SAR Phenomenology

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SAR Images

All SAR images in this presentation are Courtesy of Sandia National Laboratories, Airborne ISR, unless otherwise noted.

Image courtesy of Google Earth

Optical image

Ku-band SAR image

While SAR images share many attributes of their optical counterparts, the physics are quite different, leading to important SAR image characteristics that need to be appreciated for proper interpretation.

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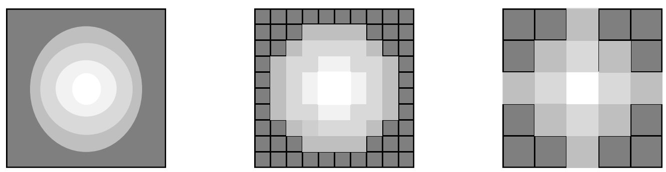
Image Basics – Pixel Spacing

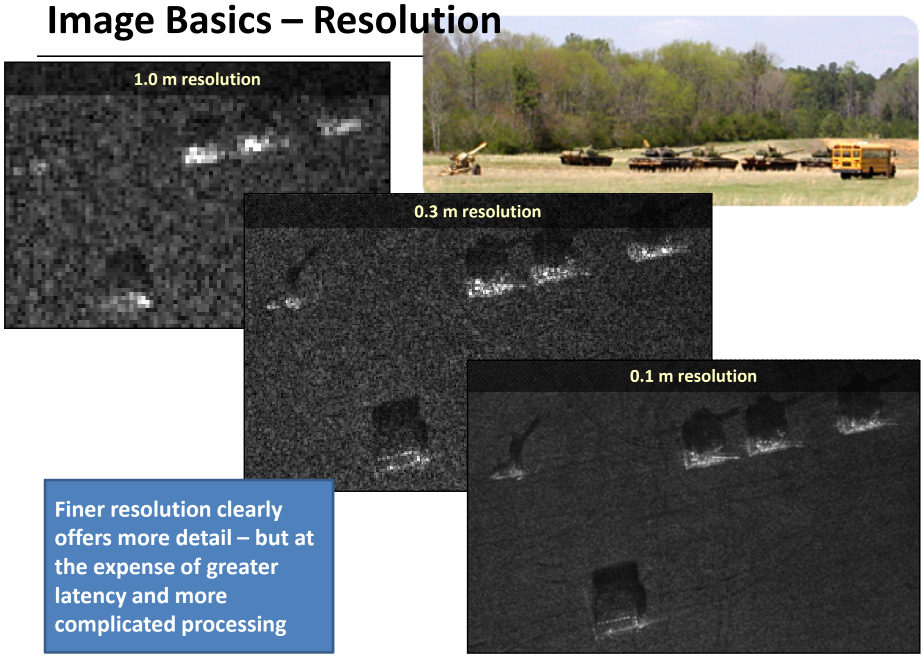
Pixel

- **Pixels are "picture elements" that make up an image.**
- **their 'spacing' is not necessarily the image resolution.**
  - the ratio of resolution to pixel spacing is the 'oversampling factor'
    - We generally desire pixel spacing to be finer than the resolution
    - typically 1.18 to 1.5 for many SAR systems.



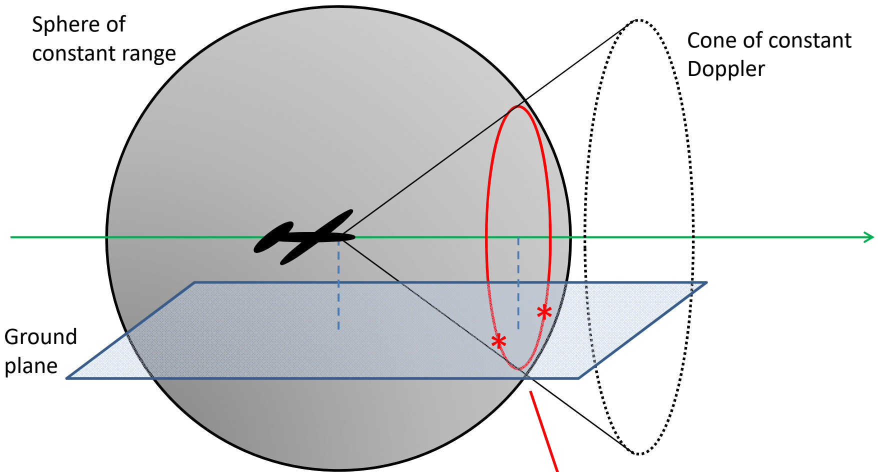
same resolution, but coarser pixel spacing

Image Basics – Resolution



Finer resolution clearly offers more detail – but at the expense of greater latency and more complicated processing

Geometric Distortions - Layover



The intersection of constant range and constant Doppler manifests as a circle. All locations on the circle have same range and Doppler. This circle intersects the ground at as many as two locations. The real antenna beam selects which of these makes it into the data. However, any target above or below the ground on the circle and in the beam will map to the ground intersection point. This is called "layover."

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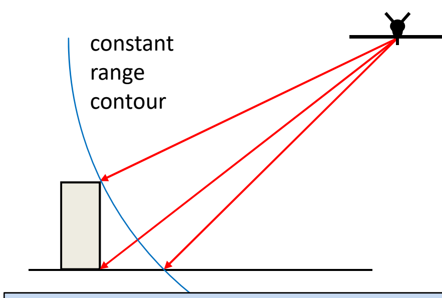
Geometric Distortions – Layover



Since the SAR renders range, tops of tall objects are nearer to the radar than their bottoms, so appear at nearer ranges in the SAR image. They 'lean forward' towards the radar, projecting to nearer ranges.

This is the opposite of optical images, which causes tops of tall objects to lean away, projecting to farther ranges on the ground.

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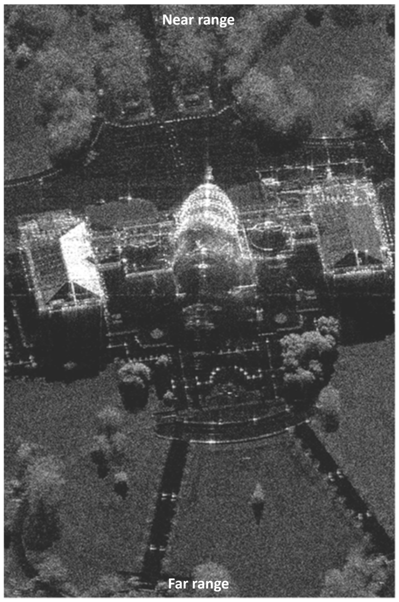
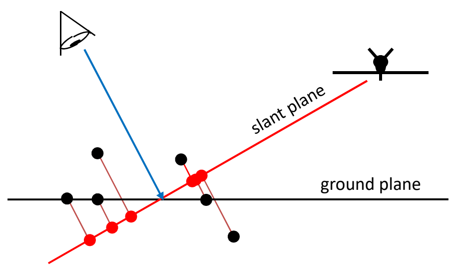
Geometric Distortions – Layover



By rotating the image so that near range is at the top of the image, the image looks more natural.

This is more a matter of personal preference.



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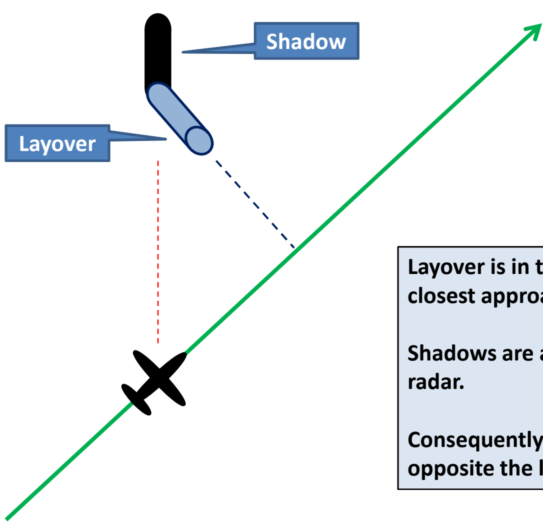
Geometric Distortions – Layover



Layover is in the direction towards the closest approach of the flight path.

Shadows are always away from the radar.

Consequently shadows are not always opposite the layover direction.

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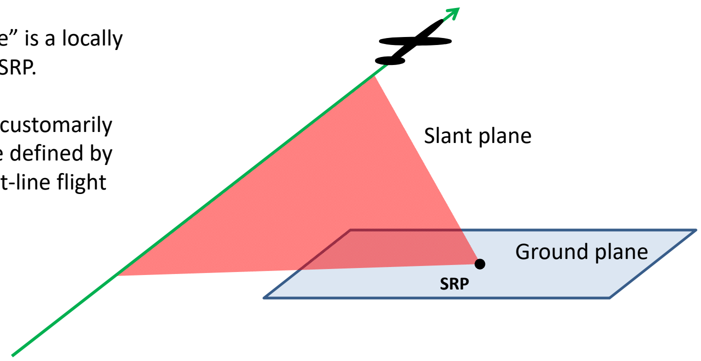
Geometric Distortions

The "Ground plane" is a locally level plane at the SRP.

The "Slant Plane" customarily refers to the plane defined by the radar's straight-line flight path and the SRP.



Literature often refers to "Slant-plane images" versus "Ground-plane images." In both cases the image is still of the ground, and focused to the ground. The distinction often refers to pixelation of the image, and whether it is in equal increments of slant range, or equal increments of ground-range. Layover is, of course, unaffected.

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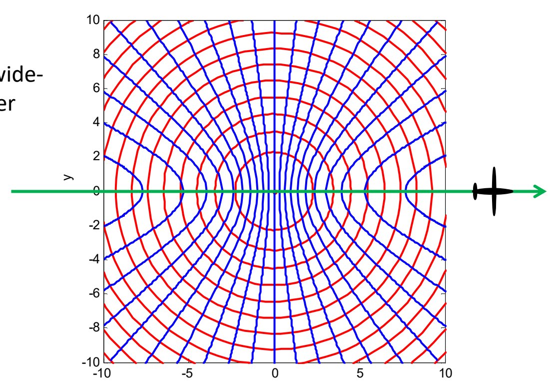
Geometric Distortions – Range-Doppler Grid

Constant-range spheres intersect the ground as circles, and constant-Doppler cones intersect the ground as hyperbolas.

Consequently, a range-Doppler grid is 'warped' with respect to a Cartesian grid on the ground.

This manifests most evident with 'wide-angle' SAR images, especially at finer resolutions and nearer ranges.

For small areas significantly far away in a broadside direction, the local range-Doppler grid is approximately square.



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Imaging Geometry

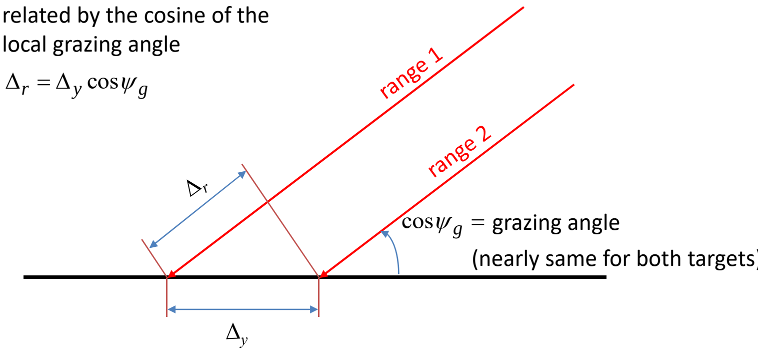
slant range vs. ground range

– **consider two targets that are not too far apart in range**

– **difference in slant range will be less than difference in ground range**

- related by the cosine of the local grazing angle

$\Delta_r = \Delta_y \cos\psi_g$



– **also true for resolution**

$\rho_r = \rho_y \cos\psi_g$

- most accurate if using the actual depression angle to the target
- using nominal depression angle at SRP often a good approximation

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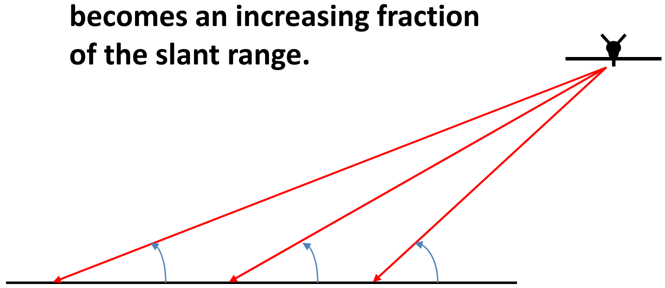
Imaging Geometry

The actual grazing angle changes slightly over the imaged swath.

- shallower at farther ranges,
- steeper at nearer ranges.

– **more noticeable as swath width becomes an increasing fraction of the slant range.**



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Imaging Geometry

Equal ground spacing does not appear as equal slant-range spacing.

- **appear farther apart at far ranges,**
- **appear closer together at near ranges.**

ground truth

SAR image with equal slant-range spacing

This is the native output for range-Doppler image formation algorithms like the Polar Format Algorithm (PFA). Of course images can always be resampled to other grids.

This is not an issue for tomographic algorithms like Backprojection

effect is in range only, not azimuth (other effects in azimuth)

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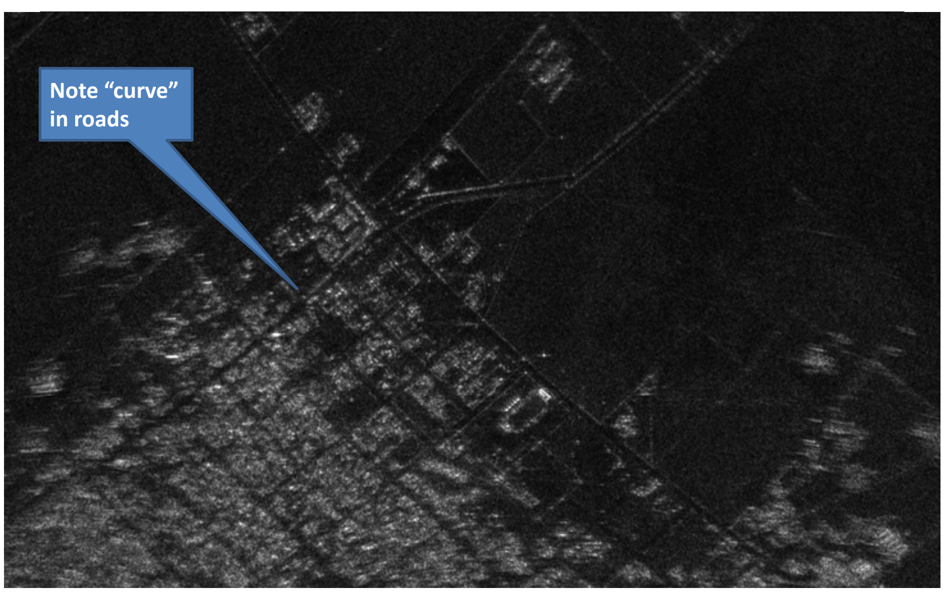
Geometric Distortions – Range-Doppler Grid



UHF

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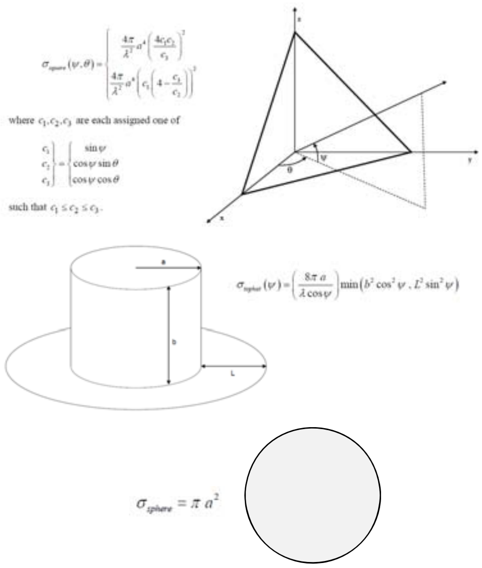
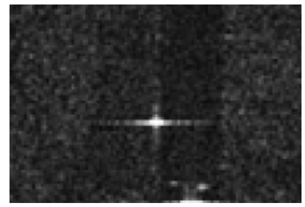
Canonical Reflectors





Canonical reflectors are those for which the RCS is simple and can be calculated in closed-form solution.

They are generally intended to approximate a singular point reflector which is particularly useful for evaluating the 'goodness' of SAR images.

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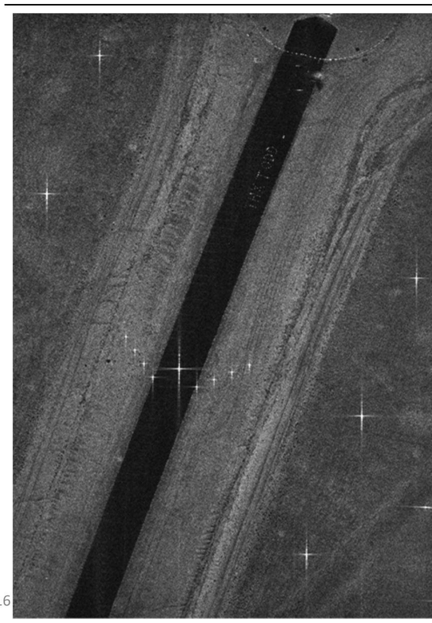
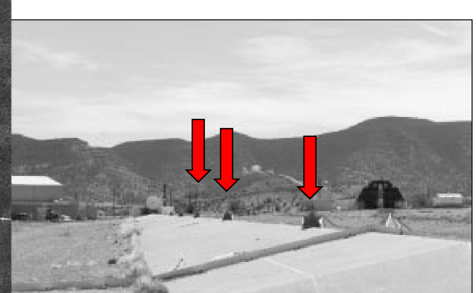
Canonical Reflectors



Canonical reflector arrays are often used as SAR system test sites, to gauge performance of the SAR system during flight.



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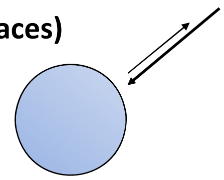
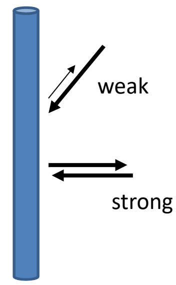
Target Scattering

– **A sphere (e.g. domed/rounded surfaces)**
  - isotropic
    – looks the same from any direction
  - RCS depends on radii of curvature
  - looks like a point target or a blob



– **Cylinder (e.g. pipelines, utility wires, structural edges, fences)**
  - single-axis isotropic
    – RCS peak broadside to cylinder
  - RCS proportional to diameter
  - looks like a line



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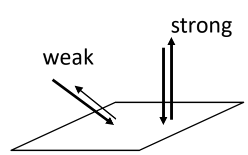
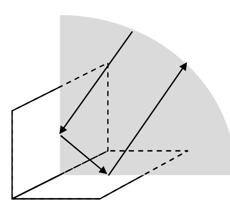
Target Scattering

– **Flat Plate (e.g. lake, roads, runways, paved areas)**
  - not isotropic at all
    – narrow RCS peak when normal to surface
    – like a mirror
  - looks like a point or blob at normal incidence
  - looks dark at non-normal incidence



– **Dihedrals (e.g. buildings, stationary vehicles)**
  - nearly single-axis isotropic
    – within inside envelope
    – RCS peak normal to dihedral joining edge
  - RCS proportional to plate sizes
  - looks like a line
    – located at joining edge



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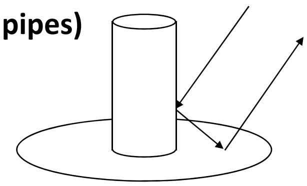
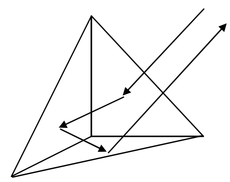
Target Scattering

- Top Hat
  (e.g. utility poles, tree trunks, vent pipes)
  - nearly isotropic
  - RCS depends on dimensions
  - looks like a point target or blob



- Trihedrals (corner reflectors)
  (e.g. building inside corners, window wells, truck beds)
  - nearly isotropic
    - within inside envelope
  - RCS proportional to plate sizes
  - looks like a point or blob
    - located at apex



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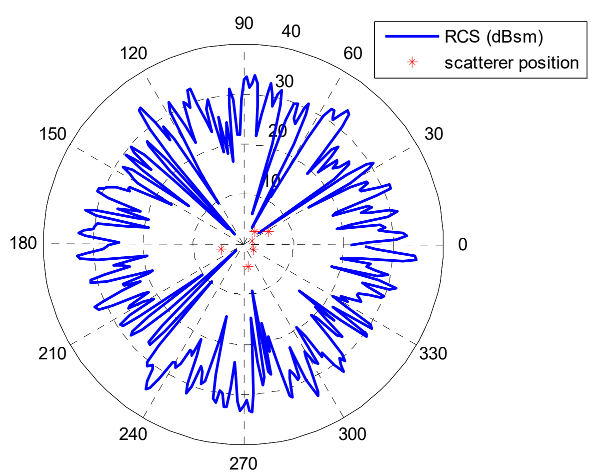
Complicated Targets

Even just a handful of scatterers within a resolution cell will interfere with each other (adding in and out of phase) so that the RCS is a complicated and sensitive function of aspect angle.

This is the basis for Swerling models; statistical models of RCS depending on nature of scatterers and whether they remain coherent from pulse-to-pulse, or scan-to-scan.



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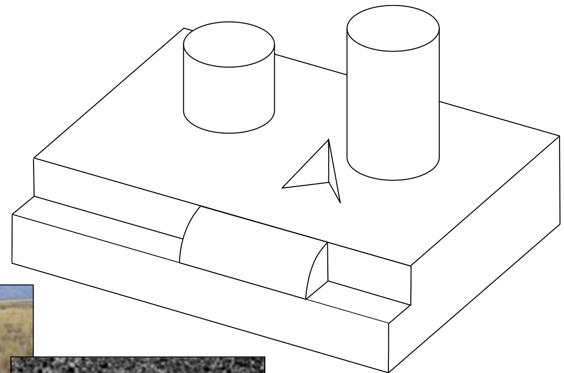
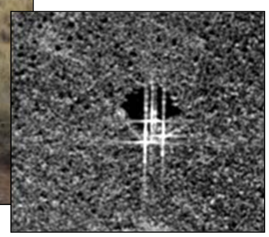
Slicy

An interesting 'quasi'-standard target for a number of SAR target recognition studies is known as "Slicy", which is made up of a special arrangement of cutouts and other canonical components.





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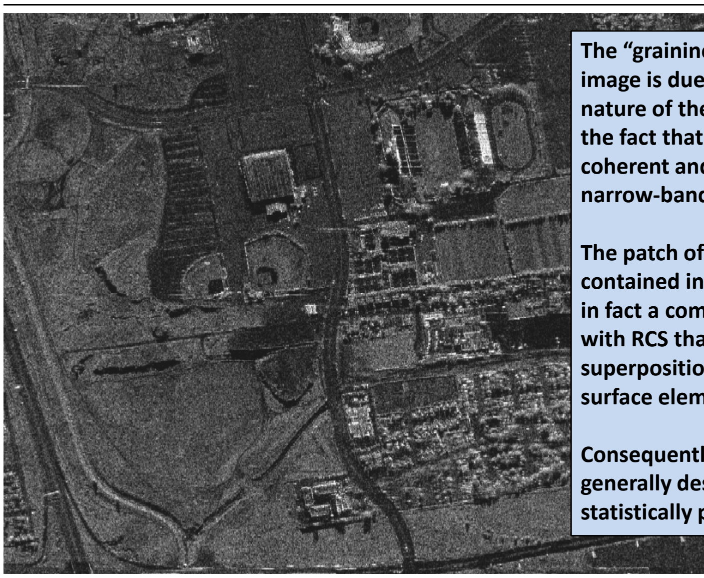
Distributed Clutter – Speckle



Ku-band

The "graininess" in a SAR image is due to the distributed nature of the target area, and the fact that the waveform is coherent and relatively narrow-band.

The patch of ground that is contained in a resolution cell is in fact a complicated scatterer, with RCS that depends on the superposition of many tiny surface elements.

Consequently, the RCS is generally described statistically per unit area.

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Smooth versus Rough

The "brightness" of an area generally corresponds to the roughness of its surface.

Ku-band

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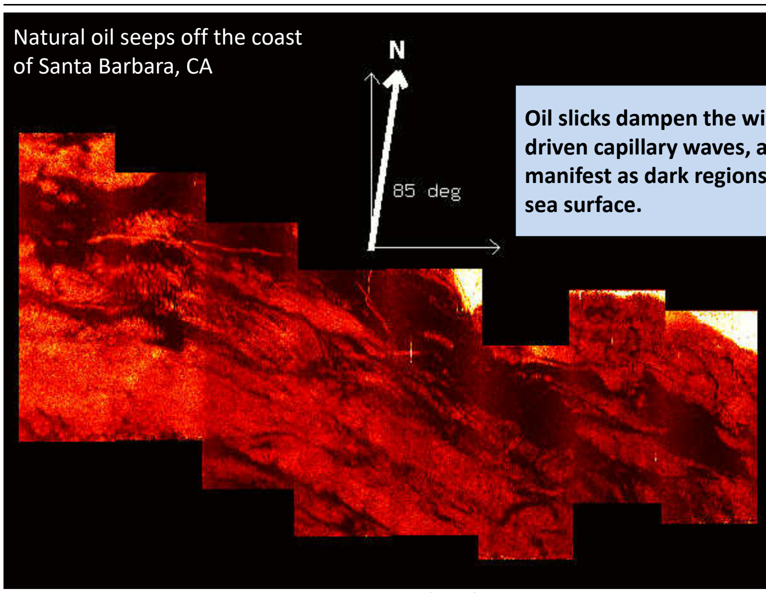
Smooth versus Rough – Oil Spills



Oil slicks dampen the wind-driven capillary waves, and manifest as dark regions on the sea surface.

Ku-band

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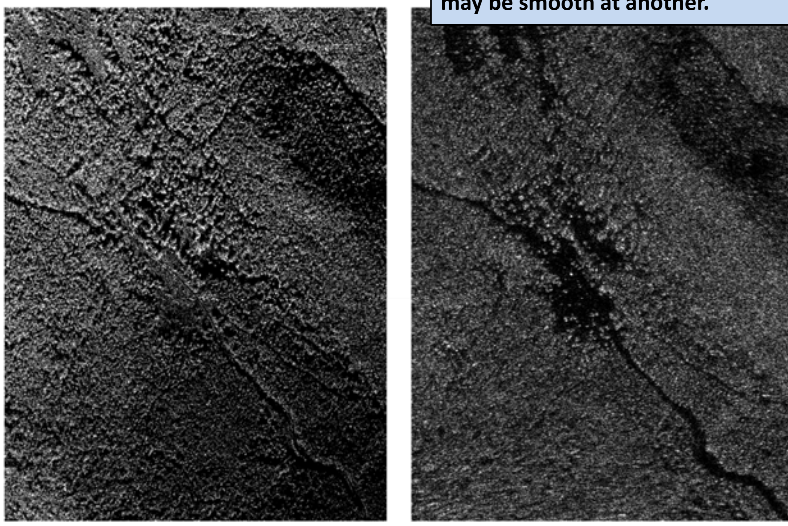
Frequency Dependence

Roughness is measured against wavelength. Rough at one wavelength may be smooth at another.



2 Meter Resolution / December 22, 1994
Ku-Band SAR, 15 GHz
Vertical Polarization

2 Meter Resolution / November 9, 1994
UHF SAR, 380 MHz
Vertical Polarization

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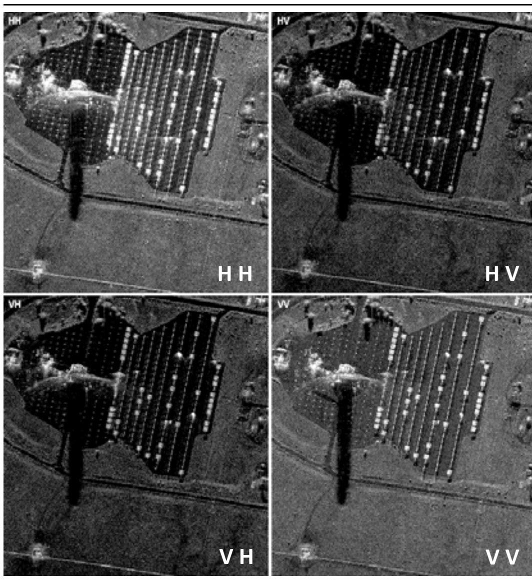
Polarization Dependence

Targets are often also sensitive to polarization of the incident radiation., and re-radiate preferred polarizations.

Some features "light up" with some polarization combinations, and others "light up" with other polarization combinations.

Sometimes, target features we want to suppress can be made to "go dark" with certain polarization combinations.



X-band

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Polarization Dependence

Different polarizations, or perhaps functions of polarizations, are often displayed with different colors.

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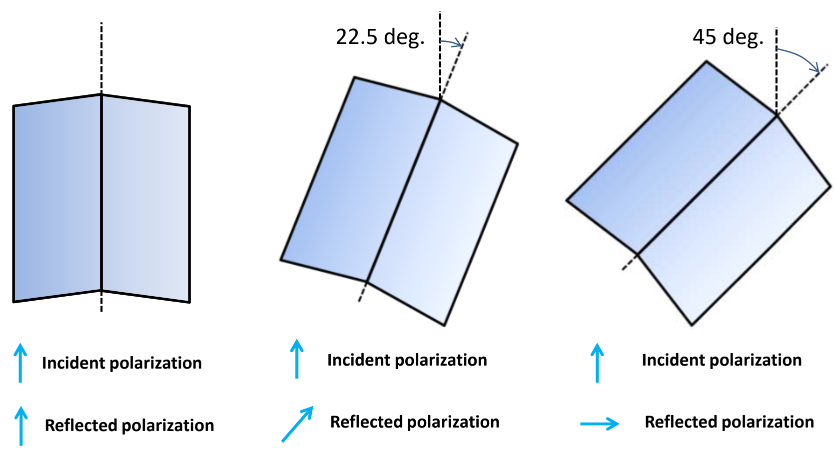
Polarization Canonical Targets



For polarimetric calibration, a popular target is the dihedral. With a boresight orientation, it will rotate polarization by twice the target rotation angle.

Polarization rotation depends on the nature of the bounce(s).

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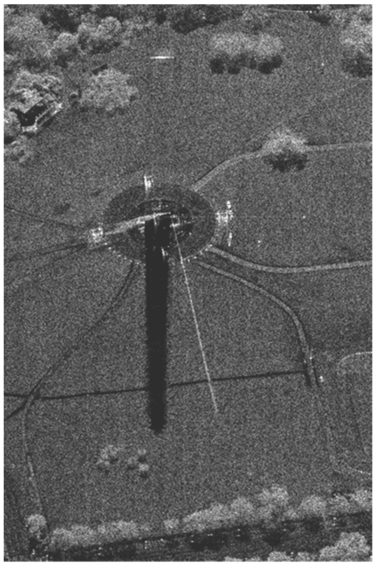
Stealth Targets



Ku-band

When a target either absorbs of redirects its reflected energy away from the receiver, it exhibits "Stealth."

While this can be relatively easy at times, and is not uncommon either by design or by accident, it is far harder to cover up a shadow.

Ku-band

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Shadows

Some objects are more readily identified by their shadows. This is also true for otherwise stealthy targets.

Ka-band

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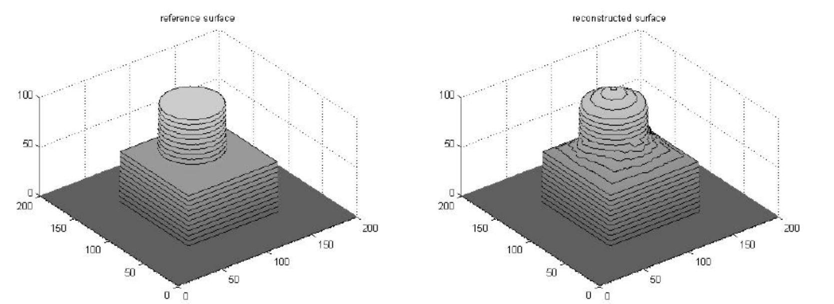
Shadow – 3D Shape Reconstruction



The radar provides not only its own shadow, but can render the shadow in the SAR image. Collecting shadows from enough different aspects allows reconstruction of the shape of the 3D target.

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Multipath Effects

The normal assumption for radar is the "Born approximation," which says essentially that the only field that scatters is the incident field.

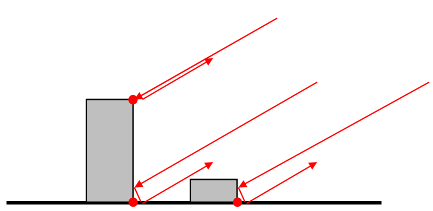
That is, the SAR image is normally assumed to be only direct scattering from an image location.

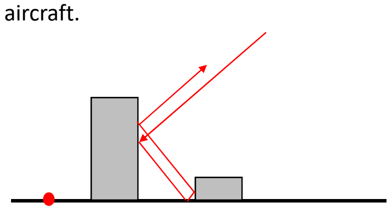
Real-life isn't quite so pretty.

"Multipath" is the phenomenon that a field may be reflected more than once before echoing back to the SAR receiver.

Energy delayed in this manner maps to locations farther in range than the scattering object.

Multipath can happen in the target scene, or can even happen at the aircraft.





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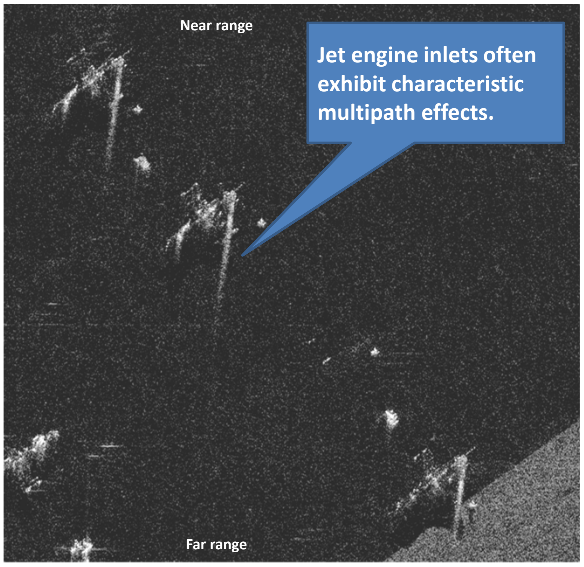
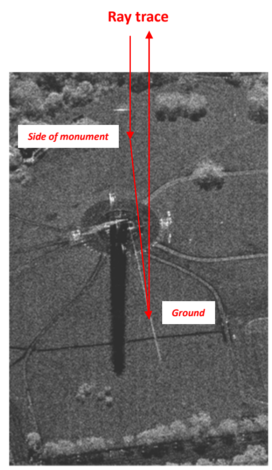
Multipath Effects



Ku-band



Ku-band

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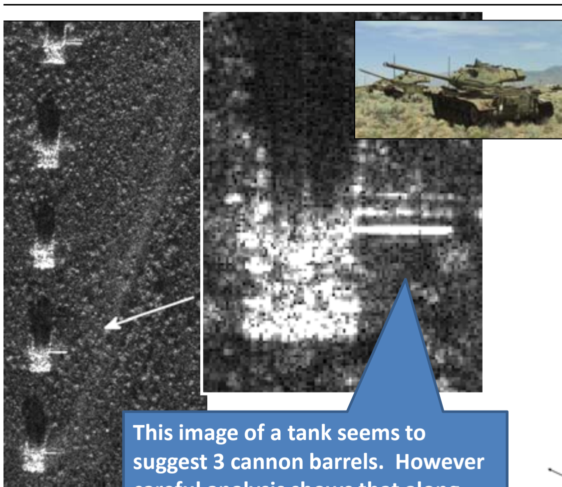
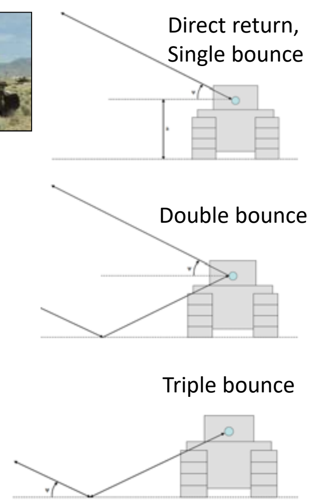
Multipath Effects – Ground Bounce



This image of a tank seems to suggest 3 cannon barrels. However careful analysis shows that along with the direct return, we have multipath effects of double and triple bounces involving the ground.



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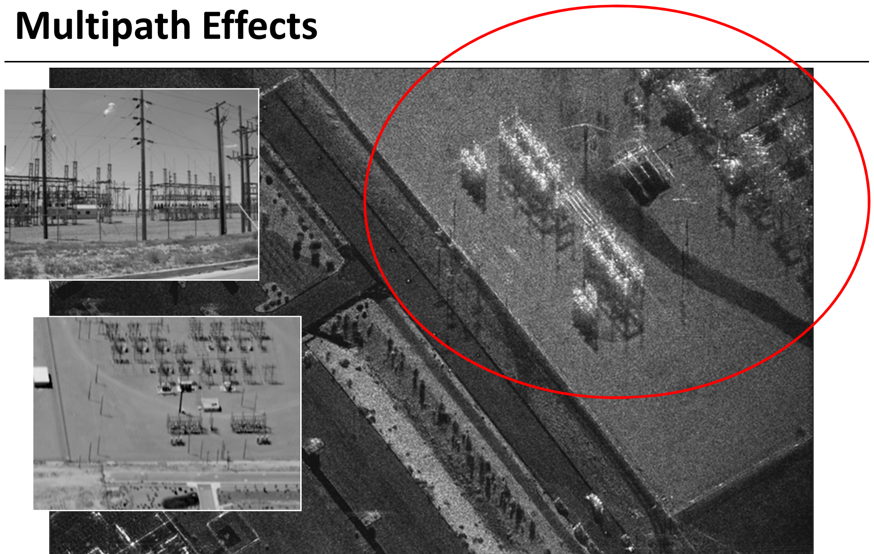
Multipath Effects



This electrical substation has a number of discrete but highly reflective features that allow substantial multipath opportunities. Images of such targets often look cluttered, with energy bleeding into shadows.

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Penetration – Weather

Microwave radiation is well known to be able to penetrate clouds, fog, rain, snow, sandstorms, dust, and smoke. This is due to its longer wavelengths than optical or even IR systems.

This image was formed at night through an overcast with occasional light rain.

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Penetration – Structures

In this SAR image, we easily penetrate the fabric tents to see the equipment that is hidden from optical view.

Ka-band

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Penetration

Foliage Penetration (FOPEN)

Generally VHF/UHF frequencies can be used to penetrate foliage. A problem is that at these longer wavelengths, we are generally limited in bandwidth, thereby limiting resolution. Furthermore, these frequencies are popular with other users, and interference can be a problem.

Shorter wavelengths in the microwave region can sometimes penetrate relatively sparse foliage. This is sometimes attributed to "peek-through," although the transmission path may not be quite so clean, exhibiting multipath effects.

Ground Penetration (GPEN)

Ground penetration is mainly a function of soil moisture. Even L-band (1-2 GHz) has been shown to penetrate dry sand to several meters. A problem for airborne SAR is that below-ground targets with significant attenuation must typically compete with surface clutter.

Seawater Penetration

While microwave frequencies cannot meaningfully penetrate seawater, it has been shown that submerged objects do in fact influence sea-surface characteristics that often can indeed be detected.

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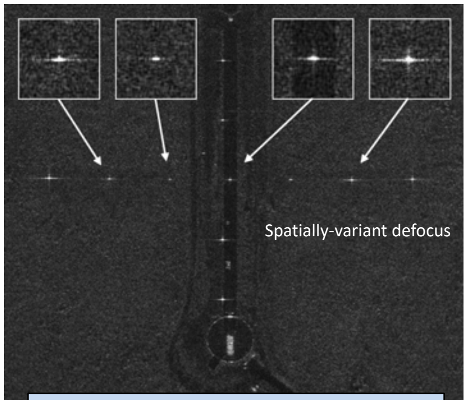
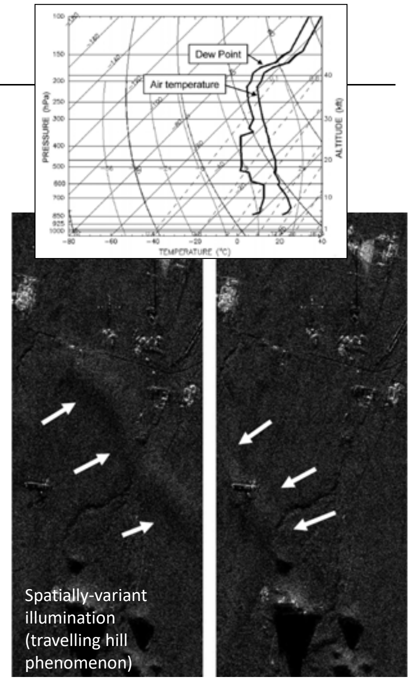
Atmosphere Issues



The assumption that the atmosphere is "free space" or even "homogeneous" ignores refraction due to gradients in the atmosphere, primarily humidity gradients. This can interfere with high-fidelity image formation.



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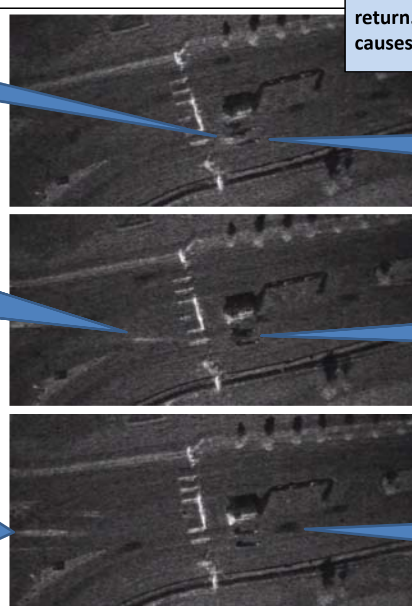
Moving Features – Translation

A line-of-sight velocity causes a shift in Doppler of the direct return. A cross-range velocity causes a smearing of Doppler.



Vehicle stopped at gate

Vehicle shadow behind direct return

As vehicle begins to move, its Doppler signature begins to shift and smear

Vehicle shadow begins to move

As vehicle begins to move faster , its Doppler signature continues to shift and smear more

Vehicle shadow continues to move

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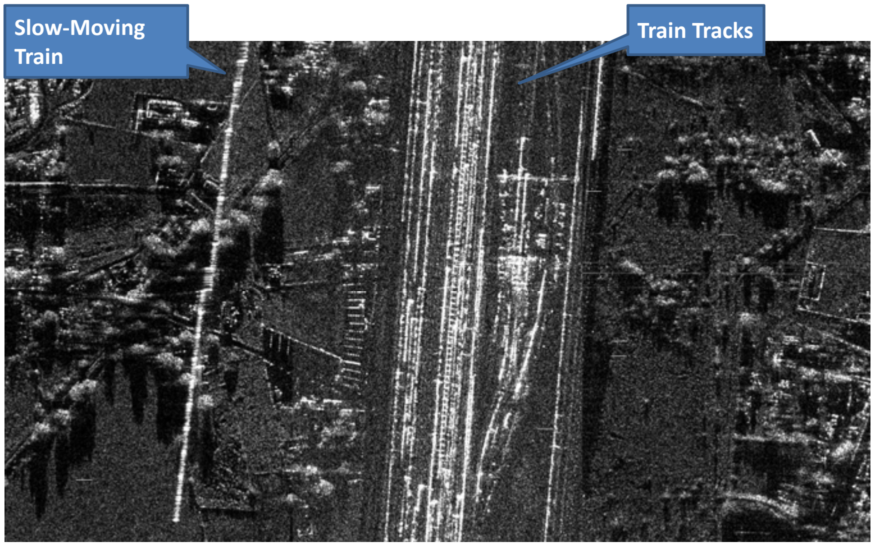
Ku-band

Moving Features – Translation



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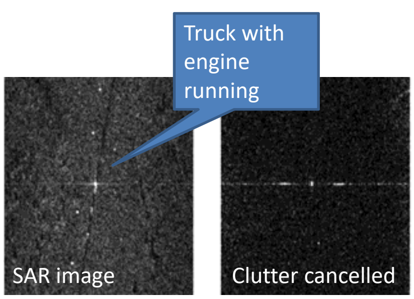
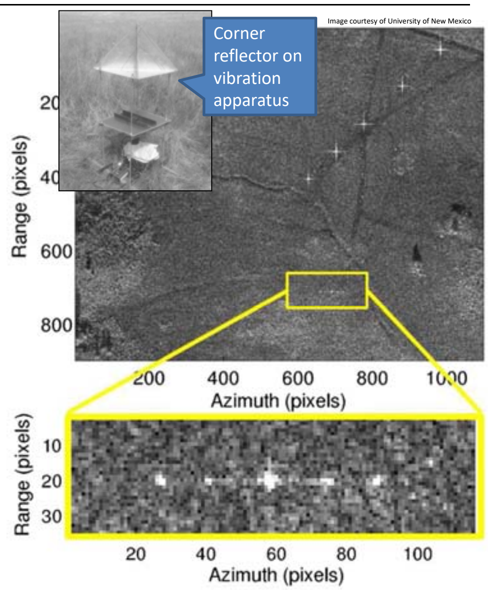
Moving Features – Vibration & Rotation

Vibration and rotation involve alternating positive and negative line-of-sight velocities during a synthetic aperture.

These will tend to throw Doppler sidelobes in both directions.





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Moving Features

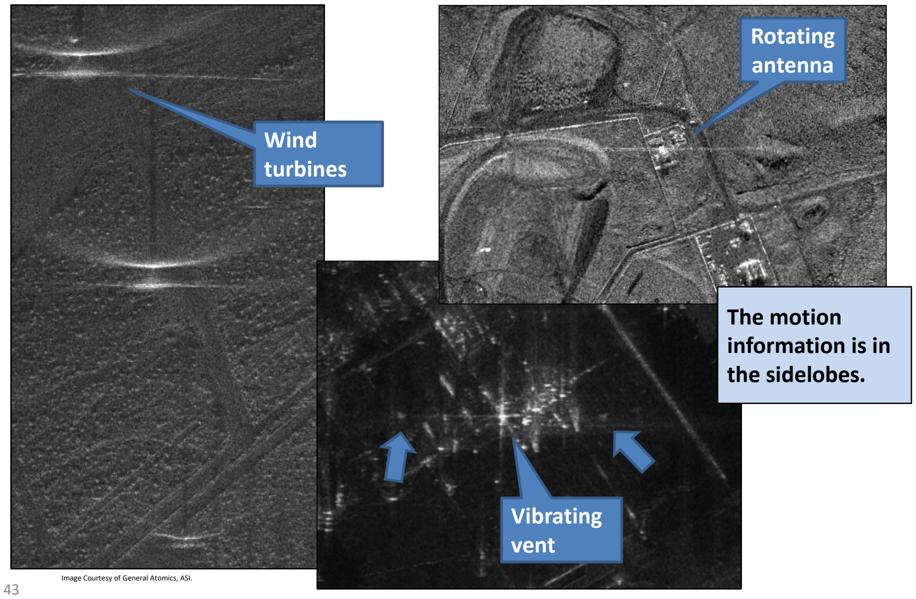

Image Courtesy of General Atomics, ASI.

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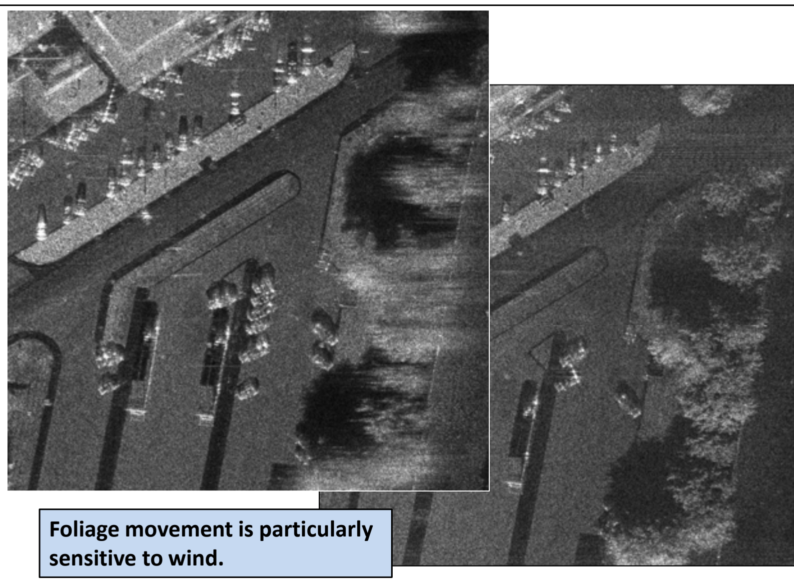
Moving Features – Blowing Trees



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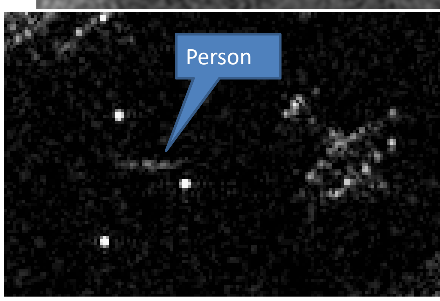
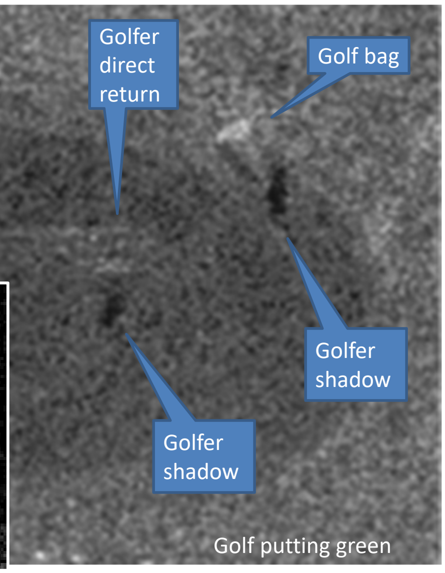
Moving Features – People

People generally can't hold still enough to focus well. They tend to smear in Doppler even when standing still. However, their shadows don't exhibit Doppler effects.



Ku-band



Ka-band

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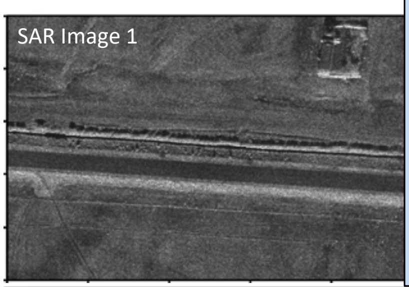
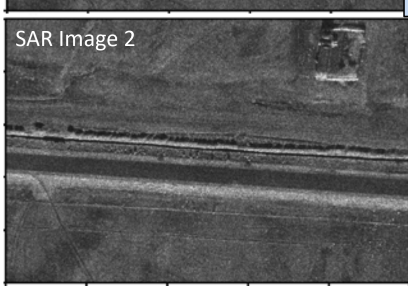
Coherence Between Images

SAR assumes a stationary target scene.

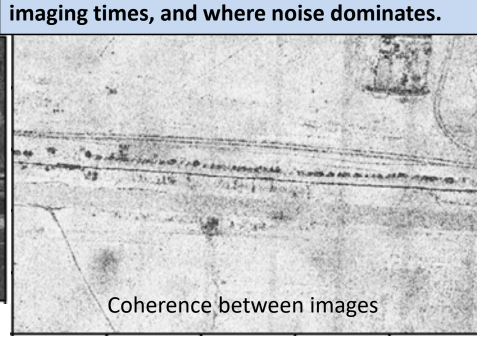
Two SAR images of the same identical scene, taken from the same geometry, but at different times, will be identical in all respects except for uncorrelated noise.

A coherence map should show high coherence except for areas of change between the imaging times, and where noise dominates.





Ku-band



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Section Summary

- SAR images contain many features that correspond to the visual world
- There are substantial differences between SAR images and EO/IR images
  - Range-Doppler image geometry
  - Much longer wavelengths
    - Can penetrate when shorter wavelengths can't
  - Requires stationary scene content to focus
- SAR images also vary considerably from one radar band to the next
- SAR image pixels also feature phase information
- Shadows might be exploited

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