HYDROSAR – WEATHER-RELATED HAZARD INFORMATION FROM SAR

Contributors:

F.J Meyer[1], A. Molthan[2], L. Schultz[2], J. Bell[2], B. Osmanoglu[3], M.J. Jo[3], D.B. McAlpin[1], T. Meyer[1], B. Kubby[1], A. Lewandowski[1], B. Chapmann[4], M. Matin[5], R. Thapa[5], B. Bajracharya[5], K. Tsering[5]

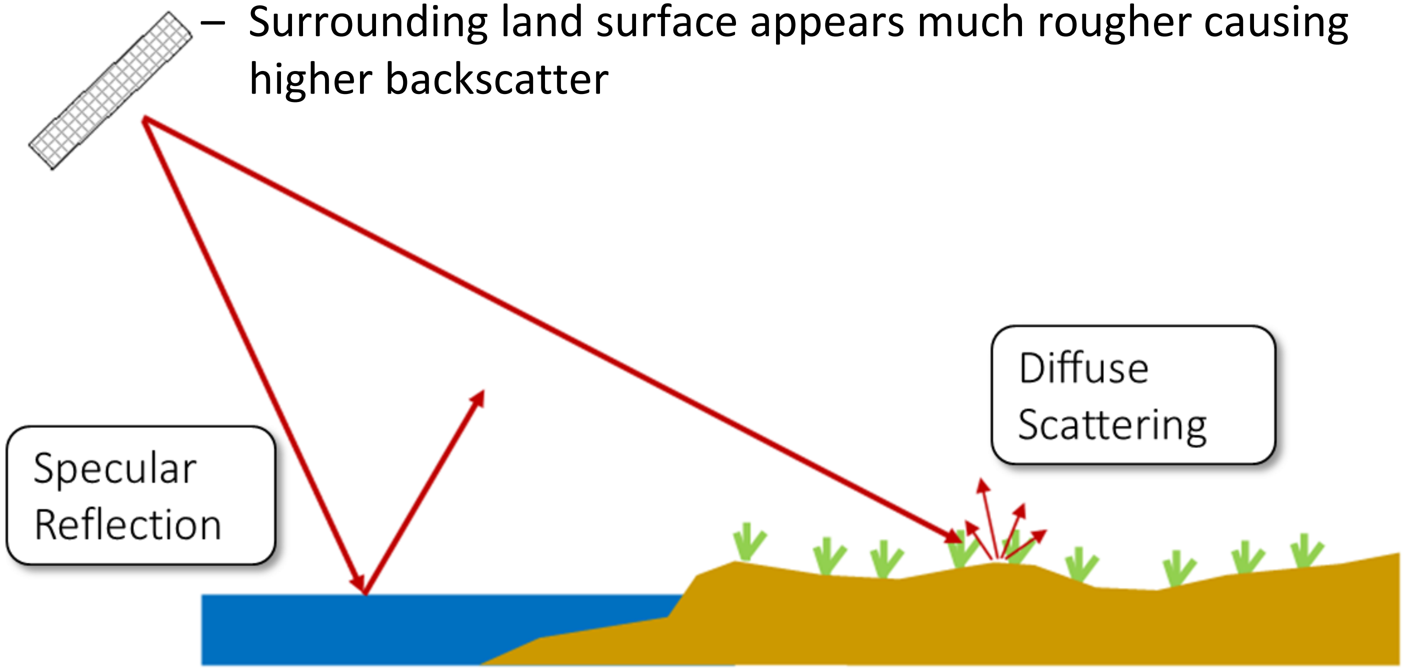
[1]Geophysical Institute, University of Alaska Fairbanks, Fairbanks; [2]NASA Marshall Space Flight Center, Huntsville, AL; [3]Goddard Space Flight Center, Greenbelt, MD; [4]Jet Propulsion Laboratory, Pasadena, CA; [5]ICIMOD, Kathmandu, Nepal

Lecture 3: Flood Extent and Flood Depth Mapping from SAR- The HydroSAR HYDRO30 and FD30 Algorithms

SURFACE WATER SIGNATURES IN SAR

Surface Water Signatures in SAR Amplitude Images

- **Mapping of water surfaces (waterbodies, wetlands, flooded areas) based on different backscatter regimes of water surface and land surface**
  - Calm water surfaces appear smooth and cause specular reflection leading to low backscatter
  - Surrounding land surface appears much rougher causing higher backscatter



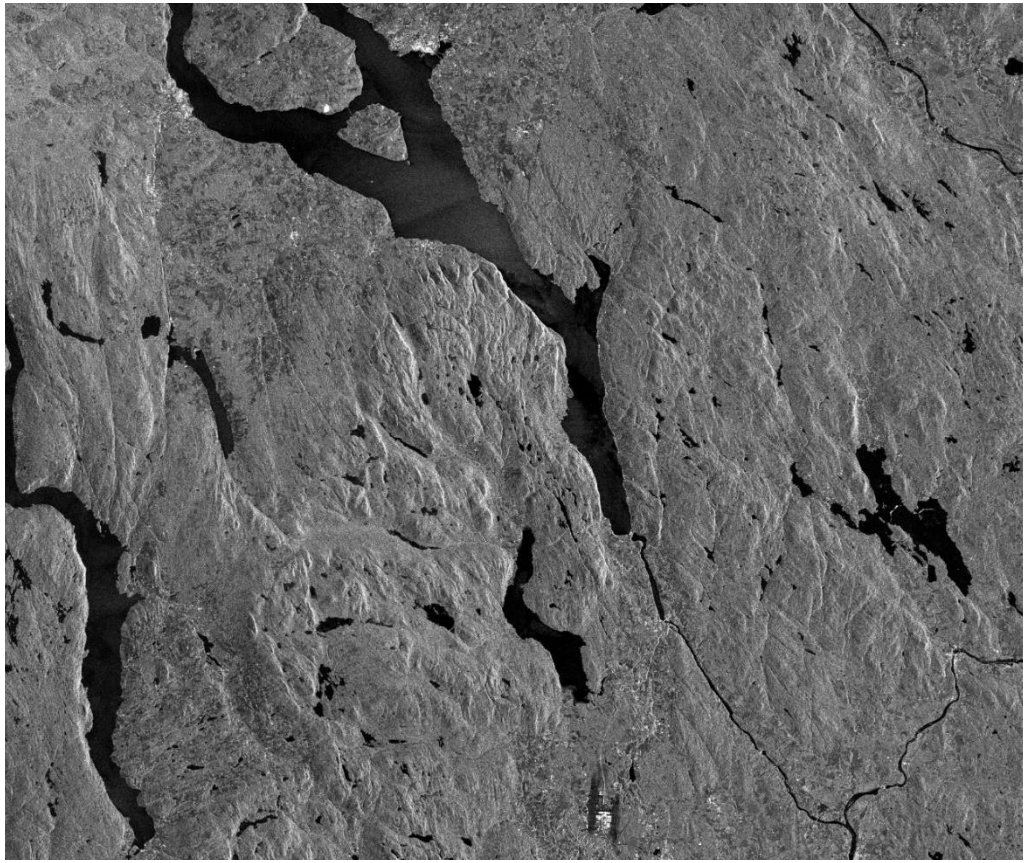


Fig.: Lake Mjosa, Norway, observed by ENVISAT ASAR Image Mode, 12 Dec 2003 (©ESA Multimedia Gallery)

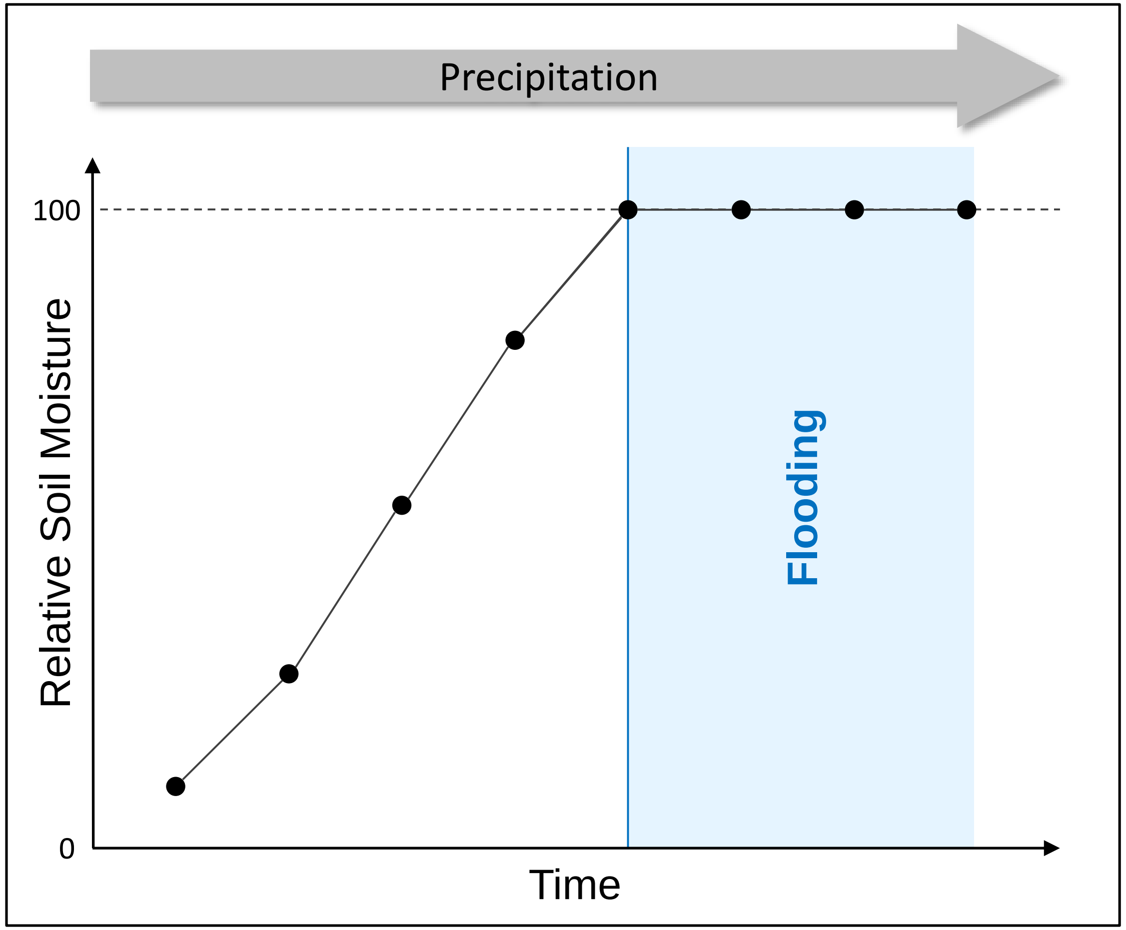
Surface Water Signatures in SAR Amplitude Images

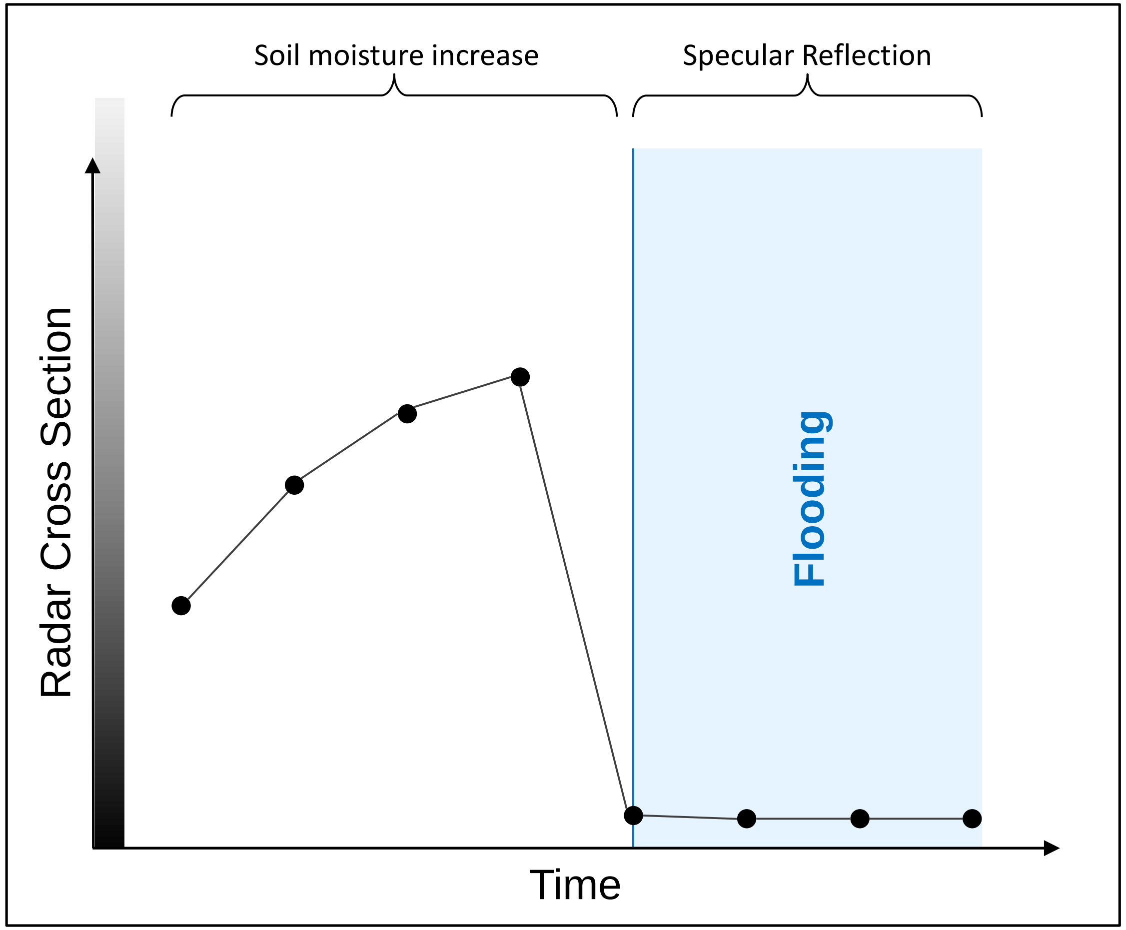
- **Waterbody mapping from SAR data is based on:**
  - **Unique sensitivity to variations in soil moisture** and presence/absence of surface water or water under vegetation
  - **Specular reflection at standing surface water patches → dark backscatter**
  - **In vegetated areas:**
    - Long wavelengths preferable due to better penetration of vegetation cover
    - Enhanced return if tree cover underlain by water (double bounce effect – smooth water surface – vertical vegetation structures)
    - Enhanced backscatter for wet soils

Surface Water Signatures in SAR Amplitude Images

1. Open Lands – Areas with Low Vegetation Cover

- **Relative SAR response over open lands as precipitation increases:**

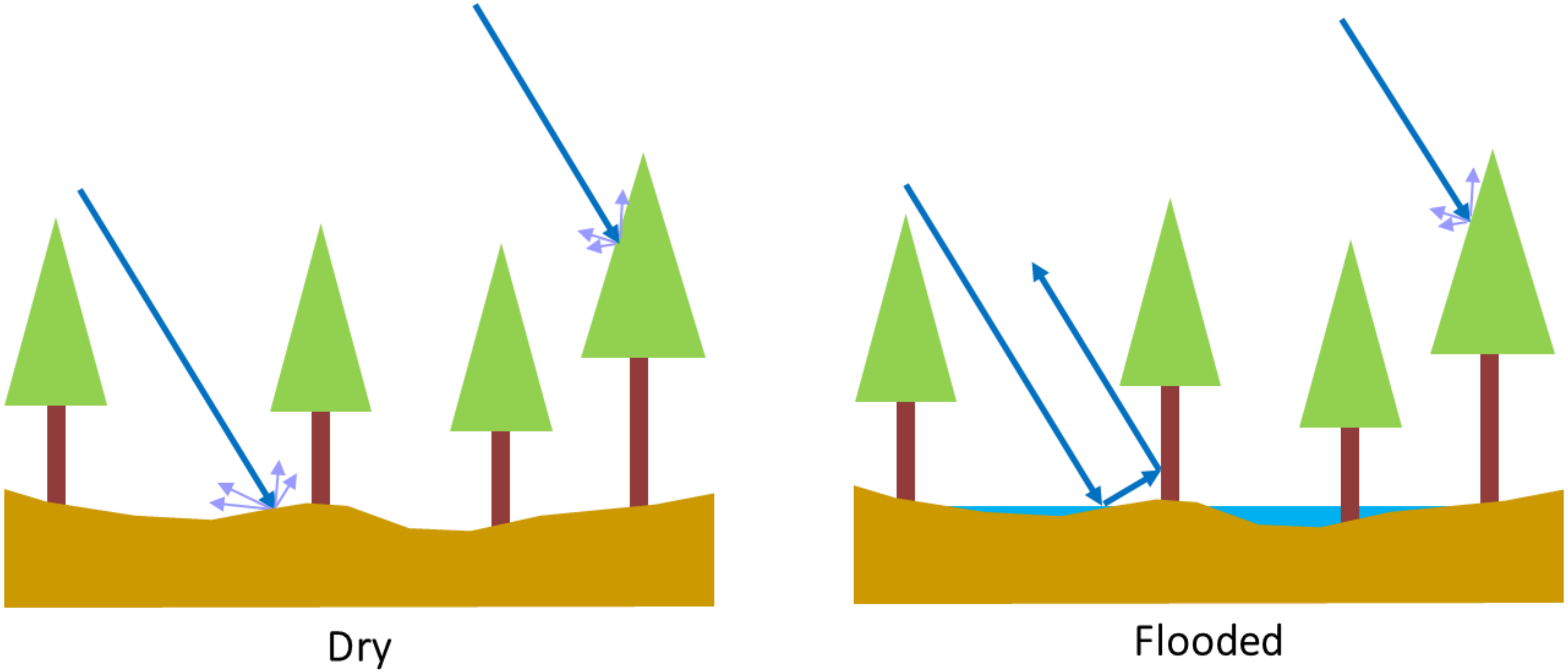




Surface Water Signatures in SAR Amplitude Images

2. Flooding under Vegetation Canopies

- **Mapping inundation under vegetation canopies:**



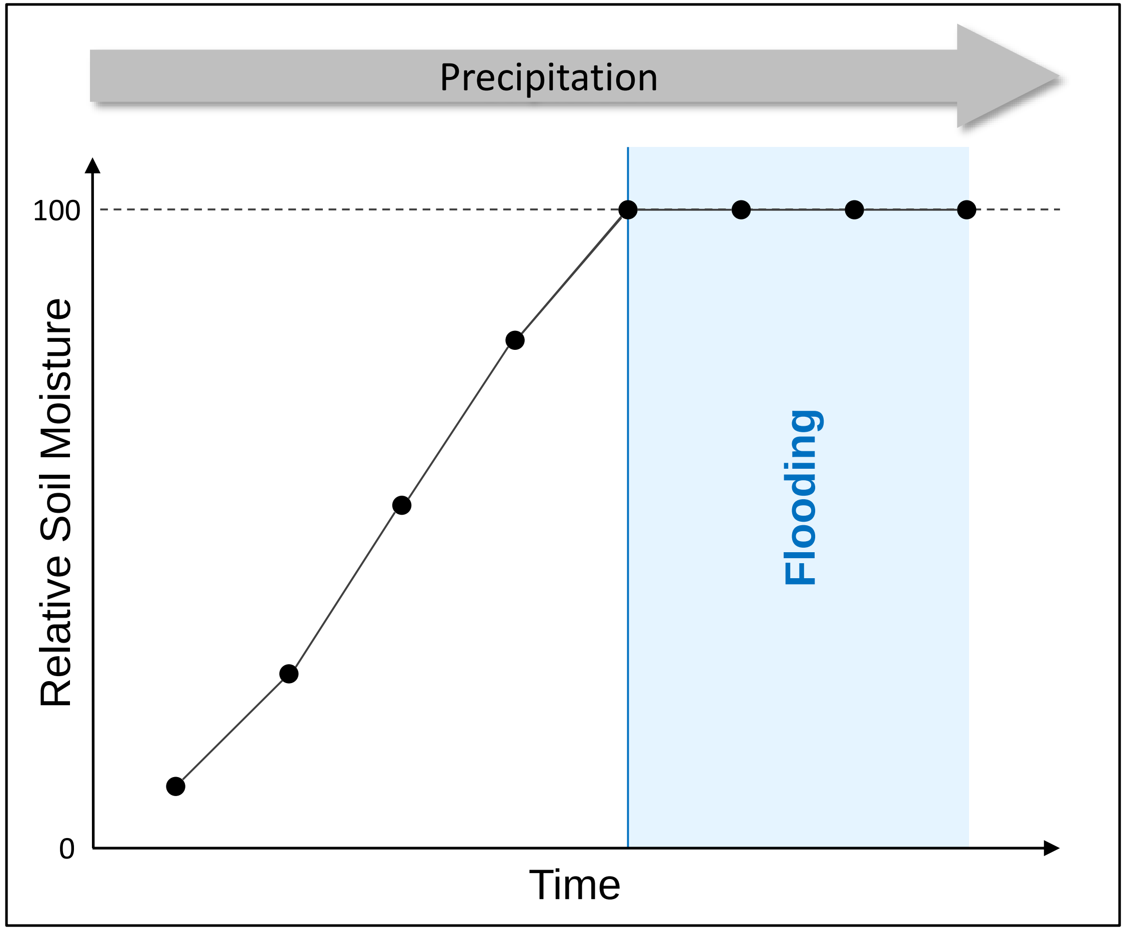
Enhanced return if tree cover underlain by water (double bounce effect – smooth water surface – vertical vegetation structures)

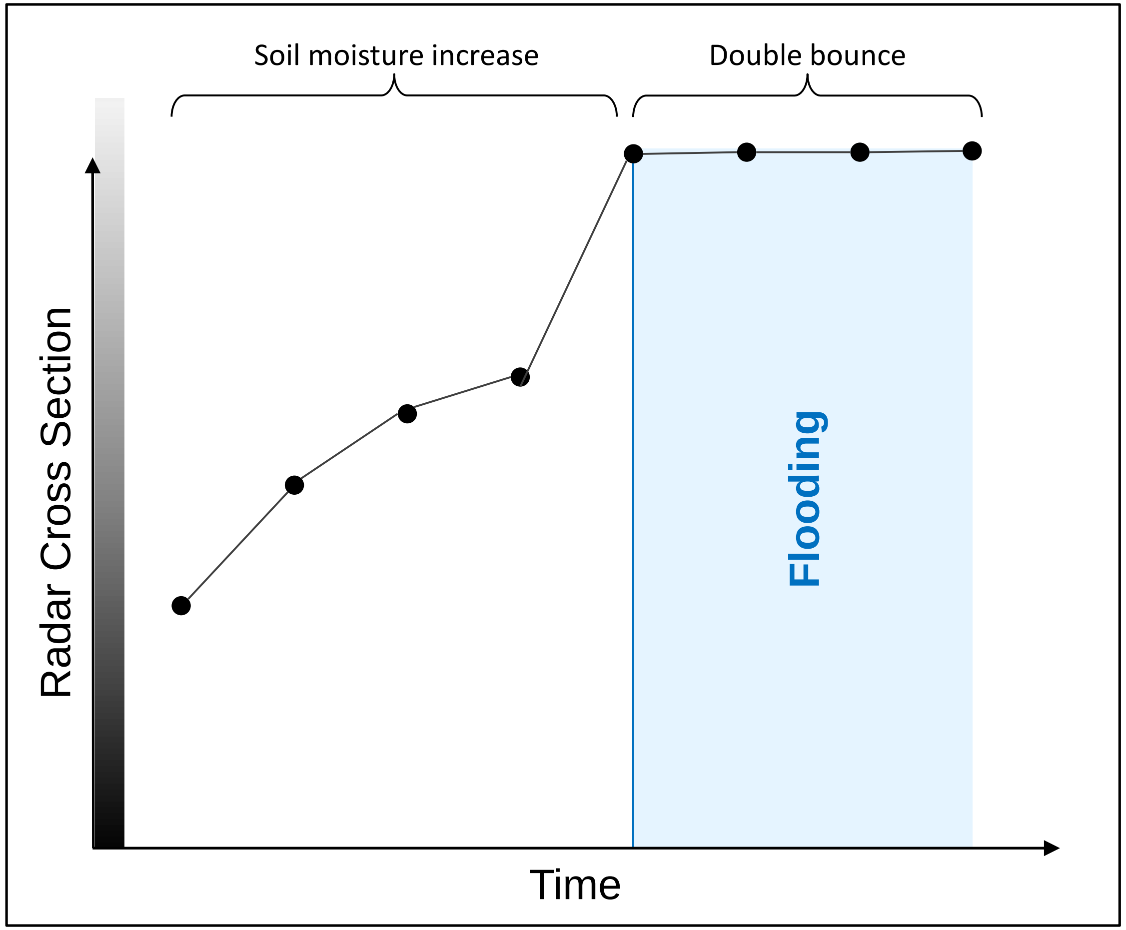
Fig.: Inundation effects on radar backscatter for forest stands (after Bourgeau-Chavez et al., 2009)

Surface Water Signatures in SAR Amplitude Images

2. Flooding under Vegetation Canopies

- **Relative SAR response in vegetated canopies as precipitation increases:**





Surface Water Signatures in SAR Amplitude Images

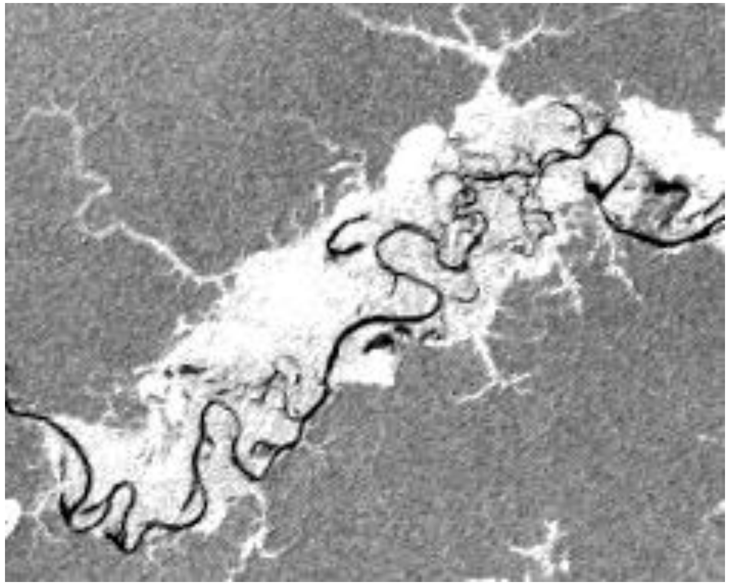
2. Flooding under Vegetation Canopies - Example

Varzea Dry Season

Varzea Wet Season

JERS-1 Dry Season

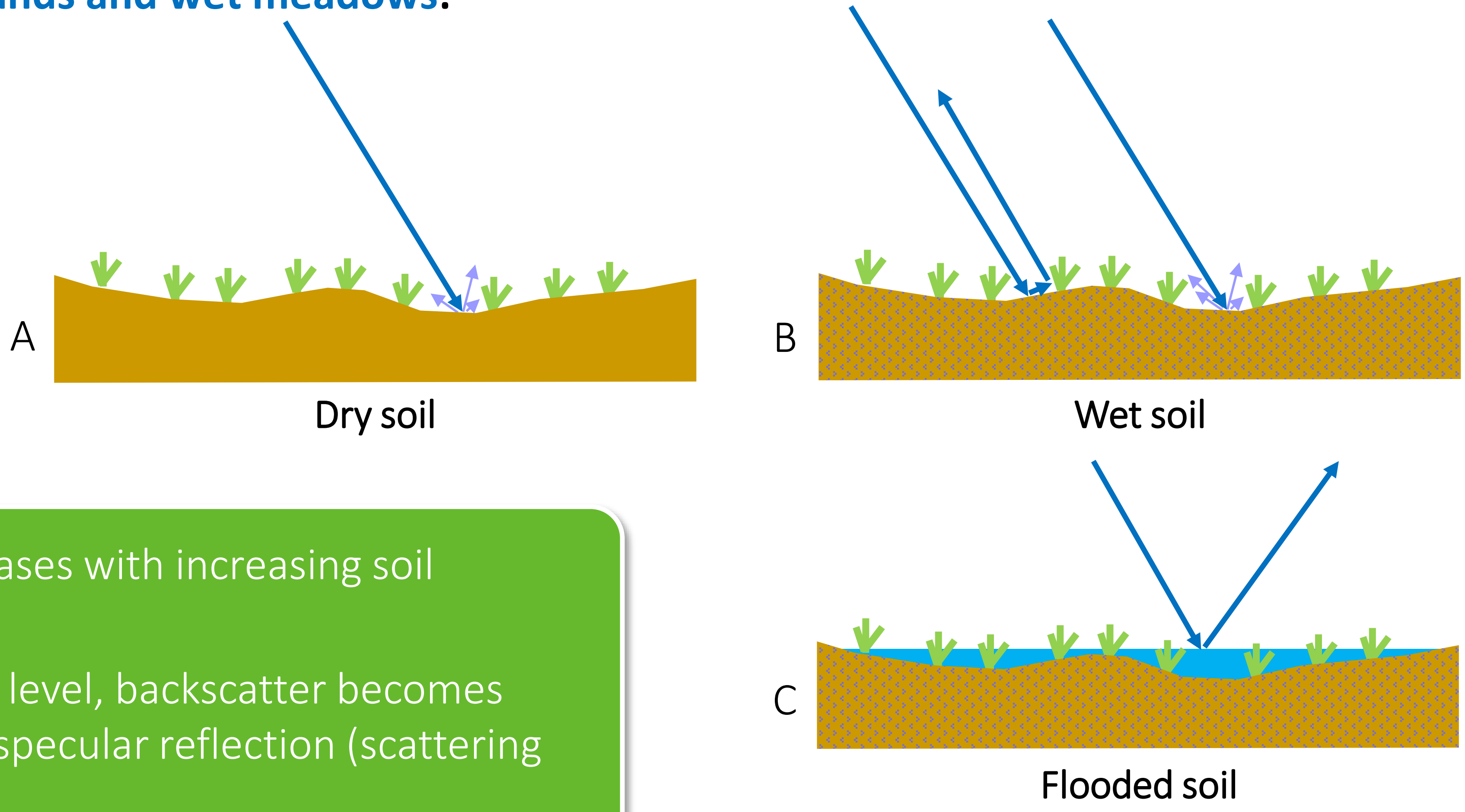
JERS-1 Dry Season



Surface Water Signatures in SAR Amplitude Images

3. Flooding in Crop Lands

- **Mapping inundation in crop lands and wet meadows:**



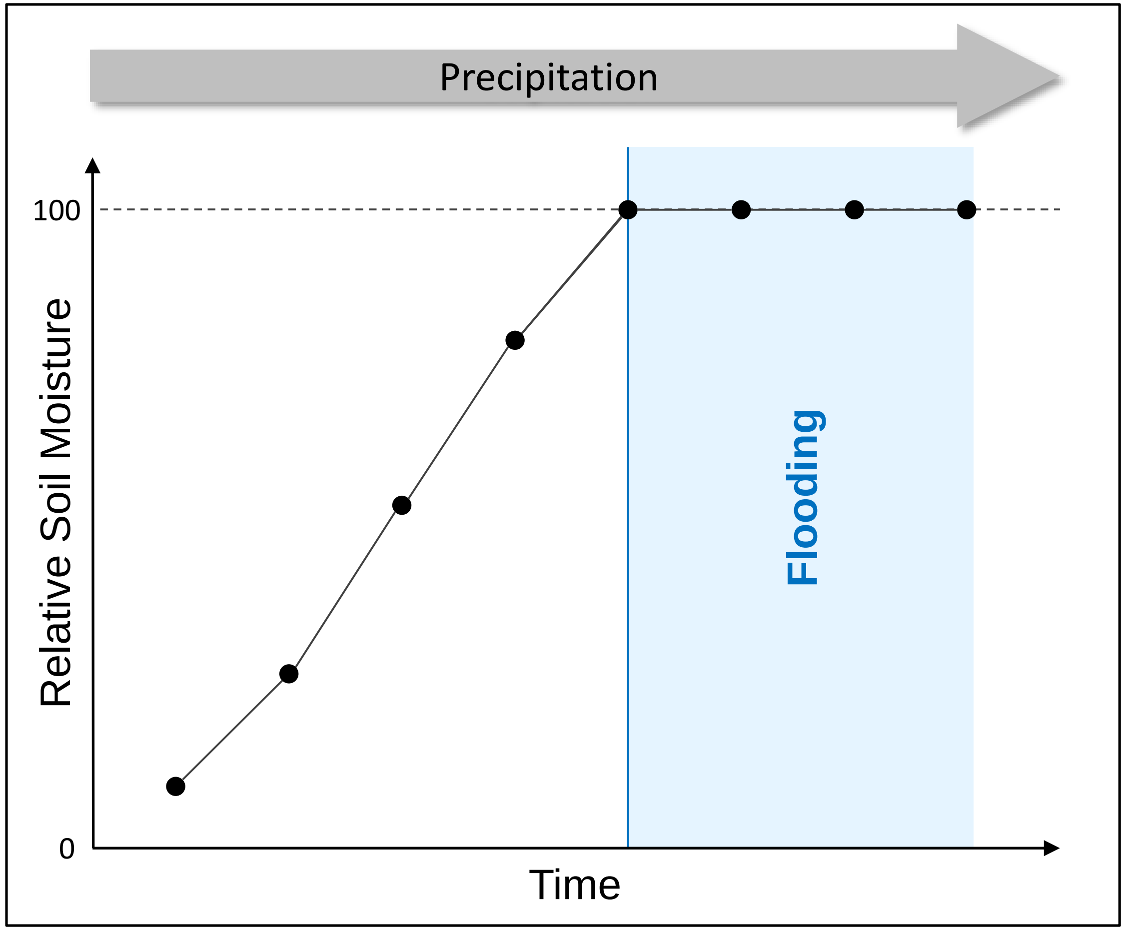
- A to B: First backscatter increases with increasing soil moisture
- C: then with increasing water level, backscatter becomes weaker with more and more specular reflection (scattering away from the sensor).

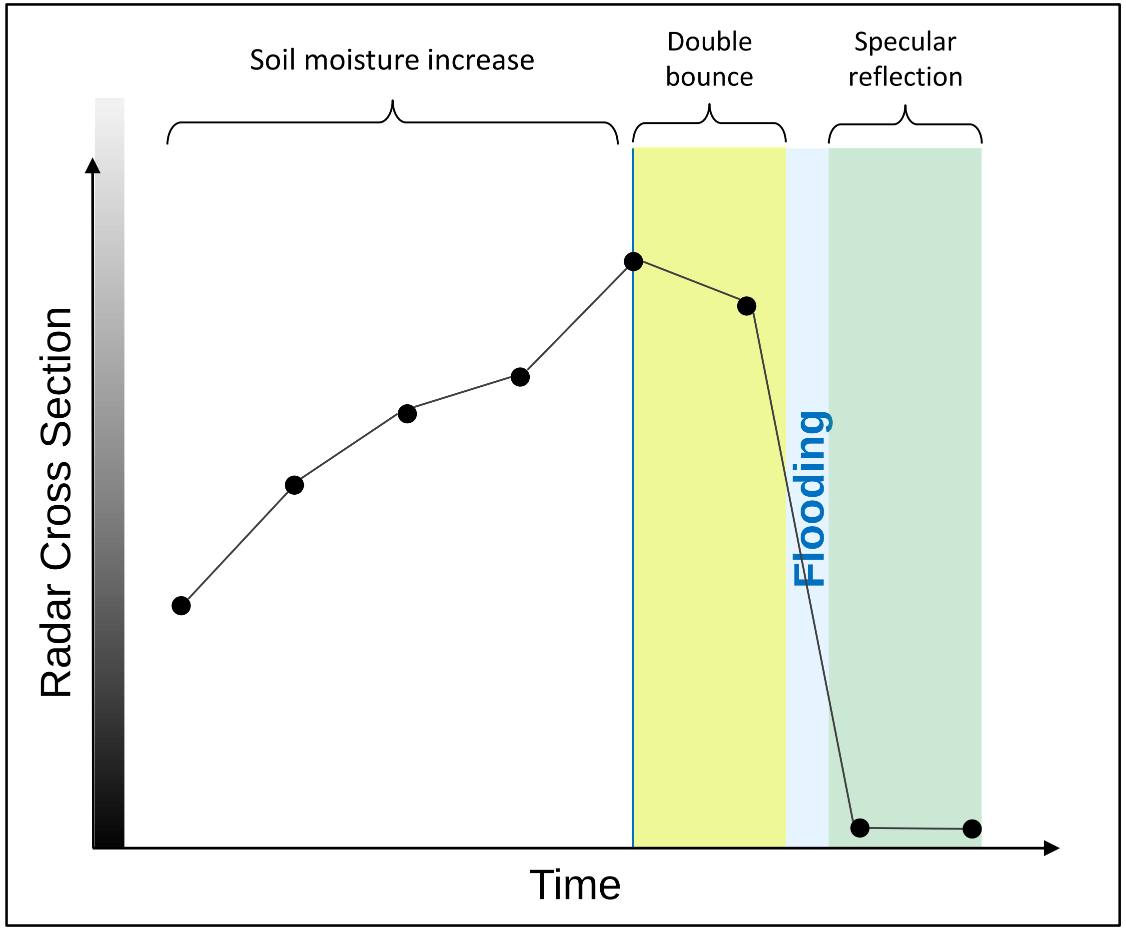
Fig.: Inundation effects on radar backscatter for wet meadows (after Bourgeau-Chavez et al., 2009)

Surface Water Signatures in SAR Amplitude Images

3. Flooding in Crop Lands

- **Relative SAR response in crop lands as precipitation increases:**

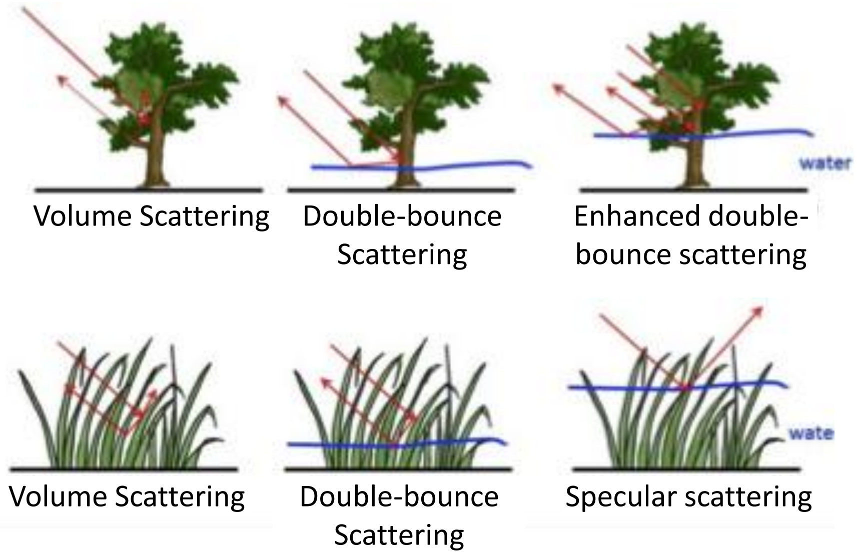




Vegetation Inundation Mapping using SAR

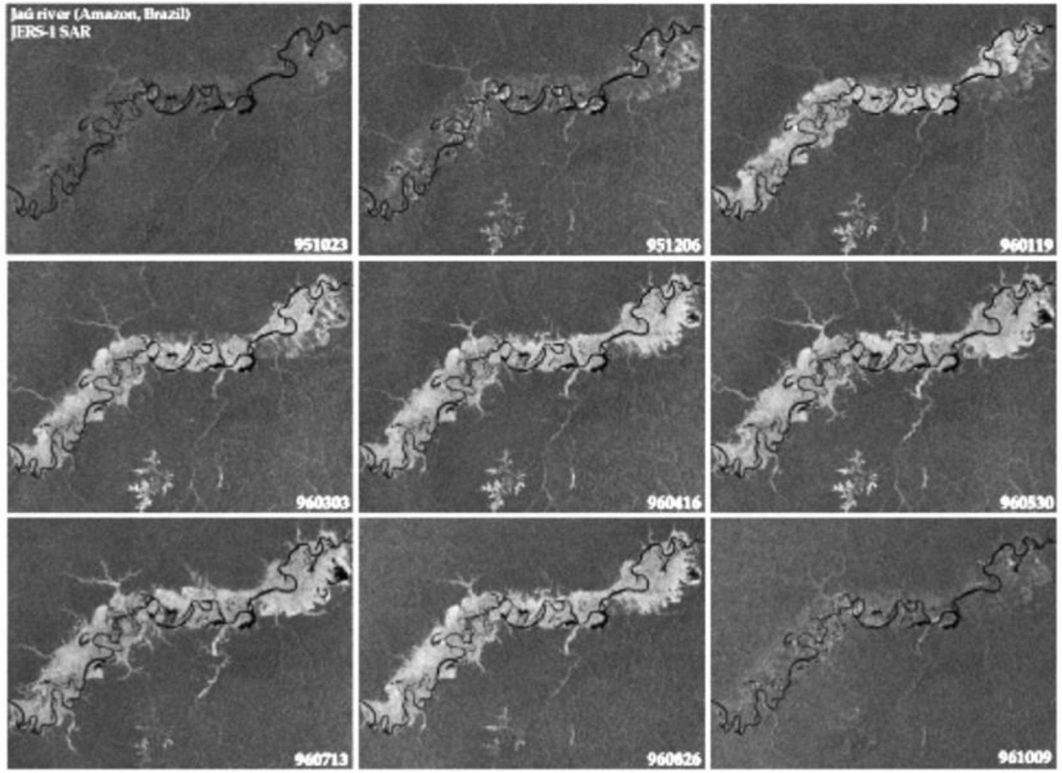
SAR observations (especially at L-band) are established as a reliable tool for mapping vegetation inundation

Observation Principle for forests and crops



- C-band sensors limited performance in densely vegetated areas
- Existing L-band SARs have limited coverage to accurately capture spatial extent and temporal variations of inundation over wetlands.
- Future sensors such as NISAR will acquire dual-pol data globally over all wetlands twice per 12 day orbit cycle → contribution to understanding wetland hydrology and the impacts of climate variations

JERS-1 L-band SAR (HH only) data showing inundation dynamics for 1 year (Jau River, Brazil)



Rosenqvist et al, 1998.

SURFACE WATER MAPPING METHODS

Surface Water Mapping Approaches from SAR Amplitude Images

Mapping of wetlands and waterbodies using similar or the same methods

- **One simple and common method for waterbody mapping is thresholding**
  - Backscatter below threshold classified as water body or inundated land
  - Backscatter above threshold classified as dry land
  - Thresholds derived from image histograms
  - Results in binary mask (0 = land, 1 = water body)

Fig.: L-HH backscatter cross sections for three different test sites (Horritt et al., 2003)

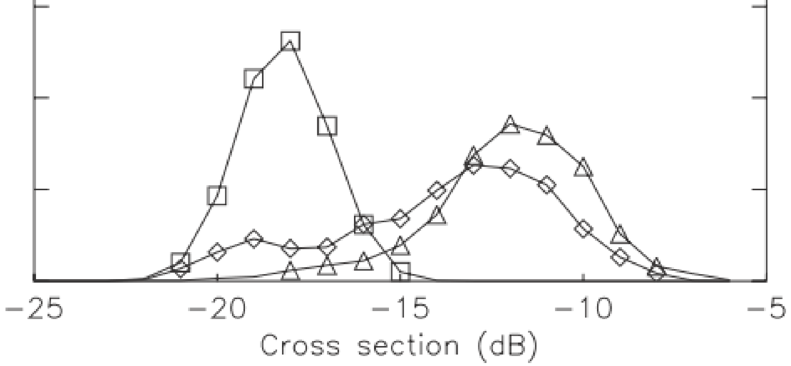
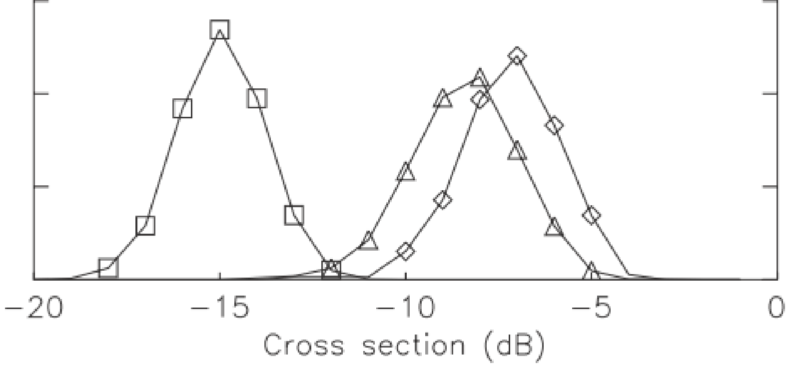


Fig.: C-VV backscatter cross sections for three different test sites (Horritt et al., 2003)



◇ Flooded vegetation △ Unflooded vegetation □ Open water

Surface Water Mapping Approaches from SAR Amplitude Images

- **Mapping water bodies using active contours ("snakes")**
  - Statistical model for identifying boundaries of image objects
  - Smooth curve initialized near target object (Target object: approx. homogenous area)
  - Snake is iteratively refined to optimize relation between internal and external energy (or forces):

$$E_{total} = E_{internal} + E_{external}$$

Tends to preserve smoothness (→ $E_{internal}$)

Attracts snake towards object edges (→ $E_{external}$)

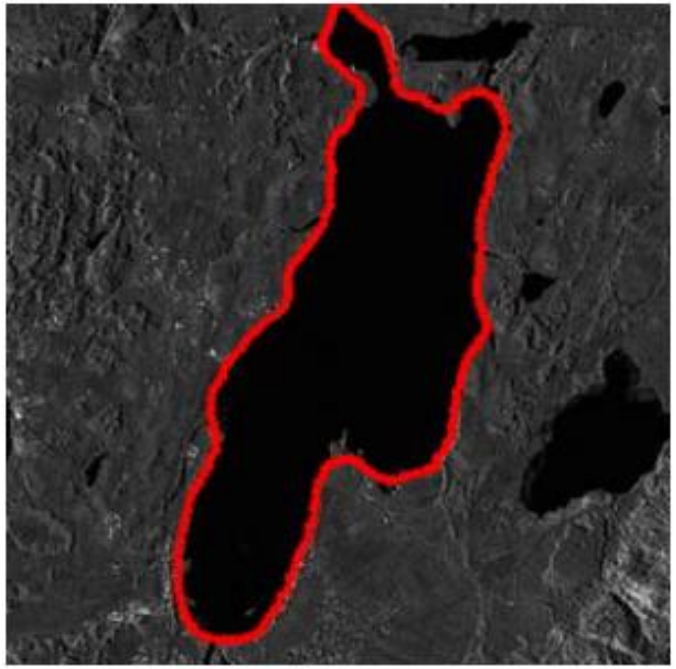


Fig.: Lake Forggensee delineated using active contours, HH-polarized TerraSAR-X Spotlight data acquired on July 17, 2008 (Hahmann & Wessel, 2010)

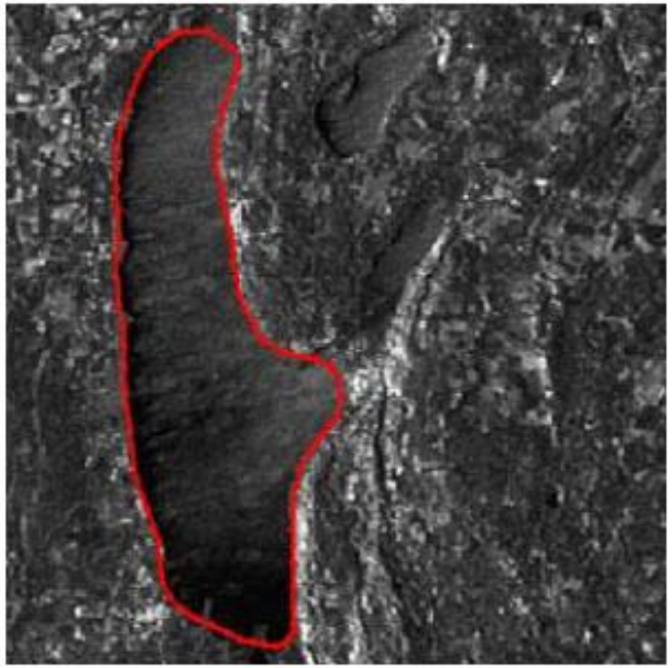


Fig.: Lake Ammersee delineated using active contours, HH-polarized TerraSAR-X StripMap data acquired on November 30, 2008 (Hahmann & Wessel, 2010)

Surface Water Mapping Approaches from SAR Amplitude Images

Other Methods for Water Body Mapping:

- **Wetland extent detection using change detection (e.g. difference images)**
  - Flooding of usually dry land
  - Changes in surface wetness/soil moisture

See Slide 32 - 35

- **Supervised image classification of multi-temporal SAR data**
- **Object-based classification of multi-temporal SAR data**

Surface Water Mapping Approaches from SAR Amplitude Images

Other Methods for Water Body Mapping:

- **Texture based classification**
- **Region growing algorithms**
- **Object based classifications**

- **Single-frequency, single-polarization radar backscatter can be used**

- **Multi-temporal analysis requires:**
  - High quality geometric correction and co-registration
  - High quality radiometric calibration and correction
  - Matching spatial resolution

Surface Water Mapping Approaches from SAR Amplitude Images

- **Example of difference images and simple change detection for inundation mapping**

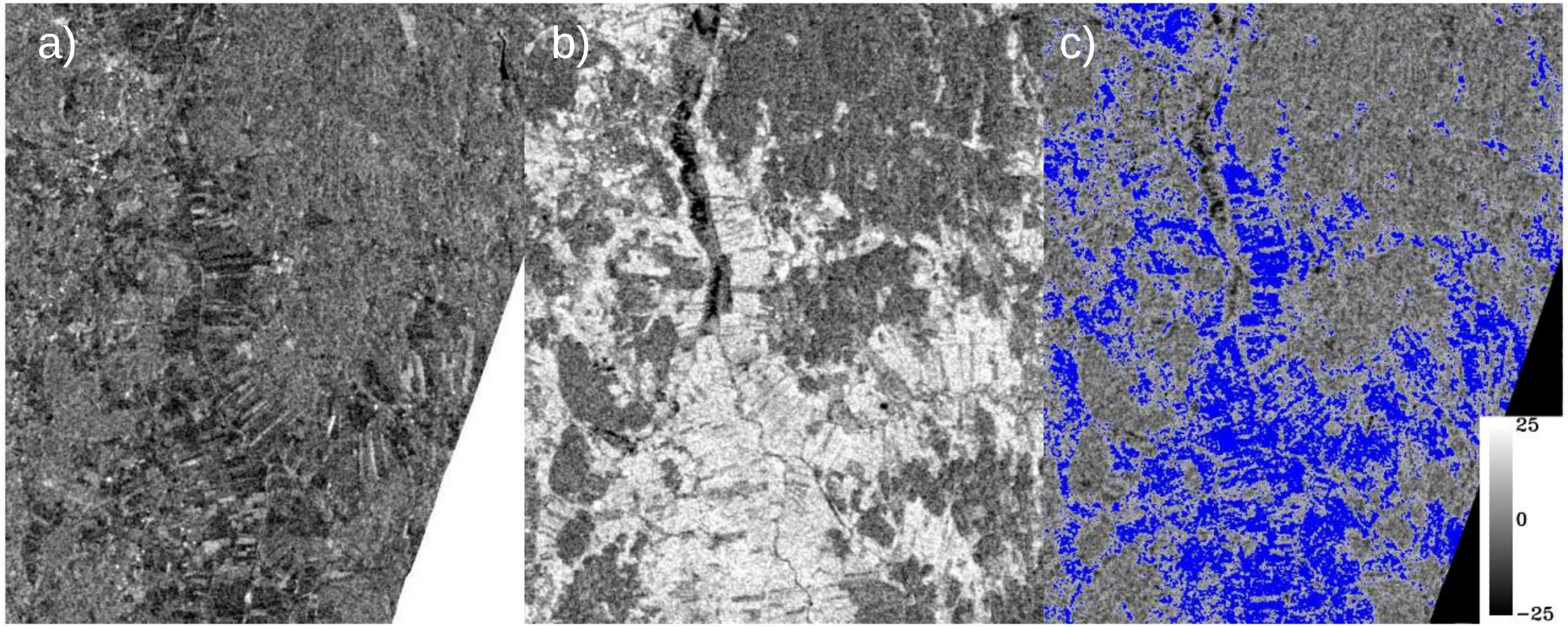


Fig.: Lapuanjoki area under normal (a) and flooded (b) conditions; difference image (c) shows flooded forest; ERS SAR Data (30m spatial resolution, acquired on 10th and 24th Jul 2001) (Solbø & Solheim, 2004)

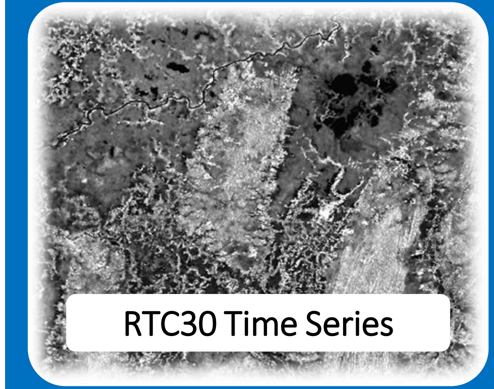
THE HYDROSAR FLOOD HAZARD MAPPING APPROACH

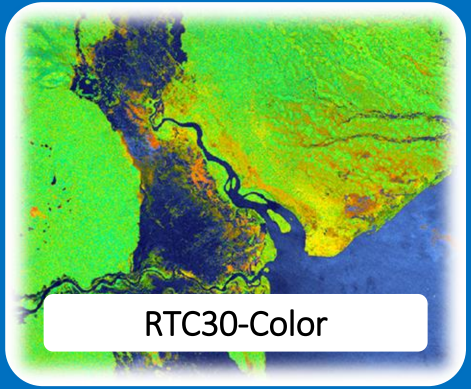
The HYDRO30, FD30, and CCD30 Products

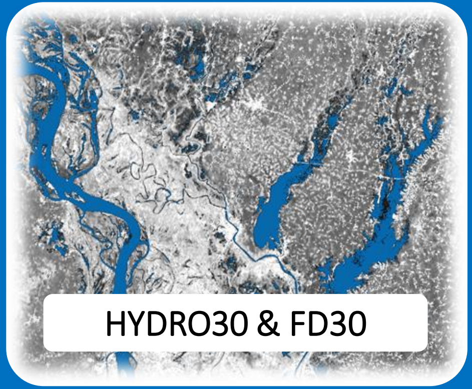
The HydroSAR Approach

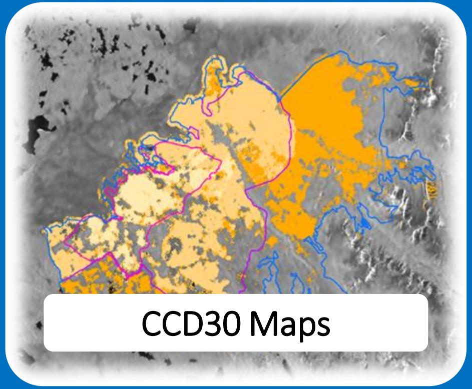
Algorithms, Products, and Tools for Monitoring Weather-Related Hazards

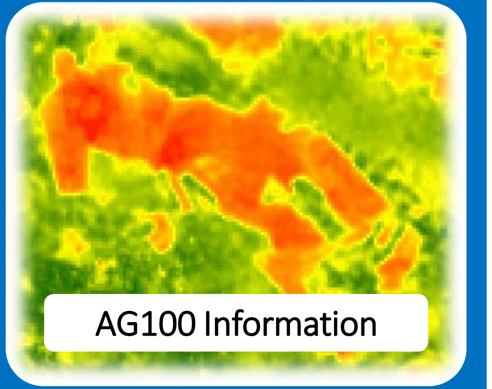
SAR-based value-added products







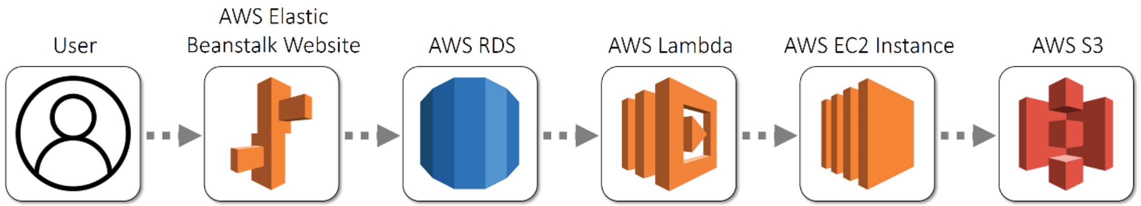




Cloud-based Computational Resources

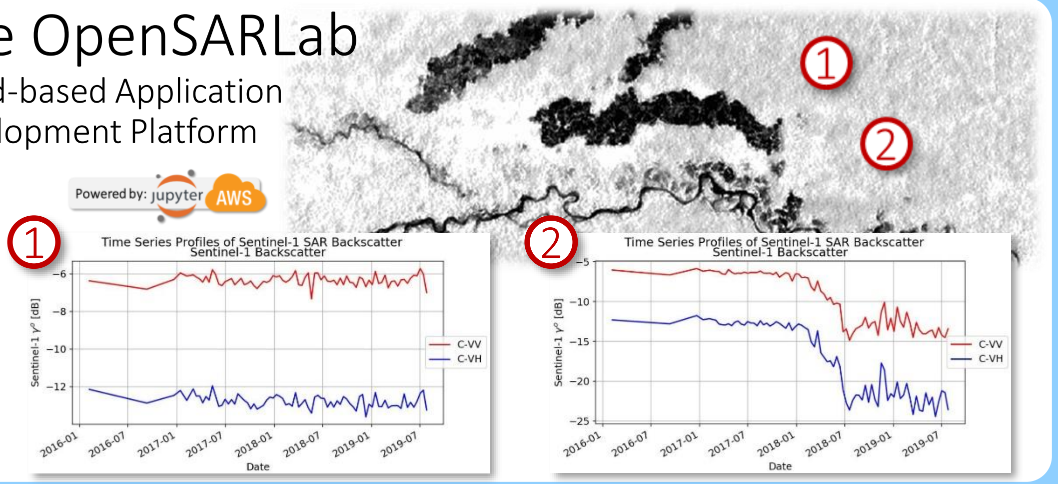
Automatic Cloud-based Production Pipelines

Exercising mature algorithm large scale
using cloud-based workflows



The OpenSARLab

Cloud-based Application
Development Platform



THE HYDROSAR HYDRO30 SURFACE WATER EXTENT PRODUCT

Surface Water Mapping Approaches from SAR Amplitude Images

- **One simple and common method for waterbody mapping is thresholding**
  - Contrast between land and open water surface increases with increasing incidence angle

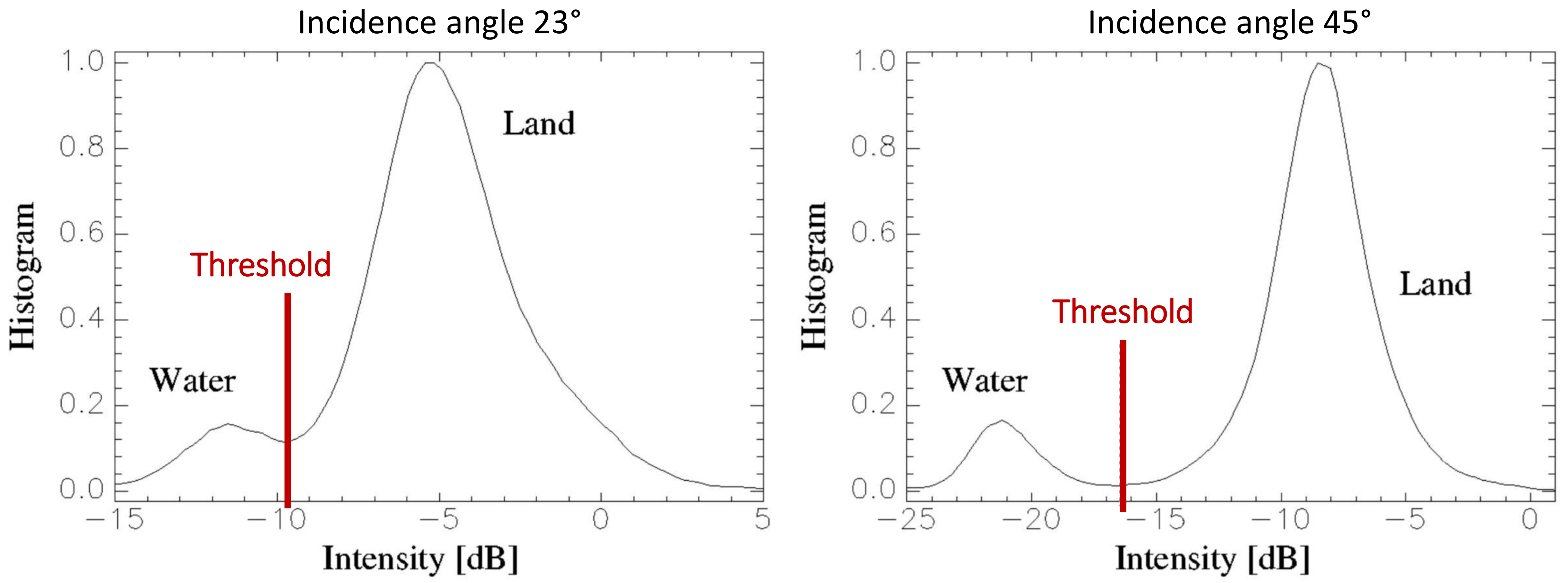


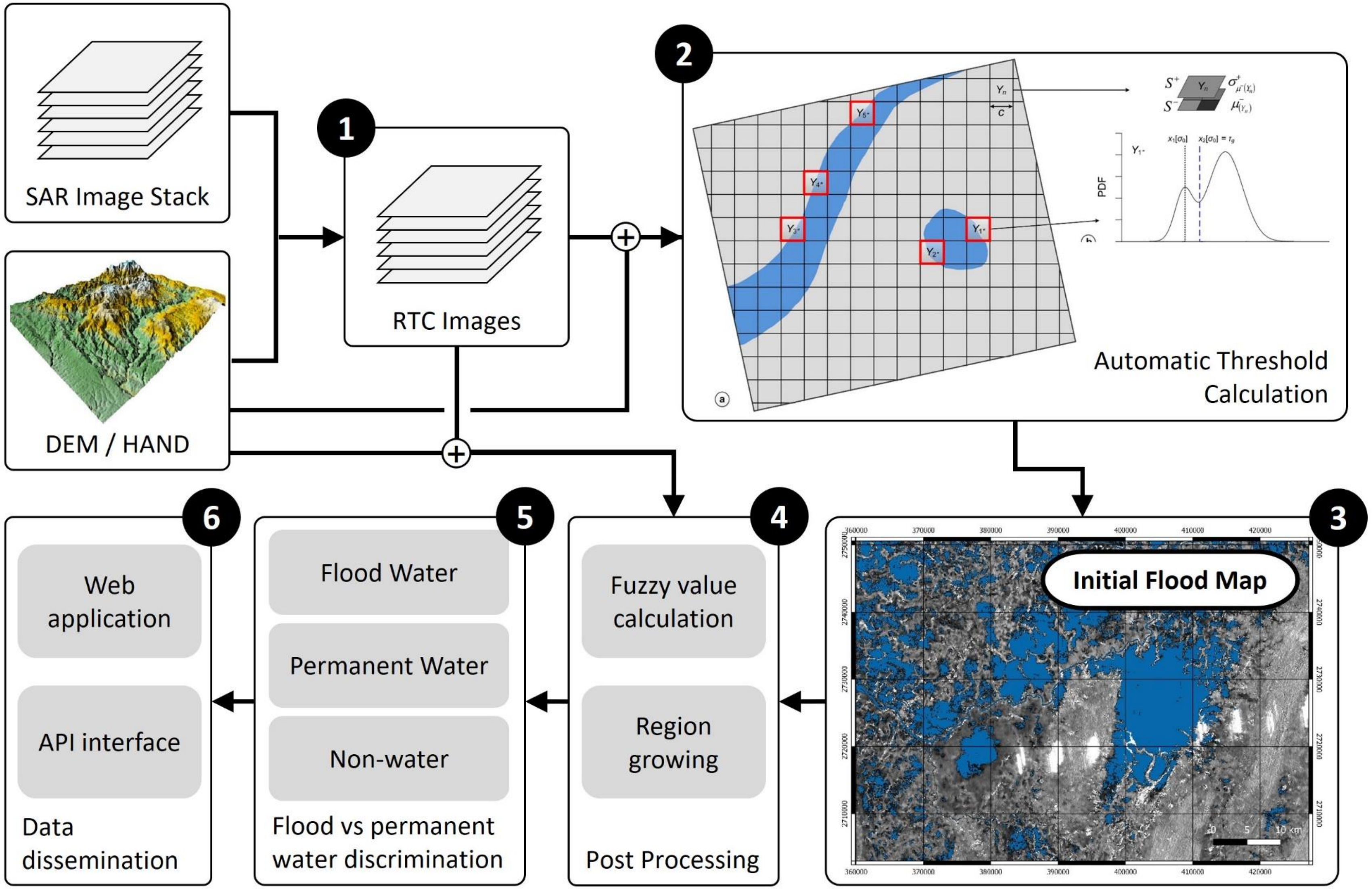
Fig.: Histogram of two Radarsat SAR images of the same region acquired under different incidence angles (Solbø & Solheim, 2004)

The HydroSAR HYDRO30 Surface Water Extent Product

Concept of Adaptive Threshold-based Surface Water Mapping Approach

HydroSAR water mapping approach composed of 6 steps:

1. Image Geocoding and Calibration (RTC Processing)
2. Automatic and adaptive threshold calculation
3. Initial flood map creating
4. Post-processing to remove false alarms
5. Discrimination of permanent and flood-related water
6. Data dissemination



The HydroSAR HYDRO30 Surface Water Extent Product

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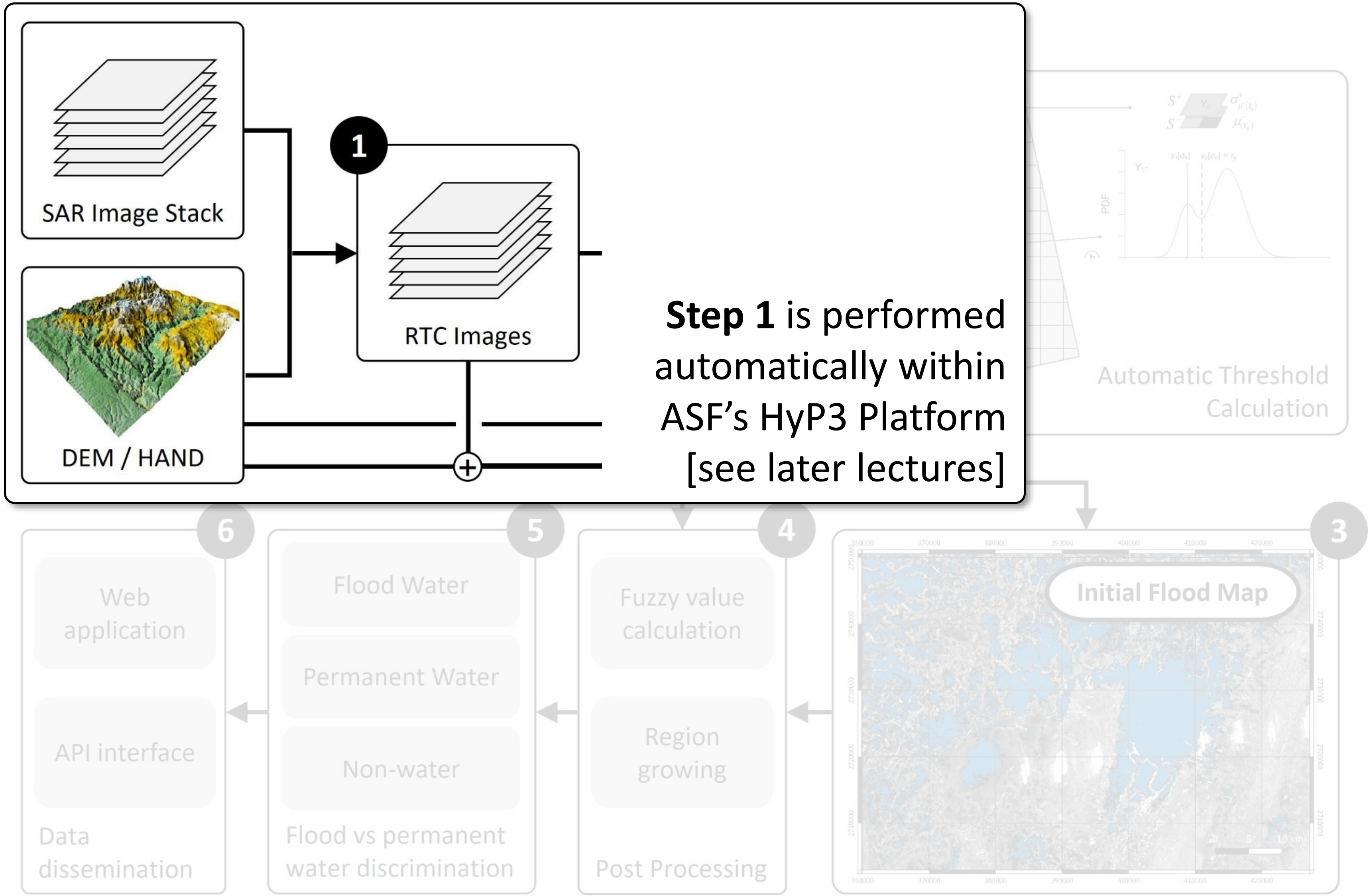
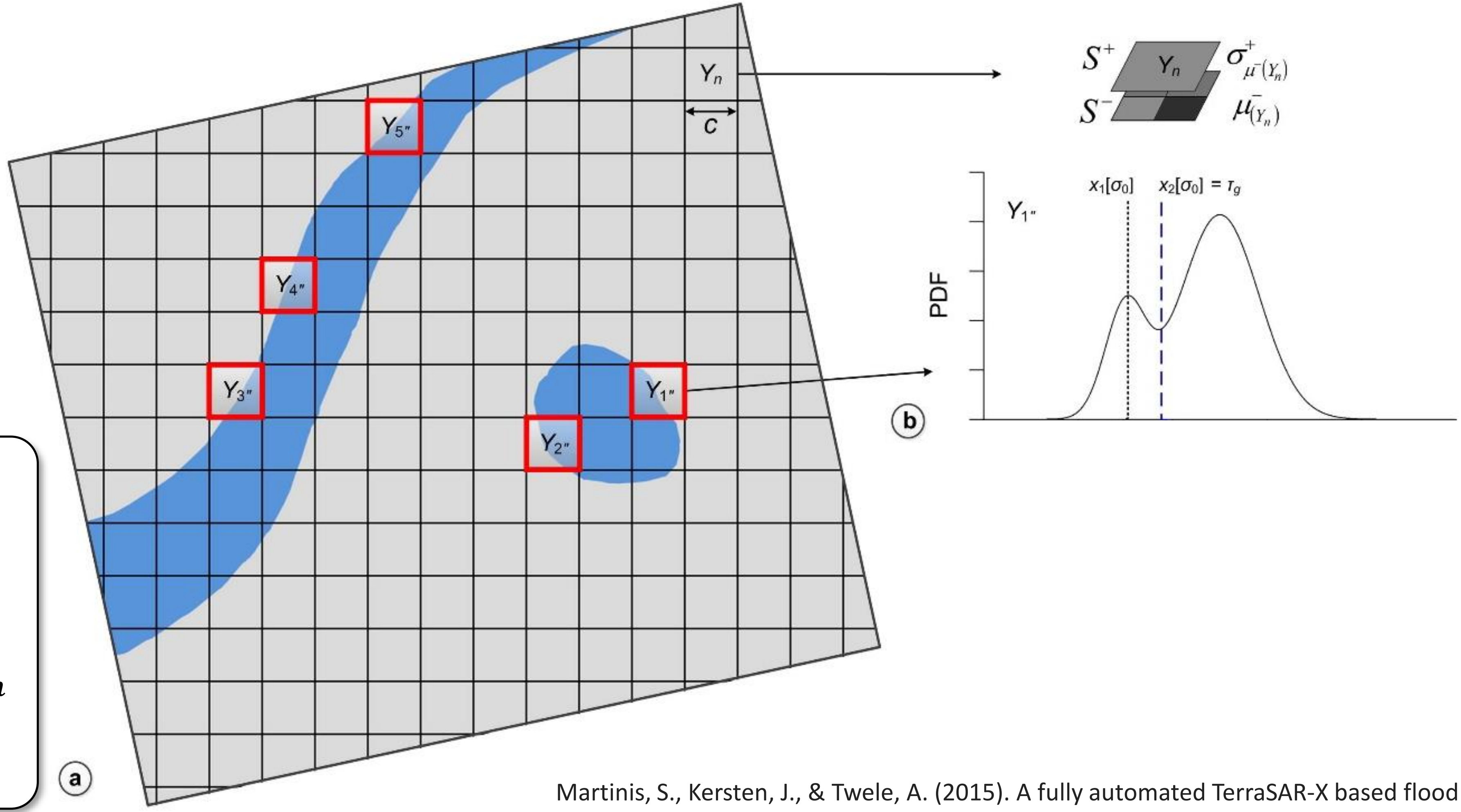


The HydroSAR HYDRO30 Surface Water Extent Product

Step 2: Automatic and Adaptive Threshold Calculation



Tile image and select pivotal tiles (best tiles for threshold calculation) using

- Tile mean μ_n
- The tile standard deviation σ_n
- Height above nearest drainage $\mathrm{HAND} < 15\mathrm{m}$

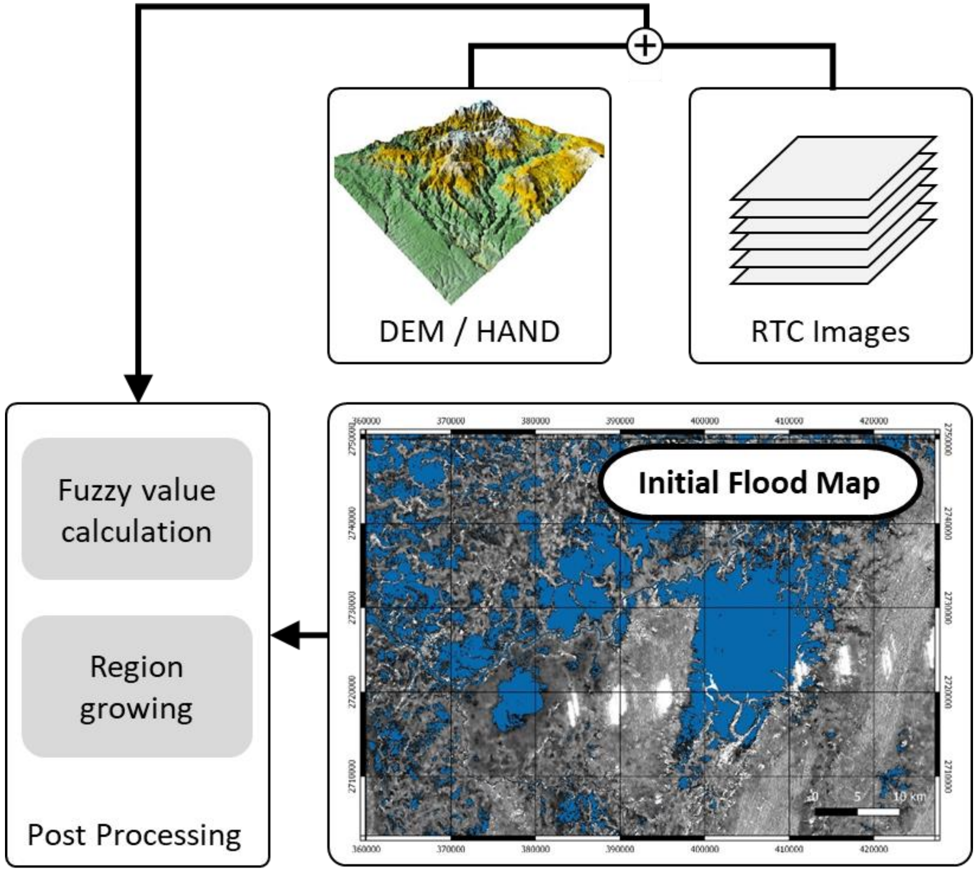
Martinis, S., Kersten, J., & Twele, A. (2015). A fully automated TerraSAR-X based flood service. *ISPRS Journal of Photogrammetry and Remote Sensing*, *104*, 203-212.

The HydroSAR HYDRO30 Surface Water Extent Product

Step 4: Post-Processing to Remove False Alarms

- **Fuzzy logic rules to remove spurious false detection and improve upon the initial flood mapping product:**
  - **Radar Cross Section (RCS) rule**: $\begin{cases} x_{u,RCS} = \tau_g \\ x_{l,RCS} = \mu_{\sigma^0_{\tau_g}} \end{cases}$ with

    $\sigma^0_{\tau_g}$ = initial flood classification and flood mapping threshold τ_g
  - **HAND elevation rule**: $\begin{cases} x_{u,HAND} = \mu_{HAND(water)} + 3 \cdot \sigma_{HAND(water)} \\ x_{l,HAND} = \mu_{\sigma^0_{\tau_g}} \end{cases}$
  - **Surface slope α rule**: $\begin{cases} x_{u,\alpha} = 15^\circ \\ x_{l,\alpha} = 0^\circ \end{cases}$
  - **Flood patch size A rule**: $\begin{cases} x_{u,A} = 10px \\ x_{l,A} = 3px \end{cases}$
- Fuzzy membership functions calculated using a Z-shaped activation function.
- Membership functions are averaged and thresholded using a fuzzy threshold of 0.45.



The HydroSAR HYDRO30 Surface Water Extent Product

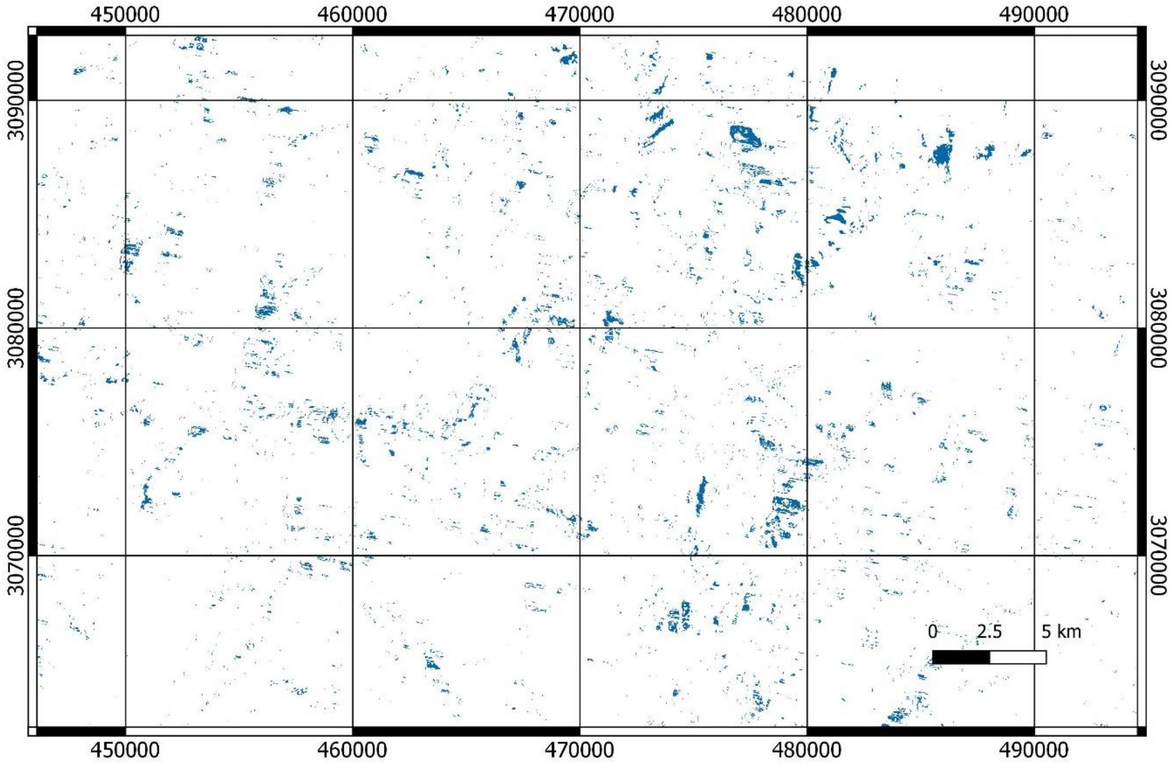
Benefit of Post Processing Steps – Case 1: Mountainous Terrain

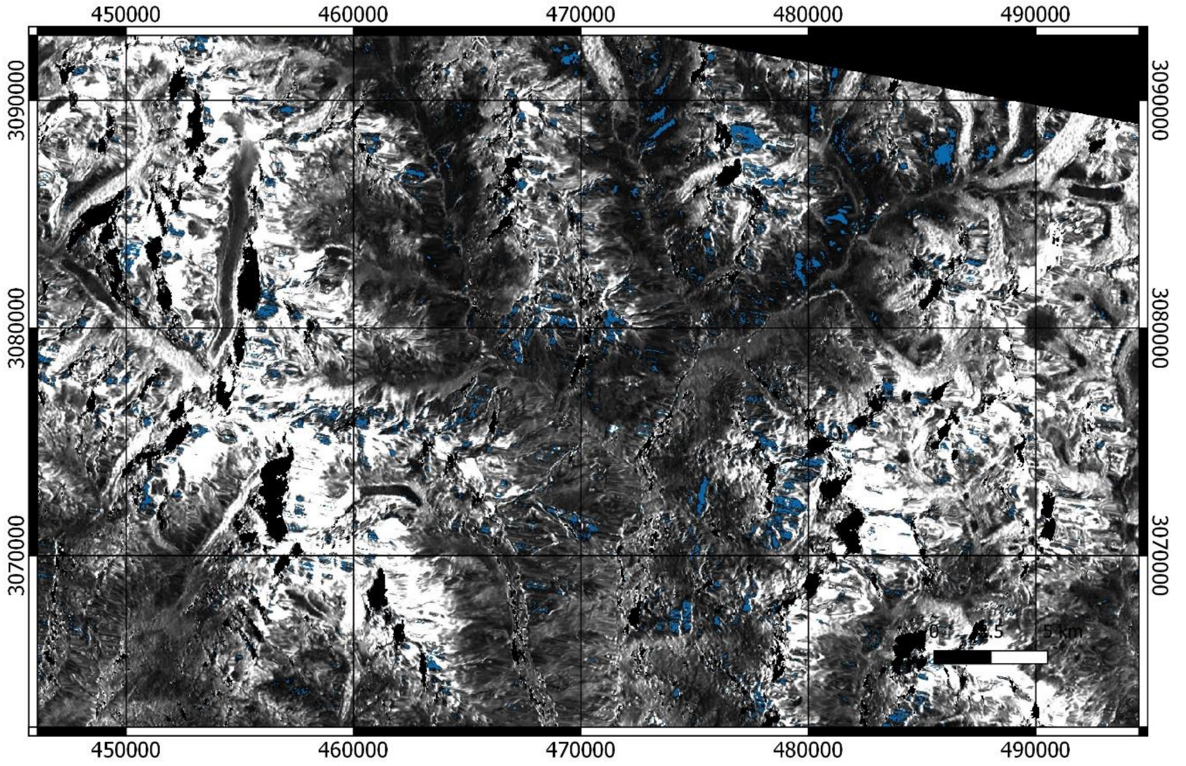
- **Mountainous terrain → flood look-alikes from layover, shadow, snow, and ice**

False alarms due to shadow ice and snow melt

HYDRO30 Product Nepal

No Post Processing





The HydroSAR HYDRO30 Surface Water Extent Product

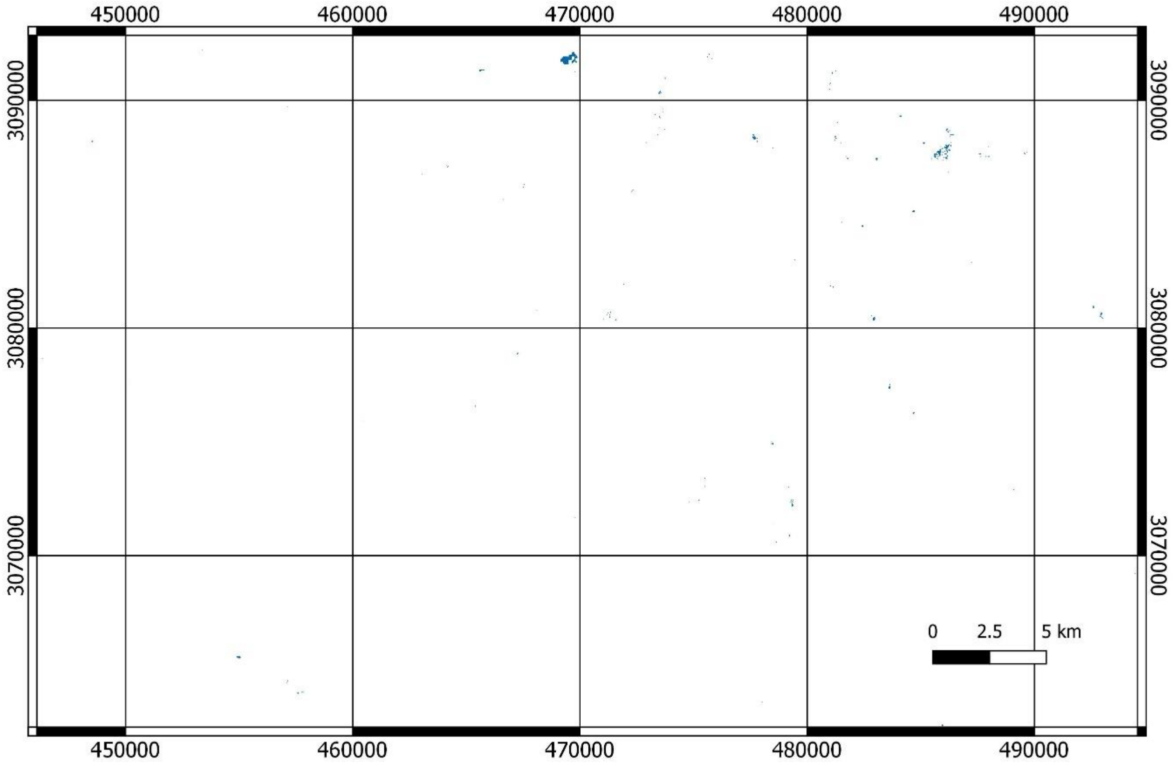
Benefit of Post Processing Steps – Case 1: Mountainous Terrain

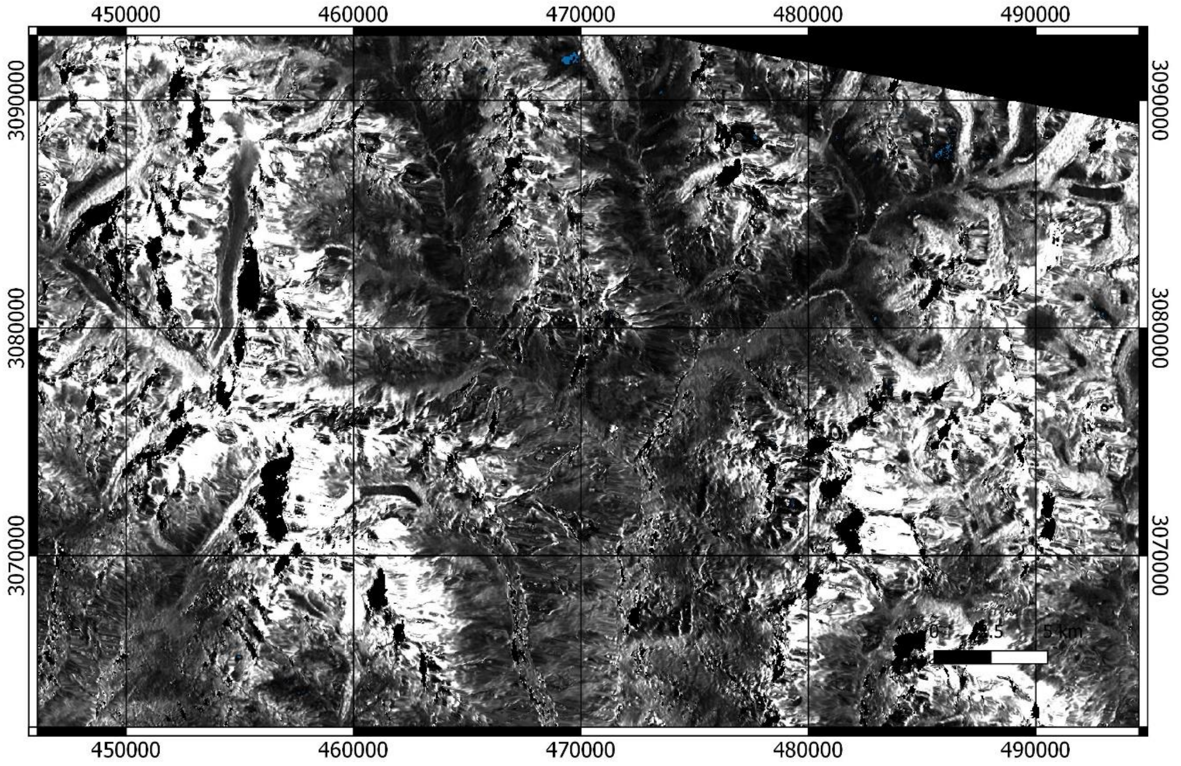
- **Mountainous terrain → flood look-alikes from layover, shadow, snow, and ice**

False alarms removed by
Fuzzy logic post processing

HYDRO30 Product Nepal

After Post Processing





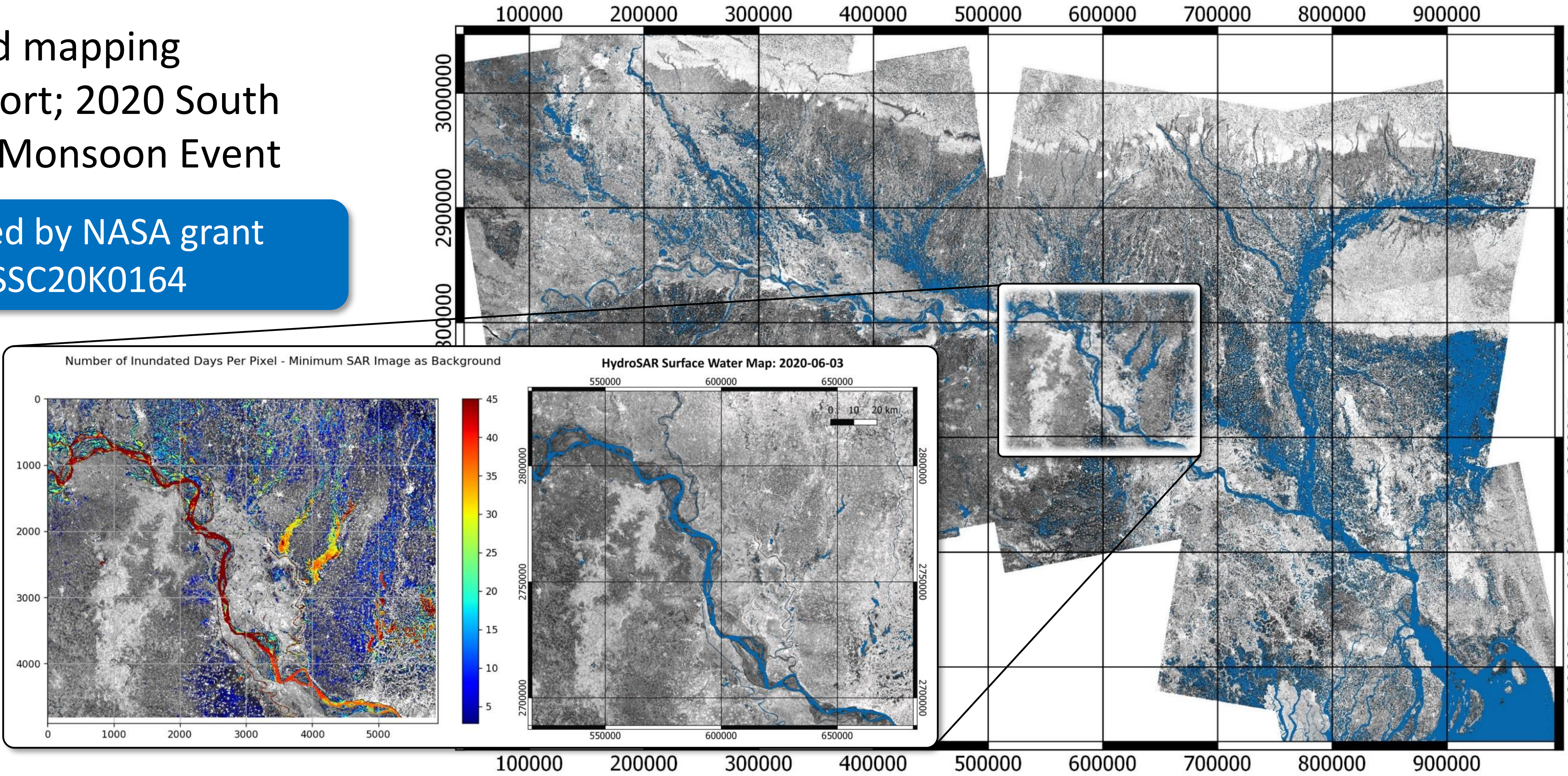
Recent ASF Outreach & User Support Activities

Spring 2020 Support of Alaska Pacific River Forecast Center

Funded by: NASA Applied Sciences Program

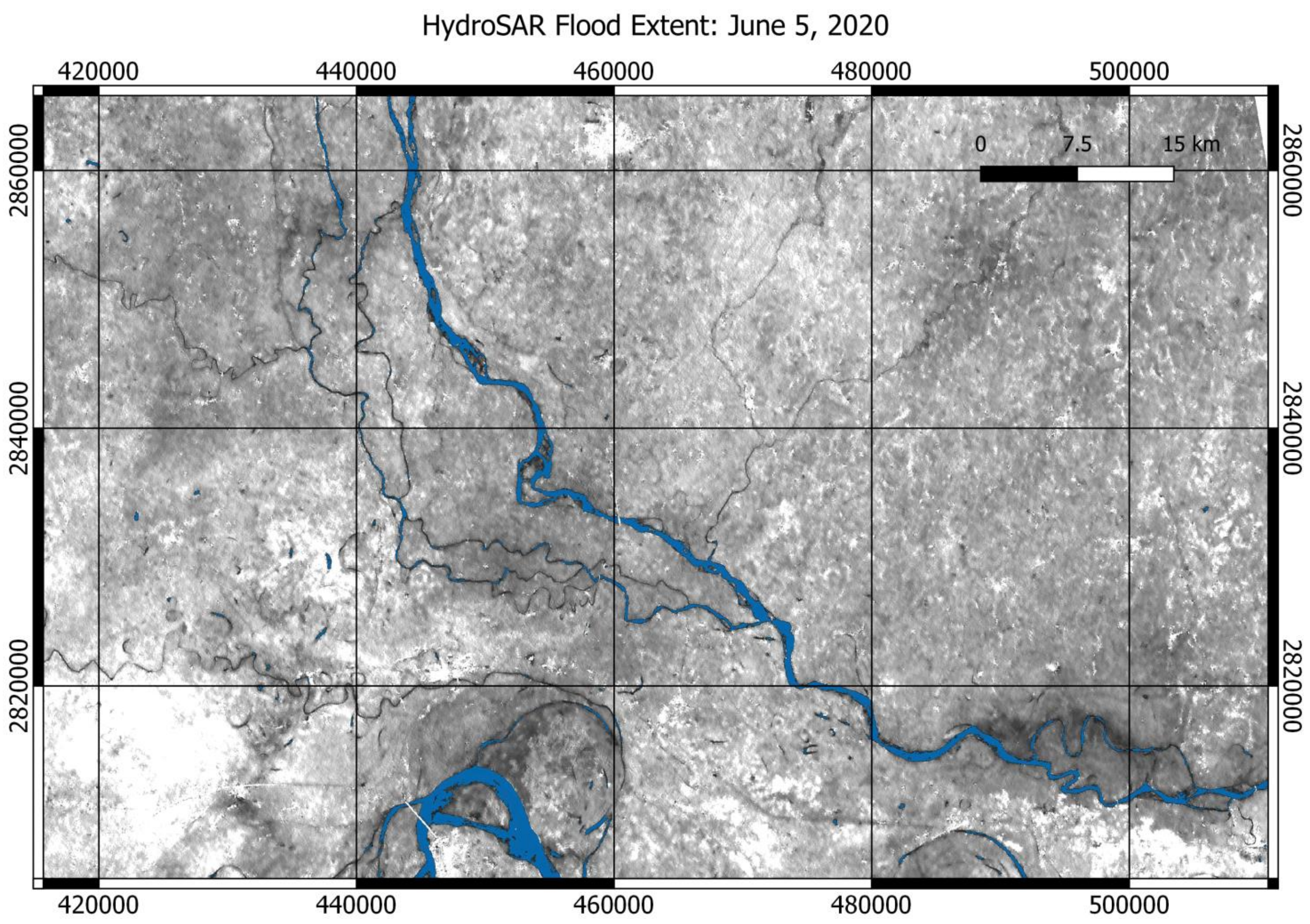
- Flood mapping support; 2020 South Asia Monsoon Event

Funded by NASA grant #80NSSC20K0164



Recently Supported Flooding Event Responses

- **03-07/19**: Midwest Flooding
- **04/20**: Cyclone Amphan
- **04-05/20**: Severe Weather Easter Outbreak
- **05/20**: Dam failures Michigan
- **05/20**: Tropical Storm Cristobal
- **05/20**: Tropical Storm Amanda
- **05/06/20**: Alaska Spring breakup
- **07/20**: Japan Flood
- **07/20**: Colombia Flood
- **06-08/20**: Bangladesh / India / Nepal event



SAR-derived Flood Maps for Jun-Aug 2020 Bangladesh / India / Nepal Event

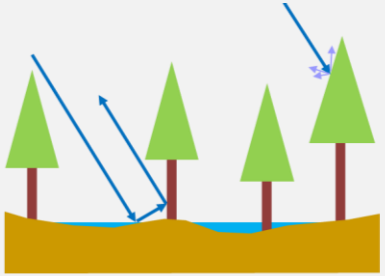
Limitations of Threshold-based Surface Water Mapping

Sensor-based limitations

Wind roughness on water

- **Problem**: Increases radar brightness and may prevent water detection
- **Mitigation**: use VH in addition to VV for water detection

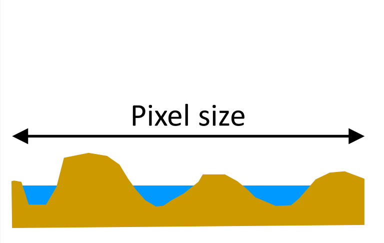
Water under dense vegetation



- **Problem**: Radar may not be able to penetrate vegetation
- **Mitigation**: Use longer wavelength radar (e.g., NISAR)

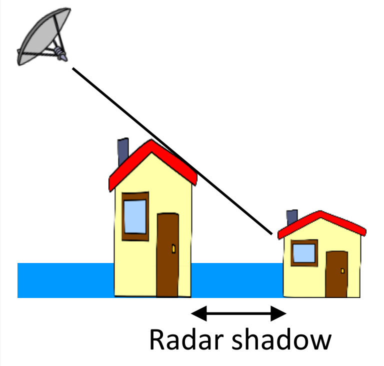
Environmental limitations

Partially inundated pixels



- **Problem**: Pixels are not dark enough for detection
- **Mitigation**: Higher-resolution radar or combine with change detection approach

Water in Urban environments



- **Problem**: Due to side-looking geometry, buildings obstruct surface water from view
- **Mitigation**: Use multiple viewing geometries – use optical data

Relevant Literature

- Twele, André, Wenxi Cao, Simon Plank, and Sandro Martinis. "Sentinel-1-based flood mapping: a fully automated processing chain." International Journal of Remote Sensing 37, no. 13 (2016): 2990-3004.
- Uddin, Kabir, Mir A. Matin, and Franz J. Meyer. "Operational flood mapping using multi-temporal sentinel-1 SAR images: a case study from Bangladesh." *Remote Sensing* 11, no. 13 (2019): 1581.
- Li, Yu, Sandro Martinis, Simon Plank, and Ralf Ludwig. "An automatic change detection approach for rapid flood mapping in Sentinel-1 SAR data." *International journal of applied earth observation and geoinformation* 73 (2018): 123-135.
- Martinis, Sandro, Jens Kersten, and André Twele. "A fully automated TerraSAR-X based flood service." *ISPRS Journal of Photogrammetry and Remote Sensing* 104 (2015): 203-212.
- Amitrano, Donato, Gerardo Di Martino, Antonio Iodice, Daniele Riccio, and Giuseppe Ruello. "Unsupervised rapid flood mapping using Sentinel-1 GRD SAR images." *IEEE Transactions on Geoscience and Remote Sensing* 56, no. 6 (2018): 3290-3299.
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- Ulloa, Noel Ivan, Shou-Hao Chiang, and Sang-Ho Yun. "Flood Proxy Mapping with Normalized Difference Sigma-Naught Index and Shannon's Entropy." *Remote Sensing* 12, no. 9 (2020): 1384.
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- Chang, Chi-Hung, Hyongki Lee, Faisal Hossain, Senaka Basnayake, Susantha Jayasinghe, Farrukh Chishtie, David Saah, Hanwen Yu, Khem Sothea, and Duong Du Bui. "A model-aided satellite-altimetry-based flood forecasting system for the Mekong River." Environmental modelling & software 112 (2019): 112-127.
- Chang, Chi-Hung, Hyongki Lee, Donghwan Kim, Euiho Hwang, Faisal Hossain, Farrukh Chishtie, Susantha Jayasinghe, and Senaka Basnayake. "Hindcast and forecast of daily inundation extents using satellite SAR and altimetry data with rotated empirical orthogonal function analysis: Case study in Tonle Sap Lake Floodplain." Remote Sensing of Environment 241 (2020): 111732.

A FIRST LOOK AT THE HYDROSAR CCD30 CHANGE DETECTION PRODUCT

Designing the CCD30 Change Detection Method

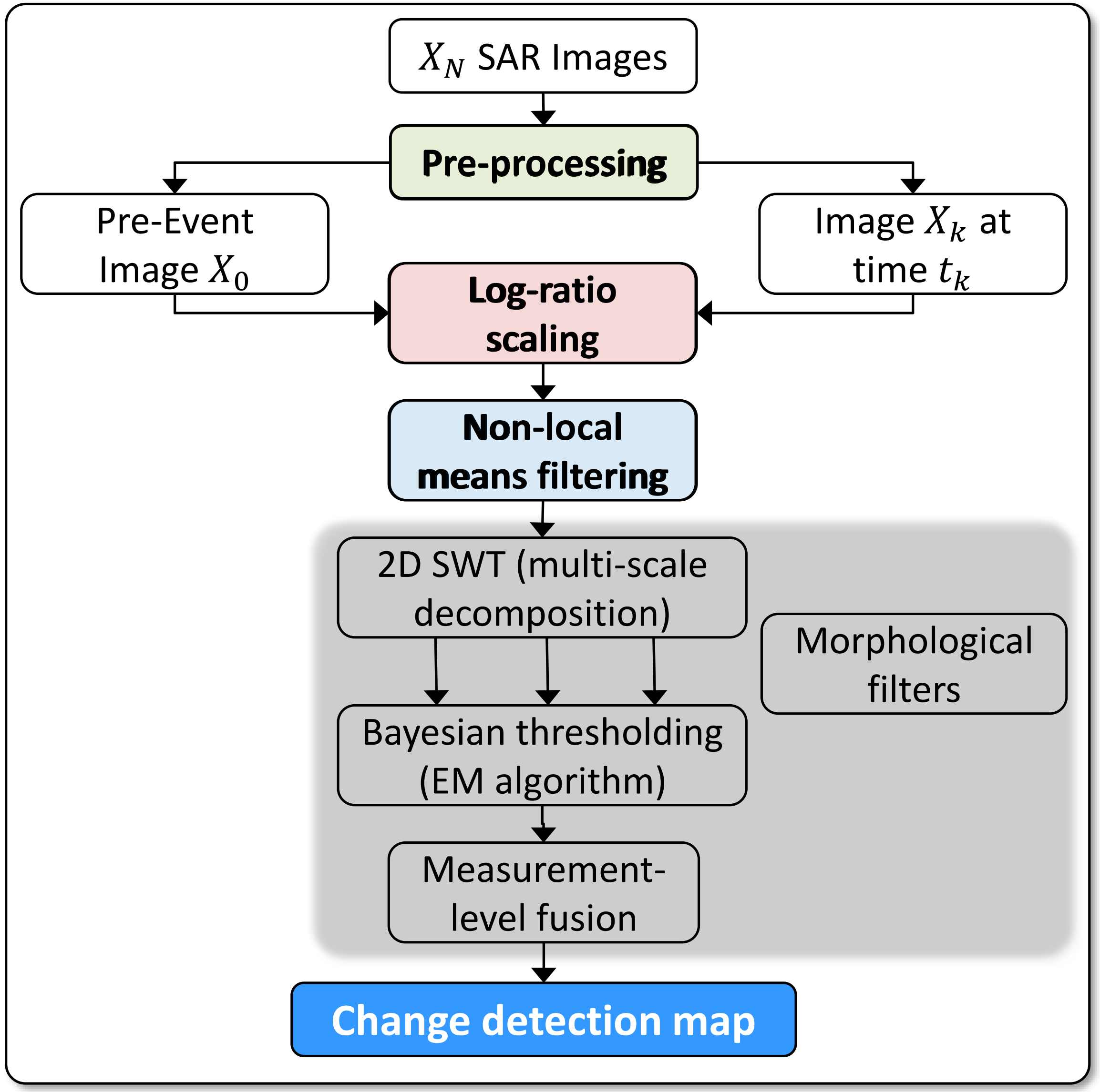
- Develop an automatic change detection approach for emergency response that lends itself for operational implementation
- This led to the following design requirements:

Desired Property	Corresponding Design Element
Can be applied to all SAR data	→ **Amplitude-based**
Applicable to a range of environments	→ **fully adaptive thresholding**
Low False alarm rates & resolution preserving	→ **Multi-scale approach** → **resolution-preserving speckle filters**
Maximizing sampling frequency	→ **Incorporation pre-processing steps**

The CCD30 Approach

- Application-dependent data enhancement
- Suppressing background clutter
- Speckle filtering and detail preservation
- Multi-scale change detection

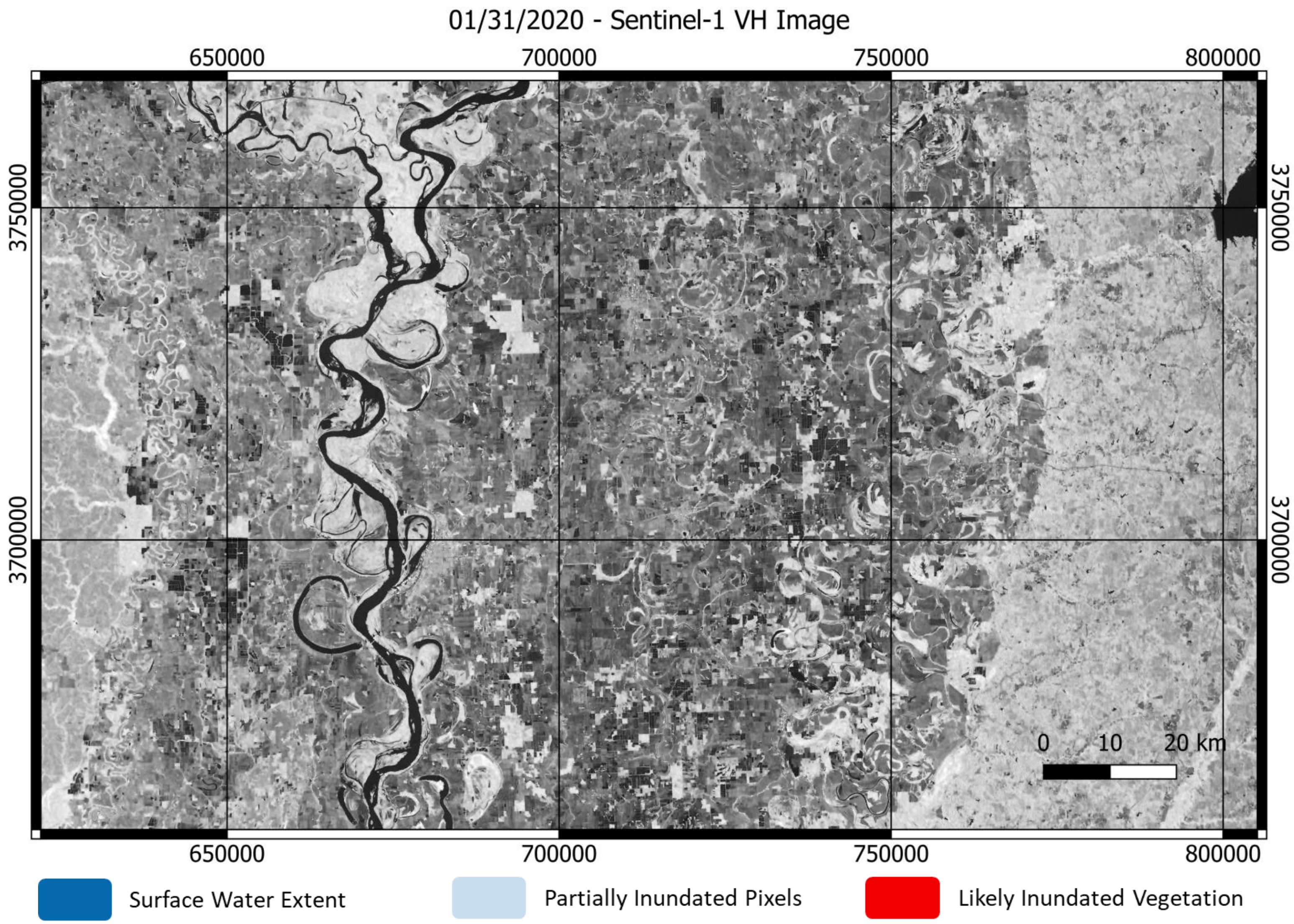
Ajadi, O., Meyer, FJ, Webley, PW, "Change Detection in Synthetic Aperture Radar Images Using a Multiscale-Driven Approach," *Remote Sensing*, 2016.

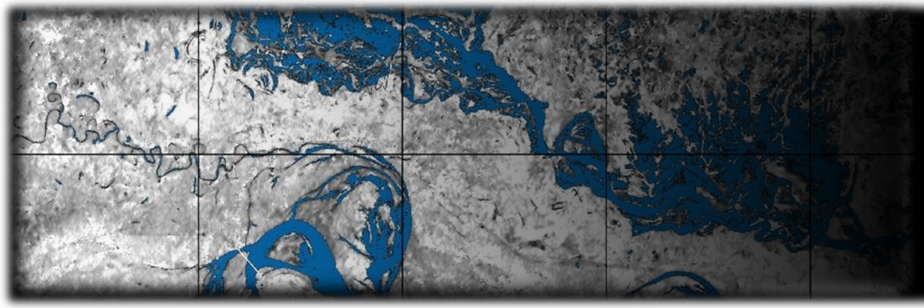


Combining HYDRO30 and CCD30 for more Complete Event Description

- **CCD30 provides additional information by containing the following information**:
  - Surface water class [cross-validation with HYDRO30]
  - Partially inundated pixels
  - Potential for detecting inundated vegetation

- **Example**: Sentinel-1 image pair over Pearl River, Missouri during 2020 flooding period
  - Jan 31, 2020 vs May 6, 2020



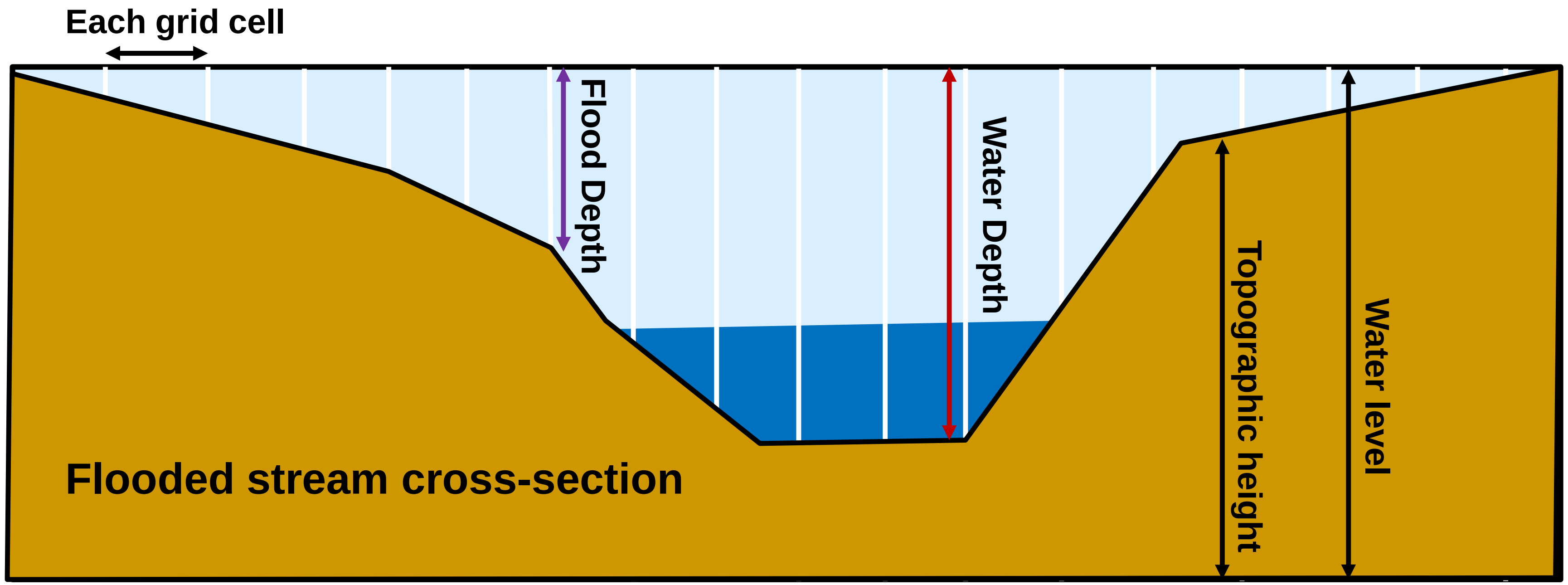


THE HYDROSAR FD30 FLOOD WATER DEPTH PRODUCT

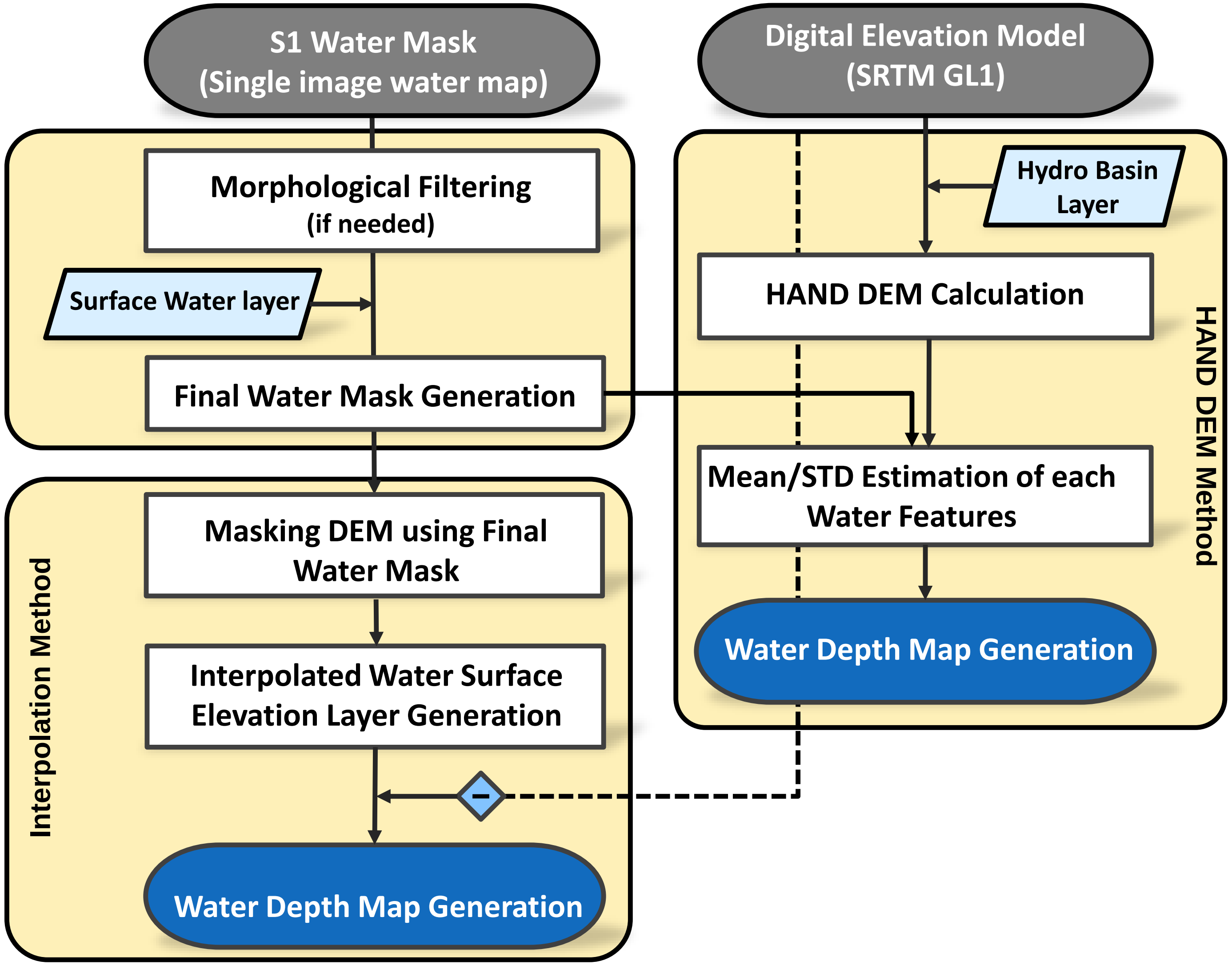
Flood Depth Mapping

Definitions of Flood Depth Mapping Terms

- **Definitions in this project**
  - Water depth: The depth of water above highest adjacent terrain.
  - Flood depth: The depth of flooded water above the existing water.
  - Water level: The elevation of surface water including terrain height.

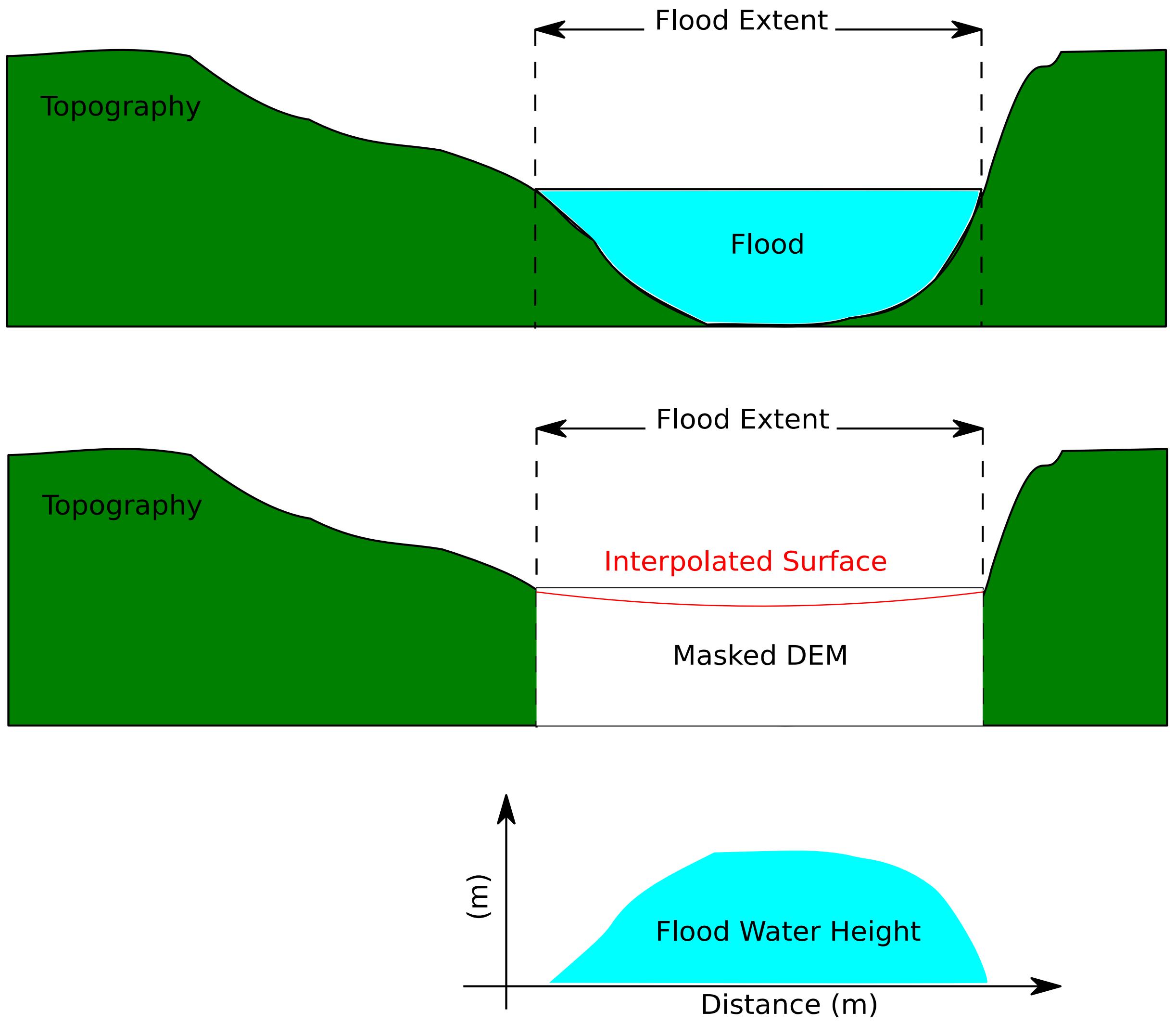


Flood Depth Mapping Workflow



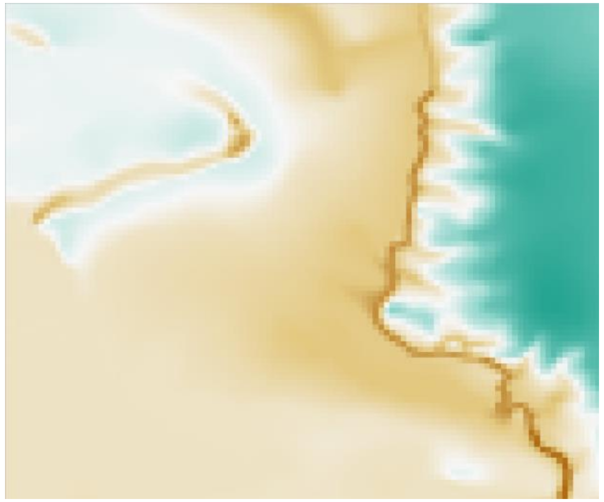
- Surface water data is produced under the Copernicus Program by **Joint Research Centre**.
- If you are using the data as a layer in a published map, please include the following attribution text: '**Source: EC JRC/Google**'
- Citation: Jean-Francois Pekel, Andrew Cottam, Noel Gorelick, Alan S. Belward, High-resolution mapping of global surface water and its long-term changes. Nature 540, 418-422 (2016). (doi:10.1038/nature20584)

Interpolation Approach

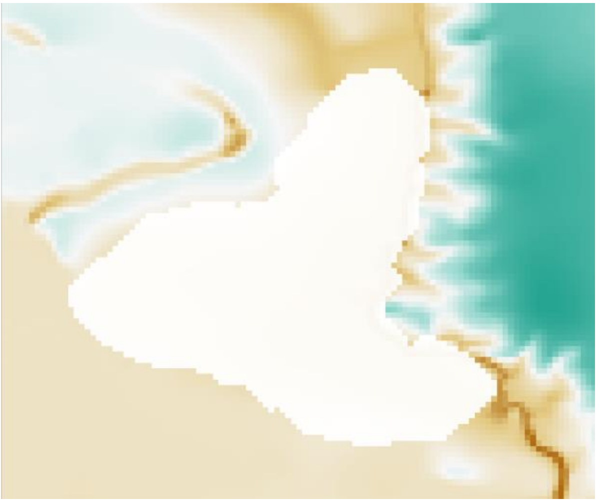


- A maximum water surface height is estimated by interpolating DEM values along the boundary of water features.
- The interpolated water surface can be obtained from different estimators.
  - Interpolated surface can show interpolation errors depends on the interpolation method.

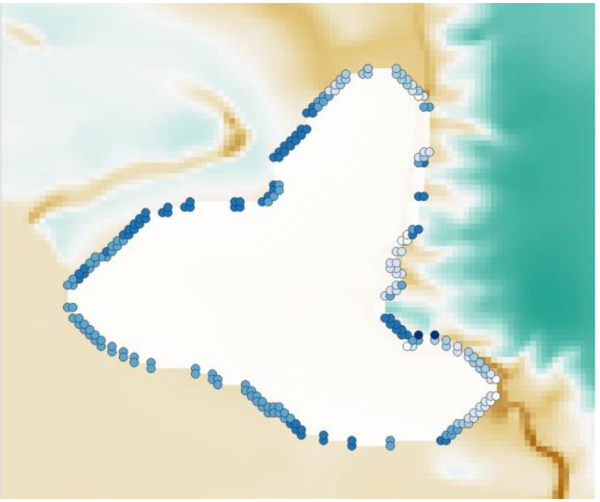
Interpolation Approach



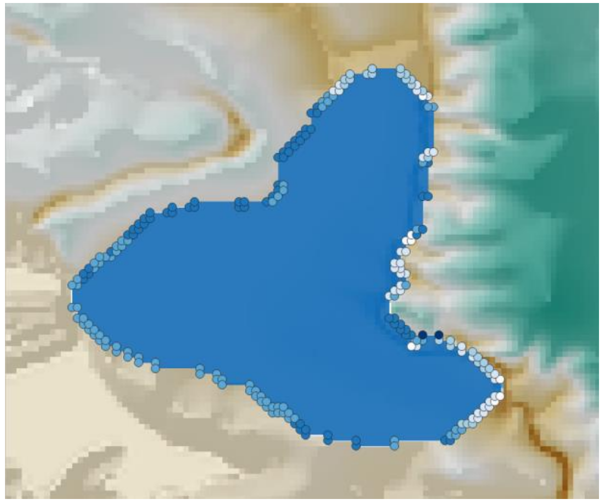
(A) DEM



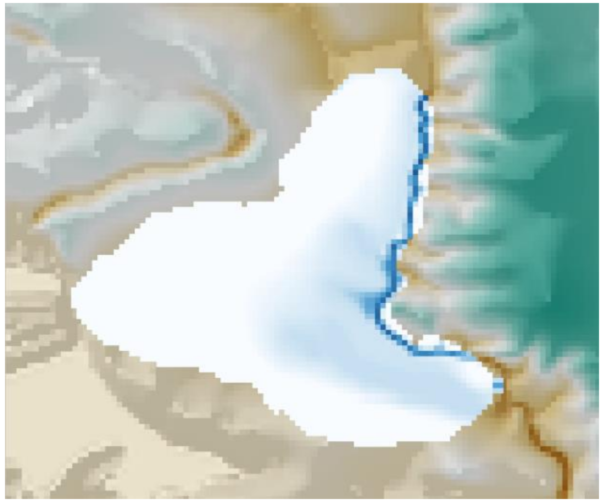
(B) Water feature



(C) Terrain height extraction



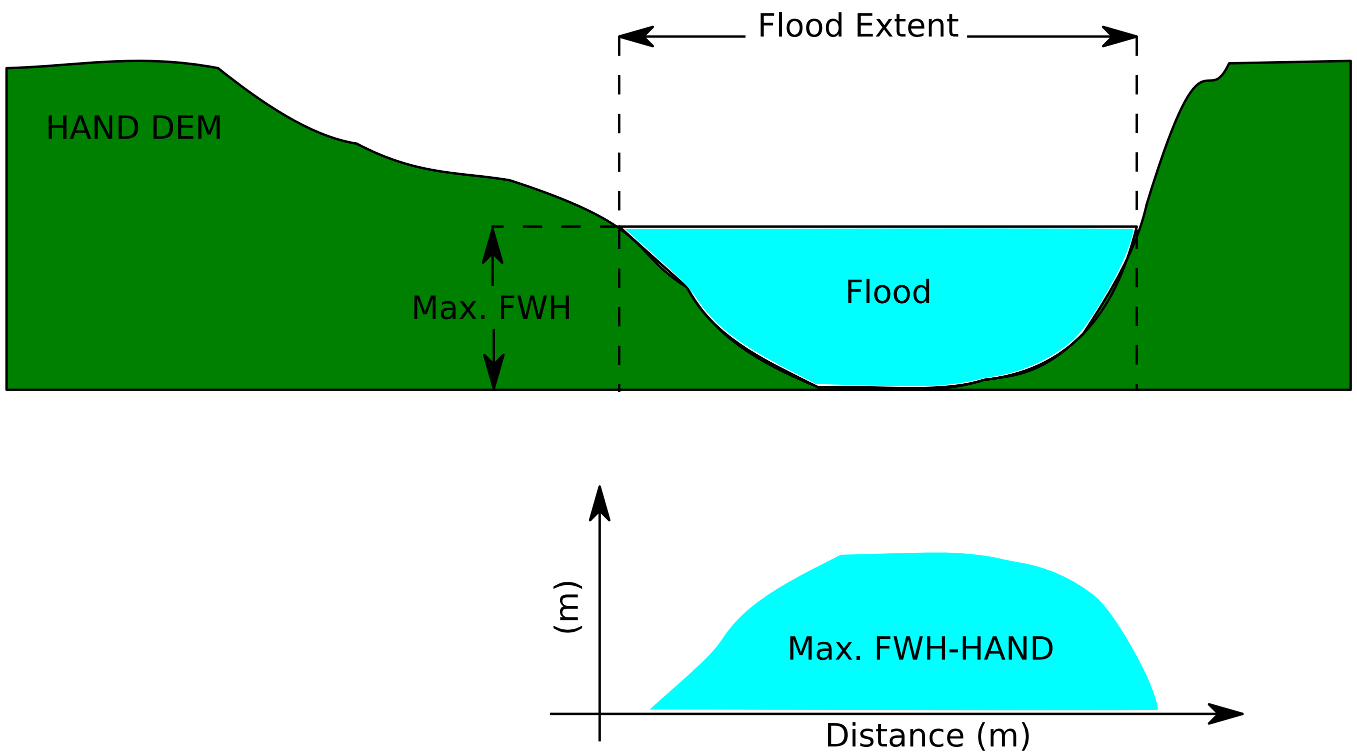
(D) Water surface elevation model



(D)-(A), Water Depth

- An example of generation of water depth map from the interpolation method.

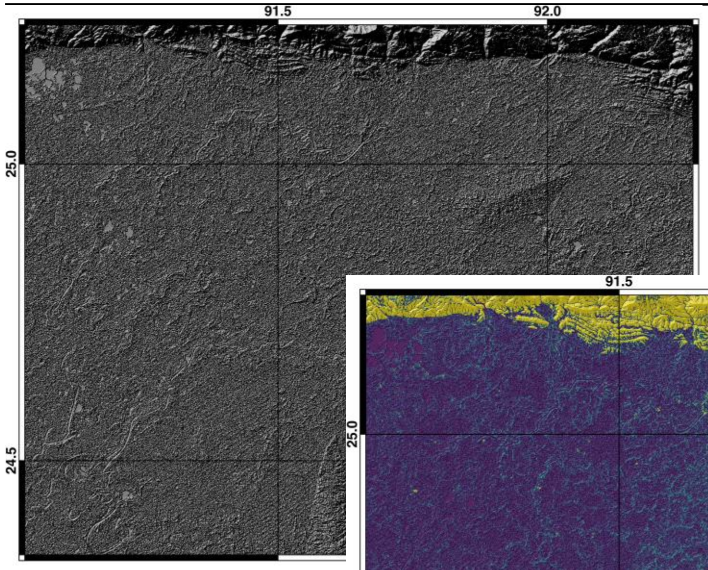
Height Above Nearest Drainage (HAND) Approach



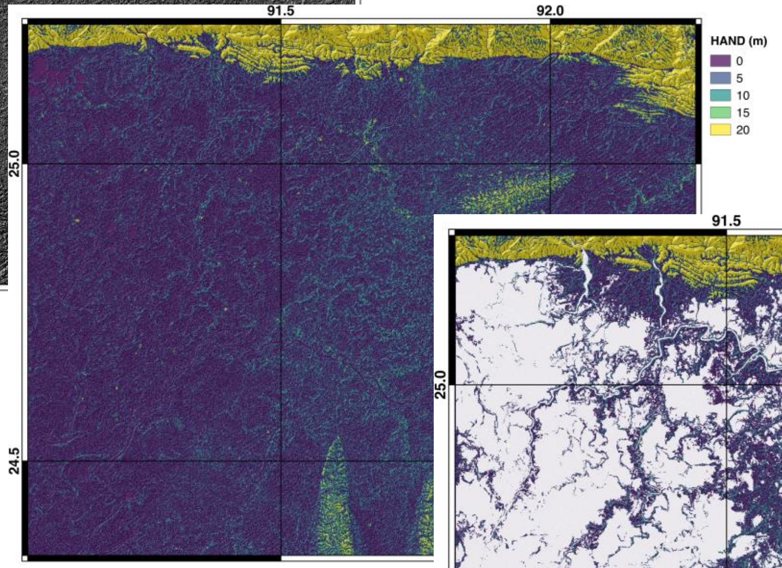
- Hydrological terrain model.
- HAND DEM is used directly to estimate a maximum flood water height.
  - The flood water depth is calculated by subtracting HAND DEM from the maximum height.

Height Above Nearest Drainage (HAND) Approach

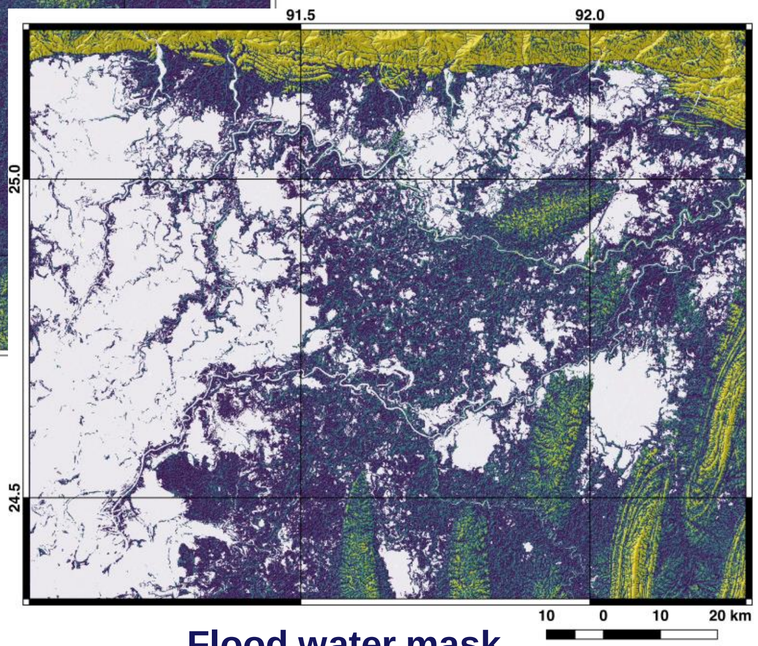
- Event: 2017 Bangladesh flood
  - Observation date: September 10, 2017



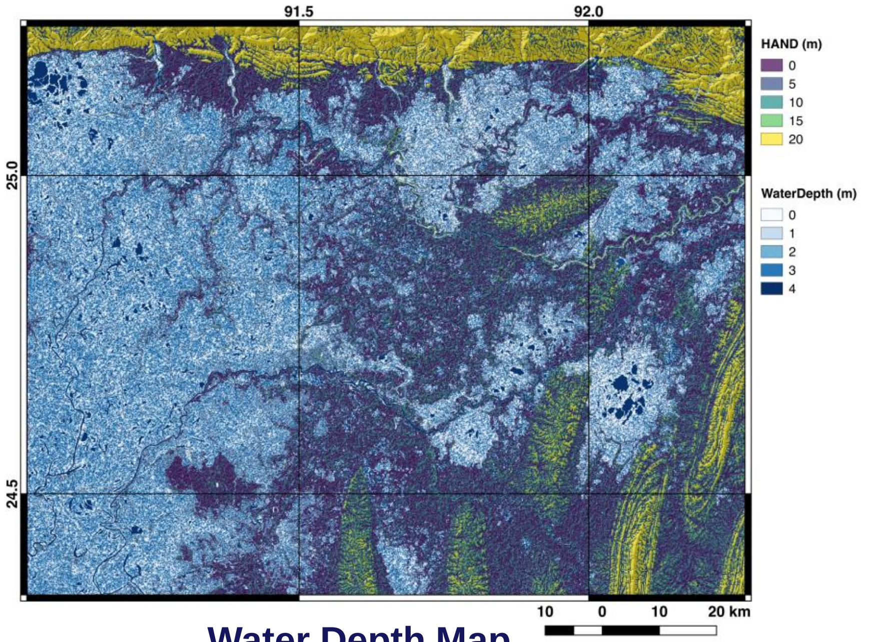
DEM



HAND DEM



Flood water mask



Water Depth Map

QUESTIONS?

Next: Flood Mapping in the OpenSARLab

- **Please log in** to https://opensarlab.asf.alaska.edu/
- **Navigate to** notebooks / SAR_Training / English / HydroSAR
- **Start notebook** Lab3_Flood_Depth_Mapping_Overview.ipynb