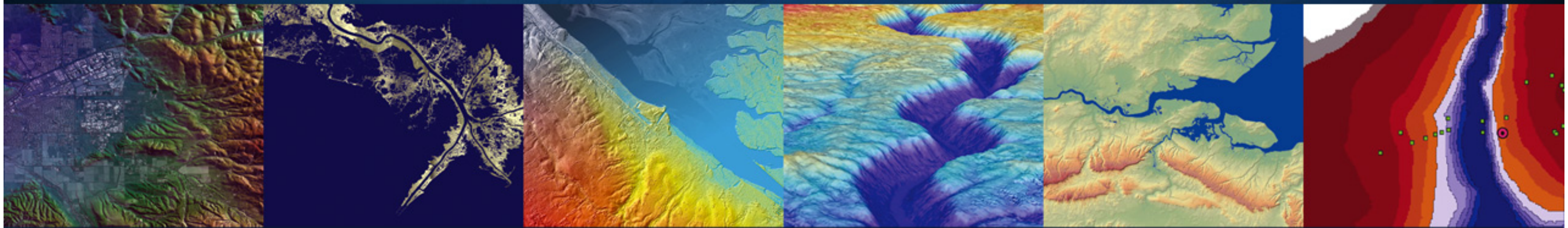
INTERMAP TECHNOLOGIES

ATLASTECH GEO-SOLUTIONS



Interferometric Synthetic Aperture Radar

Universitá IUAV di Venezia

Dottorato di Ricerca NT&ITA

Nuove Tecnologie & Informazione Territorio & Ambiente

VENEZIA, 12 Novembre 2009

www.intermap.com

PROGRAMMA

- **IFSAR Fundamentals**
- **Existing SAR Platforms (Satellite & Airborne)**
- *Coffee Break*
- **IFSAR NEXTMap Products**
- **DTM Editing Rules**
- **Validations**
- **Applications**
- **Case Studies**

IFSAR Fundamentals

- IFSAR Theory
- Interferometric Processing
- IFSAR Products
- Radar Phenomenology

Relevant Terms

SAR

- **SAR** is an acronym that stands for **S**ynthetic **A**perture **R**adar, which is a spacecraft/airborne radar that looks out to the side to collect a radar image

RADAR

- **RADAR** is an acronym for **Ra**dio **D**etection **A**nd **R**anging: which in basically describes how a radar system works

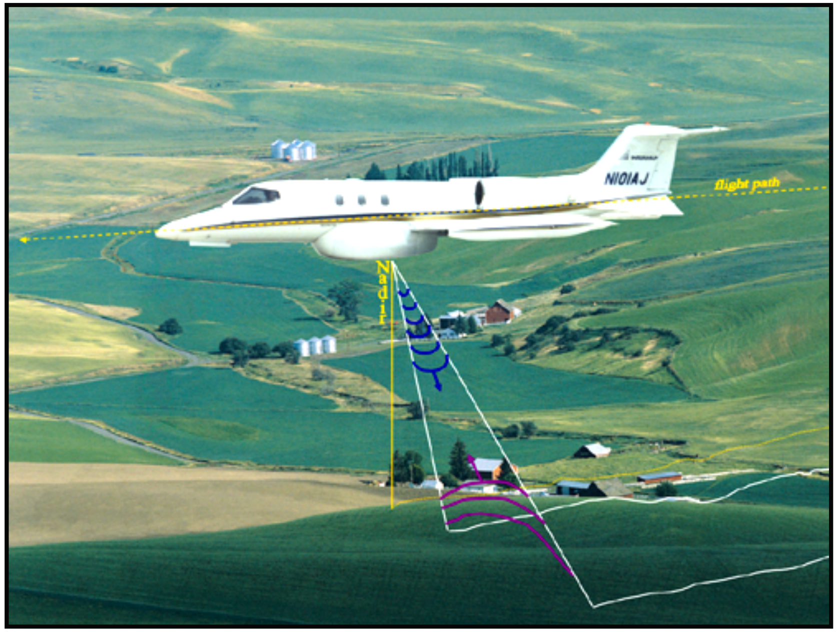
IFSAR

- **IFSAR** is an acronym that stands for **I**nter**f**erometric **SAR:** which is a powerful application technique developed in recent years to generate high-resolution digital data consisting of a Digital Elevation Model (DEM) and an orthorectified radar image

Basic Concept of SAR

- SAR systems transmit their own radiation in the form of **microwave pulses** (**radio**), out the side towards the terrain

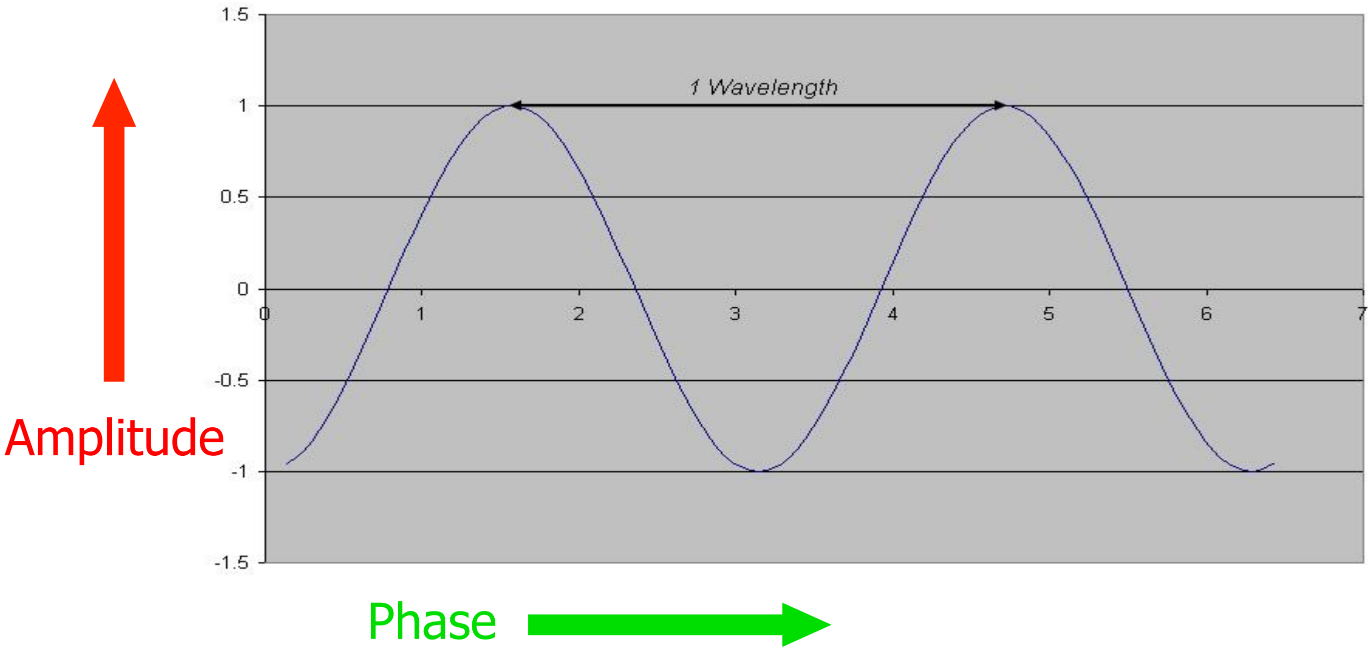
- A SAR sensor records two things:
  - the strength of the transmitted energy reflected back towards the sensor (**AMPLITUDE**)
  - the time delay (**PHASE**) of the return signals, or how long it takes the SAR signal to leave the sensor, interact with the terrain, and return back to the recorder



Waves

- Figure 11 below, shows a typical wave. One wavelength is defined as the distance between two adjacent points on the wave that have the same slope. In this case, the measurement is taken from the tops of two adjacent crests. In the case of X-band radar, a wavelength is about three centimeters, or just over one inch.

- In this figure, the vertical axis shows the amplitude of the wave, time or phase or distance could be represented on the horizontal axis.



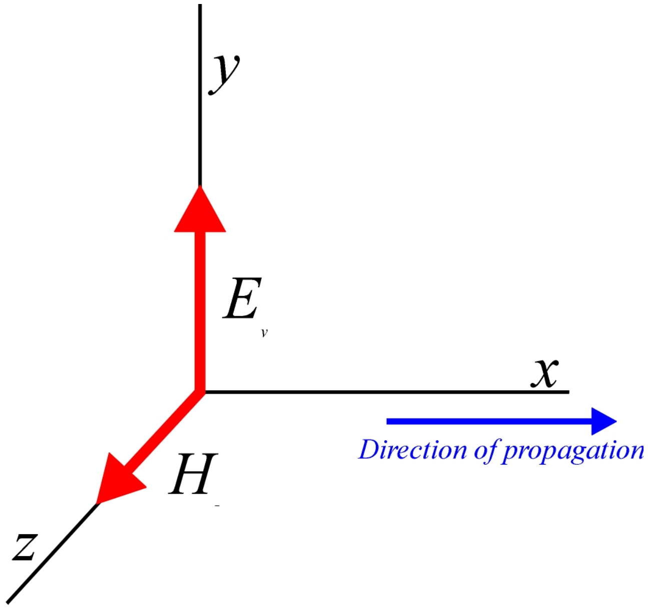
Electromagnetic Wave

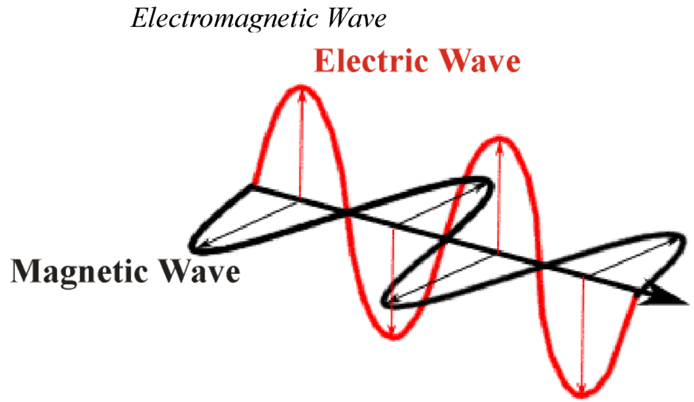
- Electromagnetic (EM) wave is propagated through empty space at the speed of light.

- The crests and troughs of the EM wave emitted follow a sinusoidal pattern.

- Electric and magnetic waves are at right angles and perpendicular to the direction of propagation.

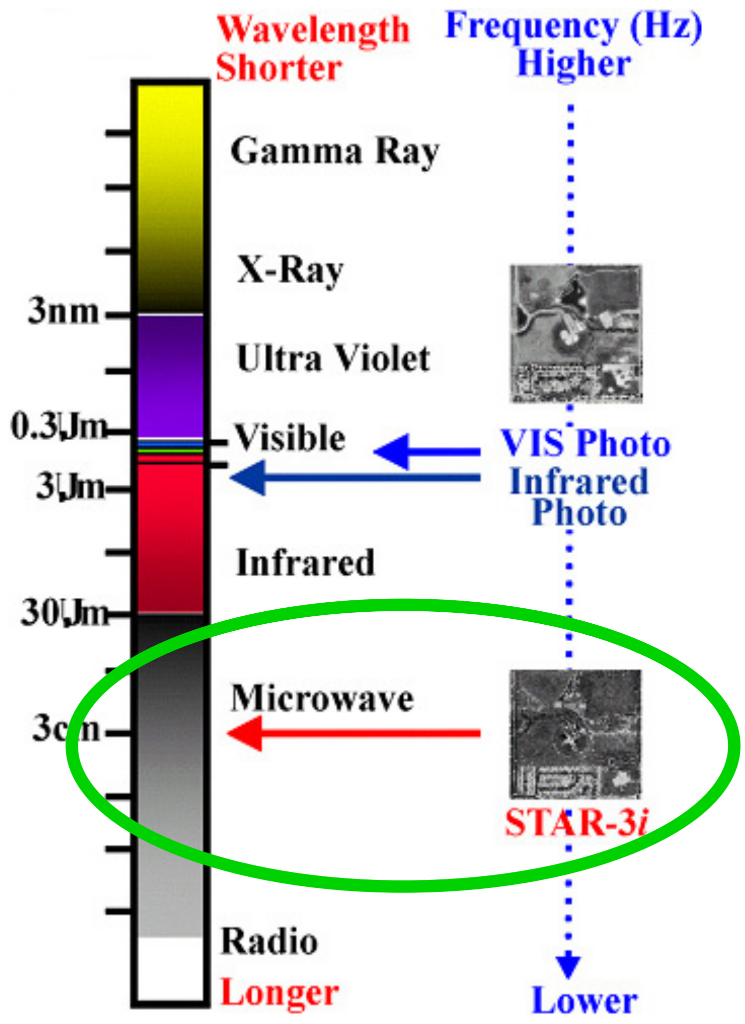
- EM is sensitive to moisture content and structure of the object being imaged





Radar Wavelength

- **Radar systems** operate with energy from the microwave portion of the electromagnetic spectrum.
- **Photo systems** operate with energy from the visible & infrared portions of the electromagnetic spectrum.
- Our eyes do not see at microwave wavelengths.
- Radar systems can not see detail like the eye nor can it recognize the “color” of objects to the degree of sophistication of which the eye is capable
- Unaffected by haze or cloud.

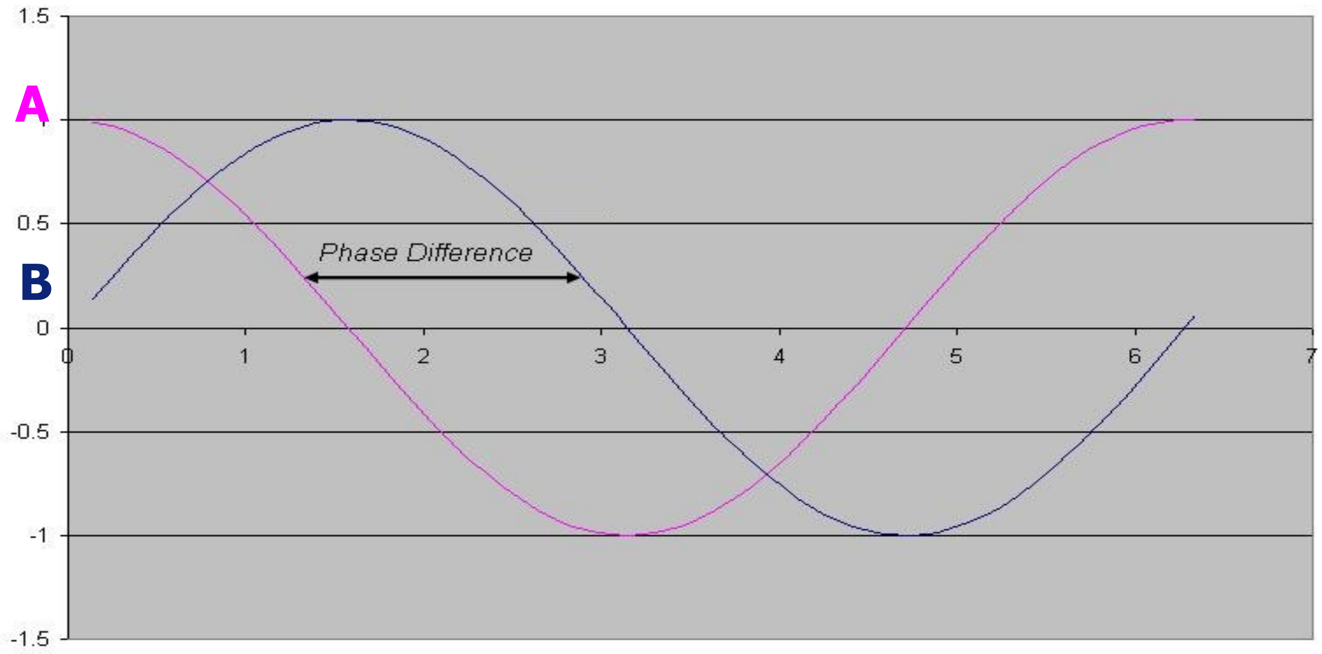


Interferometry Defined

- Interferometric SAR is a technique which uses the relative phase difference between two coherent SAR images, obtained by two antennae separated by an across track baseline, to derive an estimate of the surface height (Tennant, 1998).
  - Interferometry measures the phase difference between corresponding pixels in the two images as a measure of the path difference from the pixel to each antenna.
  - The displaced synthetic apertures provide an interferometric baseline from which the elevation measurement of each pixel may be made.
  - The technique produces the powerful combination of SAR imaging with co-registered height data.

Phase Differences

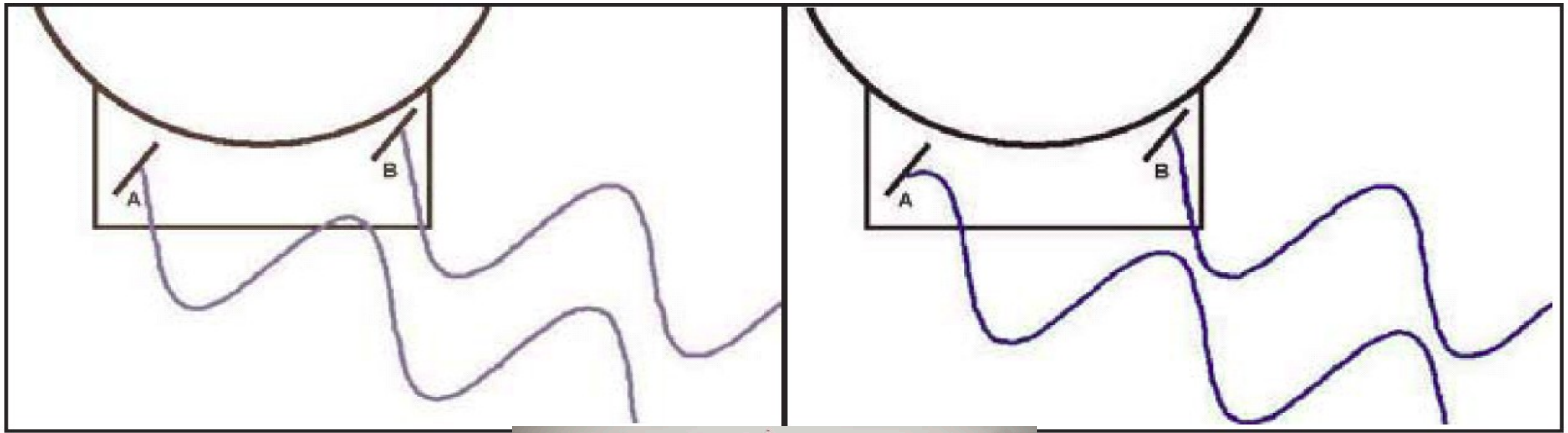
- The waves recorded at each antenna do not always overlap each other exactly, as shown in Figure 12, and are said to be *out of phase* by some amount.



  - This is known as the Phase Difference.

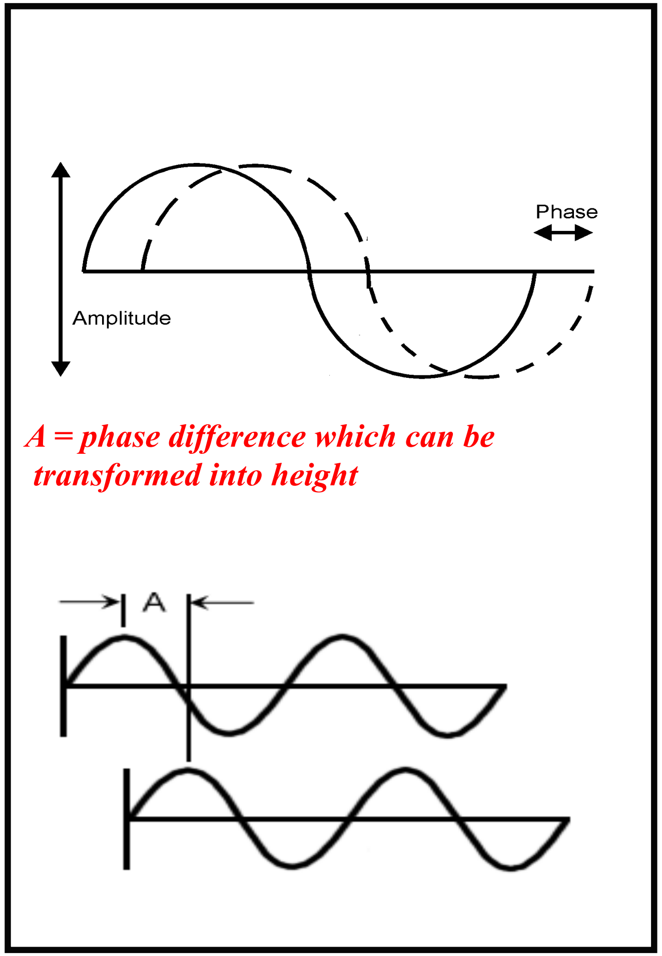
Phase Difference

- This illustration shows two cut away views of the antennas in the *radome* under the fuselage of the aircraft.



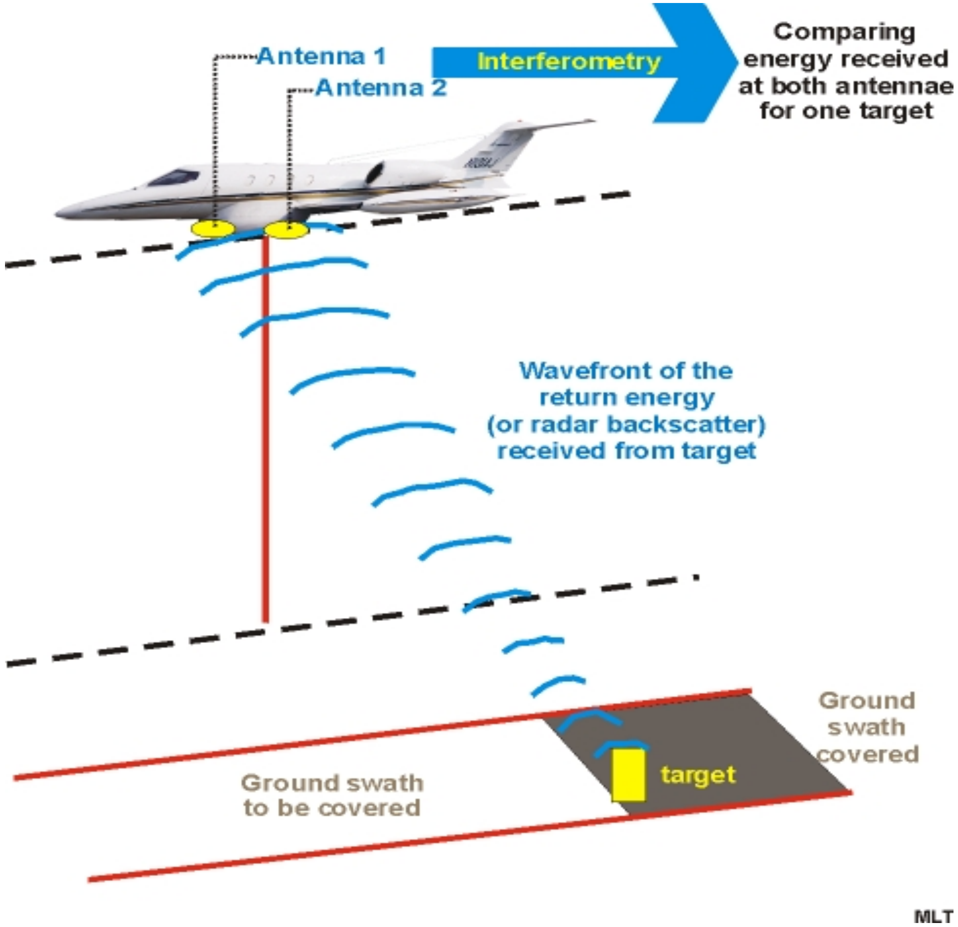
IFSAR Requires Coherent Radiation

- To detect small shifts of returned energy requires very precise measurement of the phase of the returned signal
  - propagation phase delay is simply a measure of time
  - this phase is measured relative to the transmitted signal
  - to do this, all signals must be related to the same time base or be coherent
- Phase change is the key to interferometry, the measured phase difference (A) can be transformed into height.



Measuring Phase

- Digital elevation information about the Earth's surface is derived from the phase content of the radar signal.
- The basic idea is that the height of a point on the Earth surface can be reconstructed from the phase difference between two signals arriving at two antenna.
- Phase difference is directly related to the difference in path lengths traversed by the signal between the point on the Earth surface and the two antennae.



ATLASTECH GEO-SOLUTIONS

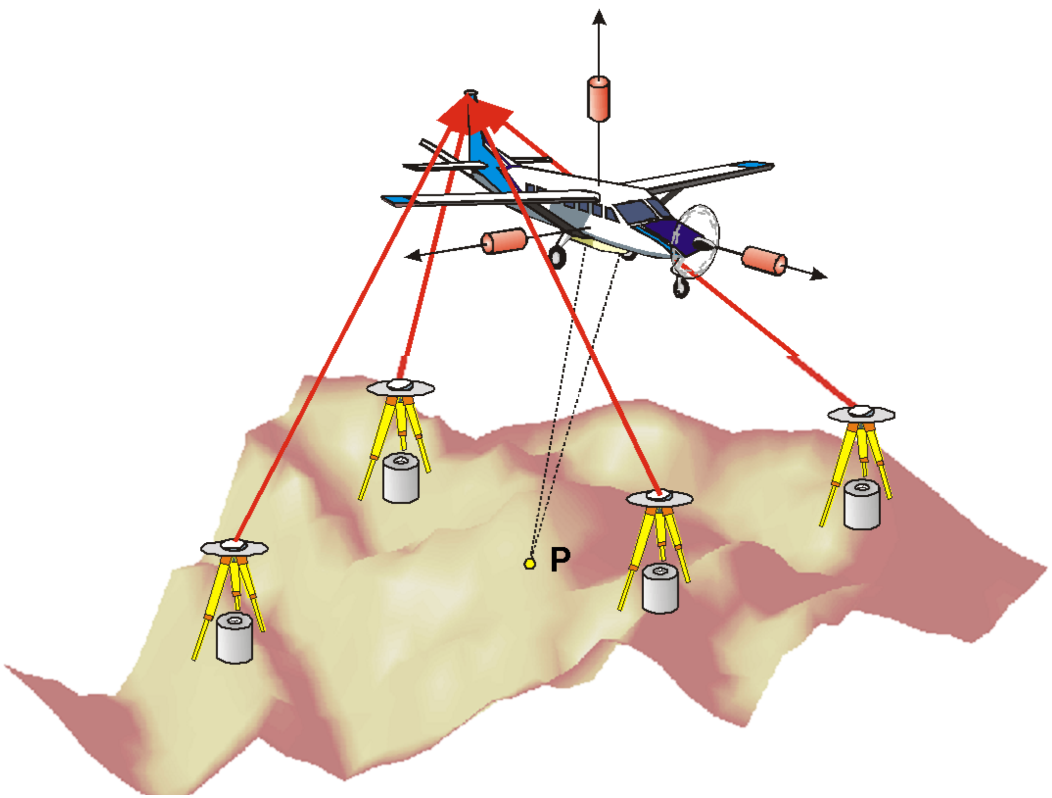
INTERMAP™ TECHNOLOGIES

Position of Platform

- Commercial IFSAR is made possible due to the technology advances in precise positioning equipment.

- If the positions of the antennae are known accurately (DGPS & IMU) then the path difference can be used to infer the position (height) of the target point on the Earth surface.

- The phase differences can be measured to the millimeter level.

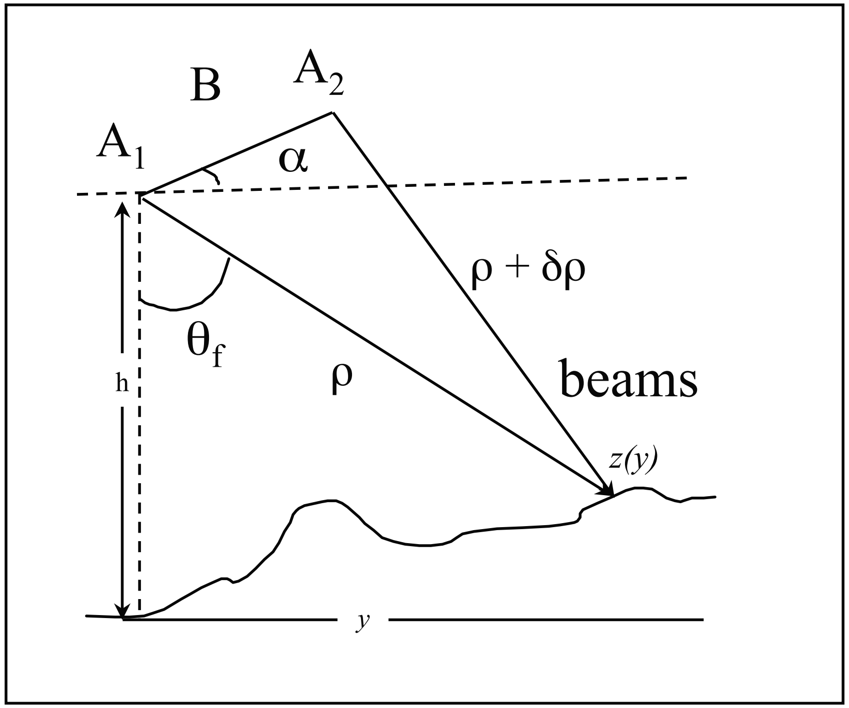


IFSAR Processor to Derive Height Measurements

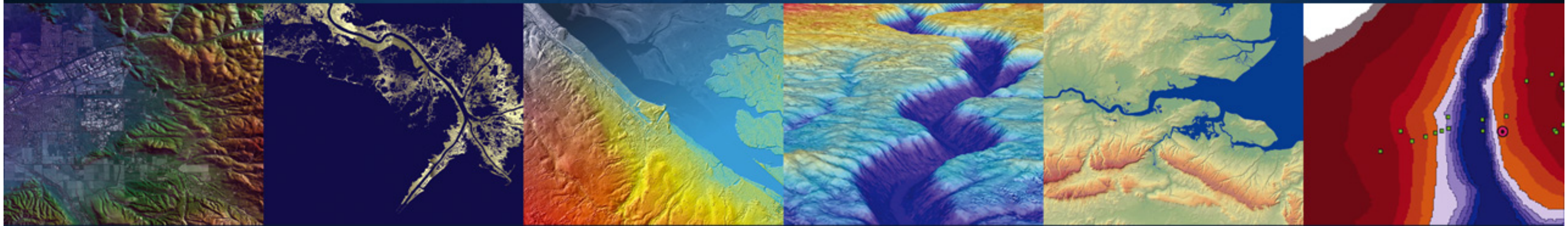
- The variation in phase difference from pixel to pixel can be converted into relative change in surface elevation through a set of (closed form) equations to yield x, y, and z.

$$z(y) = h - \left\{ \frac{\delta\rho^2 - B^2}{2\rho B \sin(\alpha - \theta) - 2\delta\rho} \right\} \cos(\theta)$$

A	Position of antenna 1
A	Position of antenna 2
ρ	Distance to target
δρ	Phase difference
B	Baseline
α	Angle of baseline w.r.t. Flight path
A	Altitude of aircraft
h	Height above the ground
z(y)	Position of target



INTERMAP TECHNOLOGIES

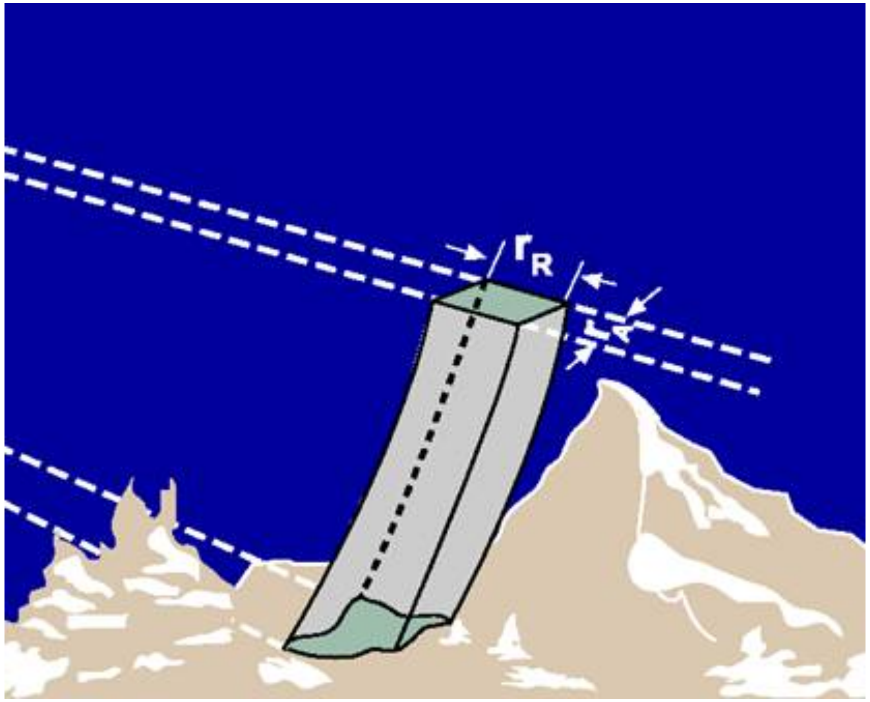


Radar Resolution

www.intermap.com

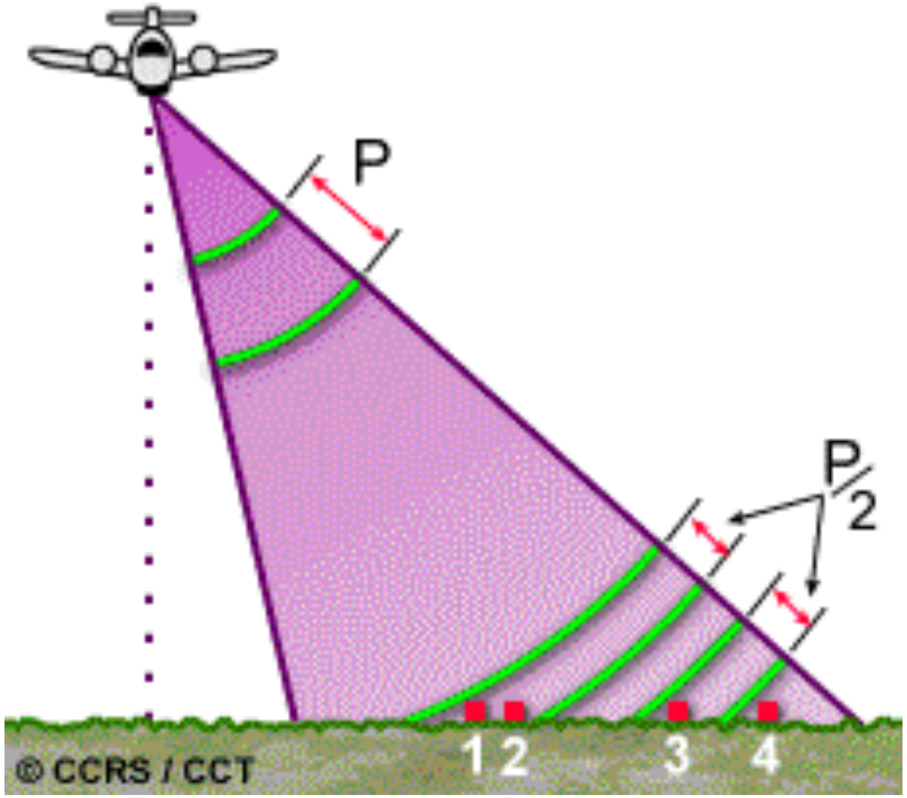
Radar Resolution

- Resolution is the ability of a sensor to distinguish two closely spaced objects as two rather than one object or line.
- Radar resolution is defined in two dimensions: range and azimuth.
- Range Resolution ($\mathbf{r_R}$)
  - Across-track direction, perpendicular to the direction of travel, in the direction of energy propagation.
  - Shorter pulses yield higher resolution.
- Azimuth Resolution ($\mathbf{r_A}$)
  - Along track direction, parallel with the direction of travel.
  - Higher resolution requires a long antenna.



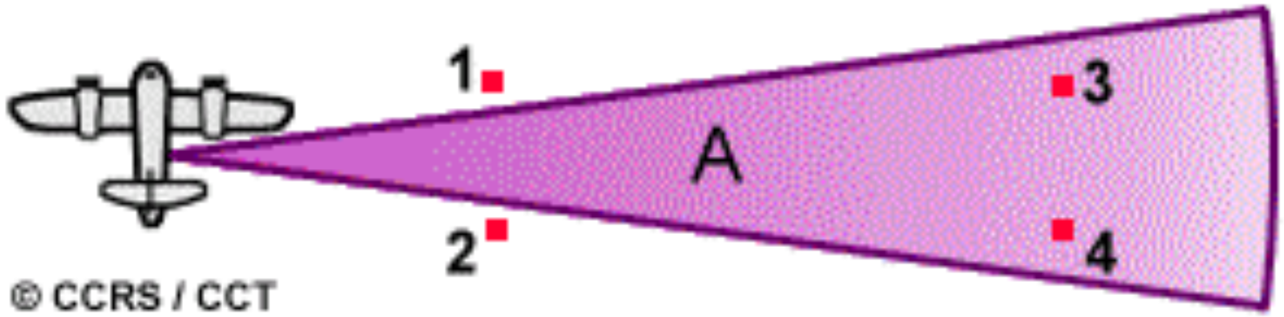
Range Resolution

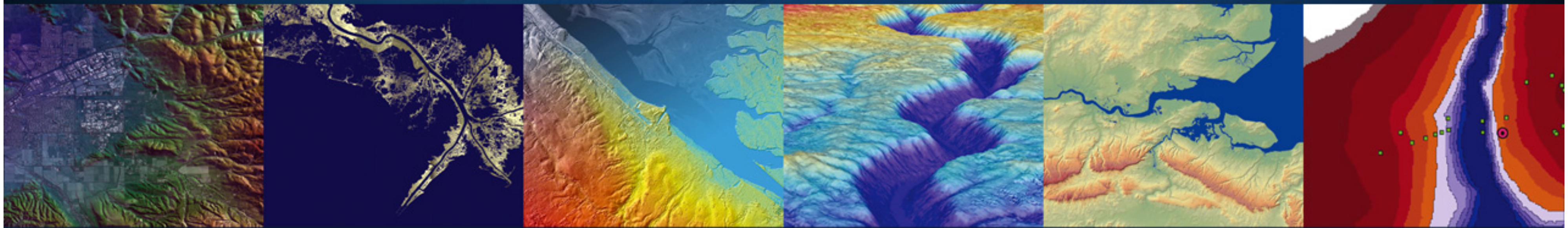
- The signal pulse length dictates resolution in the range direction.
- Shorter pulses result in a higher **range resolution**.
  - P = pulse length
  - 1, 2 = two targets that are too close together to be resolved as individual targets
  - 3, 4 = two targets with sufficient range separation to be resolved as individual targets



Azimuth Resolution

- The width of the antenna beam determines the **resolution in the azimuth direction**.
- The beamwidth is directly proportional to radar wavelength and is inversely proportional to the length of the transmitting antenna.
- Resolution deteriorates with distance from the antenna. In order to have a high resolution in the azimuth direction the radar antenna must be very long.
  - A = antenna beam
  - 1, 2, = two targets that can be resolved as being separate
  - 3, 4, = two targets that cannot be resolved as being separate





Synthetic Aperture Radar

Synthetic Aperture

- Image resolution is enhanced in the direction that is parallel to the track of the aircraft (**Azimuth**).

- Resolution is determined by the ratio of the wavelength to the length of the aperture.

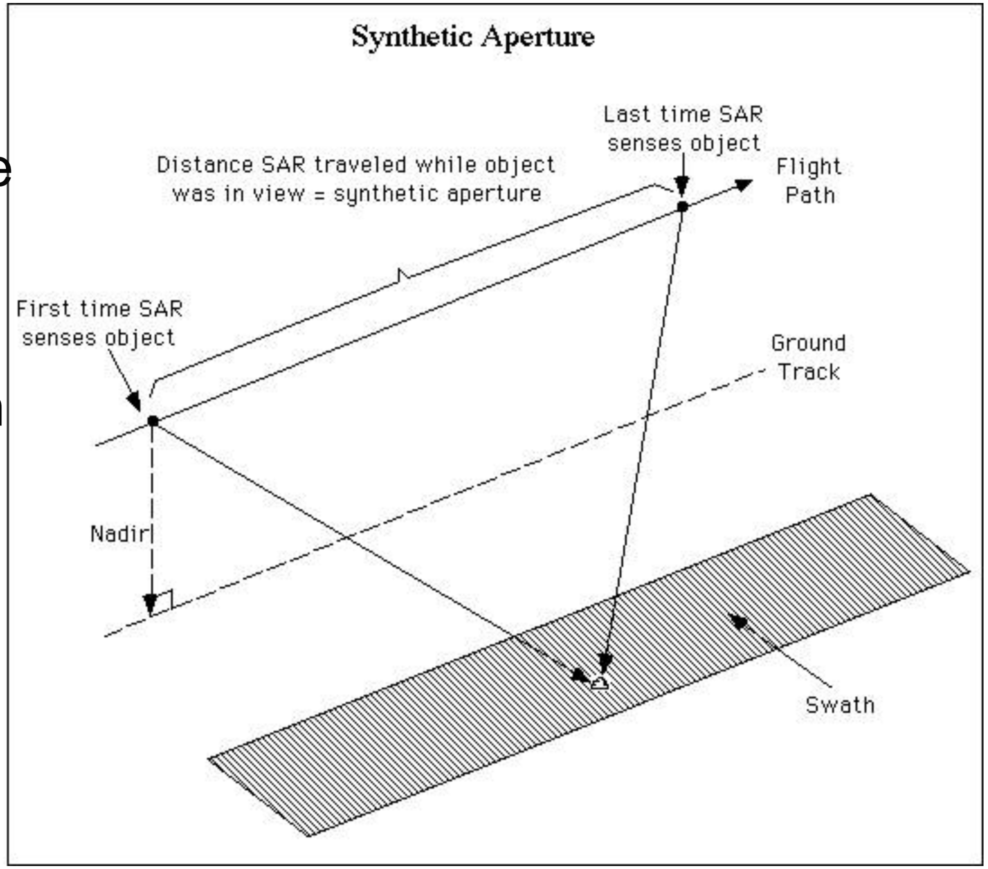
Resolution = Wavelength/Aperture

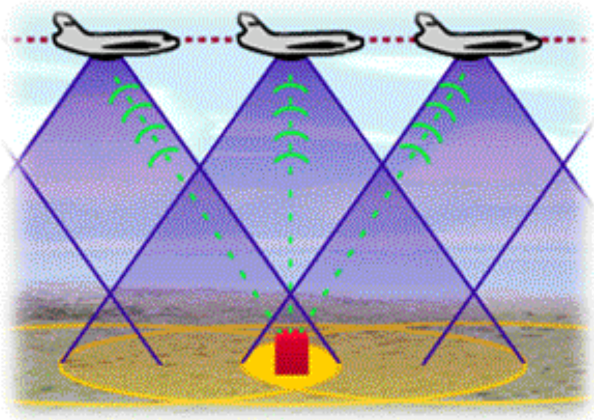
- Therefore, as we increase the aperture size the resolution will get smaller (we will be able to resolve objects that are closer together).

- Intermap radar antennas are 1 meter in length, therefore we synthesize a larger aperture to increase azimuth resolution.

Synthetic Aperture Schematic

- Digitally combine the return signals that were collected while the aircraft was flying.
- Virtually increasing in the length of the antenna.





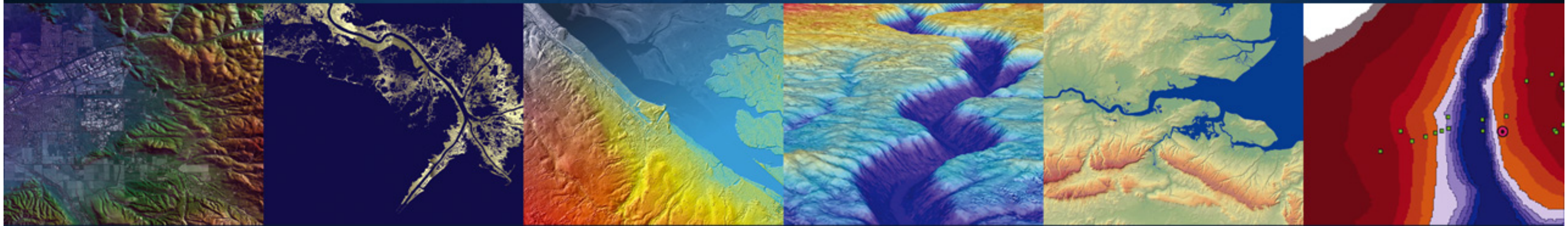
IFSAR Theory Summary

- IFSAR is fundamentally the transmission of a radar pulse, the interaction of that pulse with the terrain, and the recording of that pulse.

- **Amplitude** and **Phase** are recorded by the sensor.

- Resolution is optimized in the Range and Azimuth direction.

- Synthesizing a larger aperture improves Azimuth Resolution.

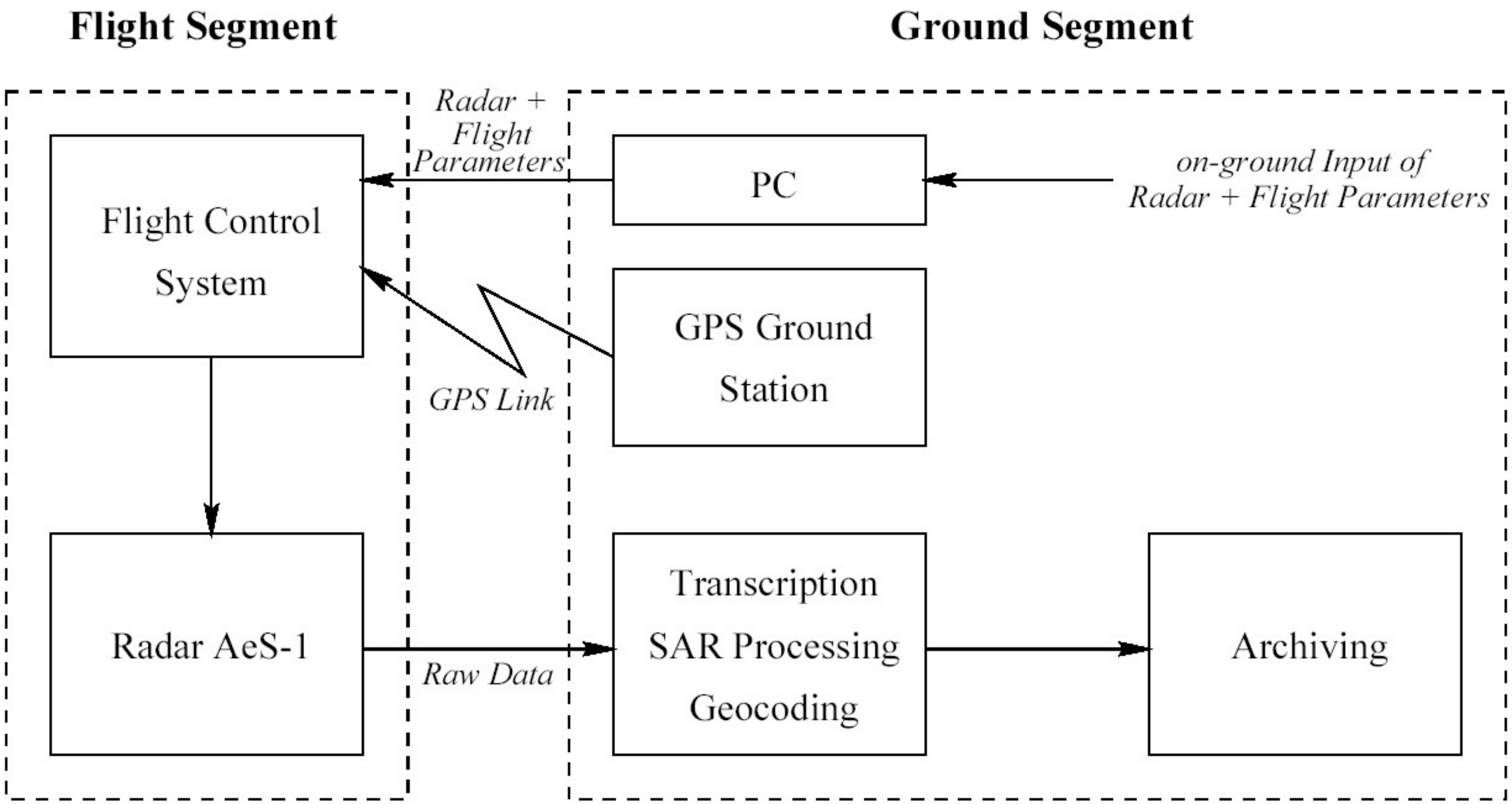


IFSAR System Components

Flight and Ground Segments

www.intermap.com

IFSAR System Components

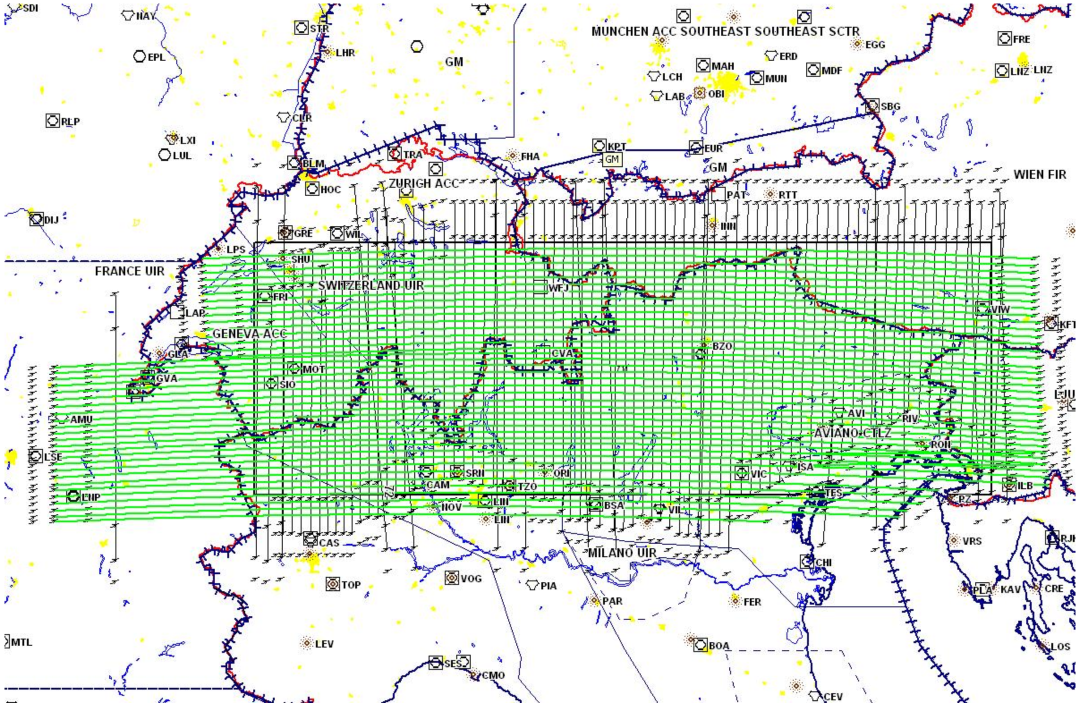


Block Diagram of the ground and flight segments

Mission Planning

Primary Lines:

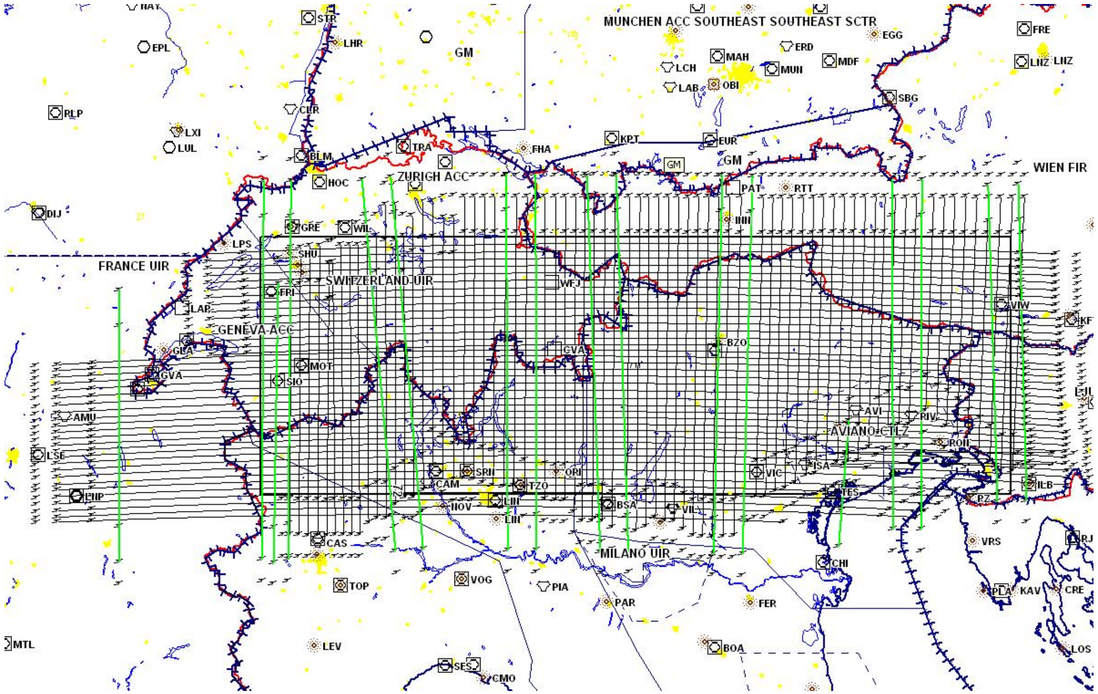
-These lines are the main method of collecting IFSAR for a project area.
-There must be complete coverage of an area with Primary Lines.
-There is some overlap between adjacent Primary Lines (~4 km).



Mission Planning

Tie Lines:

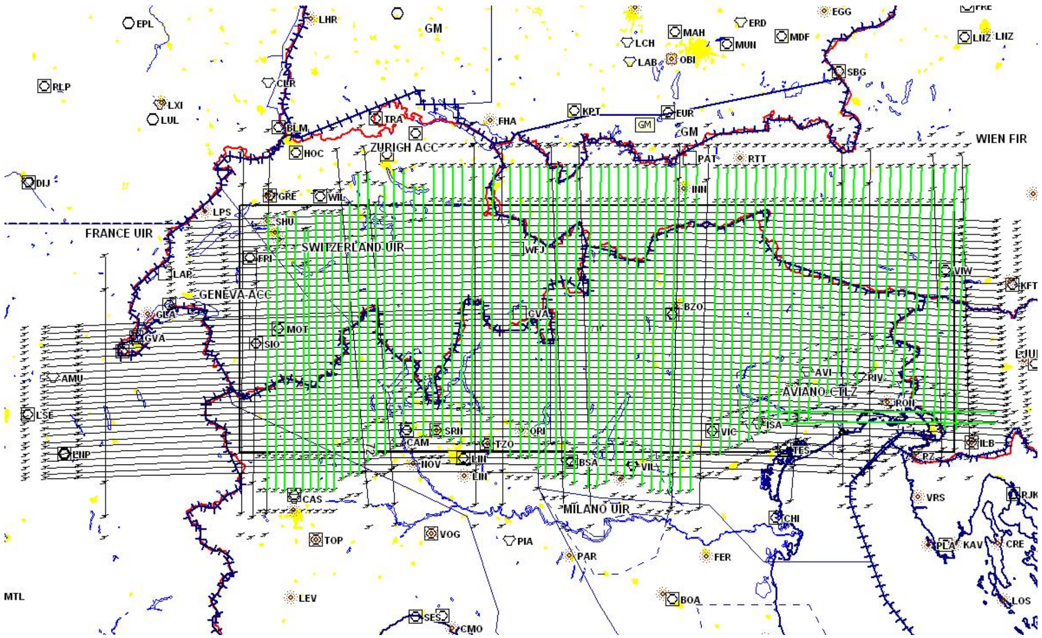
-These lines control the Primary Lines.
-Tie Lines are orthogonal to Primary Lines.
-There is at least one Tie Line every 100km along each Primary Line.



Mission Planning

Secondary Lines:

-These lines attempt to fill-in data which the Primary Lines can not acquire.
-Normally located in rugged mountains, where there are radar shadows and decorrelation effects.
-Tie Lines are orthogonal to Primary Lines.



Ground Control

Ground control is enabled by Radar Reflectors.

Ground Control

Reflectors are 90 cm x 90 cm x 90 cm aluminum.

Ground Control

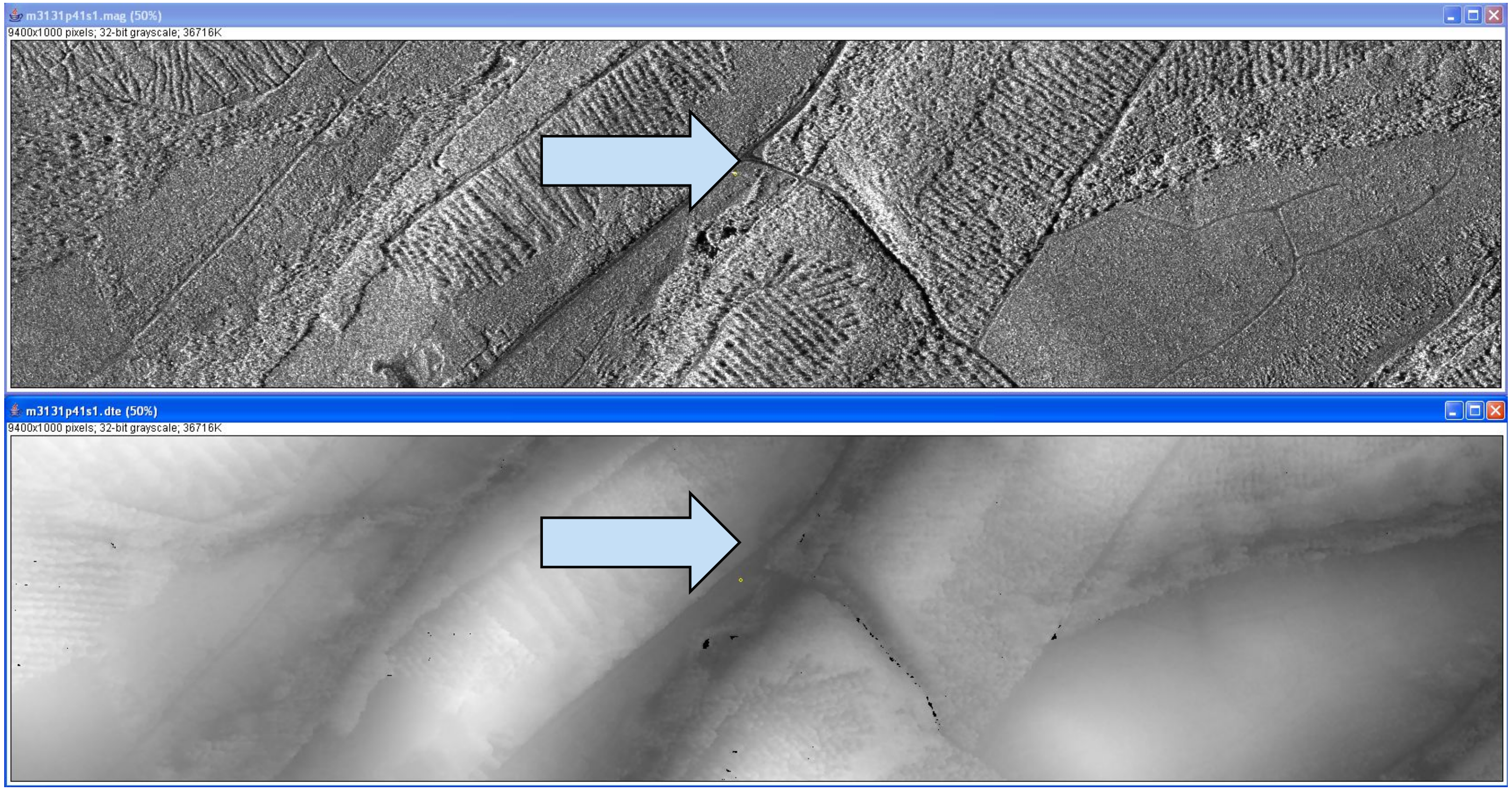
Locations are designed at the ends of Tie Lines.

Suitable locations must be found for each point, and then surveyed.

Ground Control

Reflectors can then be found in the raw IFSAR imagery.

(This is zoomed out)



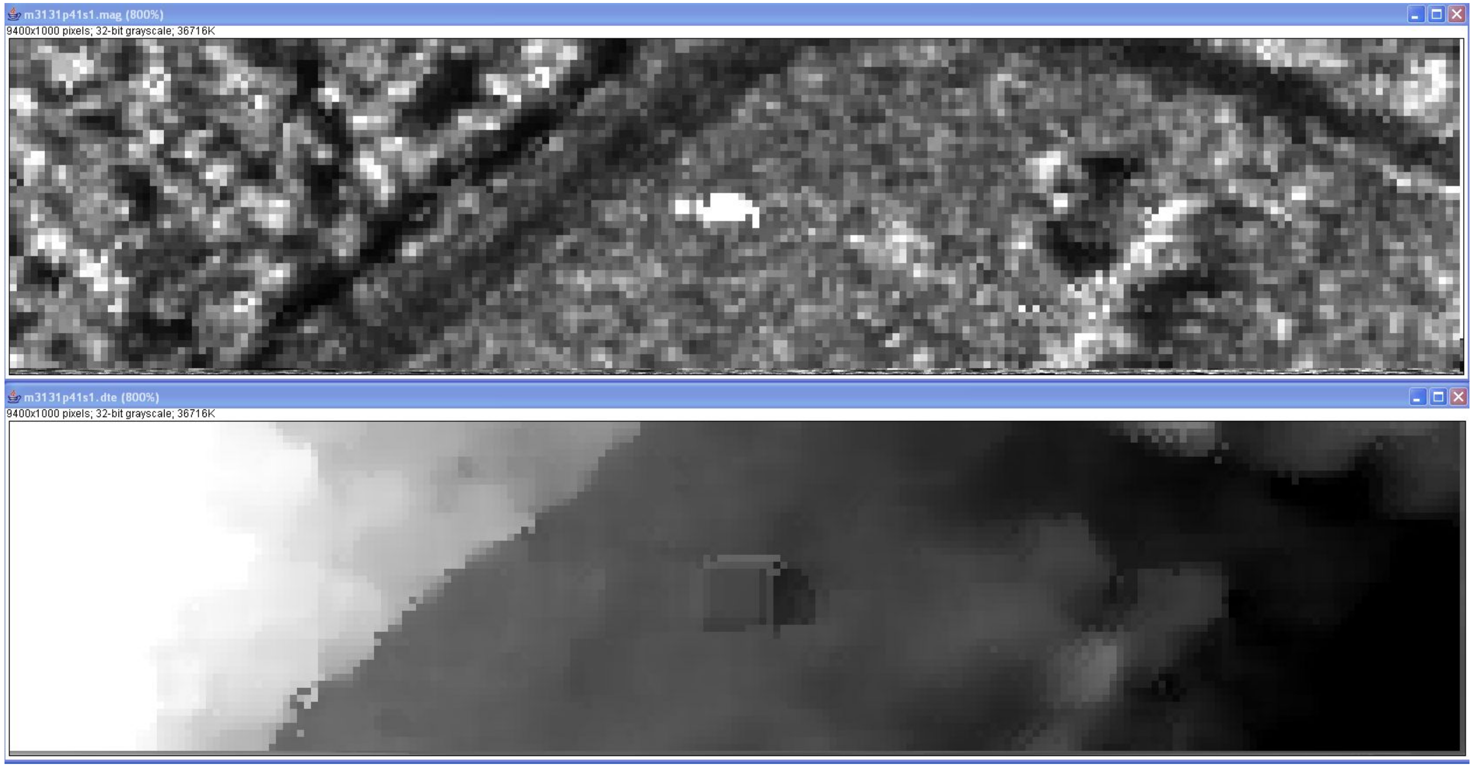
ATLASTECH GEO-SOLUTIONS

INTERMAP TECHNOLOGIES

Ground Control

Reflectors are used to control the three dimensional solution of the Tie Lines. The Tie Lines then control all the Primary Lines.

(This is zoomed in)



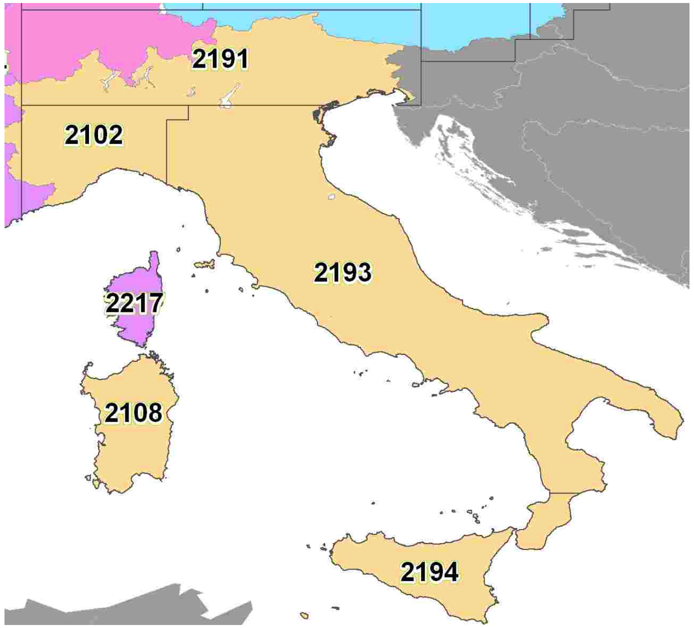
ATLASTECH GEO-SOLUTIONS

INTERMAP™ TECHNOLOGIES

Tactical Flight Planning

For NEXTMap Italia, the aircraft is initially based in ***Bastia.***

- Excellent location for flying everywhere in Italia.
- Good local conditions.



Acquisition altitude is FL340 (~ 10,300m above sea level)

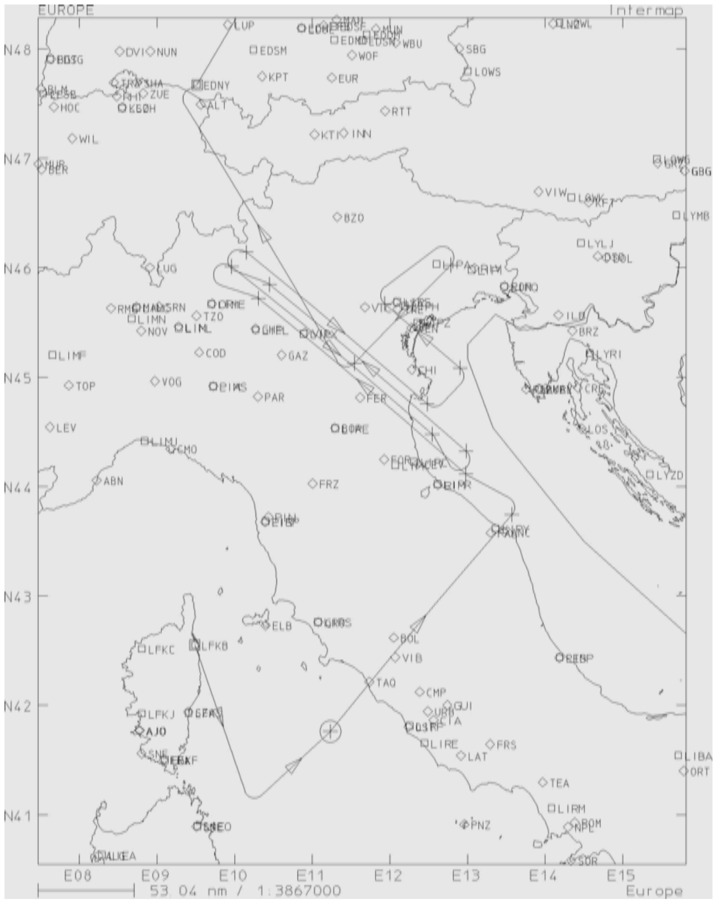
Tactical Flight Planning

Each night, two sorties are launched. The sorties are planned for:

- Weather conditions

- Efficiency

- Priority of Data



ATLASTECH
GEO-SOLUTIONS

INTERMAP™
TECHNOLOGIES

Field Operations

N101AJ – Lear Jet 36

Intermap Aircraft/Radar Platforms

STAR-6

STAR-3

TopoSAR

STAR-5

STAR-4

ATLASTECH GEO-SOLUTIONS

INTERMAP TECHNOLOGIES

Flight Segment

- Across-track antennae arrangement for DEM data collection
  - 1-meter in length antennae separated by ~ 1 meter interferometric baseline.
- Transmitter/Receiver generates a coherent radar pulse at a frequency of 16kHz.

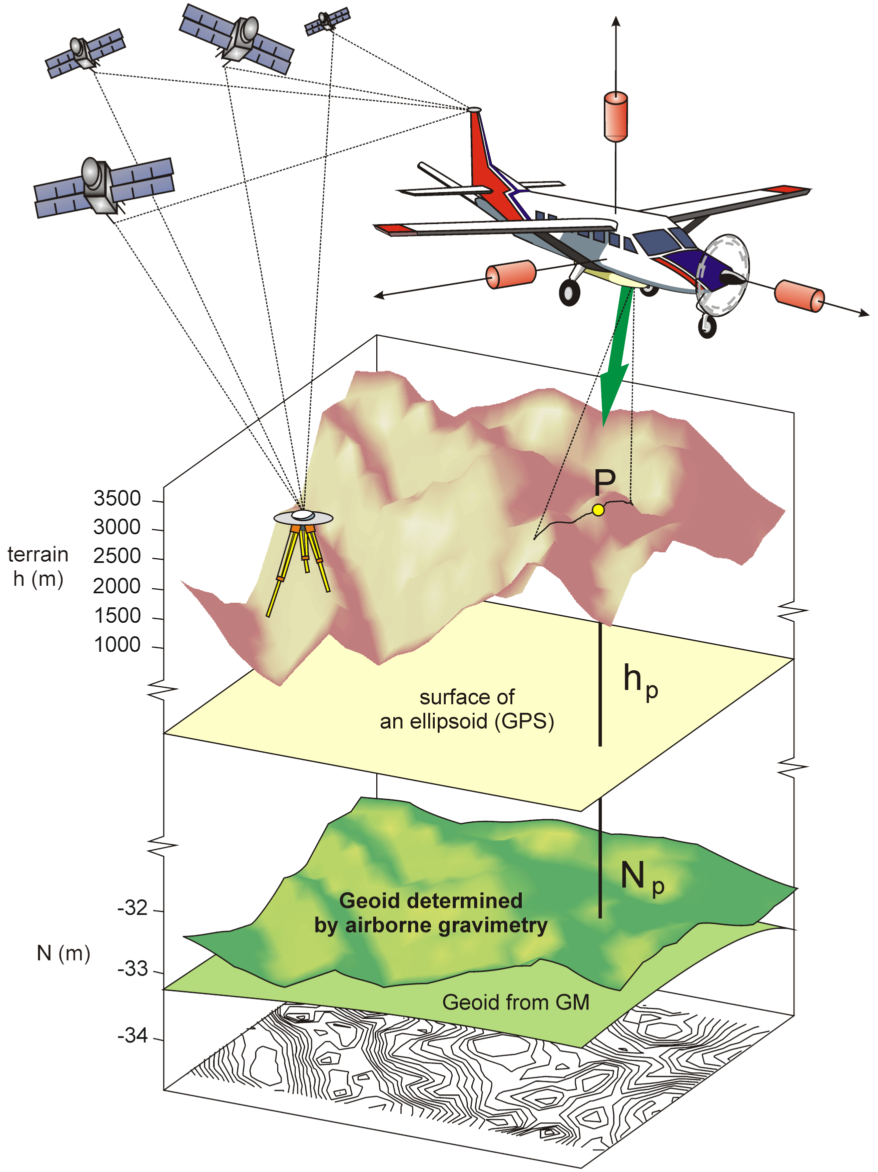
Flight Segment

- Differential GPS (DGPS) and Inertial Measurement Unit (IMU)
  - Honeywell H770 Inertial Reference Unit (IRU), which is tightly coupled, in post processing, to an Ashtech Z-12 GPS receiver it's complementary GPS base station
  - IRU is co-mounted on the INVAR frame with the antennae to eliminate lever arm errors between the aircraft and the antennae phase centers

Figure 3: AeS-1 flight segment

- Control Computer and Disk Array
  - This stores 100's of GBs of Amplitude and Phase data.

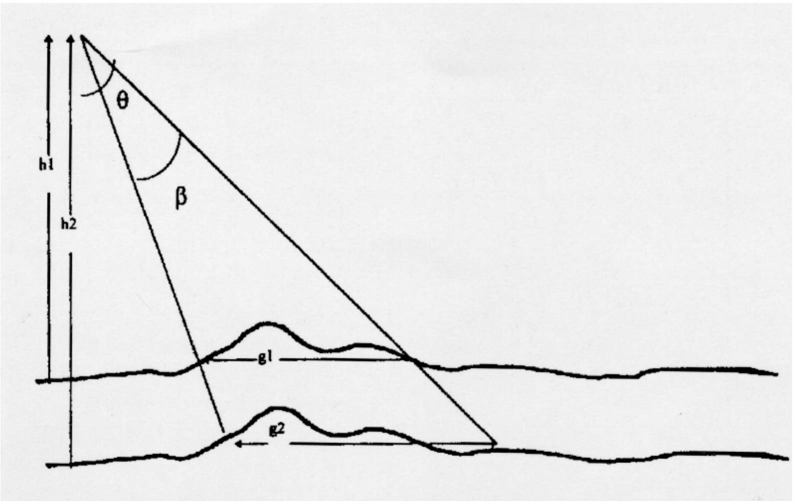
Fight Segment: Positioning the Sensor

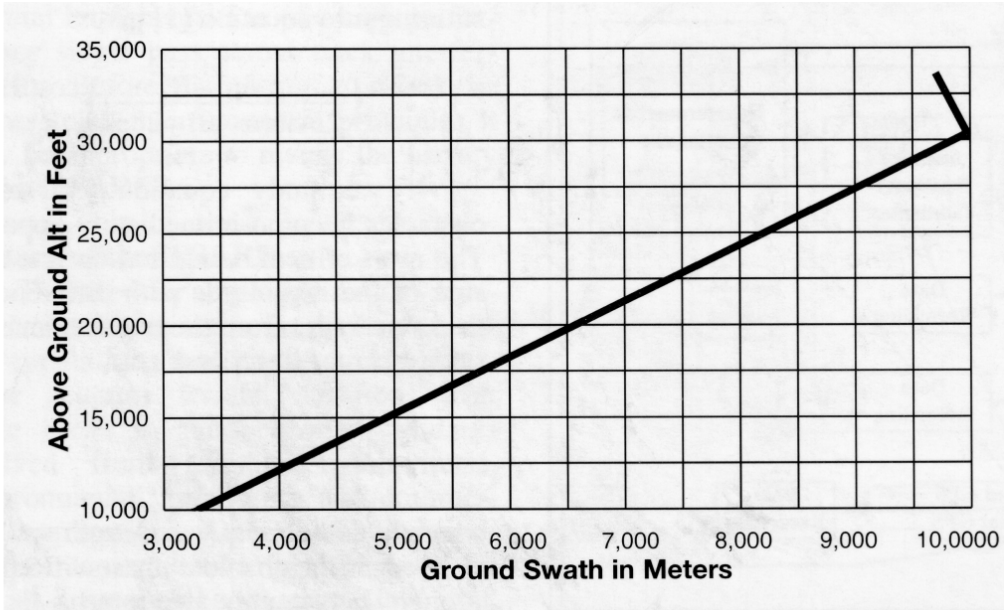


- Position of the IFSAR Sensor is provided by DGPS
- Orientation of the IFSAR Sensor is provided by an IMU/INS system.
- Incidence angle and range of the SAR pulses are derived from the IFSAR system configuration.
- The data collected is combined in post-flight processing to accurately determine/derive the position of each point on the ground.

System Coverage

- The antennae are welded to the antennae pedestal = coverage dependent on the flying height above the ground.
- Two critical parameters for coverage: far incidence angle and the antenna beam width which are constants for IFSAR Systems.
- As the aircraft height above the ground decreases, so too does the ground coverage

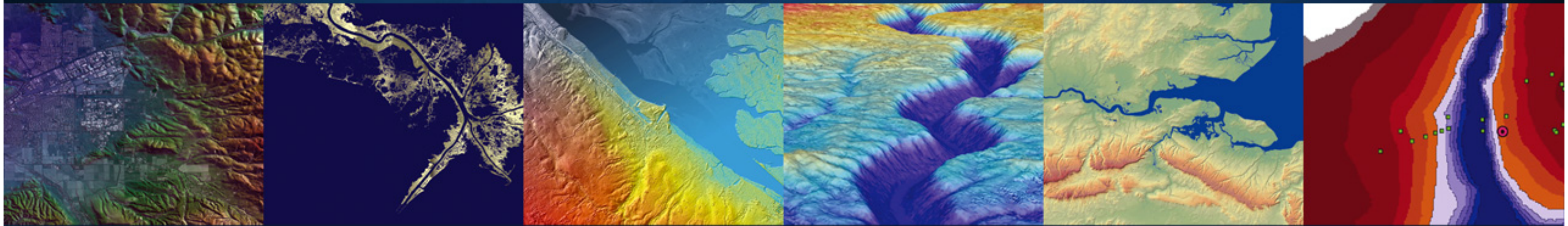




Field Data Verification

- Transcribing JBODs (Just a Bunch Of Disks) data takes about 6 hrs.
- RAW signal IFSAR processing to get a thumbs up or down on whether or not a flight line has been accepted (~ 6 hrs)
- Typically performed by Field Manager.
- Accepted data is copied to media and sent to IFSAR processing facilities.

JBODs



Interferometric Processing

www.intermap.com

IFSAR Processing

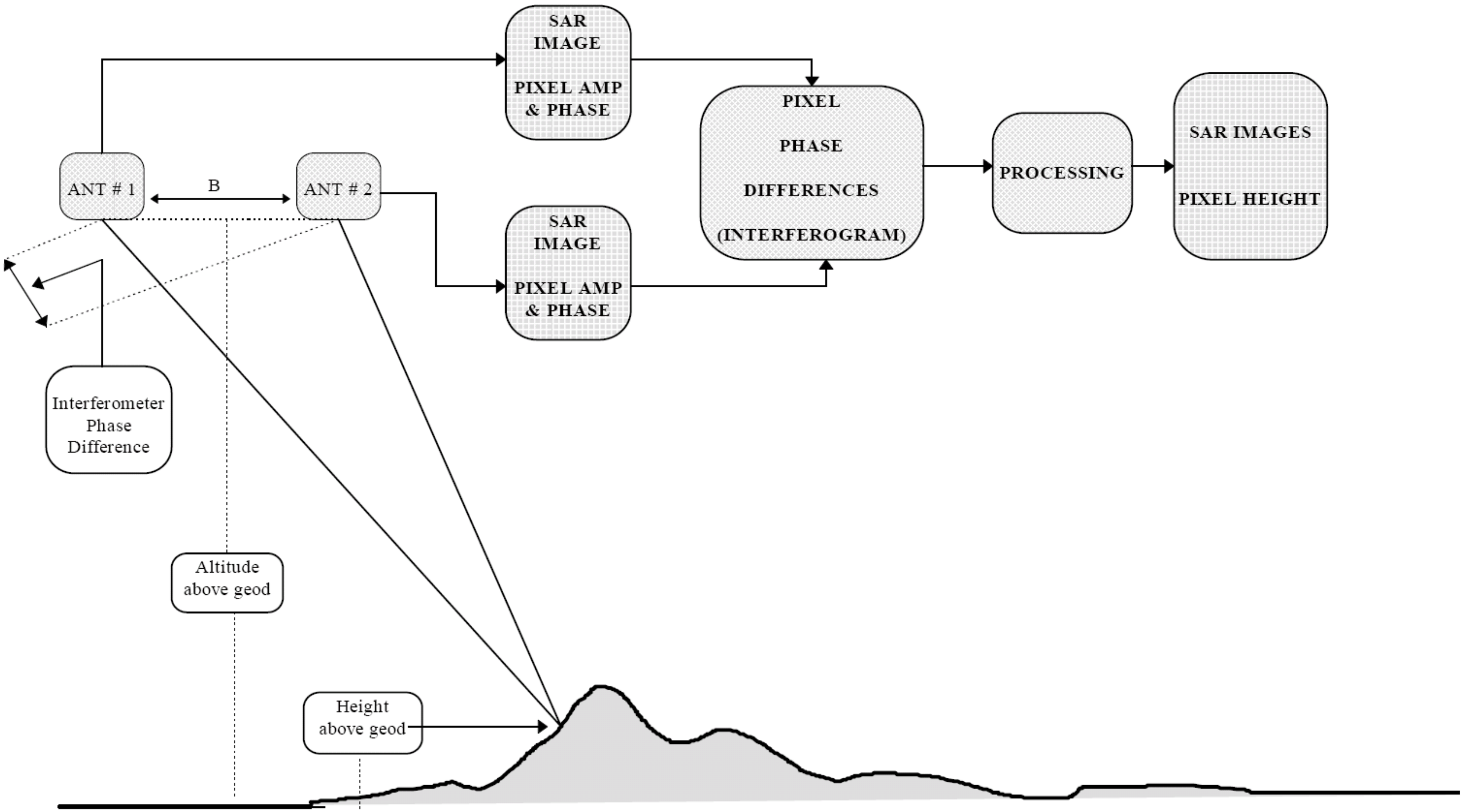
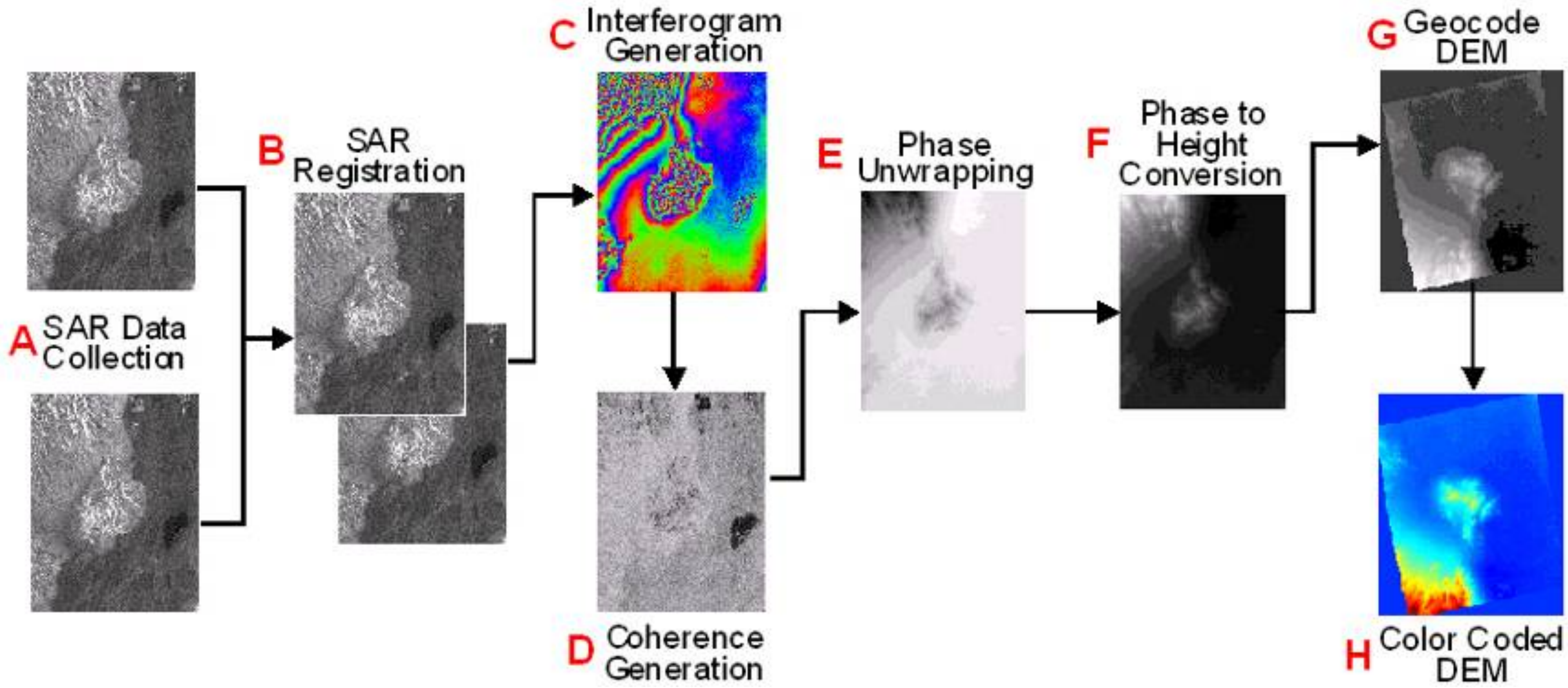


Figure 5-1, Basic IFSAR Process

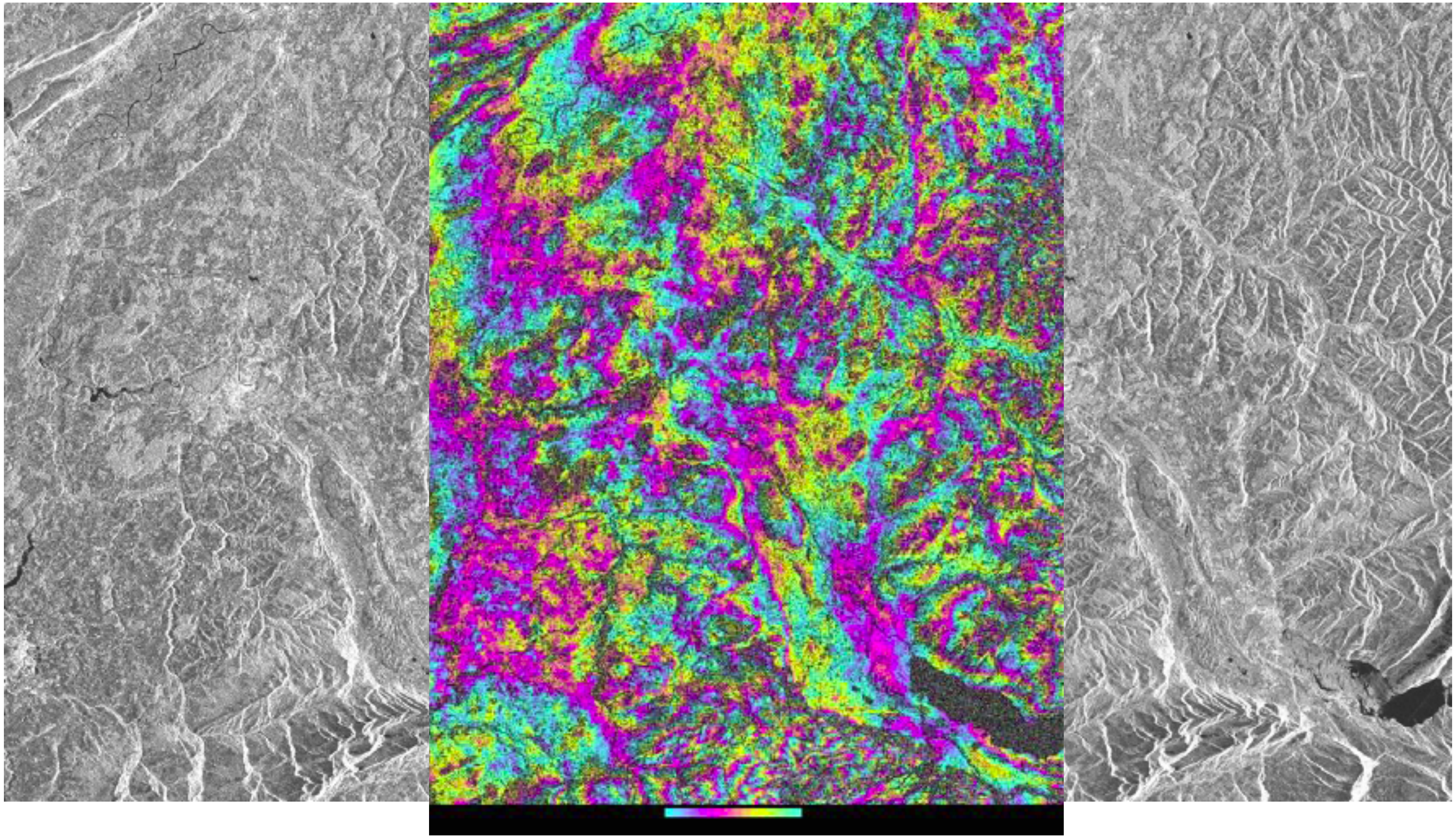
From Tennant, 1998

IFSAR Processing



Interferograms

Antenna 1 Interferogram Antenna 2

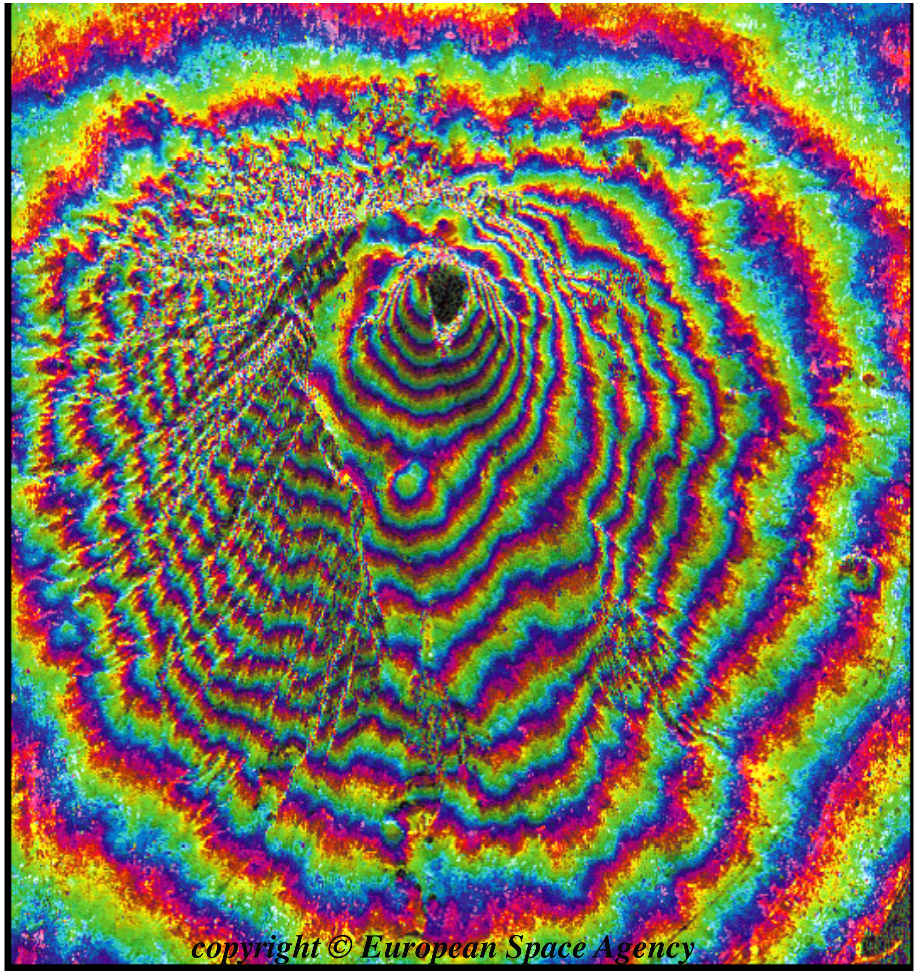


ATLASTECH GEO-SOLUTIONS

INTERMAP TECHNOLOGIES

Interferograms

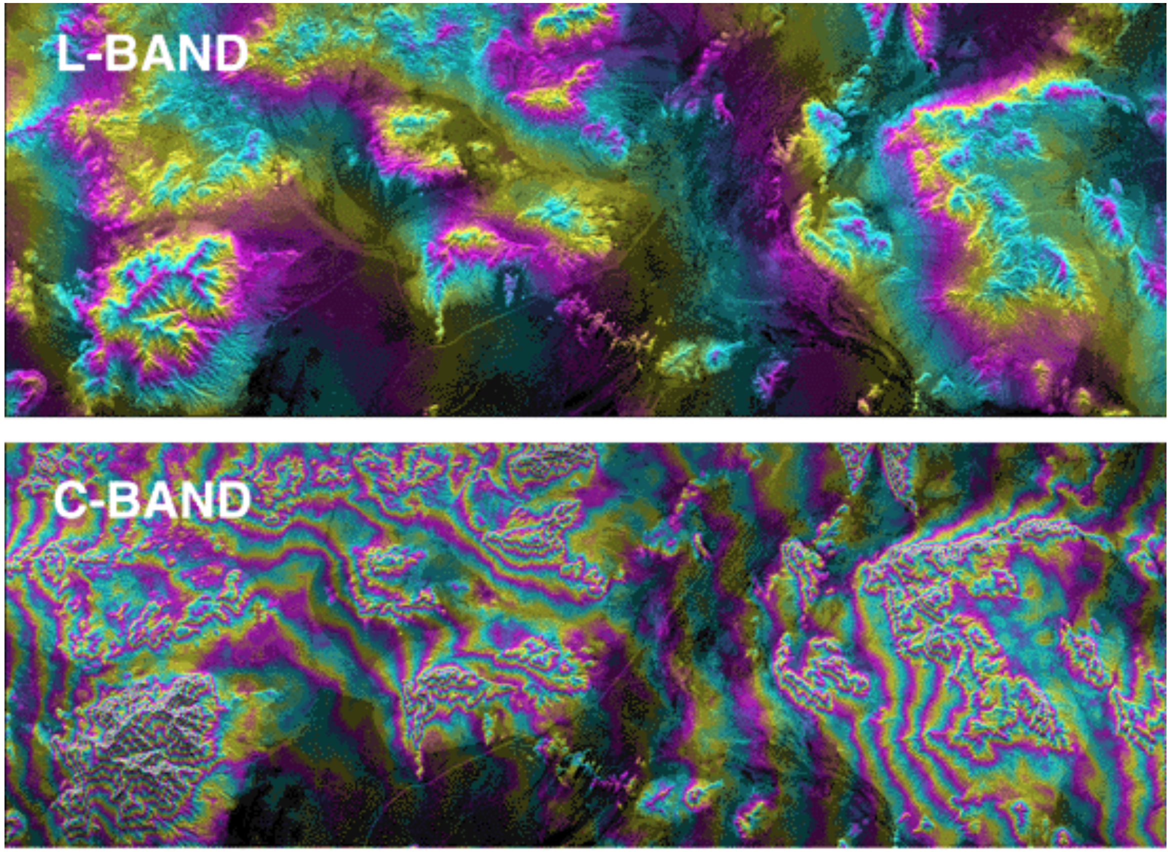
- Interferograms represent the phase variation between each corresponding pixel recorded by each antenna.
- Radar interferograms show a series of colored bands which represent the interference fringes.
- The phase fringes obtained through the interference of the two images can be used to accurately determine the distance difference in fractions of a wavelength (0 to 2π.) to each resolution cell.



Interferometric Fringes

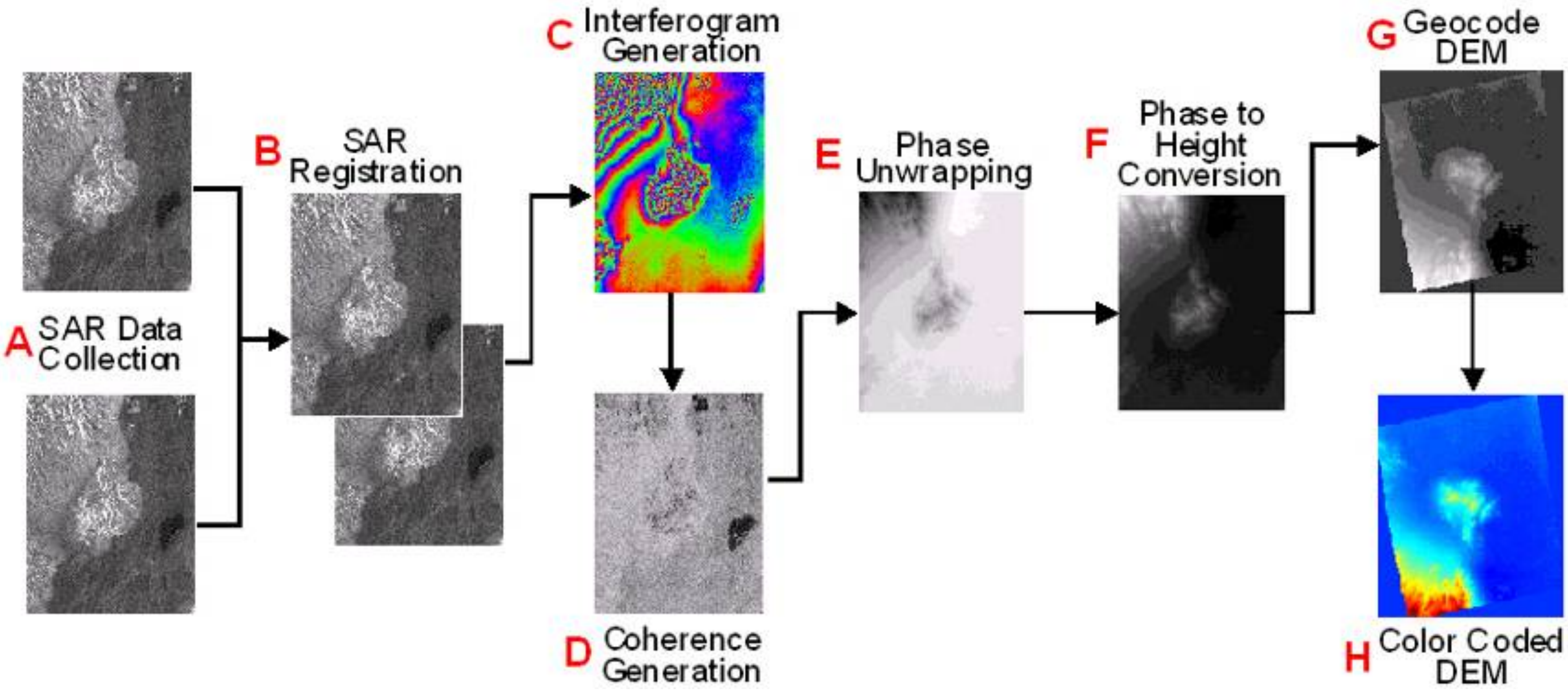
- Every colour value represents a phase value between 0 and 2π, where the colors repeat to form so-called fringes (stripes).

- It may help to think of the fringes like contours.



SIR-C L, C BAND INTERFEROGRAMS
FT. IRWIN, CALIFORNIA

IFSAR Processing



Phase Ambiguity

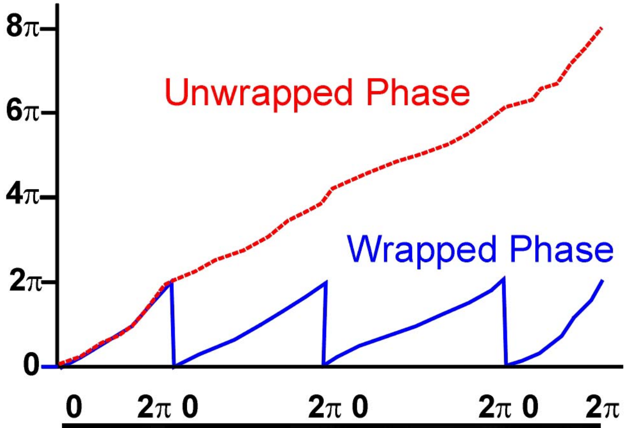
$$\delta\rho = \frac{\lambda\phi}{2\pi}$$

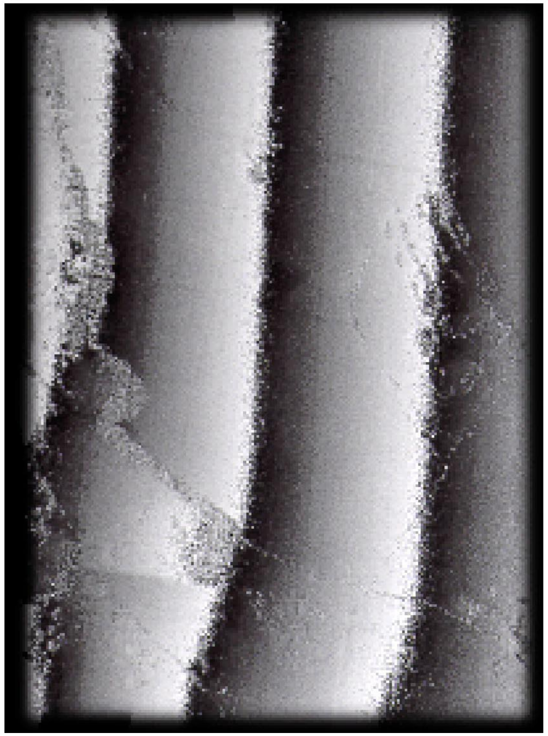
- λ is the radar wavelength and
- φ is the absolute phase difference between the two returns

- However φ can not be directly measured by the radar. The radar can only determine the fractional portion of φ (value between 0 and 2π radians) leading to an ambiguity.

- Thus additional techniques, such as “phase unwrapping” are required to solve for the integer portion of φ .

Phase Unwrapping





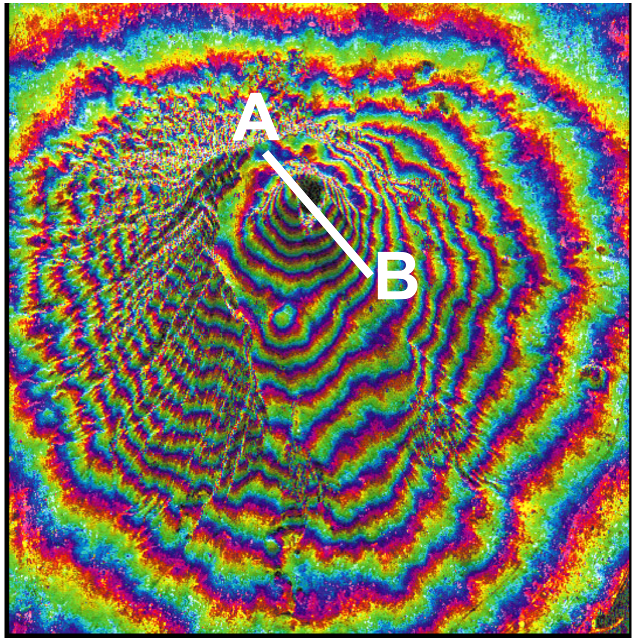
- The interferometer obtains precise measurements of phase related to wavelength
- The radar can only determine the fractional portion of absolute phase difference (value between 0 and 2π radians) leading to an ambiguity.
- Additional techniques are required to convert wrapped phase into heights.

ATLASTECH GEO-SOLUTIONS

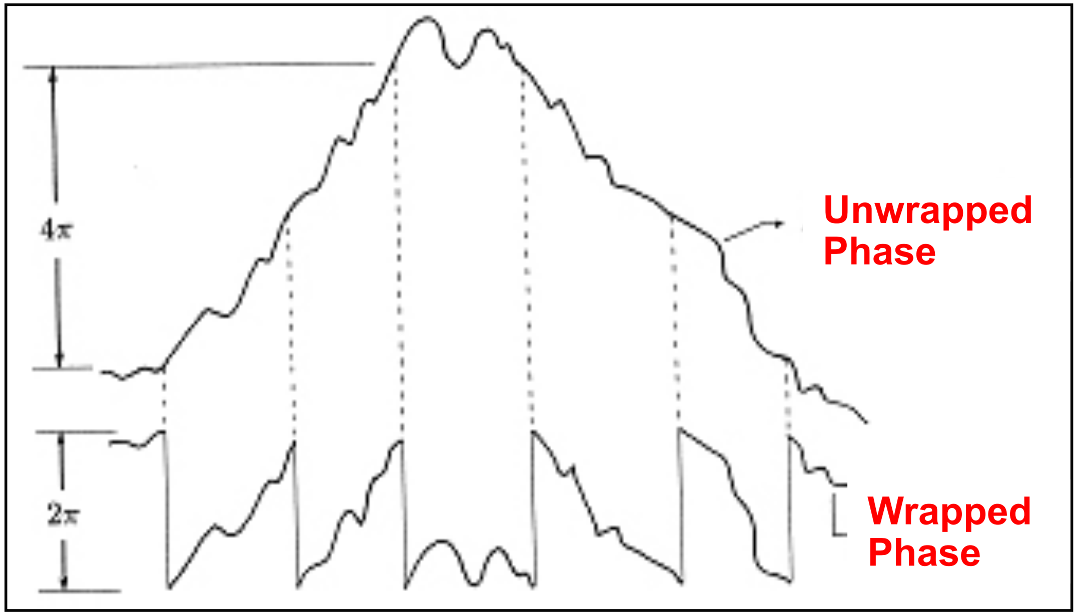
INTERMAP TECHNOLOGIES

Phase Unwrapping

Interferogram



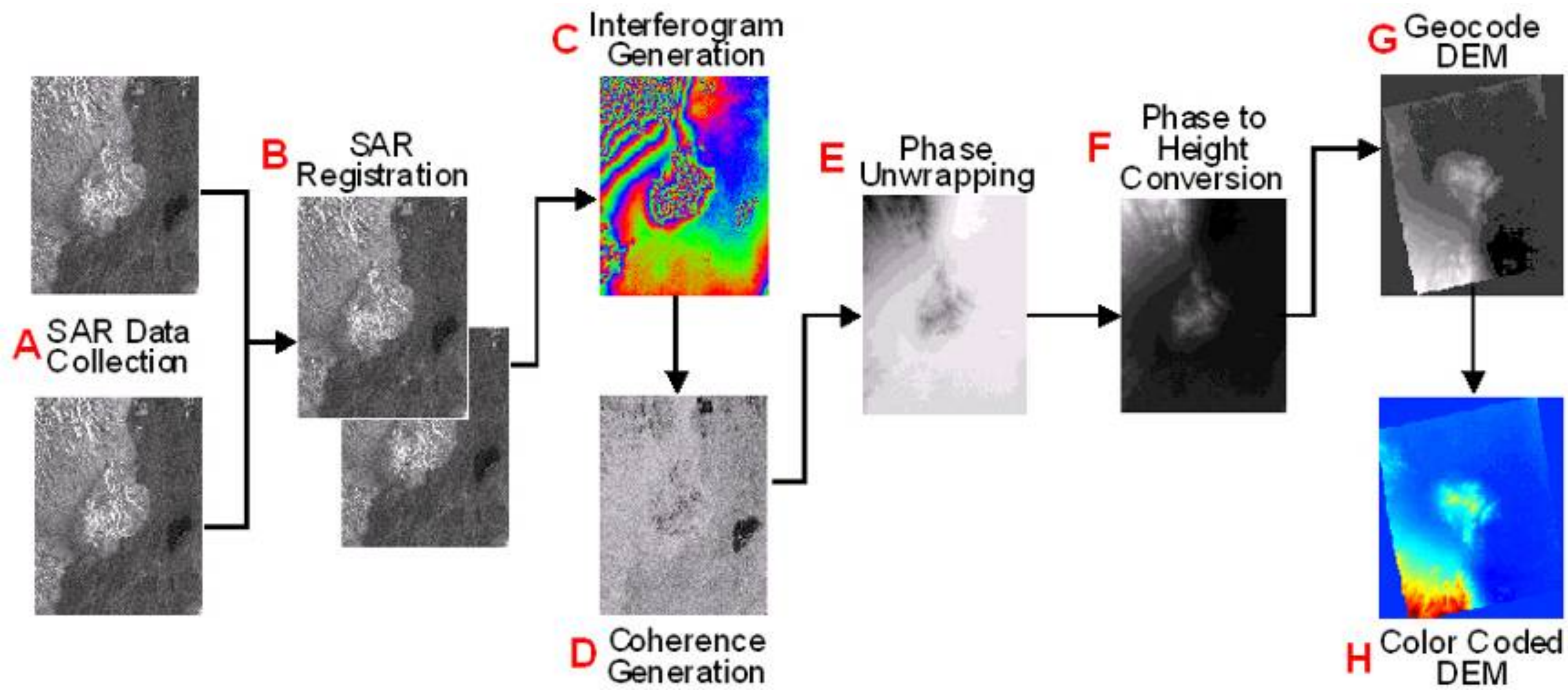
Profile Line A-B



- Interferometer is an excellent ruler, generating precise measurements of phase represented as fringes, however, a poor counter: 0 - 2π, 0 - 2π, 0 - 2π, and so on **=** ***wrapped phase.***

- Wrapped phase must be "unwrapped" (0 - 2π, 2π - 4π, 4π - 6π, 6π - 8π) in order to generate a continuous height surface (DEM).

IFSAR Processing



Coherence

- The coherence determines the visibility of the fringes in the interferogram.

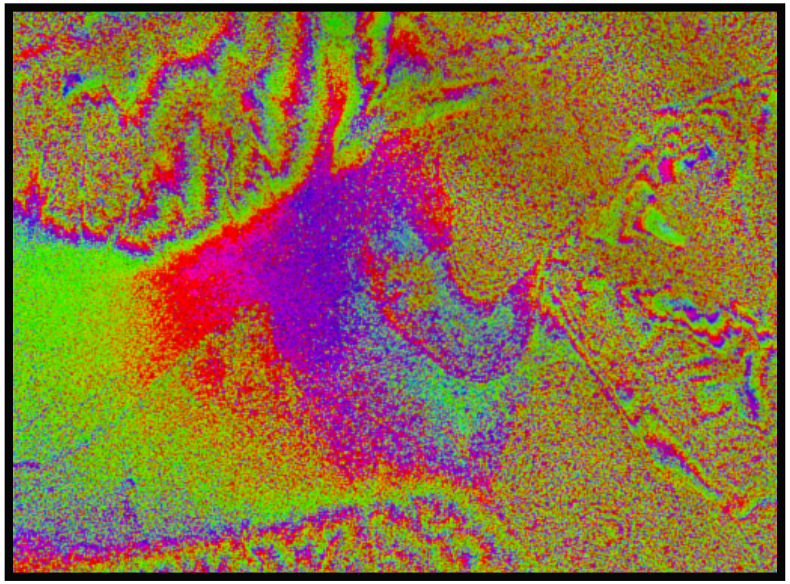
- Interferometric coherence is an additional information channel generated during the IFSAR process.

- Coherence is primarily used as an interferometric quality check ~ a good indicator of how well the interferometer is performing.

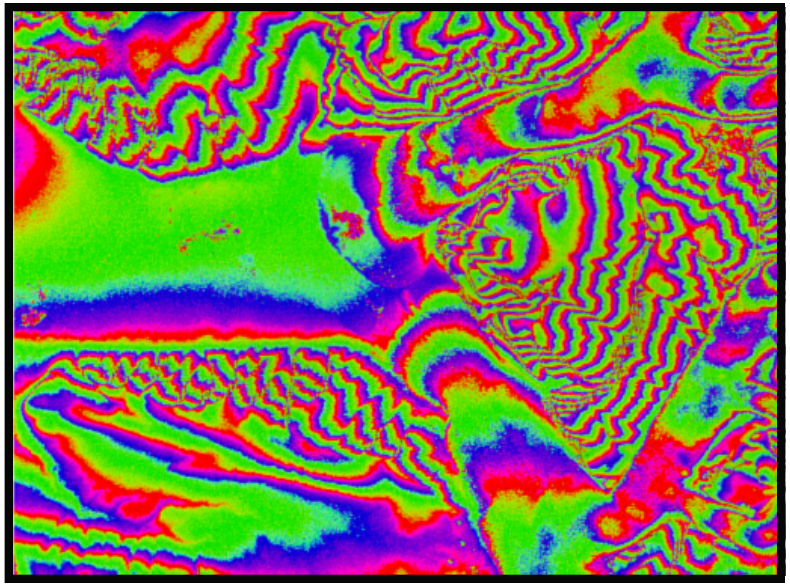
- Coherence magnitude varies between 0 (incoherence) and 1 (perfect coherence):
    - 0.3-0.5 is useable, but noisy
    - 0.5-0.7 is good
    - 0.7-1.0 excellent

Interferogram Examples

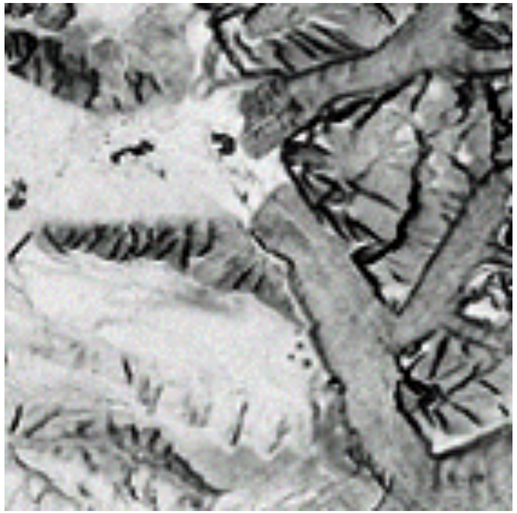
Data with Low Coherence



Data with High Coherence

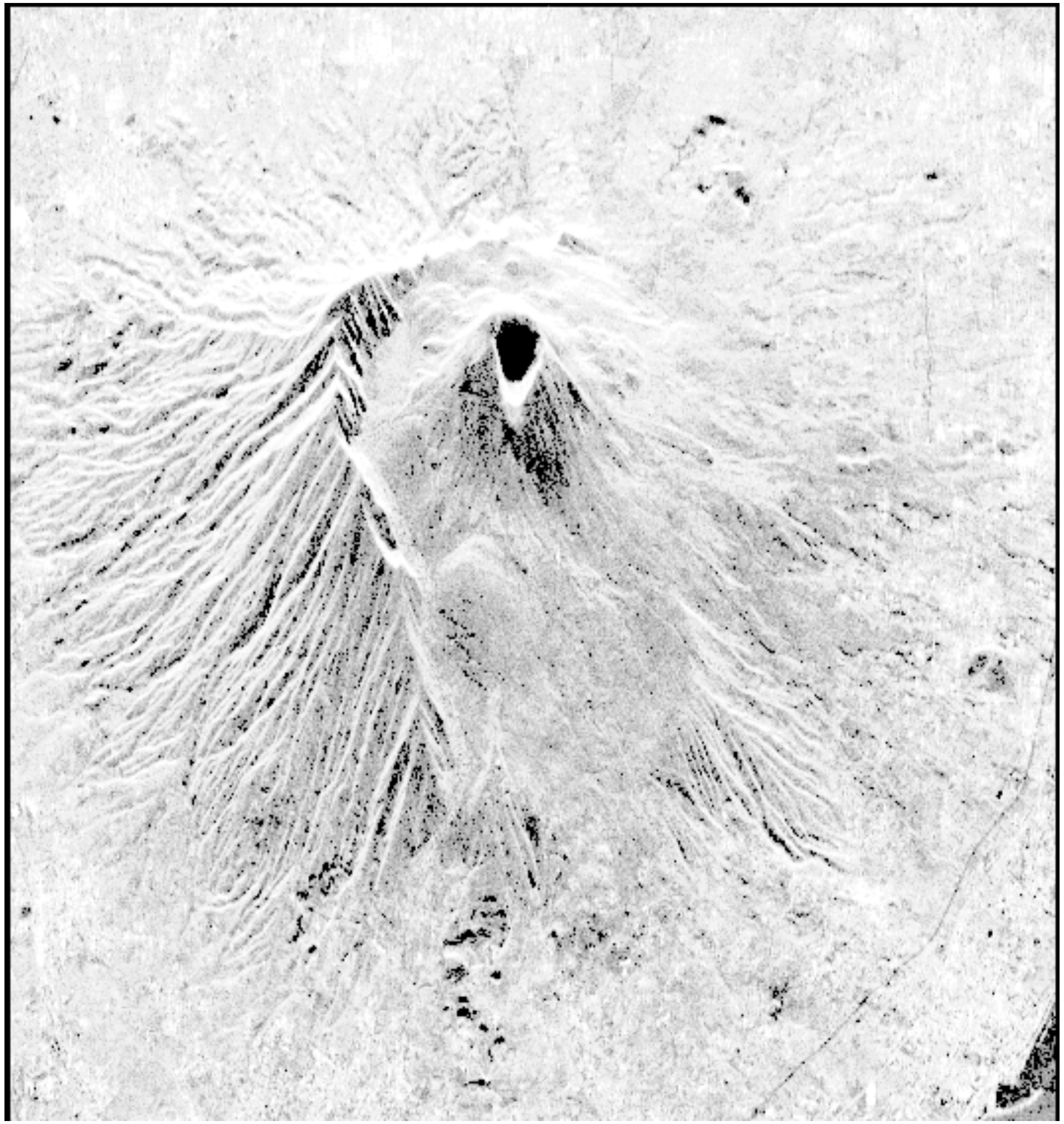


Corresponding DEM



Coherence

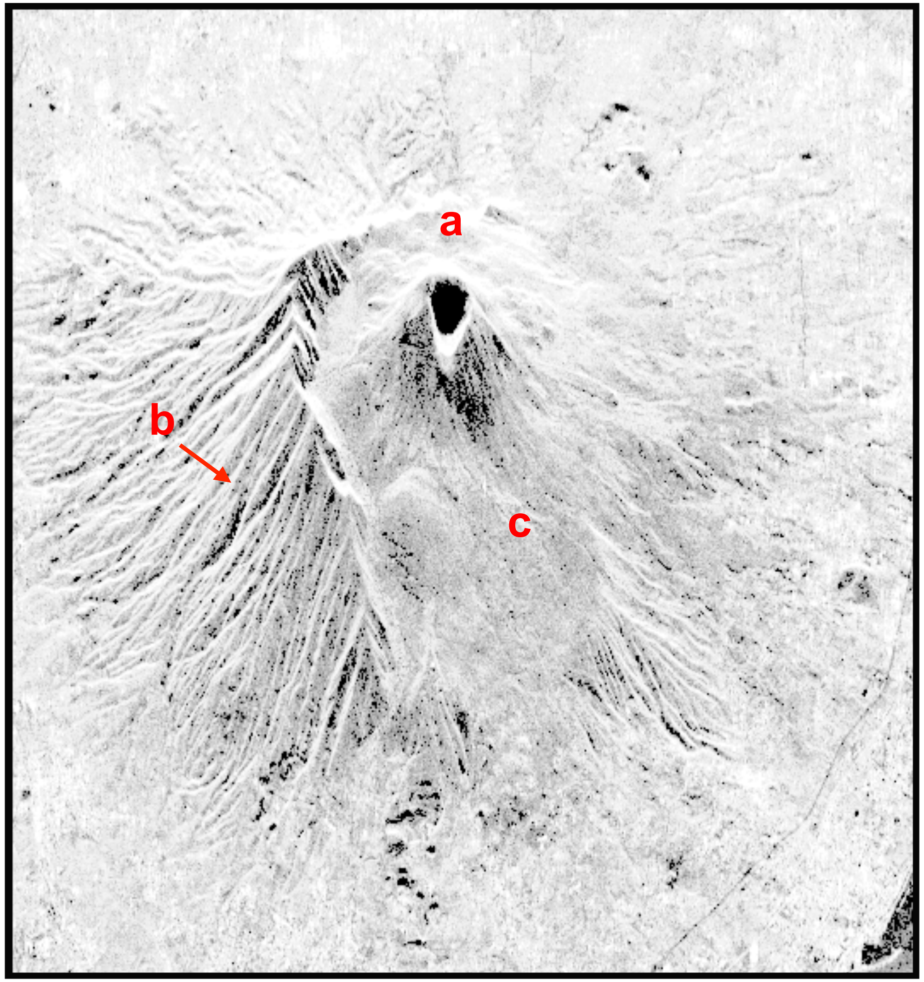
- Coherence is an indicator of how well the interferometer is performing.
- Measure for the correlation of the corresponding signals, ranges from 1 to 0.
- Low coherence areas (black or 0 value) result in large errors in the DEM.
- Is the phase difference a true measure of height or does it reflect other things?



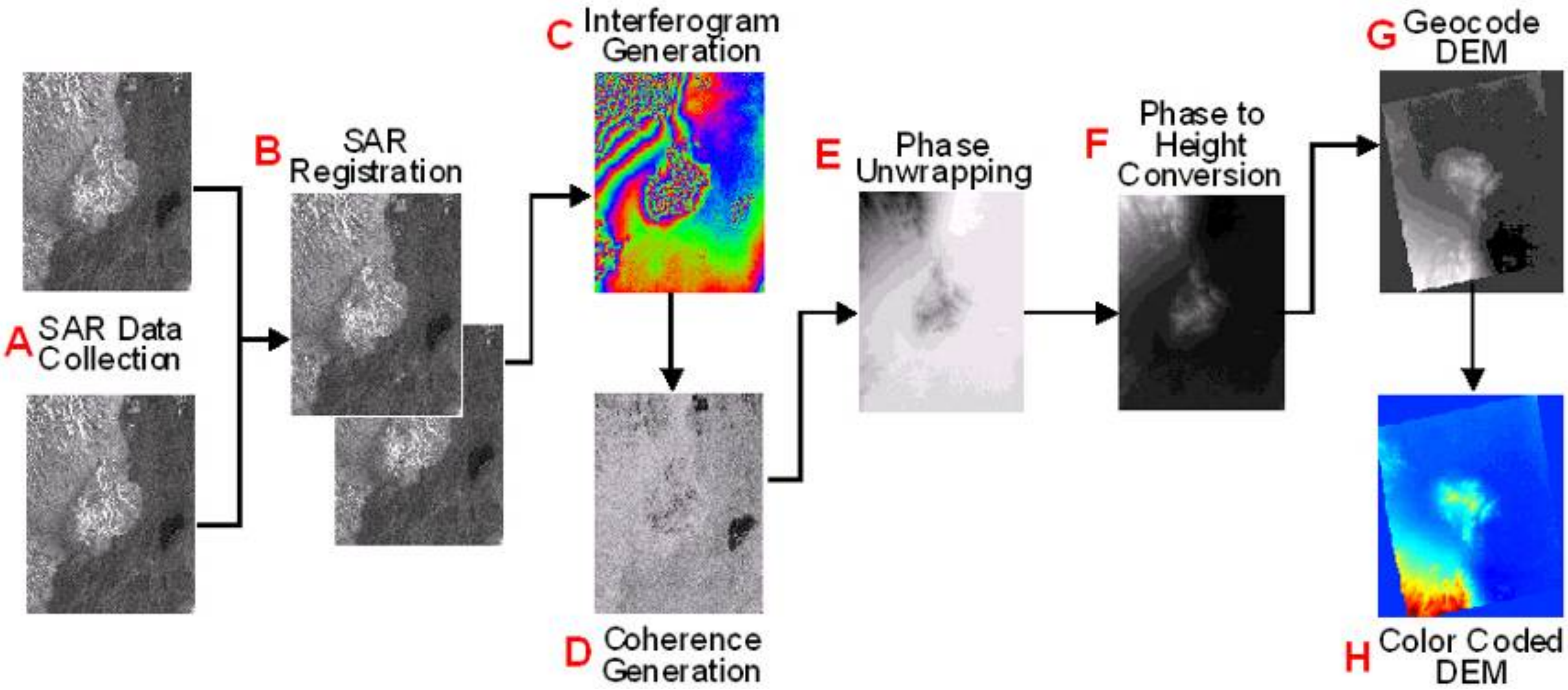
copyright © European Space Agency

Coherence Measurements

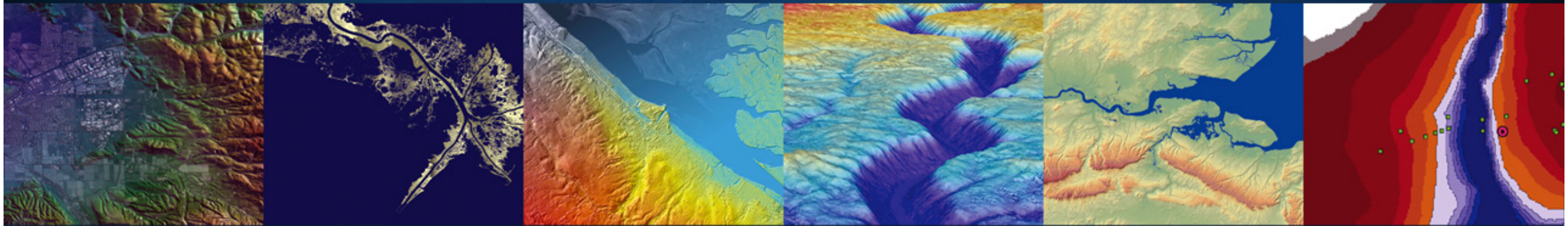
- a) Low coherence (<0.5) Dark in the coherence image :
  - Causes degradation of the precision of the IFSAR point processing
  - Causes problems in the phase unwrapping
  - Decrease in DEM quality
  - Occurs where there is water and shadow
- b) Medium mean coherence (0.5-0.7) Bright regions on the coherence image:
  - Occurs in areas of growing or moving vegetation
- c) High mean coherence (> 0.7) Bright regions on the coherence image:
  - Occurs in areas characterized by gentle terrain variations which translates to quite good precision DEMs
  - Occurs in desert, city, and other stable features



IFSAR Processing



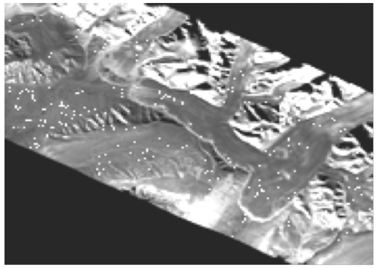
INTERMAP™ TECHNOLOGIES

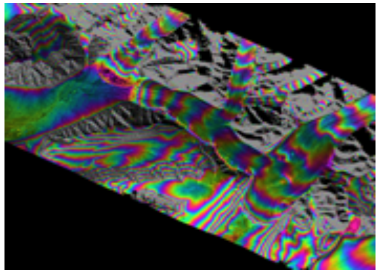


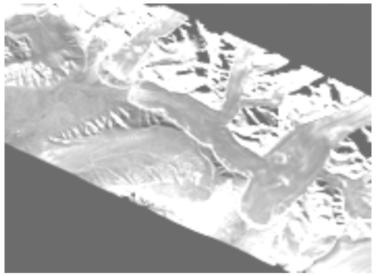
IFSAR Products

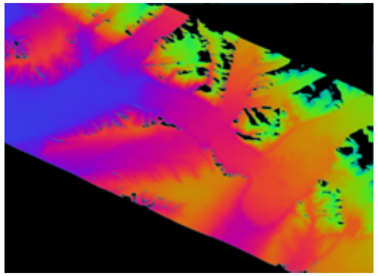
www.intermap.com

IFSAR System Products

A


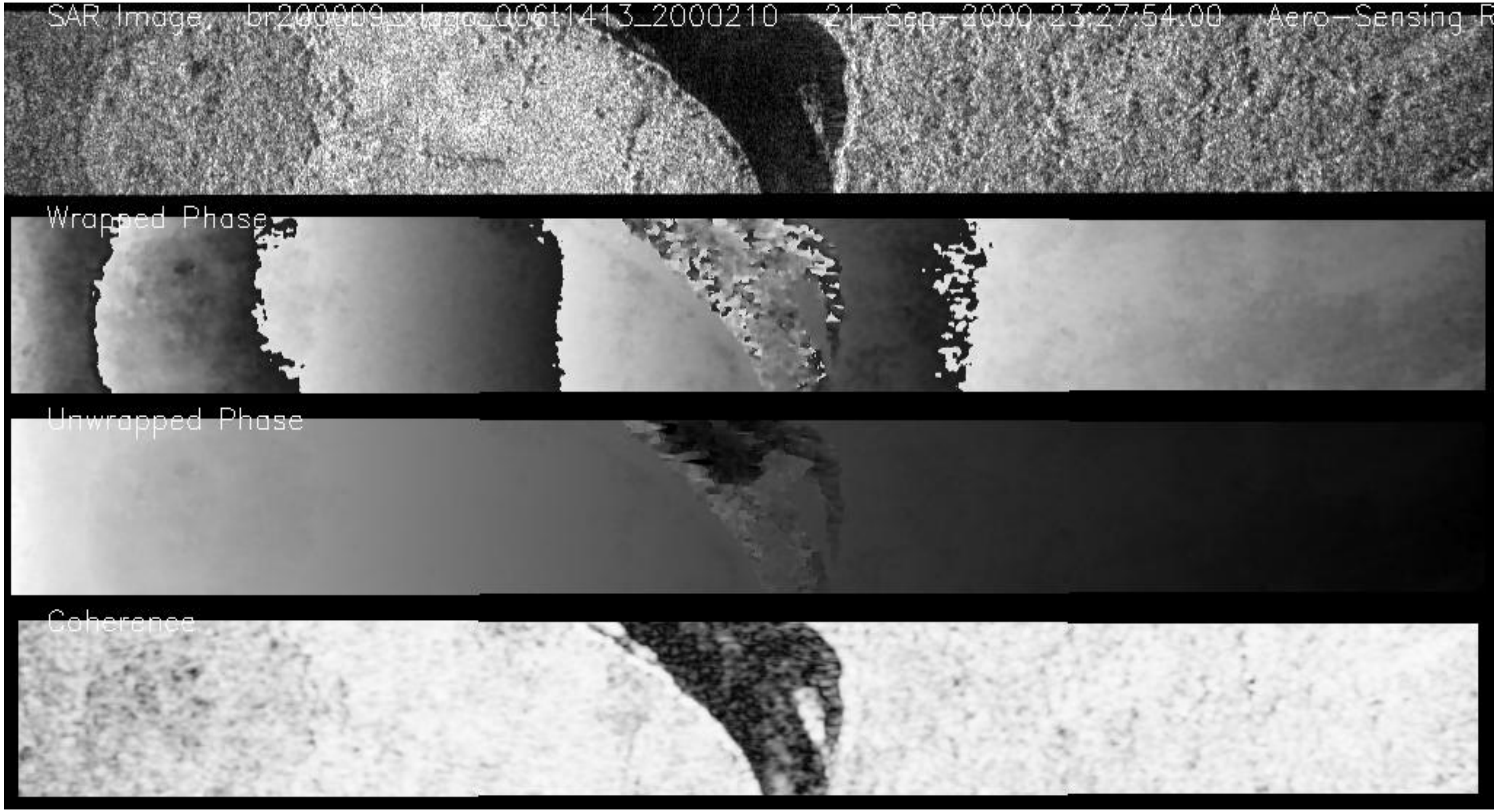
B


C


D


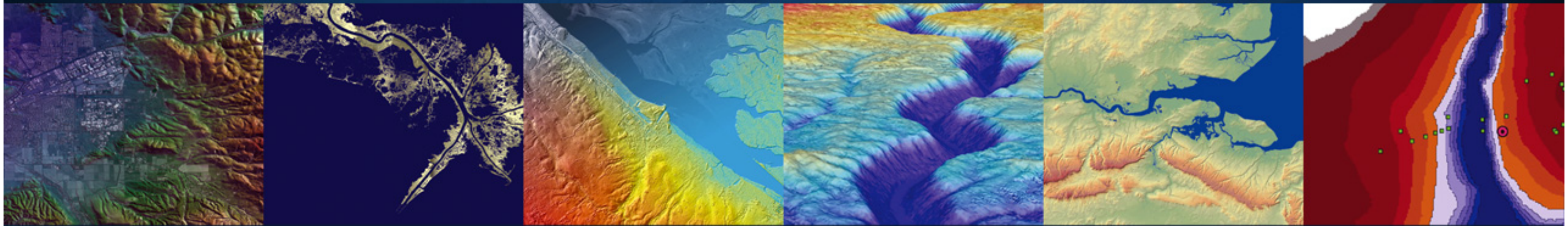
- **A Magnitude Image:** radar image created from the radar **Amplitude**
- **B Interferogram:** pixel by pixel phase difference – intermediate product
- **C Coherence Image:** measures how well the interferometer is working
- **D DEM:** digital elevation model generated from **Phase** interferometry

IFSAR Products



IFSAR Fundamentals Summary

- IFSAR involves the processing of Phase and Amplitude of a radar signal.
- Phase interferometry creates elevation information
- Interferograms and Coherence are intermediate products.
- DEM and ORI are raw outputs



Radar Phenomenology

www.intermap.com

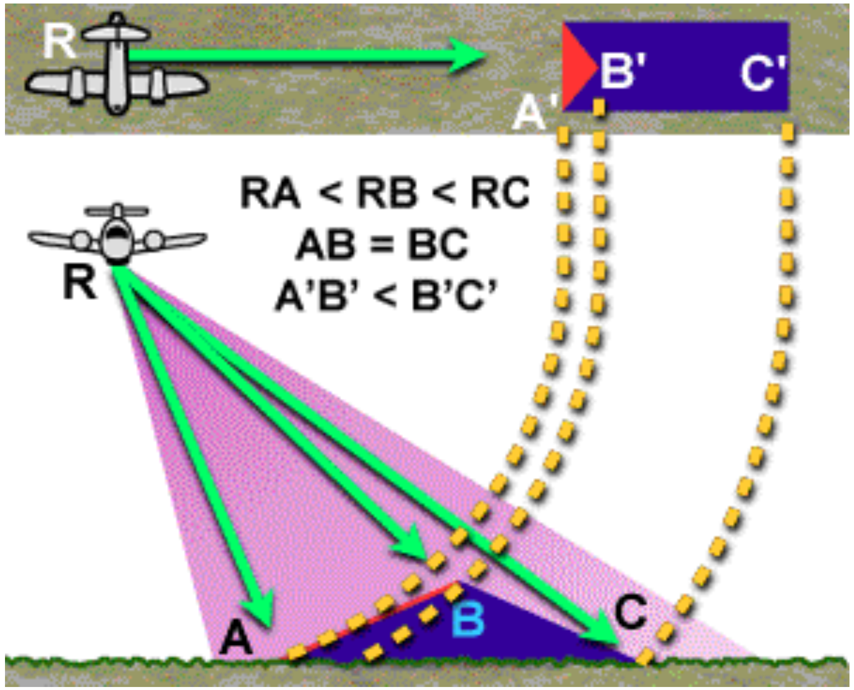
Core Products Artifacts

- Due to the nature of IFSAR technology and how data is captured, there are a number of artifacts that may affect product quality and accuracy.

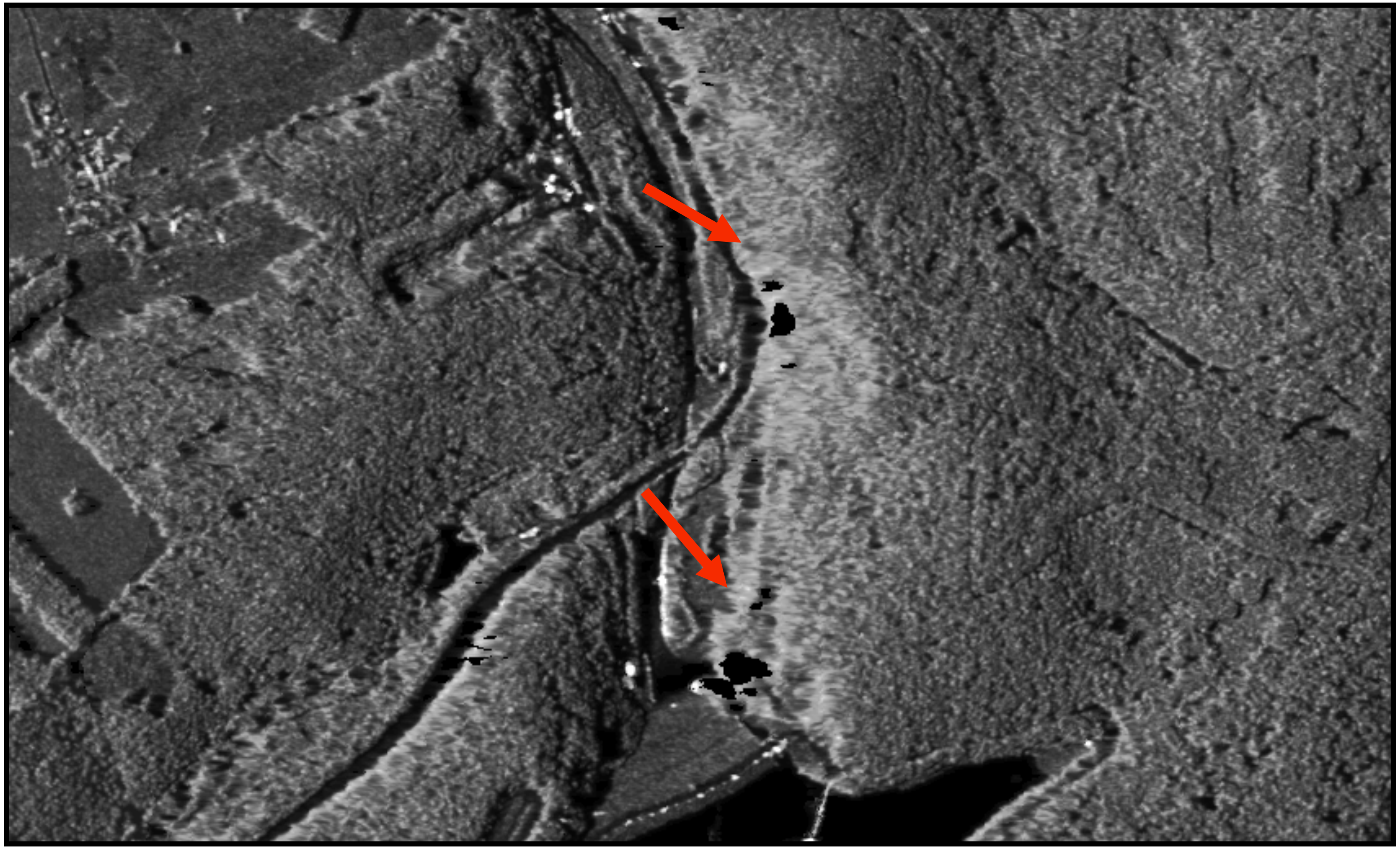
- These artifacts occur for different reasons and affect the data in different ways.
  - Foreshortening
  - Layover
  - Radar Shadow
  - Signal Saturation

Geometric Attribute: Foreshortening

- The appearance of compression of those features in the image which are tilted toward the radar.
- Leads to relatively brighter appearance of affected slope in the image.
- Maximum foreshortening occurs when a steep slope is *orthogonal* to the radar beam, such that the top, slope and base of the hill are imaged simultaneously (occupy the same position in the image).
- Foreshortening effects are reduced with increasing incidence angles (far range).



Foreshortening Illustrated

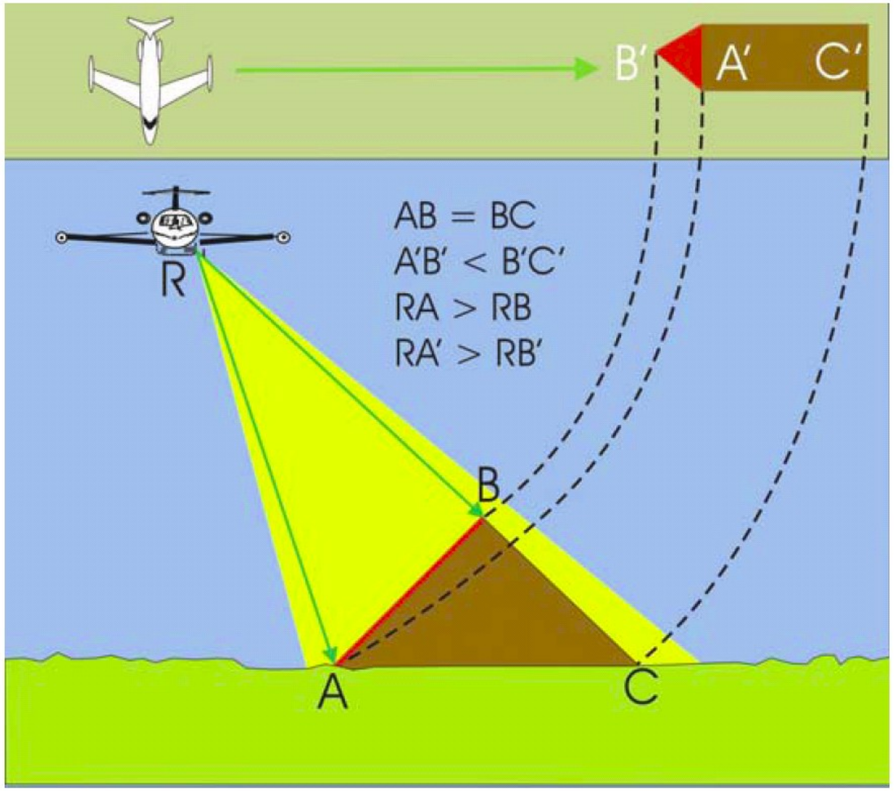


- Stretching of imagery in areas of foreshortening

Layover Illustrated

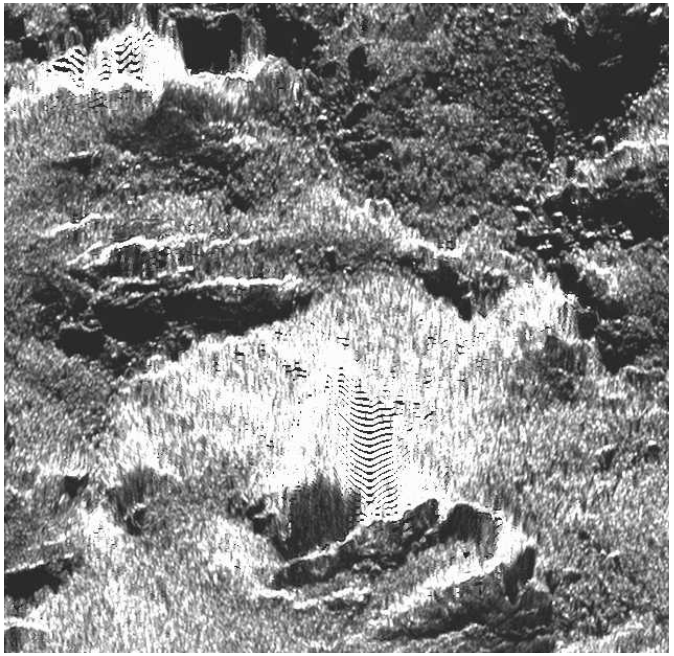
- This figure illustrates the geometric relationship that must exist between the ground and the radar for layover to occur.

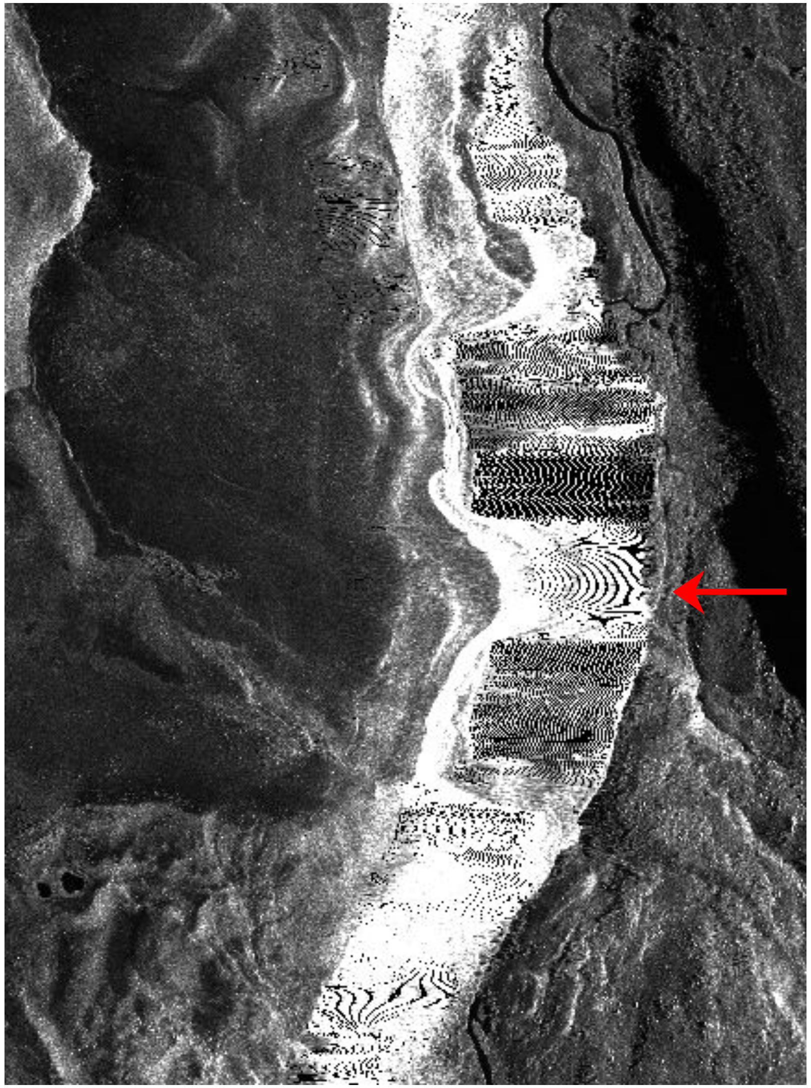
- The dotted lines show the time that the radar pulse takes to reach various parts of the mountain. Because the top of the mountain (B) is closest to the aircraft, it is imaged ahead of everything else (B’). The effect is to eclipse the view of the front of the mountain (in red).



Layover Examples

- In these examples, the striped pattern exists in layover regions. In most cases, such regions would simply appear black to indicate missing data.
- Intermap works to mitigate layover in the most cost effective way possible during the flight planning and acquisition process.



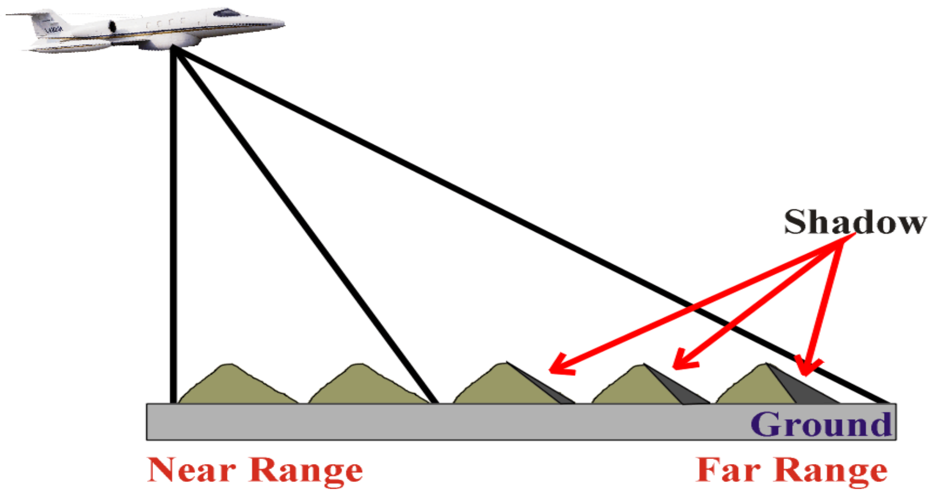


Radar Shadow

- Shadows indicate those areas on the ground *NOT* illuminated by the radar and appear very dark in tone on imagery because no return signal is received, shadows occur in down-range direction behind tall objects

- RADAR shadow occurs when the radar pulse cannot reach both sides of high objects, such as mountains. Areas of shadow have no reflectivity and appear black on the imagery.

- Shadow can be seen in the illustration on the right. Note that the location of the shadow gives an obvious clue as to the look direction of the radar. In this case the radar is looking to the right and as a result areas of shadow are on the right sides of the mountains. Conversely, the left sides return the strongest signals and hence appear brighter.



Radar Shadow Example

- Shadow is a geometric artifact that cannot be easily rectified.
- If an adjacent pass covers the shadow area it is possible that the area will be filled with data during the merge. If a large part of the pass is affected by shadow, second look data may need to be acquired to fill these areas in the DEM.
- Intermap works to minimize the amount of shadow in the ORI through effective mission planning.

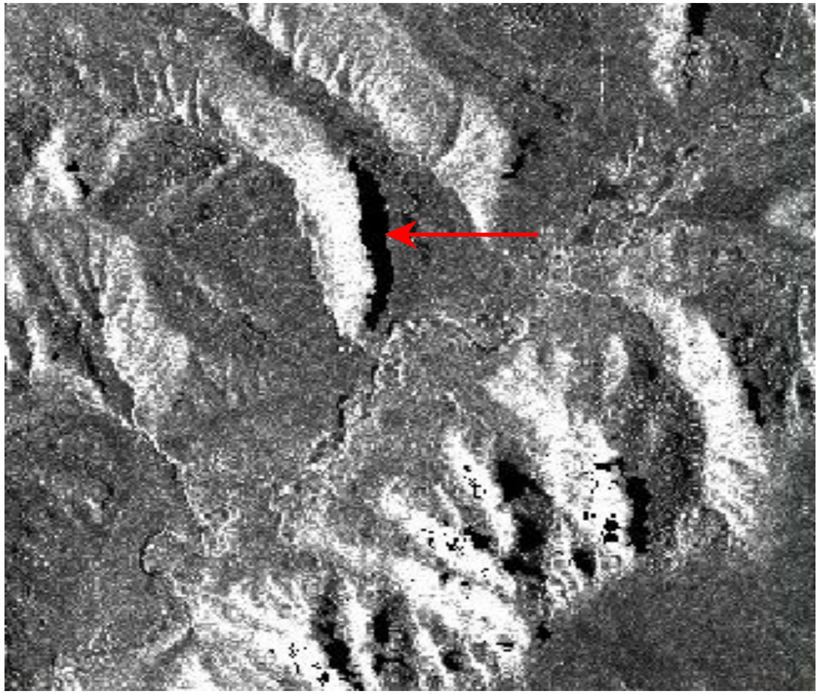
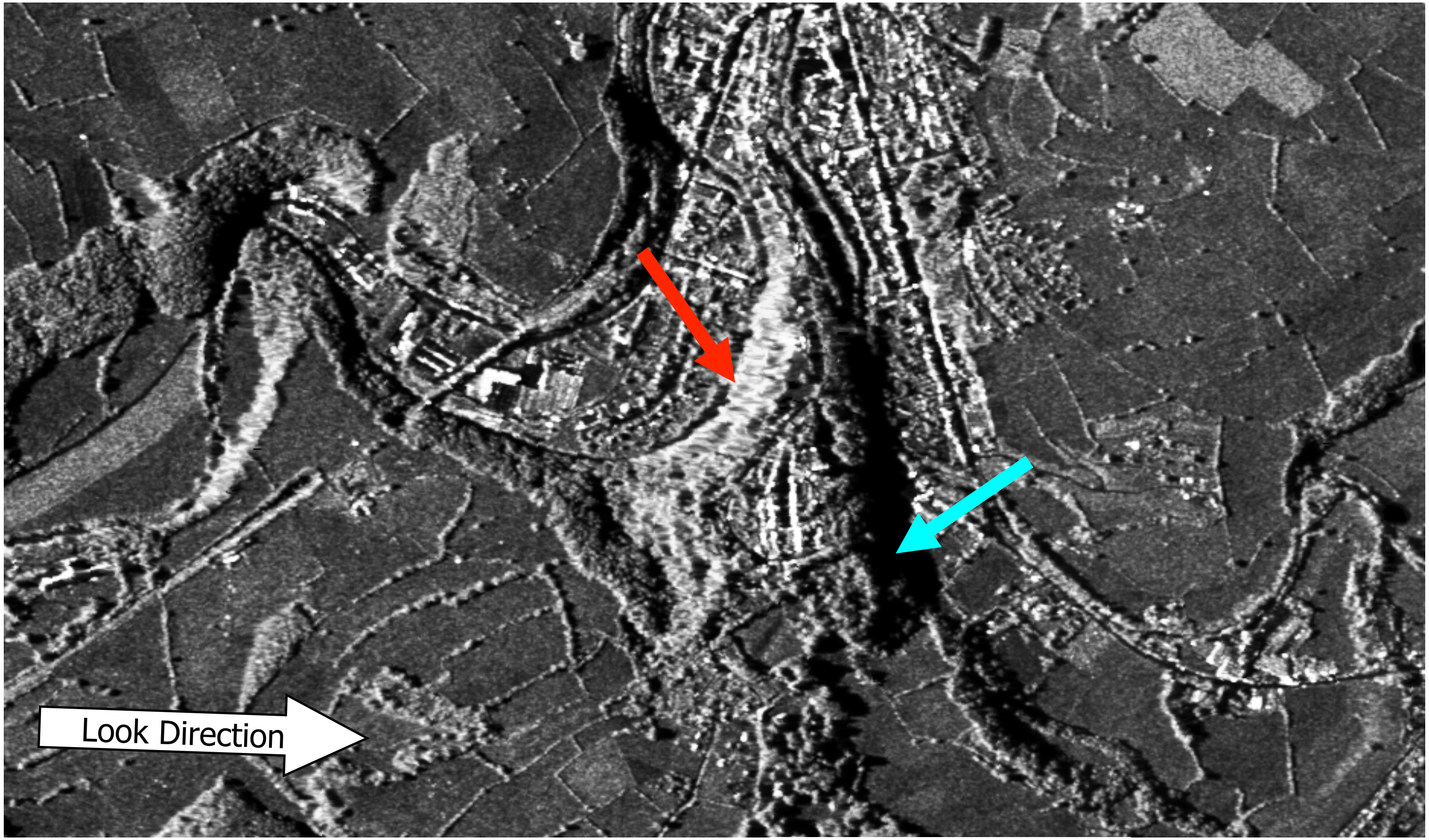


Figure: Dark region in center of image is an area of shadow where the radar pulse was not able to reach

Layover & Shadow Example

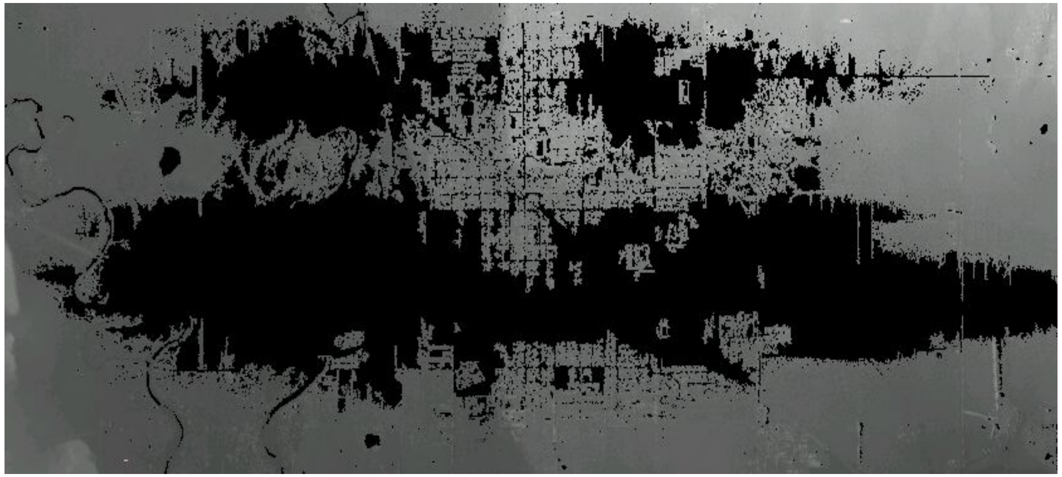
- There is always a trade off between amount of shadow and amount of foreshortening/layover.

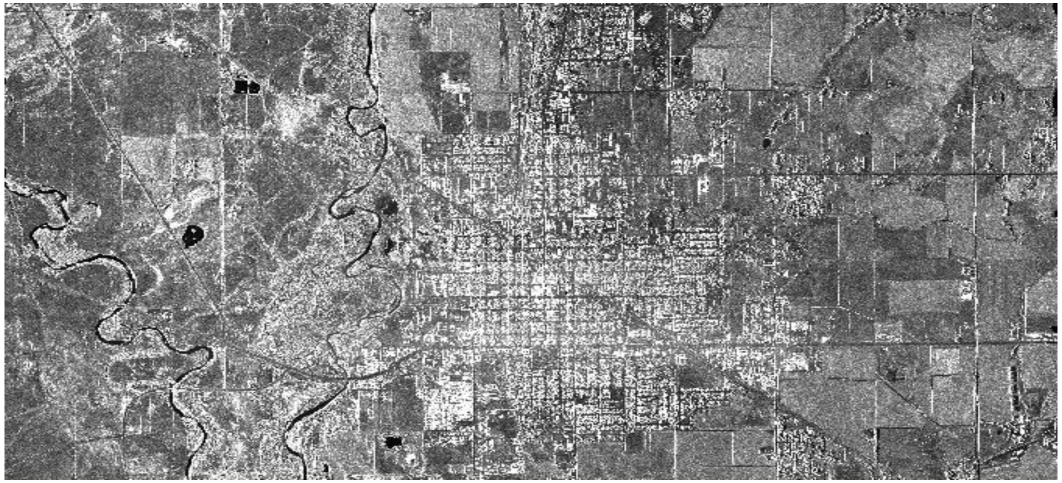


Signal Saturation

- The top figure shows a DSM where signal saturation has occurred. Intermap deals with this by generalizing the DSM across the affected areas, which means the vertical accuracies, are slightly degraded in those regions.

- However, in many cases, the ORI data can be completely recovered, as shown in the bottom figure.





IFSAR Fundamentals Summary

- IFSAR Theory
- Interferometric Processing
- IFSAR Products
- Radar Phenomenology

Questions?