SAR Image Post-Processing and Exploitation

Post-Image-Formation Processing

Once an image is formed, there are a number of post-processing steps that might be implemented

- Geometric corrections
- Radiometric calibration
- Autofocus correction of residual phase errors
- Speckle reduction
- Dynamic Range reduction
- Sidelobe apodization

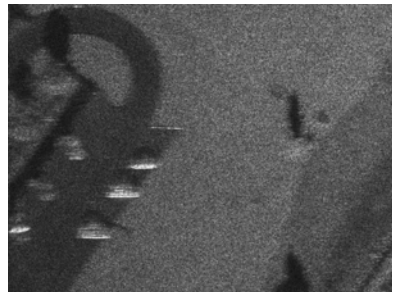
Some of these are cosmetic
Some facilitate some exploitation techniques
Some interfere with some exploitation techniques

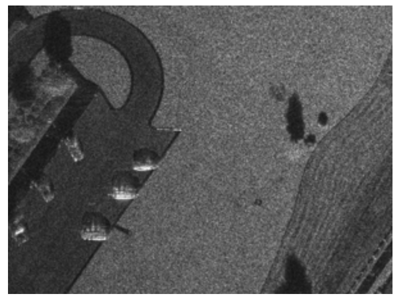
Autofocus

Autofocus is a blind deconvolution of a common phase error. These phase errors are typically due to uncompensated radar motion due to inadequate motion measurement accuracy.

Various techniques exist. All somehow measure the “blur” and attempt to de-blur the image.

- Phase-Gradient autofocus
- Map-drift autofocus
- Contrast optimization
- Prominent Point
- Entropy techniques





3

Autofocus

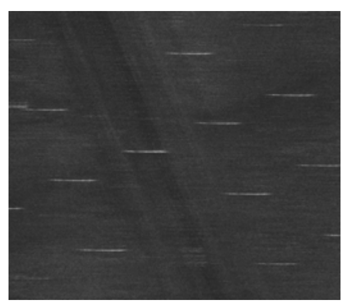
For large scenes, the misfocus might vary across the SAR image

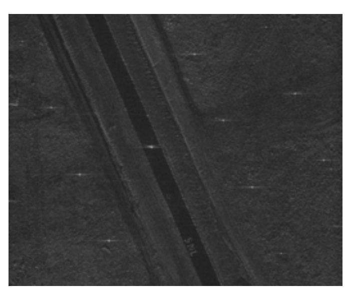
- Need spatially variant autofocus
  - Different autofocus solution in different parts of the image

Sometimes the residual motion errors exceed the range resolution of the radar

- A ‘phase’ error correction no longer suffices
  - Need migration corrective autofocus

Even with ‘perfect’ motion measurement, there may be unmeasured ‘apparent’ range variations due to nonhomogeneous atmospheric effects





4

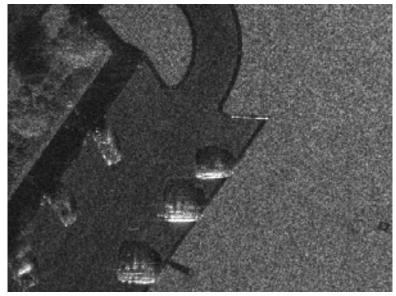
Speckle Reduction

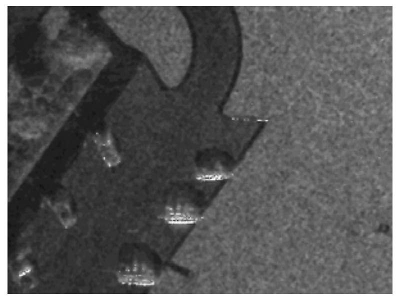
Speckle is the graininess that manifests primarily in distributed target areas. It is highly sensitive to imaging geometry.

Traditionally, speckle is 'filtered' by noncoherently averaging multiple SAR images of the same scene, but from different geometries.

Speckle can also be filtered within a single SAR image via a number of techniques, most of which involve noncoherent area filters (e.g. mean, median, etc.) to blur the distributed target areas. The challenge is to *not* blur discrete scatterers in the process.

Noncoherent averaging destroys phase information.



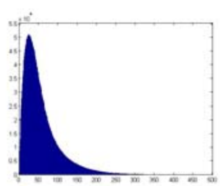


5

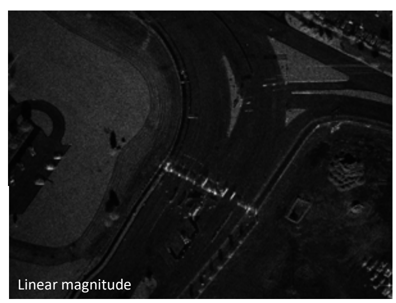
Dynamic Range Reduction

SAR images may exhibit more than 100 dB of dynamic range. However, the human eye can perceive only about 42 dB of dynamic range in any one image. Common 8-bit displays render only about 48 dB of dynamic range

Histograms show that SAR images are very Rayleigh-like with long tails. Information is concentrated at lower magnitudes.



Lookup Tables (LUTs) can compress the dynamic range of a SAR image for display, and improved human perception.



Linear magnitude

Square-root magnitude

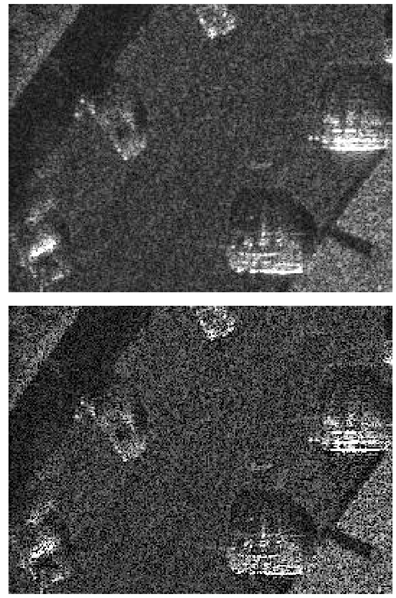
6

Sidelobe Apodization

Sidelobe Apodization is a non-linear processing technique that attempts to identify a pixel's energy as due to a sidelobe or not. If so identified, then the pixel value is reduced. If identified as 'not' a sidelobe, then the pixel value is left alone.

This technique makes use of the property that sidelobes are sensitive to the window taper function employed. 'Modulating' the window function will modulate sidelobes but not the mainlobe.

IPRs become more 'needle'-like. However, phase information often becomes unreliable.



7

Caution

There is an important distinction between

- **Making the image "look" nicer, and**
- **Improving the accuracy and precision of the rendering**

They are 'not' the same

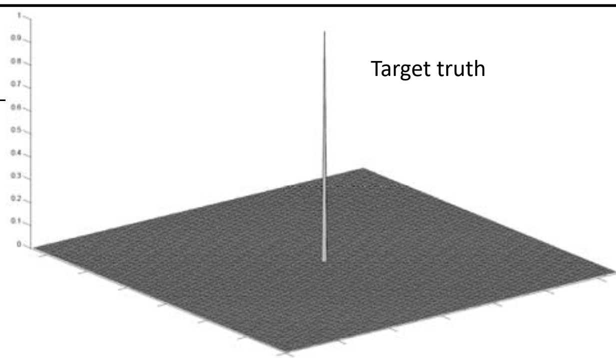
8

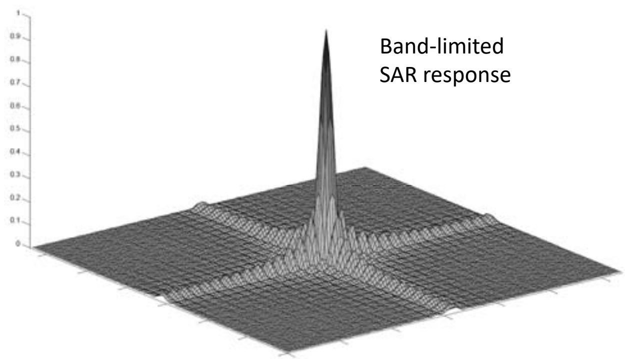
IPR Testing

The measure of goodness for the performance of a SAR is usually an evaluation of its “Impulse Response” (IPR).

This is the rendering in a SAR image of an echo of a mythical point target.

This mythical target can be approximated fairly well both on the lab bench, and with real targets during flight tests.





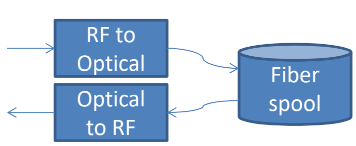
9

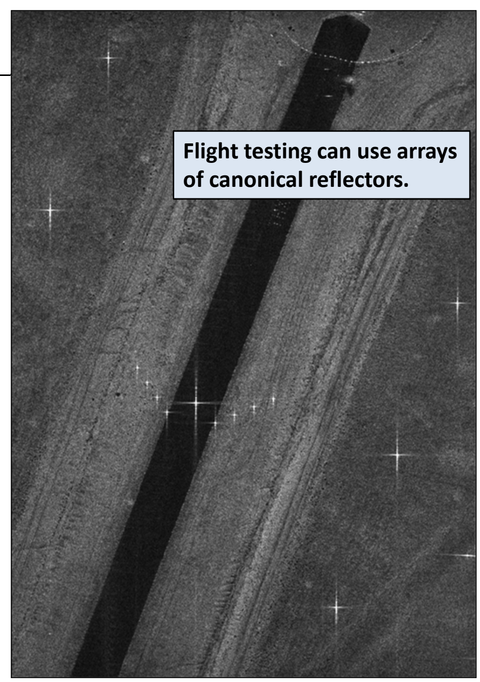
IPR Testing

In a laboratory environment, an essential tool is the Fiber Optic Delay Line (FODL).

This allows us to simulate many kilometers of range-delay for a transmitted signal; equivalent to a point-target response.

They can be either directly connected to the radar front-end, or function as a remote transponder in a compact range.





10

SAR Image Exploitation

Once an image is properly formed, including all necessary and relevant post-processing, it is available for exploitation.

- **Exploitation may require only a single image, sometimes image pairs, and sometimes image groups or longer sequences**

- **3D topography mapping**
- **Coherent Change Detection**
- **Polarimetry**
- **VideoSAR**
- **Automatic target Recognition**

11

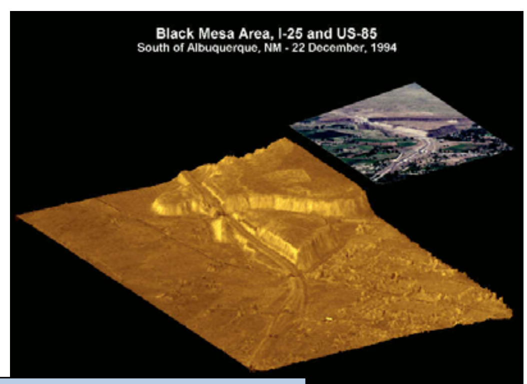
3D Topography Mapping

SAR naturally maps range and azimuth. Elevation angle collapses and manifests as layover.

If we treat the target scene as a 3D surface, the surface height can be discriminated by collecting two (or more) SAR images from slightly different geometries.

Two classes of techniques allow us to discriminate elevation angle, and ultimately surface height.

- **Interferometric SAR (IFSAR, or InSAR)**
- **Stereo SAR**



The typical assumption is that each pixel location contains only a single height.

12

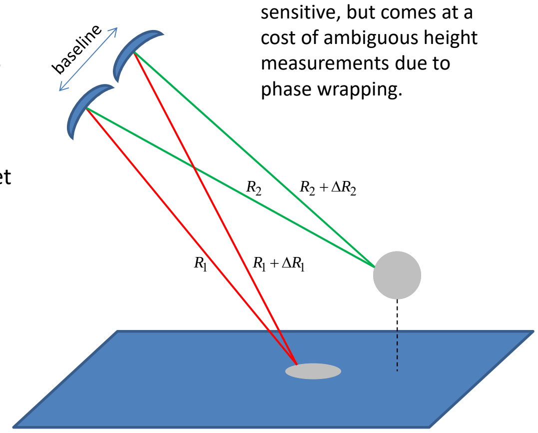
IFSAR

Consider two antennas offset in elevation, and a SAR image from each.

Corresponding pixels will exhibit different ranges between the two antennas, that in turn manifests as a phase difference.

This phase difference depends elevation angle offset, due to target height.

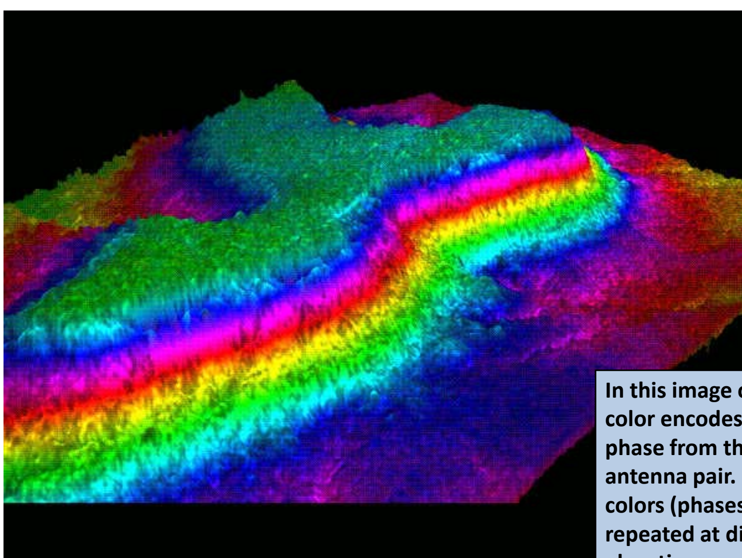
A platform can either
1. Carry both antennas for a single-pass configuration, or
2. Carry one antenna and fly two passes, with offset collection geometries.



A bigger baseline makes the interferometer more sensitive, but comes at a cost of ambiguous height measurements due to phase wrapping.

13

IFSAR



In this image of a mesa, color encodes relative phase from the IFSAR antenna pair. Note how colors (phases) are repeated at different elevations.

14

IFSAR

Absolute accuracy depends on how well the antenna baseline orientation can be determined.

Relative accuracy (precision) depends on how system noise affects the height estimate. The standard deviation of the height estimate can be expressed as

$$\sigma_z = \frac{\lambda R \cos\psi}{2\pi b_\perp \sqrt{SNR}}$$

Assumes transmitting on one antenna and receiving on both simultaneously

where

$\lambda =$ Nominal wavelength

$R =$ Nominal range

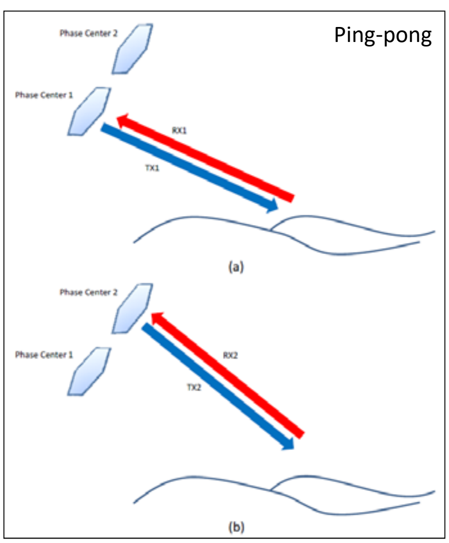
$\psi =$ Nominal grazing angle

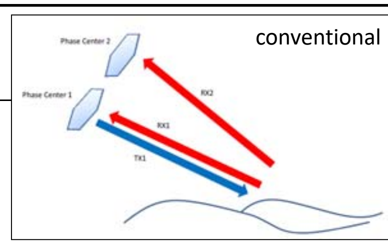
$b_\perp =$ Perpendicular baseline projection

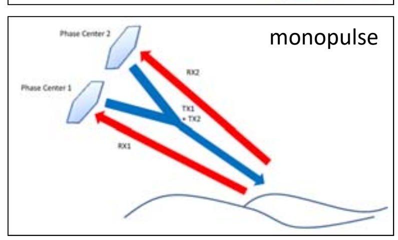
$SNR =$ Effective Signal to Noise Ratio

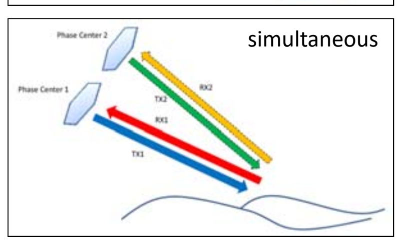
15

IFSAR









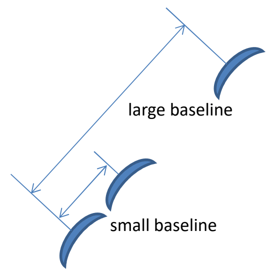
16

IFSAR

Phase ambiguities require phase-unwrapping algorithms to be applied to disambiguate heights.

Alternatively, more complicated antenna arrangements with multiple baselines might be employed to resolve the ambiguities.

A smaller baseline for good ambiguity performance might be paired with a larger baseline for good height sensitivity.



In this antenna assembly, there are two dish antennas, but one is also used as an elevation monopulse antenna.

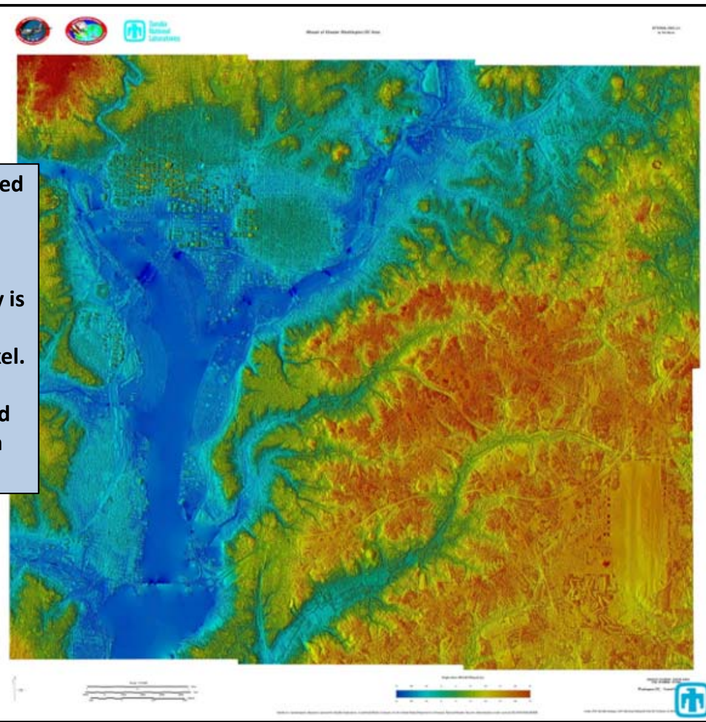
17

IFSAR

This is a color coded height map of Washington, DC.

Absolute accuracy is in the 1-2 meter range for each pixel.

Data was collected from about 10 km standoff range.

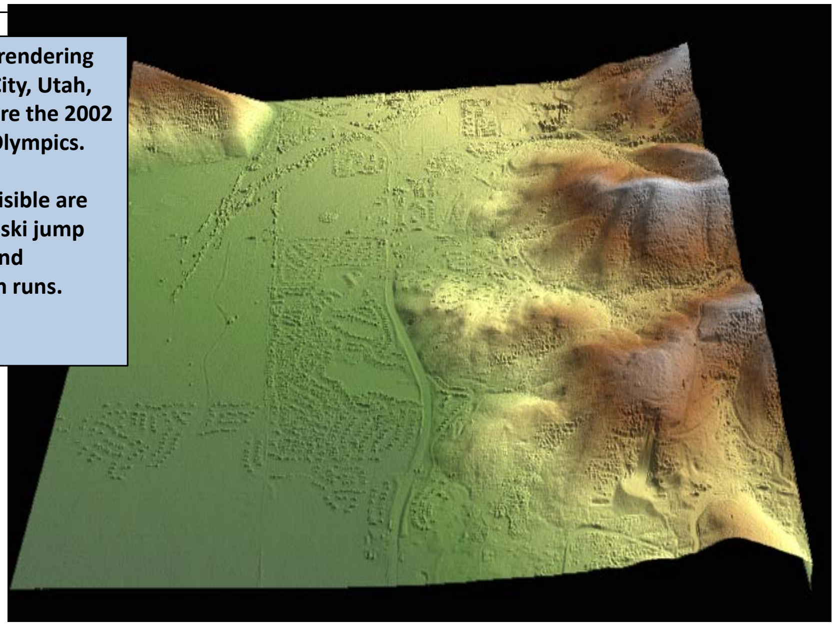


18

IFSAR

This is a rendering of Park City, Utah, just before the 2002 Winter Olympics.

Clearly visible are ski runs, ski jump venue, and toboggan runs.

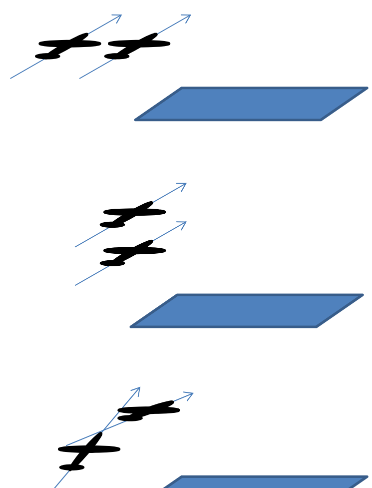


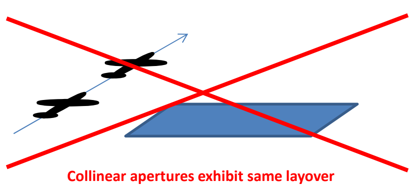
19

Stereo SAR

Consider two SAR images that exhibit different layover characteristics. The differences can be measured, and target height can be calculated from the amount of difference. This is stereo SAR.

The key is to form images with measurable displacement differences due to layover differences from different collection geometries.





20

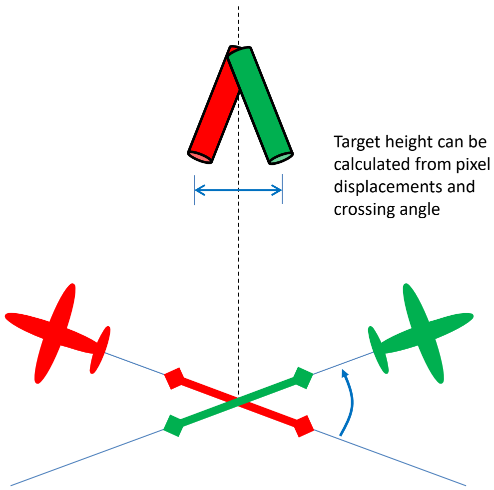
Stereo SAR

A problem with stereo SAR is that for corresponding distributed clutter pixels to be identified, the clutter needs to be coherent.

Consequently, both synthetic apertures need to have the same center.

But layover still needs to be different.

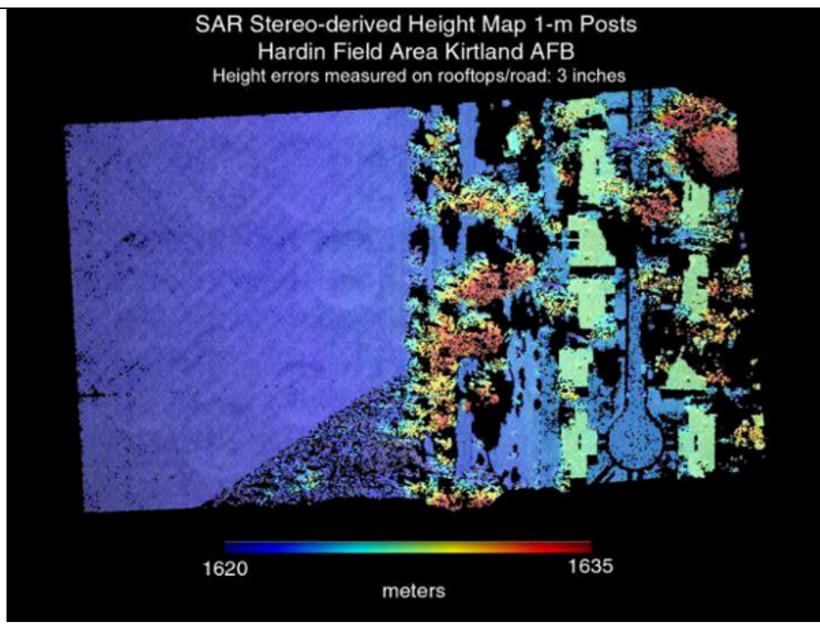
This leads to crossed-track collection geometries.



This is all because we want to correspond pixels.
Non-distributed clutter pixels may not need this.

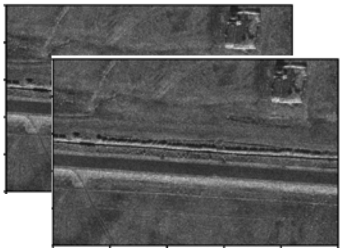
21

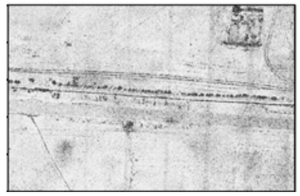
Stereo SAR



22

Coherent Change Detection (CCD)





Recall that if two images are in all respects identical, except for different collection times, then they will be coherent with each other.

Coherence is essentially the normalized cross-correlation coefficient between the two images.

$$r_{xy}(\tau)=\frac{|R_{xy}(\tau)|}{\sqrt{R_{xx}(\tau)R_{yy}(\tau)}}=\frac{\left|\int_{-\infty}^{\infty}x^*(t)y(t+\tau)dt\right|}{\sqrt{\int_{-\infty}^{\infty}x^*(t)x(t+\tau)dt\int_{-\infty}^{\infty}y^*(t)y(t+\tau)dt}}$$

For images, we calculate the coherence of pixel (m,n) using a local neighborhood of K points around the pixel

$$\mu(m,n)=\frac{\left|\sum_{k\in K}x_k^*y_k\right|}{\sqrt{\sum_{k\in K}x_k^*x_k\sum_{k\in K}y_k^*y_k}}$$

This is an estimate of the total coherence of pixel (m,n)

23

Coherent Change Detection (CCD)

Many things can affect coherence

$$\mu_{total}=\mu_{\text{geometry}}\mu_{\text{focus}}\mu_{\text{interpolation}}\mu_{\text{pol}}\mu_{\text{registration}}\mu_{\text{snr}}\mu_{\text{change}}$$

Collection geometry differences
Focus differences
Interpolation errors
Polarization differences
Registration errors
SNR due to uncorrelated noise

We want to control these to minimize their influence

Actual change between the image scene content

This is the one we are interested in

24

Coherent Change Detection (CCD)

- High SNR Geometry ← Typically a range issue
- Precise Repeat-Pass Collection Geometry ← Typically an aircraft pilot/autopilot issue. But also a Timing & Control issue
- Excellent Focusing ← Typically an autofocus quality issue
- Excellent Registration and Warping ← **Often the hard part, and made harder if the other factors aren't adequately dealt with**

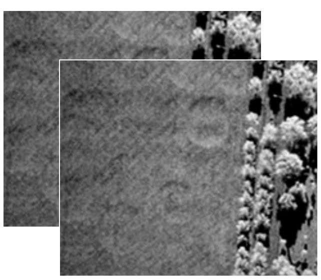
↓

Good results

Resolution requirements depend on the size of the changes that need to be detected.

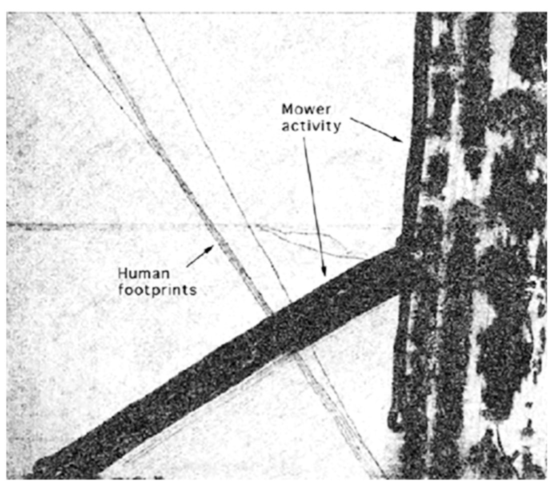
25

Coherent Change Detection (CCD)



Some apparent changes are natural and unavoidable (e.g. foliage, shadows, etc.)

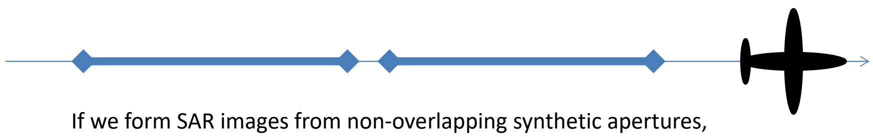
We are generally interested in those changes due to activities of interest, often human, but not always.



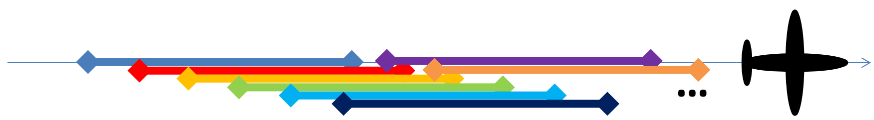
Ku-band, 4-inch resolution

26

VideoSAR



If we form SAR images from non-overlapping synthetic apertures, then the “image-rate” might be one in anywhere from seconds to perhaps minutes.



To increase the SAR image rate, we need to reuse collected data, essentially using overlapped synthetic apertures. Doing so allows us to make “movies” with frame rates of several images per second or more.

For examples, see http://www.sandia.gov/radar/video/index.html

VideoSAR

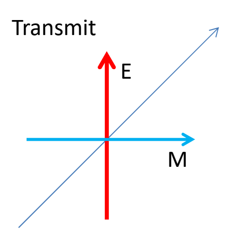
VideoSAR is particularly useful for tracking shadows.

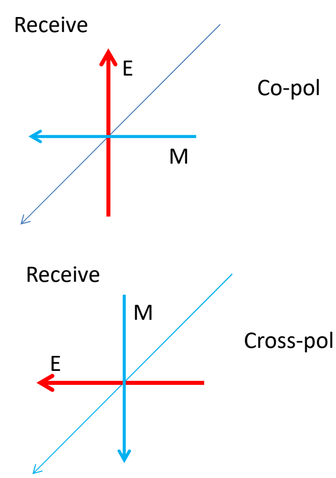
Shadows don’t exhibit Doppler shift, so there is no Minimum Detectable Velocity.

In the following video, note the vehicle shadows.

Kirtland AFB Eubank Gate

Polarimetric SAR





Some targets are polarization sensitive; they favor reflection of some polarizations over others.

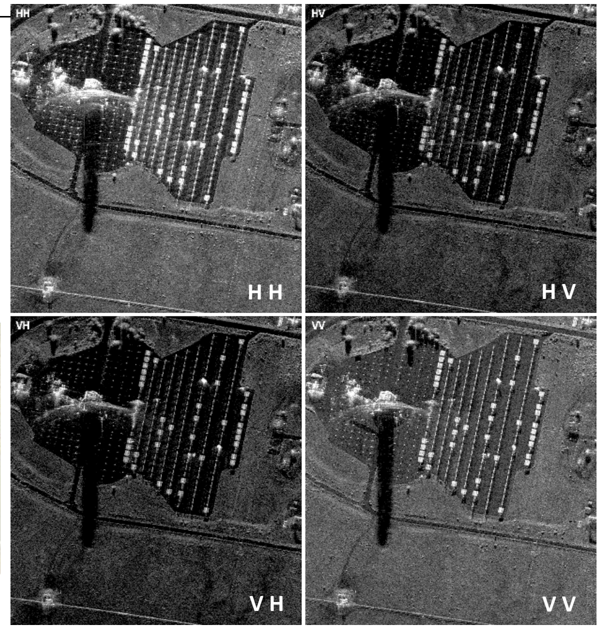
This can sometimes be exploited to understand the underlying scattering properties, and perhaps for target discrimination.

30

Polarimetric SAR

Sandia solar collection tower and Heliostat array.

(X-band, Polarimetric SAR)



31

Polarimetric SAR

It is often more convenient to display or otherwise render a function of the various polarimetric responses into a single image, using color as a display dimension.

These functions are often called "decompositions," and are chosen to feature specific attributes, like even/odd bounces, and polarization rotations.

One such decomposition is the Yamaguchi decomposition which assumes all scattering in a scene can be attributed to some combination of

1) Bragg rough surface scattering,
2) even bounce from orthogonal surfaces,
3) canopy (i.e. volumetric scattering), and
4) helical scattering.

Often only display these (items 1–3)

- Red: Even bounce
- Green: Volumetric
- Blue: Bragg Surface

32

Polarimetric SAR

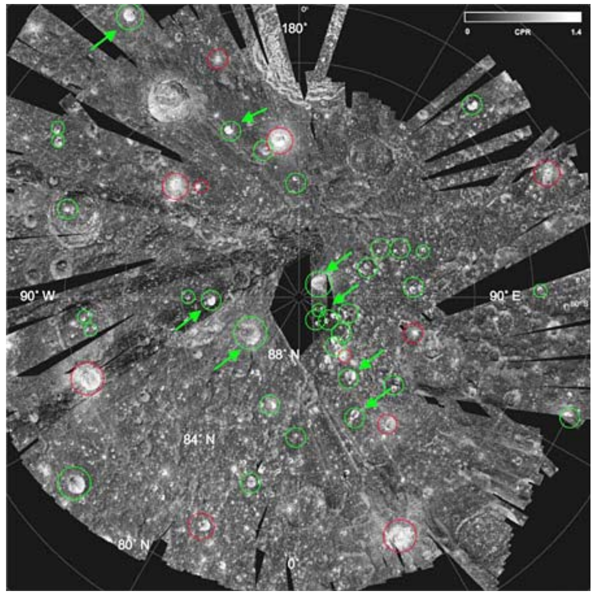
"Mini-SAR map of the Circular Polarization Ratio (CPR) of the north pole of the Moon. Fresh, "normal" craters (red circles) show high values of CPR inside and outside their rims.

This is consistent with the distribution of rocks and ejected blocks around fresh impact features, indicating that the high CPR here is surface scattering.

The "anomalous" craters (green circles) have high CPR within, but not outside their rims. Their interiors are also in permanent sun shadow.

These relations are consistent with the high CPR in this case being caused by water ice, which is only stable in the polar dark cold traps. We estimate over 600 million cubic meters (1 cubic meter = 1 metric ton) of water in these features."

-- NASA



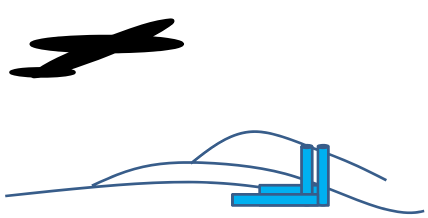
Courtesy NASA

33

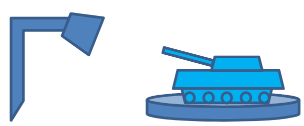
Inverse SAR (ISAR)

SAR usually assumes that the relative motion between target and radar is known, at least to some bound on error, often the range resolution of the radar.

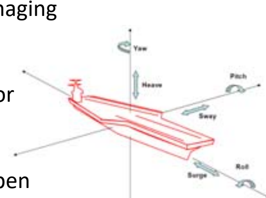
Typically the ground target scene is stationary, and only radar position/motion needs to me measured.



Inverse SAR originally meant that the radar was stationary and the relative motion was all in the target. An example was a turntable that allowed aspect changes with a pole-mounted radar.



More recently, ISAR has come to mean any range-Doppler imaging where the target exhibits motion, whether known or otherwise. An example is a ship moving on the open ocean.



34

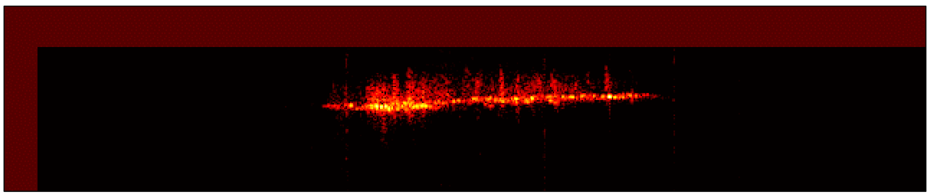
Inverse SAR (ISAR)

In this case, the ship's own motion provides the perspective change to allow resolution of scattering centers.

Unlike SAR, the radar's own motion is incidental; not required. Consequently, the radar can image forward of the aircraft flight path.

Doppler

range

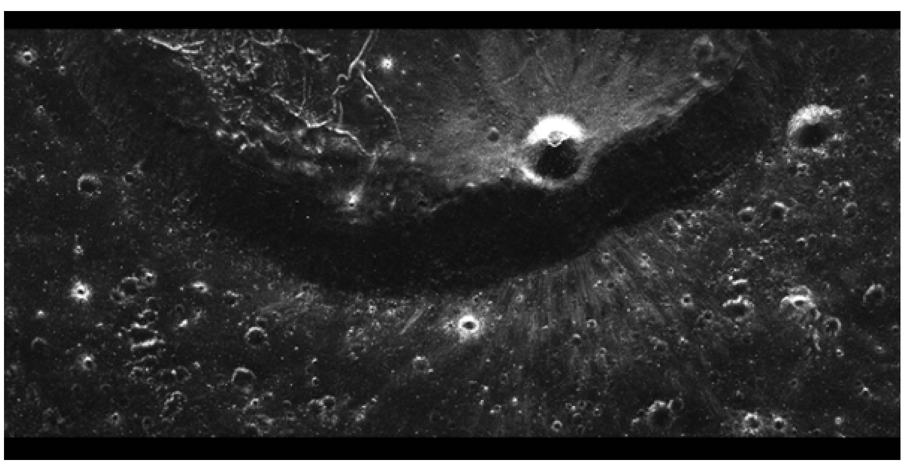


Courtesy General Atomics, ASI, Inc.

35

Bistatic SAR

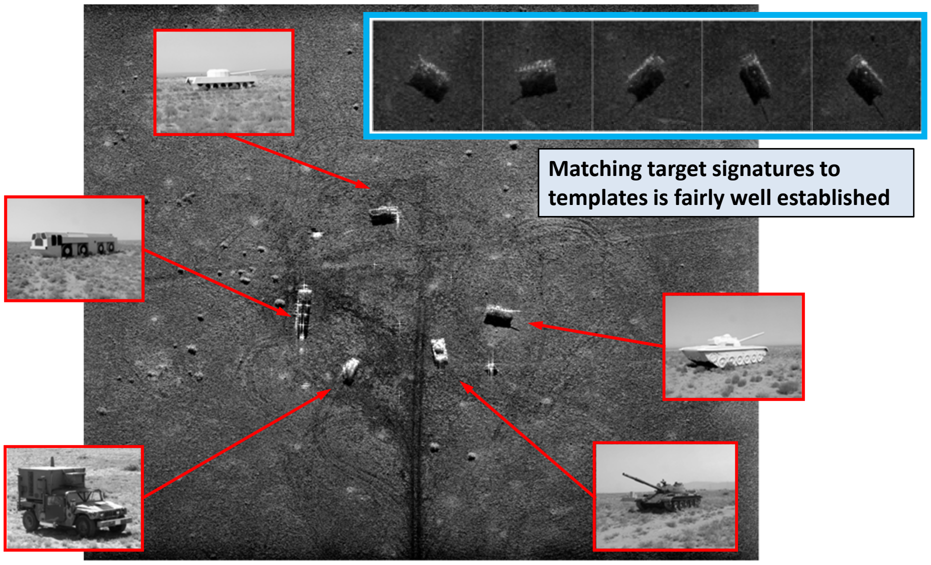
Until now we have discussed monostatic configurations, where TX and RX antennas were collocated. SAR images can be formed with TX and RX antennas substantially separated.



Bistatic Synthetic Aperture Radar (SAR) image from Sandia's Mini-RF on board the Lunar Reconnaissance Orbiter (LRO), using earth-based TX and orbital RX.

36

Automatic Target Recognition (ATR)



A Note About SAR Command and Control

SAR systems are often just one component of a larger sensor suite; operated by a "sensor operator" typically responsible for more than just the SAR.

It is critical to not neglect the User Command and Control (C2) Interface.

If the SAR is difficult to use, or its use otherwise handicaps the sensor operator, then it will never be turned on, and just becomes "dead weight" to the platform. Exploitation will never happen.

If you want your sensor to be used, it needs to be 'easy' to use.

Section Summary

- After image formation, there are a variety of post-processing techniques that might improve the utility of the SAR image
- The usual measure of 'goodness' for the focus of a SAR image is the Impulse Response (IPR)
  - Can be measured in the laboratory with a delay line
  - Can be measured in flight with canonical reflector array
- One or more SAR images might be exploited to reap substantial additional information
  - E.g. topographical maps, change detection, video sequences, polarimetric analysis, etc.

39

Select References

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40

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41