Advanced Multidisciplinary System Engineering
or
"How I learned to think outside of MY box!"

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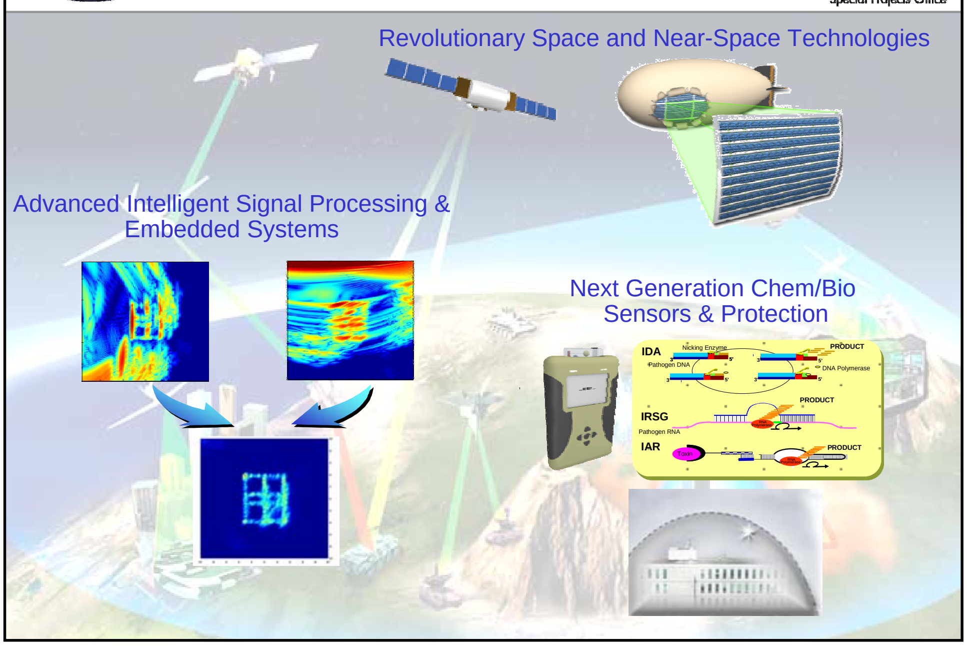
All material cleared for Public Release

Outline

- Breakthrough systems/technologies are almost always multidisciplinary
  - Arise from cross-fertilization
  - “Cross-fertilization” occurs in someone’s *mind*
- “Thinking outside the box” = “Thinking outside *your* box”
  - Examples:
    - KASSPER
    - HISS
- New Trend in Multidisciplinary Systems Engineering
  - Level 1: System = Interconnected set of single-purpose subsystems
  - Level 2: System = Interconnected set of multi-purpose subsystems
  - Level 3: System = Embedded multi-purpose subsystems w/o clear boundaries
- Example: ISIS
- Summary

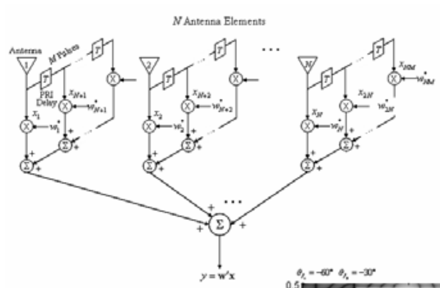
Sample SPO Projects
(A Multidisciplinary Systems Technology Office)

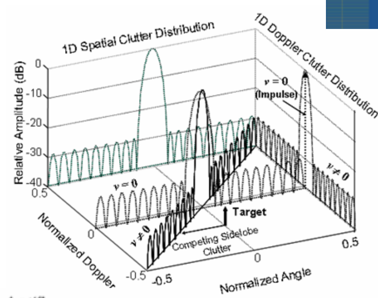


mD Adaptive Signal Processing

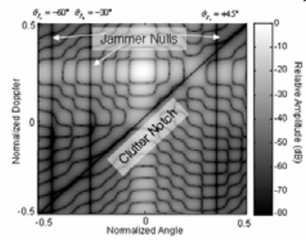
- Example: Space-Time Adaptive Processing (STAP)

Space-Time Adaptive Beamformer





"Ideal" Adapted Pattern



Optimum Solution

- Weiner-Hopf

(Optimum space-time beamformer weights) → $\mathbf{w} = R^{-1}\mathbf{s}$ ← (Desired signal "steering vector")

(Inverse of total interference covariance matrix)

$$\mathbf{w}, \mathbf{s} \in C^{NM}$$

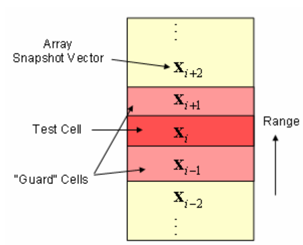
$$R \in C^{NM \times NM}$$

$$NM \sim 10's - 100's$$

Covariance Estimation Problem

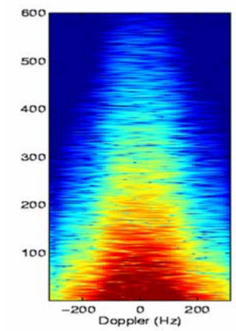
- Practical implementation example and real data example (White Sands DARPA Mountain Top Radar)

Sample Covariance Estimation

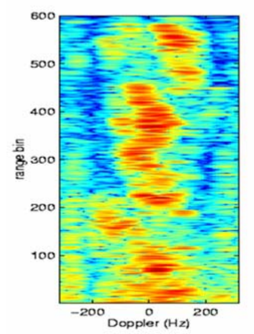


$$\hat{R} = \sum_{i\in\Omega} \mathbf{x}_i \mathbf{x}_i'$$

Ideal (Stationary) Data



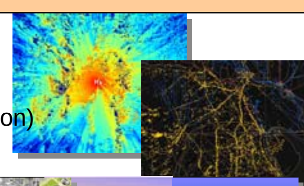
Measured Data

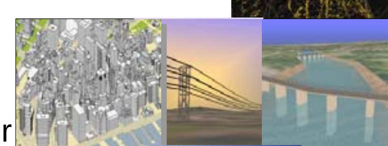


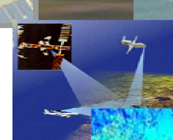
Welcome to the Real-World!

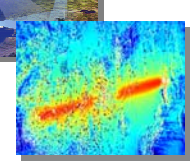
Extremely suboptimal radar performance can occur if one or more of the following occurs:
(High false alarm rates and/or low P_d)

- 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)





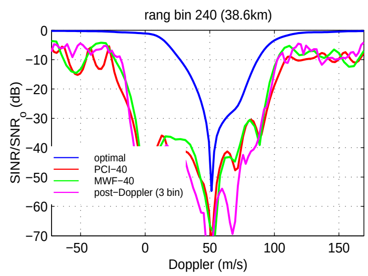


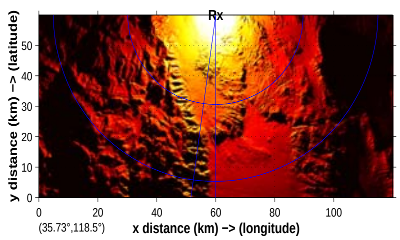


One or More of the Above is Almost Always Present in Real-World Ops!

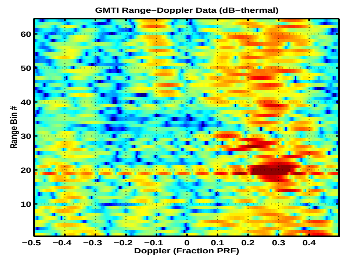
Serious Performance Impacts!!
(KASSPER '02 Data Cube & APTI Data Set)

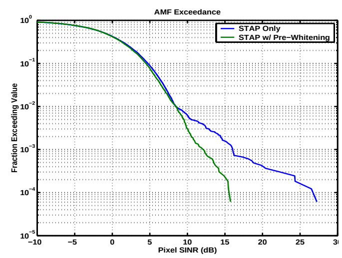
SINR Loss





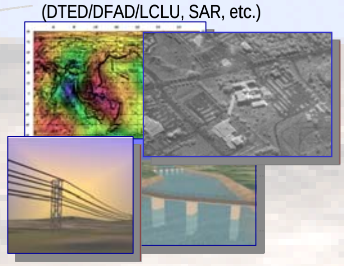
High False Alarm Rates

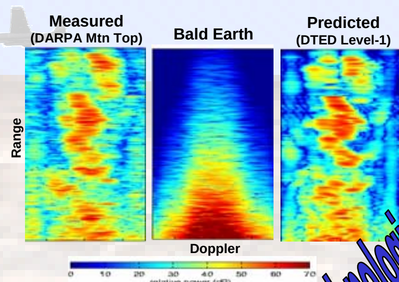




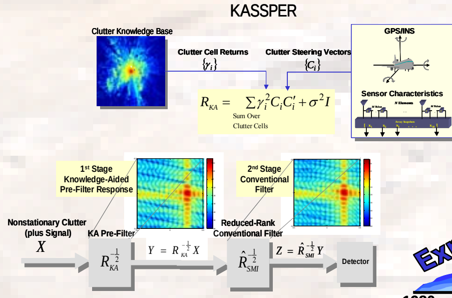
Knowledge-Aided Sensor Signal Processing & Expert Reasoning (KASSPER)

Radar Environmental Knowledge Bases (DTED/DFAD/LCLU, SAR, etc.)

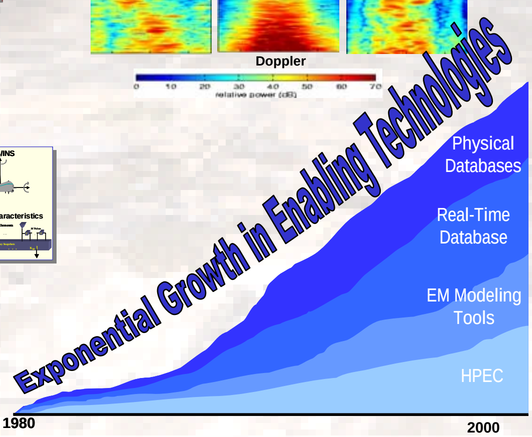


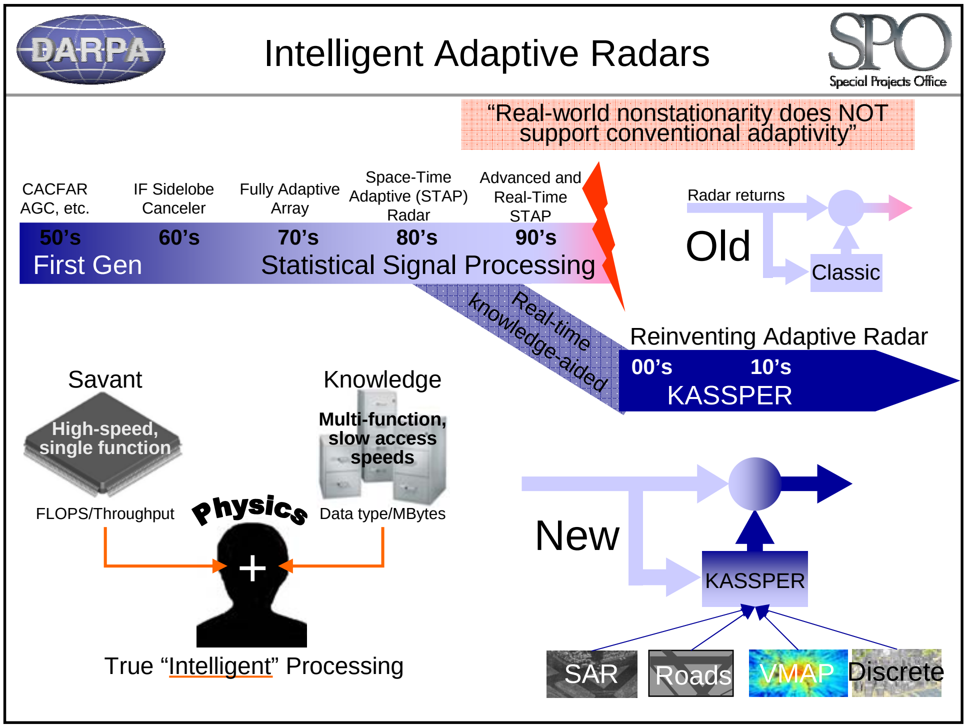


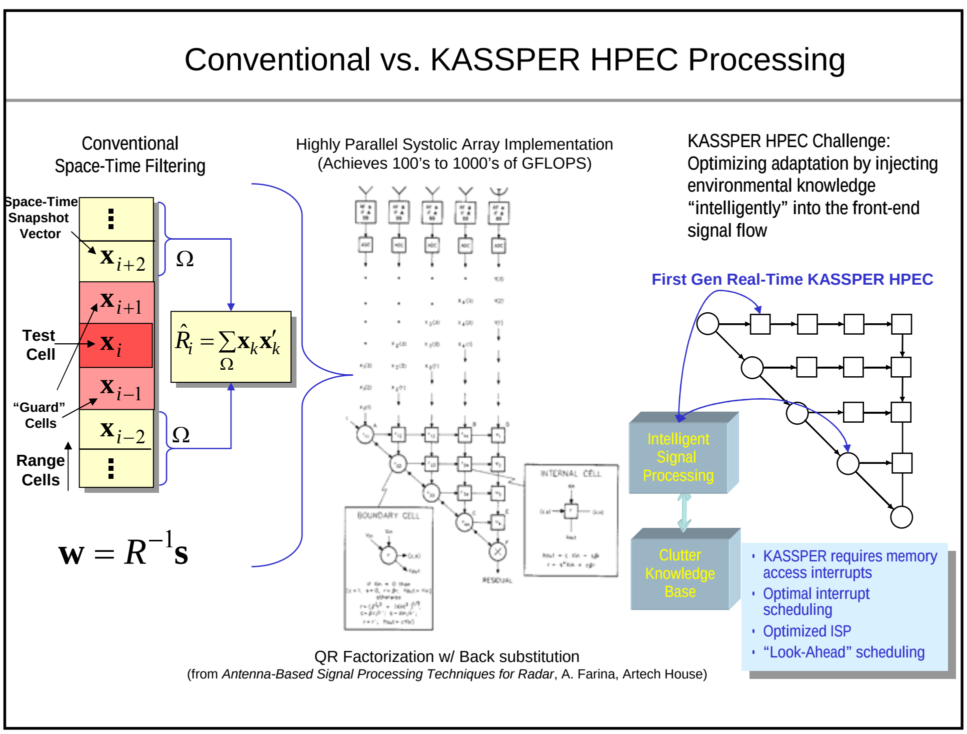
KASSPER



$$R_{KA} = \sum \gamma_i^2 C_i C_i' + \sigma^2 I$$

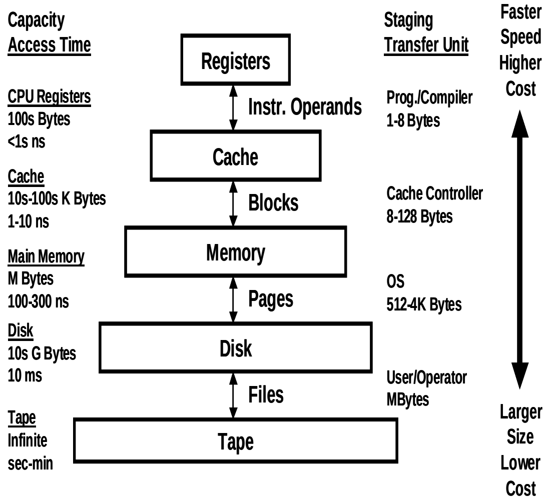



DARPA
Intelligent Adaptive Radars
SPO
Special Projects Office
"Real-world nonstationarity does NOT support conventional adaptivity"
CACFAR AGC, etc.
IF Sidelobe Canceler
Fully Adaptive Array
Space-Time Adaptive (STAP) Radar
Advanced and Real-Time STAP
50's
60's
70's
80's
90's
First Gen
Statistical Signal Processing
Real-time knowledge-aided
Radar returns
Old
Classic
Reinventing Adaptive Radar
00's
10's
KASSPER
Savant
High-speed, single function
FLOPS/Throughput
Knowledge
Multi-function, slow access speeds
Data type/MBytes
Physics
+
True "Intelligent" Processing
New
KASSPER
SAR
Roads
VMAP
Discrete


Conventional vs. KASSPER HPEC Processing
Conventional Space-Time Filtering
Space-Time Snapshot Vector
$\mathbf{x}_{i+2}$
$\mathbf{x}_{i+1}$
$\mathbf{x}_{i}$
$\mathbf{x}_{i-1}$
$\mathbf{x}_{i-2}$
Test Cell
"Guard" Cells
Range Cells
Ω
Ω
$\hat{R}_i = \sum_{\Omega} \mathbf{x}_k \mathbf{x}_k'$
$\mathbf{w} = R^{-1}\mathbf{s}$
Highly Parallel Systolic Array Implementation
(Achieves 100's to 1000's of GFLOPS)
INTERNAL CELL
BOUNDARY CELL
RESIDUAL
QR Factorization w/ Back substitution
(from *Antenna-Based Signal Processing Techniques for Radar*, A. Farina, Artech House)
KASSPER HPEC Challenge:
Optimizing adaptation by injecting environmental knowledge "intelligently" into the front-end signal flow
First Gen Real-Time KASSPER HPEC
Intelligent Signal Processing
Clutter Knowledge Base
KASSPER requires memory access interrupts
Optimal interrupt scheduling
Optimized ISP
"Look-Ahead" scheduling

"Look-Ahead" Scheduling Addresses Memory Latency Issues

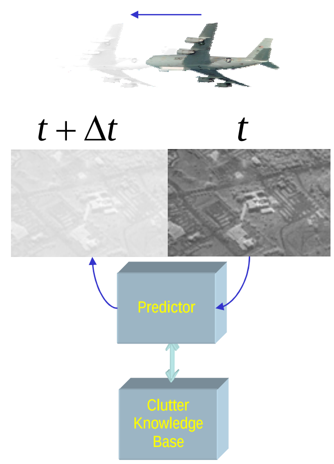
Problem:



Source: Dave Patterson, Graduate Computer Architecture Course, University of California, Berkeley, Spring, 2001

Solution:

KASSPER
"Look-Ahead"
Interrupt Scheduling

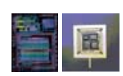


Next-Gen KASSPER HPEC Testbed

- 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
- 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

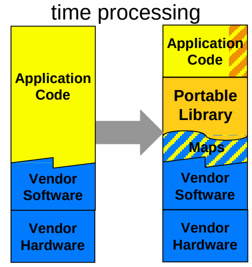
MP-510 mercury processing

Multiple high-speed RAID drives



ASIC high-speed cache memory devices

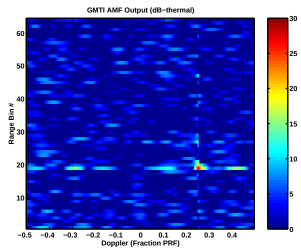
Open standards for real-time processing



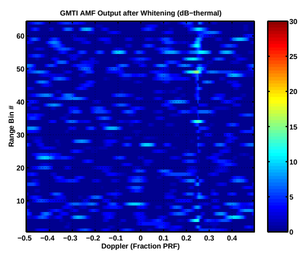
- Upgrades restricted to hardware remapping & new features

Pre-filtering Followed by Conventional STAP

Adaptive Matched Filter

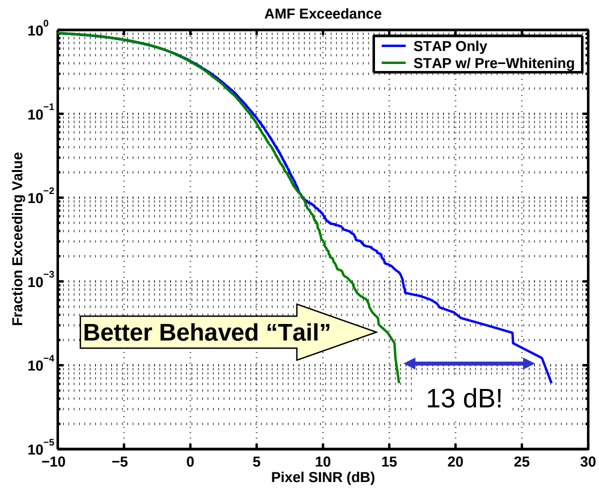


Without Prefiltering



With Prefiltering

Pre-Filtering Reduces The “Tail” of the Exceedance Function



KASSPER:

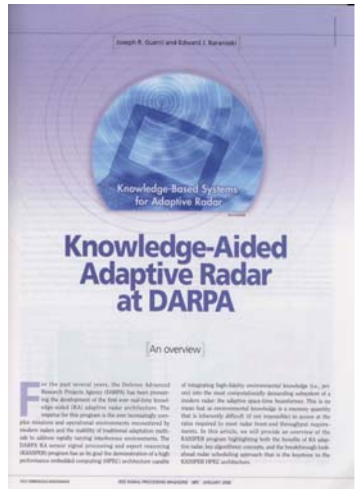
“It’s an Architecture, NOT an Algorithm”

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 as “read/write” scratch memory
  - What is “implementable”? 2010? 2020?
  - Environmentally aware sensors have a future!

Emerging Field

- Special Issue of *IEEE Signal Processing Magazine*



Handheld Isothermal Silver Standard Sensor (HISSS)

DARPA

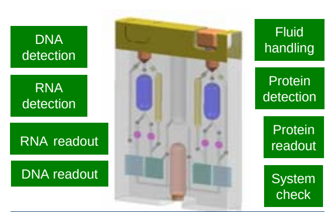
SPO Special Projects Office

The goal of the HISSS program is to develop a handheld sensor that is capable of identifying biological threats including bacteria, viruses and toxins.

How to shrink into a handheld?
- Order-of-mag faster!
- At least as accurate!

Polymerase Chain Reaction (PCR) Machine

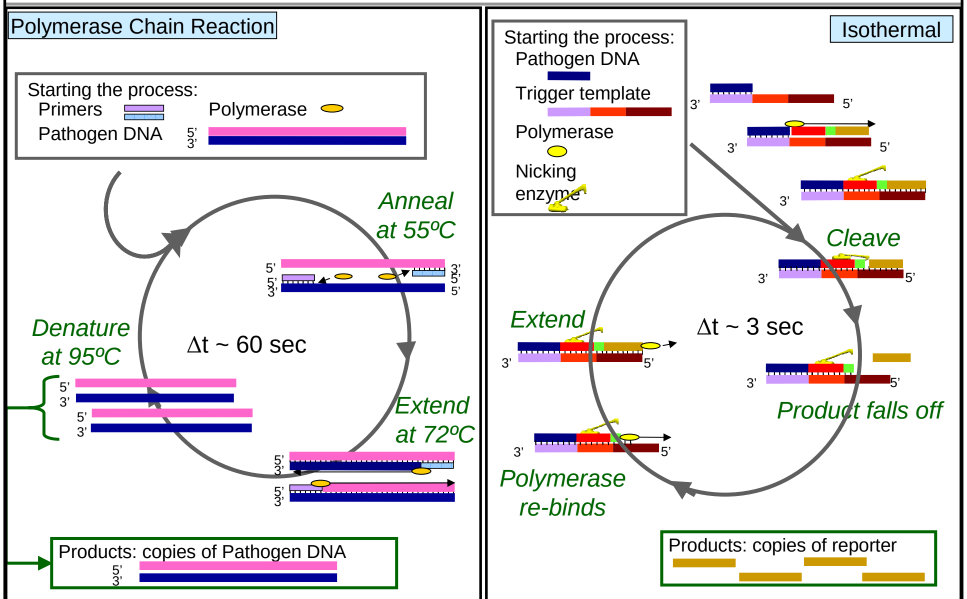
Notional Sensor



Notional Sample Cartridge

PCR vs. Isothermal

Special Projects Office

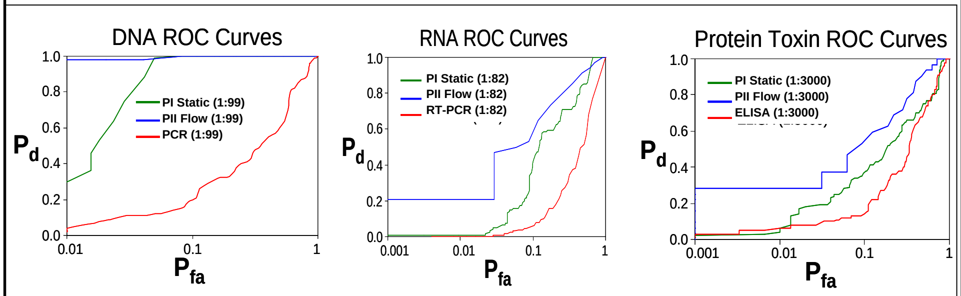


HISS DNA Amplification

Special Projects Office

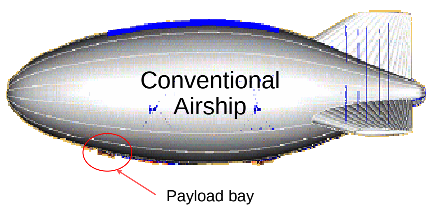
HISSS Progress

- Progress:
  - Demonstrated false alarm rates, using ROC curve analysis for HISSS assays that are equal to or better than current DNA, RNA, and protein assays
  - Successfully developed and utilized a flow-through testbed to test all assays



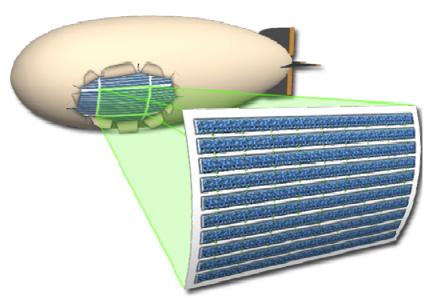
New Airship Design Philosophy

Capability cannot be added to airship after development



Payload: ~2% of system mass

ISIS requires integration of sensor and airship



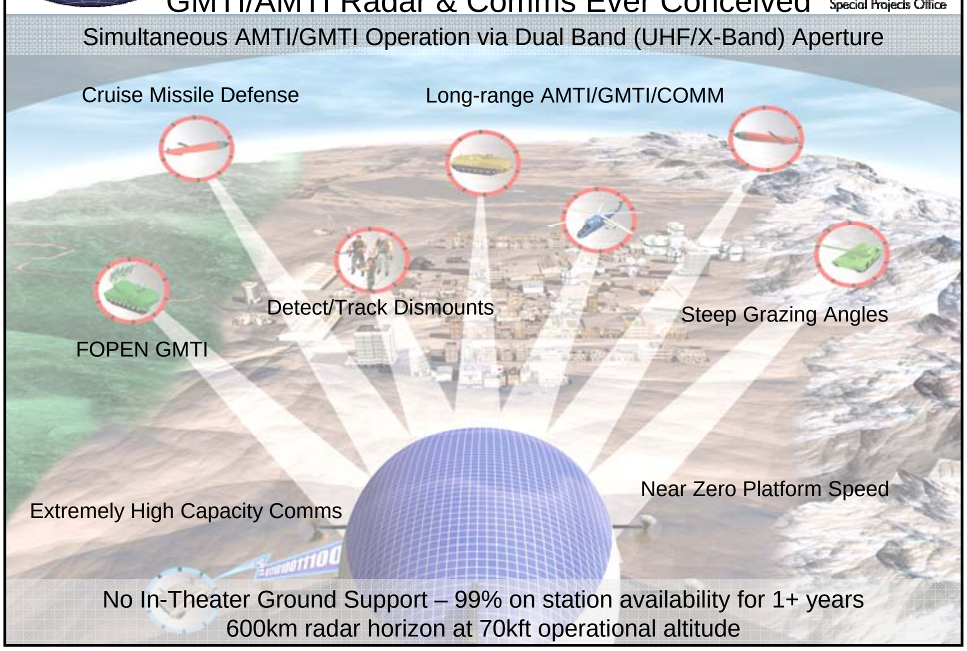
Payload: 30-40% of system mass

Turn a disadvantage (large size) into an advantage (large antenna)!

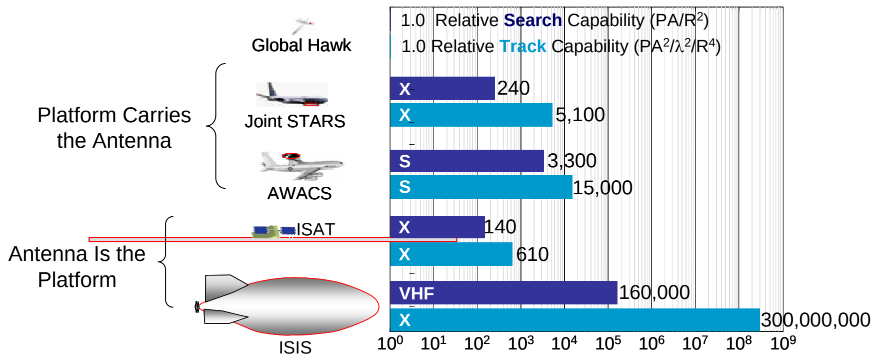
The "First" ISIS?

Echo 1

Most Powerful Airborne GMTI/AMTI Radar & Comms Ever Conceived

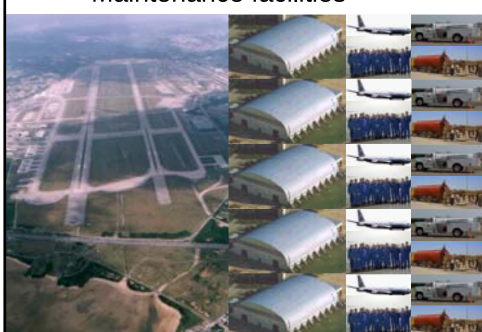


Unprecedented Radar Performance



Sustained Operations Logistics

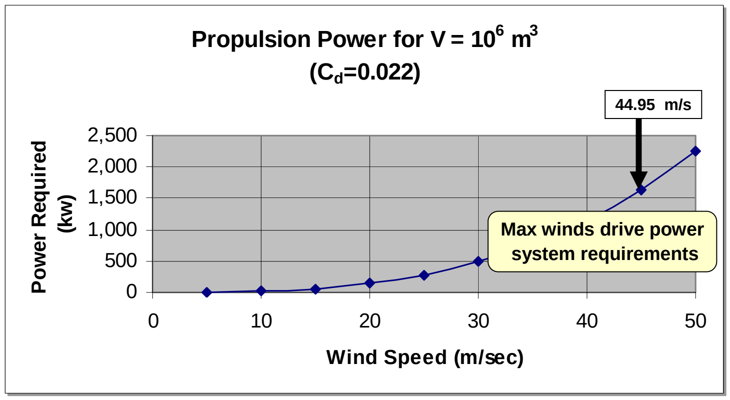
- Aircraft-based ISR Requires
  - Local air base
  - Multiple aircraft to keep 1 flying
  - Air crews
  - Ground crews
  - Fuel supplies
  - Maintenance facilities
- ISIS
  - Unmanned
  - Deploys worldwide from U.S. base
  - Regenerative Fuel Sources
  - One-year continuous ISR capability



Wind Conditions Drive Propulsion Power Needs

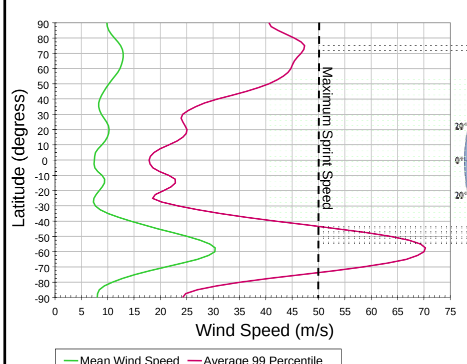
$$P = \frac{\rho \cdot C_d V^{2/3} v^3}{2\eta}$$

Where ρ = air density at altitude
V = volume of airship
v = relative velocity of air
η = efficiency of propellers

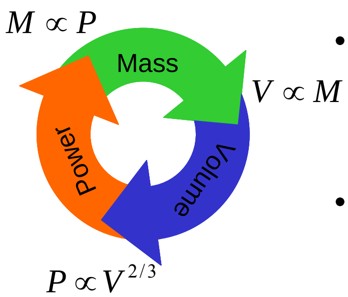


Station Keeping

- ISIS Objective: 99% on-station availability for 1 year
  - Function of airship speed (sustained and sprint) and available energy (regenerative and stored fuel)
- Need operational algorithms for maximizing availability
  - Managing airship energy ala satellite delta-v



Requires Large Mass Reductions



- ISIS designs are mass-centric
  - Lifting gas has reached the maximum limit:
  - 0.061kg per 1m^3 of He @ 21km
  - 0.066kg per 1m^3 of H_2 @ 21km
- ISIS focusing on:
  - Removing mass from largest contributors
  - Integration, INTEGRATION, INTEGRATION!

Integration

$$M_{displacedair} = M_{liftinggas} + M_{structure} + M_{radar} + M_{power} + M_{propulsion} + M_{avionics}$$

$$M_{ISIS} = \rho_{gas} V + c_h \rho_{hull} V^{2/3} + \rho_{aperture} A + \frac{\rho_{power}}{\eta_{power}} \left(P_{radar} + \frac{\rho_{air} C_d V^{2/3} v^3}{2\eta_{propulsion}} \right) + M_{propulsion} + M_{avionics}$$

Components

Summary

- Breakthrough systems/technologies are almost always multidisciplinary
  - System engineers need to be continually learning about new technologies and methods across *ALL* disciplines
    - "*Be an annoying know-it-all!*"
  - Tactic: "*Can the thermal engineer give the flight control engineer's briefing*?"
  - Often "cross fertilization" can occur even if with only a 1st or 2nd order understanding of multiple disciplines
    - Balance of depth and breadth
  - How should engineering programs be structured in light of above?
    - Undergraduate programs typically have the breadth, but don't seem to "close the deal"
      - Example: Senior class semester devoted to dissecting a complex system
- Emergence of a "Level 3" systems integration
  - Multidisciplinary from its inception!