SAND200-####C

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Multinomial Pattern Matching

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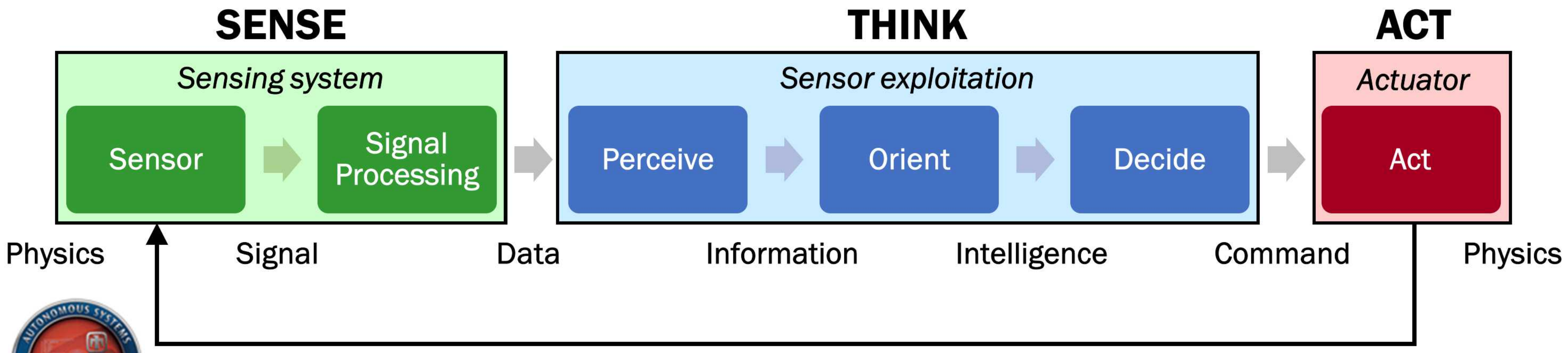
Overview

Multinomial pattern matching (MPM) is an object recognition algorithm designed for use with synthetic aperture radar (SAR) imagery

- Context: autonomous sensing systems
- Provide the "think" in the Sense-Think-Act loop
- Automate tasks and workflows for collaboration between users and machines



Commercial vs. defense applications

Commercial applications

- Structured environments
- Larger tolerance for error
- Large, well-labeled data sets
- Closed-set recognition often viable
- Common imaging modalities
- Usually involves class-level ID
- Will accept high Pfa to get high Pd
- Black-box systems are acceptable
- Good network connectivity
- Can compute in the cloud

Defense applications

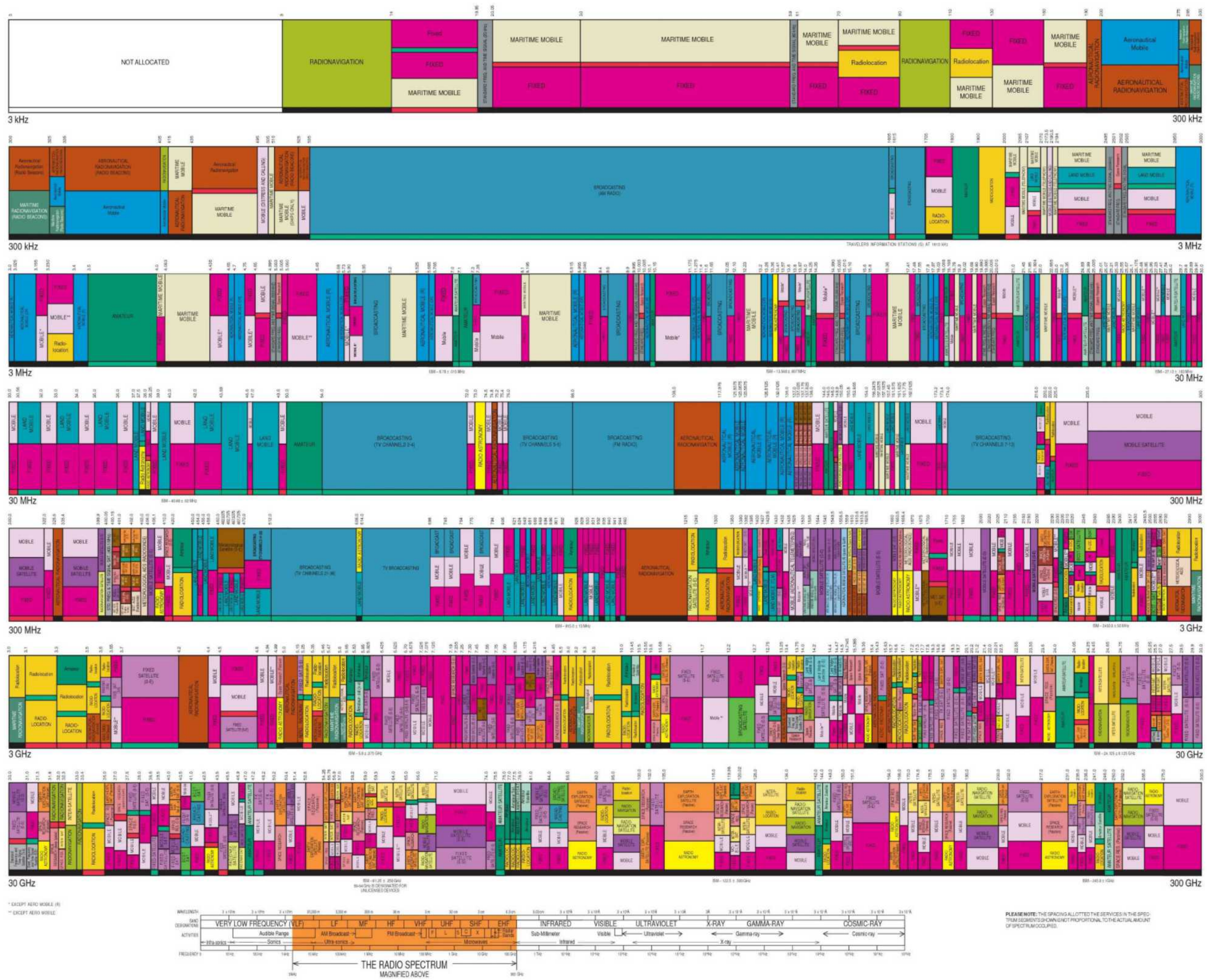
- Adversarial environments
- Very low tolerance for error
- Limited, poorly-labeled data sets
- Open-set recognition usually essential
- Esoteric imaging modalities
- Usually requires type-level ID
- Will accept low Pd to get low Pfa
- Results must be fully explainable
- Little or no network connectivity
- All computation must be on-board

Defense applications generally must operate in different contexts and under different constraints than commercial applications

Radar sensing

- Long standoff
- All-weather
- Day/night
- Wide-area
- Fine resolution
- Operational use

US radio frequency allocations



Synthetic aperture radar (SAR)

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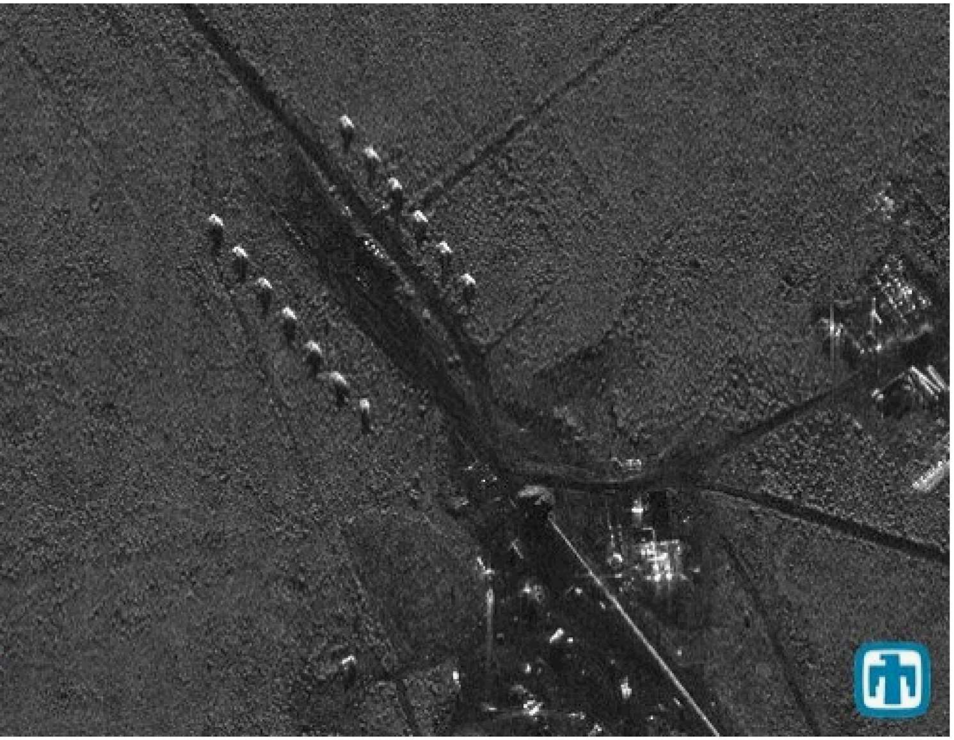
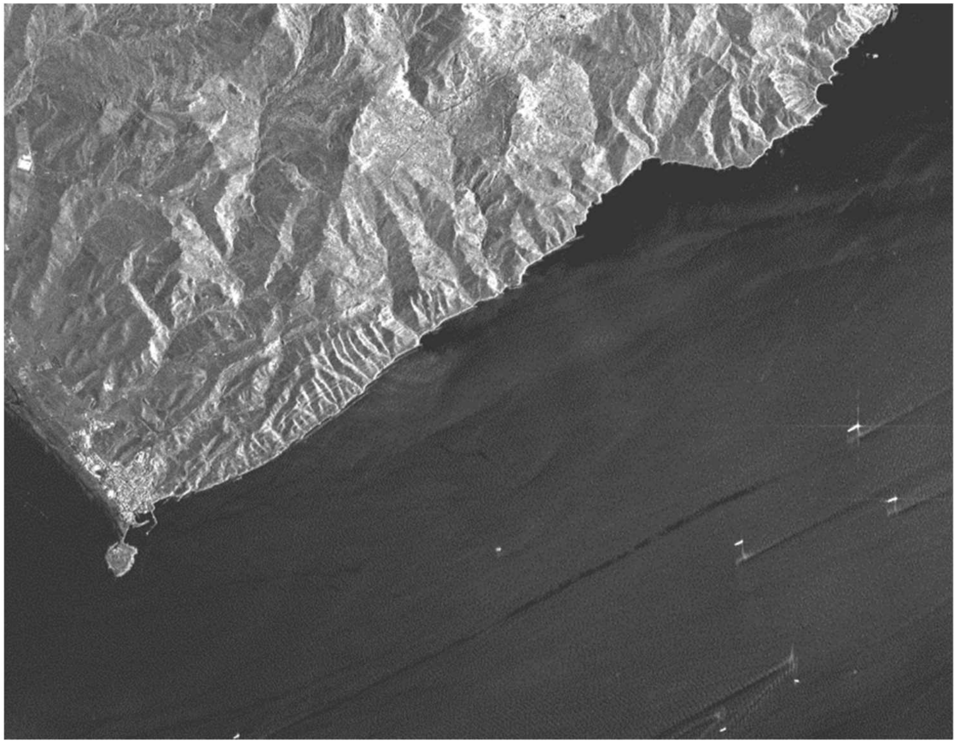




Optical imagery vs. SAR imagery

Optical imagery

- Signatures dominated by diffuse returns
- Signatures stable across wide changes in geometry
- Resolution varies with range
- Angle/angle axes
- Magnitude-valued imaging
- Often abundant
- Simulation often fast and high-fidelity

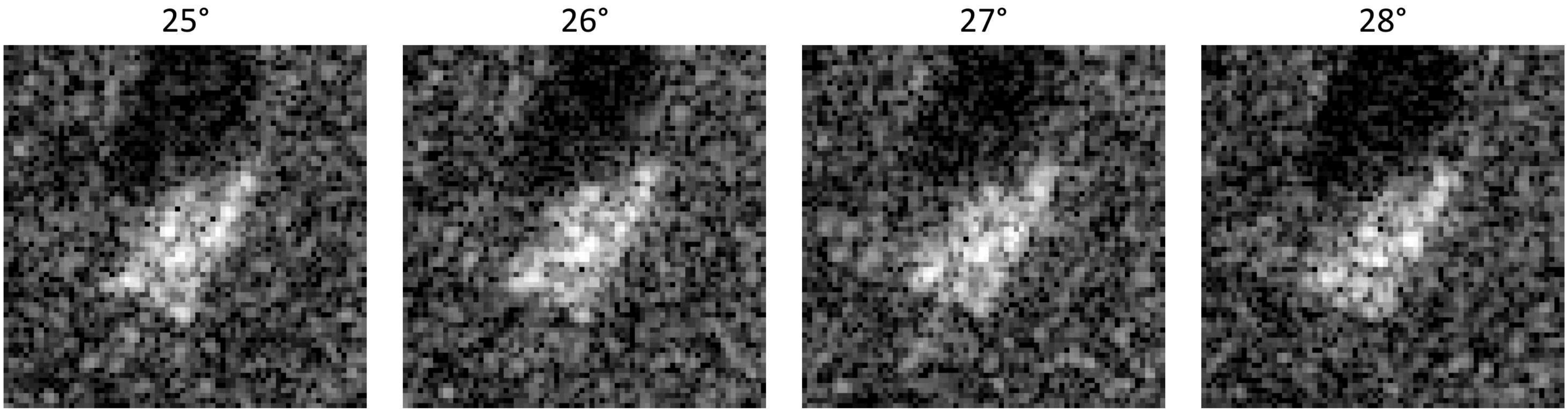
SAR imagery

- Signatures dominated by specular returns
- Signatures vary strongly with small changes in geometry
- Resolution fixed with range
- Range/angle axes
- Complex-valued imaging
- Usually limited
- Simulation usually slow and low-fidelity

Object recognition approaches designed for optical imagery usually do not work well with SAR imagery

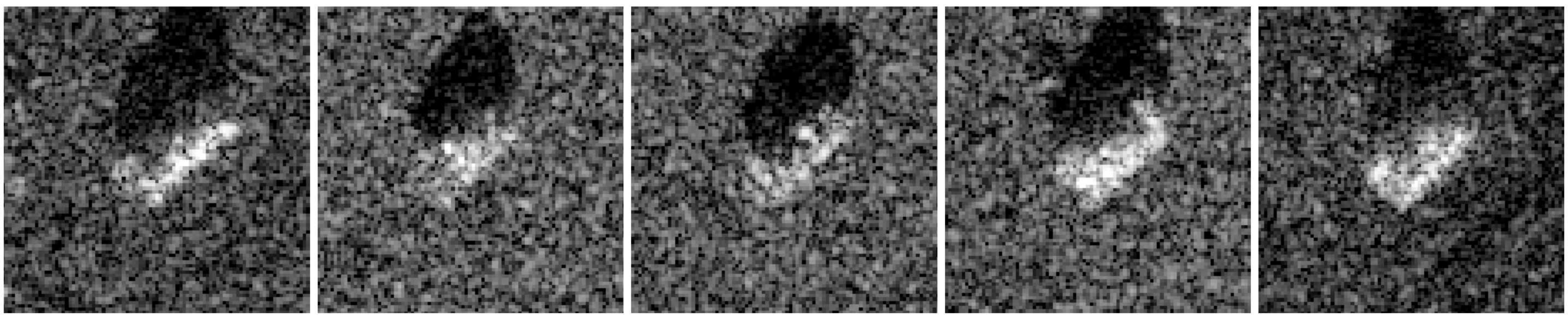
SAR target signatures

T72 SAR chips (25°–28°)



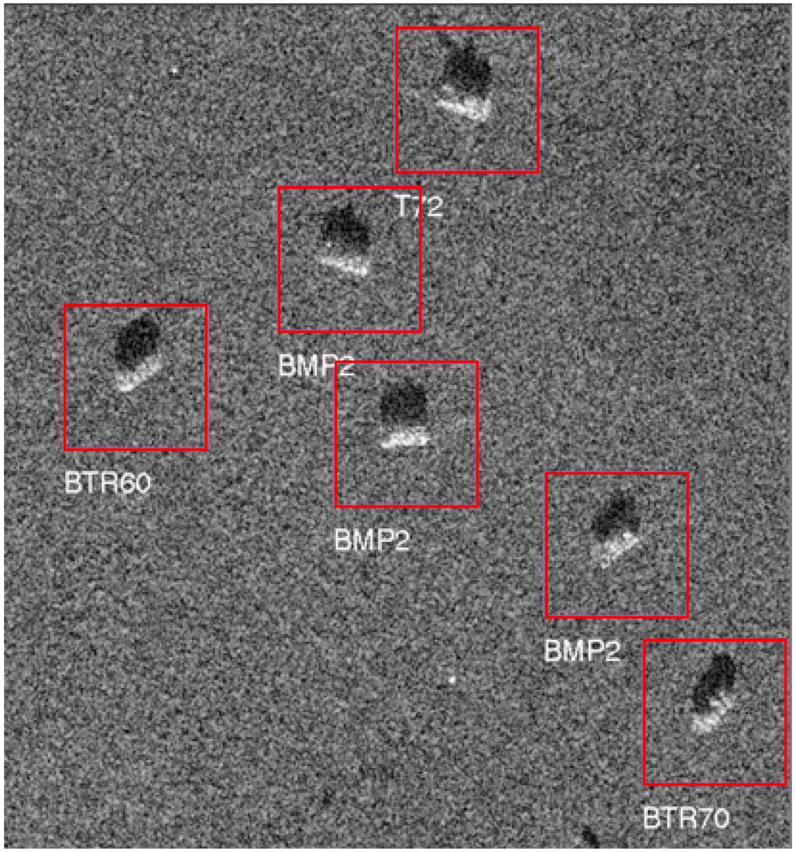
SAR target signatures

2S1 BMP2 BTR70 T72 ZSU23

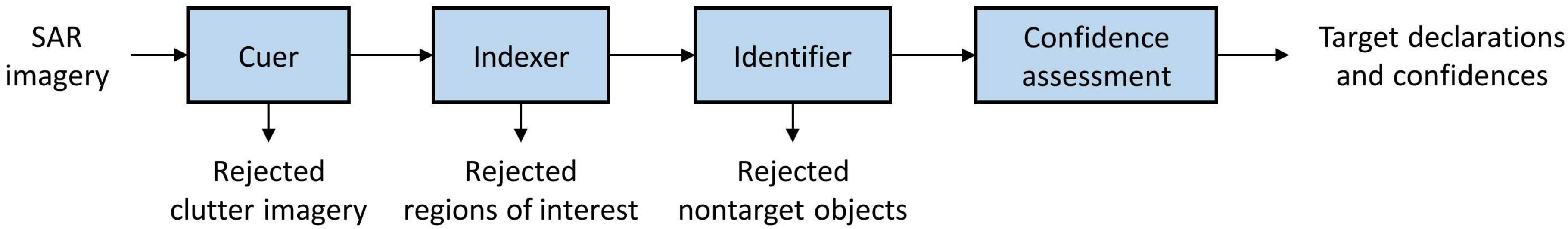


Automatic target recognition (ATR)

- Operational goals
  - Detect and identify targets of interest
  - Direct human or machine attention to relevant portions of imagery or signal data streams
  - Provide target-identity results for analyst or machine interpretation
- Link to synthetic aperture radar
  - In wide operational use
  - Operational SAR spurred the need for ATR in national security applications
- Implementation requirements
  - Must operate in real time
  - Must reject unknown target types
  - Must be trainable with almost no real data



A typical SAR ATR

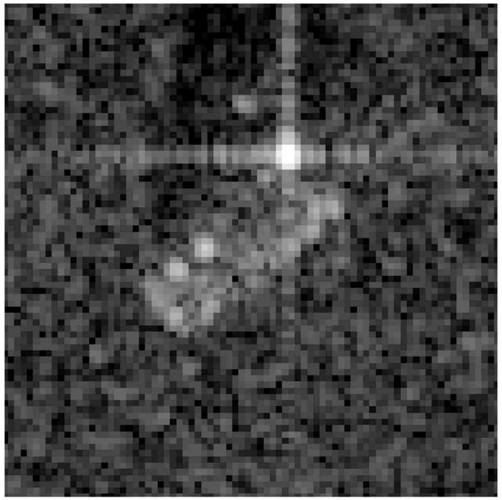


- Cuer
  - Strips potential target regions from background clutter
  - Processes large amounts of imagery very quickly
- Indexer
  - Rejects obvious nontarget regions falsely passed by cuer
  - Passes likely targets to identifier with type and pose hypotheses
- Identifier
  - Tests signatures against type and pose hypotheses
  - Calculates match scores indicating similarity of signature to each hypothesis
- Confidence assessment
  - Assigns probabilities to each target type possibility
  - Quantifies uncertainty for machine processing and human interpretation

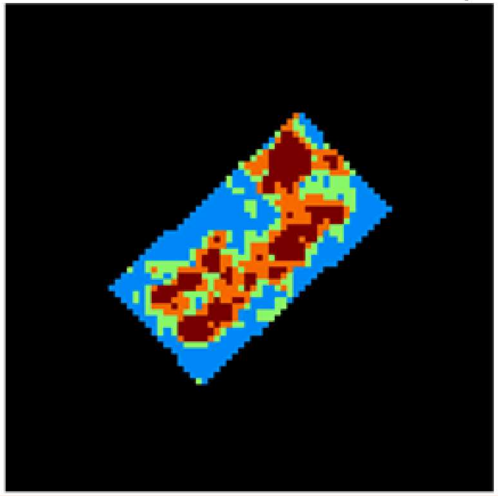
Multinomial pattern matching (MPM)

- Identifier algorithm
  - Produces match scores representing similarity between observed signatures and target models
  - Tests ROIs and hypotheses provided by cuer and indexer
- Employs multinomial transform
  - Maps amplitudes to quantiles
  - Discards absolute pixel amplitudes in favor of relative pixel amplitudes
- Represents targets with statistical models of multinomial distributions at each pixel
  - Accommodates real-world signature variation
  - Models attributes of each target type, not differences between types
- Match scores separate targets, nontargets
  - Can be thresholded to yield declarations
  - Can be fused with other identifiers
  - Can be used to calculate confidences
  - Open-set classification

Raw SAR chip



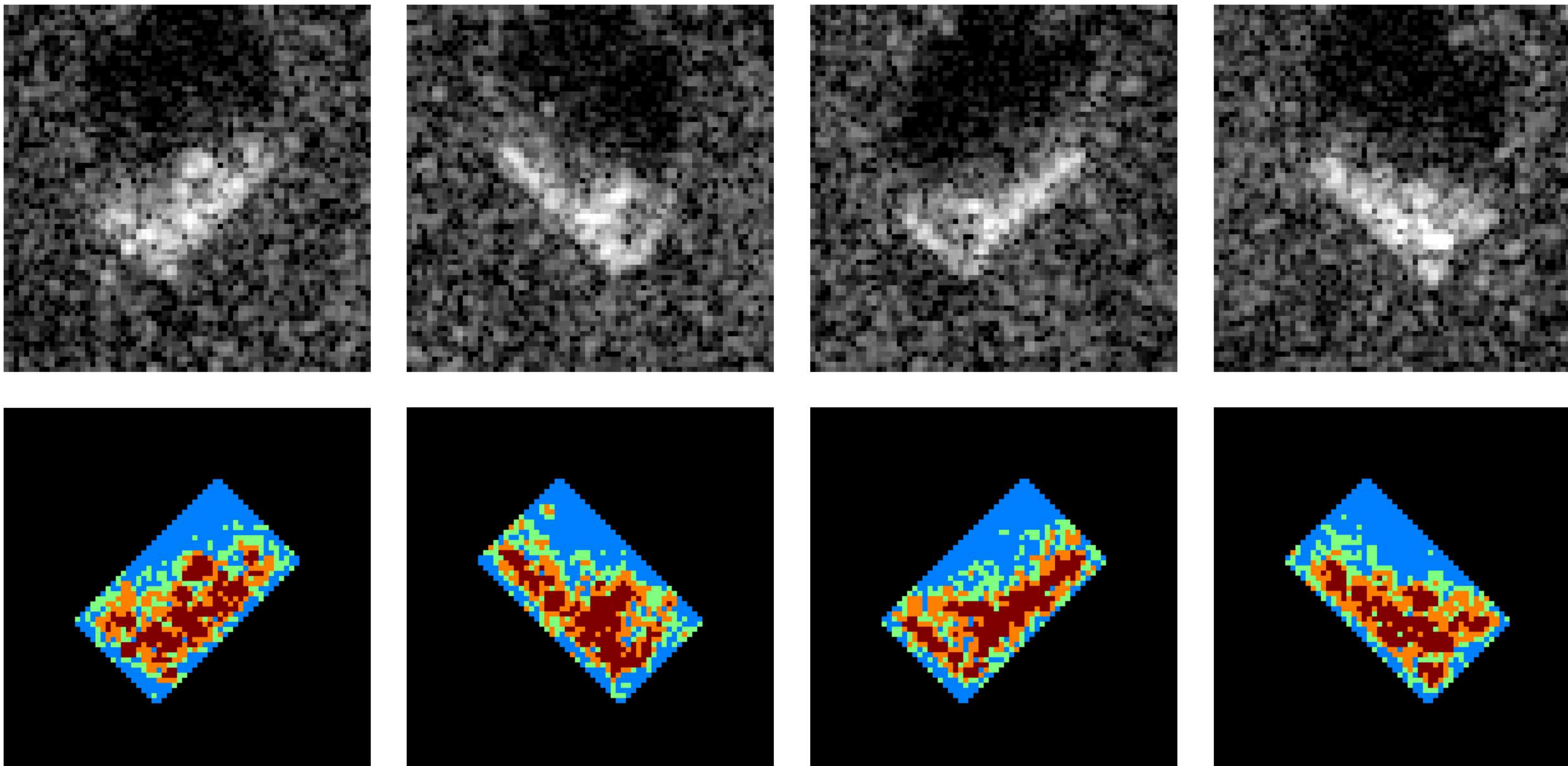
Multinomial-transformed chip



MPM examples

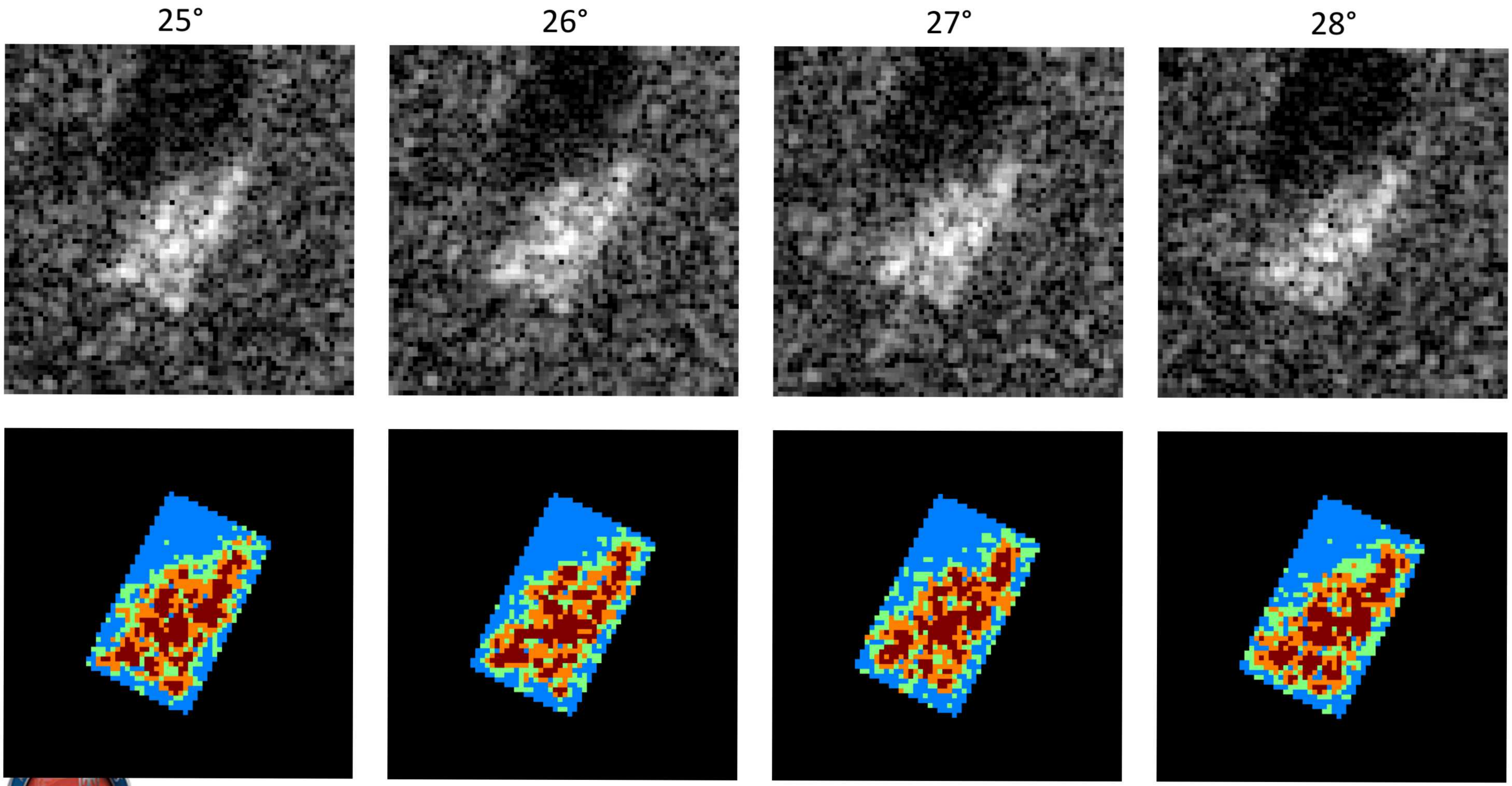
Four-quantile MPM transform applied to T72 SAR chips (45°–315°)

45° | 135° | 225° | 315°



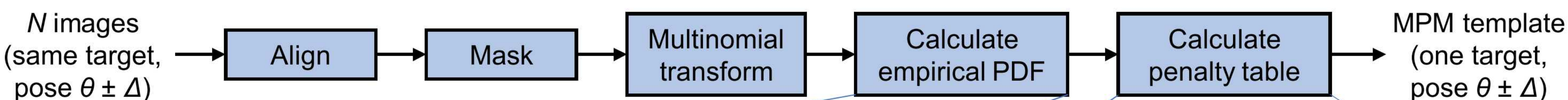
MPM for SAR

Four-quantile MPM transform applied to T72 SAR chips (25°–28°)



MPM training

- Offline process for statistical characterization
  - Each statistical representation is called a template
  - A template is a pixelwise lookup table of quantile penalties
  - Distinct templates for each target at each geometry
- Templates are usually trained from simulated data
- Rule of thumb: ≥ 10 signatures per template

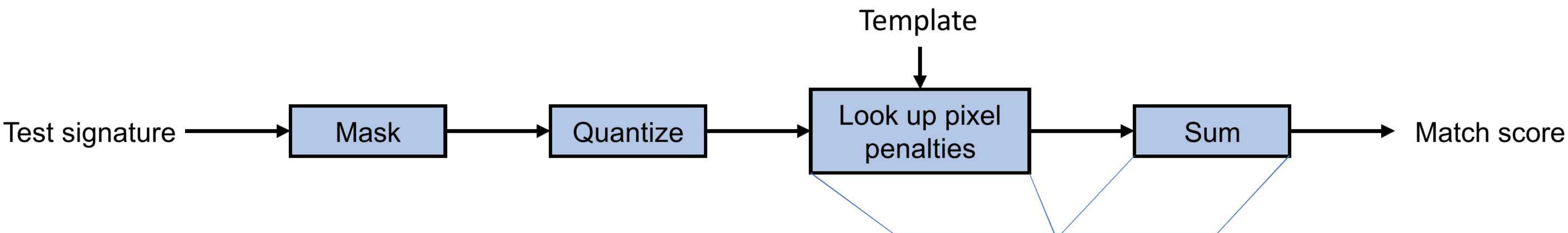


$$\tilde{p}_{k,m} = \frac{\mathrm{count}(q_k = m) + v}{N + vM}$$

$$t_{k,m} = \frac{\left(1 - \tilde{p}_{k,m}\right)^2 - \mu_{k,m}}{\sigma_{k,m}}$$

MPM testing

- Online process for match-score calculation
- Compare collected signature (cuer ROI) to template (indexer hypo)
- Process signature match scores to yield identification

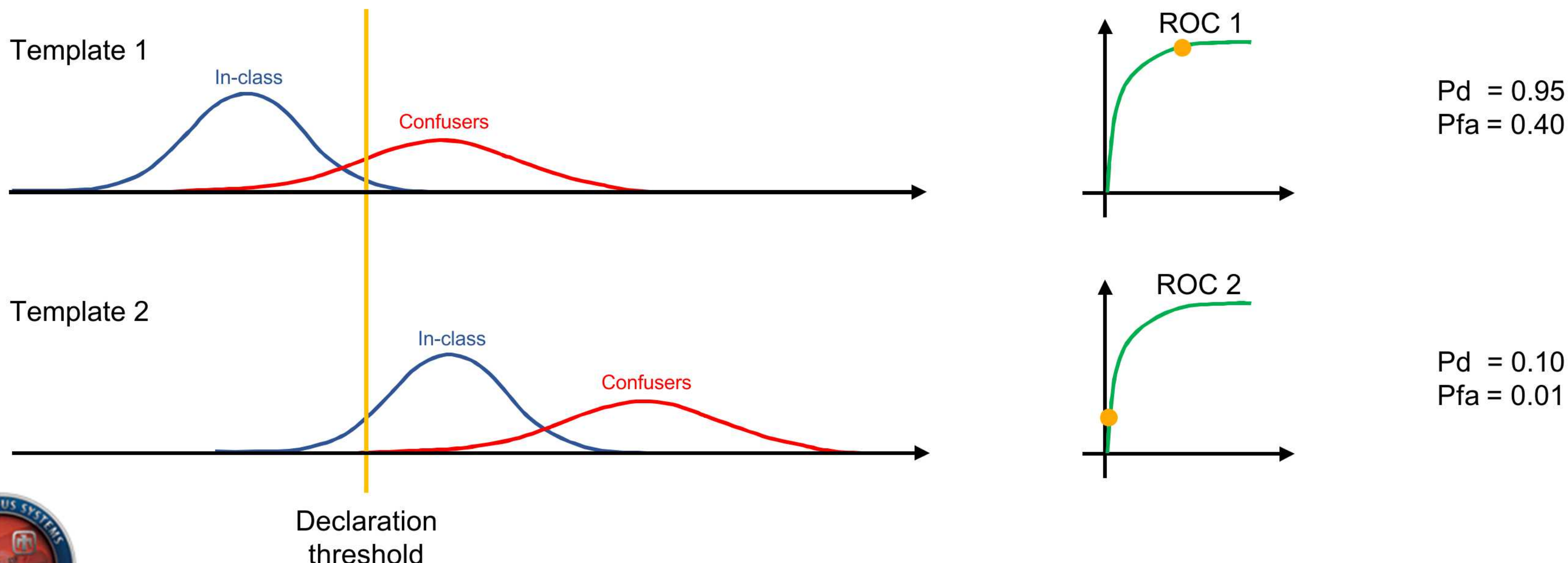


$$Z = \frac{1}{\sqrt{K}} \sum_{k=1}^{K} t_{k,q_k}$$

- For signatures drawn from training distribution, $Z \sim N(0,1)$
- For signatures drawn from another distribution, $Z >> 0$
- Simple thresholding operation provides open-set recognition

MPM validation

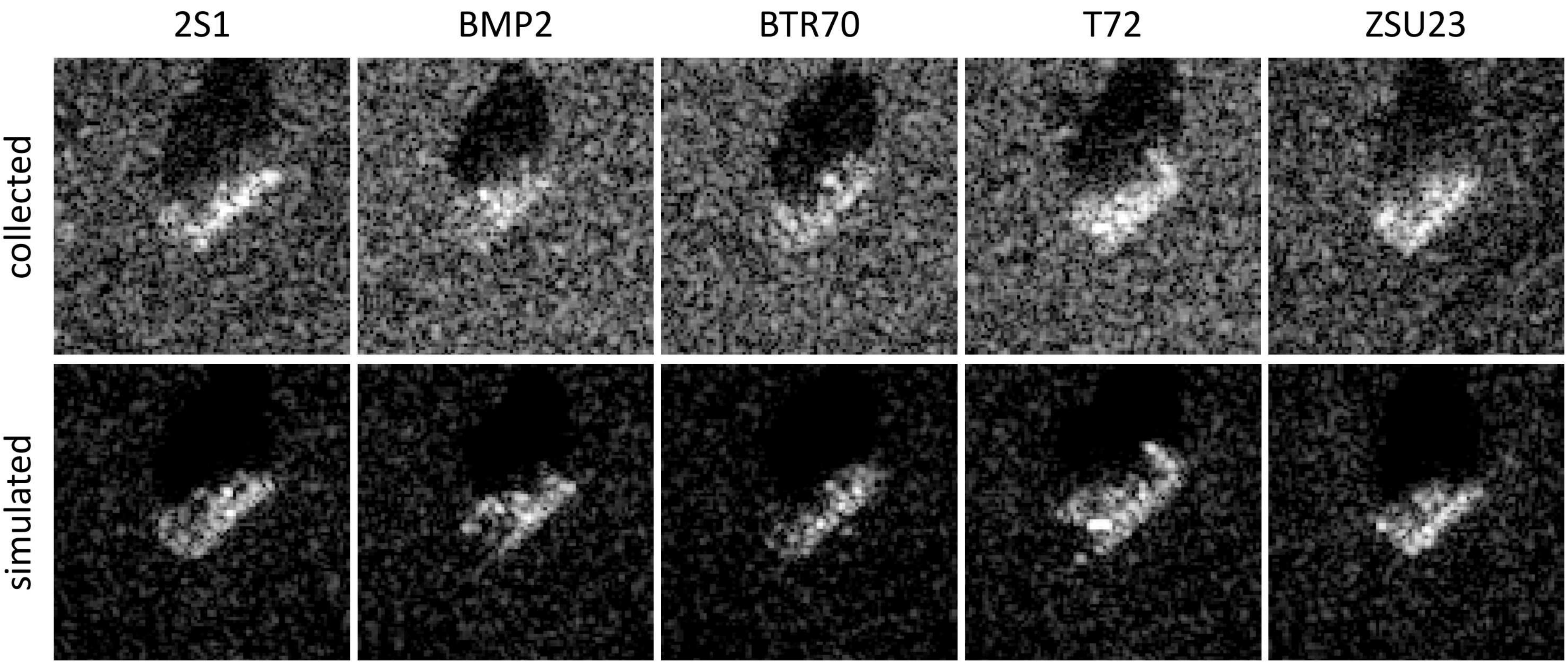
- Offline process performed after training
- Bias and scale empirical template match-score distributions
- Accommodate unmodeled variability and simulation effects
- Equalize response between templates
- Allows approximate dialing-in of Pd (given in-class validation data) or Pfa (given out-of-class validation data)



SAMPLE dataset

- Public SAR dataset from AFRL
- Multiple targets
- Multiple geometries
- Simulated and collected data

SAMPLE dataset



MPM SAMPLE experiment

- Train templates from simulated data
  - Four targets: 2S1, BMP2, BTR70, T72
  - Five-degree azimuth pose bins from 10°–80°

- Validate/bias templates with 10 random collected signatures per target

- Test all collected data for five vehicles
  - Four trained targets: 2S1, BMP2, BTR70, T72 (correct ATR response: ID as trained type)
  - One untrained confuser: ZSU23 (correct ATR response: reject)

- Assume naïve indexer
  - Each signature is tested against all four templates
  - Each signature is tested at all poses within 20° of truth

2S1

BMP2

BTR70

T72

ZSU23

MPM SAMPLE experiment results

Confusion matrix

	2S1	BMP2	BTR70	T72	Reject
2S1	**0.397**	0.006	0.086	-	0.512
BMP2	0.065	**0.411**	-	-	0.523
BTR70	0.022	-	**0.500**	-	0.478
T72	-	-	0.019	**0.574**	0.407
ZSU23	0.006	-	0.086	-	**0.908**

- Pdec = 0.516 — "When given a target, how often does the ATR speak?"
- Pid|dec = 0.891 — "When the ATR speaks about a target, how often is it correct?"
- Pcc = 0.837 — "When the ATR speaks, how often is it correct?"
- Pfa = 0.092 — "When given a nontarget, how often does the ATR speak?"
- CRR = 0.908 — "When given a nontarget, how often is the ATR remain silent?"

Summary

Multinomial pattern matching (MPM) is an object recognition algorithm designed for use with synthetic aperture radar (SAR) imagery

- Statistically grounded
- Template-based
- Fully explainable
- Computationally efficient
- Trainable from simulated data
- Robust to SAR variation
- Type-level recognition
- Open-set recognition