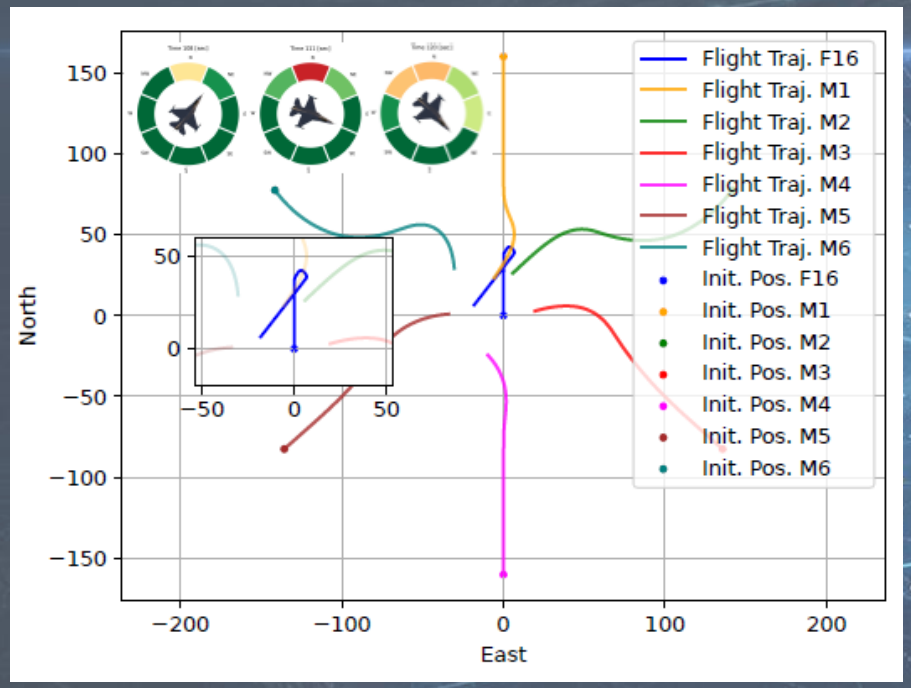
Can the result be expressed as a spatial layer that a risk-aware path planner is able to consume directly?

Q1 is answered by the instrumentation pipeline, Q2 by the grid sweep results, Q3 by the hit map handed to the planner.

Literature survey

Deep Learning Based Situation Awareness for Multiple Missiles Evasion





2024 International Conference on Unmanned Aircraft Systems (ICUAS)
June 4-7, 2024. Chania, Crete, Greece

Deep Learning Based Situation Awareness for Multiple Missiles Evasion

Edvards Scukins [1,3], Markus Klein[2], Lars Kroon[1], and Petter Ögren[3]

[1]Aeronautical Solutions division, SAAB Aeronautics
[2]Tactical Control and Data Fusion division, SAAB Aeronautics
[3]Robotics, Perception and Learning Lab., Royal Institute of Technology (KTH)

***Abstract*—As the effective range of air-to-air missiles increases, it becomes harder for pilots and Unmanned aerial vehicle (UAV) operators to maintain the Situational Awareness (SA) needed to keep their aircraft safe. In this work, we propose a decision support tool to help pilots in Beyond Visual Range (BVR) air combat scenarios assess the risks of different options and make decisions based on those. Building upon earlier research that primarily addressed the threat of a single missile, we extend these ideas to encompass the complex scenario of multiple missile threats. The proposed method uses Deep Neural Networks (DNN) to learn from high-fidelity simulations and provide the pilots with an outcome estimate for a set of different strategies. Our results demonstrate that the proposed system can manage multiple incoming missiles, evaluate a family of options, and recommend the least risky course of action while accounting for all incoming air-to-air threats.**

***Index Terms*—Machine Learning, Beyond Visual Range Air Combat, Situation Awareness**

I. Introduction

Since the First World War, air combat has evolved drastically. Advances in sensors, weapons, and communication allow pilots to engage enemy aircraft at longer and longer distances. Such advances have driven the transition from Within Visual Range (WVR) air combat to Beyond Visual Range (BVR) air combat [1]. In BVR, incoming missiles can fly for up to several minutes, which makes it very difficult for pilots or potential Unmanned aerial vehicle (UAV) operators to evaluate all incoming data and choose the best course of action. In fact, there is a tendency for the operator to lose track of some of the incoming threats [1]. A support tool that can handle several threats simultaneously and provide an overall analysis is thus needed. Such a tool should support the pilots in balancing the risk against the mission goals, as the lowest risk option is often, unfortunately, to ignore the mission entirely, while on the other hand, ignoring the risks ultimately might lead to hefty losses.

As the flight time of a radar-guided missile can be very long, BVR air combat includes an element that might be compared to real-time strategy games like Starcraft [2]. Significant challenges include highly nonlinear dynamics, information uncertainty, and opponents' unknown strategies and goals. Onboard sensors can output estimates of opponent locations that depend on the type of hostile aircraft, the electronic warfare countermeasure equipment, and the weather. However, although precise information is not always available when facing an enemy, operators are typically aware of the capabilities of the enemy's aircraft and weapons systems, and the proposed approach will make use of this information.

In our previous work [3], we have studied the case of an aircraft facing one incoming BVR missile. Using Reinforcement Learning (RL), we computed the optimal evasive maneuver and the resulting miss distance (MD) when performing the maneuver. However, that approach cannot be applied when faced with several adversarial aircraft engaging at the same time. When considering multiple incoming missiles from different angles, the optimal evasive maneuver relative to one missile differs from the other, and you clearly cannot execute two different maneuvers simultaneously. Furthermore, the most effective evasive action for one pair of incoming missile threats might be determined by solving a specific problem offline and storing the outcome, but this approach becomes impractical due to the vast number of possible threat combinations.

Fig. 1: Symbolic representation of a situation where a high-performance aircraft faces three incoming missiles. The exact current locations of the missiles are unknown, but estimates of the time and location of the launches are available. In Figures 3-6, the colored fields around the aircraft icon are used to show the predicted miss distance (MD) of an evasive maneuver in that direction. Based on this, the aircraft operator can make a trade-off between mission goals and risks when determining what course to choose.

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Positioning This Work

	Scukins et al. (2024)	Risk-aware hybrid planner (2026)	This work
Threat	Air-to-air missile, BVR	IADS — SAM and AAA layers	**Surface-to-air threat system**
Fidelity source	JSBSim FDM + trained DNN	Assumed threat model	**CPE native weapon endgame**
Risk metric	Miss distance (MD)	Continuous probability field	**Kill probability by nose bearing**
Output	Per-heading MD estimate	Flyable, risk-weighted path	**Hit map as planner input**

The gap.

→ The planner needs a probability field over geometry.

→ Existing survivability work produces miss distance from an external flight dynamics model plus a learned surrogate.

→ Neither line of work delivers a bearing-resolved kill probability obtained from one commercially available tool.

The engagement chain and where P_k is evaluated

Only the terminal node is resolved by the tool's endgame model — the earlier nodes are conditions, not outputs.

Detection

Radar acquisition of the target

Launch decision

Doctrine and ROE gate the shot

Intercept

Guidance flyout to the target

Terminal endgame

Kill probability evaluated and reported

Two quantities that must not be conflated

Predicted kill probability

reported as Final PH in the endgame report

A model output.

Available for every engagement without repetition, because the tool exposes the computed value directly rather than requiring it to be inferred from outcome counts.

Realised hit rate

hit / miss outcome after the stochastic draw

A sample statistic.

The probability is re-rolled per engagement, so the realised rate converges on the predicted value only with sufficient s amples in each bearing bin.

From scenario to bearing-binned records

1

Scenario build

Threat site and transit lanes placed on a fixed grid

2

Batch execution

Repeated case-runs with the evasion policy removed

3

State export

Truth positions and engage ment events written per run

4

Geometry reduction

Nose bearing, intercept angl e and LOS rate derived per e ngagement

5

Binning

Records aggregated into bea ring sectors for polar present ation

Collected in this run

7	700	3,151	238	2,913
cases	case-runs	engagements	hits 7.6% of engagements	misses

Transit lanes run from −5 nm to +5 nm at 1 nm spacing, giving repeated passes at each offset.

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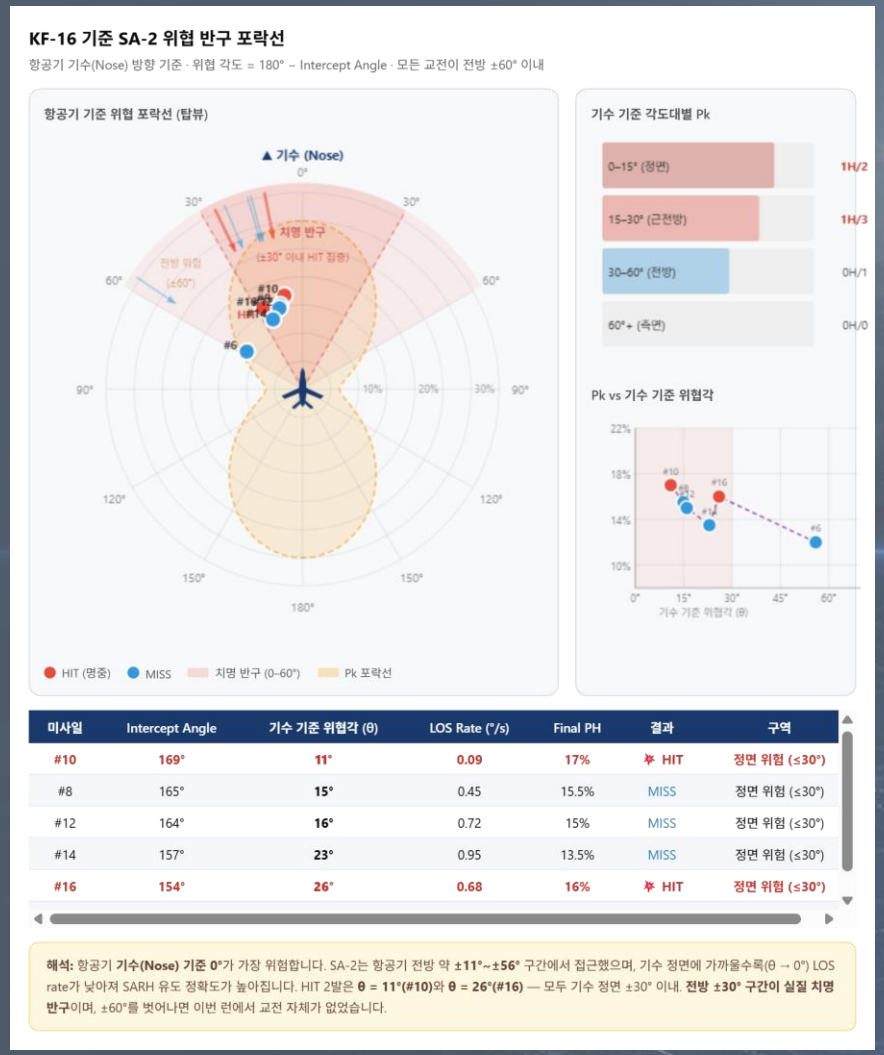
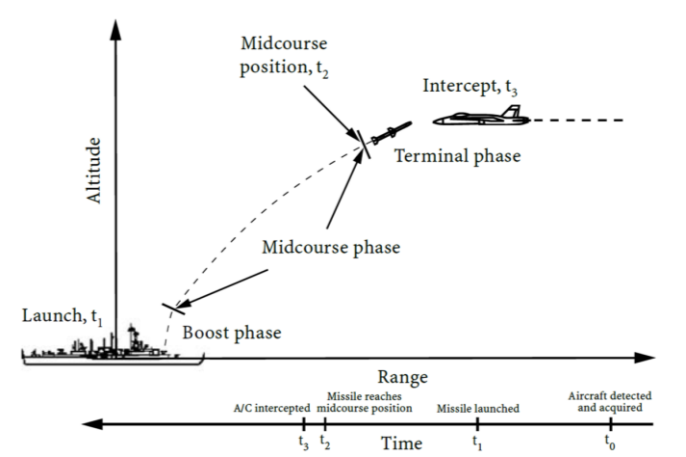
Experiment Plan Concept for Kill-Zone Characterization

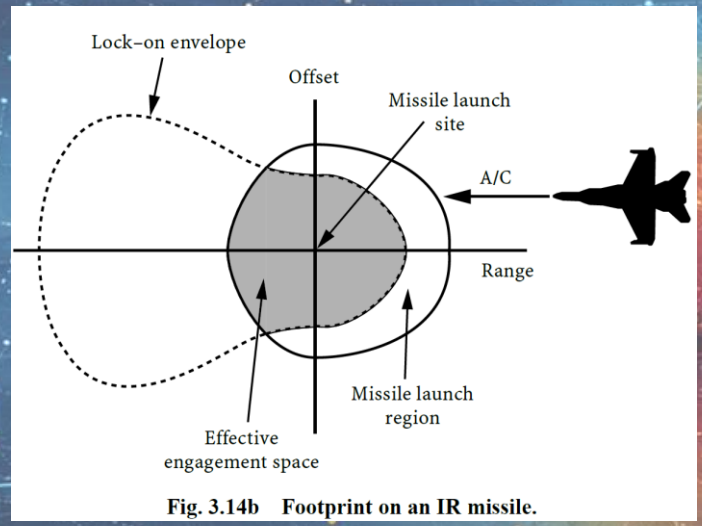


미사일	Intercept Angle	기수 기준 위협각 (θ)	LOS Rate (°/s)	Final PH	결과	구역
#10	169°	11°	0.09	17%	HIT	정면 위험 (≤30°)
#8	165°	15°	0.45	15.5%	MISS	정면 위험 (≤30°)
#12	164°	16°	0.72	15%	MISS	정면 위험 (≤30°)
#14	157°	23°	0.95	13.5%	MISS	정면 위험 (≤30°)
#16	154°	26°	0.68	16%	HIT	정면 위험 (≤30°)

Kill-Zone Characterization



Missile launch ad flyout to intercept



Footprint on an IR missile

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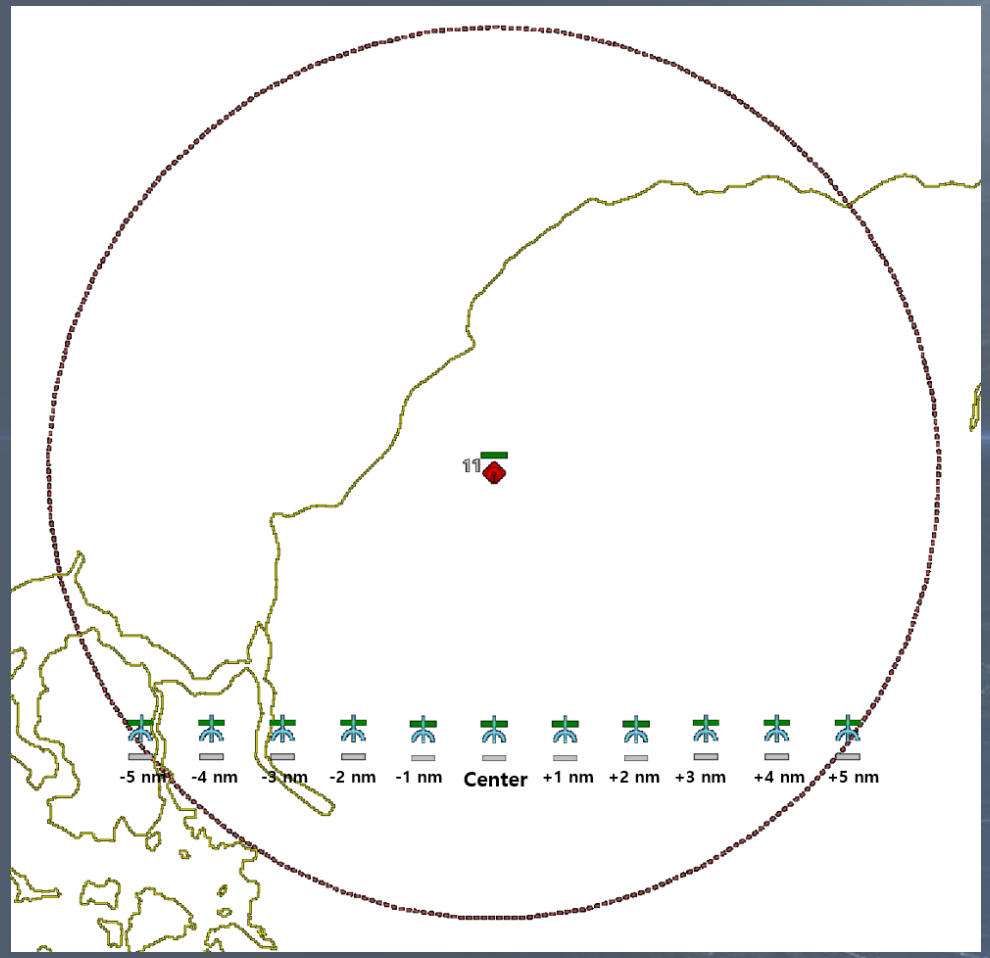
Experimental Design Setup

Grid Layout of Transit Paths Within the Threat Radius



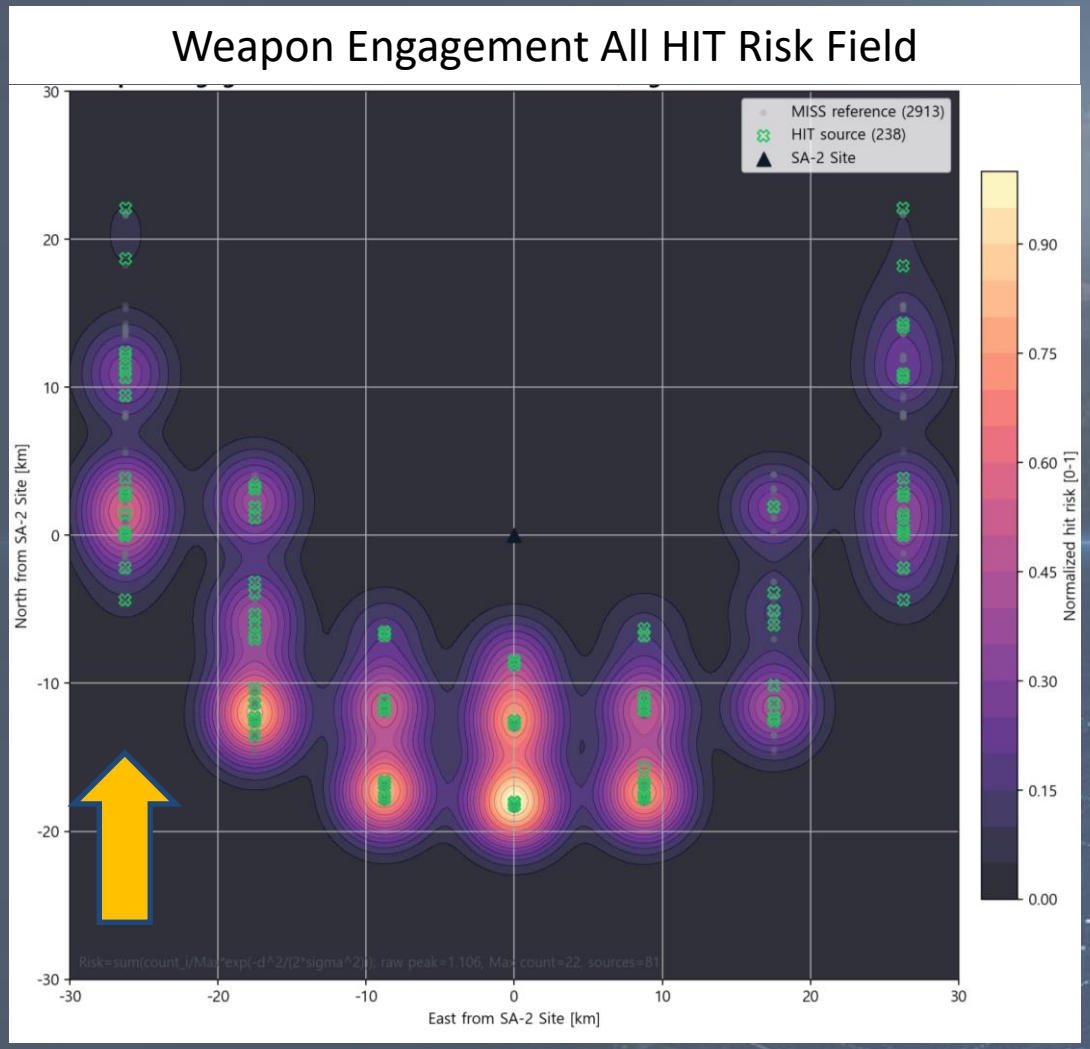
Blue Force Tactical Aircraft Specifications

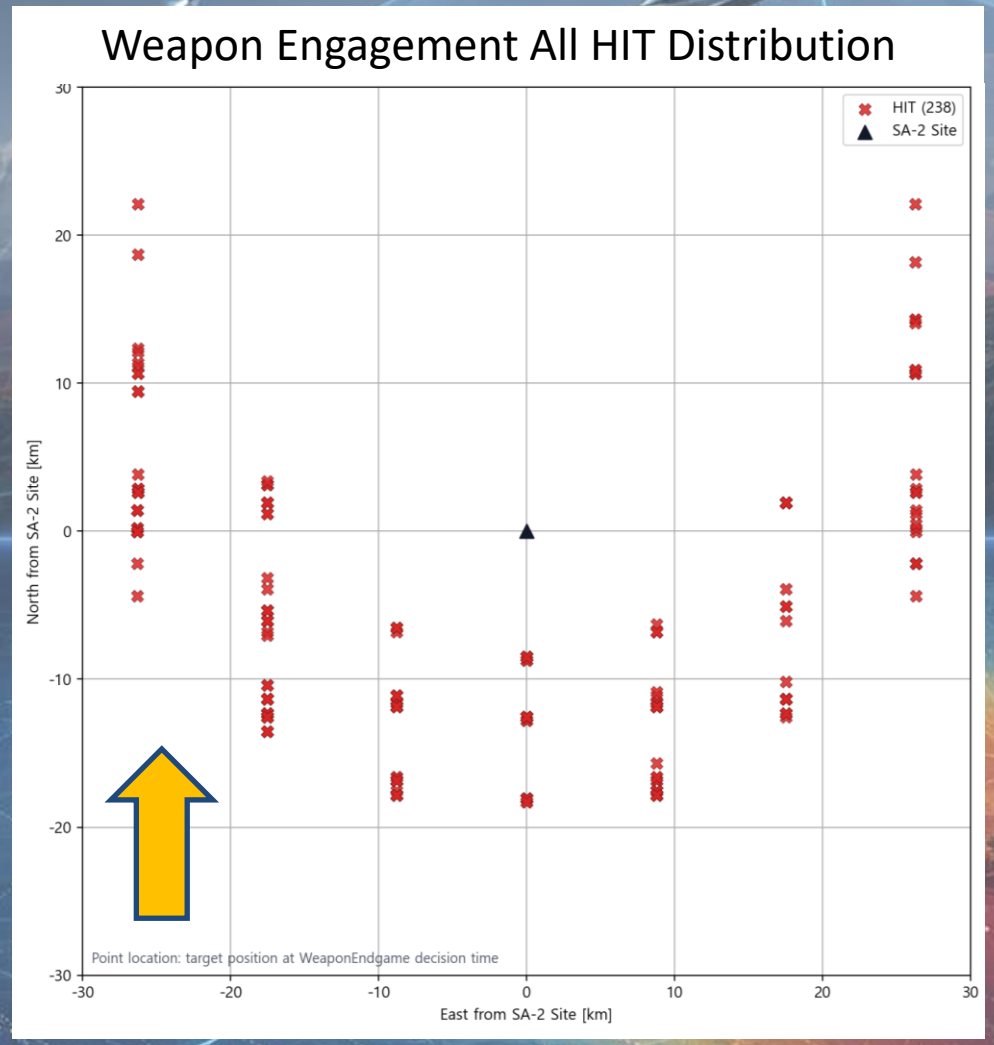
Summarizes the target-role aircraft's key engagement parameters, including detection, targeting, and evasion reaction times (OODA).

Red Force Surface-to-Air Threat System Specifications

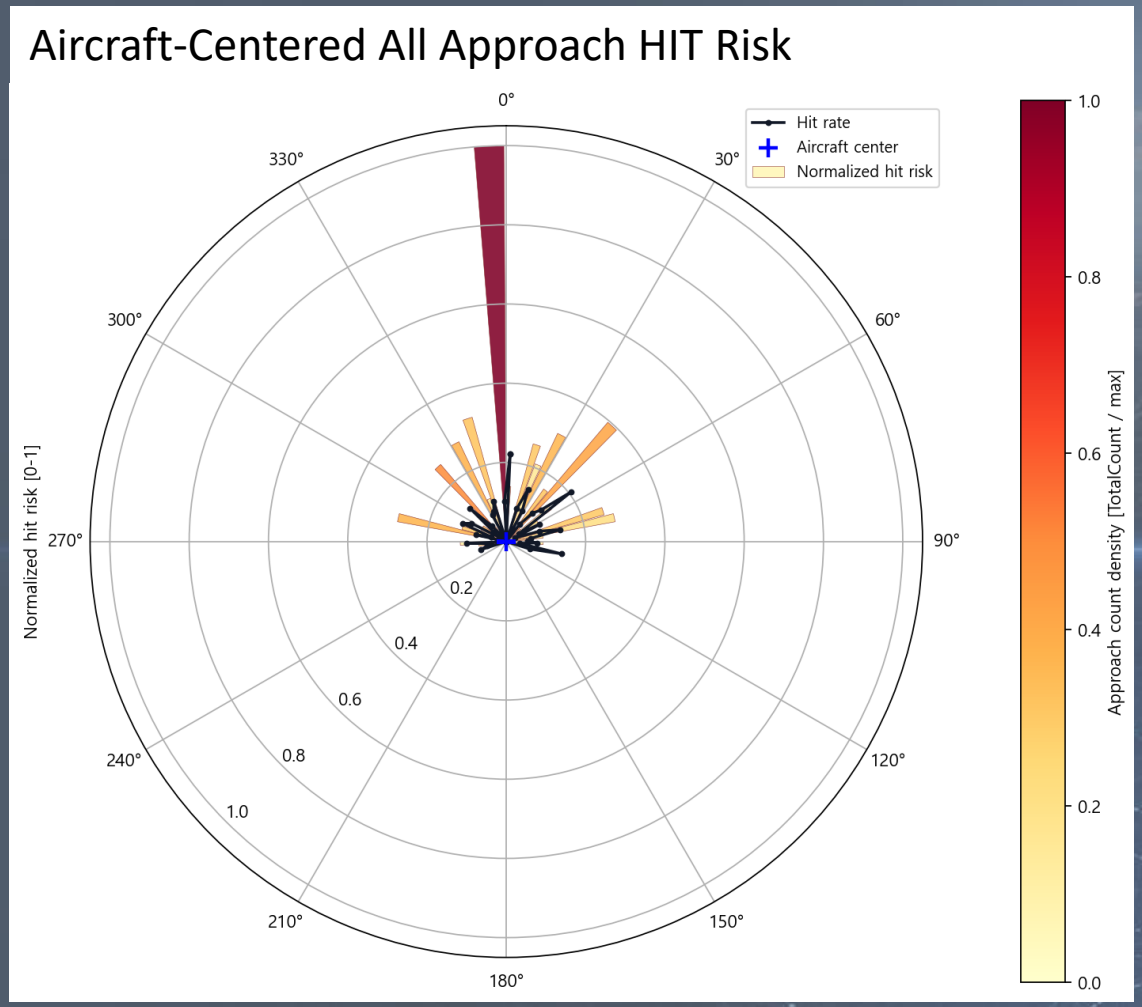
Summarizes the threat system's detection/targeting reaction times and engagement parameters, and supports that its SARH guidance characteristics are the source of the bearing-dependent Pk.

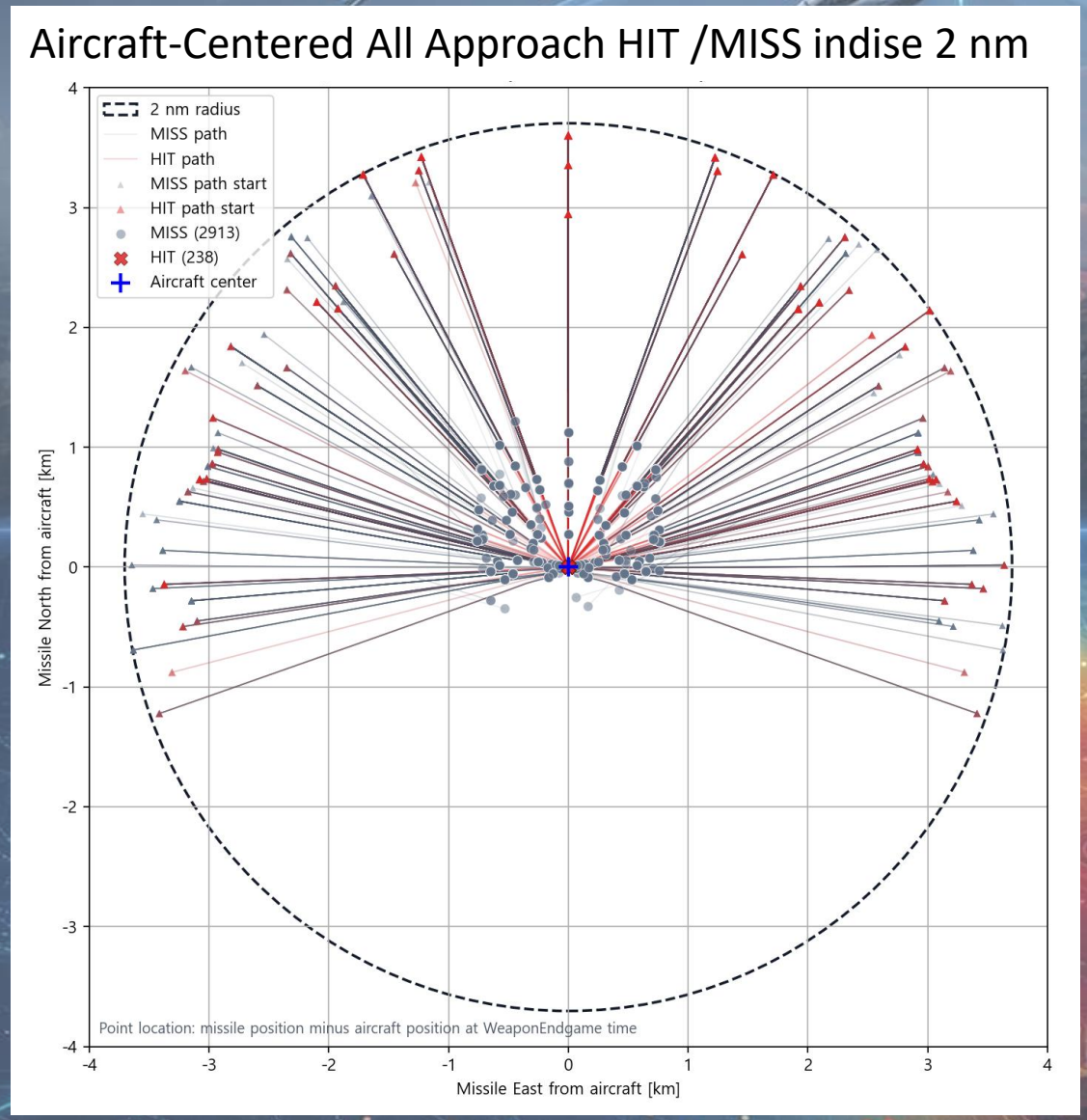
Site-Centered Hazard Field and Distribution





Aircraft-Centered All Approach HIT Risk





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Conclusion

Geometry-dependent survivability assessment using a COTS wargaming tool

MD Prior work — Scukins et al. (2024)

- High-fidelity JSBSim flight dynamics, BVR air-to-air missile ev asion
- Deep neural network trained on large-scale simulation data
- Miss distance predicted for each compass-direction evasion policy
- Requires an external flight dynamics model and a learned sur rogate

Pk This work

- Command Professional Edition only — no external FDM, no l earned surrogate
- Surface-to-air threat system engaged over a straight-line tran sit grid
- Kill probability mapped by aircraft nose bearing instead of mi ss distance
- Values read directly from the native weapon endgame report

Both approaches answer the same question — which heading is survivable — through different methods.

Key contribution

01 The native endgame model is sufficient

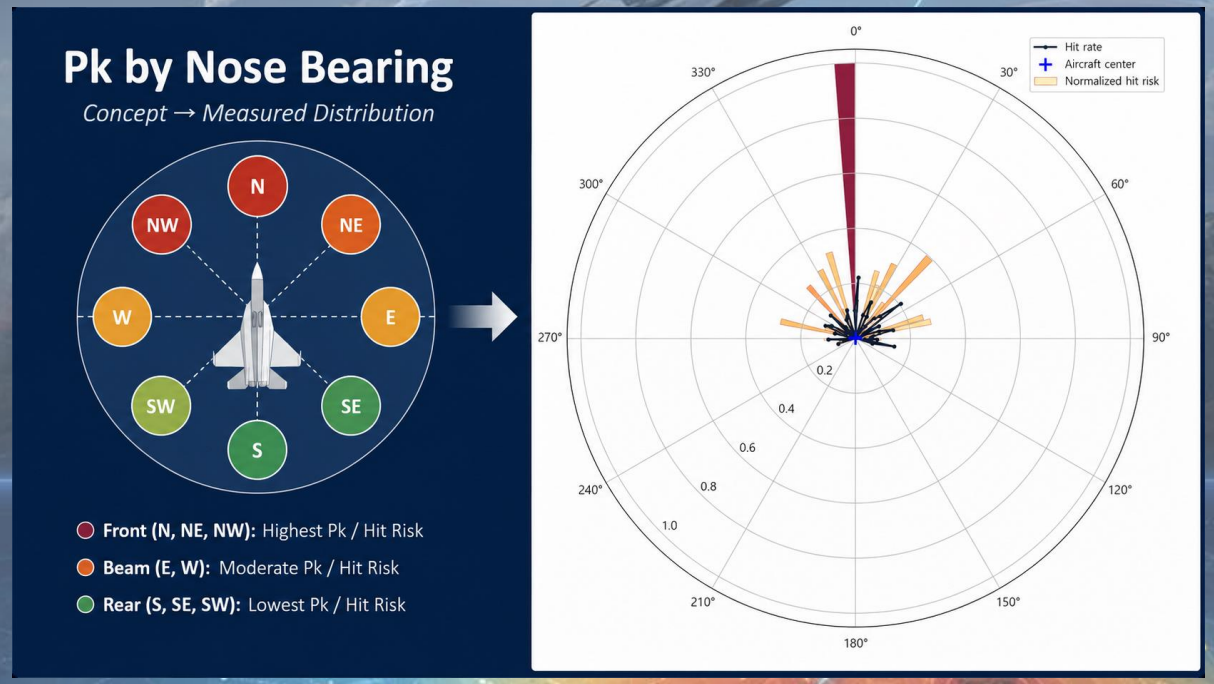
Geometry-dependent engagement exposure (Pk) can be assessed wi th the tool's own weapon endgame model → no deep-learning surr ogate and no external flight-dynamics model need to be integrated i nto the pipeline

02 A bearing-parameterized risk metric

Engagement outcomes are aggregated in polar form by aircraft nose bearing, giving a directly interpretable exposure profile across the sampled headings.

03 Reproducible with existing COTS tooling

The pipeline runs on a commercially available tool using its native reports plus light scripting → for teams already operating that tool, it removes the need for a data-generation and model-training pipeline, lowering the methodological barrier to replication and reuse.



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QUESTIONS?

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