INTEGRATED SENSOR IS STRUCTURE

ISIS KASSPER

KNOWLEDGE-AIDED SENSOR SIGNAL PROCESSING AND EXPERT REASONING

Knowledge-Aided Sensor Signal Processing and Expert Reasoning

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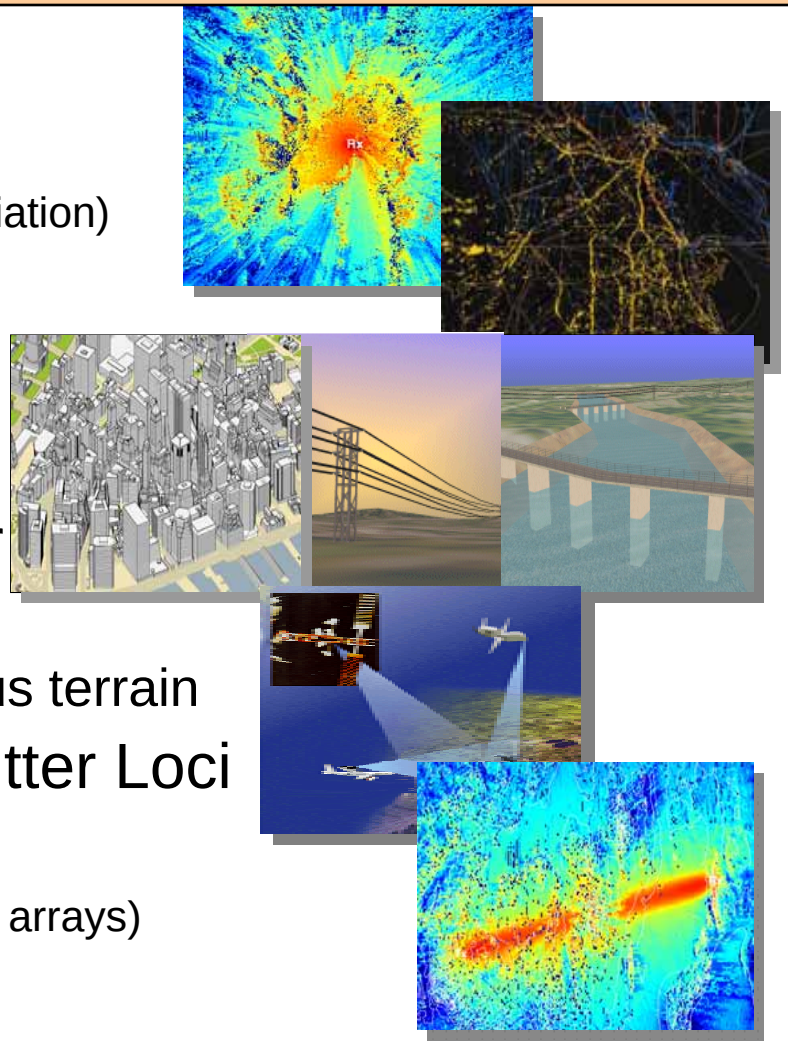
DARPA/SPO

23 February 2005

When is There a Problem?

Extremely suboptimal radar performance can occur if one or more of the following occurs:
(High false alarm rates and/or low P_d)

- Heterogeneous Clutter
  - Rapidly varying terrain
    - Mountainous (rapid elevation/reflectivity variation)
    - Rapid land cover variations (e.g., littoral)
- Dense "Target" Backgrounds
  - "Moving Clutter"
    - Military/civilian vehicles
- Large Discretes and "Spiky" Clutter
  - Urban clutter
  - Power lines, towers, steep mountainous terrain
- Range-Varying (Nonstationary) Clutter Loci
  - Bi/Multistatics
  - Nonlinear array geometries (e.g., circular arrays)

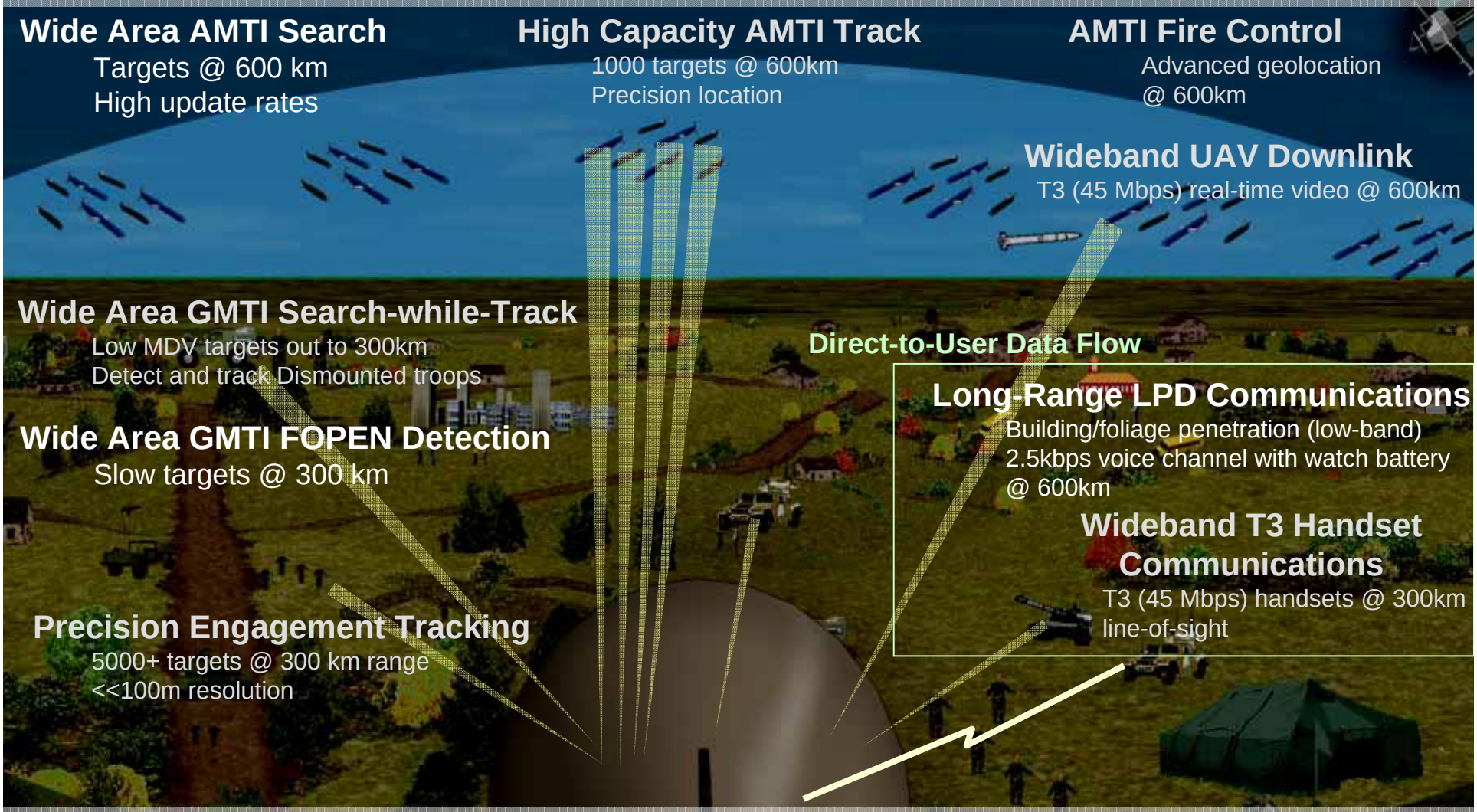


One or More of the Above is Almost Always Present in Real-World Ops!

Integrated Sensor Is the Structure (ISIS)

Special Projects Office

Simultaneous AMTI/GMTI Operation Via Dual Band (VHF/X-Band) Aperture



No In-Theater Ground Support – 99% on station availability for 1+ years
600km radar horizon at 70kft operational altitude

GMTI Challenges -- Solutions

Challenges	Solutions		DARPA Response
• Terrain			
– Blockage	Higher grazing angles/Multi-sensor coverage		ISIS
– Discretes	Improved physical and adaptive clutter isolation	KASSPER	ISIS
– Nonstationarity	Improved physical and adaptive clutter isolation	KASSPER	ISIS
• Tracking targets			
– Identification	Excess SNR		ISIS
– Reduced MDV	Improved physical and adaptive clutter isolation	KASSPER	ISIS
– Dense background	Improved training and reduced resolution	KASSPER	ISIS
• Signature management			
– Persistence	Multi-sensor coverage/slow moving platforms		ISIS
– RCS alteration	Excess SNR designs		ISIS

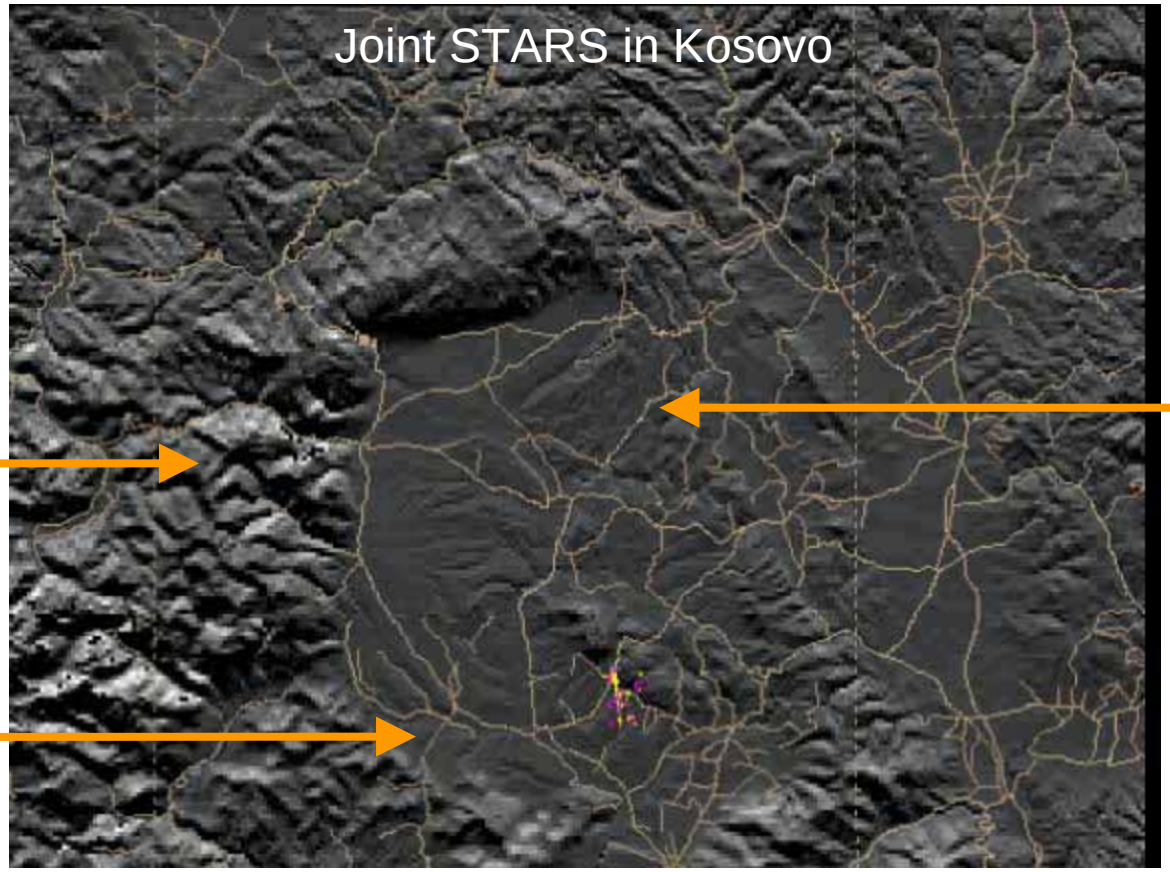
Outline

- Knowledge-aided tactical surveillance systems
- KASSPER program
  - Objective
  - Architecture
  - Algorithms & results
  - Implementation & results
  - FY05 plans
- Future knowledge-aided processing challenges
- KASSPER Workshop agenda

Today: Operator Provides Knowledge

Joint STARS operator attempts to sort “real” information from false positives

Click on Image to Play



Knowledge-aids:

DTED

VMAP Road Network

“Smoke-Trail” MTI Display

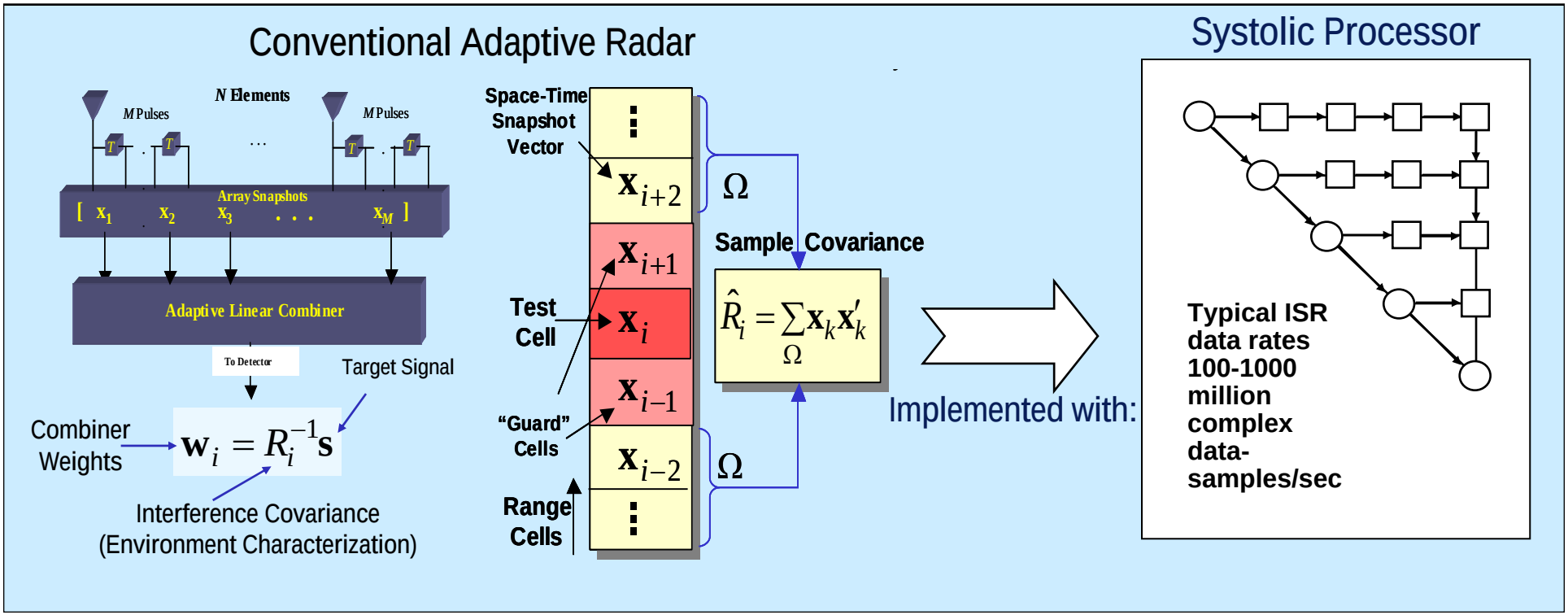
Where are the “real” targets?

High P_{fa}, Low P_d (which you can’t see) in Complex Clutter Regions

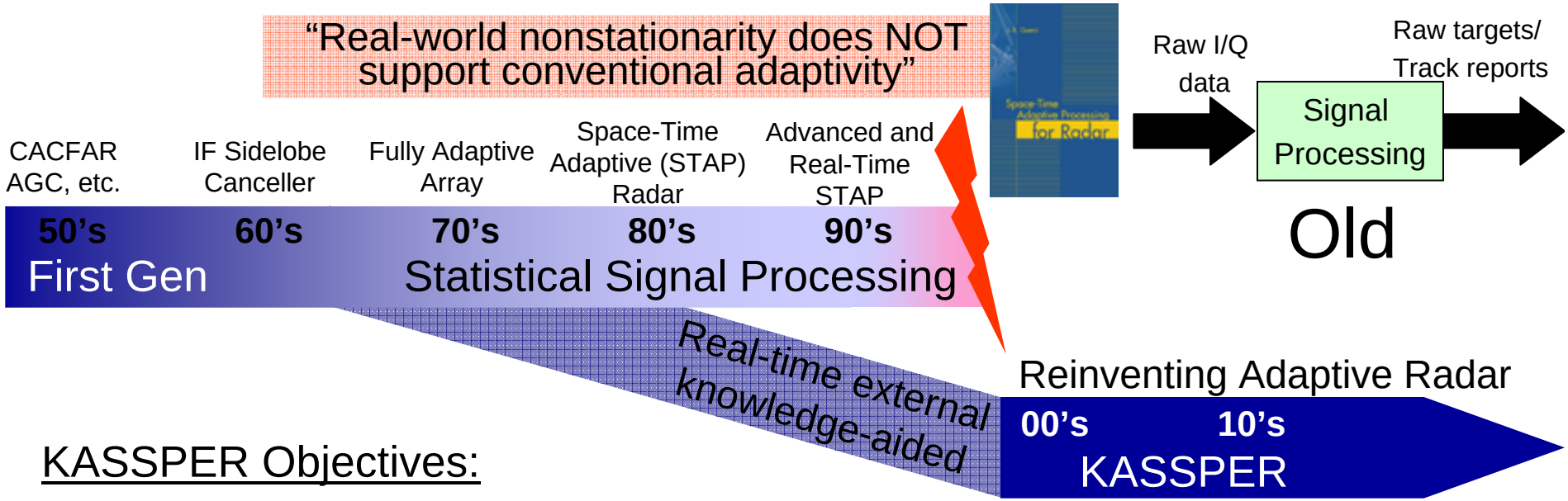
Significant Impediment to Critical Target Tracking

What are the Problems?

- Highly Restrictive Adaptation Techniques
  - Model the environment as a covariance matrix
- Ad-hoc Algorithmic Approaches
  - Tweaks of traditional statistical signal processing
- Fundamental Shift in the Basis for Adaptation Required
  - Comprehensive approach must be considered

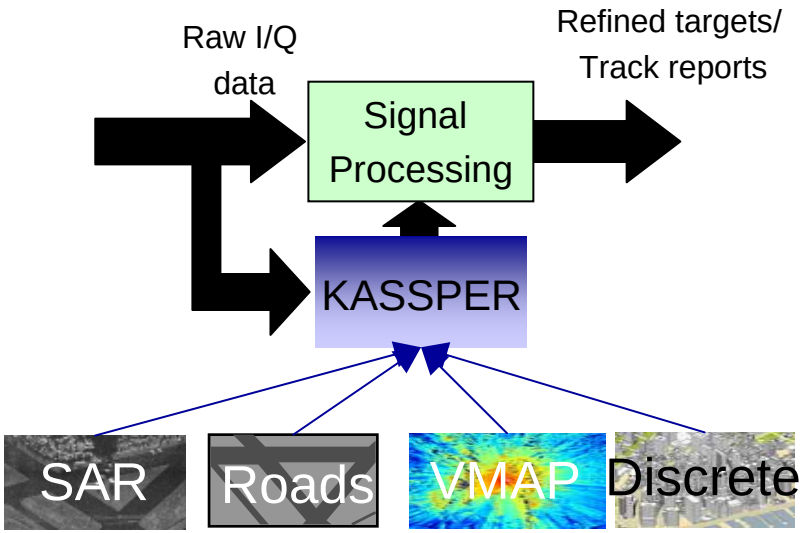


Intelligent Adaptive Radars



KASSPER Objectives:

- Dramatic improvement in P_d and P_{fa}
  - In challenging *real world* clutter environments
- Real-time, knowledge-aided sensor processing architecture
  - Moving "knowledge" from "memory" into the adaptive front-end (i.e., HPEC)



KASSPER Phased Objectives

Phase I (FY02)

Hi-Fidelity Environmental Models

Simulated data

Algorithms (non-real-time)

Real data

Go/No Go #1

✓ 10dB gains (SINR, P_{fa})

Phase II (FY03)

KASSPER Real-Time Demonstration Design
(8 channel X-band GMTI/SAR throughput)

Algorithms (real-time)

Go/No Go #2

✓ 10dB gains (SINR, P_{fa}) in real-time

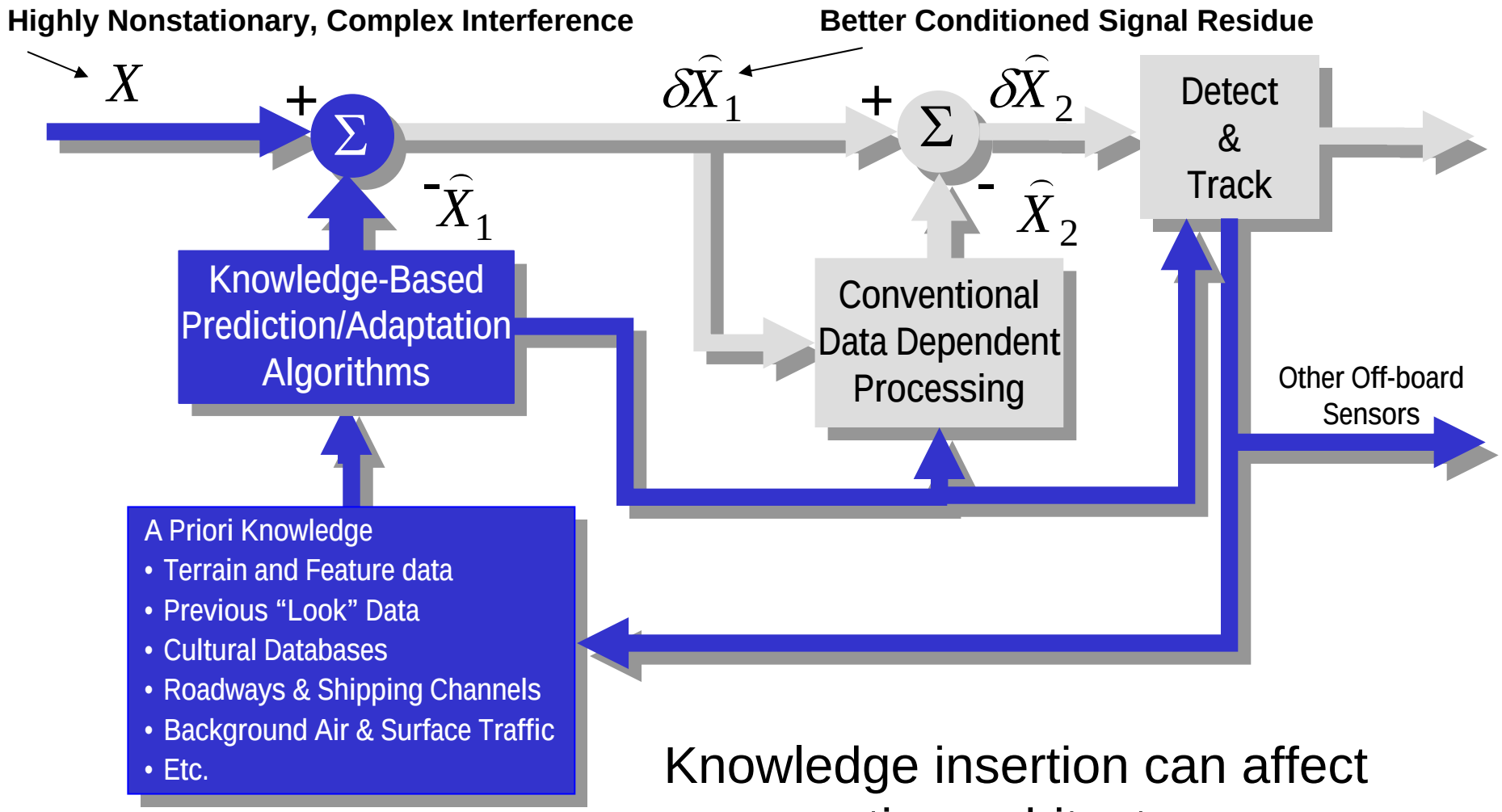
Phase III (FY04-05)

Build and Demonstrate Real-Time KASSPER Processing

Products:

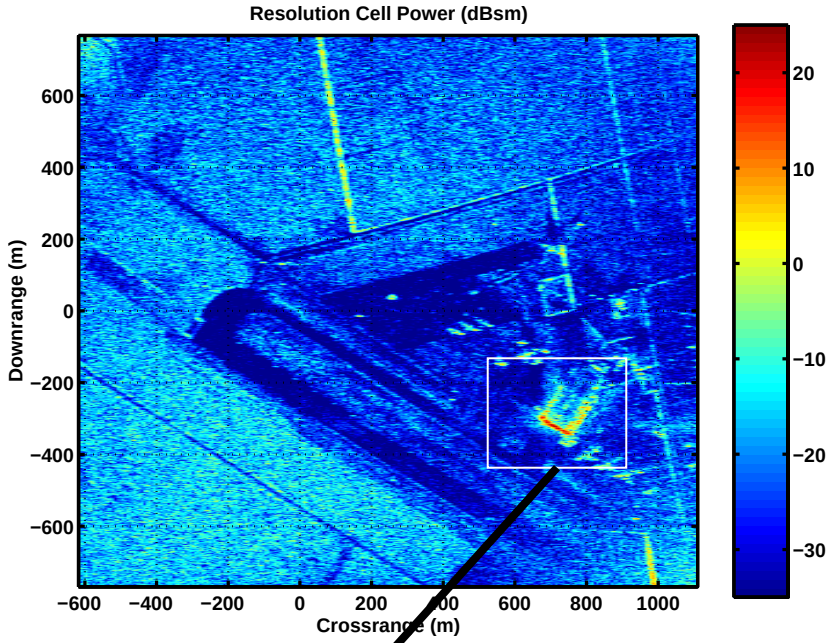
- Real-time KASSPER demo
- Near-term transition designs for JSTARS, JSF, MP-RTIP, SBR, and ASARS

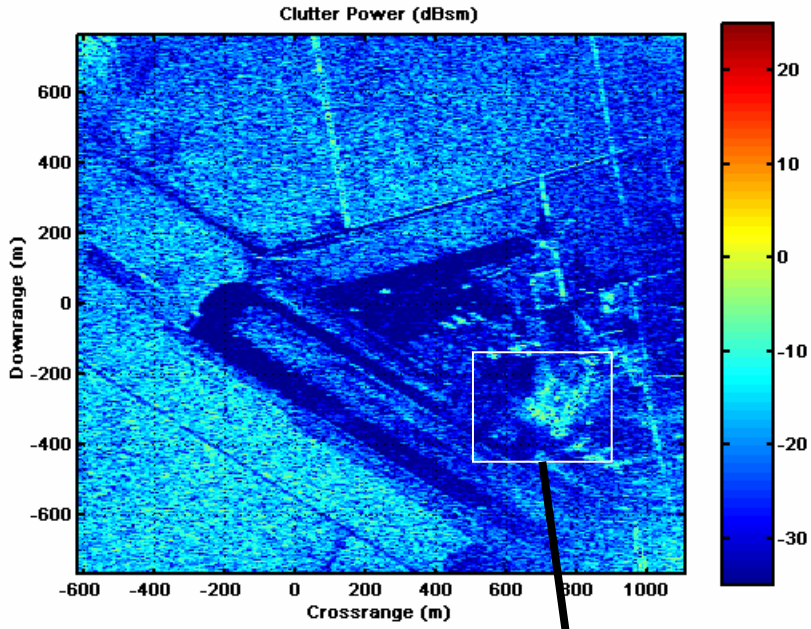
KASSPER Architecture

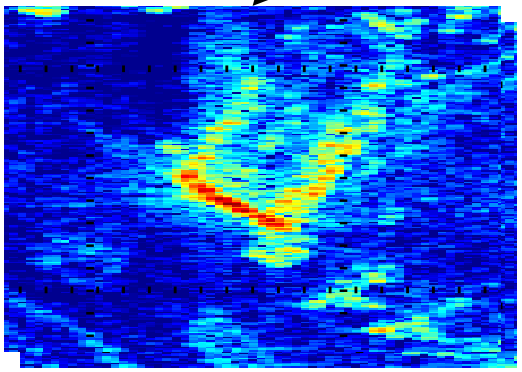


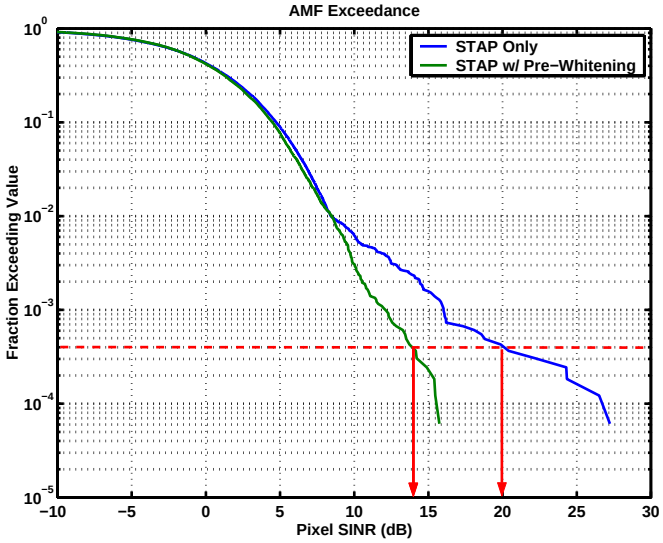
Knowledge insertion can affect entire architecture

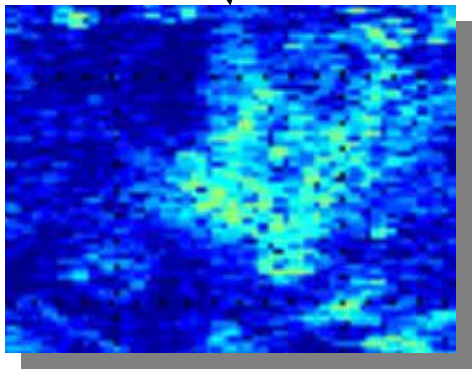
Discrete Suppression





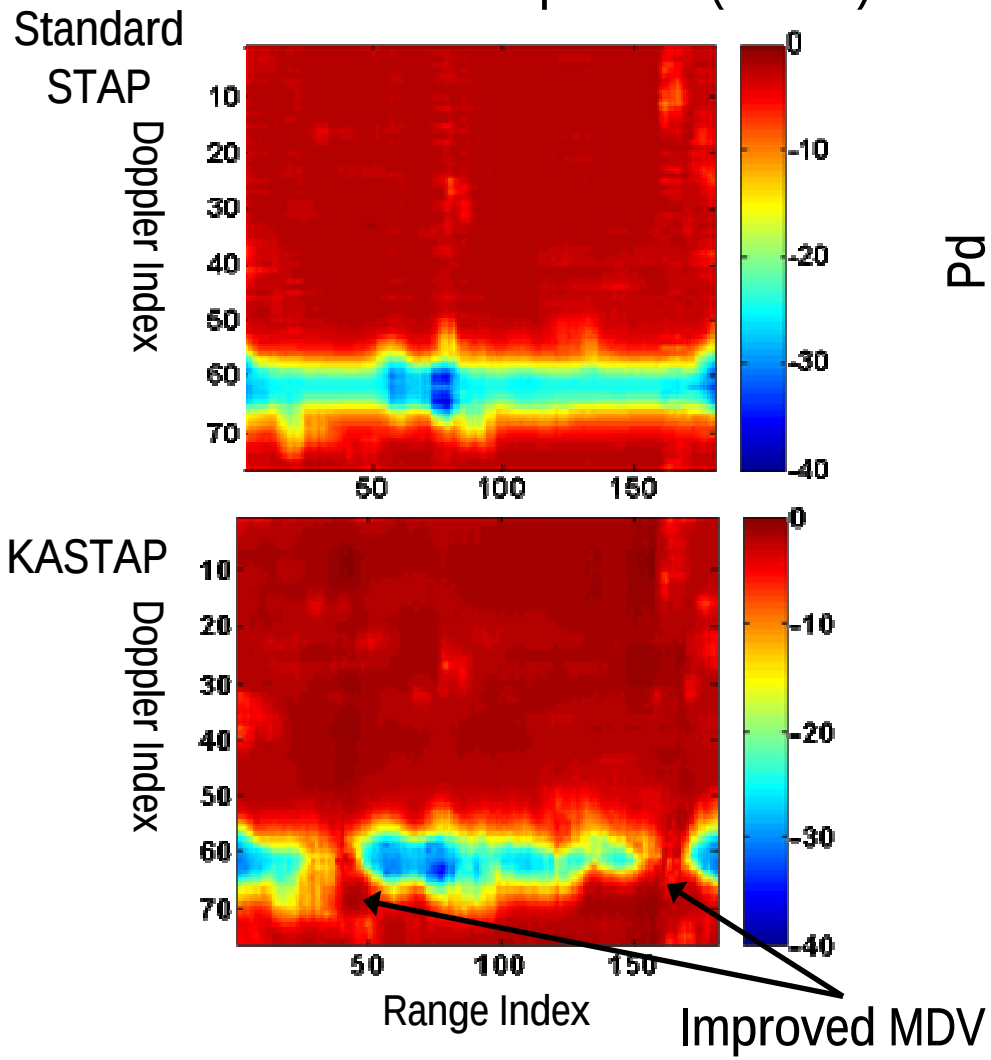




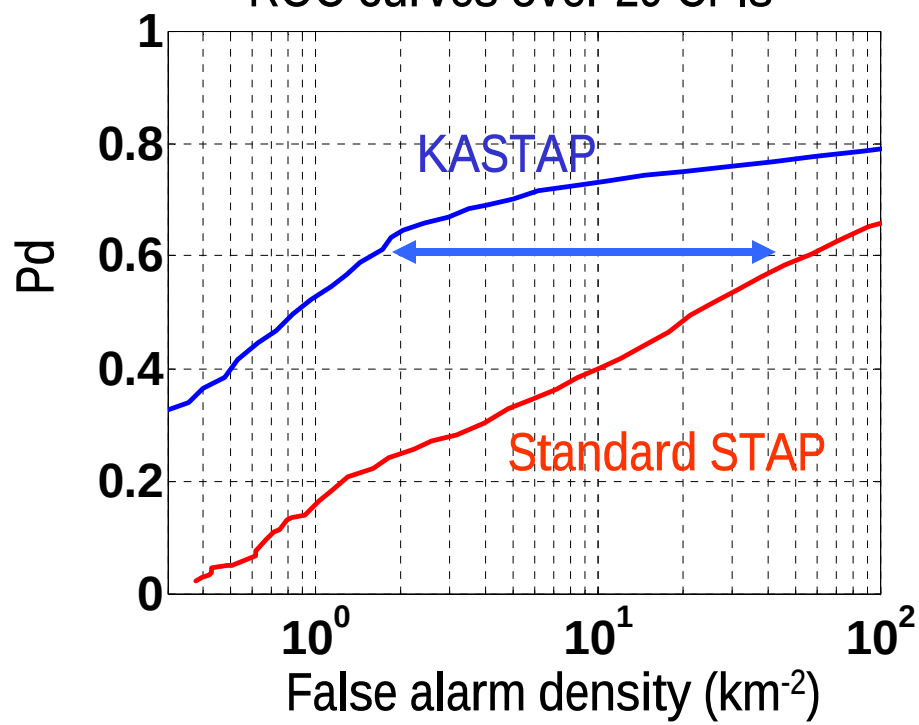


KASTAP Results, KASSPER Data Set 2

SINR Loss Comparison (CPI 22)



ROC curves over 29 CPIs



False alarm density at Pd=60%:

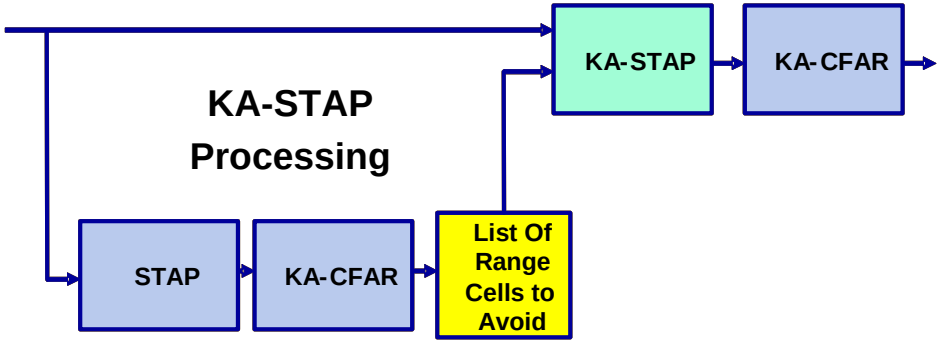
Standard STAP: 55/km^2

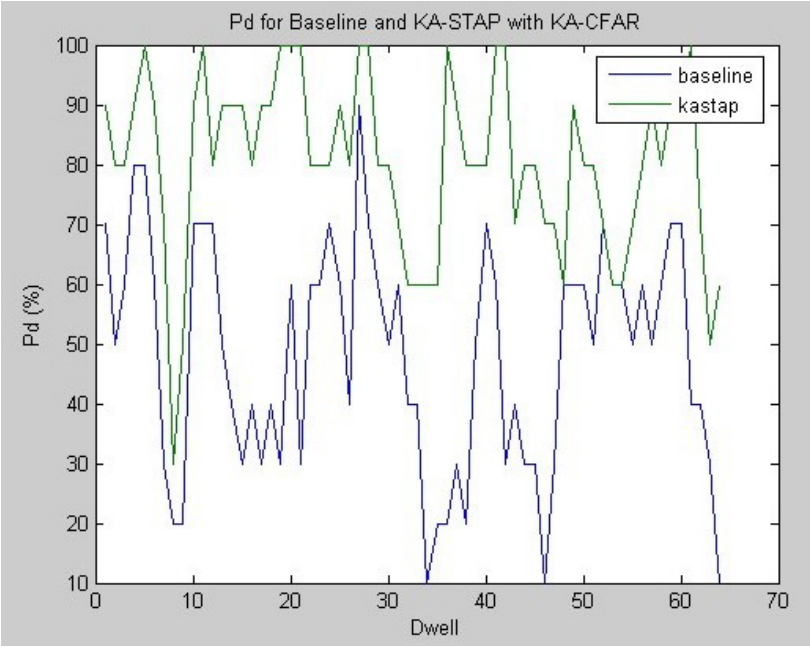
KASTAP: 1.5/km^2

Tracker Performance

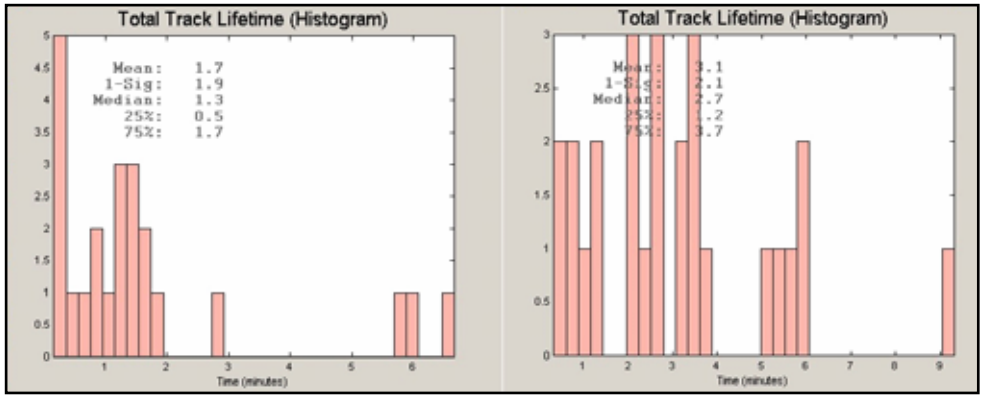
KA-CFAR: Adaptively chooses one of four different CFAR types based on the local statistics

KA-STAP: Data conditioned by nulling large discretes





Pd Improved from 48% to 80% with Use of KA-STAP & KA-CFAR



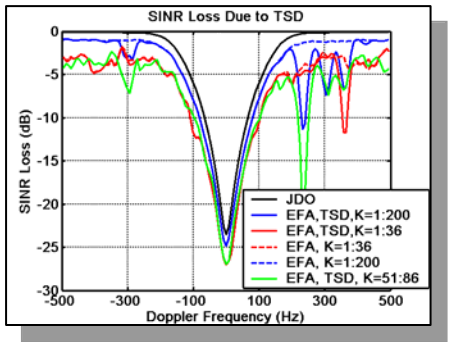
Maximum Track Life Increased from 6 minutes to 9 minutes

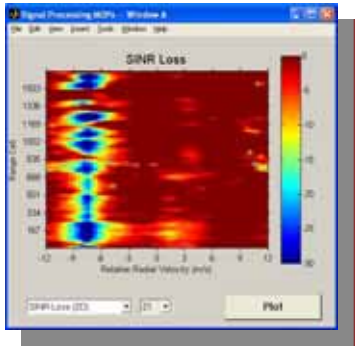
Measuring KASSPER Performance Gains

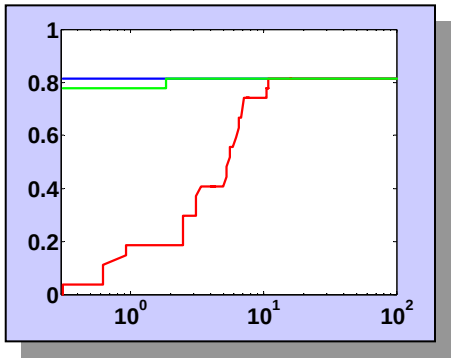
Signal Quality
- SINR Loss
- Amplitude/Spectral Mismatch
- PSD
- Eigenspectra

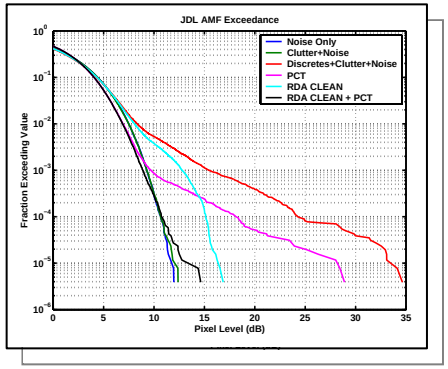
Target Detection Performance
- Average Time to Detect vs. Search Volume
- Prob. Accurate Est. of # Targets vs. Time
- Prob. Of Correct Detection
- False Alarms Rate
- Missed Detections

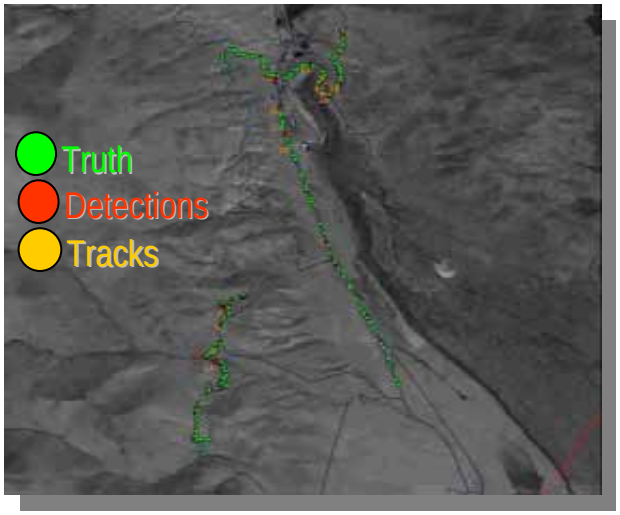
Tracker Performance
- % Targets In Track vs. Time
- # Targets In Track vs. SNR
- % Desired Targets In Track vs. SNR
- Average Track Error vs. Time Step
- Track Continuity
- Gap Time



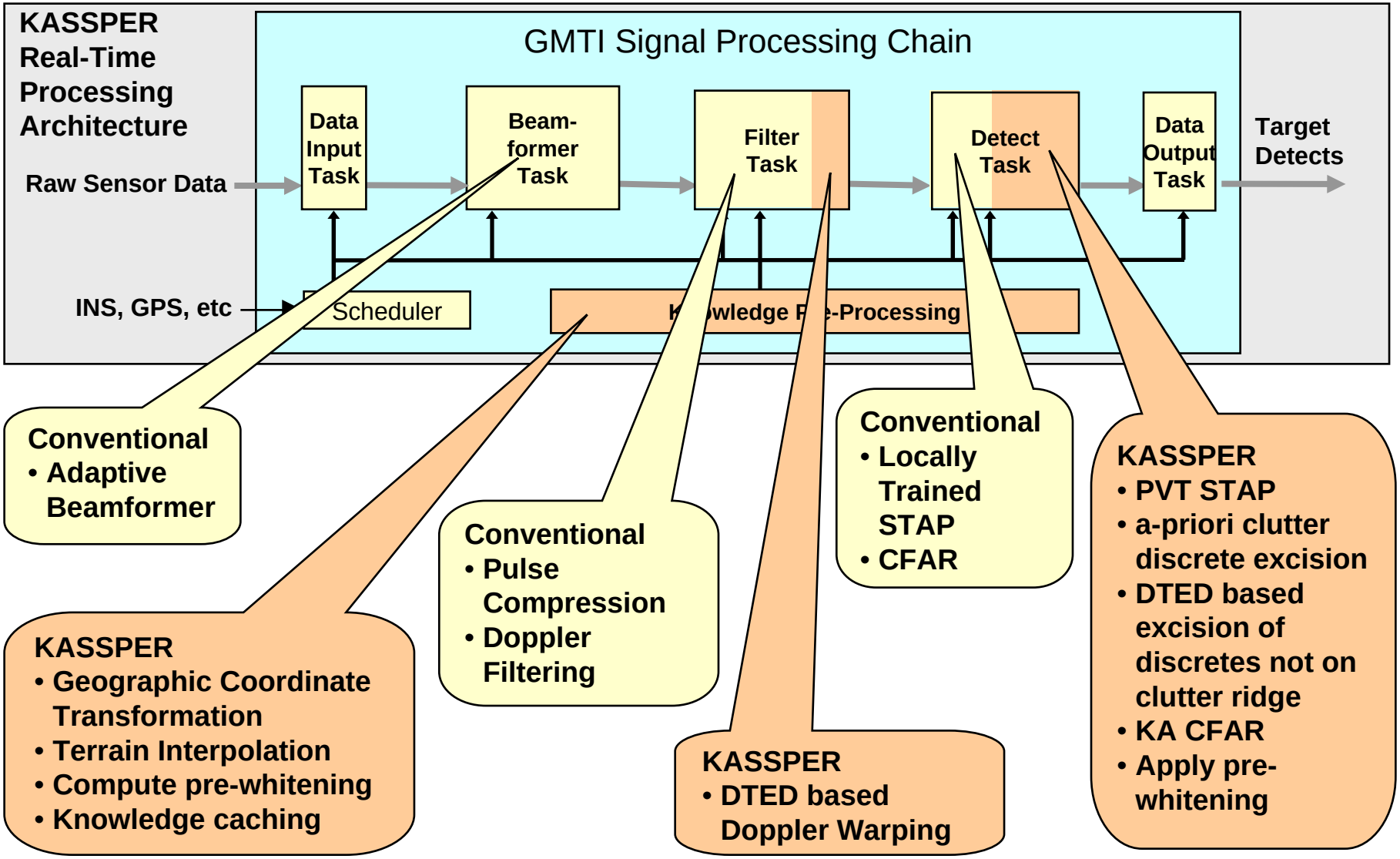






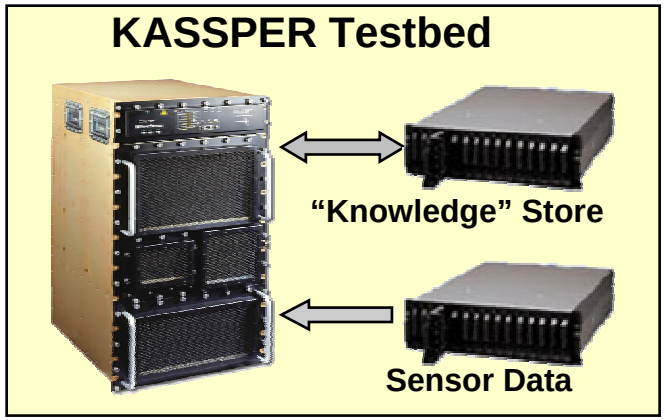


KASSPER GMTI Signal Processing Techniques



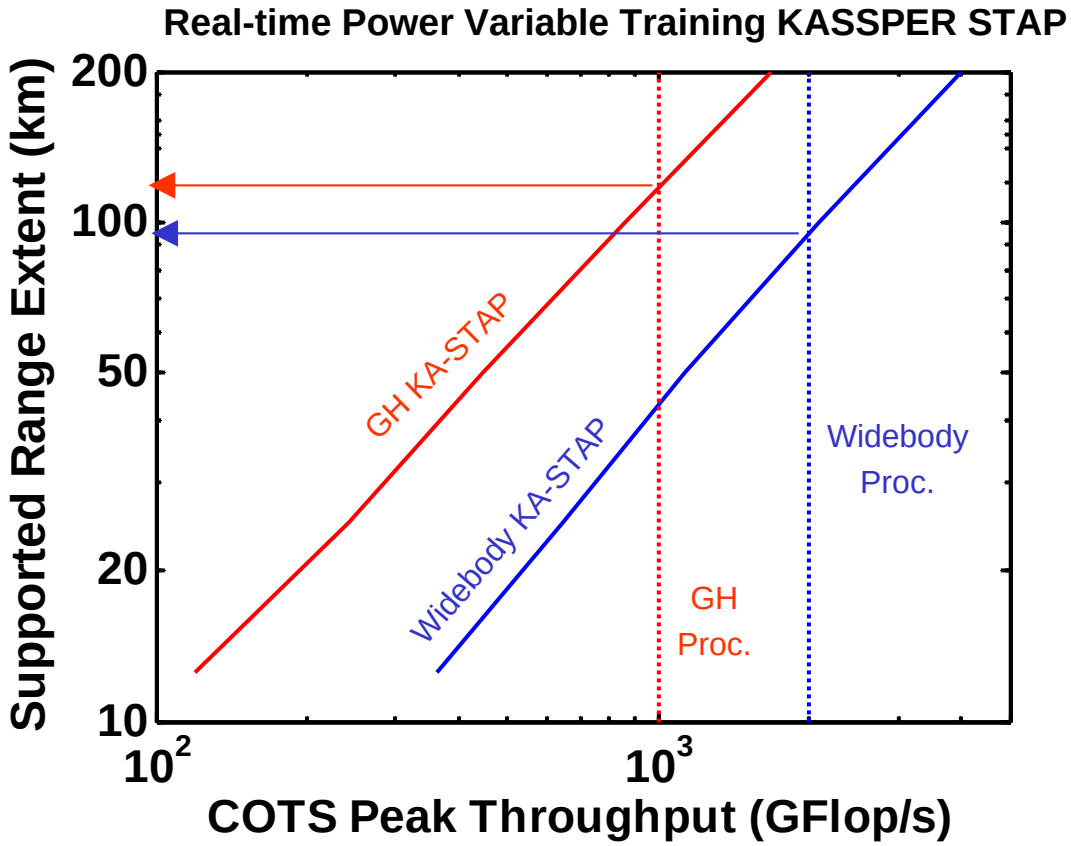
*** Based on Tuxedo data**

Real-time Processor Performance



Mercury MP-510 processor

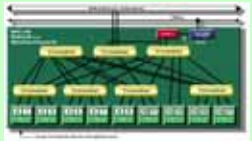
- 120 Power PC G4s at 500 MHz
- RAID system provides real-time input data



- Baseline real-time existence proof for Global Hawk or Widebody implementation
  - Current real-time parallel processor implementation only covers highest nonstationarities
- Remaining areas to be addressed in Phase III
  - Performance vs. implementation cost
  - Potential hybrid architectures

Real-Time Processing Architecture

Success with look-ahead scheduling and intelligent data caching



- Processor implementation is very inefficient for *applying* knowledge to the data
  - Range dependent operations
  - Irregular data flow and memory access
- Heterogeneous architecture may increase efficiency
  - Study on potential effectiveness of FPGAs, ASICs

Radar data

Pre-Filter

Filter

Detect & Track

Knowledge database:
VMAP
Previous GMTI -clutter
SAR
Cultural
Roadways
Other sensor

Clutter Prediction and Adaptation Algorithms

Optimal Clutter Estimation

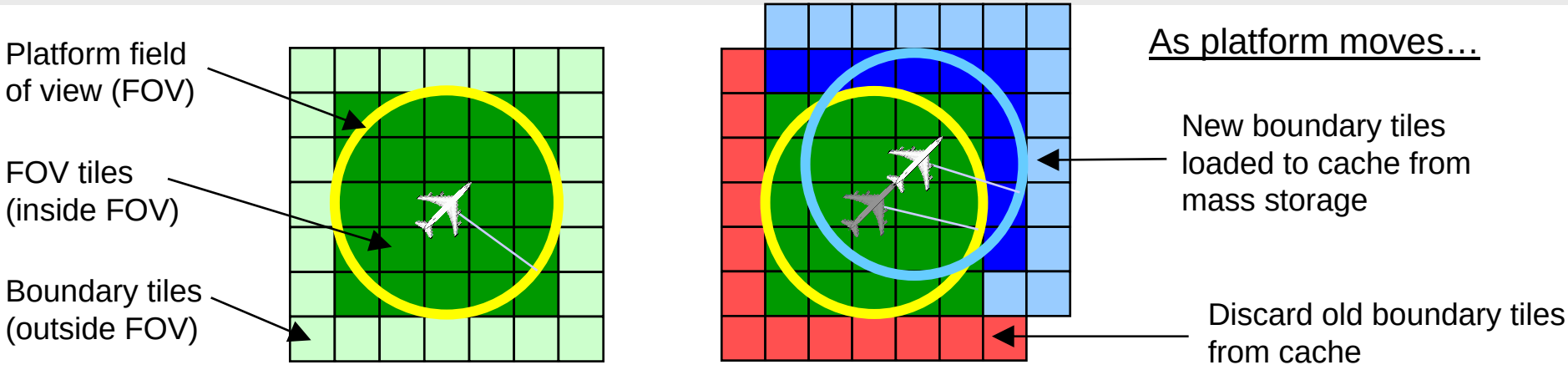
Historical track correction

"Look-ahead" scheduling

Real-time covariance matrix manipulation

“Look-Ahead” Scheduling

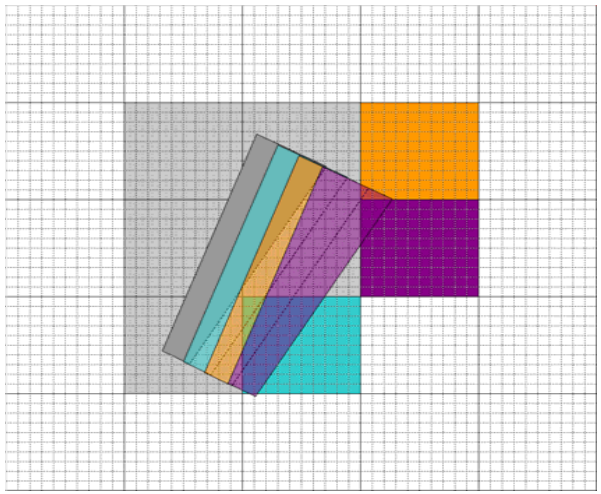
Intelligent data caching derived from flight physics



- Geographic knowledge is segmented into tiles processed independently
- New tiles needed every 380sec for 100KM^2 tiles and 510kt

Radar scheduler directs final specific L1 caching

- Resource manager schedules beam-position, radar mode, and processing
- KASSPER adds requirement for L1 caching of sub-tiles
- Increases processing speeds by reducing off-chip data manipulations



Transferring between L2 and L1 cache:

CPI 1
Pre-Fetch 5 Sectors

CPI 2
Pre-Fetch 1 Sector

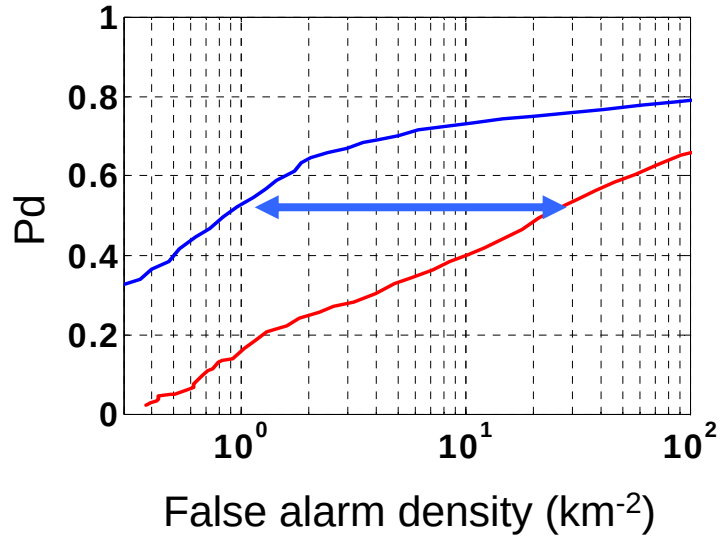
CPI 3
Pre-Fetch 1 Sector

CPI 4
Pre-Fetch 1 Sector

Performance vs. Cost Metrics

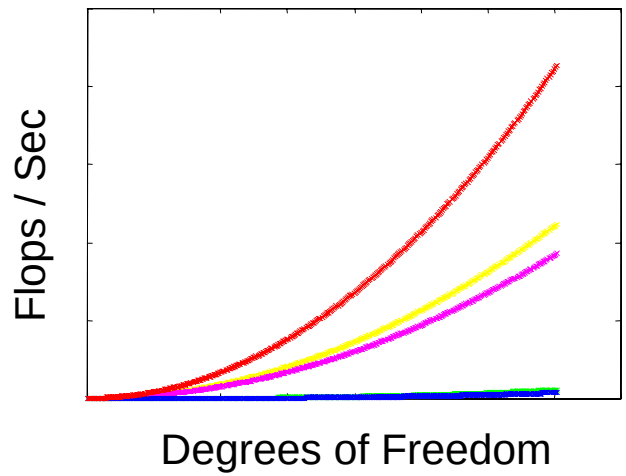
Performance

- Processed Signal Quality
- Target Detection Performance
- Tracker Performance



Cost

- Throughput, # Processors
- Memory Bandwidth, Memory Size
- $ Cost, Power Consumption
- Database Access Rates, Data Locality



Finding the Sweetspot Critical in a Real-World Environment

KASSPER FY05 Plans

Phase I

Hi-Fidelity Environmental Models

Simulated data

Algorithms (non-real-time)

Real data

Go/No Go #1

✓ 10dB gains (SINR, P_{fa})

Phase II

KASSPER Real-Time Demonstration Design

(8 channel X-band GMTI/SAR throughput)

Algorithms (real-time)

Go/No Go #2

✓ 10dB gains (SINR, P_{fa}) in real-time

Phase III

Build and Demonstrate Real-Time KASSPER Processing

Products:

- Real-time KASSPER demo
- Near-term transition designs for JSTARS, JSF, MP-RTIP, SBR, and ASARS
- Performance metrics vs. implementation cost

The “Eye-Watering” Scenario

Background

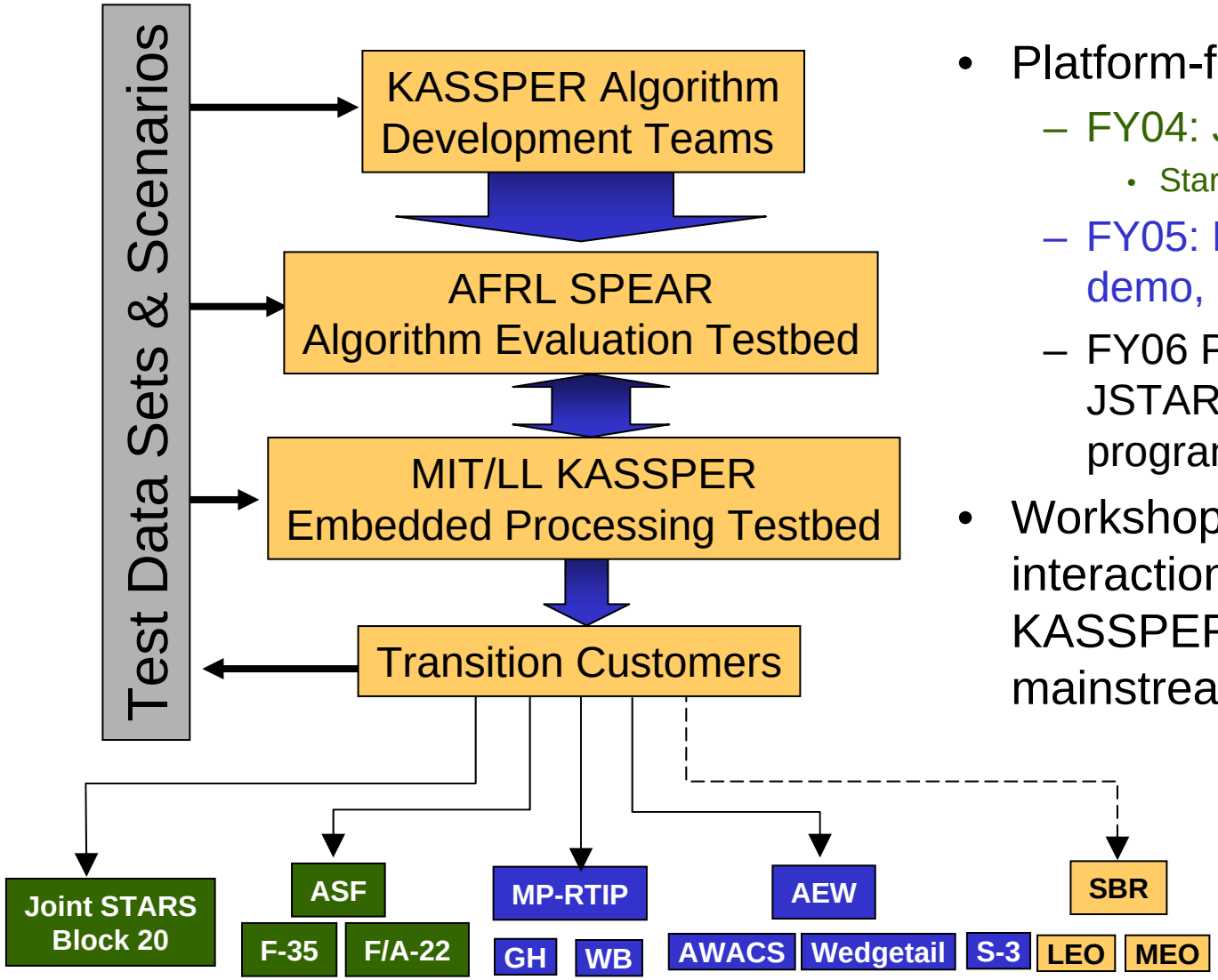
- Global Hawk MP-RTIP
  - 30 Minute Military Scenario in North Korea
  - 6 Convoys of 100 Vehicles Each
  - Discretes, Confusers and Static Rotators
  - Simulation Using GVS
- Notional Global Hawk MP-RTIP Radar Parameters
  - 8 Channel Phased Array for KA-STAP Analysis

Makeup of Scenario

- 600 Military Vehicles
- 100 Static Rotators
- 200 Buildings
- 1200 Civilian Vehicles as Confusers
- 100 Communication Towers

Representative Vehicles

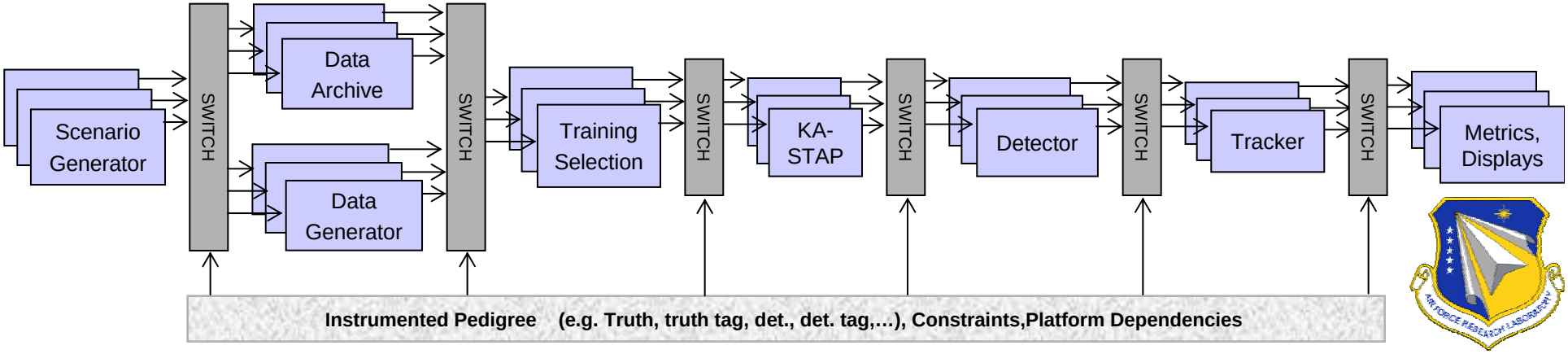
KASSPER Technology Transition



- Platform-focused transition:
  - FY04: Joint STARS, ASF
    - Started MP-RTIP, AEW outreach
  - FY05: MP-RTIP demo, AEW demo, ESC/AFRL ATD
  - FY06 POM wedge in JSTARS and MP-RTIP programs
- Workshops and contractor interactions getting KASSPER approach into mainstream

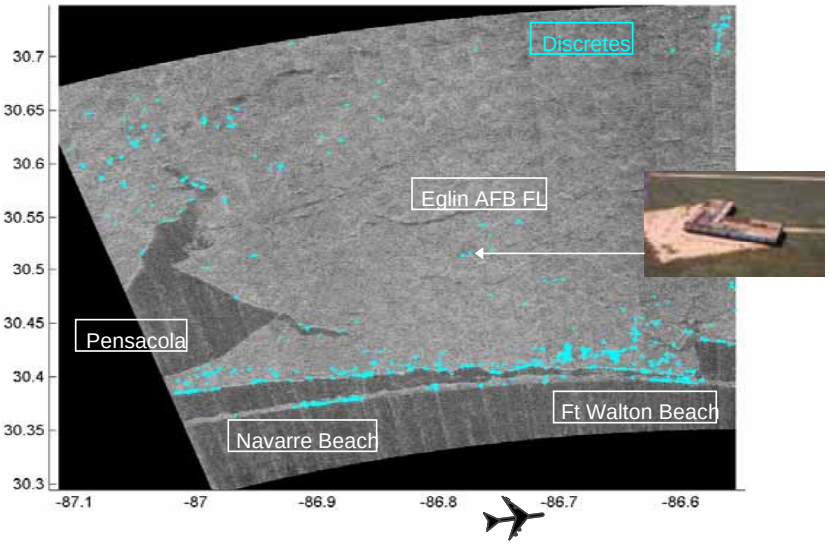
AFRL SPEAR Testbed

SPEAR: Signal Processing Engineering Analysis Research



- SPEAR Testbed is community-wide common architecture and repository for KASSPER algorithms
- Performance tradeoff analysis for KASSPER algorithm variants
  - End-to-end analytical tool for complex interactions of KASSPER components
- Feeds performance vs. cost architecture implementation analysis

KASSPER Joint STARS Objectives



- Demonstrate improvements in GMTI performance (i.e. Improve P_d, Reduce P_{fa}) through the use of knowledge-based techniques
- Address known limitations currently observed on the Joint STARS platform
  - False alarm reports due to mountain ridges and peaks
  - False alarm reports due to large discretes such as buildings
  - False alarm reports associated with shorelines (littoral environments)
  - Redundant targets
- Maintain or improve MDV in support of tracking and targeting of TCTs.

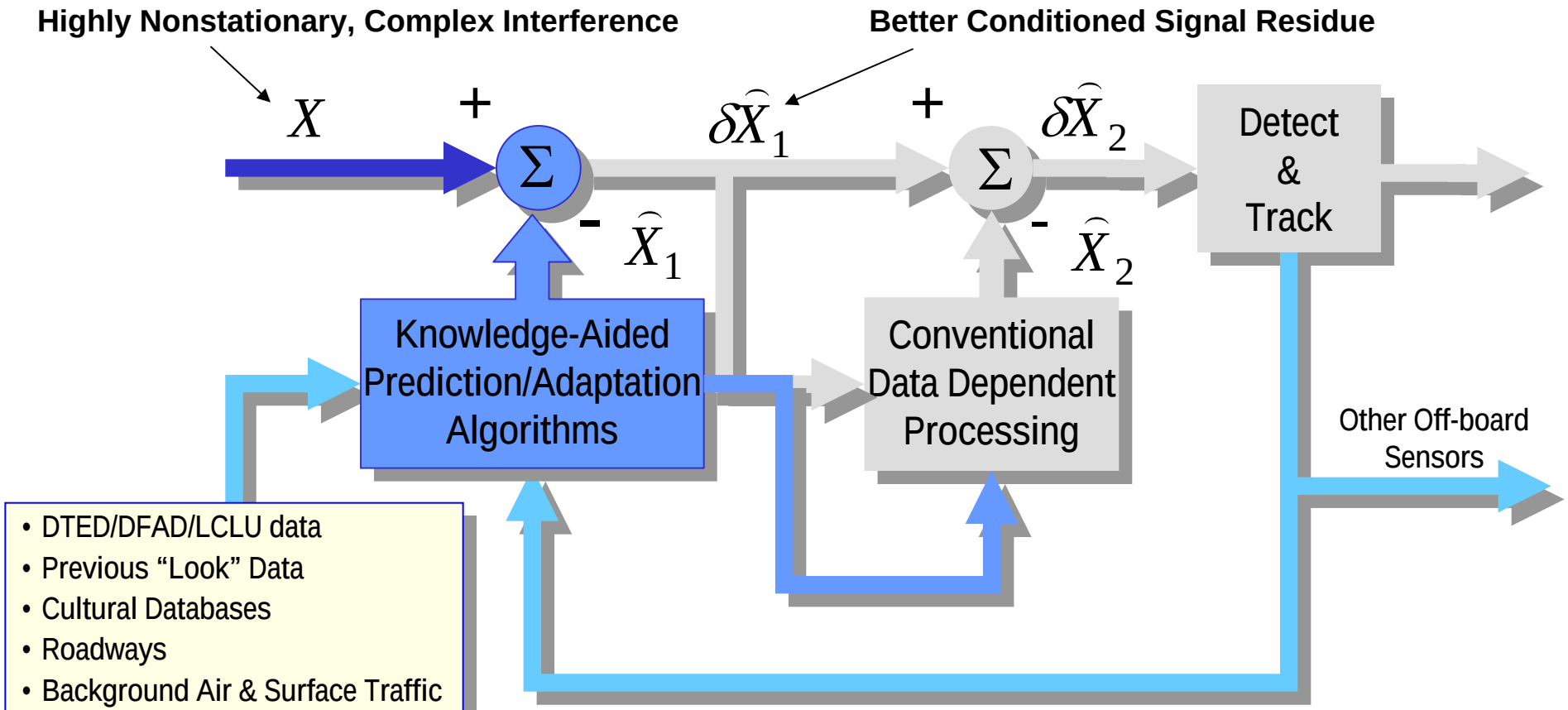
Outline

- Knowledge-aided tactical surveillance systems
- KASSPER program
- Future knowledge-aided processing challenges
- KASSPER Workshop agenda

KASSPER: Just the Beginning…

- Knowledge-aided processing evolution
  - KASSPER uses knowledge to avoid things that hurt you
    - Clutter discretes
    - Heterogeneous clutter and irregular terrain
    - Road networks
  - Future knowledge-aided processing incorporate things that help you
    - Waveform diversity
    - Transmitters of opportunity
    - Constraint-based sensing
    - Model-based scene representation
- Future examples:
  - Urban GMTI: Multi-static multi-frequency integration
  - ISR for building interiors

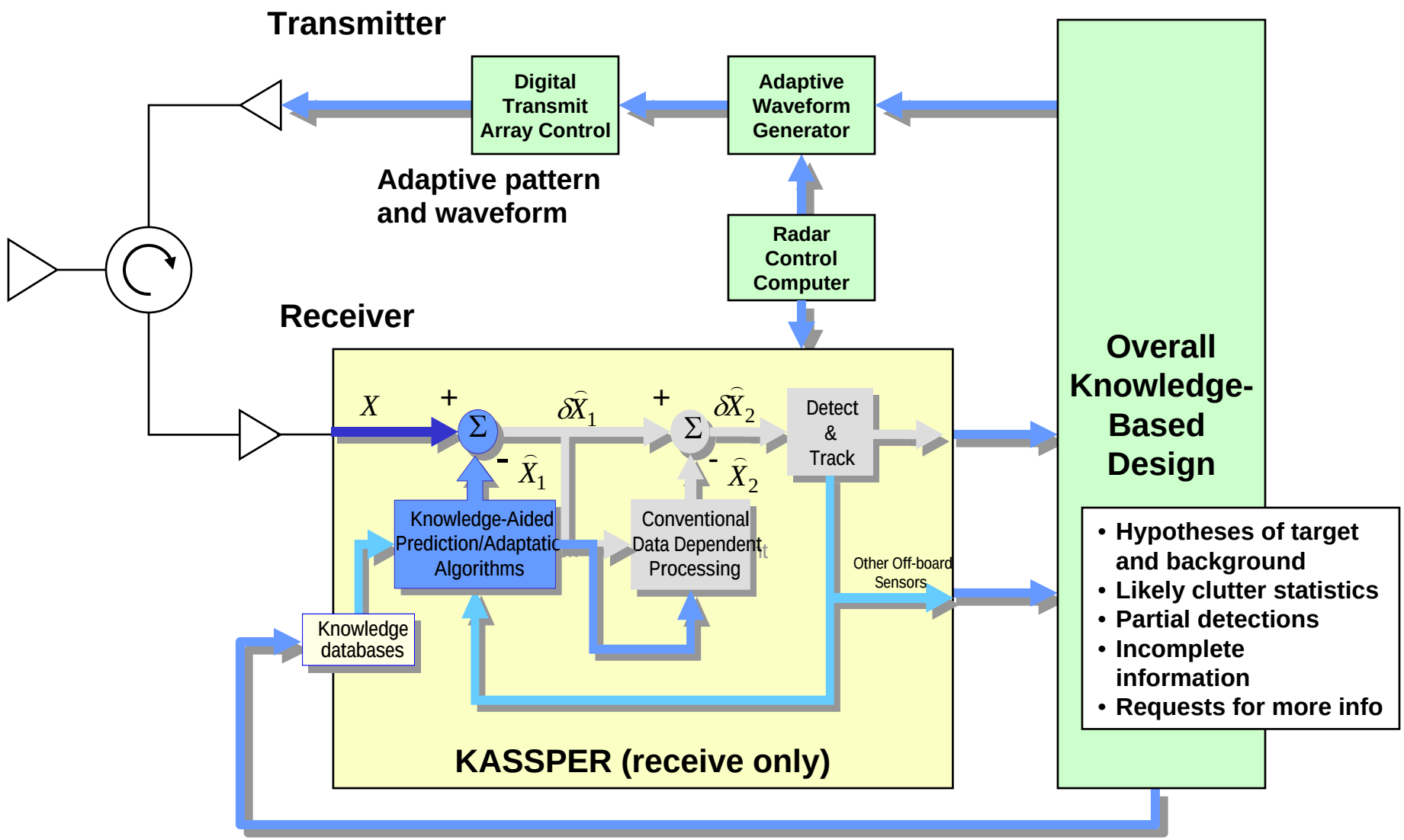
High-Level KASSPER Processing Chain



- DTED/DFAD/LCLU data
- Previous "Look" Data
- Cultural Databases
- Roadways
- Background Air & Surface Traffic
- Ownship Position, Velocity, Orientation
- System Calibration Information
- EMI Data
- Other

- KASSPER will:
  - Develop next generation intelligent signal processing algorithms
  - New HPEC architecture for real-time ISR
  - Real-time flight demos (including JSTARS T-3)

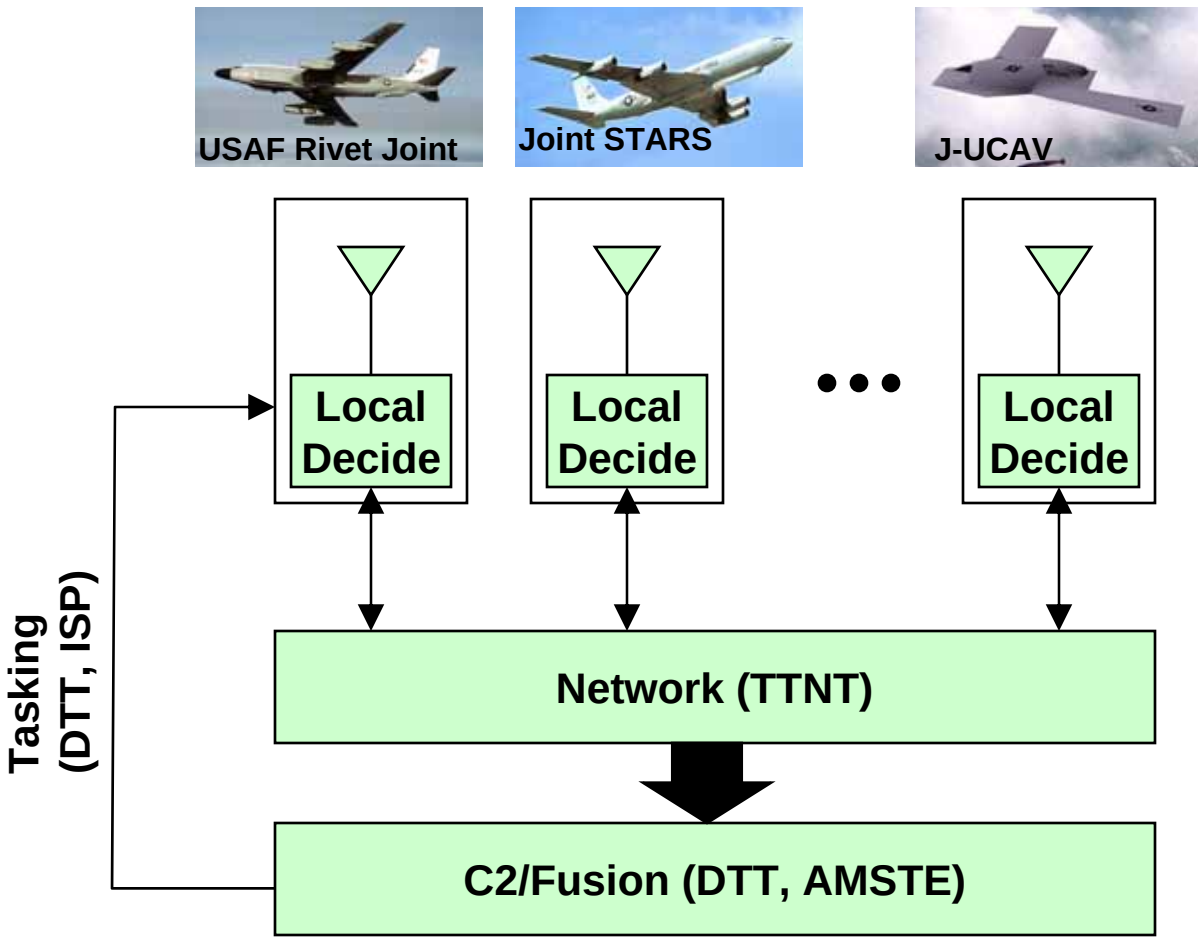
Knowledge-Based Radar Design



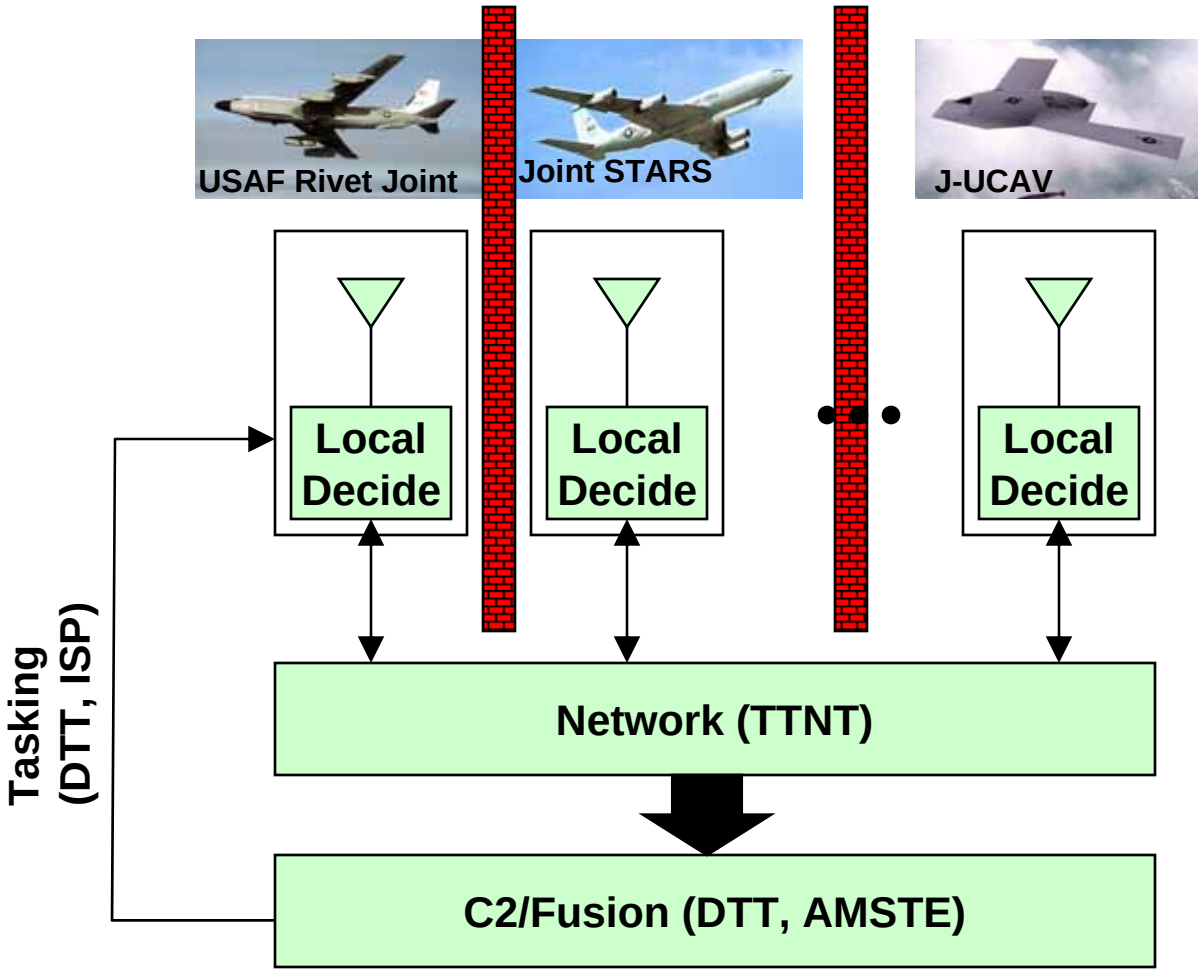
Hypotheses Integration Dimensions

- Multi-sensor: different modes with relatively similar aspect angles
  - e.g., Stand-off SAR followed by EO/IR
- Multi-spectral: stitch together discontiguous bandwidth
- Multi-temporal: Use different collection periods
  - Multi-pass change detection (currently requires same aspect angle and same ambient conditions)
- Multi-static: different modes on different platforms from widely disparate look angles
  - e.g., SBR SAR followed by Global Hawk EO/IR
- Multi-threaded: extract knowledge threads about targets from different sensors/platforms/modes/etc.

Networked Sensor Fusion

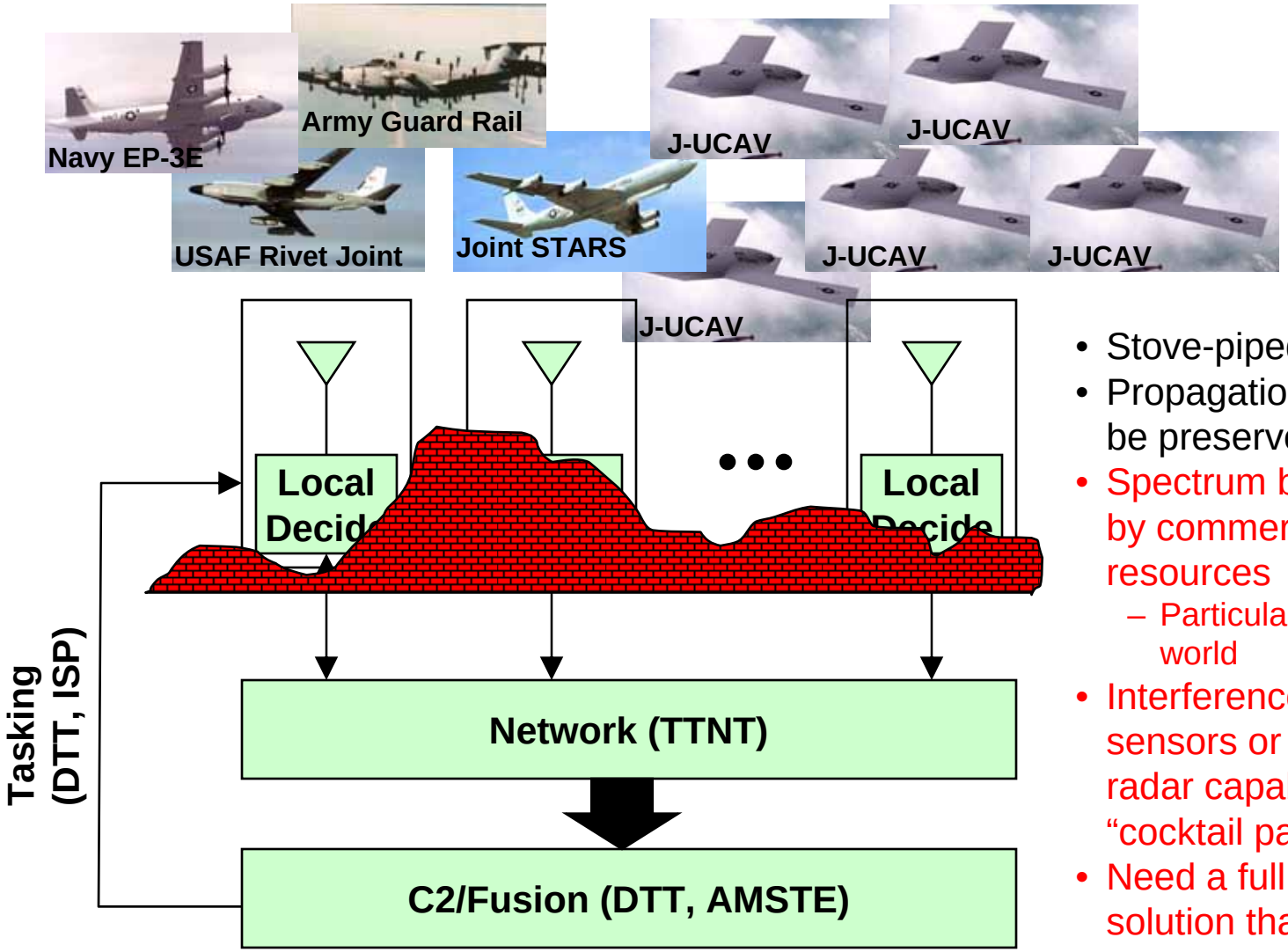


Networked Sensor Fusion



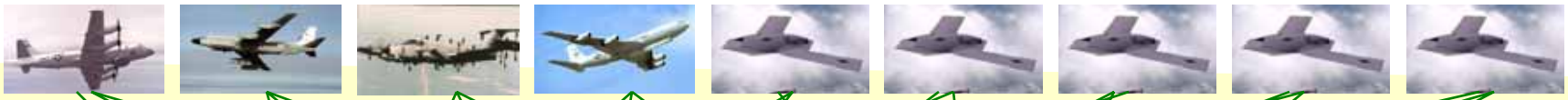
- Stove-piped sensing
- Propagation isolation must be preserved

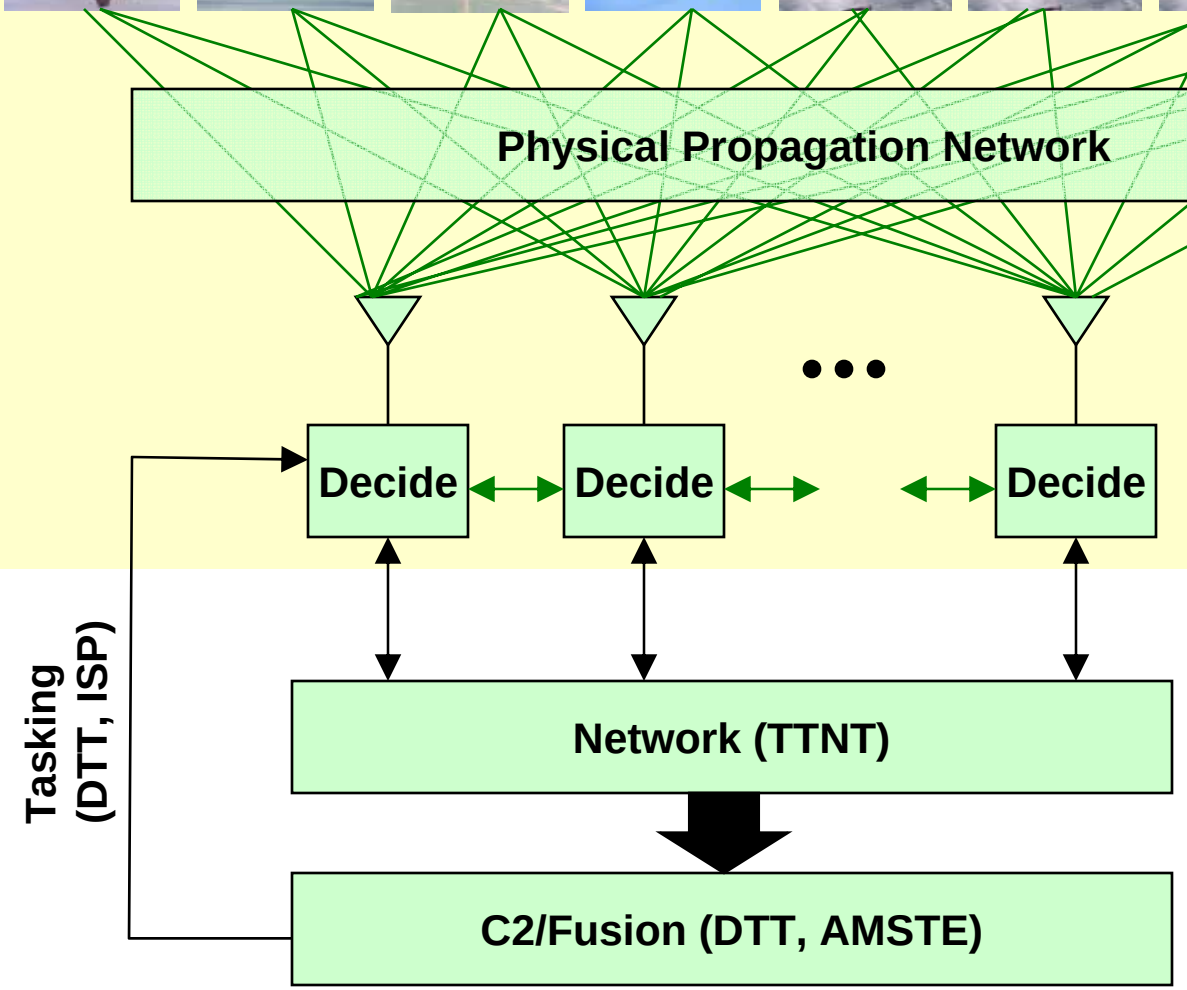
Networked Sensor Fusion



- Stove-piped sensing
- Propagation isolation must be preserved
- Spectrum being consumed by commercial wireless resources
  - Particularly bad in third world
- Interference with other sensors or sources will kill radar capability (RF "cocktail party" problem)
- Need a full spectrum RF solution that exploits sensing *propagation* network, not just decision network

Networked Detection and Ranging (NetDAR)





NetDAR:

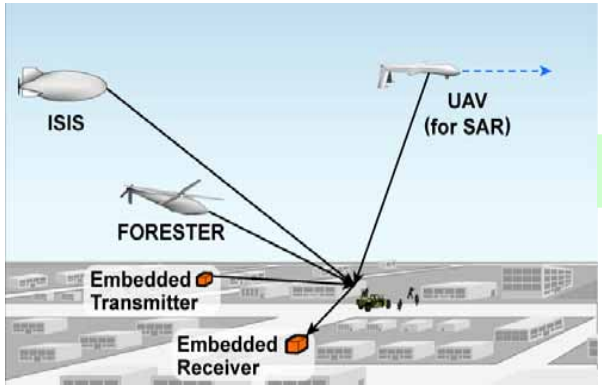
- Exploit *physical propagation* network
- Multi-spectral, multi-static integration at RF propagation level
- Knowledge-based full spectrum radar
  - Passive and active sources (multi-channel PCL)
  - Multi-platform adaptive waveform diversity
  - MIMO radar

Turning Problems Into Solutions!

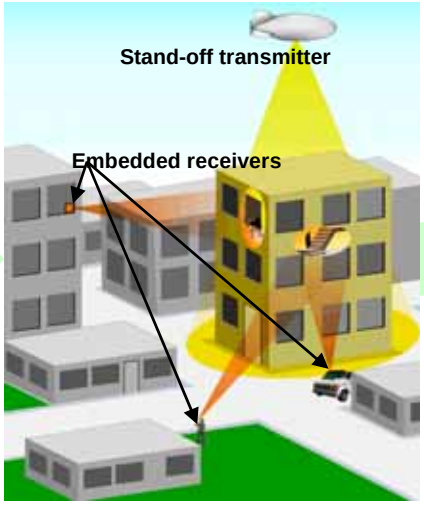
Phenomenon	Effect on Current Radar Systems	Future NetDAR full-spectrum exploitation
Unwanted transmitters	• Increased noise, reduced range • Reduced resolution due to limited bandwidth	• Multi-static sources of opportunity • Spatial diversity
Spectrum limitations	• Reduced range resolution • Higher transmit power required in narrower bands	• Resolution can be built up coherent signal processing across bands
Single-purpose RF systems	• Stove-piped; not intercompatible • SIGINT, COMINT, ELINT, SAR and GMTI don't interact	• Extract all useful information from all available signals • Cross-cuing between modes
Monostatic operation	• Aspect diversity not exploited • Stove-piped by frequency	• Exploits all transmit sources • Multi-aspect (cross-range resolution), multi-frequency (range resolution), multi-temporal (better tracking)
Counter-measures	• Can be jammed • Denial of bandwidth or azimuth coverage	• Jamming of passive sources not feasible • Full utilization of all sources (including jammers)
Lack of system memory	• Little knowledge of past incorporated into current understanding	• Model-based physical representation of environment

Urban Tactical Surveillance

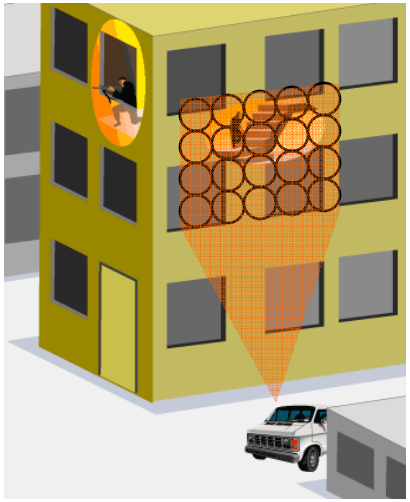
Localized GMTI Surveillance
Vehicle and dismount traffic



Building Penetration



High Value Localization



- GMTI for wide area surveillance
- Wide-area tactical observation of buildings
  - Building-by-building screening
  - Presence of personnel in building
- Detailed high value building search
  - Directional arrays of low-power receivers (panel of a truck)
  - Localized transmitter(s)

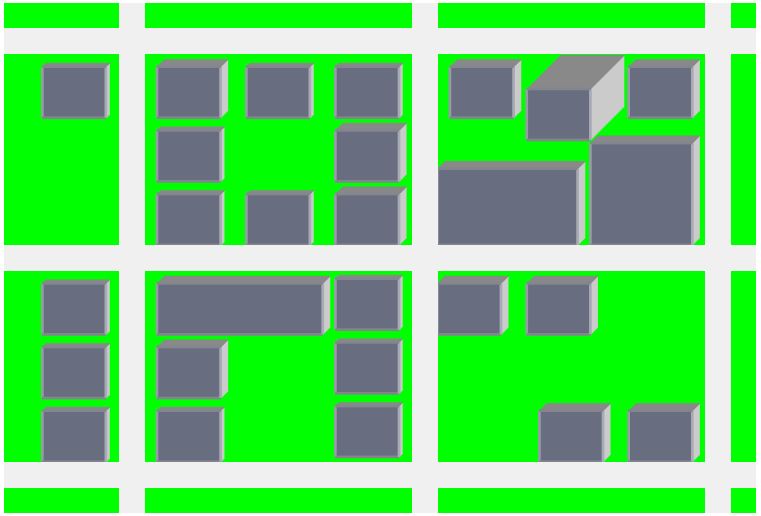
Urban ISR Problem

- Wars increasingly fought in urban domain, but Warfighter has no ISR capability inside of buildings
  - Maps and imagery only provide knowledge of exterior
  - HUMINT is unreliable
- Building-to-building searches yield advantage to the enemy
  - We do not where to search
  - We do not know where threatening personnel might be
- Lack of knowledge affects planning, preparation, search strategies, attrition

Warfighters lack the information necessary to own the interior urban space

ISR for Building Interiors Objective

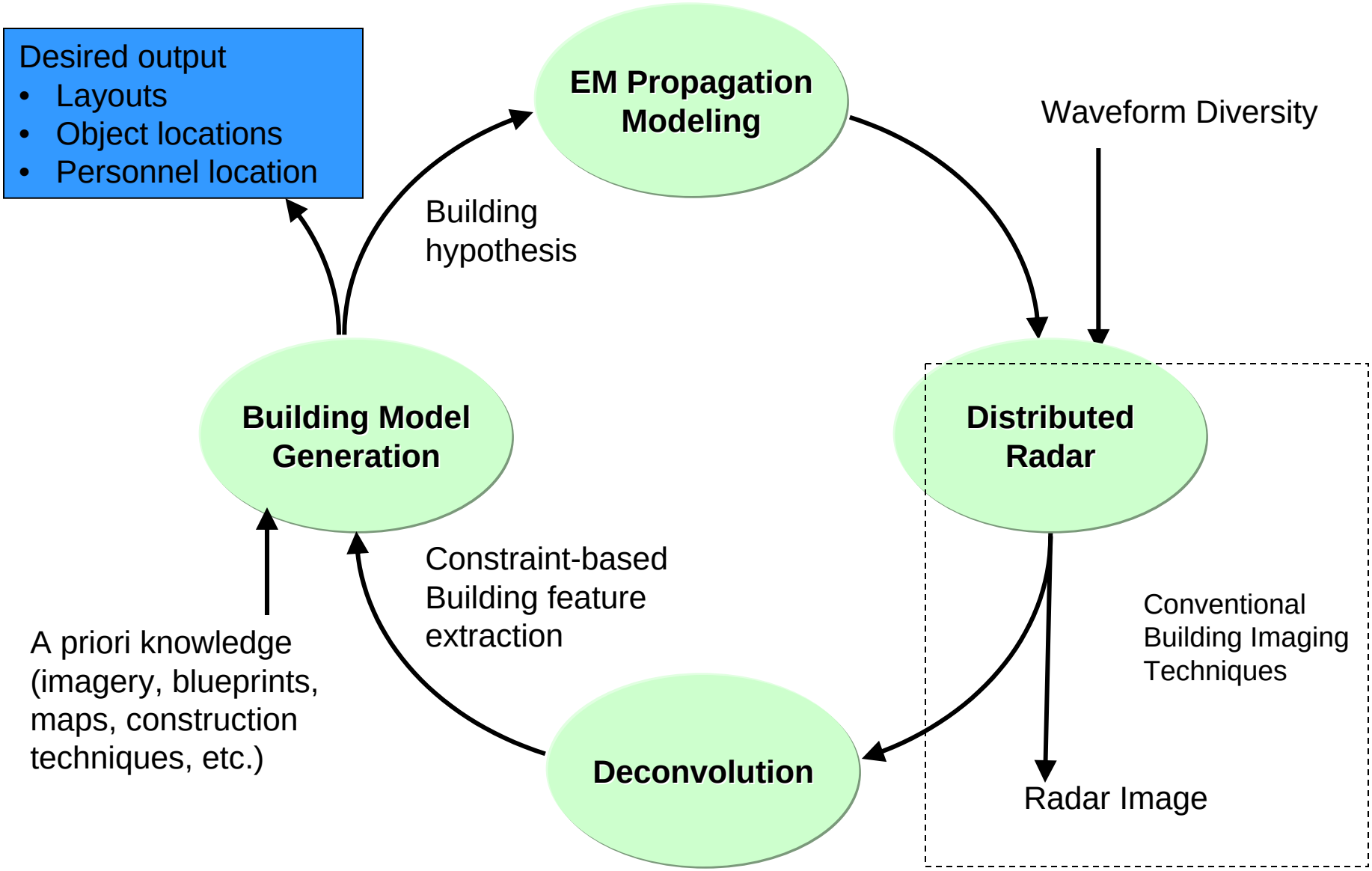
- Expand ISR capabilities into interior building spaces
  - Provide building layouts (walls, rooms, stairs, doorways)
  - Identify weapons caches, shielded rooms, etc.
  - Find personnel inside of buildings



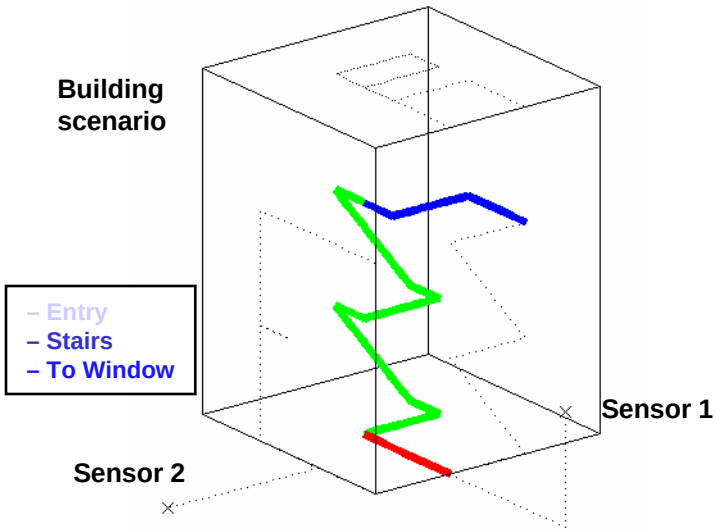
Current Urban ISR

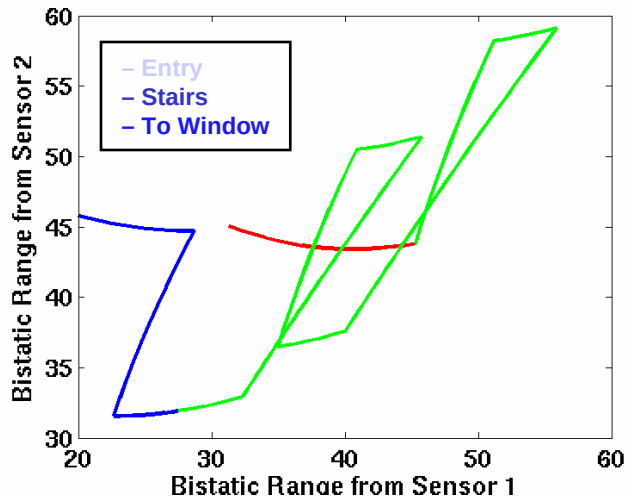
3-D Urban ISR of interior spaces

Model-Based Imaging
"Re-solve to Resolve"



Internal Building Observation





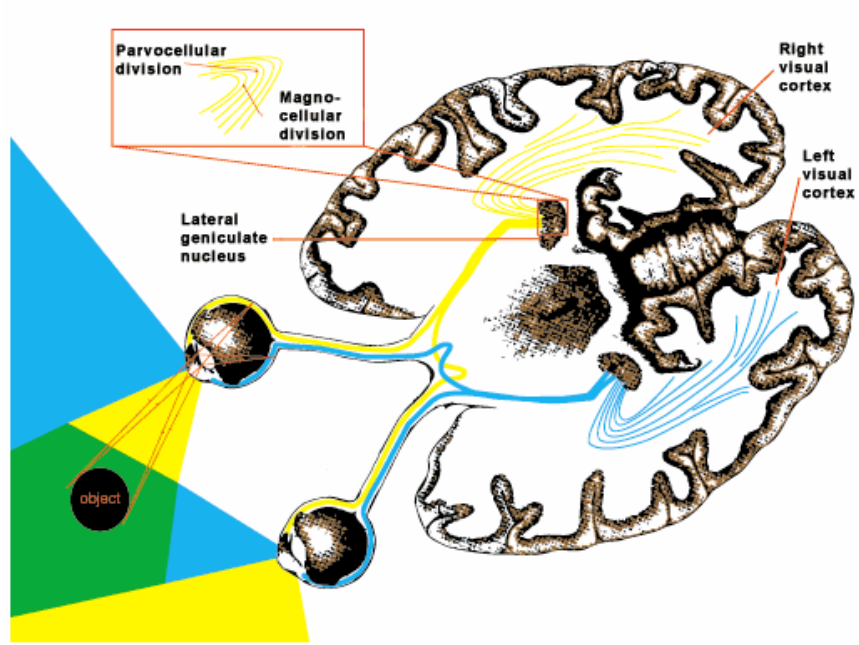
- Approach: Track threads over time establish unique traversal patterns
  - Target location projects onto observation space
    - Projection into target space can exploit known constraints (floor locations, stair angles)
  - Develop traffic patterns, floor plans, schedules over time
- Challenge:
  - Inverse mapping of observation space into grid coordinates
  - Cross-sensor target association to resolve ambiguities
  - Multipath disentanglement
  - CONOPS for covertness

Bi-Directional Sensor/Processor (Human Visual System)

The human visual system employs bi-directional information flow at nearly all levels

The lateral geniculate nucleus (LGN) is the earliest visual processing stage after the retina

- Feedforward connections from retina to LGN:
  ~10^6 fibers
- Feedback connections from cortex to LGN:
  ~6×10^6 fibers



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- **Can sensor signal processing develop a model-based understanding of the environment?**
- **How will this model affect signal processing decisions?**

Summary

- KASSPER technology has moved adaptive radars from ideal “sand paper earth” into the real world
  - Irregular terrain, clutter discretes, background traffic, etc.
  - Demonstrated >10 dB reduction in false alarms in stressing environments
- KASSPER has revolutionized the way radar systems are developed, but it is only the beginning
- Looking for ideas to leverage knowledge-aided processing
  - Urban GMTI: Multi-static multi-frequency integration
  - ISR for building interiors
  - Model-based reasoning