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Multi-Mode, Fine-Resolution, Miniaturized Radar Systems for UAVs

Military Radar Summit

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Sandia National Laboratories

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Presentation Outline

- Introduction
- Next-Generation Miniature Radar Concept
  - Follow-on to “miniSAR” suite of sensors
  - Optimally Applicable to Small Tactical UAS
- Advanced Real-Time, Fine-Resolution Imaging Modes for Surveillance and Reconnaissance
  - Simultaneous VideoSAR/GMTI Mode Combining
  - Enables Target Tracking Through all Ranges of Motion
- Summary

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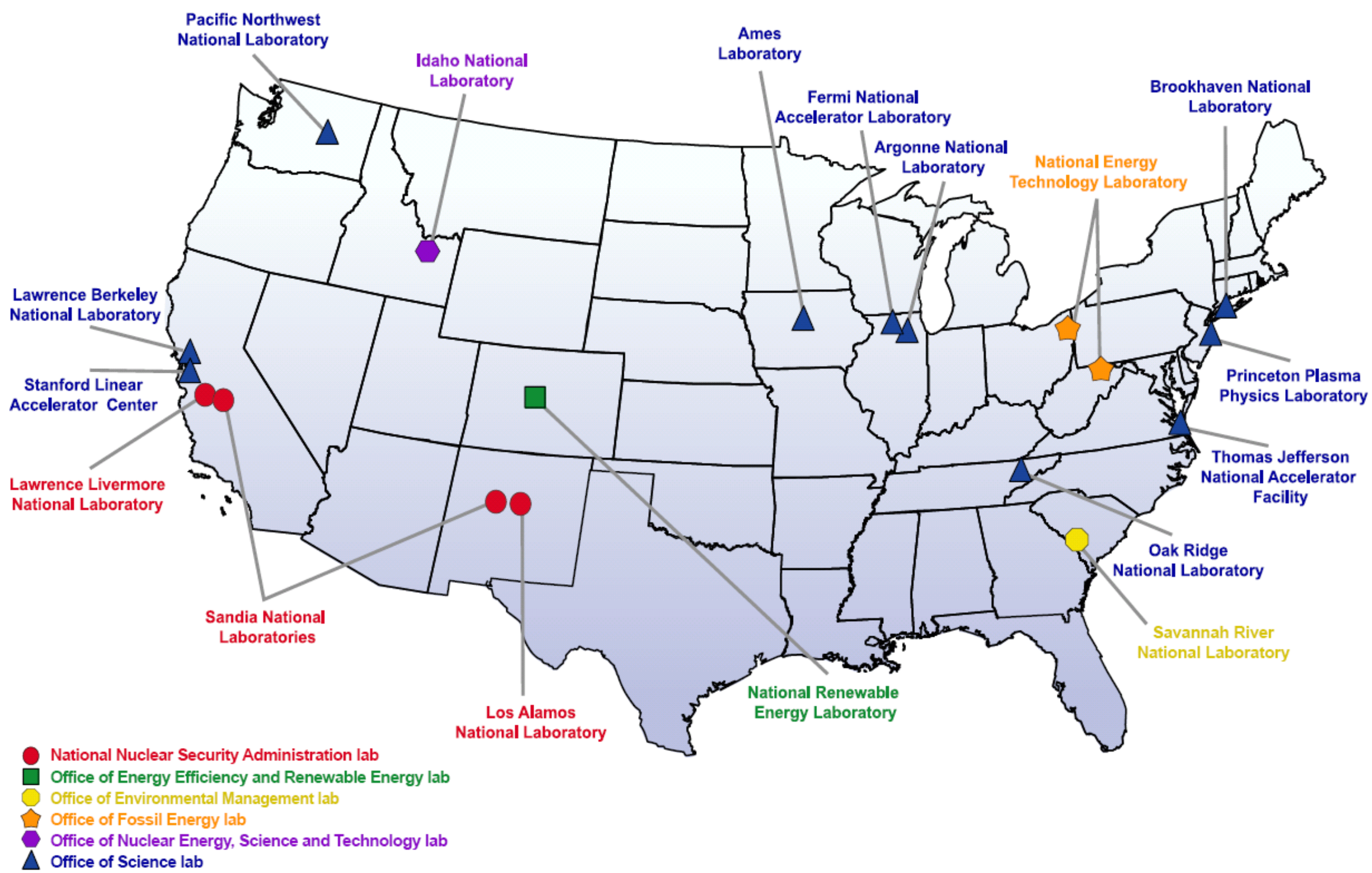
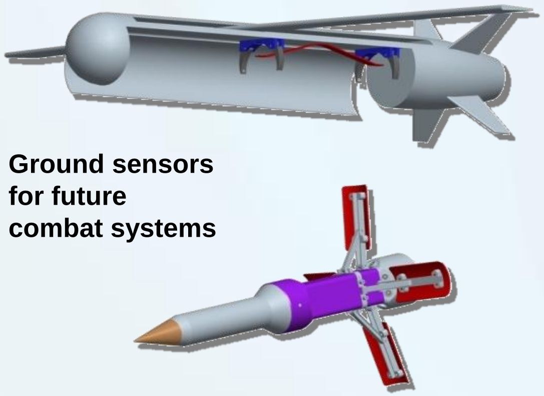


Strategic National Security, Multi-Program Laboratory

Defense Systems & Assessments

Small robotic vehicle

Ground sensors for future combat systems

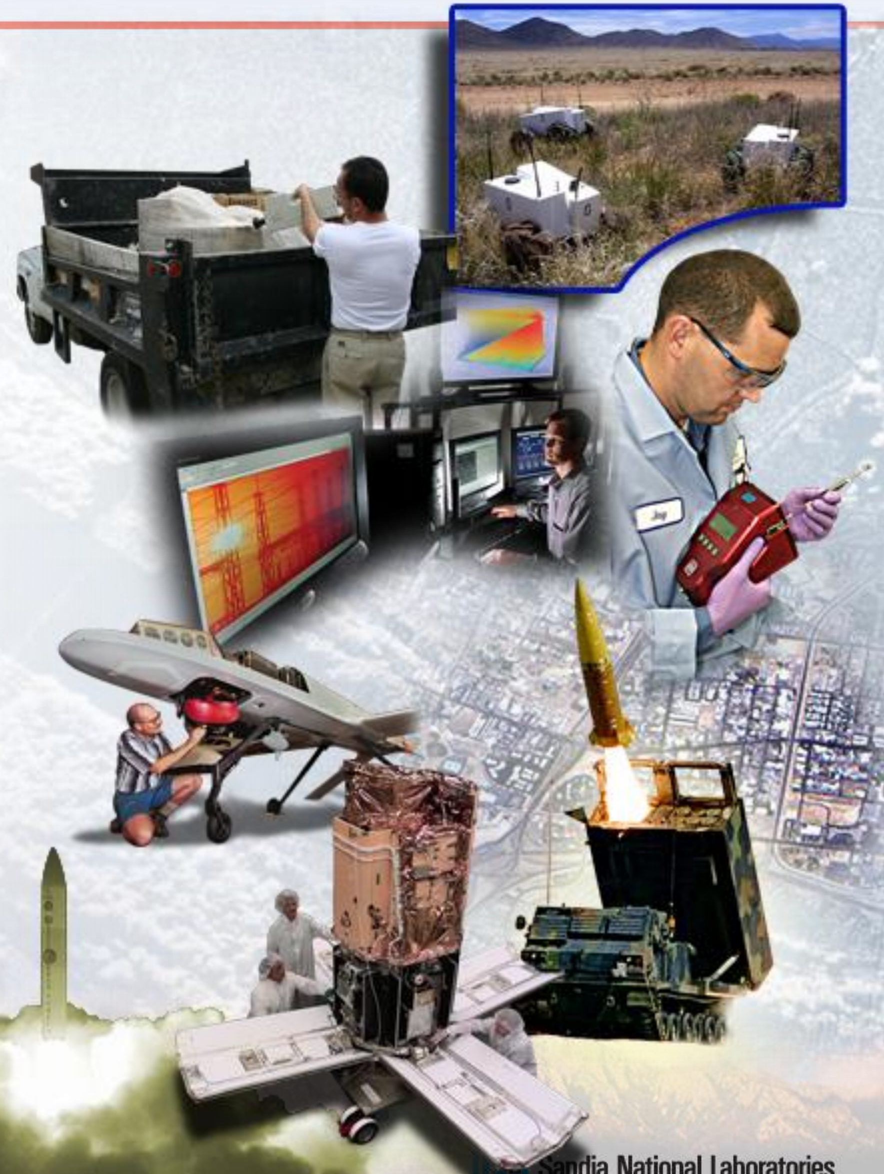


International, Homeland, and Nuclear Security

Energy, Climate, and Infrastructure Security

Defense Systems & Assessments Programs

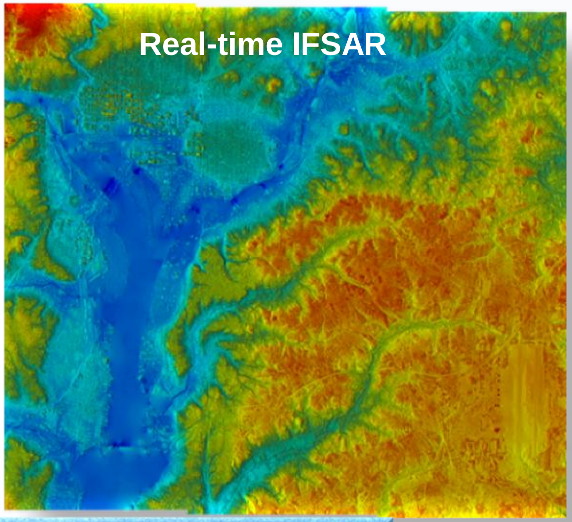
- **Science & Technology Products**
- **Surveillance & Reconnaissance**
- **Integrated Military Systems**
- **Remote Sensing and Verification**
- **Information Operations**
- **Space Missions**
- **Proliferation Assessment**



Defense Systems & Assessments Programs

- Science & Technology Products
- **Surveillance & Reconnaissance**
- Integrated Military Systems
- Remote Sensing and Verification
- Information Operations
- Space Missions
- Proliferation Assessment

- Program Thrusts:
  - Military Space
  - Sensor Systems
  - Microwave ISR
- **Highlights:**
  - Full modality, miniaturized radar systems
  - Rapid Terrain Visualization
  - Coherent Change Detection

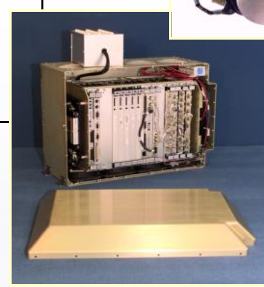


Manned and Unmanned SAR

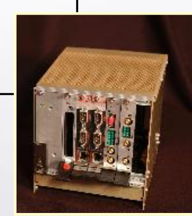
Sandia Miniature SAR Evolution

- **Sandia has been improving radar performance and shrinking sensor size for over two decades**
  - Sandia SAR systems known for fine resolution, high image quality, real-time processing
  - MiniSAR and derivative systems are current state-of-the-art in miniature radar sensors
  - "Next Generation SAR" design architecture underway

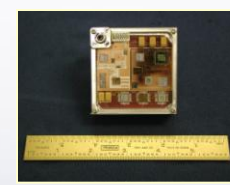

1991
500 lbs, 15 GHz
6-in resolution
16 km range

1998
120 lbs, 16.7 GHz
4-in resolution
35 km range
CCD & GMTI

2005
27 lbs, 16.7 GHz
4-in resolution
8 km range

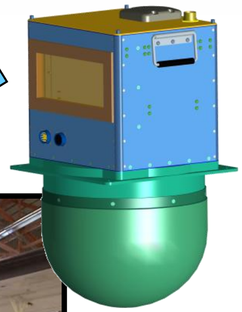


201?
"Next-Gen SAR"
RT, 4-in res.
Agile, scalable

“MiniSAR” Specifications

(Multiple Versions and Configurations Implemented)

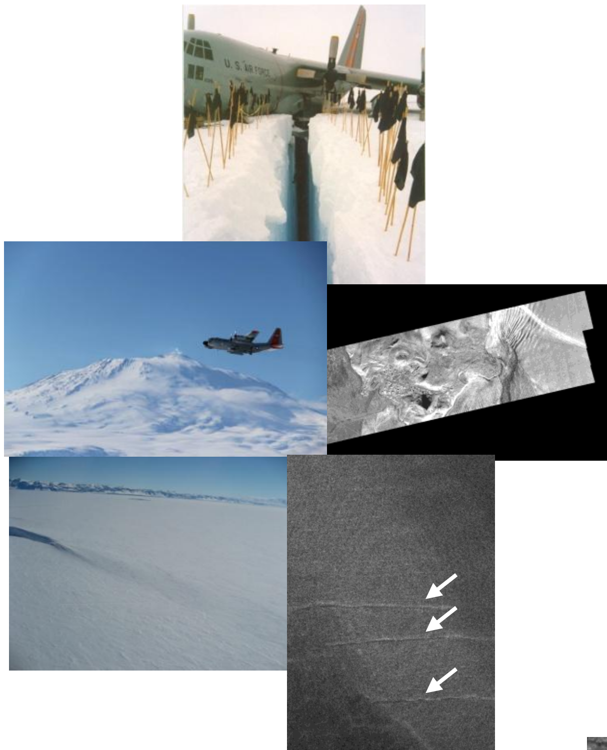
Parameter	Value
Weight	27 - ~60 lbs (configuration dependent)
Power	+28VDC at 280 – 550 W (configuration dependent)
Center Frequency	16.7 GHz/9.9 GHz
RF Bandwidth	3 GHz (Ku-Band)
Transmitter Power	60 W peak
Antenna Type	Wideband patch arrays (patented)
Resolution	0.1 – 10 m (adjustable)
Image Size	4k X 4k pixels max
MNR	< -20 dB
Maximum Range (at finest resolution)	7 - 10 km (antenna dependent)
Gimbal Type	Dual axis
SAR Imaging Modes	Spotlight, stripmap, CCD, exoclutter GMTI, VideoSAR
SAR Image Formation	PFA with PGA; OSAPF



MiniSAR-based radar systems currently operate on both manned and unmanned platforms, daily producing extensive fine-resolution, high-quality real time SAR/CCD/GMTI/VideoSAR imagery

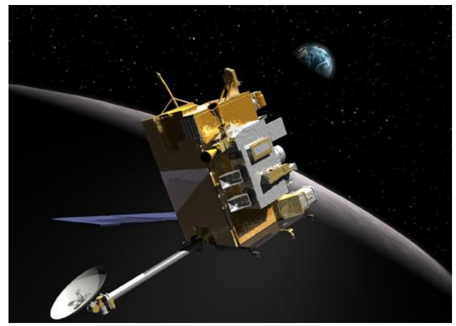
SNL MiniSAR Technology Engaged in a Wide Variety of Missions

Antarctica Crevasse Detection in support of NSF/NYANG (X-Band)



Crevasse Detection

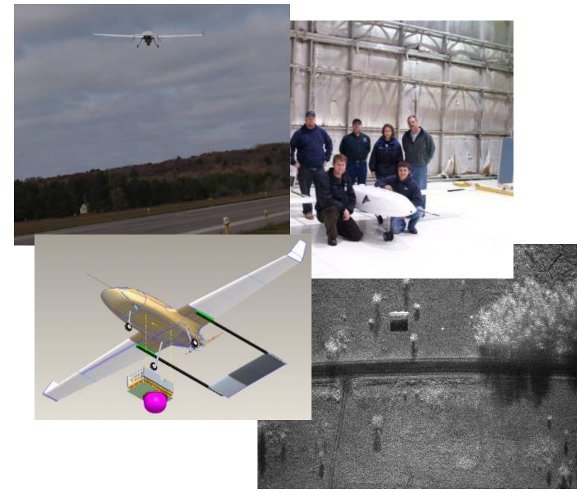
Lunar Reconnaissance Orbiter Mission



Mini-RF Technology Demonstration (Sponsored by NASA/NAWC)

- Aided in location of subsurface water ice deposits. Imaged entire lunar surface, including high-resolution imagery of permanently-shadowed regions. (S-Band)
- Space-qualified version of MiniSAR core HW used in imaging system electronics

Multiple UAS Integrations/Missions



Real-time, 0.1m resolution SAR on small UAVs

- Stripmap, spotlight, CCD images downlinked in real time to groundstation

Next-Generation Miniature Radar Concept

- **The “miniSAR” suite of sensors have demonstrated that high quality, fine resolution imagery and exploitation products can be achieved in a SWaP compatible with operation of a small UAS platform in real-time, tactical environments**
- **Highly integrated, further miniaturized, fully mission-capable radar sensors offer potential for additional impact**
  - Further, significant SWaP reduction beyond miniSAR while maintaining/enhancing operational performance.
- **Newly-developed modalities significantly enhance achievable performance characteristics of small radar sensors**
  - Miniature radar sensors generally limited by operating range and processing constraints
    - Range limitations associated with available transmitter power
      - Generally an acceptable compromise for small UAS operation
    - On-board processing capacity is continuously improving
      - Rates roughly associated with “Moore’s Law”

Next-Generation Miniature Radar

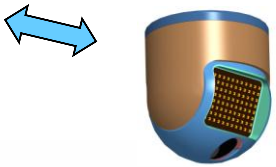
Required Attributes/Features for High Impact

"High Impact"

- Actionable Intelligence
  - Interpretability: High fidelity imaging
    - Ultra-fine resolution
    - Low-noise, high dynamic range
  - Coherent Phenomenology Exploitation,
    - e.g., Coherent Change Detection, VideoSAR, etc.
  - Aided Target recognition, Tagging, Tracking
  - Moving target detection, tracking
- Availability to End User
  - System Availability: Persistence
    - Further Radar Miniaturization
    - Cost reduction
  - Data Availability: RT Exploitation
    - On-board Real-time Processing
    - Data compression

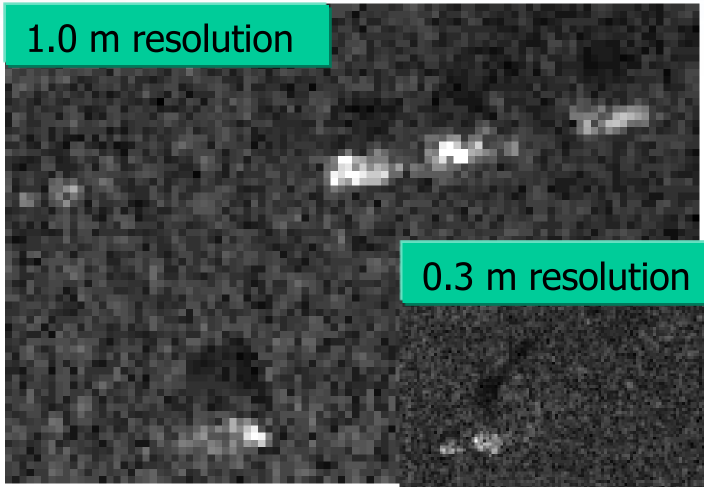
Present Radar

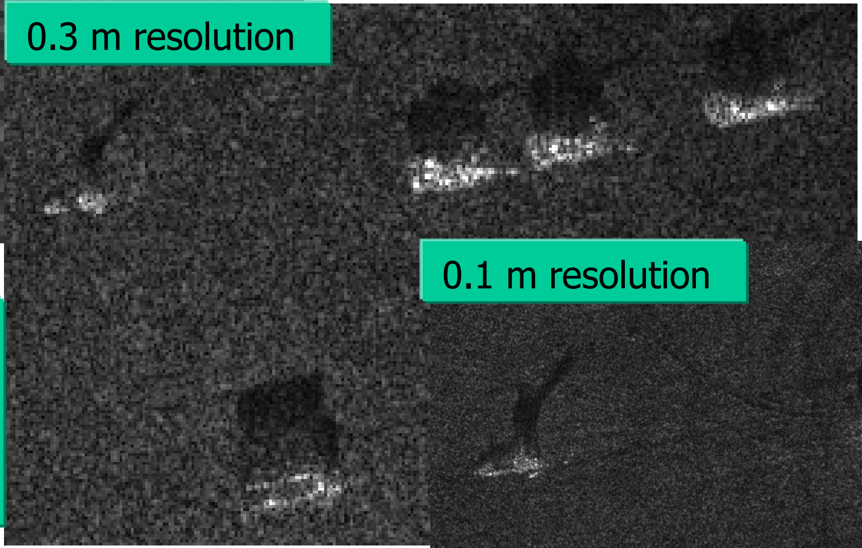
"Next-Gen" Radar Concept

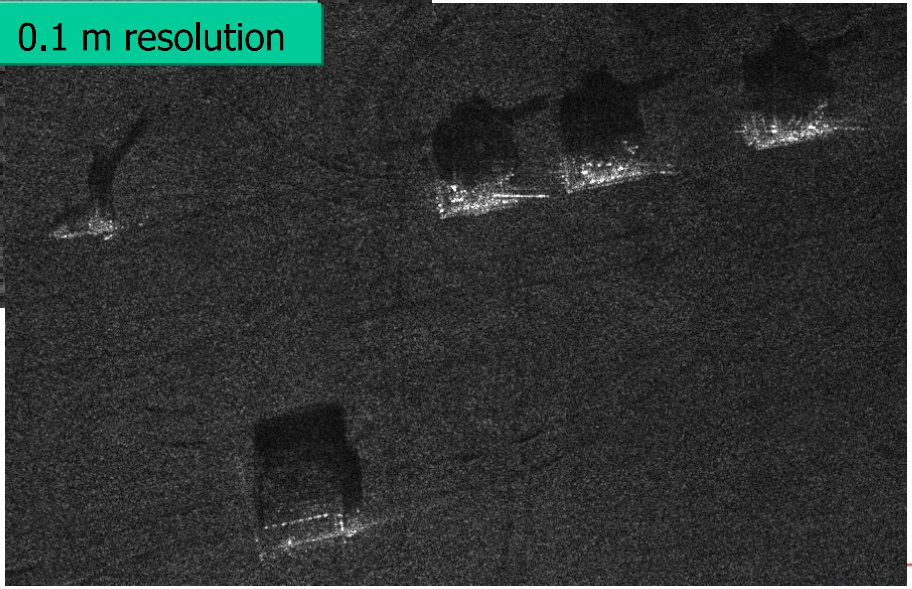


Parameter	Value
Weight	~35 - 40 lbs
Power	+28VDC at < 300W
Frequency Band	Ku/Ka-Band
RF Bandwidth	3 GHz
Transmitter Power	60 – 100 W peak
Antenna Type	Active Flat Panel Array
Resolution	0.1 – 10 m (adjustable)
Image Size	4k X 4k pixels
Max Range (at finest res)	7 - 10 km
Gimbal Type	Dual axis
Radar Imaging Modes	Spotlight/stripmap SAR, CCD, GMTI, VideoSAR, VICTR

Why Fine Resolution?







Notes:

- Ka-Band Radar
- 3.5 km range
- 15° grazing angle

Paradox: ***The more tactical the platform, the greater the need for fine resolution and high image quality!***

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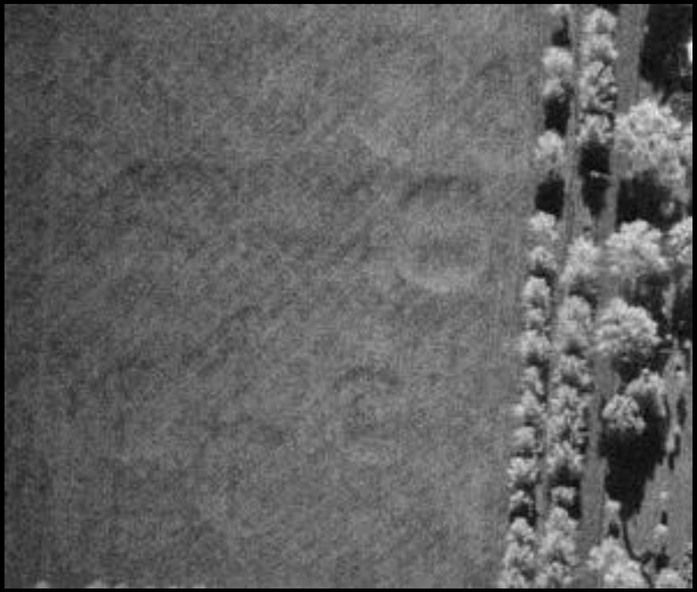
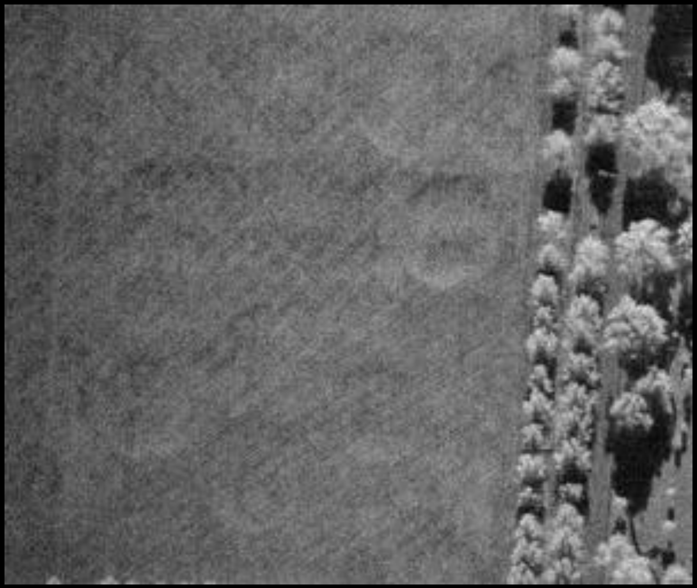
Real-Time miniSAR Image

Tijeras Arroyo Golf Course: 4-inch resolution, 3.3 km range, 20050519:PASS005

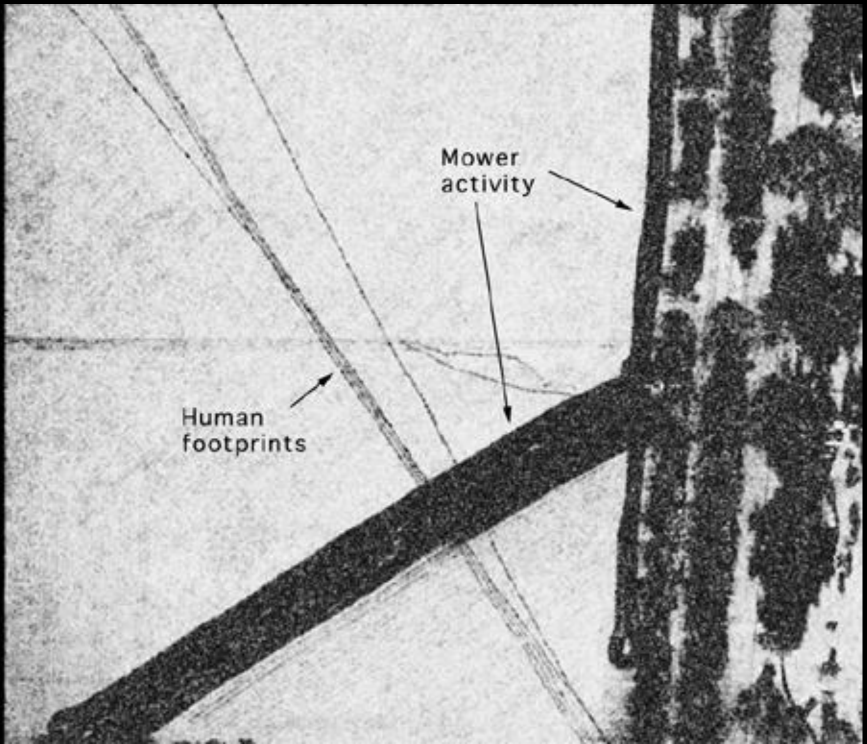
Data Exploitation Example: Coherent Change Detection



Reference Image



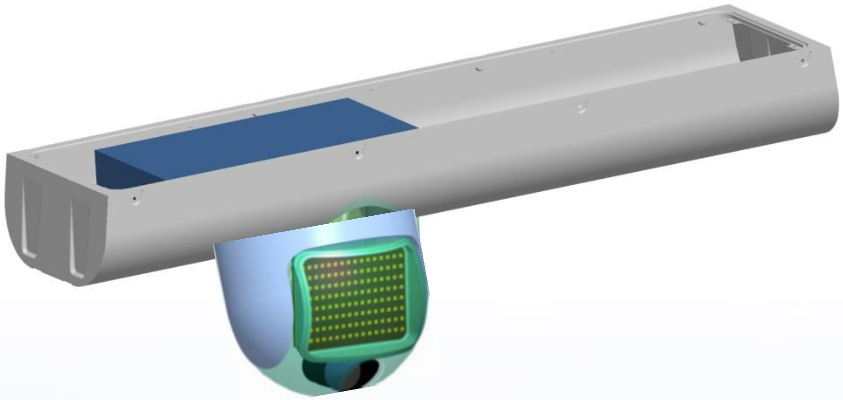
Comparison Image



CCD Map

Next-Generation Miniaturized Radar Enablers

- **The key to attaining a small, compact design is the co-location and integration of radar functionality.**



Leverages developments in small, low power, embedded processors, custom electronics miniaturization, extreme system integration and elimination of COTS interfaces and form factors.

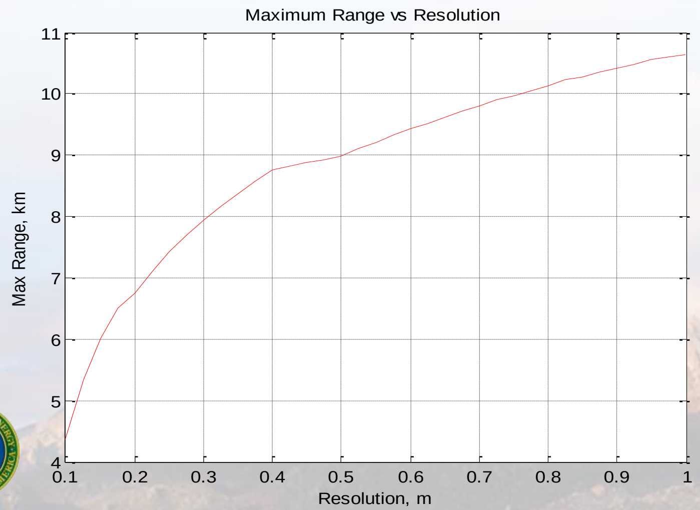
- **Next-Gen Radar Concept**
  - AGA Contains All Phase History Generator Components
    - Active Array Antenna
    - Digital Combo Board Functionality
      - DWS/DRx
    - RF Front-End
    - RF Module
    - Integrated AGA Electronics
    - IMU
  - Image Formation Processing in Separate Housing

Next-Generation Miniaturized Radar

Sample of Estimated Performance Parameters

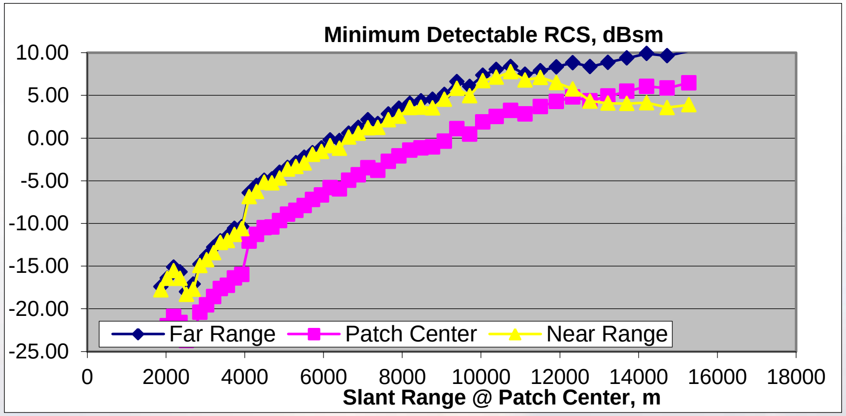
SAR

Parameter	Value
Aircraft ground velocity	90 kts maximum
Radar Altitude	5000 ft AGL
General architecture	Irregular sub-array, embedded T/R elements, azimuth monopulse
Physical aperture size	6.7 X 4.4 inches (Az X El)
Operating frequency	16.8 GHz center, 3 GHz bandwidth
Gain at boresite	25.6 dBi
Weather	Clear air, 50% relative humidity
Radar resolution	4.8 inch Az and Rng
Operating frequency	16.8 GHz center, 3 GHz bandwidth
Range swath	340 meters in slant range
Maximum transmitter duty factor	35 %
SAR mode	Spotlight, continuous strip-map, etc.



GMTI

Parameter	Value
Radar range resolution	3 meters nominal
Maximum range FFT length	4096
Minimum target SNR	21 dB (Pd=0.9, Pfa=1E-6, Swerling type 1 target)
GMTI modes	Spot-mode and area scan, moving target detection. Clutter suppression utilized at or near broadside.
Squint Angle	-170 to +170 degrees (referenced to ground velocity vector)



Target Type	RCS Range, X and Ku-Band
Large Military Vehicles (trucks, tanks, etc.)	+10 to +35 dBsm
Small to Medium Vehicles (cars, pickups, etc.)	0 to +20 dBsm
People	-15 to 0 dBsm

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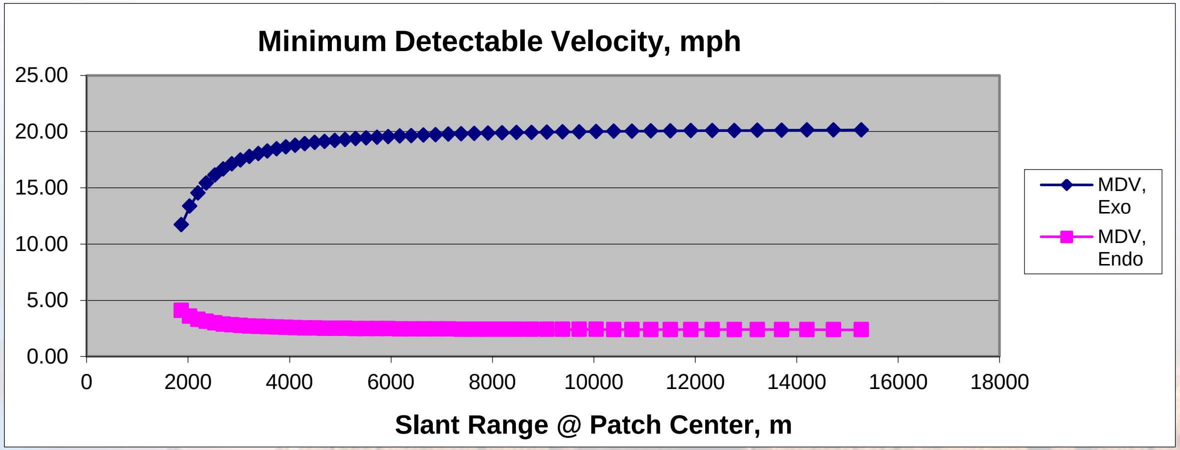
Next-Generation Miniaturized Radar Challenges

- **The basic challenge:**
  - How to yield high quality SAR and GMTI products from a sensor with limited antenna aperture size and constrained on-board processing
- **GMTI operation is particularly challenging in a small SWaP environment:**
  - Large antenna apertures typically required for low MDV GMTI
    - Even larger apertures are needed for simultaneous low-MDV GMTI and precision target location
  - High processor throughput needed due to high raw phase history data rates for GMTI
  - A small antenna aperture combined with relatively low Tx power (SWaP limitations) severely limits area coverage rate in “search-mode” (dots on a map) GMTI
    - Search mode GMTI will be confined to small areas



- **Exo-clutter and endo-clutter (clutter suppression) MDV versus range.**
  - Exo-clutter MDV performance best when operating in near-nose-on configuration
  - Endo-clutter mode affords a significant reduction in MDV
    - ~ Factor of 8 (assuming adequate clutter suppression)

Next-Generation Miniaturized Radar Enhancements

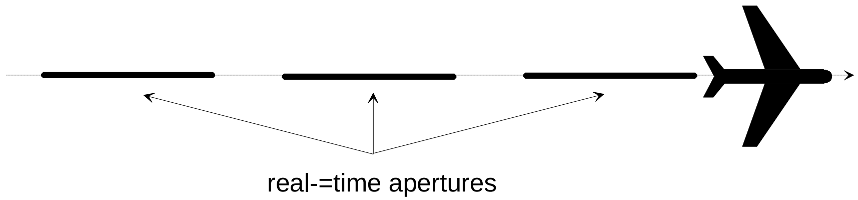
- **Next generation miniaturized radar concept incorporates modalities highly-advantageous for surveillance and reconnaissance in a tactical environment**
  - Optimal employment of radar sensor for tactical engagement
- **VideoSAR**
  - Continuous collection/processing of phase history data
  - Enables observation of slow-moving targets
  - “Qualifiers”
    - Processing/downlink BW capacity impact VideoSAR frame rate, frame size (pixel count), and downlinked image quality (if lossy compression is utilized)
- **Velocity Independent Continuous Tracking (VICTR)**
  - Enables ability to detect and track “movers” through all ranges of velocity, including “stopped”
  - “Qualifiers” – see “VideoSAR”

VideoSAR Mode

Traditional SAR vs. VideoSAR

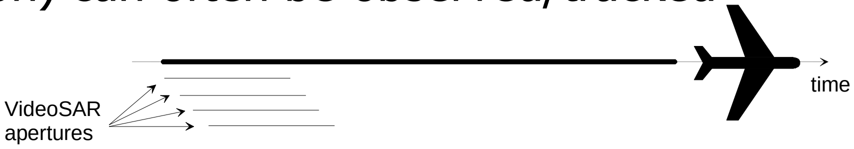
Traditional SAR

- phase histories are only collected during real-time apertures
- time between images = time to collect real-time aperture + time to process image (many tens of seconds at long ranges)
- Moving targets disappear or smear, difficult to locate/track



VideoSAR

- phase histories are collected continuously
- images are formed from overlapping sets of phase histories
- time between images is user selectable and is independent of aperture length (0.1 to 0.3 seconds seems best)
- slow moving targets (< 15 mph) can often be observed/tracked
- Latency < 8 sec.



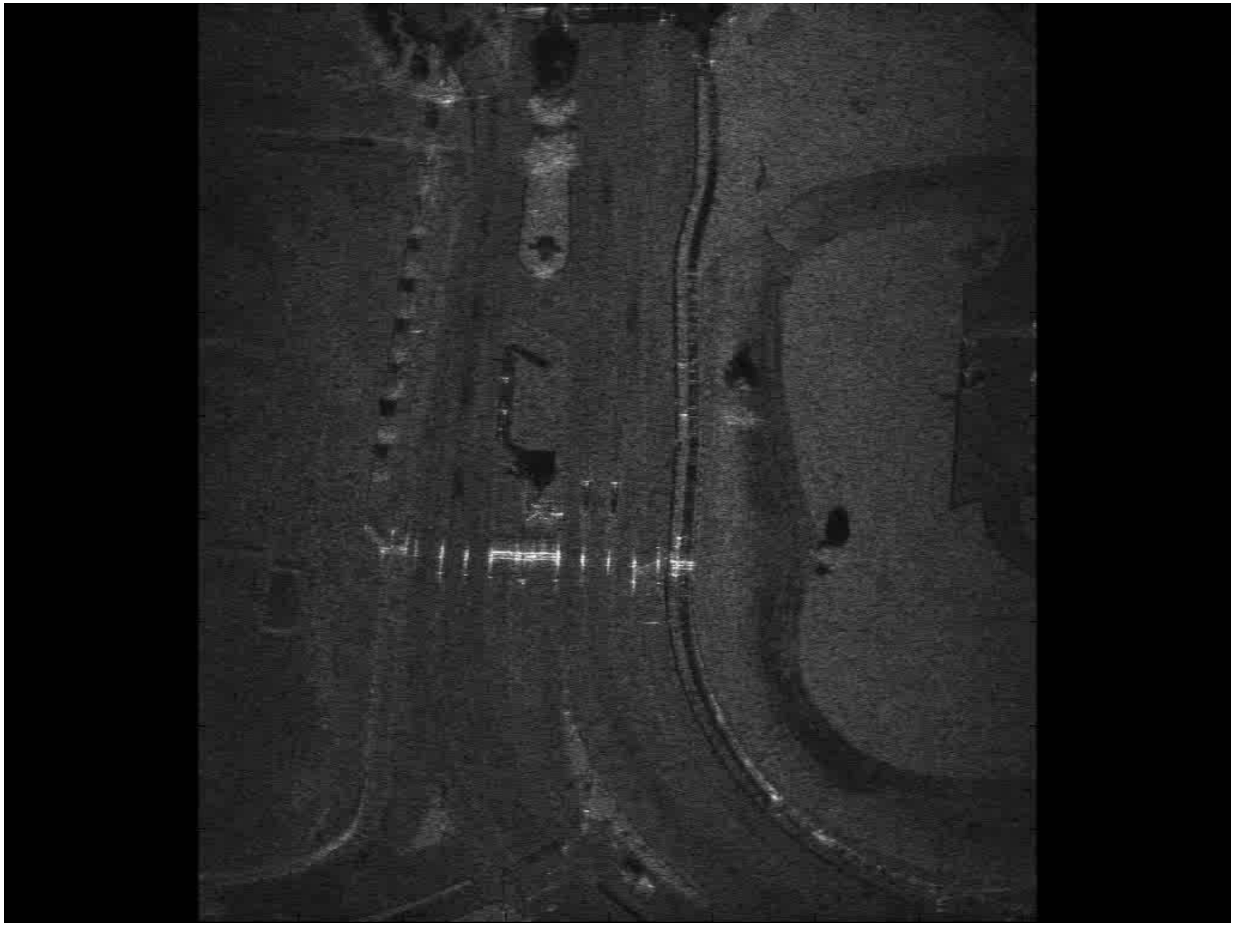
A rapid sequence of SAR images (> 1 Hz) can permit observation of target shadows

Real-Time miniSAR Image

Eubank Gate, KAFB: 4-inch resolution, 3.3 km range, 20050519:PASS007

Video SAR

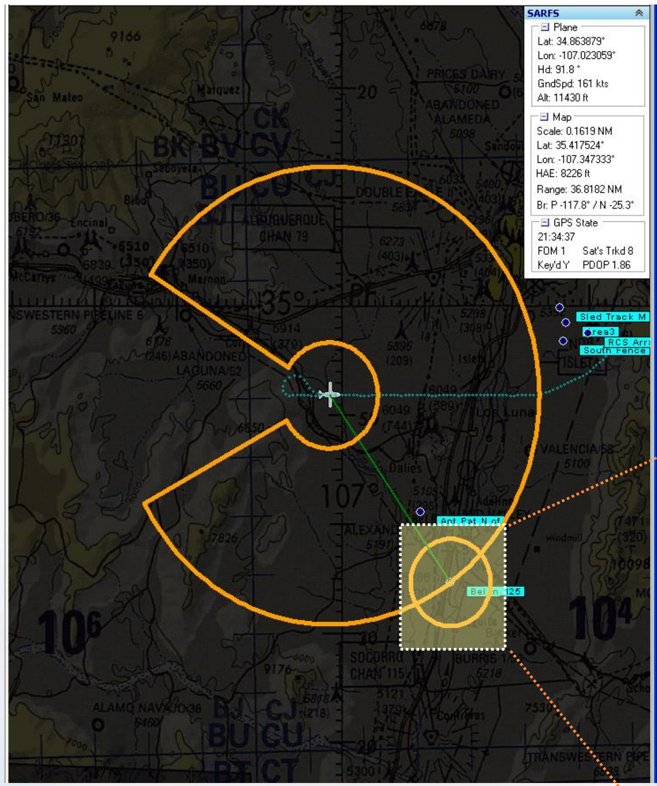
(Movie Clip)

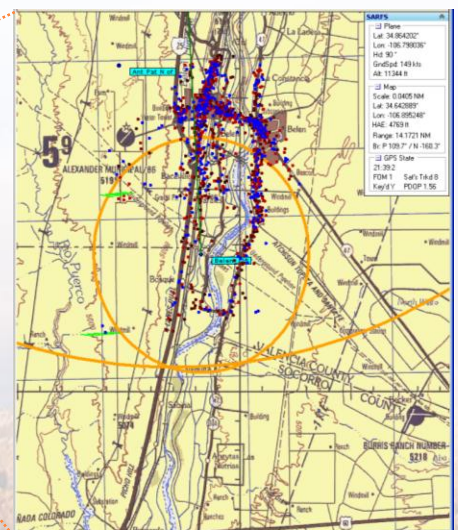


Velocity Independent Continuous Tracking Radar Mode

Background

- **GMTI traditionally refers to the problem of detecting moving objects with a radar**
  - Typically includes location and tracking of the movers
- **GMTI takes advantage of the coherent properties of the radar signals to find movers (i.e., Doppler)**
- **GMTI is often divided up into two regions**
  - exoclutter – region outside the Doppler spread of the “stationary” clutter
  - endoclutter – region including the Doppler spread of stationary





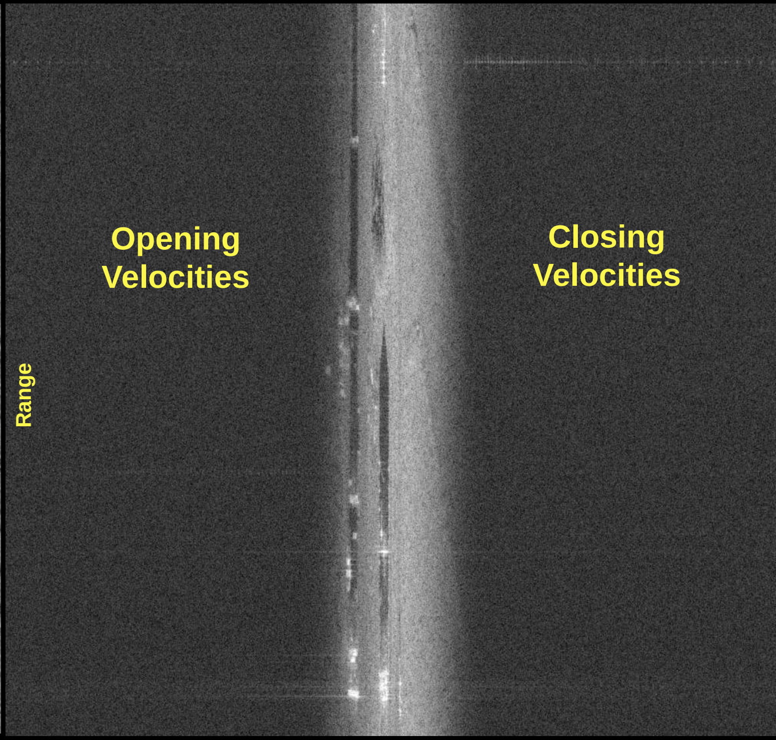
Each dot represents a detected “mover” in the scene traveling toward or away from the radar sensor

Background: Range-Doppler Image

A SAR Image (static scene) corresponds to the endoclutter region

Range-Doppler Image (dynamic scene)

Exoclutter Region | **Endoclutter Region** | **Exoclutter Region**



Doppler

Challenges and Issues

- **Systems trying to exploit slower movers (in endoclutter) require more sophisticated designs and signal processing to filter the stationary clutter**
- **Filtering performed in angle and Doppler space**
  - This filtering also attenuates the desired movers
- **Location in the endoclutter is complicated by the presence of the stationary clutter**
- **Typical GMTI systems**
  - Tend to be large and expensive
  - Scan large areas and monitor general traffic flow
  - Lose track when vehicle stops

- **VICTR approach for GMTI on small, tactical radar systems:**
  - Targeting small size/cost systems
  - Follow a single high value target
  - Maintain track through all ranges of motion, including “stopped”
  - Combine multiple modes simultaneously to handle different ranges of velocities

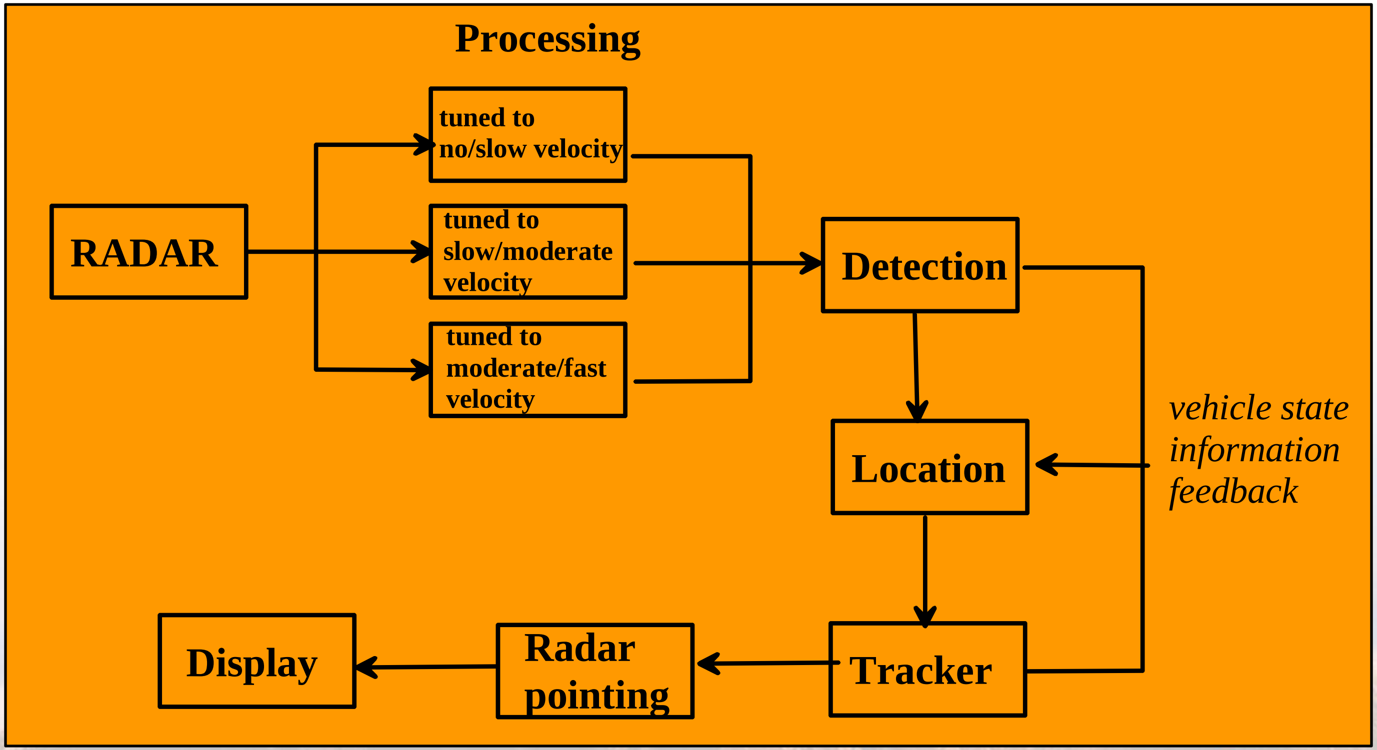
Example: Difficult Tracking Environment

VideoSAR

Range-Doppler

Velocity Independent Continuous Tracking (VICTR) Concept

- Simultaneous (parallel) processing of a continuous stream of radar data into different products (or modes)
- Each product is optimized for a particular task, or in this case, a different velocity; e.g.,
  - VideoSAR for slow to stationary movers
  - Clutter attenuated for slow to moderate movers
  - Exoclutter GMTI for moderate to faster movers
- As the mover goes through different velocity states, a different velocity filter "follows" the mover



Recent VICTR Demonstration

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Status and Future Work

- **Current Status**
  - Algorithms and tracker have been run against many radar data sets
    - Multiple sets of data collected with varying degrees of scene complexity
    - Data collected/processed from varying geometries
  - Tracker functionality successfully implemented to automatically guide antenna pointing
- **Continued/Future ATR Investigations**
  - Track continuity
    - HRR signature matching
  - Operation in transitional phases
    - "Moving to stopped" – verification of ID
    - Start up phase – recognition within a group of stopped vehicles

Summary

- **The "miniSAR" suite of sensors have demonstrated high quality, fine resolution imagery and exploitation products**
  - Achievable in a SWaP compatible with operation of small UAS platforms
- **"Next-Gen" highly integrated, highly miniaturized, fully mission-capable radar sensors offer potential for significant impact in tactical surveillance and reconnaissance mission space**
- **Algorithmic extensions to conventional SAR/GMTI processing facilitates advanced capabilities in realizable HW with relatively low cost platforms and sensors**
  - VideoSAR/VICTR optimally applicable to small tactical radar systems
  - Combining GMTI and VideoSAR concepts allows all ranges of velocity to be accommodated, including "stopped"
- **Sandia continues to pursue improvements and extensions to the miniSAR architecture in several areas:**

Targeting	Imaging	Tracking	Modes	SWAP

Questions?