Performance Models for Airborne EO/IR Sensor Deployment Planning Considering the Complete Image Chain

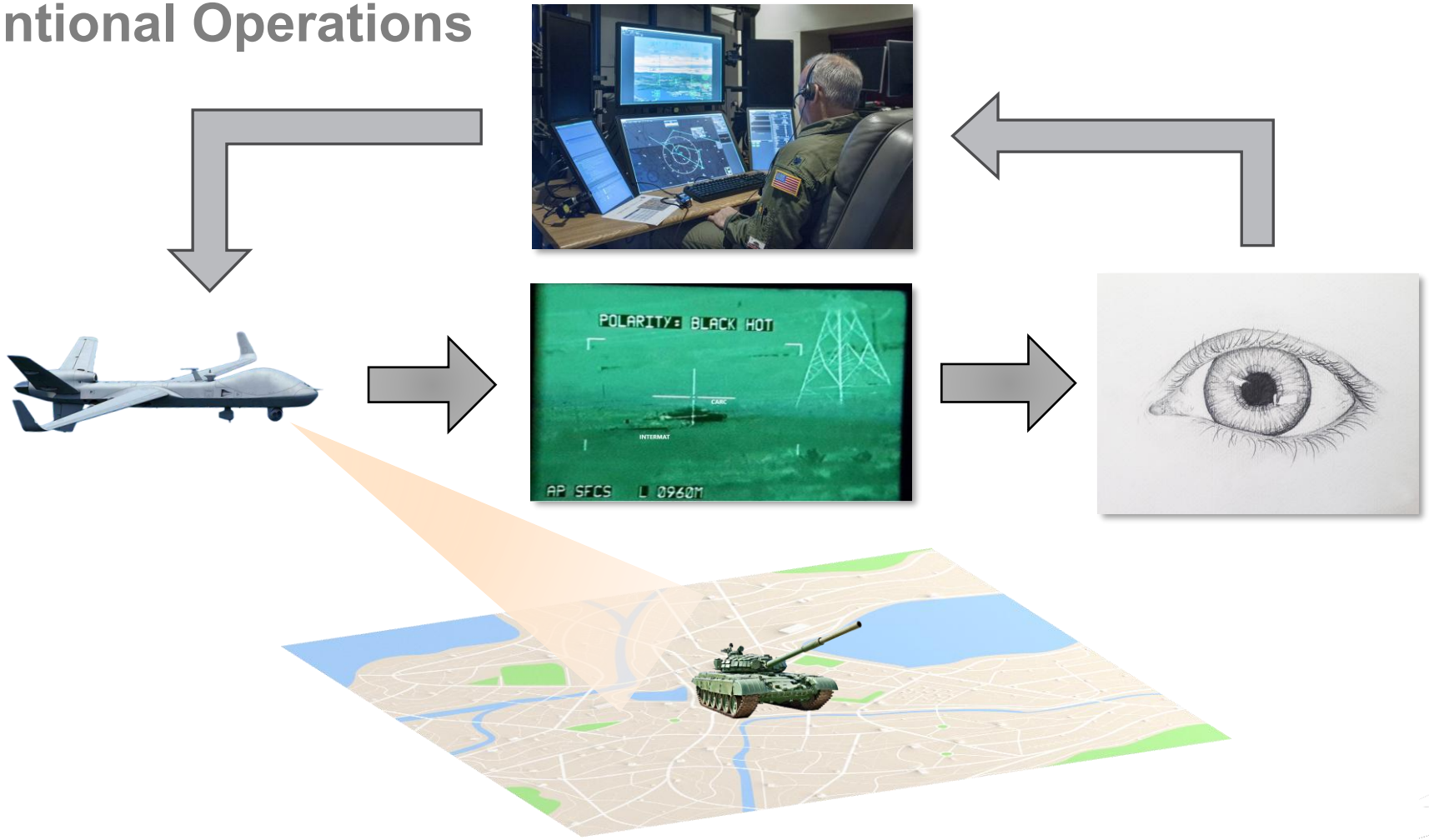
ADRIAN ALBERT

PROF. DR.-ING PETER STÜTZ



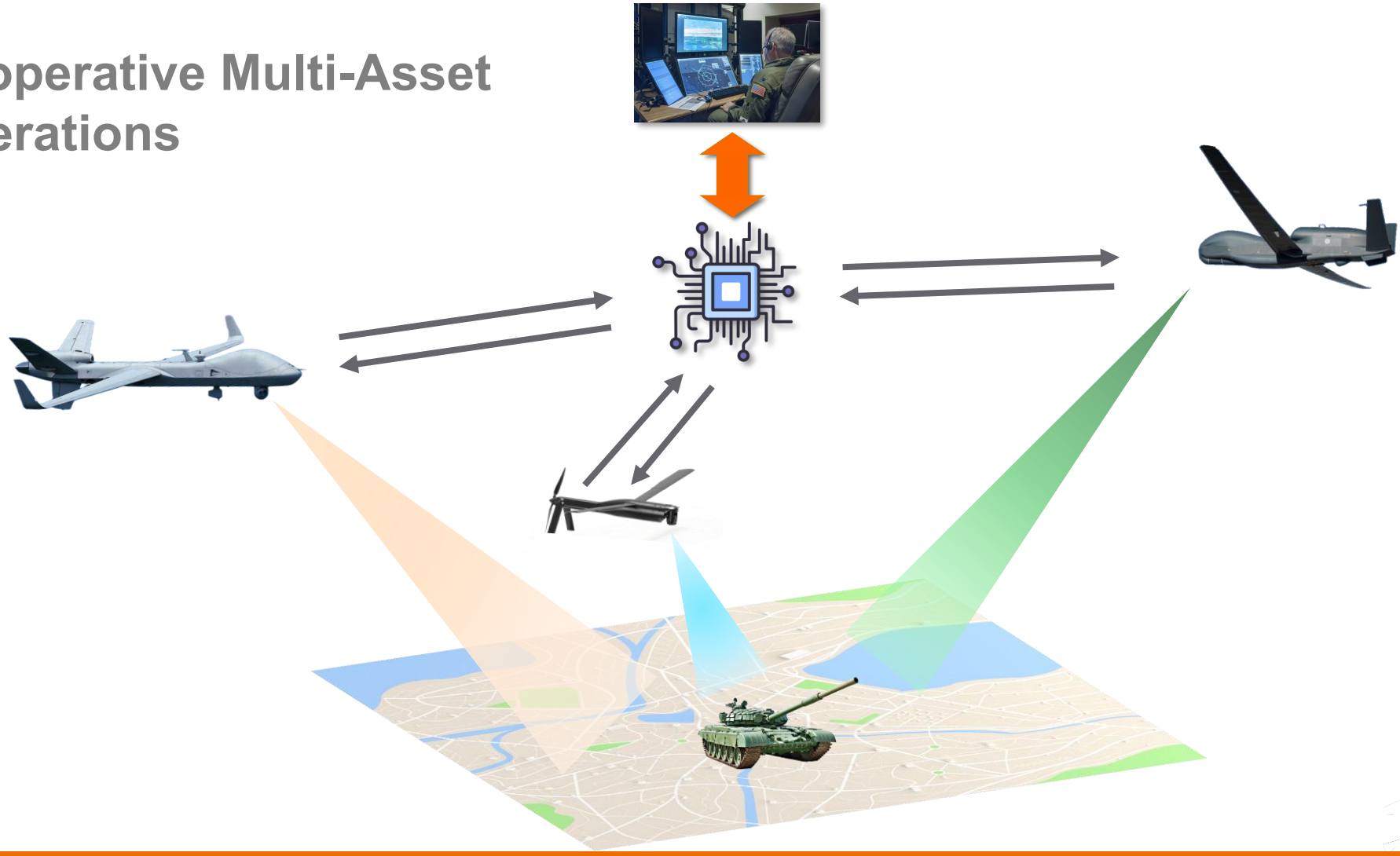
Motivation

Conventional Operations

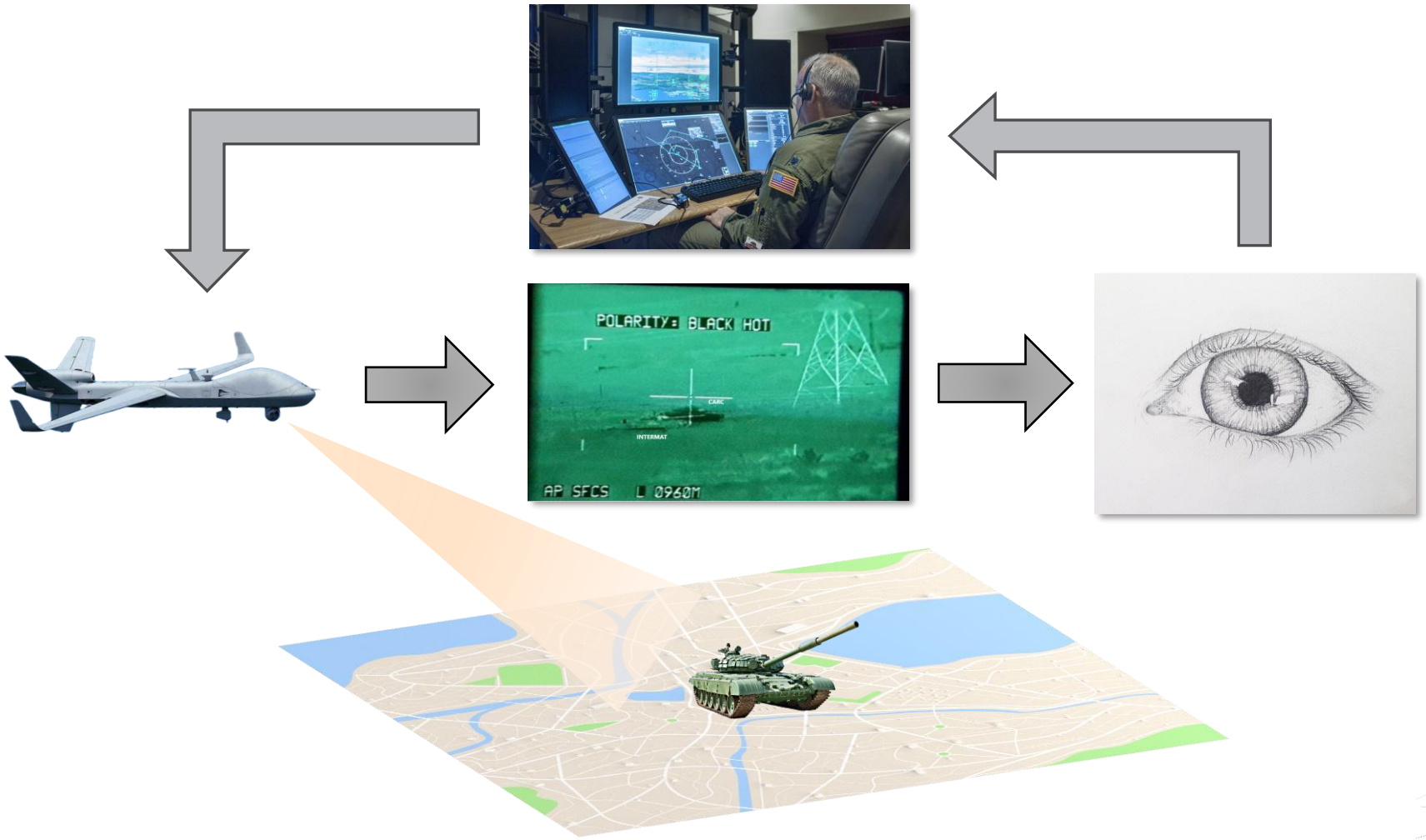


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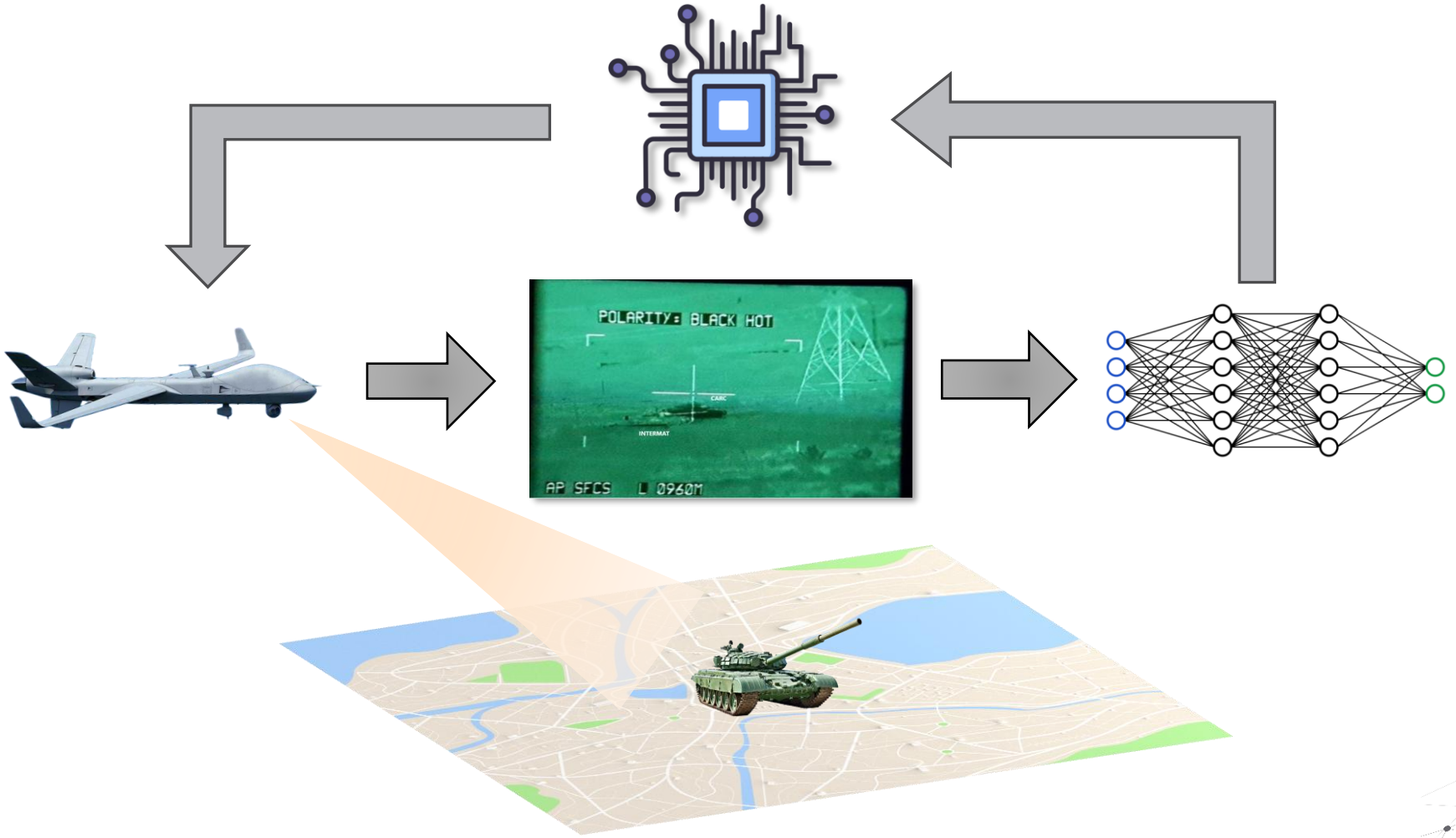
Cooperative Multi-Asset Operations



Motivation



Motivation

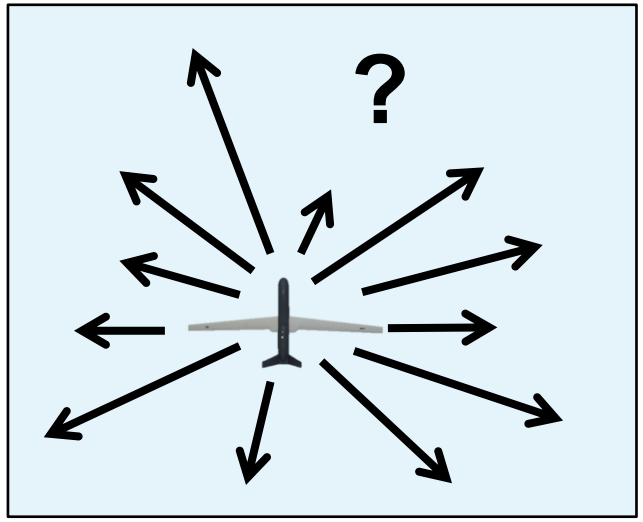


Motivation

Target Area



Operational Area



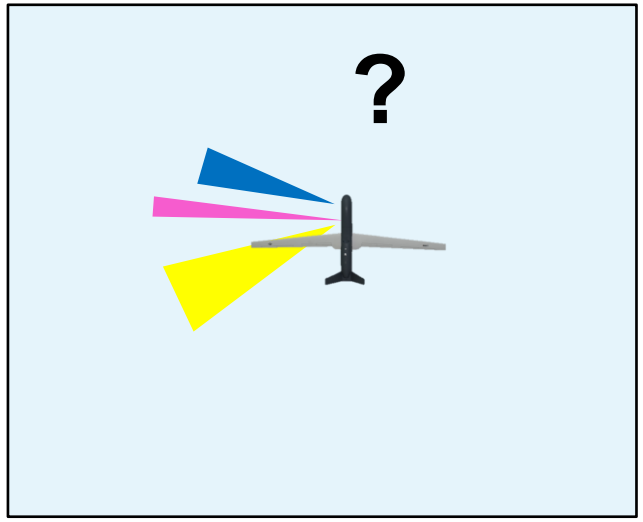
- **Where to place the airborne asset?**
- Where to direct the sensor?
- Which Zoom level shall be used?

Motivation

Target Area



Operational Area



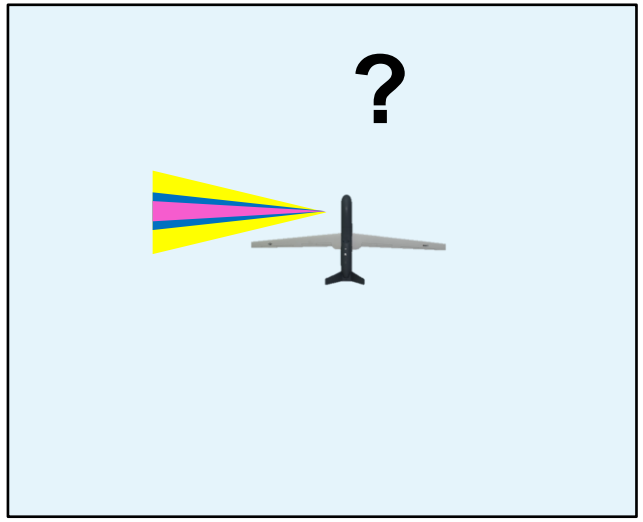
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Motivation

Target Area



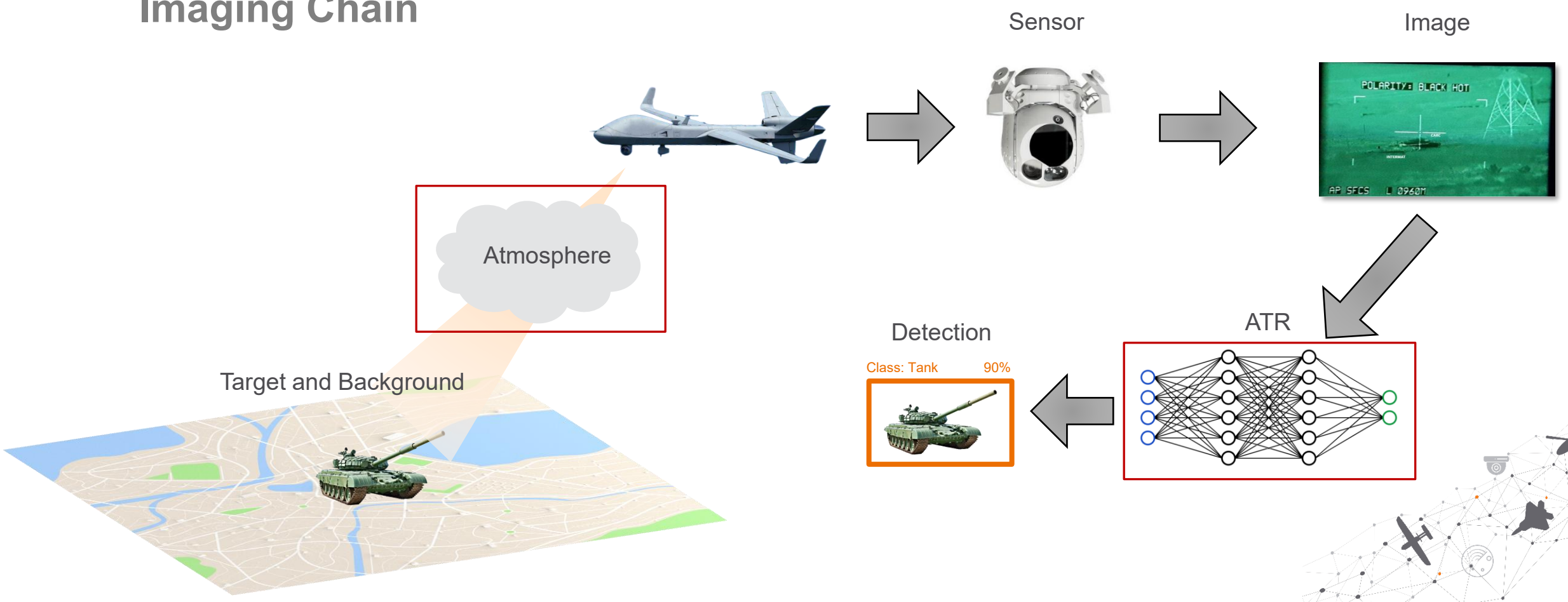
Operational Area



- Where to place the airborne asset?
- Where to direct the sensor?
- **Which Zoom level shall be used?**

Motivation

Imaging Chain



Automatic Target Recognition

Why Performance Models for ATR?

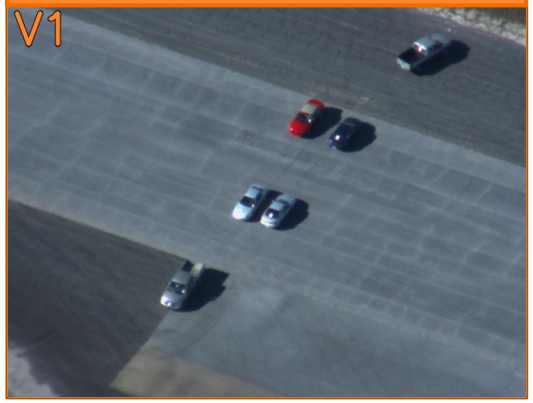
- **Existing** imaging-system performance models are **primarily** designed for **human observers**
- Identify the **image characteristics** that determine **successful target detection and classification**
- Determine the **required image quality** and **contrast** for **successful target detection** and **classification** and, consequently, the appropriate sensor settings
- Use this knowledge to **enable** performance-based **EO/IR sensor deployment planning**



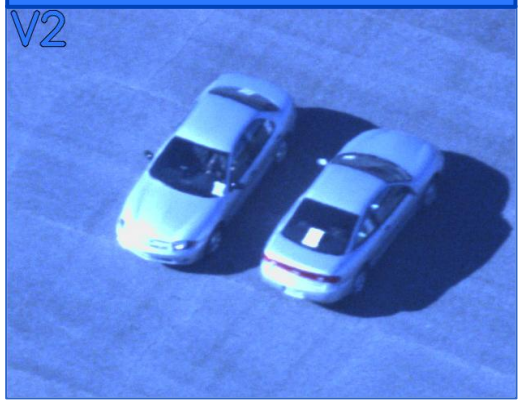
Automatic Target Recognition - Dataset

Air Force Research Laboratory – SDMS – Video Sample Set #1

EO Daylight TV



EO Spotter



Infrared (IR)



Dataset Overview

- **Simultaneous acquisition by three sensors** covering the same scene
- **Various air-to-ground scenarios**
- Total of **30 video clips**

Key Dataset Advantage

Variation in target contrast and spatial resolution enables analysis of their influence on ATR performance

	V1	V2	V3
Type	EO	EO Spotter	IR
Resolution	640 × 480	640 × 480	320 × 256
HFOV	0.92°	0.22°	0.80°

Automatic Target Recognition - Dataset

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Automatic Target Recognition – Data Generation

The same physical target can be detected by ATR in some sensor streams, but missed in others.

YOLO v8

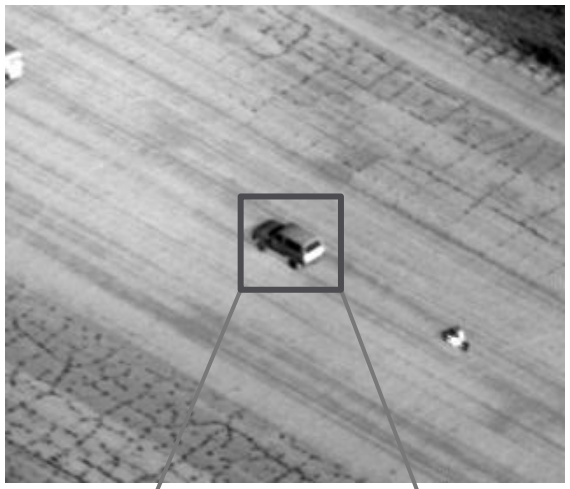
Used Models	
Model Variant	**Training Data**
yolov8n	VisDrone
yolo11n	COCO
yolo8s	COCO
yolo8x	COCO



Missed



Detected



Detected

Automatic Target Recognition – Data Generation



Geometric Projection



Geometric Projection



Detections at geometrically corresponding positions

Same physical target

Project target position into other streams using sensor geometry

Automatically generated sample



Image Crop

Bounding Box

ATR result

- Detected (correctly classified)
- Detected (missclassified)
- Missed
- Model used

Automatic Target Recognition – Data Generation



Automatic Target Recognition – Data Generation

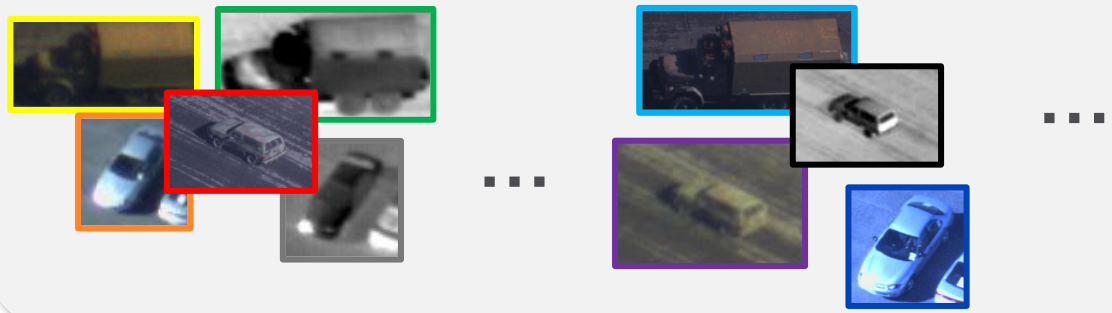






334,267
data samples generated

Large automatically generated dataset



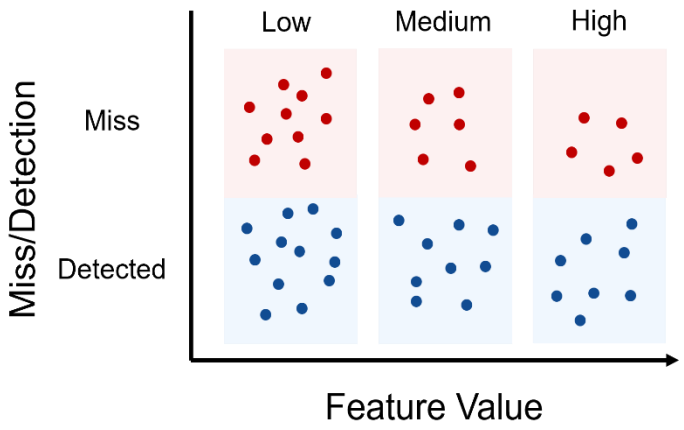
Statistical ATR Performance Analysis

Automatic Target Recognition – Data Analysis

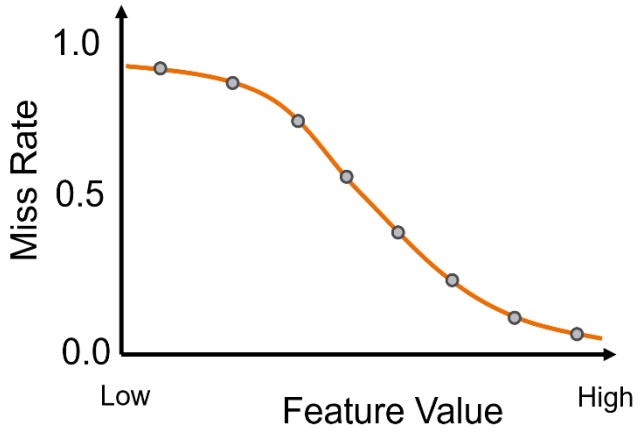
Analysis Method

- 334,265 target samples provide a **robust statistical basis**
- **24 image features** extracted from target and surrounding background regions
- Samples **grouped into feature-value bins** and **miss rate calculated for each bin**
- Resulting **trends reveal the influence of individual image characteristics** on ATR performance

Sort Samples into Corresponding Bin



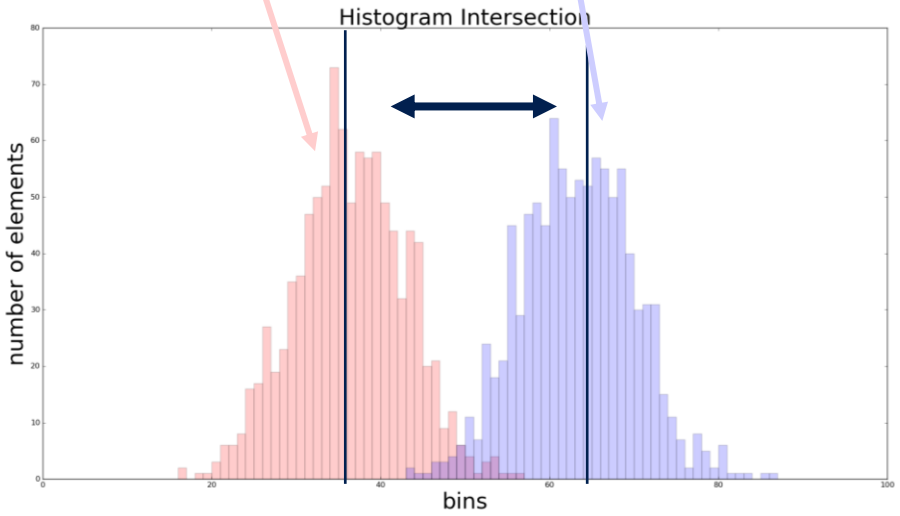
Performance Trend Analysis



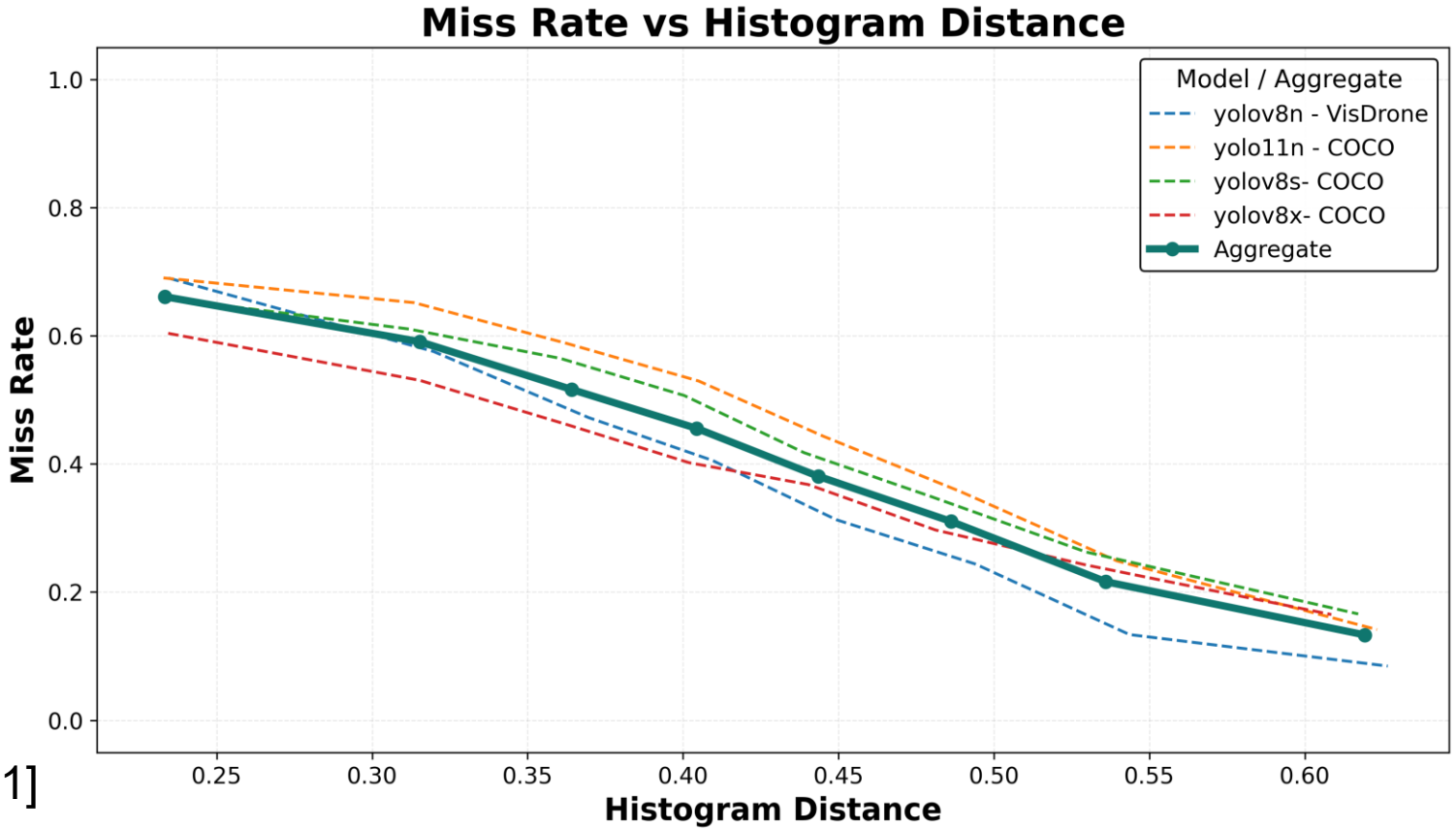
Target-to-Background Histogram Distance shows the strongest influence on miss rate among the investigated features

Automatic Target Recognition – Target-to-Background Histogram Distance



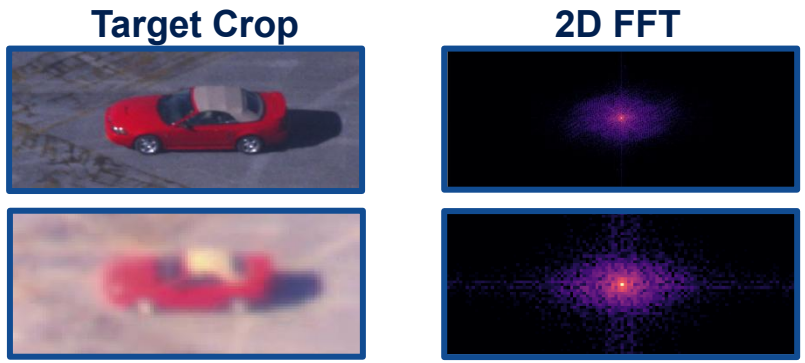


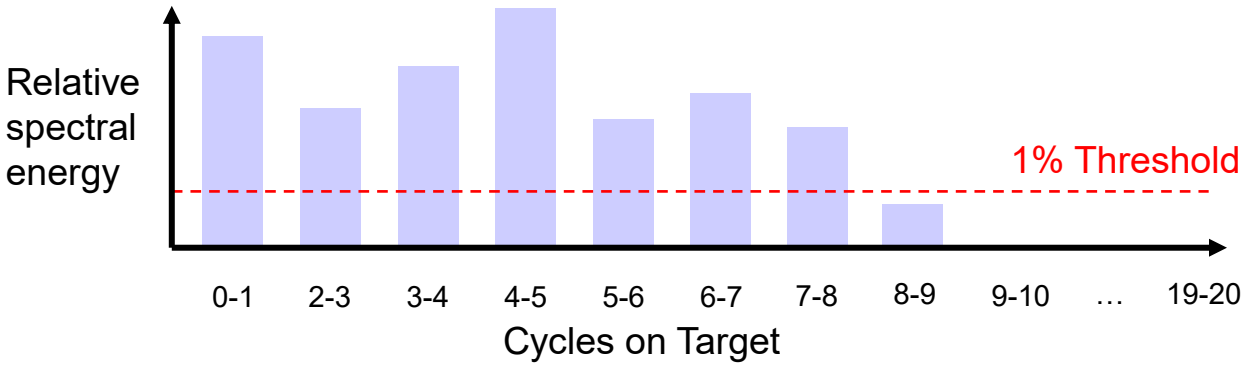
[1]

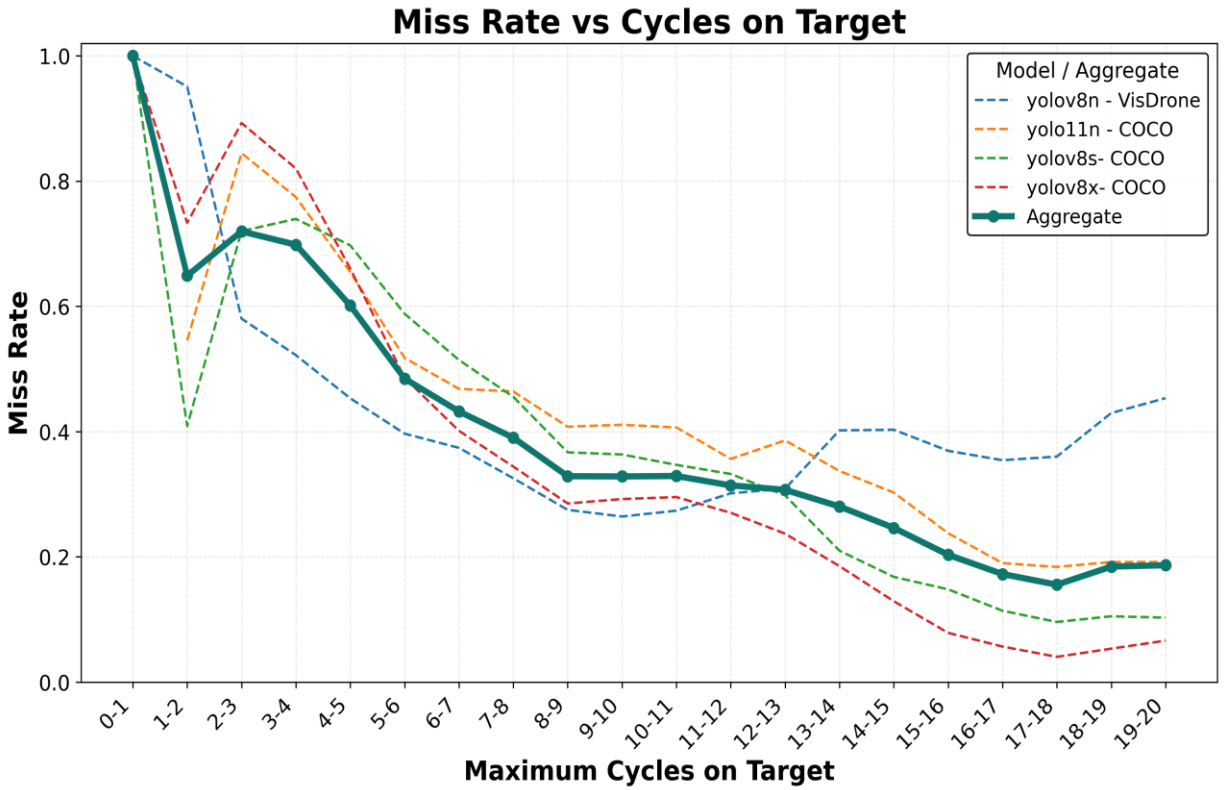


Automatic Target Recognition – Spatial Effects

Pixels on Target ≠ Spatial Information

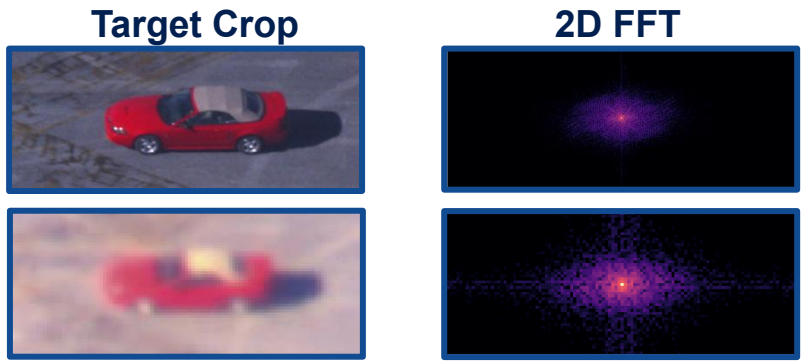


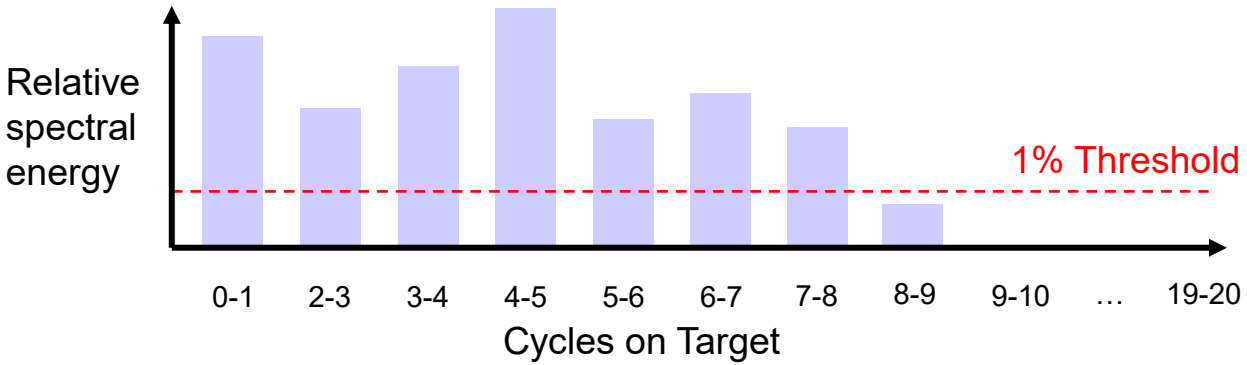


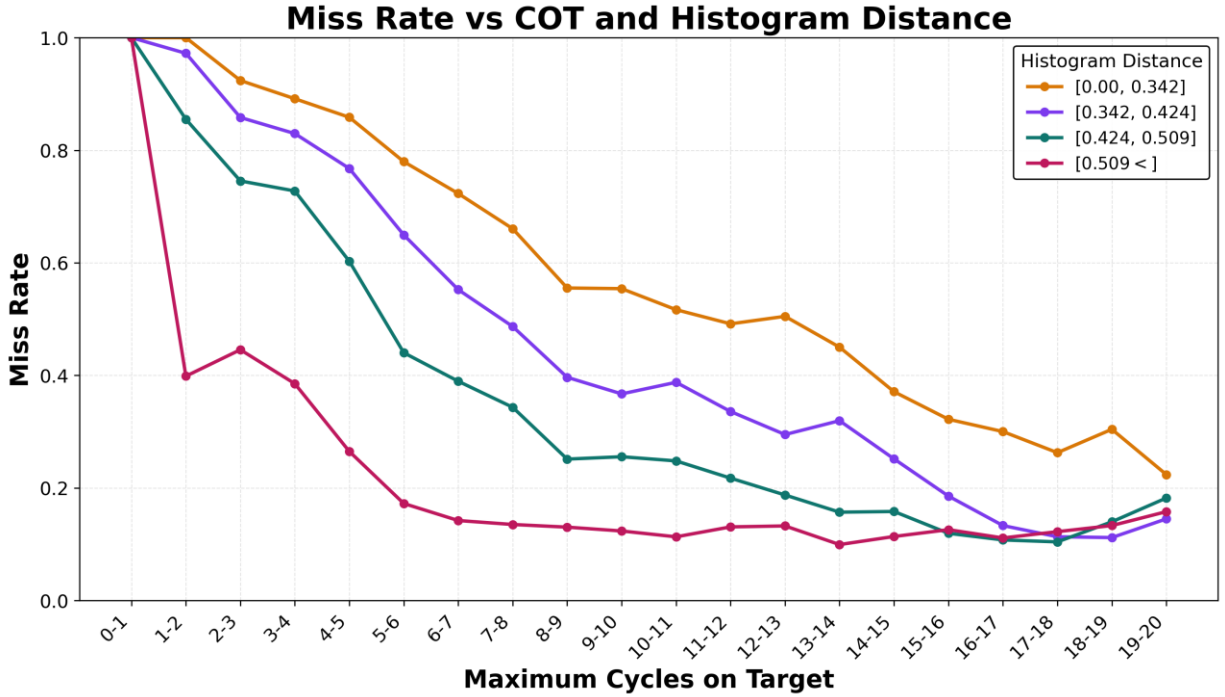


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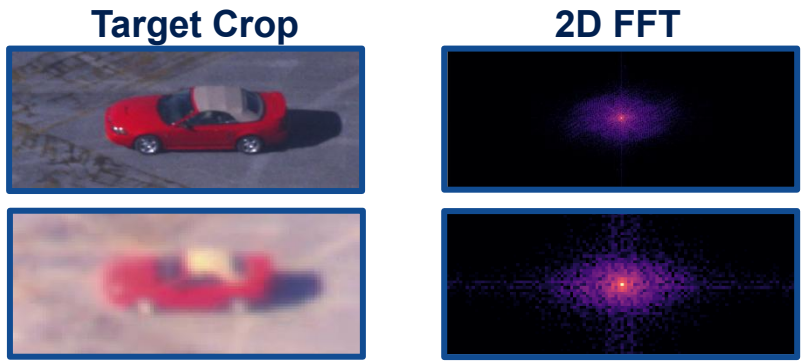


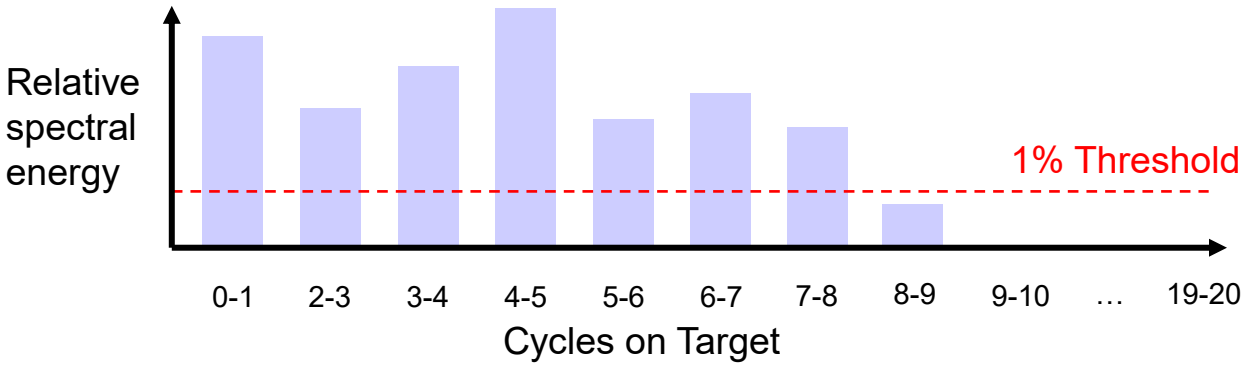


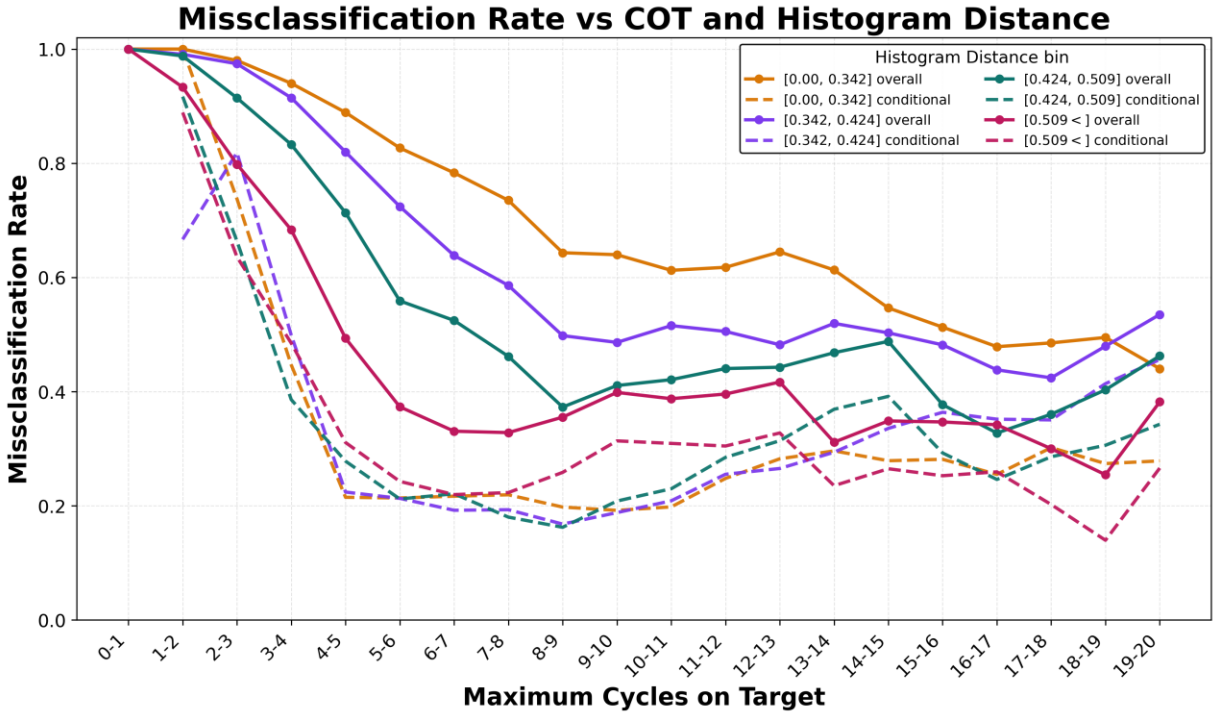


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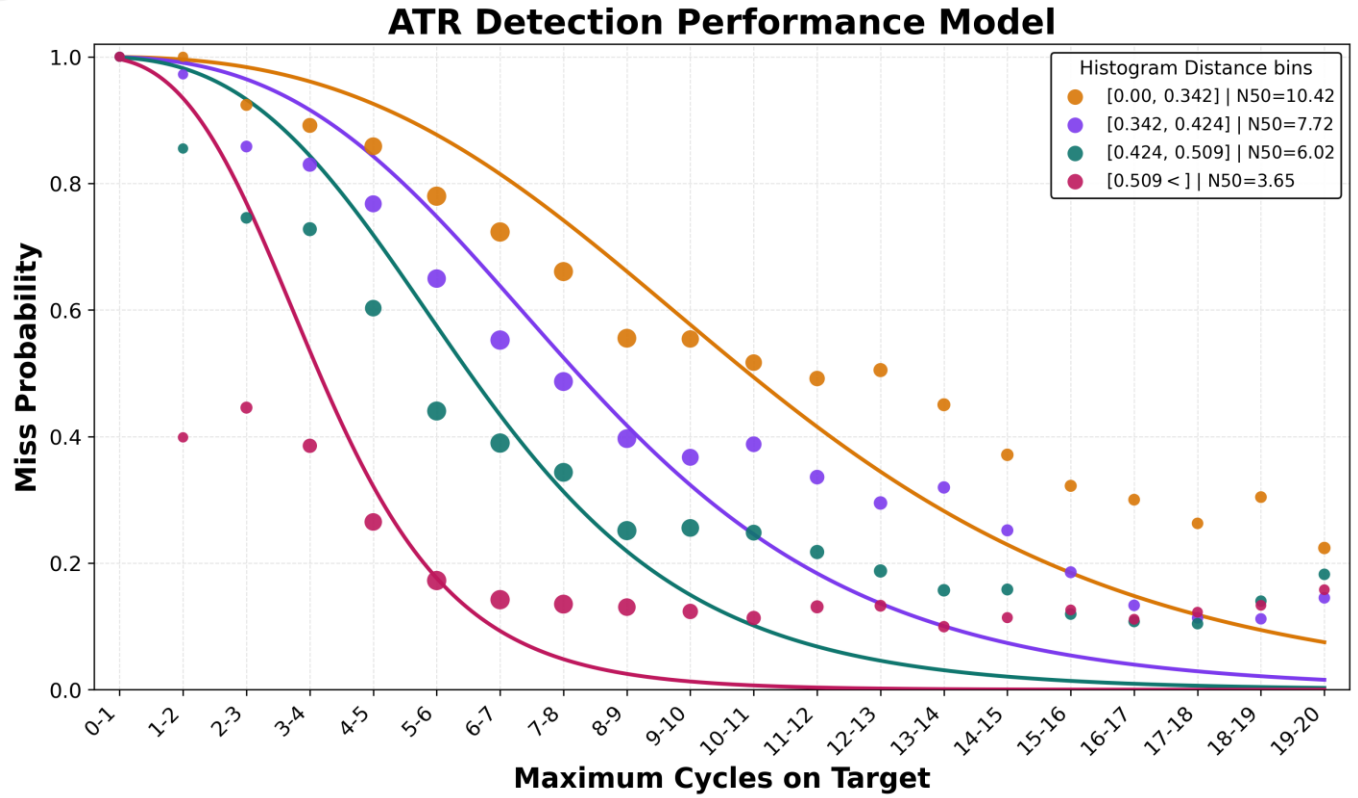
Automatic Target Recognition – Performance Modelling

Adapt Johnson Criteria curves for human observers to ATR

$$P_D = \frac{\left(\frac{N}{N_{50}}\right)^E}{1 + \left(\frac{N}{N_{50}}\right)^E}$$

$$E = 2.7 + 0.7\left(\frac{N}{N_{50}}\right)$$

Bin	Histogram Distance	N_{50} Detection	N_{50} Classification
1	[0.00, 0.342]	10.42	12.58
2	[0.342, 0.424]	7.72	9.50
3	[0.424, 0.509]	6.02	7.76
4	[0.509 <]	3.65	5.61



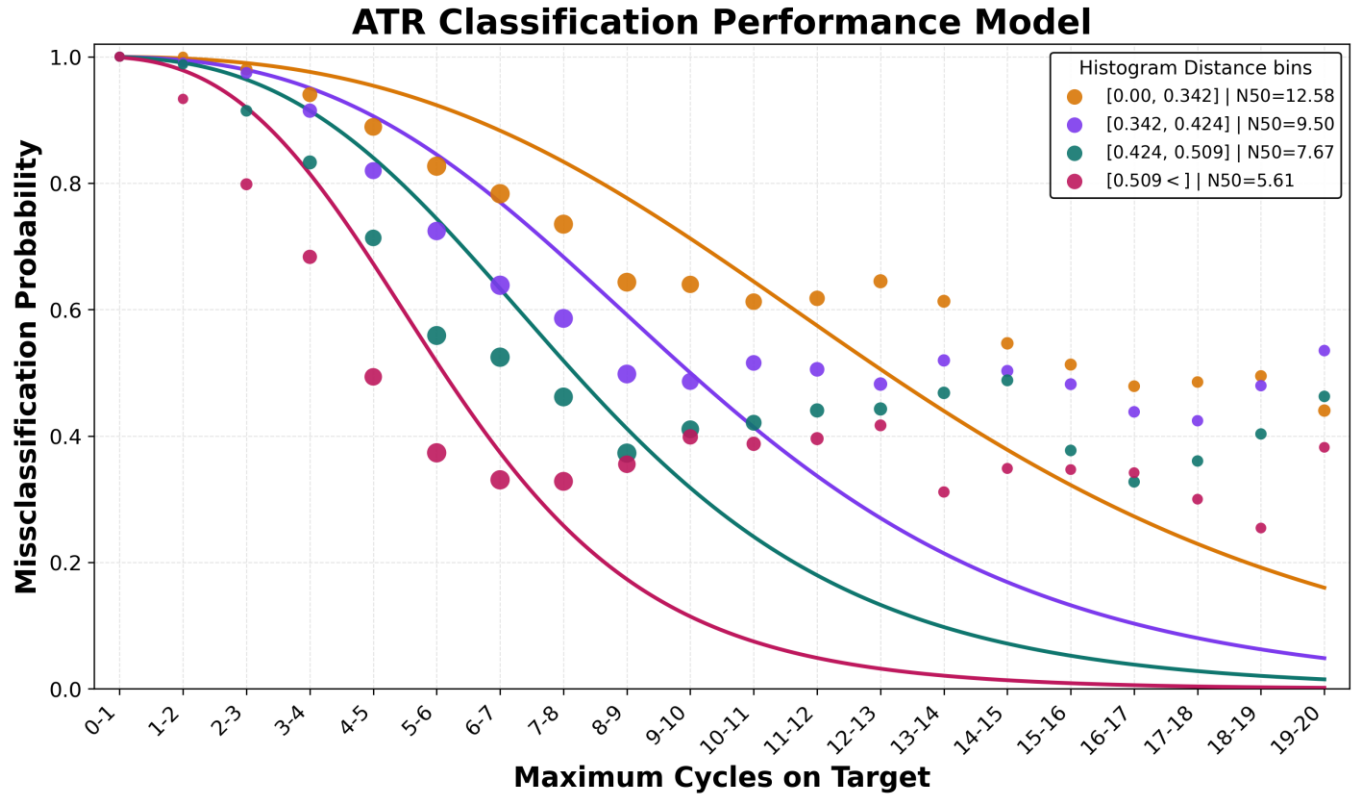
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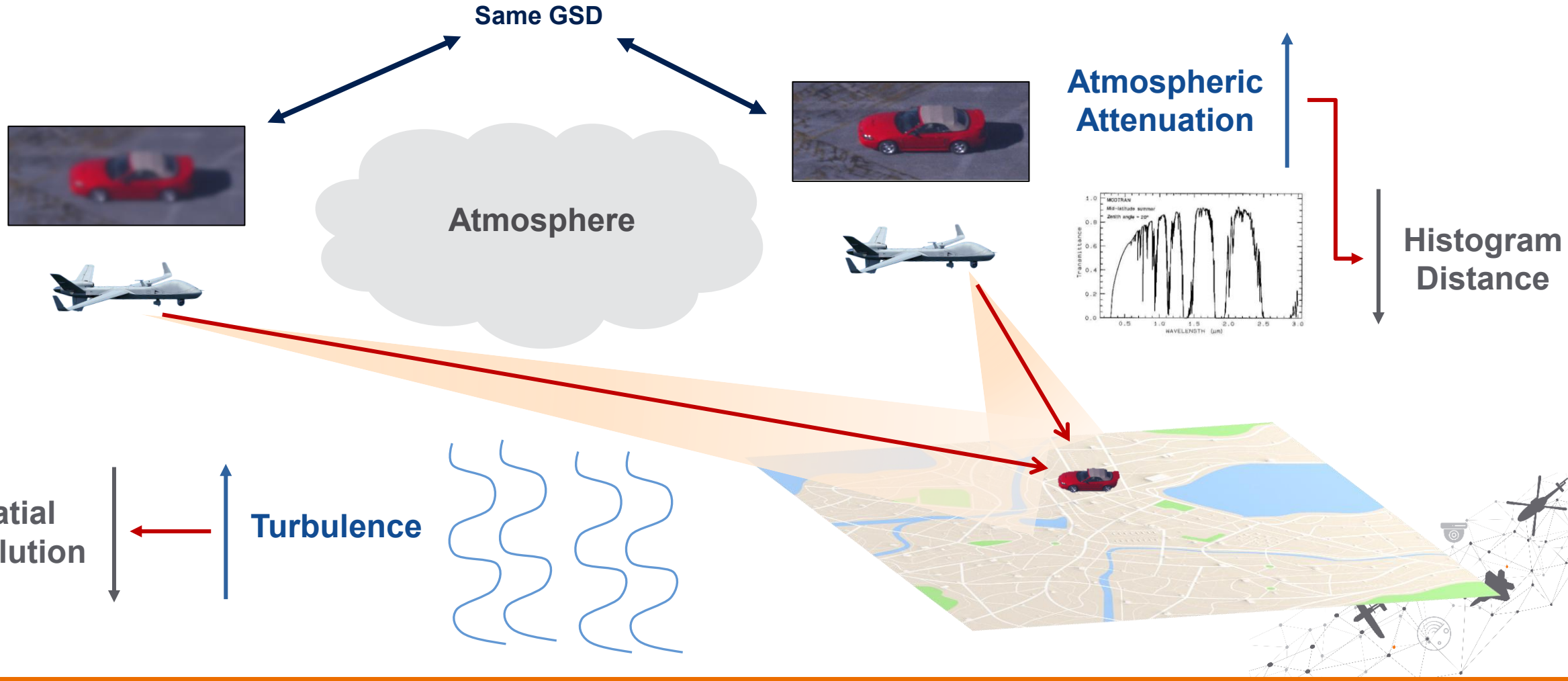
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Impact of the Atmosphere on Detection Performance



EO/IR Sensor Performance Model

1 Mission Inputs

- Target & Background
- EO/IR spectral band
- Atmosphere
- Task: Detection/ Classification

2 Expected Image Quality

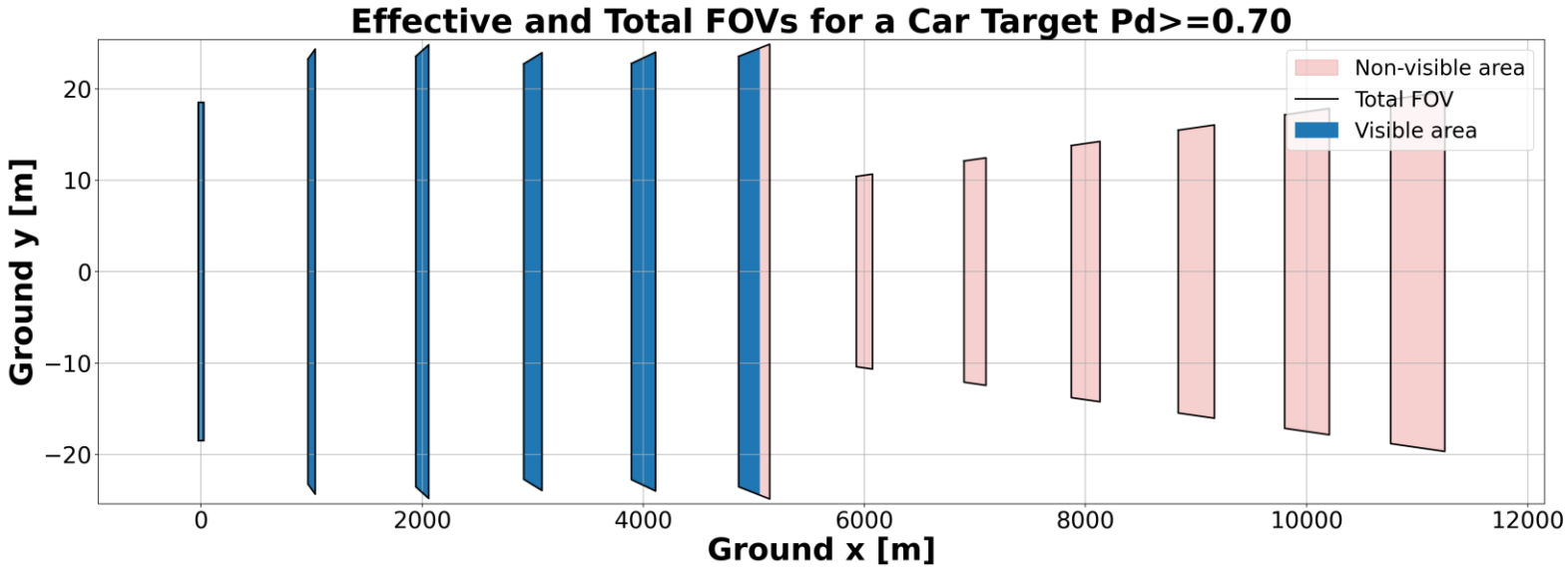
- Target-background Histogram Distance
- Spatial detail (COT)

2 ATR Performance

- Detection / Classification probability

4 Sensor Optimization

- Select configuration that maximizes usable coverage



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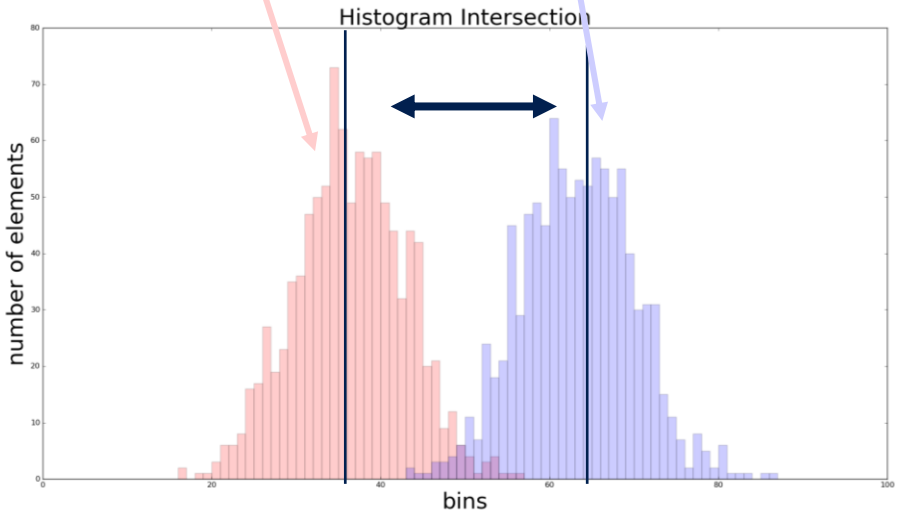
Peter Stütz *(Professor for Aeronautical Engineering)*
Institute of Flight Systems
University of the Bundeswehr Munich
Neubiberg, Germany
peter.stuetz@unibw.de

[1] : https://mpatacchiola.github.io/blog/2016/11/12/the-simplest-classifier-histogram-intersection.html

Performance Models for Airborne EO/IR Sensor Deployment Planning Considering the Complete Image Chain

Automatic Target Recognition – Target-to-Background Histogram Distance





[1]

$$R_B = R_C \setminus R_T$$

$$p_T(k) = \frac{n_T(k)}{\sum_{j=1}^{N} n_T(j)}, \qquad p_B(k) = \frac{n_B(k)}{\sum_{j=1}^{N} n_B(j)}, \qquad k = 1, \ldots, N,$$

$$\sum_{k=1}^{N} p_T(k) = \sum_{k=1}^{N} p_B(k) = 1$$

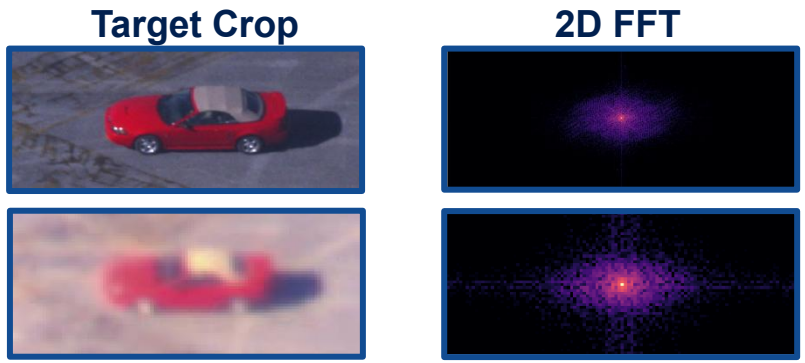
Bhattacharyya Distance

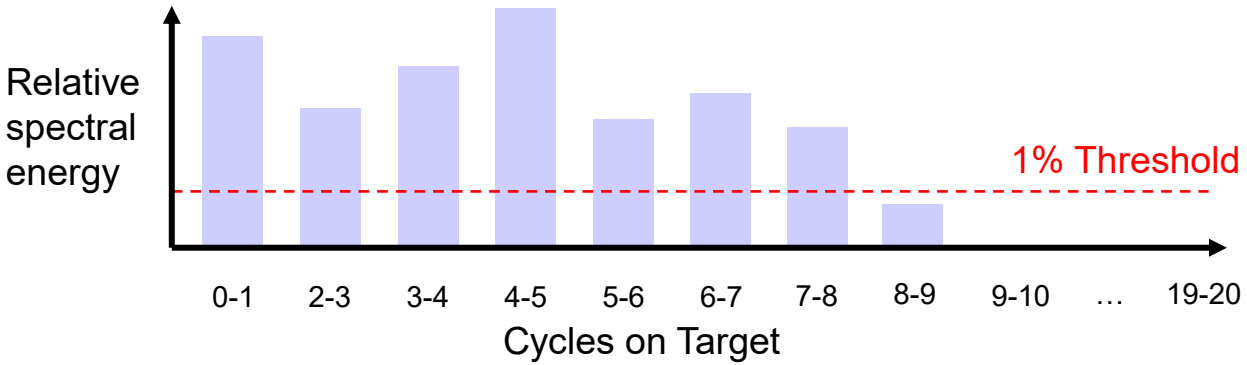
$$BC(p_T, p_B) = \sum_{k=1}^{N} \sqrt{p_T(k) p_B(k)}.$$

$$D_{\text{hist}} = \sqrt{1 - BC(p_T, p_B)}.$$

Automatic Target Recognition – Spatial Effects

Pixels on Target ≠ Spatial Information





$$E(u,v) = |F(u,v)|^2$$

$$C(u,v) = L_T f_r(u,v)$$

$$R_E(C_1, C_2) = \frac{\sum\limits_{C_1 \leq C(u,v) < C_2} |F(u,v)|^2}{\sum\limits_{u,v} |F(u,v)|^2}.$$

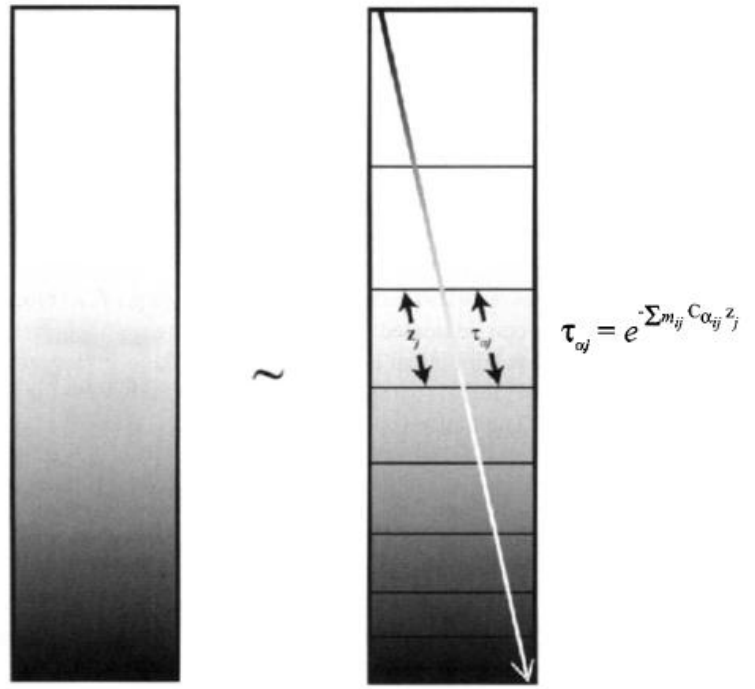
Atmosphere

Atmospheric Transmission

$$L_{\text{sensor}}(\lambda) = \tau(\lambda) L_0(\lambda) + L_{\text{path}}(\lambda)$$

$$\Delta L_{\text{sensor}} \approx \tau(\lambda) \Delta L_0$$

$$\tau(\lambda) = \prod_{i=1}^{N} \tau_i(\lambda) = \exp\left(- \sum_{i=1}^{N} \beta_i(\lambda) z_i \right)$$



(a) Continuously varying atmosphere.

(b) Approximation to atmosphere (a) with nine layers, each of which is homogeneous.

Atmosphere

Atmospheric Turbulence

$$\mathrm{MTF}(u) = \exp\left[-3.44\left(\frac{Du}{r_0}\right)^{5/3}\right]$$

$$u = \frac{\lambda F v}{D}$$

$$r_0 = \left[0.423\left(\frac{2\pi}{\lambda}\right)^2 \sec(\zeta)\int_0^H C_n^2(h)\left(\frac{h}{H}\right)^{5/3} dh\right]^{-3/5}$$

