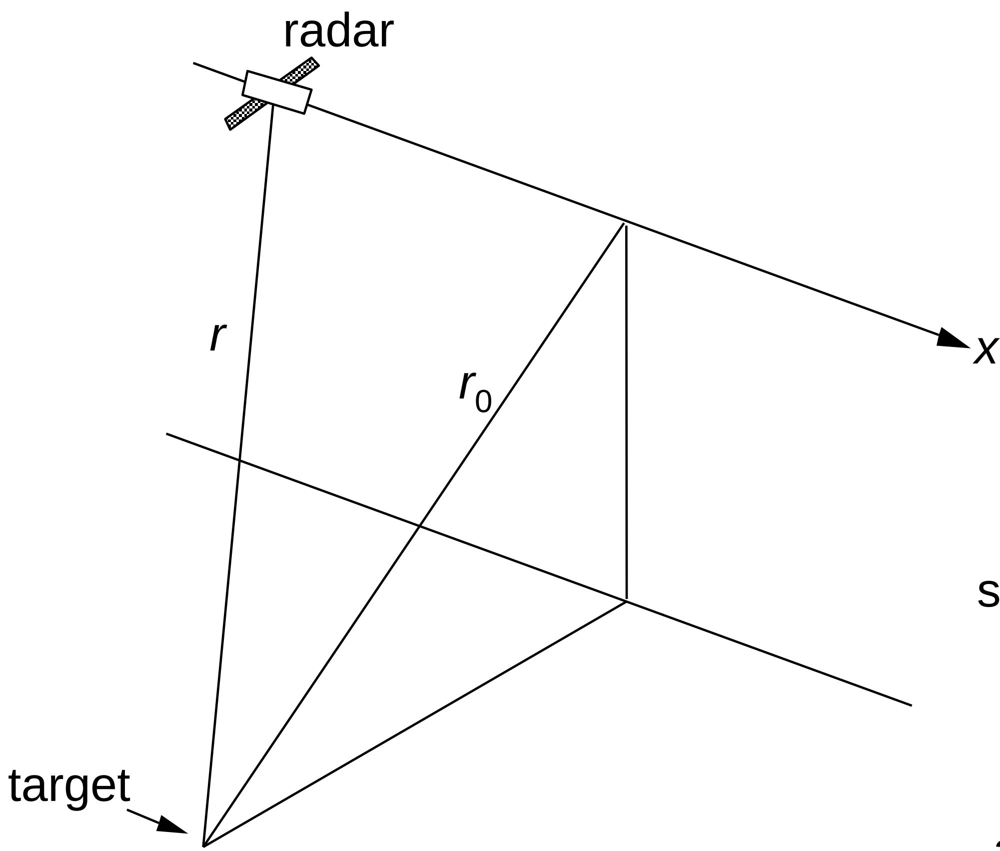
Bistatic SAR

- Several different geometries: moving tx, moving rx, or both
- and aircraft-borne or satellite-borne or UAV-borne systems
- examples of systems and results
    - COVIN REST
    - TBIRD
    - Sandia National Labs
    - Wright-Patterson Labs
    - QinetiQ
    - UCL
    - ONERA/DLR

Monostatic SAR geometry



$$r = \left(r_0^2 + x^2\right)^{1/2}$$

$$= r_0\left(1 + x^2/r_0^2\right)^{1/2}$$

$$= r_0\left(1 + \frac{x^2}{2r_0^2} - \frac{x^4}{8r_0^4} + \ldots\right)$$

so, taking just the first two terms :

$$r = r_0 + \frac{x^2}{2r_0}$$

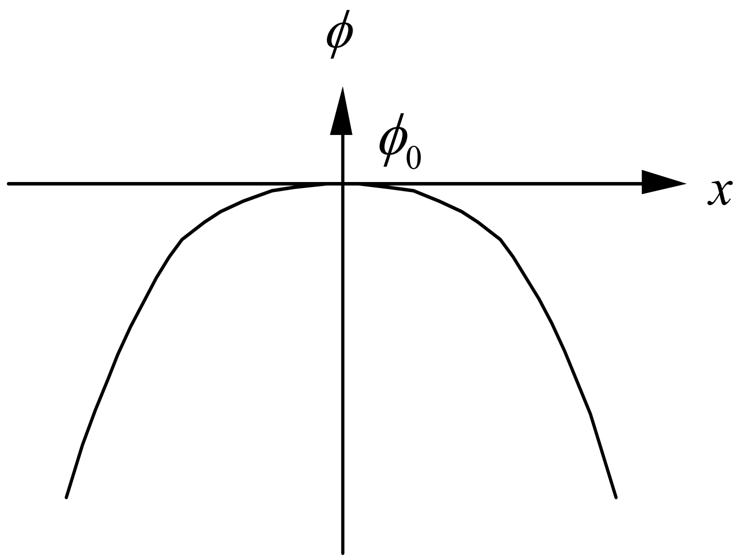
and

$$\phi(x) = -\frac{2\pi}{\lambda}.2r$$

Monostatic SAR geometry

$$\phi(x) = -\frac{2\pi}{\lambda}.2r$$

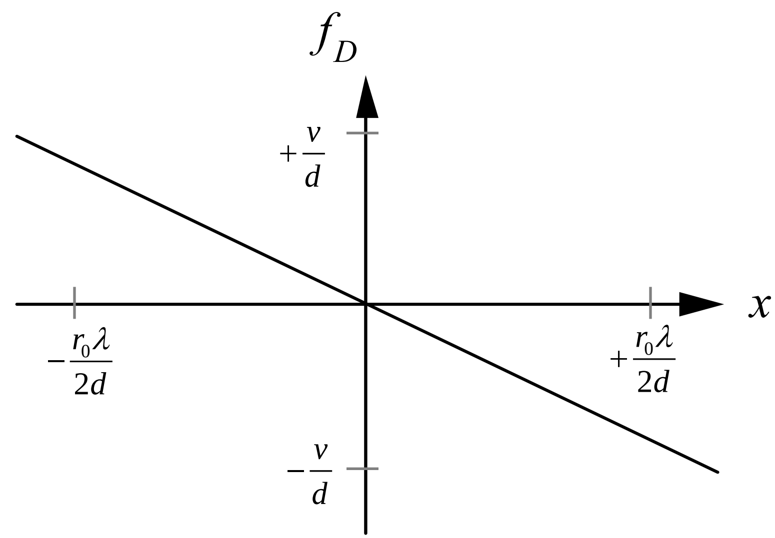
$$= \phi_0 - \frac{2\pi x^2}{r_0\lambda}$$



or in terms of Doppler frequency **:**

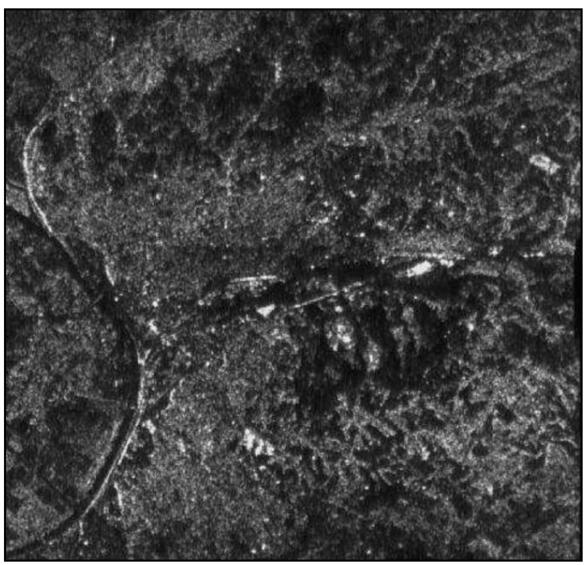
$$f_D = \frac{1}{2\pi}.\frac{d\phi}{dt}$$

$$= -\frac{2vx}{r_0\lambda}$$

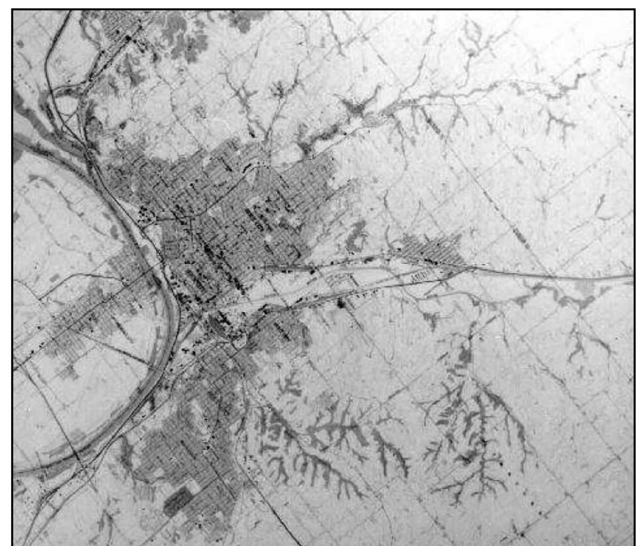


COVIN REST

- **Covert, In-Wx Recce/Strike**
- **USAF, mid-1980s**
- **L-band, Shuttle Imaging Radar tx, aircraft-borne rx (Convair CV990)**



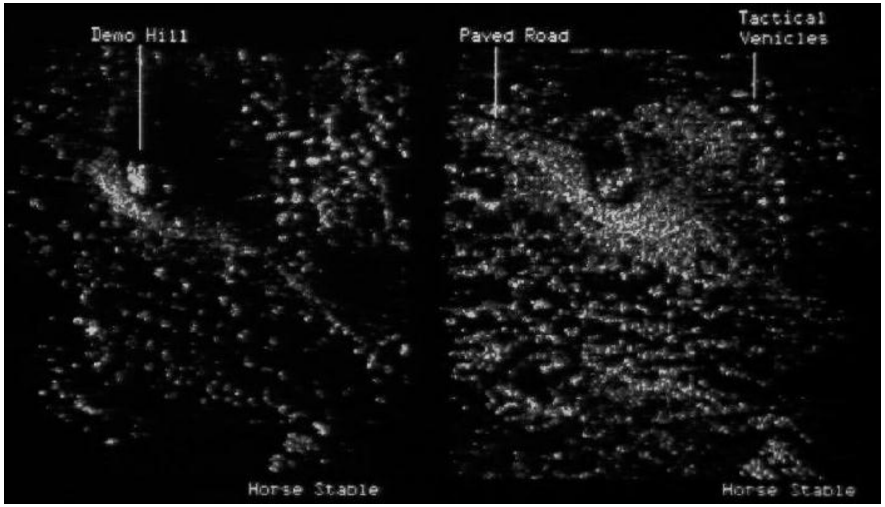
60-foot resolution image of Sioux City, Iowa



Ground truth map

TBIRD

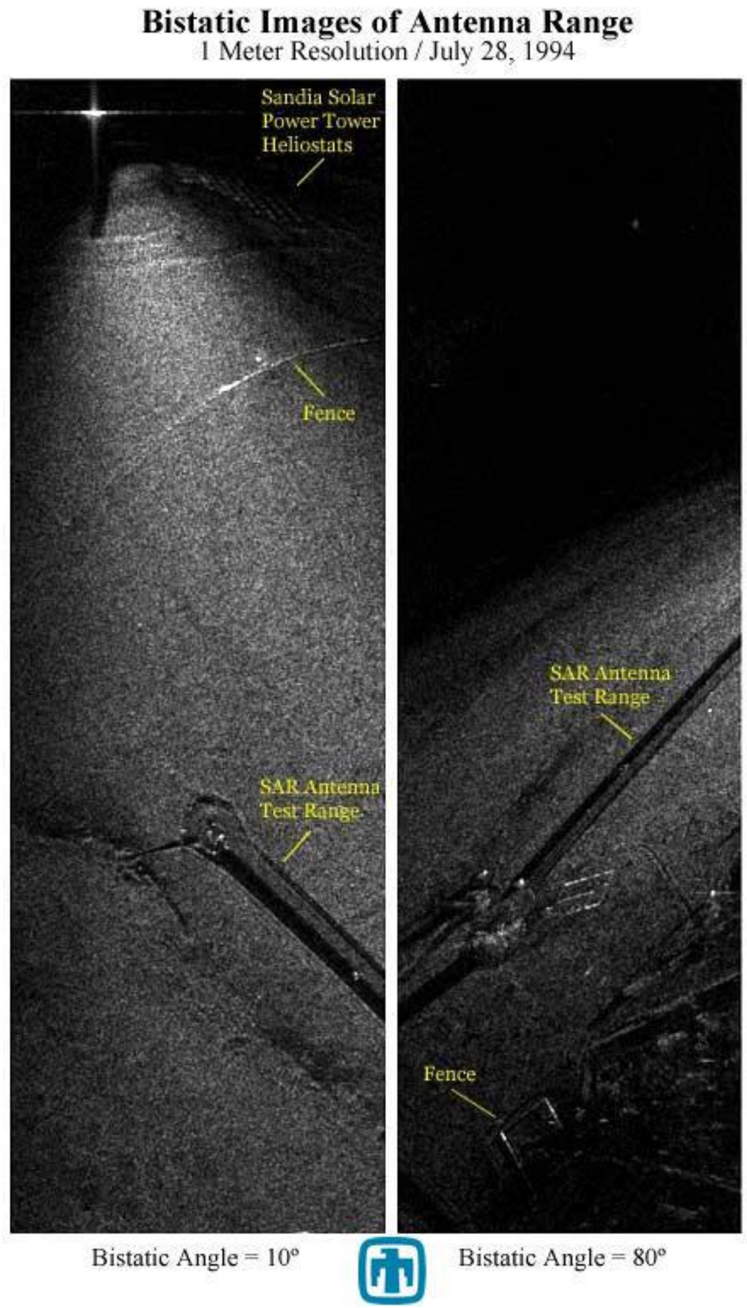
- **Tactical Bistatic Radar Demonstration**
- **DARPA, mid-1980s**
- **C-141 tx at 20 – 30 km range, C-130 rx, forward-looking**



10 foot resolution image of Demonstration Hill within Fort Huachuca, Arizona

Artist's rendition of the *Tactical Bistatic Radar Demonstration* (*TBIRD*) concept. A stand-off SAR-equipped aircraft (F-4, upper right) detects and illuminates a target (lower right) while designating an attack aircraft (A-10, left) equipped with a bistatic receiver to the target area. The A-10 acquires and attacks the target directly on its velocity vector in RF silence.

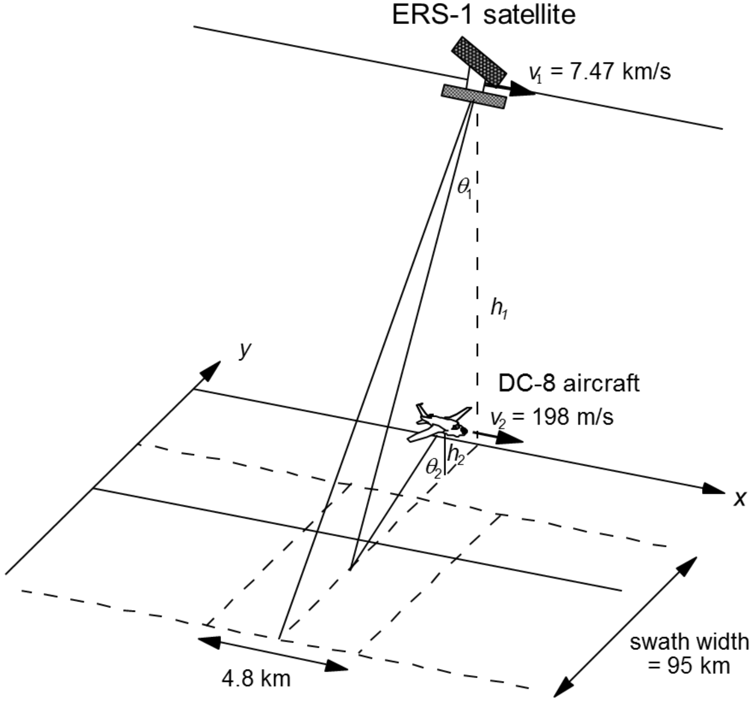
Bistatic SAR image



source: Sandia Corporation -http//www.sandia.gov

Sandia National Laboratories

Bistatic SAR

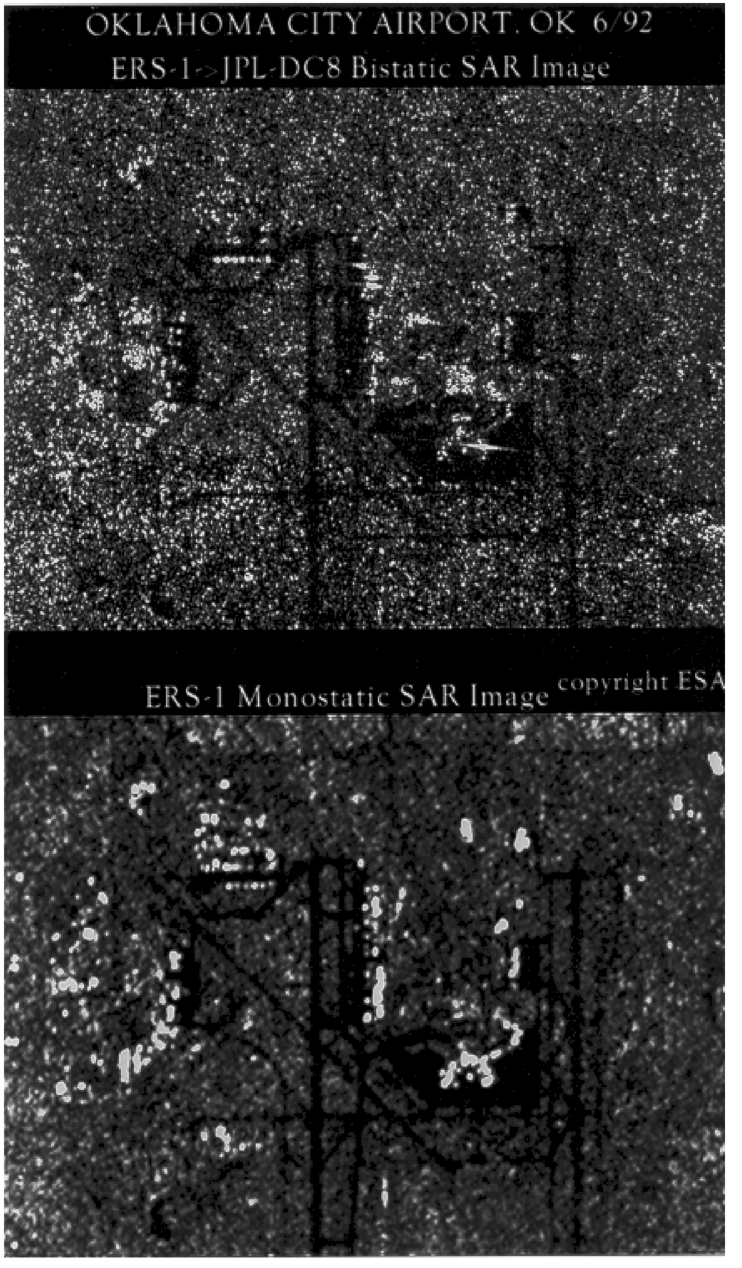


$\theta_1 = 22°$

$\theta_2 = 45°$

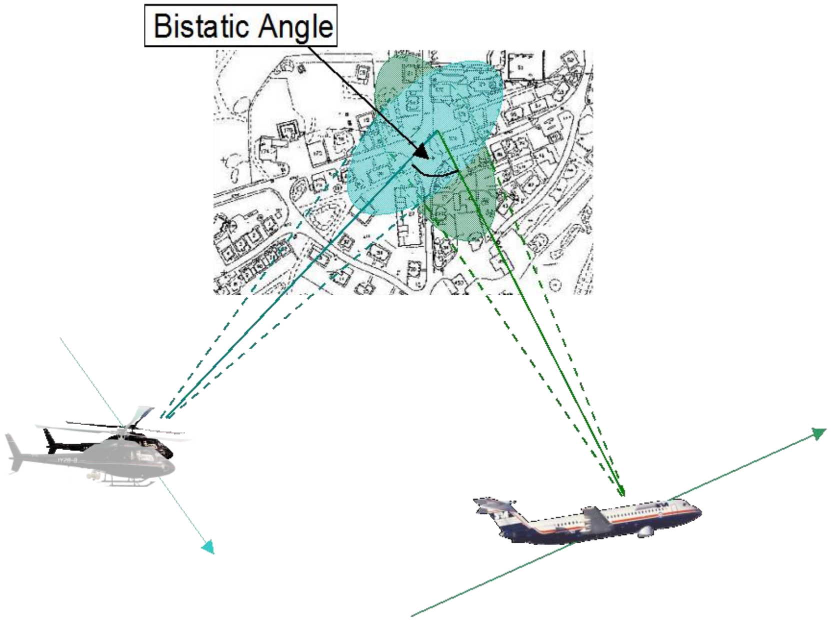
h_1 = 783.28 km

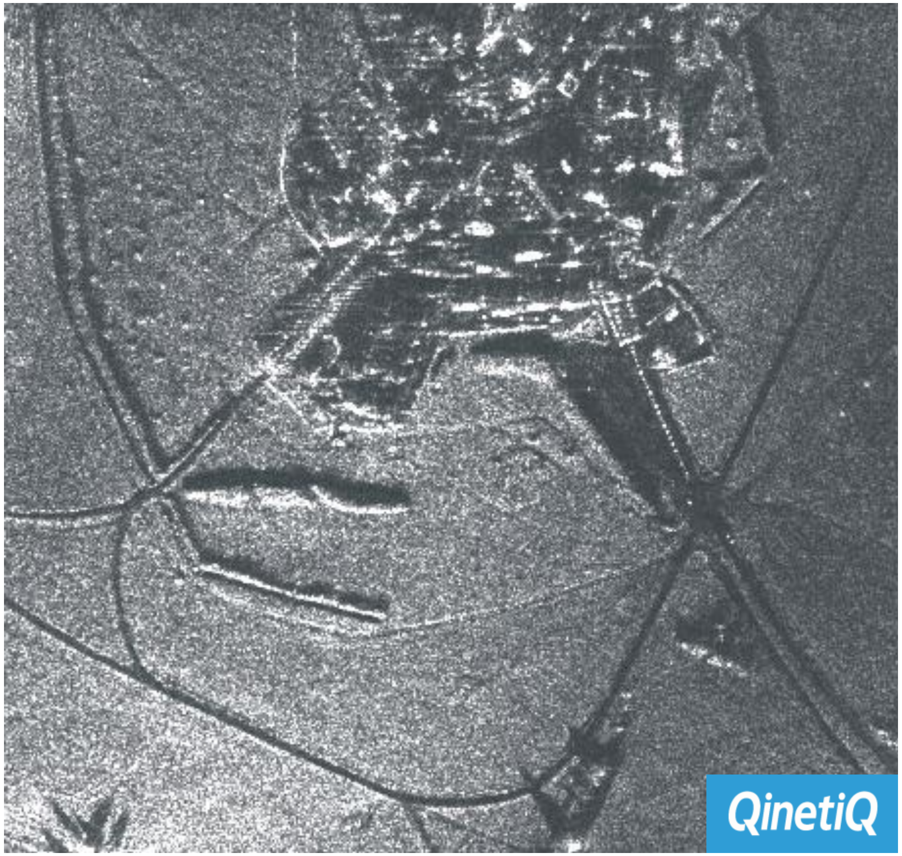
h_2 = 7.87 km



Martinsek, D. and Goldstein, D., 'Bistatic radar experiment', Proc. EUSAR'98 conference, Friedrichshafen, 25-27 May 1998, pp31-34.

QinetiQ bistatic SAR imagery





Bistatic angle ~50°

Yates, G.A., 'Bistatic Synthetic Aperture Radar', PhD thesis, University College London, January 2005.

Synchronisation

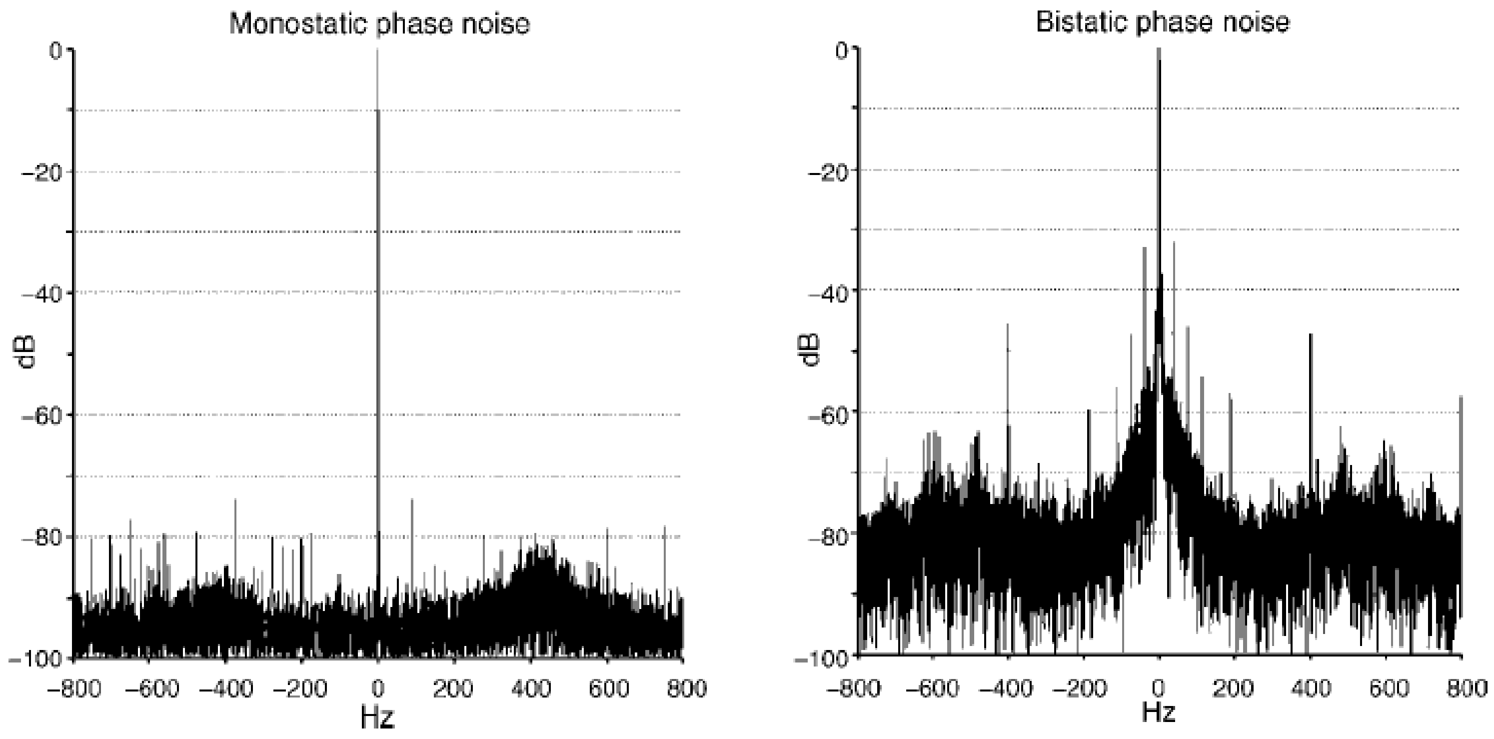
- Synchronisation between transmitter and receiver can be achieved by:
  - extremely accurate time and frequency standards on each platform, or
  - continuous transfer of time and frequency standards, using direct-path reception of the transmitted waveform, dedicated RF link between platforms, or GPS
- In these experiments caesium atomic clocks were used at transmitter and receiver

Yates, G.A., ‘Bistatic Synthetic Aperture Radar’, PhD thesis, University College London, January 2005.

Bistatic SAR image

Yates, G.A., ‘Bistatic Synthetic Aperture Radar’, PhD thesis, University College London, January 2005.

Phase noise



Yates, G.A., ‘Bistatic Synthetic Aperture Radar’, PhD thesis, University College London, January 2005.

Bistatic SAR processing

- Polar Format Algorithm (PFA)
  - Compensation of raw data for motion of imaging platform seen at scene centre
  - Mapping of resulting (approximate) polar *k*-space data onto rectangular *k*-space representation
  - Fourier transform to image domain
  - For bistatic variant, motion compensation to scene centre includes motion of both transmitter and receiver

- Range Migration Algorithm (RMA)
  - Exact for monostatic geometry
  - But for bistatic geometry simplifications need to be made

Yates, G.A., ‘Bistatic Synthetic Aperture Radar’, PhD thesis, University College London, January 2005.

Rigling, B.D. and Moses, R.L., ‘Polar format algorithm for bistatic SAR’, *IEEE Trans. Aerospace and Electronic Systems*, Vol.40, No.4, pp1147–1159, October 2004.

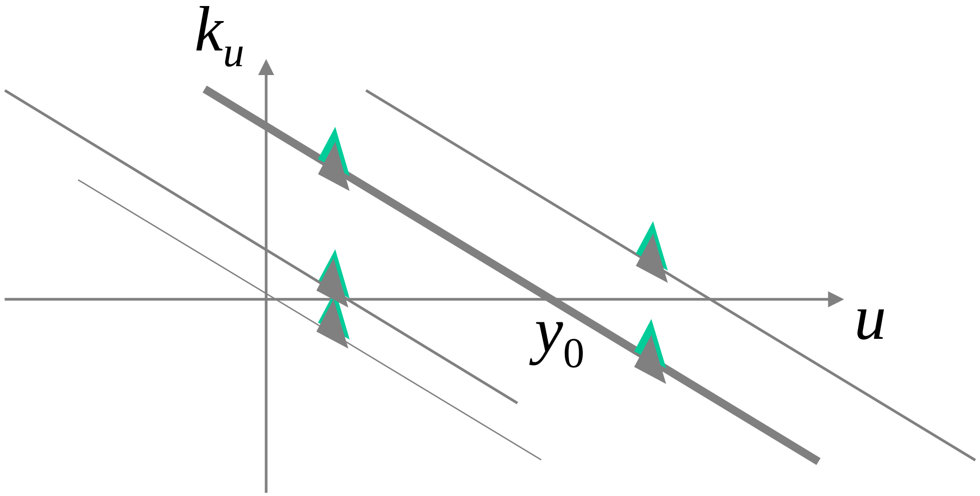
Autofocus

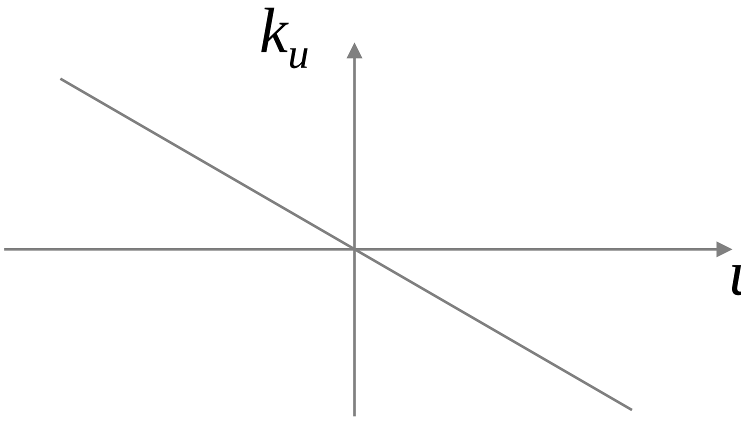
- Corrects for motion-induced phase errors
- Phase Gradient Algorithm (PGA) exploits fact that all scatterers are defocused by same phase error
  - Selects brightest scatterer, and estimates phase gradient
  - Integrate twice to get motion error

- But Autofocus algorithms have a limited frequency response

Yates, G.A., ‘Bistatic Synthetic Aperture Radar’, PhD thesis, University College London, January 2005.

Phase Gradient Algorithm (1)

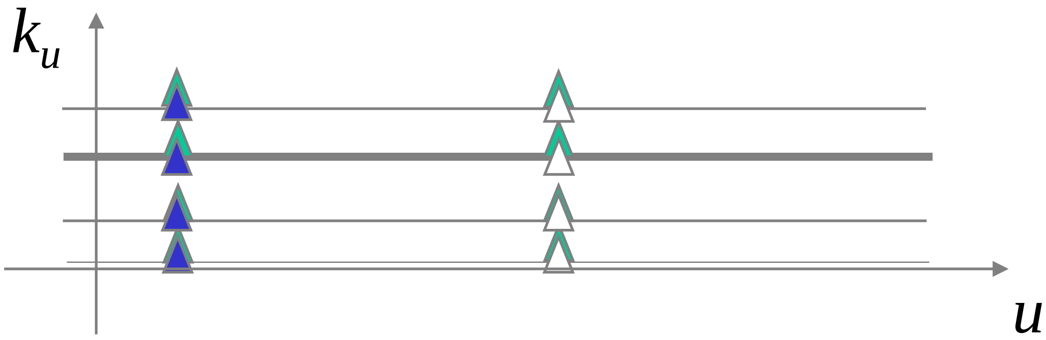




Response of a field of scatterers
(with platform motion disturbances)

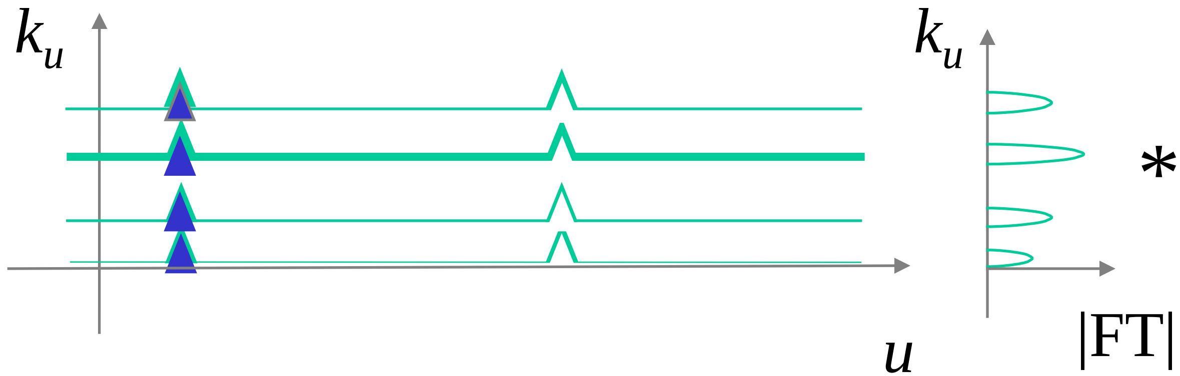
matched filter,
same aperture,
complex conjugate

For each range line,
multiply to give:

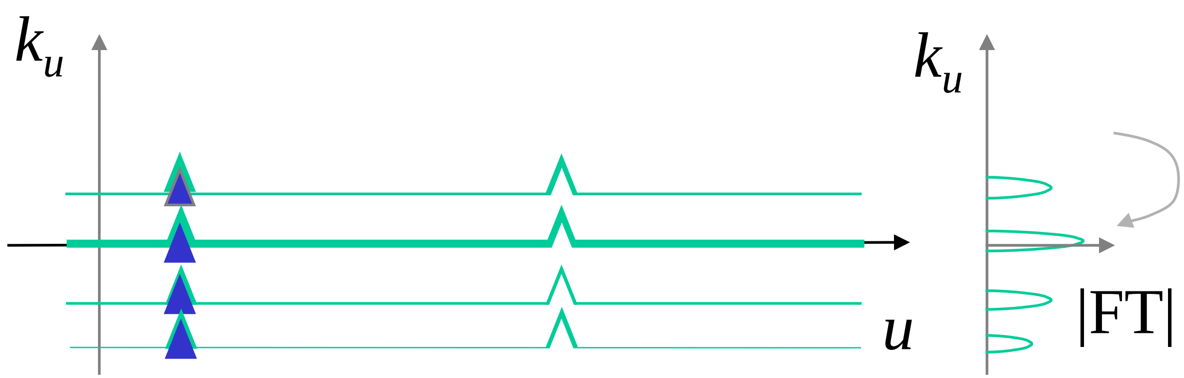


Phase Gradient Algorithm (2)

Take the along-track Fourier transform

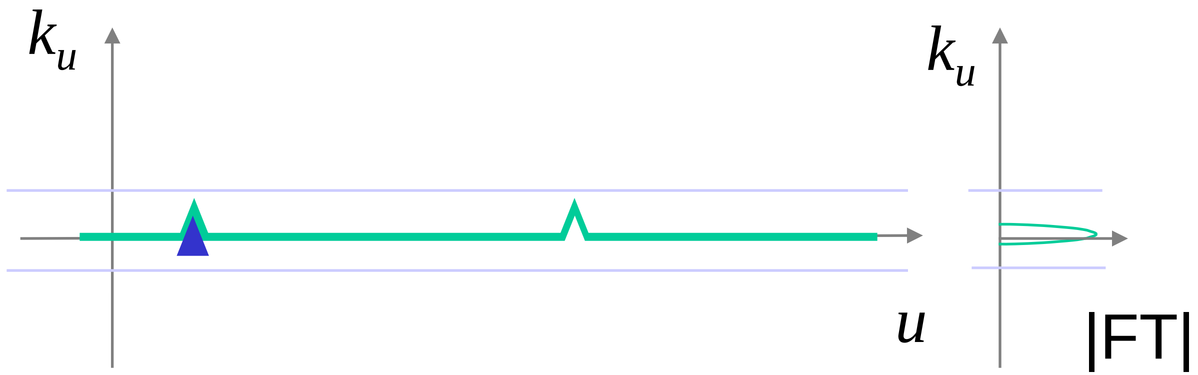


Select strongest scatterer and shift to origin



Phase Gradient Algorithm (3)

Apply window to exclude other scatterers



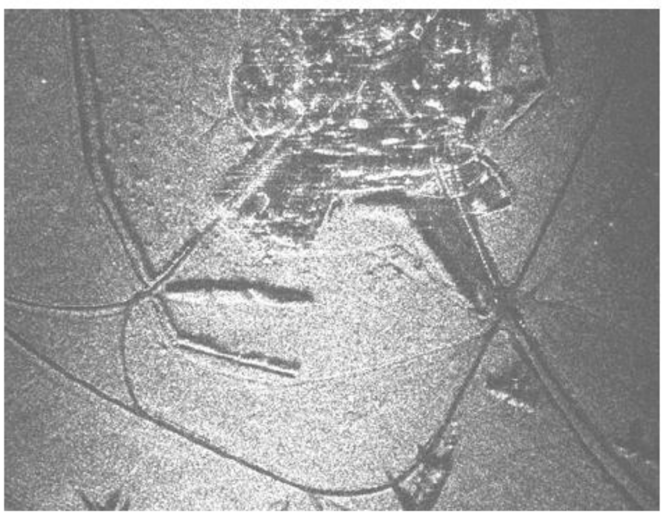
Inverse Fourier transform yields a signal $g(u)$ which depends on the phase error, $\phi_e(u)$:

$$g(u) = A \exp(j\phi_e(u))$$

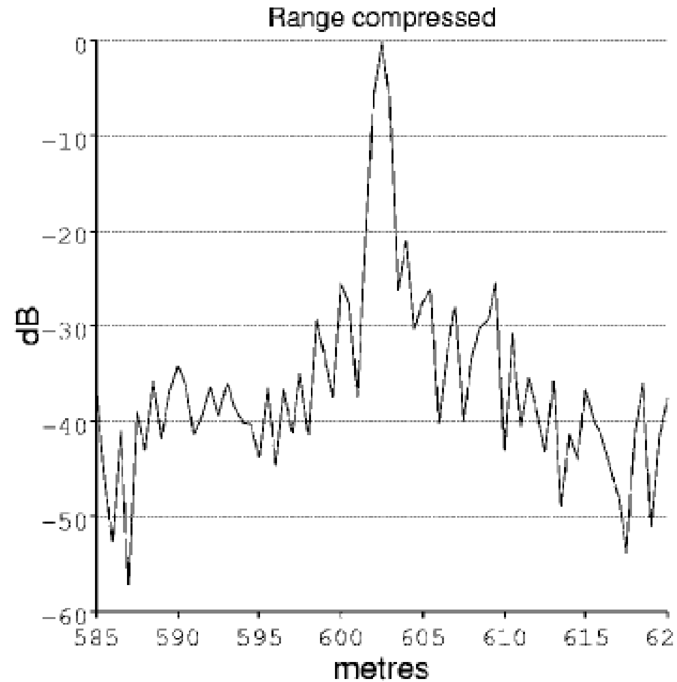
The *phase gradient* can be readily extracted from $g(u)$ and dg/du. Integrate numerically to find $\phi_e(u)$ and hence platform motion.

Bistatic SAR image

before autofocus



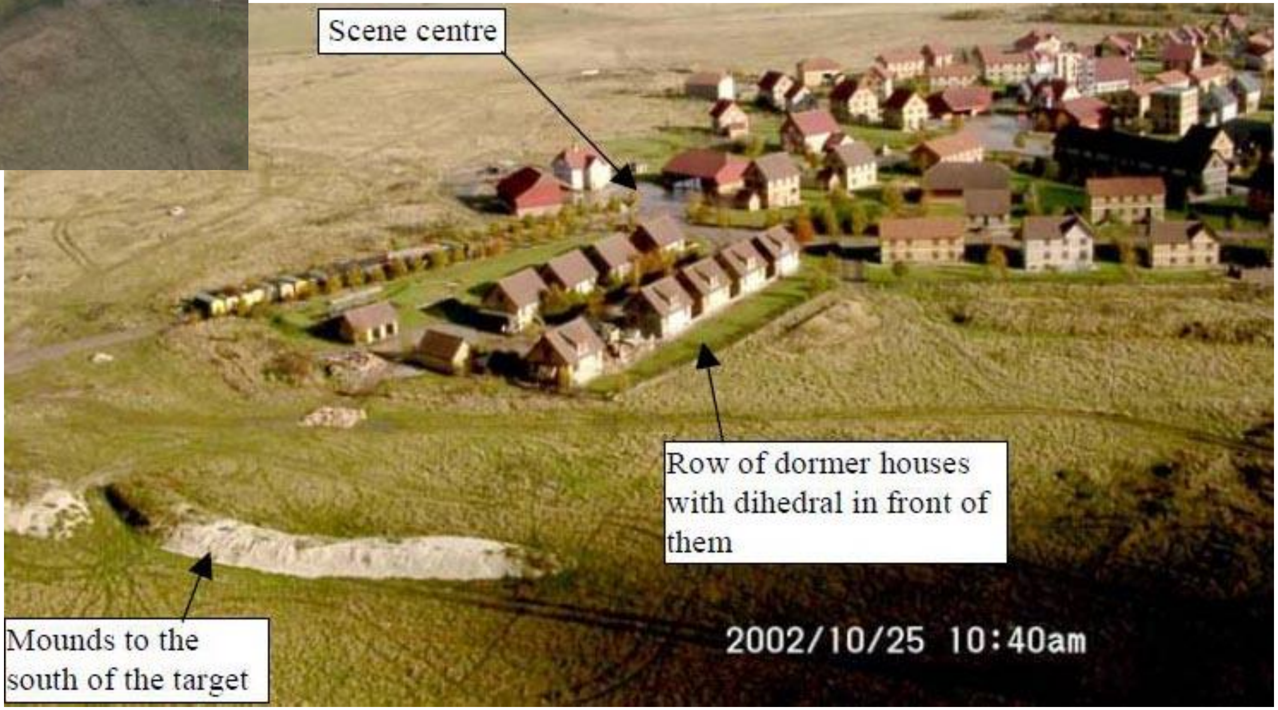
after autofocus



measured point-spread function

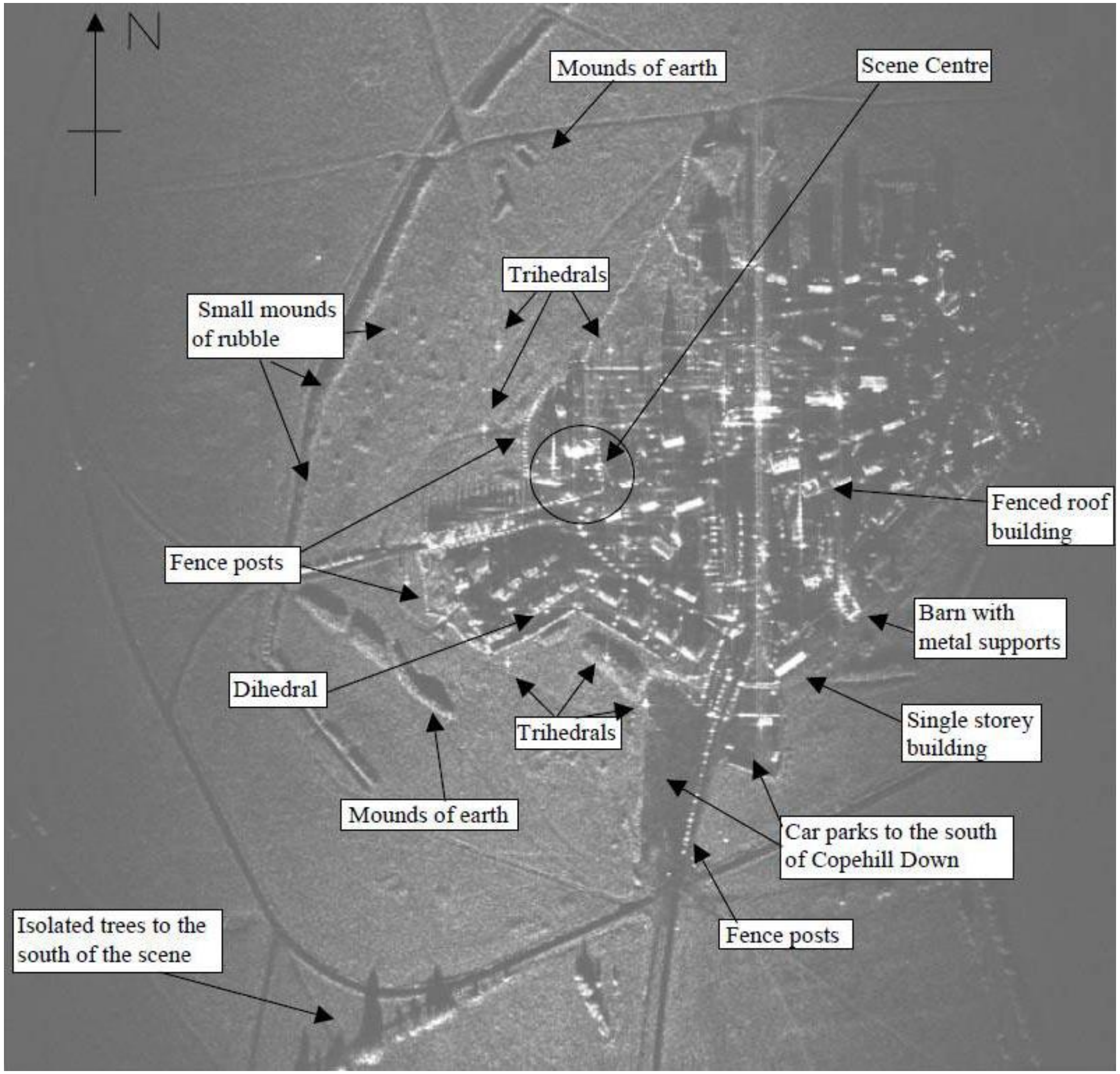
Yates, G.A., 'Bistatic Synthetic Aperture Radar', PhD thesis, University College London, January 2005.

Bistatic SAR image



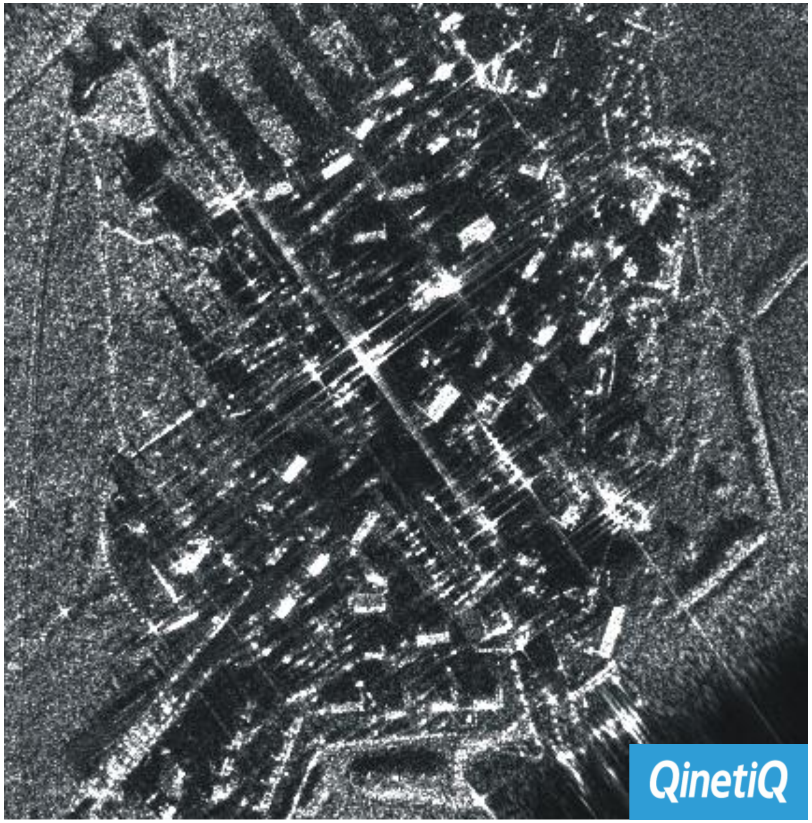
Yates, G.A., ‘Bistatic Synthetic Aperture Radar’, PhD thesis, University College London, January 2005.

Bistatic SAR image

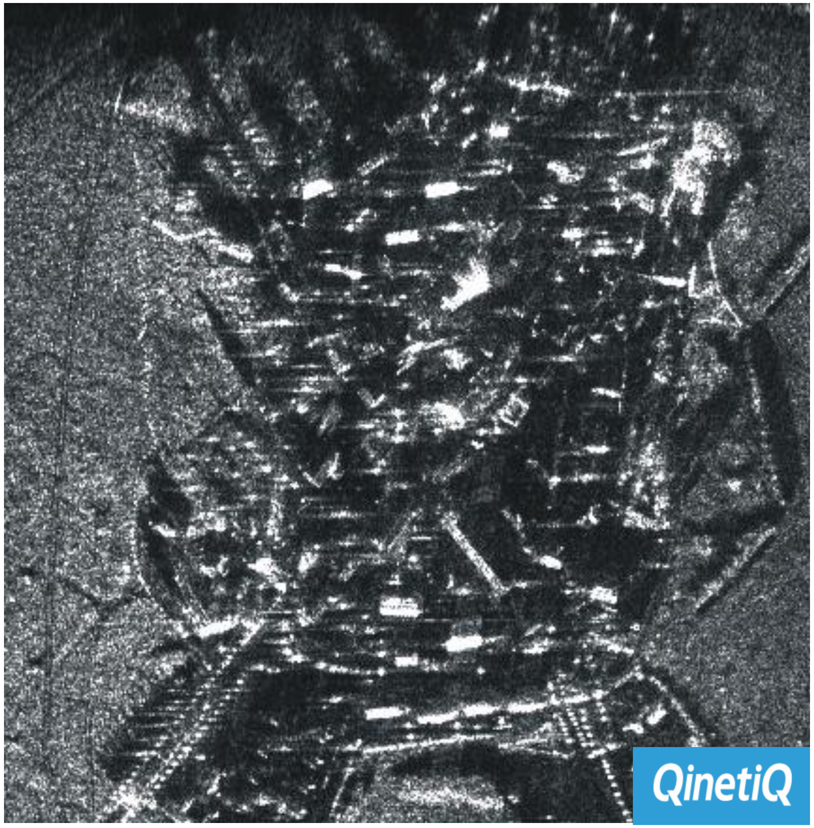


Yates, G.A., ‘Bistatic Synthetic Aperture Radar’, PhD thesis, University College London, January 2005.

Comparison of monostatic and bistatic SAR



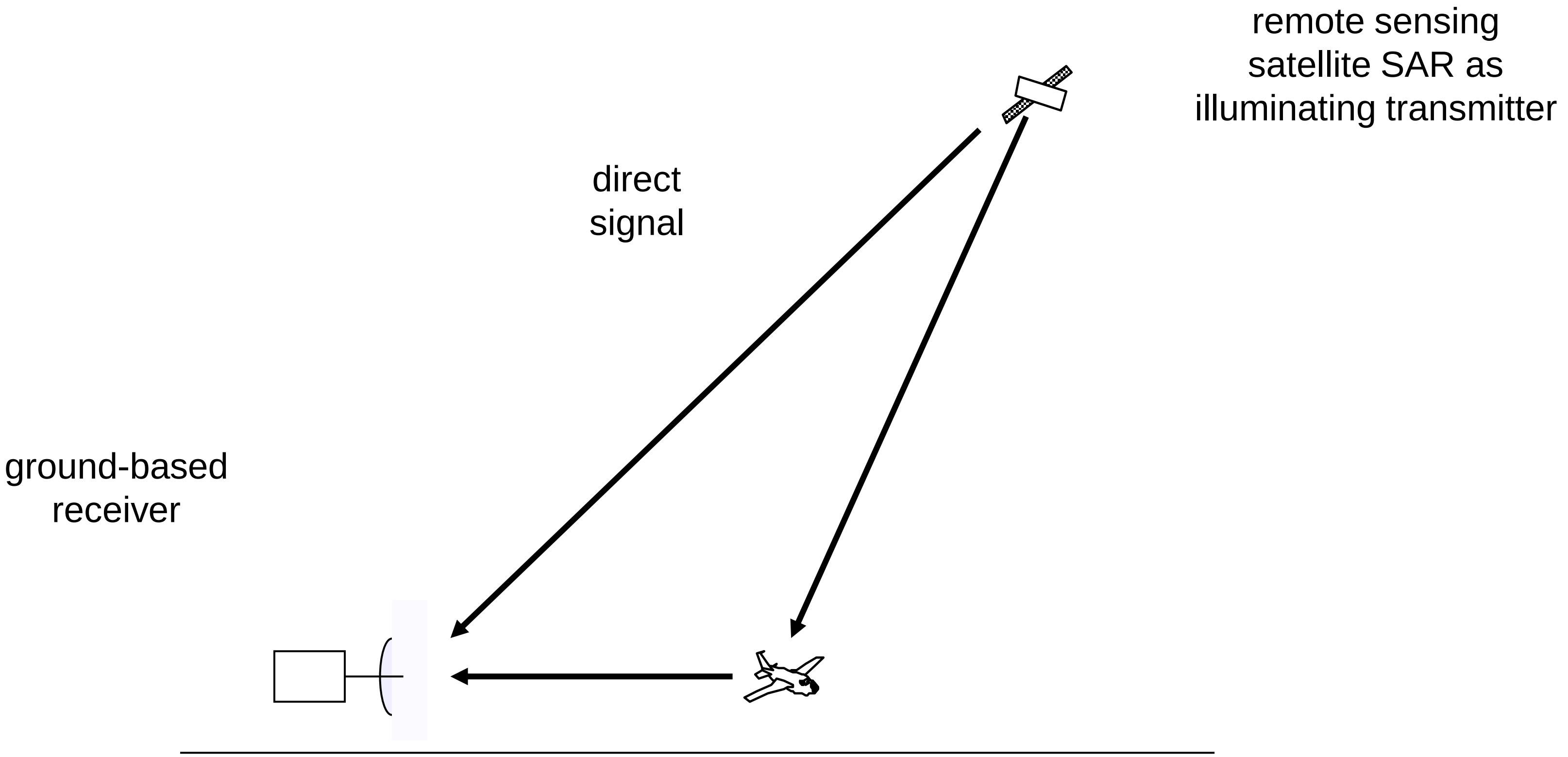
Monostatic



Bistatic (~70°)

Yates, G.A., 'Bistatic Synthetic Aperture Radar', PhD thesis, University College London, January 2005.

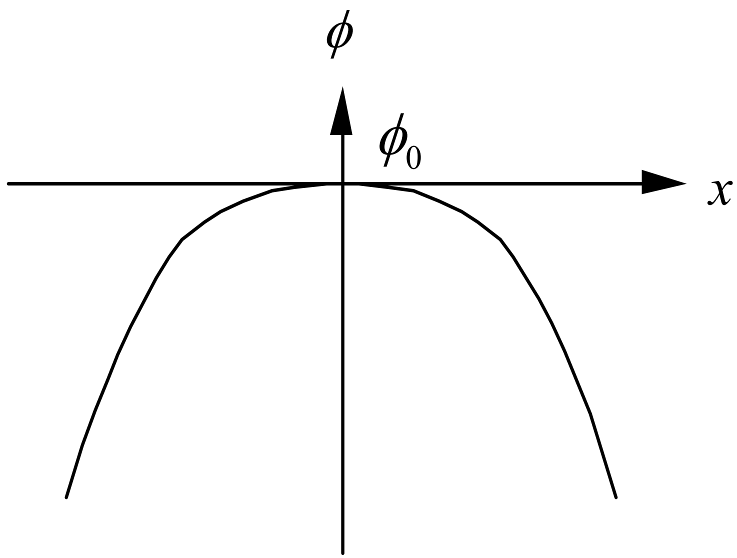
Bistatic SAR using satellite-borne illuminator of opportunity



Monostatic SAR geometry

$$\phi(x) = -\frac{2\pi}{\lambda}.2r$$

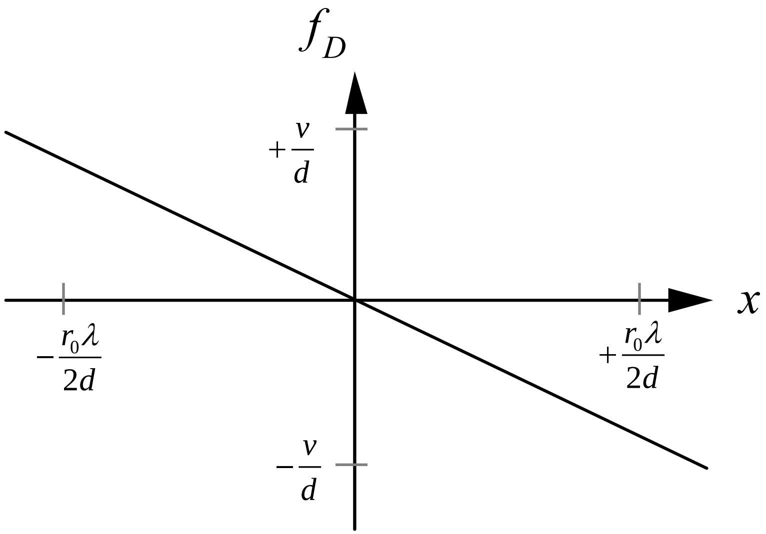
$$= \phi_0 - \frac{2\pi x^2}{r_0\lambda}$$



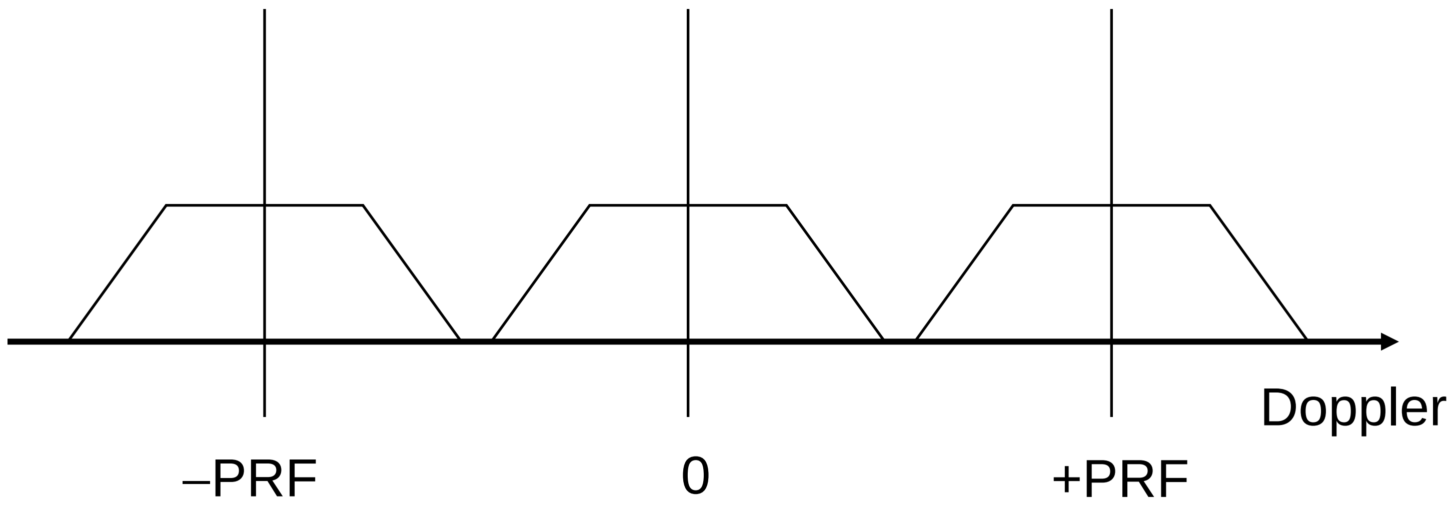
or in terms of Doppler frequency **:**

$$f_D = \frac{1}{2\pi}.\frac{d\phi}{dt}$$

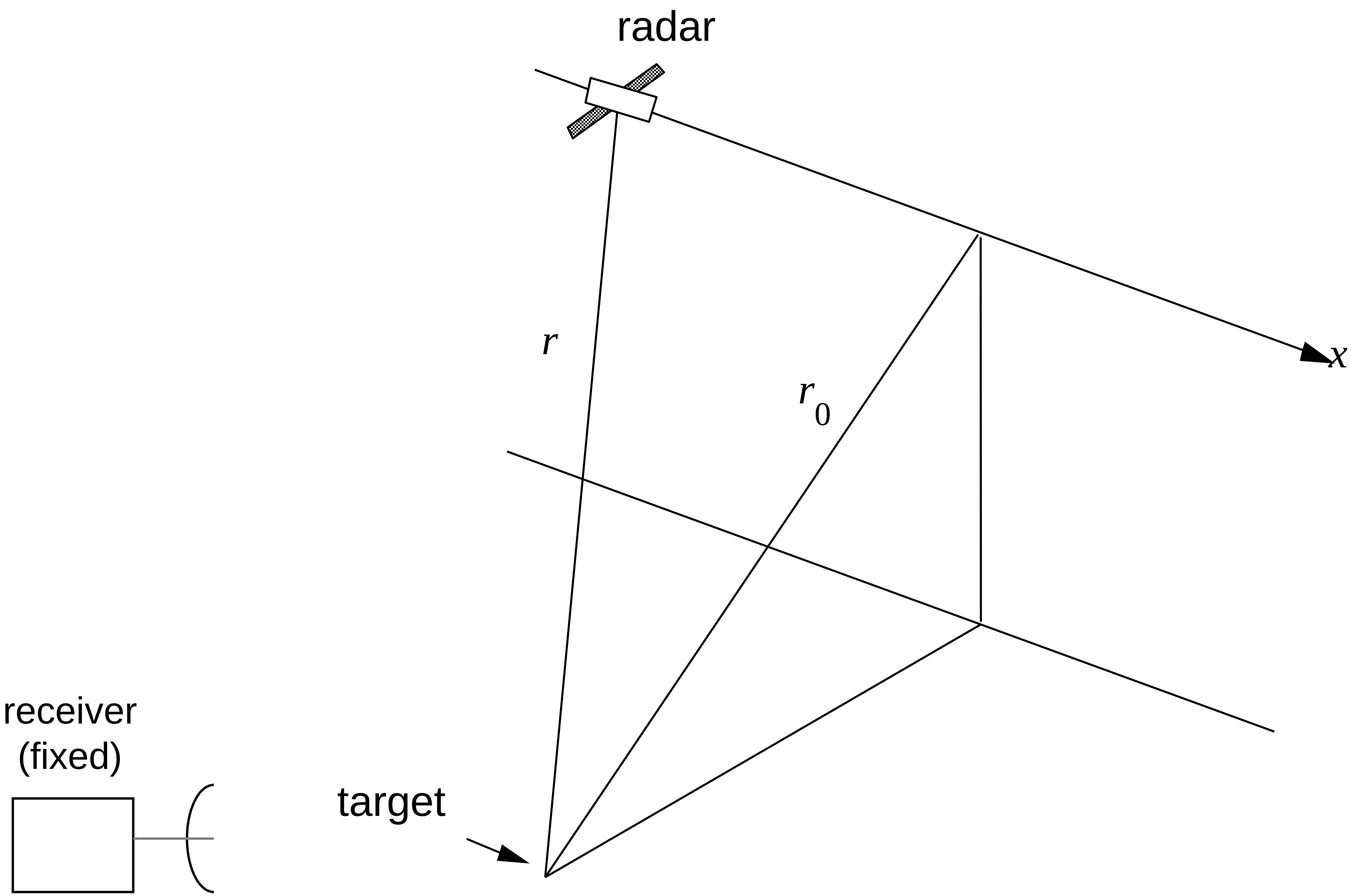
$$= -\frac{2vx}{r_0\lambda}$$



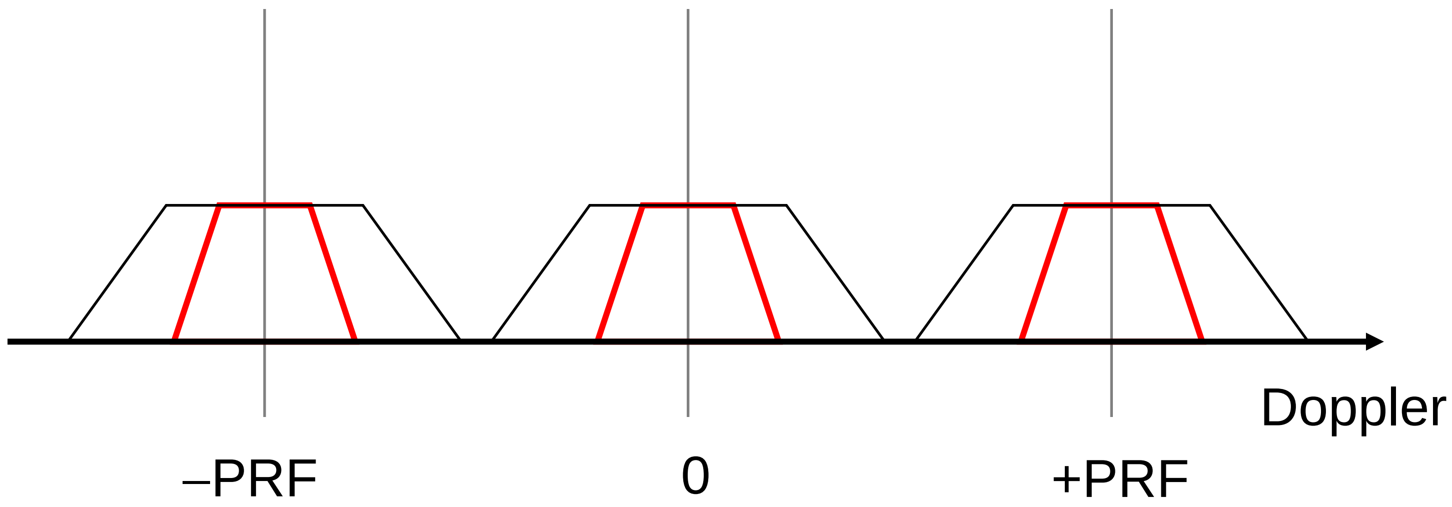
Doppler spectrum



Bistatic SAR geometry



Doppler spectrum

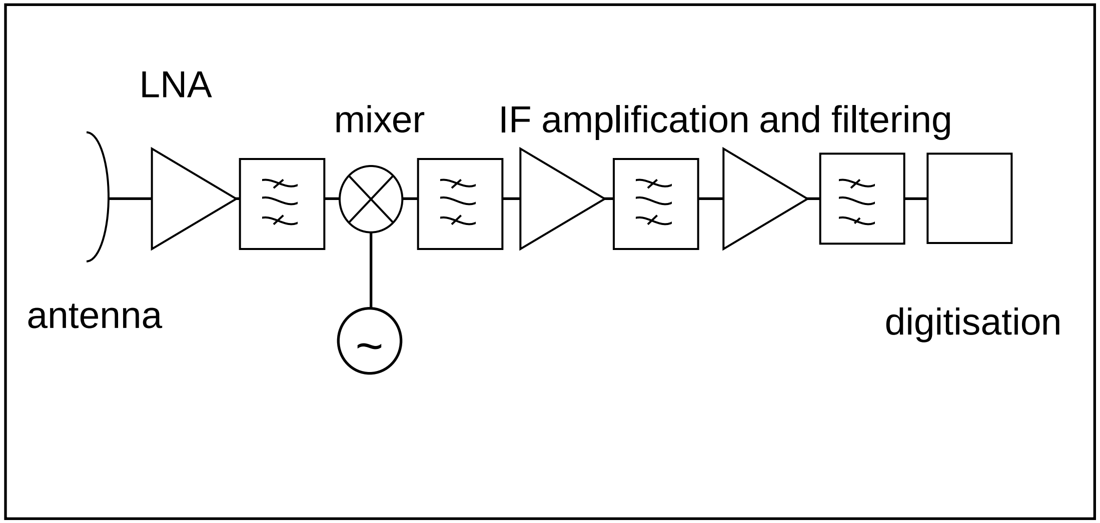


ENVISAT

ASAR parameters

• Frequency:	5.331 GHz
• Antenna:	320-element electronically-scanned array, 10 m x 1.3 m
• Transmit power:	1365 W
• PRF:	1650 to 2100 Hz
• Pulse bandwidth:	up to 15 MHz
• Pulse length:	20 μs
• Polarisation:	VV or HH
• Swath width:	up to 100 km
• Orbit:	sun-synchronous, 800 km mean altitude, 1, 3, or 35-day repeat cycle

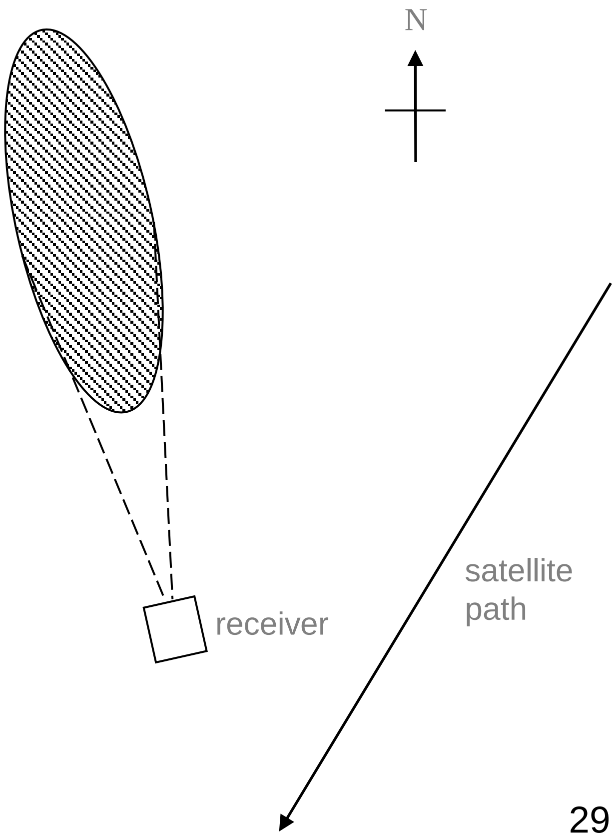
Receiver hardware



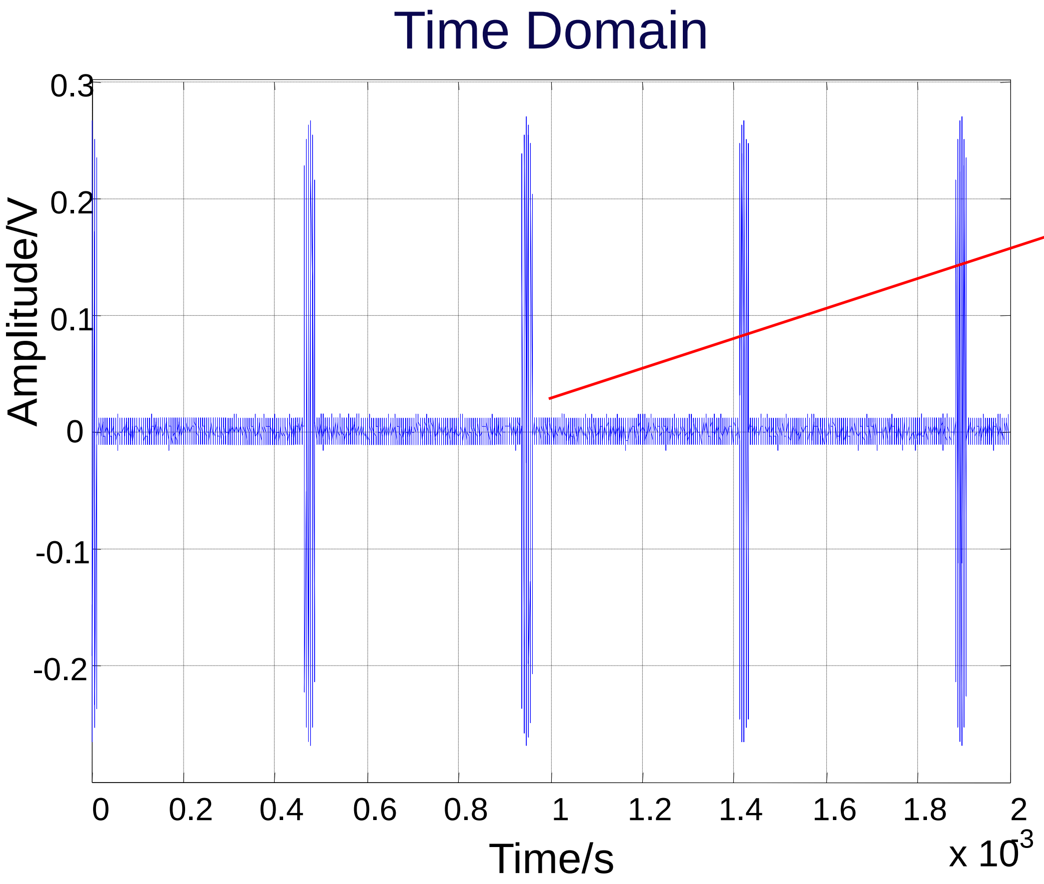
Bistatic SAR imaging

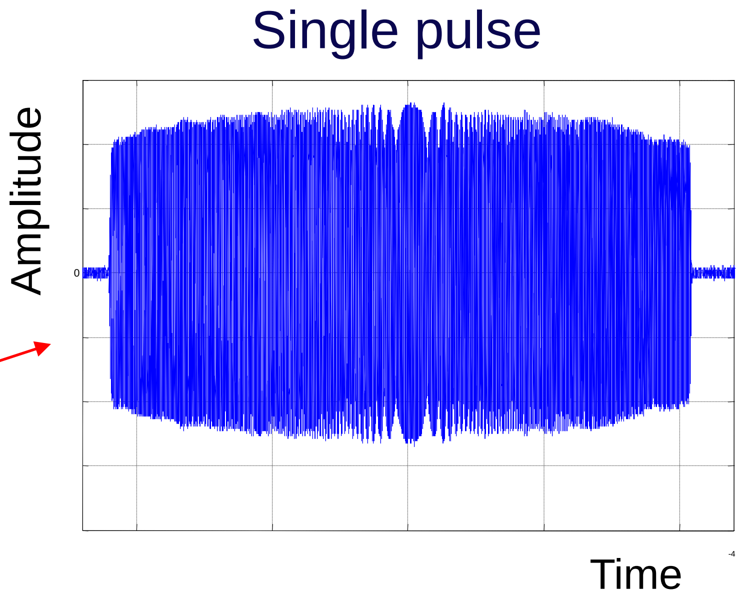
- Receiver placed on the roof of a ten-storey building in UCL
- Over-the-shoulder geometry – satellite is behind receiver – so transmitter and receiver are looking in approximately the same direction

Scene to be imaged



Direct signal capture

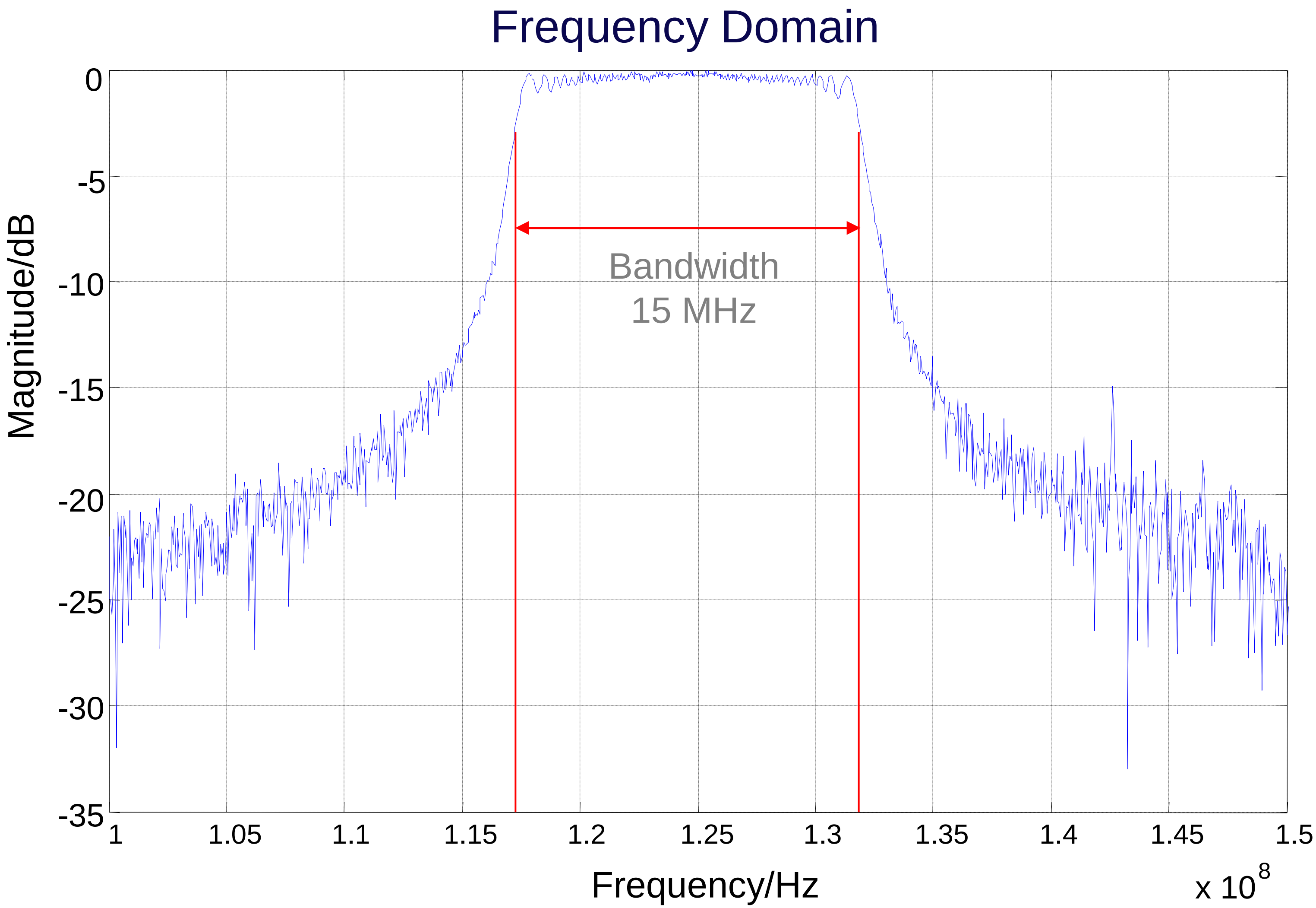




Pulse duration: 20μs

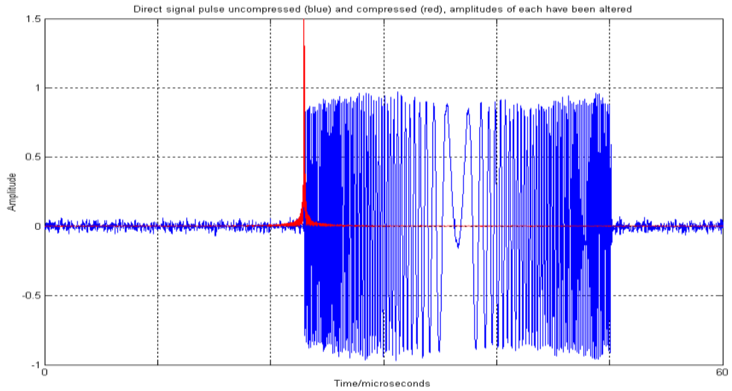
Signal-to-noise ratio: 25dB

Direct signal capture



Imaging: signal processing

- Direct signal is pulse compressed with ideal ASAR chirp -> series of peaks
- Locations of peaks gives the start point of each pulse:



- This information is used to extract pulses from direct *and* reflected signal channel

- Two data arrays are formed, from direct and reflected channels respectively, each row of array contains one pulse

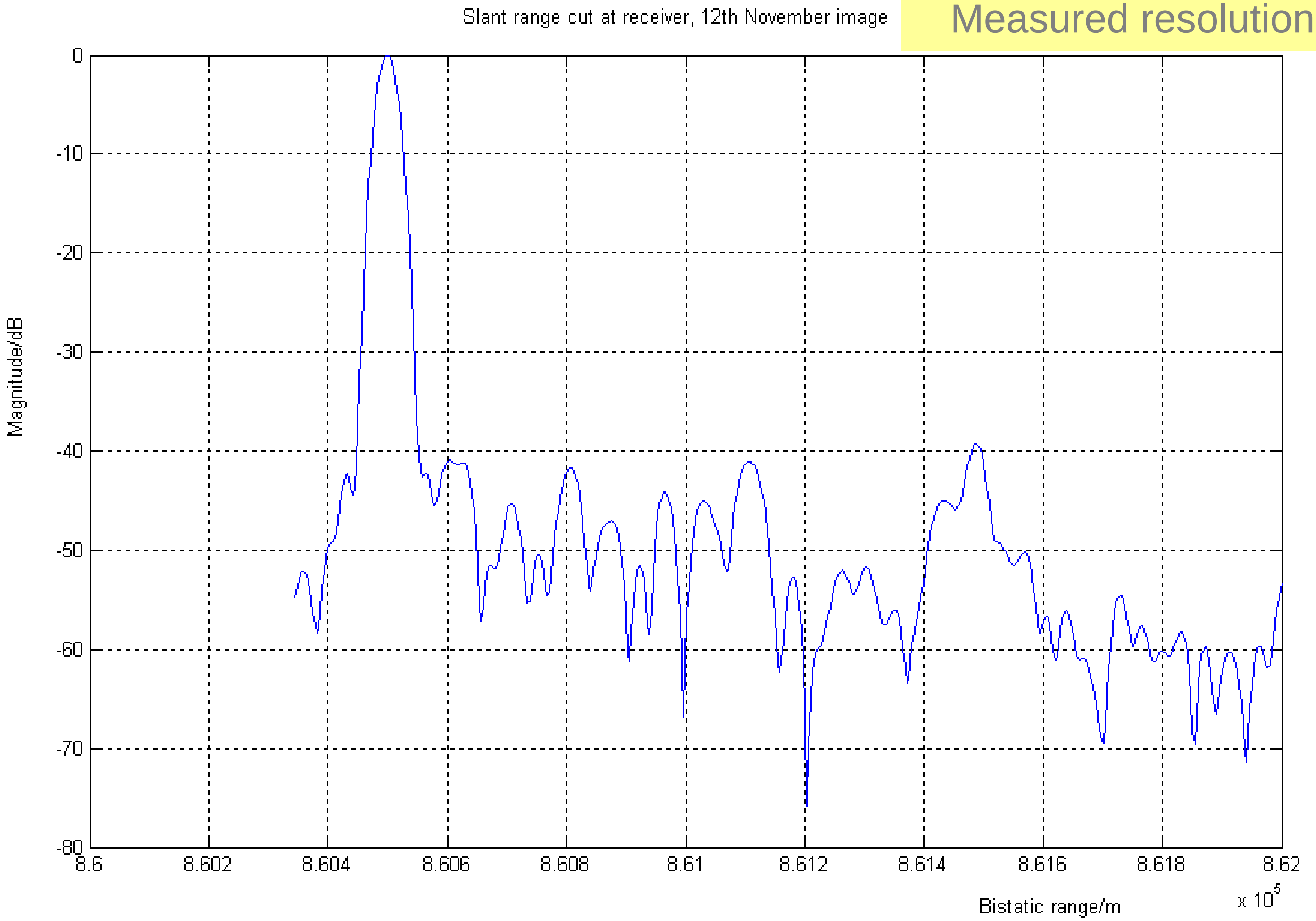
- Reflected signal pulses are pulse compressed with corresponding direct signal pulses, amplitude weighting may be applied e.g. Blackman

Imaging: results from 12 November 2004

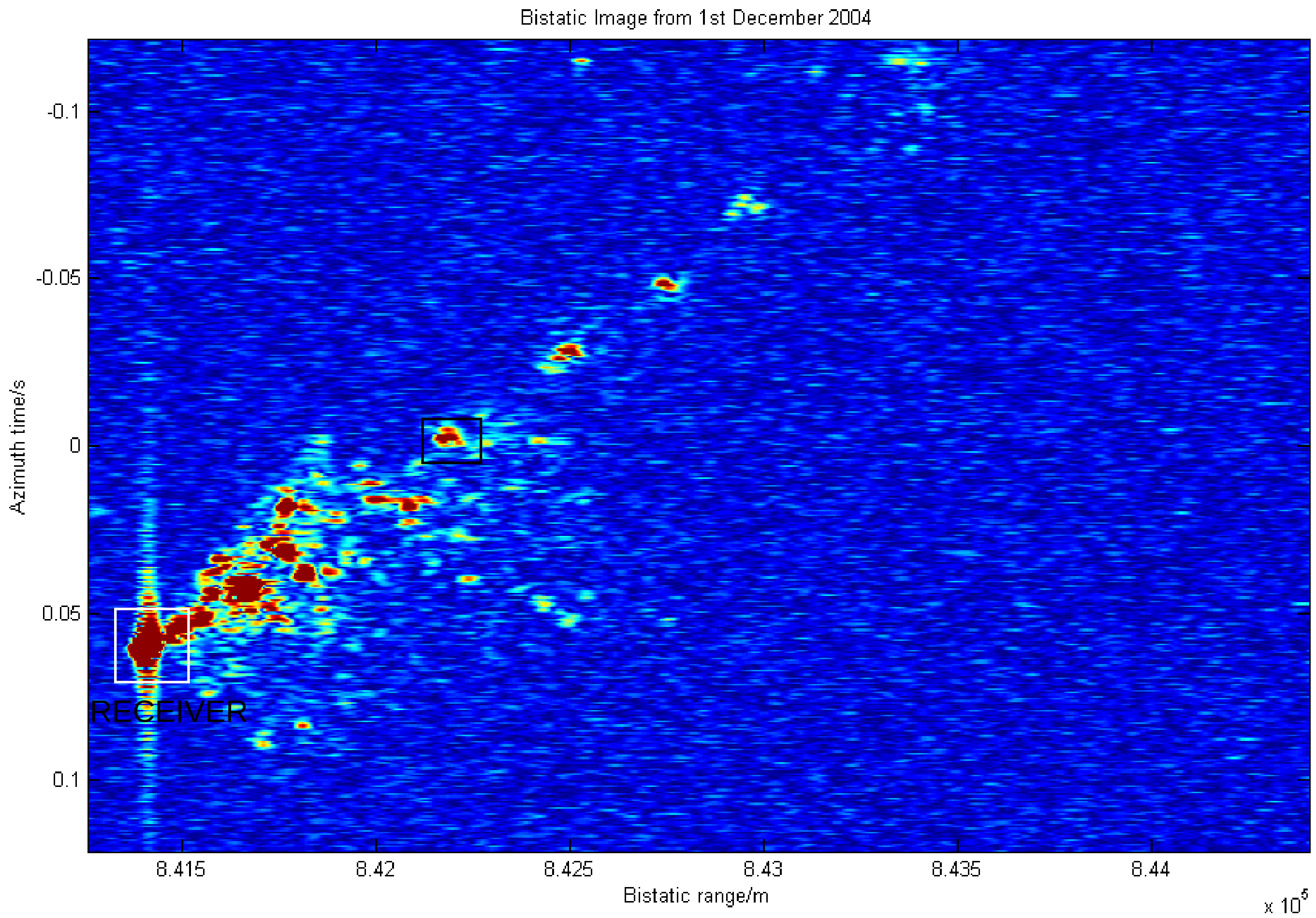
Receiver

Theoretical resolution = 18.8m

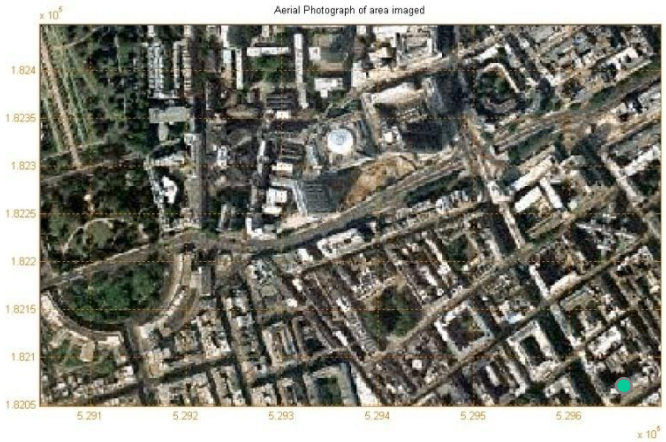
Measured resolution = 15.6m

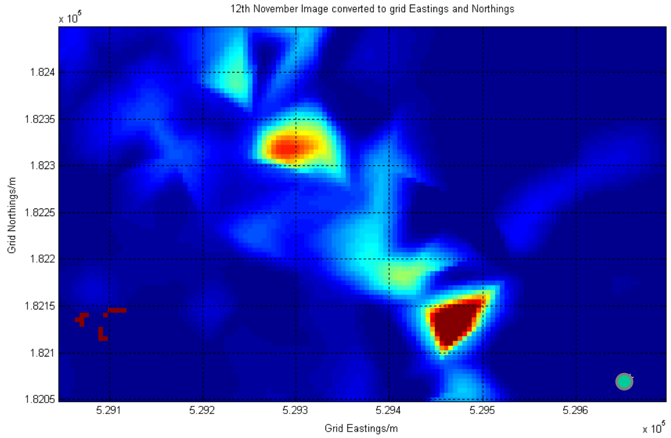


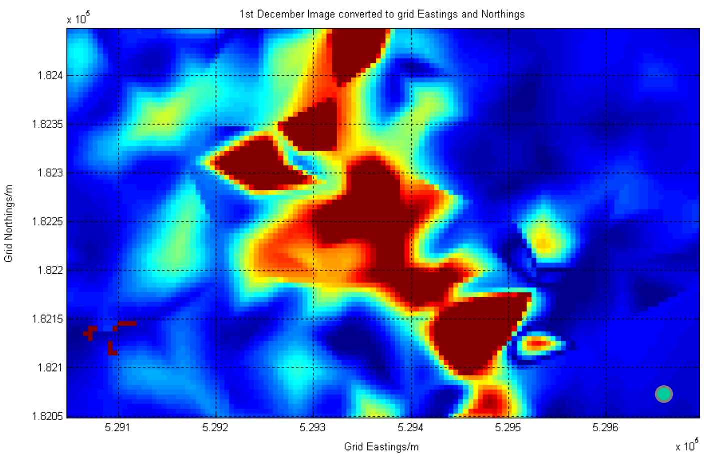
Imaging: results from 1 December 2004



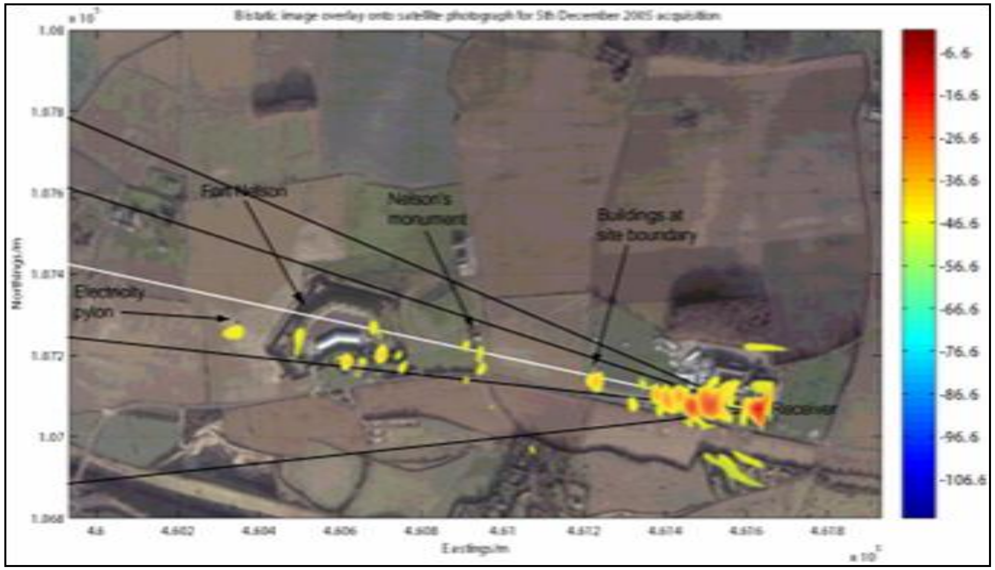
Imaging: comparison with aerial photographs

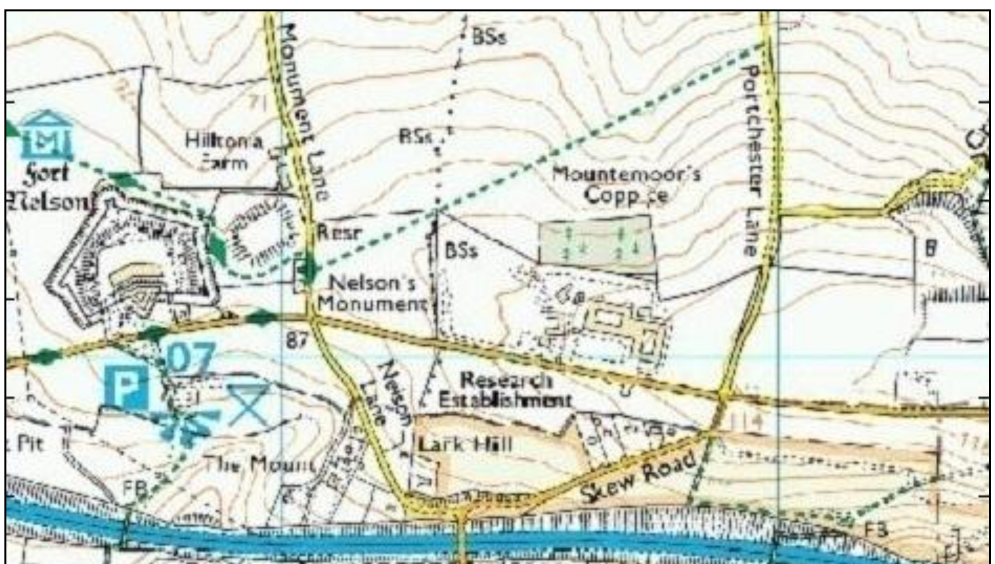






Imaging: comparison with aerial photographs





Experimental results from satellite bistatic experiments: imaged targets overlaid on aerial photograph (upper); corresponding map data (lower).

Bistatic SAR campaign: ONERA - DLR

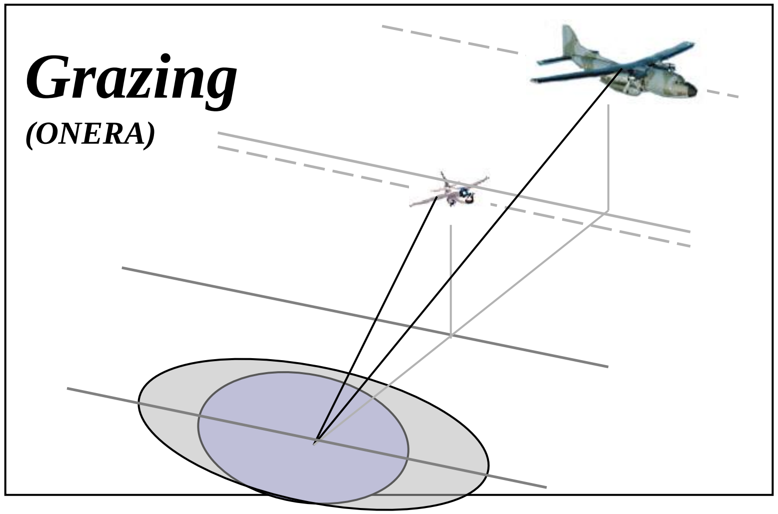
DLR with E-SAR

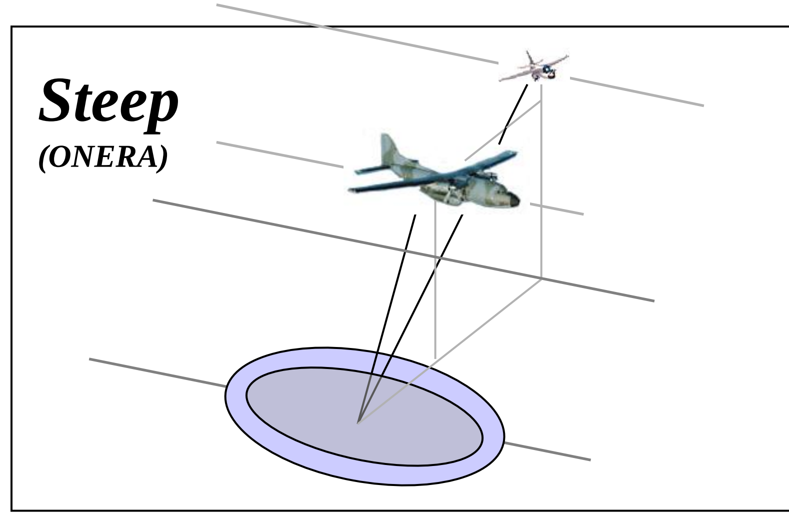
ONERA with RAMSES

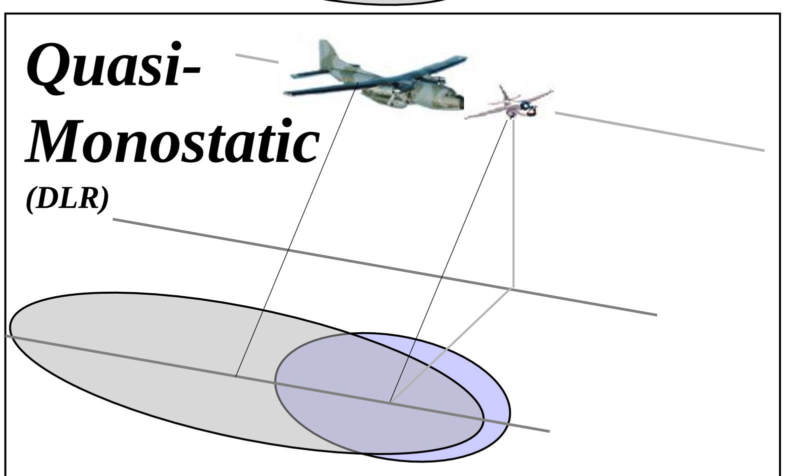
- **Flexible multi-channel SAR-Systems**
- **X-Band**
- **Right side looking (E-SAR incidence angle set to 55°)**
- **Do-228 - Transall**

Bistatic SAR campaign: ONERA - DLR

Flight configurations



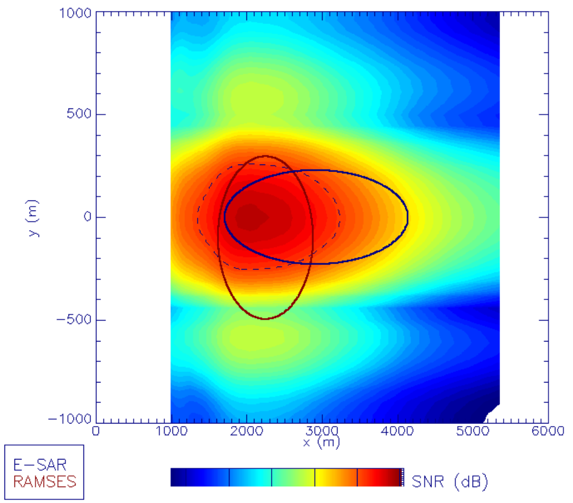




Bistatic SAR campaign: ONERA - DLR

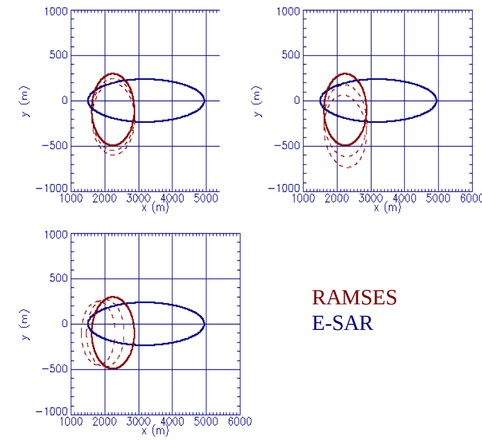
Signal to noise ratio

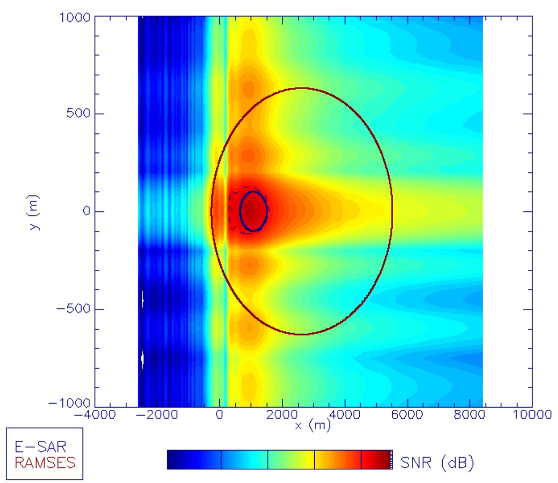
Geometry (position, roll, squint)



DLR

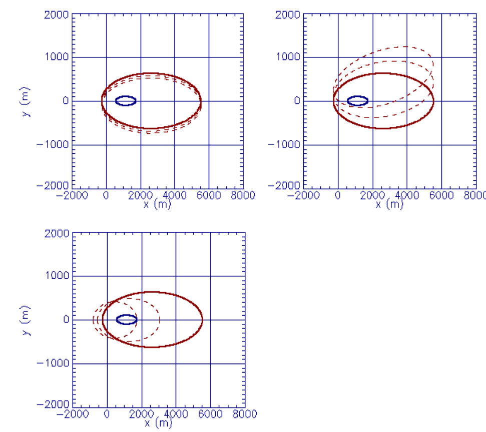
Configuration





ONERA

Configuration



Bistatic SAR campaign: ONERA - DLR

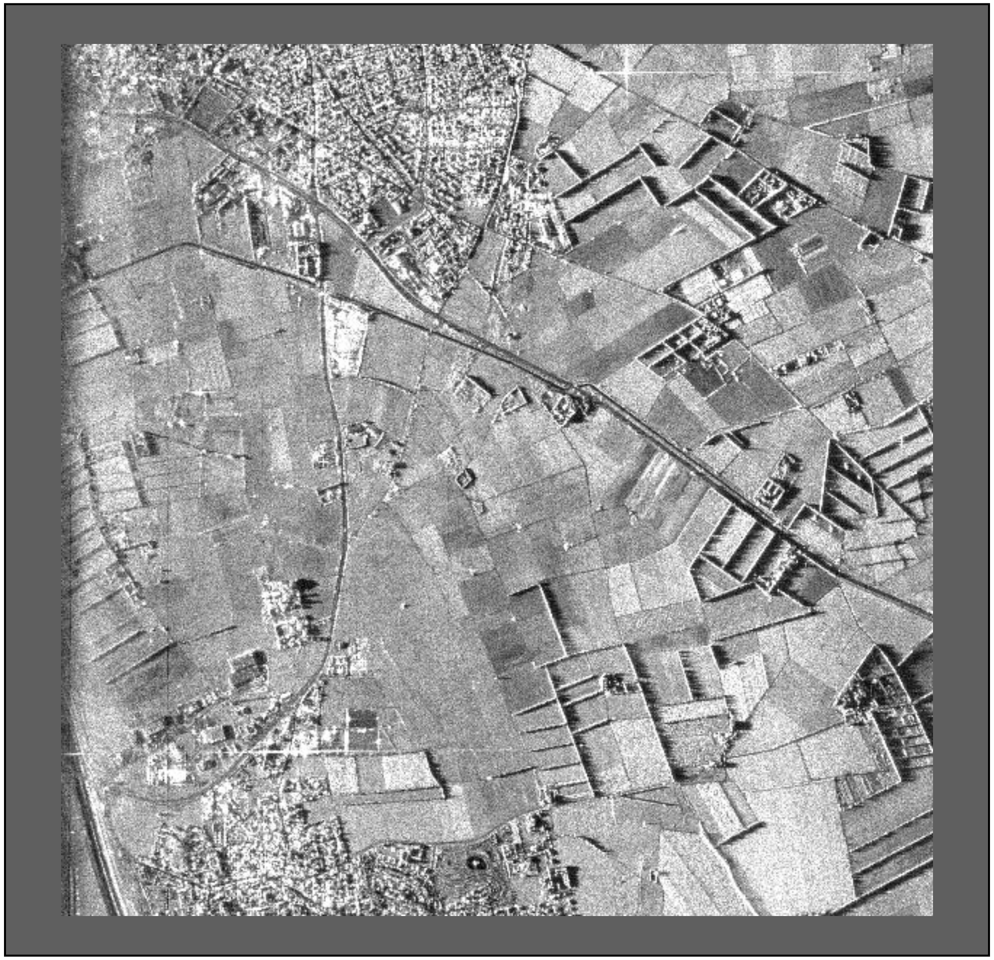
Bistatic image: Steep Configuration

Bistatic SAR campaign: ONERA - DLR

Bistatic image: Quasi-monostatic Configuration

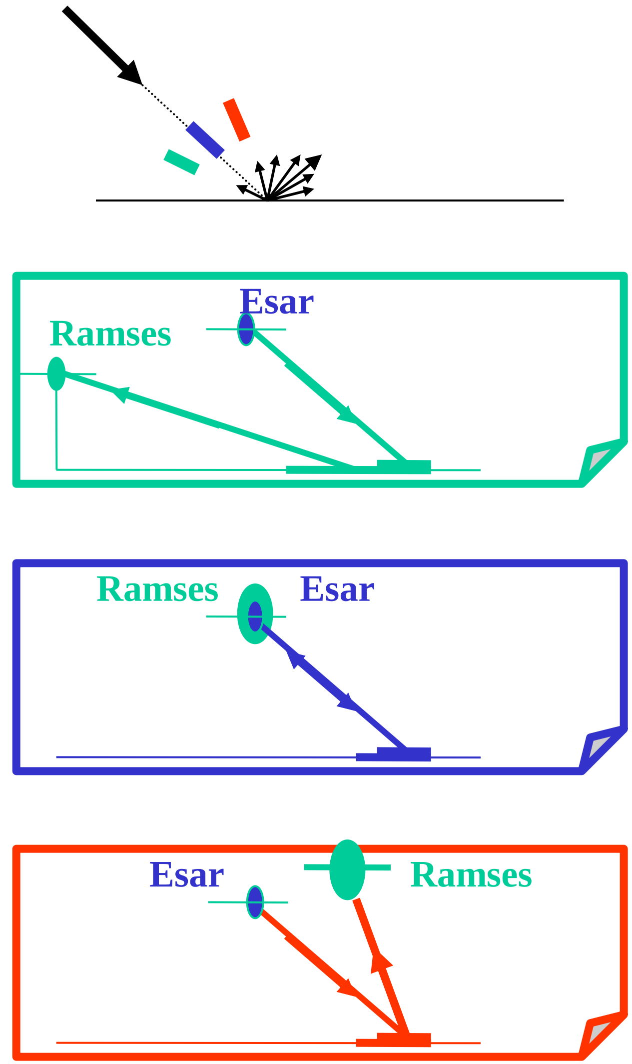
Bistatic SAR campaign: ONERA - DLR

Bistatic image: Grazing Configuration



Bistatic SAR campaign: ONERA - DLR

Effect of Bistatic angle



Bistatic SAR campaign: ONERA - DLR

Monostatic Configuration

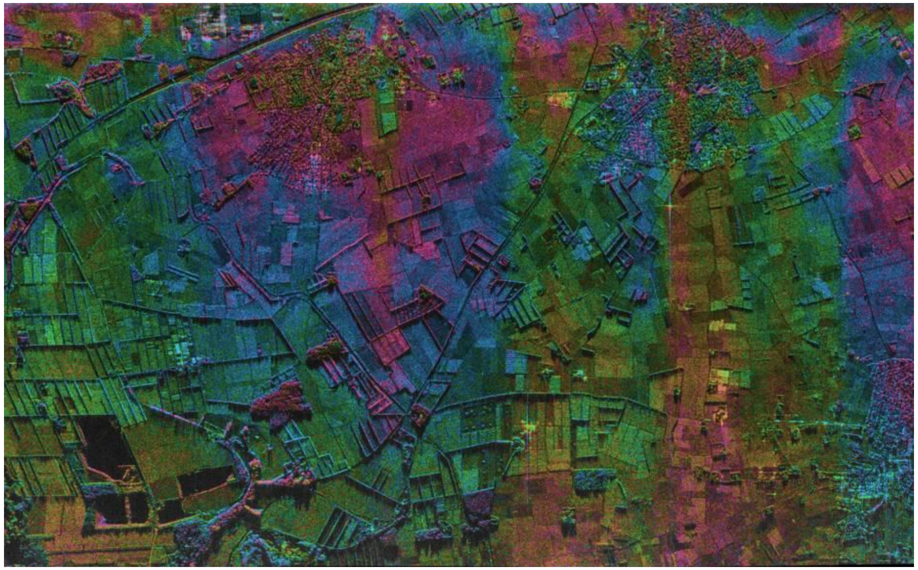
Bistatic SAR campaign: ONERA - DLR

Quasi-monostatic Configuration

Bistatic SAR campaign: ONERA - DLR

Quasi-monostatic/ Monostatic differences

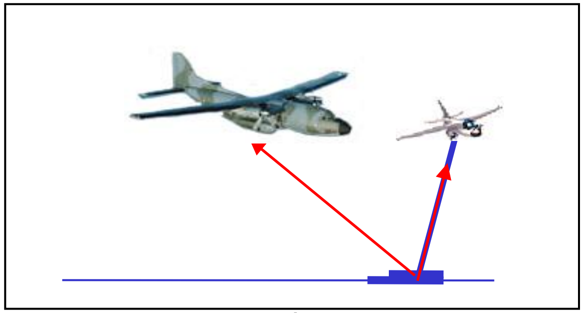
Bistatic SAR campaign: ONERA - DLR

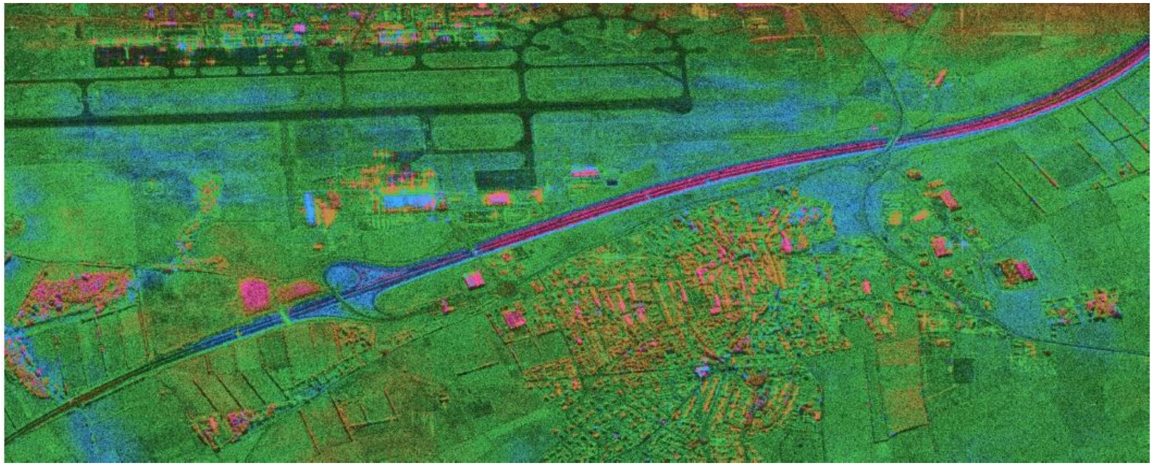


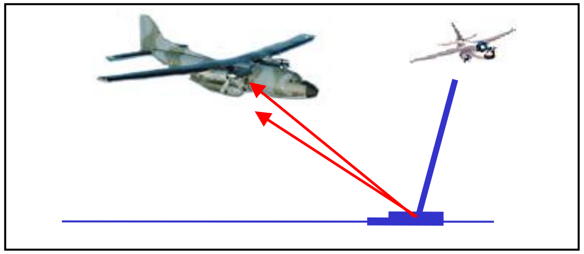
Bistatic interferometry

Cross-platform interferometry:

- Within the « critical baseline »
- After residual clock drift compensation (vertical fringes removal)







Two bistatic images,
baseline obtained on one platform

Summary

- Bistatic SAR can involve a wide variety of geometries, with the synthetic aperture formed by a moving transmitter, moving receiver, or both.

- And the moving platform may be an aircraft, satellite, UAV, or conceivably even a land vehicle.

- In general, autofocus will be necessary to remove platform motion errors.