SAR resolution/corrections, InSAR
November 15, 2023

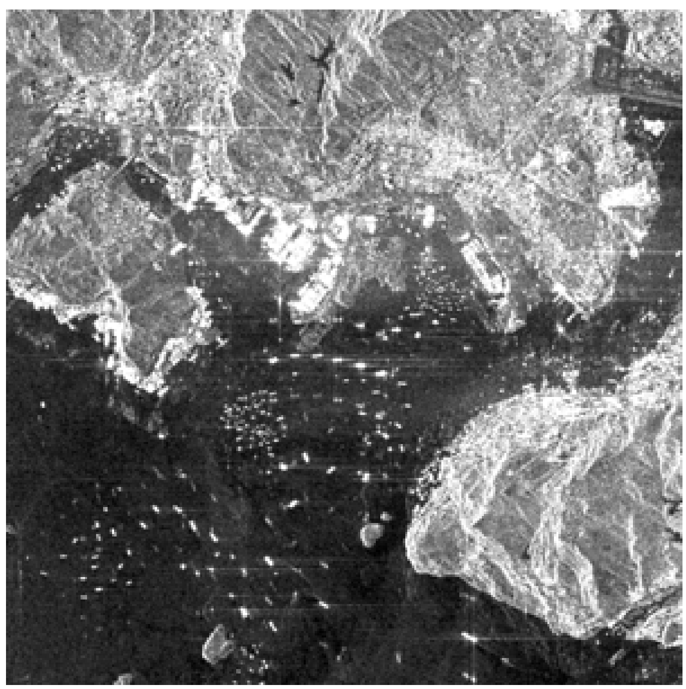
I. Class Reminders

- **the write-up for lab #3 is due after Thanksgiving *(Nov. 29th by 6pm)***
  - please be on time and make sure that when you email your report that it is actually sent *(and not stuck in your outbox)*
  - points are taken off immediately once the report is late *(no excuses)*

- we will have a standard lecture tonight and on the 29th
- no class next week for Thanksgiving
- the last lecture on Dec. 6th will only be for the first hour or so followed by the graduate student presentations
- ***your Final Projects are due on Friday Dec. 8th by 6pm!***
- finally, if you want to see/go over your exam, please come to office hours

II. Radar Operation

- details
  - large antenna needed - *see why this is the case later*
  - beam pulse transmitted to surface
    - illuminates a narrow strip of land
  - returned energy (aka, backscatter) is received by the antenna and the timing logged
    - energy only returned if the surface is "rough" compared to the wavelength
    - "corner reflector" is an object on the surface with a certain geometry with respect to the incident energy that returns nearly 100% of the energy to the antenna



X-band radar of Hong Kong *(note: corner the reflectors)*

- geometry
  - near-range is received first (shorter travel time) and then the far-range
  - <u>major point:</u> all backscatter within any given zone of the swath width <u>parallel</u> to the azimuth (flight) direction is received at the same time!!
    - no way to resolve features within this strip *(this is the azimuth resolution in simple RAR images)*

- range direction
  - determines the position from a measurement of the travel time from the antenna to the surface *(assuming a fixed depression angle)*

$$\boldsymbol{R_g = R_s \cdot \cos\theta}$$

  - where, R_s = slant range distance and θ = depression angle
    - *remember your geometry of right triangles!*

  - slant range distance is a function of the travel time (speed of light, c):

$$\boldsymbol{R_s = \frac{c \cdot \tau_o}{2}}$$

  - therefore,

$$\boldsymbol{R_g = \frac{c \cdot \tau_o}{2} \cdot \cos\theta}$$

  - range resolution *(direction perpendicular to the flight direction)*
    - *the ability to distinguish between two objects in the range direction of the radar return*
    - only can happen if the received pulse from the object closest to the antenna ends before the returned pulse of the far-range object begins
    - can be defined in terms of the pulse duration and the ground range distance:

$$\boldsymbol{r_r = \frac{c \cdot \tau_o}{2\cos\theta}}$$

    - therefore, shorter pulse duration and smaller depression angles result in better range resolution
    - common pulse duration (τ) = 0.05 – 0.3 μsec → r_r = 8 – 25 m
    - however, there is a tradeoff:
      - small depression angles produce larger radar shadows
      - short pulse durations result in less return and more noise

    - so, what happens to range resolution in the near vs. the far range??
      - range resolution gets <u>*better*</u> in the far range *(sounds counterintuitive?)*
      - *example:* τ = 0.1 μsec, and θ_{near} = 50° and θ_{far} = 35°
      - r_r (near) = 23.4m / r_r (far) = 18.3m

        - therefore, an object 20m in length in the range direction, will be resolved in the far range, but will not be resolved in the near range

    - how to compensate??
        - decrease the pulse length
            - problem: lower the returned signal, increase noise

        - decrease the depression angle
            - problem: increase the shadows

- azimuth resolution *(direction parallel to the flight direction)*
    - already mentioned that the azimuth resolution equals the swath width
        - this is true for RAR systems only!

    - real aperture radar (RAR)
        - simpler design -- one pulse sent, one received
        - very coarse resolution

$$r_a = \frac{0.7\,\lambda \cdot R_s}{D}$$

            - the 0.7 term is a factor included which accounts for the elliptical footprint of the beam spot on the surface

        - therefore, azimuth resolution gets *worse* in the far range
        - *example:* D = 5m, imaging with L band, R_s (near) = 10km, R_s (far) = 15km
            - r_a (near) = 329m / r_a (far) = 493.5m

            - therefore, an object 400m in length in the azimuth direction, will be resolved in the near range, but will not be resolved in the far range

        - how can you improve r_a ??
            - decrease the wavelength
            - increase the antenna length
            - decrease the slant range distance
                - varies from near to far-range

            - best resolution achieved with commercial systems in the 90s and early 2000s = 15-60m
            - now, better processing and larger antennas allow sub-5 m SAR data to be acquired

    - synthetic aperture radar (SAR)
        - is way "around" the RAR limitation by using the motion of the plane *(artificially enlarge the antenna length)*
        - uses the principle of Doppler shift to track the motion of objects in the azimuth direction through successive, overlapping pulses

- objects in the near range are observed for shorter times than those in the far-range
- synthesized beam is much narrower than the original swath width azimuth resolution can be decreased to just a few meters!

- summary:
  - for a given radar pulse
    - near range (closer to the nadir point)
      - R_s is smaller, θ is larger, r_r is worse, r_a is better

    - far range (further from the nadir point)
      - R_s is larger, θ is smaller, r_r is better, r_a is worse

III. Geometric Distortions

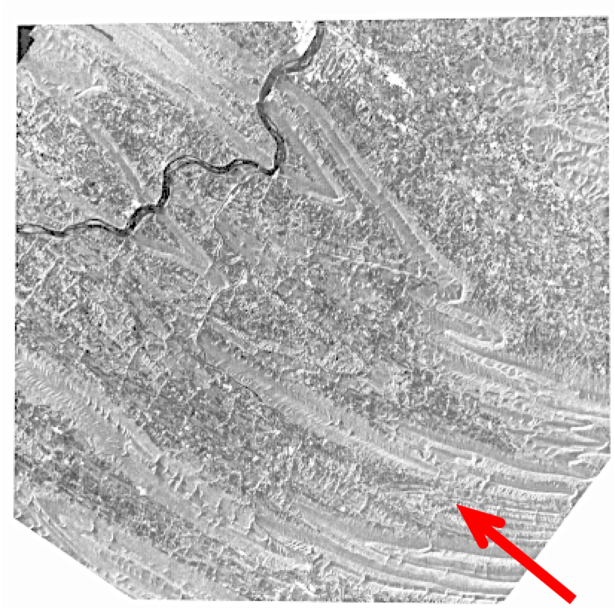
- background
  - recall that all radar image data is recorded as a function of signal strength (backscatter) and timing
  - as such it is measured in the slant range direction (R_s)
  - must be re-projected onto the ground range direction (R_g) in order to create an interpretable image
  - done through the following, knowing the altitude (H) and depression angle (θ) for every pixel:

$$\boldsymbol{R_g = H\sqrt{\left(\frac{1}{\sin^2\theta} - 1\right)}}$$

  - this is for projection onto a flat plane
    - what about local topography??

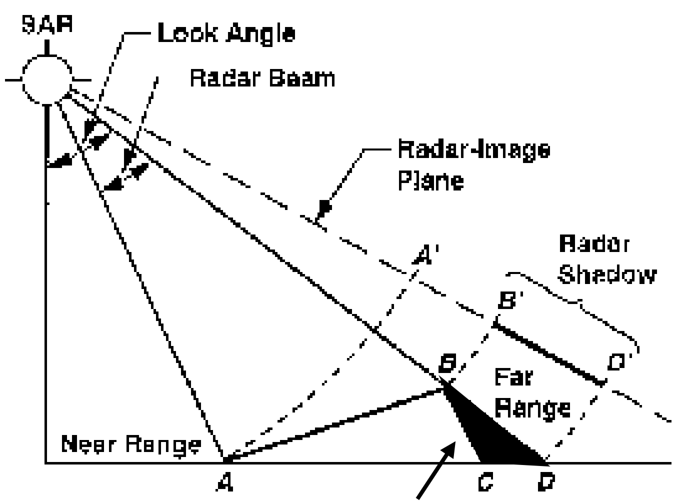
- illumination (look) direction
  - same principle as solar reflected region of the spectrum
    - accentuates linear features that are at an angle offset from the illumination
    - advantage over terrains with differences in orientation of mountain ridges, fault valleys, etc.

  - depends on the orientation of those features with respect to the look direction
    - generally, not a large geometric distortion
    - may misinterpret data or make it impossible to identify key topographic targets

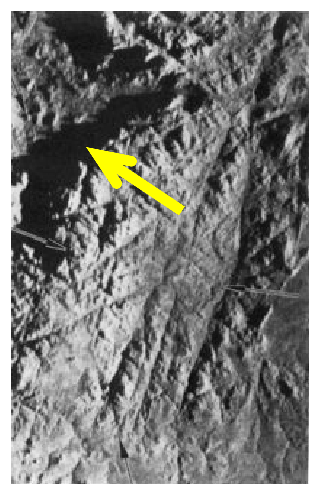


plunging folds *(look dir = NW)* **same scene *(look dir = S)***

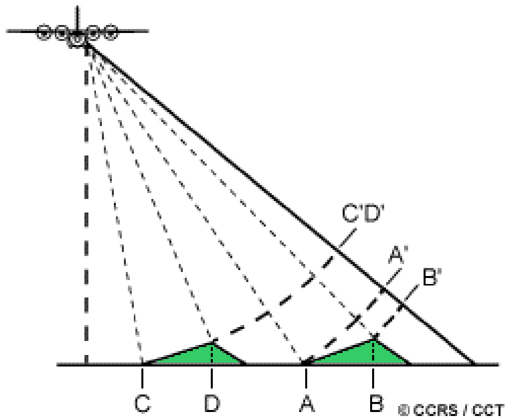
- shadows
  - same principle as solar reflected region of the spectrum
  - steep topography blocks incident energy
  - no return from regions in shadow → data loss
  - shadows become worse with smaller depression angles
  - *example:* $\theta_{SeaSat} = 70°$ / $\theta_{SIR\text{-}A} = 40°$

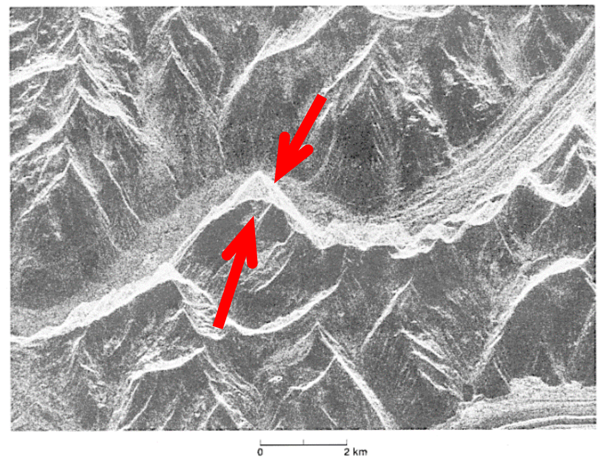


radar shadow



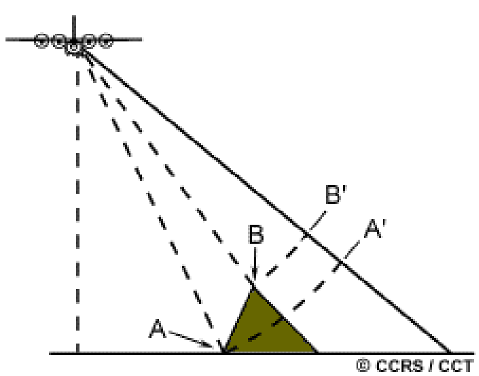
- foreshortening
  - occurs in uneven terrain
  - width of ground objects appears to increase toward the far range
  - elevated points are displaced toward the antenna
    - leads to a return from the <u>bottom</u> of the feature prior to the top
    - the illuminated slope lengths (top to bottom) will appear to decrease
    - eventually to a length of zero in the worse case scenario (C – D) below





- lay-over
    - also occurs in uneven terrain, related to foreshortening
    - leads to a return from the <u>top</u> of the feature prior to the base
        - <u>foreshortening:</u> the radar wave front is steeper than the slope angles
        - <u>lay-over:</u> the slope angle is steeper than the wave front

    - both are very hard to correct (especially in extreme topography)
    - also a data loss
        - example: inter-glacial ridges are laid over toward the antenna (therefore the look direction can be inferred to be from the left)



IV. Interferometric SAR (InSAR)

- *we will only touch on the next few topics*
  - *the material can get very involved*
  - *I go over more details in the Applied Remote Sensing course*

- capability
  - 2-dimensional wide-area, all-weather radar imaging used to create 1-2 cm vertical accuracy for deformation mapping under favorable conditions

- applications
  - used to study processes such as:
    - earthquakes, volcanoes, glacier flow, landslides, and ground subsidence

- disadvantages
  - temporal decorrelation of ground surface due to dense vegetation and other environmental changes
  - atmospheric delay anomalies

- solutions
  - observations from independent images
  - interferometric permanent scattering technique
  - longer wavelength radar
  - shorter revisit cycle

- basic principle:
  - combine two or more SAR images of the same area
  - use them to detect change
    - elevation → DEM's
    - surface change maps

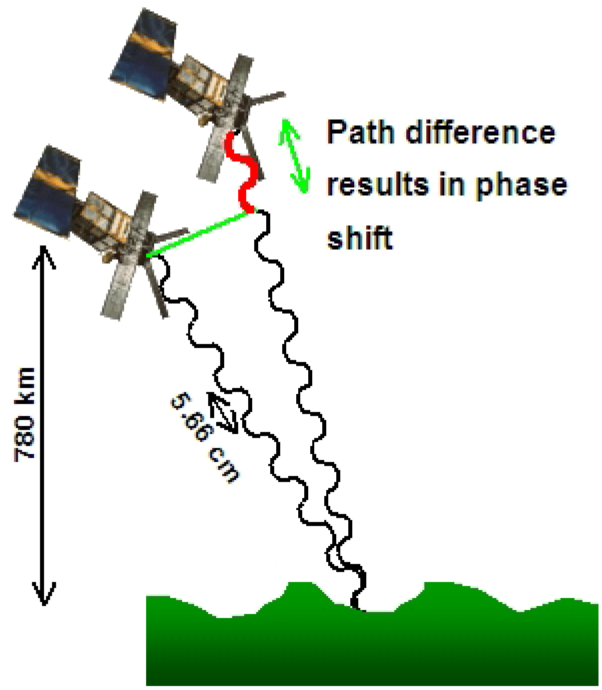
- principles of InSAR
  - measure the phase change in the returned signal from the surface
    - example: if the ground subsided 5 cm in the time between the C-band SAR images were acquired
      - the radar wave travels two more complete wavelengths before returned to the antenna
      - travel time is doubled
      - phase is altered

  - sensitivity to ground displacement is ~1000's times greater than the sensitivity to topography
    - displacement detection of ~mm's is possible

- difference between to precisely registered SAR images produces an interferogram image
  - interferometric fringes depict variations of the antenna to ground path length difference between the two images

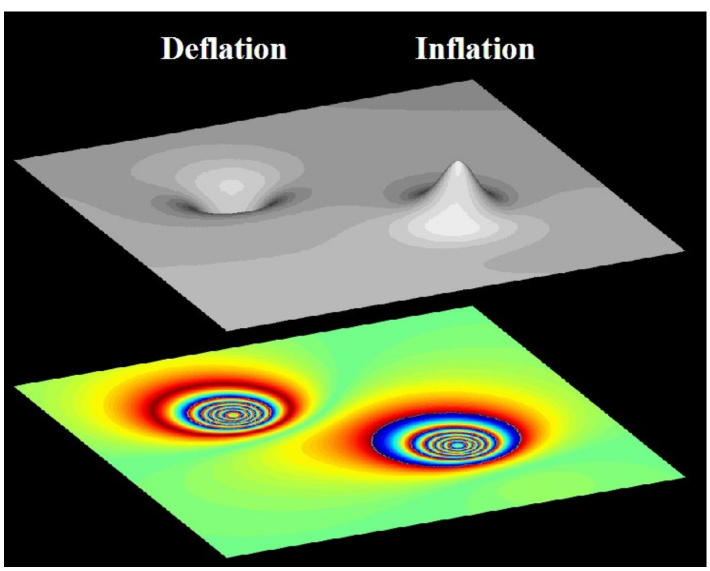
- need at least 2 images of the same area
  - from same satellite/air-craft with different overpass times
    - "repeat-pass interferometry"

  - from same satellite/air-craft with 2 different antennas

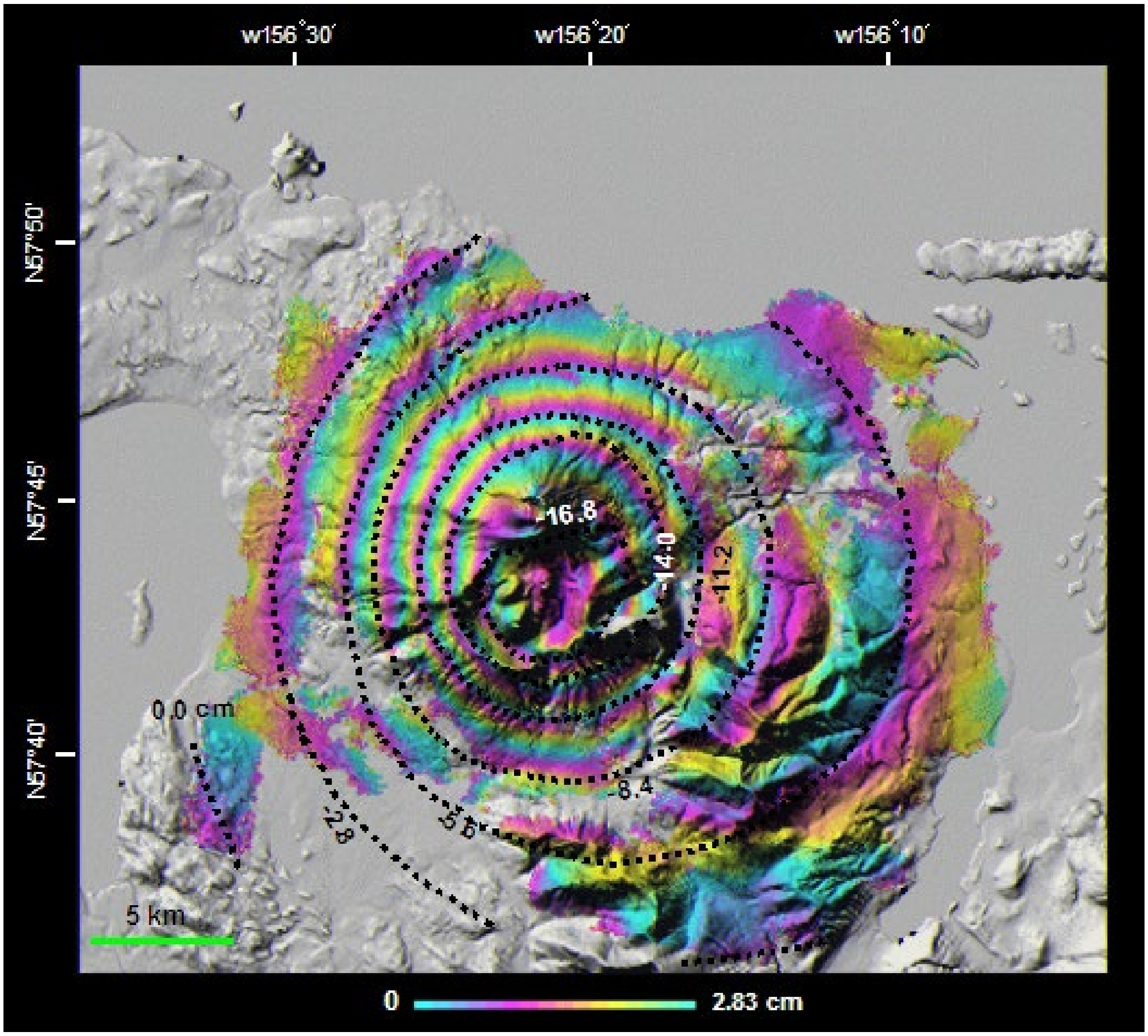


- fringe patterns in interferograms
  - one color cycle from blue to red = change of 1/2 wavelength
  - sense of displacement from the color order
  - R → B
    - surface moving away the sensor *(deflation)*

  - B → R
    - surface moving toward the sensor *(inflation)*



(click on this image to view the animated gif that I will talk about in class)



Example of a deflationary interferogram at a volcano