→ 6th ESA ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

Synthetic Aperture Radar (SAR): Principles and Applications

Marwan Younis

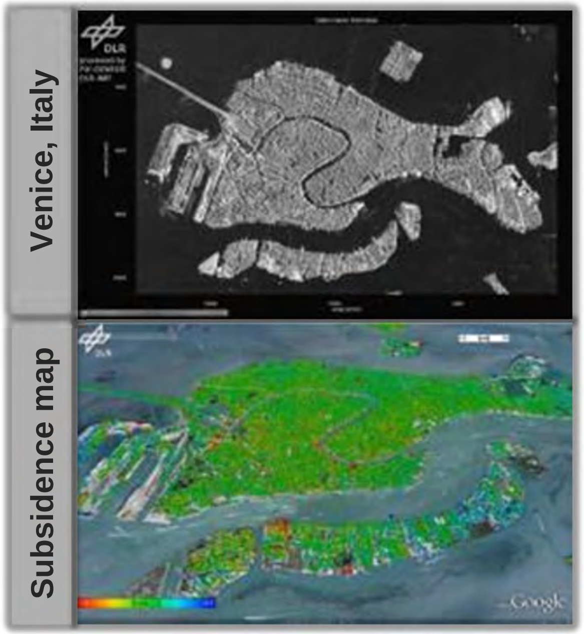
German Aerospace Center (DLR)
Microwaves and Radar Institute
82230 Oberpfaffenhofen, Germany

e-mail: marwan.younis@dlr.de / Web: www.dlr.de/HR

14–18 September 2015 | University of Agronomic Science and Veterinary Medicine Bucharest | Bucharest, Romania

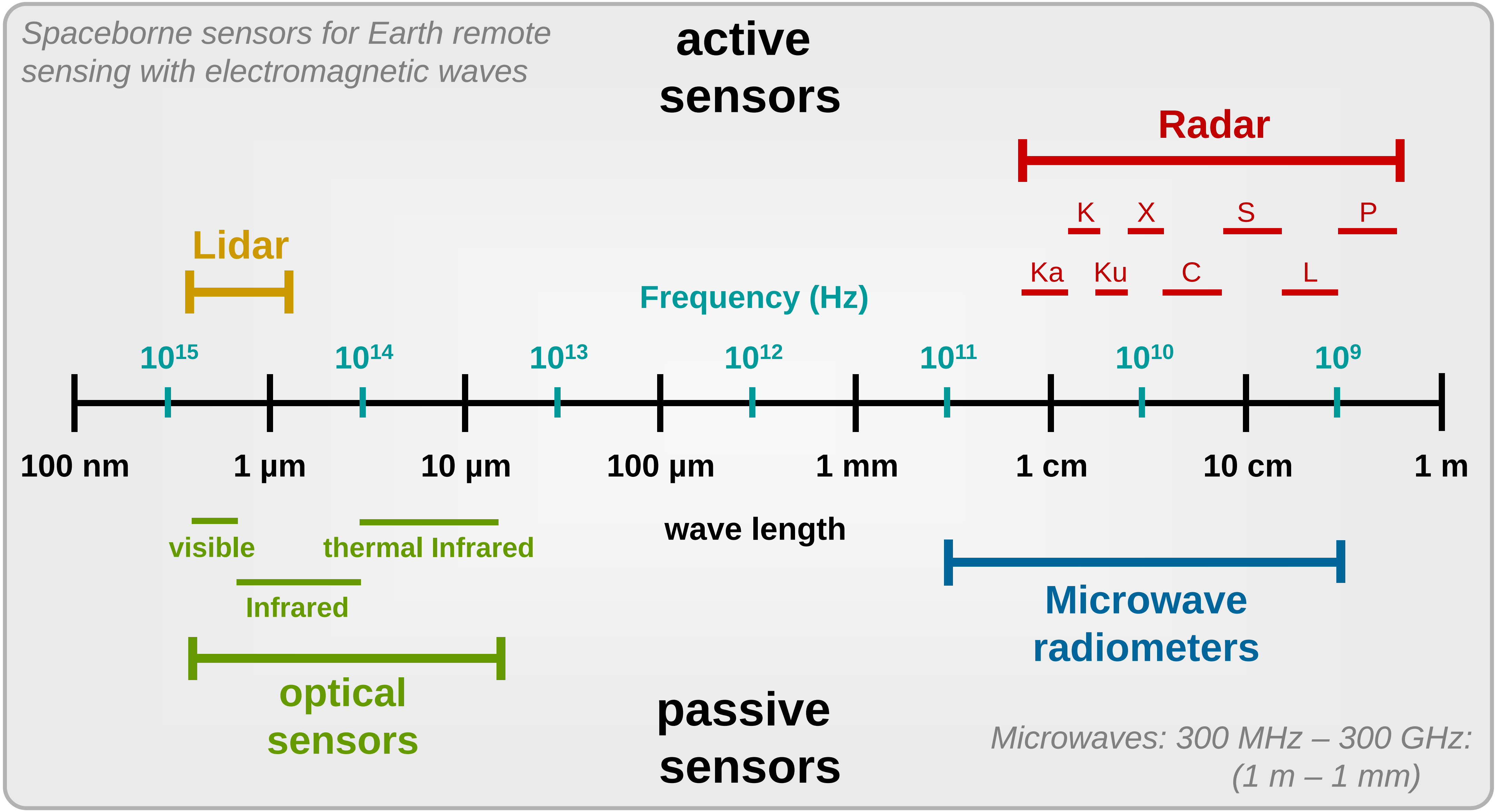
Remote Sensing

- Measuring objects properties from distance with dedicated instruments
- Aerial photography is the original form of remote sensing
- Acquired information
  - spatial (geometric resolution)
  - spectral (frequency resolution)
  - intensity (radiometric resolution)
  - temporal (revisit time)



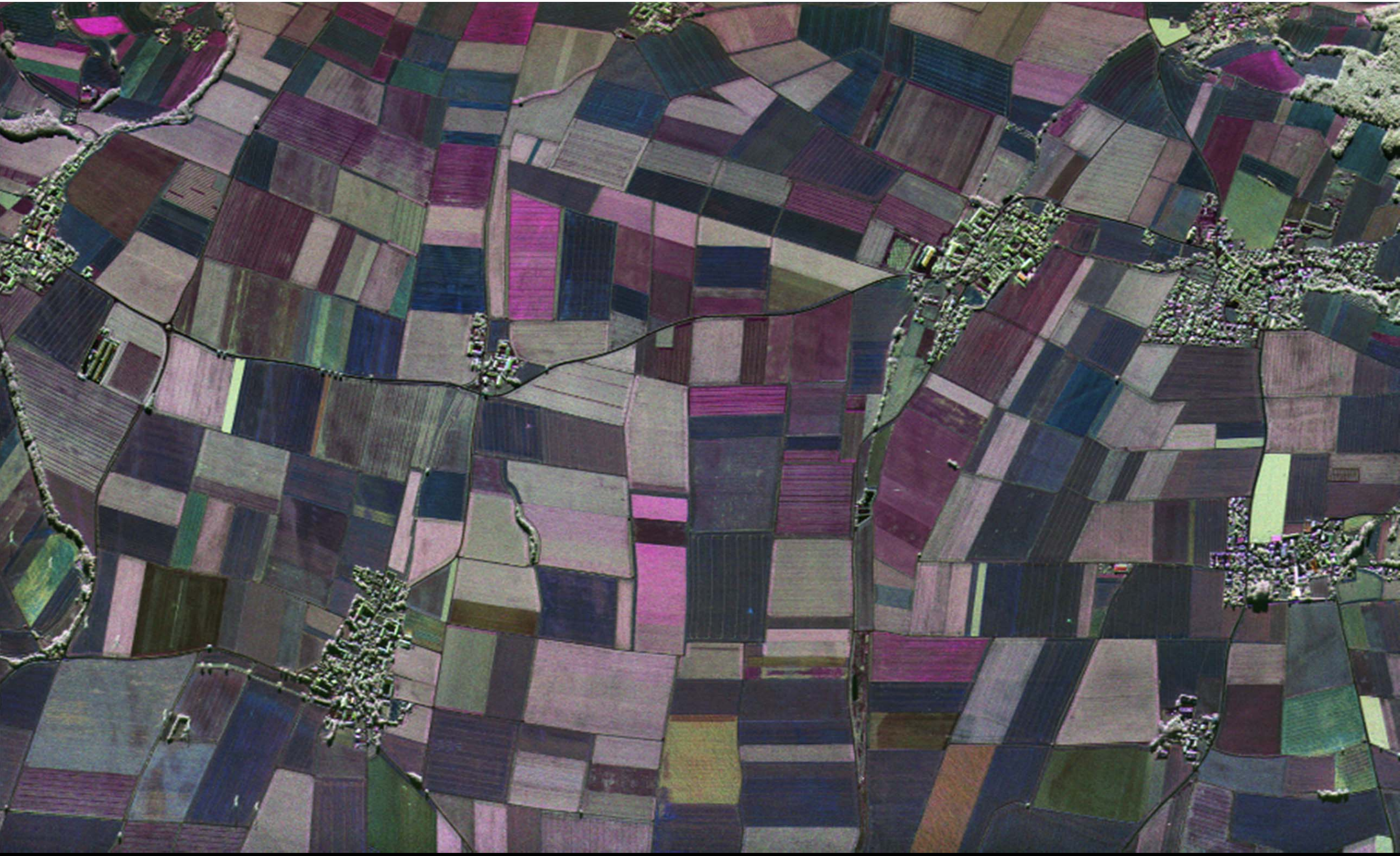
- Different types of remote sensing sensors:
  - Microwave sensors
    - passive (radiometers)
    - active (radars)
      - Scatterometer, Altimeter
      - Synthetic Aperture Radar - SAR

Types of Remote Sensing Sensors

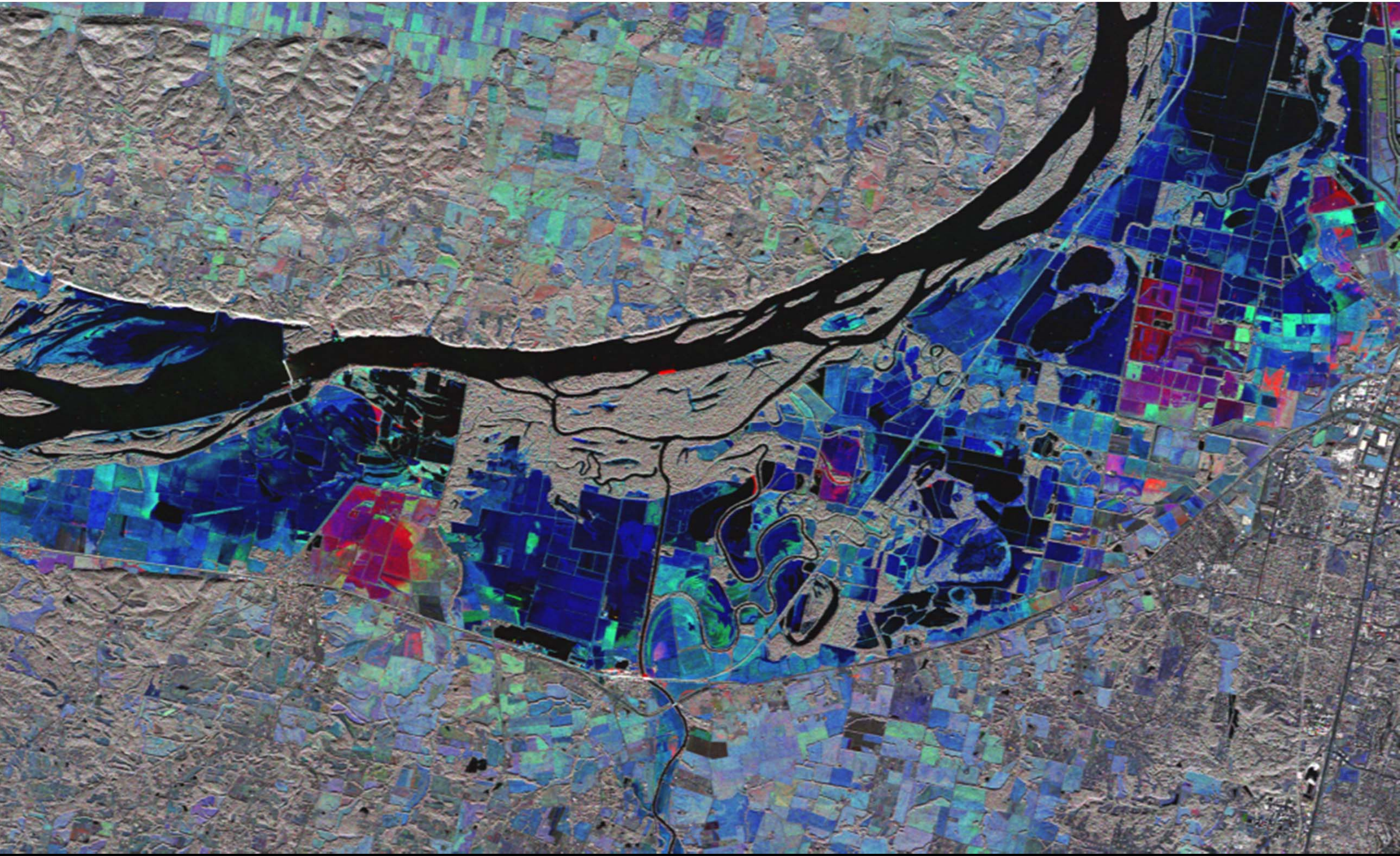


X-band, High Resolution Airborne SAR, F-SAR, Kaufbeuren, Germany

X-band, Airborne SAR, F-SAR, Full Polarimetric



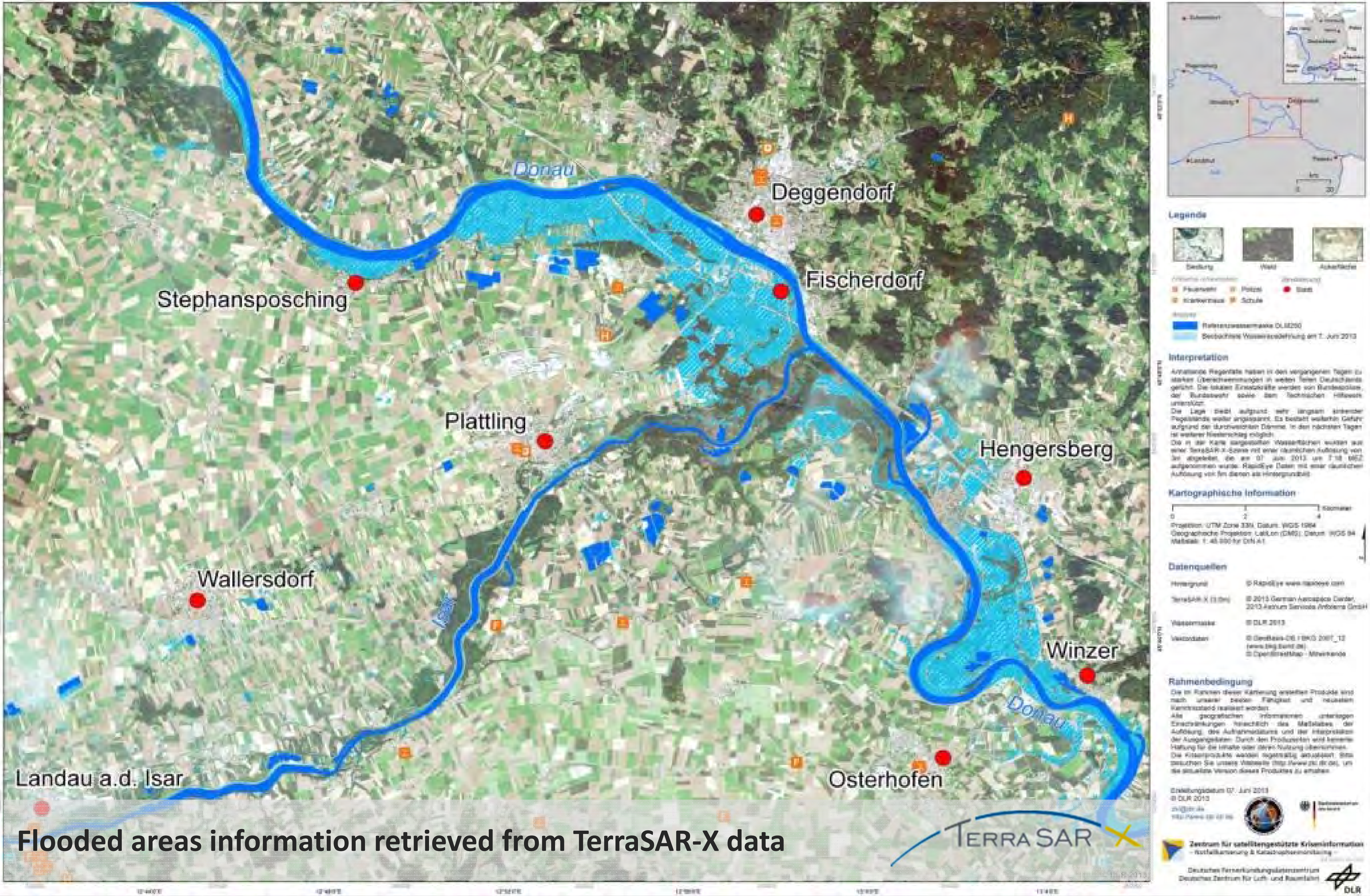
C-band, Airborne SAR, F-SAR, Full Polarimetric



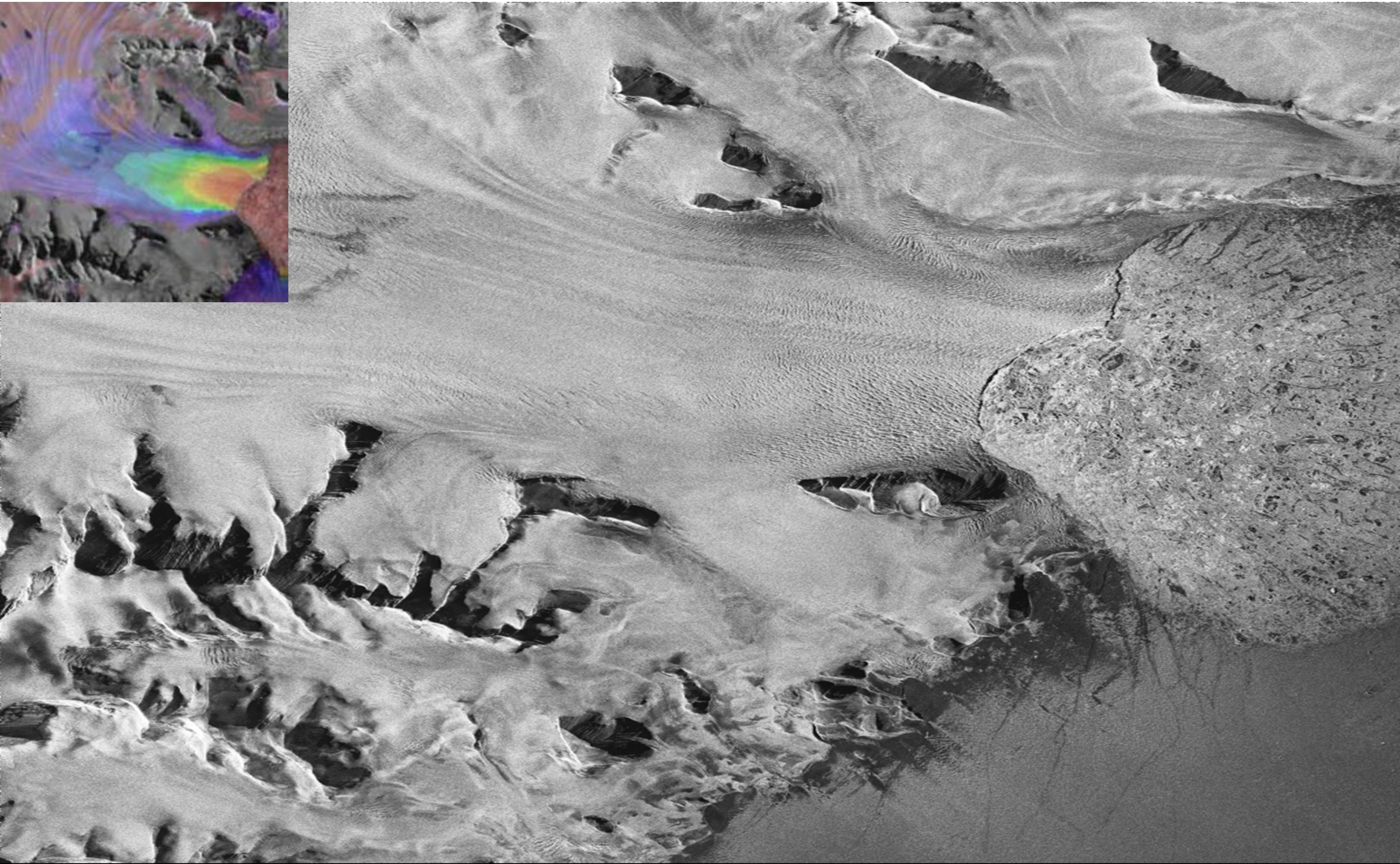
TerraSAR-X, Mississippi, USA - Flooding

DEUTSCHLAND - Deggendorf

Hochwassersituation am 7. Juni 2013 - Betroffene Fläche - Übersicht 1: 45.000

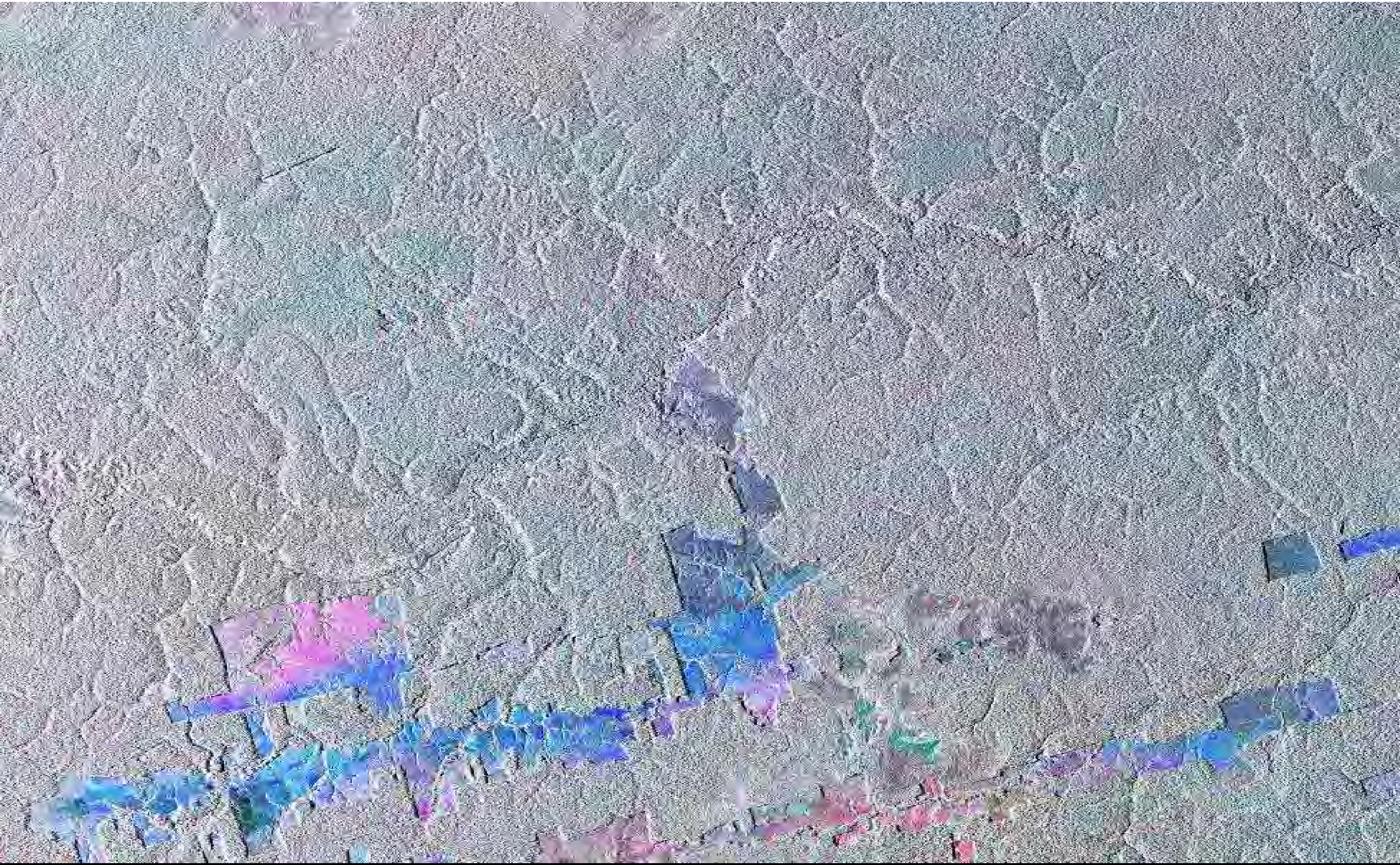


Flooded areas information retrieved from TerraSAR-X data

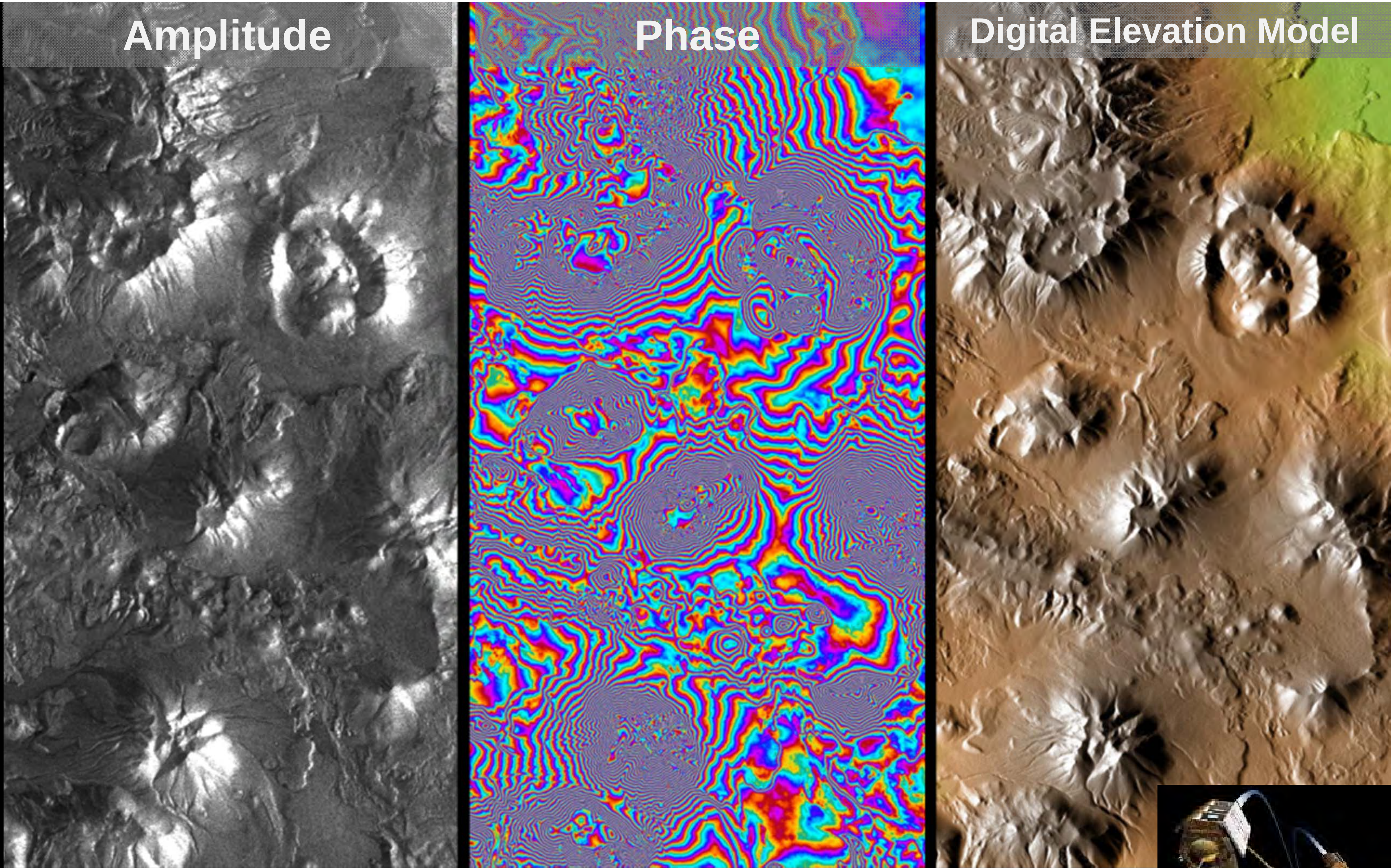


TerraSAR-X, Drygalski Glacier, Oct 2007 – July 2008

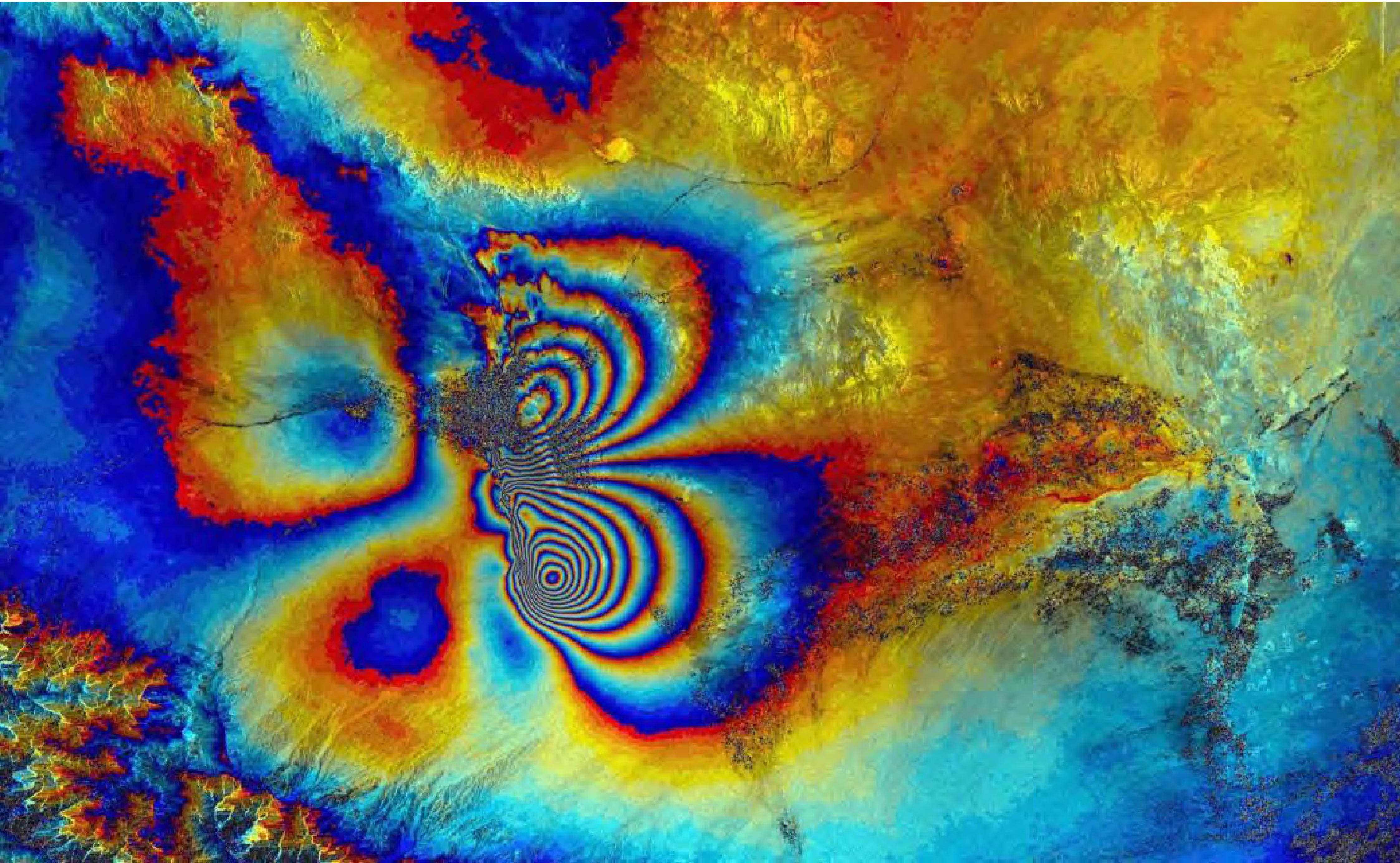
TerraSAR-X, Las Vegas, USA (time series of 20 images)



Mato Grosso, Brazil - Deforestation



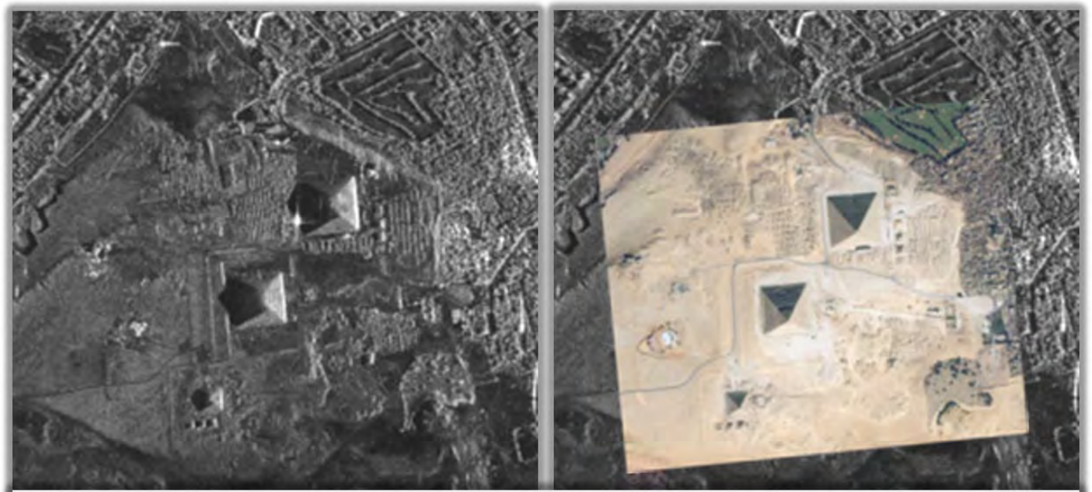
TanDEM-X, Atacama Desert, Chile



ENVISAT/ASAR, Bam Earthquake, 2003 (© ESA)

Motivation for Spaceborne SAR

- Complementary information to optical systems (e.g. polarimetry)


TerraSAR-X, Pyramids of Giza, Egypt

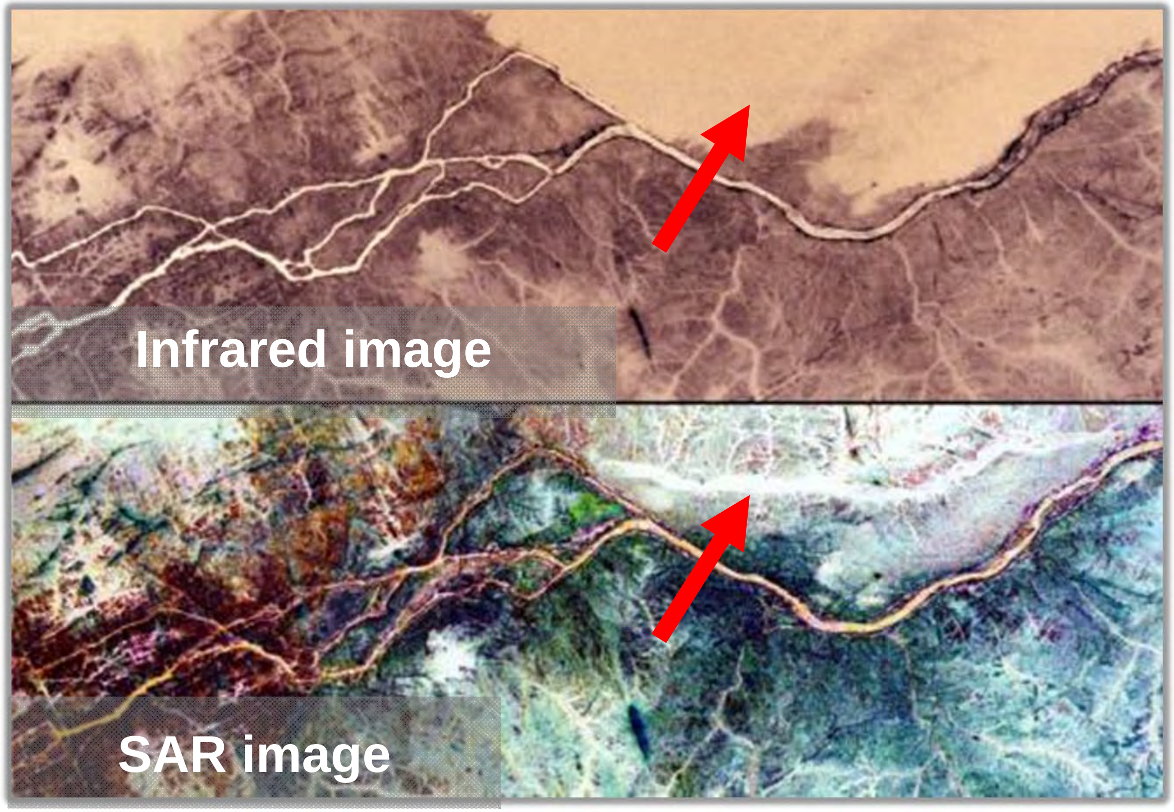

F-SAR, Kaufbeuren, Germany


F-SAR, Oberpfaffenhofen, Germany

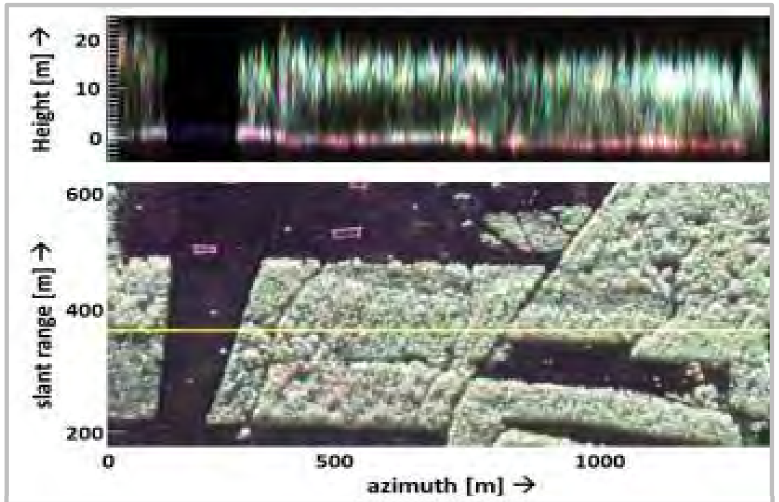
DLR

Motivation for Spaceborne SAR

- Complementary information to optical systems
- Penetration of radar waves



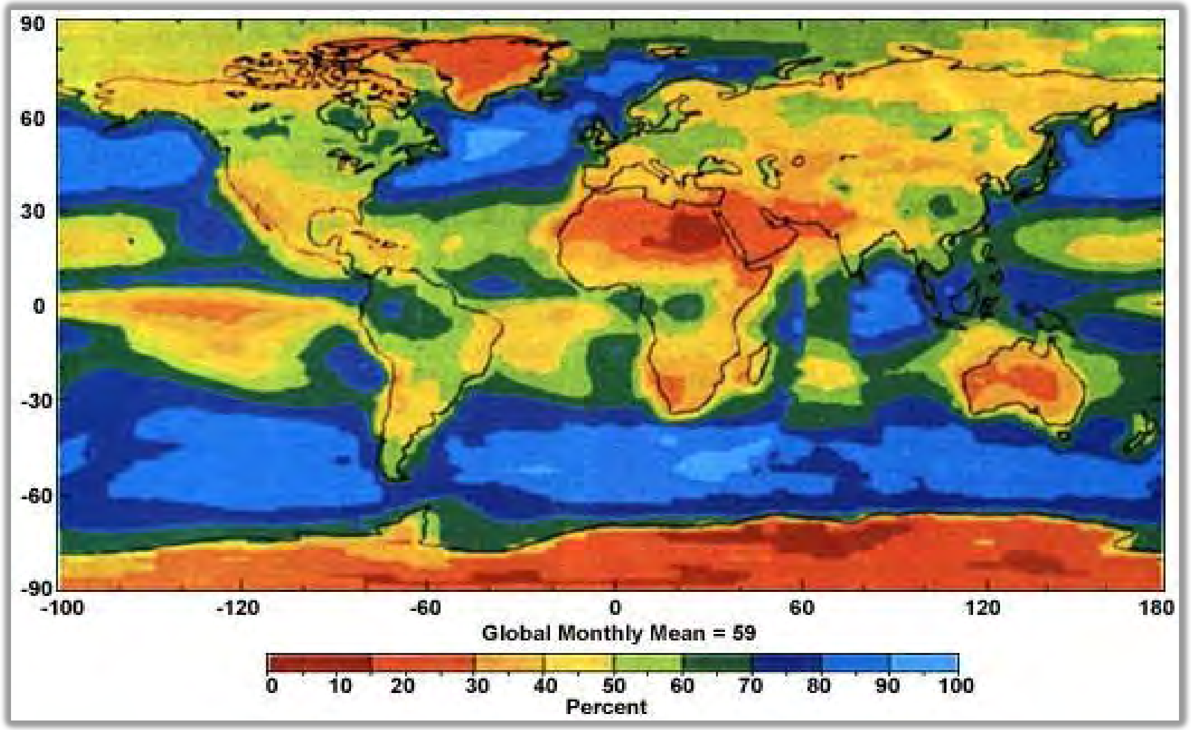
Forest height with
polarimetric SAR interferometry



Forest profile with SAR tomography

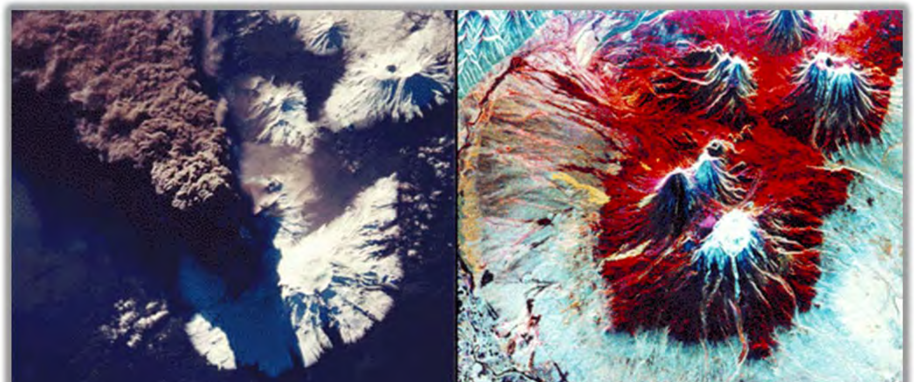
Motivation for Spaceborne SAR

- Complementary information to optical
- Penetration of radar waves
- Weather independent

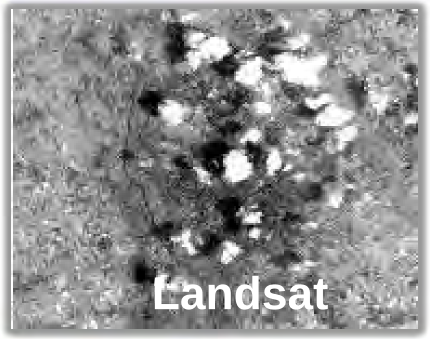


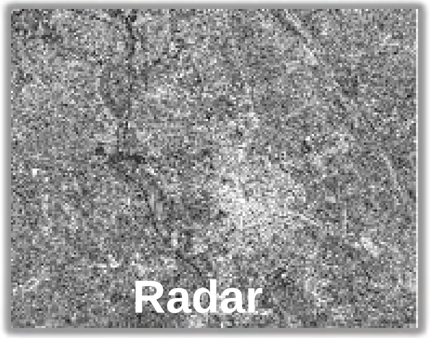
average global cloud coverage

ENVISAT (ASAR and MERIS), Alps, Austria



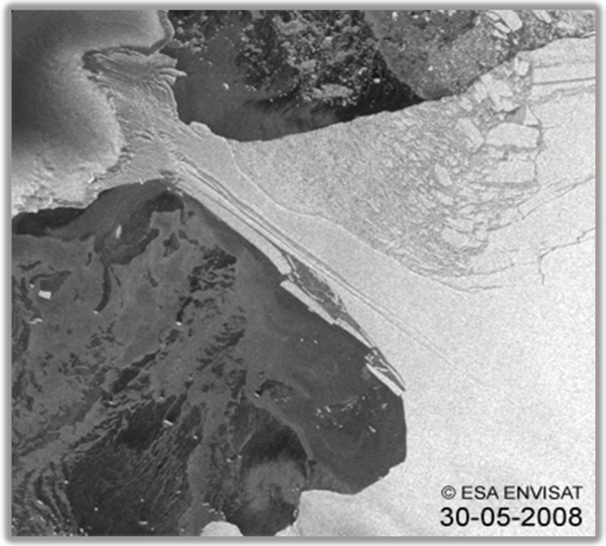
SIR-C/X-SAR image, Kamchatka, Russia

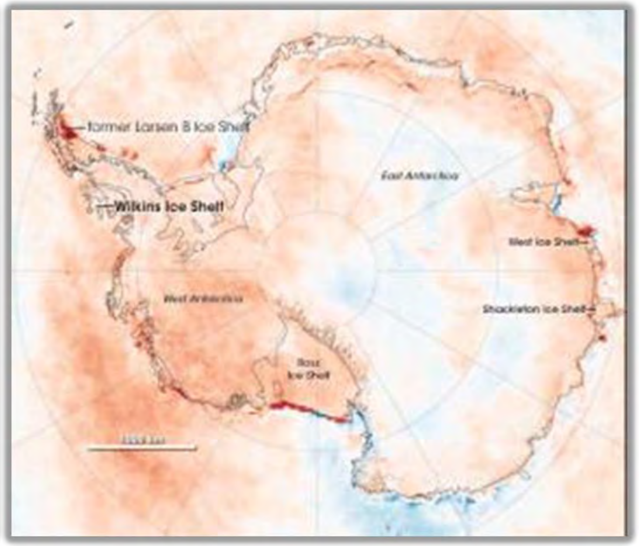




Motivation for Spaceborne SAR

- Complementary information to optical systems
- Penetration of radar waves
- Weather independent
- Day-and-night imaging capability





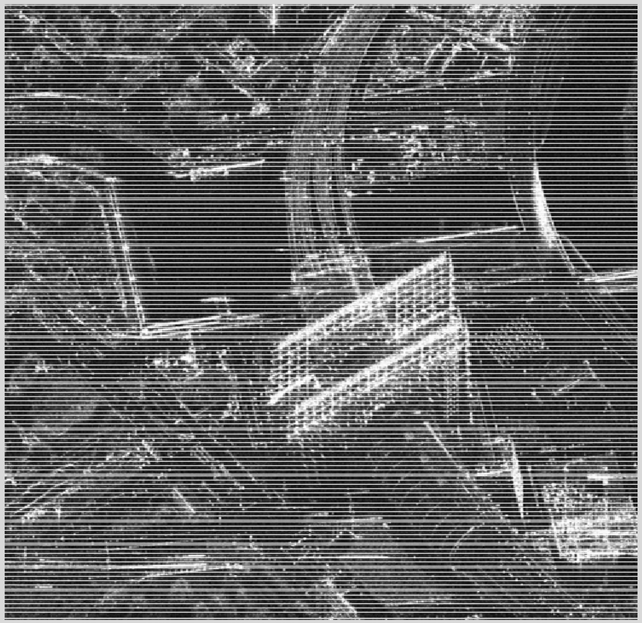
Wilkins ice shelf collapse during the antarctic winter

Flooding, Deggendorf, Germany

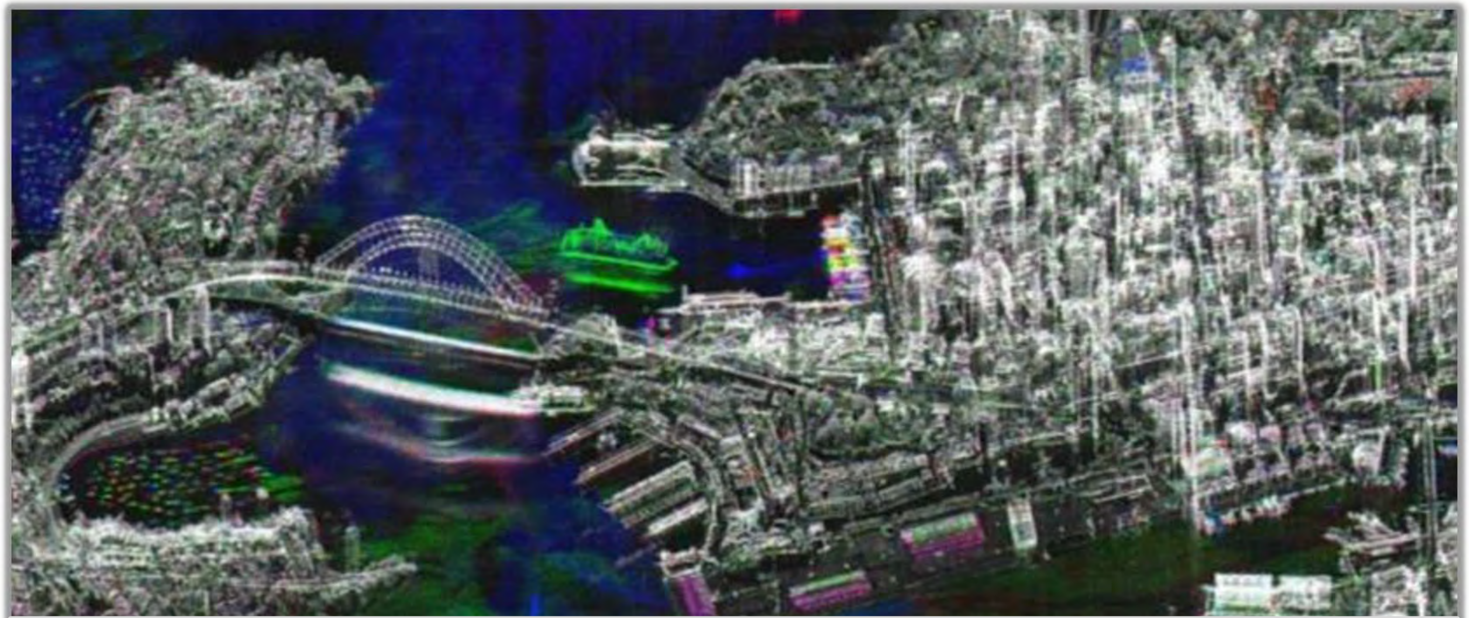
TERRA SAR X

Motivation for Spaceborne SAR

- Complementary information to optical systems
- Penetration of radar waves
- Weather independent
- Day-and-night imaging capability
- Geometric resolution independent of the distance



TerraSAR-X, Berlin

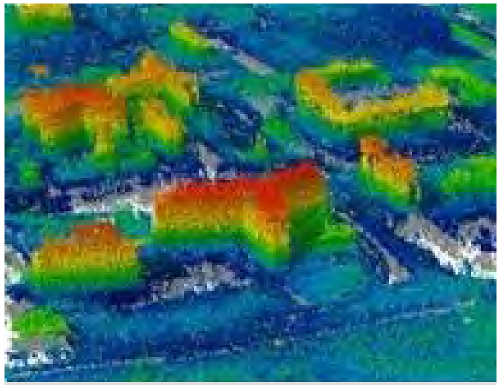


TerraSAR-X, multi-temporal, Sydney, Australia

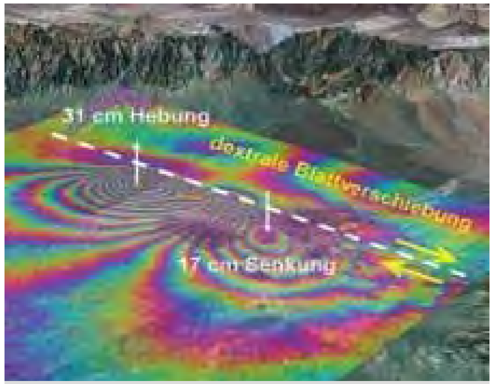
Motivation for Spaceborne SAR

- Complementary information to optical systems
- Penetration of radar waves
- Weather independent
- Day-and-night imaging capability
- Geometric resolution independent of the distance
- New image products by coherent combination of radar images (i.e. using phase information in the radar images)

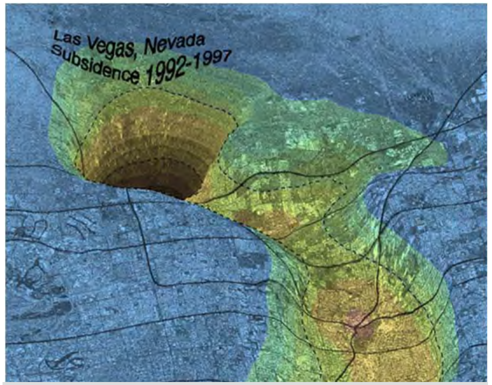
3D Mapping
(Digital Elevation Model)



Tomography
(Urban Mapping)



Differential Interferometry
(Earthquake deformation)



Differential Interferometry
(Subsidence)

SAR Main Properties and Applications

- high resolution capability (independent of flight altitude)
- weather independence by selecting proper frequency range
- day/night imaging capability due to own illumination
- complementary to optical systems
- polarization signature can be exploited (physical structure, dielectric constant)
- innumerous applications areas:

  - Topography (DEM generation with interferometry)
  - Oceanography (wave spectra, wind speed, ocean currents)
  - Glaciology (snow wetness, snow water equivalent, glacier monitoring)
  - Agriculture (crop classification and monitoring, soil moisture)
  - Geology (terrain discrimination, subsurface imaging)
  - Forestry (forest height, biomass, deforestation)
  - Moving Target Indication (MTI)
  - Volcano and earthquake monitoring (differential interferometry)
  - Environment monitoring (oil spills, flooding, urban growth, global change)
  - Military surveillance and reconnaissance (strategic policy, tactical assessment)

DLR

Outline of Lecture

- ***Part I : Motivation for Spaceborne SAR Remote Sensing*** ✓

- ***Part II : Basics of Synthetic Aperture Radar***

  Radar principle, SAR basic principles, backscattering coefficient, geometric resolution, spaceborne SAR systems, frequency bands, summary

- ***Part III: Theory: SAR Image Formation, Image Properties***

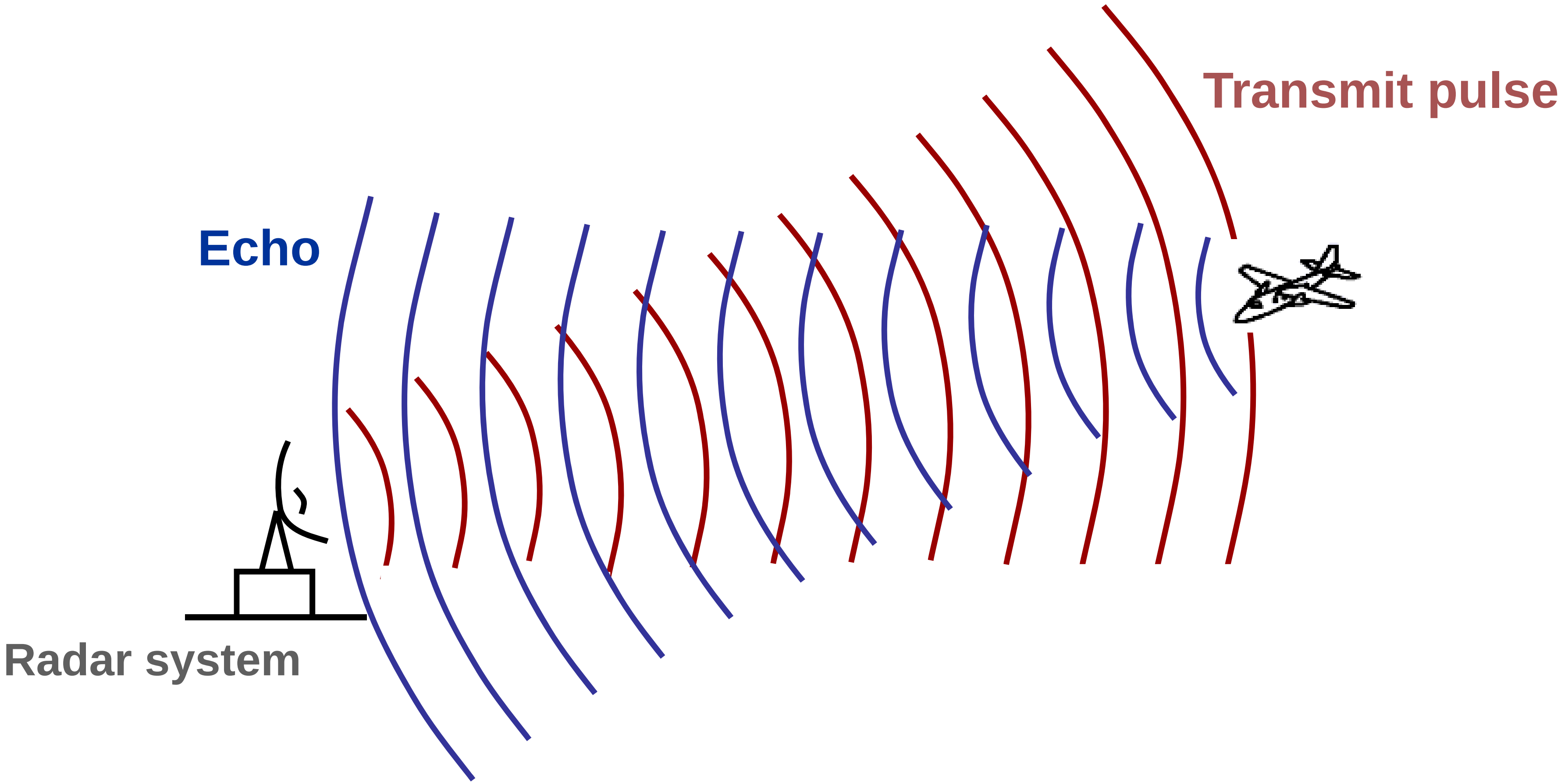
  SAR block diagram, synthetic aperture, SAR image formation, impulse response function, calibration, SAR signal for distributed targets, speckle, multi-look processing

- ***Part IV: Advanced SAR techniques and Future Developments***

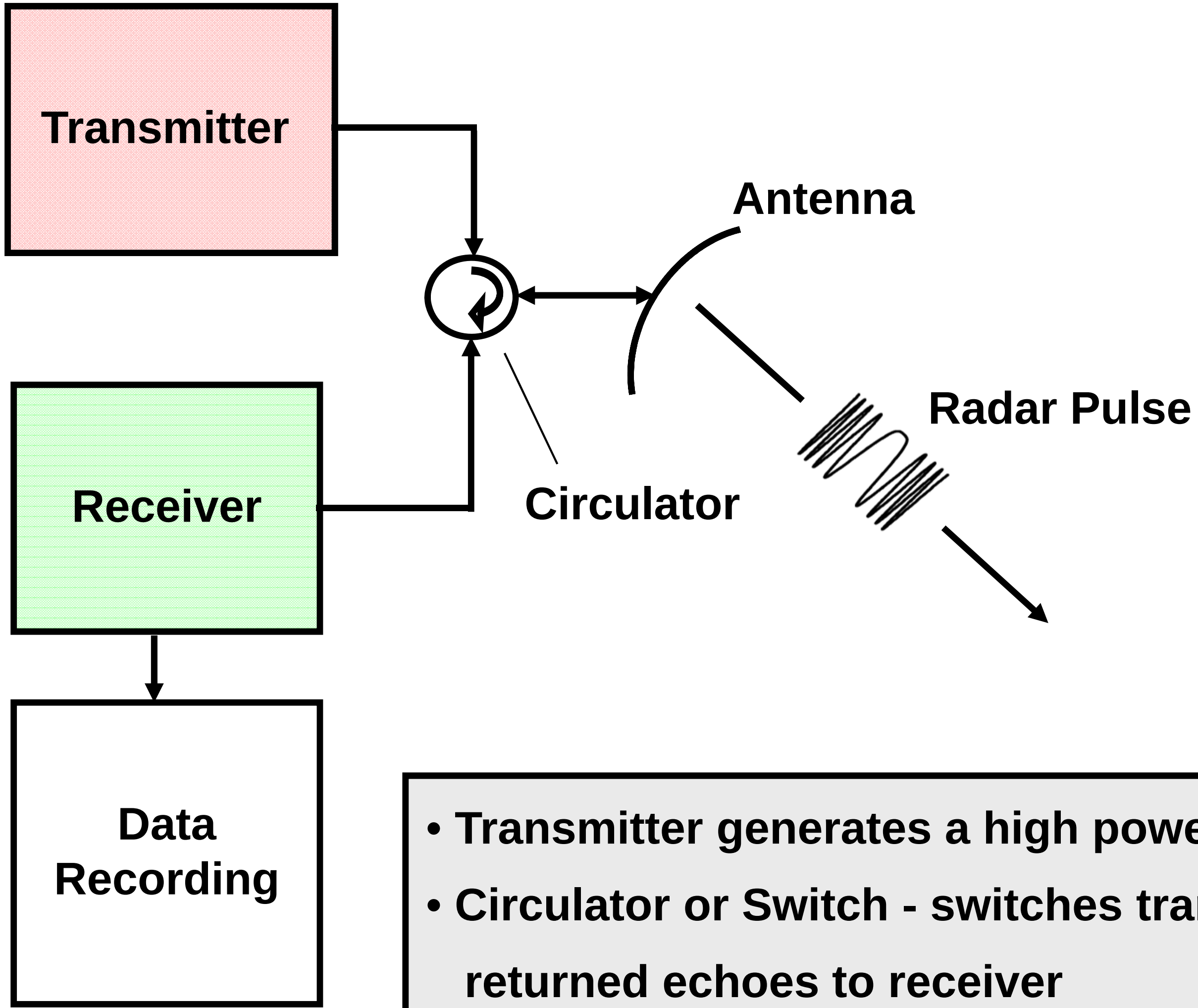
  ScanSAR imaging, Spotlight SAR imaging, outlook, references

Radar: Radio Detection and Ranging

Radar Principle

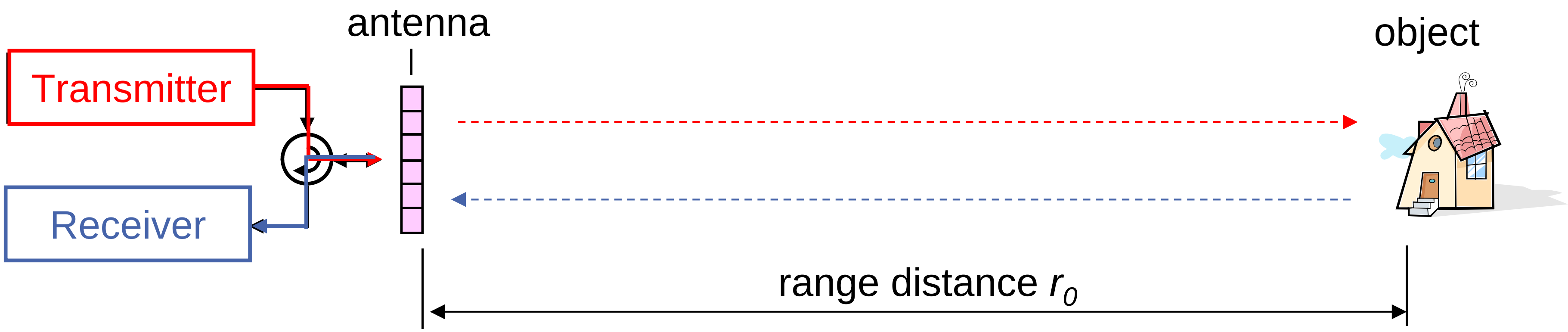


Basic Radar Block Diagram

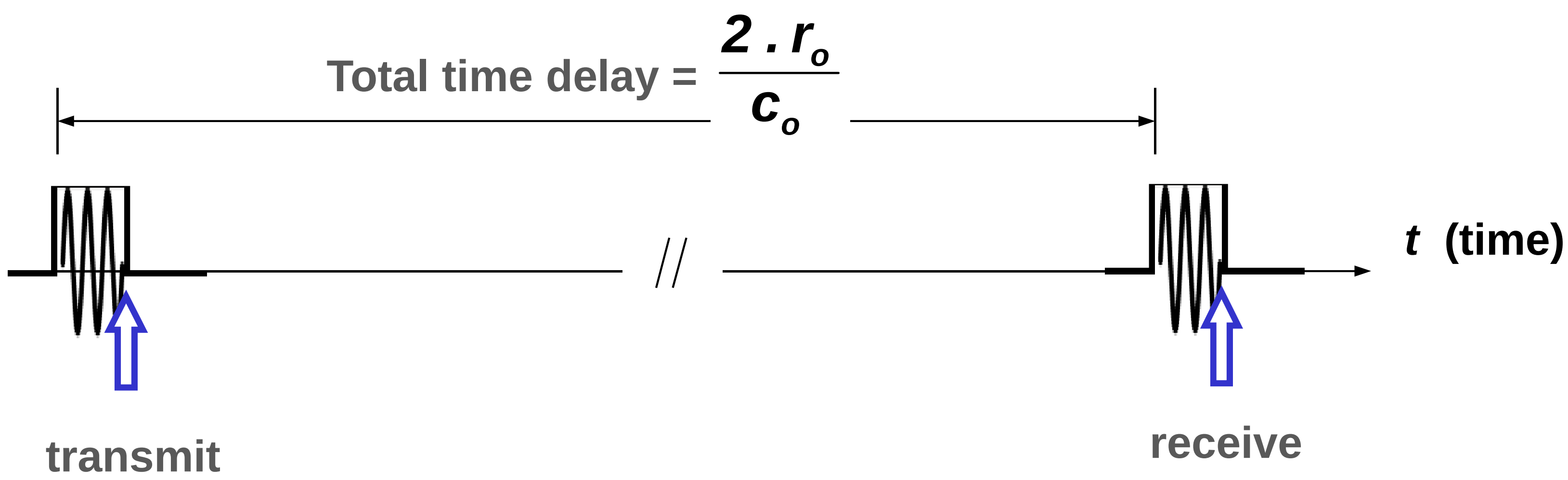


- Transmitter generates a high power pulse
- Circulator or Switch - switches transmitted pulse to antenna, returned echoes to receiver
- Antenna directs transmitted pulses towards the target area
- Receiver amplifies the received signal and converts to base band

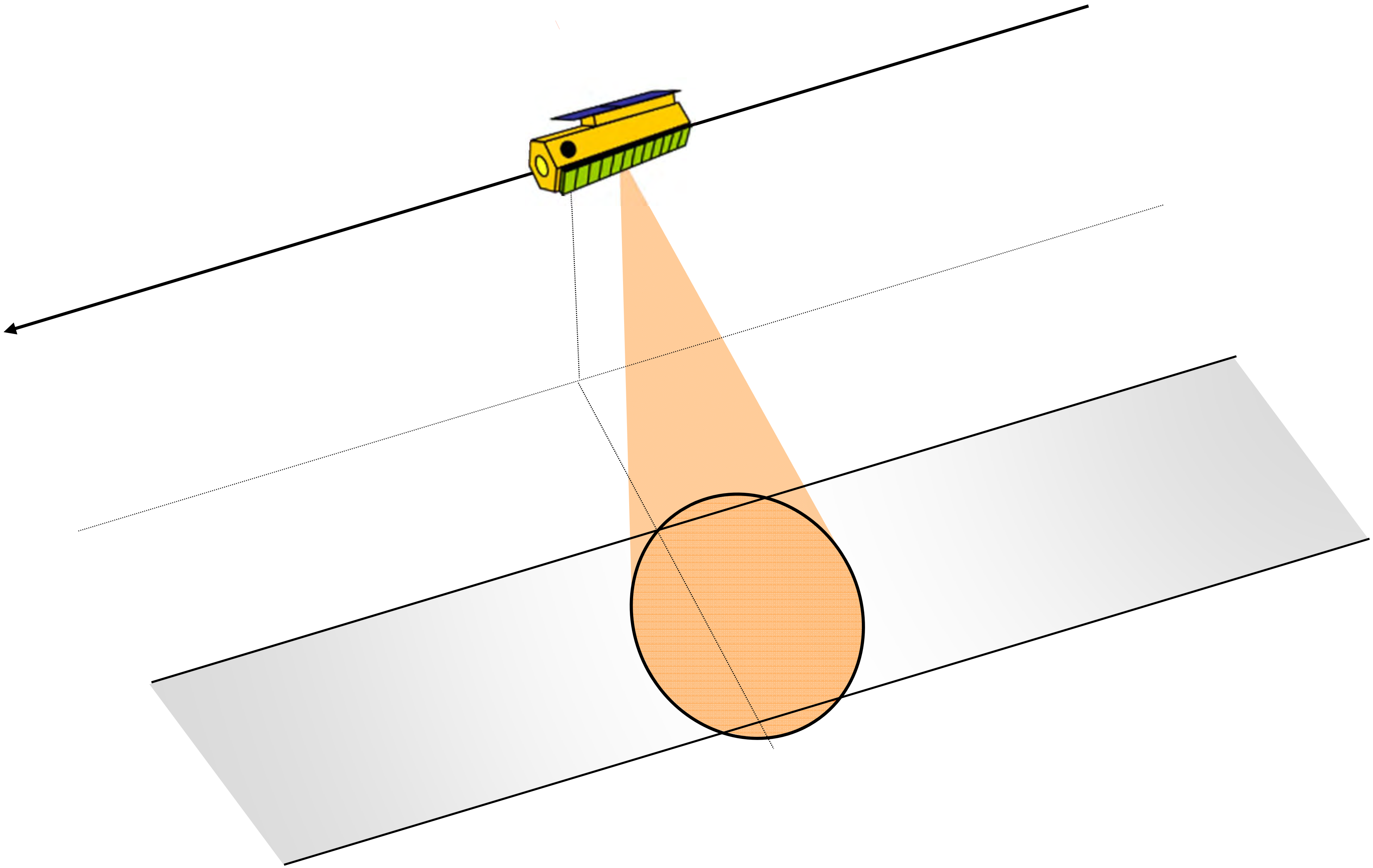
Radar Measurement Principle



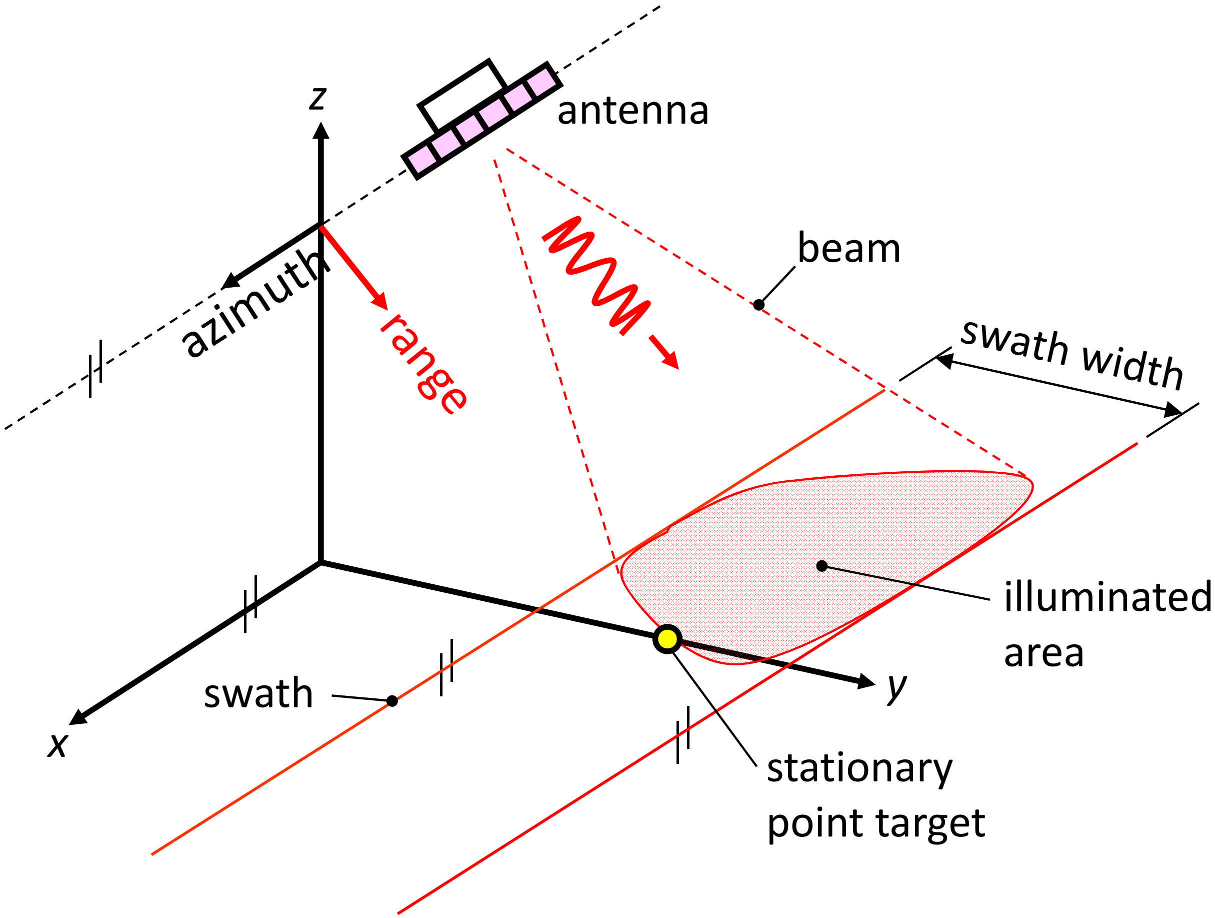
• **Received echo signal (back-scattered signal of imaged object):**

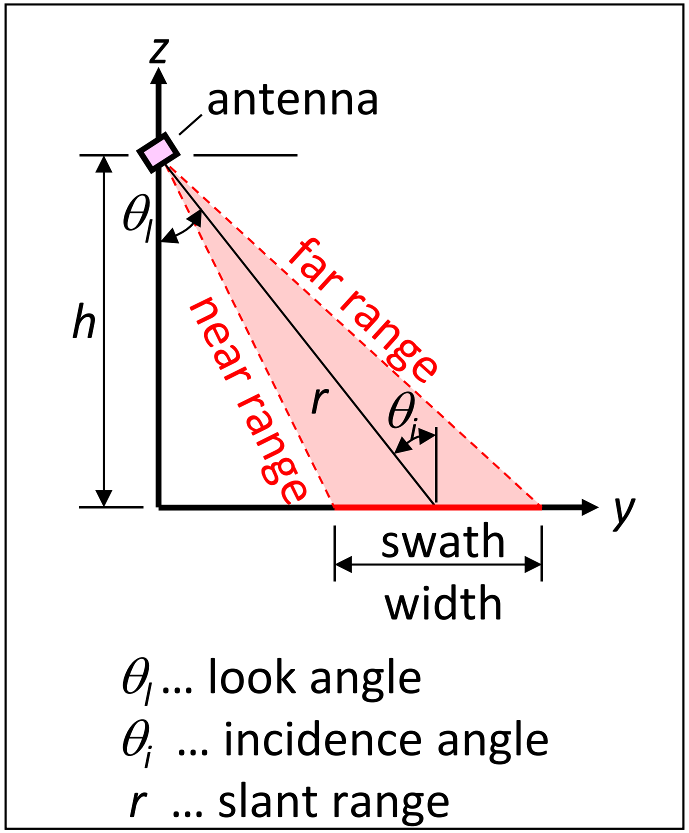


Side-Looking Radar Imaging Geometry



Acquisition Geometry

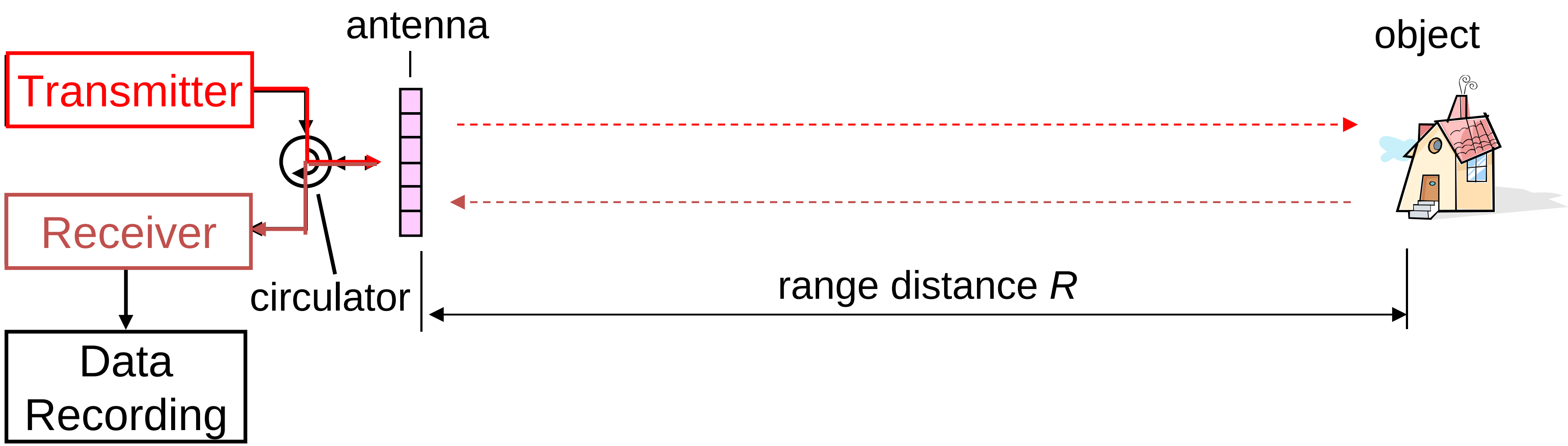


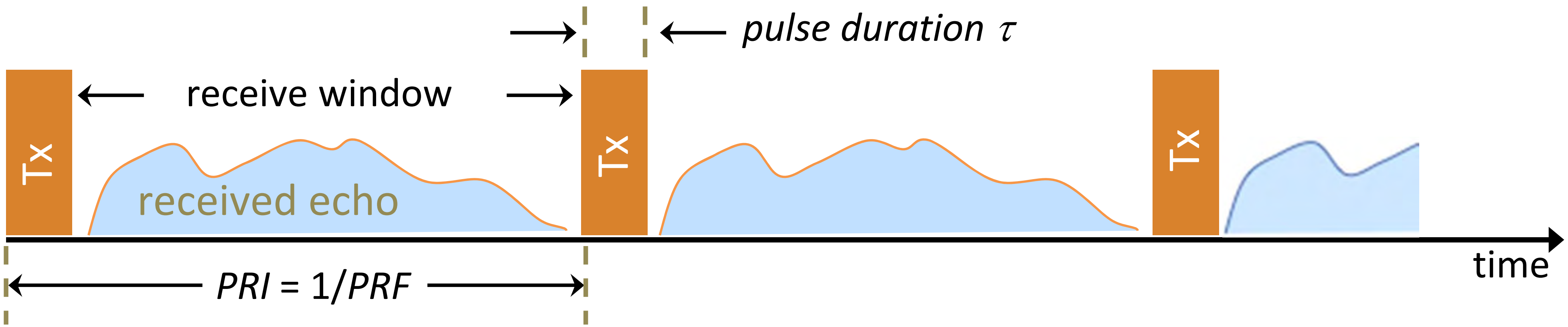


- Pulsed Radar system (PRF: pulse repetition frequency)
- Side-looking antenna

⇒ discrimination of objects along ground-range possible

SAR Measurement Principle





Timing is an important issue for SAR:

It determines the duration of the receive echo window (swath width), which is inversely proportional to the *PRF* and τ

Side Looking Geometry and Timing

- **Time delay for received signal t_d**

$$t_d = \frac{2 \cdot r_0}{c_0}$$

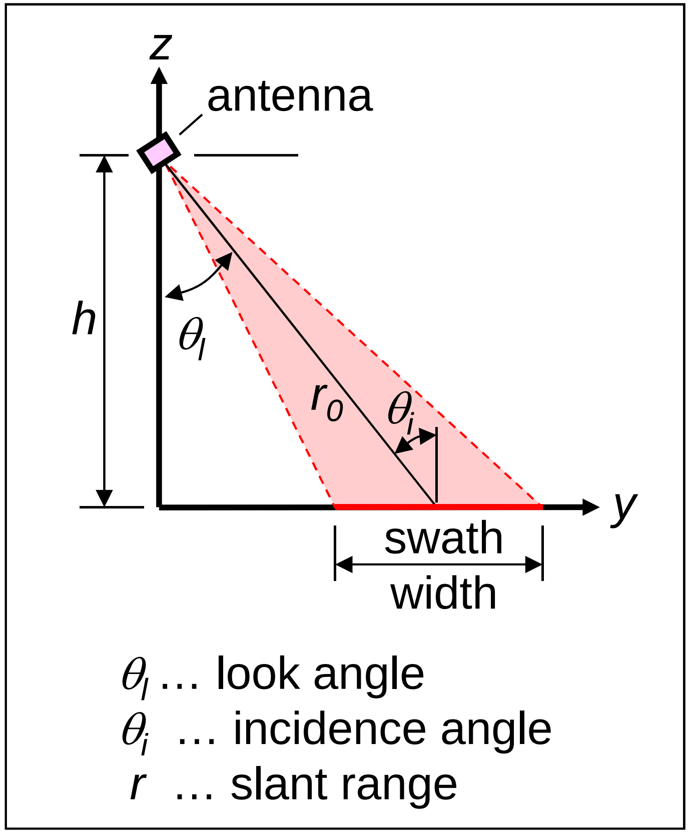
- **Maximum swath width SW_{max}**

$$SW_{\max} \approx \frac{c_0}{2 \cdot PRF \cdot \sin\theta_i}$$

- **Incidence angle θ_l**

$$\cos\theta_l \approx \frac{h}{r_o}$$

($\theta_l = \theta_i$, valid only for flat terrain)

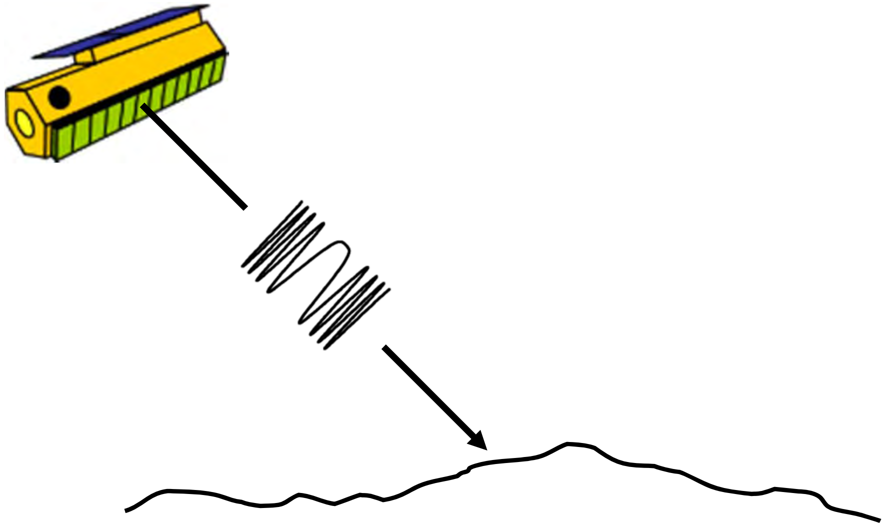


- **Typical values of look angle: 20 degrees to 60 degrees**

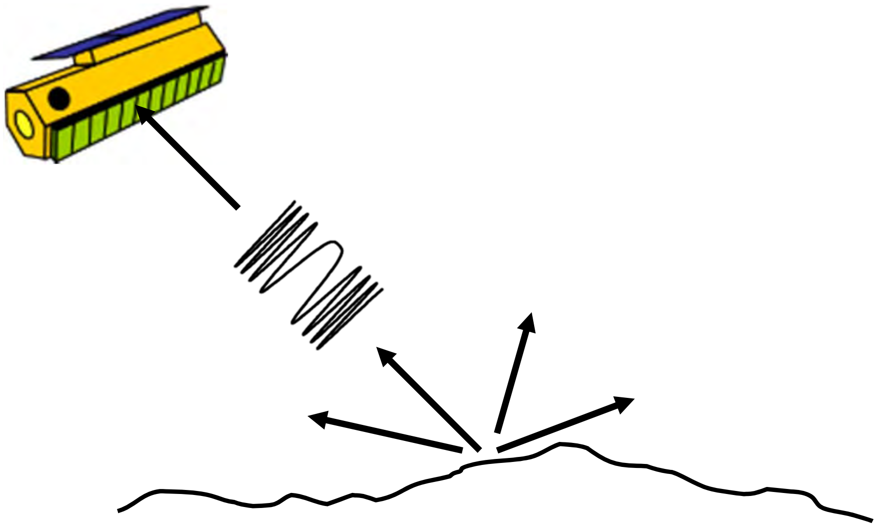
DLR

What does the Radar measure ?

- ***Radar reflectivity (backscattered signal) of targets as a function of their position***



radar transmits a pulse (travelling velocity is equal to velocity of light)



some of the energy in the radar pulse is reflected back towards the radar.
This is what the radar measures.

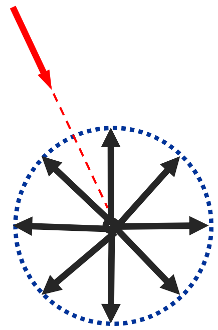
It is known as radar backscatter σ_o

(sigma nought or sigma zero).

What does the Radar measure ?

- Normalized radar cross-section (backscattering coefficient) is given by:

$$\boxed{\sigma_o\,(dB) = 10.\ Log_{10}\,(\text{energy ratio})}$$

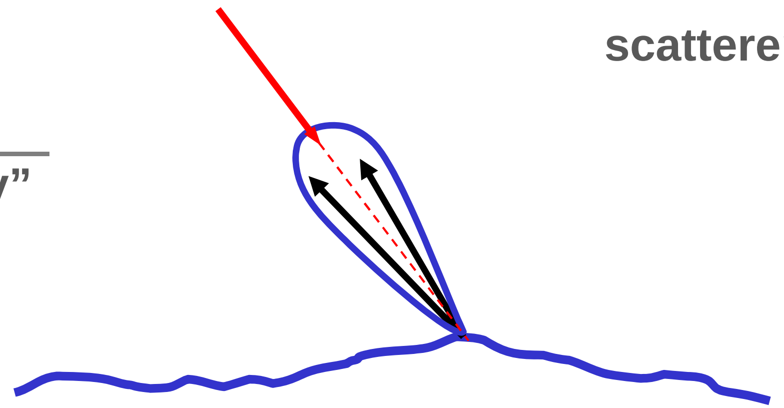


Isotropic

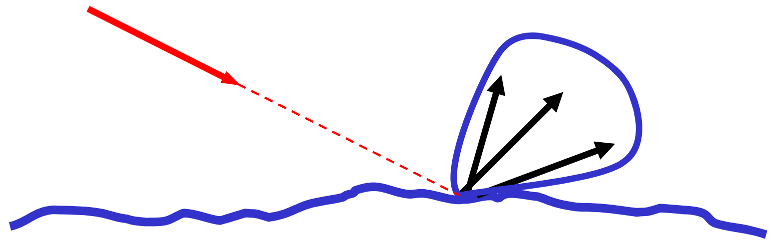
scatterer

whereby

$$\text{energy ratio} = \frac{\text{received energy by the sensor}}{\text{“energy reflected in an isotropic way”}}$$



The backscattered coefficient can be a positive number if there is a focusing of backscattered energy towards the radar



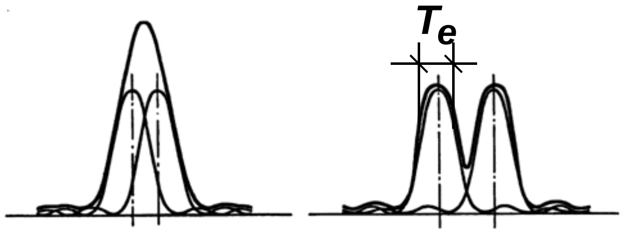
or

The backscattered coefficient can be a negative number if there is a focusing of backscattered energy way from the radar (e.g. smooth surface)

Range and Azimuth Resolution for a Radar System

- *Range Resolution* depends on the bandwidth or pulse duration of transmitted signal

$$\delta_r = \frac{c_o \cdot T_p}{2} = \frac{c_o}{2B_p}$$

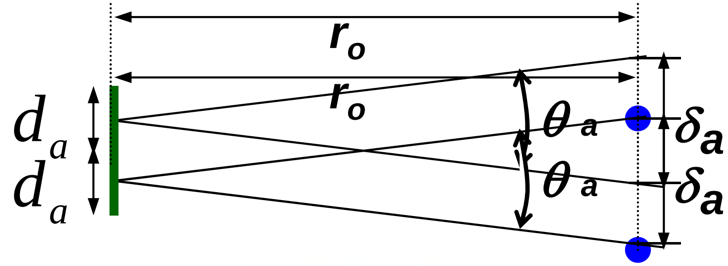


$$T_p = \frac{1}{B_p}$$

B_p ... *Bandwidth of the radar*

- *Azimuth Resolution* depends on the azimuth size of the antenna and increases with range

$$\delta_a = \theta_a \,.\, r_o = \frac{\lambda}{d_a} \,.\, r_o$$



- ***Example 1:*** **Airborne system in X-Band, 25 MHz bandwidth, 3 m antenna, 3000 m range**

  $\delta_r = 6\ m$ $\qquad$ $\delta_a = 30\ m$

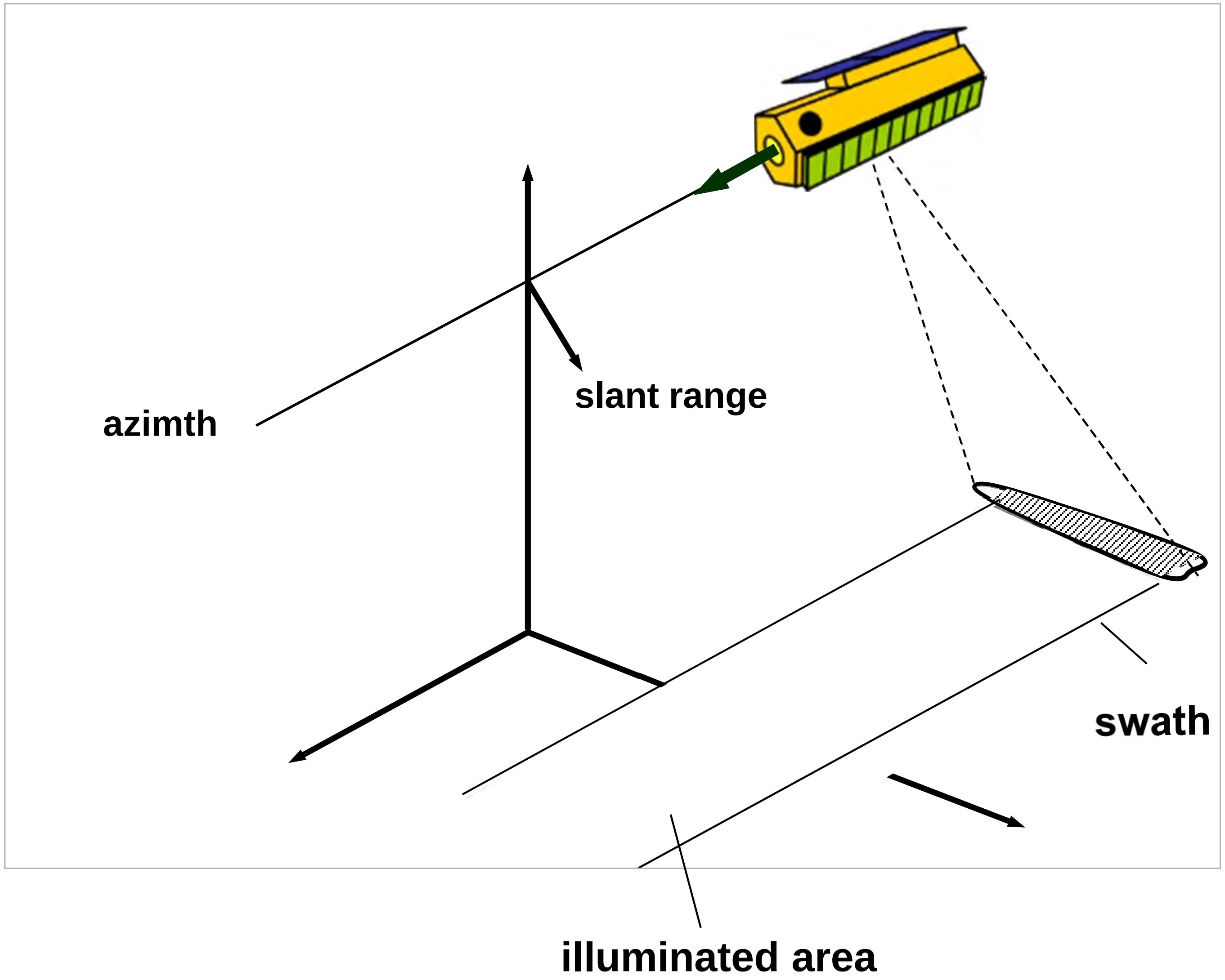
- ***Example 2:*** **Satellite system in X-Band, 25 MHz bandwidth, 12 m antenna, 800 km range**

  $\delta_r = 6\ m$ $\qquad$ $\delta_a = 2000\ m$!

DLR

Synthetic Aperture Radar (SAR)

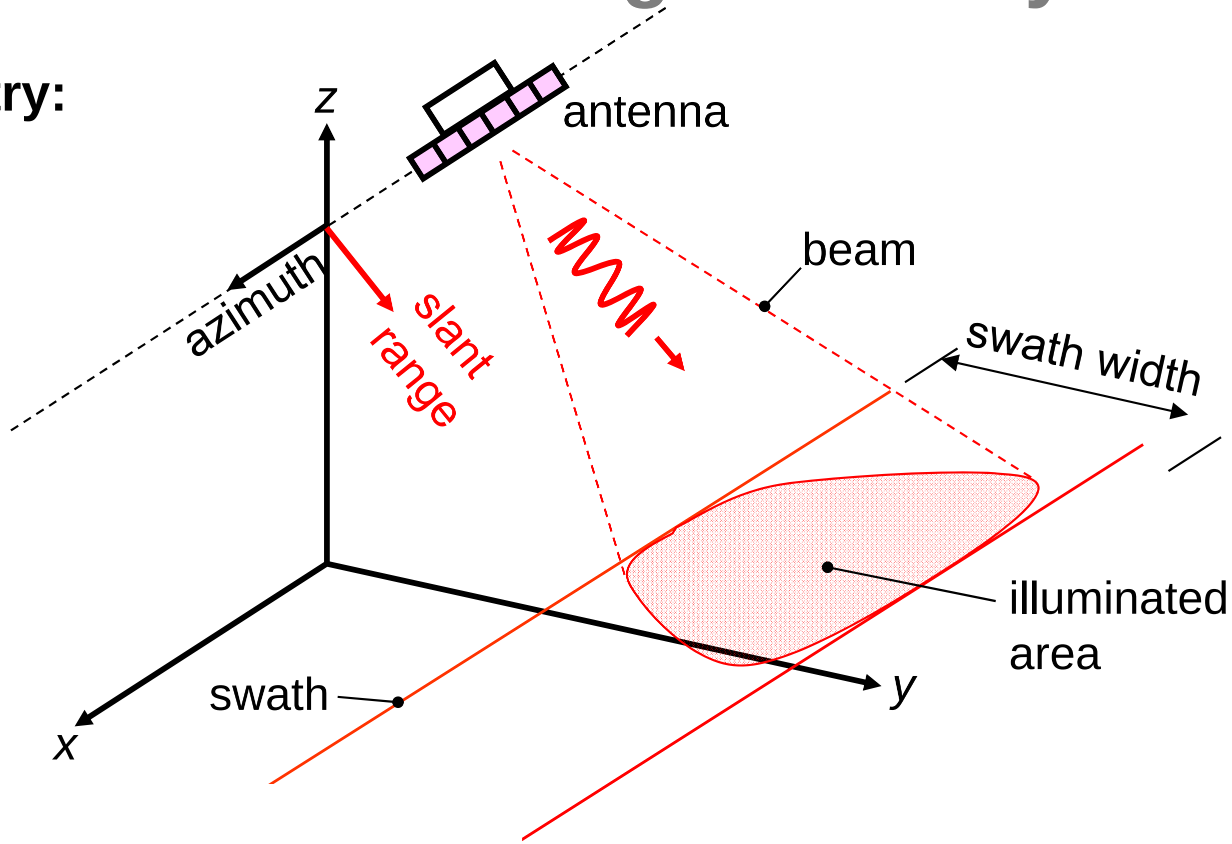
Side-Looking Radar Imaging Geometry

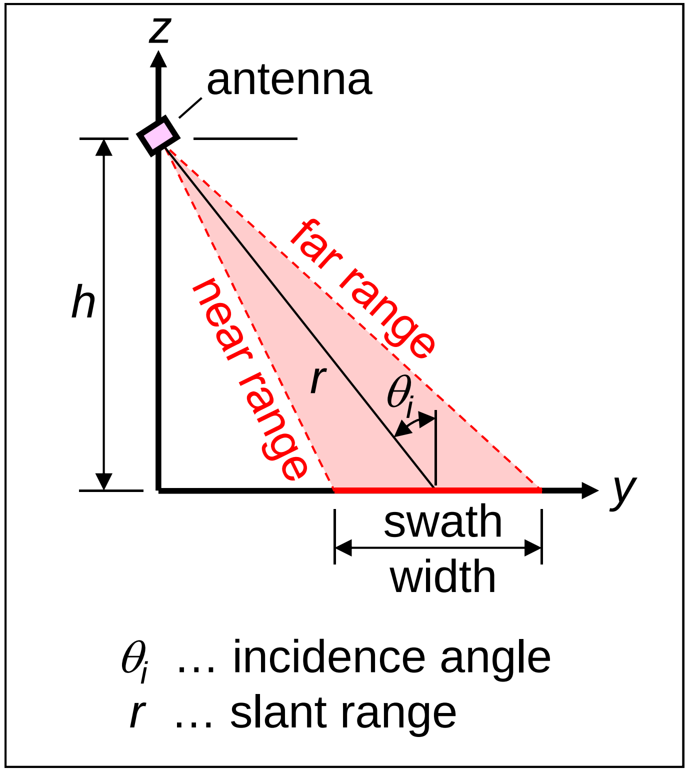


- Pulsed radar system
- Two-dimensional imaging (azimuth x slant range)

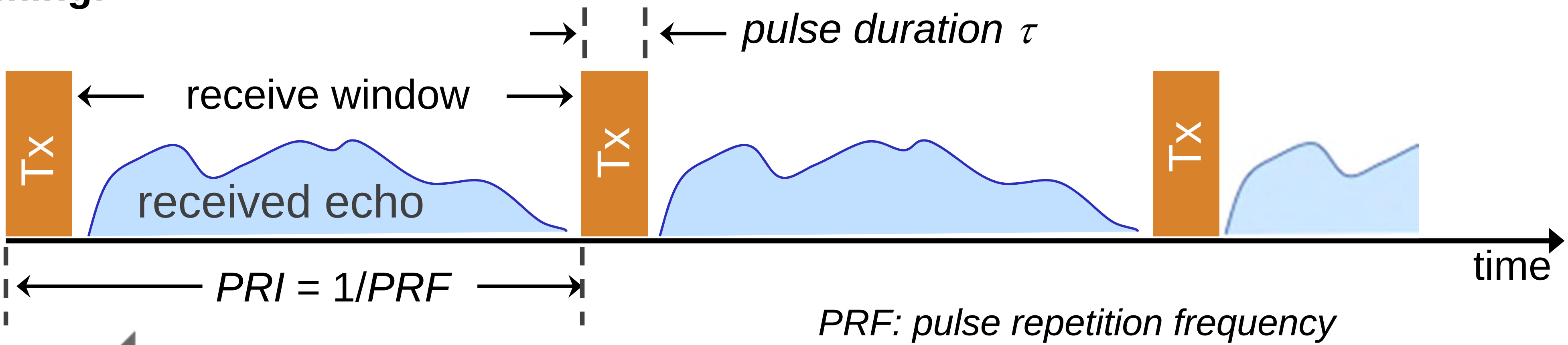
Side Looking Geometry and Timing

Geometry:



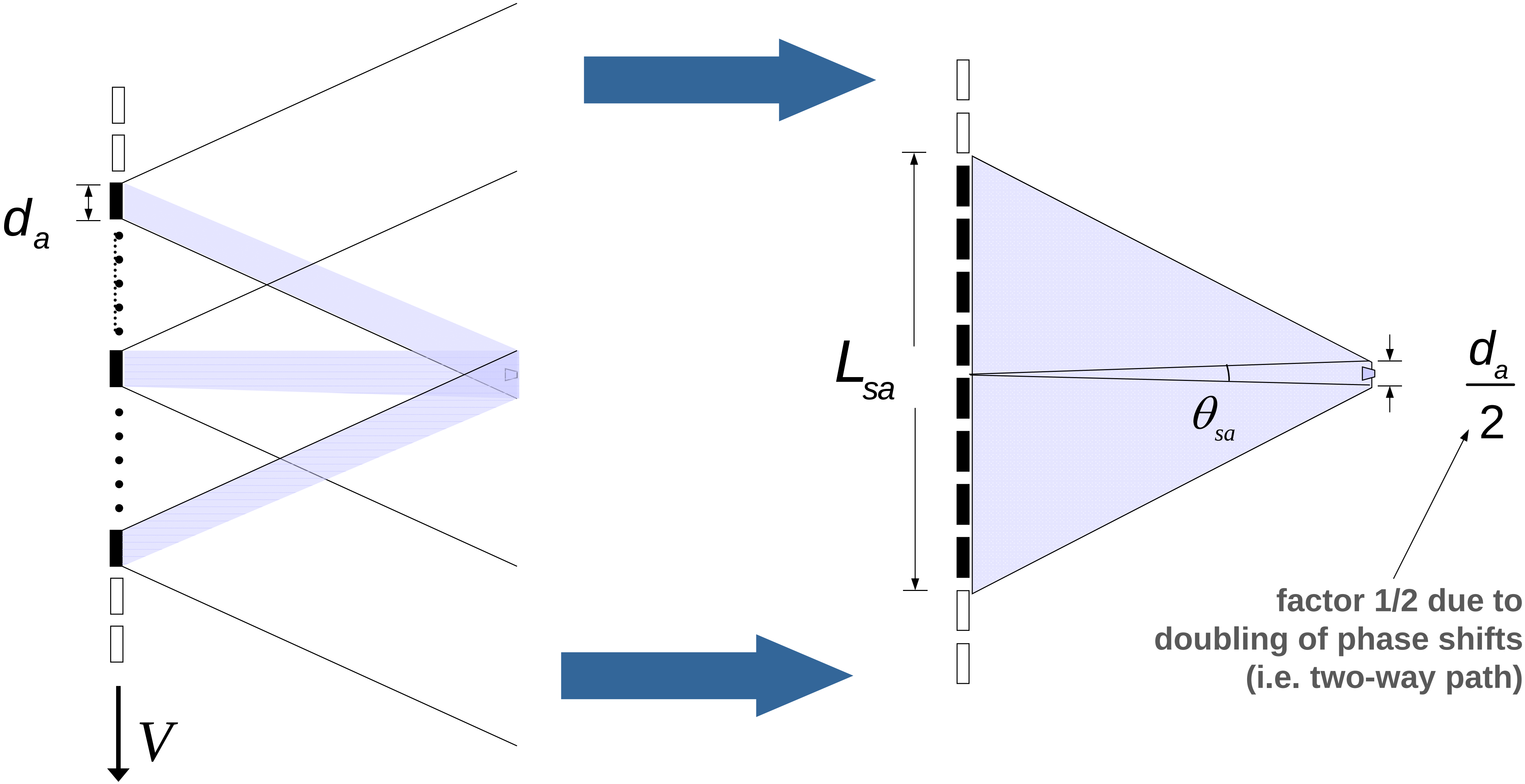


Timing:



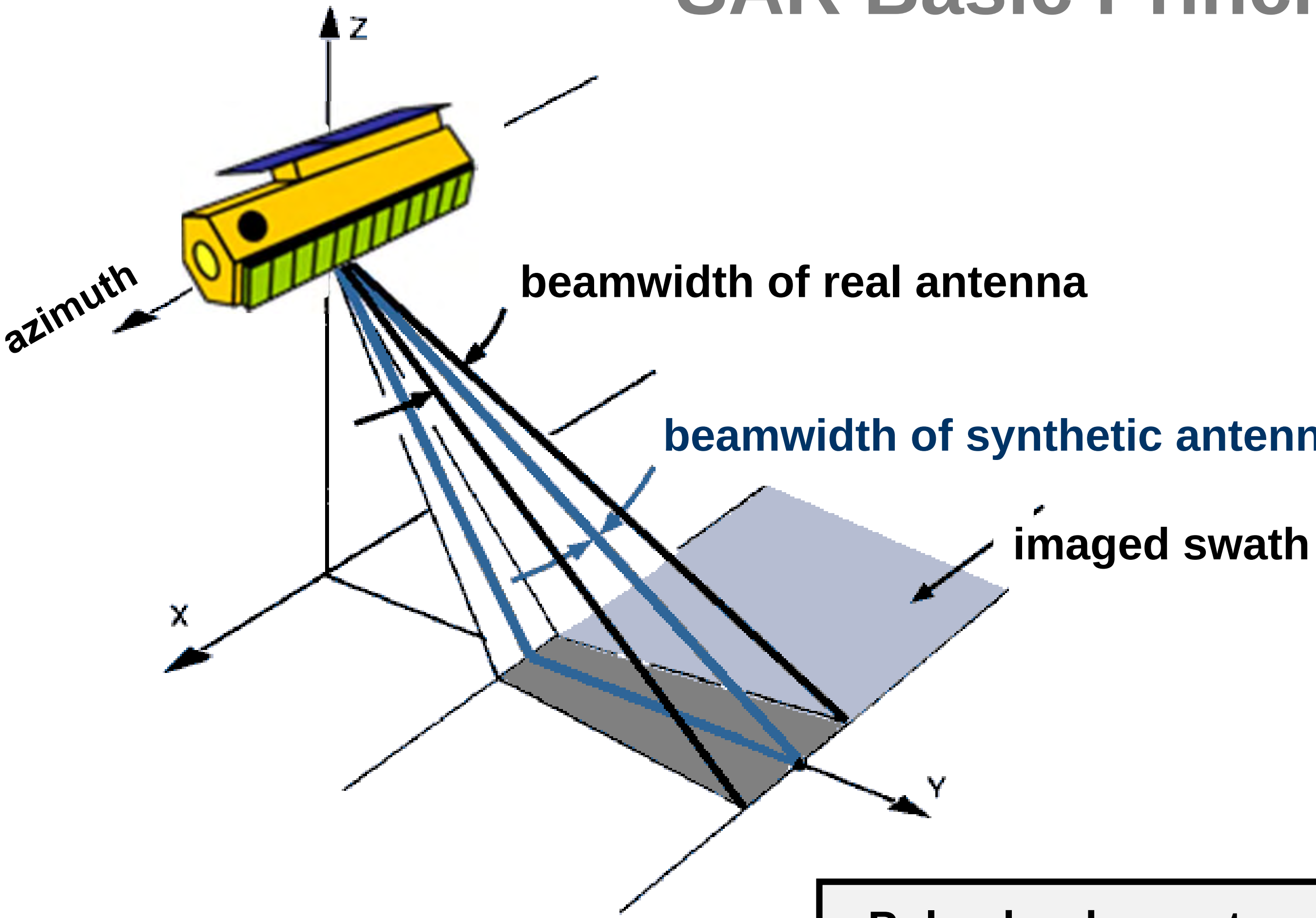
DLR

Formation of a Synthetic Aperture



formation of synthetic aperture
(i.e. SAR processing)

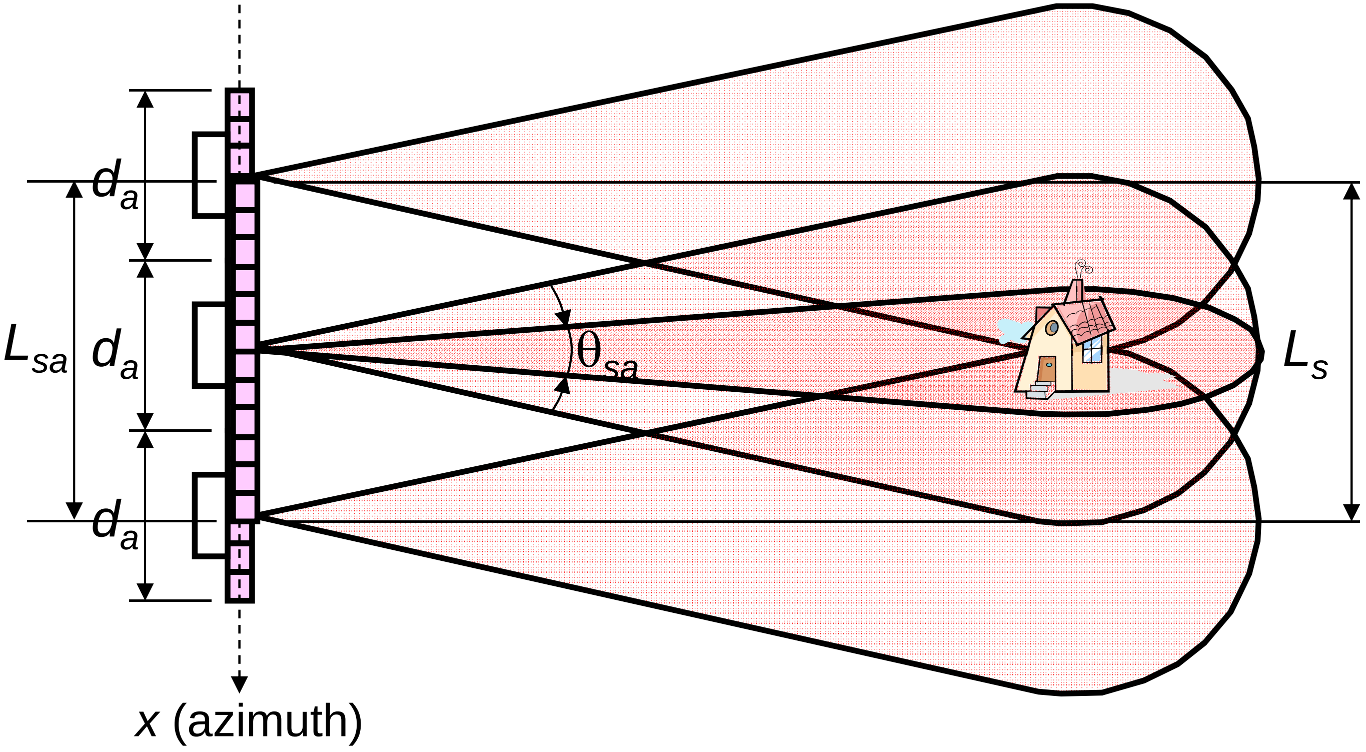
SAR Basic Principle



- Pulsed radar system
- Radar system must be coherent (stable local oscillator). Phase information is preserved
- Two-dimensional imaging (azimuth x slant range)

Concept of Synthetic Aperture (Simplified)

Motion of the short "physical" antenna La along azimuth



Element Resolution:

$$\Delta x_{Element} = \theta_a \cdot R = \frac{\lambda}{d_a} R$$

Array aperture:

$$L_{sa} = \Delta x_{Element} = \frac{\lambda}{d_a} R$$

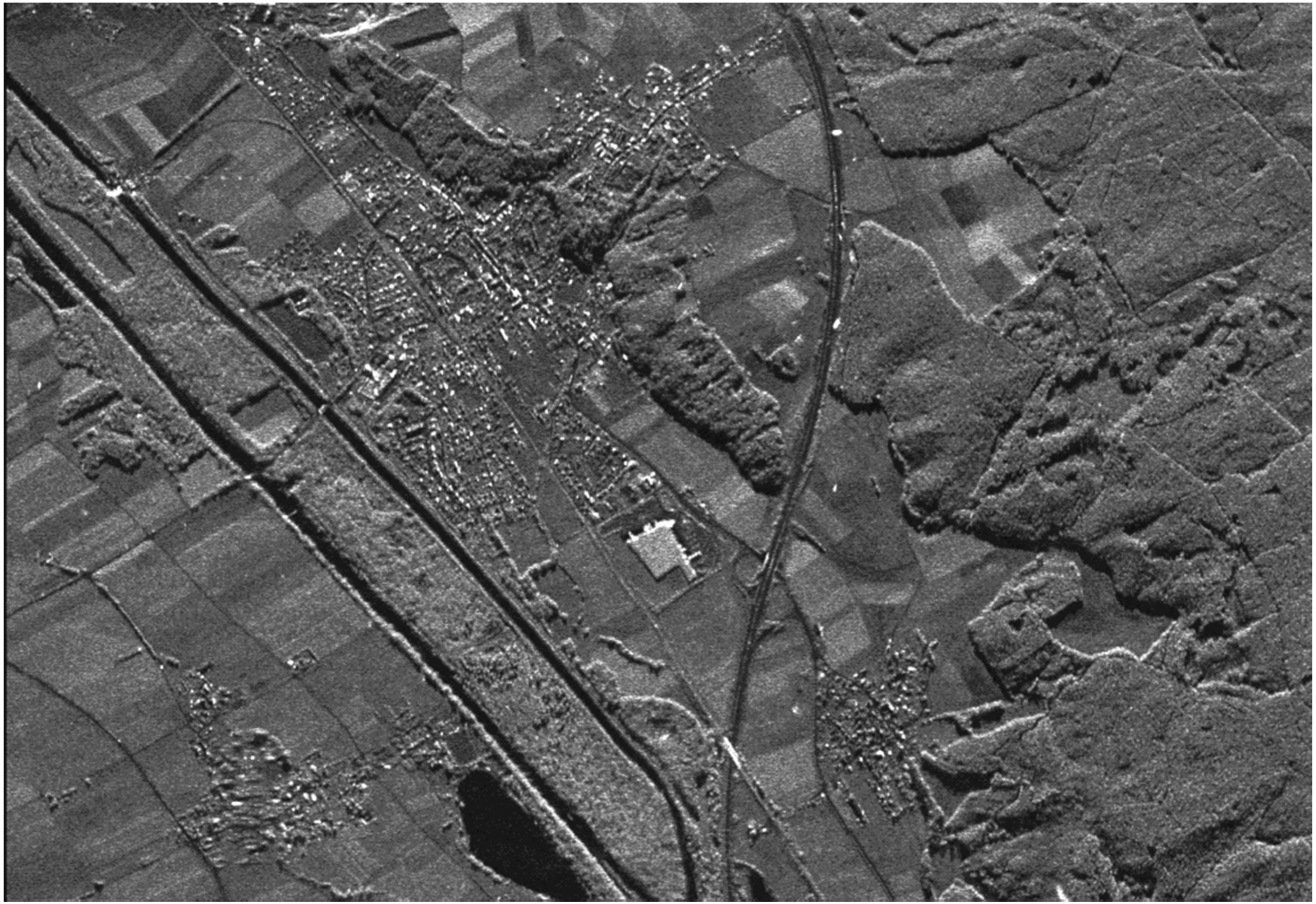
Array Resolution:

$$\delta x_{sa} = \theta_{sa} \cdot R = \frac{\lambda}{2 L_{sa}} R = \frac{\lambda R d_a}{2 \lambda R} = \frac{d_a}{2}$$

due to doubling of phase shifts in two-way SAR configuration

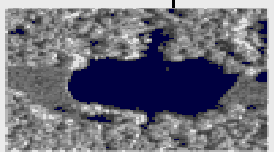
Azimuth resolution independent of range and Frequency!

Single Channel Radar Image



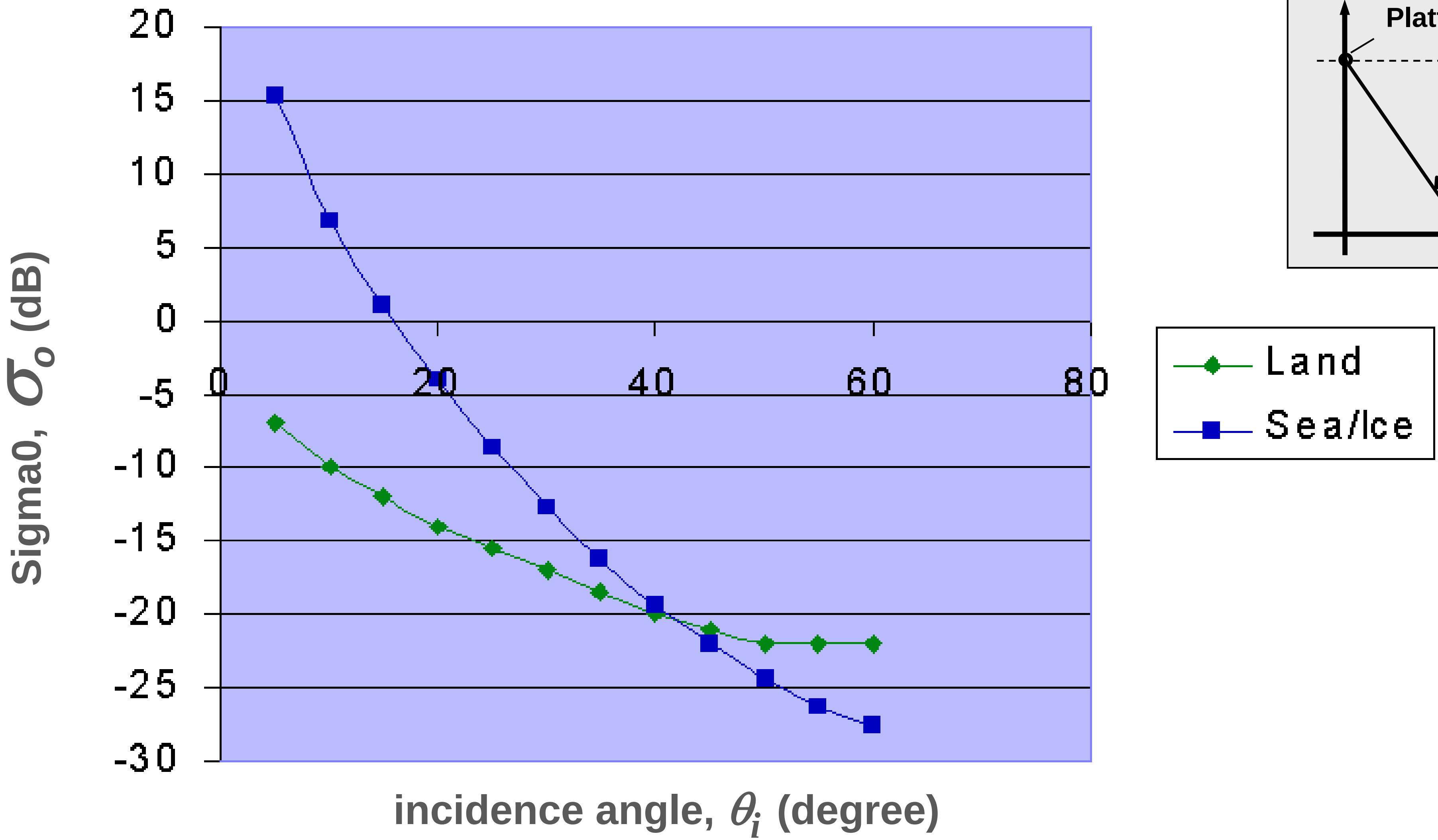
E-SAR image (X-band) processed in real-time, 3 x 3 m resolution, 6 looks

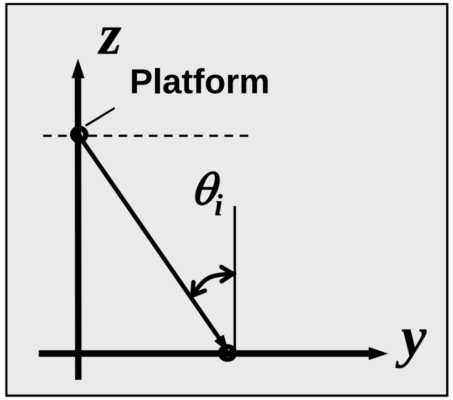
Backscattering Coefficient σ_o

Levels of Radar backscatter		*Typical scenario*
• *Very high backscatter (above -5 dB)*		*Man-Made objects (urban)* *Terrain Slopes towards radar* *very rough surface* *radar looking very steep*
• *High backscatter (-10 dB to 0 dB)*		*rough surface* *dense vegetation (forest)*
• *Moderate backscatter (-20 to -10 dB)*		*medium level of vegetation* *agricultural crops* *moderately rough surfaces*
• *Low backscatter (below -20 dB)*		*smooth surface* *calm water, road* *very dry terrain (sand)*

Backscattering Coefficient σ_o

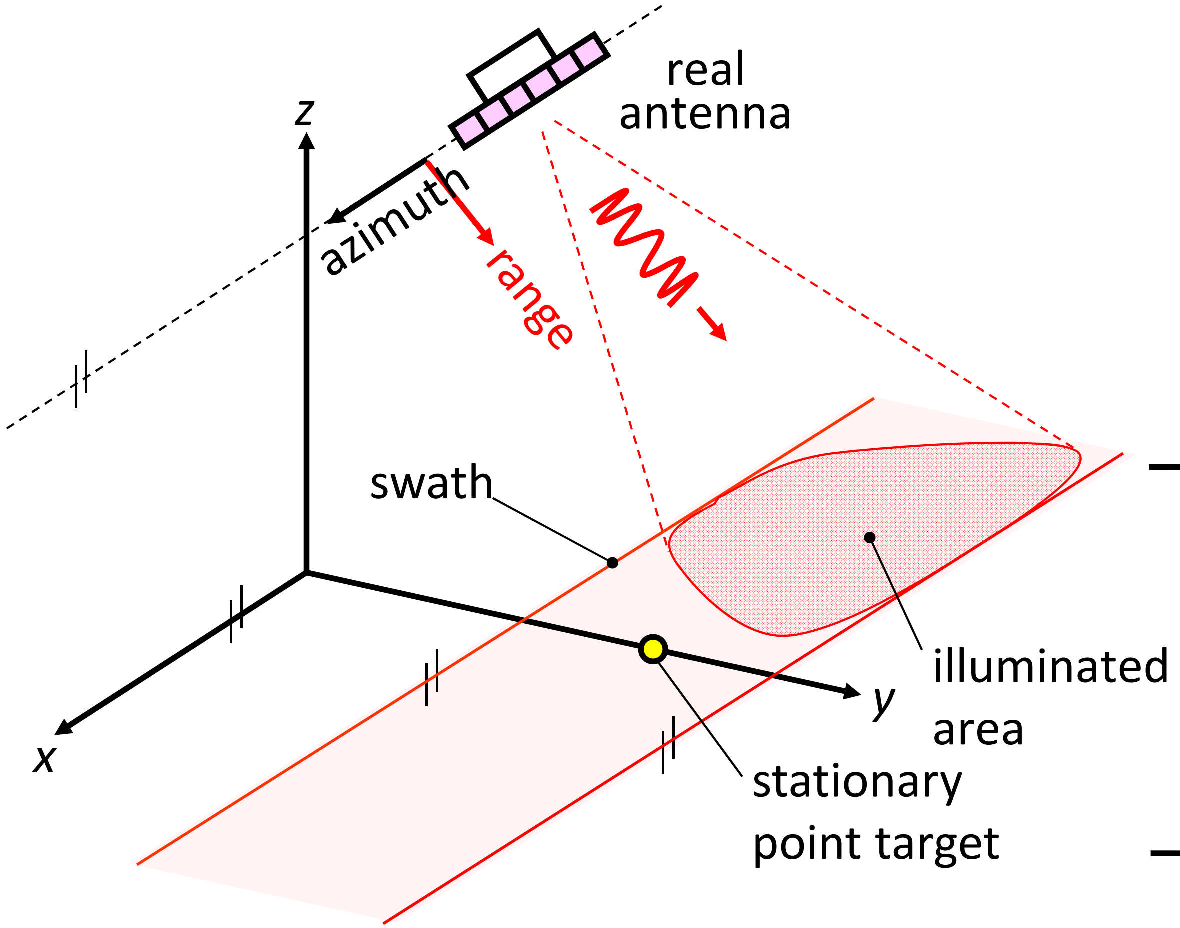
- ***Variation of σ_o as a function of incidence angle θ_i***

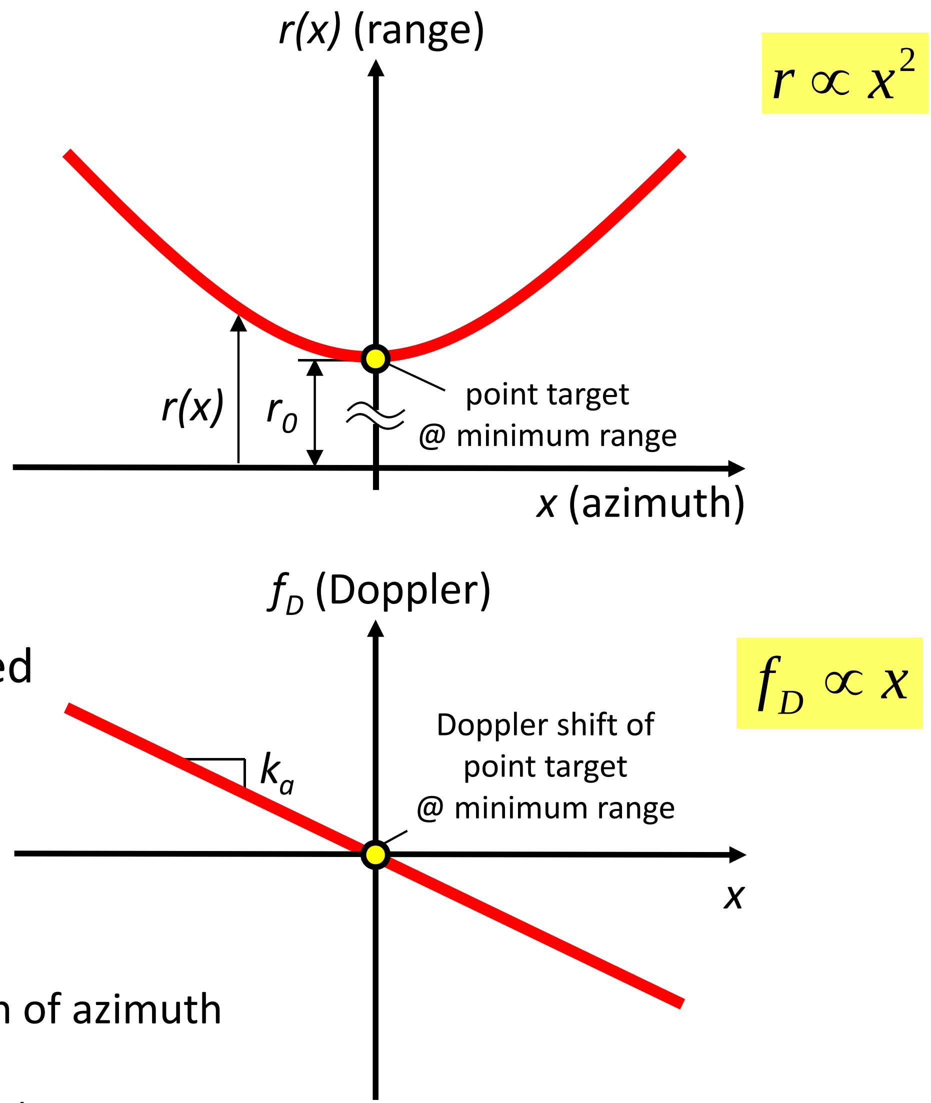




- **Dynamic range of received SAR signal is usually greater than 50 dB**

SAR Acquisition for Single Point Target





$r(x)$ range as a function of azimuth

R_0 minimum range

k_D Doppler rate (slope)

Azimuth Signal

Azimuth position of the platform

$$x(t) = v_p\, t$$

Range variation for a point target

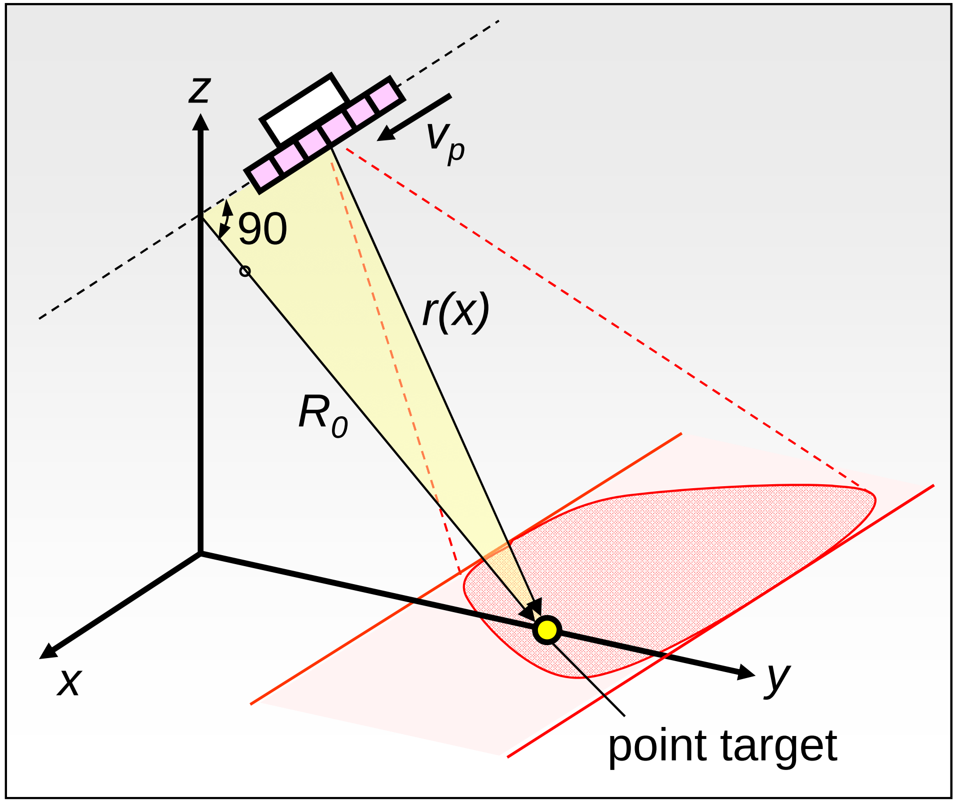
$$r(x) = \sqrt{R_0^2 + x^2} \xrightarrow[\text{Taylor approx.}]{2^{nd}\text{ order}} r(x) \cong R_0 + \frac{x^2}{2R_0}$$

Azimuth phase variation

$$\varphi_a(t) = -\frac{4\pi}{\lambda} r(t) \cong -\frac{4\pi}{\lambda}\left[R_0 + \frac{(v_p\, t)^2}{2R_0}\right]$$

Azimuth (Doppler) frequency variation

$$f_D(t) = \frac{1}{2\pi}\frac{\partial \varphi_a(t)}{\partial t} \cong -\frac{2 v_p^2}{\lambda R_0} t = k_D\, t$$



Azimuth signal (reference function for focusing is complex conjugated and time reverted)

$$s_a(t) = \underline{A}_a(t)\exp\left(-j\frac{4\pi}{\lambda} r(t)\right) \cong \underline{A}_a \exp\left(j\, 2\pi\, k_D\, t^2\right)$$

$\underline{A}_a$ complex amplitude

Azimuth Signal

Azimuth (Doppler) frequency variation

$$f_D(t) = \frac{1}{2\pi}\frac{\partial \varphi_a(t)}{\partial t} \cong -\frac{2v_p^2}{\lambda R_0} t$$

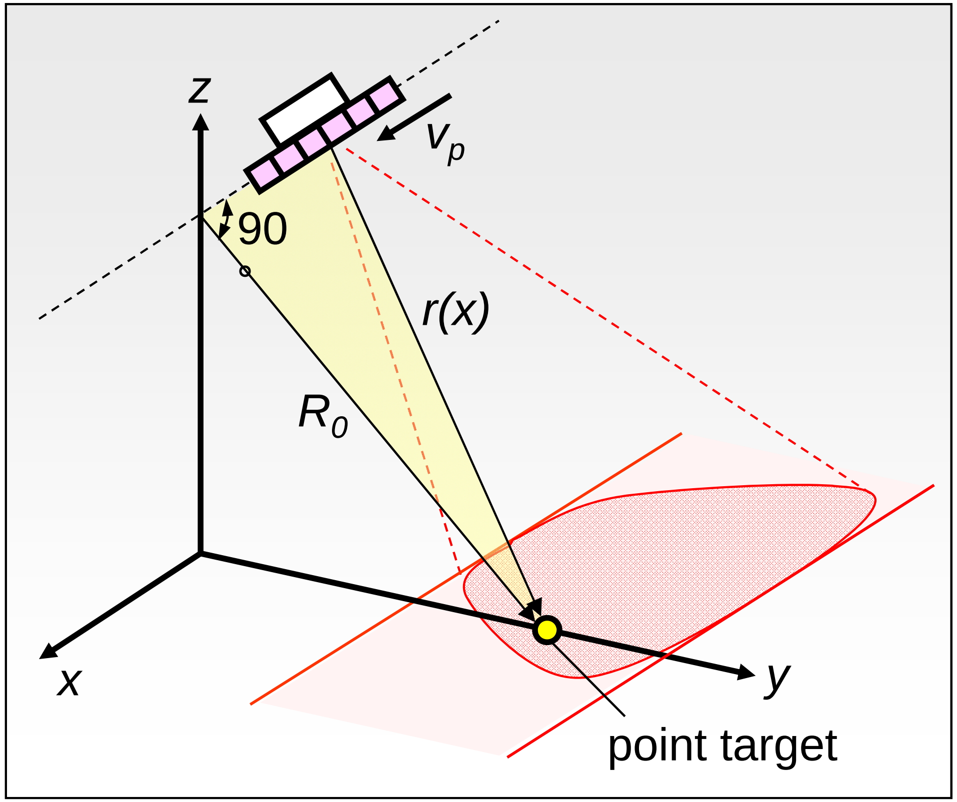
Illumination time

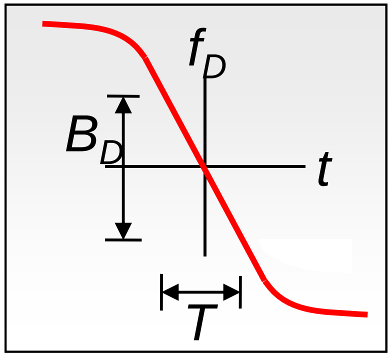
$$T = \frac{L_s}{v_p} = \frac{\Theta_a \cdot R_0}{v_p} \approx \frac{\lambda / L_a \cdot R_0}{v_p}$$

Max. Doppler (azimuth) bandwidth

$$B_D = f_D(t)\Big|_{t=-\frac{T}{2}} - f_D(t)\Big|_{t=+\frac{T}{2}}$$

$$B_D \cong \frac{2v_p \Theta_a}{\lambda} = \frac{2v_p}{L_a}$$



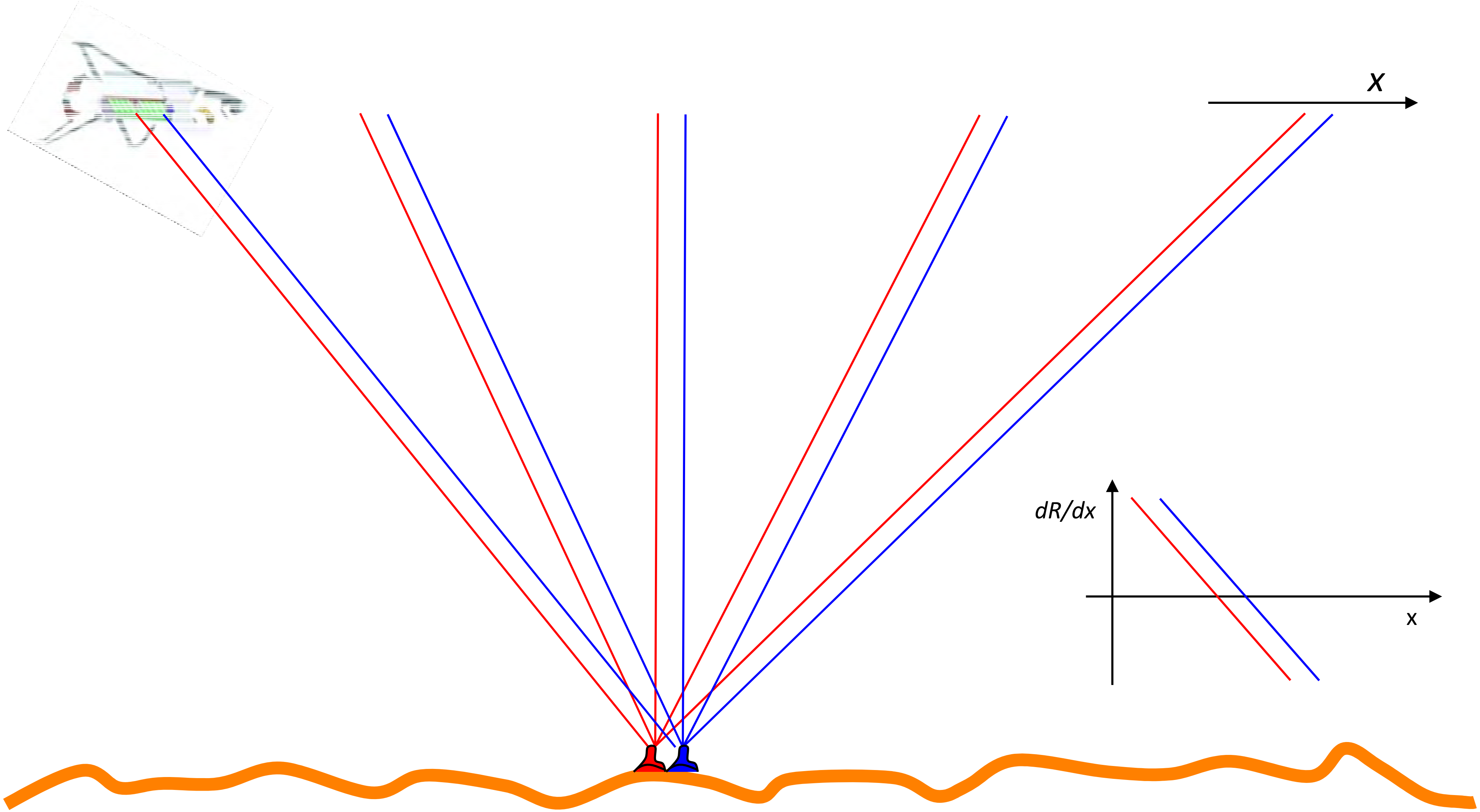


Azimuth resolution

$$\Delta x = \frac{v_p}{B_D} = \frac{L_a}{2}$$

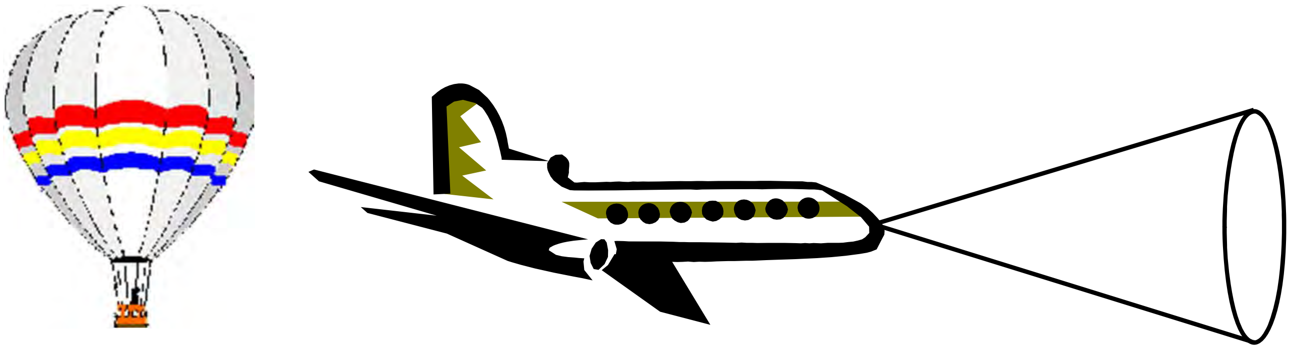
DLR

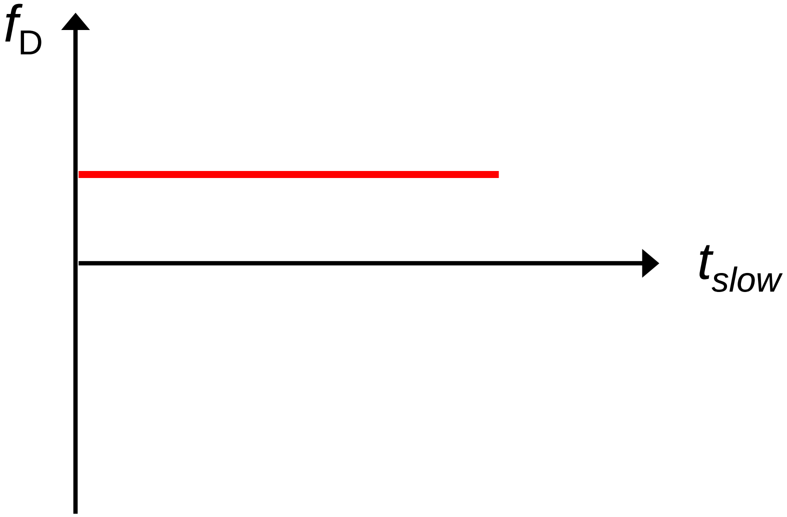
Synthetic Aperture Radar Principle



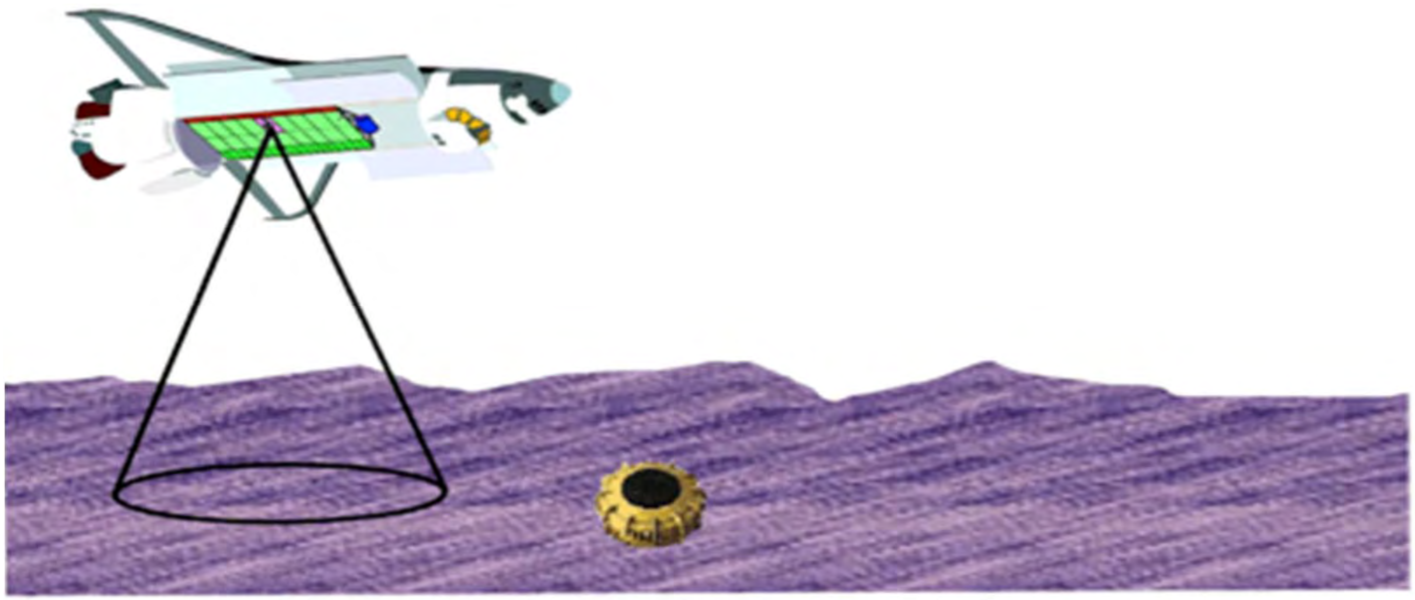
$$\frac{dr}{dx} \propto \frac{dr}{dt} \propto \frac{d\varphi}{dt} \propto f_D$$

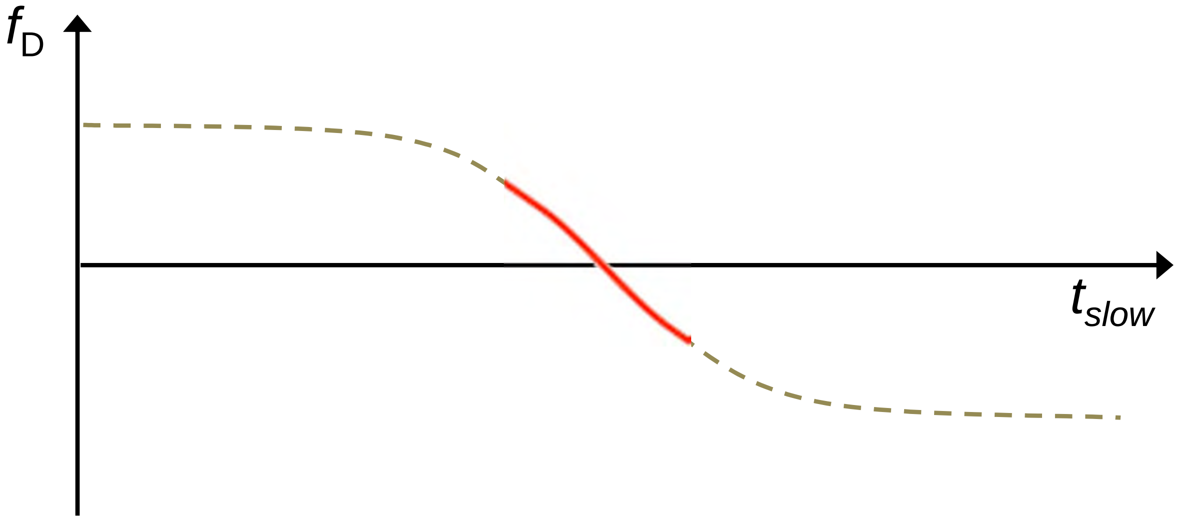
Constant Doppler Frequency - Animation



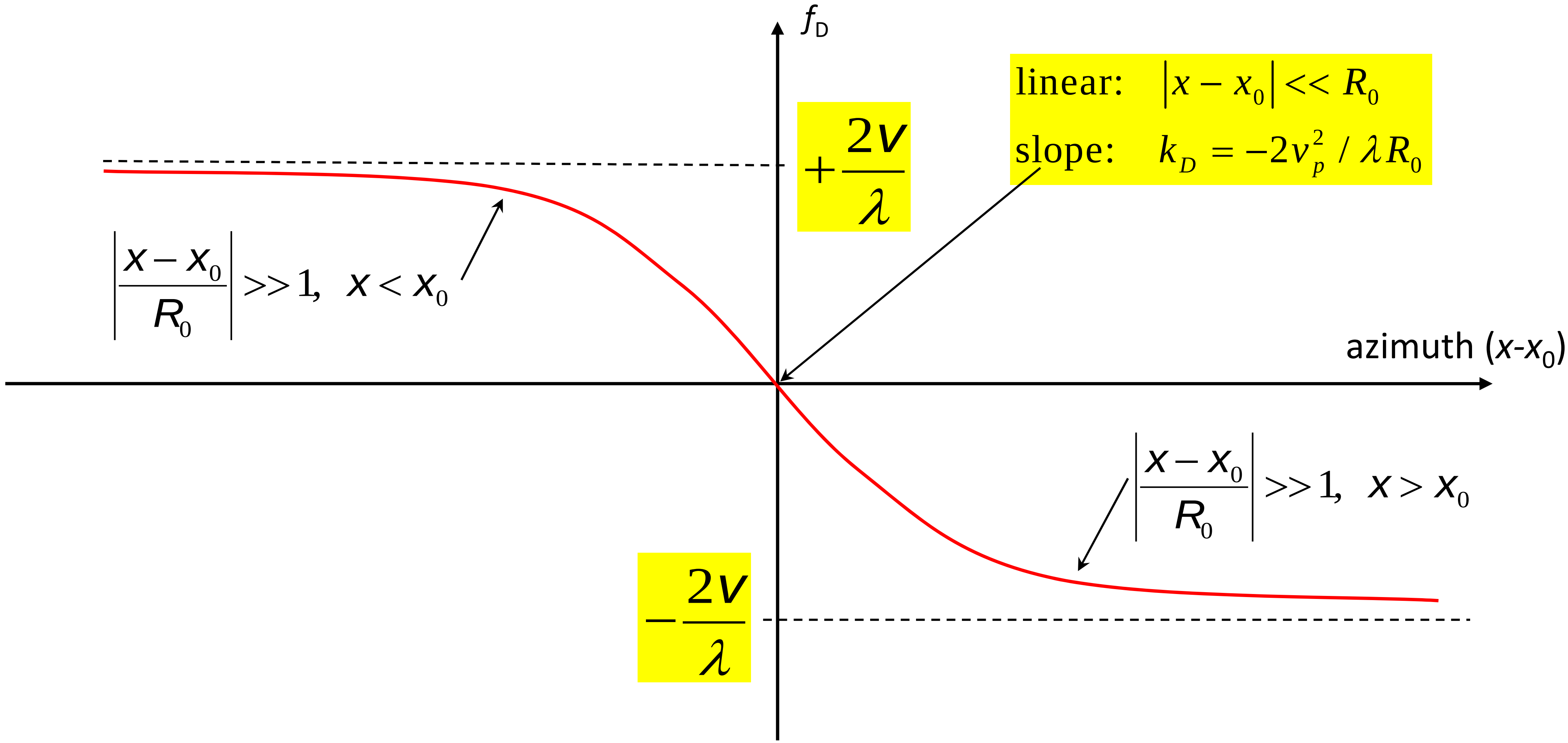


Symmetric Doppler History

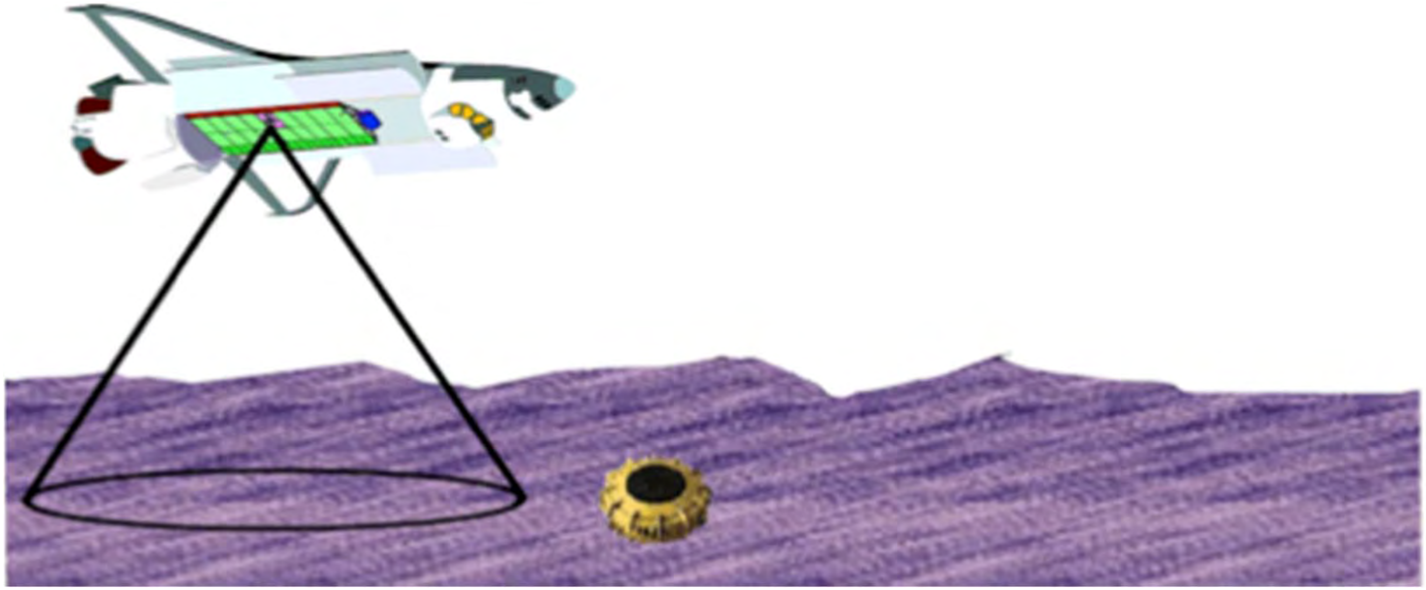


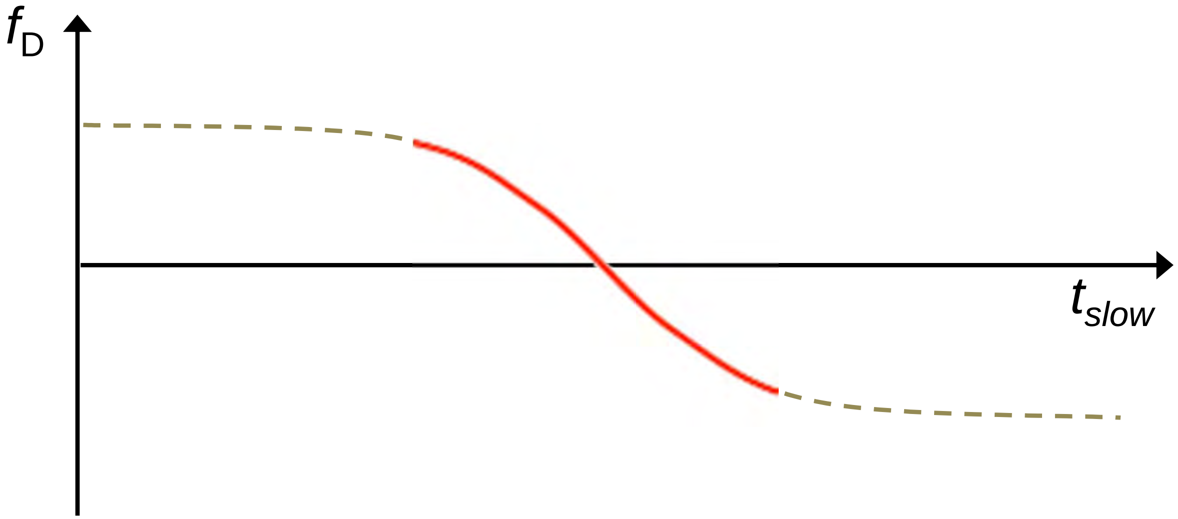


Doppler History of a Point Target

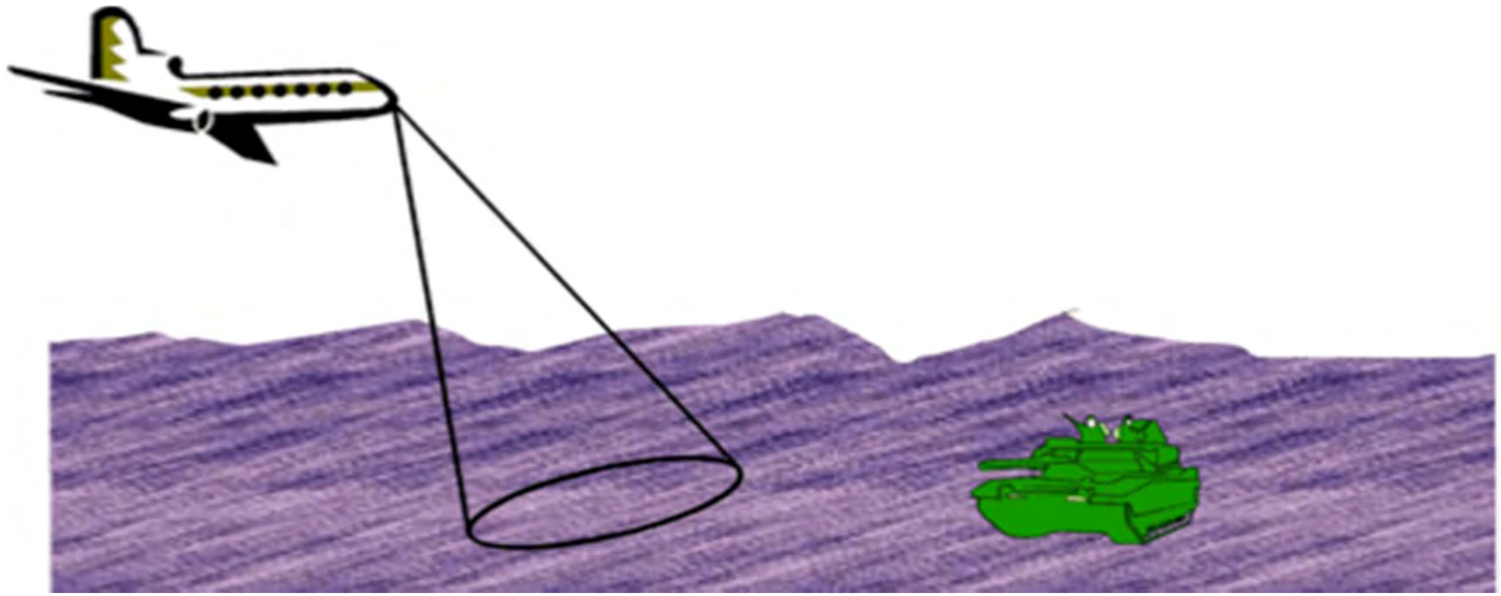


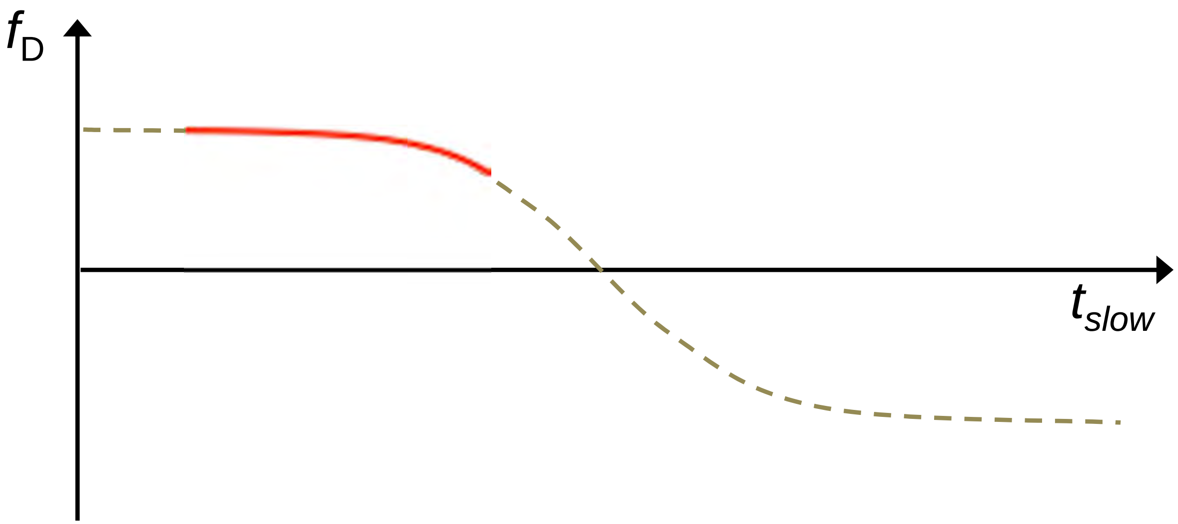
Symmetric, Wide Doppler History



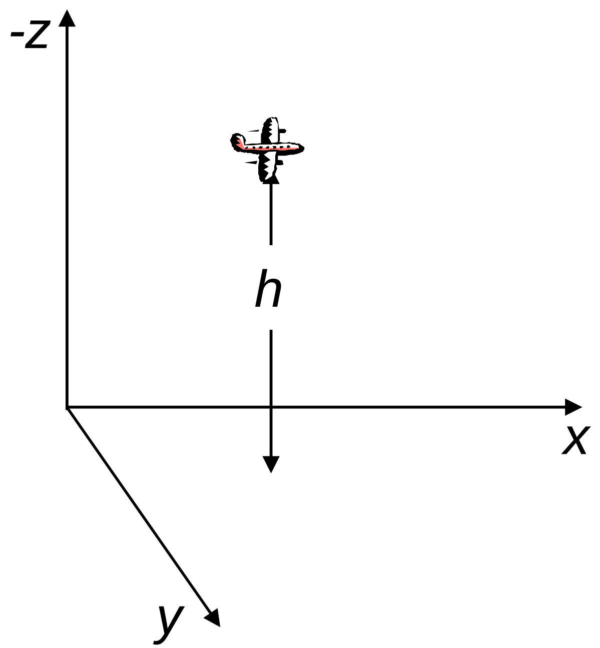


Doppler History Forward Looking SAR

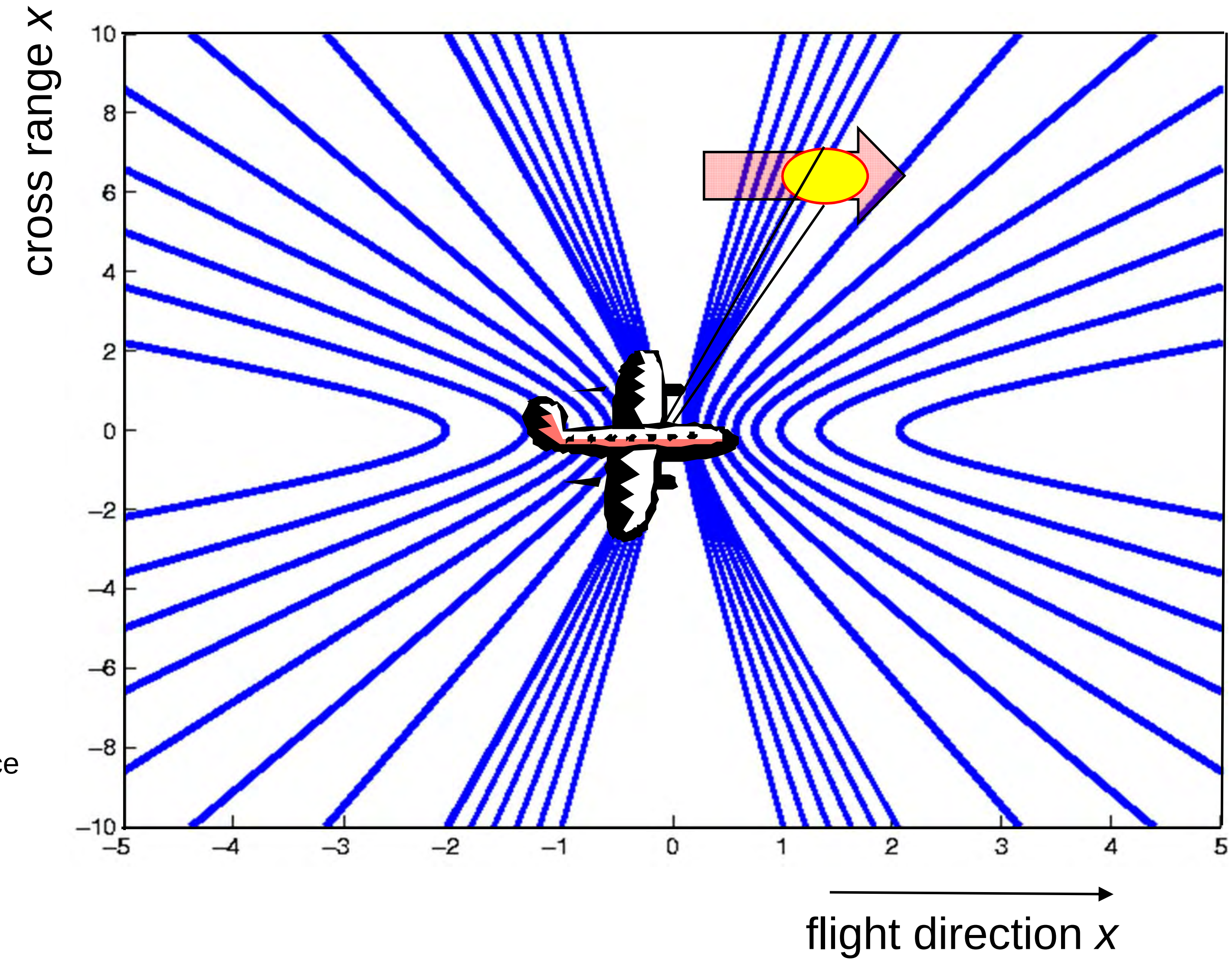




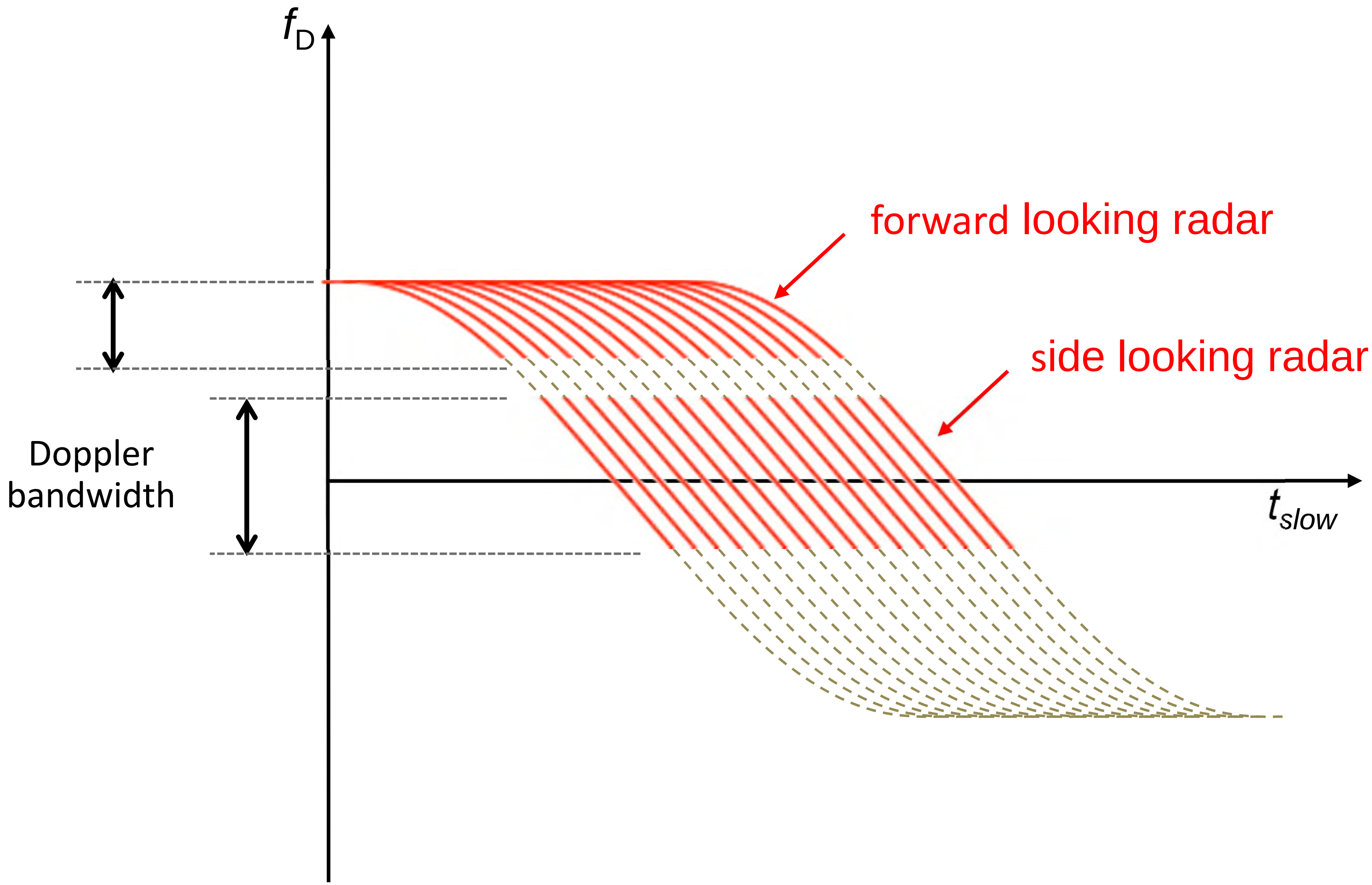
Lines of Constant Doppler (Isodops)



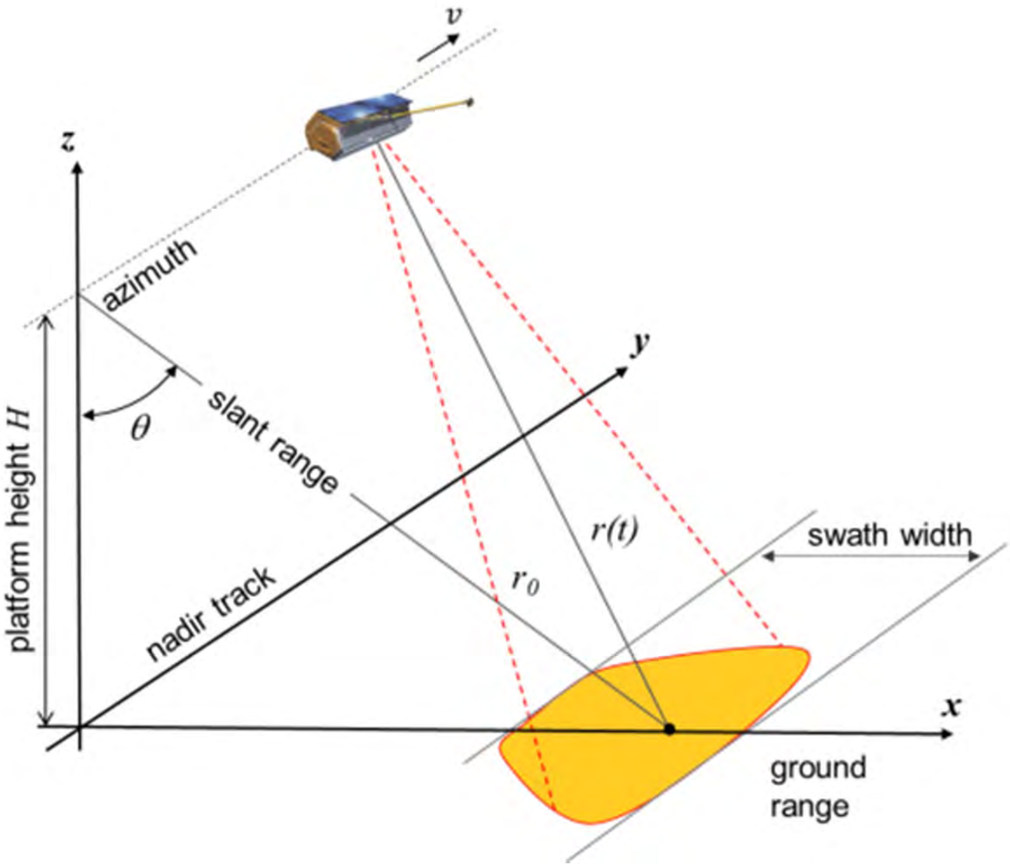
Geometry for Doppler calculation for horizontal motion above a plane surface

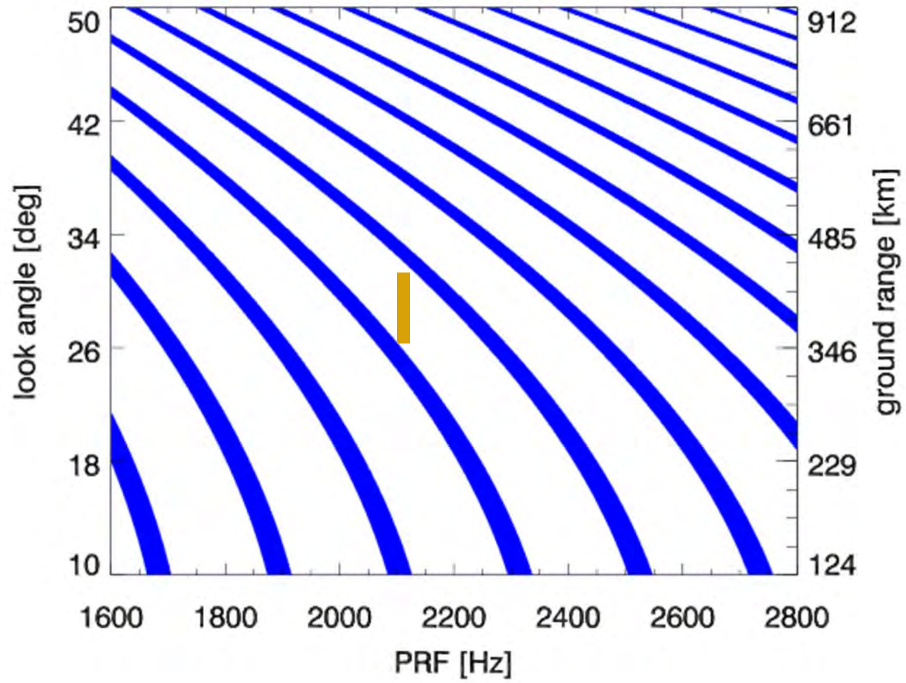


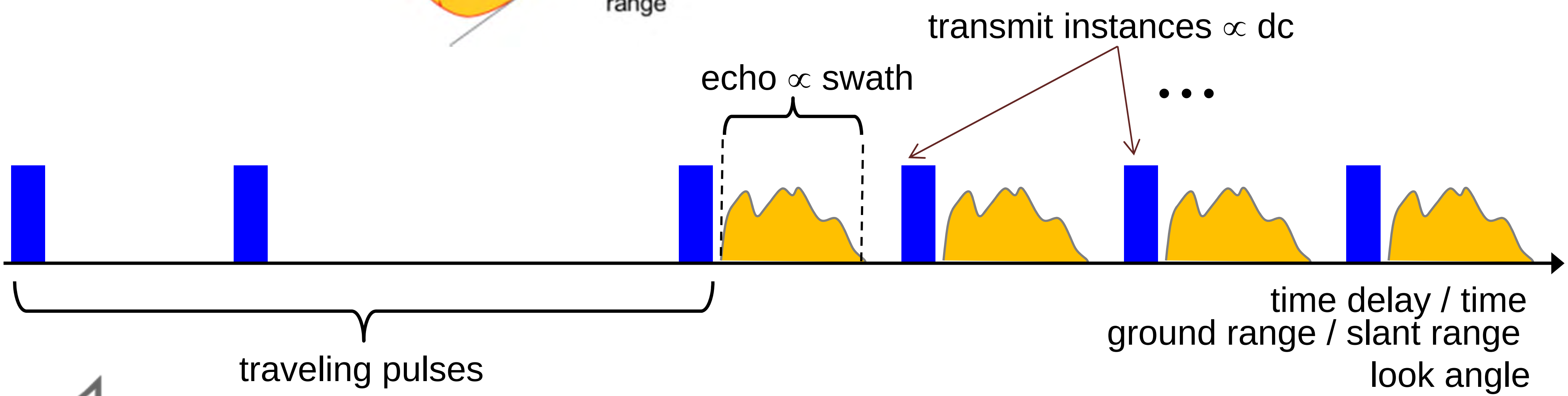
Doppler History of Multiple Targets



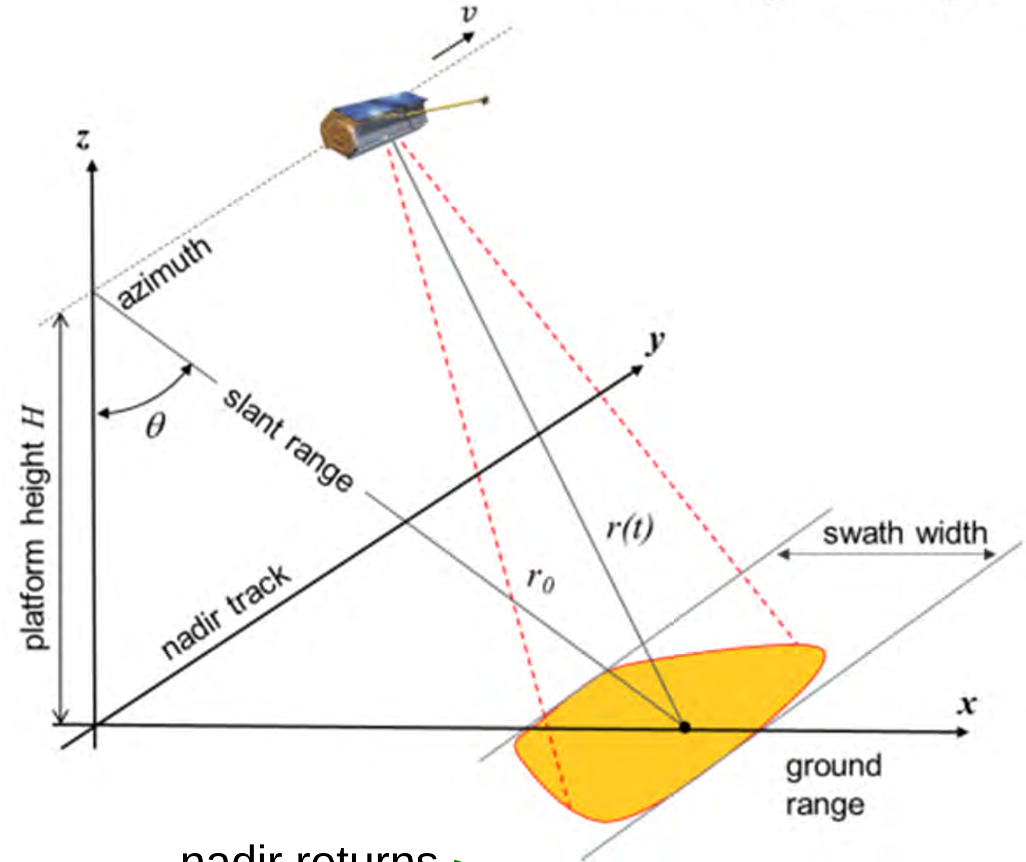
Timing in Spaceborne SAR

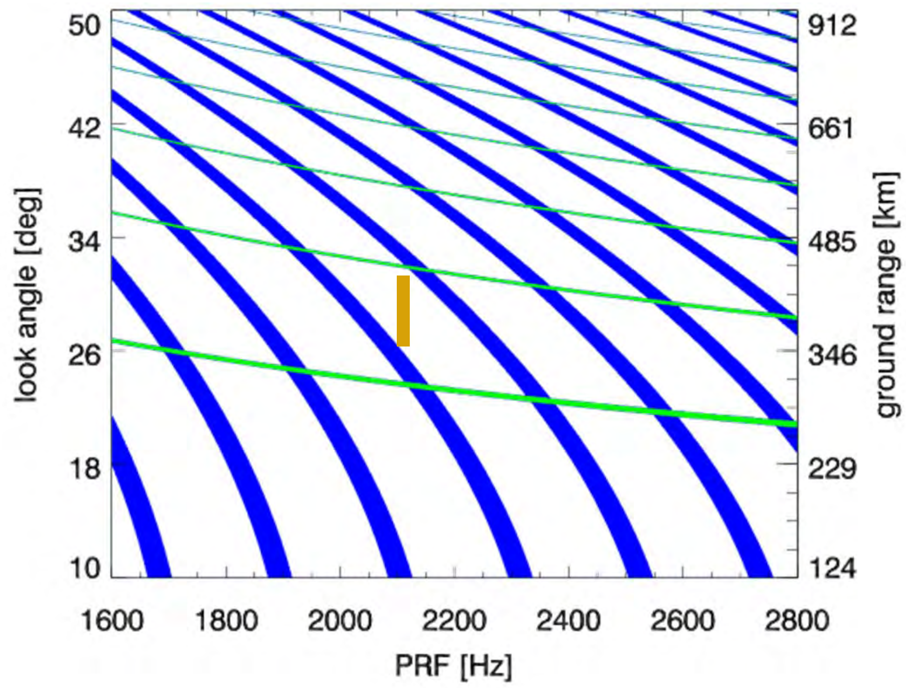


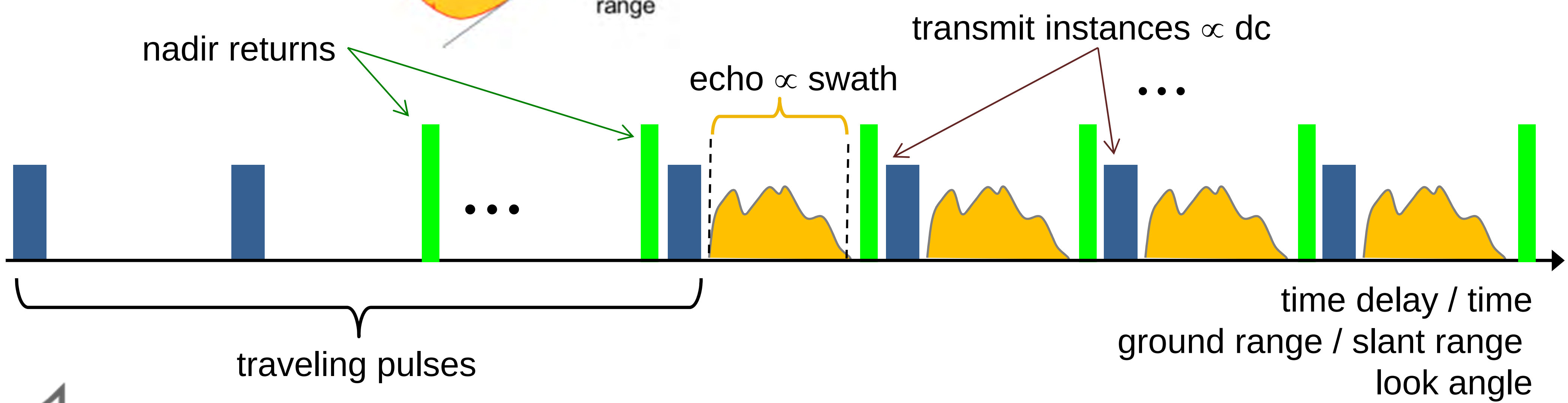




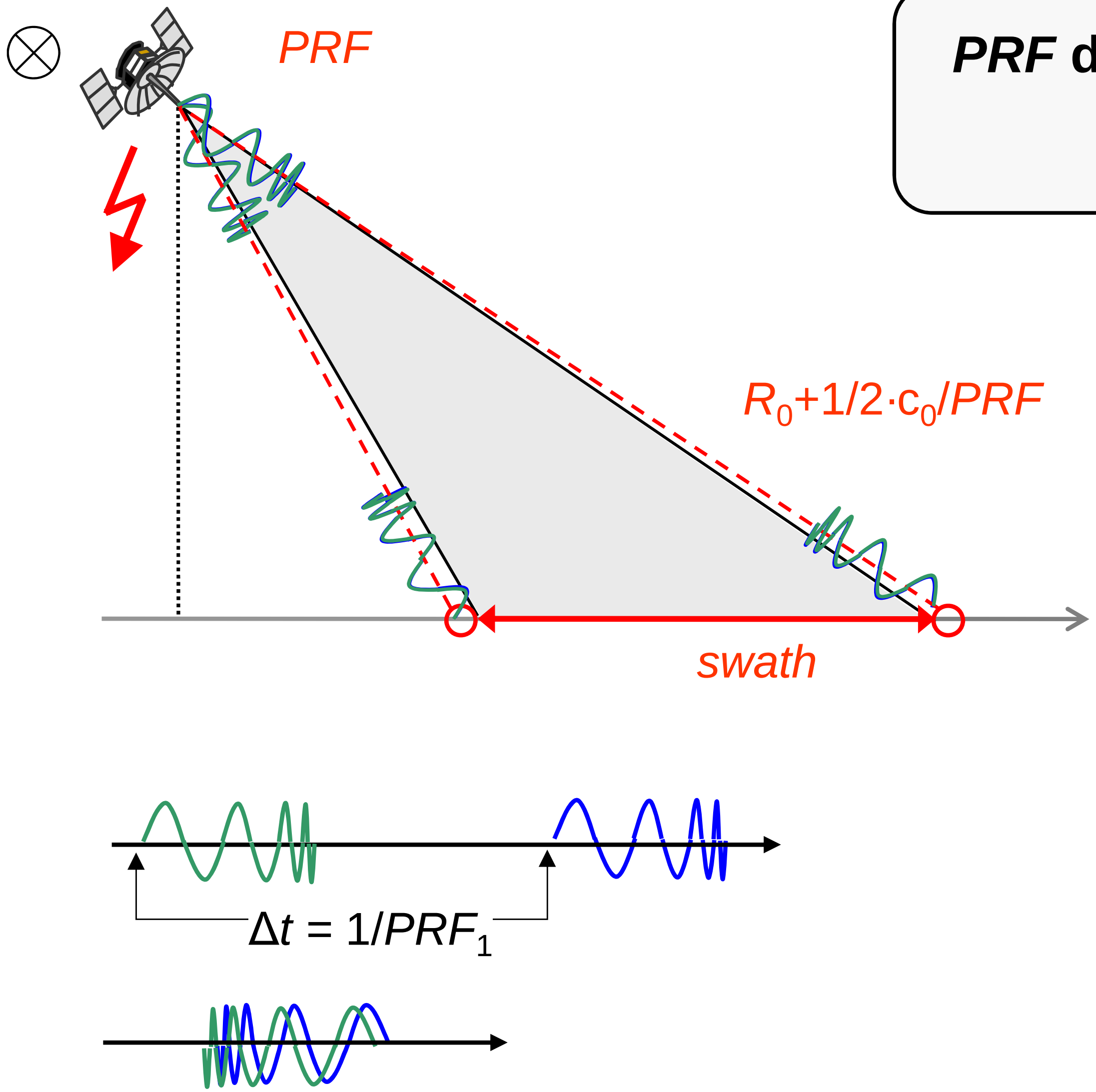
Timing in Spaceborne SAR







Swath Width and Range Ambiguities



***PRF* determines unambiguous range**

wide swath ↔ low PRF

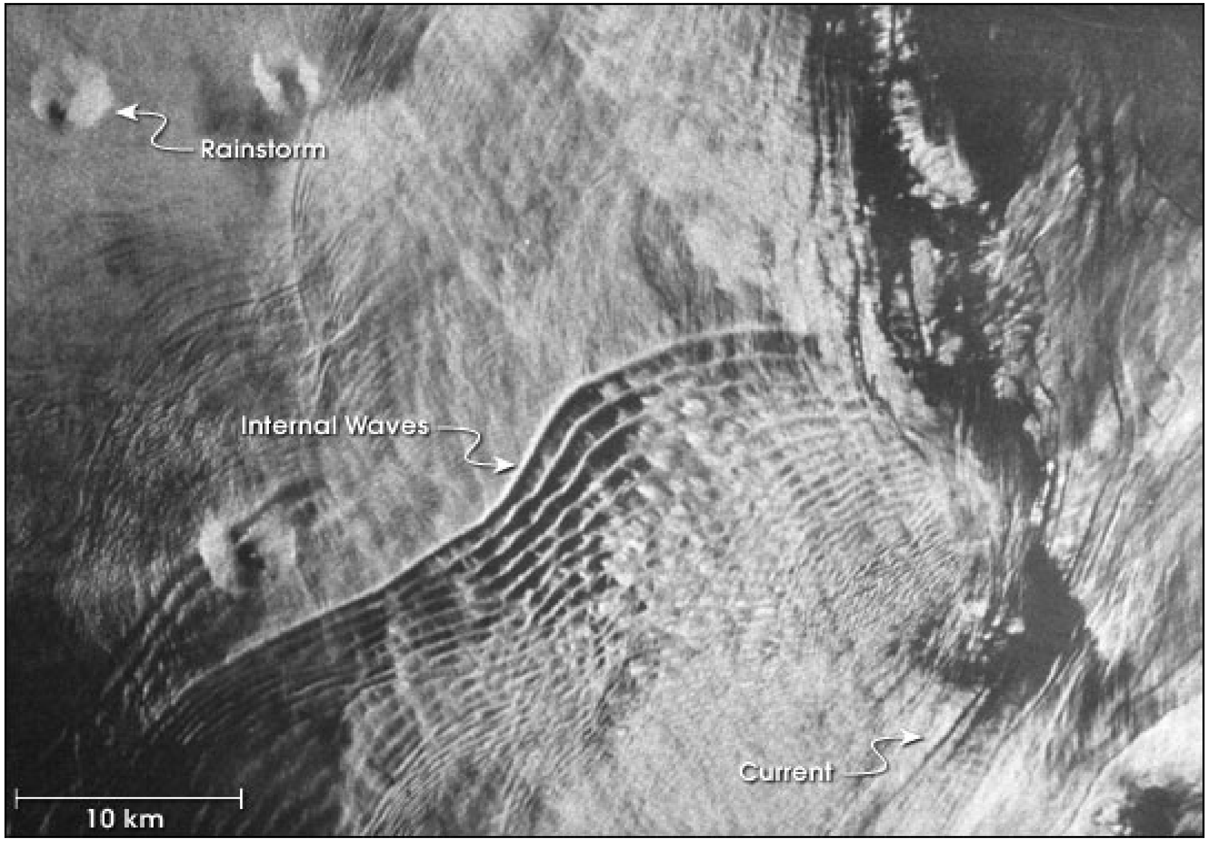
$$\frac{2R_{far}}{c_0} \le \frac{2R_{near}}{c_0} + PRI$$

$$PRF \le \frac{c_0}{2\cdot(R_{far} - R_{near})}$$

$$\text{swath} \le \frac{c_0}{2PRF\cdot\sin(\theta_{inc})}$$

Spaceborne SAR Systems

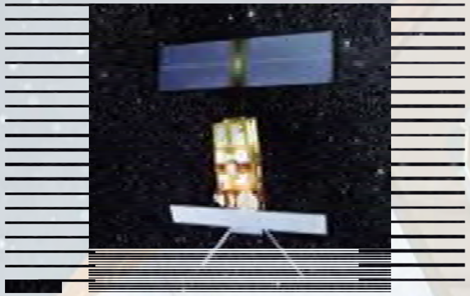
First Civilian SAR Satellite: SEASAT (1978)



Launch	June 26, 1978	Frequency	1,275 GHz
Altitude	~780 km	Bandwidth	19 MHz
Weight	2300 kg	Antenna Size	10,74 m x 2,16 m
Inc. Angle	~ 23°		
Swath Width	100 km	Resolution	25 m x 25 m

Spaceborne SAR Systems

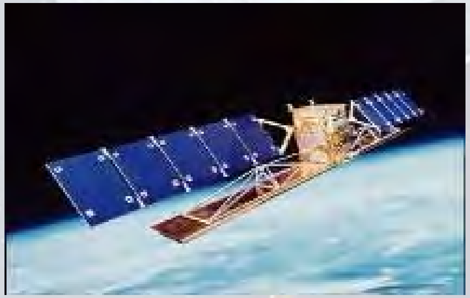
SEASAT
NASA/JPL (USA)
L-Band, 1978



ERS-1/2
European Space Agency (ESA)
C-Band, 1991-2000/1995-2011

J-ERS-1
Japanese Space Agency (JAXA)
L-Band, 1992-1998

SIR-C/X-SAR
NASA/JPL, L- and C-Band (quad)
DLR / ASI, X-band 1994



RadarSAT-1
Canadian Space Agency (CSA)
C-Band, 1995-2013

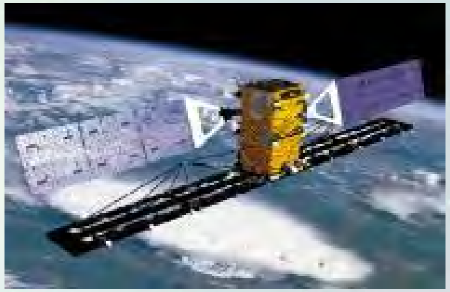
Shuttle Radar Topography Mission (SRTM)
NASA/JPL (C-Band), DLR (X-Band)
February 2000

ENVISAT / ASAR
European Space Agency (ESA)
C-Band (dual), 2002-2012

ALOS / PALSAR
Japanese Space Agency (JAXA)
L-Band (quad), Jan. 2006-2011

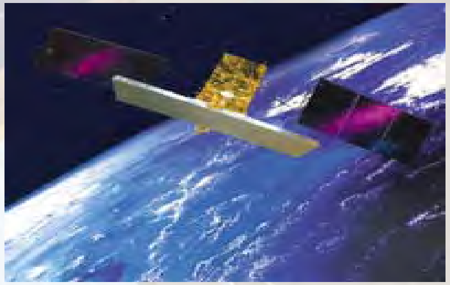
SAR-Lupe
BWB, Germany
5 satellites, X-Band, 2006/2008

Spaceborne SAR Systems



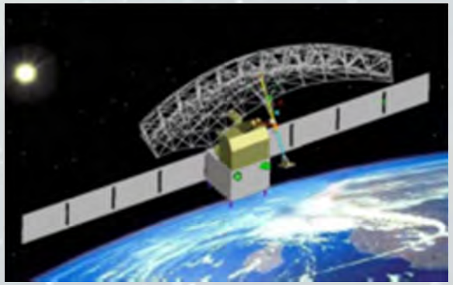
RadarSAT-II
Canadian Space Agency (CSA)
C-Band (quad), 2007

TerraSAR-X/TanDEM-X
DLR /Astrium, Germany
X-Band (quad), 2007/2010

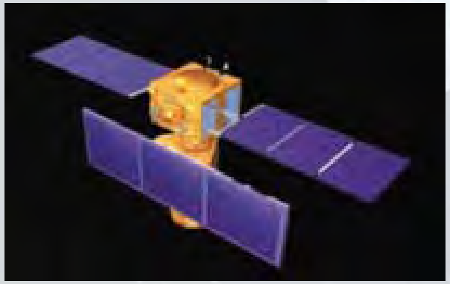


COSMO-SkyMed
ASI, Italy
4 Satellites, X-Band (dual), 2007/2010

Kompsat-5
KARI, Korea
X-band (dual), 2013



HJ-1C -SAR
CRESDA/CAST/NRSCC, China
S-Band (HH or VV), 2013

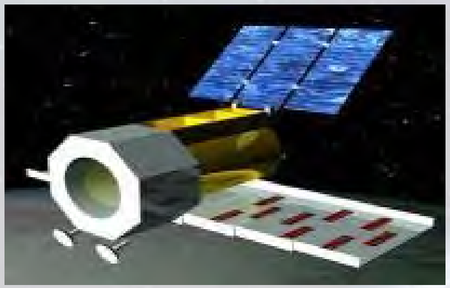


RISAT-1
Indian Space Agency (ISRO), India
C-Band (quad), 2012

SENTINEL-1a/b
ESA, Europe
C-Band (dual), 2014/2015

PAZ
Ministry of Defence, Spain
X-Band (quad), 2014

ALOS-2
Japanese Space Agency (JAXA)
L-Band (quad), 2014



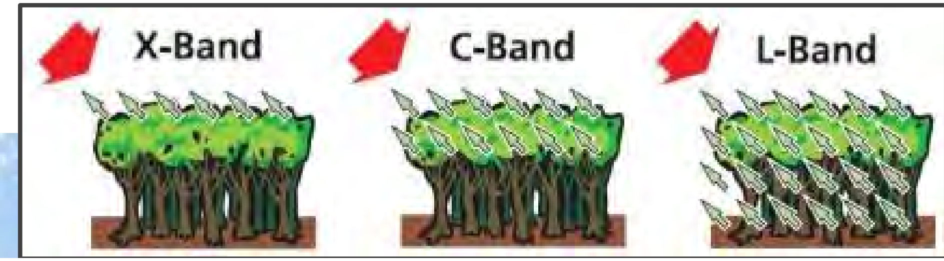
SAOCOM-1/2
CONAE/ASI, Argentina
L-Band (quad), 2016/2018

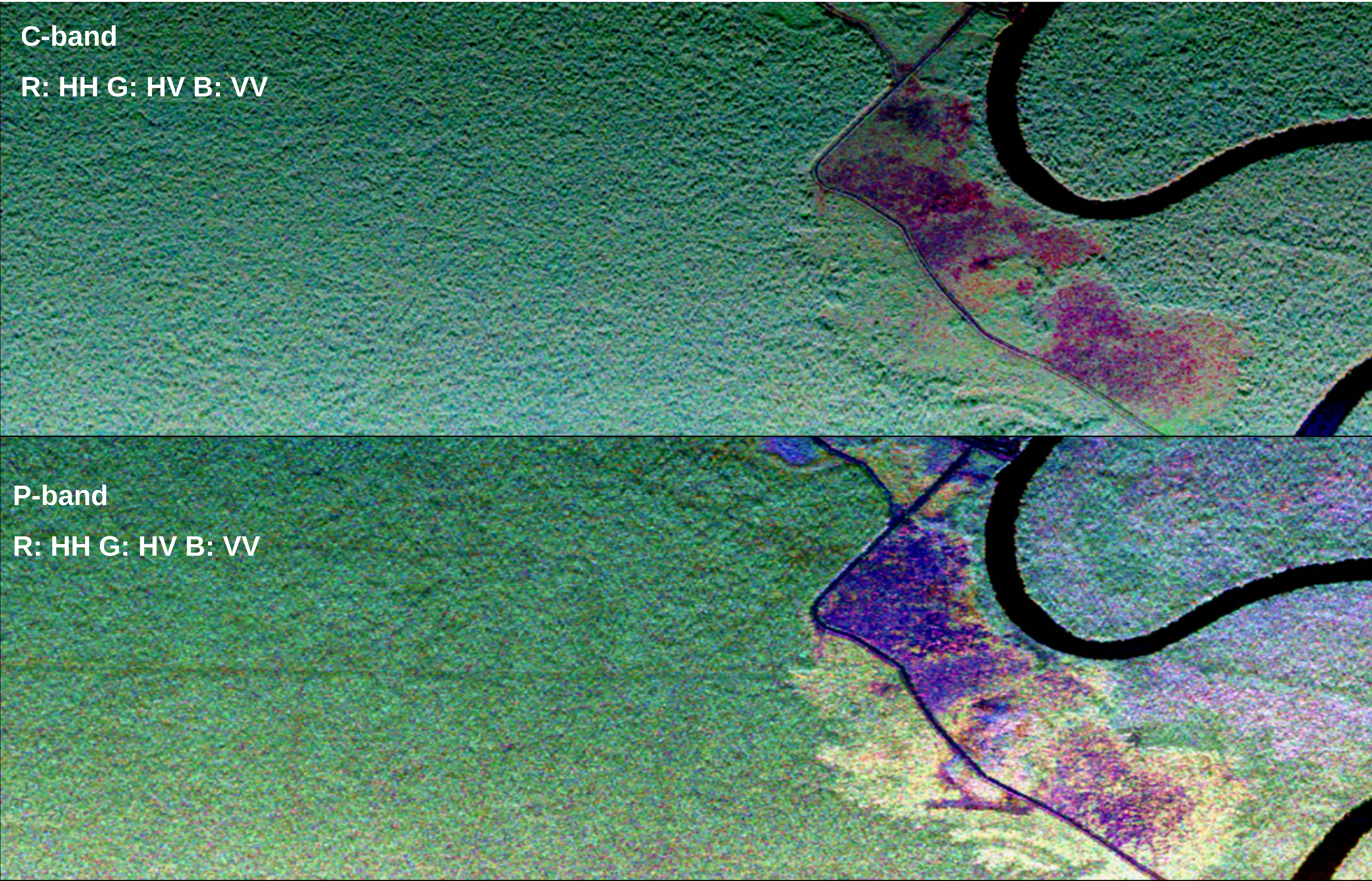
Radarsat Constellation 1-3
CSA/MDA, Canada
C-band (dual), 2018

BIOMASS
ESA, Europe
P-Band (quad), 2020

Commonly Used Frequency Bands

Frequency band	***Frequency range***	***Application Example***
• VHF	300 KHz - 300 MHz	Foliage/Ground penetration, biomass
• P-Band	300 MHz - 1 GHz	biomass, soil moisture, penetration
• L-Band	1 GHz - 2 GHz	agriculture, forestry, soil moisture
• C-Band	4 GHz - 8 GHz	ocean, agriculture
• X-Band	8 GHz - 12 GHz	agriculture, ocean, high resolution radar
• Ku-Band	14 GHz - 18 GHz	glaciology (snow cover mapping)
• Ka-Band	27 GHz - 47 GHz	high resolution radars





Frequency and Polarisation Diversity