



Dynamical segmentation of avalanche debris from a time-series of Sentinel-1 SAR images

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AVALANCHES

A large amount of ice, snow and rock falling quickly down the side of a mountain



Illustration of a snow avalanche in Queyras valley, Haute Alpes in 2015

SAR IMAGES AND AVALANCHES : BASIC CONCEPTS

Pre-Event SAR Image



Smooth Snow Surface

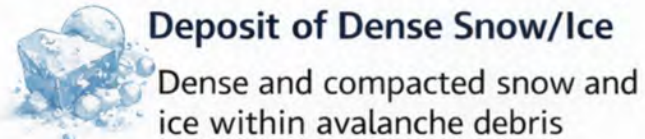
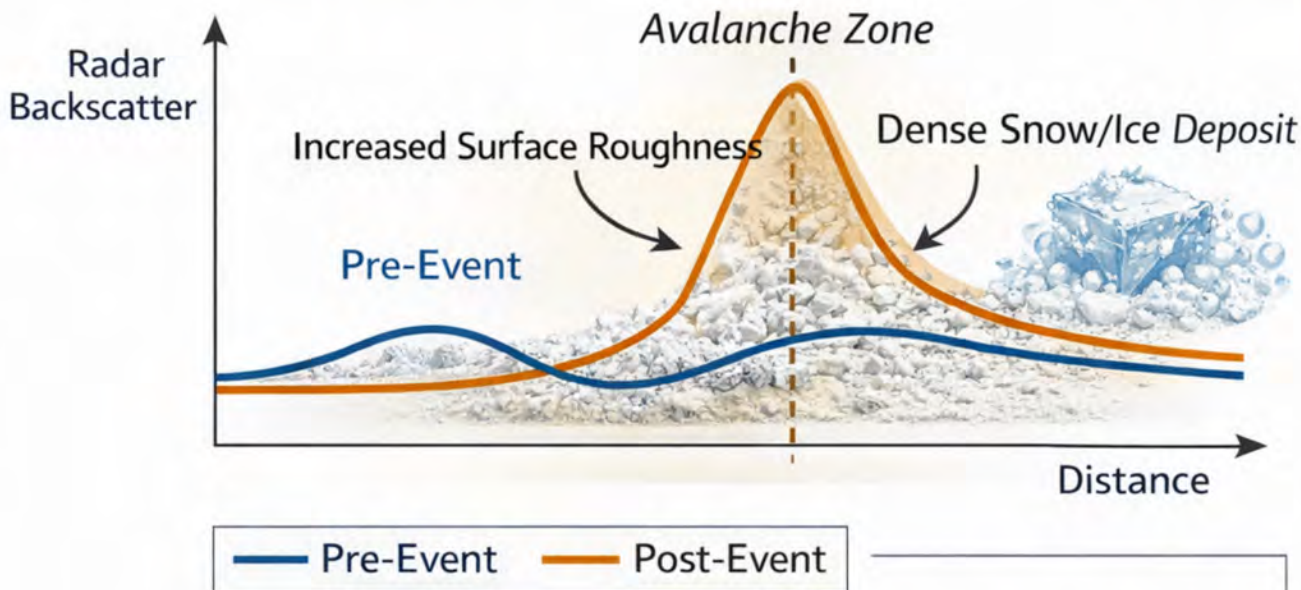
Low Backscatter

Post-Event SAR Image (After Avalanche)




Rough Avalanche Debris

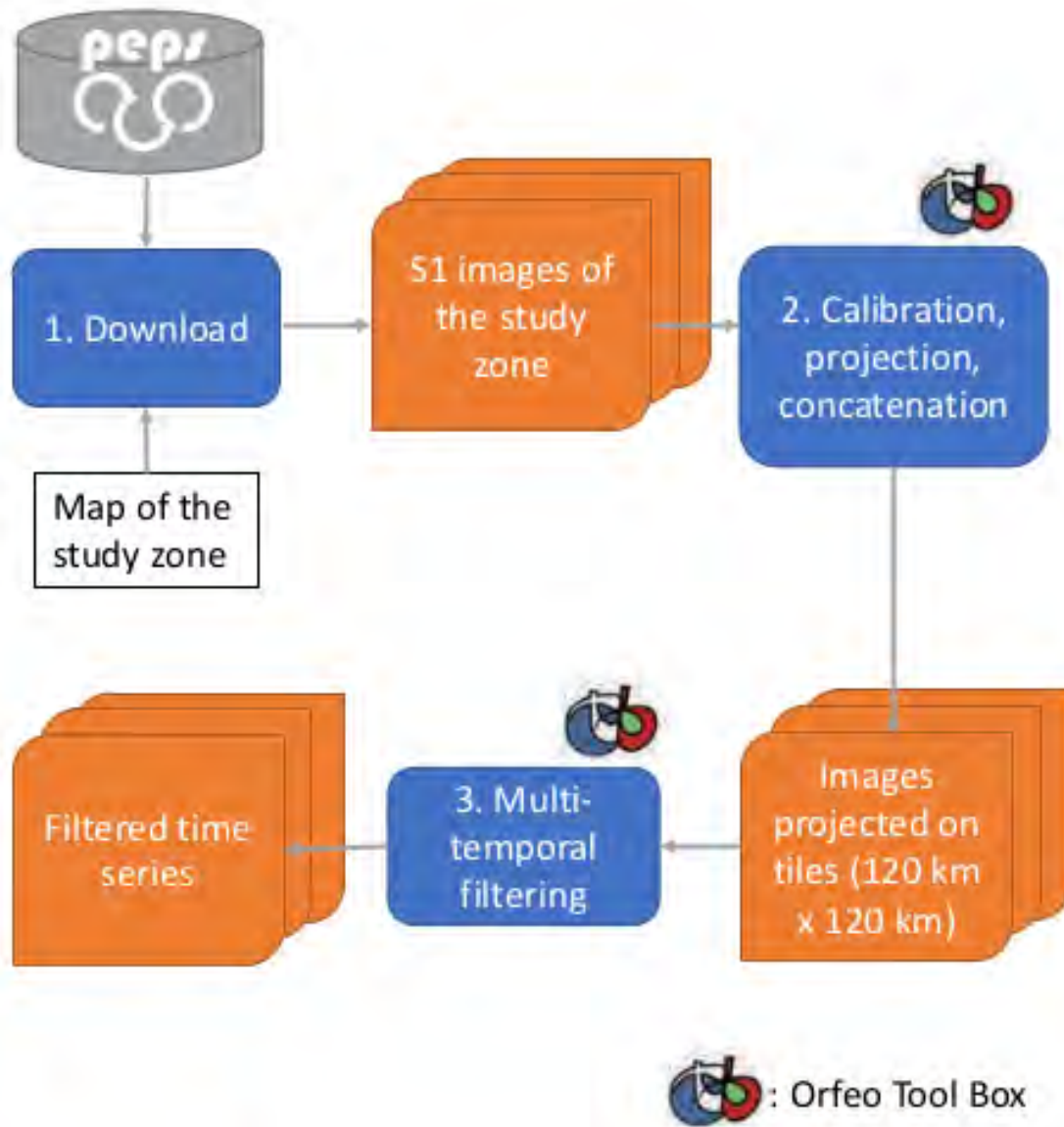
High Backscatter



Causes of Increased Backscatter:

- **Increased Surface Roughness:**
Irregular, rough and uneven avalanche debris leads to stronger backscattering.
 - **Deposit of Dense Snow/Ice:**
Dense and compacted snow and ice within avalanche debris increase return signal.
 - **Enhanced Volume Scattering:**
Air voids and ice crystals within the deposit enhance multiple scattering.
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Pre-processing of Sentinel-1 SAR images



- Orbit correction
- Thermal noise removal
- Terrain correction
- Radiometric calibration (σ_0)

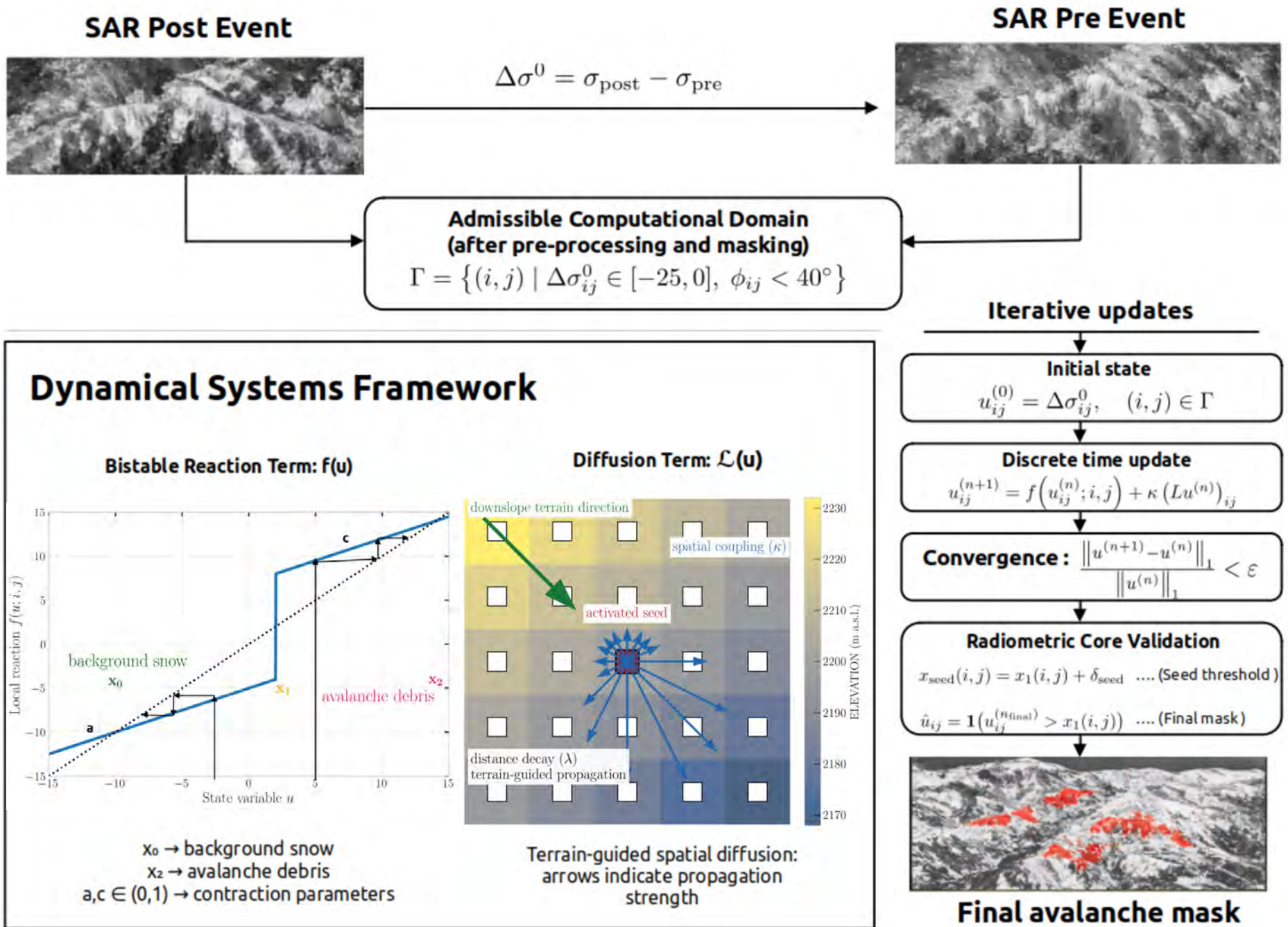
TABLE I: Sentinel-1 acquisition parameters

Satellite	Acquisition Time (UTC)	Orbit	Mode	Polarizations
Davos, Switzerland (2018)				
S1A	17 Jan 2018, 05:26	168 (desc)	IW (GRD)	VV, VH
S1B	23 Jan 2018, 05:26	168 (desc)	IW (GRD)	VV, VH
S1A	18 Jan 2018, 17:15	15 (asc)	IW (GRD)	VV, VH
S1B	24 Jan 2018, 17:14	15 (asc)	IW (GRD)	VV, VH
Davos, Switzerland (2019)				
S1A	12 Jan 2019, 05:26	168 (desc)	IW (GRD)	VV, VH
S1B	18 Jan 2019, 05:26	168 (desc)	IW (GRD)	VV, VH
S1A	13 Jan 2019, 17:15	15 (asc)	IW (GRD)	VV, VH
S1B	19 Jan 2019, 17:14	15 (asc)	IW (GRD)	VV, VH

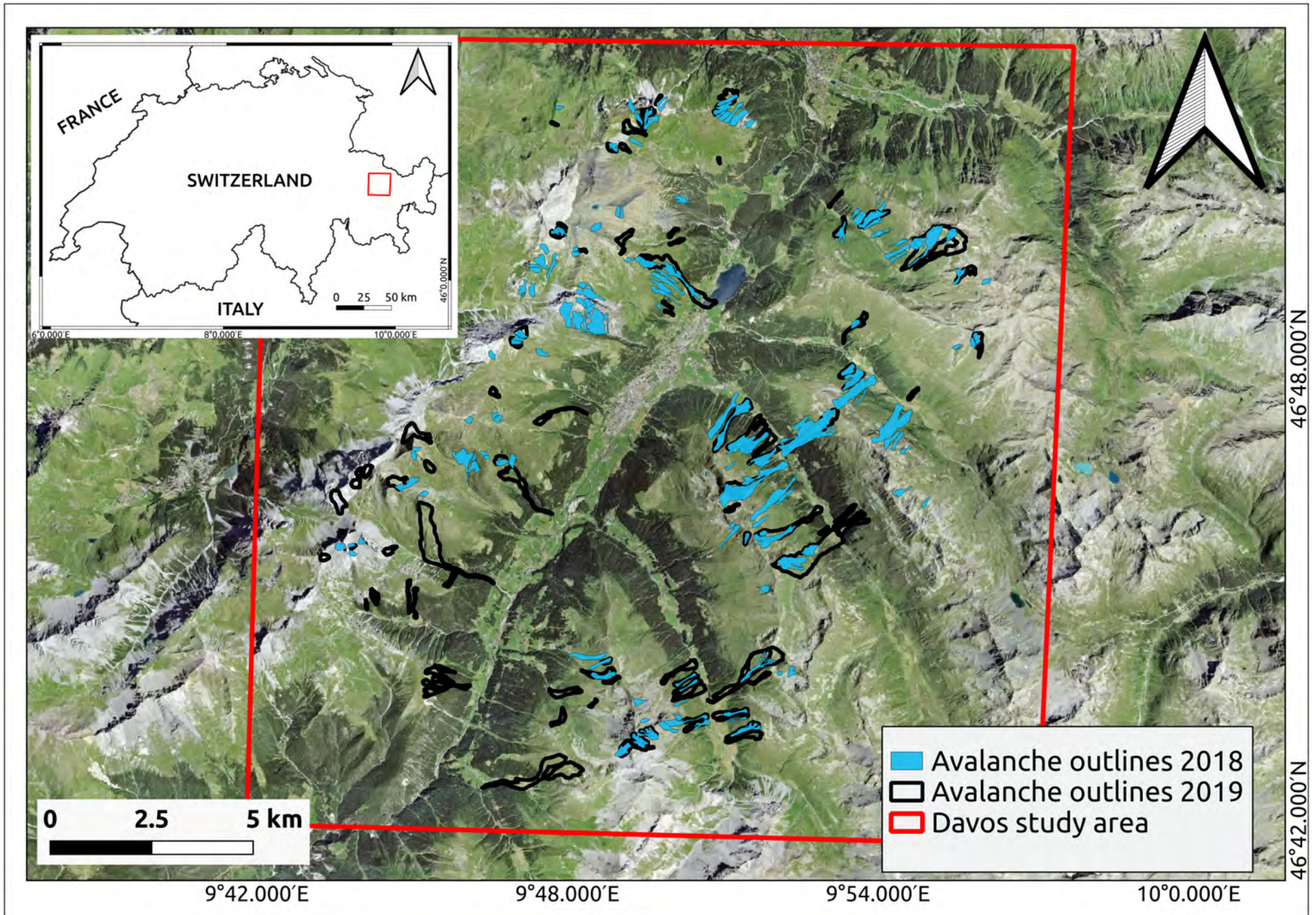
Pre-processing of Sentinel-1 images using S1-Tiling chain developed by the CNES radar service

Thanks : Adrien Mauss (CMS, Lannion, Meteo France)

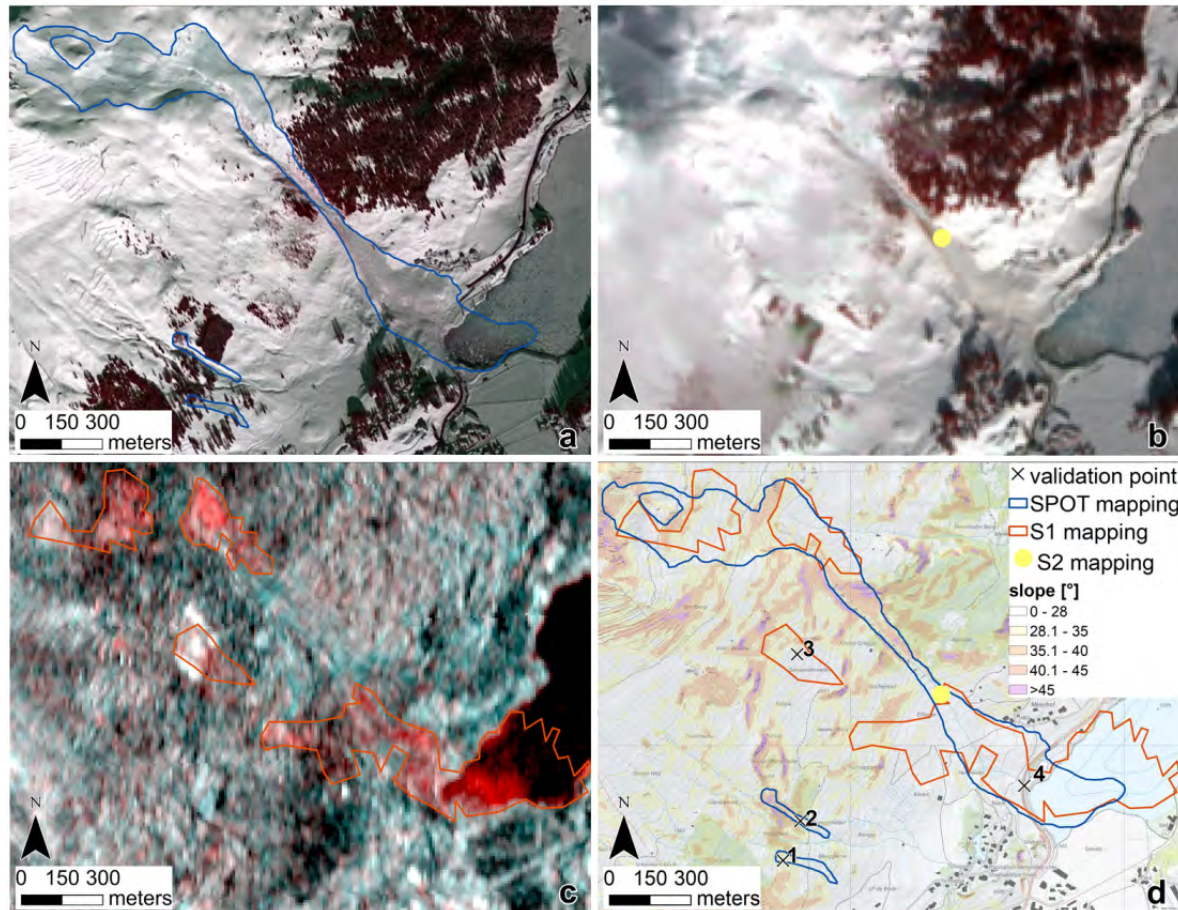
Dynamical systems (DyN) framework for avalanche segmentation



TEST SITE AND PERIOD



VALIDATION DATASETS



Avalanche outlines from SPOT-6 and Sentinel-1 for both years (2018 and 2019) are published online in **Hafner et al, 2021**.

- **Avalanche outlines mapped over high-resolution SPOT-6 optical images**

- **Manually mapped outlines using Sentinel-1 images and using colour composite images**

TABLE II: Description of the SPOT avalanche inventory for both study periods

Year	Satellite	Avalanche count	Min. Size (m ²)	Max. Size (m ²)	Median (m ²)
2018	SPOT-6	139	4,139	1,75,577	8,149
2019	SPOT-6	103	4,373	7,07,272	35,133

Source : Hafner et al, 2021

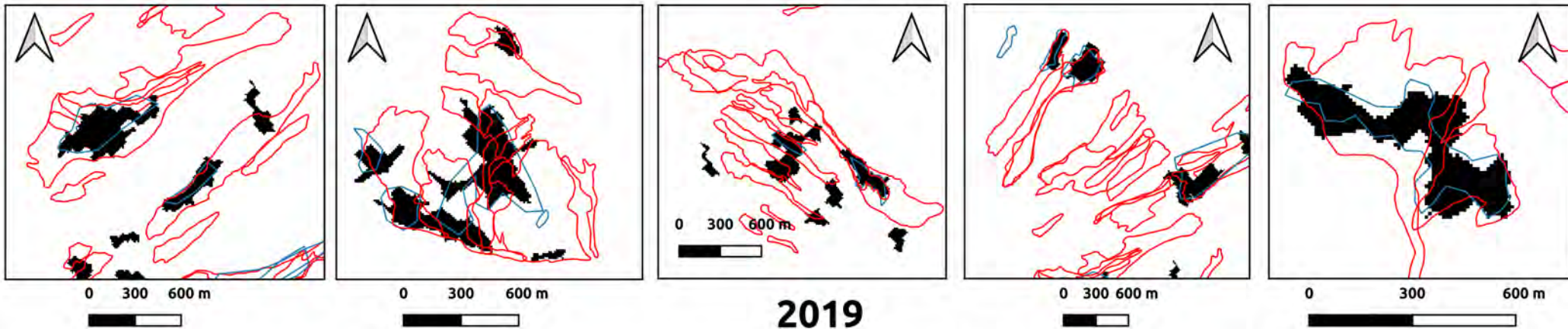
Dataset link: E. Hafner, S. Leinss, F. Techel, and Y. Bühler, “Satellite avalanche mapping validation data,” 2021. <https://www.envidat.ch/dataset/satellite-avalanche-mapping-validation>

Reference paper link : E. D. Hafner, F. Techel, S. Leinss, and Y. Bühler, “Mapping avalanches with satellites – evaluation of performance and completeness,” *The Cryosphere*, vol. 15, no. 2, pp. 983–1004, 2021. [Online]. Available: <https://tc.copernicus.org/articles/15/983/2021/>

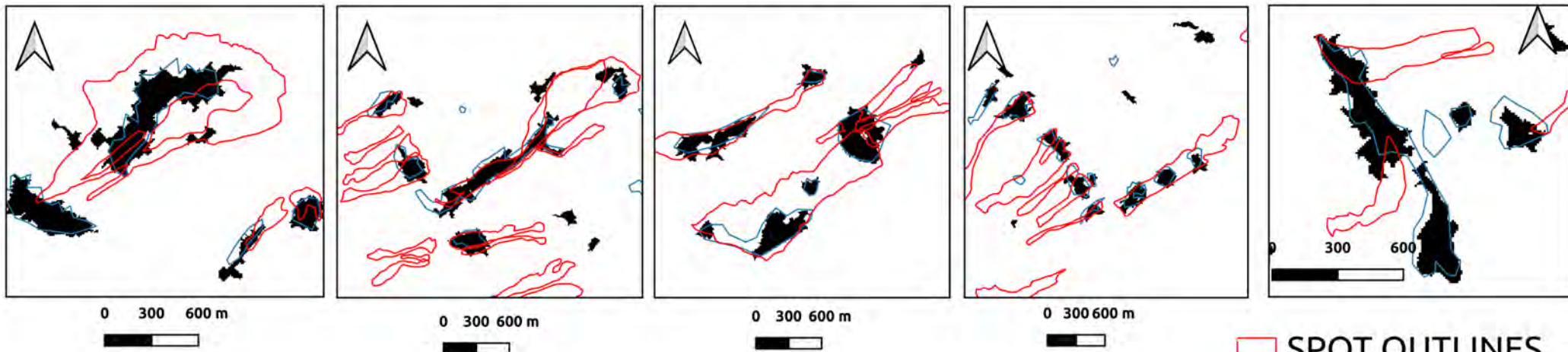


RESULTS : Comparison of mapped avalanche zones (in black) with SPOT-6 and reference Sentinel-1 outlines

2018



2019



□ SPOT OUTLINES
□ S-1 REF OUTLINES

Performance metrics for m-DyN avalanche mapping with SPOT-2019 avalanche outlines

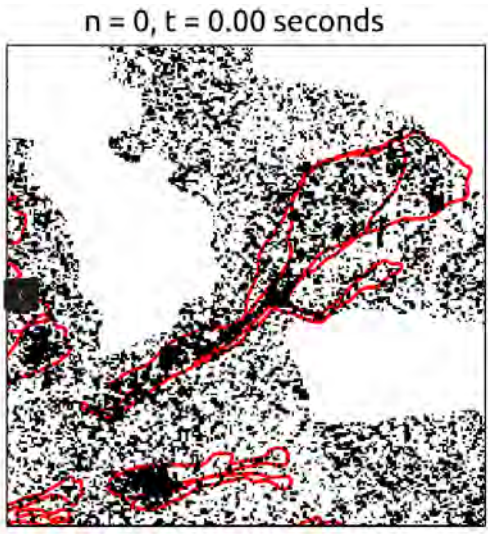
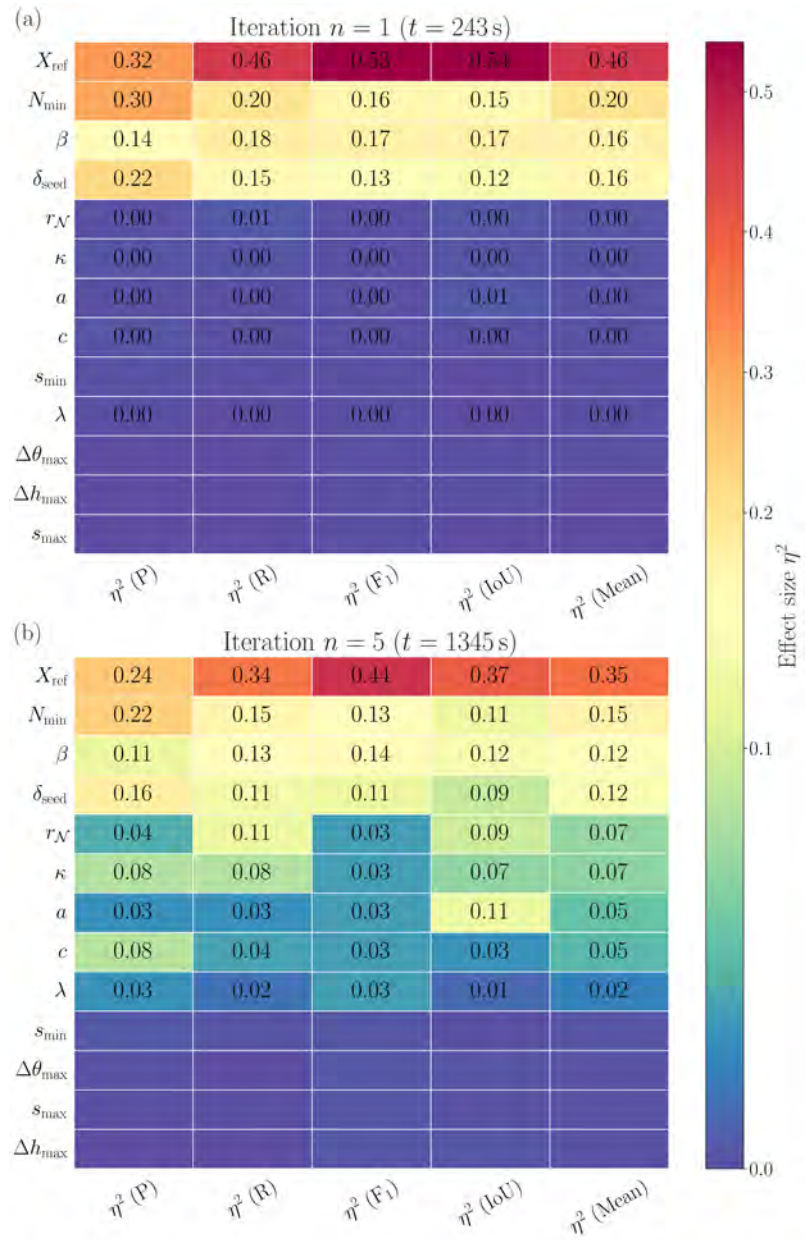
TP	FP	FN	TN	Precision	Recall	F1	IoU
17382	11089	75727	4116220	0.61	0.18	0.28	0.16

Performance matrix for reference SAR-based avalanche outlines (S-1 reference) with SPOT-2019

TP	FP	FN	TN	Precision	Recall	F1	IoU
19231	15246	73878	4112063	0.55	0.20	0.30	0.17

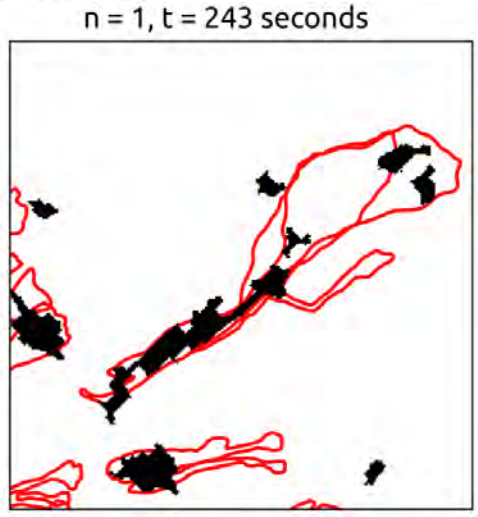
SENSITIVITY ANALYSIS

Based on 2500 random parameter combination runs

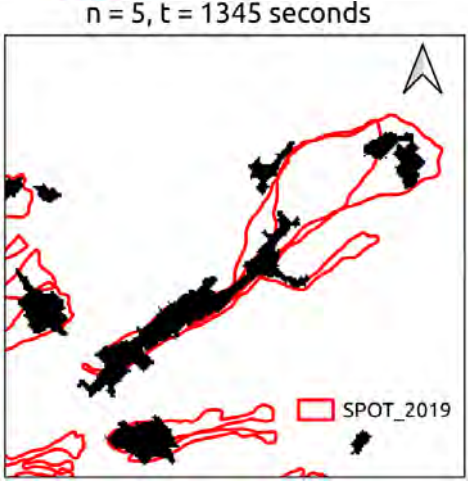


Simple threshold :
2.5 dB diff.

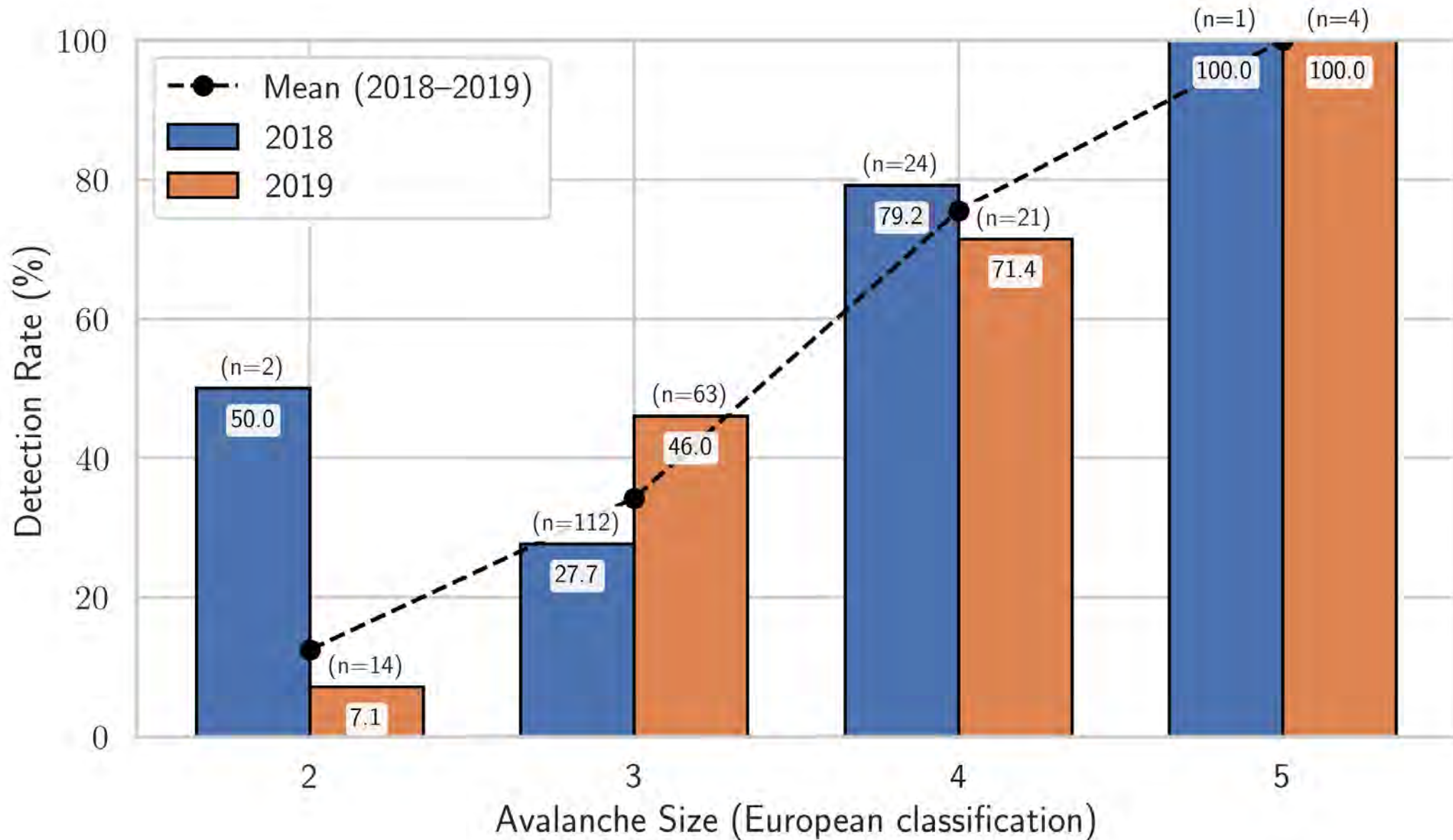
Avalanche segmentation
at $n = 1$: **Seeding**
dominates



Avalanche segmentation
at $n = 5$: **Diffusion**
influences

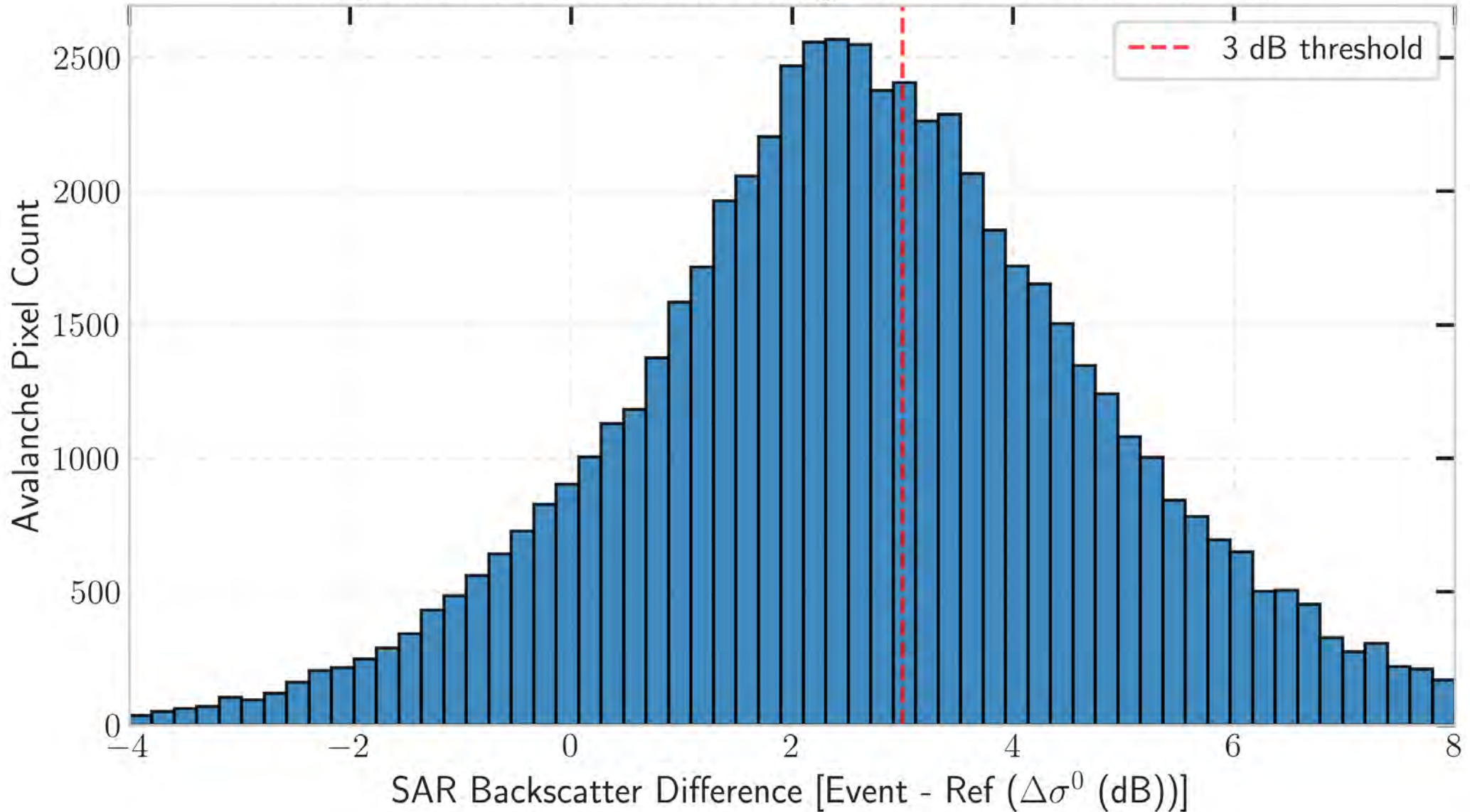


DyN mapping performance with Avalanche sizes



Histogram of SAR backscatter differences for DyN avalanche pixels

Histogram of SAR Backscatter Change for Detected Avalanche Pixels



CONCLUSIONS



- Avalanche detection formulated as a nonlinear excitation–diffusion process
- Tested in Swiss Alps (for two seasons 2018–2019) using Sentinel-1 SAR images
- Validated against SPOT and reference Sentinel-1 avalanche inventories with comparable performance
- **Two dynamical regimes identified:**
 - Reaction-dominated early iterations
 - Diffusion-driven spatial propagation with increasing iterations
- Medium–large avalanches reliably detected; small events often missed
- Captures low and moderate backscatter changes, improving detection beyond fixed-threshold SAR methods.

