Synthetic Aperture Radar Cold Regions Hazard and Surveillance Monitoring

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Sandia Airborne ISR: www.sandia.gov/radar/

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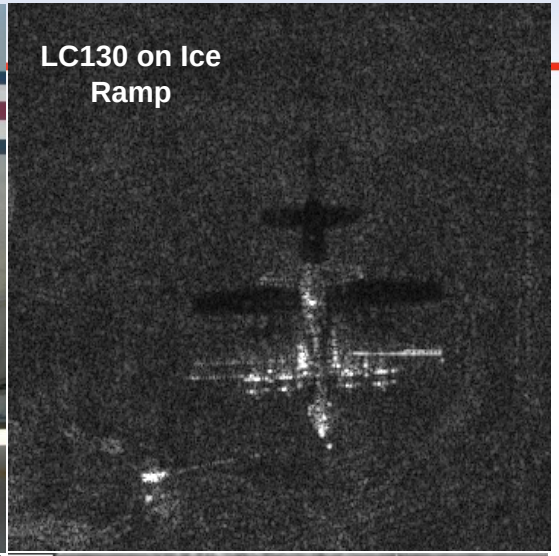
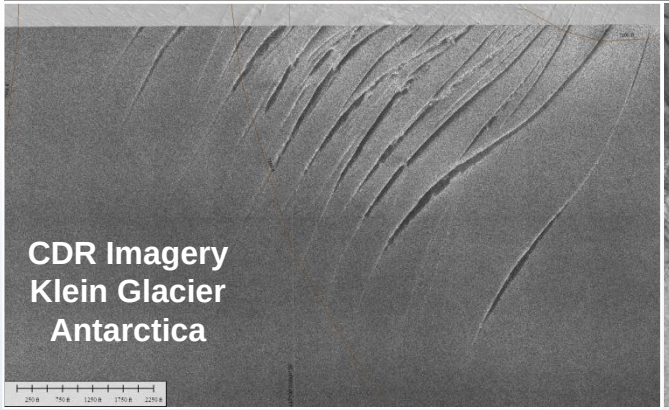
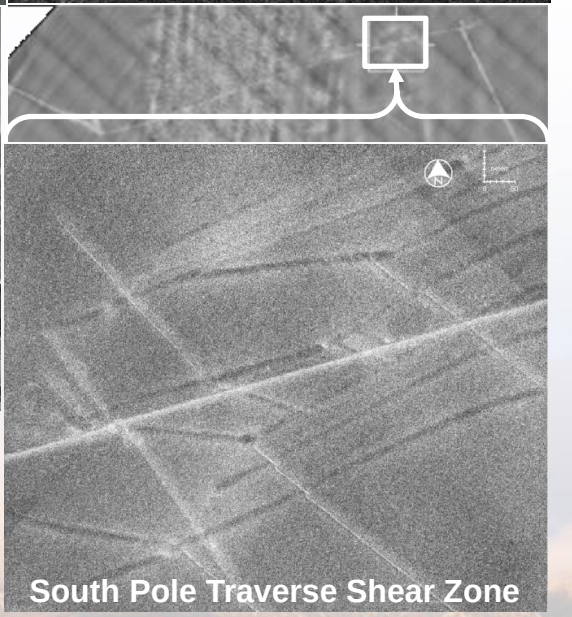
General Outline

- **Finding Crevasses in Antarctica with CDR**
  - Considerations – how do you detect crevasses with SAR?
  - What we learned
  - What we wanted to do, but didn't get to
- **FARAD - Facility for Advanced RF and Algorithm Development**
  - Capabilities
  - Coherent Modes of Diversity
  - Arctic Applications and Limitations
- **So what?**
- **Potential Novel Arctic Radar Applications**

Operational Crevasse Detection Radar







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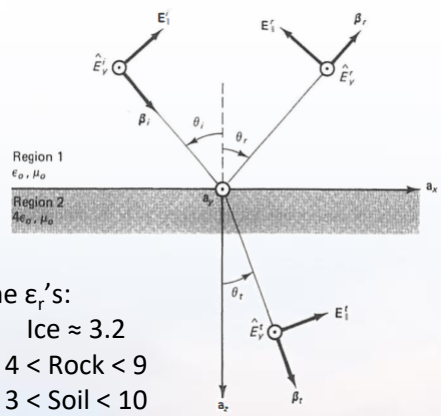
RF Remote Sensing 101

Plane wave reflection, refraction, diffraction, and scattering

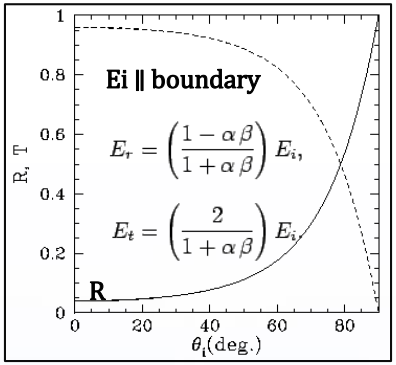
Reflection at boundary between two regions having different dielectric properties

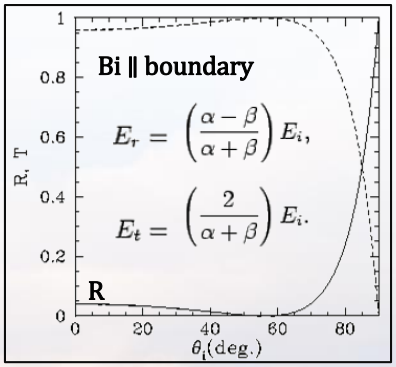
Example: Air to Snow
n2 > n1



Some ε_r's:
Ice ≈ 3.2
4 < Rock < 9
3 < Soil < 10
2 < Veg < 15
Water ≈ 81

Note: Refractive index n = sqrt(ε_r)

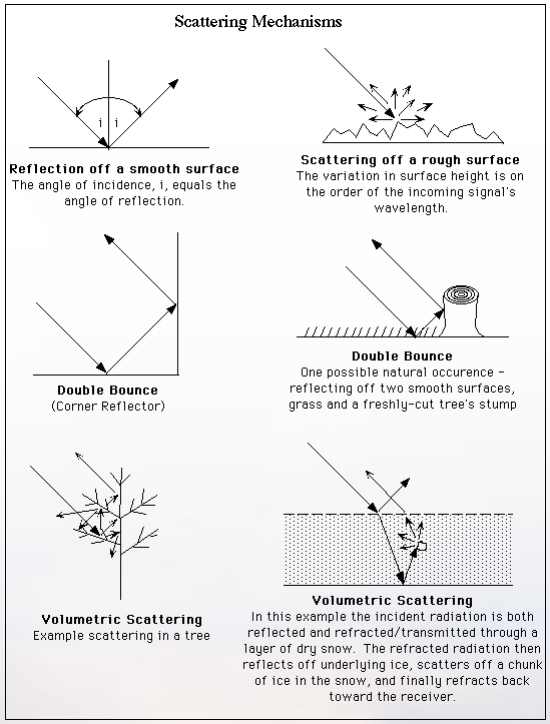




$$\alpha = \frac{\cos\theta_t}{\cos\theta_i} \qquad \beta = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

Backscatter coefficients

Point scatter: $\sigma\ [m^2]$
Area scatter: $\sigma_0 = \sigma_c/A_c\ [m^2/m^2]$
Volume scatter: $\eta = \sigma_c/V_c\ [m^2/m^3]$



From ESA's "The ASAR User Guide"

RF Remote Sensing 101

Surface smoothness and wavelength (Area Scatter)

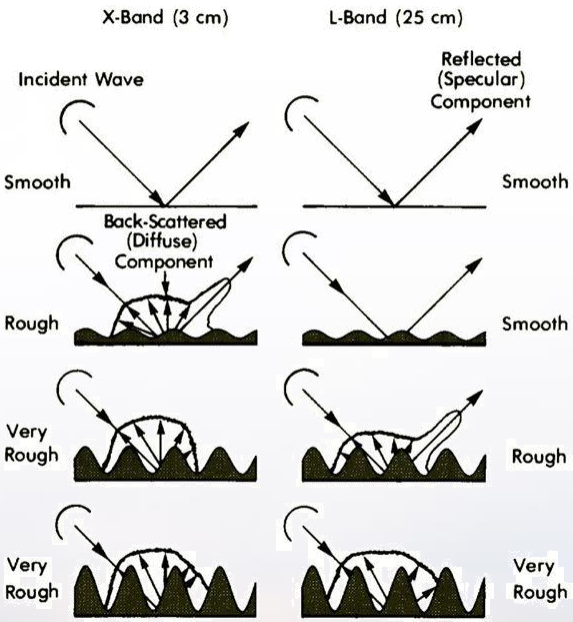
	L	S	C	X	Ku	K	Ka
F GHz	1-2	2-4	4-8	8-12	12-18	18-27	27-40
λ_l cm	30.0	15.0	7.50	3.75	2.50	1.67	1.11
λ_h cm	15.0	7.5	3.75	2.5	1.67	1.11	.75

Smooth surface – specular reflection
Rough surface – diffuse reflection

Quantify "smoothness" with the phase difference $\Delta\Phi$ between 2 reflected waves from heights differing by h.

$$\Delta\Phi = 2h \cdot 2\pi/\lambda \cdot \cos\theta_i$$

Rayleigh criterion: $\Delta\Phi < \pi/2 \rightarrow \mathrm{std}(h) < \lambda / (8\cos\theta_i)$
Frauenhofer criterion: $\Delta\Phi < \pi/8 \rightarrow \mathrm{std}(h) < \lambda / (32\cos\theta_i)$



Example: X band, $\theta_i = 60$,

Rayleigh: $\mathrm{std}(h) < 0.75\mathrm{cm}$
Frauenhofer: $\mathrm{std}(h) < 0.19\mathrm{cm}$

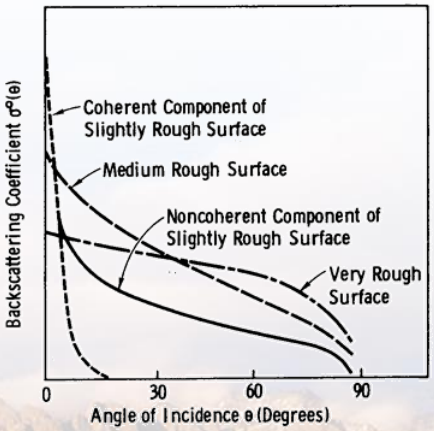
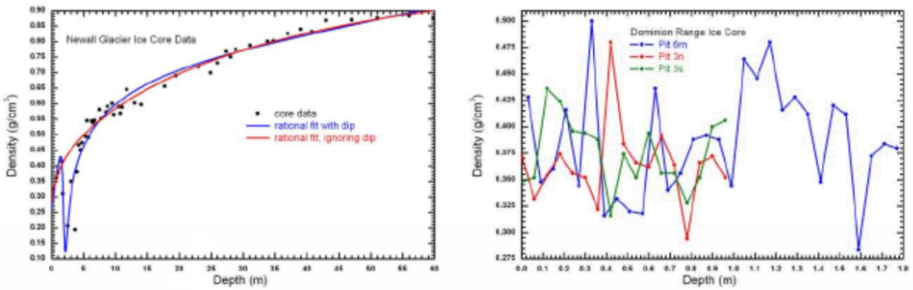


Fig. 7. Angular variation of backscatter for different roughness conditions (Ulaby et al., 1982b).

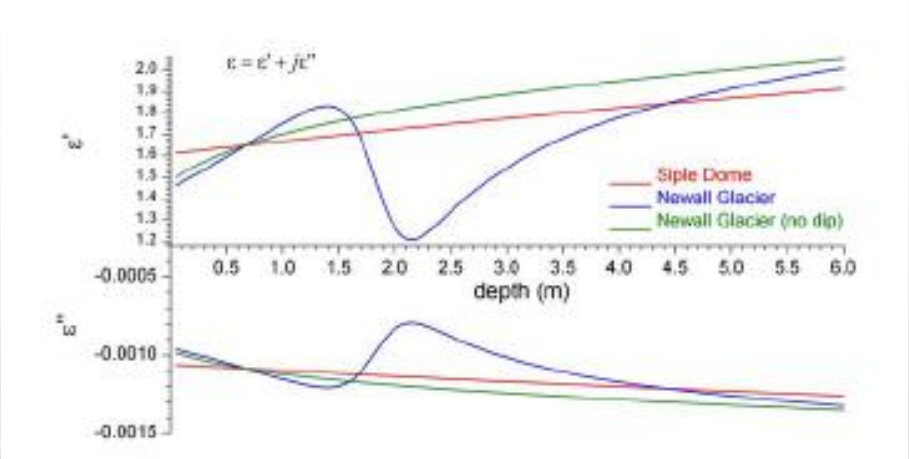
Antarctic Snow & Ice Scattering Model

- **Dielectric properties of snow/ice**
- **Function of wavelength, temperature, volume % ice**
- **Determines transmittance, reflectance, and absorbance**
  - Relative amount of reflected and transmitted energy
  - Penetration

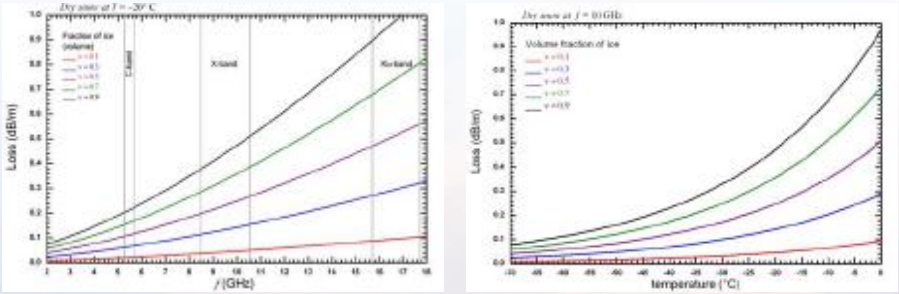
Antarctic Glacial Ice Core Densities



Antarctic Glacial Ice Dielectric Model



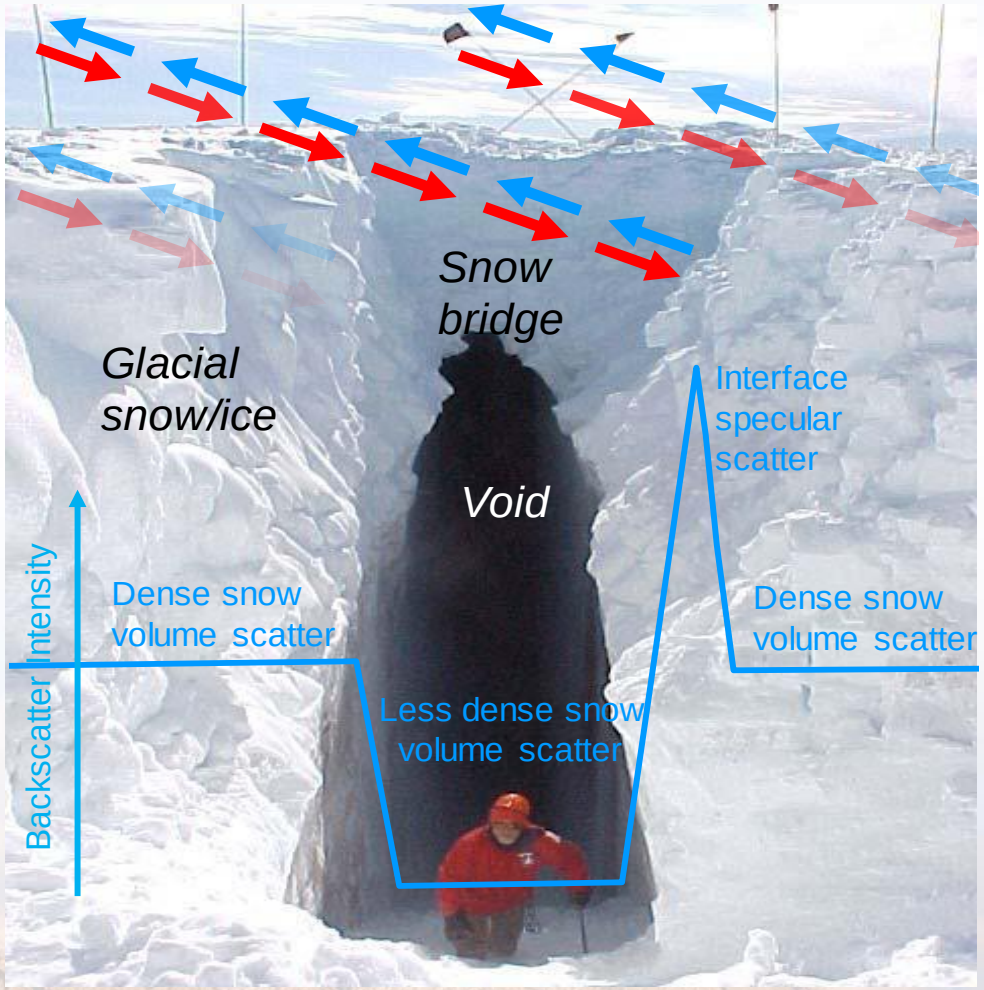
Antarctic Dry Snow Loss Model



Presumed Scatter Mechanism

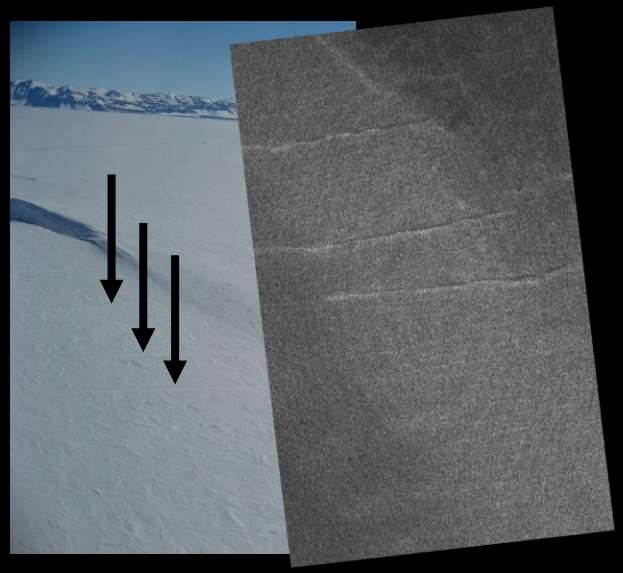
Antarctic bridged crevasse, 2.5 – 3m wide

Beneath the snow bridge – hoar frost

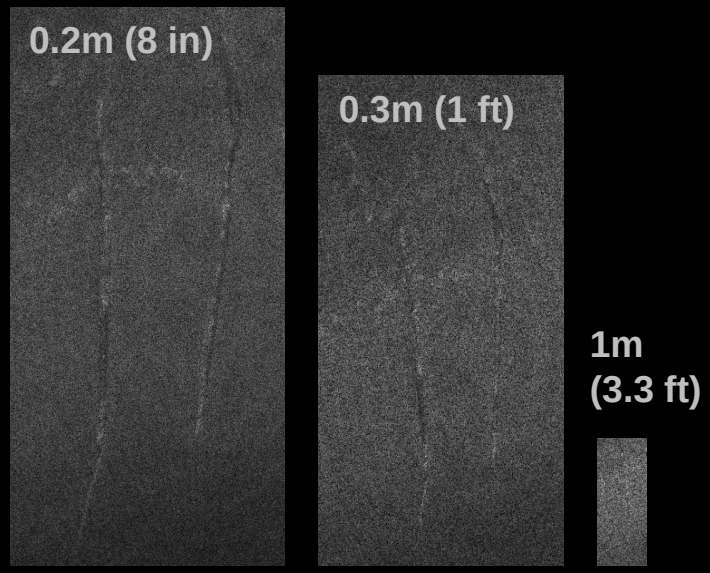


Some Empirical Results

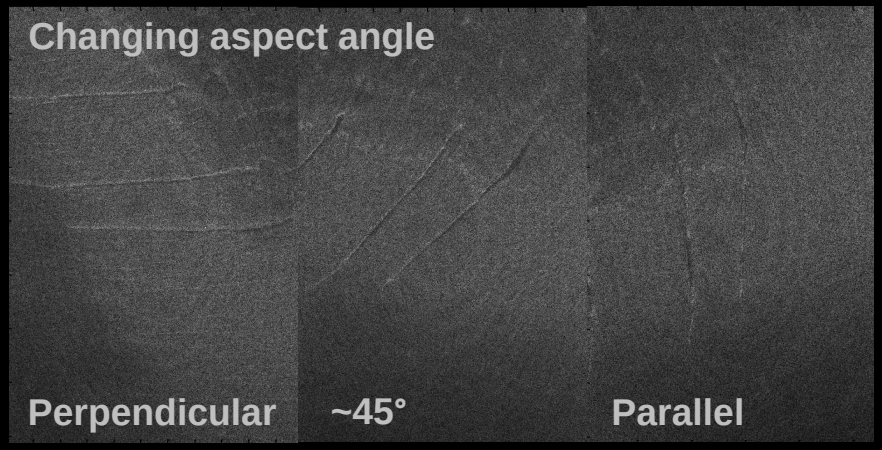
Optical comparison

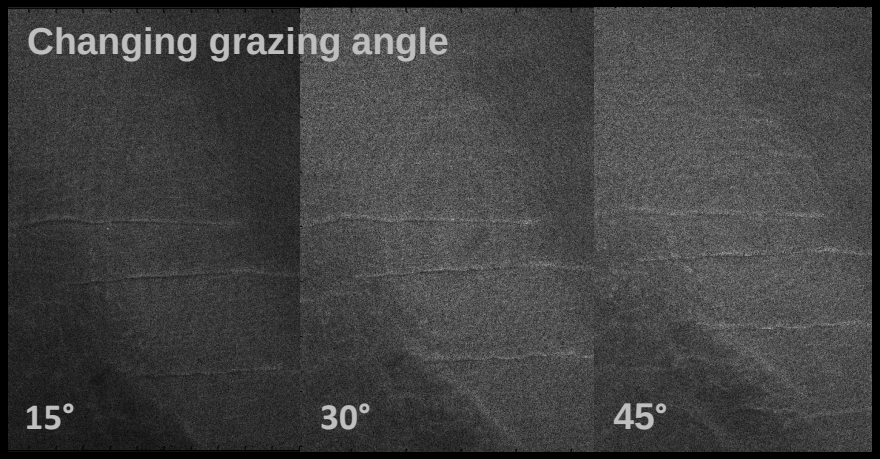


Changing resolution

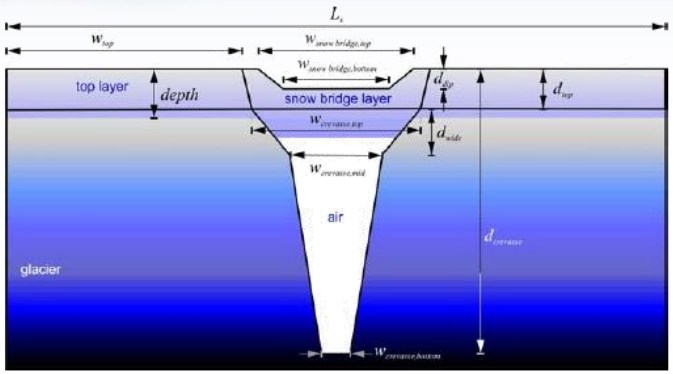


- Resolution trumps grazing and aspect angle
- Can detect at all aspect angles
- Low to mid grazing angles seem better
- Scatter model seems reasonable





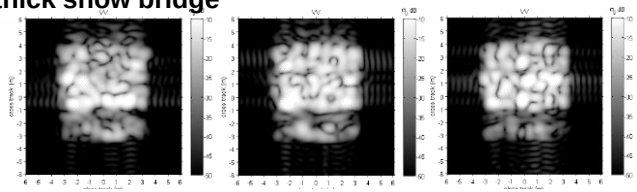
Exploring Deeper



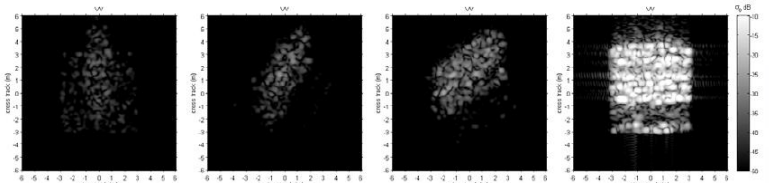
Bridged Crevasse Simulation

1.5m wide crevasse, 2m thick snow bridge

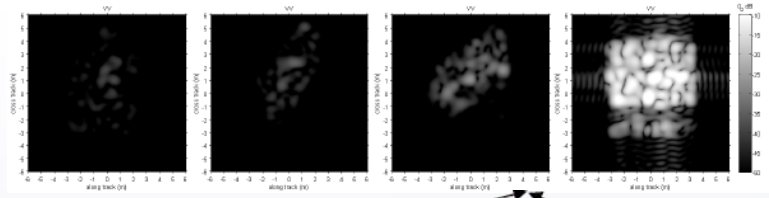
C, X, Ku, 18in res, 30° grz, -90° az VV Pol



X, 8in res, 30° grz 0°, -30°, -60°, -90° az VV Pol

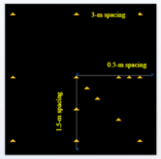


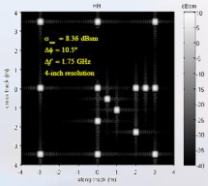
Ku, 8in res, 30° grz 0°, -30°, -60°, -90° az VV Pol



Penetration Study

Simulated 6m x 6m Array:





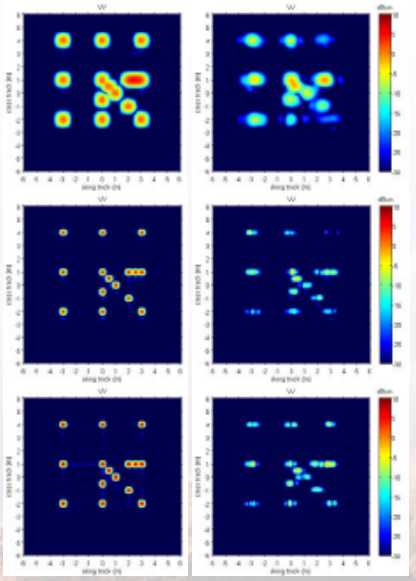
2m below:

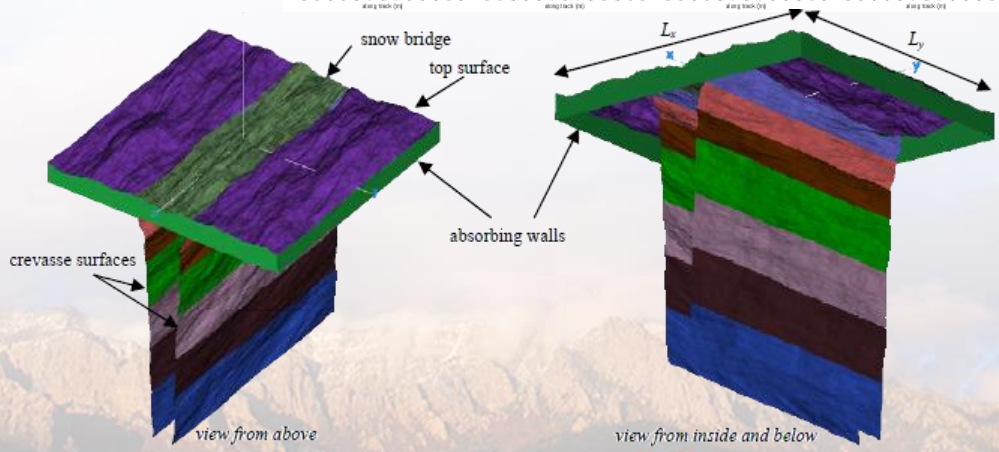
smooth. flat | **fractal**

C 18in

X 8in

Ku 8in





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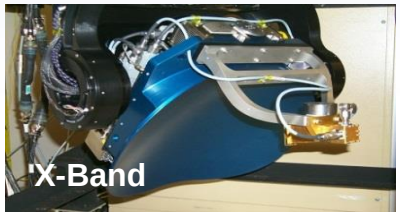
CDR Comments and Conclusions

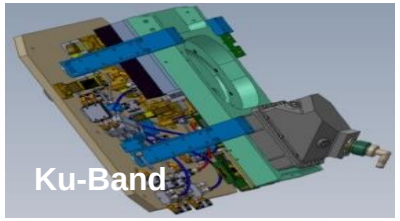
- **During our proof of concept mission on 2006 we performed experiments to try and determine the optimal resolution, grazing and aspect angles for detecting crevasses**
- **Unfortunately, once CDR utility was demonstrated, R&D on RF remote sensing of snow, ice, and crevasses took a back seat to fielding the CDR on the LC-130**
- **We did model and simulate the scattering mechanism**
  - C-band results were limited to FCC allowed BW (18”)
  - Long simulation run times limited the simulation to the 1 crevasse model, with no snow bridge sag, and snow bridge surface rougher than adjacent glacier
  - Simulation results suggest that the scattering from the bottom of the snow bridge is predominant, and the return from the glacier walls is negligible (doesn’t quite match the empirical results)
- **<u>We did not get to research SAR modes exploiting polarization or phase diversity, particularly polarimetry, CCD, or interferometry</u>**

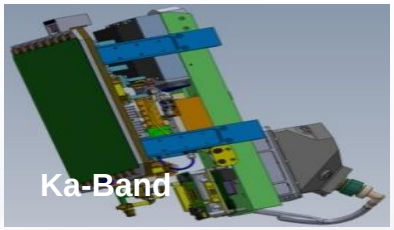
FARAD

Facility for Advanced RF and Algorithmic Development (FARAD)

- **X-Band (9.6 GHz)**
  - Fully polarimetric
  - Fully integrated dual-channel front end
- **Ku-Band (16.8 GHz)**
  - Quad-phase-center antenna
  - 4-channel front end
  - Dual receive channel
- **Ka-Band (35 GHz)**
  - Ultra-fine resolution
  - Azimuth monopulse antenna
  - Low-minimum detectable velocity simultaneous SAR/GMTI
- **DeHavilland DHC-6**

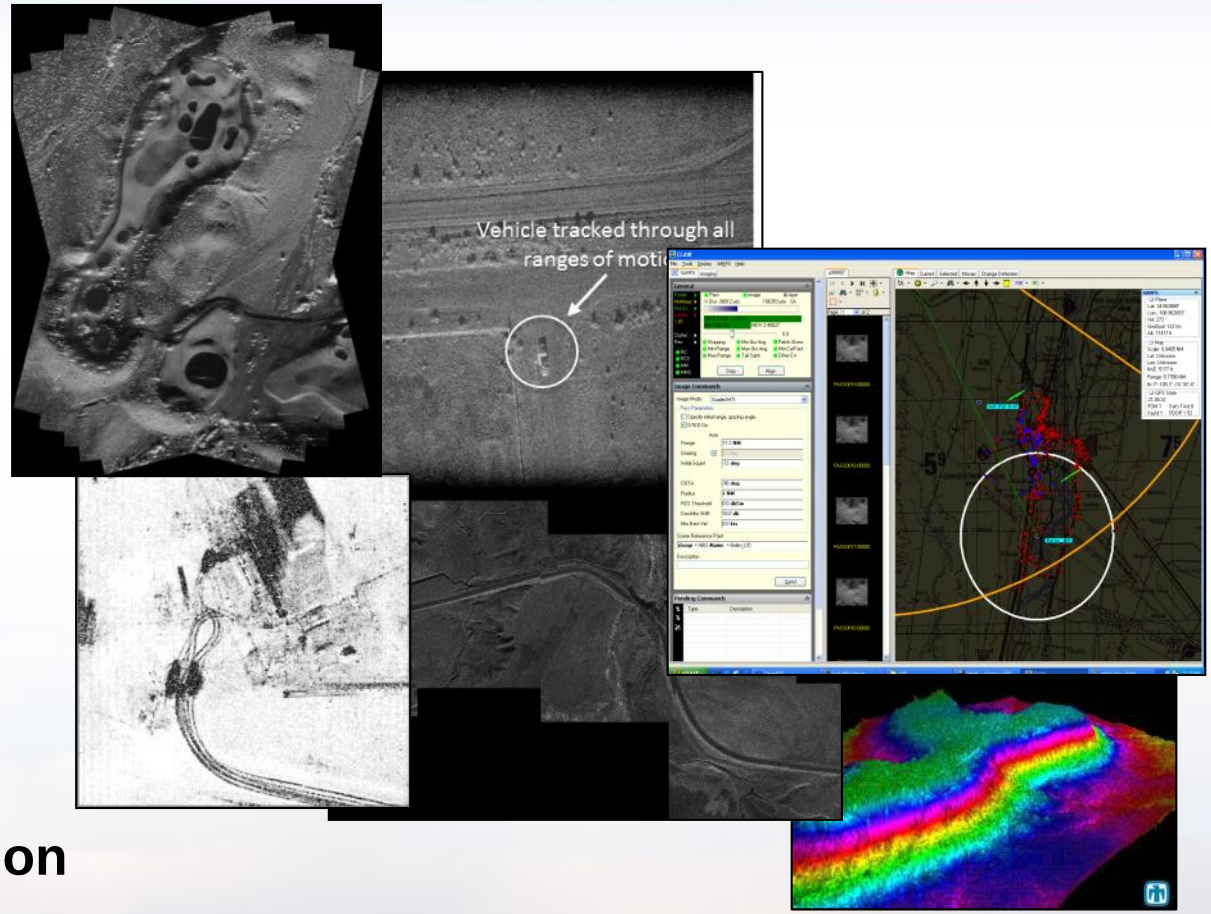






Multi-Mode Functionality

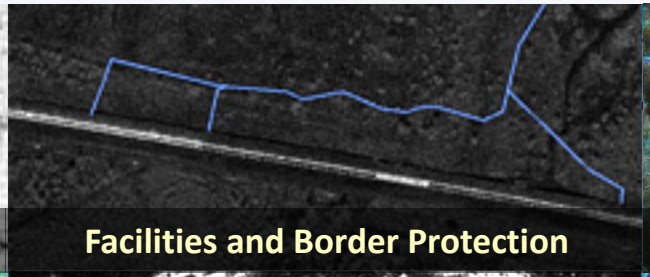
- Spotlight
- SpotDwell
- Circle
- Stripmap
- Arbitrary Stripmap
- CCD/NCP
- IFSAR
- VideoSAR/VICTR
- GMTI/DMTI
- Wide Area Search
- High Range Resolution

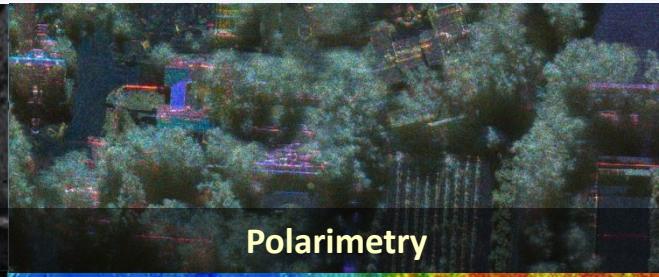


As new radar modes are developed they can be integrated into existing Sandia radars during product improvement phases without redeveloping the entire system

Real World Applications

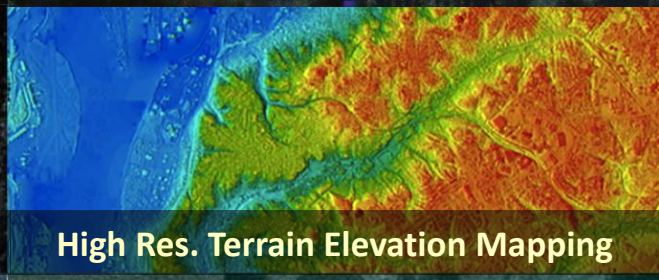
Coherent Change Detection


Facilities and Border Protection


Polarimetry

Environmental Monitoring

Space Missions

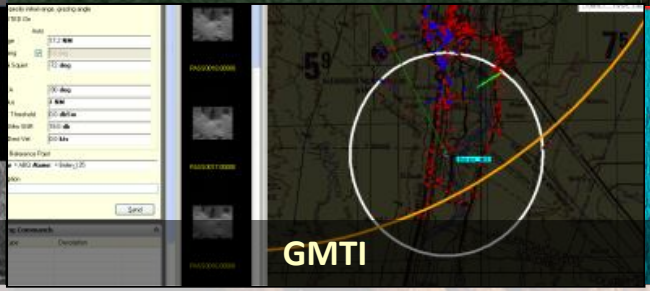

High Res. Terrain Elevation Mapping

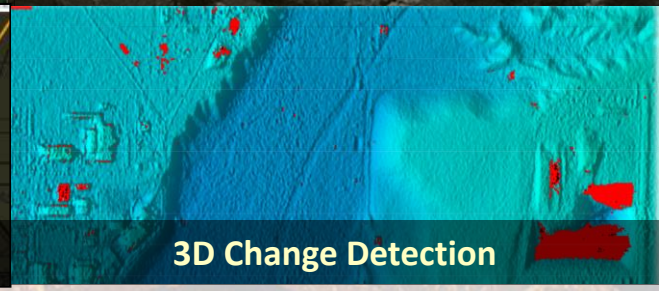
Maritime & Littoral

Vehicle and Dismount Tracking

S&R and Targeting

C-IED & Route Reconnaissance


GMTI


3D Change Detection

Polarimetry

- **Compared to single polarization SAR, polarimetric SAR provides additional information on:**
  - Type of target: trihedral, dihedral, dipole etc.
  - Orientation of the target about the radar line of sight
  - Ellipticity: degree of target symmetry
  - Entropy: significance of the polarimetric information
  - Many, many polarization decompositions and parameters to exploit

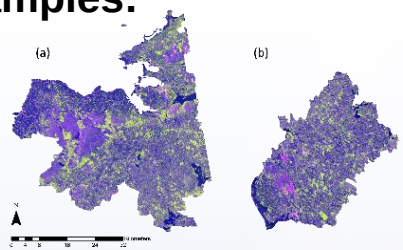
$$E_s = \frac{e^{ikr}}{r} S E_i$$

$$\begin{bmatrix} E_{sv} \\ E_{sh} \end{bmatrix} = \frac{e^{ikr}}{r} \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \begin{bmatrix} E_{iv} \\ E_{ih} \end{bmatrix}$$

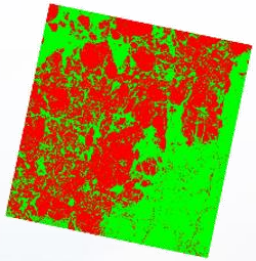
$$S_{ij} = |S_{ij}| e^{i\phi_{ij}}$$

The scattering matrix contains information on the nature and characteristics of the target

- **Examples:**

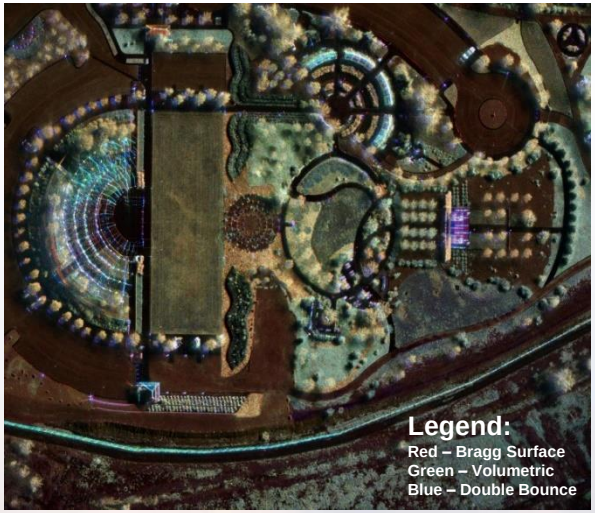


Ireland Forest Cover [1]
HH-red, HV-green, HH/HV ratio-blue



Victoria Strait Sea Ice Classification [2]
Green FYI, Red MYI.

- **Arctic Applications:**
  - Land classification: forest, tundra, permafrost, marsh, moisture content
  - Ice Classification, Ice edge detection
  - Ship detection & classification
  - Ocean surface state



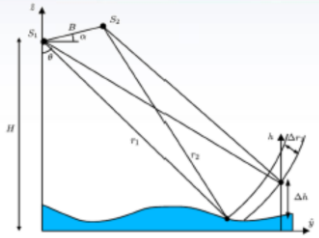
FARAD X-Band Polarimetric SAR, Multi-look, Yamaguchi decomposition, New Mexico Veterans Memorial

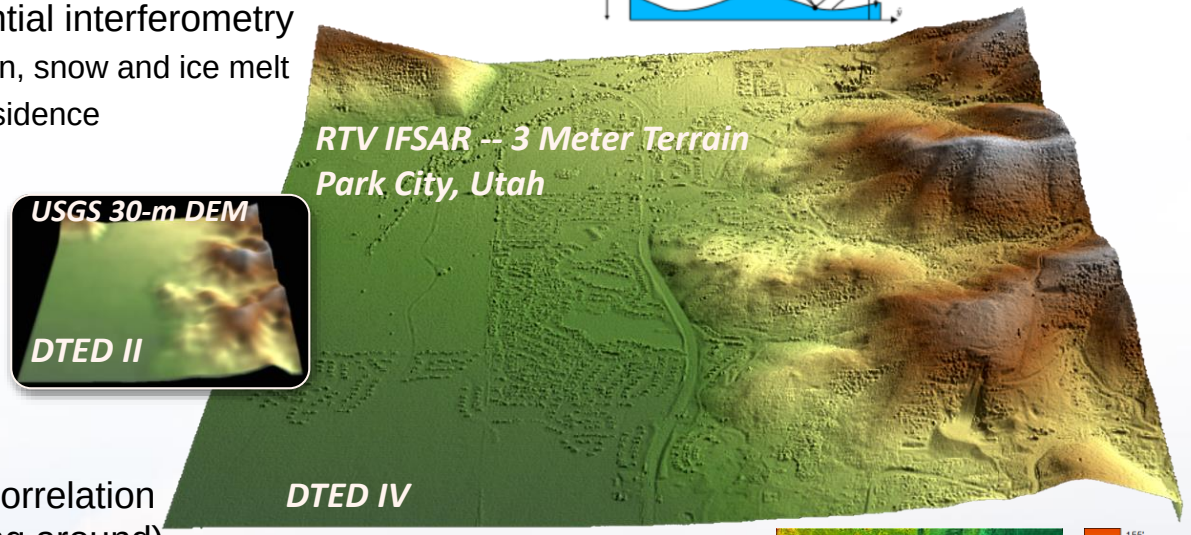
[1] Devaney J, Barrett B, Barrett F, Redmond J, O`Halloran J (2015) Forest Cover Estimation in Ireland Using Radar Remote Sensing: A Comparative Analysis of Forest Cover Assessment Methodologies. PLoS ONE 10(8): e0133583. https://doi.org/10.1371/journal.pone.0133583

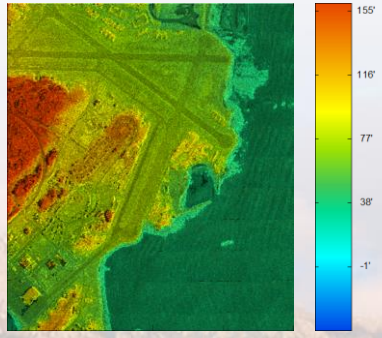
[2] Dabboor, M.; Montpetit, B.; Howell, S. Assessment of the High Resolution SAR Mode of the RADARSAT Constellation Mission for First Year Ice and Multiyear Ice Characterization. *Remote Sens.* 2018, *10*, 594.

Interferometry (InSAR) – Terrain Mapping

- **Arctic Applications:**
  - High resolution DEM generation (general SA, development, etc.)
  - Crevasse, fracture, lead detection
  - 3D change detection / differential interferometry
    - Glacial accretion/depletion, snow and ice melt
    - Permafrost melt and subsidence
    - Coastal erosion
- **FARAD Capabilities**
  - 2 pass InSAR at X, Ku & Ka
  - Single pass InSAR at Ku
- **Limitations & Issues**
  - Image registration, tie points?
  - 2 pass - surface temporal decorrelation between passes (snow blowing around)
  - Penetration and volumetric scattering → random phase → reduced coherency
  - Need to know InSAR baseline length and orientation very accurately
    - 2 pass solution at X & Ka band, limited by Navigator (GPS & IMU) accuracy
    - Possible degraded GPS performance at high latitudes
  - Existence of lower resolution "bootstrap" DEMS for scale & tilt corrections
  - Not real time – post processing required







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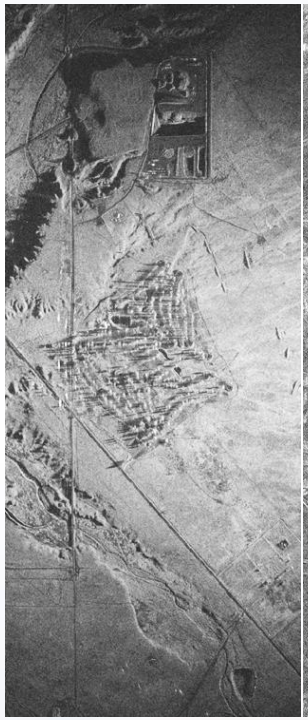
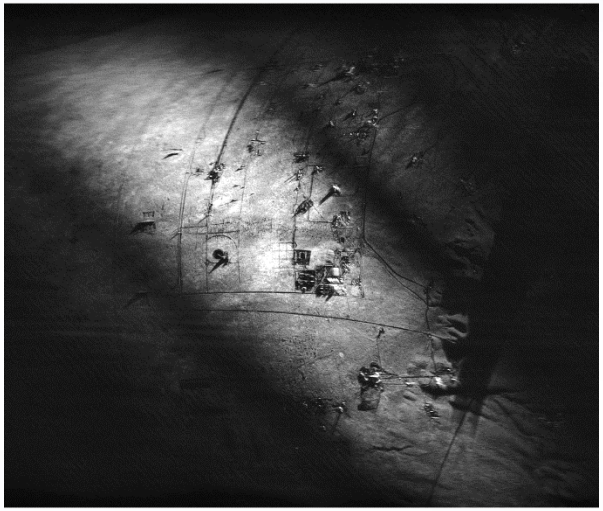
Bistatic Radar

- **X-Band, 9.6 GHz**
- **700 MHz RF bandwidth**
- **Dual Channel**
- **1.6 Gb/sec/channel**
- **2nd system being integrated and tested includes X, S, and C-Bands**
- **Multiple collects done with satellite (COSMO-SkyMed and TerraSAR-X) and airborne (SNL FARAD X-Band) illuminators**
- **Arctic Applications:**
  - Low cost, stealth SA from a temporary encampment or forward operating base
- **Issues**
  - Need a high point for passive receiver



TSX Bistatic

TSX Monostatic



FARAD Bistatic

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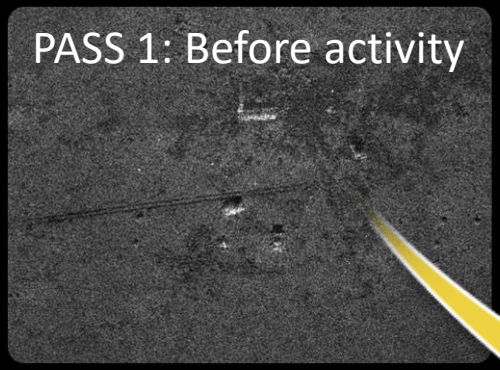
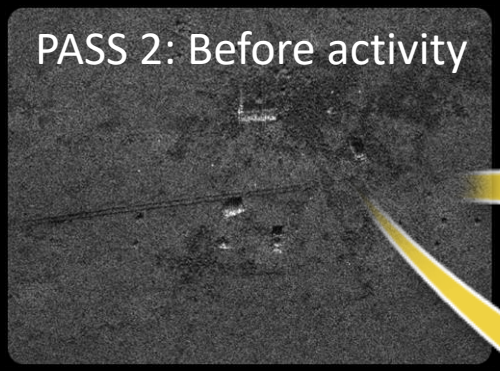
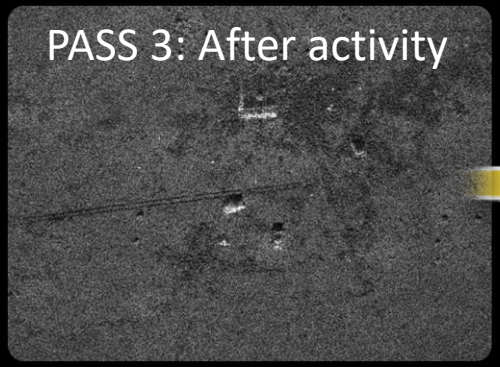
Coherent Change Detection (CCD)

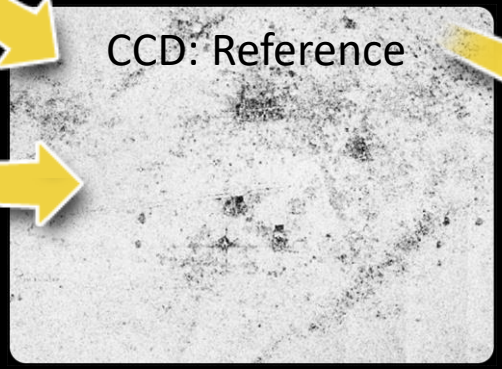
Normalized Coherent Product (NCP)







- Foot paths
- Tire tracks
- Bicycle tracks
- Ground disturbances
- *Often the changes cannot be seen at visible wavelengths*



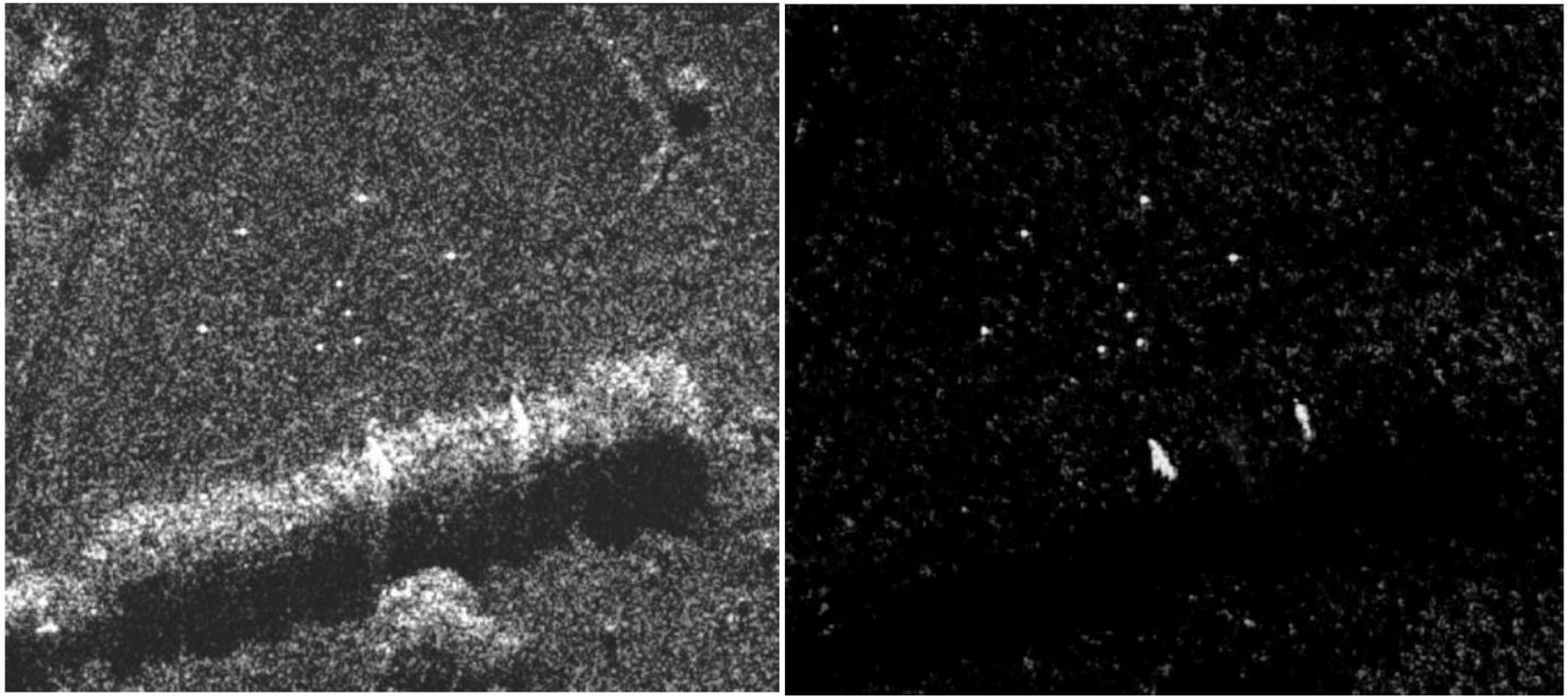
Will this work in the Arctic?

- Image registration, tie points?
- Penetration & Volume scattering?
- Max inter pass Δt?
- Other issues?

Potential Arctic Applications:

- Treaty Verification / Border Security
- Law Enforcement
- Search & Rescue
- Wildlife tracking

Inverse or Unchanged Detection



Conventional 15-GHz SAR Image of Two Mobile Targets in a Tree Line (left) and After ICCD Processing (right)

Will this work in the Arctic?

- **Image registration, tie points?**
- **Other issues?**

Potential Arctic Applications:

- **Search & Rescue**
- **Finding drifted over / buried man made objects**

Computed Tomography

Date: June 2000

Place: Hardin Field, Kirtland AFB, Albuquerque, NM

Center freq.: 16.8 GHz

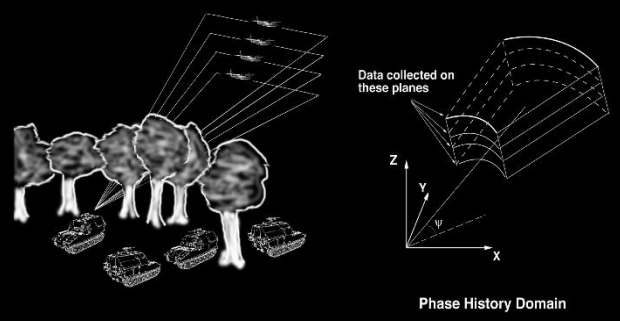
Resolution of imagery: 10 inches

Span of depression angles: 30.76 to 31.21 deg (0.45 deg spread)

Number of planes of PHD collected: 16

Vertical resolution: 2 meters

Concept for FOPEN Employing 3-D Tomographic Reconstruction of Spotlight-Mode SAR Imagery



Results of 3-D Tomographic Imaging with Sandia Labs Ku-Band 4-Inch SAR Multiple-Plane Data Collected Against Housing Area Near Hardin Field Reconstruction of Slice at 3-m Above Ground Shows Rooftops Becoming Visible Beneath Trees

Conventional SAR Image

Reconstruction of Slice at 3-Meters Above Ground Elevation Showing Rooftops Now Appearing Through Trees

Sandia National Laboratories

Courtesy Daniel E. Wahl, Sandia ISR Advanced **Exploitation**

What makes Sandia/FARAD Special

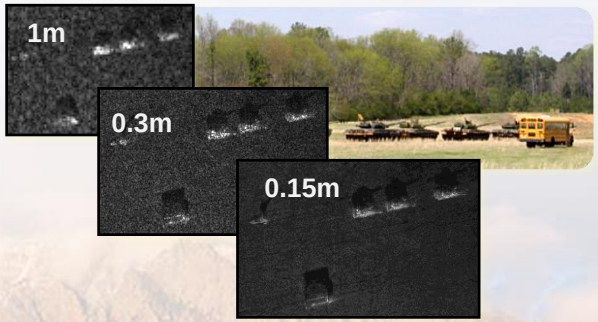
- **So what? There are plenty of SAR assets available today (L, C & X mostly)**
  - L-Band: JAXA – JERS (6,44), ALOS (5,7), …
  - C-Band: ESA – ERS, Envisat (10,3), Sentinal (9,12); CSA – Radarsat (8,5), …
  - X-Band: DLR – TerraSAR/Tandem X (1,11); ASI - Cosmo SkyMed (1,5), …
  - Ka: JPL/NASA – GLISTIN (airborne)

Space based
- Very large swath
- Coarser resolution
- No ground tether

- **FARAD Advantages in the Arctic**
  - Frequency diversity
    - Ka – almost no penetration, less volumetric scattering ➔ better coherence, better InSAR, better CCD; very sensitive to surface roughness, very fine resolution
    - Ku – less penetration, high roughness sensitivity
    - X – full polarization, moderate penetration and roughness sensitivity
    - S – more penetration, less roughness sensitivity
  - High resolution capability (sub meter)
  - Multi-channels – more phase centers, simultaneous collection
  - Total collection control
    - Shorter revisit time – less temporal decorrelation
    - Geometry not orbit constrained, larger incidence angles
    - Less atmospheric unknowns
  - National Security / ISR Focus

Airborne
- Reduced coverage
- Finer resolution
- Airstrip/FOB required
- Coverage limited by tether to FOB

Resolution Matters



Some Arctic National Security Applications

- **Power/Force Projection – Setting up a Forward Operating Base**
  - High res recon for site selection with: flat, smooth, hard area, aligned with the predominant winds for landing & offloading equipment (LC-130); stable, flat area for camp and power generation sites
  - Bi-Static for passive SA; GMTI & MWAS from tethered balloon
- **Sea ice: extent, burghs, floes, depth, and ice free waterways**
- **Search & Rescue**
  - High res recon for damage assessment, hazards, landing sites, and evacuation routes
  - Inverse CCD to find wreck in very bad weather
- **Monitoring facilities and borders, Treaty Verification**
  - Ensuring people and things are where they're supposed to be and not where they aren't (mining, fishing, encampments, shelters, buildings)
  - Threat awareness - keeping tabs on what adversaries are up to.
  - Border Security & Law enforcement (smuggling, Illegal immigration)
  - Environmental protection (petroleum, mining development)

Conclusions and Comments

- **Advantages of SAR Remote Sensing extend to the Arctic**
  - All weather*, day and night operation; limited effect of dust, smoke, and pollution
  - Sensitivity to dielectric properties (water content, biomass, ice)
  - Sensitivity to target structure (polarimetry)
  - Sensitivity to surface roughness
  - Sensitivity to man made targets
  - Subsurface penetration, enables crevasse detection, and (?)
  - Coherent, enables exploitation of coherent phase diversity
    - CCD, Interferometry, Tomography
- **Disadvantages of SAR Remote Sensing**
  - Complex interactions
  - Speckle effect
  - Penetration (surface ambiguity, volumetric scattering)
  - Topographic effects (SAR range/angle image geometry issues)
    - Foreshortening, layover, and shadowing
- **FARAD's frequency diversity, polarization diversity, and multi-channel capability are well suited for researching advanced remote sensing applications in the Arctic**

***Small sensitivity to clouds and light rain with increasing frequency, esp. Ka-Band**

Questions?

Douglas L. Bickel, Billy C. Brock, Dale F. Dubbert,
Armin W. Doerry, Ann M. Raynal, Judd A. Rohwer
Martin E. Thompson

Sandia Airborne ISR: www.sandia.gov/radar/
May 17, 2018

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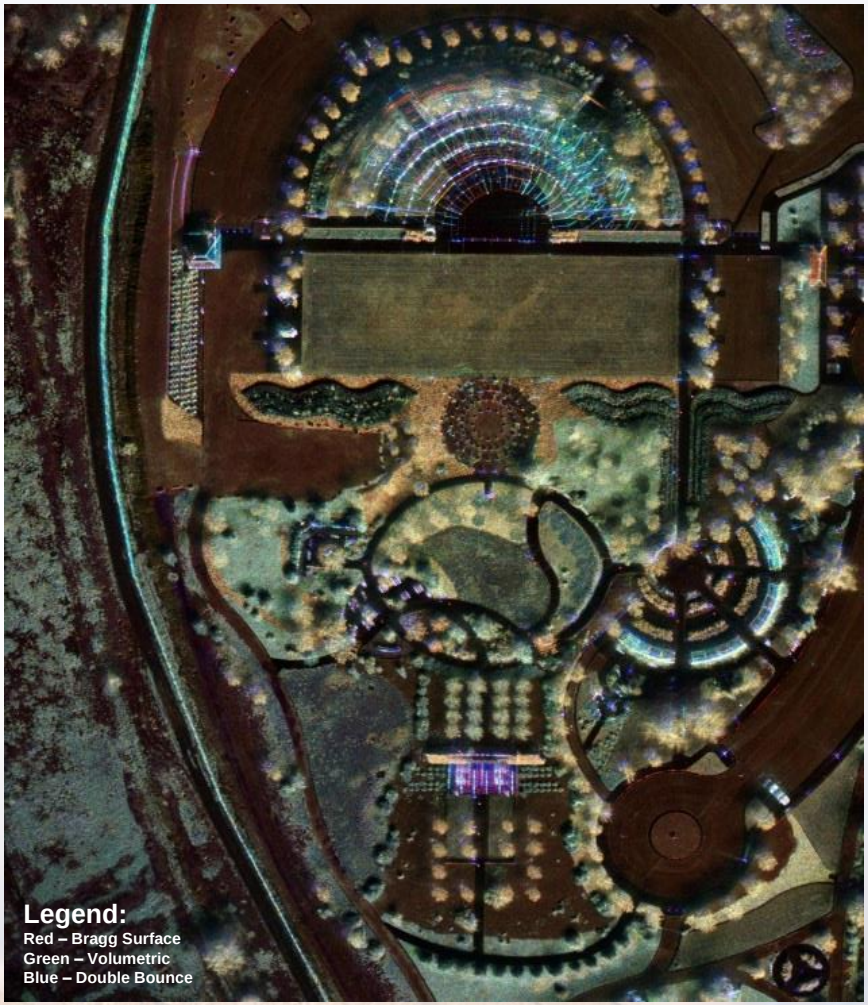
Sandia National Laboratories

PhoeniX

- 9.6 GHz center frequency
- 3 GHz RF bandwidth
- 4-inch resolution (spot mode)
- 1-foot resolution (contiguous stripmap)
- 300 Watt TWTA
- Single hardware RX channel
- Fully polarimetric (4:1 multiplex)
- 12 km single-pol, 8 km full pol max range at finest resolution*
- Real-time image formation on single polarization
- Operating modes:
  - SAR (spot circle, straight-line spot, stripmap)
  - VideoSAR
  - Exoclutter GMTI
  - Single or quad-polarization on all modes
  - Bistatic modes with ground-based RX/acquisition system

**Assumes < -25 dB noise reflectivity maintained at far corners of image with max image size (4k pixels range, 3 dB beamwidth azimuth)*



Multi-look X-Band Polarimetric SAR, Yamaguchi decomposition, New Mexico Veterans Memorial

Ku-Band

- 16.8 GHz center frequency
- 3 GHz RF bandwidth
- 70 Watt MPM*
- 4-inch resolution (spot mode and contiguous stripmap)
- Dual hardware RX channels
- 2:1 multiplexing each channel (4 data channels)
- Quad phase center antenna
- 8 km max range at finest resolution
- Real-time image formation on two channels
- Operating modes:
  - SAR (spot circle, straight-line spot, stripmap)
  - VideoSAR
  - Endoclutter GMTI

Ku-Band 4-inch resolution SAR image, Tijeras Arroyo Golf Course, KAFB, New Mexico

**L-3 Comm Microwave Power Module*

Ka-Band

- 35.6 GHz center frequency
- 5 GHz RF bandwidth
- Ultra-fine spot-mode resolution
- 1-foot resolution (contiguous stripmap)
- 50W NanoMPM®
- Single hardware RX channel
- Azimuth monopulse antenna
- 2:1 multiplex (Σ/Δ)
- 6 km max range at finest resolution
- Real-time image formation on single channel
- Operating modes:
  - SAR (spot circle, straight-line spot, stripmap)
  - VideoSAR
  - Endoclutter GMTI
  - VICTR

Ka-Band 4-inch resolution SAR interleaved stripmap, UNM Golf Course, overlay on Google-Earth.

® L-3 Communications, Electron Devices Division