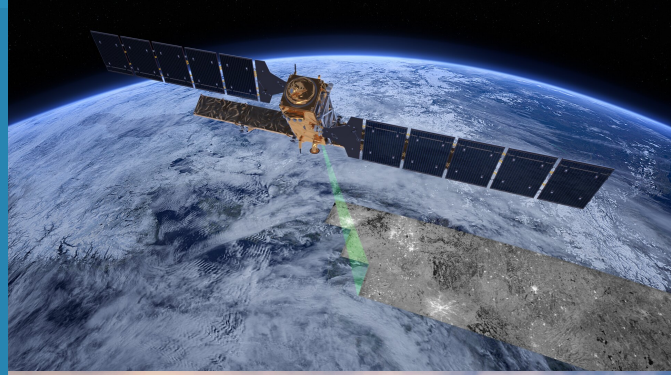
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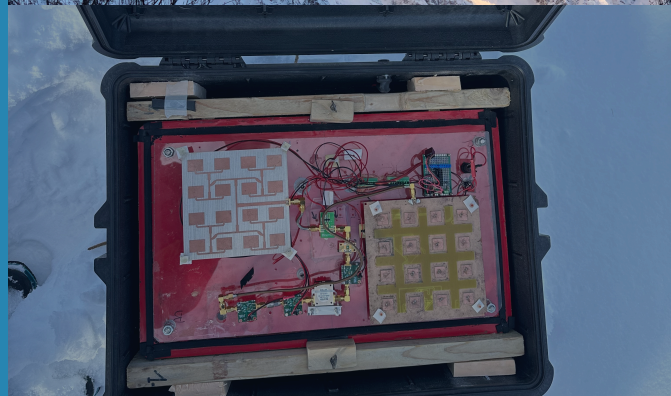
Direct Retrieval of Snow Water Equivalent Using the Sentinel-1 Interferometric Phase Response of an Active Reflector

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Motivation and Scientific Challenge

Why SWE Matters

Seasonal snowpack is a critical natural water reservoir, storing precipitation and releasing it through spring and summer.

Snow Water Equivalent is the fundamental variable for hydrological management, flood forecasting, and water resource assessment.

Current Limitations

In-situ methods: accurate but sparse distribution in alpine terrain

Optical sensors: only snow cover extent, not mass

Passive microwave: coarse resolution, saturates in deep snow

C-band InSAR: promising but limited by temporal decorrelation

Corner Reflector

> 1.7 m

side length required for passive C-band CRs

Snow-free

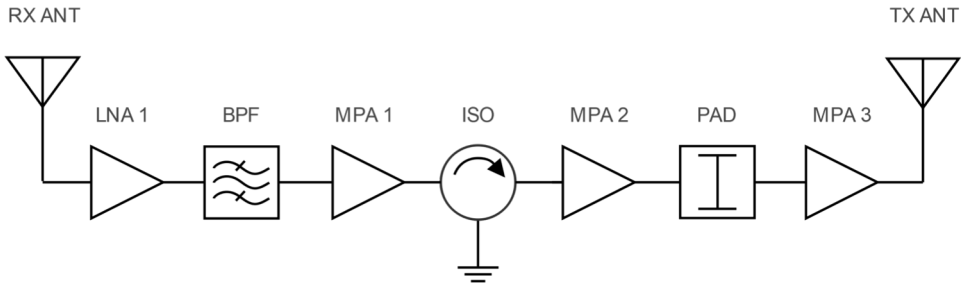
difficult deployment and maintenance in alpine terrain

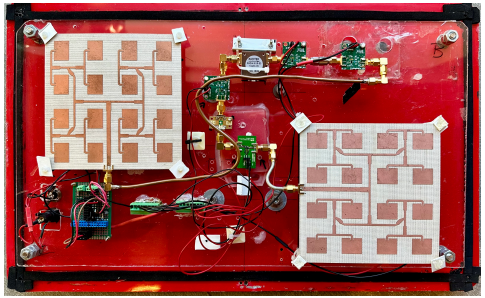


Our Approach: Active Reflector

A compact C-band Active Reflector positioned flush with the ground surface, allowing natural snow accumulation directly over the device for direct SWE measurement through interferometric phase analysis.

RF Signal Chain Architecture





42 dB

Total RF amplification

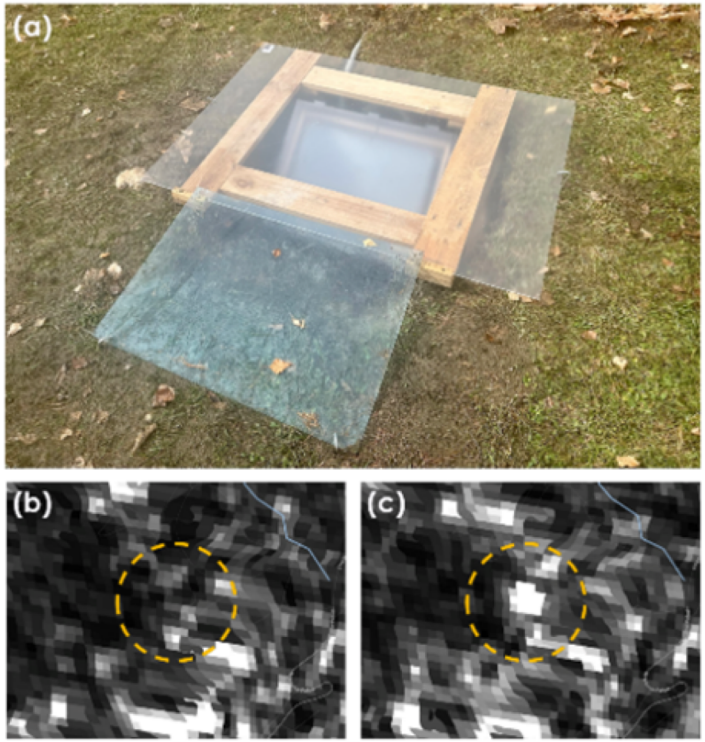
52 × 32 × 7 cm

Compact enclosure vs.
>1.7 m passive CR equivalent

< 0.6 W

Continuous power draw
Solar + 12 V battery

Experimental Setup: Courmayeur, Italy



(a) Flush-mounted installation (b) SAR amplitude before (c) After AR activation

Site Characteristics

Location: Courmayeur (45.82°N, 6.96°E)

Elevation: 1450 m a.s.l.

Season: Winter 2024 - 2025

Orbits: Sentinel-1 descending relative orbits 066 & 139

Installation Design

AR buried in excavated pit, covered by rigid polycarbonate sheet flush with terrain.

Minimizes wind scouring and preferential drifting. Snow layer is representative of local snowpack.

VH cross-polarization mode to maximize Signal-to-Clutter Ratio over snow.

SAR amplitude: from -10 dB (background) to +2.9 dB after AR activation

Methodology: InSAR Processing and SWE Retrieval

InSAR Processing Chain

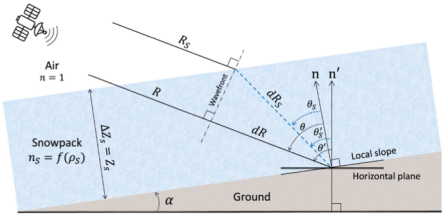
1. Sentinel-1 IW SLC coregistration (orbits 066 & 139)
2. Interferogram generation (reference: late autumn, snow-free)
3. Single-pixel phase extraction at AR coordinates
4. Geometric phase removal
5. Atmospheric correction via differential PS
6. Supervised phase unwrapping constrained by ground truth

$$\Delta\phi_{int} = \Delta\phi_{geom} + \Delta\phi_{atm} + \Delta\phi_{snow} + \Delta\phi_{noise}$$

SWE Retrieval Model

Leinss et al., 2015
Bovenga et al., 2025

$$\Delta\mathrm{SWE} = \frac{\Delta\phi_{snow} \cdot \lambda}{2\pi \cdot \beta \cdot (1.59 + \theta^{2.5})}$$



λ ≈ 5.6 cm (C-band wavelength)
θ = local incidence angle (rad)
β = 1 (optimization parameter)
1.59 empirical constant for dry snow permittivity

Phase ambiguity: 1 cycle (2π) about 30 mm of SWE at C-band → supervised unwrapping is required

Wet Snow Detection

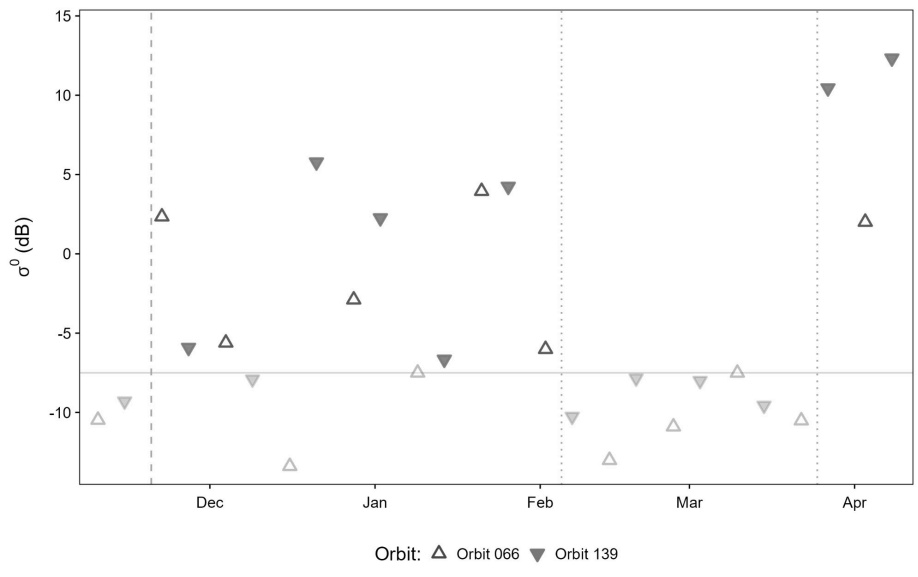
Backscatter threshold: **σ^0 = −7.5 dB (VH)**

Below threshold → wet snow, high absorption

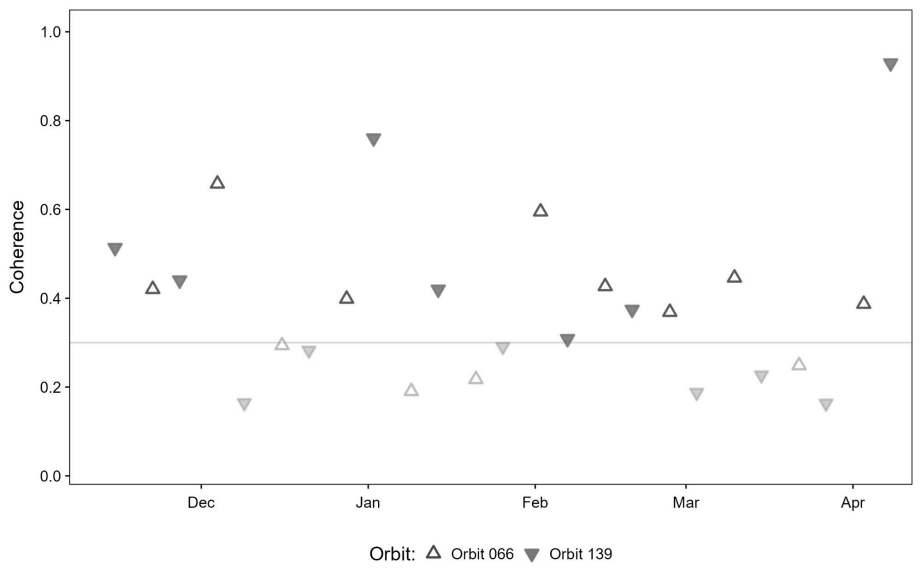
Coherence threshold: **γ = 0.3**

Below threshold → decorrelation, phase unreliable

Results: Radiometric Stability and Coherence



Backscatter Coefficient σ^o (VH)

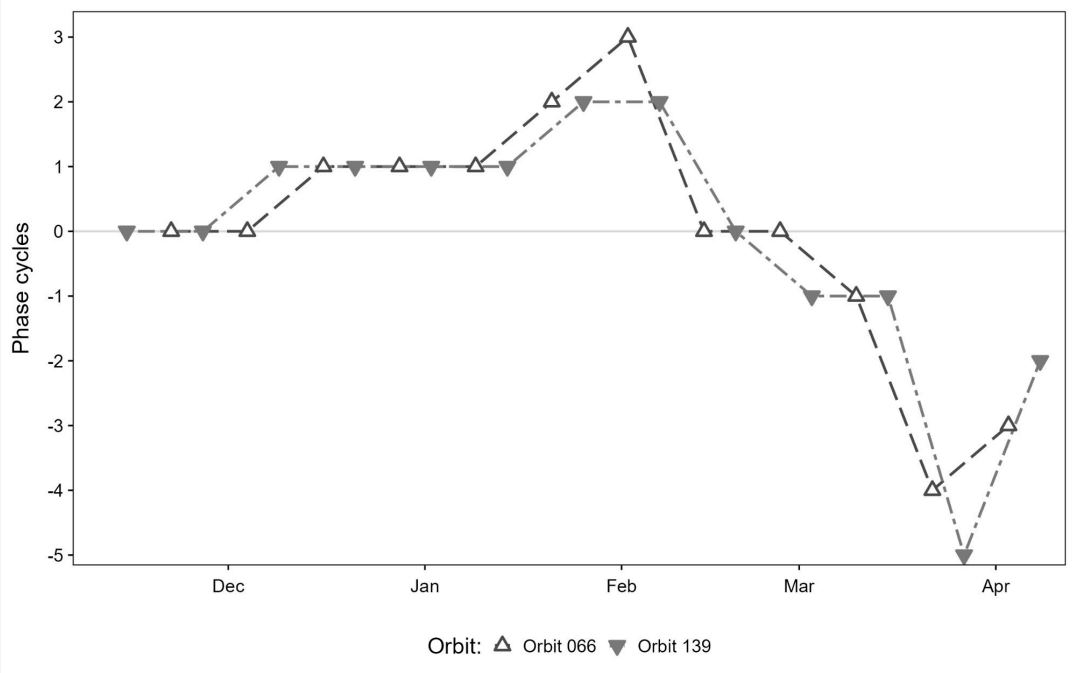


Interferometric Coherence (VH)

Dry snow period (Nov – Jan): σ^o stable between −5 and +5 dB, coherence > 0.3 → dry snow transparent to C-band.

Wet snow period (Feb – Mar): σ^o drops below −7.5 dB, coherence degrades → liquid water absorption invalidates retrieval.

Results: Phase Evolution and Unwrapping



Integer phase cycles (2π wraps) added to reconstruct total SWE from wrapped signal

Accumulation period

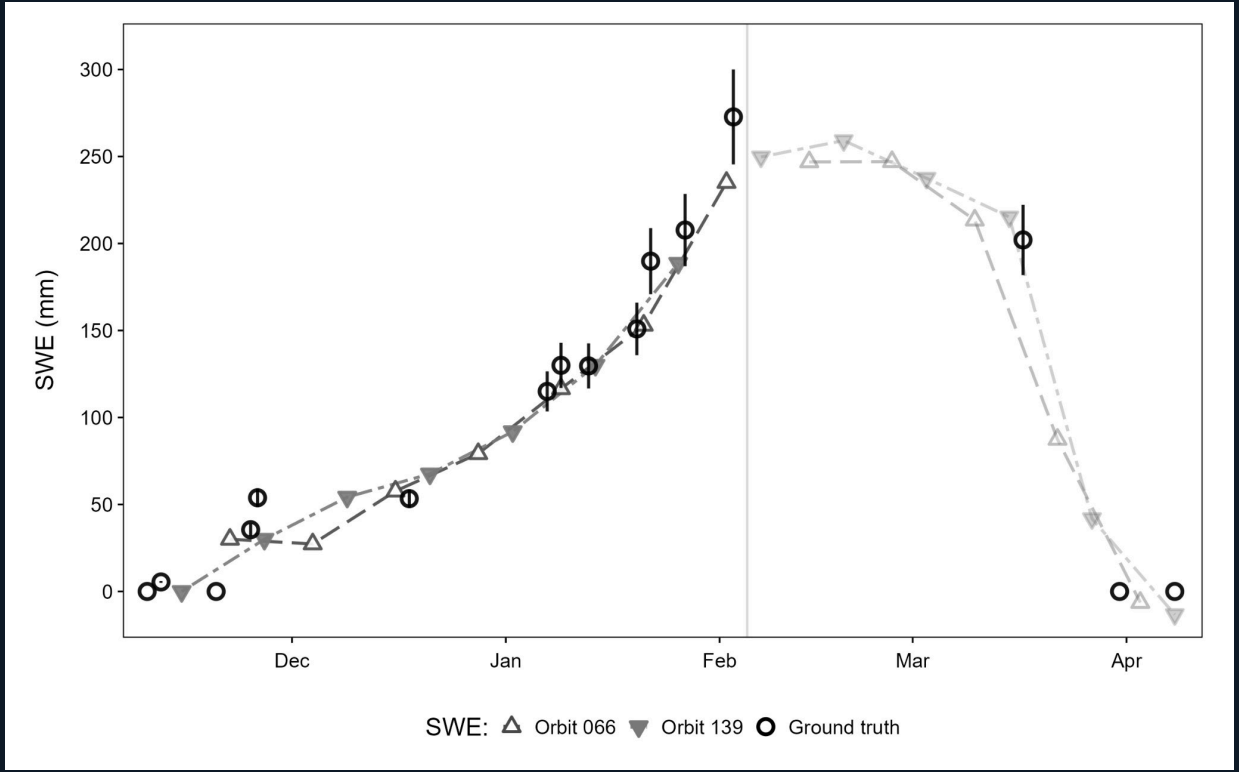
Positive stepwise trend from Dec to Feb: up to 3 full cycles (about 90 mm of SWE per 3 wraps).

Melting period

After February onset of melting: negative cycles introduced. Erratic behavior and discontinuities confirm that liquid water invalidates the linear phase - SWE relationship.



Key Result: SWE Time Series



InSAR-derived SWE (dashed) vs. Ground Truth (black circles) · Vertical line = melting onset

Peak of SWE

250 mm

InSAR estimate
vs. 273 mm ground truth

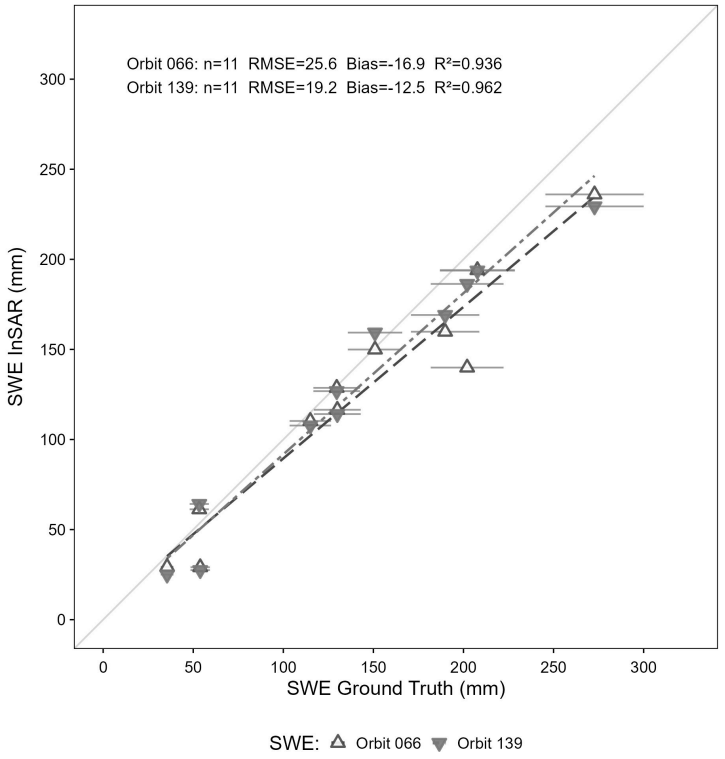
Accumulation period

Good agreement between InSAR and ground truth during dry snow period (Nov – Jan)

Melting period

Divergence after February: liquid water invalidates the refraction-based model.

Statistical Validation



Slight negative bias suggests systematic underestimation, likely due to the linear approximation of snow permittivity not fully capturing basal densification.

Orbit 139

R^2	RMSE	Bias
0.962	**19.2 mm**	**−12.5 mm**

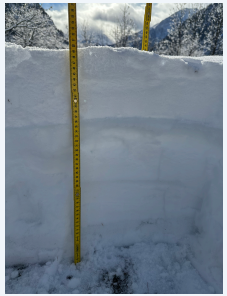
n = 11 acquisitions during dry snow period

Orbit 066

R^2	RMSE	Bias
0.936	**25.6 mm**	**−16.9 mm**

n = 11 acquisitions during dry snow period









Discussion and Future Perspectives

Advantages

Compact and deployable: 52×32 cm vs. >1.7 m of a passive CR

Visible under deep snow: 42 dB active gain ensures target dominance

Direct snow column sensing: Flush configuration measures the actual overlying SWE

Dual-sensor capability: SWE gauge in winter and wet-snow detector in spring

Current Limitations

C-band phase ambiguity: 30 mm/cycle → requires supervised unwrapping

12-day revisit time: only S-1A during winter 2024/25 (S-1C in commissioning)

Wet snow limitation: Retrieval of SWE is invalid when liquid water content >1%

Point-scale measurement: single small area above the AR, spatial representativeness to be assessed

Future Work and Outlook

Sentinel-1C Integration

6-day revisit → reduced decorrelation, easier automated unwrapping

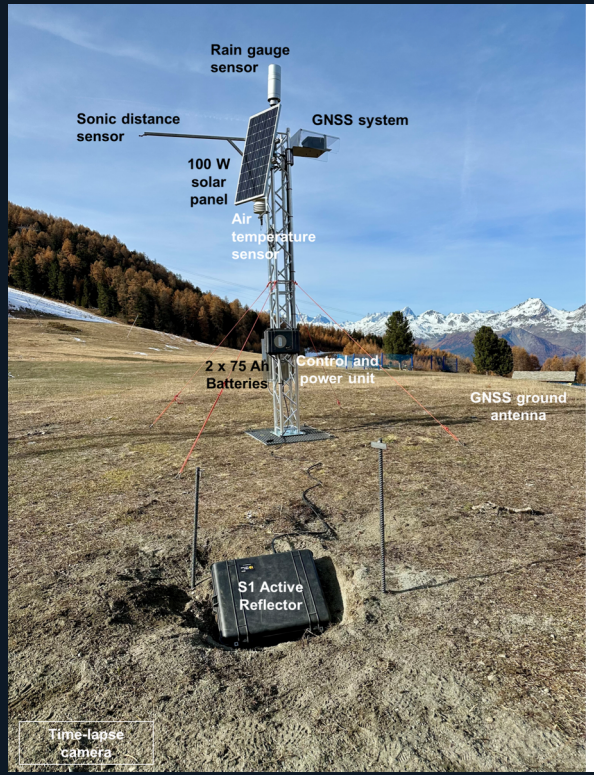
Automated Workflows

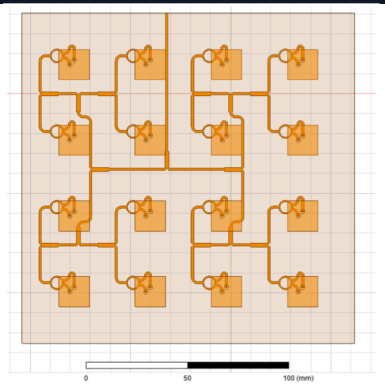
Real-time AWS data integration for constrained automatic phase unwrapping

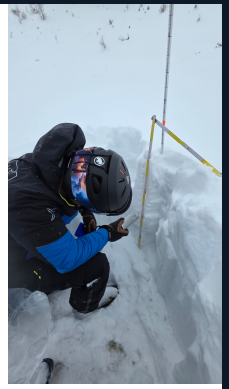
L-band Missions

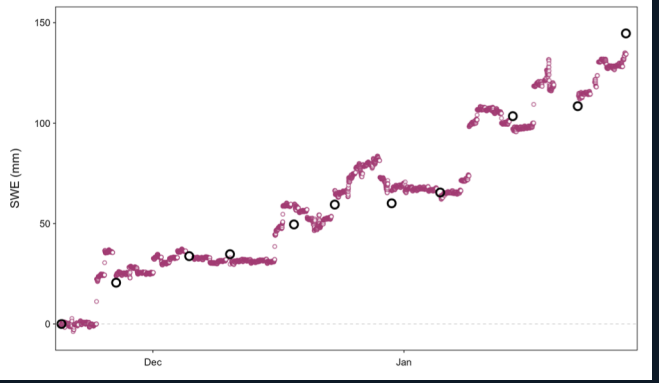
NISAR / ROSE-L: $\lambda \approx 24$ cm → wider unambiguous SWE range

Pila Campaign in 2025 - 2026









Active Reflector Upgrade

Replacement of the linear VH patch with a circularly-polarized microstrip array.

Multi-Polarization Capability

Enables simultaneous VV and VH acquisitions to investigate different scattering mechanisms.

AWS and GNSS Refractometry

Combination of GNSS refractometry or AWS observations to resolve phase ambiguities.

Conclusions

01

Active Reflector for SWE

Low-cost, flush-mounted Active Reflectors provide reliable, direct SWE measurements from Sentinel-1 C-band InSAR, overcoming the logistical and physical limitations of passive corner reflectors.

02

High Accuracy

RMSE of 19 - 26 mm and $R^2 > 0.93$ against manual ground truth during the dry snow accumulation period, demonstrating the precision of the interferometric phase-delay model.

03

Wet Snow Detection

Radiometric thresholds ($\sigma^o < -7.5$ dB, $\gamma < 0.3$) successfully identify the dry-to-wet snow transition, enabling robust quality control and dual-sensor functionality.

04

Scalable Calibration Nodes

The approach offers a practical, scalable solution for establishing calibration and validation nodes in alpine environments, with potential for integration with upcoming L-band SAR missions.

Thank You

Questions & Discussion

Contact

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University of Pavia · Fondazione Montagna Sicura

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