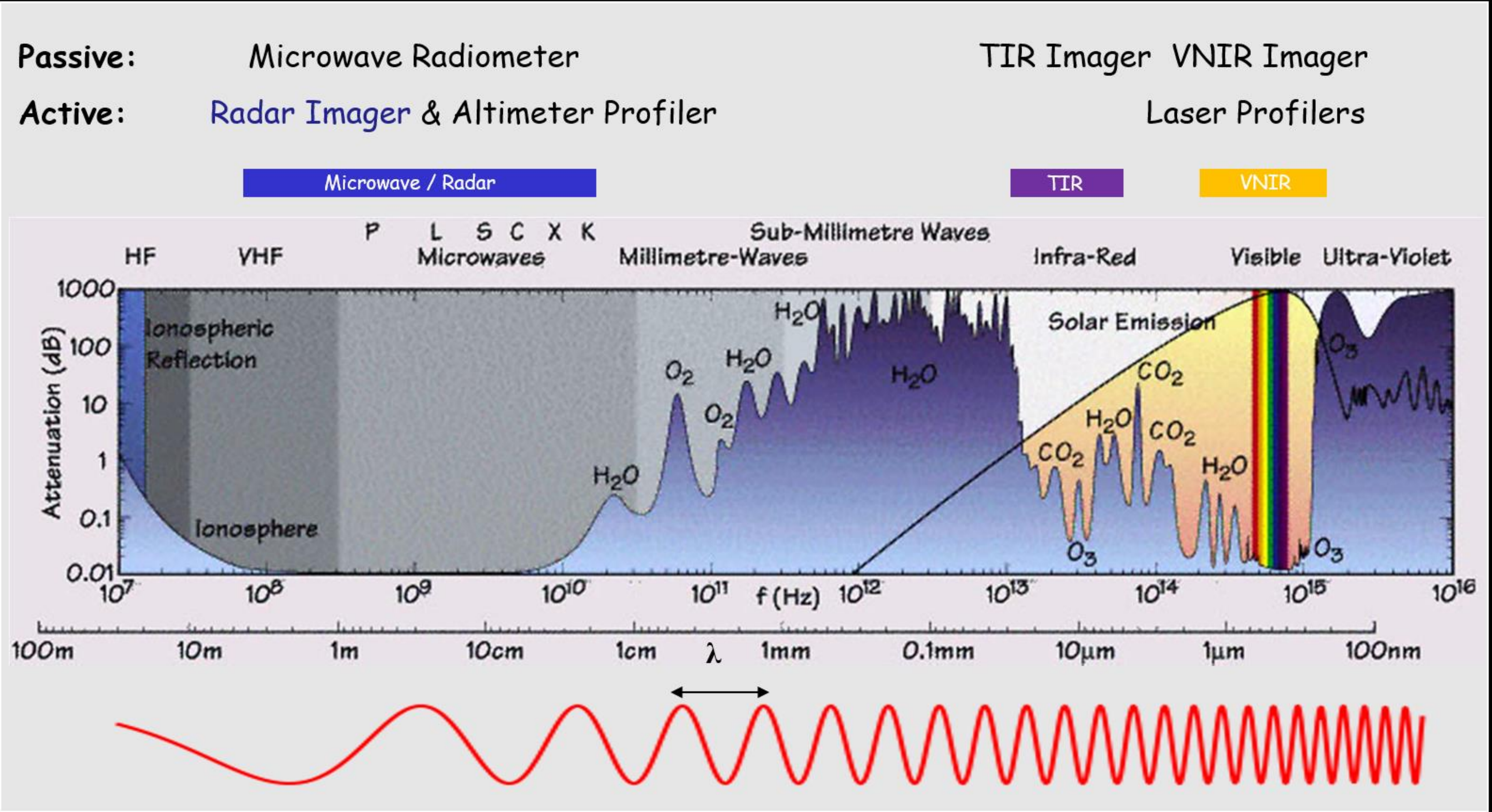
Introduction to Synthetic Aperture Radar (SAR) for Forest (In-SAR and Pol-SAR)

Irena Hajnsek
ETH Zurich
Institute of Environmental Engineering
Email: hajnsek@ifu.baug.ethz.ch
Web: http://www.eo.ifu.ethz.ch/

German Aerospace Center
Microwaves and Radar Institute
Department: Radar Concepts
Research Group: Pol-InSAR

Electromagnetic Spectrum & Remote Sensing Techniques



Electromagnetic spectrum and attenuation caused by Earth's atmosphere

Unique Characteristics of Microwave Remote Sensing

- **Independent of Weather Conditions: Penetrate clouds, rain, (smoke);**

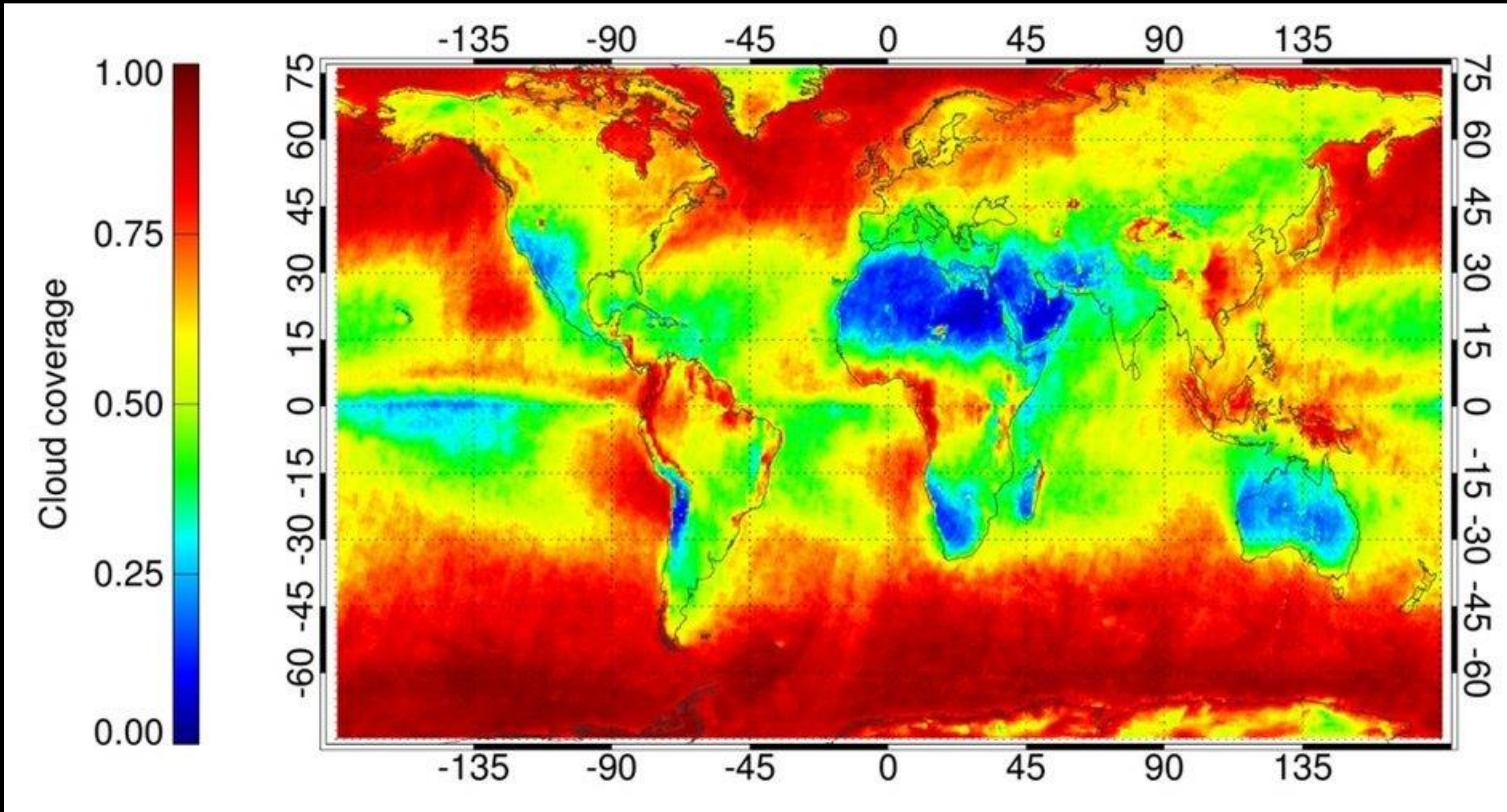
- **(Lower Frequencies) Penetrate into / through a wide class of natural cover types as: Sand / Ice / Vegetation;**

- **Sensitive to objects of dimensions from cm to m: (Complementary to Optical and IR remote sensing);**

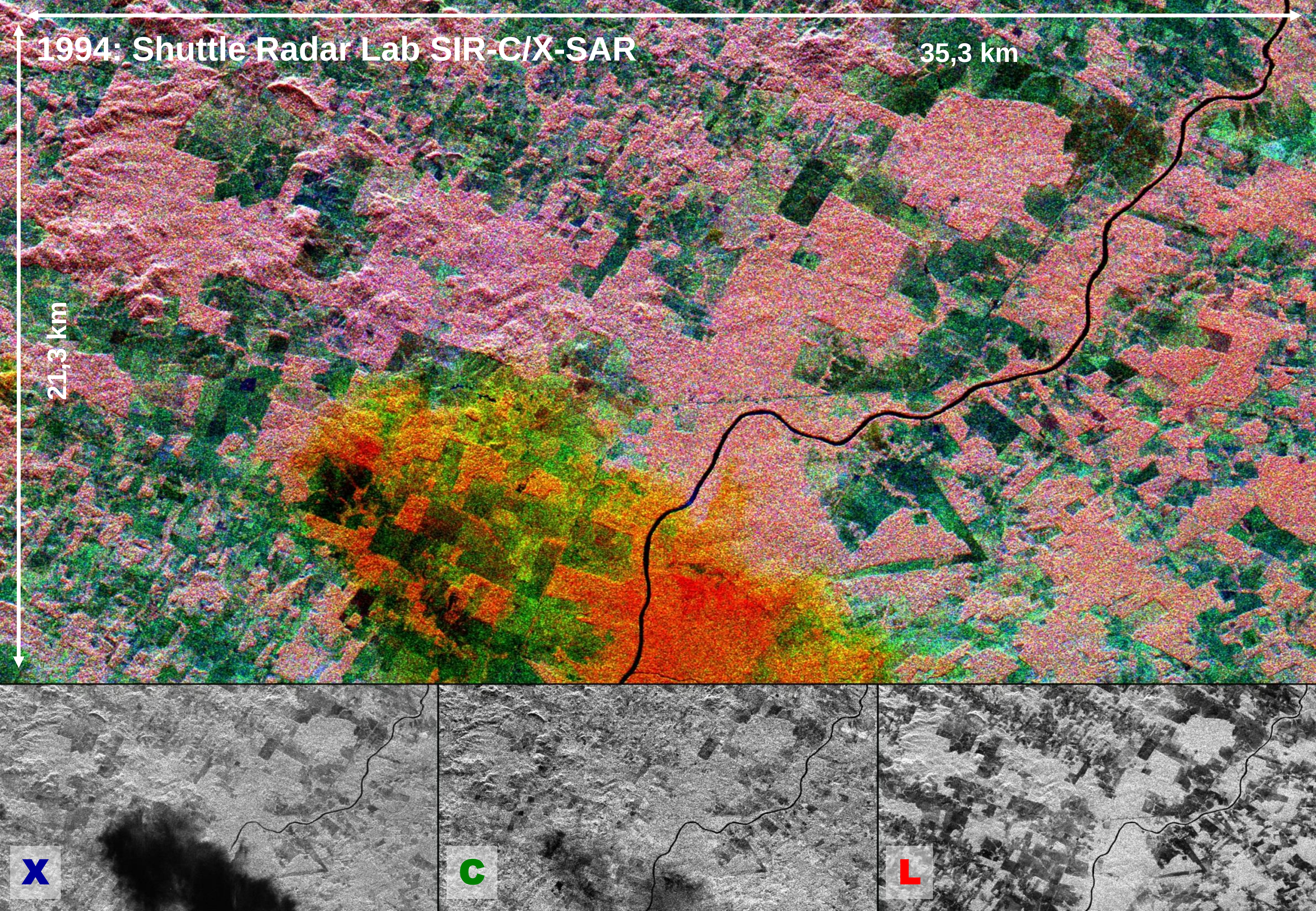
- **Very accurate (differential) distance measurements (employing interferometric techniques);**

- **(Active) Microwave systems are able to operate day and night.**

Global Annual Mean Cloud Cover (2007-2009)



From MERIS and AATSR on ENVISAT


1994: Shuttle Radar Lab SIR-C/X-SAR
35,3 km
21,3 km
X
C
L

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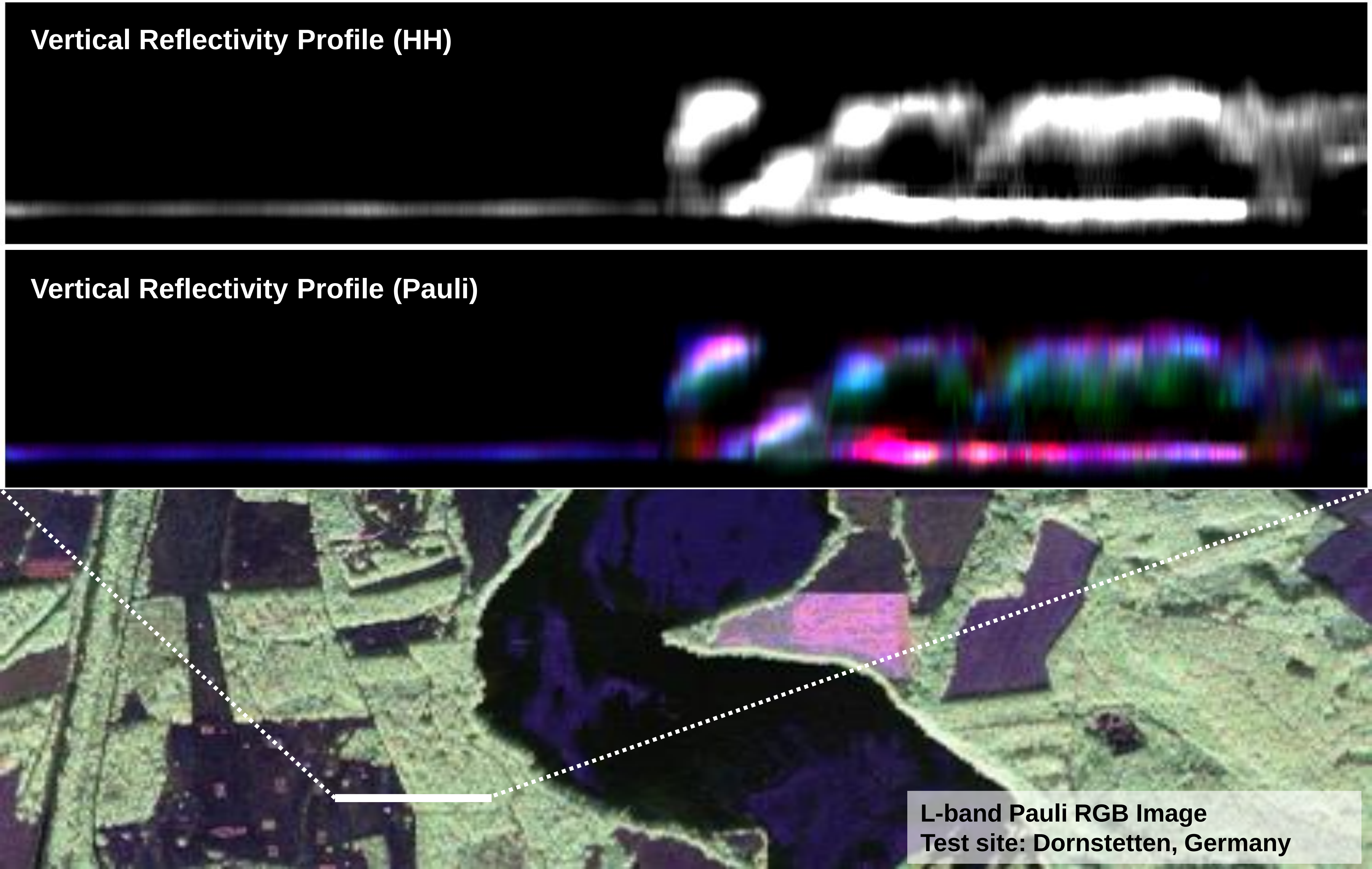
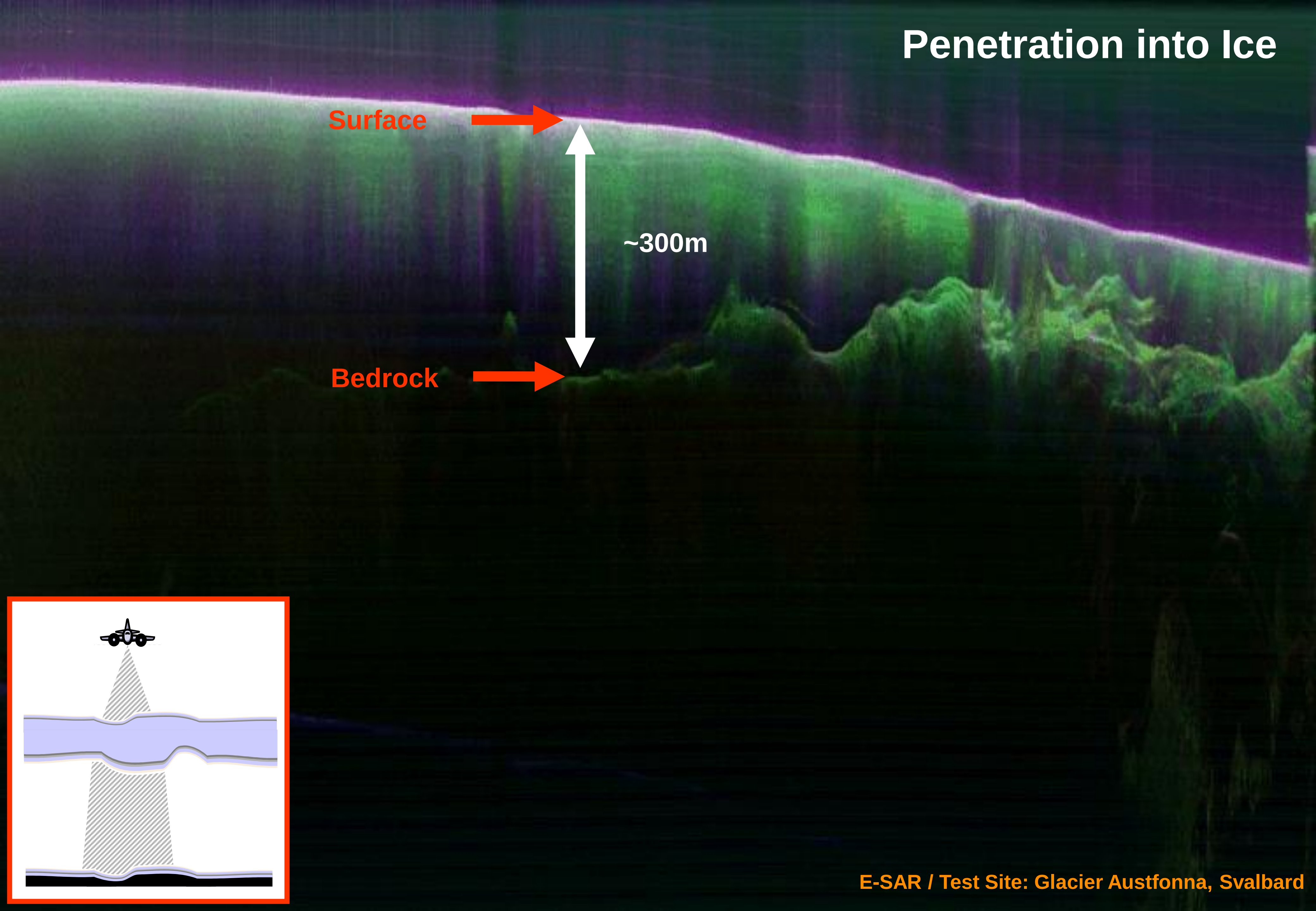
Penetration into Vegetation





Penetration into Ice
Surface
~300m
Bedrock
E-SAR / Test Site: Glacier Austfonna, Svalbard

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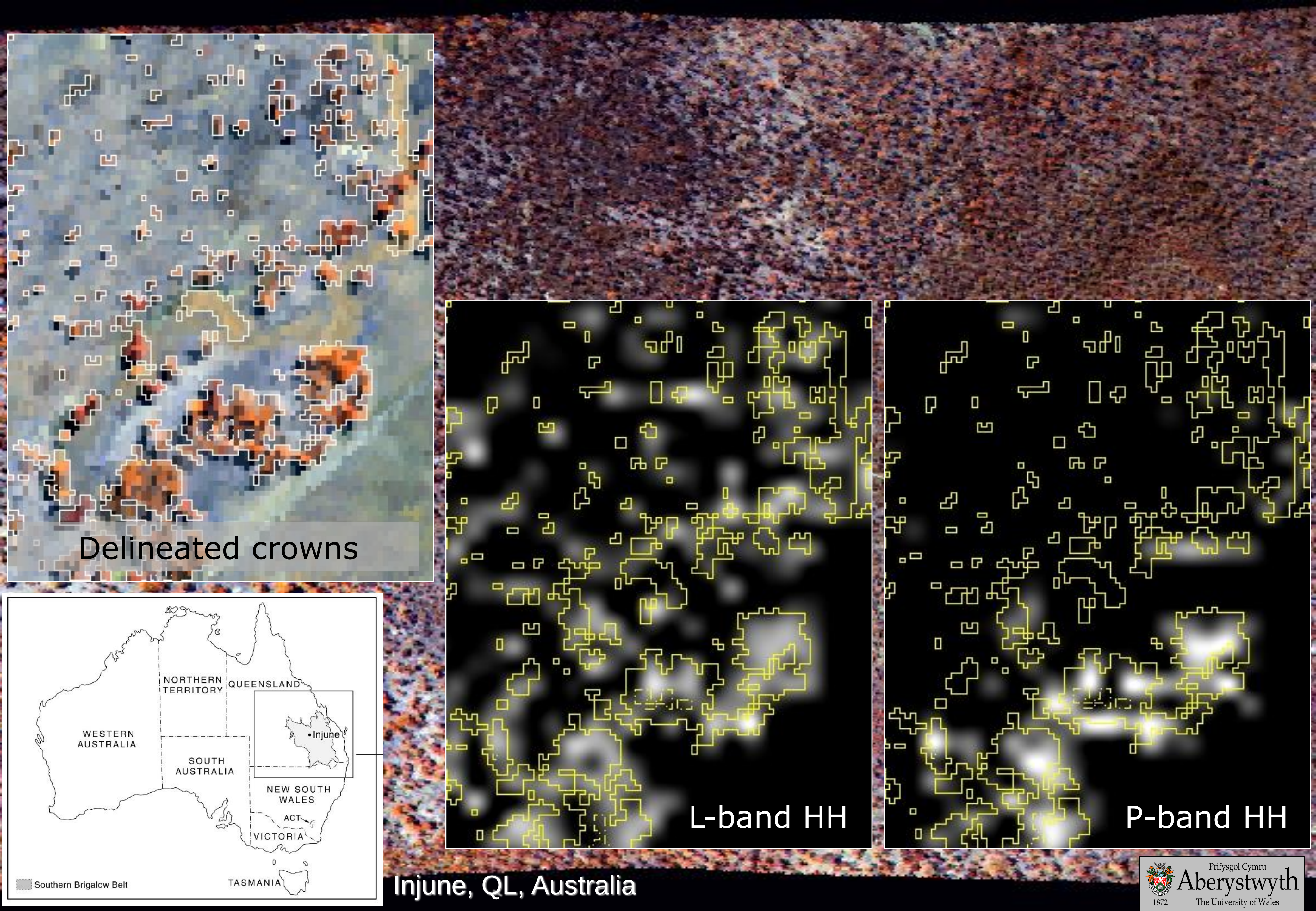
Delineated crowns
L-band HH
P-band HH
NORTHERN TERRITORY
QUEENSLAND
WESTERN AUSTRALIA
SOUTH AUSTRALIA
NEW SOUTH WALES
ACT
VICTORIA
TASMANIA
Injune
Southern Brigalow Belt
Injune, QL, Australia
Prifysgol Cymru
Aberystwyth
1872
The University of Wales

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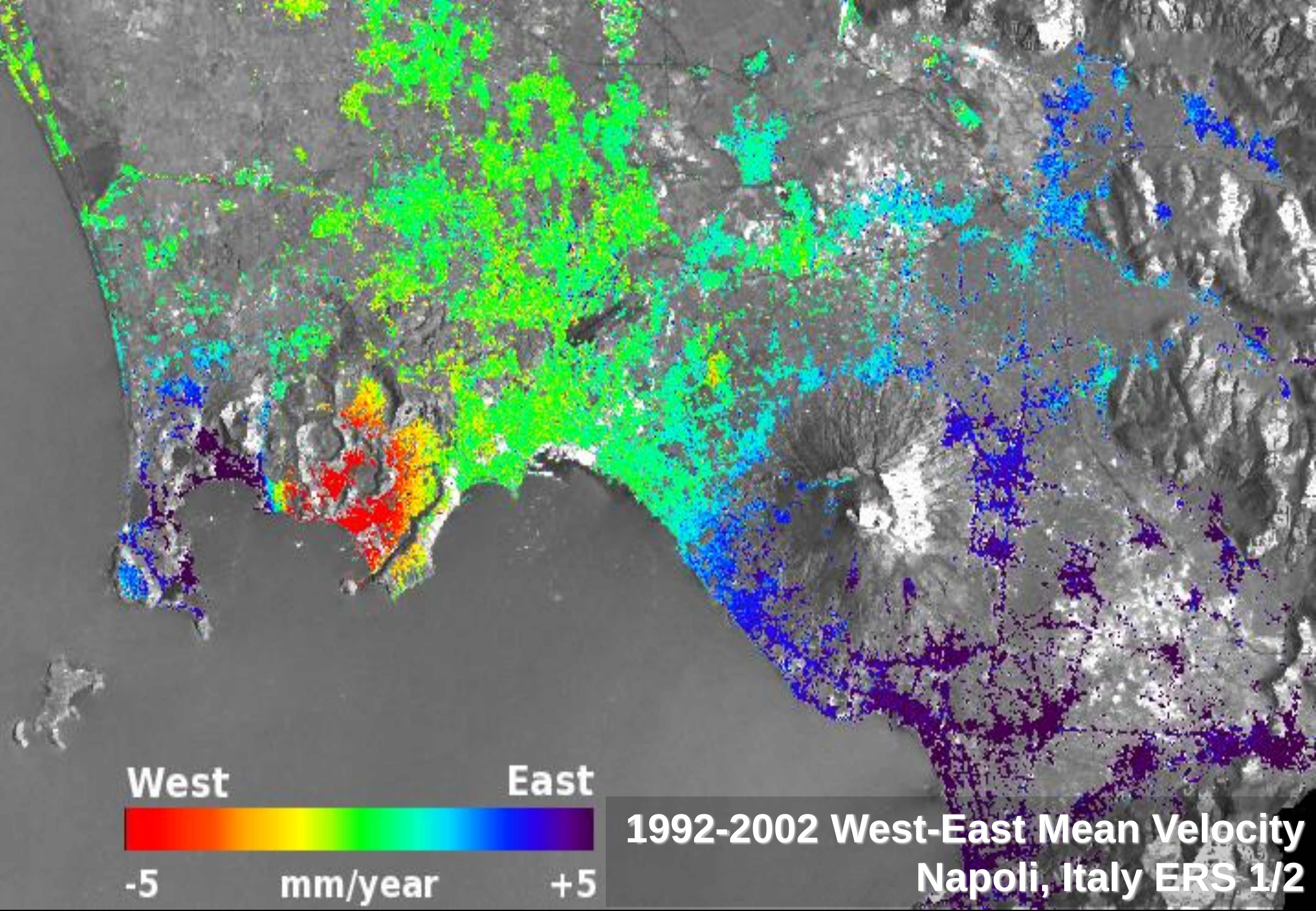
West
East
-5
mm/year
+5
1992-2002 West-East Mean Velocity
Napoli, Italy ERS 1/2

Unique Characteristics of Microwave Remote Sensing

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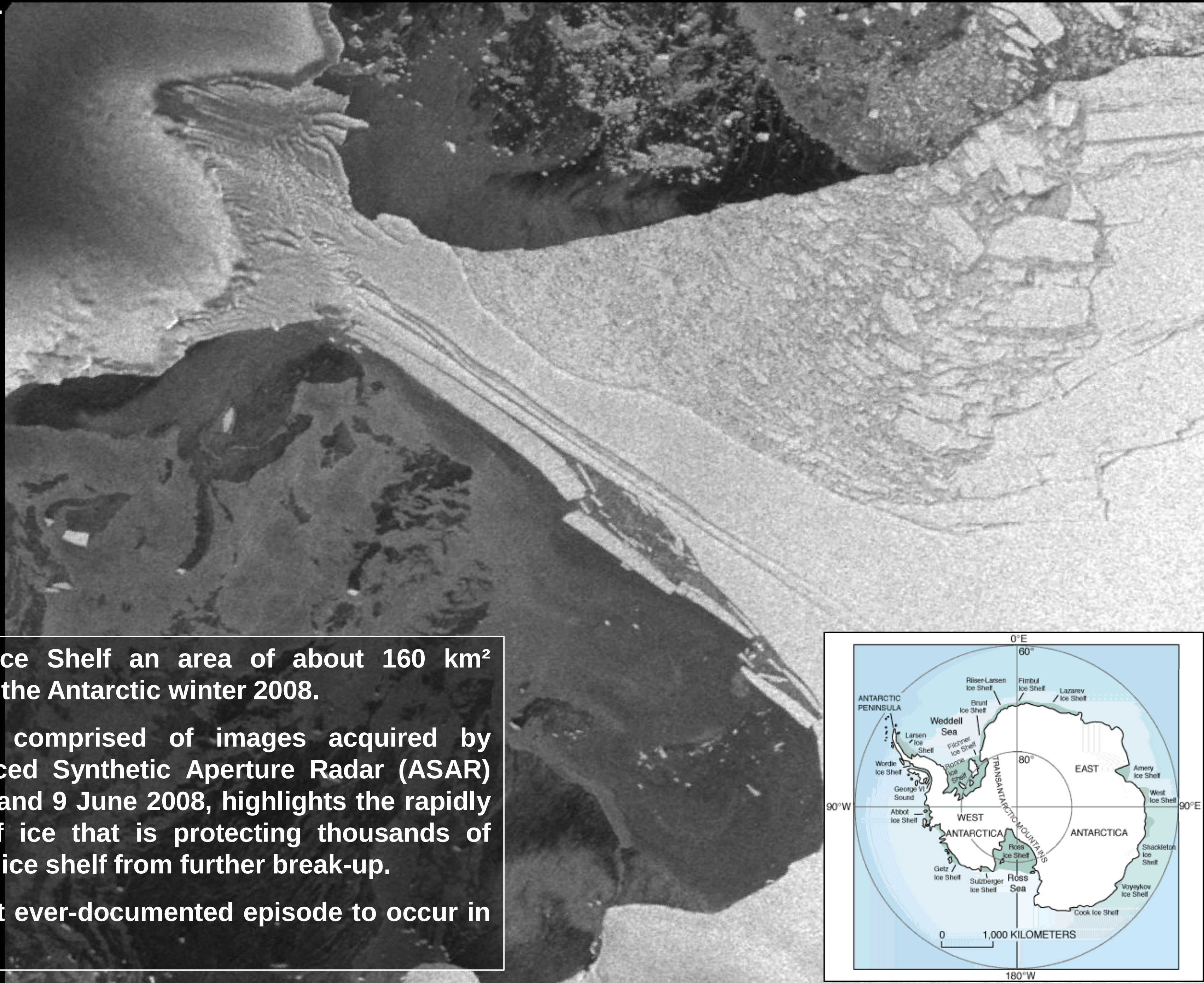
© ESA ENVISAT
30-5-2008

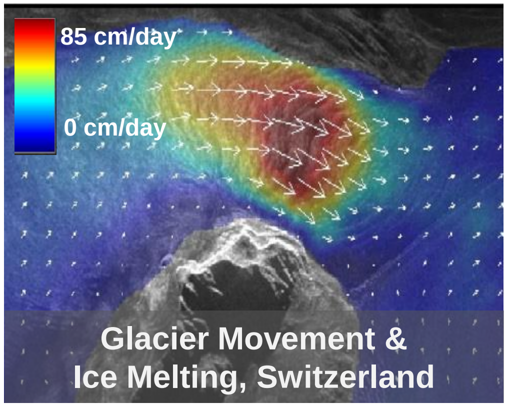


In the Wilkins Ice Shelf an area of about 160 km² collapsed during the Antarctic winter 2008.

This animation, comprised of images acquired by Envisat's Advanced Synthetic Aperture Radar (ASAR) between 30 May and 9 June 2008, highlights the rapidly windling strip of ice that is protecting thousands of kilometres of the ice shelf from further break-up.

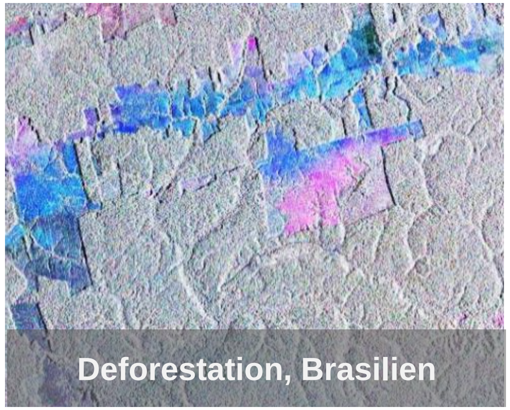
This was the first ever-documented episode to occur in winter.

SAR Remote Sensing and Global Societal Challenges

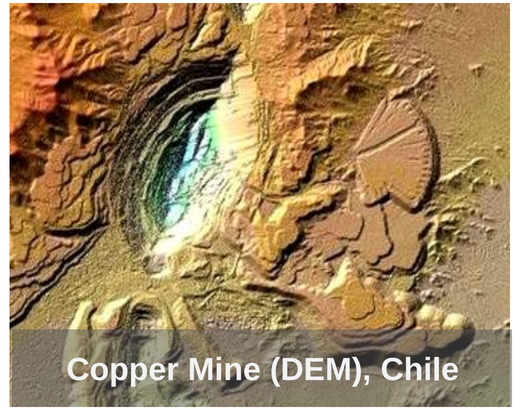


Glacier Movement & Ice Melting, Switzerland

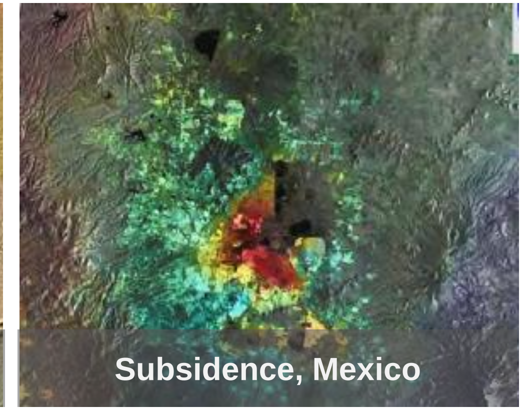
Climate Change


Deforestation, Brasilien

Environment


Copper Mine (DEM), Chile

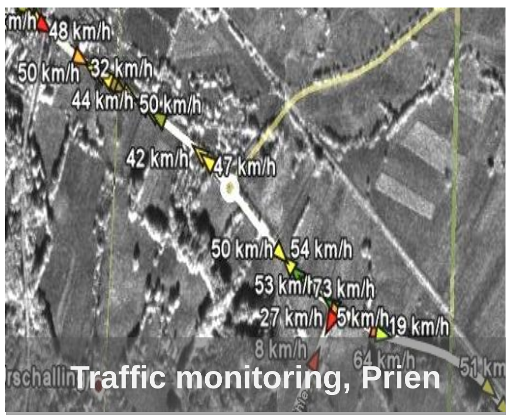
Resources


Subsidence, Mexico

Sustainable Development

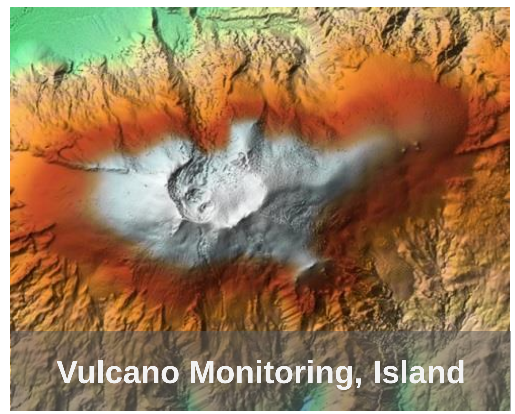

Urban Planing, Istanbul

Megacities



Traffic monitoring, Prien

Mobility

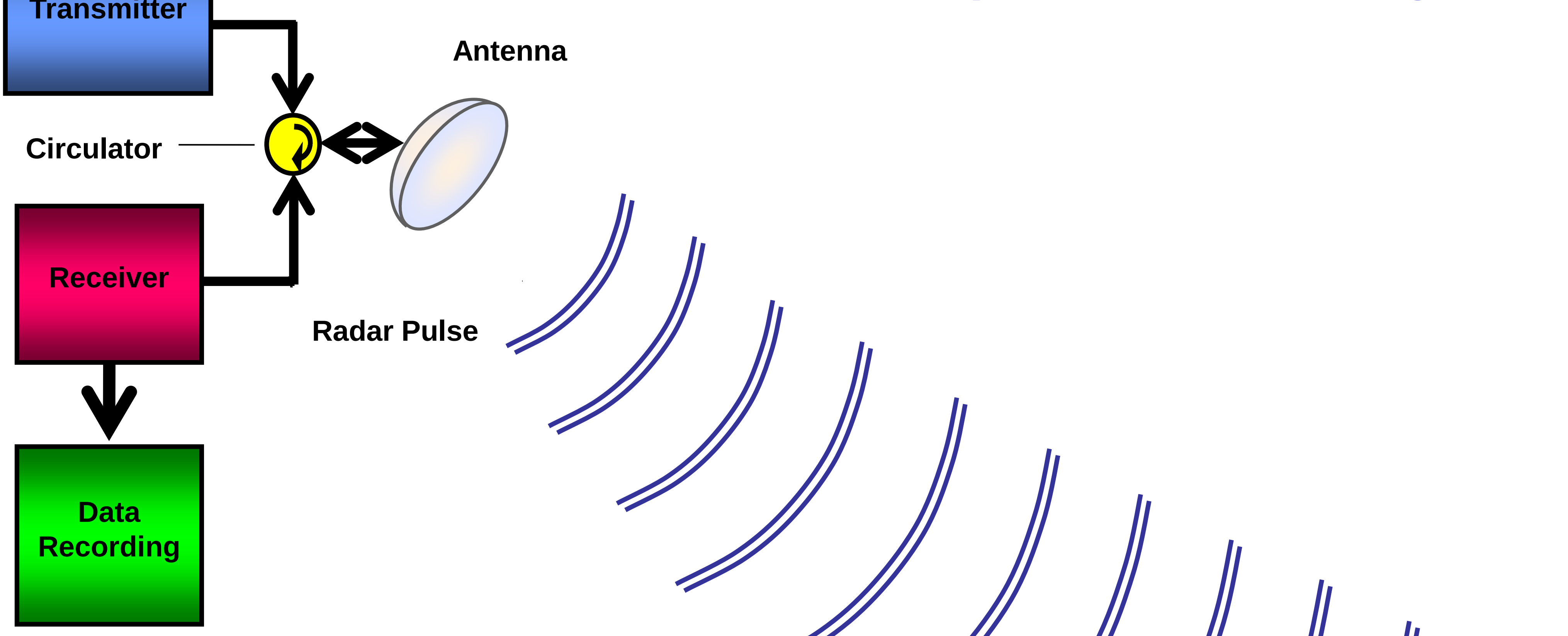

Vulcano Monitoring, Island

Hazards

Flooding, Deggendorf, Germany

Disaster

Basic Radar Operation Block Diagram



- **Transmitter: generates a high power pulse;**
- **Circulator** (Switch)**: switches the transmitted pulse to the antenna, & the returned echoes to the receiver;**
- **Antenna directs the transmitted pulse towards the scene;**
- **Receiver amplifies the received signal and converts to base band.**

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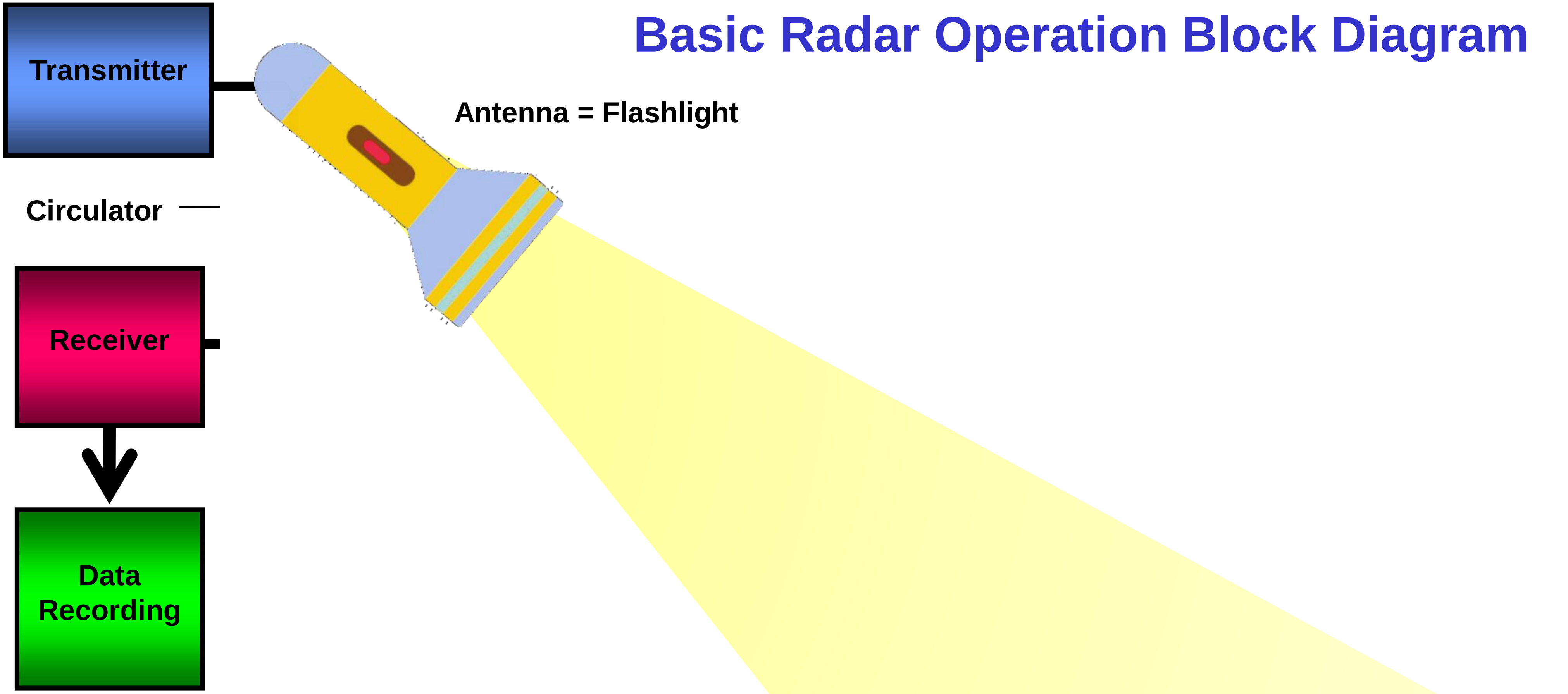

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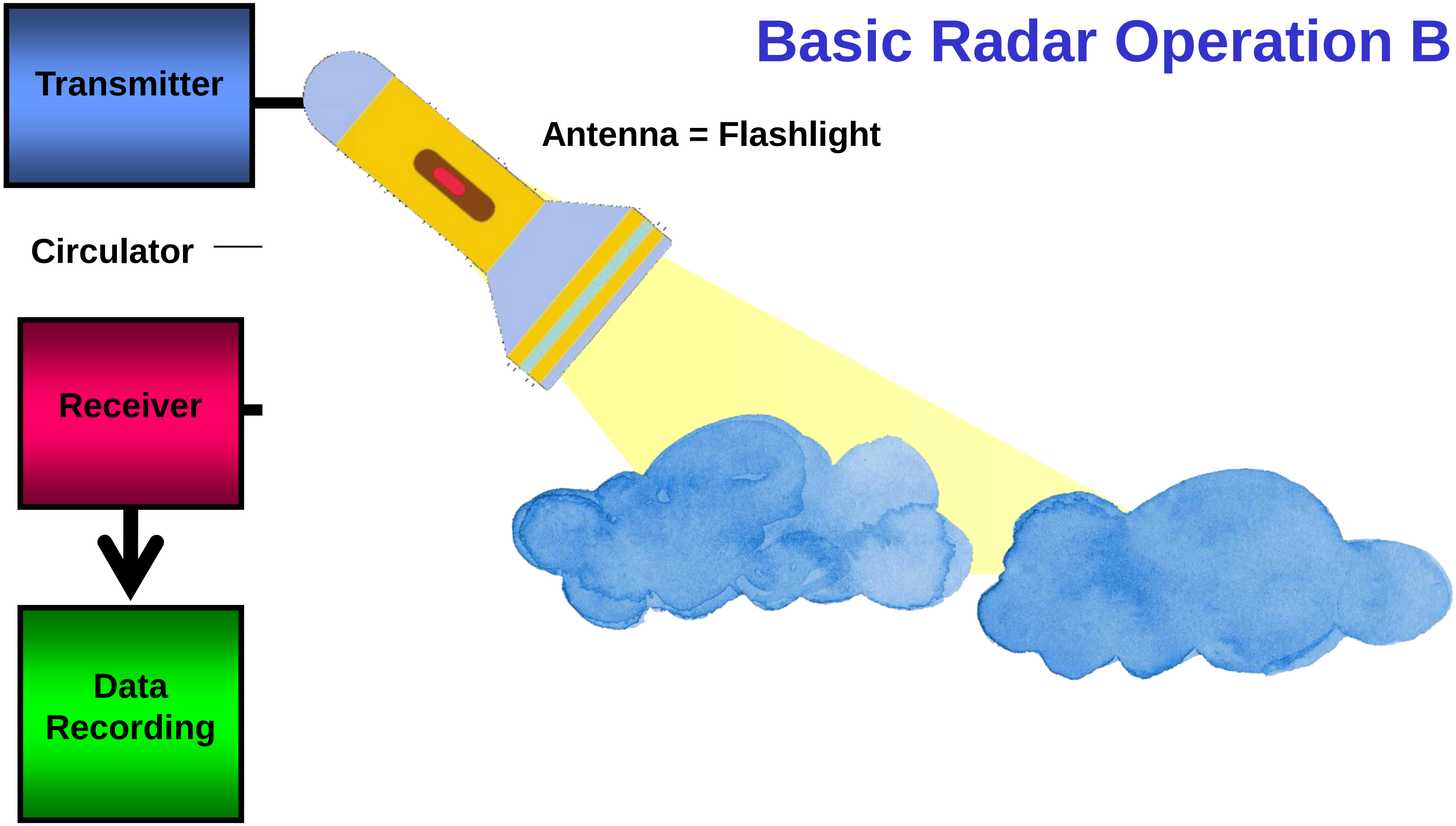

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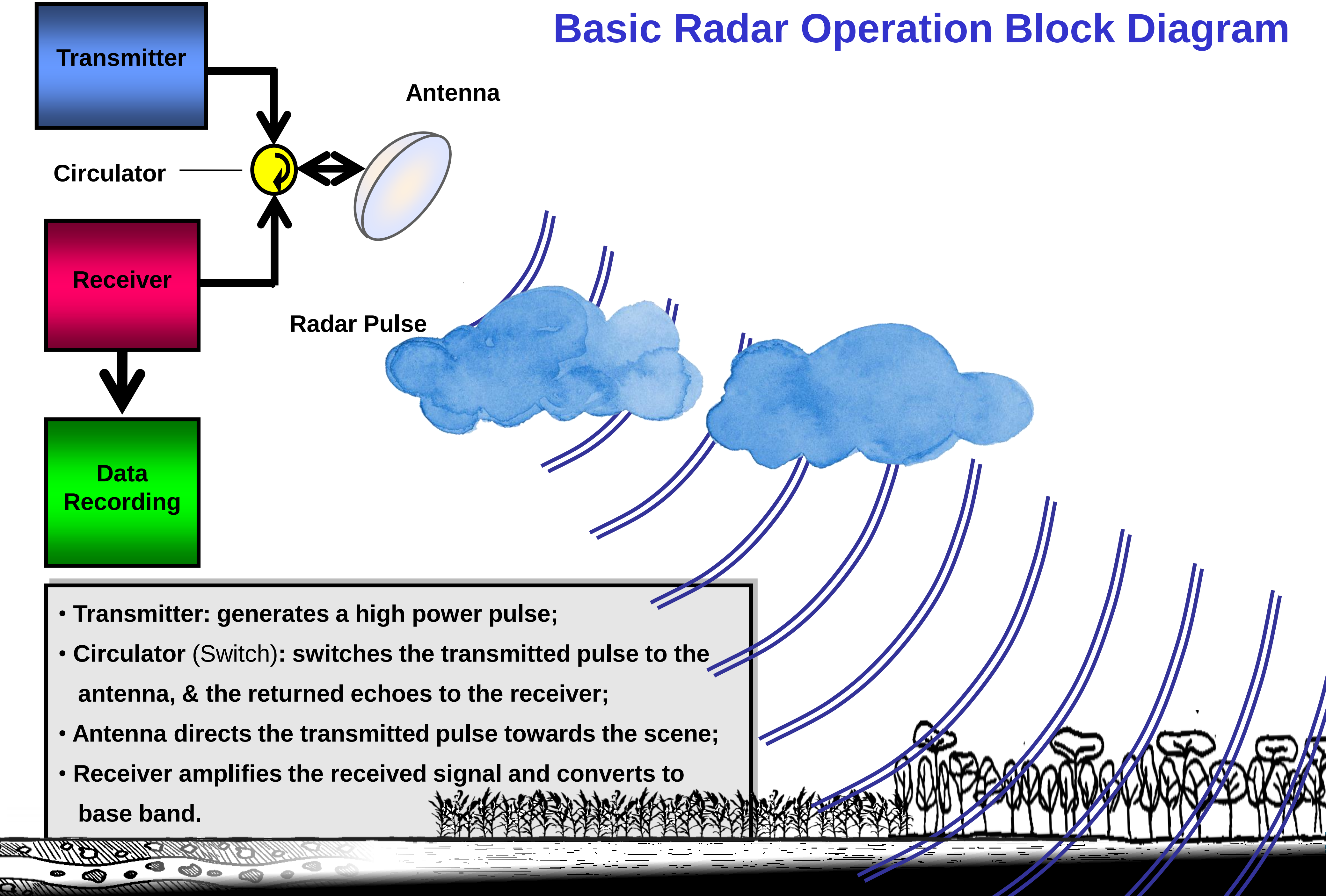

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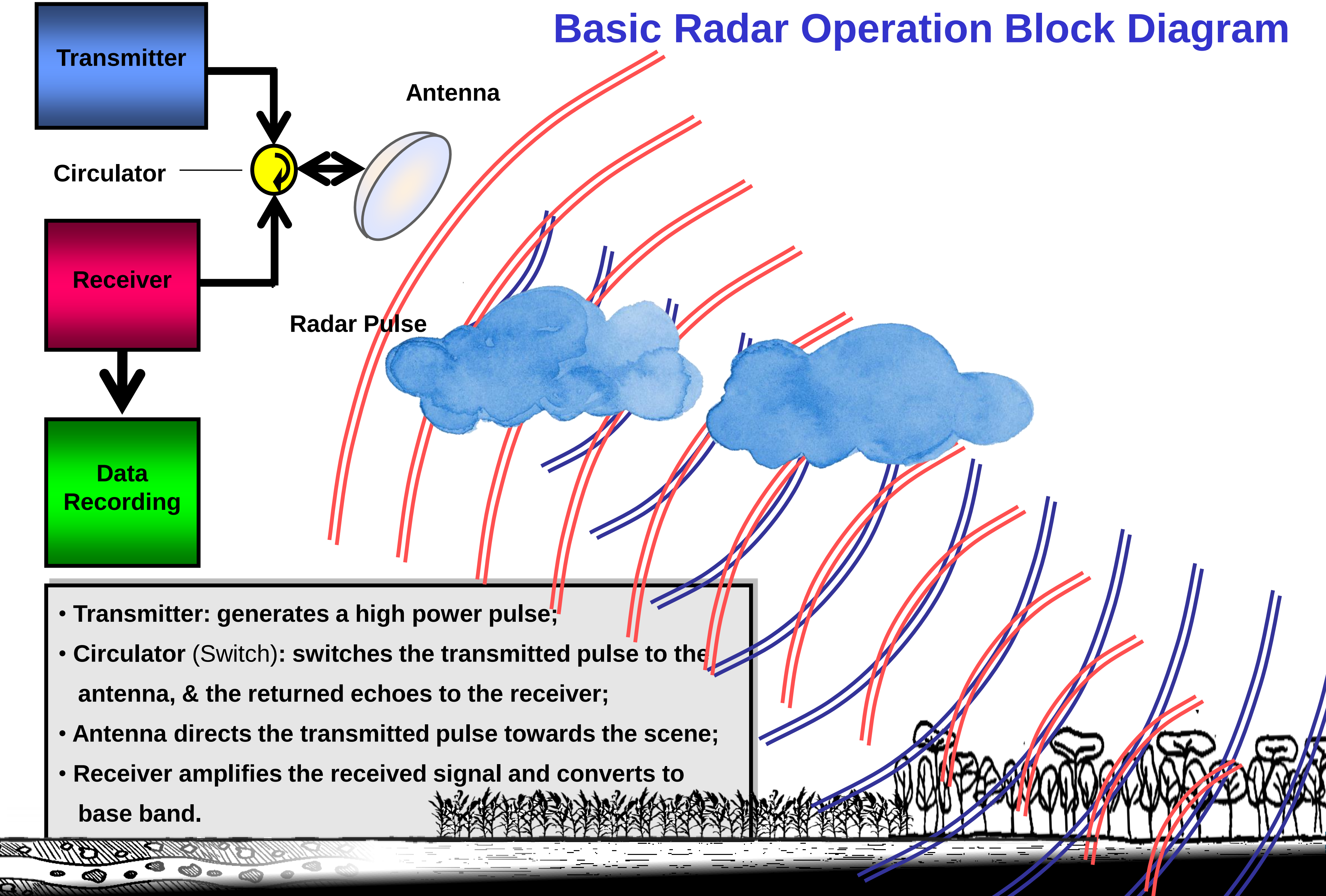

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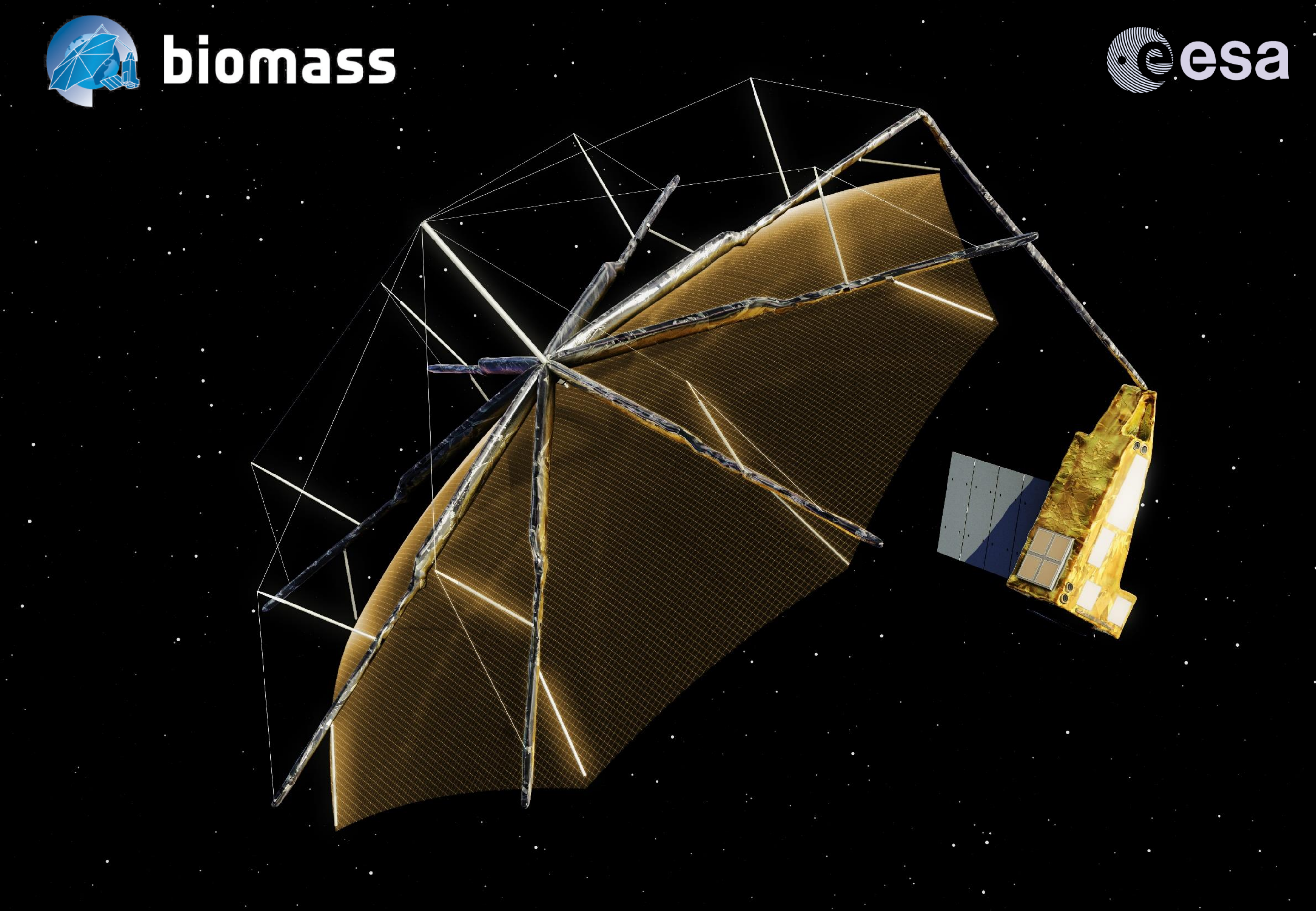
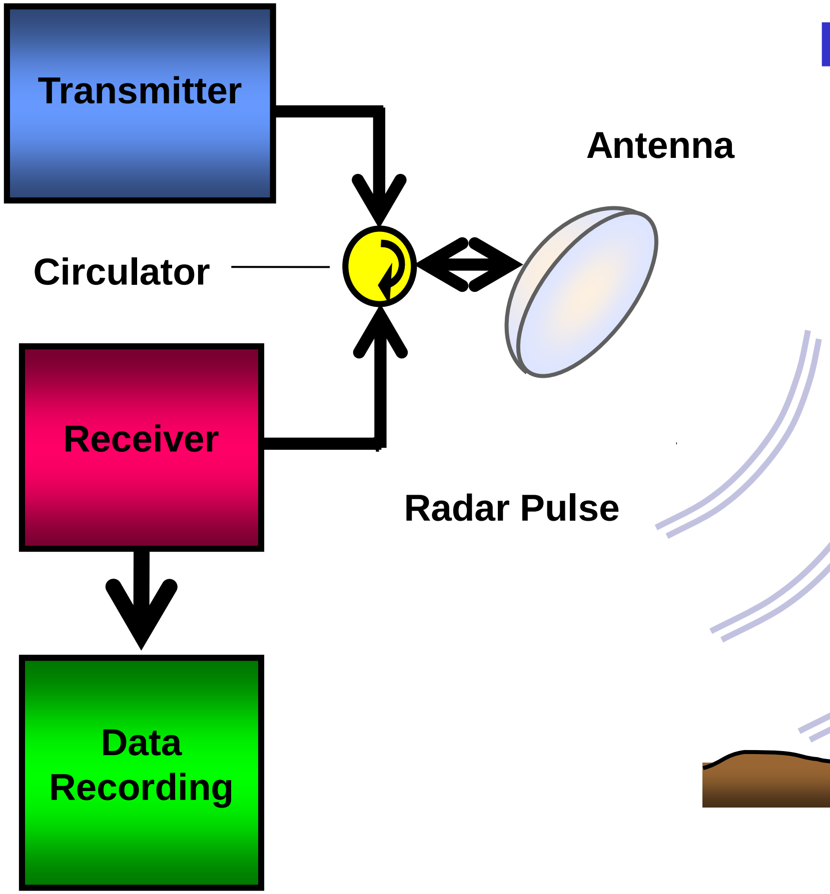
sentinel-1
esa


biomass
esa

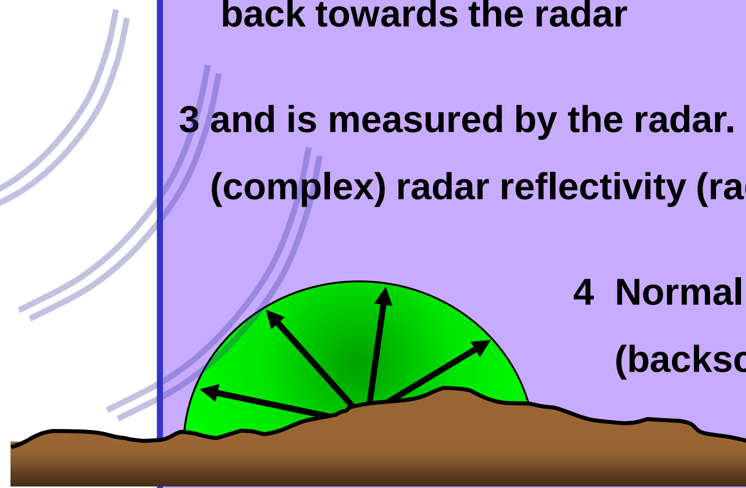
Basic Radar Operation Block Diagram



1 The transmitted pulse interacts with the scene / scatterer;

2 Some of the energy of the incident radar pulse is scattered back towards the radar

3 and is measured by the radar. It is known as the scatterer's (complex) radar reflectivity (radar brightness).

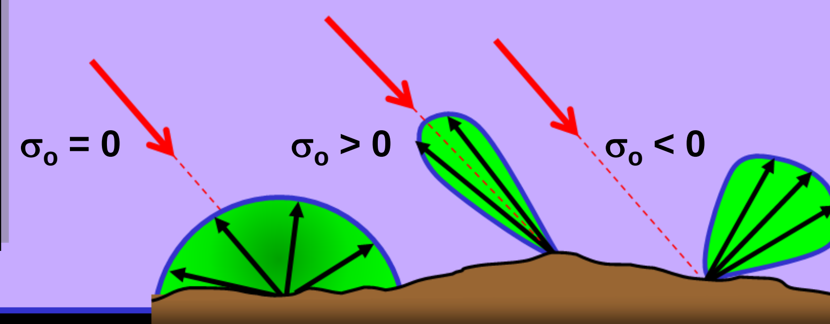


4 Normalized radar cross-section (backscattering coefficient):

$$\sigma_o\,[dB] = 10.\,\log_{10}\left(\frac{E}{E_{ISO}}\right)$$

E: Energy received from (backscattered by) the scatterer

E_{ISO}: Energy received from (backscattered by) an isotropic scatterer



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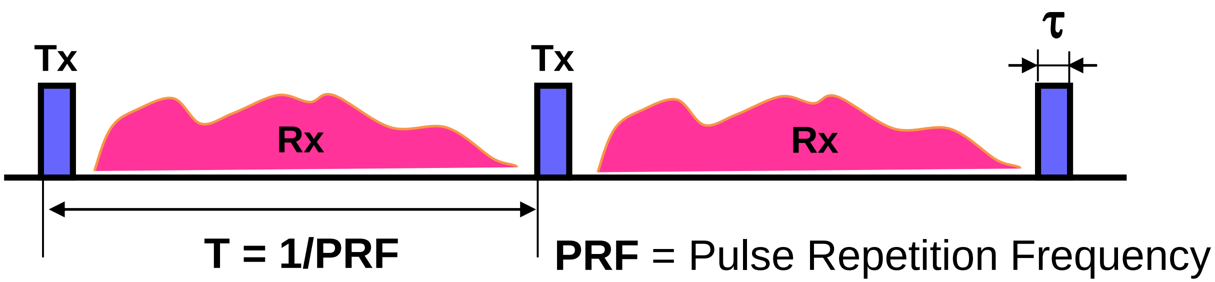
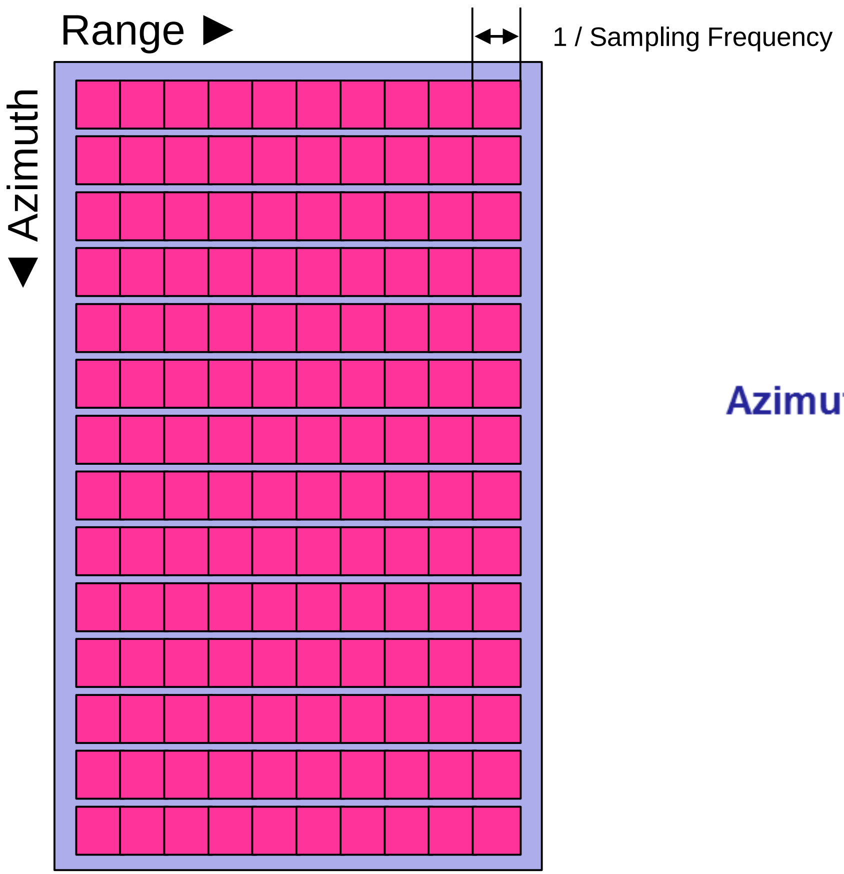
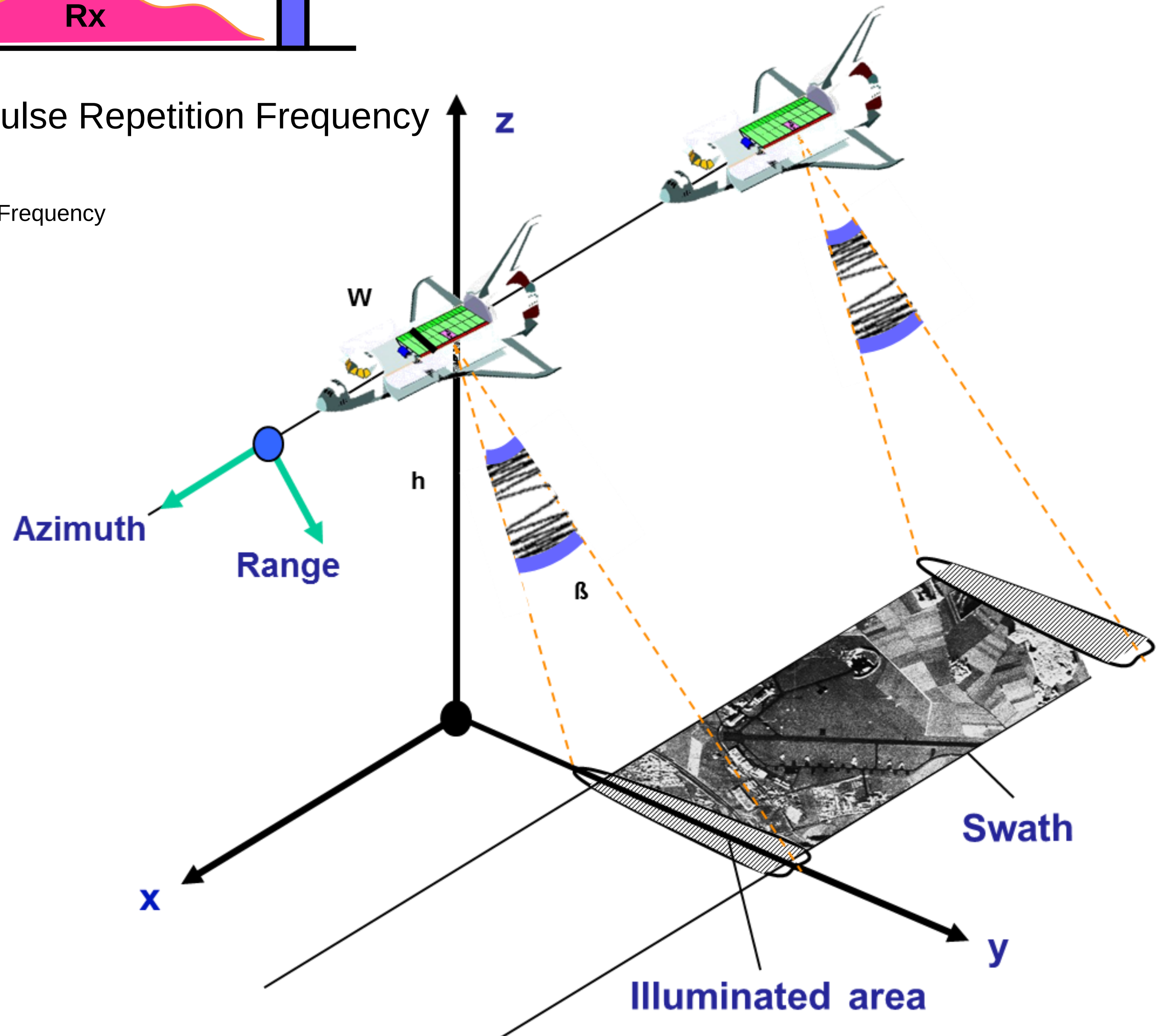
2-D Imaging

Pulsed radar system





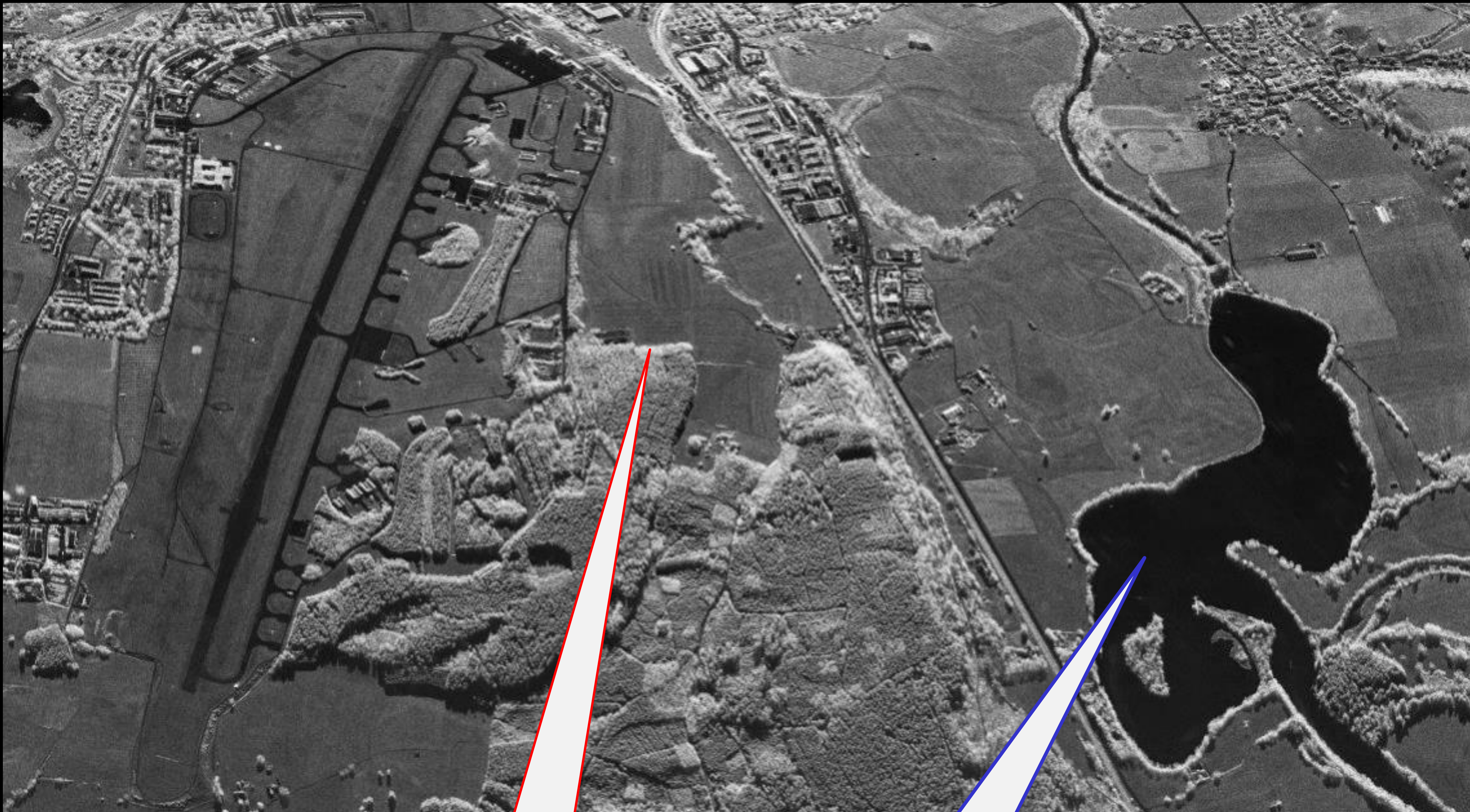
2-D SAR Image



Backscattering Coefficient σ_o

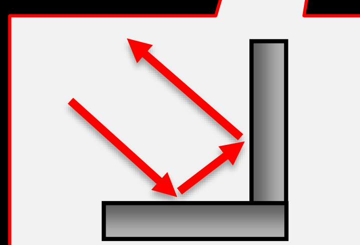
Levels of Radar backscatter	Typical scenario
Very high backscatter (above -5 dB)	Man-Made objects (urban) Terrain slopes towards radar Very rough surface Radar looking very steep
High backscatter (-10 dB to 0 dB)	Rough surface Dense vegetation (forest)
Moderate backscatter (-20 to -10 dB)	Medium level of vegetation Agricultural crops Moderately rough surfaces
Low backscatter (below -20 dB)	Smooth surface Calm water Road Very dry terrain (sand)

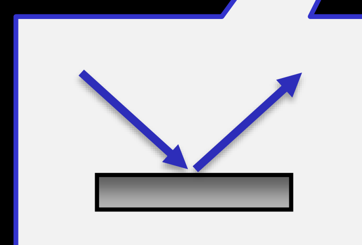
F-SAR (DLR), Kaufbeuren, X-Band



Kaufbeuren, **Germany**

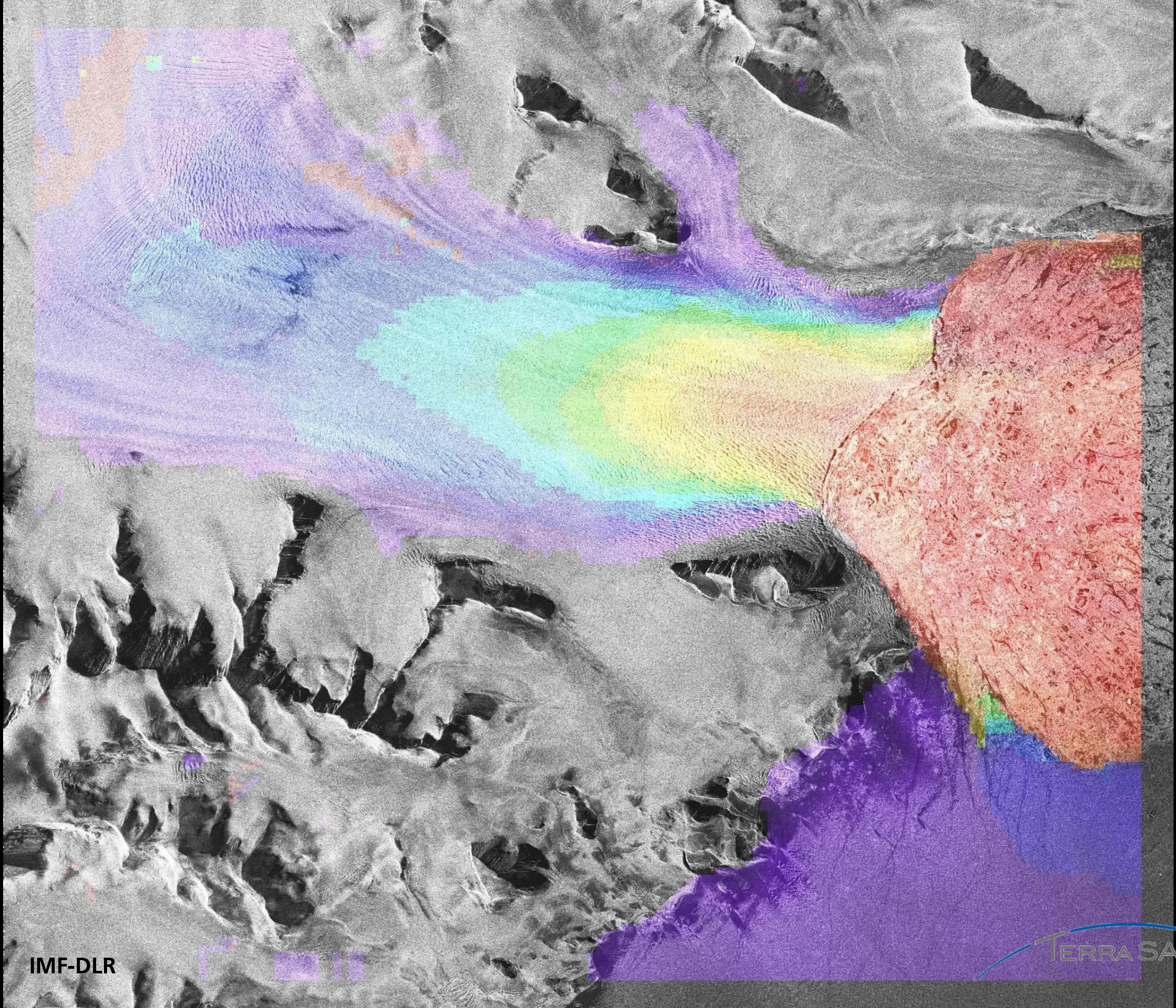
F-SAR C-band HV





Amazon Deforest Watch (Santarem) ALOS PalSAR

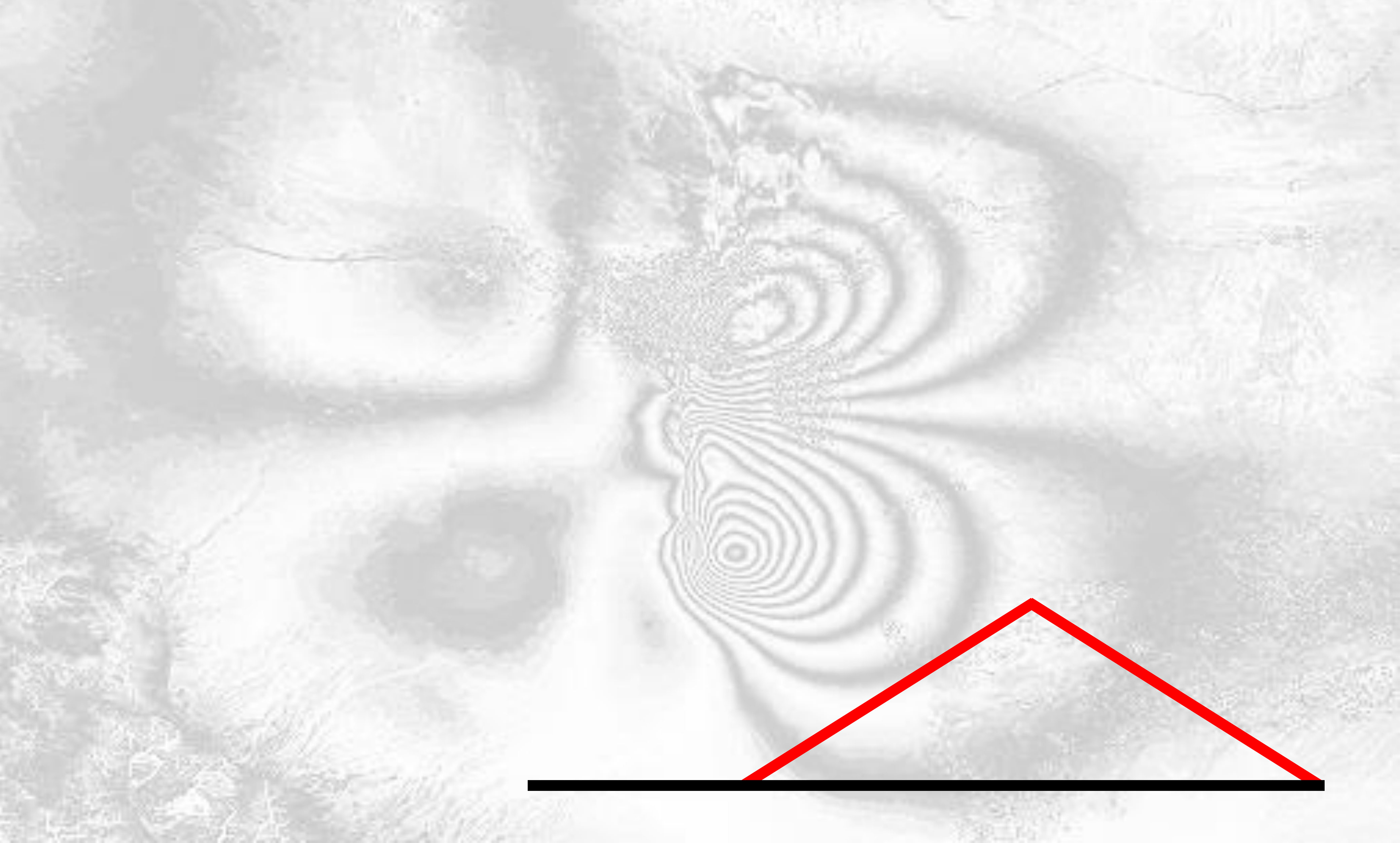
Drygalski Glacier Oct 2007 – Jul 2008

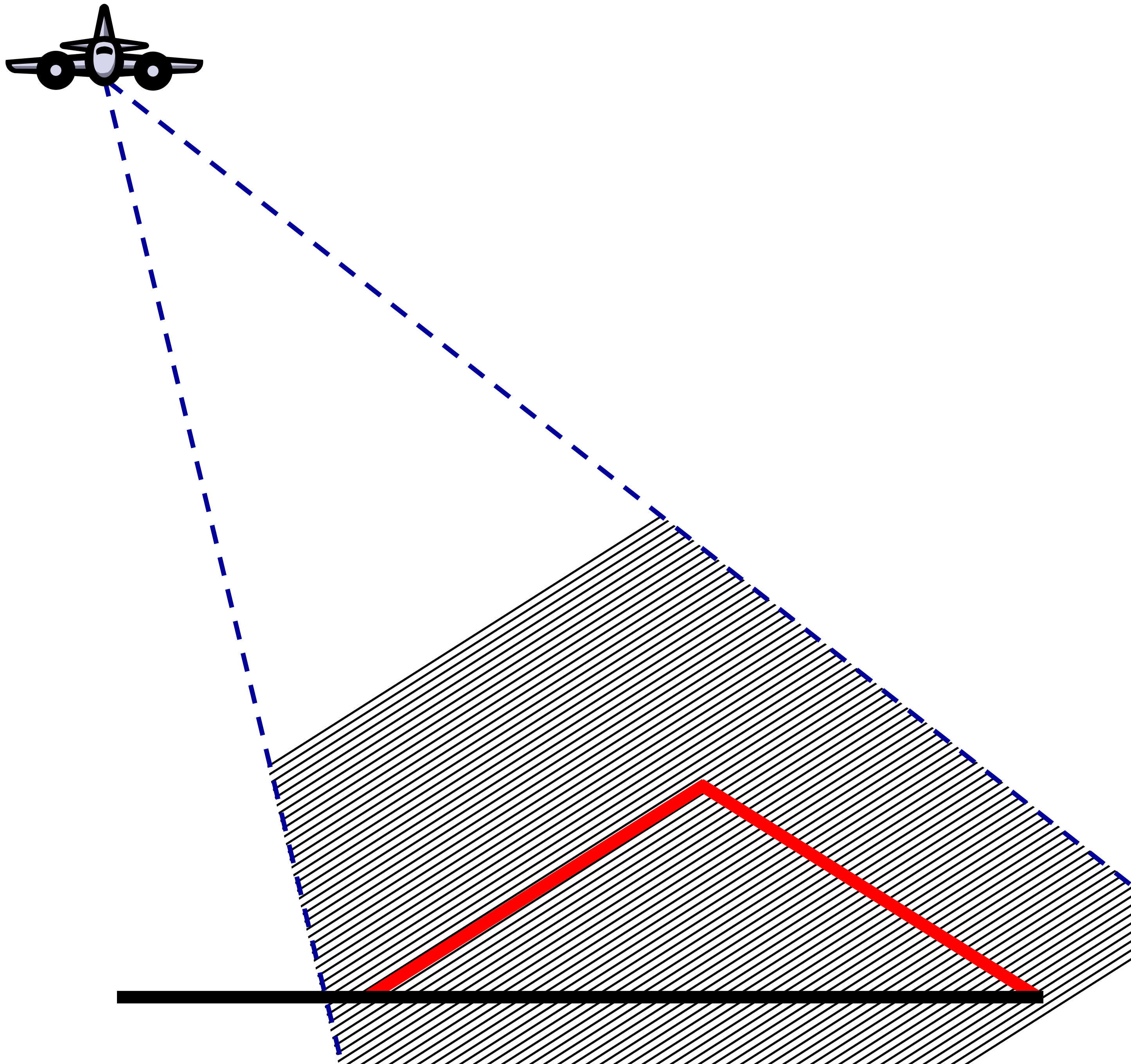


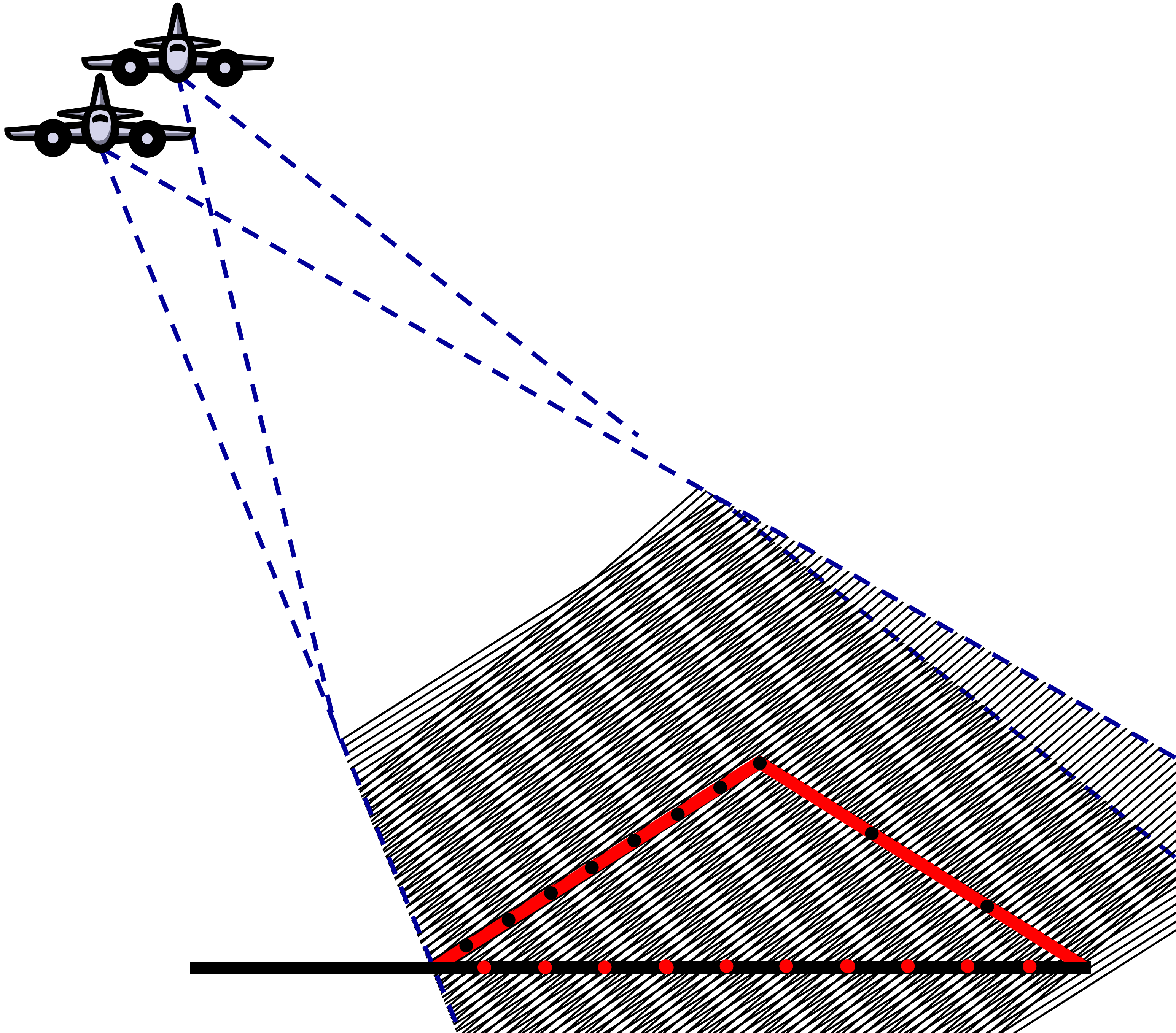
6 m/day

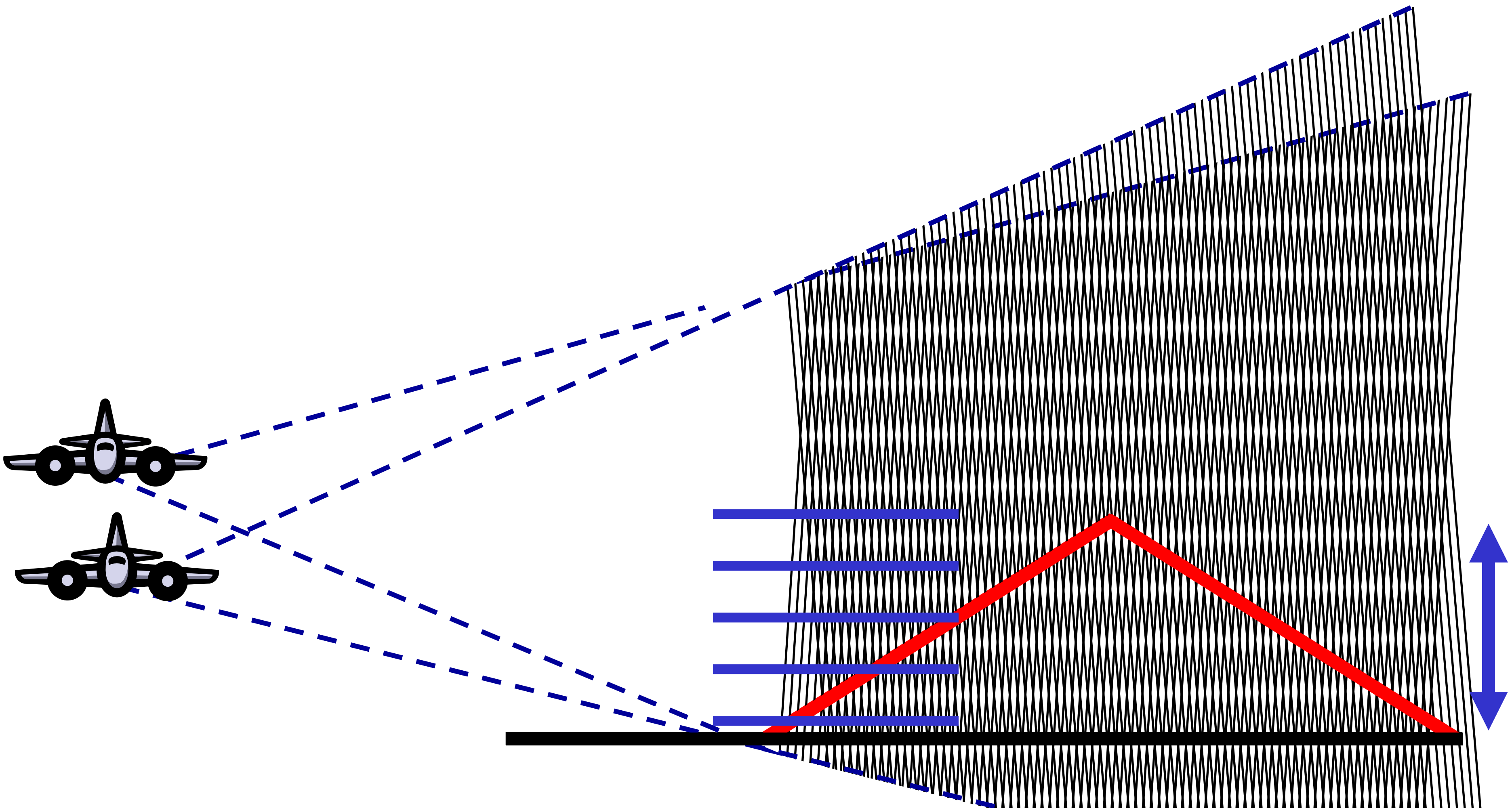
DLR

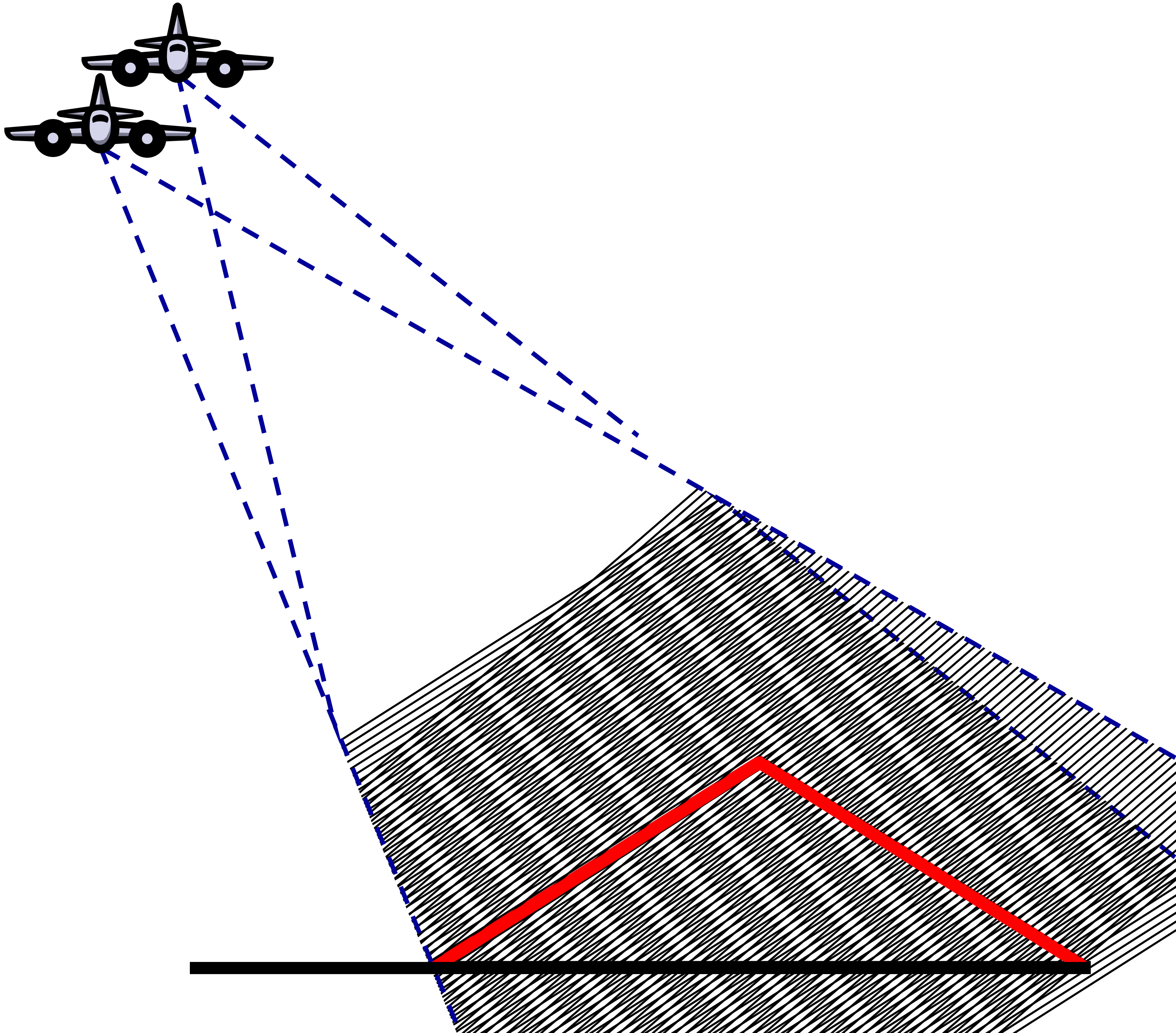
SAR Interferometry (InSAR)

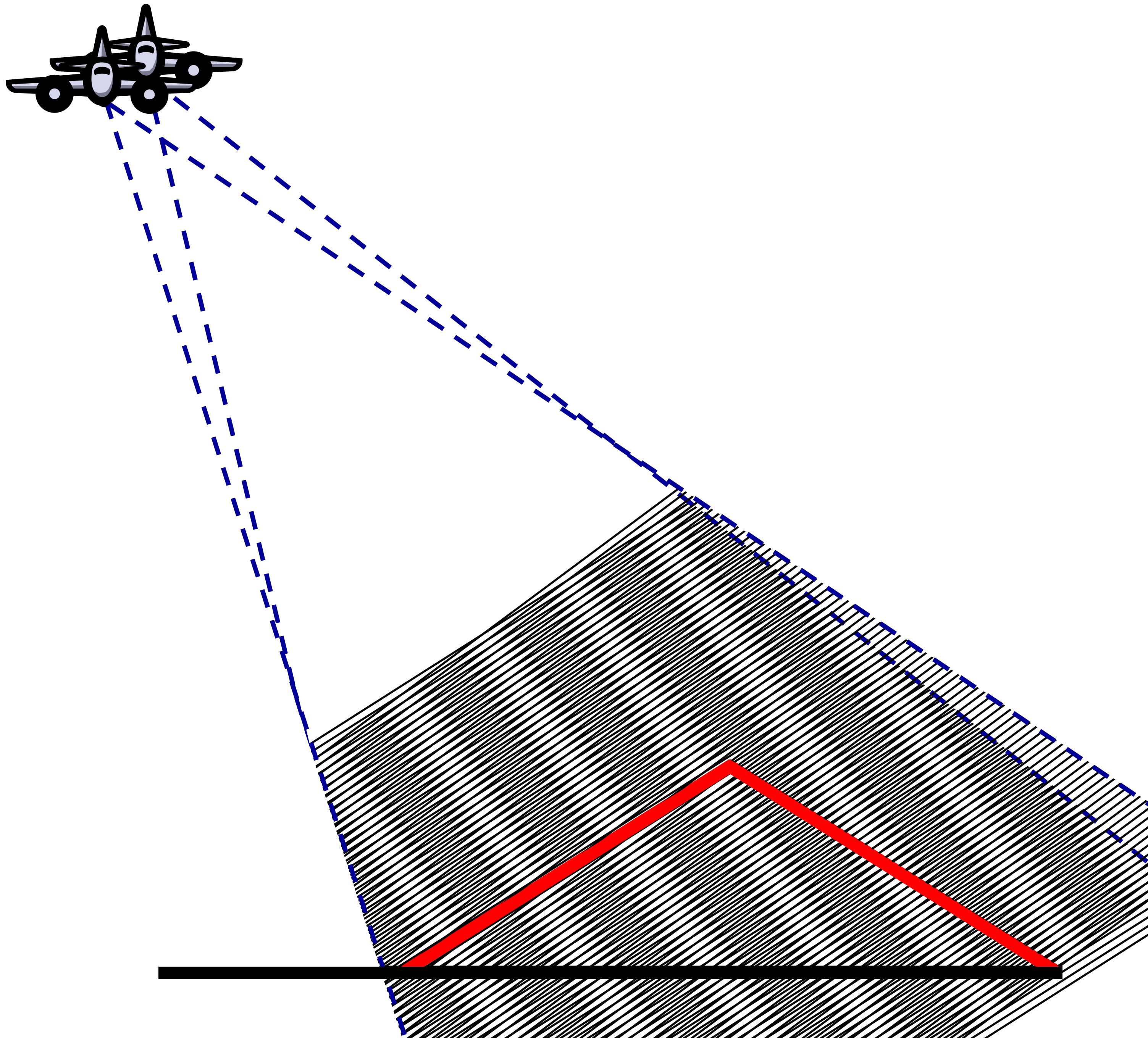


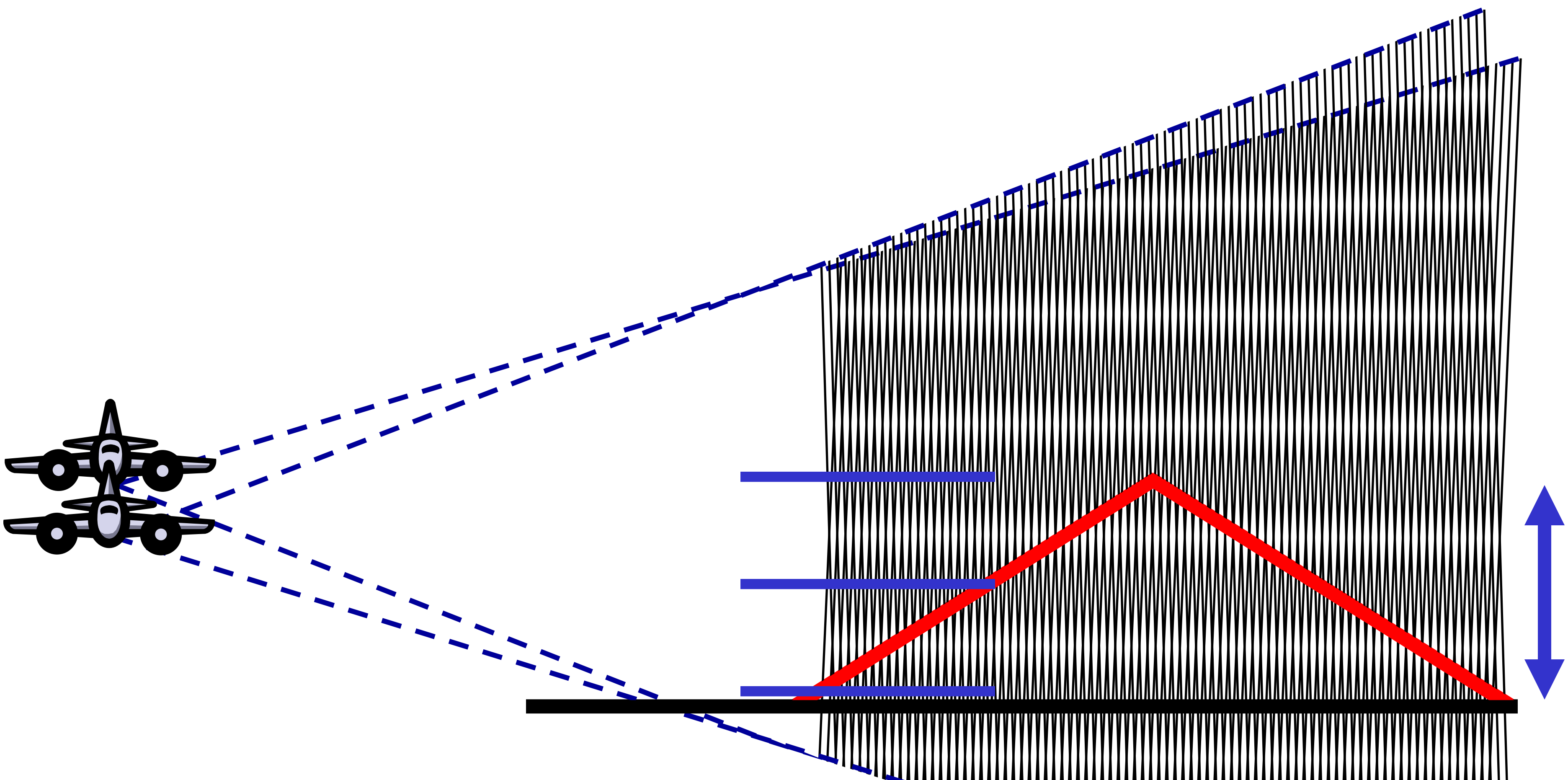




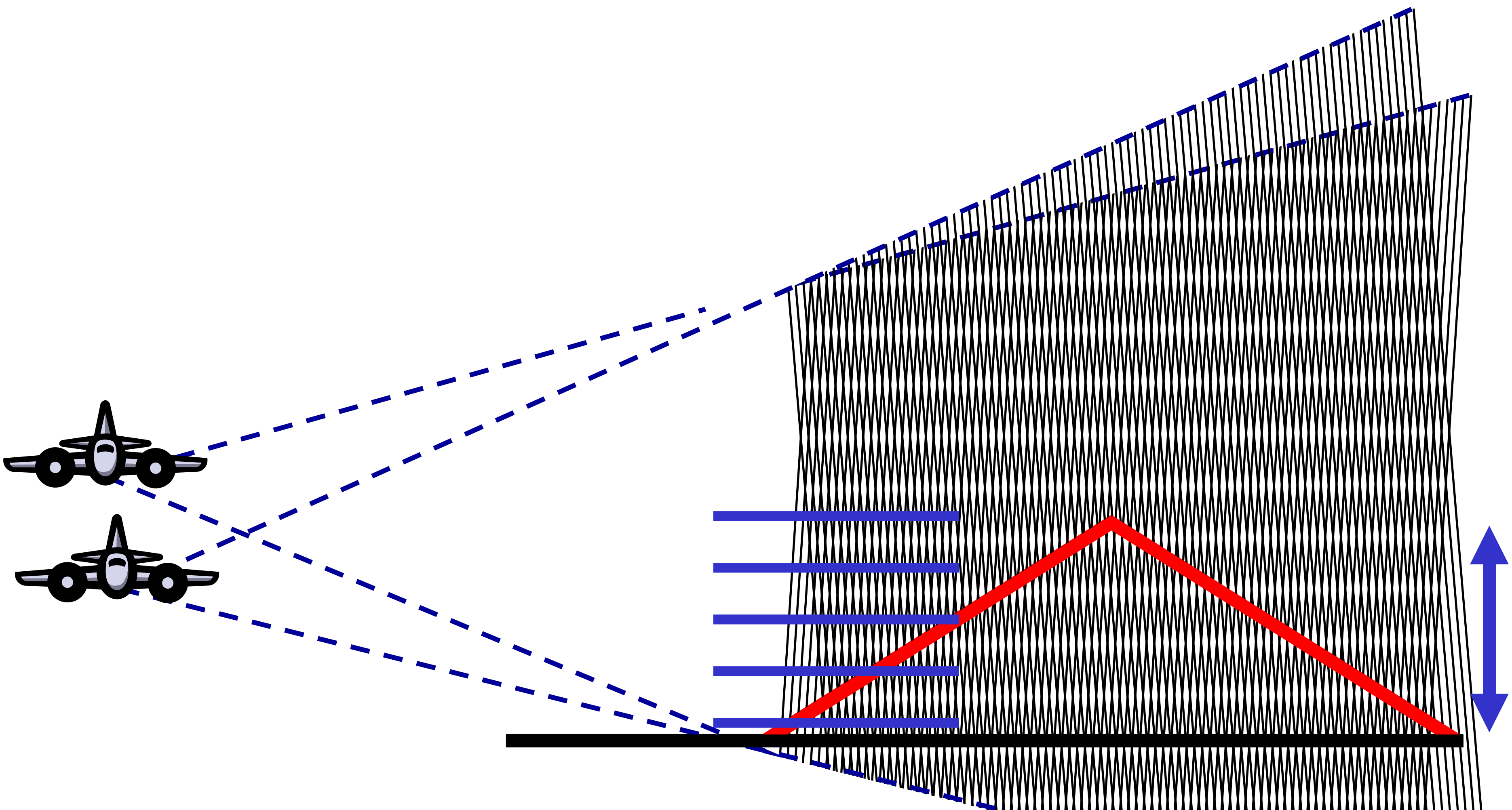


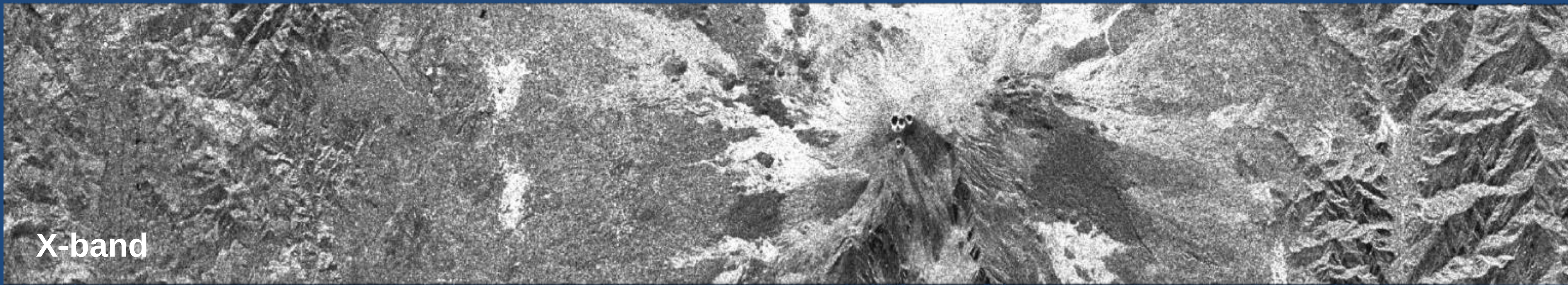






The Phase-to-Height Sensitivity increases with increasing the spatial baseline (i.e. $\Delta\theta$ or $B_{\perp}$);

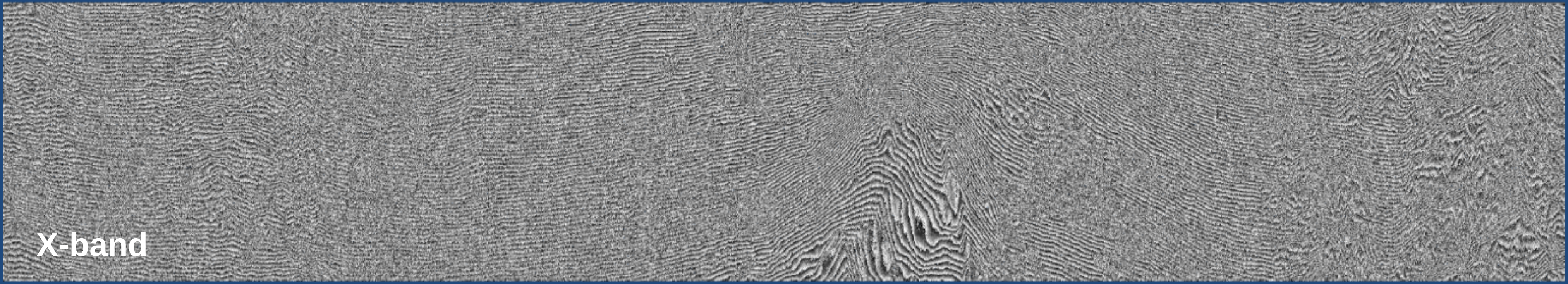




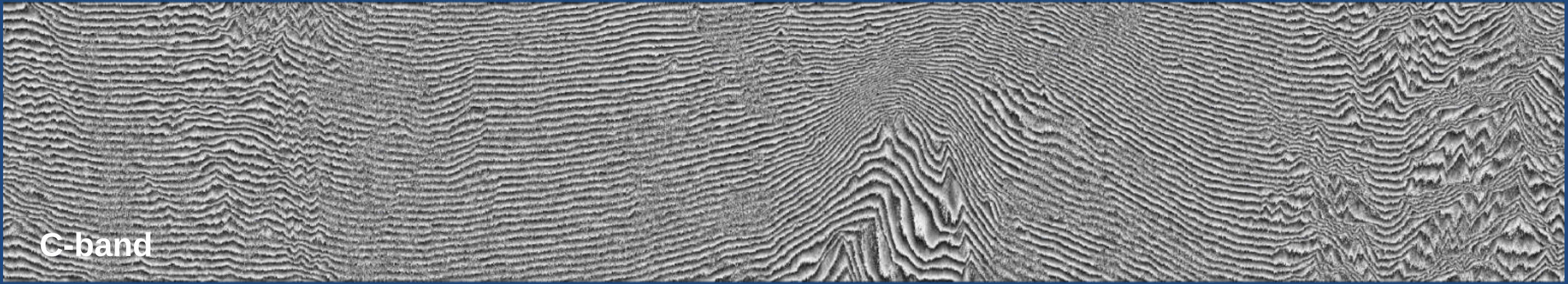
Amplitude Images

24 Hours Temporal Baseline

SIR-C / Test Site: Mt. Etna, Italy



Phase Images



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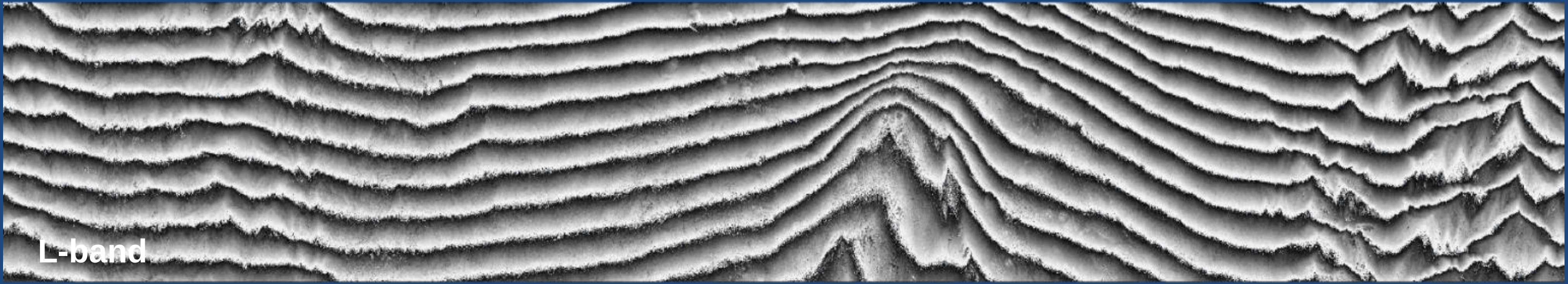
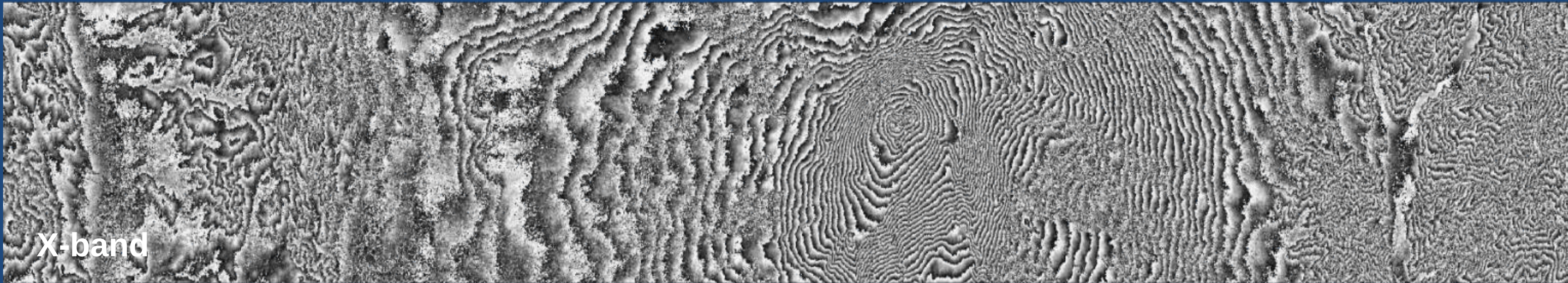
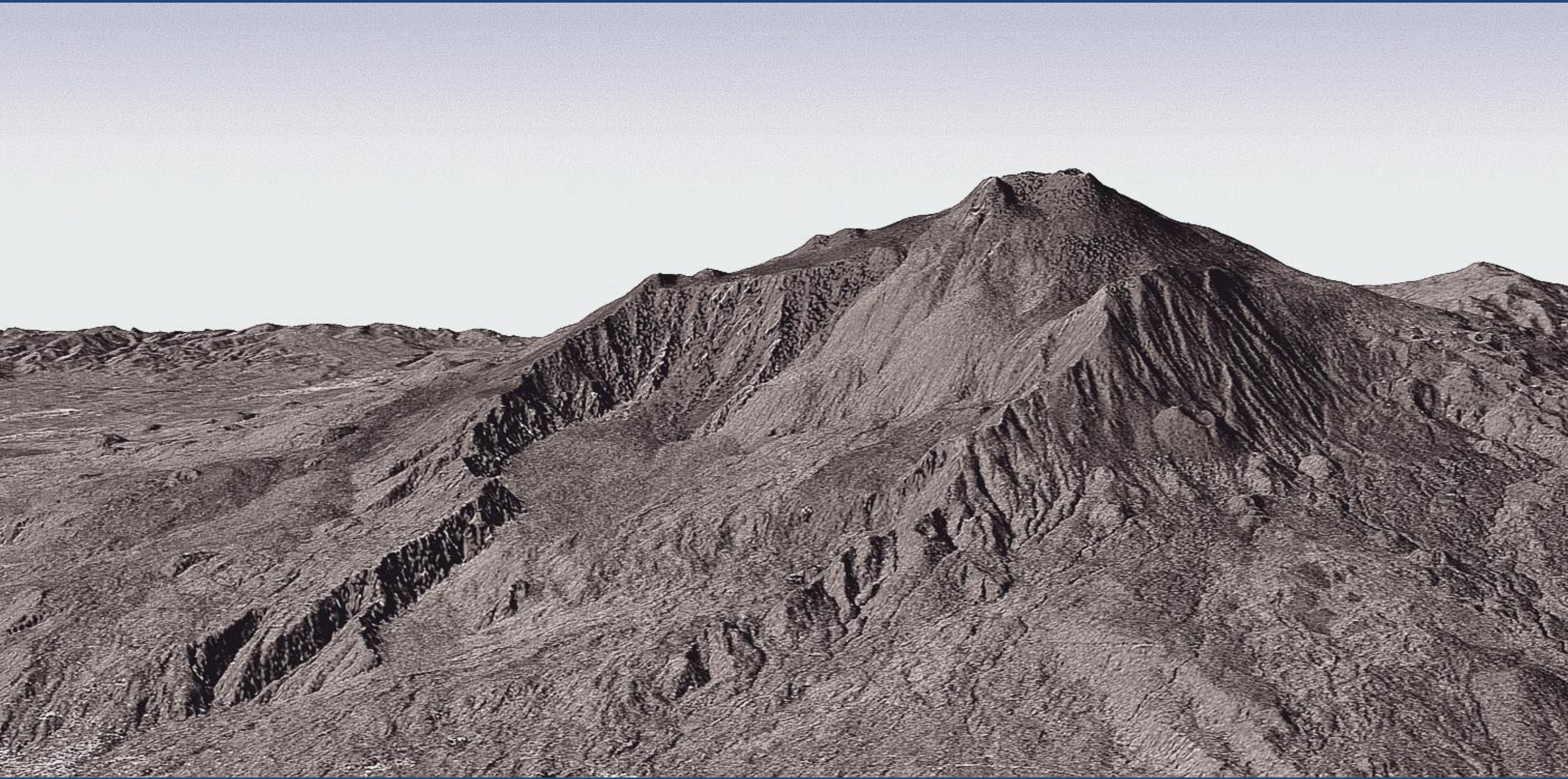




Phase Images

SIR-C / Test Site: Mt. Etna, Italy

Mt. Etna



Interferometric SAR Implementations: Single vs. Repeat-Pass

Single-Pass or **Simultaneous Interferometry**

The two acquisitions are performed simultaneously

(Zero temporal baseline)

Single Platform
with two antennas

Two Platforms
flying in (close) formation

Repeat-Pass Interferometry

The two acquisitions are performed at different times

(Non-Zero temporal baseline)

Single Platform
in repeated orbit(s)
or
Two Platforms
flying on the same orbit

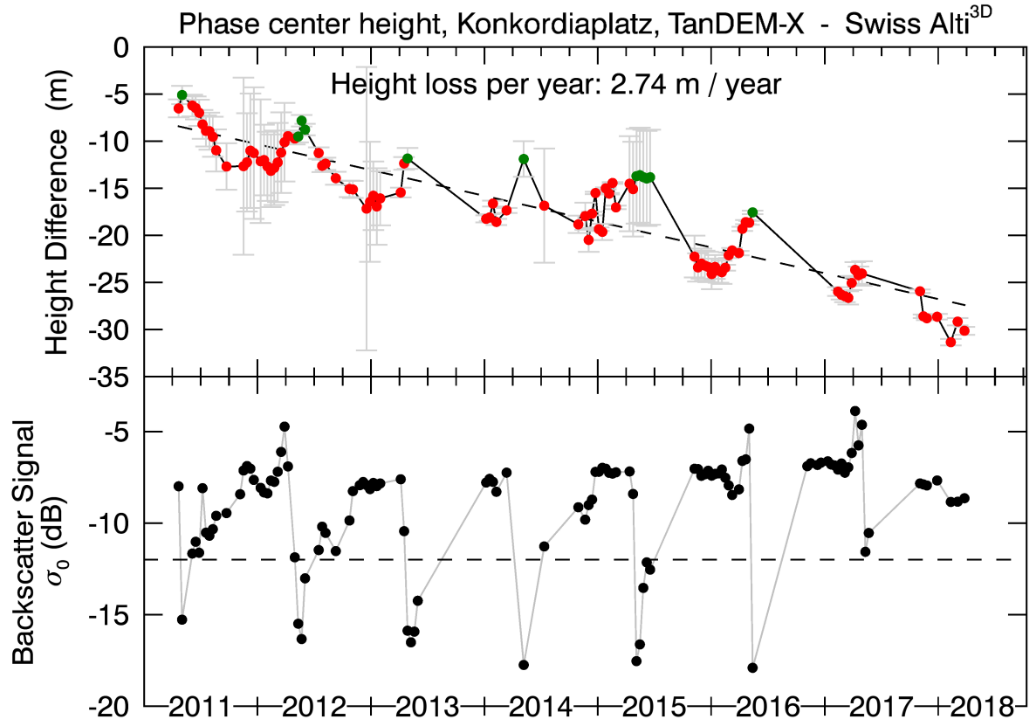
Aletsch Glacier Switzerland, Swiss Topo DHM 25 (1993)

Aletsch Glacier Switzerland, TanDEM-X Digital Elevation Model (2012)

Height loss of Aletschgletscher 2011 - 2018

TanDEM-X vs. SwissAlti3D (2009)

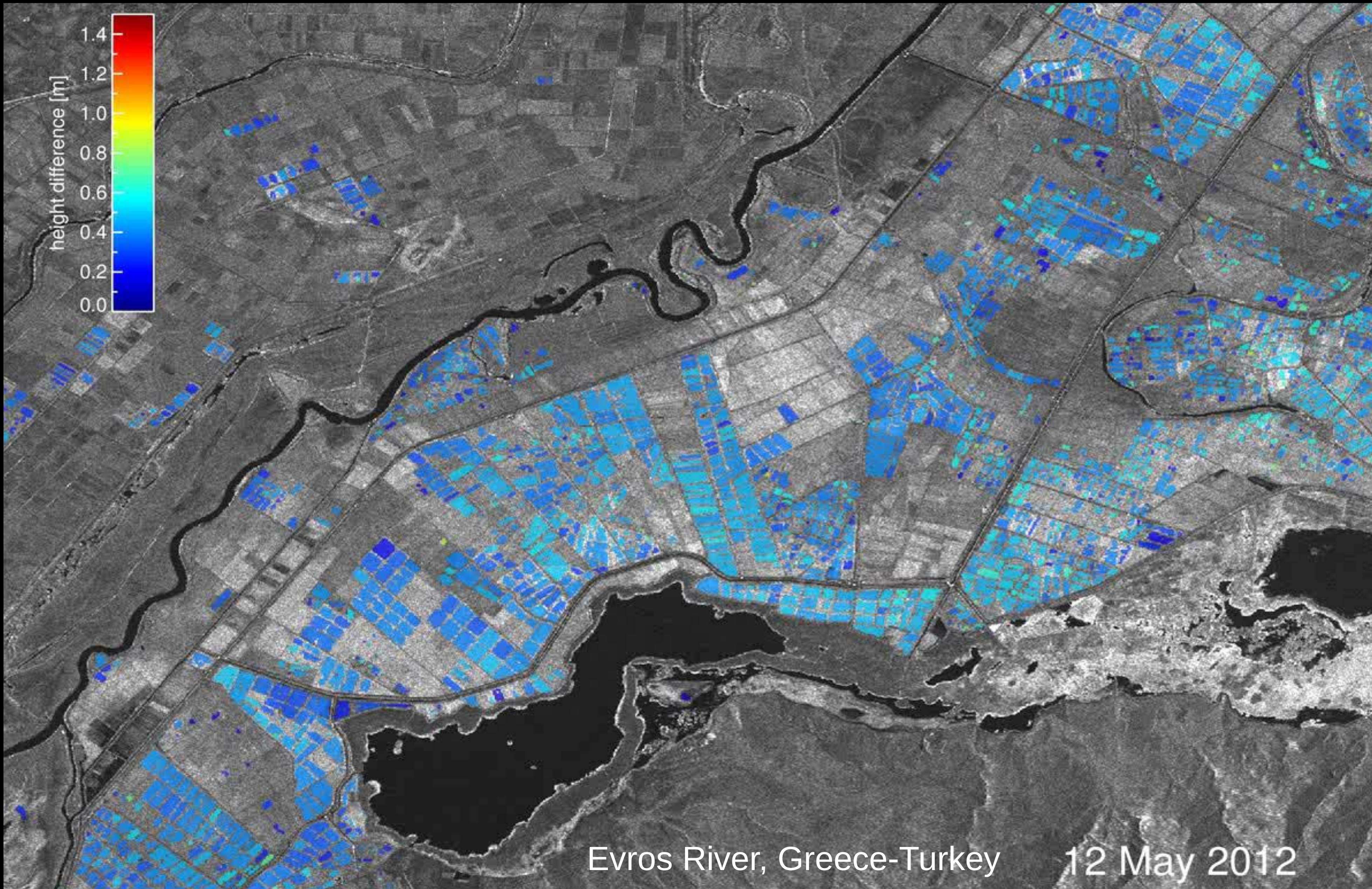
08.11.2015



- **Agreement with results of climate scenarios:**
  DEG2: -2.1 m / year (political aim)
  ENSmed: -3.6 m / year (business as usual)

L. Leinss

Paddy Rice Monitoring by Means of DEM's



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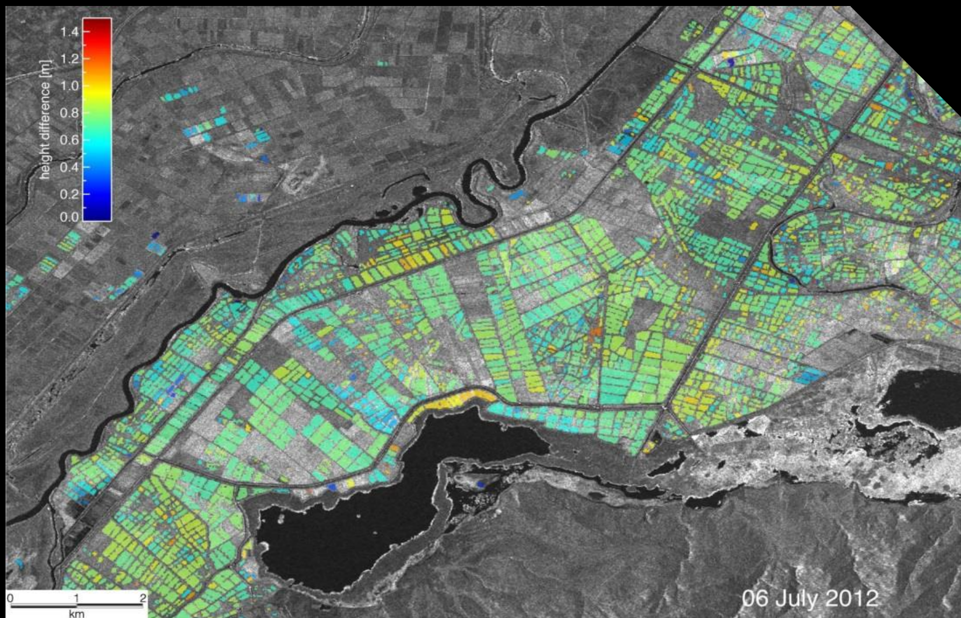
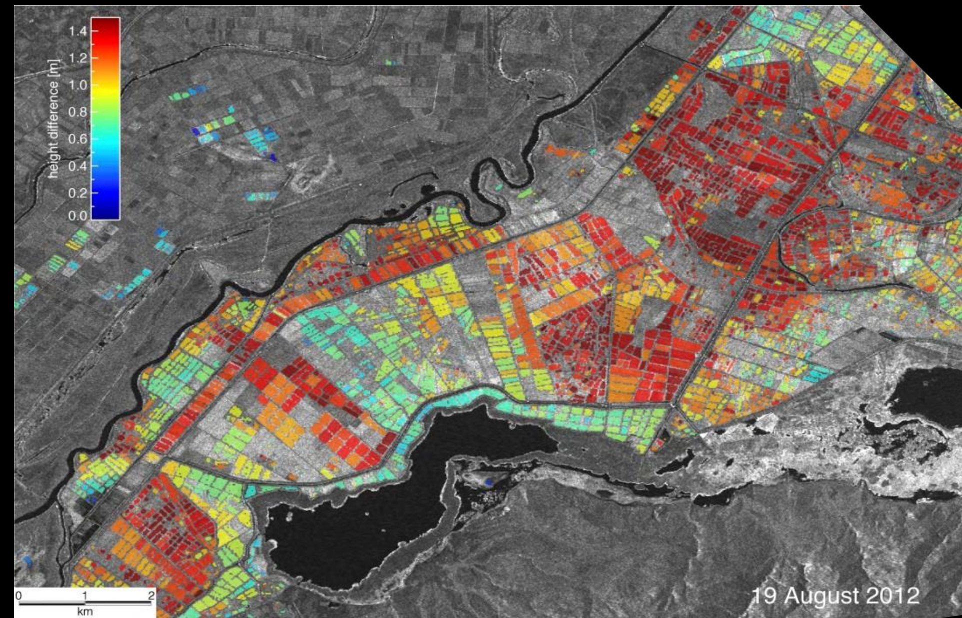
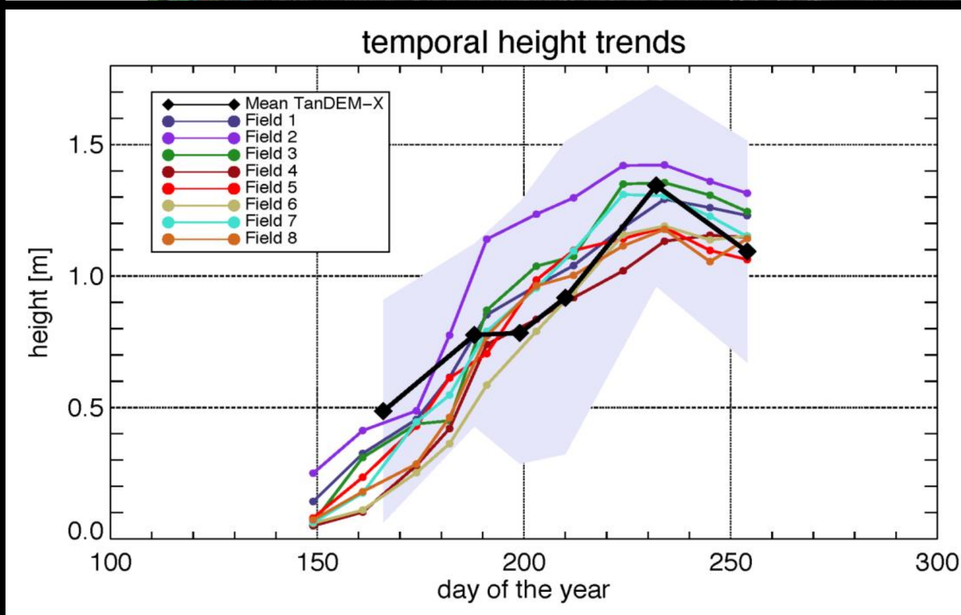
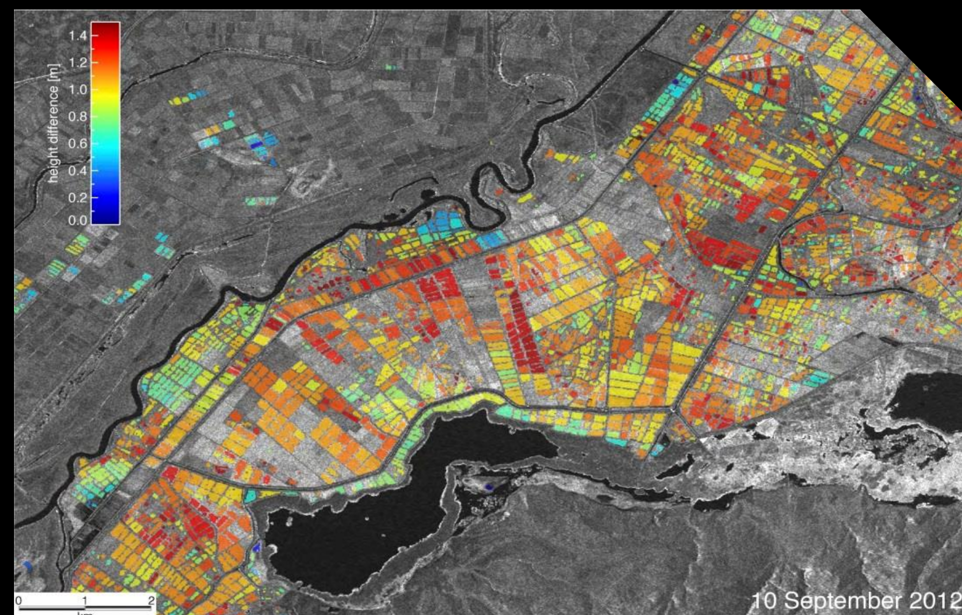








C. Rossi, and E. Erten, "Paddy rice monitoring using TanDEM-X", IEEE Transaction on Geoscience and Remote Sensing, 2015.

Radar Backscattering Image @ X-Band

F-SAR (DLR), Kaufbeuren, X-Band

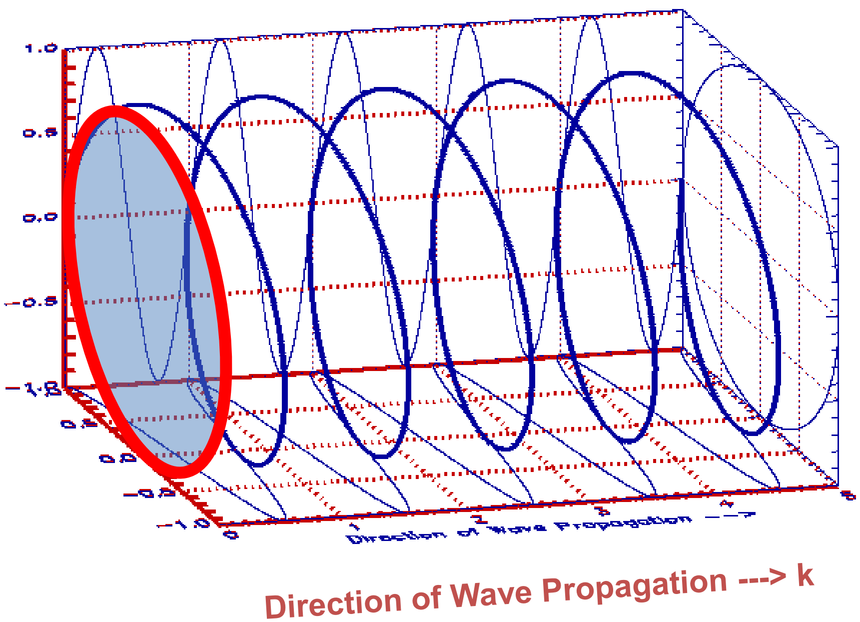
SAR Polarimetry (R:HH+VV,G:2*HV, B:HH-VV)

F-SAR (DLR), Kaufbeuren, X-Band, fully polarimetric

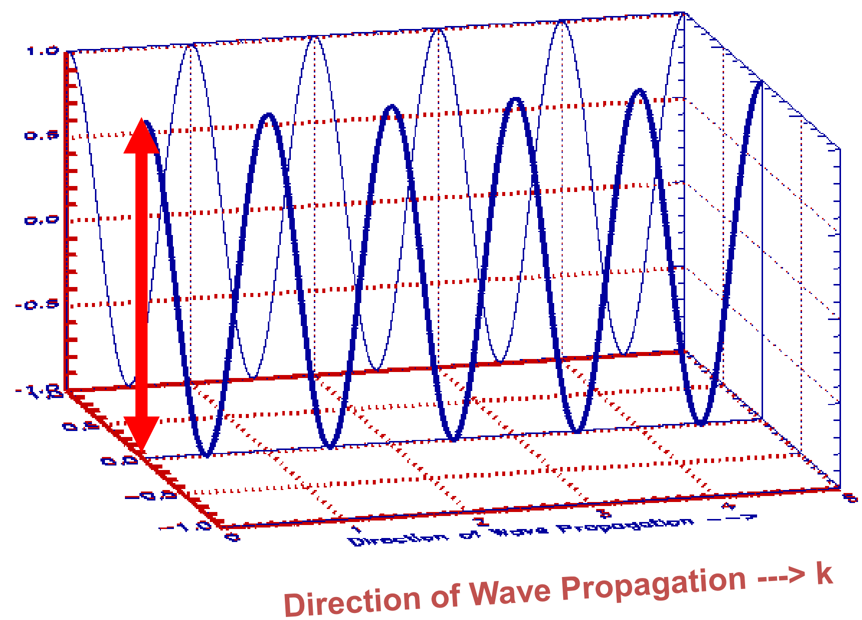
What is polarisation ?

For all vector waves polarisation refers
to the behaviour of the wave field vectors in time observed at a fixed point in space.
(AZZAM & BASHARA)

Elliptical Polarisation



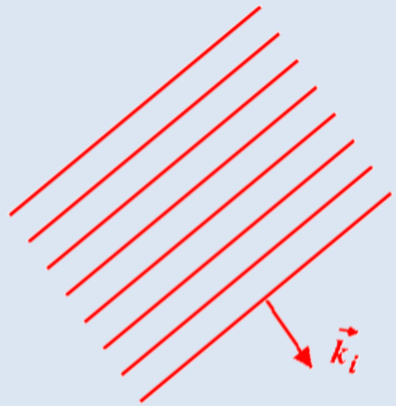
Linear Polarisation



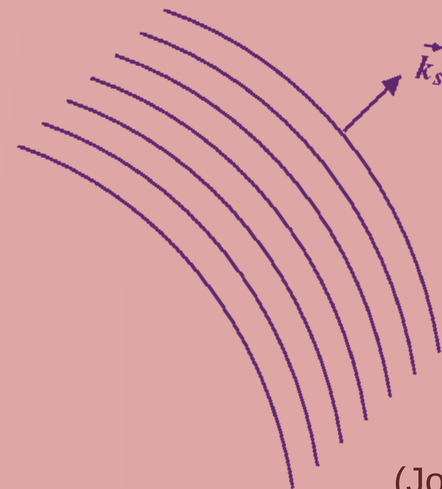
The Polarimetric Scattering Problem

Incident (Plane) Wave

$$\vec{E}^{i}_{hv}(\vec{r}) = \begin{bmatrix} E^{i}_{h}(\vec{r}) \\ E^{i}_{v}(\vec{r}) \end{bmatrix}$$



(Jones Vector Representation)



Scattered Field

In the far zone region

$(\; |\vec{r}| >> \lambda \quad |\vec{r}| >> |\vec{r}'| \;)$

$$\vec{E}^{s}_{hv}(\vec{r}) = \begin{bmatrix} E^{s}_{h}(\vec{r}) \\ E^{s}_{v}(\vec{r}) \end{bmatrix}$$

(Jones Vector Representation)

Scatterer

Transforms the incident

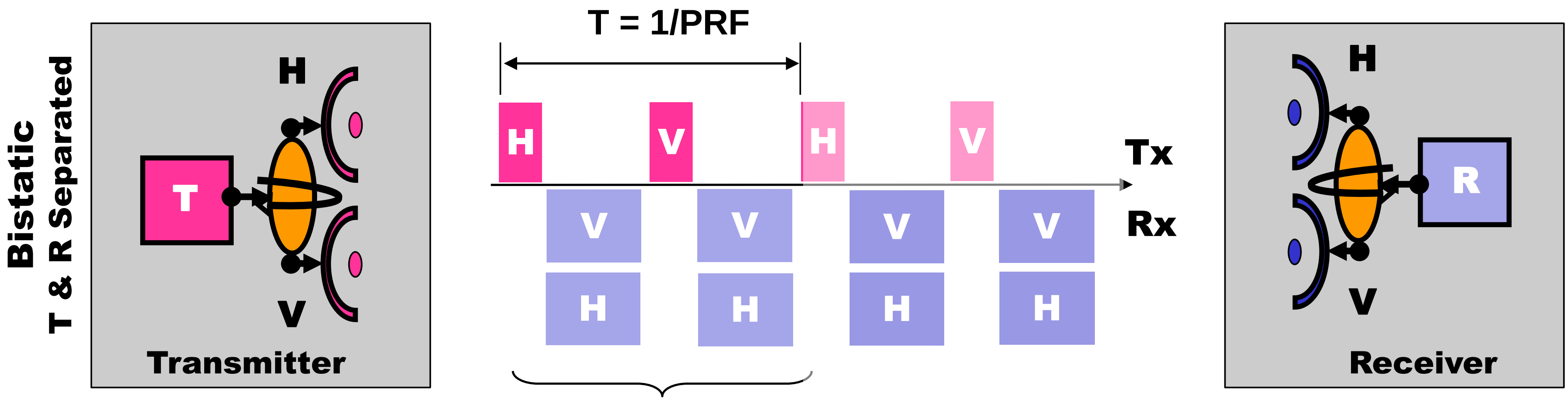
into the scattered wave

2x2 Complex Scattering Matrix

$$\begin{bmatrix} E^{s}_{h}(\vec{r}) \\ E^{s}_{v}(\vec{r}) \end{bmatrix} = \frac{\exp(i\kappa r)}{r} \begin{bmatrix} S_{HH}(\vec{r}) & S_{HV}(\vec{r}) \\ S_{VH}(\vec{r}) & S_{VV}(\vec{r}) \end{bmatrix} \begin{bmatrix} E^{i}_{h}(\vec{r}) \\ E^{i}_{v}(\vec{r}) \end{bmatrix}$$

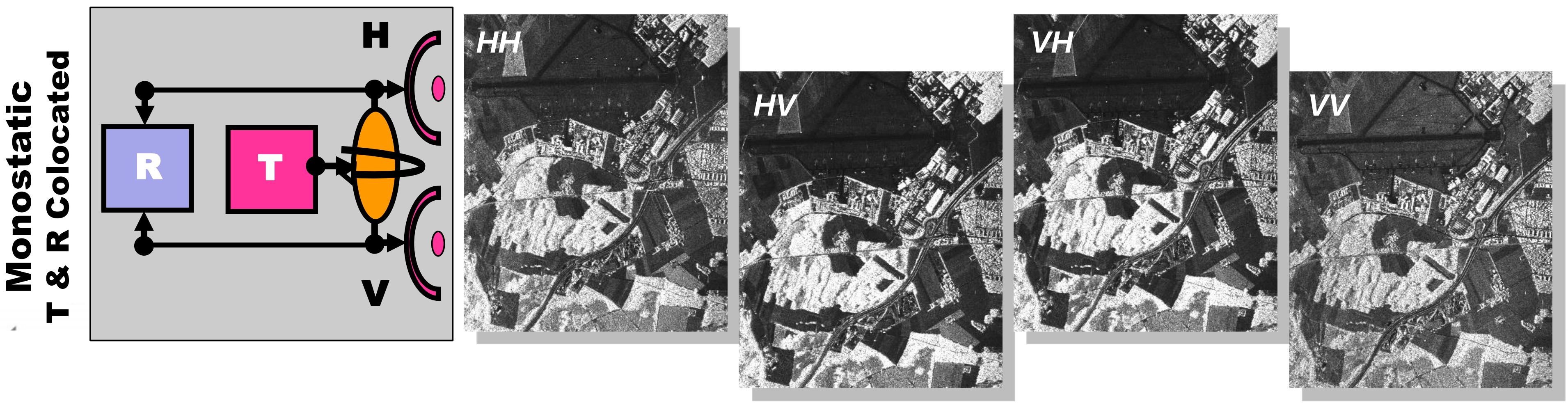
Mapping of the 2-dim incident vector $\vec{E}^{i}_{hv}(\vec{r})$ into the 2-dim scattered vector $\vec{E}^{s}_{hv}(\vec{r})$

Bi- & Mono-Static Measurement of the Scattering Matrix



H: $\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}1\\0\end{bmatrix}$ H, V: $\begin{bmatrix}E_H^R\\E_V^R\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix}=\begin{bmatrix}S_{HH}&0\\S_{VH}&0\end{bmatrix}$

V: $\begin{bmatrix}E_H^T\\E_V^T\end{bmatrix}=\begin{bmatrix}0\\1\end{bmatrix}$ H, V: $\begin{bmatrix}E_H^R\\E_V^R\end{bmatrix}=\begin{bmatrix}......&.......\\......&.......\end{bmatrix}\begin{bmatrix}....\\....\end{bmatrix}=\begin{bmatrix}S_{HH}&S_{HV}\\S_{VH}&S_{VV}\end{bmatrix}\begin{bmatrix}0\\1\end{bmatrix}=\begin{bmatrix}0&S_{HV}\\0&S_{VV}\end{bmatrix}$



Coherent Scattering Matrix

… also known as the Jones Matrix in the bistatic and Sinclair Matrix in the monostatic case

$$\begin{bmatrix} E_H^s \\ E_V^s \end{bmatrix} = \frac{\exp(i\kappa r)}{r} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} E_H^i \\ E_V^i \end{bmatrix}$$

Complex Scattering Amplitudes:

$$S_{IJ} = |S_{IJ}| \exp(i\varphi_{IJ}) = f(\text{ Frequency, Scattering, Geometry })$$

Total Scattered Power: $TP = \text{Span}\ ([S]) = \text{Trace}([S][S]^{+}) = |S_{HH}|^2 + |S_{HV}|^2 + |S_{VH}|^2 + |S_{VV}|^2$

Absolute Phase Factor

Bistatic Scattering Matrix: $S_{HV} \neq S_{VH}$

$$[S] = \frac{\exp(i\kappa r)}{r} \begin{bmatrix} |S_{HH}|\exp(i\varphi_{HH}) & |S_{HV}|\exp(i\varphi_{HV}) \\ |S_{VH}|\exp(i\varphi_{VH}) & |S_{VV}|\exp(i\varphi_{VV}) \end{bmatrix} = \frac{e^{i\kappa r} e^{i\varphi_{VV}}}{r} \begin{bmatrix} |S_{HH}|\exp i(\varphi_{HH} - \varphi_{VV}) & |S_{HV}|\exp i(\varphi_{HV} - \varphi_{VV}) \\ |S_{VH}|\exp i(\varphi_{VH} - \varphi_{VV}) & |S_{VV}| \end{bmatrix}$$

The bistatic scattering matrix contains seven independent parameters: 4 Amplitudes & 3 Phases

Monostatic Scattering Matrix: $S_{HV} = S_{VH} = S_{XX}$

$$[S] = \frac{\exp(i\kappa r)}{r} \begin{bmatrix} |S_{HH}|\exp(i\varphi_{HH}) & |S_{XX}|\exp(i\varphi_{XX}) \\ |S_{XX}|\exp(i\varphi_{XX}) & |S_{VV}|\exp(i\varphi_{VV}) \end{bmatrix} = \frac{e^{i\kappa r} e^{i\varphi_{VV}}}{r} \begin{bmatrix} |S_{HH}|\exp i(\varphi_{HH} - \varphi_{VV}) & |S_{XX}|\exp i(\varphi_{XX} - \varphi_{VV}) \\ |S_{XX}|\exp i(\varphi_{XX} - \varphi_{VV}) & |S_{VV}| \end{bmatrix}$$

The monostatic scattering matrix contains five independent parameters: 3 Amplitudes & 2 Phases

Scattering Vector

Vectorial formulation of the scattering problem in terms of system vectors

Scattering Matrix:
$$[S]=\begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$$

Frobenious Norm of $[S]$:
$$TP = Span([S]) = |S_{HH}|^2 + |S_{HV}|^2 + |S_{VH}|^2 + |S_{VV}|^2$$

Scattering Vector:
$$\vec{k}_4 := V([S]) = \frac{1}{2} Trace([S]\Psi) = [k_1 \quad k_2 \quad k_3 \quad k_4]^T \in C_4$$

$V([.?.])$ ... Matrix Vectorisation Operator

Ψ ... Complete Set of 2x2 Basis Matrices

Frobenious Norm of $\vec{k}_4$:
$$\|\vec{k}_4\|^2 = \vec{k}_4^+ \cdot \vec{k}_4 = Span([S]) = |S_{HH}|^2 + |S_{HV}|^2 + |S_{VH}|^2 + |S_{VV}|^2$$

Lexicographic & Pauli Scattering Vectors

Scattering Vector: $\vec{k}_4 := V([S]) = \frac{1}{2} Trace([S]\Psi)$

Ψ ... any complete set of four matrices leaving the norm of $\vec{k}_4$ invariant

- Lexicographic Matrix Set: $\Psi_L = \left\{ 2\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad 2\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad 2\begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}, \quad 2\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \right\}$

Lexicographic Scattering Vector:

$$\vec{k}_4 = [S_{HH} \quad S_{HV} \quad S_{VH} \quad S_{VV}]^T$$

Advantage: Directly related to the system measurable

- Pauli Matrices Set: $\Psi_P = \left\{ \sqrt{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \sqrt{2}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad \sqrt{2}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \sqrt{2}\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \right\}$

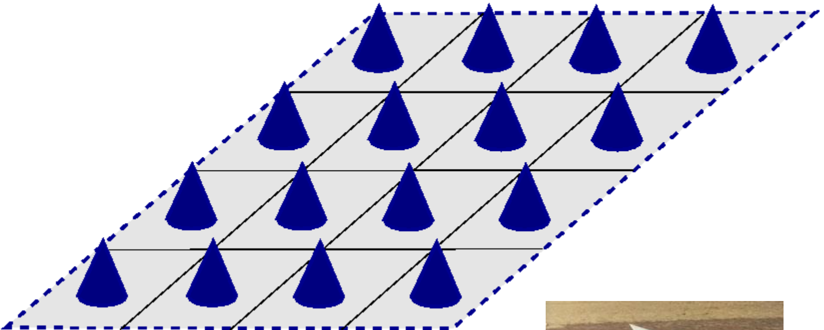
Pauli Scattering Vector:

$$\vec{k}_4 = \frac{1}{\sqrt{2}}[S_{HH} + S_{VV} \quad S_{HH} - S_{VV} \quad S_{HV} + S_{VH} \quad i(S_{HV} - S_{VH})]^T$$

Advantage: Closer related to physical properties of the scatterer

Partial Scatterers

Deterministic Scatterers



Point Scatterers

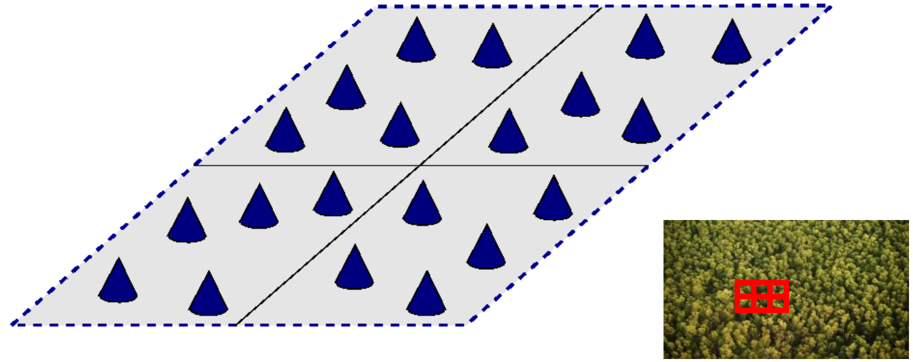
- Change the polarisation state of the wave
- Do not change the degree of polarisation

Monochromatic Incident Wave

Monochromatic Scattered Wave

Completely described by [S]

Partial Scatterers



Scatterers with Space or Time Variability

- Change the polarisation state of the wave

and also change the degree of polarisation

Depolarisation described by second order statistics

Cannot be described by a single [S]

Covariance & Coherency Matrices in Backscattering

Lexicographic Scattering Vector: →

$$\vec{k}_{3L} = [S_{HH} \quad \sqrt{2}S_{XX} \quad S_{VV}]^T$$

Covariance Matrix [C]:

$$[C_3] := <\vec{k}_{3L} \cdot \vec{k}_{3L}^{+}>$$

$$[C_3] := \begin{bmatrix} <|S_{HH}|^2> & \sqrt{2}<S_{HH}S_{HV}^*> & <S_{HH}S_{VV}^*> \\ \sqrt{2}<S_{HV}S_{HH}^*> & 2<|S_{HV}|^2> & \sqrt{2}<S_{HV}S_{VV}^*> \\ <S_{VV}S_{HH}^*> & \sqrt{2}<S_{VV}S_{HV}^*> & <|S_{VV}|^2> \end{bmatrix}$$

Pauli Scattering Vector: →

$$\vec{k}_{3P} = \frac{1}{\sqrt{2}}[S_{HH}+S_{VV} \quad S_{HH}-S_{VV} \quad 2S_{XX}]^T$$

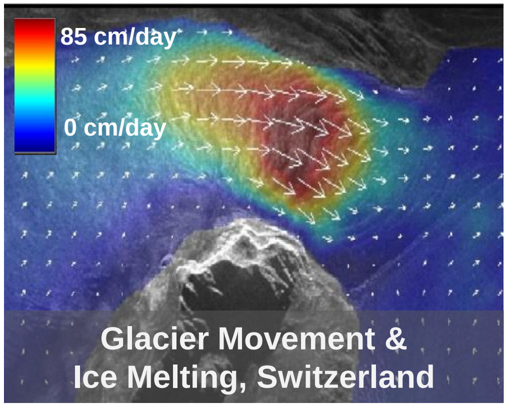
Coherency Matrix [T]:

$$[T_3] := <\vec{k}_{3P} \cdot \vec{k}_{3P}^{+}>$$

$$[T_3] := \begin{bmatrix} <|(S_{HH}+S_{VV})|^2> & <(S_{HH}+S_{VV})(S_{HH}-S_{VV})^*> & 2<(S_{HH}+S_{VV})S_{HV}^*> \\ <(S_{HH}-S_{VV})(S_{HH}+S_{VV})^*> & <|(S_{HH}-S_{VV})|^2> & 2<(S_{HH}-S_{VV})S_{HV}^*> \\ 2<S_{HV}(S_{HH}+S_{VV})^*> & 2<S_{HV}(S_{HH}-S_{VV})^*> & 4<|S_{HV}|^2> \end{bmatrix}$$

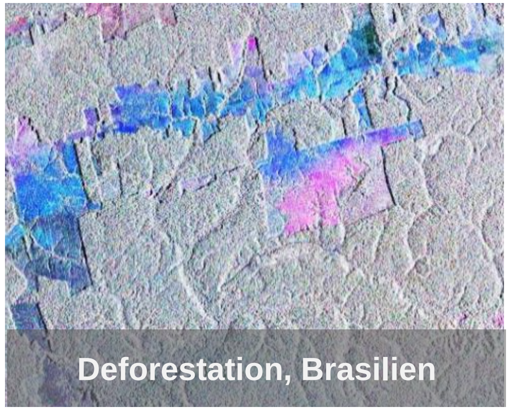
$[C_3]$ **and** $[T_3]$ **are by definition 3x3 hermitian positive semi-definite matrices & contain in general 9 independent parameters**

SAR Remote Sensing and Global Societal Challenges

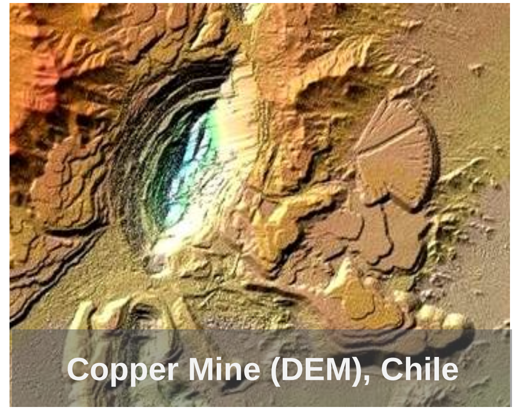


Glacier Movement & Ice Melting, Switzerland

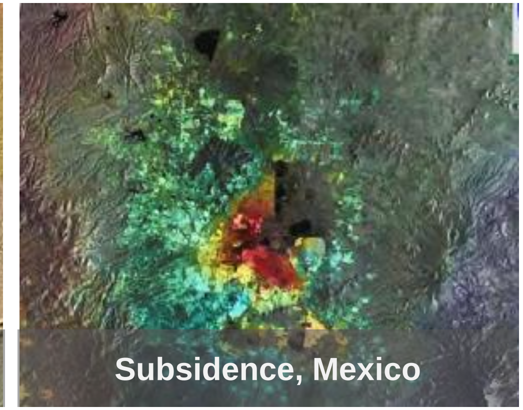
Climate Change


Deforestation, Brasilien

Environment


Copper Mine (DEM), Chile

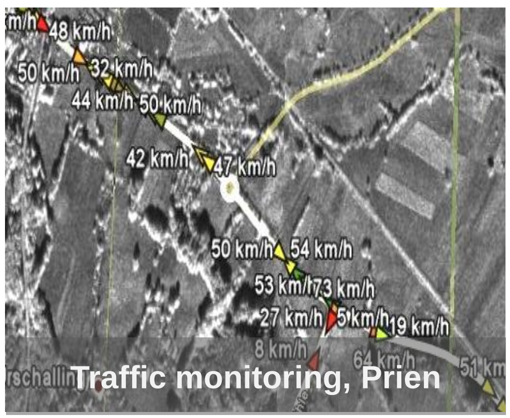
Resources


Subsidence, Mexico

Sustainable Development

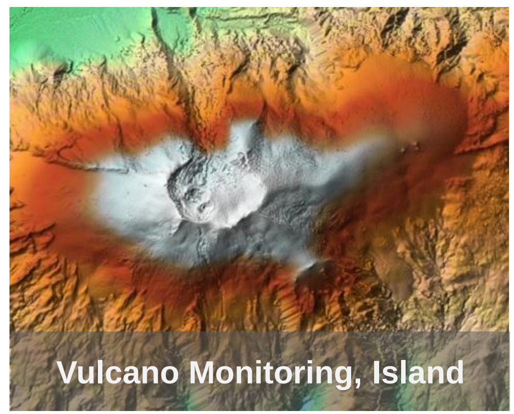

Urban Planing, Istanbul

Megacities



Traffic monitoring, Prien

Mobility


Vulcano Monitoring, Island

Hazards

Flooding, Deggendorf, Germany

Disaster