Knowledge-Aided Sensor Signal Processing and Expert Reasoning

KASSPER

Workshop 2004

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DARPA/SPO

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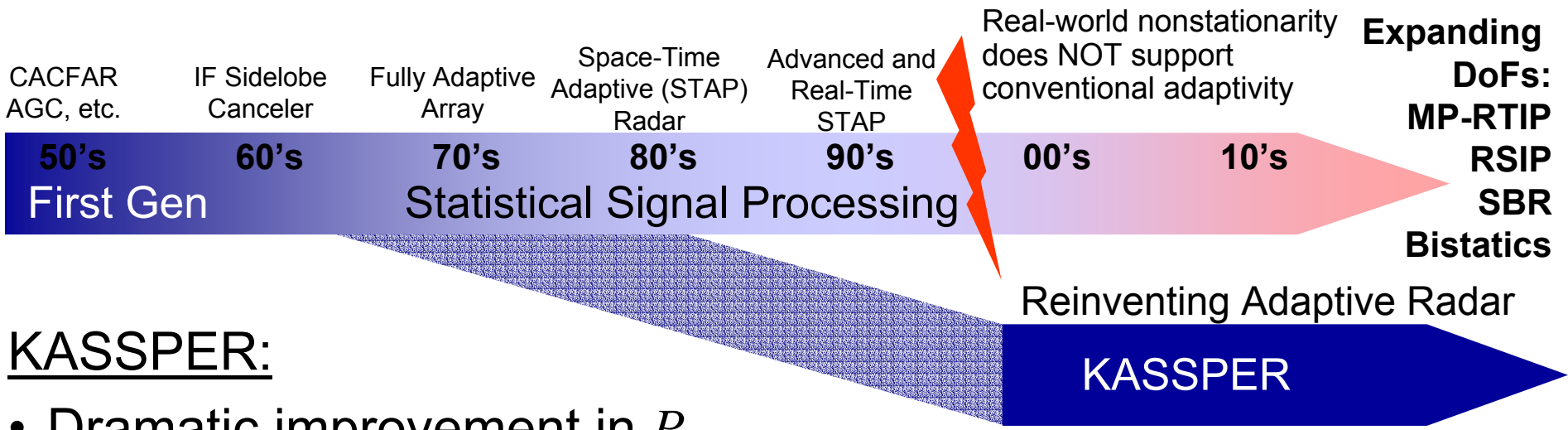
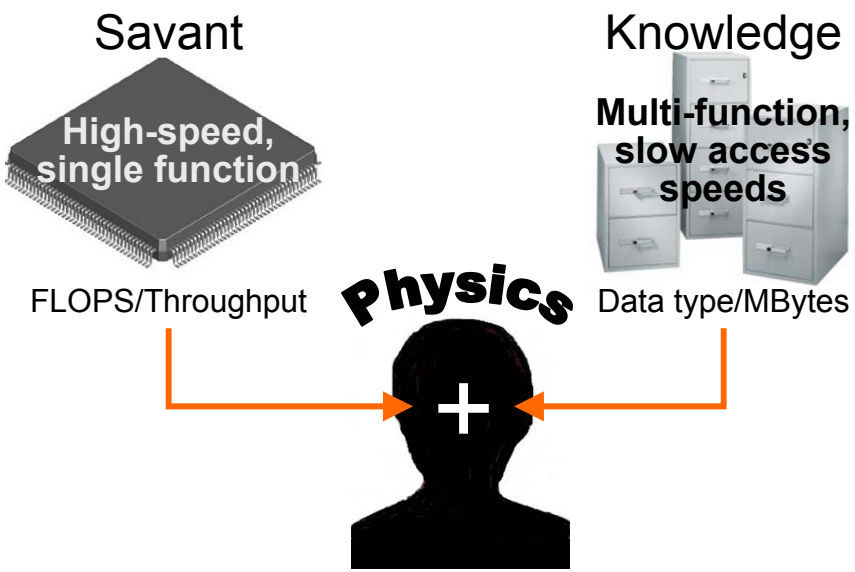
Intelligent Adaptive Radars



KASSPER:

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

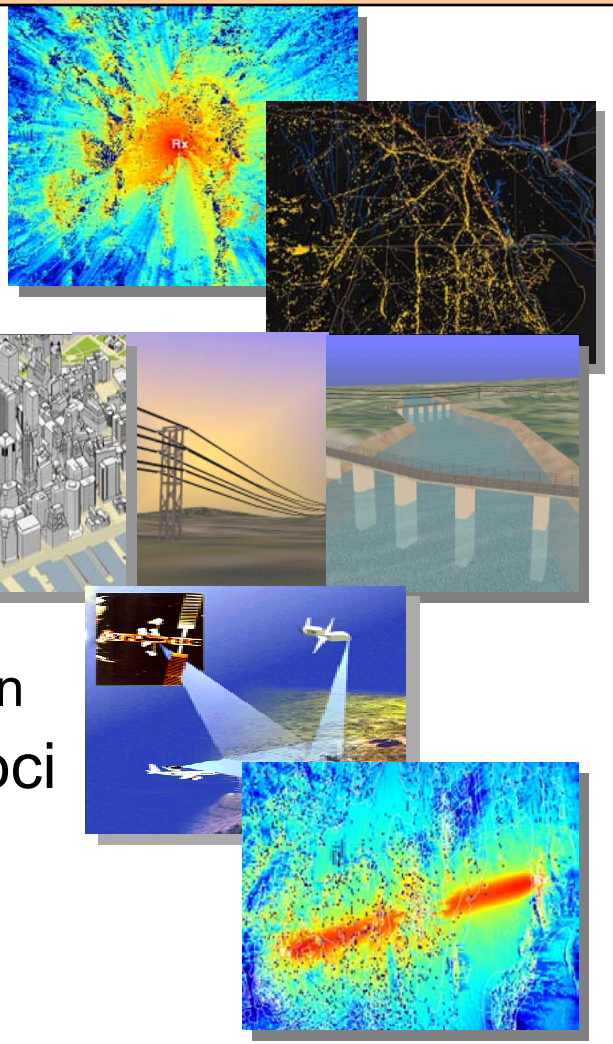


True "Intelligent" Processing

When is There a Problem?

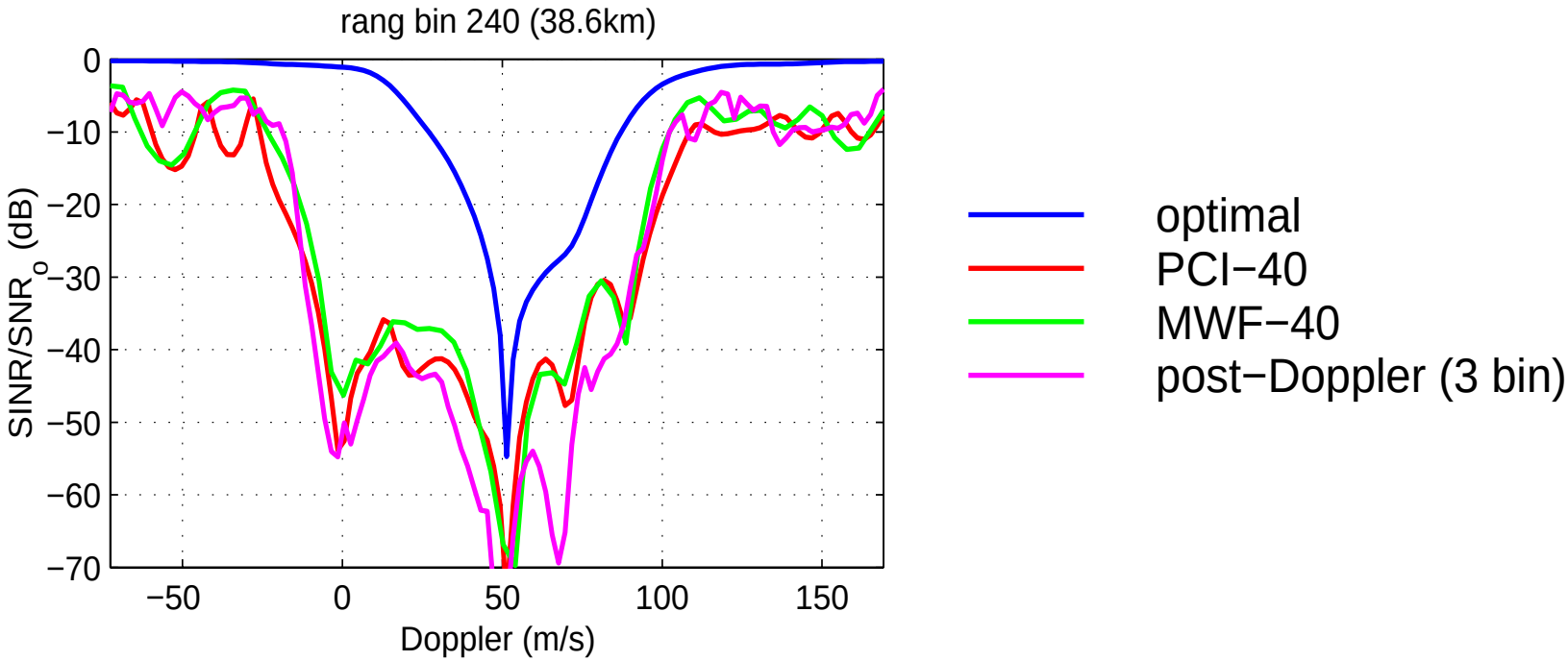
Extremely suboptimal radar performance can occur if one or more of the following occurs:
(High false alarm rates and/or low P_d)

- 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!

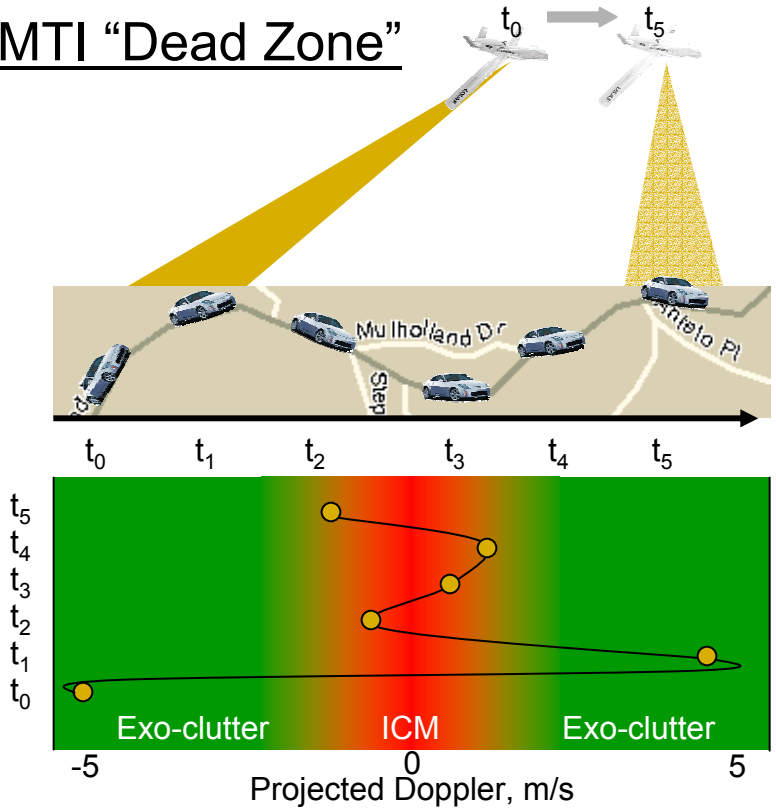
Serious Performance Impacts!!

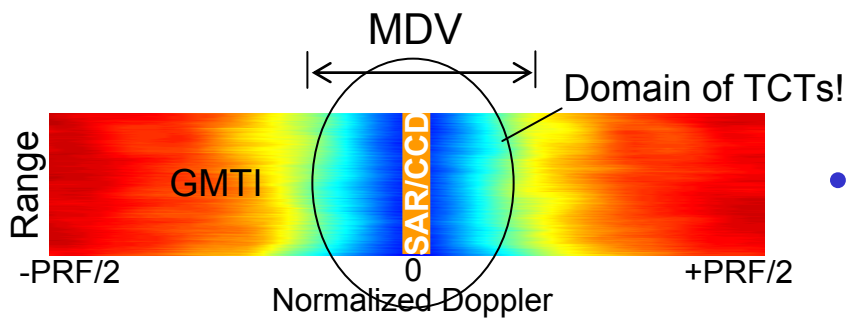


- MWF and PCI : 40 DoFs and 100 training samples
- Post-Doppler: 3 bins, 11 elements (33 DoFs) and 66 training samples
- MWF SINR loss only computed for a single range bin due to computational requirements

MDV is Critical

GMTI "Dead Zone"



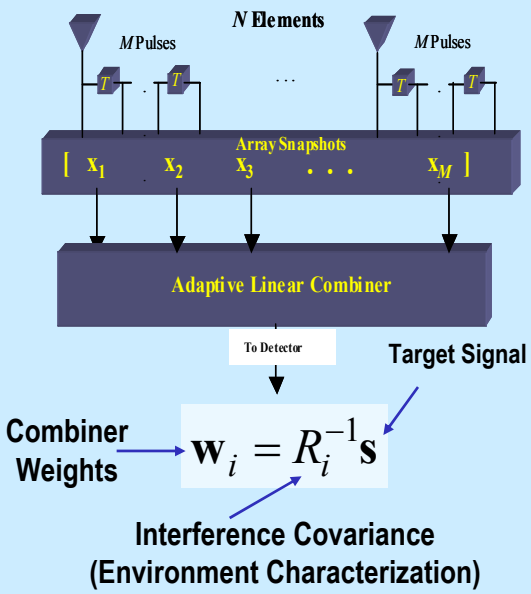


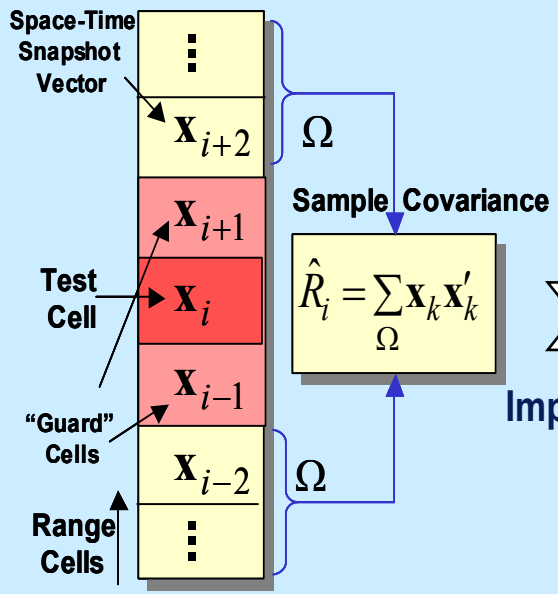
- GMTI = Wide Area Search & Track of Moving Targets
- SAR/CCD = "Soda Straw" Coverage for Stationary Targets
- Birth-to-Death Tracking Requires Both
  - Seamless Integration of GMTI & SAR Modes
  - Current systems have extremely poor MDV performance in challenging clutter/background environments
- MDV is key to tracking of TCTs

What are the Problems?

- Current systems implement highly restrictive adaptation techniques
  - Require environment to remain “stationary” and “homogeneous” during “adaptation” (e.g., CACFAR, STAP)
  - Significant performance degradation in “complex” interference environments
- Only suboptimal piecemeal “patches” to problem have been considered
  - No potential solutions exist that comprehensively address the totality of issues
- Fundamental shift in the basis for adaptation required

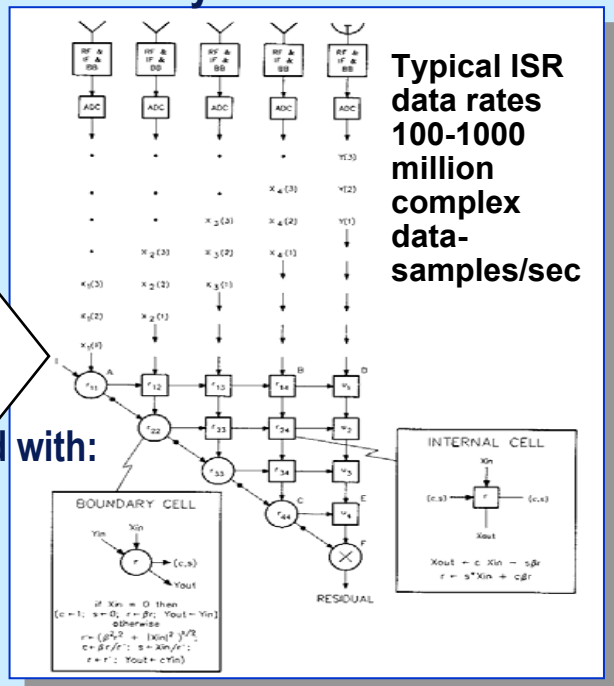
Conventional Adaptive Radar





Implemented with:

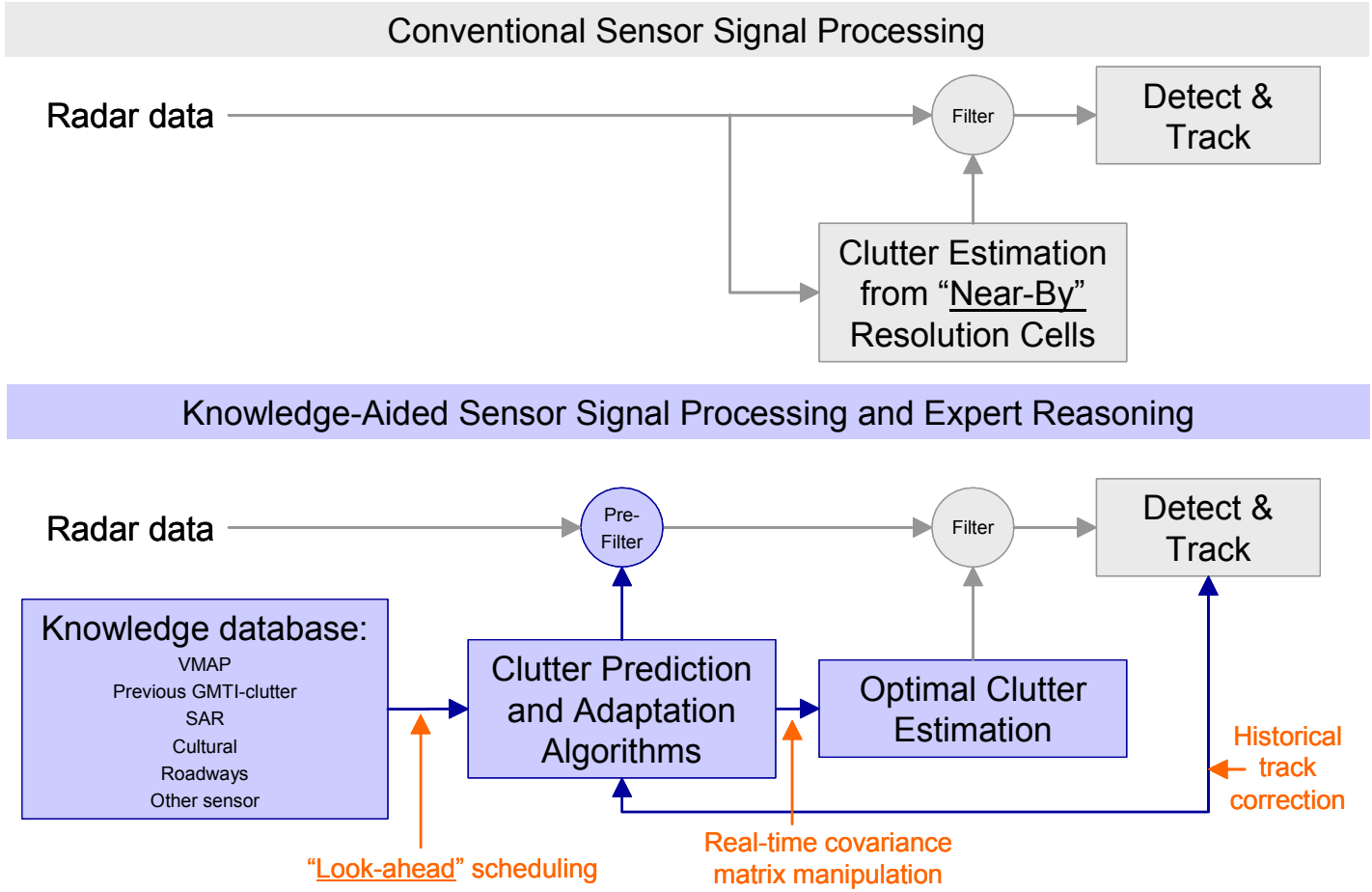
Systolic Processor



Typical ISR data rates 100-1000 million complex data-samples/sec

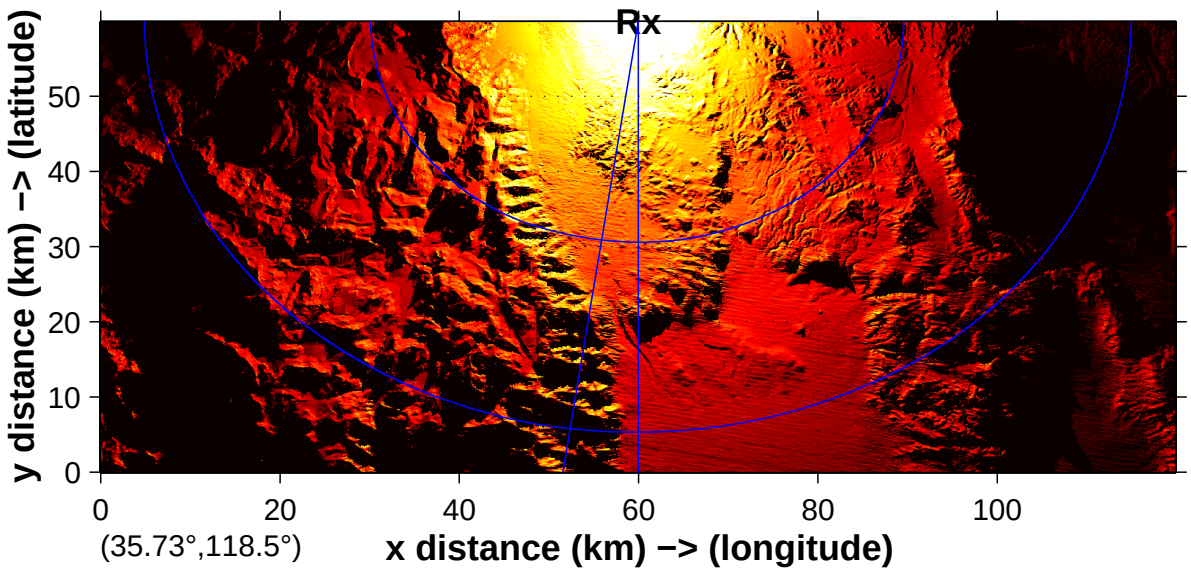
Key Technology Leaps

- Look-ahead scheduling architecture



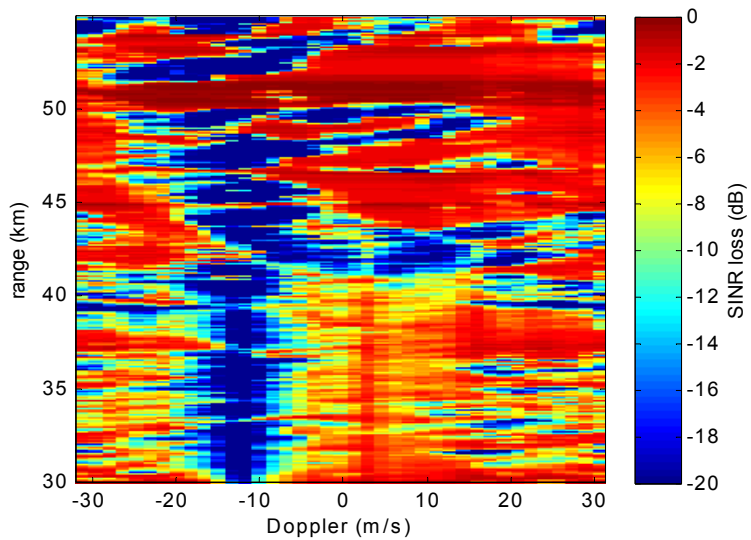
- Real-time knowledge-aided processing algorithms

FY02: Hi-Fidelity Environmental Modeling & Knowledge-Aided STAP Performance

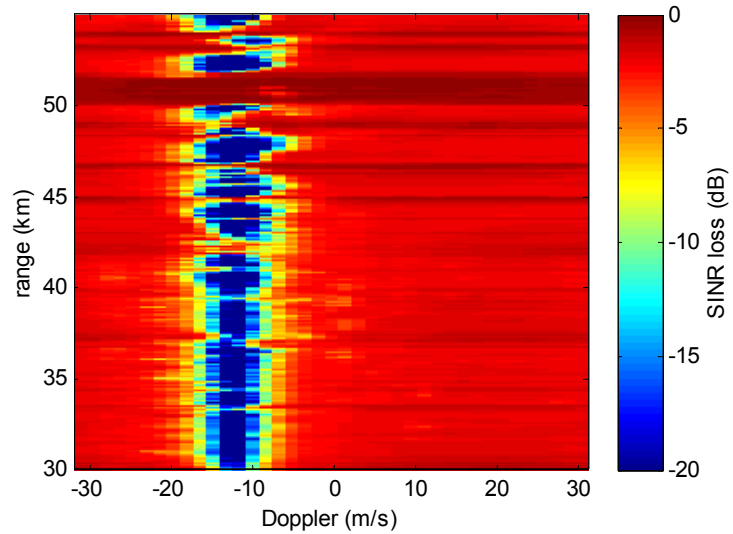


Parmeter	Value
RF frequency	10000 MHz
Bandwidth	10 MHz
PRF	2000 Hz
Peak Power	10 kW
Duty factor	10%
Noise figure	5 dB
System losses	7 dB
Platform speed	150 m/s
Platform altitude	7 km ASL
Receive aperture	1.425 m x 0.285 m
Number of subarrays	12
crab	~3 degrees
Number of Pulses	38

Conventional

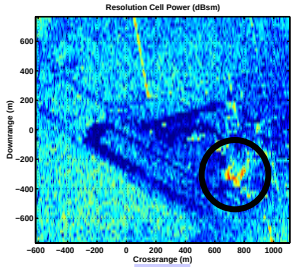


Potential KASSPER Performance

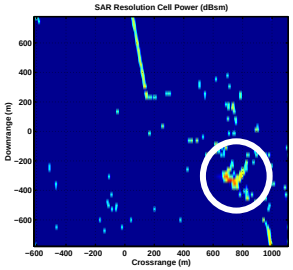


FY03: Progress with Real Data

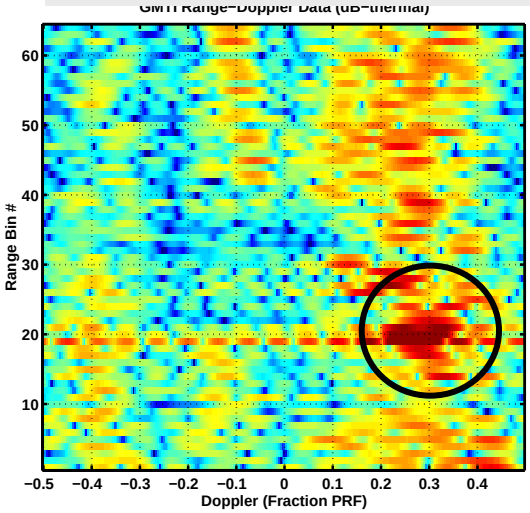
Low-Res SAR

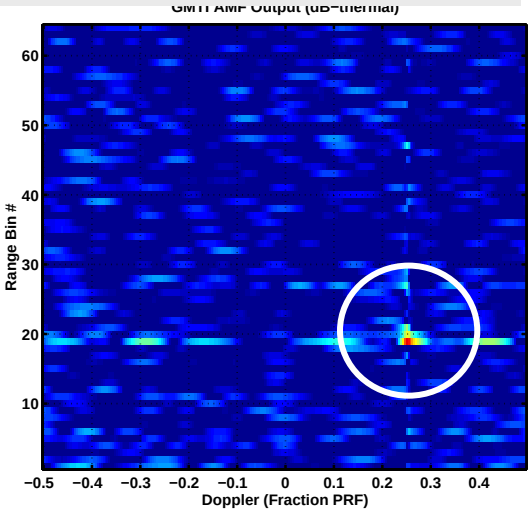


Discrete Detection

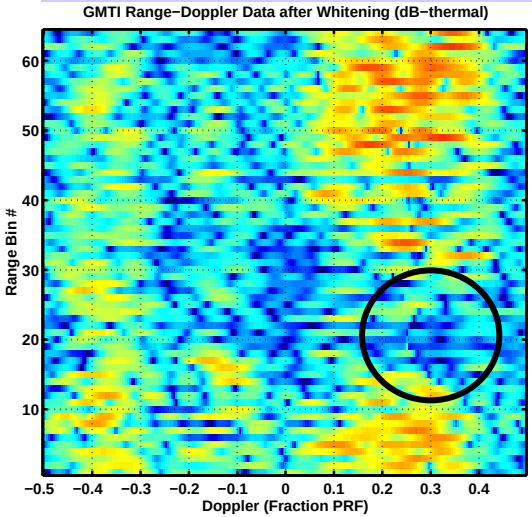


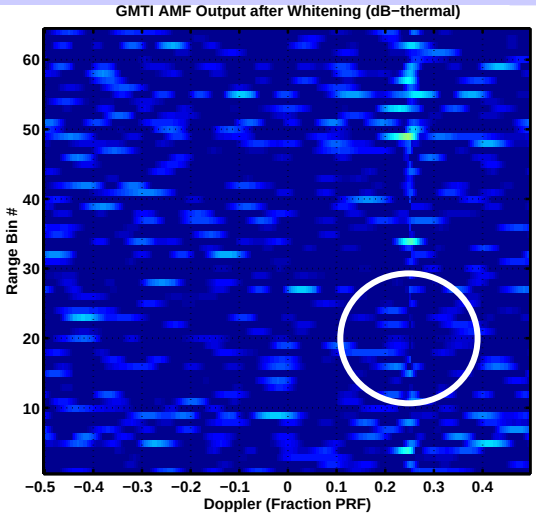
Conventional STAP



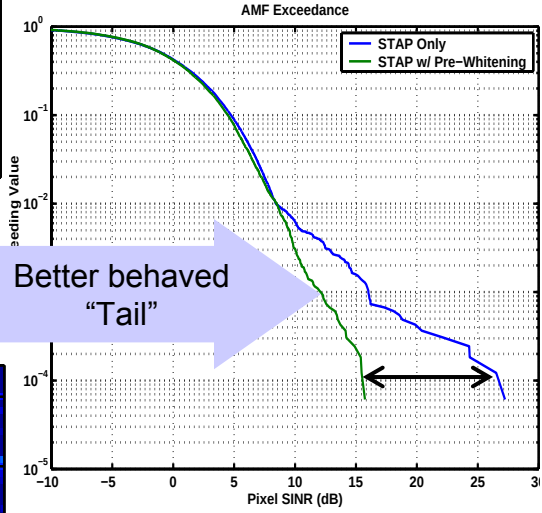


KASSPER Pre-Filtering & STAP





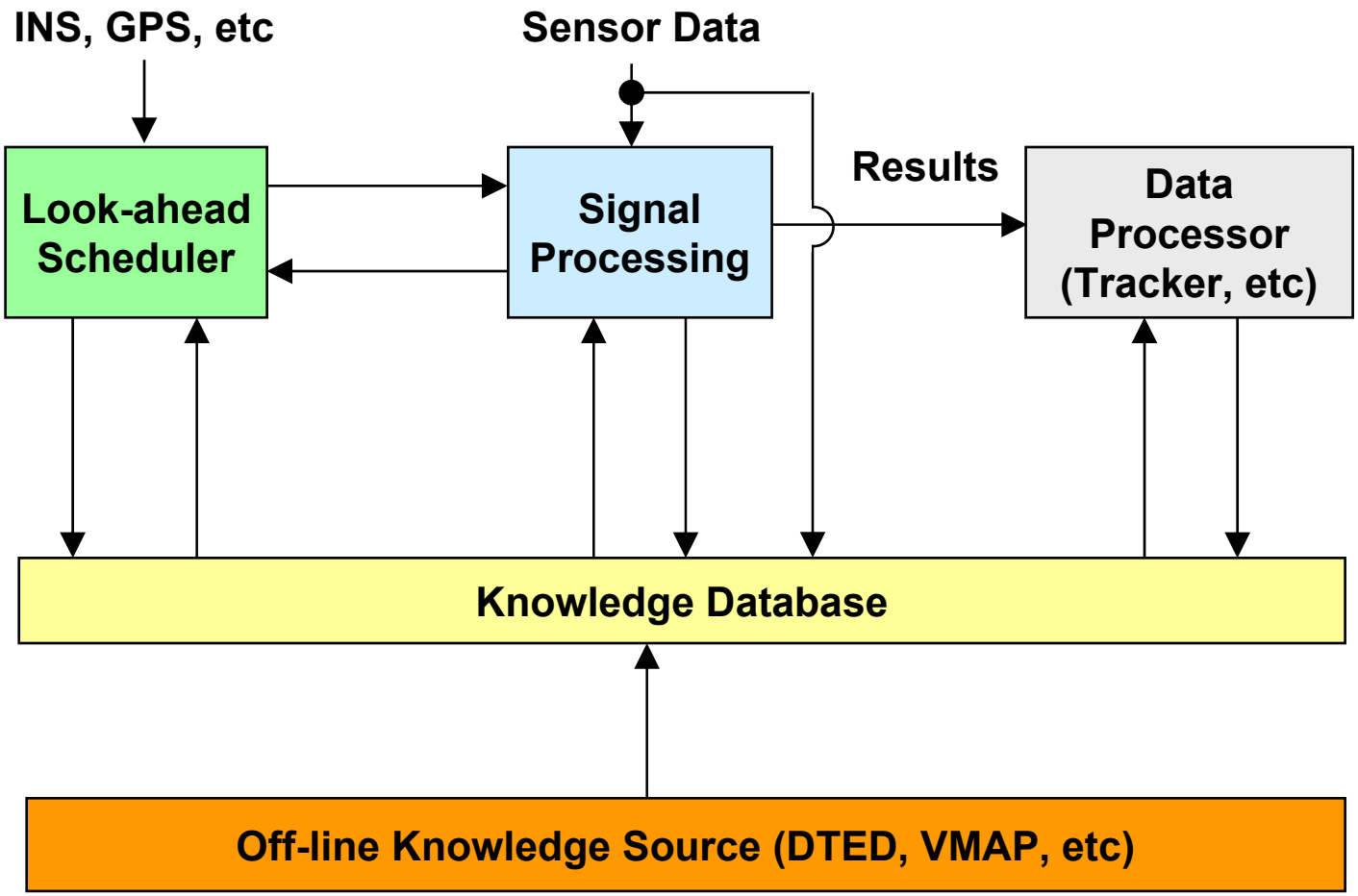
Pre-Filtering Reduces The "Tail" of the Exceedance Function



Better behaved "Tail"

~12dB improvement in P_{fa}!

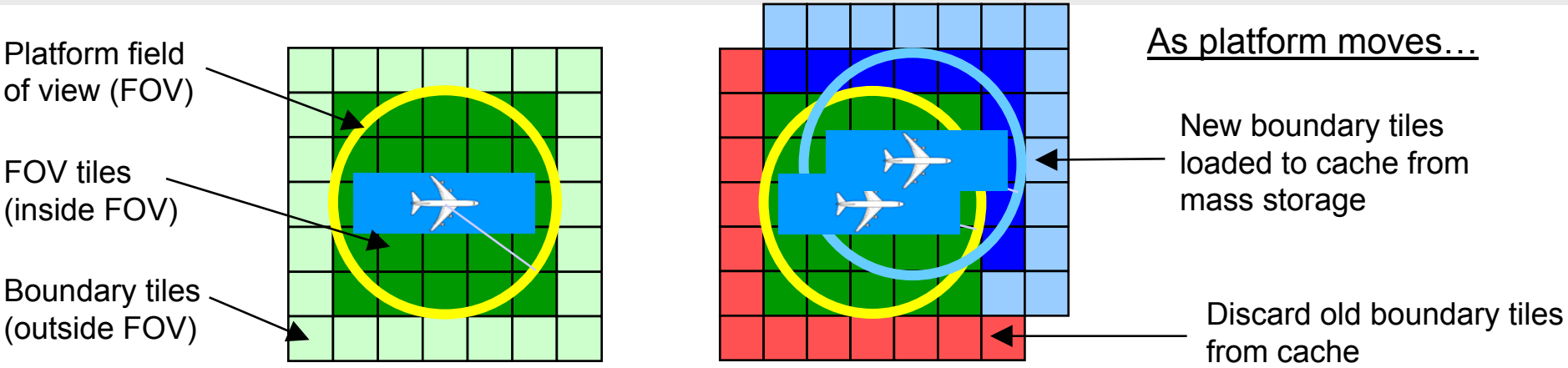
FY04: Enabling KASSPER Architecture



How to Implement in Real-Time?

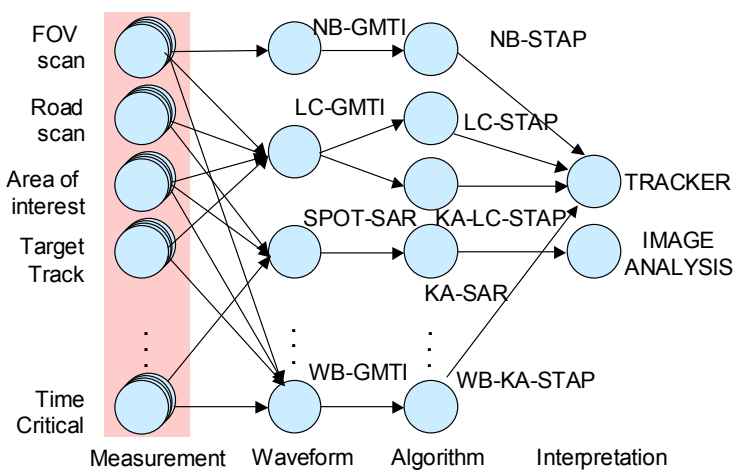
Right Knowledge, Right Time

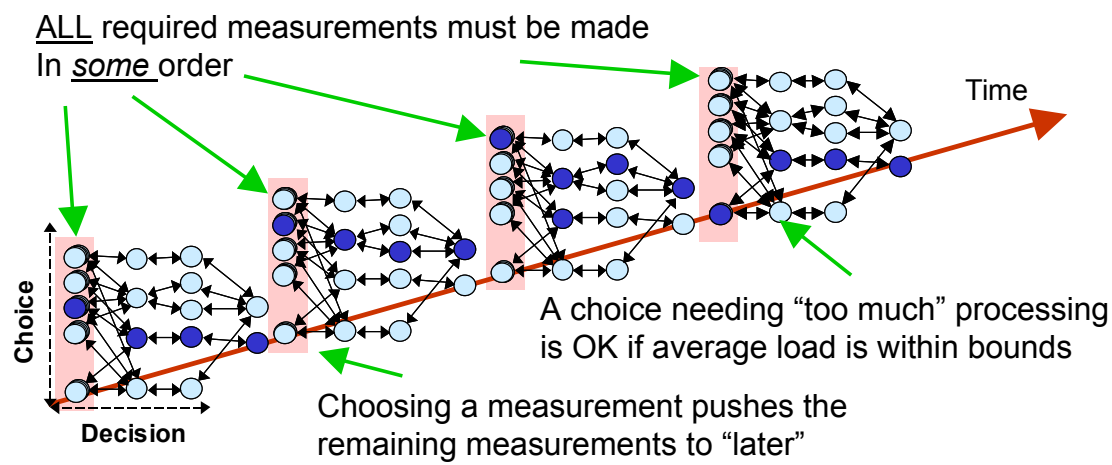
Geographic knowledge management



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

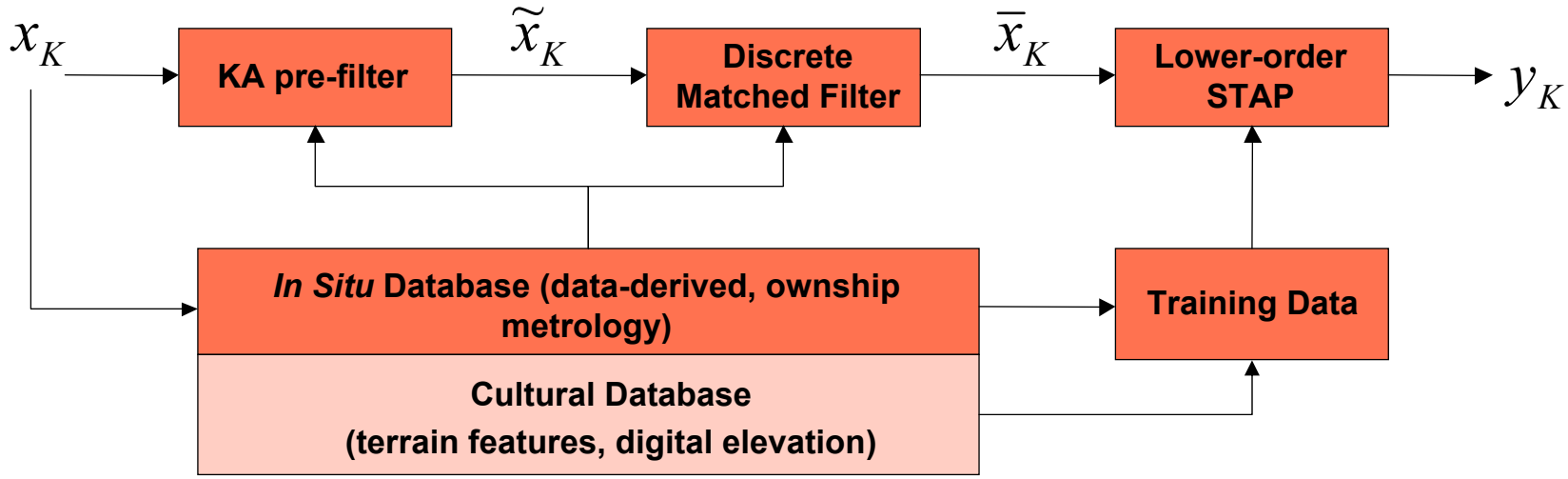
Intelligent processor resource scheduling



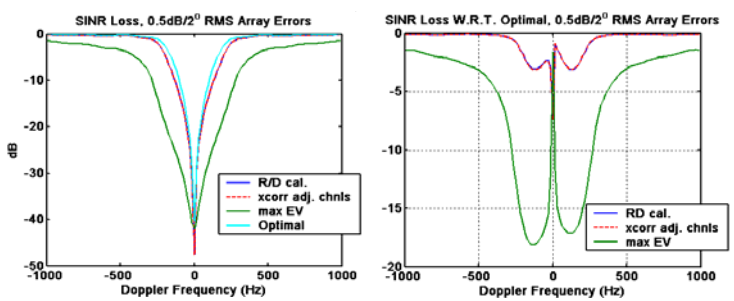


Enabling Advanced STAP Architectures

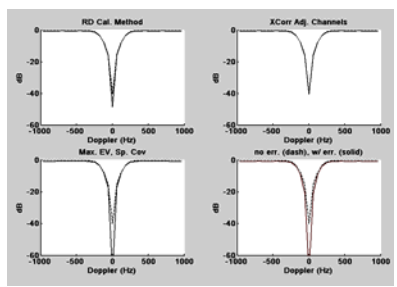
Knowledge Aided-STAP Architecture



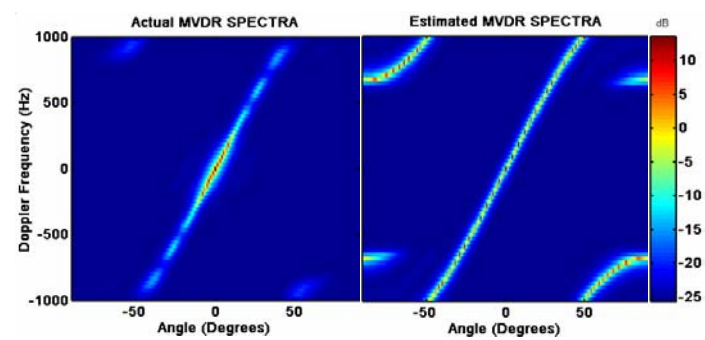
Data-Derived KA Pre-Whitening



KA Calibration

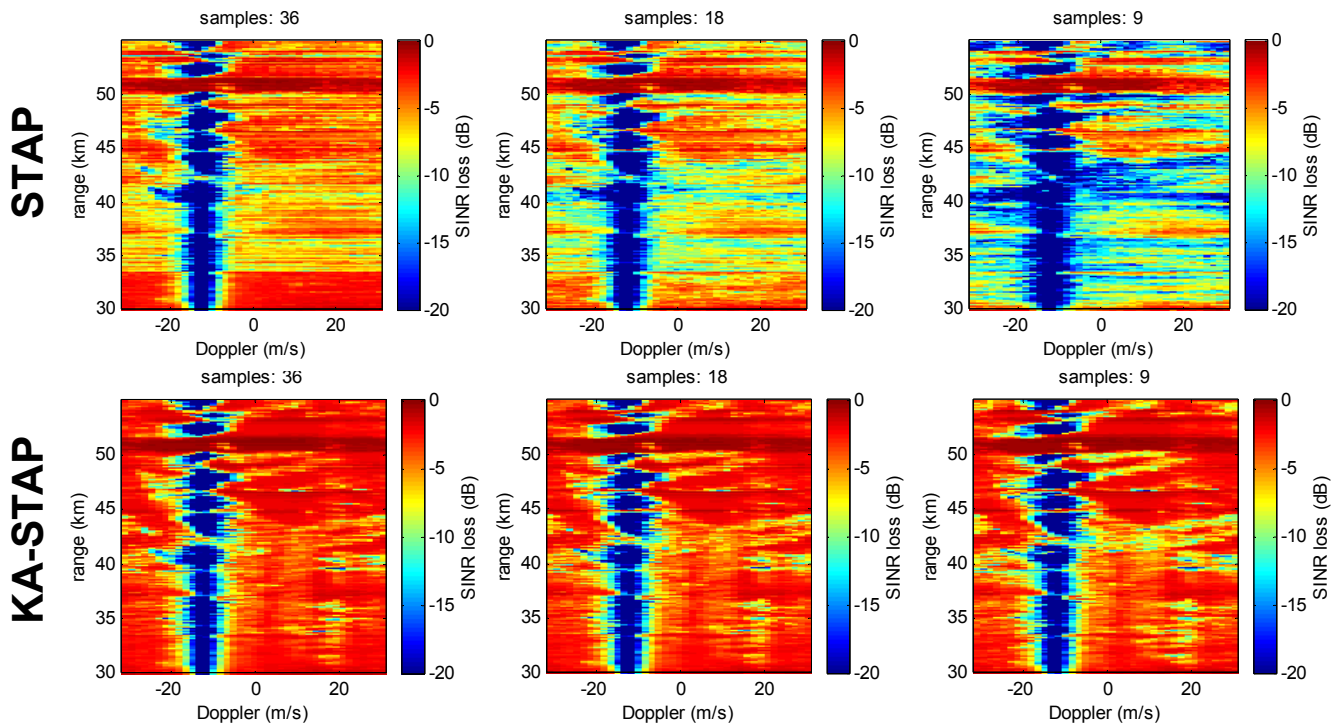


Actual & Estimated Clutter Spectra



Reduced Sample Support

decreasing sample support →



$$\min_{\mathbf{w}} \; E\{|\mathbf{w}^H\mathbf{x}|^2\} \quad \text{s.t.} \quad \begin{cases} \mathbf{w}^H\mathbf{v} = 1 \\ \mathbf{w}^H\mathbf{R}_c\mathbf{w} \le \delta_d \\ \mathbf{w}^H\mathbf{w} \le \delta_L \end{cases}$$

want weights to be "orthogonal" to *a priori* clutter model

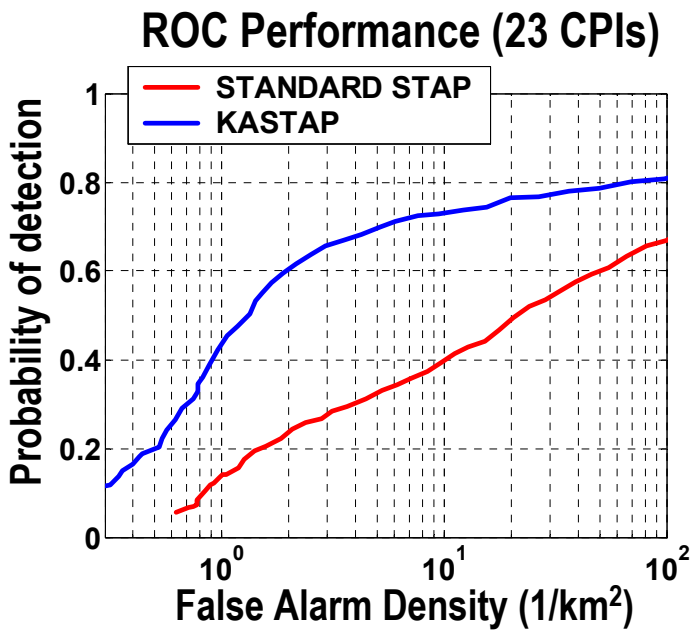
$$\mathbf{x} \longrightarrow \underbrace{\boxed{(\beta_d\mathbf{R}_c + \beta_L\mathbf{I})^{-1/2}}}_{\textbf{deterministic}} \xrightarrow{\tilde{\mathbf{x}}} \underbrace{\boxed{\begin{array}{c}\textbf{STAP}\\ \textbf{covariance est.}\\ \textbf{constraint}\\ \textbf{diagonal loading}\end{array}}}_{\textbf{adaptive}} \longrightarrow$$

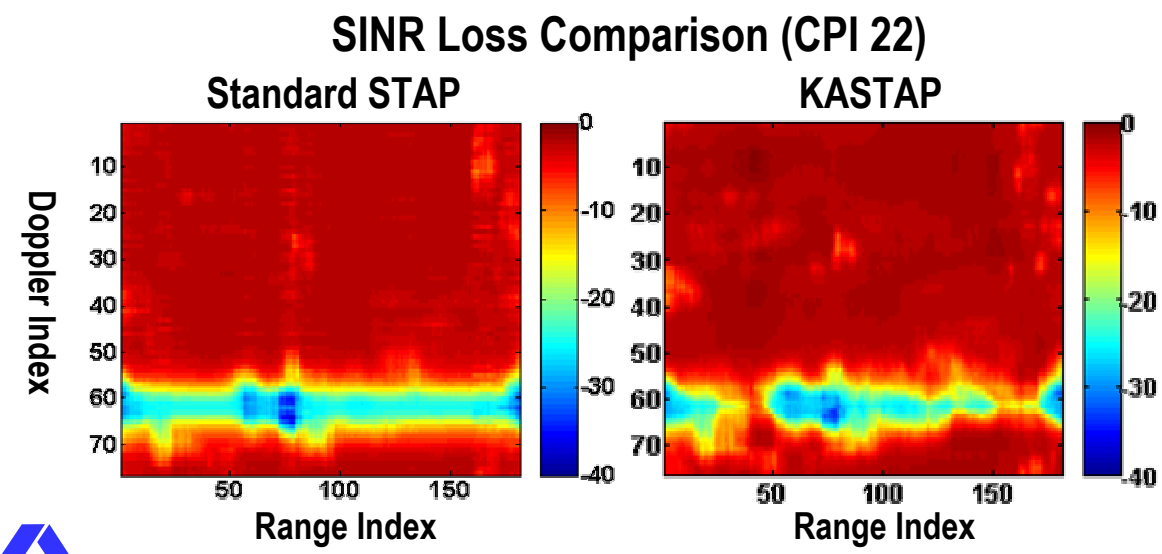
Equivalent to 2-stage filter: deterministic followed by adaptive

Improved P_d and P_{fa} for Tracking

Knowledge-aided techniques developed and applied to KASSPER Data Set 2

- Geo-registration and adaptive combination of multiple-CPI data-cubes to form earth-referenced clutter reflectivity maps
- Adaptive estimation and correction for angle-dependent gain and phase errors in each antenna channel
- Calculation of current-CPI clutter covariance matrices using reflectivity maps
- Range-Doppler masking to reduce the effects of target contamination of KASTAP training data
- Knowledge-aided pre-whitening and eigenvalue rescaling





False alarm density at Pd=60%:

Standard STAP: 50/km^2

KASTAP: 2/km^2

FY05: Real-Time Demonstration

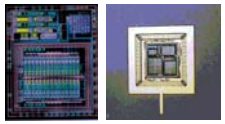
- Demonstrate intelligent “look-ahead” resource scheduling
  - Recognizing and preloading pertinent data into cache
  - Performing predictive *a priori* data adaptation (i.e. generate clutter pre-whitening mask for covariance matrix and discrete detection from low-resolution SAR imagery)
  - Real-time, “look ahead” processor resource management
- Demonstrate real-time data operations in front-end signal processing
  - Multiple manipulations of the covariance matrix within processing latencies
- Demonstrate > order of magnitude improvement over classical STAP
  - >10dB improvement in P_d and P_{fa}
  - Detection and tracking of targets in the GMTI “Dead Zone”!

Next-Gen KASSPER HPEC Testbed

- Architecture:
  - Base computer and I/O cards purchase order completed
  - Lab computer configuration complete
  - Various processing concepts in review
  - PDR planned for late June 03
  - Demonstration at DARPATech 04

MP-510 mercury processing

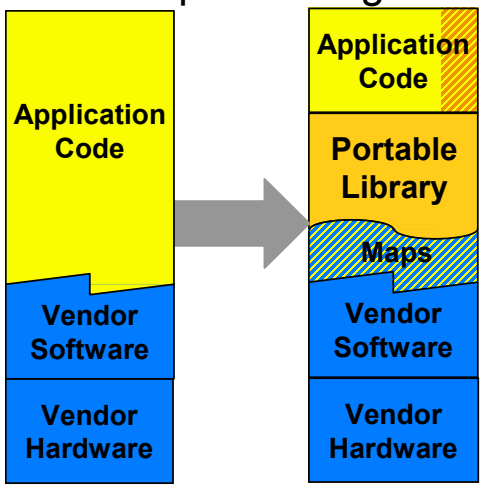
Multiple high-speed RAID drives



ASIC high-speed cache memory devices

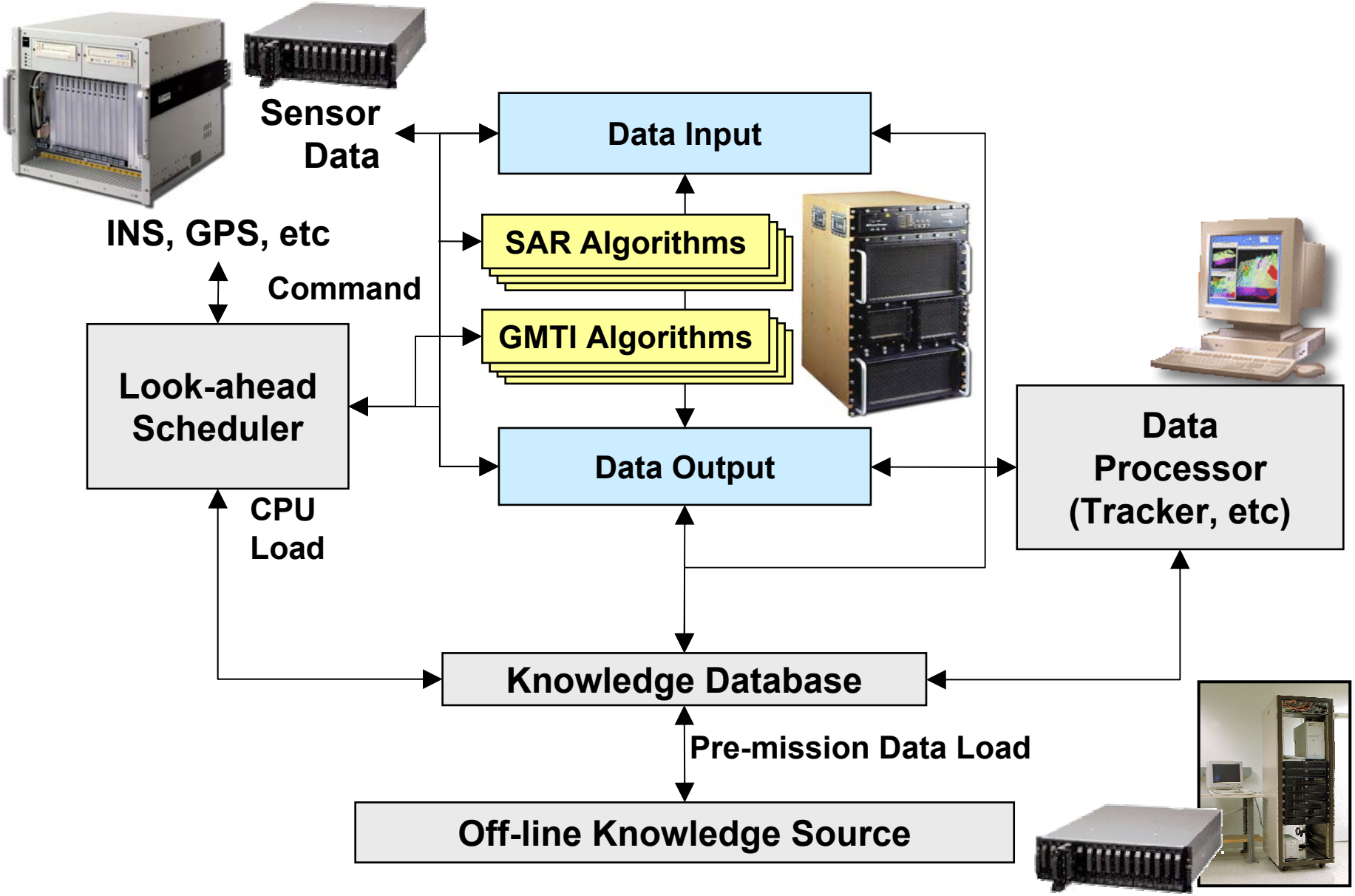
- Parallel Vector Library (PVL) chosen for open standards programming language
  - LL reviewing initial KASSPER algorithms for library impacts
  - Coding started on basic radar signal processing components (pulse compression, data retrieval, etc.)
  - Algorithm developers will program the hardware

Open standards for real-time processing



- Upgrades restricted to hardware remapping & new features

Real-time Demonstration Processor



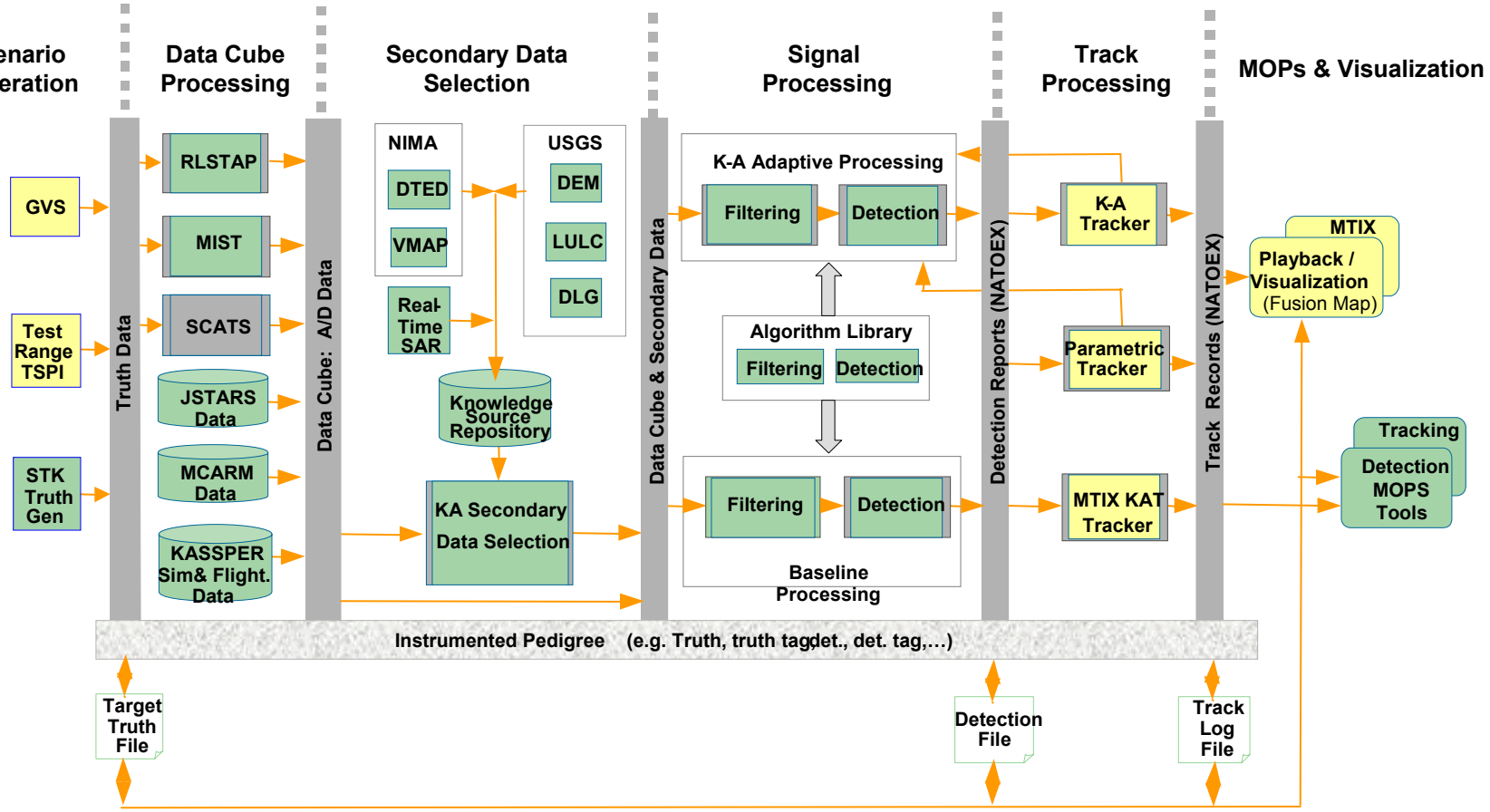
FY05: Transition

- Government owned real-time demonstration testbed and off-line algorithm analysis suite
  - Signal Processing Evaluation, Analysis & Research (SPEAR) Facility
  - AFRL/SN providing FY06 funds to continue KASSPER technologies and annual workshop
- Platform focused simulation and design at Prime contractors
  - Supports specific platform transition while educating contractors and government program office
  - Focusing on Joint STARS, JSF, MP-RTIP, SBR, and ASARS
- Annual workshops keeping technology in forefront
  - Advanced concept and implementation work on-going at non-KASSPER contractor, government agencies, and universities
  - DARPA/AFRL workshops providing focus via KASSPER architecture

Signal Processing Evaluation, Analysis & Research (SPEAR) Facility

Objective

Develop Knowledge-Aided (KA) Signal Processing Techniques for Conventional & Future GMTI Sensors Such as JSTARS, GH, MP-RTIP, MC2A & SBR



KASSPER:
"It's an Architecture, NOT an Algorithm"

KASSPER is an architecture for real-time adaptation of multidimensional sensor systems in real-world environments

- KASSPER Architecture
  - Environmental context is key to efficient adaptation
    - Sensors, like humans, benefit from context!
  - Key enablers: "look-ahead" scheduling and resource allocation
  - Multiresolution philosophy: blurring the boundaries between SAR and GMTI
  - KASSPER as a modern manifestation of the "Bayesian" method!
    - KA-STAP → Bayesian STAP
- The DARPA KASSPER Challenge: Creatively explore the possibilities
  - Re-examine entire adaptive signal processing paradigm with an eye towards maximizing knowledge-aided "robust" methods
  - Robust STAP algorithms AND KASSPER architecture
    - Environmental knowledge base is "read/write"
  - What is "implementable"? 2010? 2020?
  - Environmentally aware sensors have a future!