CEOI SAR Workshop 22 November 2011

Introduction to SAR Techniques and Technologies

(Basic SAR Theory)

Presented by

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All the space you need

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Topics

- **fundamental principles;** synthetic optics along track with radar range delay across track

  ambiguities (along and across track)

- *statement, not derived* antenna area $\geq$ 4 vs λ R_{slant} tan i / c
- spatial resolution including waveform types; pulse, chirp,

- **phenomenology,** concept of sigma0 / reflectivity

  frequency / polarisation

- **sensitivity,** noise equivalent sigma0 leads to

  statements, not derived radar equation for SAR

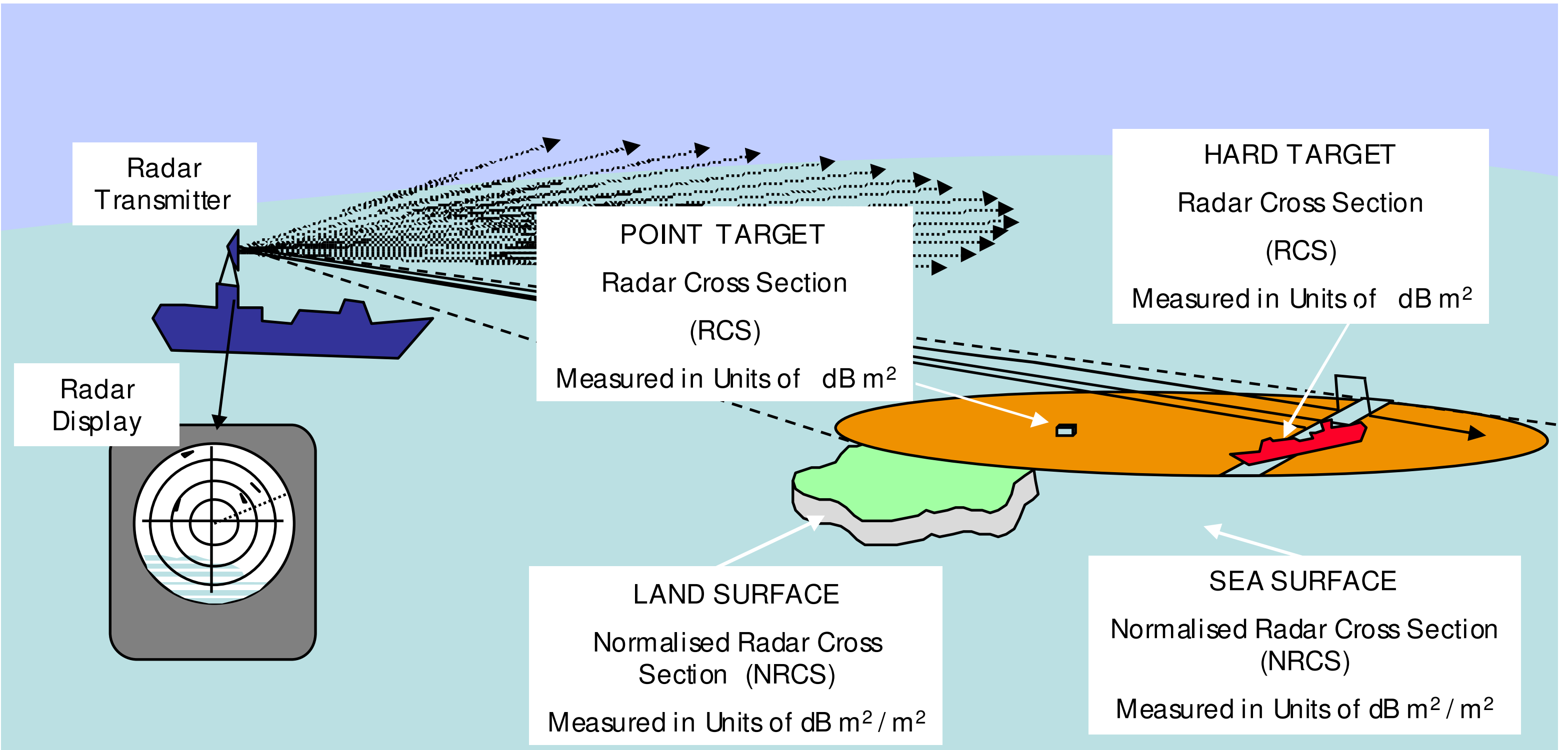
Topics

- **fundamental principles**
- **ambiguities and associated constraints**
- **phenomenology & aspects of reflectivity**
- **sensitivity for radar and SAR**
- **operating modes**

SAR Fundamental Principles

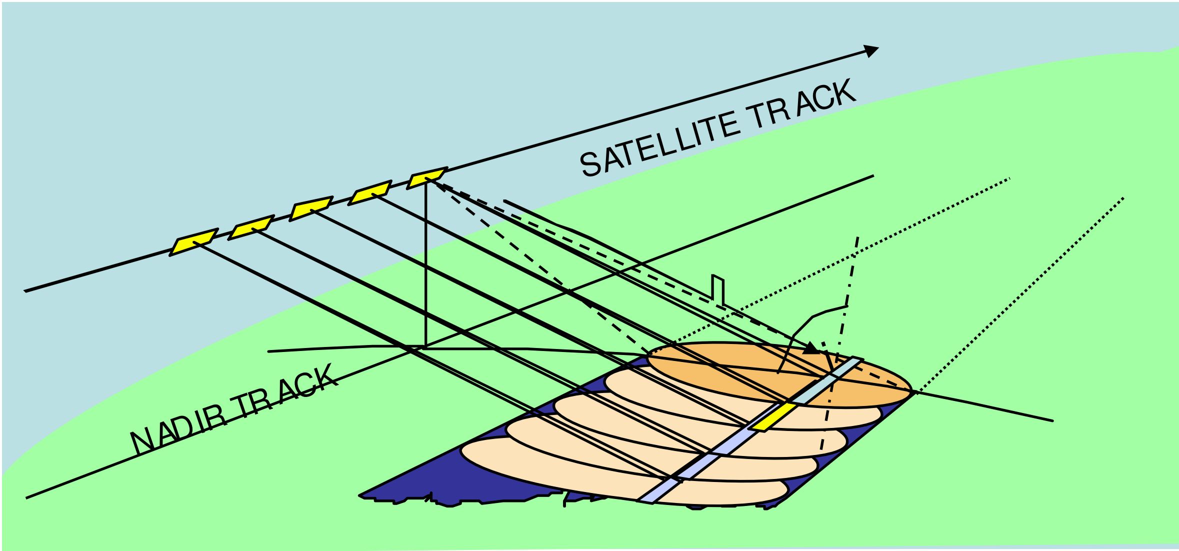
Fundamental Radar Principles polar scanning radar

- Use the **aperture** to define a beam in a polar axis around the radar
- Use **time delay** to measure distance in the other axis



Fundamental Principles along track, side looking radar

- Use the side-looking aspect to achieve across-track discrimination by virtue of echo return time
- Use progression along the trajectory to achieve along-track discrimination instead of rotation

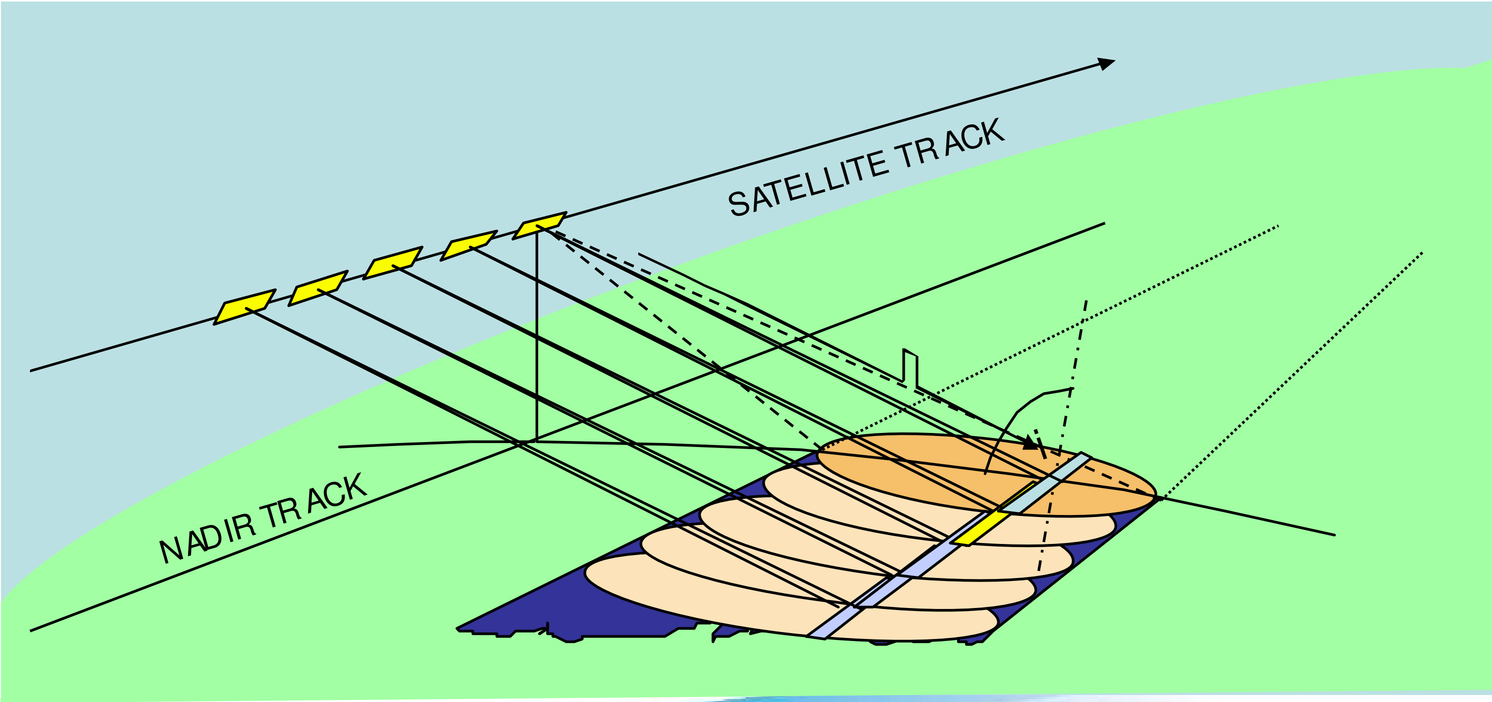


- Thus, the system defines two orthogonal axes to enable convenient image generation and display

Fundamental Principles along track, side looking radar

- Uses **antenna beam-width** to achieve along-track spatial discrimination i.e beam width = along-track resolution

- BUT - requires VERY long antenna to get fine resolution



Fundamental Principles – why radar rather than optics

- **Why use radar to view the Earth?**
  - We'd rather use optical sensors because we understand the image content better and the acuity (resolution) can be superb

  BUT
  - radar operates at night as well as by day
  - radar sees through cloud and rain

- **So what are the differences?**
  - Optical systems provide 2D images referenced to 2 orthogonal ANGULAR axes

  - Radar systems provide 2D images BUT referenced to 1 ANGULAR axis, and 1 RANGE DELAY axis

Fundamental Principles – measured parameters

- SAR in action measures three principal parameters of the features being observed:
  - along-track location of each given feature
  - across-track location of each given feature
  - reflectivity of each given feature

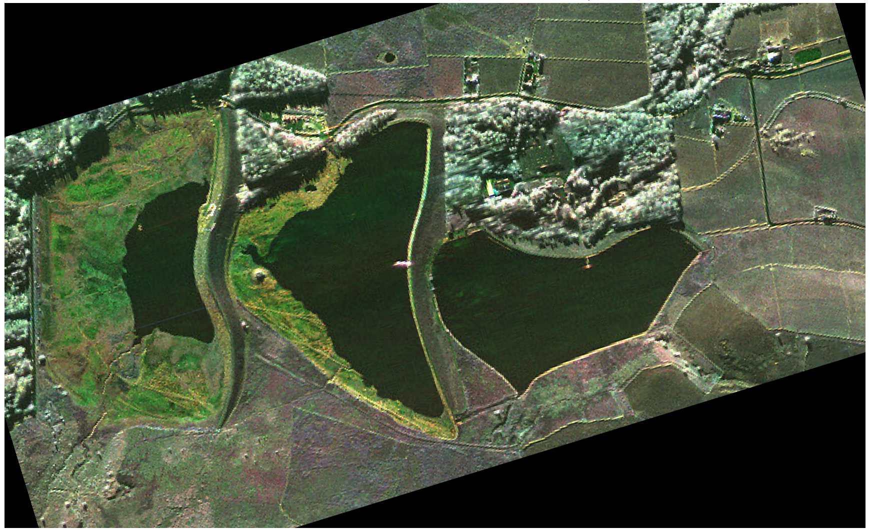
- Additionally, the measurement of reflectivity is made with respect to the polarisation state of the radar instrument
- Four possible states exist
  - Transmit H-pol and receive H-pol (co-polar HH)
  - Transmit V-pol and receive V-pol (co-polar VV)
  - Transmit H-pol and receive V-pol (cross-polar HV)
  - Transmit V-pol and receive H-pol (cross-polar VH)

Fundamental Principles Optics vs Radar

- Location, Redmires dams (near Sheffield)
  - (acquired at different times)

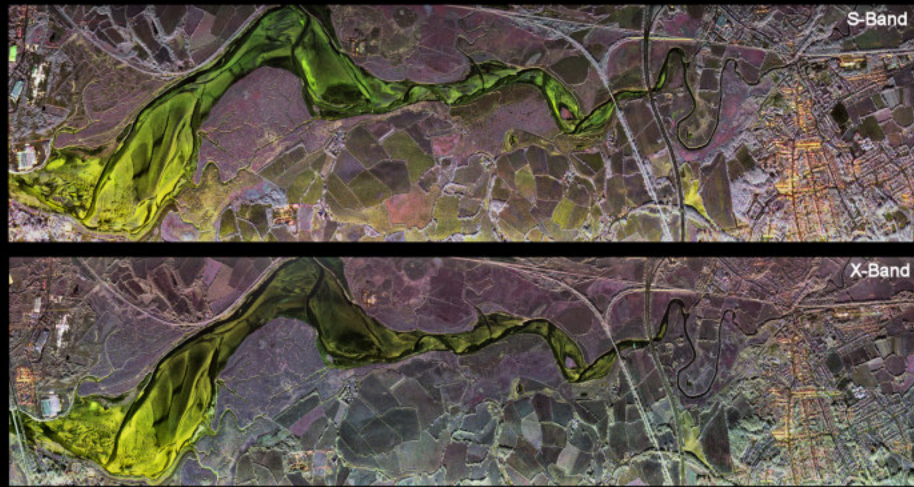
- Optical Image (Google Maps) — SAR image (Astrium X-band airborne SAR)

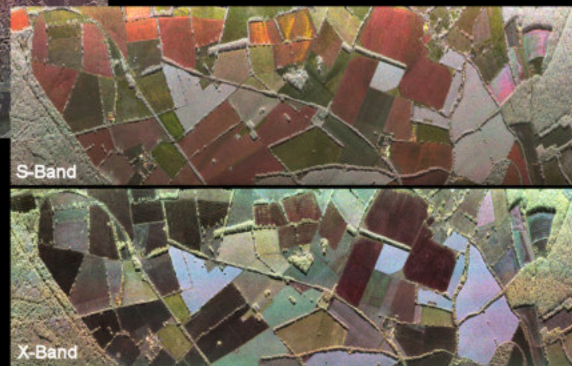
	Optical Image	SAR image
operating frequency	600, 000 GHz	10 GHz
wavelength	0.5 µm	0.03 m (30,000 µm)



Astrium UK Airborne SAR Facility

Simultaneous S+X Band Imaging
S-Band (3.2GHz), Quad Polar, <3m res
X-Band (9.6GHz), Quad Polar, <3m res
Swath Width ~2km
Sensitivity < -30dB





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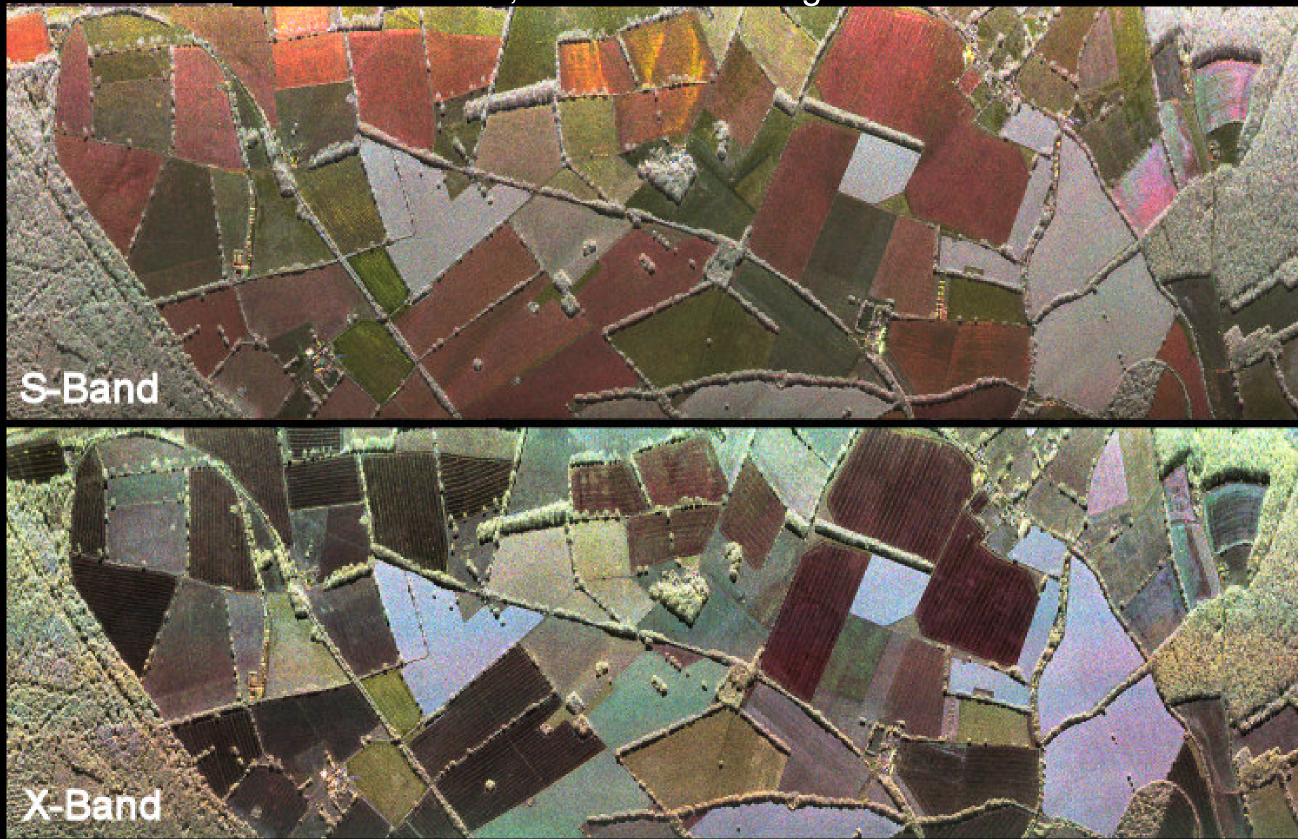
Fundamental Principles Radar Polarimetry

3.2 GHz, 9.4 cm wavelength

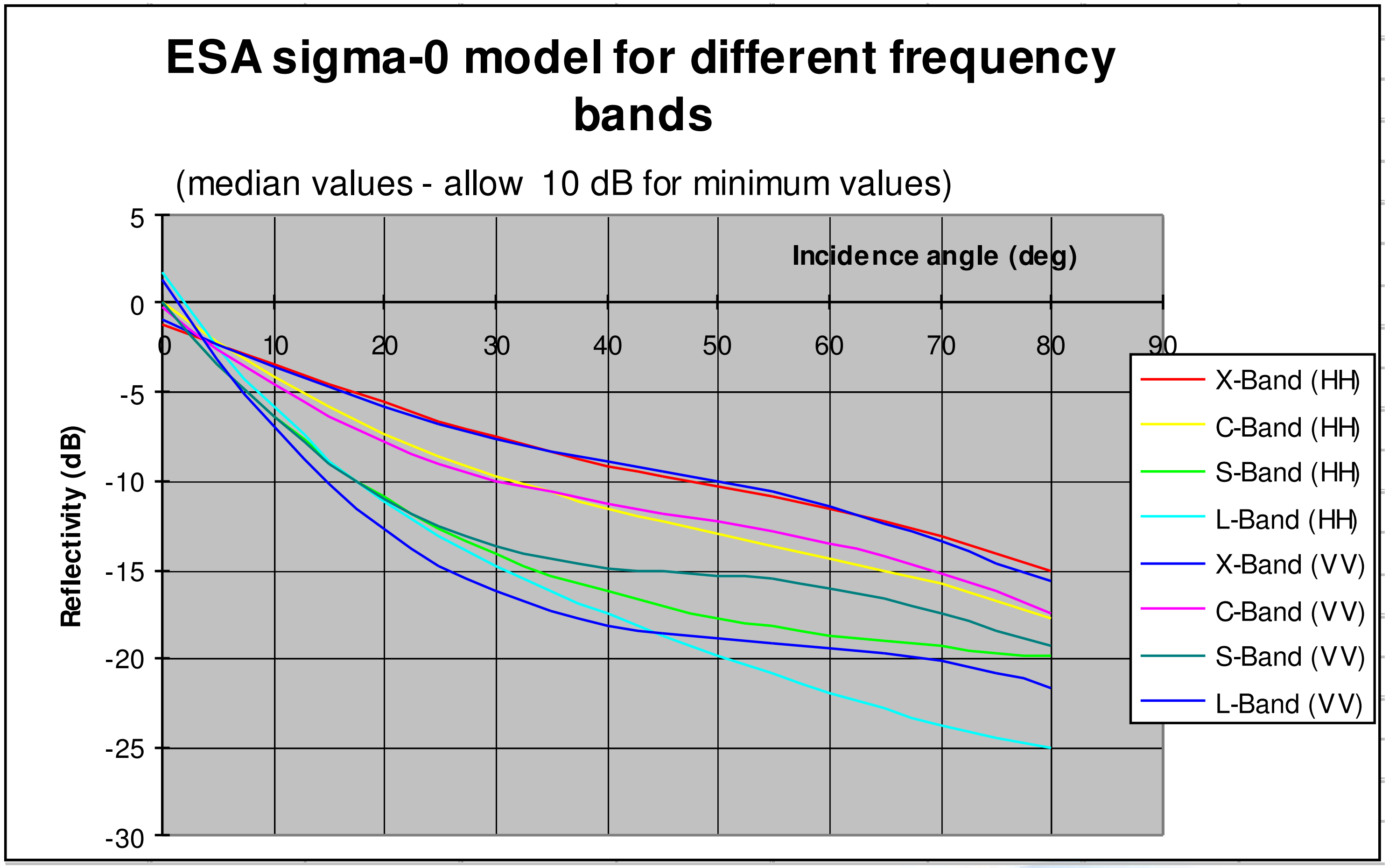


9.6 GHz, 3.1 cm wavelength

HH red VV green HV + VH blue

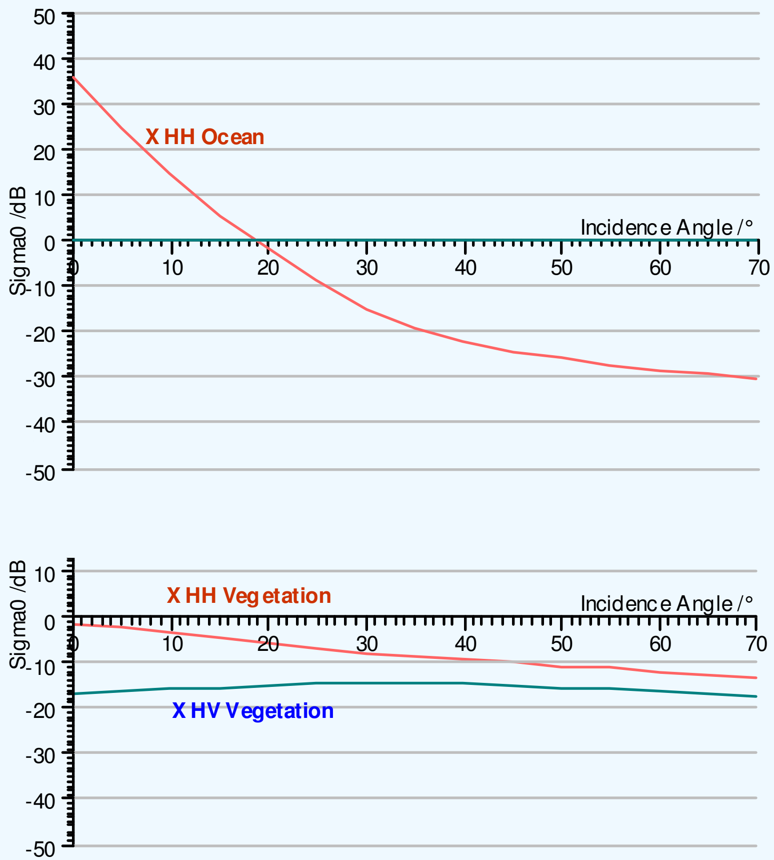
Colours still TBC

Reflectivity of Targets

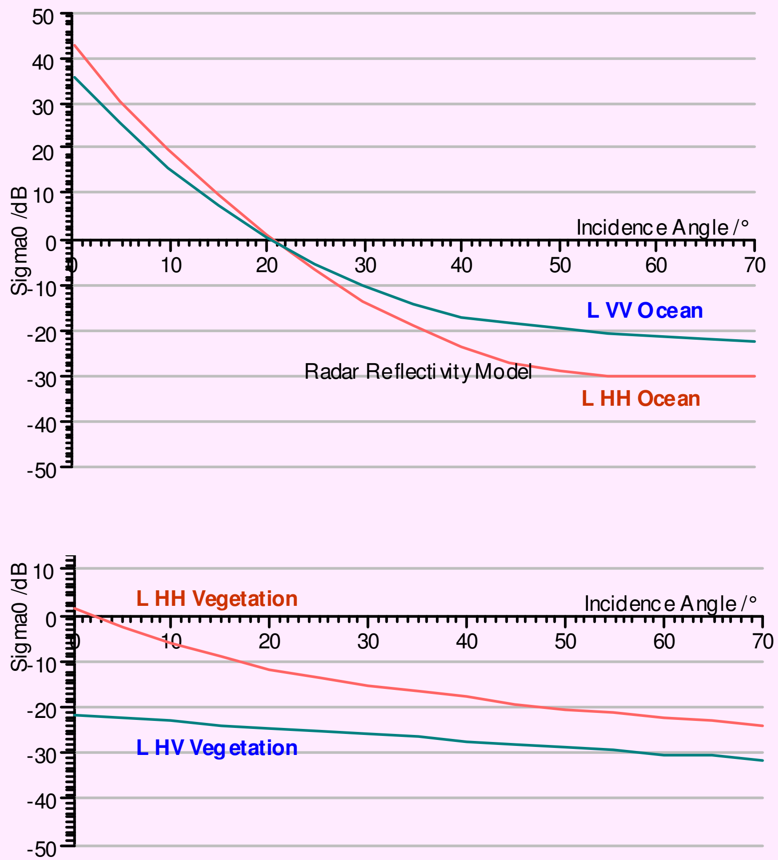


Reflectivity of Targets

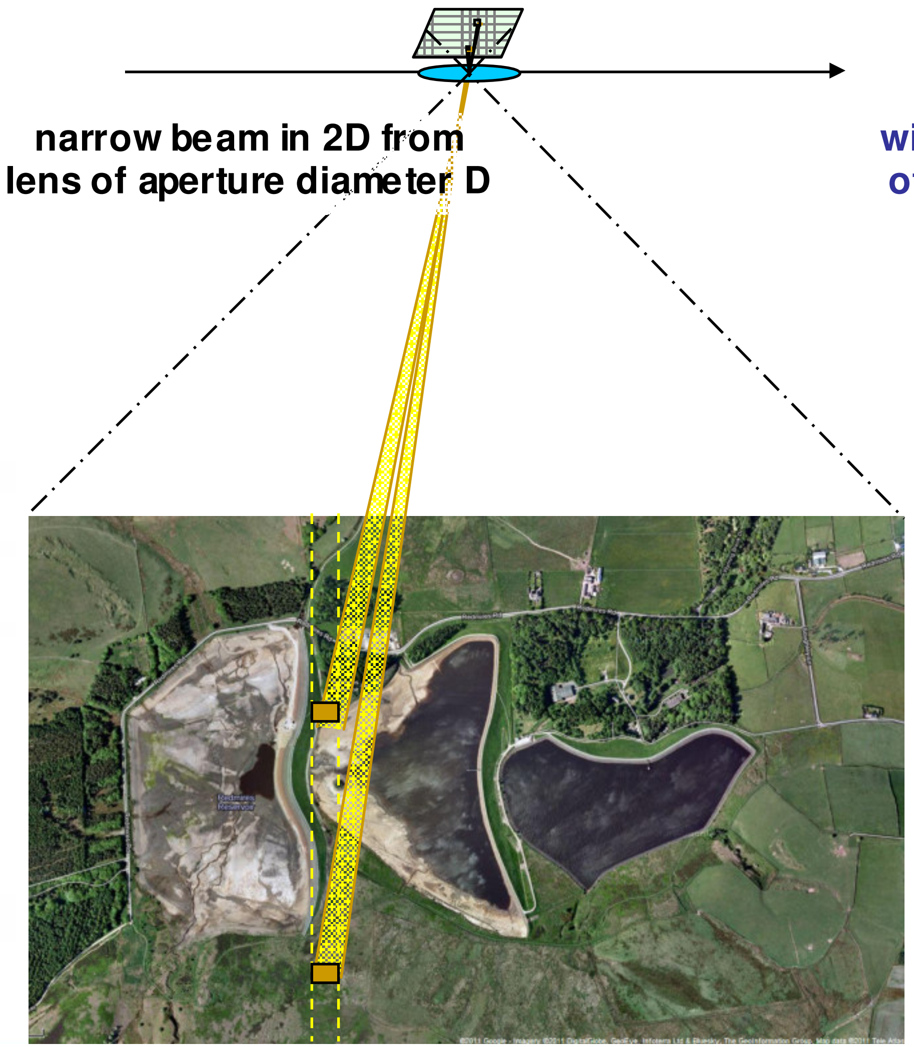
X-band Radar Reflectivity Models

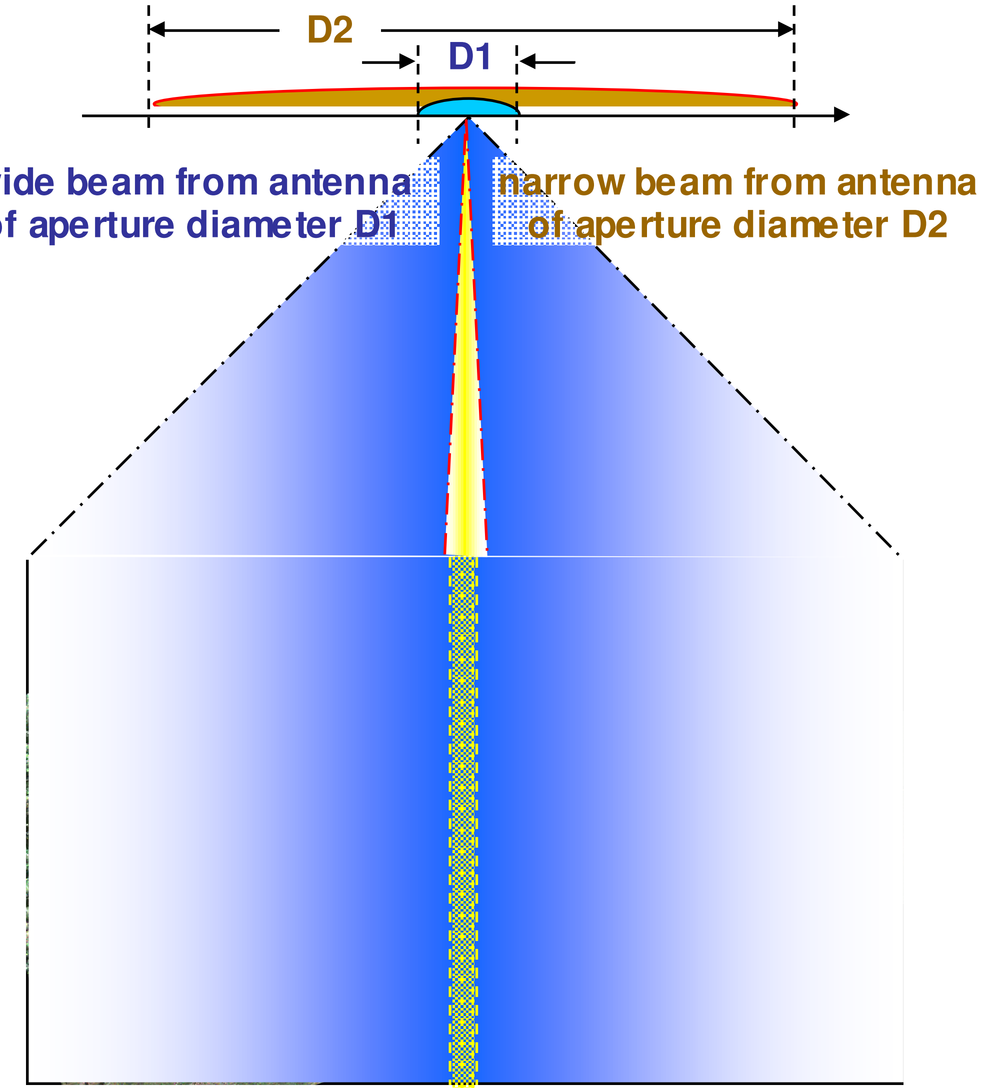


L-band Radar Reflectivity Models



Fundamental Principles Optics vs Radar





Fundamental Principles essence of SAR

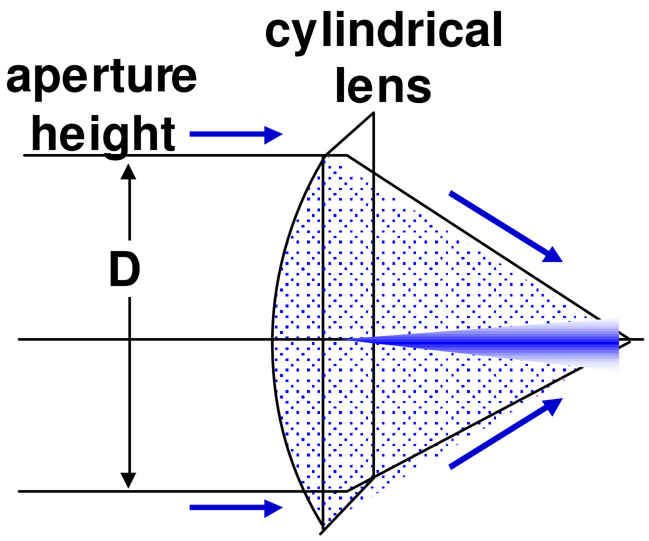
- Aperture synthesis
  - very difficult to realise an aperture sufficiently large to achieve fine resolution at radar operating frequencies, particularly from space

- Suppose we operate from 500km, and seek to achieve spatial resolution of 1m, while viewing at 45° at X-band
  - slant range to ground ~ 700km
  - need an aperture whose length is ~ 10km

- This length of 10km is not realistic for an antenna in space
- Instead, acquire coherent samples over 10km and synthesize the aperture

Fundamental Principles - optical spatial resolution

- Consider the simple lens, phase-path lengths to the focus are identical, all inputs add in-phase at the focus – but nowhere else - which is why we get a focal spot
- …. and **all paths** to the focus are **one way**

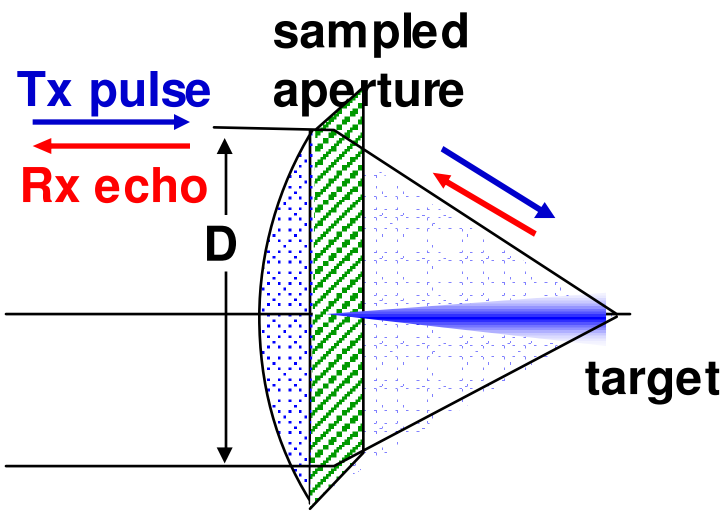


angular width θ of focal spot is given by

$$\theta = \frac{\lambda}{D}$$

Fundamental Principles - SAR spatial resolution

- With the SAR technique, phase-path lengths to the focus are caused to be identical during the processing, so all signals from the target location add in-phase – but those from elsewhere do not
- **Each path** to the focus is **two way** so the phase shifts are doubled compared with the simple lens

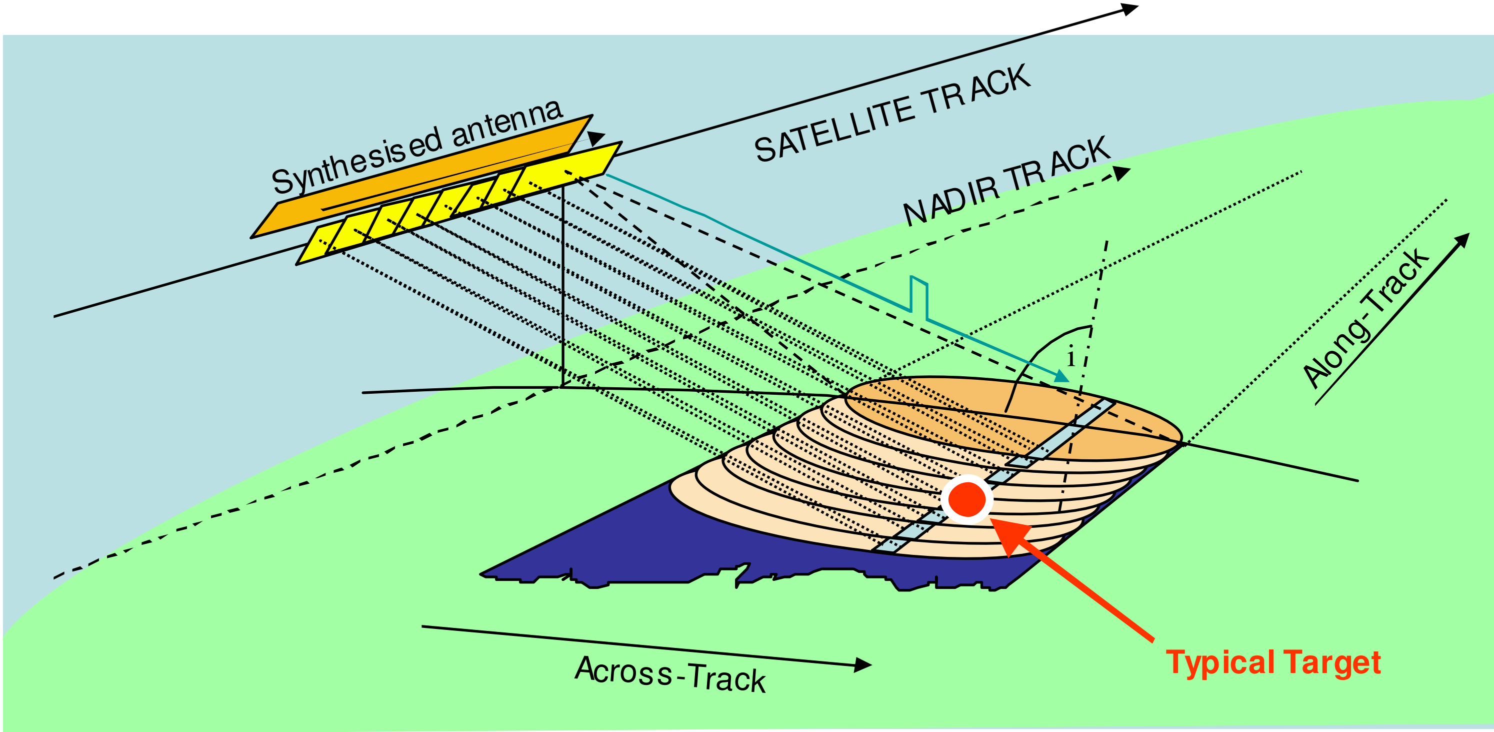


angular width θ of focal spot is halved and is given by

$$\theta = \frac{1}{2}\frac{\lambda}{D}$$

Fundamental Principles synthetic aperture radar (SAR)

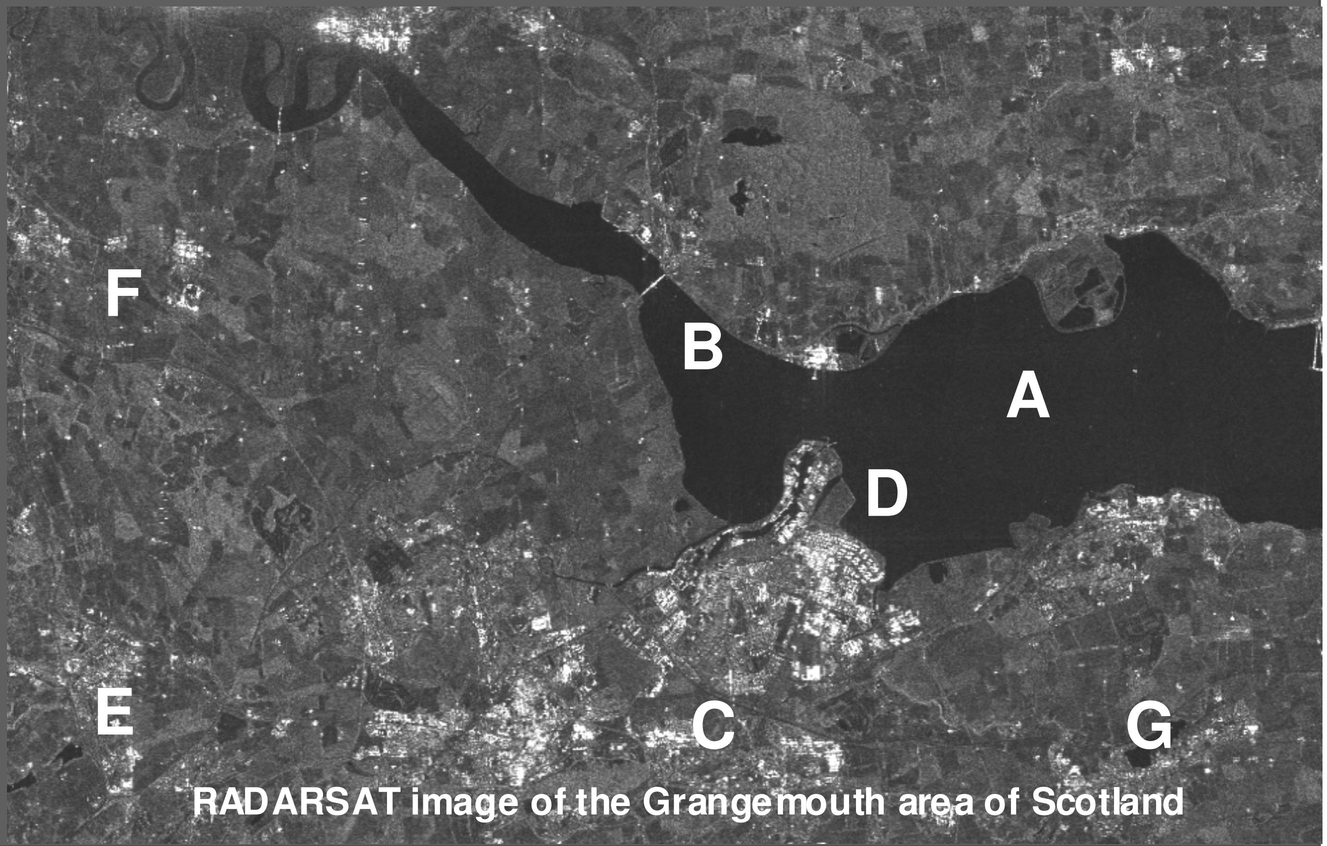
- Take multiple samples of echo returns as radar beam footprint traverses the target



- Oversampling compared with footprint enables tracking of phase history from each elemental target

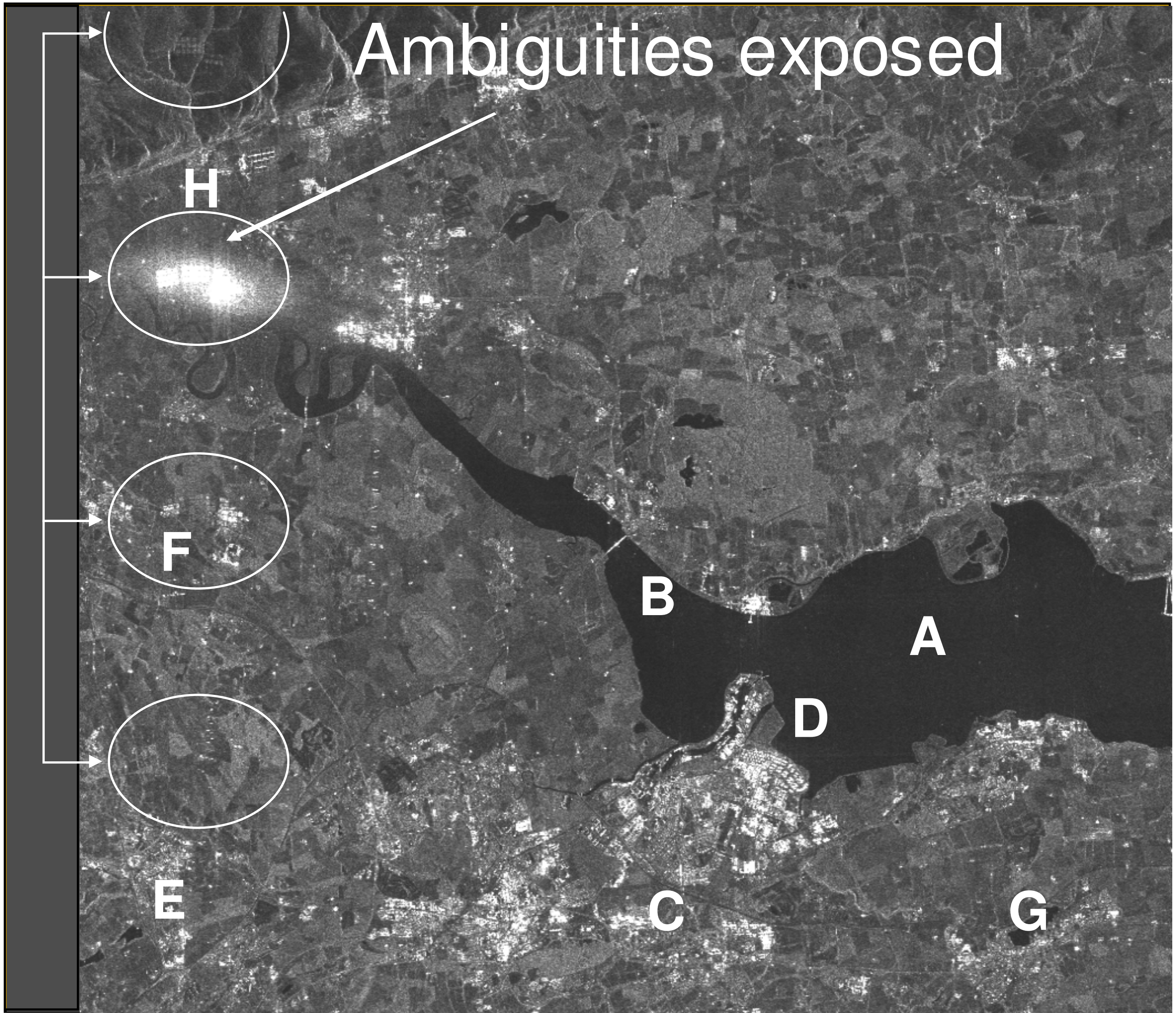
Radar Range and Azimuth Ambiguities

SAR scene containing ambiguities



RADARSAT image of the Grangemouth area of Scotland

Ambiguities exposed

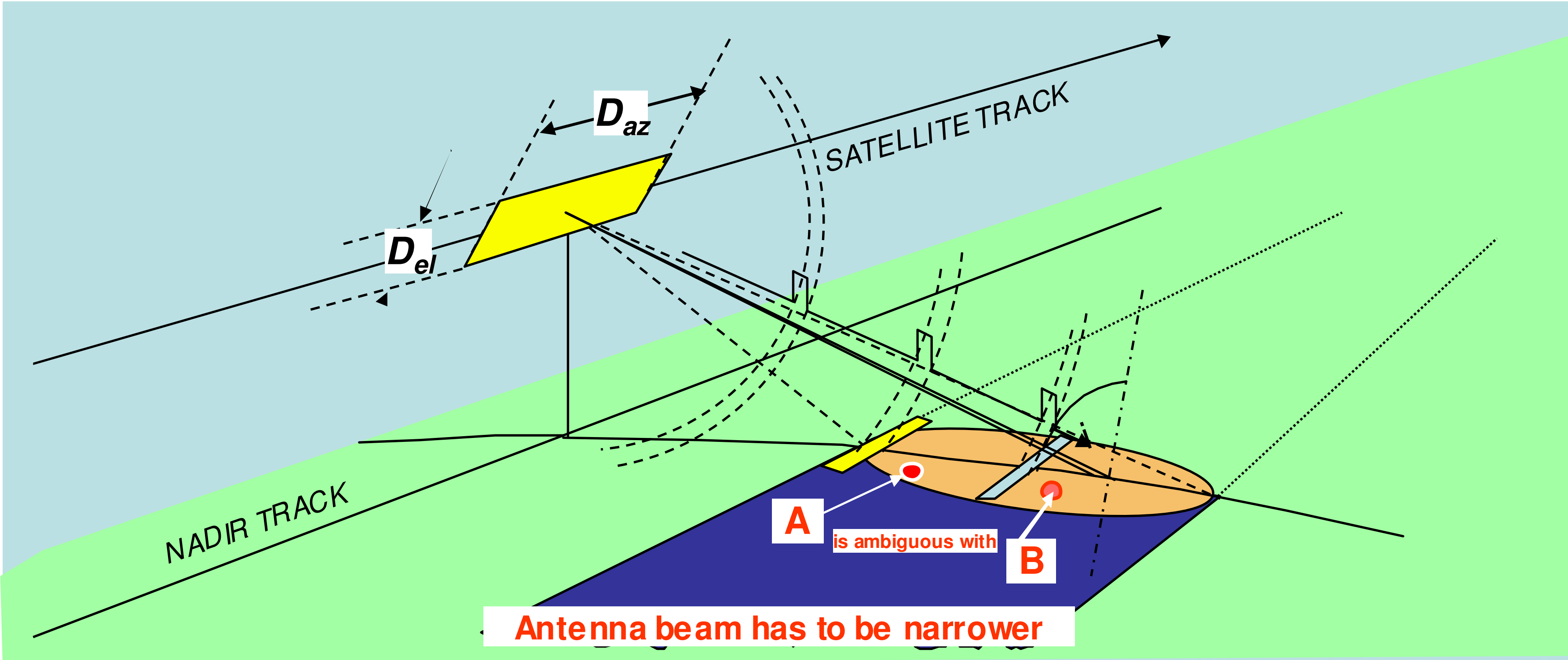


SAR system design

- We need to sample along the satellite track at a rate adequate to maintain the phase shift from sample to sample at less than π otherwise we encounter azimuth ambiguities
- For example, a satellite in typical SAR orbit (height around 600km) flies at around 7.5km/sec, and a typical SAR satellite antenna might be anything between 3 and 30m in length - 10 m is quite typical so that the spacing is slightly smaller than 5m.
- The footprint length is several km, so a few Hz would sample the "real aperture" (RAR) case adequately
- But in the SAR case the PRF is in the region of 1500Hz

SAR system design

- There is a disadvantage from operating at such a high PRF from our 600km orbit, we have several pulses on the fly at any instant.
- We can tolerate only one pulse crossing the footprint at any instant, otherwise we encounter ‘range’ ambiguities



Combined constraints on antenna area

- The constraint on the azimuth antenna dimension is

$$D_{az} \geq 2 \frac{v_{sat}}{prf}$$

- The constraint on the elevation antenna dimension is

$$D_{el} \geq \frac{2 \lambda R \, prf \, \sin\iota}{c \, \cos\iota} = \frac{2 \lambda R \, prf \, \tan\iota}{c}$$

These constraints coupled with the antenna height constraint enable us to make a statement about the minimum area required of the antenna to avoid ambiguities

$$A_{ant} = D_{az} D_{el} \geq 4 \frac{v_{sat} \lambda R \tan\iota}{c}$$

- a bit of algebra from the student will confirm this!

Radar Pulse waveform

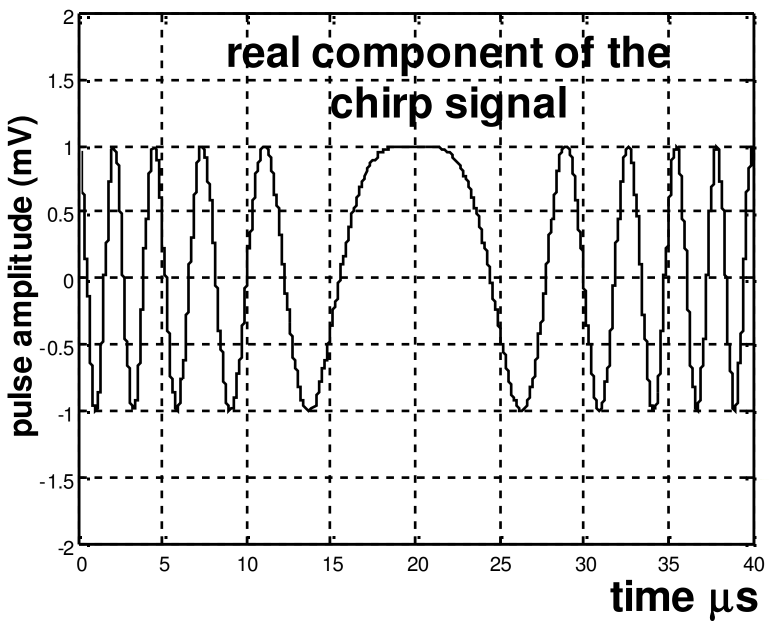
Fundamental Principles back to the radar part of SAR

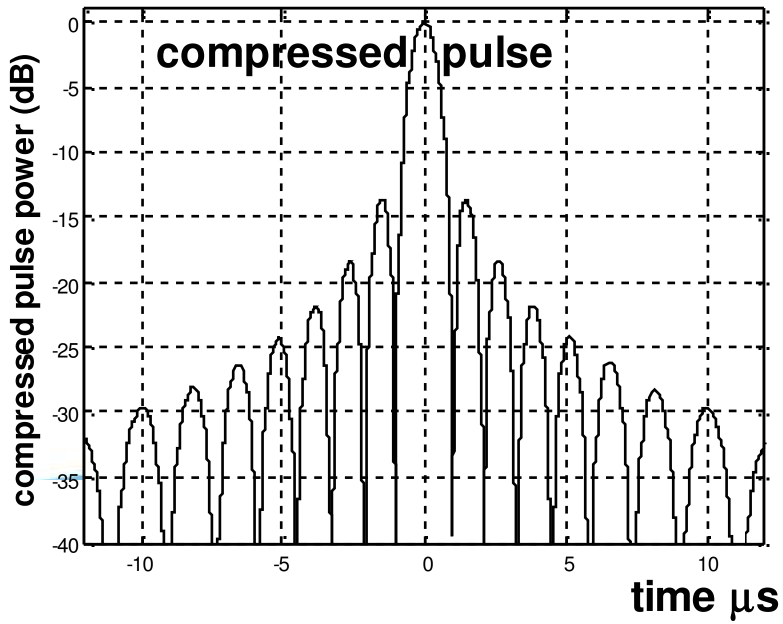
- So far we have talked about the radar pulse as short burst of RF energy projected towards the ground.
- However, short bursts deliver only low levels of energy and demand (very) large peak powers to achieve adequate sensitivity - which becomes a hard driver of Tx technology

- An alternative approach to delivering adequate energy is to transmit a long duration pulse of smaller peak power
  - which is easier on the technology
- .... but long pulses make it more difficult to provide fine across-track resolution

Fundamental Principles back to the radar part of SAR

- The outcome of this issue is the provision of internal modulation of the long pulse.
- It has been found that if that internal modulation is provided as a linear FM ramp (chirp), then it is possible to use correlation techniques to “compress” the energy associated with echoes from such illumination into a (much) shorter burst enabling fine across-track resolution.





Radar radiometry for SAR

Radar radiometry for SAR - single pulse

- Of the scattered flux, a proportion P_{echo} is intercepted at the antenna (by its angular subtense relative to the scatterer) and delivered to the initial receive amplifier (the LNA) where the system noise figure is defined.

$$P_{echo} = J_{echo} \frac{A_{ant}}{R^2} = \left(\frac{P_{pk} \; A_{ant}}{4 \, \pi \, R^2 \, \lambda^2} \, \sigma_{echo} \right) \frac{A_{ant}}{R^2}$$

- So far we have assumed a loss free system, but now, acknowledging that the world is not quite like that, we introduce the following loss factors
  - between HPA and antenna
  - between antenna and target
  - between target and antenna
  - between antenna and LNA

and associate these with a single system loss factor L_{sys} and get

$$P_{echo} = \left(\frac{P_{pk} \; A_{ant}^2}{4 \, \pi \, R^4 \, \lambda^2} \, \sigma_{echo} \right) L_{sys}$$

Radar radiometry for SAR - noise on a single pulse

- The echo signal intercepted at the antenna and delivered to the LNA is associated with a noise signal from the LNA given by

$$P_n = k\,T\,B\,N_f$$

- so that the single pulse signal to noise ratio is given by

$$SNR = \left(\frac{P_{pk}\, A_{ant}^2}{4\,\pi\, R^4\, \lambda^2\, k\,T\,B\,N_f}\, \sigma_{echo} \right) L_{sys}$$

Radar radiometry for SAR - multiple pulses

- The radiometry described so far applies to the echo resulting from a single pulse.
- However, when we exploit aperture synthesis, we integrate a set of echoes, each component of which is phase weighted to give a signal corresponding to that small region that we identify as the SAR azimuth resolution cell
- Suppose we integrate M, phase adjusted echoes, then the amplitude of the phase adjusted signal rises by a factor M, while the amplitude of the noise level rises by a factor $M^{1/2}$
- Thus, the signal power rises by M^2 while the noise power rises by M,
- **Values now need to be determined for** σ and $\boldsymbol{M}$

Radar radiometry for SAR - SNR for SAR

- Simplifying the expression for *SNR*, we get

$$SNR = \frac{P\, A_{ant}^2}{4\,\pi\, R^3\, \lambda\;\, k\, T\, B\, N_f} \left(\frac{c}{4\, v_{sat} \sin\iota}\, \sigma_0 \right) L_{sys}$$

- Now, we define a parameter Noise Equivalent σ0 as NEσ0 = σ_0 when SNR = 1

$$NE\sigma_0 = \frac{4\,\pi\, R^3\, \lambda\;\, k\, T\, B\, N_f}{P\, A_{ant}^2\, c} \left(\frac{4\, v_{sat} \sin\iota}{L_{sys}} \right)$$

- Alternatively, expressing NE σ0 in terms of antenna gain where $A = G\left(\frac{\lambda^2}{4\,\pi}\right)$

$$NE\sigma_0 = \frac{(4\,\pi)^3\, R^3\;\, k\, T\, B\, N_f}{P\, G^2\, \lambda^3\, c} \left(\frac{4\, v_{sat} \sin\iota}{L_{sys}} \right)$$

SAR Operating Modes

SAR Operating Modes

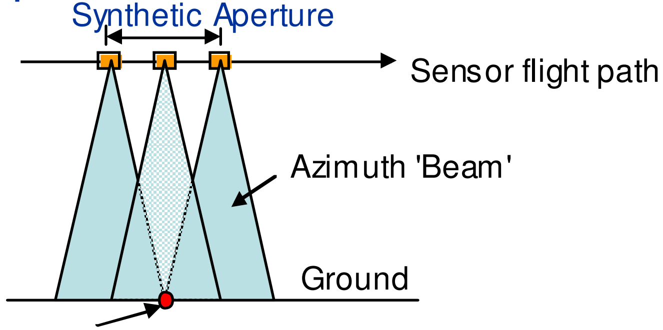
- **Classical SAR Operating Modes** include:
  - Stripmap (provides a single swath to view the target scene)
  - ScanSAR (provides wide swath by imaging contiguous swaths, but degrades the resolution)
  - Spotlight (provides vignettes of the image scene at finer resolution than the ultimate achievable from Stripmap)

- Additionally, sub-sets of these modes can be defined depending on **polarisation** and **number of looks** (image quality)

SAR Operating Modes

Stripmap

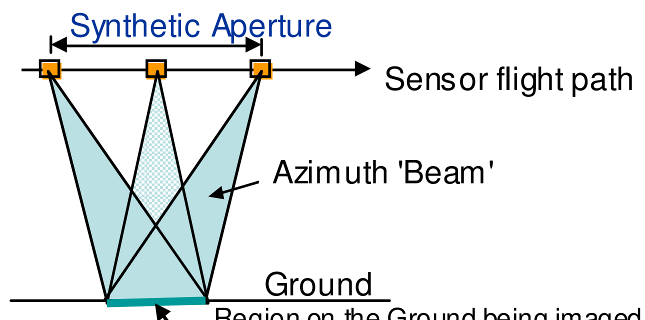
'Basic' SAR mode



Point on the Ground being imaged
Continuous image length possible, 1 swath only

Staring Spotlight

Improved azimuth resolution



Region on the Ground being imaged (image 'length')
Image length constrained to azimuth footprint, 1 swath c
Non-uniform sensitivity along-track

ScanSAR

Improved swath width at the expense of azimuth resolution

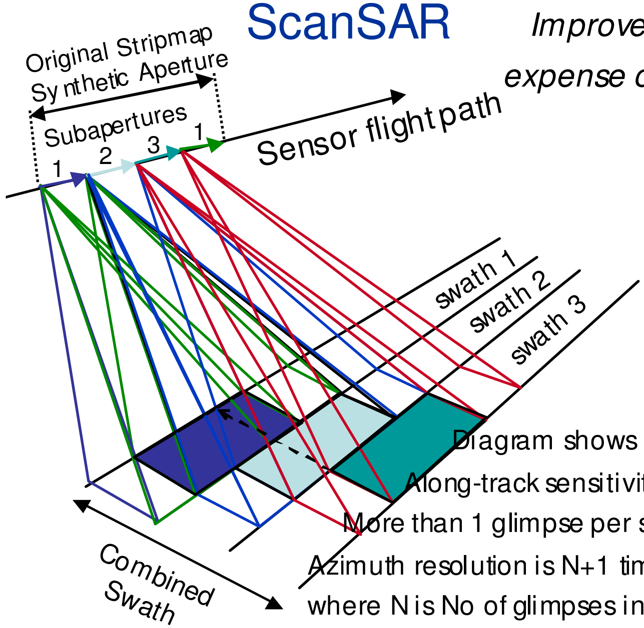
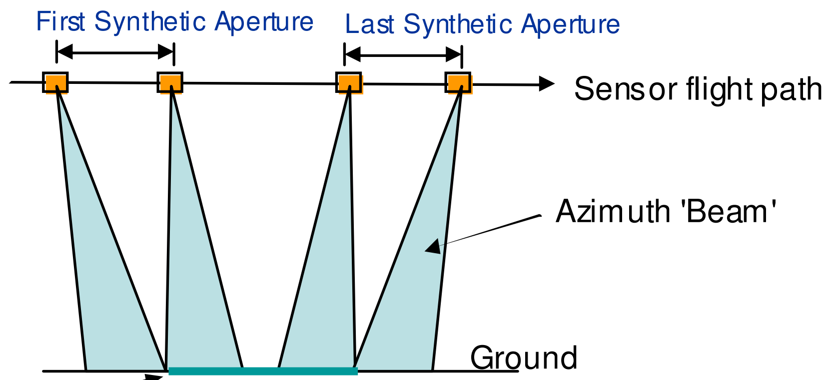


Diagram shows 3 'glimpses', 1 per swath
Along-track sensitivity variation : "Scalloping"
More than 1 glimpse per swath reduces scalloping
Azimuth resolution is N+1 times worse than Stripmap
where N is No of glimpses in the ScanSAR sequence

Sliding Spotlight

Improved azimuth resolution

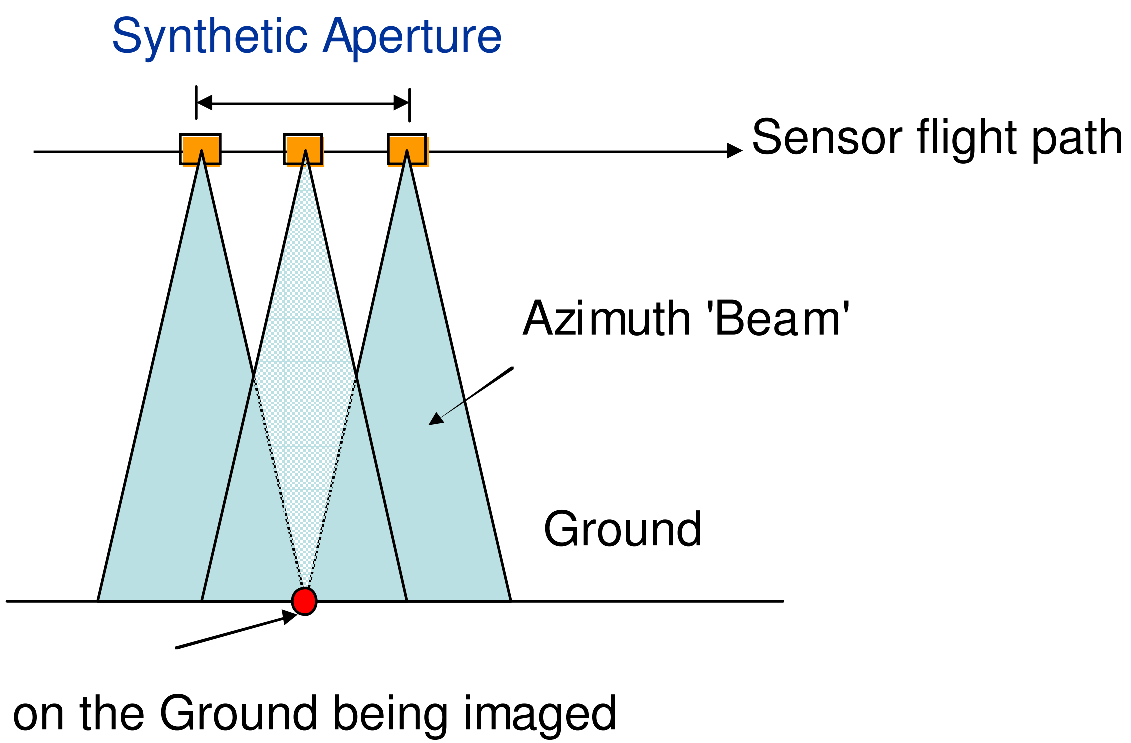


Region on the Ground being imaged (image 'length')
Image length not constrained to azimuth footprint, 1 swath only
Larger image length that Staring Spotlight
Uniform sensitivity along-track
More azimuth steering required as image length increases

SAR Operating Modes

Stripmap Mode

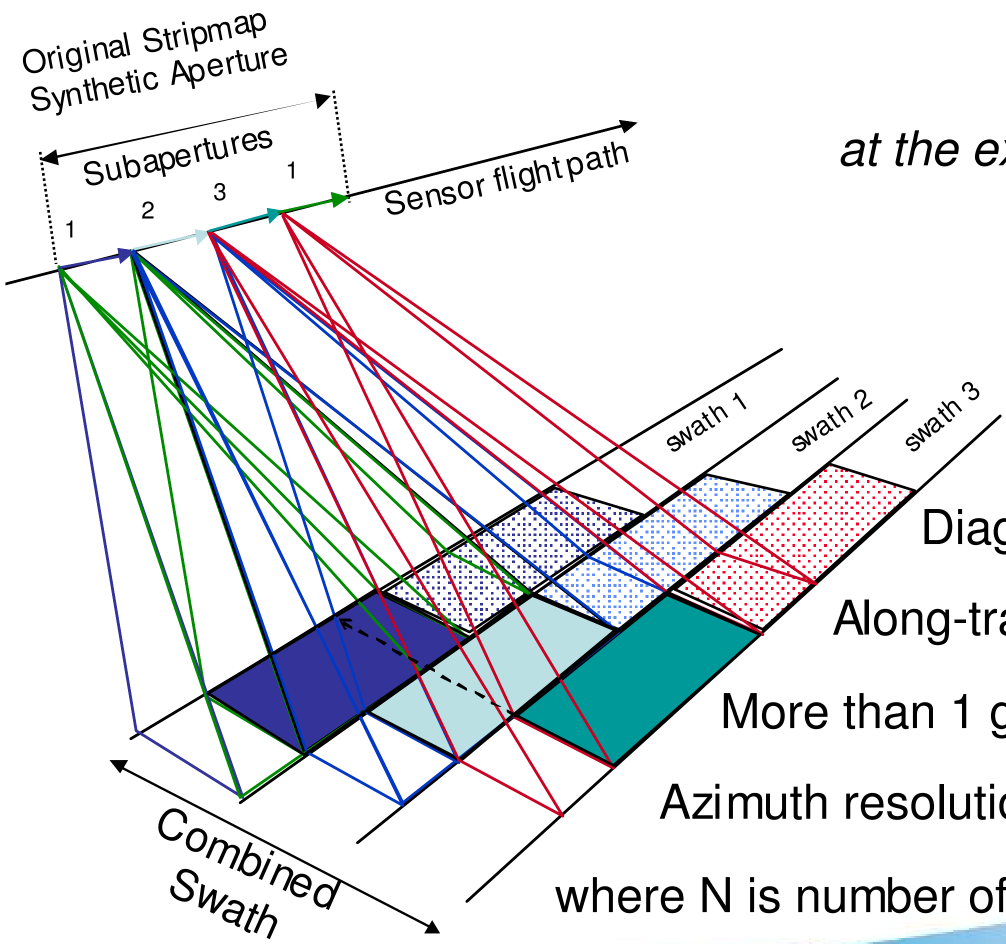
'Basic' SAR mode



Continuous image length possible, single swath

SAR Operating Modes

ScanSAR



ScanSAR provides improved swath width

but

at the expense of azimuth resolution

Diagram shows 3 'glimpses', 1 per swath

Along-track sensitivity variation : "Scalloping"

More than 1 glimpse per swath reduces scalloping

Azimuth resolution is N+1 times worse than Stripmap

where N is number of glimpses in the ScanSAR sequence

SAR Operating Modes

Staring Spotlight

provides Improved azimuth resolution

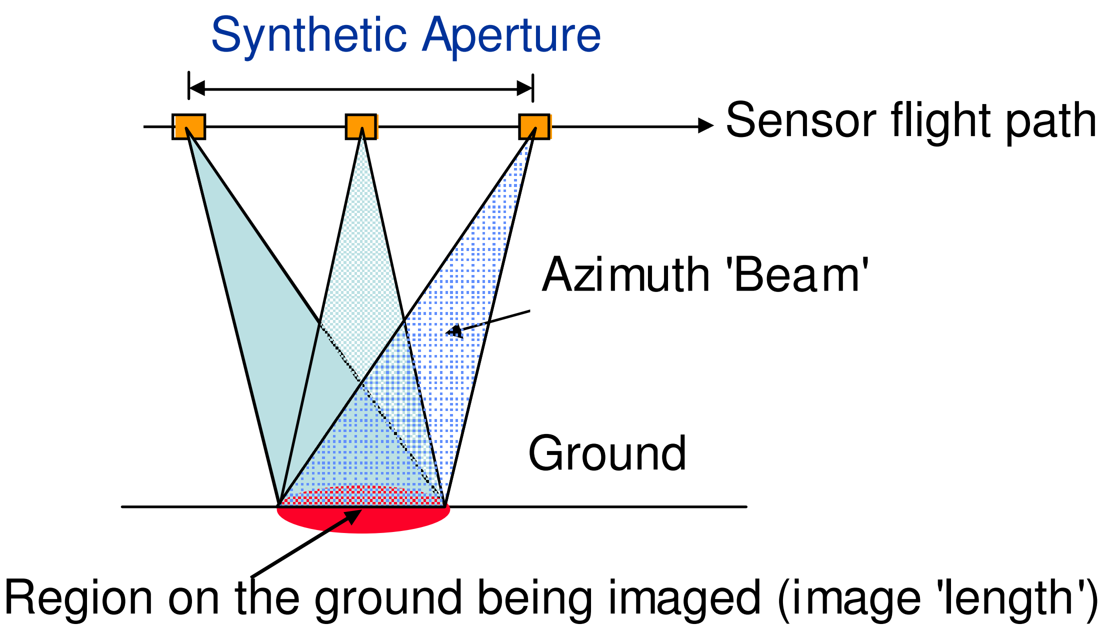
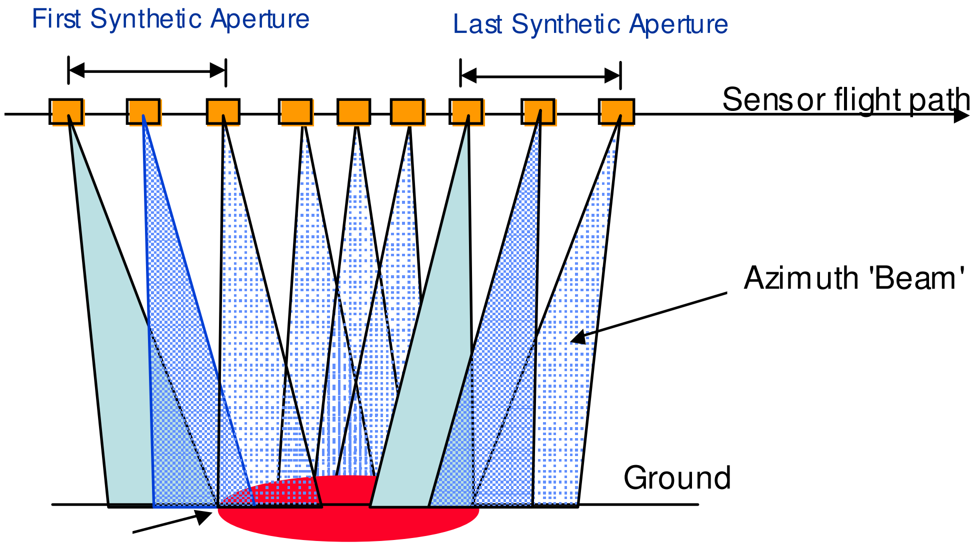


Image length constrained to azimuth footprint, 1 swath only

Non-uniform sensitivity along-track

SAR Operating Modes

Sliding Spotlight *provides Improved azimuth resolution*



Region on the Ground being imaged (image 'length')

image length <u>not</u> constrained to azimuth footprint, 1 swath only

larger image length that Staring Spotlight

uniform sensitivity along-track

but more azimuth steering required as image length increases