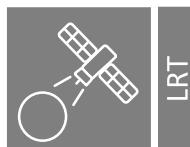


Machine Learning for SAR Image analysis

From zero to hero

Dr. Francescopaolo Sica

Deputy Head - Earth Observation Lab
Faculty of Aerospace Engineering
University of the Bundeswehr Munich



Universität der Bundeswehr München
Professur für
Erdbeobachtung

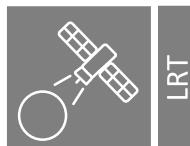
der Bundeswehr
Universität  **München**

Machine Learning for SAR Image analysis

From zero to hero

Dr. Francescopaolo Sica

Deputy Head - Earth Observation Lab
Faculty of Aerospace Engineering
University of the Bundeswehr Munich

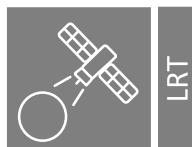


Universität der Bundeswehr München
Professur für
Erdbeobachtung

der Bundeswehr
Universität  **München**

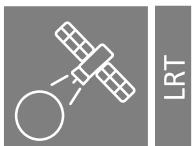
Outline

- Intro: *From zero to hero*
- SAR basics, missions and the Sentinel-1
- Machine Learning for SAR image analysis
 - Choice of the data and procurement
 - SAR processing
 - Pre-processing for ML
- Takeaways

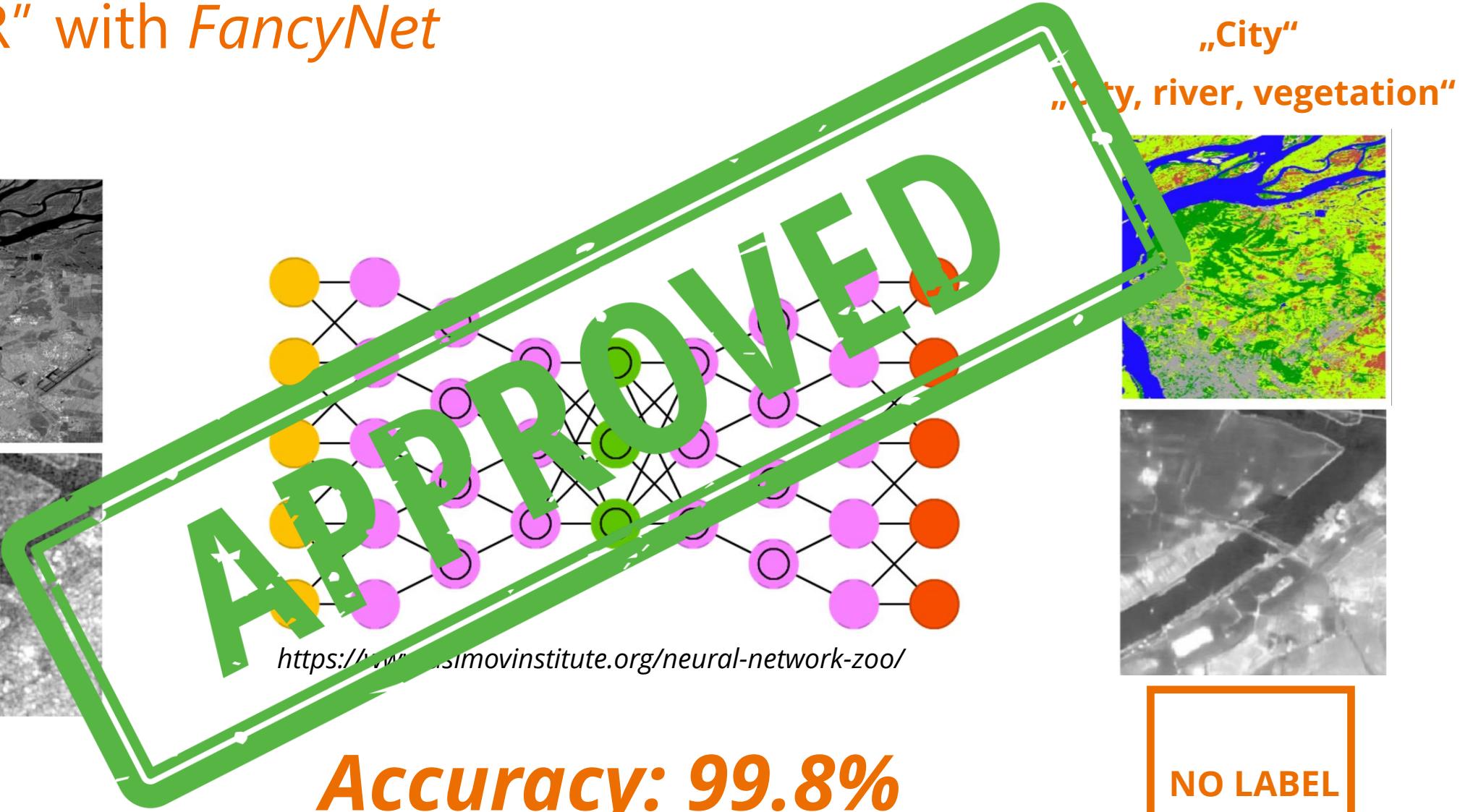
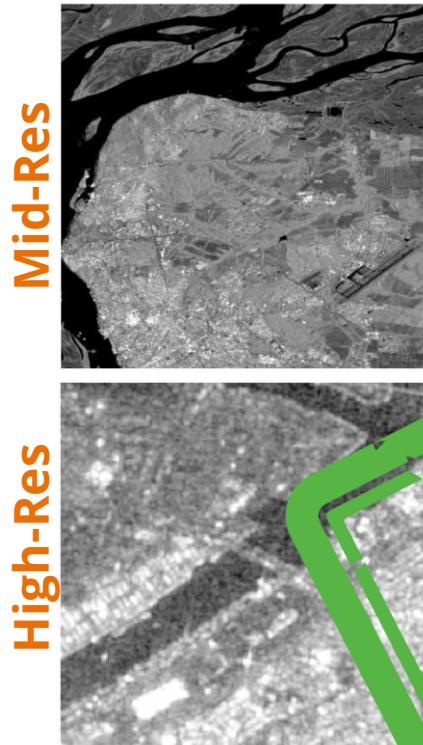


Tools

- Interactive lecture – Hands on approach
- Materials:
 - Slides
 - Online data access
 - Free and open software (SNAP)
 - Google Earth
 - Jupyter notebook
- Questions: anytime during the lecture



“ML4SAR” with *FancyNet*



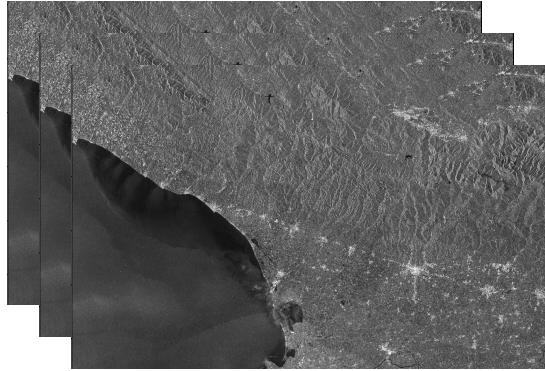
Accuracy: 99.8%

NO LABEL

So you want to apply ML to SAR data - brainstorming

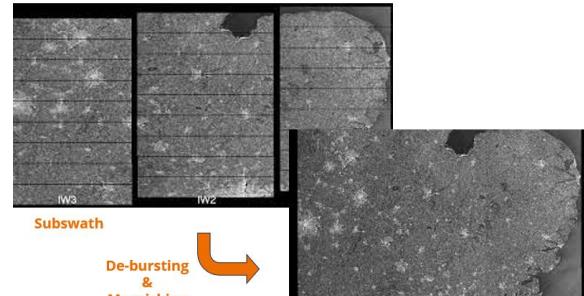
- Who among you has experience with SAR?
- Where should we start?
- What can go wrong?
- What went wrong for you in the past?
- What are your main "open points"?

In one slide



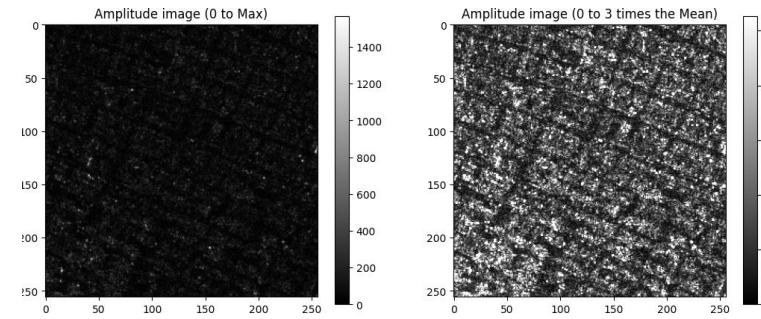
Data download

*Data type
Sensor
Download*



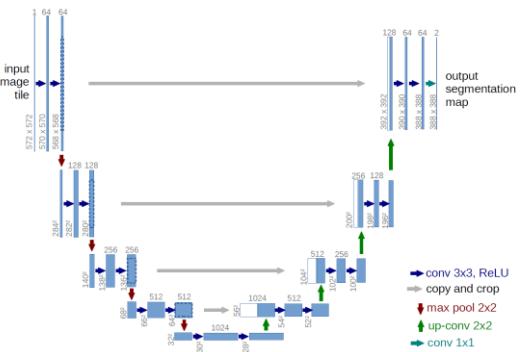
SAR processing

*Reading the data
Input variables*



Preprocessing for ML

*Dataset generation
Data normalization*

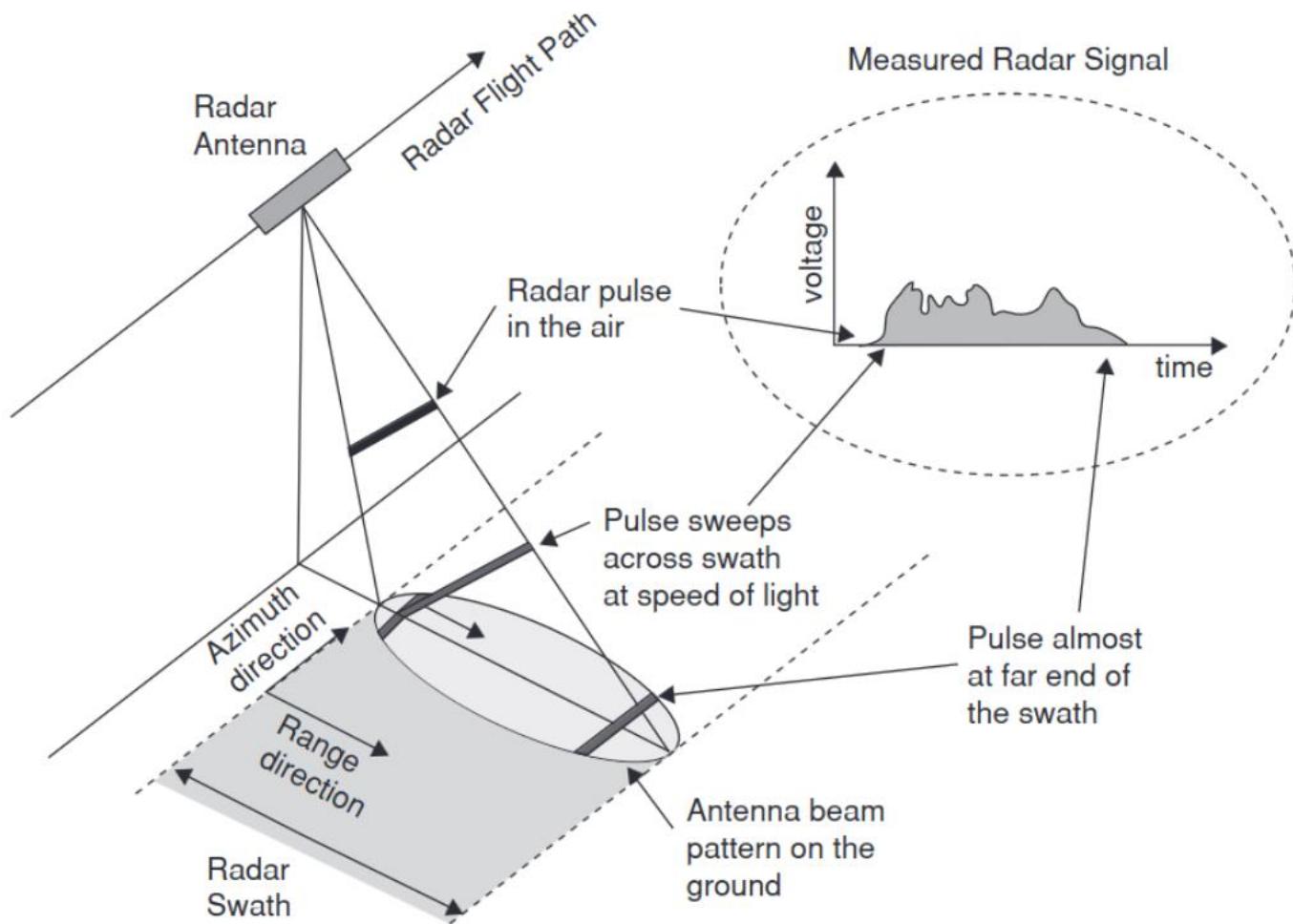


ML Training

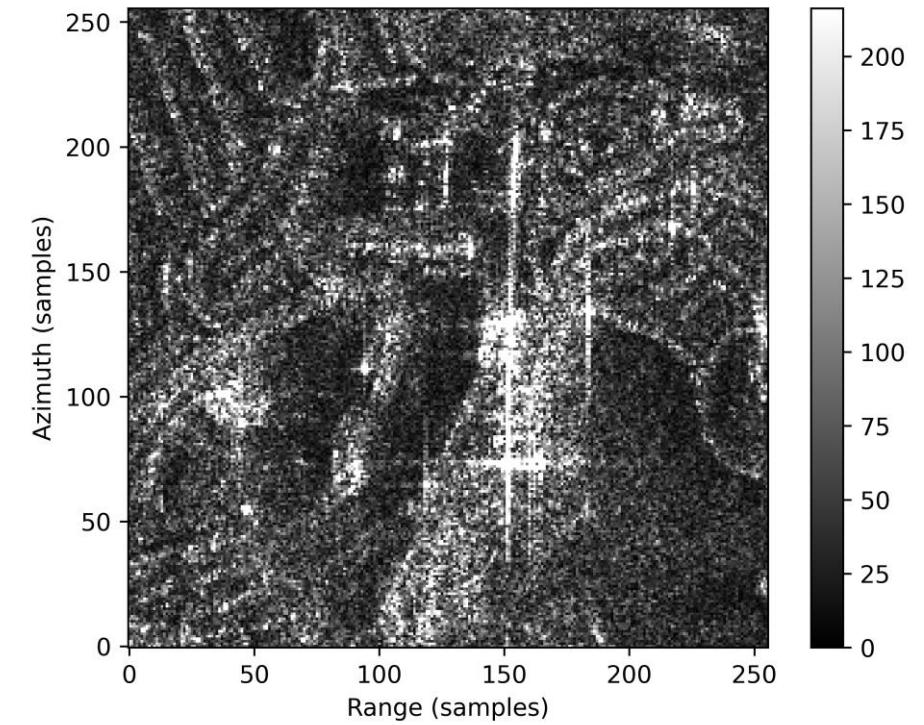
*Dealing with biases
Dealing with data independence*

- Intro: *From zero to hero*
- **SAR basics, missions and the Sentinel-1**
- Machine Learning for SAR image analysis
 - Choice of the data and procurement
 - SAR processing
 - Pre-processing for ML
- Takeaways

SAR basics



Complex valued image



Van Zyl & Kim (2011) Synthetic Aperture Radar Polarimetry. John Wiley & Sons, Inc

der Bundeswehr

SAR missions

Existing

TanDEM-X



COSMO-SkyMed



ALOS-2

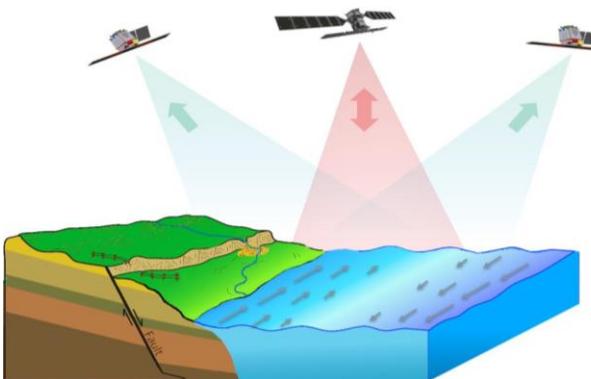


Sentinel-1



Upcoming

Harmony



ROSE-L



NISAR



BIOMASS



Artist's concept - Credits: DLR, ESA, NASA-JPL, JAXA

der Bundeswehr

Sentinel-1

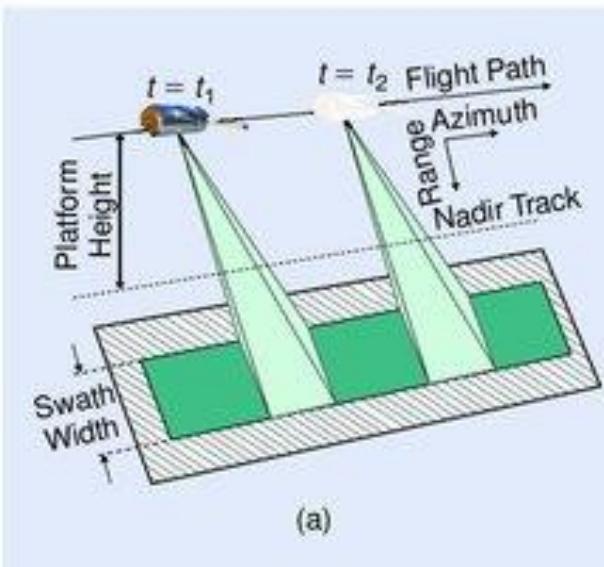


Some info:

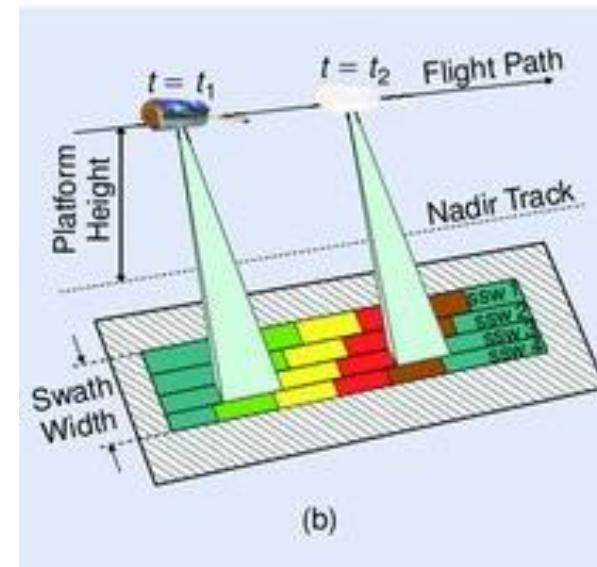
- C-Band SAR Instrument
- Different acquisition modes
- Interferometry
- VV, VH polarizations
- Constellation of 2 satellites
- Continuity assured through multiple satellites: S1-A, -B, -C, -D
- Revisit time (IW mode): 12 days (6 days)

Acquisition modes

Stripmap



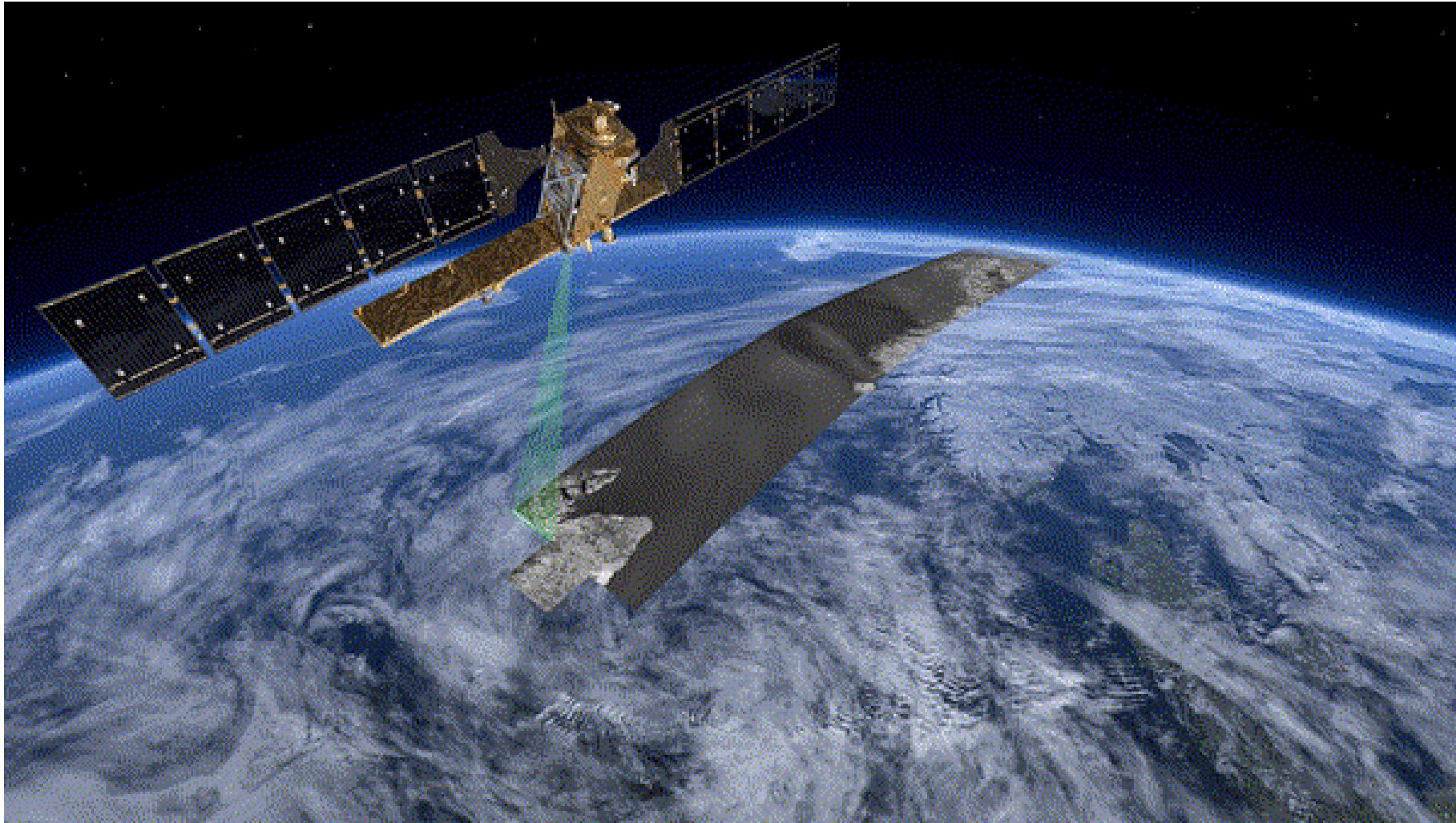
SCANSAR, TOPSAR



- Mid to high resolution
- Low coverage
- Today: X-band systems
- Science + Surveillance
- TerraSAR-X, ICEYE, Capella
- Commercial + free options for research

- Low to mid resolution
- High coverage
- Today: C- and L-band systems
- Science
- Sentinel-1, ROSE-L, BIOMASS
- Open data

Sentinel-1

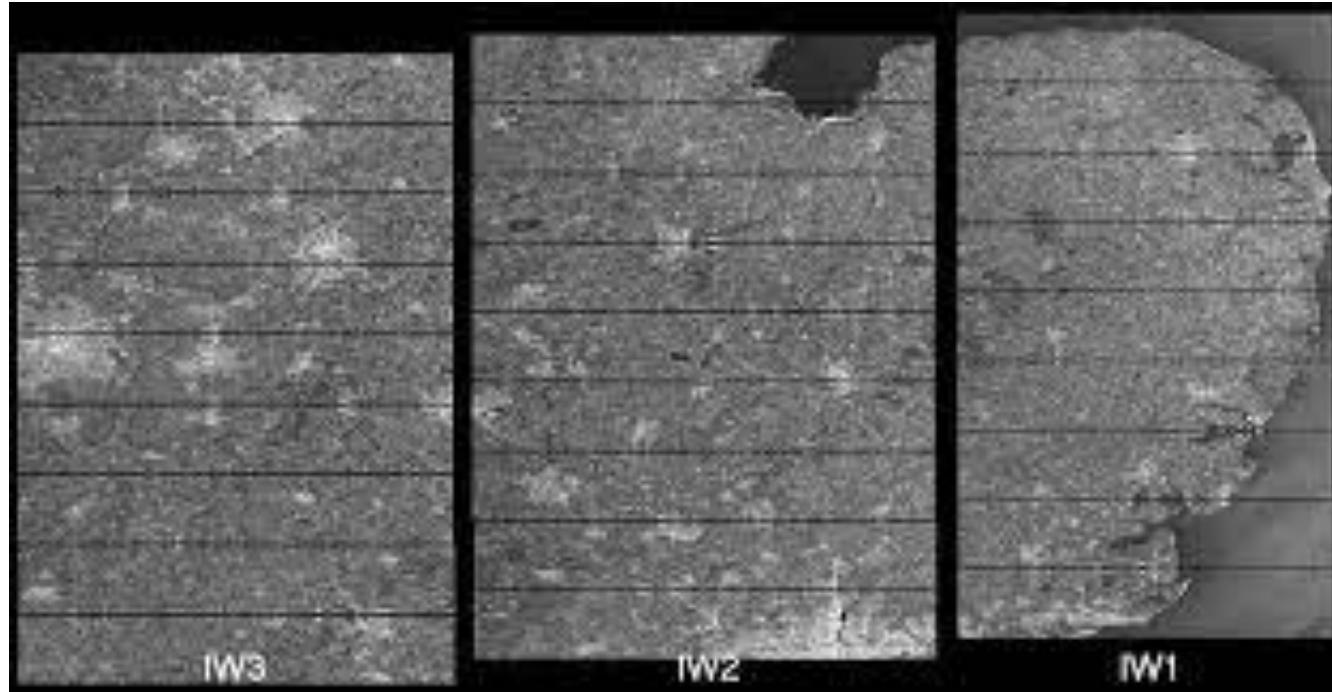


Artist's concept - Credits: ESA

der Bundeswehr

Sentinel-1 – TOPS data

Burst ↑



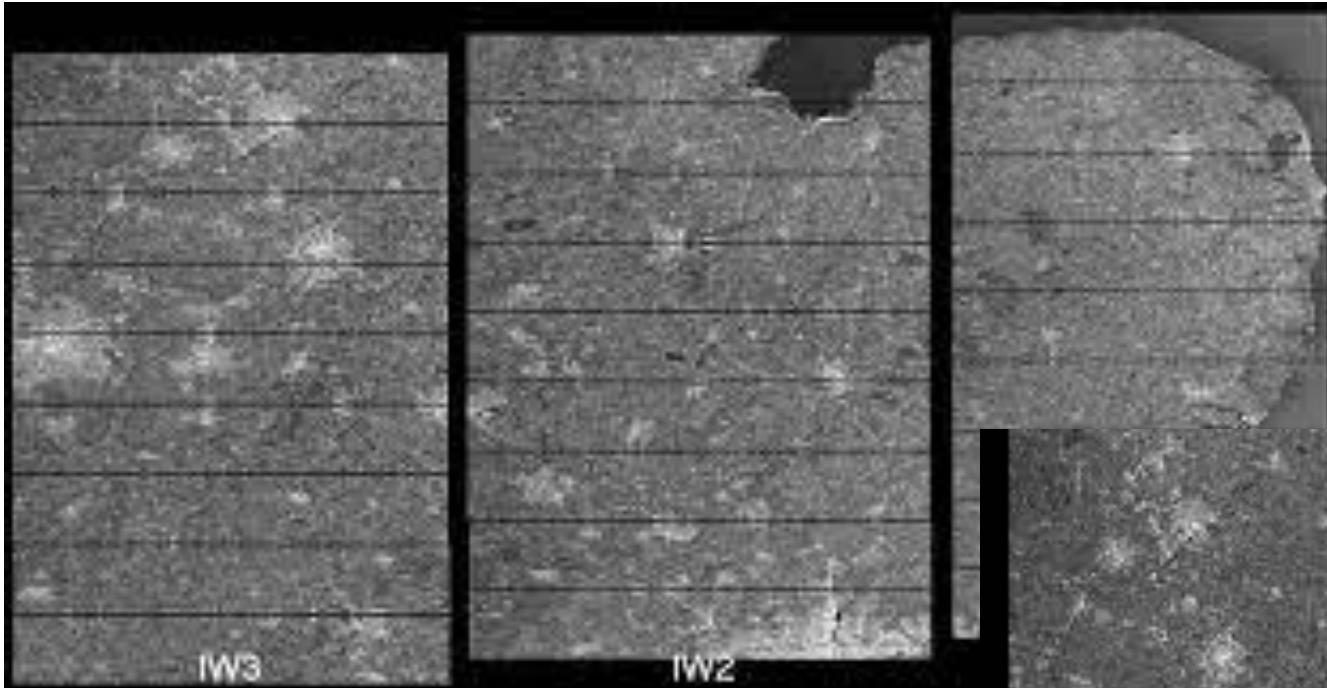
Flight
direction

Subswath

der Bundeswehr

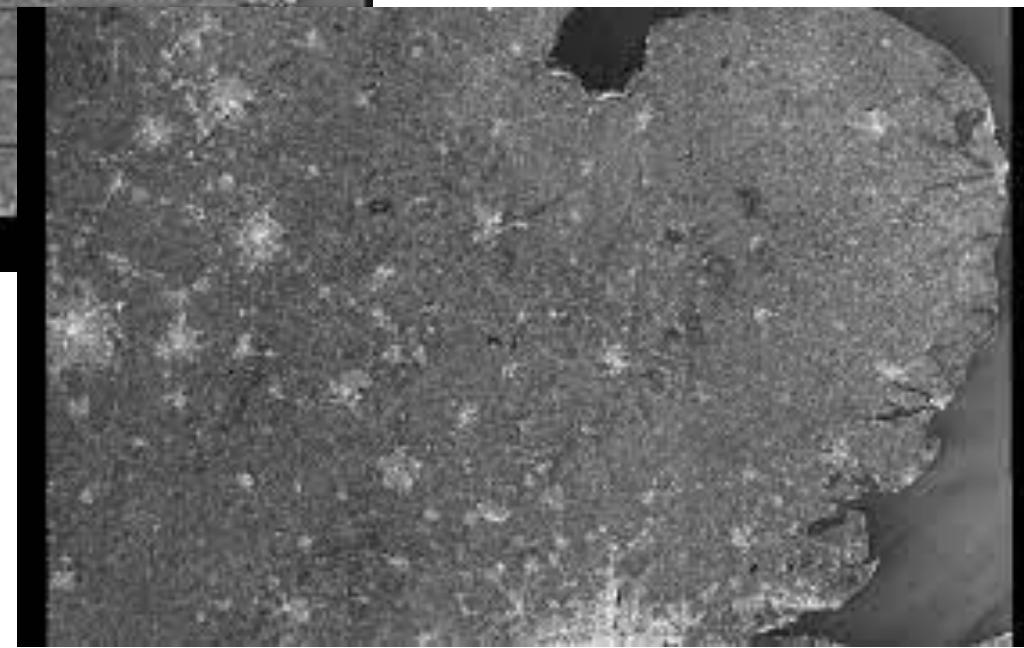
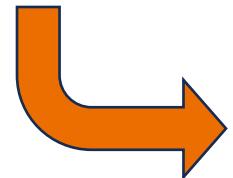
Sentinel-1 – TOPS data

Burst ↑



Subswath

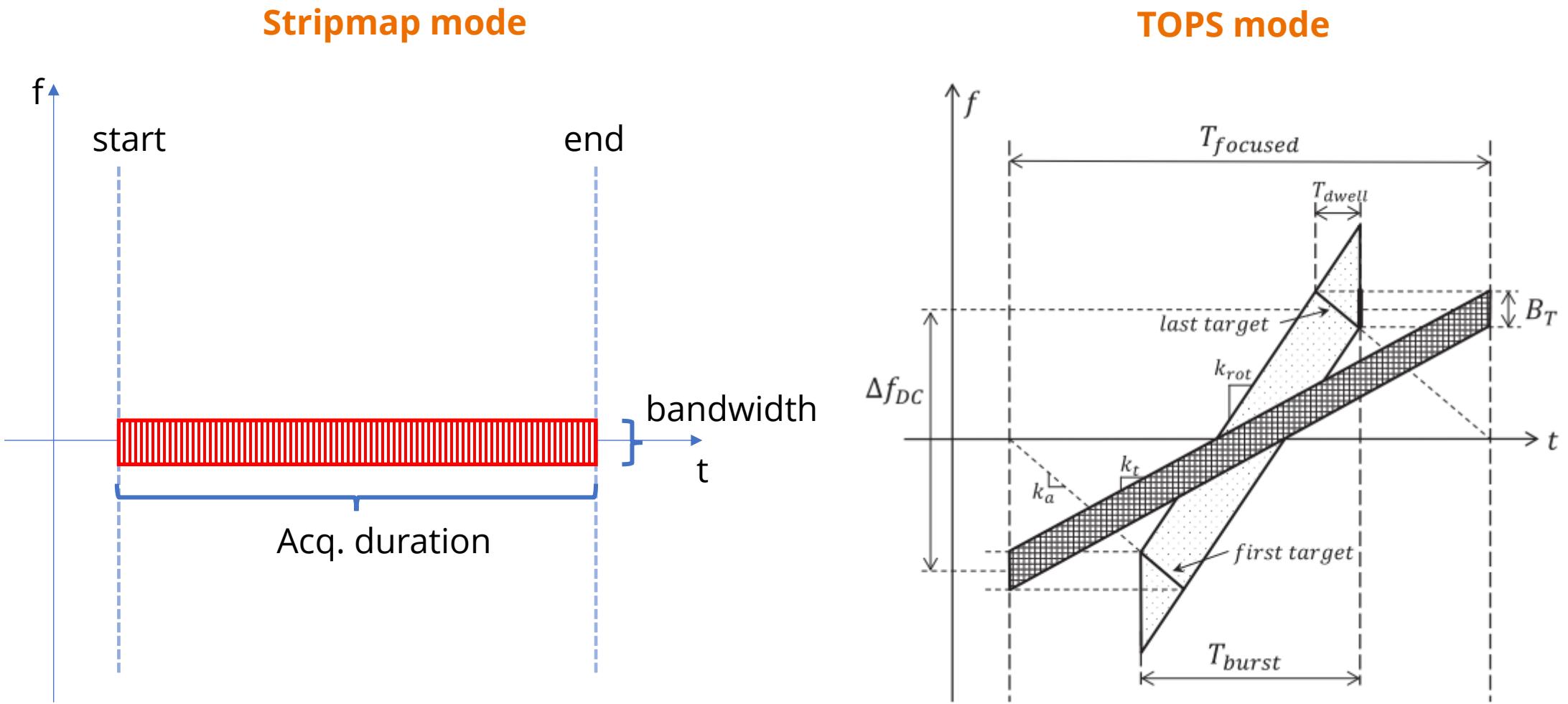
De-bursting
&
Mosaicking



Flight direction

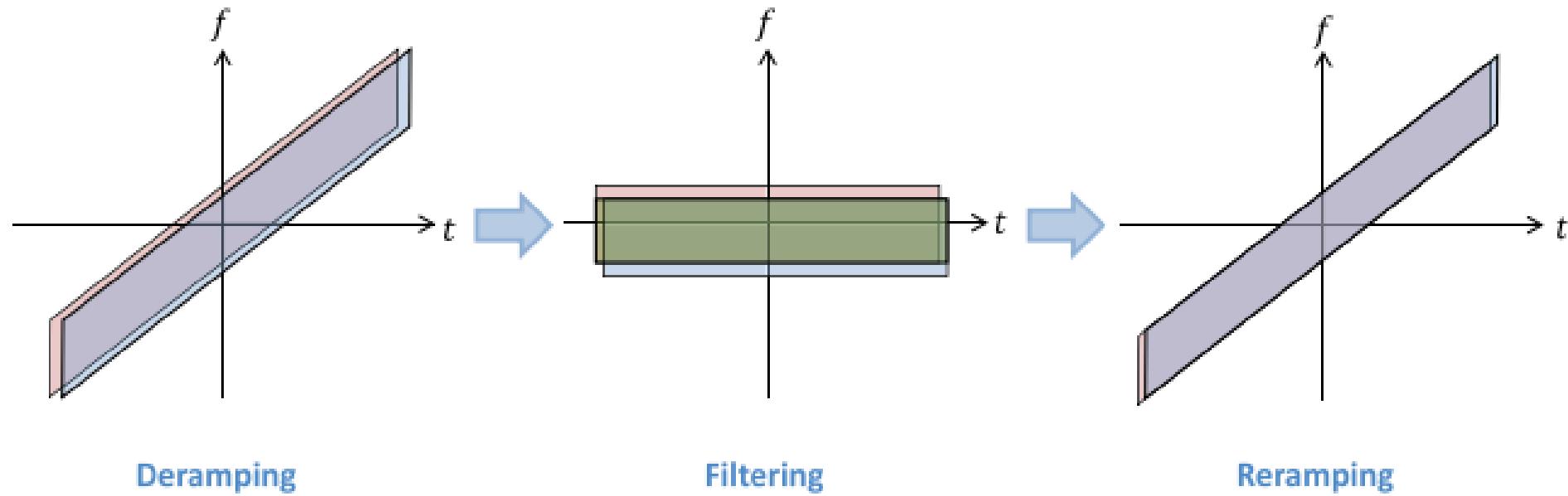
der Bundeswehr

Sentinel-1 – frequency modulation in TOPS data



Interferometric Processing of Sentinel-1 TOPS Data. Nestor Yague-Martinez et al.

Sentinel-1 – frequency modulation in TOPS data



Deramping

Filtering

Reramping

- Intro: *From zero to hero*
- SAR basics, missions and the Sentinel-1
- Machine Learning for SAR image analysis
 - **Choice of the data and procurement**
 - SAR processing
 - Pre-processing for ML
- Takeaways

Data procurement

Different **missions** provide only some data free of charge

- **National missions** often have policies to share selected data
- **Private companies** are increasingly sharing part of their data
 - Good for prototyping, but less suitable for science and technology applications requiring systematic acquisitions or a specific region of interest

New free and open data policies led by ESA

- Example: Copernicus and Sentinel-1, specifically for SAR applications.
- ESA also serves as a hub for third-party mission data, including:
 - DLR's TerraSAR-X and TanDEM-X, JAXA's ALOS, ICEYE

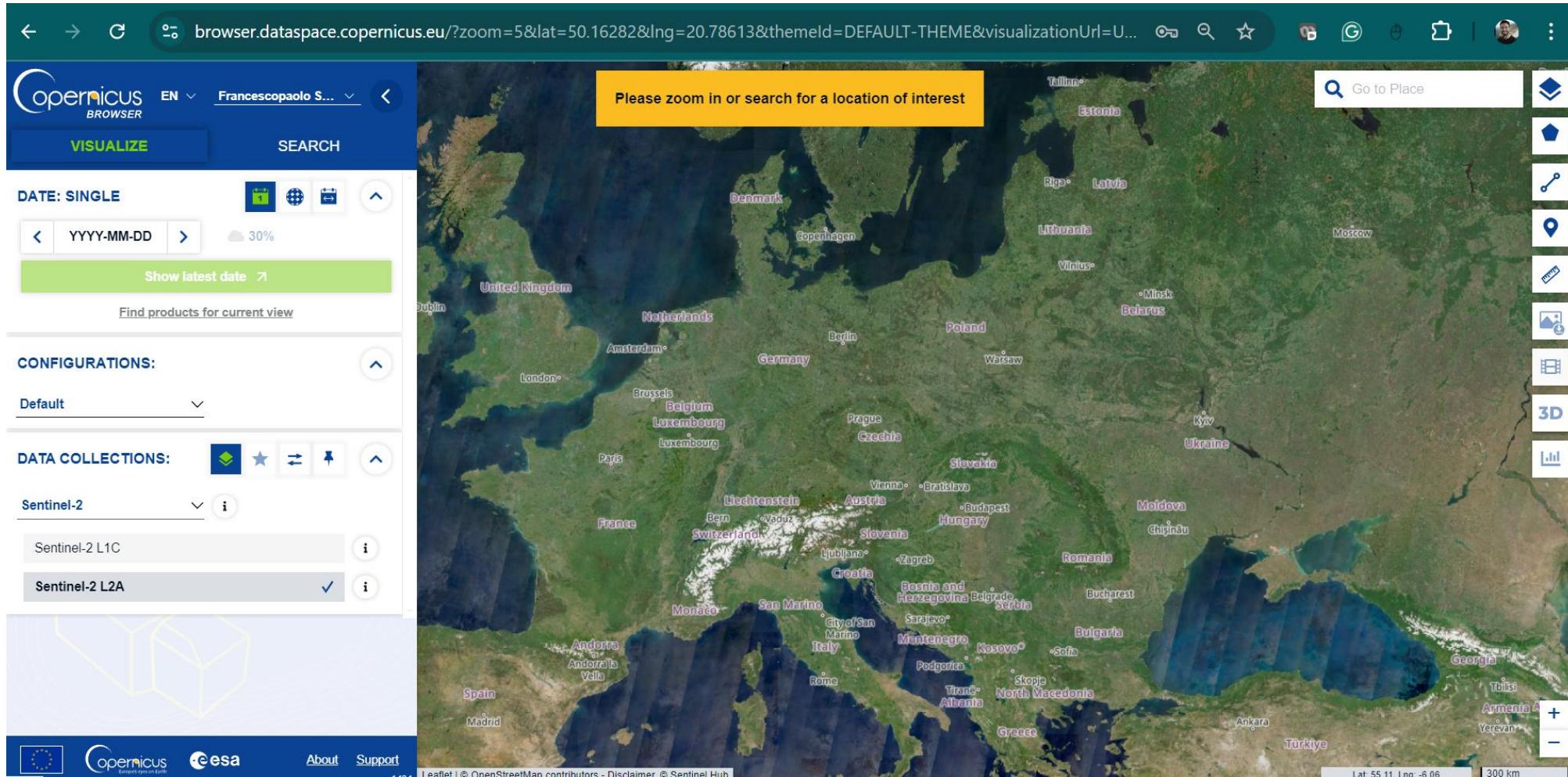
Google Earth Engine also provides Sentinel-1 data (GRD format)

Data download

Create an account on:

<https://browser.dataspace.copernicus.eu/>

- Provided by ESA
- Only recent data are available – offline archive data
- Possible use of python interfaces



der Bundeswehr

Data download

Graphic interface

- Select the area
- Select the data

Data parameters

- Sensor
- Acquisition mode
- Dates
- Acquisition geometry
- Orbit
- etc.

The screenshot shows the Copernicus Browser interface. At the top, there is a header with the Copernicus logo, language selection (EN), user name (Francescopaolo S...), and a back arrow. Below the header are two buttons: "VISUALIZE" and "SEARCH". The "SEARCH" button is highlighted in green. The main area is divided into sections:

- SEARCH CRITERIA:** A "Product name" input field and a note: "To apply a location filter, please define an AOI/a POI".
- DATA SOURCES:** A list of sensors with checkboxes:
 - SENTINEL-1
 - C-SAR
 - Level-0 RAW
 - Level-1 SLC
 - Level-1 GRD
 - Level-1 GRD COG
 - Level-2 OCN
 - ETAD
 - Auxiliary Data File
 - SENTINEL-2
 - SENTINEL-3
 - SENTINEL-5P
 - SENTINEL-6
 - CCM Optical
 - CCM DEM
 - CCM SAR
- FILTERS:** Buttons for "Filters →" next to each sensor section.
- SATELLITE PLATFORM:** Buttons for S1A and S1B.
- ORBIT DIRECTION:** Buttons for Ascending and Descending.
- RELATIVE ORBIT NUMBER:** Input field set to 1-175.
- ACQUISITION MODE:** Buttons for SM, IW, EW, and WV.
- BEAM ID:** Input field for Beam id.
- POLARISATION:** Buttons for HH, VV, VV+VH, and HH+HV.
- PRODUCT AVAILABILITY:** Buttons for Immediate and To order.
- RESET FILTERS:** A button at the bottom of the filter sidebar.

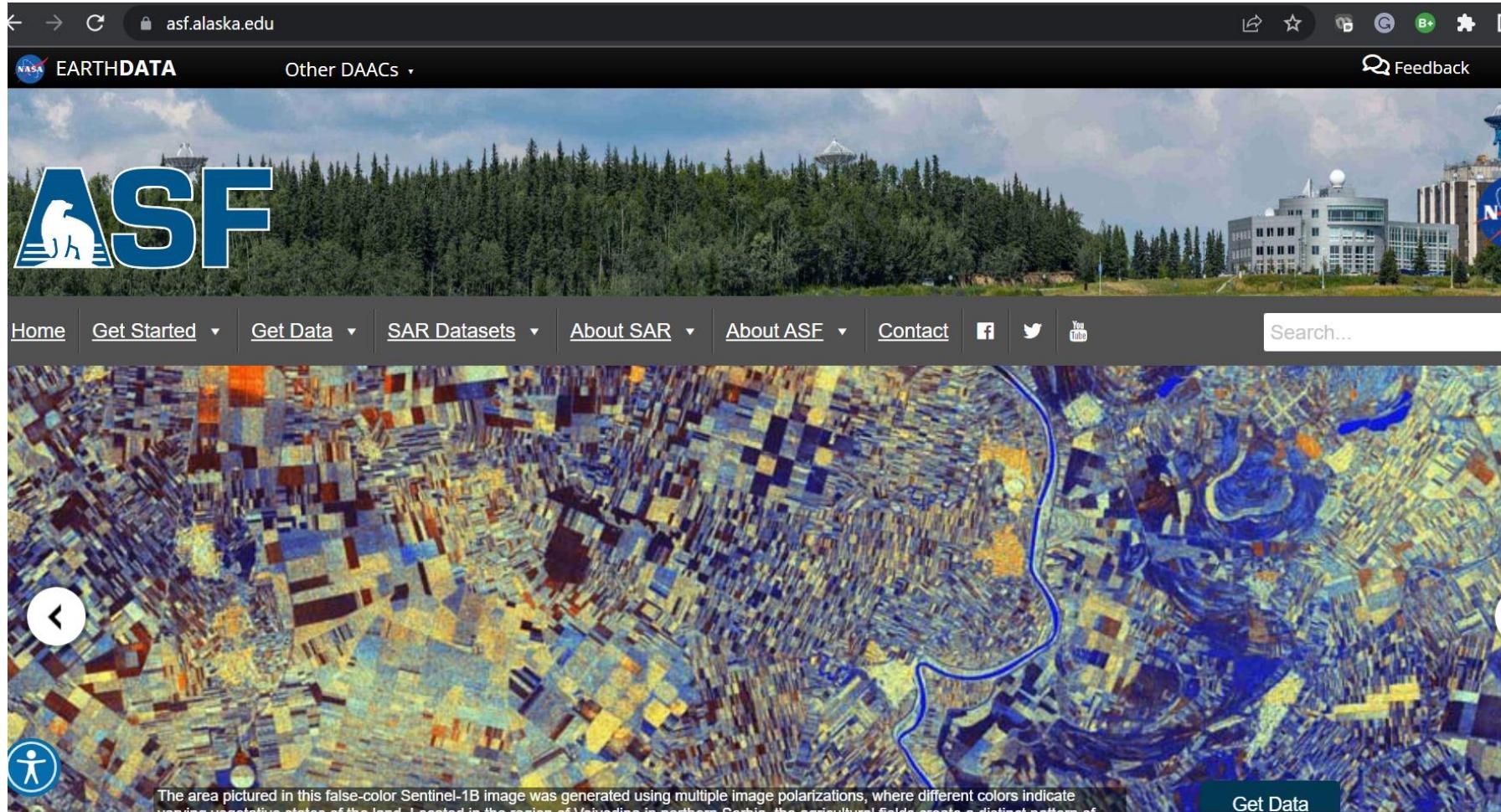
On the right side of the interface, there is a large map of Europe and North Africa. The map shows landmasses in green and brown, and bodies of water in blue. Country names are labeled across the continent. The map is overlaid with several dark, jagged shapes representing satellite footprints or acquisition areas.

Data download

[Alaska Satellite Facility](https://ASF.alaska.edu/)
<https://ASF.alaska.edu/>

Create an account
<https://urs.earthdata.nasa.gov/>

Education platform SAR training



der Bundeswehr

Data download

<https://www.earthdata.nasa.gov/>

The screenshot shows the homepage of the NASA Earthdata website. At the top, there is a dark blue header bar with the URL "earthdata.nasa.gov" in the address bar and various browser icons. Below the header is a light blue navigation bar with the NASA logo, the text "EARTHDATA OPEN ACCESS FOR OPEN SCIENCE", and five menu items: "Data", "Topics", "Learn", "Engage", and "About". To the right of the "About" menu item is a search icon. The main content area features a large, semi-transparent image of the Earth's globe. Overlaid on this image are nine circular icons, each representing a different Earth science discipline: a sun in clouds (orange), a tree (green), a snowflake (teal), a head profile with a globe (orange), a mountain range (green), waves (teal), a globe (green), a sun over a globe (orange), and a landscape (teal). Below these icons, the text "Your Gateway to NASA Earth Observation Data" is centered. Underneath this text, a paragraph explains the purpose of the site: "The Earth Science Data Systems (ESDS) Program provides full and open access to NASA's collection of Earth science data for understanding and protecting our home planet. Begin your Earthdata exploration by clicking on any of the discipline icons above." At the bottom of the page are three green buttons with white text: "Get Started", "Find Data", and "Use Data".

der Bundeswehr

Data download

<https://search.earthdata.nasa.gov/search>

The screenshot shows the Earthdata Search interface. On the left, there is a sidebar with a search bar and a 'Filter Collections' section. The 'Filter Collections' section includes categories like Features, Keywords, Platforms, Instruments, Organizations, Projects, and Processing Levels. Under 'Features', there are options for 'Available from AWS Cloud', 'Customizable', and 'Map Imagery'. The main area displays a list of 8,682 matching collections, showing 20 of them. The first item is 'SENTINEL-1A_SLC', which has 1,275,981 Granules and is ongoing. It is associated with the 'Earthdata Cloud' and is a Sentinel-1A slant-range product. The second item is 'SENTINEL-1B_SLC', with 789,393 Granules and is ongoing. It is also associated with the 'Earthdata Cloud' and is a Sentinel-1B slant-range product. The third item is 'SENTINEL-1A_DUAL_POL_GRD_HIGH_RES', with 1,088,935 Granules and is ongoing. It is associated with the 'Earthdata Cloud' and is a Sentinel-1A Dual-pol ground projected high and full resolution images. To the right of the search results is a map of the Indian Ocean and surrounding regions, with a legend on the far right.

8,682 Matching Collections

Showing 20 of 8,682 matching collections

Export Sort View

SENTINEL-1A_SLC

1,275,981 Granules 2014-04-03 ongoing Earthdata Cloud

Sentinel-1A slant-range product

GEOSS • SENTINEL-1A SLC v1 - ASF

No image available

SENTINEL-1B_SLC

789,393 Granules 2016-04-25 ongoing Earthdata Cloud

Sentinel-1B slant-range product

GEOSS • SENTINEL-1B SLC v1 - ASF

No image available

SENTINEL-1A_DUAL_POL_GRD_HIGH_RES

1,088,935 Granules 2014-04-03 ongoing Earthdata Cloud

Sentinel-1A Dual-pol ground projected high and full resolution images

GEOSS • SENTINEL-1A DP GRD HIGH v1 - ASF

No image available

SENTINEL-1B_DUAL_POL_GRD_HIGH_RES

v1.171.2 · Search Time: 1.4s · NASA Official: Stephen Berrick · FOIA · NASA Privacy Policy · USA.gov

Earthdata Access: A Section 508 accessible alternative

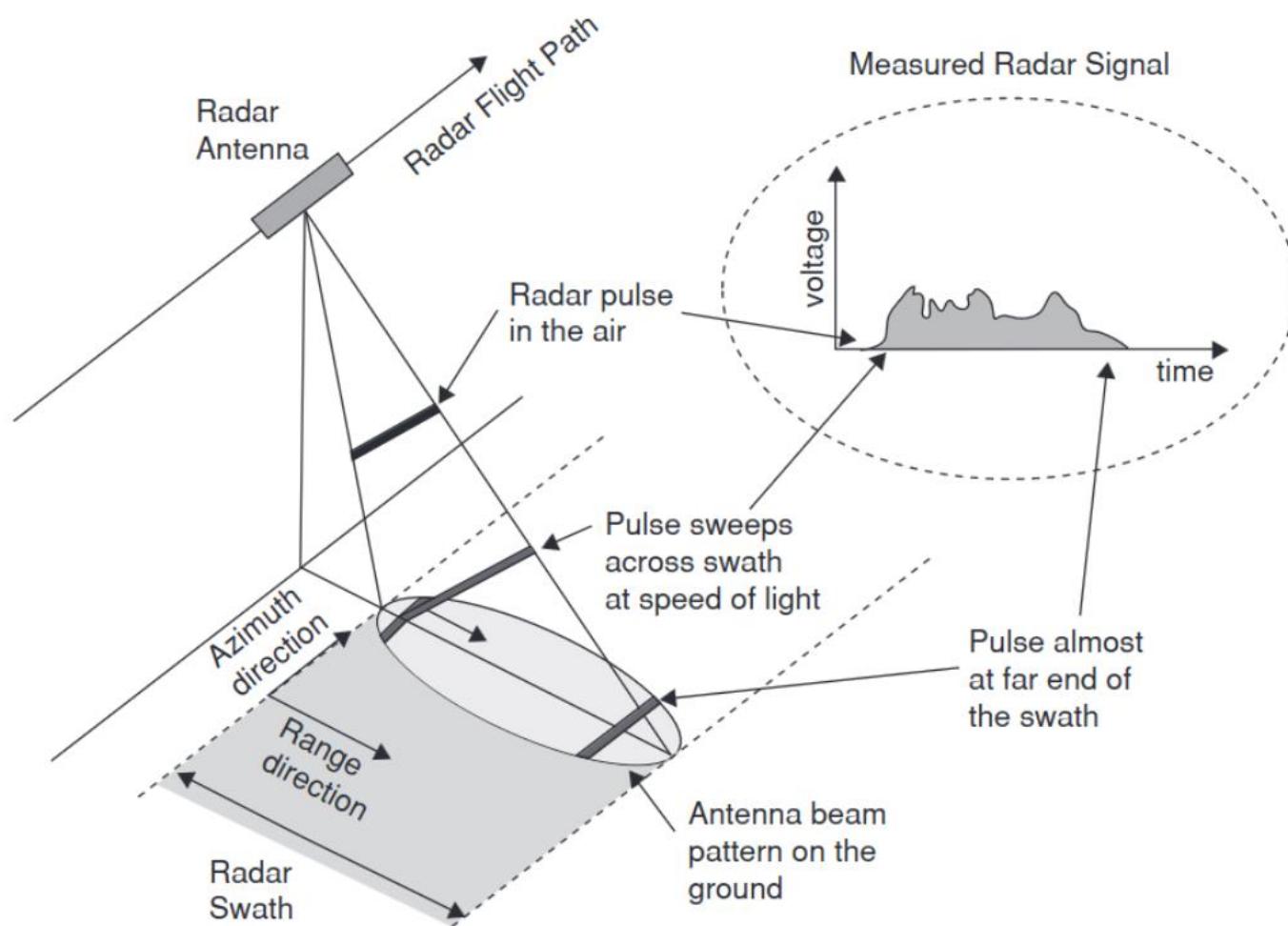
der Bundeswehr

Online demo: Sentinel-1 data download

(acquisition mode, type of data, orbits, etc.)

- Intro: *From zero to hero*
- SAR basics, missions and the Sentinel-1
- Machine Learning for SAR image analysis
 - Choice of the data and procurement
 - **SAR processing**
 - Pre-processing for ML
- Takeaways

SAR image characteristics



- **Spatial properties:** geometrical deformations
- **Radiometric properties:** brightness of a pixel
- **Statistical properties:** speckle

Van Zyl & Kim (2011) Synthetic Aperture Radar Polarimetry. John Wiley & Sons, Inc

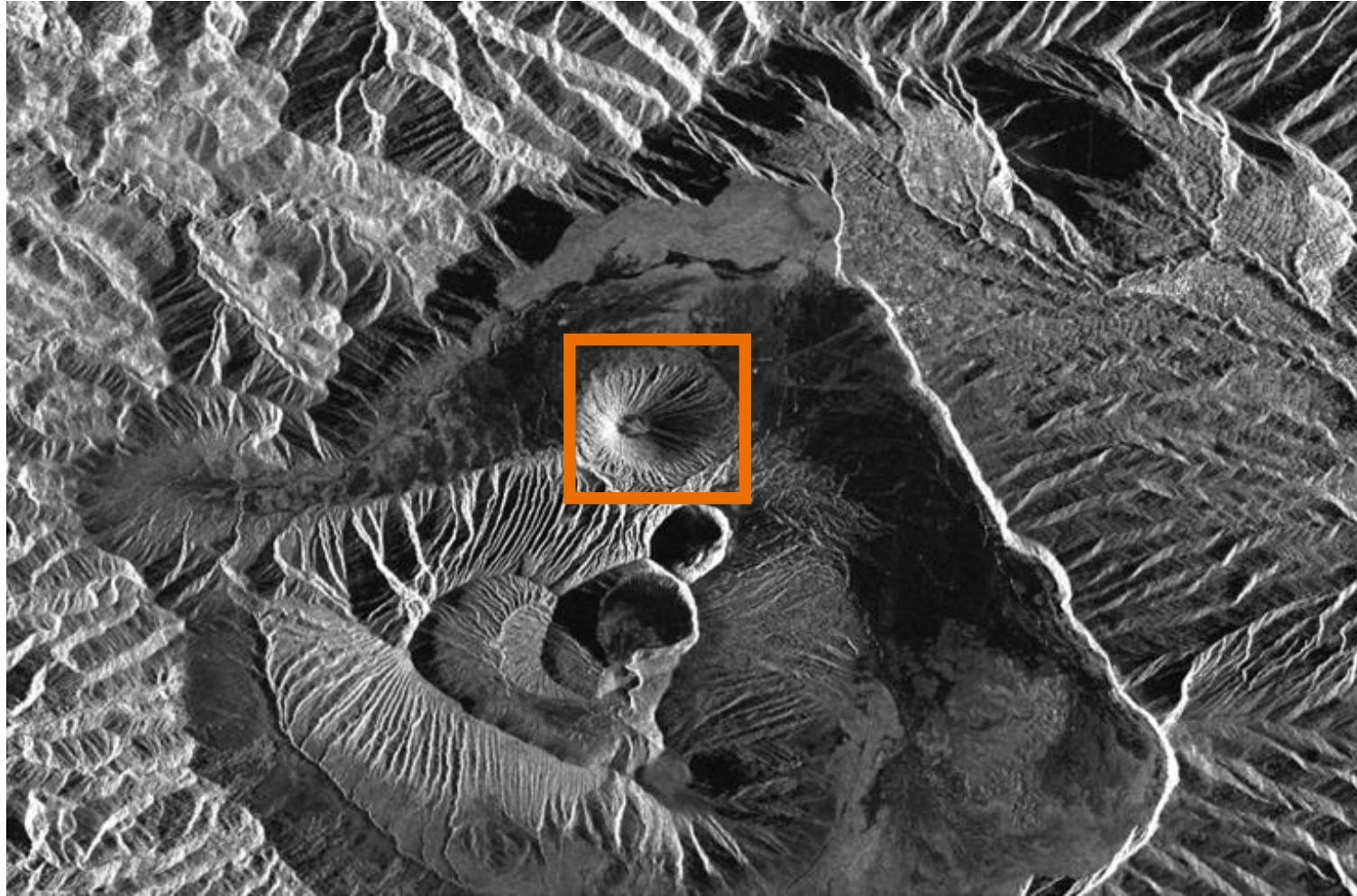
SAR image characteristics



Mount Bromo (Indonesia) – **optical image** – Google Earth (Maxar)

der Bundeswehr

SAR image characteristics



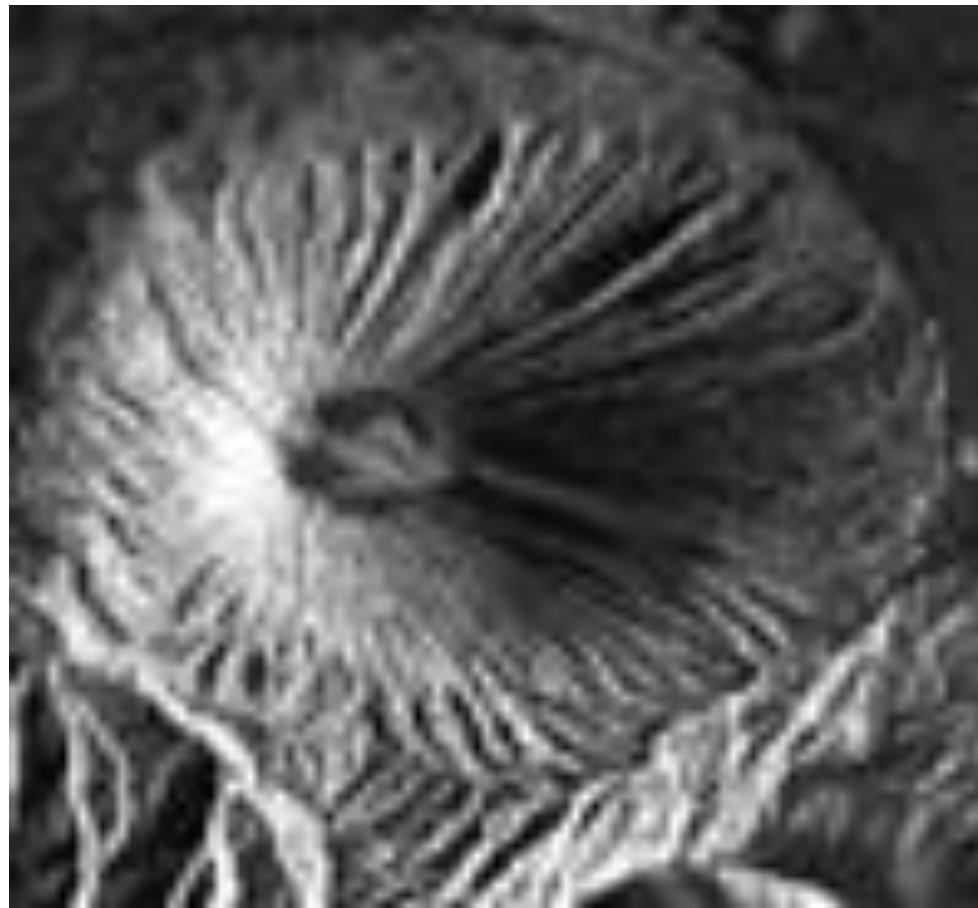
Mount Bromo (Indonesia) – **SAR image** – TerraSAR-X Spotlight image

der Bundeswehr

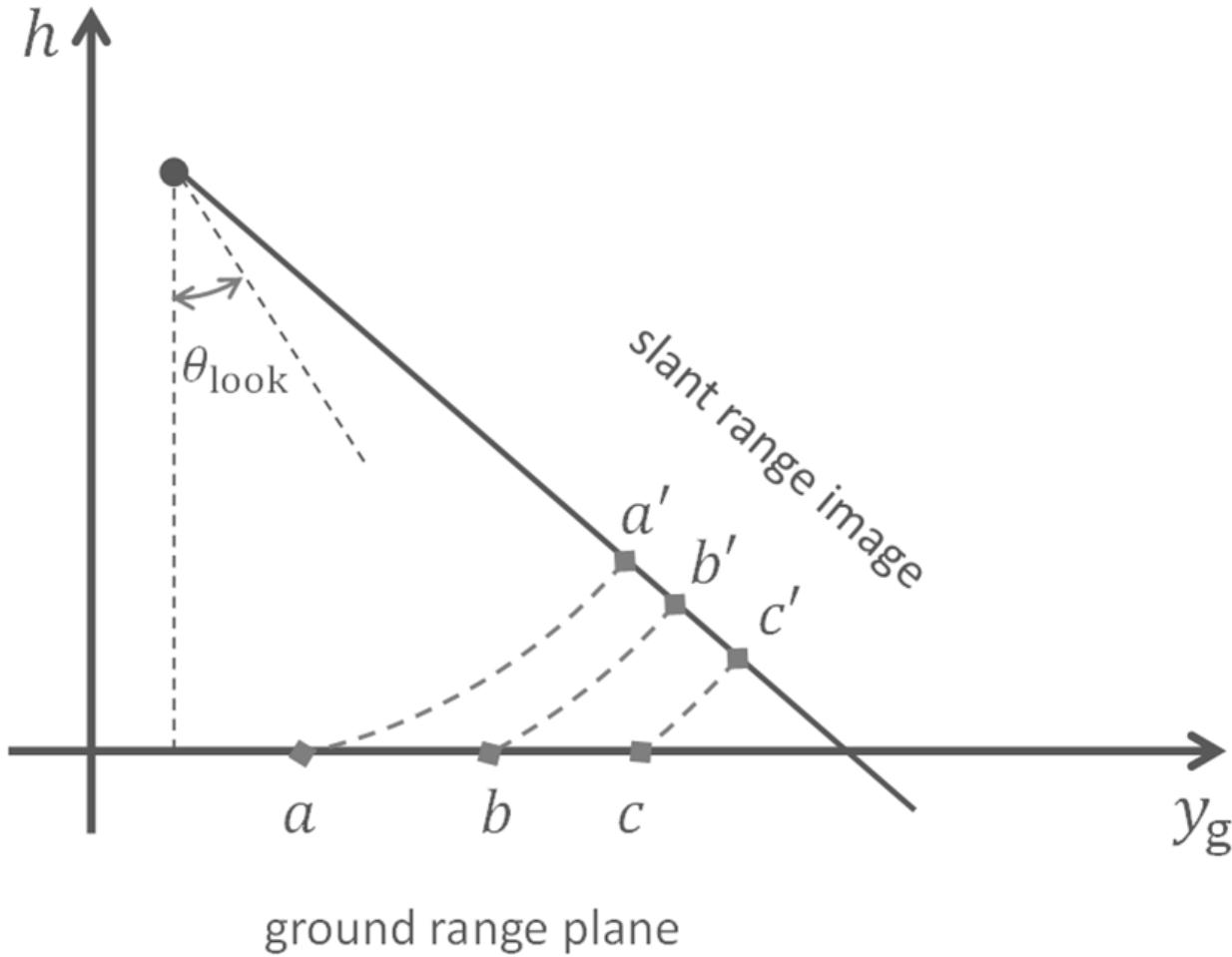
SAR image characteristics



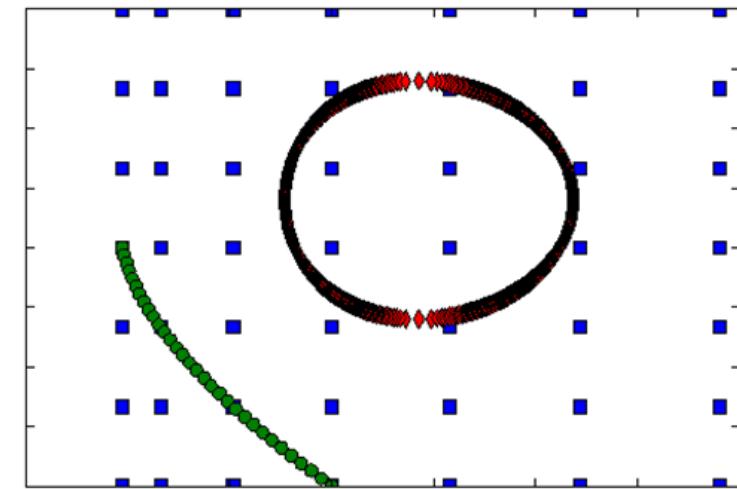
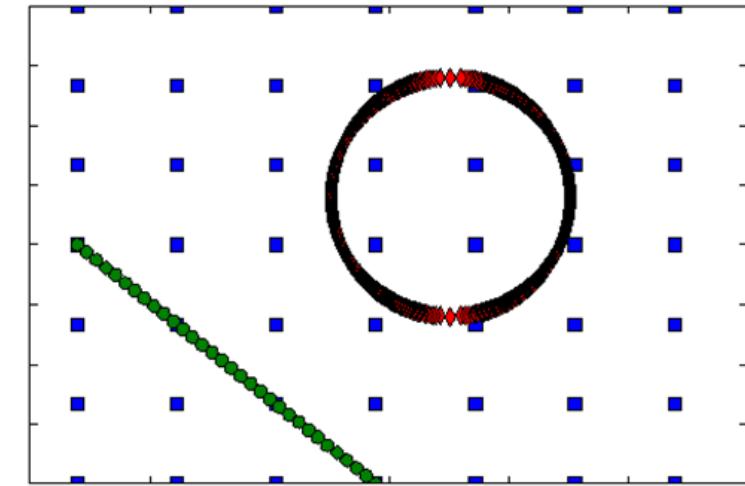
SAR image characteristics



Spatial characteristics: geometric distortions

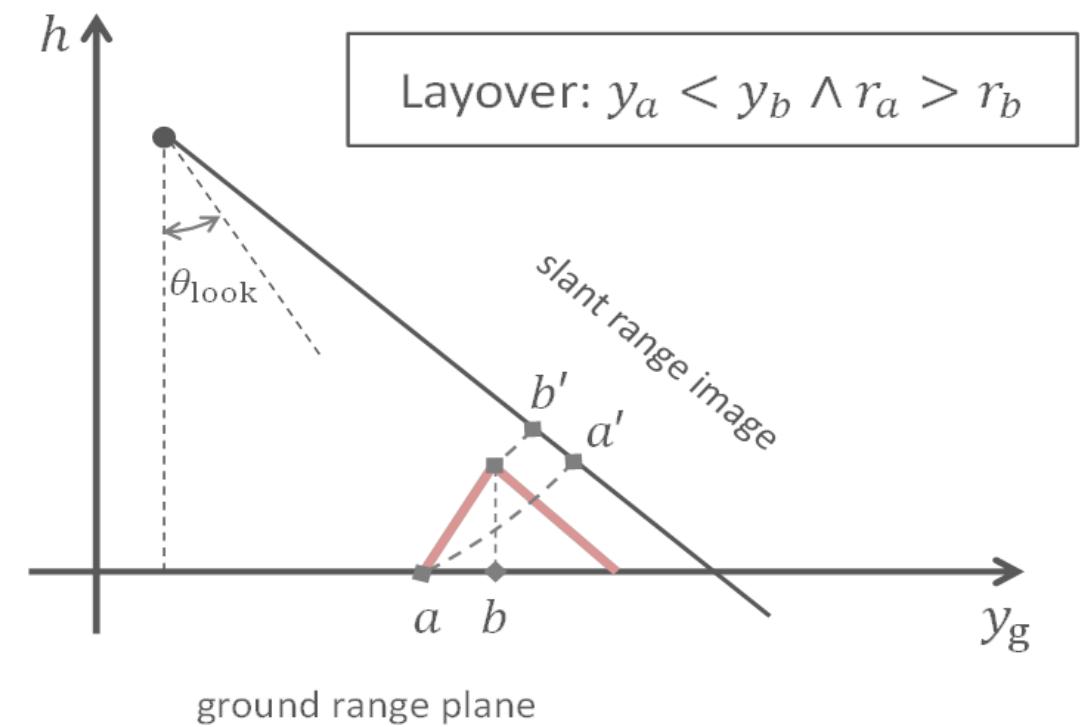
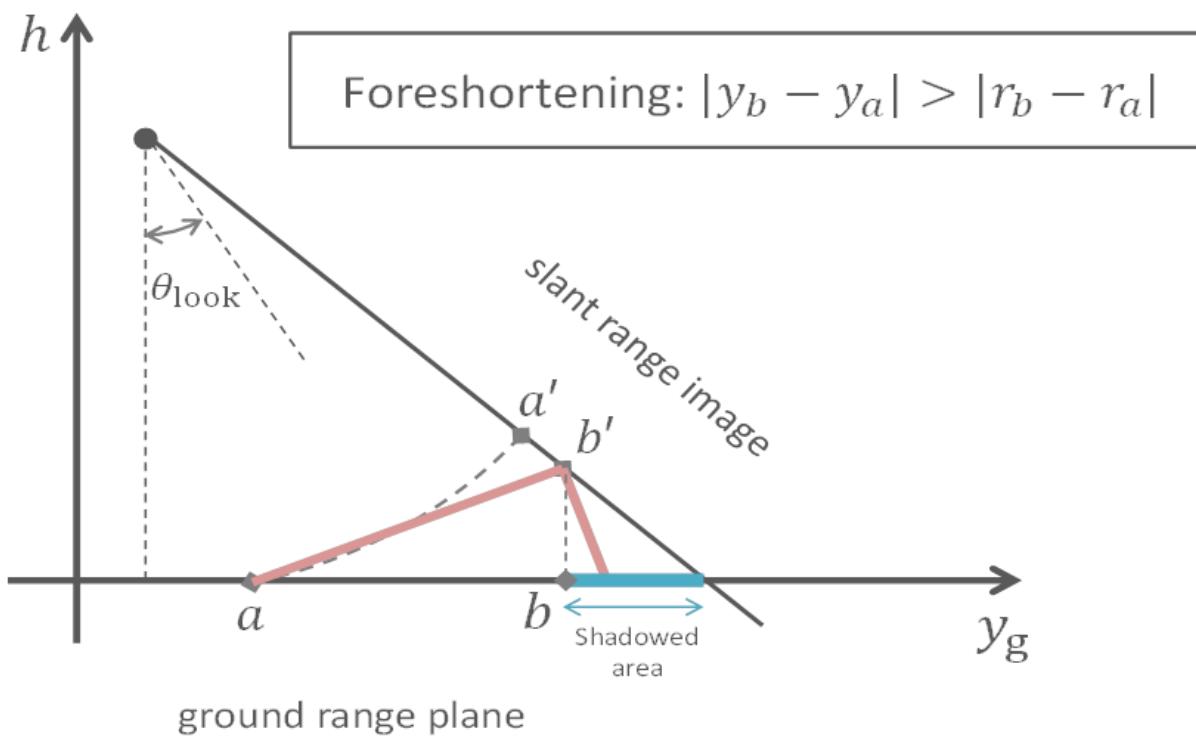


Actual geometry



SAR geometry

Spatial characteristics: geometric distortions



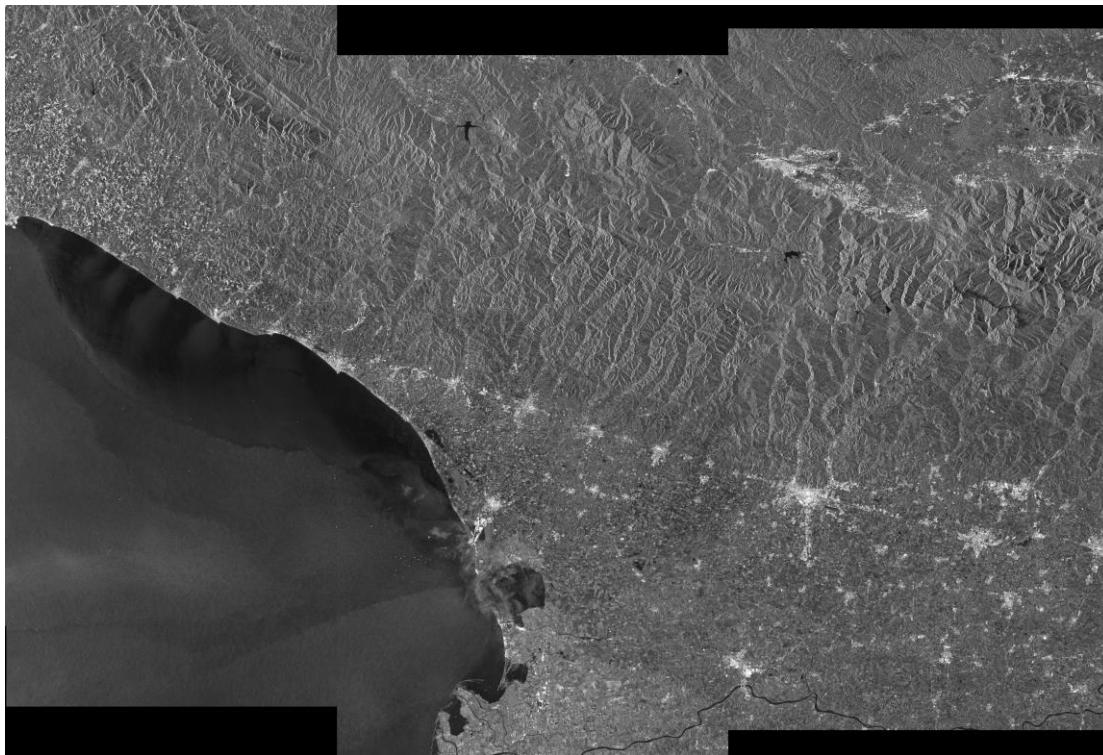
Spatial characteristics: geometric distortions



Spatial characteristics: geometric distortions



Distortion correction: Geocoding (a.k.a. Terrain Correction)



Slant-range / Azimuth grid

Distortion correction: Geocoding (a.k.a. Terrain Correction)



Slant-range / Azimuth grid

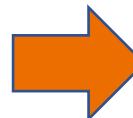
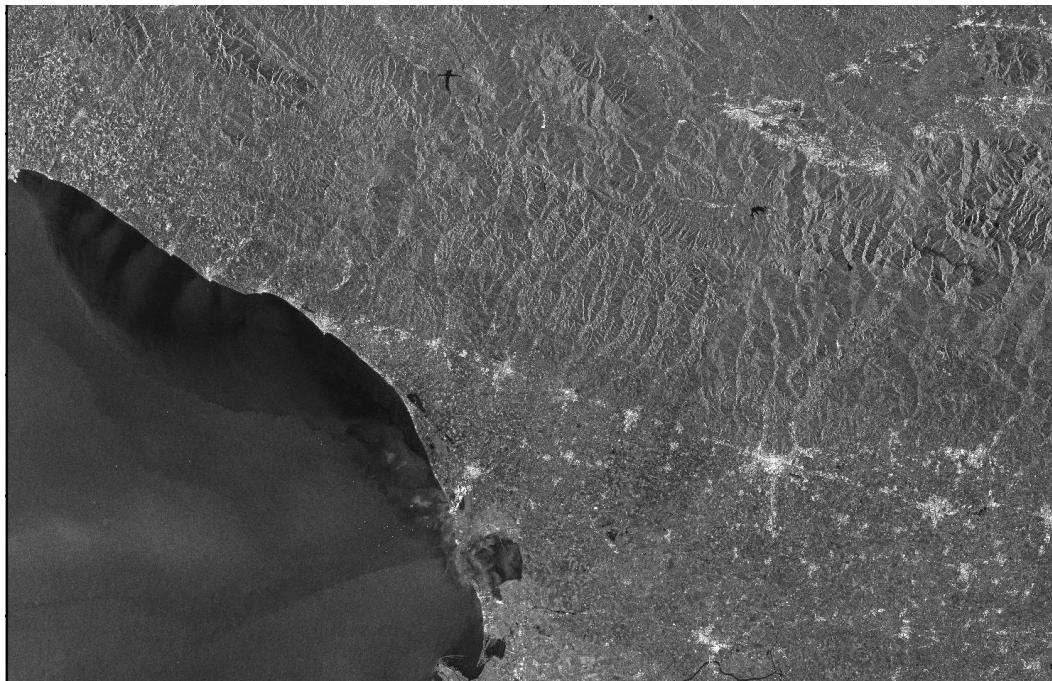
Geocoding



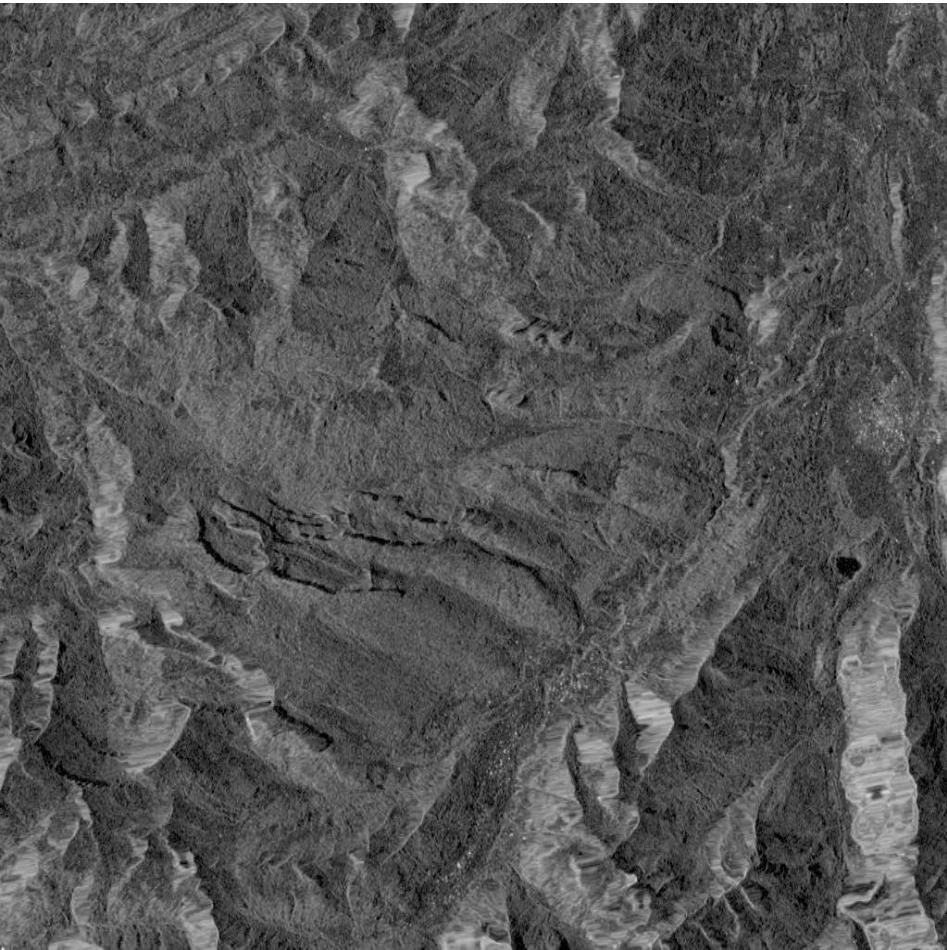
Latitude / Longitude grid

What about GRD data?

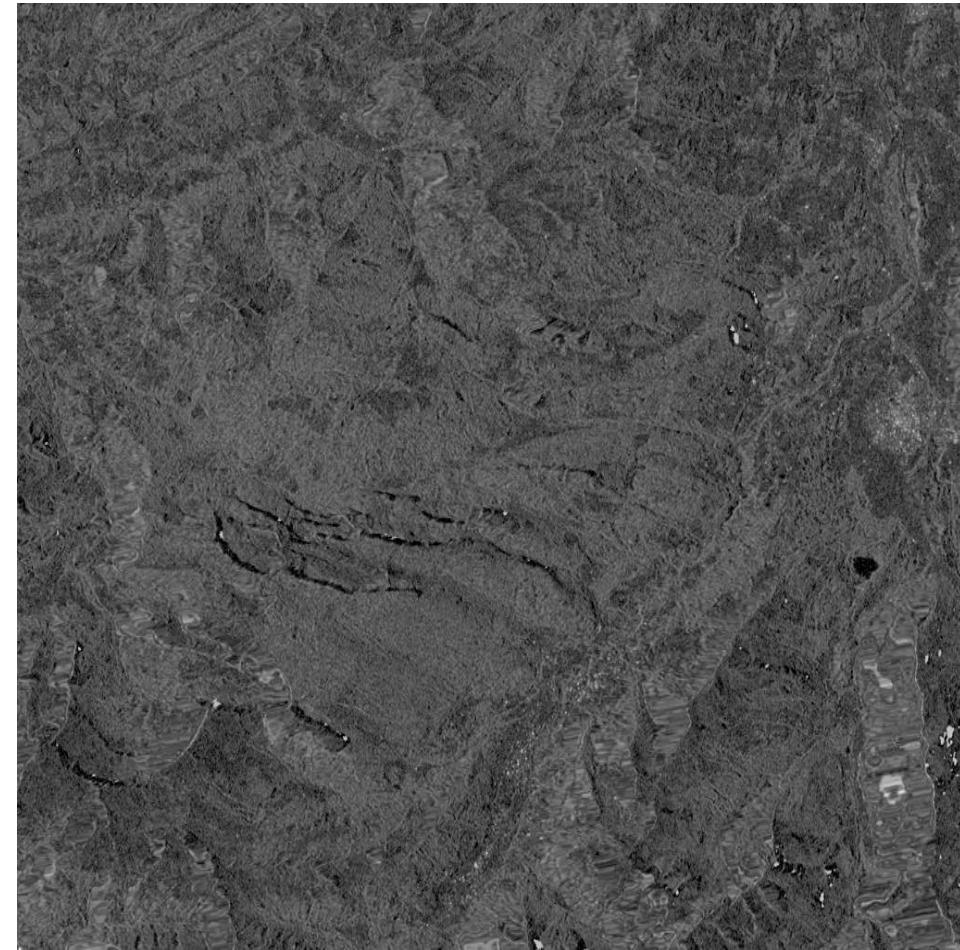
GRD: *Ground Range Detected*
Only amplitude data – no geocoded grid!



Radiometric characteristics



σ_{VV}^0 , with Terrain Correction (TC)



σ_{VV}^0 , with Radiometric Terrain Correction
a.k.a. TC + Terrain Flattening (TF)

Radiometric characteristics

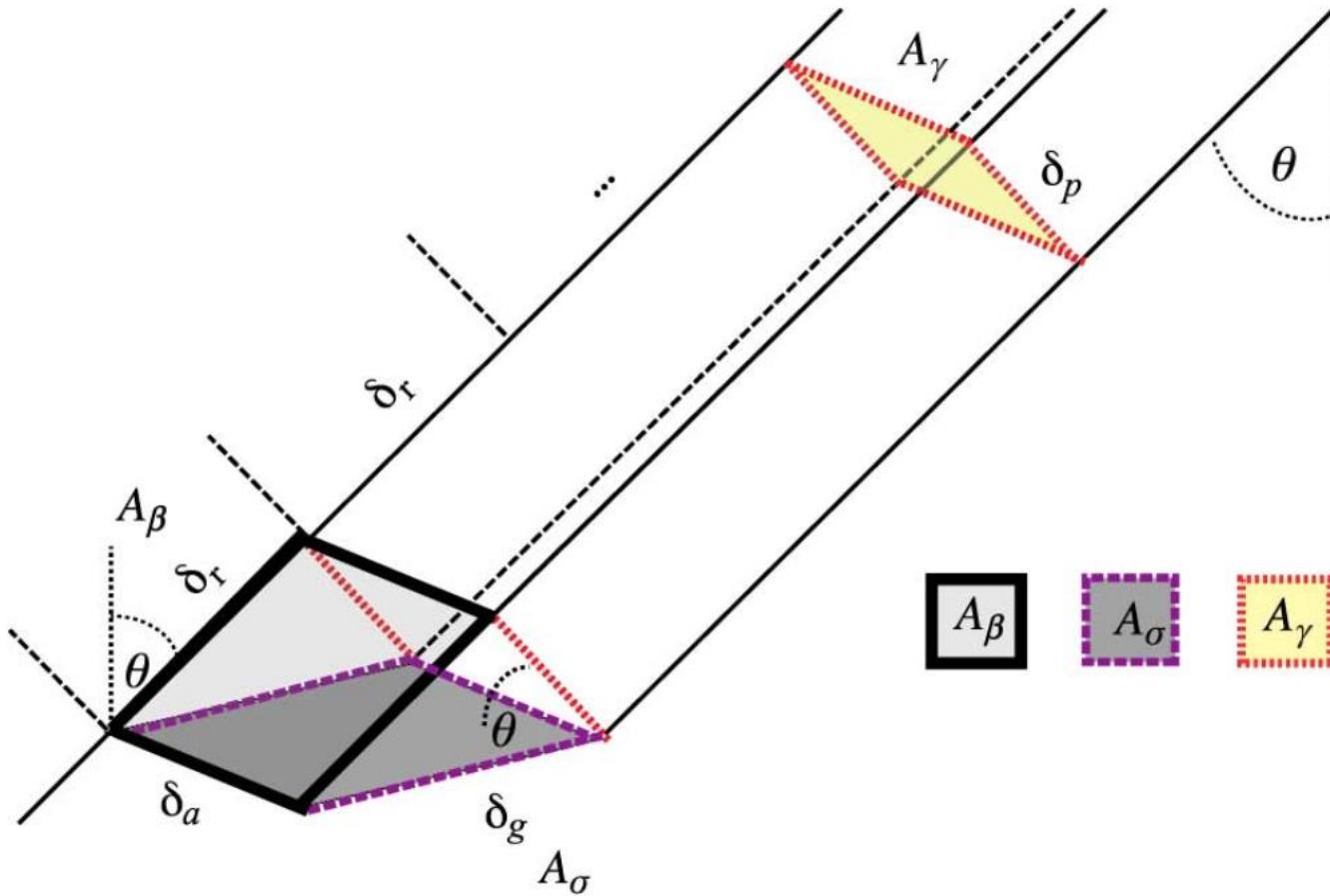
Radar measures **physical properties** of the imaged target. Specifically, we can describe the target through its capability to reflect an electromagnetic wave, given by the **Radar Cross Section** (RCS)

$$\sigma = \frac{P_r}{P_i} 4\pi r^2 \quad \sigma^0 = \frac{\sigma}{A}$$

Derived by the radar equation, RCS tells us how well a target reflects the signal in a given direction with respect to a uniform sphere.

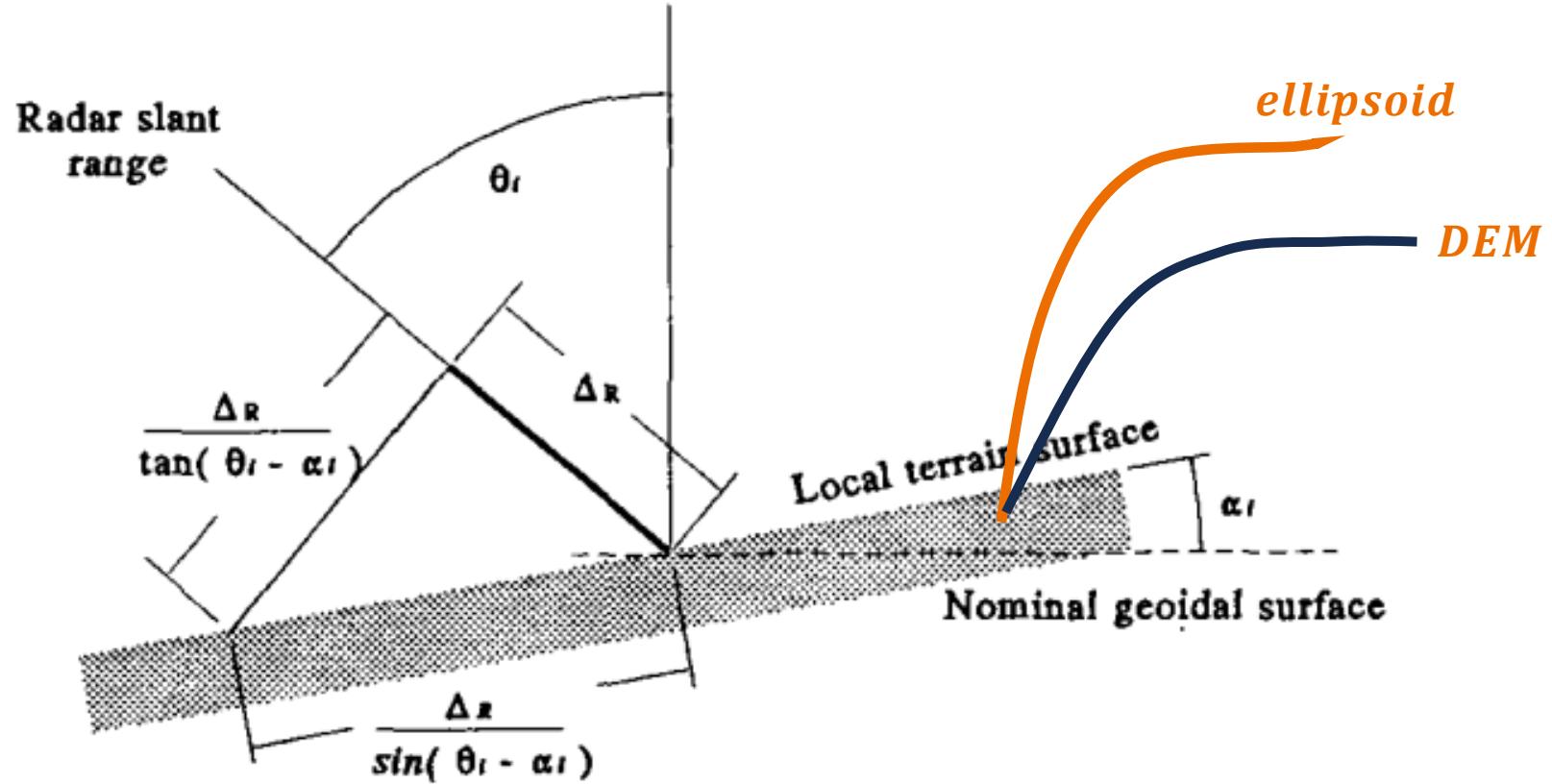
Emery, W., & Camps, A. (2017). *Introduction to satellite remote sensing: atmosphere, ocean, land and cryosphere applications*. Ch.5. Elsevier.

Radiometric characteristics: geometry



D. K. Atwood, D. Small and R. Gens, "Improving PolSAR Land Cover Classification With Radiometric Correction of the Coherency Matrix," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 5, no. 3, pp. 848–856, June 2012, doi: 10.1109/JSTARS.2012.2186791.

Radiometric characteristics: geometry



Raney, R. K., Freeman, T., Hawkins, R. W., & Bamler, R. (1994, August). A plea for radar brightness. In *Proceedings of IGARSS'94-1994 IEEE International Geoscience and Remote Sensing Symposium* (Vol. 2, pp. 1090-1092). IEEE.

Radiometric characteristics: what about Sentinel-1 data?

What do we get once we download Sentinel-1 data?

The **Digital Number (DN)**

$$\beta^0 = \frac{|DN|^2}{A_\beta}$$

- DN is the digital number read from the Sentinel-1 data.
- $A_\beta, A_\sigma, A_\gamma$ are the incremental areas (relative to Small's paper*, given as the square root) found on the official Sentinel-1 (calibration) datum.

$$\sigma^0 = \frac{|DN|^2}{A_\sigma}$$

In addition

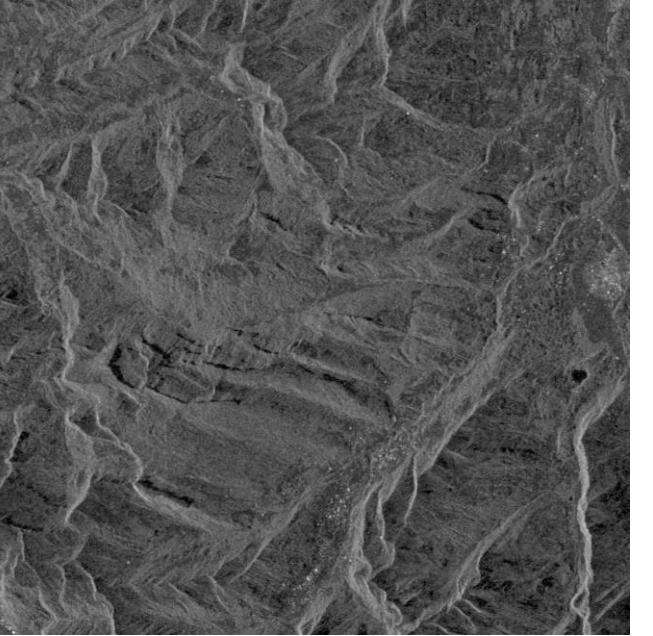
- these areas are undersampled and need a cubic interpolation to resample them to the SLC
- A_β is constant and therefore DN and Beta0 differ by a scaling factor.
- A_σ, A_γ approximation of what one could do by using the local incidence angle.

Note that: no DEM is taken into account. Areas (i.e. local incidence angle) are related to the ellipsoid

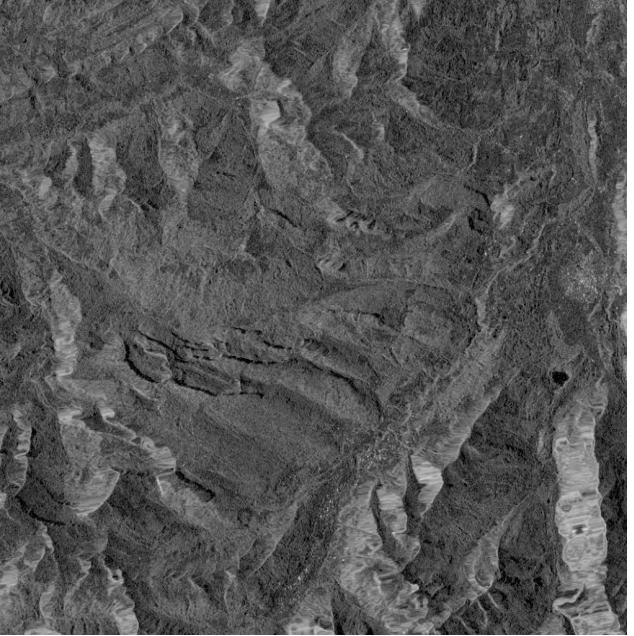
<https://sentinels.copernicus.eu/web/sentinel/radiometric-calibration-of-level-1-products>

*Small, D. (2011). Flattening gamma: Radiometric terrain correction for SAR imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 49(8), 3081-3093.

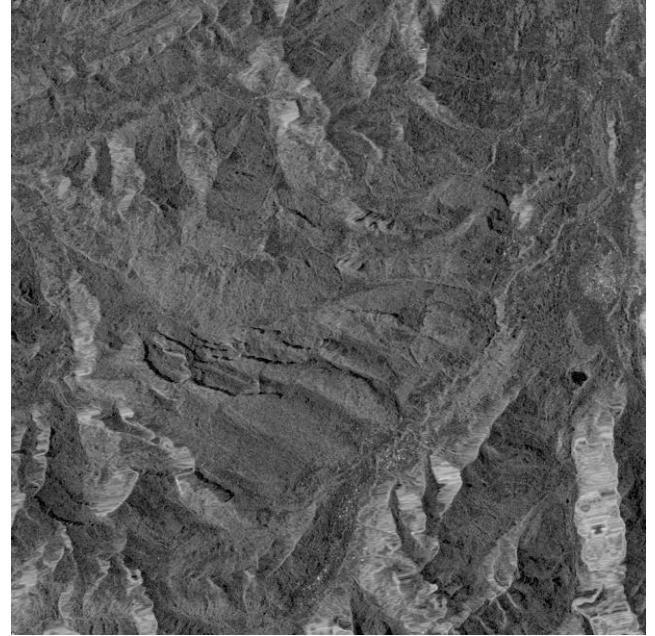
σ_{VV}^0 , no TF, no TC



σ_{VV}^0 , no TF, with TC



γ_{VV}^0 , no TF, with TC

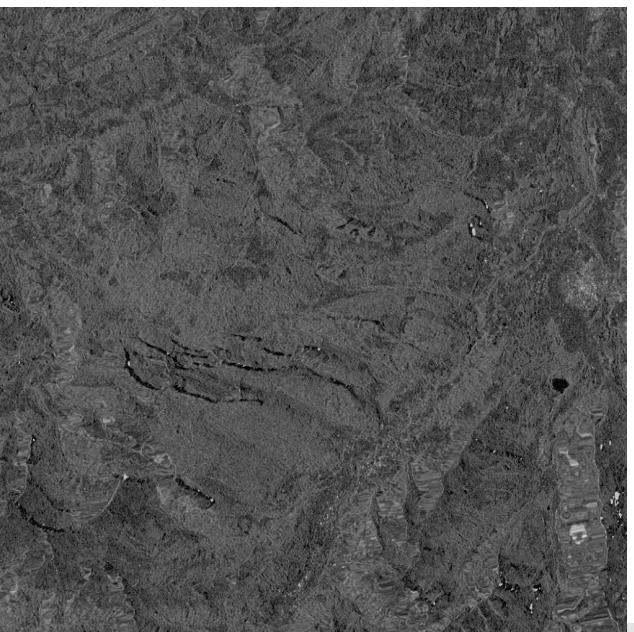


**Comparison between
different projections and
radiometric corrections**

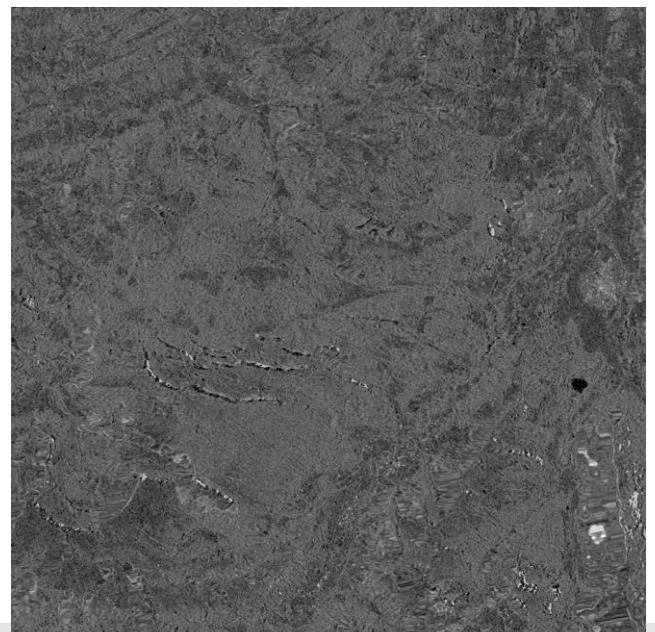
TC - Terrain Corrected
TF - Terrain Flattened

Credits: data processed by Thomas Roßberg (UniBw)

der Bundeswehr



σ_{VV}^0 , with TF, with TC



γ_{VV}^0 , with TF, with TC

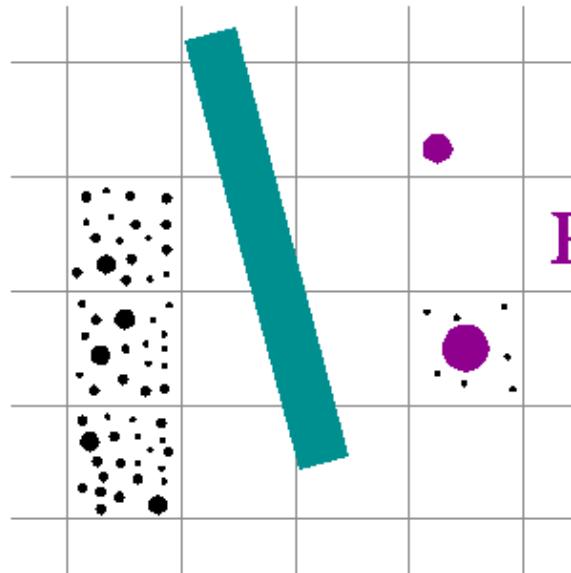
Radiometric characteristics: what to use?

	Pro	Contra	Use it when...
β^0	<ul style="list-style-type: none">• Most general term• No variation with the incidence angle• No need of an external DEM	<ul style="list-style-type: none">• May suffer from strong variations due to geometry	<ul style="list-style-type: none">• No knowledge of the scene's topography• The local incidence angle is something you want to retrieve (i.e. geology)• The satellite system has few look angle option (difference between TSX and S1)
σ^0	<ul style="list-style-type: none">• Physical meaning• Scattering properties of the target for a specific incidence angle.	<ul style="list-style-type: none">• Need precise DEM• Despite normalization, still varies due to local incidence angle	<ul style="list-style-type: none">• Applications where you want to invert scene parameters (Land cover classification, soil moisture, etc.)• Geometry dependent characterization (i.e., need to additionally use the local incidence angle)
γ^0	<ul style="list-style-type: none">• Values are independent on range and local incidence angle	<ul style="list-style-type: none">• Need precise DEM	<ul style="list-style-type: none">• Achieving complete independence on local incidence angle (sensors like TSX may use different look angles)• Achieve sensor independence target characterization (e.g. change detection)

SAR signal properties

Type of scatterers

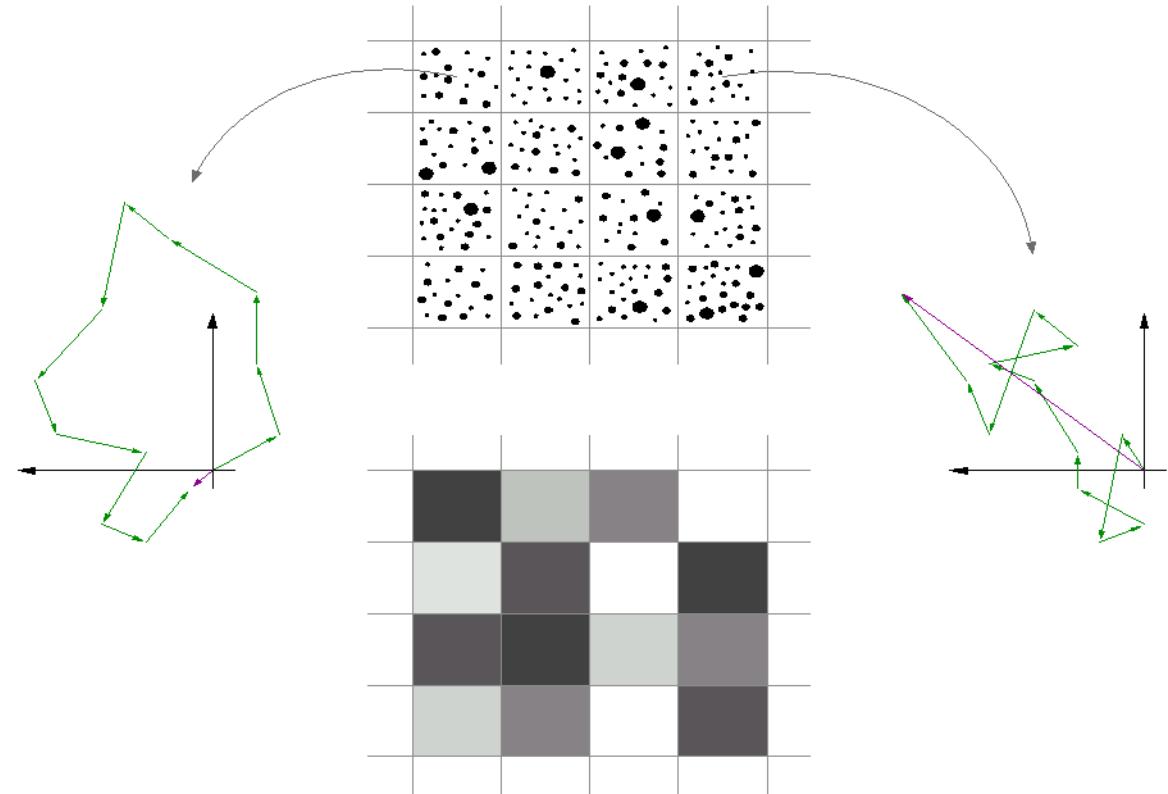
Extended target



Point target

Distributed target

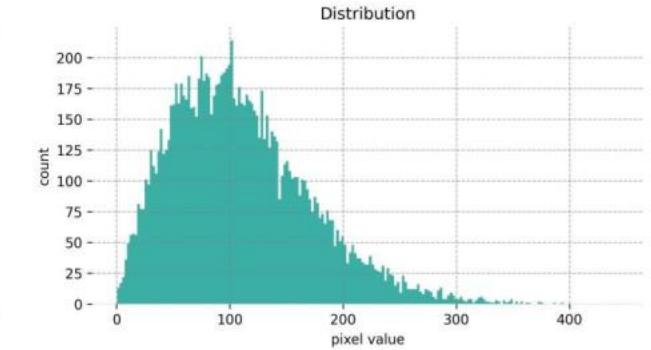
Speckle effect



Statistical properties



Non-gaussian speckle statistics



Intensity mainly dependent on roughness and geometry

Phase φ
Amplitude $|z|$

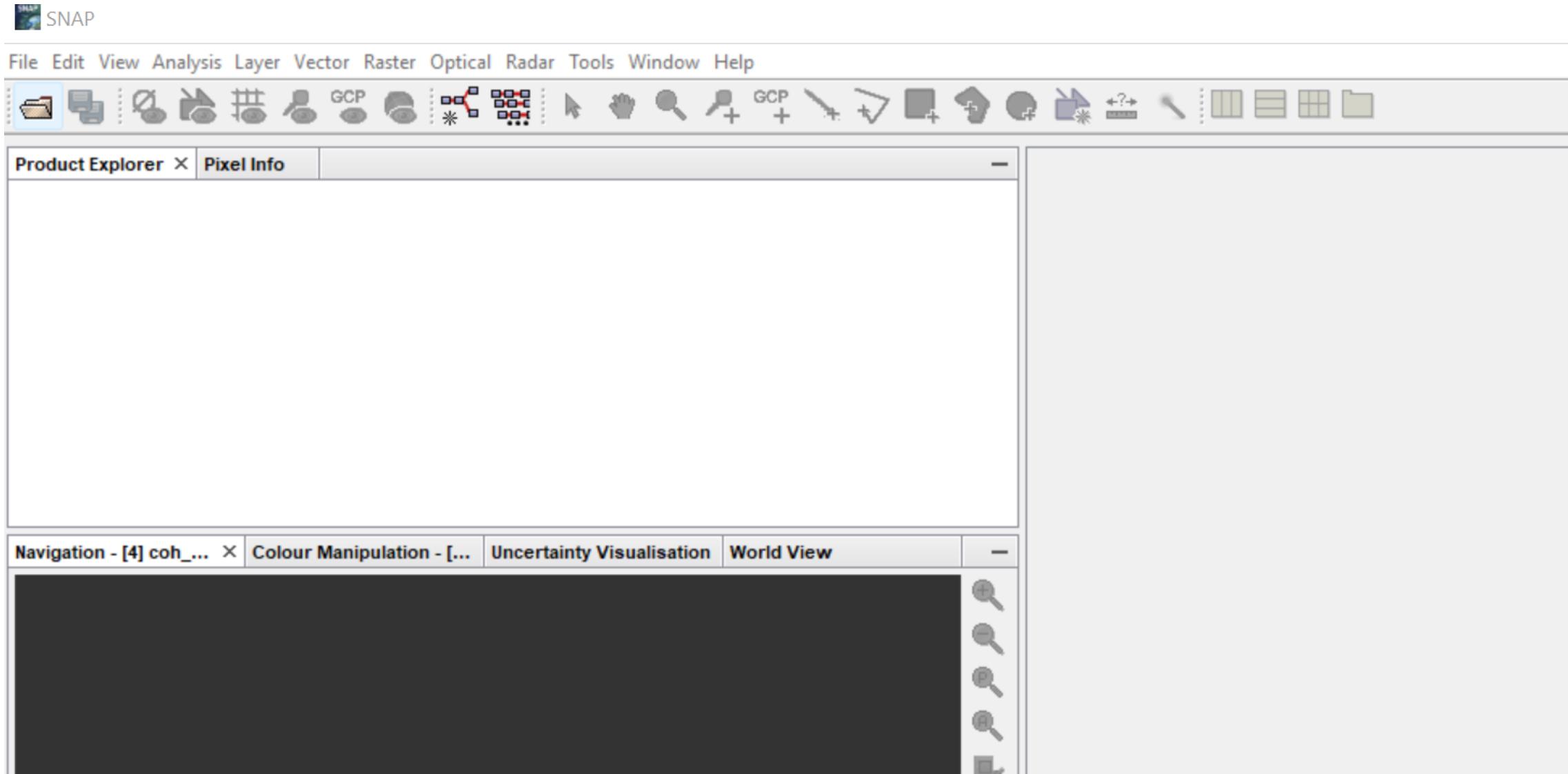
Complex signal $z = |z|e^{j\varphi}$

Data preparation

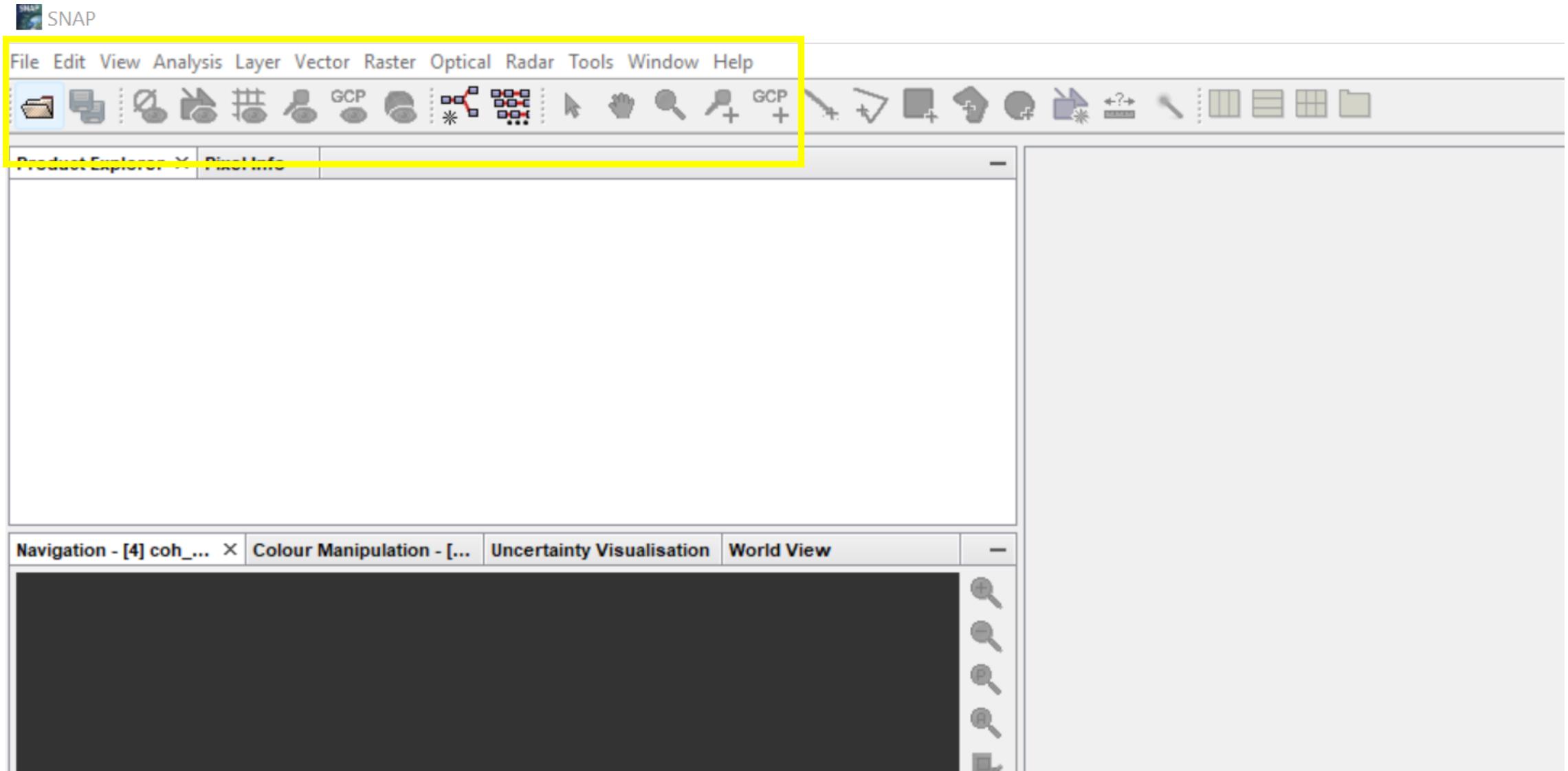


- ESA
- Data from Sentinel missions
- Free software and open source
- Sentinel-1, -2, -3
- Good system specifications required
- Download from:
<https://step.esa.int/main/download/snap-download/>

SNAP interface



SNAP interface



SNAP interface



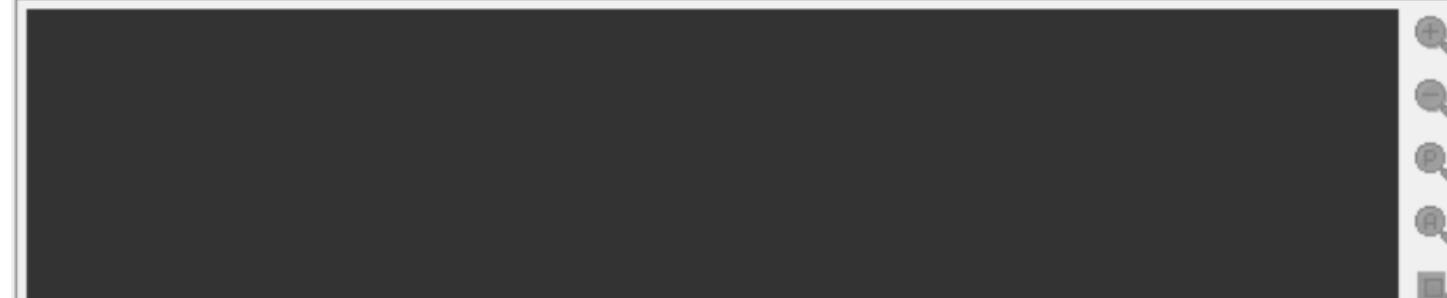
File Edit View Analysis Layer Vector Raster Optical Radar Tools Window Help



Product Explorer X Pixel Info

Graphs: processing using block schemes

Navigation - [4] coh_... X Colour Manipulation - [...] Uncertainty Visualisation World View



der Bundeswehr

SNAP interface



File Edit View Analysis Layer Vector Raster Optical Radar Tools Window Help



Graphs: processing using block schemes

Data & results

Data
visualization

Navigation - [4] coh_... X Colour Manipulation - [...] Uncertainty Visualisation World View



der Bundeswehr

Demo: SNAP (short) tutorial

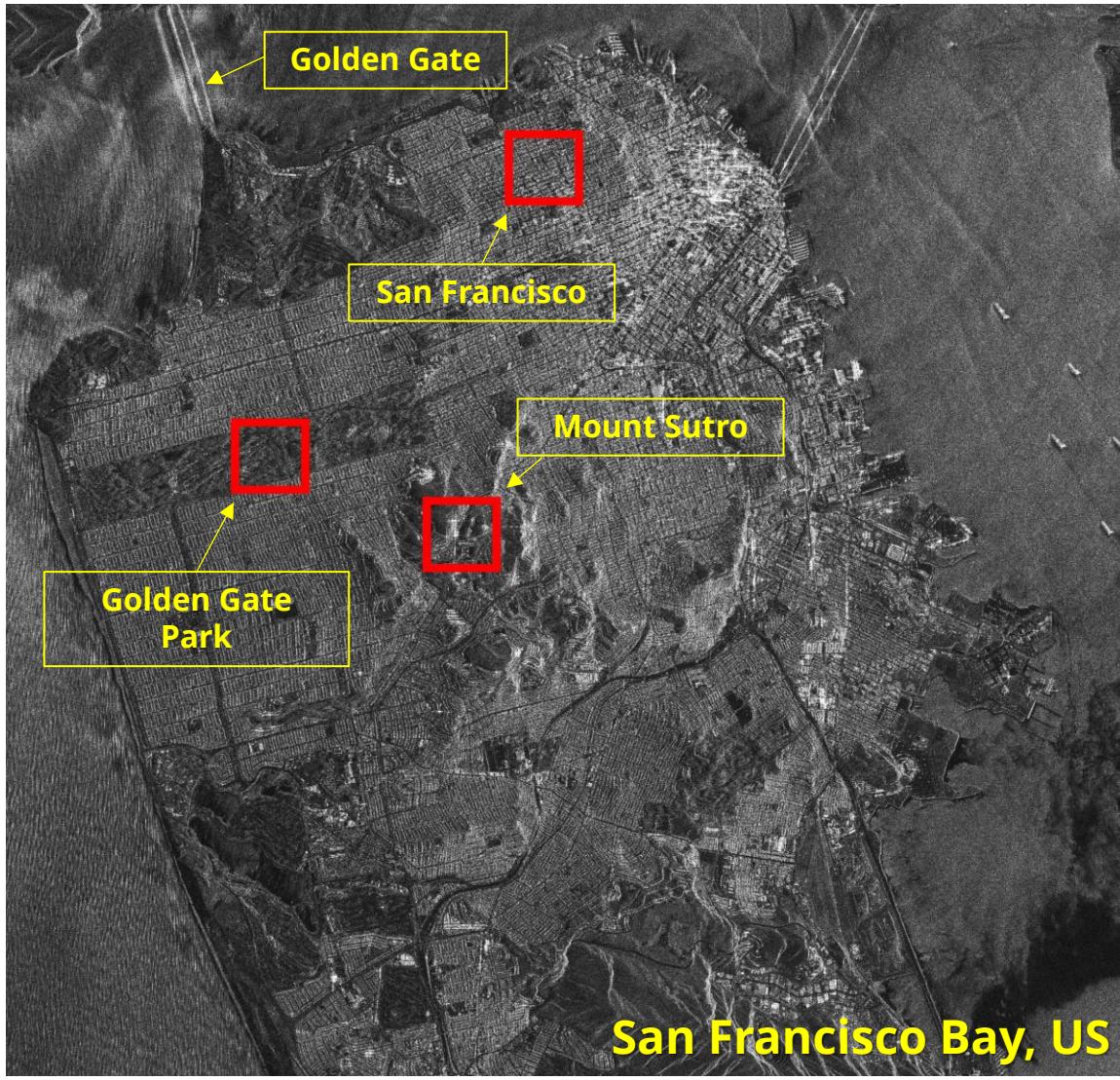
- Intro: *From zero to hero*
- SAR basics, missions and the Sentinel-1
- Machine Learning for SAR image analysis
 - Choice of the data and procurement
 - SAR processing
 - **Pre-processing for ML**
- Takeaways

Pre-processing of SAR data

Once we have created the correct quantities that we want to use, we are ready to create the actual input to our network. At this purpose we will see:

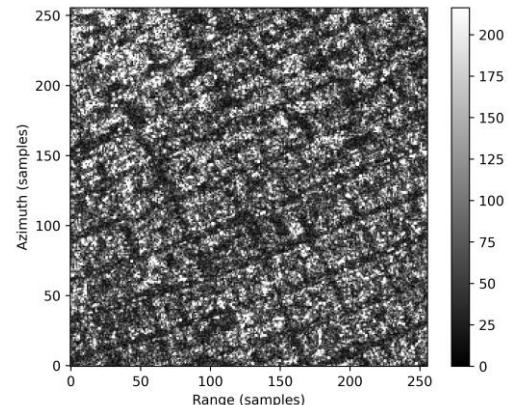
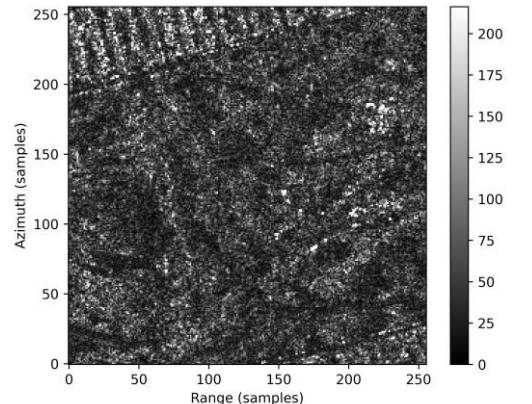
- Distribution of amplitude, intensity, and phase
- Distribution of real and imaginary parts of the SLCs
- ML-ready SAR data: how to pre-process
- Log-transformation: why and what implication it has

Sample SAR data

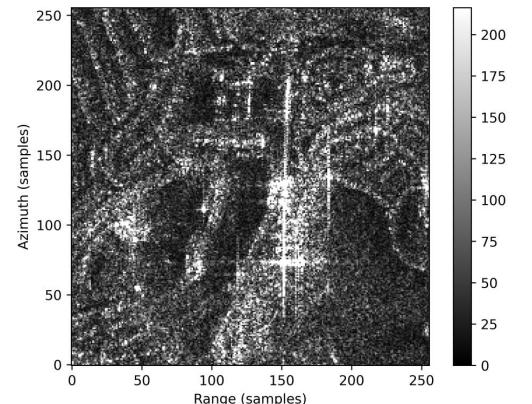


Type of scatterers:

(1) Distributed



(2) Extended

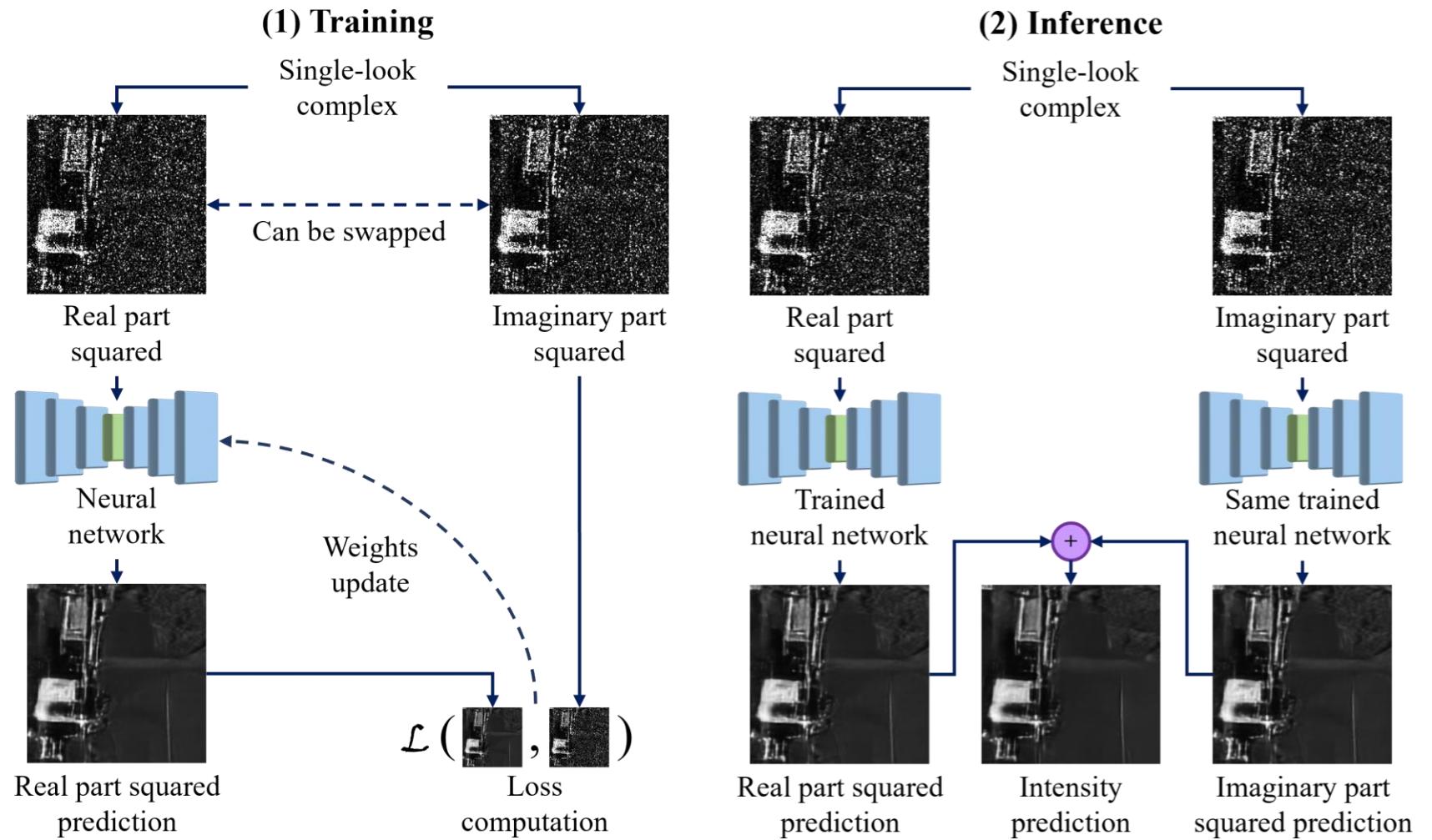


(3) Point

Demo: Jupyter notebook

Training examples: Self-supervised despeckling

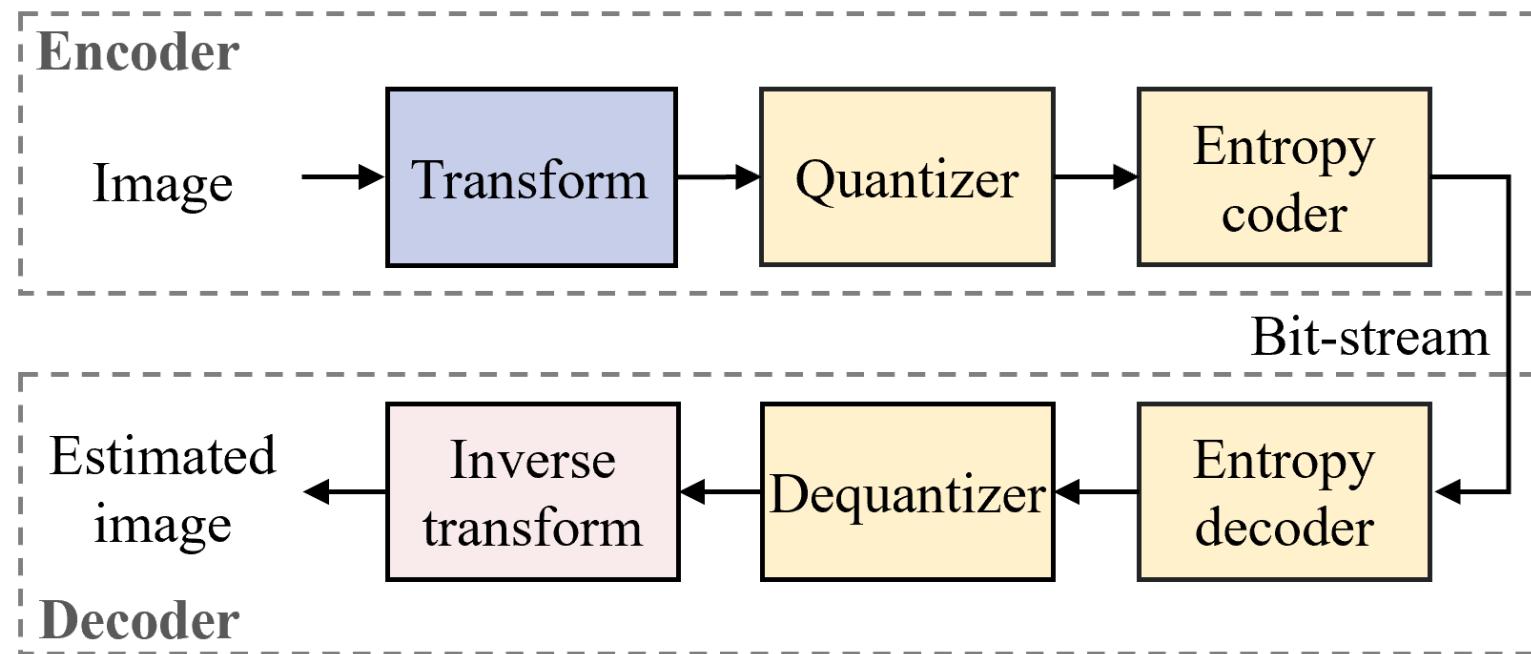
- Single Look Complex :
$$z = a + ib$$
- Gaussian, independent and identically distributed
- Intensity image :
$$I = a^2 + b^2 = Re^2 + Im^2$$



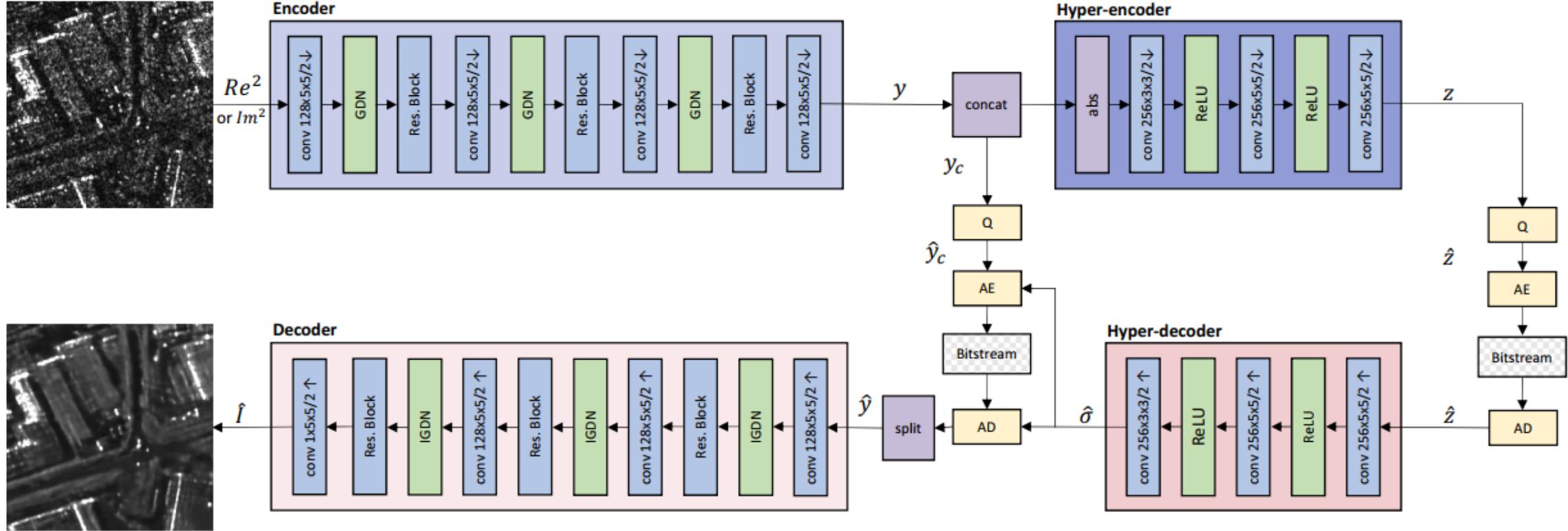
E. Dalsasso, L. Denis, and F. Tupin, "As If by Magic: Self-Supervised Training of Deep Despeckling Networks With MERLIN", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 60, pp. 1–13, 2022.

Joint SAR despeckling and compression

Objective: To obtain an algorithm capable of generating a compressed version of the SAR detected image as small (data size) as possible and reconstructing a despeckled version with the least possible distortion.



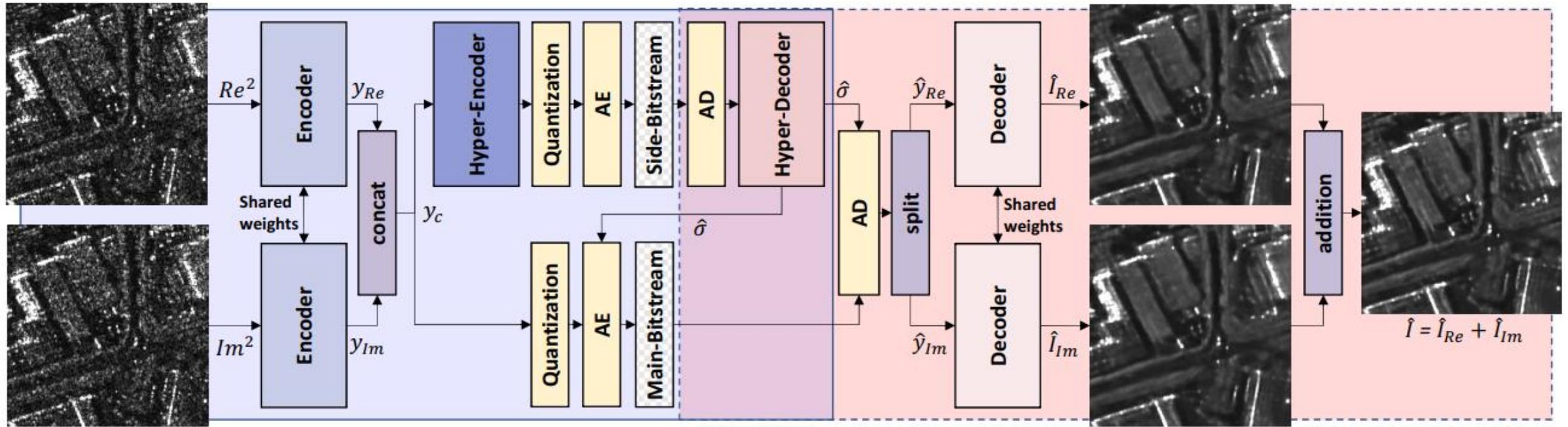
Joint SAR despeckling and compression: training



Sica, F., Foix-Colonier, N., & Amao-Oliva, J. (2024, July). Self-Supervised Joint SAR Image Compression and Despeckling. In *IGARSS 2024-2024 IEEE International Geoscience and Remote Sensing Symposium* (pp. 2188-2190). IEEE.

der Bundeswehr

Joint SAR despeckling and compression: estimation



Sica, F., Foix-Colonier, N., & Amao-Oliva, J. (2024, July). Self-Supervised Joint SAR Image Compression and Despeckling. In *IGARSS 2024-2024 IEEE International Geoscience and Remote Sensing Symposium* (pp. 2188-2190). IEEE.

- Intro: *From zero to hero*
- SAR basics, missions and the Sentinel-1
- Machine Learning for SAR image analysis
 - Choice of the data and procurement
 - SAR processing
 - Pre-processing for ML
- **Takeaways**

Takeaways

Most of the effort is required in data preparation

- Data processing is highly **application-dependent**
- A **deep understanding of the problem** you aim to solve is crucial

Preprocessing challenges

- Standard preprocessing techniques may not be applicable or are more complex for SAR data
- **Preprocessing choices** can complicate post-processing or even **compromise** results

In-depth SAR domain knowledge is essential for specific applications

- Understanding key concepts such as **Beta nought**, **Sigma nought**, and **Gamma nought**
- Familiarity with **polarizations**, **acquisition geometries**, and **acquisition modes**
- Awareness of **data availability** for your region or application

Training models must be adapted to the **unique statistical properties** of SAR signals.

Thank you for the attention

*Dr. Eng. Francescopaolo Sica
Deputy Head - Earth Observation Lab
Faculty of Aerospace Engineering
Institute for Space Technology and Space Applications*

University of the Bundeswehr Munich
Werner-Heisenberg-Weg 39, 85579 Neubiberg, Germany

Francescopaolo.Sica@unibw.de

Tel.: +498960043685

Mobile: +491705743074