Persistent Scatterer Interferometry for Early Detection of **Glacial Lake Outburst Floods**: A **Case study** of the 2024 Thyanbo GLOF near Thame, Nepal

AK Fernerkundung – 30.09.25 – Niels Dedring

Geomatics
Urban Remote Sensing

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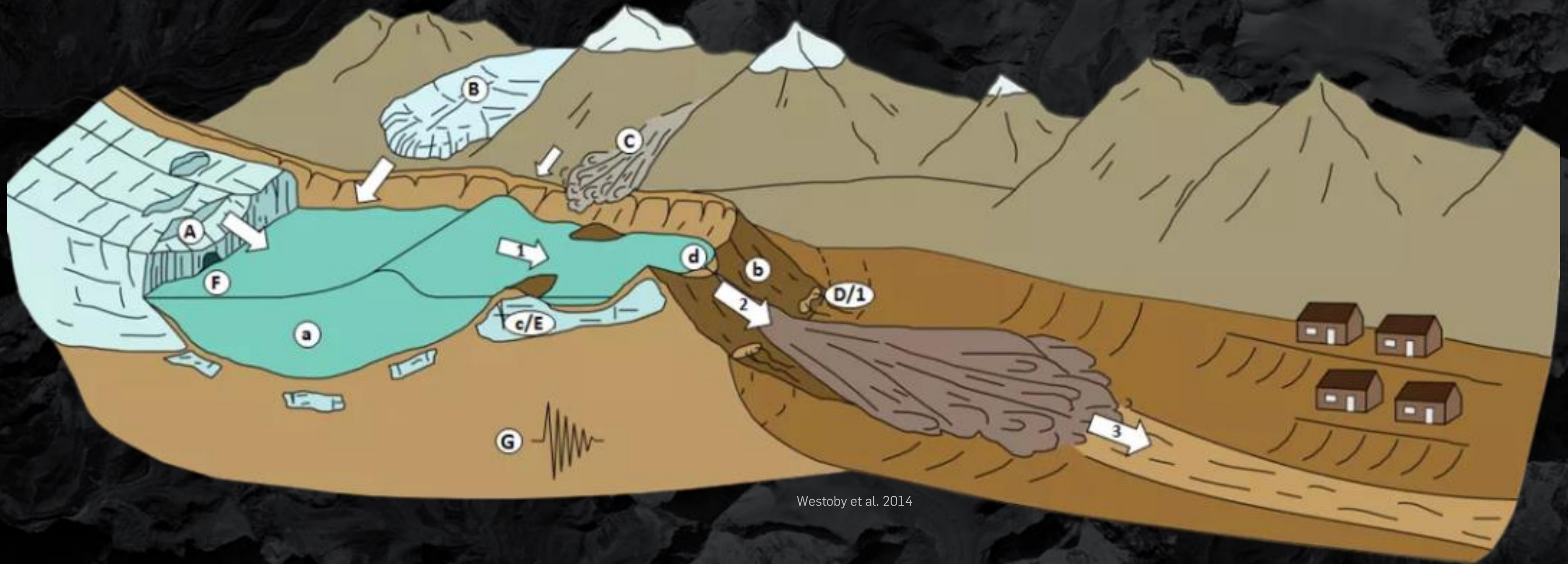
What is a Glacial Lake Outburst Flood (GLOF)?



Westoby et al. 2014

Thame GLOF

- GLOF occurred on 16.08.2024
- 0 casualties
- ca. 135 people displaced
- 20 houses, 1 school, 1 medical station destroyed
- Damages even 85 km downstream

Sharma, K. 2024

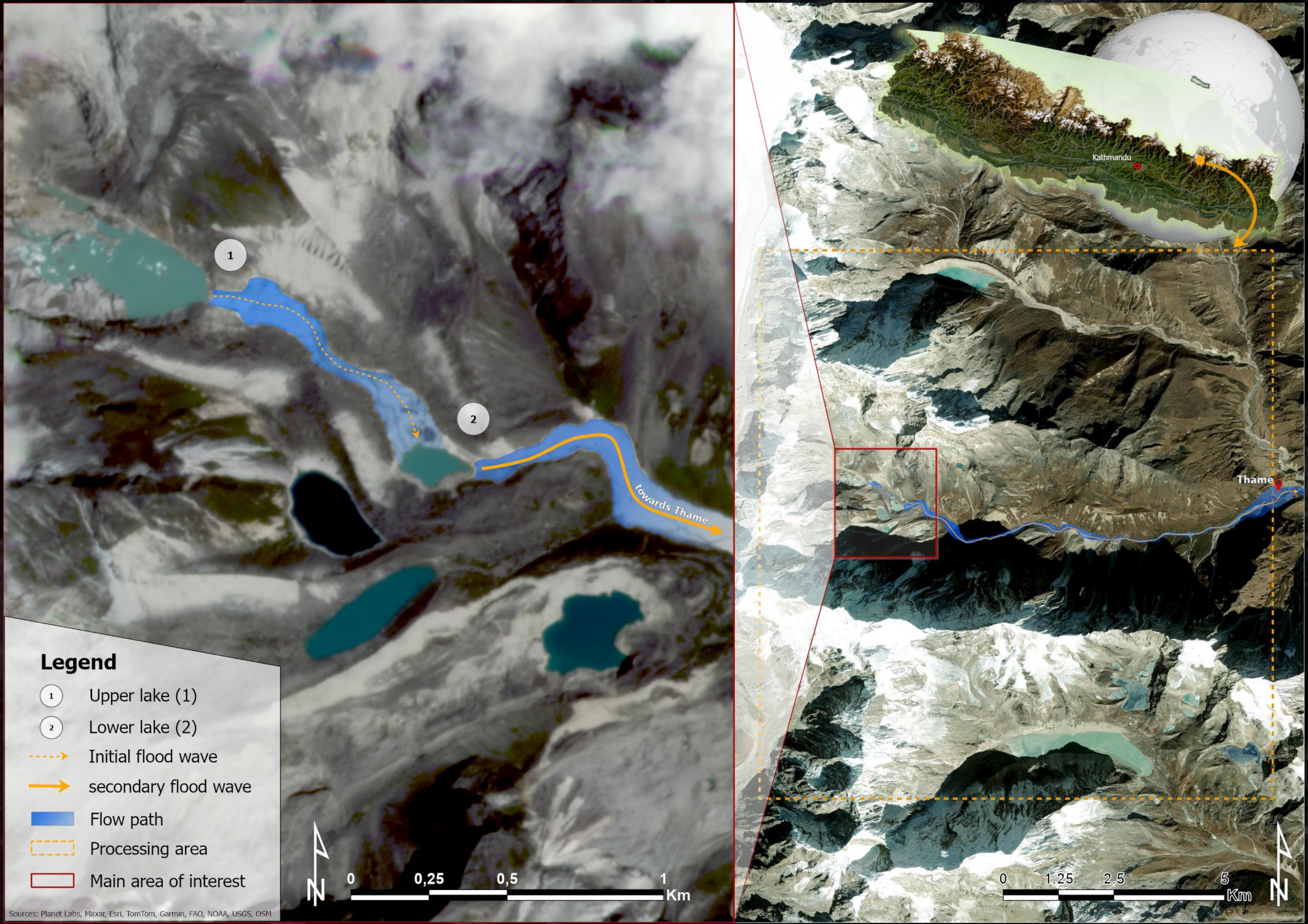
The Kathmandu Post 2024

McGill, T. 2024

Silwal, R. 2024

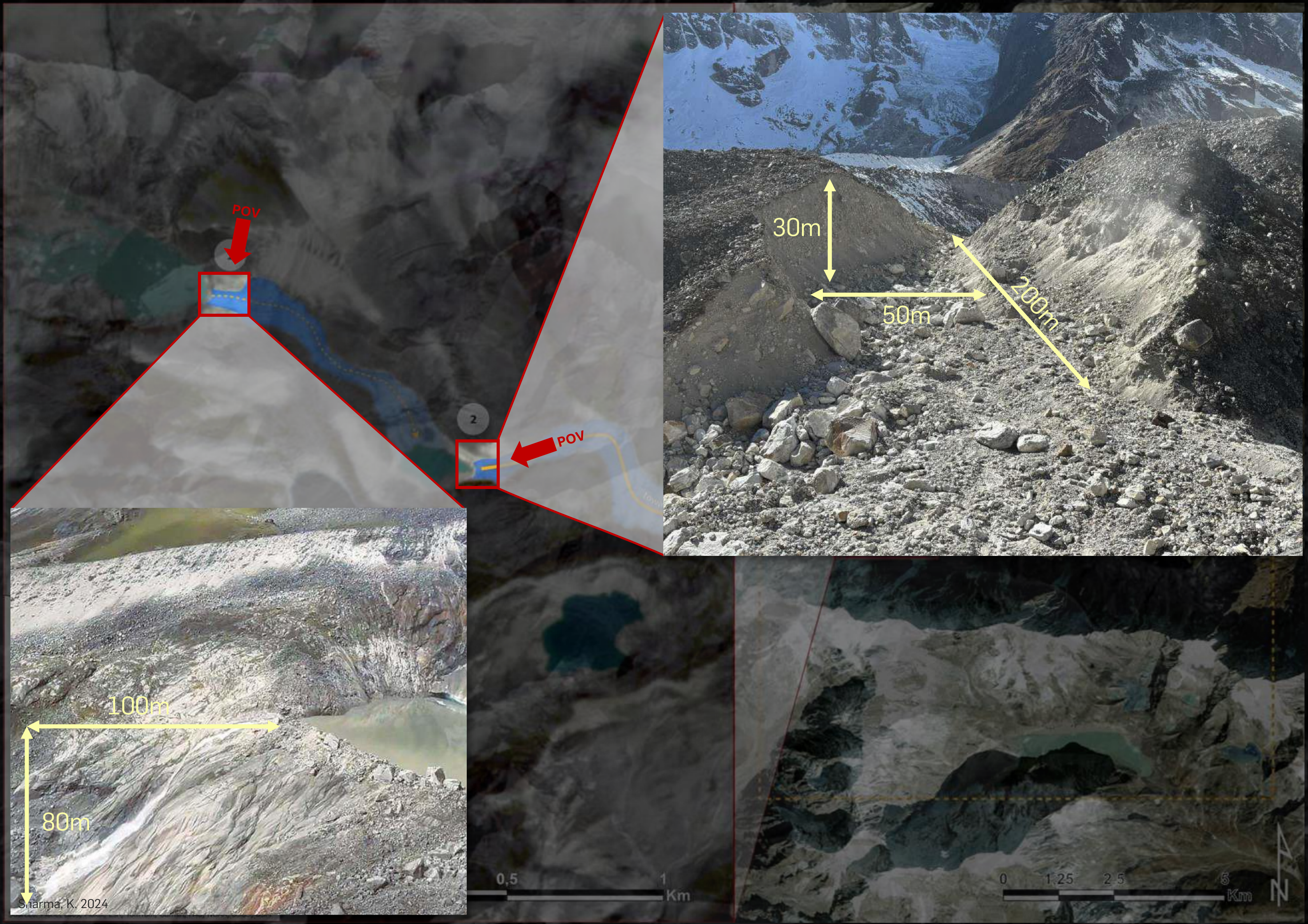
Thame GLOF

- 39 km from Mt Everest
- AOI situated ~4.800m asl
- Initial GLOF from upper Tso Mutse (1) which caused a second GLOF at lower Tso Mutse (2)



Thame GLOF

- 39 km from Mt Everest
- AOI situated ~4.800m asl
- Initial GLOF from upper Tso Mutse (1) which caused a second GLOF at lower Tso Mutse (2)
- Upper lake (1) has got a solid & steep terminal moraine
- Lower lake (2) has a flat and loose moraine



Research Questions

1. What was the exact cause and course of the Thyanbo GLOF?

Dynamics of the Lakes → planet.

2. Could this GLOF or the potential impacts have been foreseen by ground movements of the terminal moraines?

Preprocessing SNAP2StaMPS (SNAP) → PSI-Processing StaMPS (MATLAB) → Postprocessing Displacements

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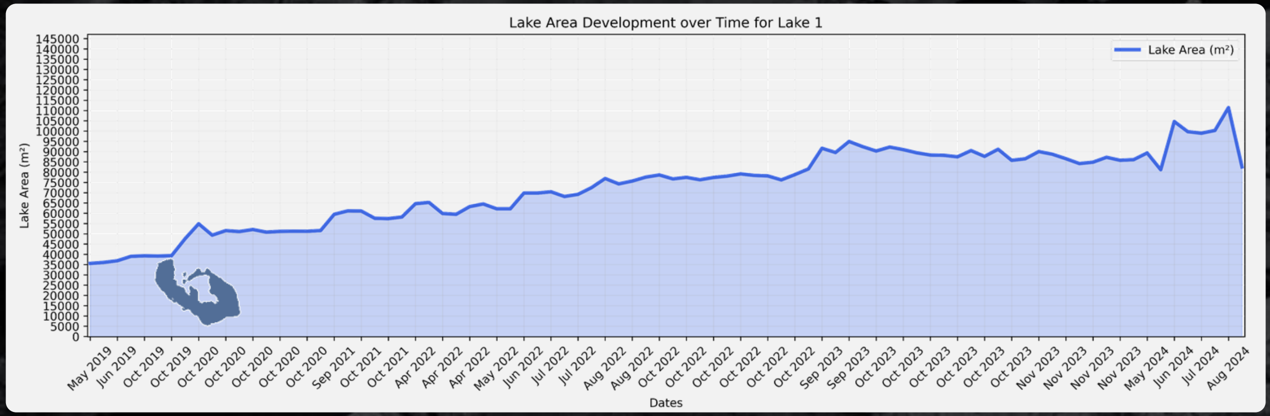
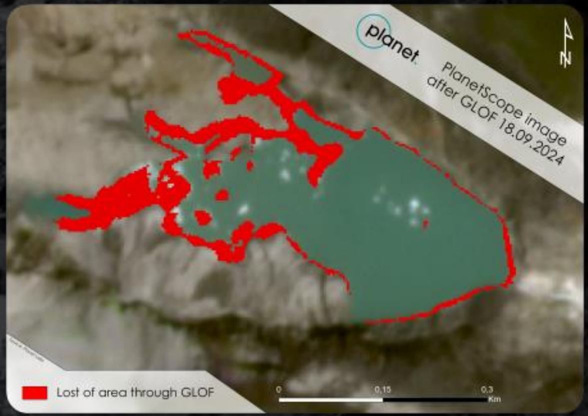
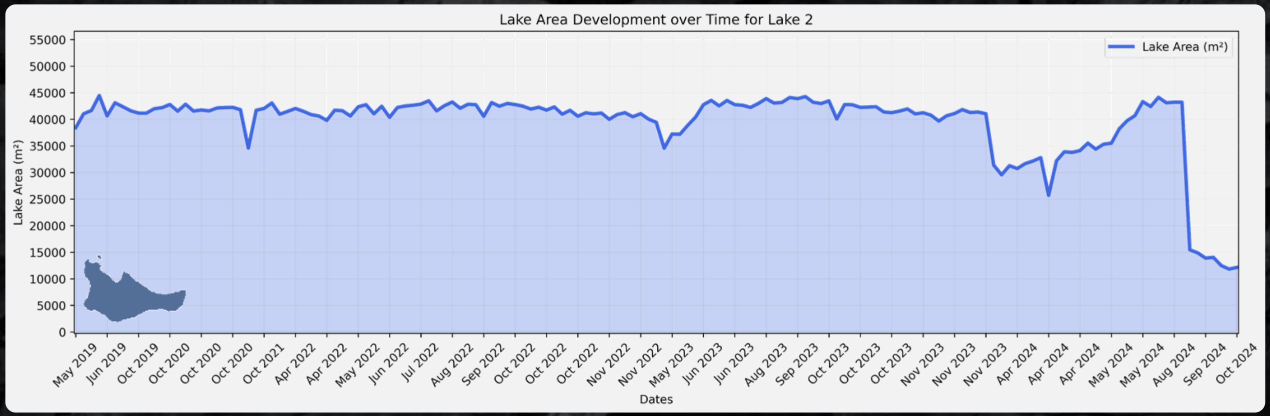
Preprocessing: SNAP2StaMPS (SNAP) → PSI-Processing: StaMPS (MATLAB) → Postprocessing: Displacements

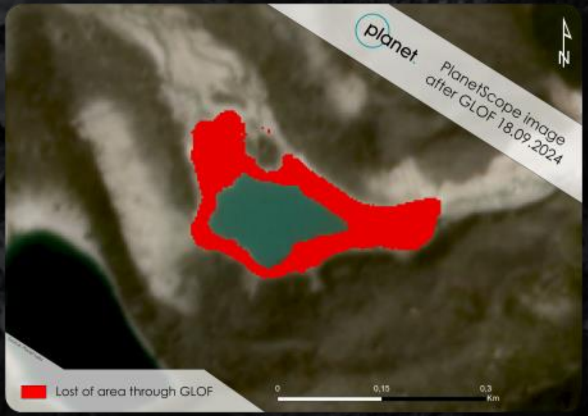
1. Dynamics of the Lakes





PlanetScope 2019-2024 → $NDWI = \frac{(G - NIR)}{(G + NIR)}$ → Water Mask Otsu's Thresholding





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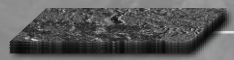
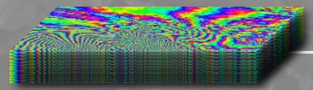
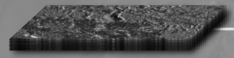
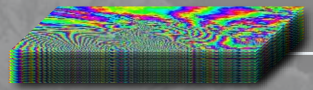
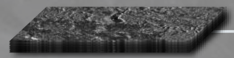
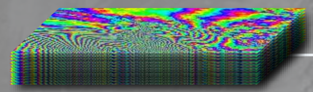
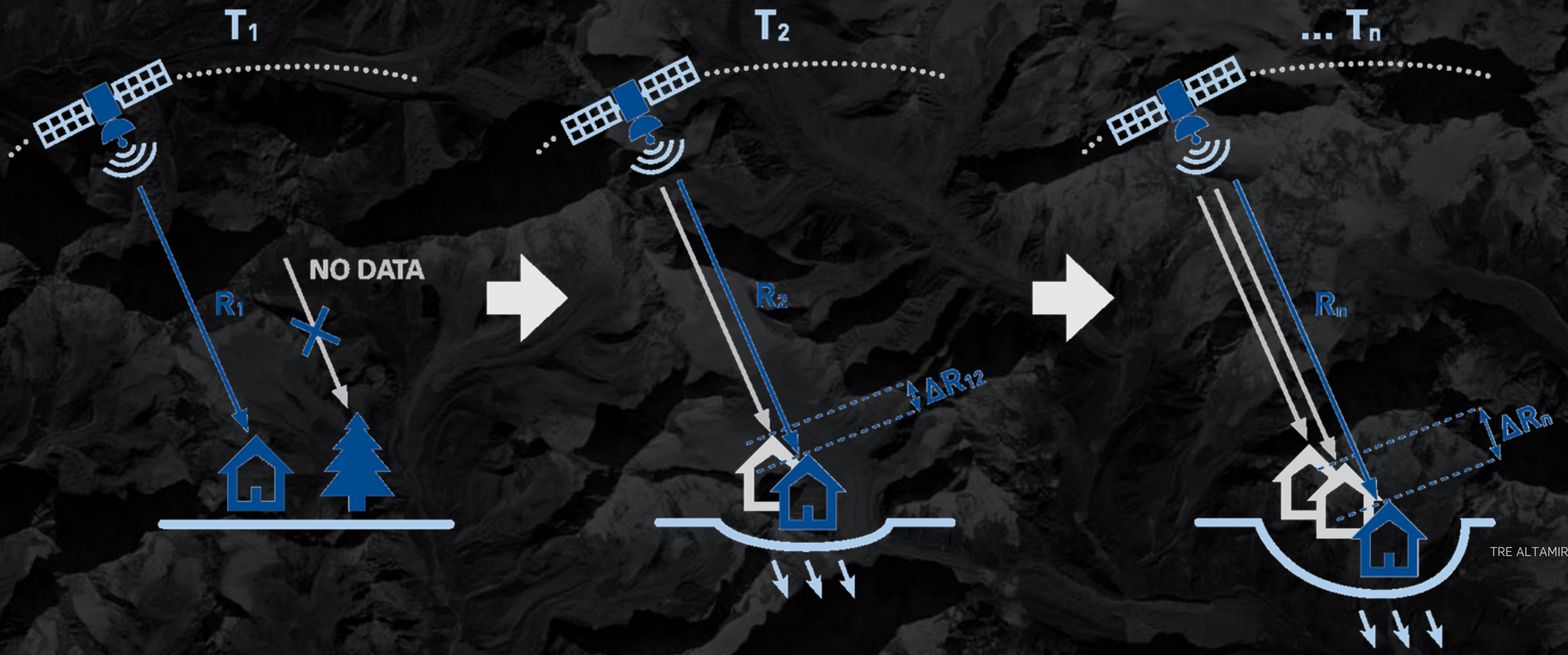
Preprocessing SNAP2StaMPS — SNAP → PSI-Processing StaMPS — MATLAB → Postprocessing Displacements

2.1 Preprocessing SNAP2StaMPS

Orbit-direction	Rel. Orbit	IW & Burst	2020 Season	2021 Season	2022 Season	2023 Season	2024 Season	Master-date	Num. images	SLC-data	After SNAP2StaMPS	
ASC	12	IW1, 8+9	31.05.20 21.12.20	07.06.21 22.11.21	21.05.22 16.01.23	28.05.23 24.11.23	16.04.24 14.08.24	01.08.22	81			StaMPS processing
ASC	85	IW3, 1	05.06.20 26.12.20	31.05.21 27.11.21	26.05.22 21.01.23	02.06.23 17.11.23	21.04.24 07.08.24	06.08.22	79			StaMPS processing
DES	121	IW2, 1	08.06.20 29.12.20	03.06.21 30.11.21	17.05.22 24.01.23	05.06.23 20.11.23	24.04.24 10.08.24	28.07.22	79			StaMPS processing

2.2 PSI-Processing StaMPS MATLAB

How does Persistent Scatterer Interferometry work?

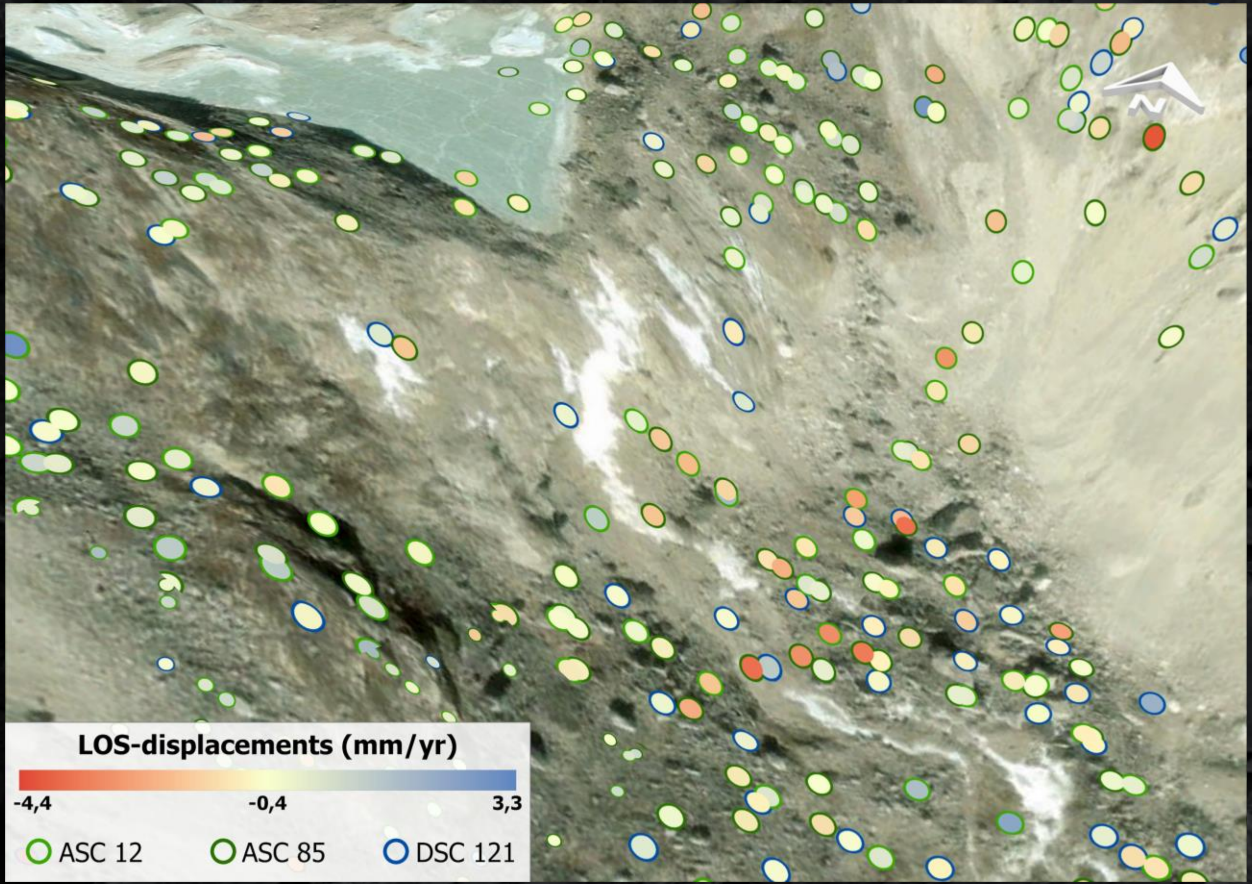


TRE ALTAMIRA n.d.

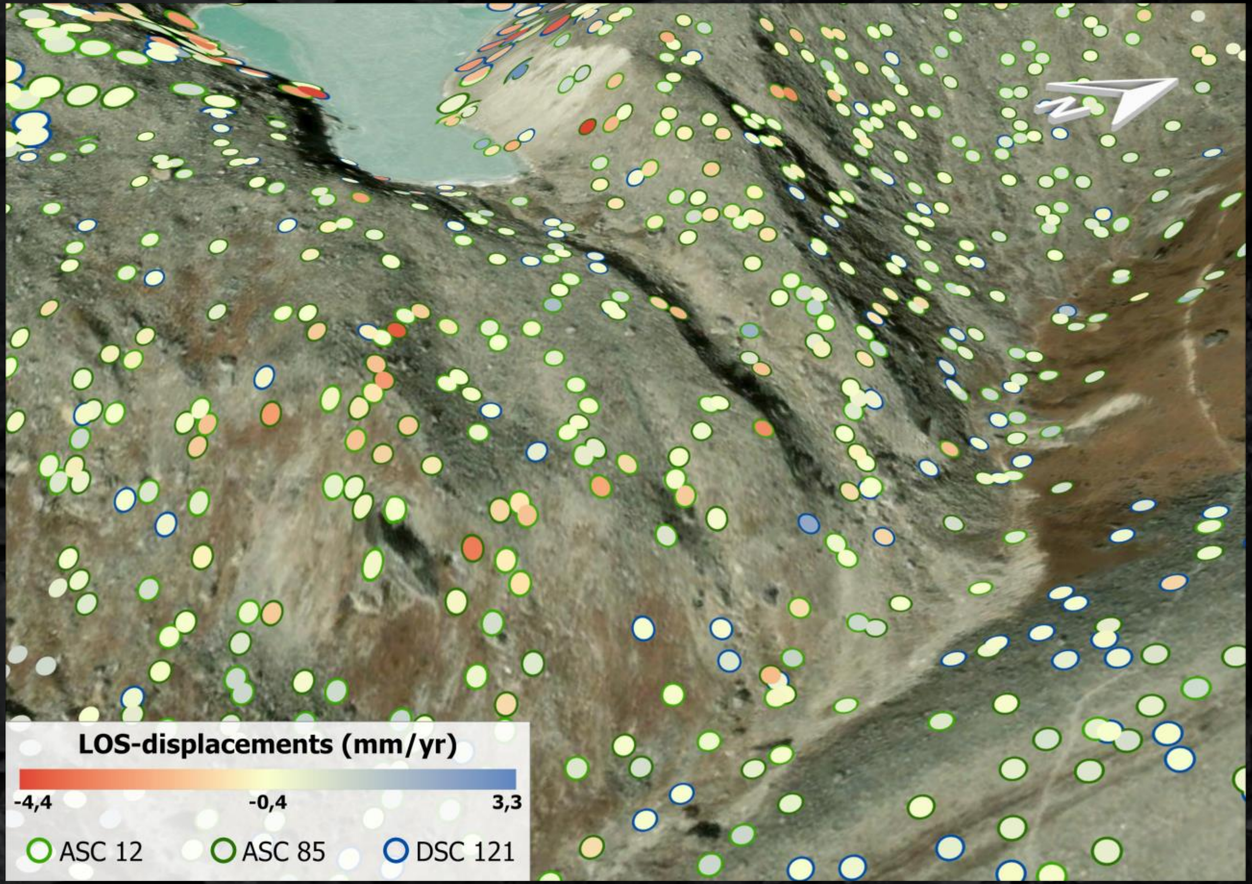
2.2 PSI-Processing StaMPS

MATLAB

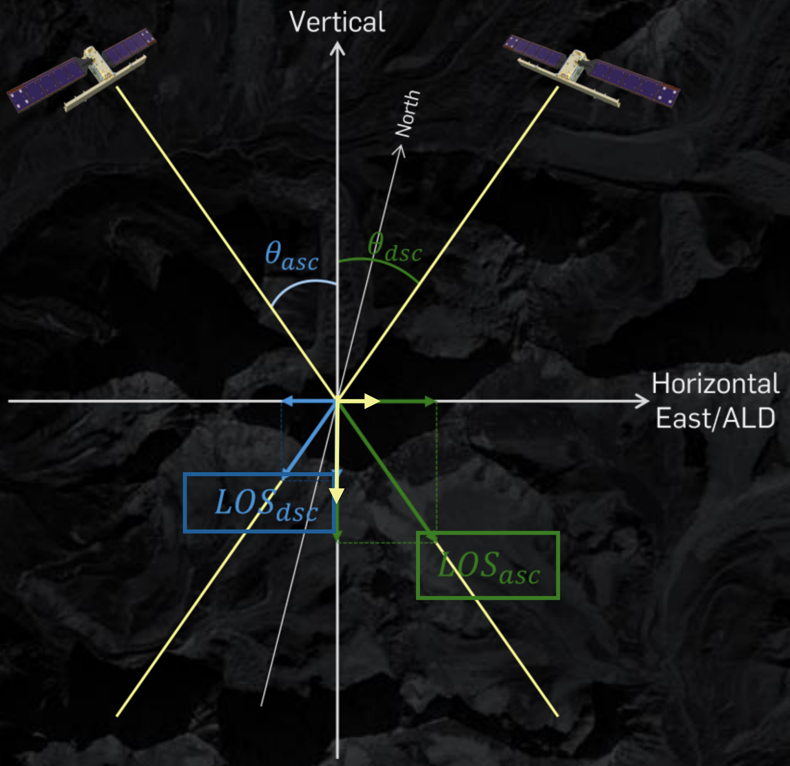
Terminal moraine of upper Tso Mutse (1)



Terminal moraine of lower Tso Mutse (2)

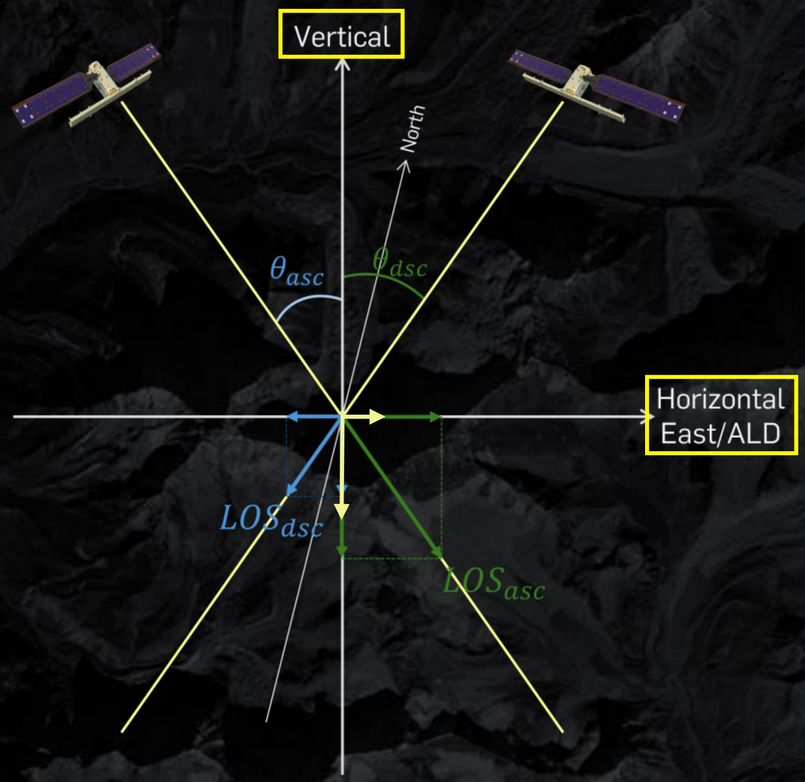


2.3 Postprocessing Displacements



2.3 Postprocessing Displacements

Vertical displacements
+uplift/-subsidence

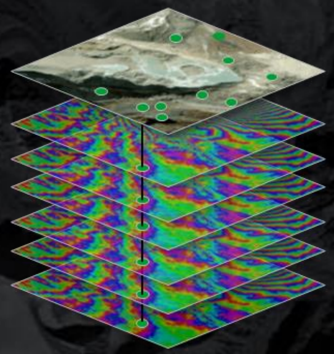


Horizontal displacements
(along Azimuth Look Direction = ALD)
+east / -west

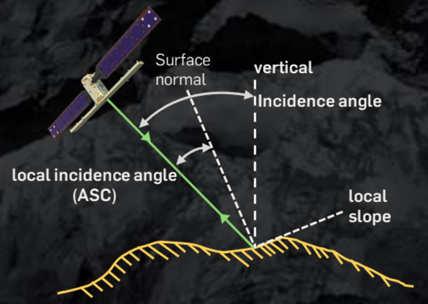
$$\begin{bmatrix} d_v \\ d_{h_{ald}^{dsc}} \end{bmatrix} = \begin{bmatrix} d_{LOS}^{asc} \\ d_{LOS}^{dsc} \end{bmatrix} \begin{bmatrix} \cos\theta^{asc} & \dfrac{\sin\theta^{asc}}{\cos\Delta\alpha} \\ \cos\theta^{dec} & \sin\theta^{dsc} \end{bmatrix}^{-1}$$

ASC orbit

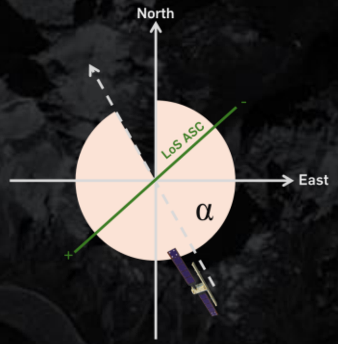
LoS displacements



Local Incidence Angle

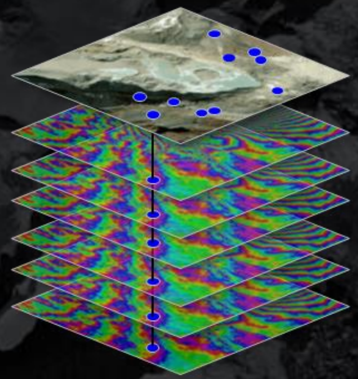


Heading of S1

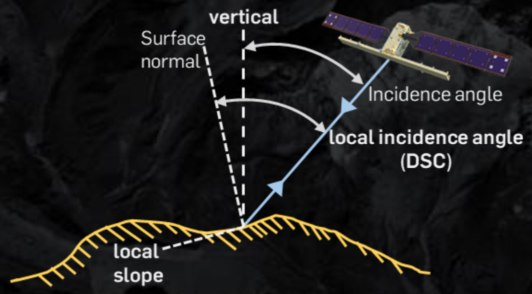


DSC orbit

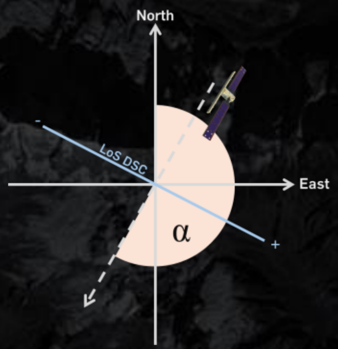
LoS displacements



Local Incidence Angle



Heading of S1



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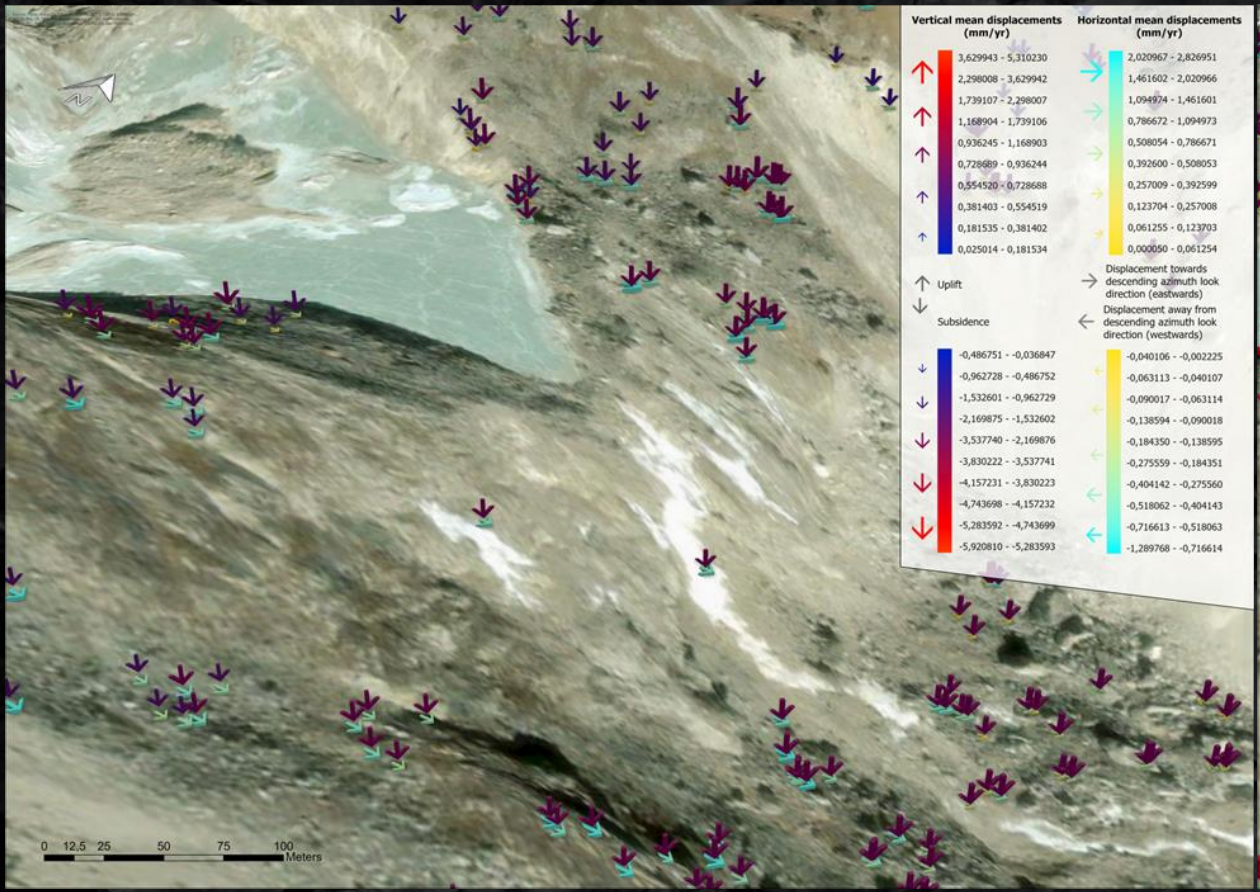
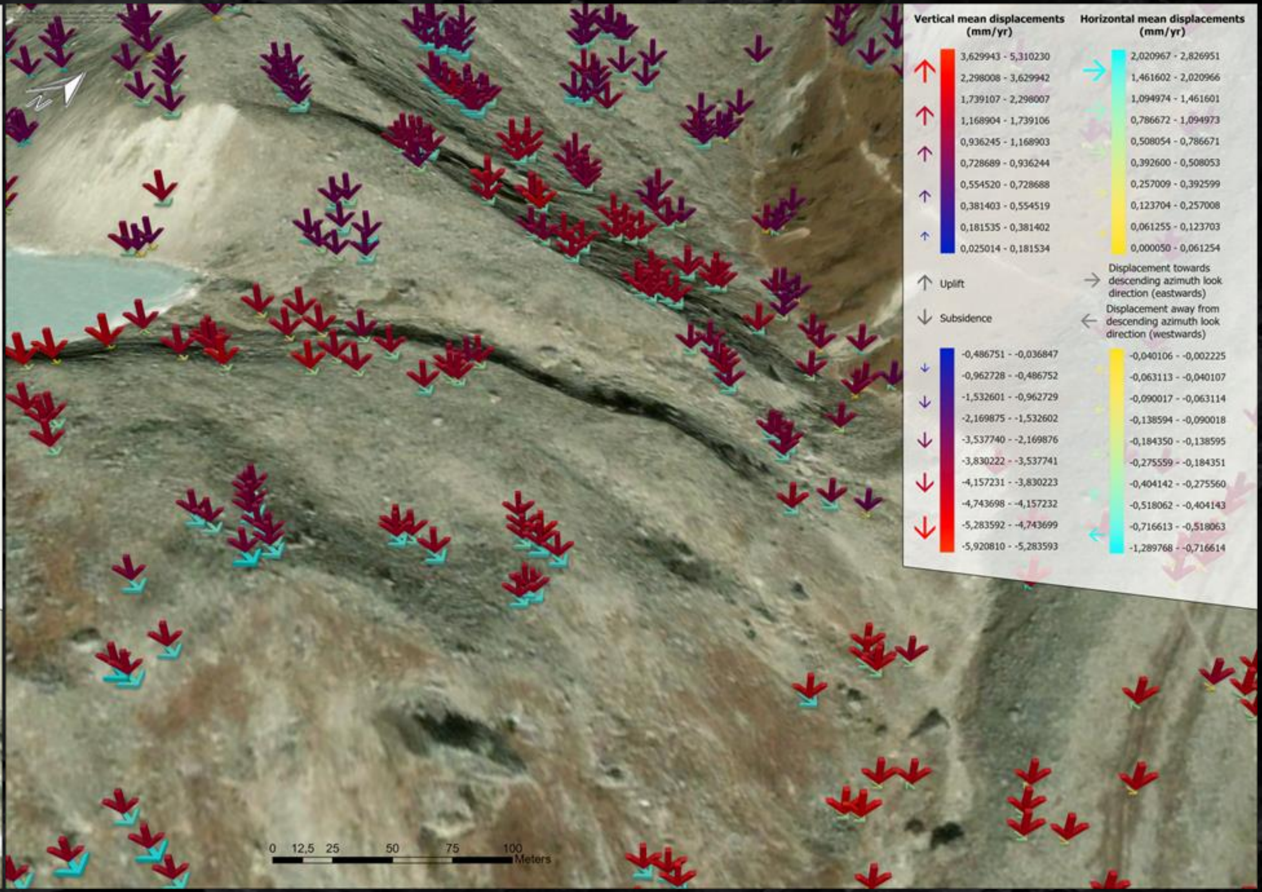
2.3 Postprocessing Displacements

Terminal moraine of upper Tso Mutse (1)



Terminal moraine of lower Tso Mutse (2)



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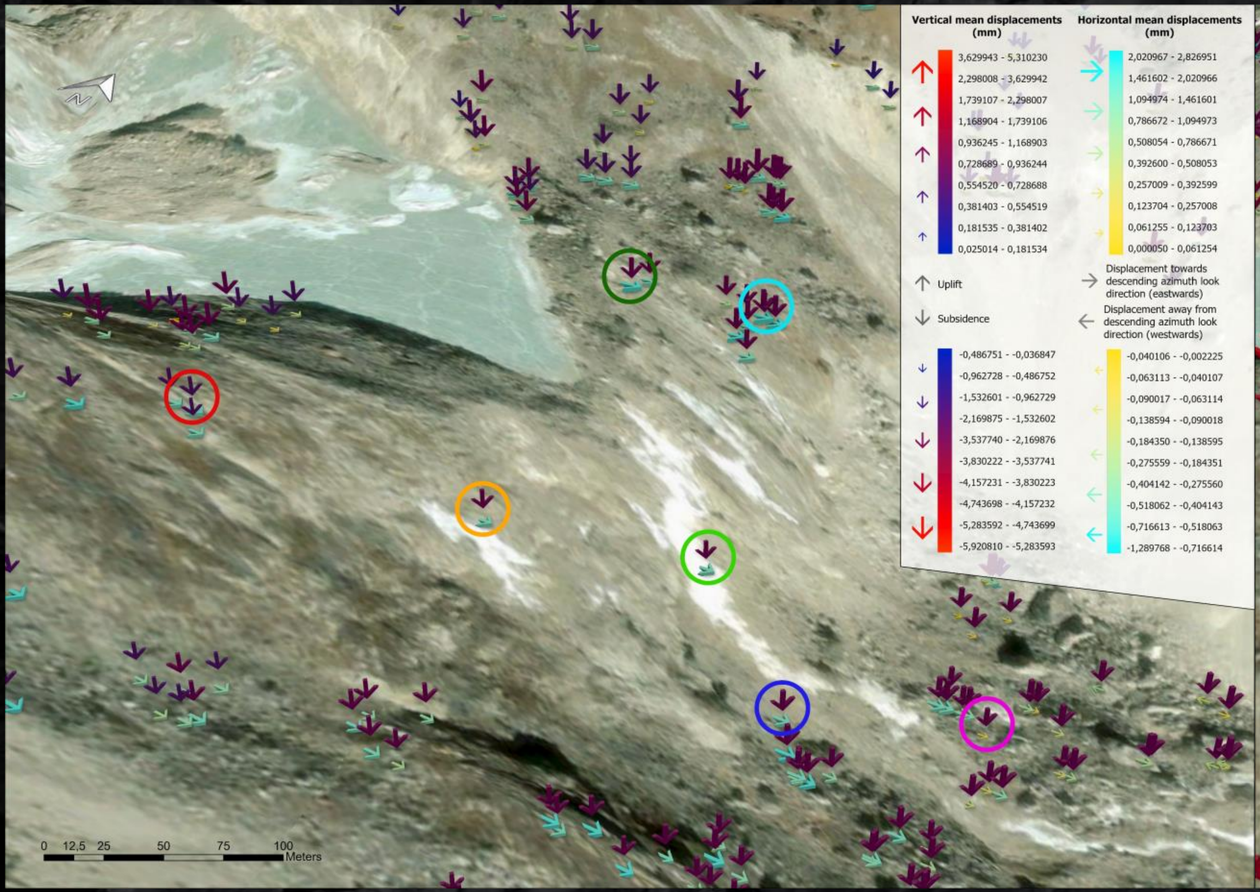
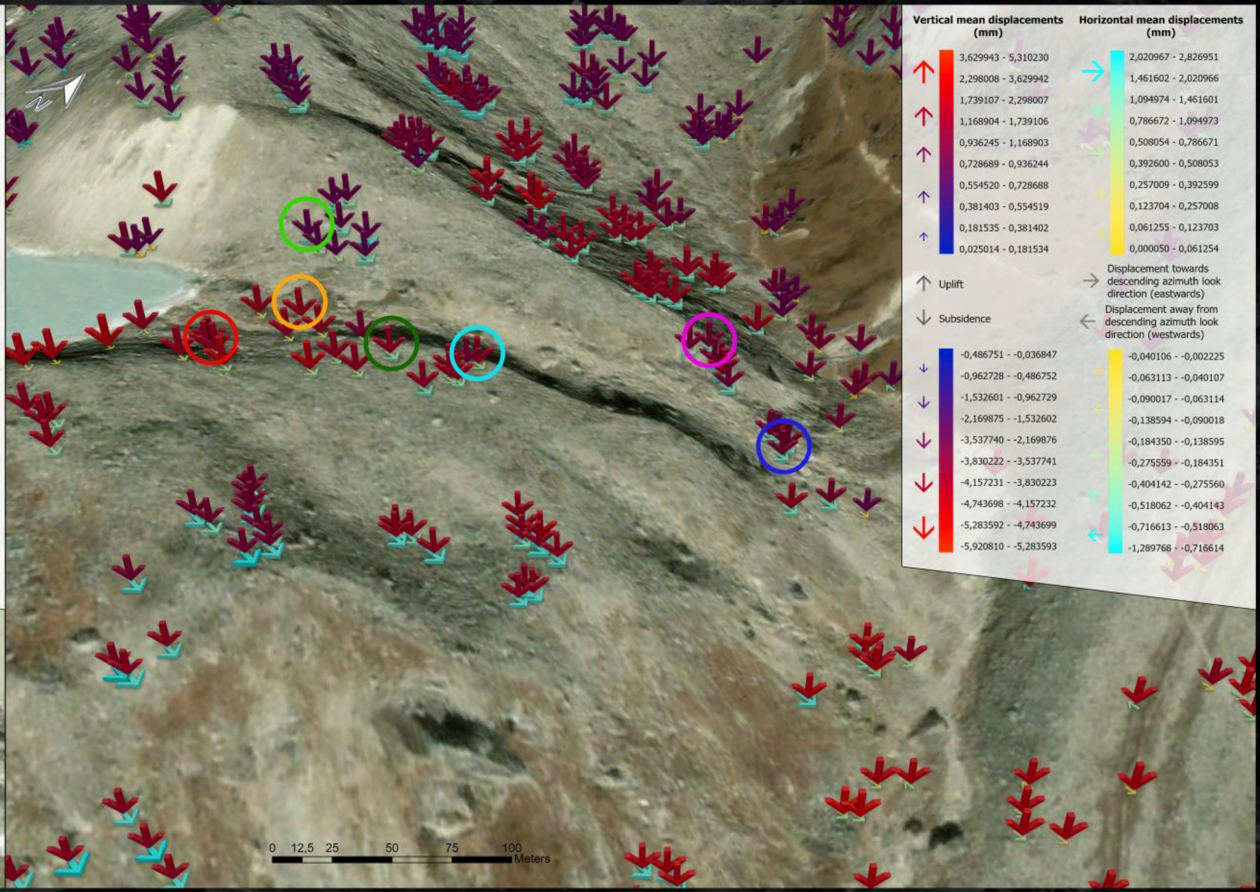


Terminal moraine of lower Tso Mutse (2)



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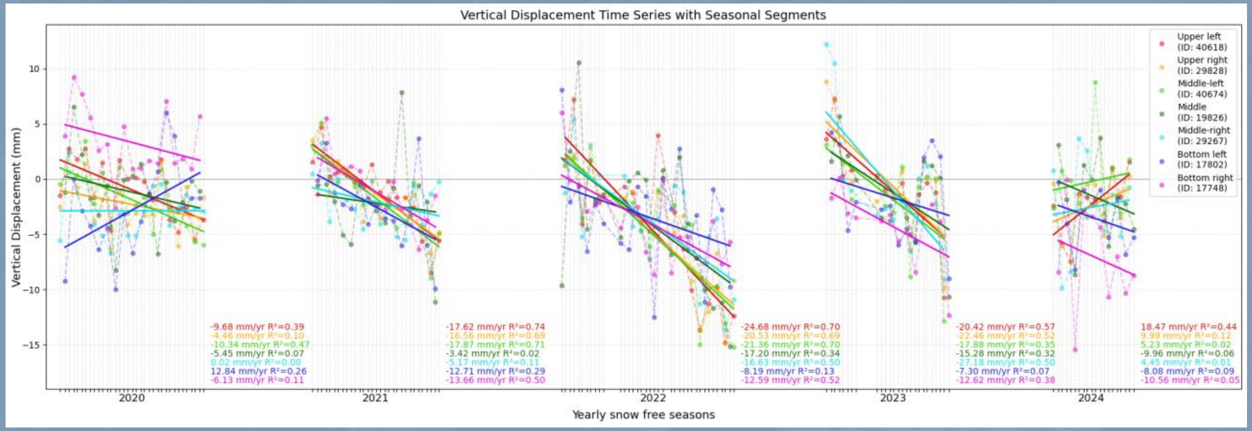

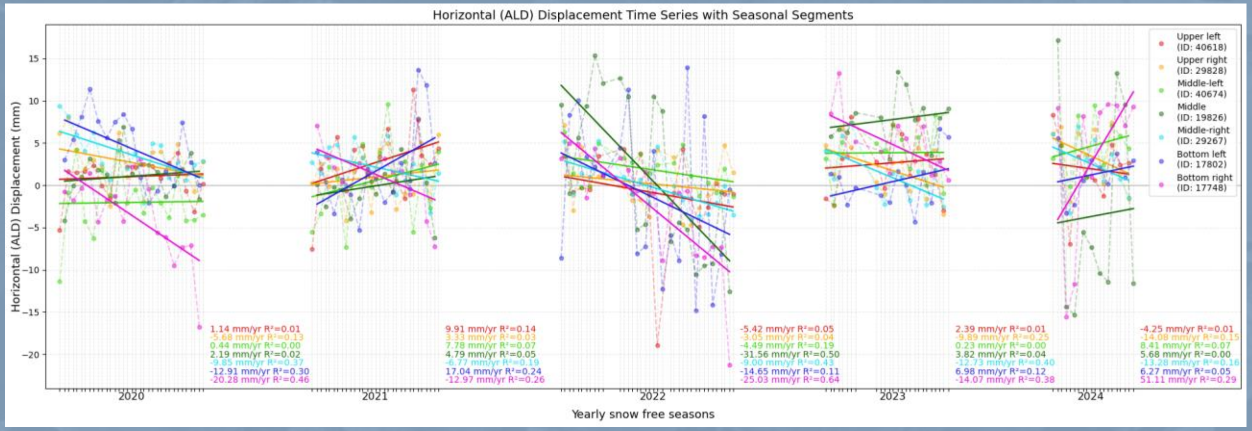

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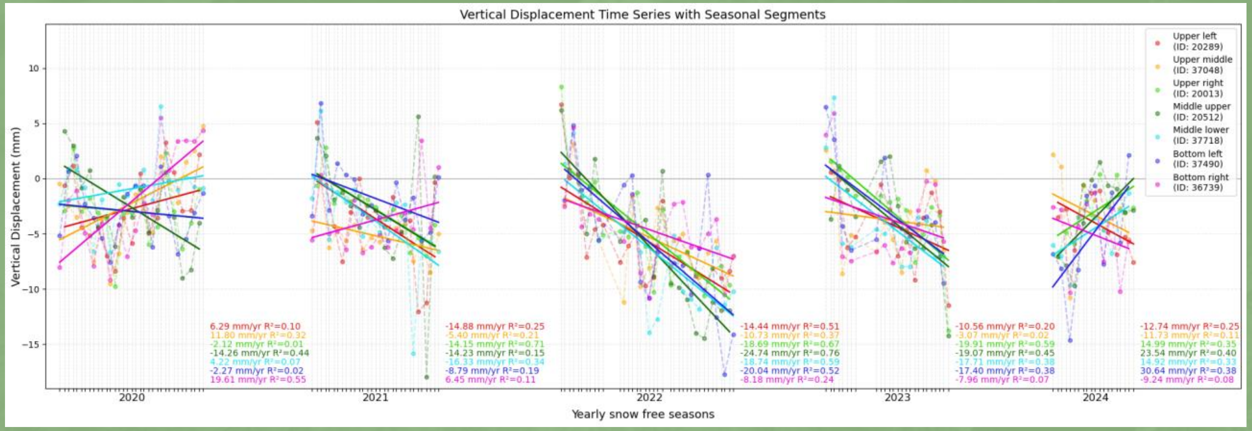

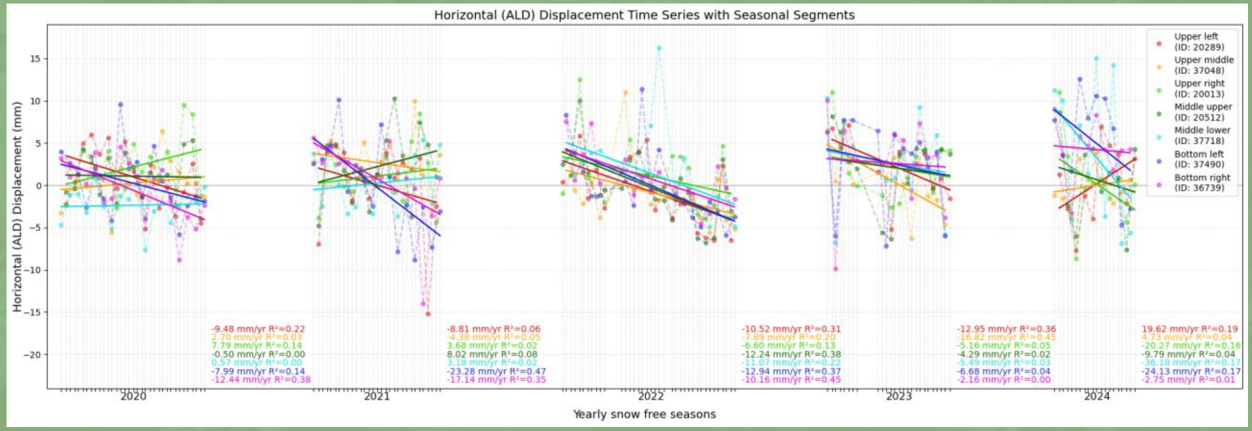

2.3 Postprocessing Displacements

		Vertical Displacements (mm)						Horizontal (ALD) Displacements (mm)					
	ID	max	min	SD	sum	mean	median	max	min	SD	sum	mean	median
Terminal moraine of upper Tso Mutse (1)	17748	9.277	-15.459	4.796	-166.510	-2.532	-2.220	13.269	-21.268	6.452	12.776	1.224	0.170
	17802	8.088	-12.507	4.009	-212.453	-2.686	-2.833	13.945	-14.814	5.935	95.924	1.072	1.279
	19826	10.600	-15.168	4.561	-163.910	-1.546	-2.185	17.164	-15.344	7.448	106.930	1.341	1.426
	29267	12.244	-13.693	4.214	-188.584	-2.700	-2.514	9.381	-4.091	3.160	135.782	1.611	1.810
	29828	8.838	-14.866	4.150	-178.198	-1.695	-2.376	8.000	-4.744	3.326	126.944	1.939	1.693
	40618	7.295	-14.848	4.376	-153.171	-1.390	-2.042	11.318	-18.915	4.176	99.211	1.647	1.323
	40674	8.811	-15.236	4.297	-173.701	-2.191	-2.316	9.566	-11.352	4.100	101.503	1.776	1.353
	mean				**-176.647**						**97.010**		
Terminal moraine of lower Tso Mutse (2)	20013	8.359	-13.807	3.593	-260.381	-2.981	-3.472	12.482	-8.676	3.795	104.195	0.869	1.389
	20289	6.699	-12.058	3.812	-309.197	-4.363	-4.123	7.116	-15.185	4.104	35.257	1.279	0.470
	20512	6.226	-17.985	4.882	-291.105	-3.502	-3.881	10.262	-7.664	4.036	81.830	1.485	1.091
	36739	5.934	-10.851	3.942	-279.965	-4.467	-3.733	10.019	-14.018	4.223	90.540	1.264	1.207
	37048	4.760	-11.187	3.531	-301.313	-4.487	-4.018	11.037	-6.256	3.440	38.789	0.474	0.517
	37490	6.818	-17.750	4.555	-282.410	-3.590	-3.765	12.571	-8.802	5.122	86.326	1.076	1.151
	37718	7.331	-15.845	4.474	-296.185	-3.767	-3.949	16.290	-7.658	5.176	58.354	0.109	0.778
	mean				**-288.651**						**70.756**		

2.3 Postprocessing Displacements

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	36739	5.934	-10.851	3.942	-279.965	-4.467	-3.733	10.019	-14.018	4.223	90.540	1.264	1.207
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	37718	7.331	-15.845	4.474	-296.185	-3.767	-3.949	16.290	-7.658	5.176	58.354	0.109	0.778
	mean				**-288.651**						**70.756**		

Research Questions

2. Could this GLOF or the potential impacts have been foreseen by ground movements of the terminal moraines?

No clear trend or pattern in 2024

Terminal moraine 2 showed greater ground movements and also suffered from more severe erosion due to the GLOF

Discussion & Improvements

- **Topographic Limitations:** SAR data in mountainous regions affected by radar shadow, layover, and foreshortening, potentially biasing displacement results.
- **Data Availability:** Limited Sentinel-1 coverage (especially after Sentinel-1B failure); future missions (Sentinel-1C/D, Harmony) expected to improve temporal resolution.
- **Orbit Selection:** Suboptimal master image selection for some orbits may have caused spatial decorrelation and reduced PS quality.
- **DEM Accuracy:** Use of SRTM DEM (lower accuracy at high altitudes); higher-resolution DEMs (e.g., High Mountain Asia 8m DEM) recommended.
- **ETAD product:** Use and implementation of the ETAD correction in SNAP2StaMPS could improve the overall results.
- **Parameter Tuning:** StaMPS results highly sensitive to user-defined parameters; more systematic fine-tuning needed.
- **Atmospheric Correction:** GACOS less effective in mountainous terrain; empirical phase-based corrections may yield better results.
- **Lack of Reference Data:** No GNSS/in situ data for referencing; mean velocity referencing may suppress local deformations.
- **Temporal Decorrelation:** Longer time series (5 years) led to decorrelation; shorter periods (3 years) may improve consistency.
- **Methodological Alternatives:** SBAS technique could be compared with PSI for GLOF studies.
- **Software Accessibility:** StaMPS requires MATLAB; Python-based alternatives and workflow automation are desirable.
- **Point Merging Threshold:** 30 m threshold for merging PS points may be too high, risking decorrelation; smaller thresholds recommended.
- **Ground Truthing:** Absence of ground-truth/in situ data limits validation; need for long-term on-site measurement stations.
- …

Discussion & Improvements

Upcoming Sentinel-1C & -1D data could improve the overall number & quality of PS candidates.

Overall improvement potential along the workflow:
Higher resolution DEM, ETAD correction for S1, StaMPS parameter, ...

GPS-reference points near the terminal moraine would improve the accuracy of the PSI.

A 3-year time series would lead to less temporal decorrelation and consequently to more valid results.

And much more...

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Conclusion

- The application of a PSI did not clearly indicate the GLOF upfront.

+ The PSI was able to make statements about the general stability of the two terminal moraines.

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» *Although the affected lakes weren't classified as "Potentially Dangerous Glacial Lakes", a glacial lake outburst flood did occur.*

A new and more comprehensive risk assessment for glacial lakes is therefore urgently needed.

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+ The PSI was able to make statements about the general stability of the two terminal moraines.

» *Although the affected lakes weren't classified as "Potentially Dangerous Glacial Lakes", a glacial lake outburst flood did occur.*

A new and more comprehensive risk assessment for glacial lakes is therefore urgently needed.

Outlook → **Applying PSI on a greater number of terminal moraines in the Himalayas.**

Thank you for your interest!

Esa 2018

Questions?

Literature

Ratna Bajracharya, S., Bikash Maharjan, S., Shrestha, F., Chogyal Sherpa, T., Wagle, N., & Bhakta Shrestha, A. (2020). Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region of China, and India. https://doi.org/10.53055/ICIMOD.773

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What could have led to the GLOF?

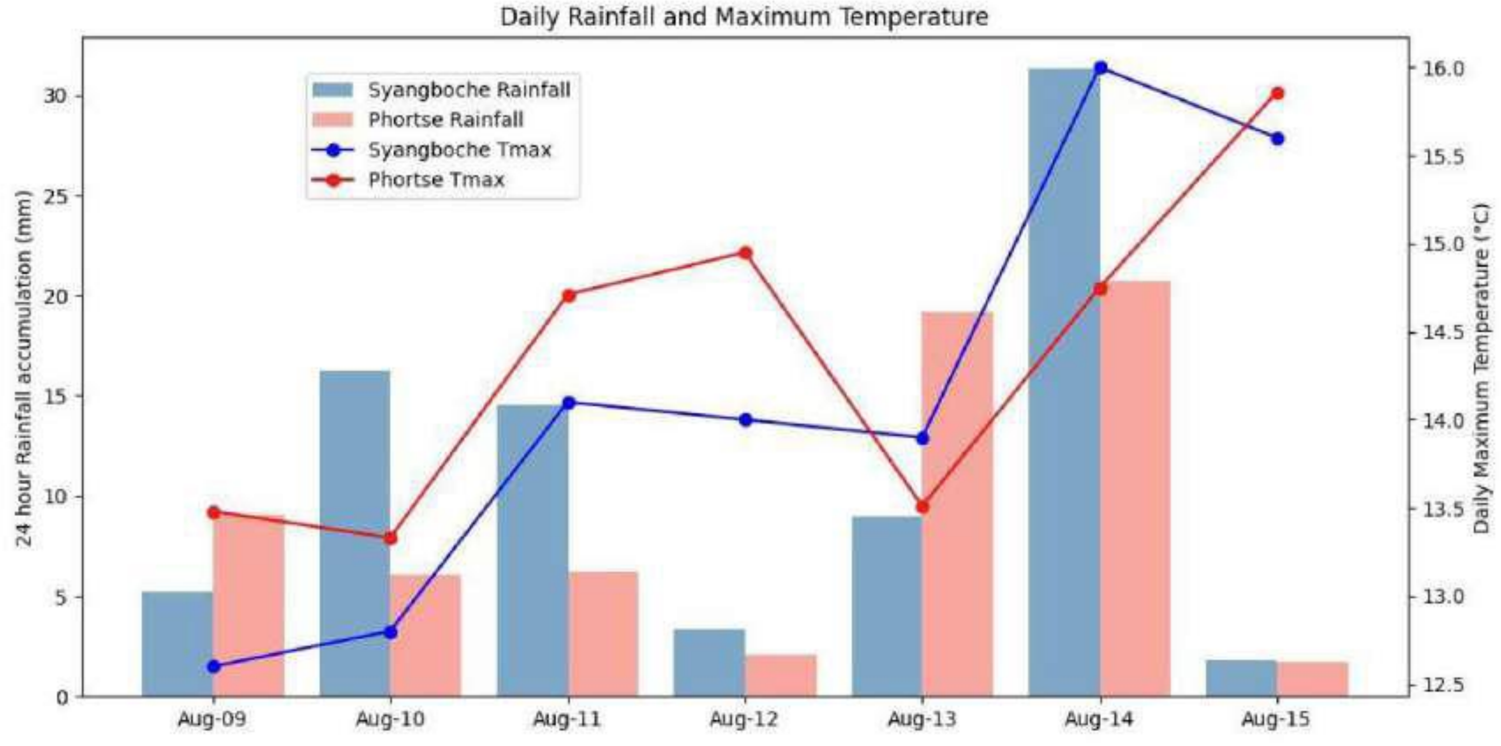
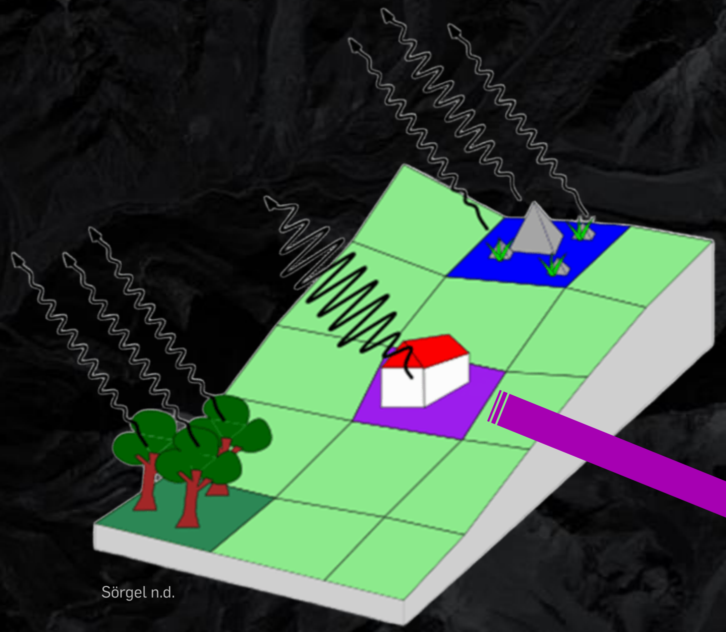
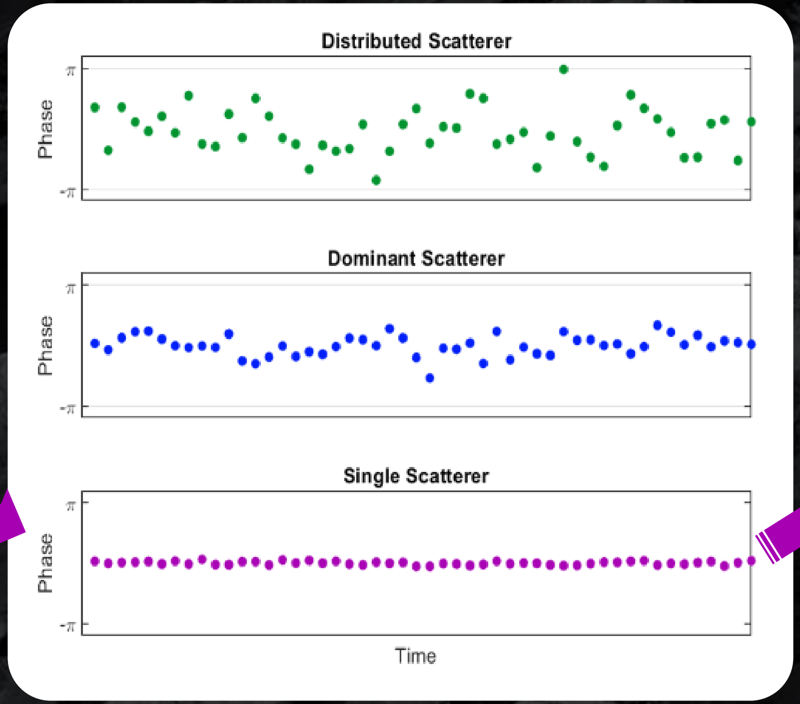


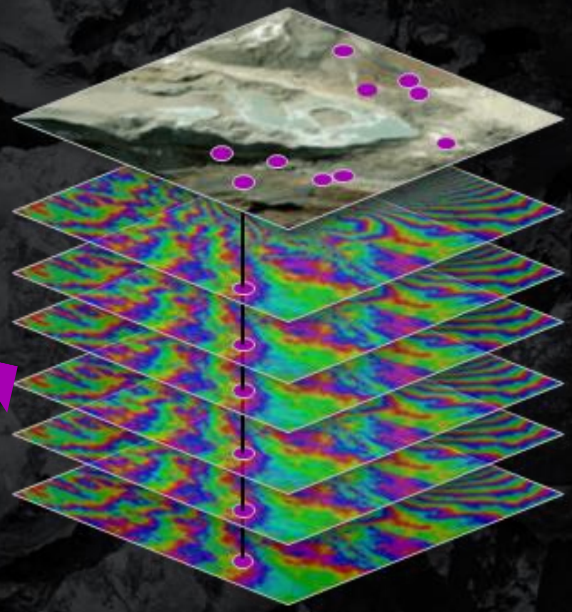
Figure 4: Rainfall and maximum temperature recorded at Syangboche and Phortse between August 9 and 15

- Significant amount of rainfall in the previous week
- Increase in temperature
- Glacier/ice melt or avalanches may have caused the upper lake to overflow into the lower leading to the outburst of the lower lake

2.2 PSI-Processing StaMPS

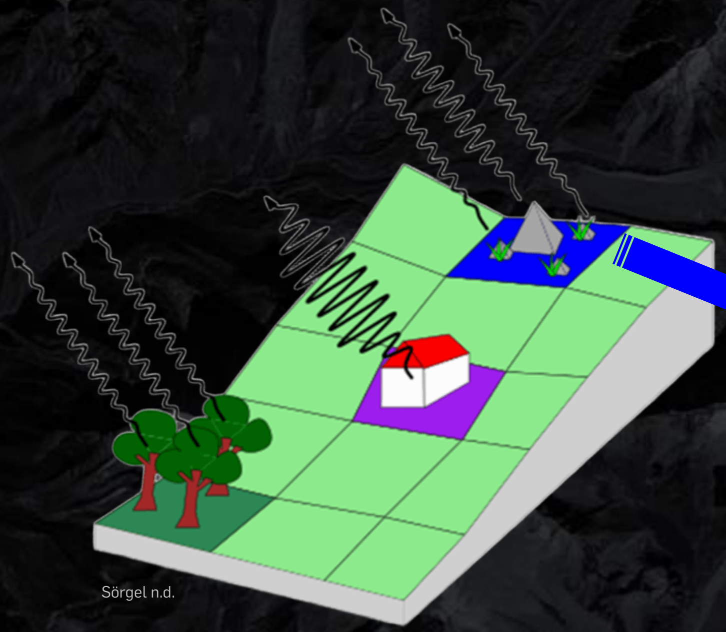




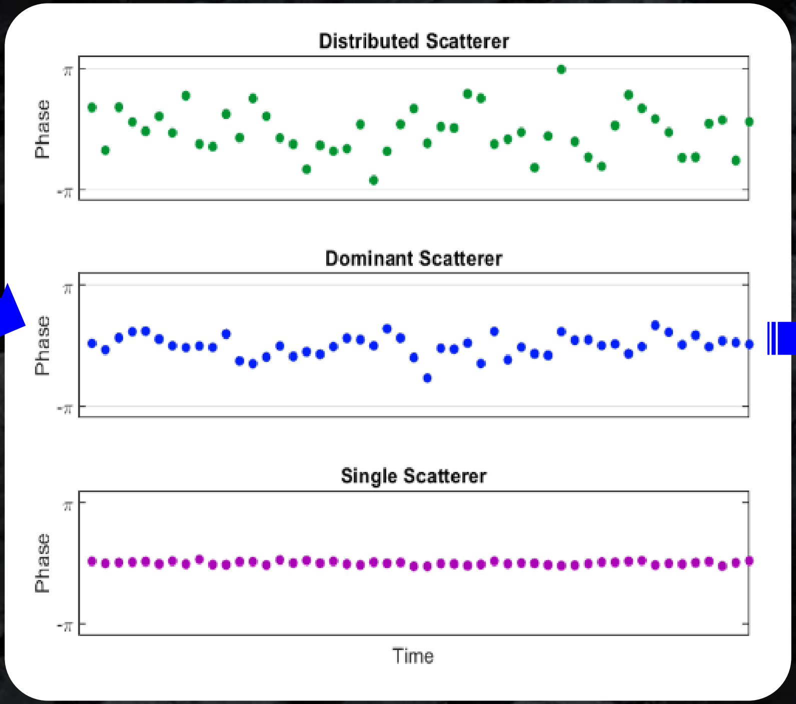


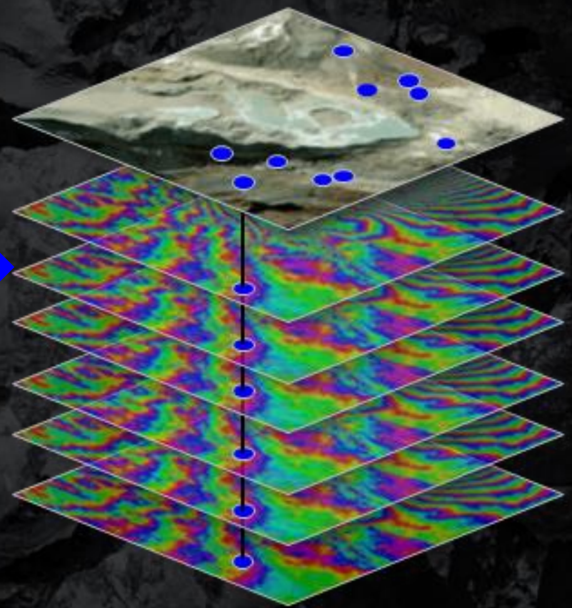
2.2 PSI-Processing StaMPS

MATLAB



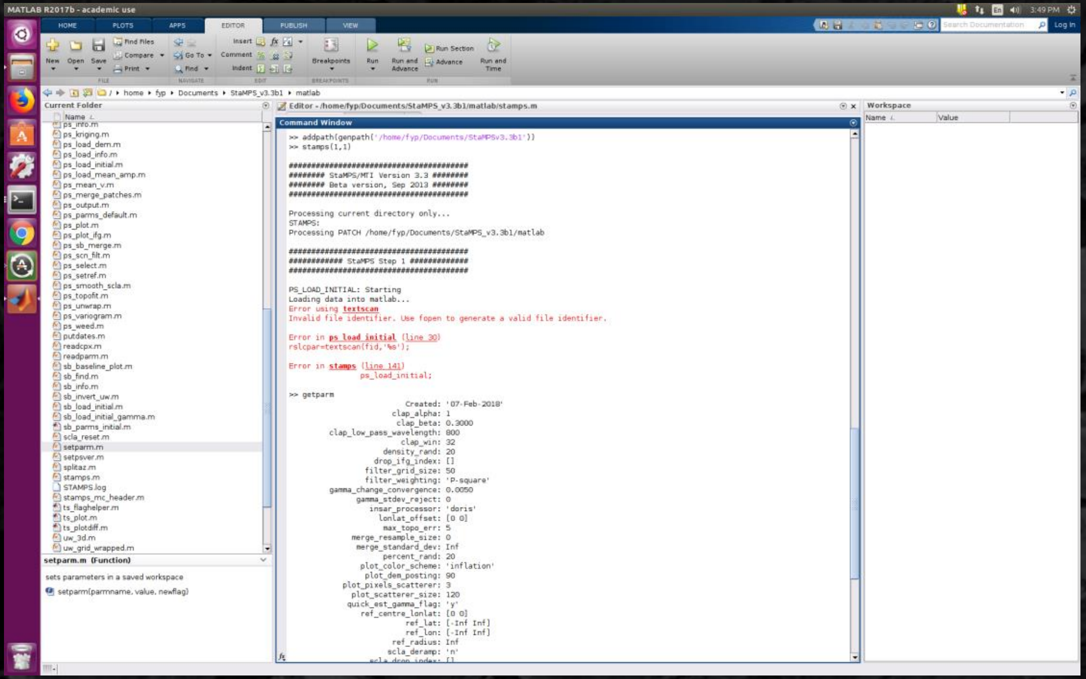
Sörgel n.d.

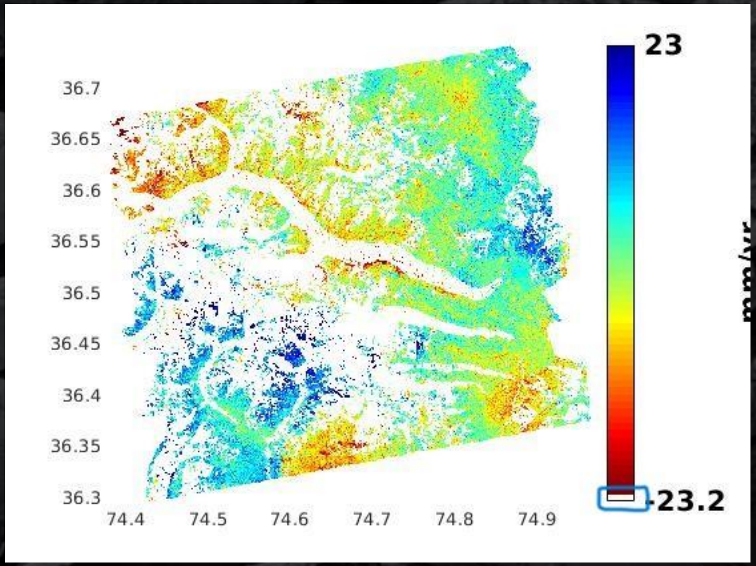


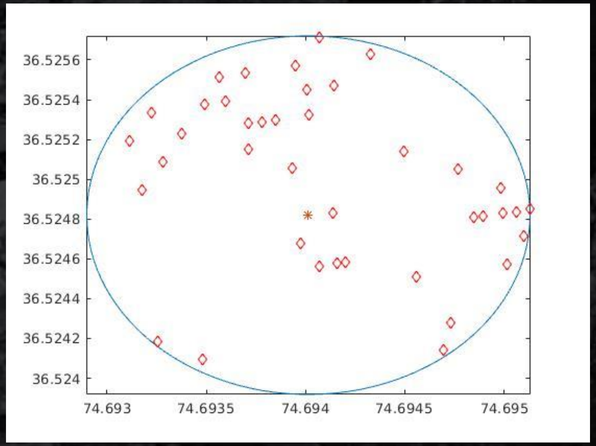


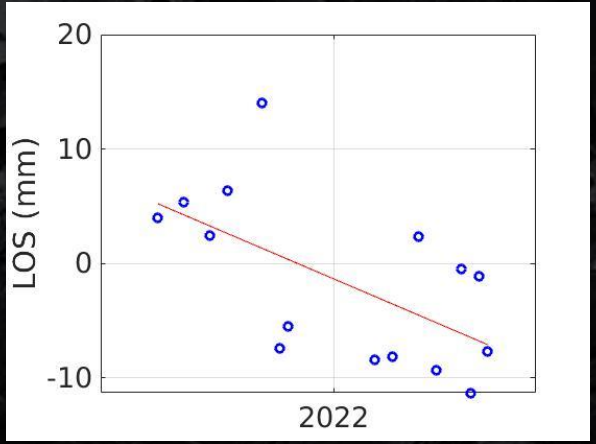
2.2 PSI-Processing StaMPS

1: Load data → 2: Estimate phase noise → 3: PS selection → 4: PS weeding → 5: Phase correction → 6: Phase unwrapping → 7: Estimate spatially-correlated look angle error → 8: Atmospheric filtering → 9: TRAIN → 10: LoS export









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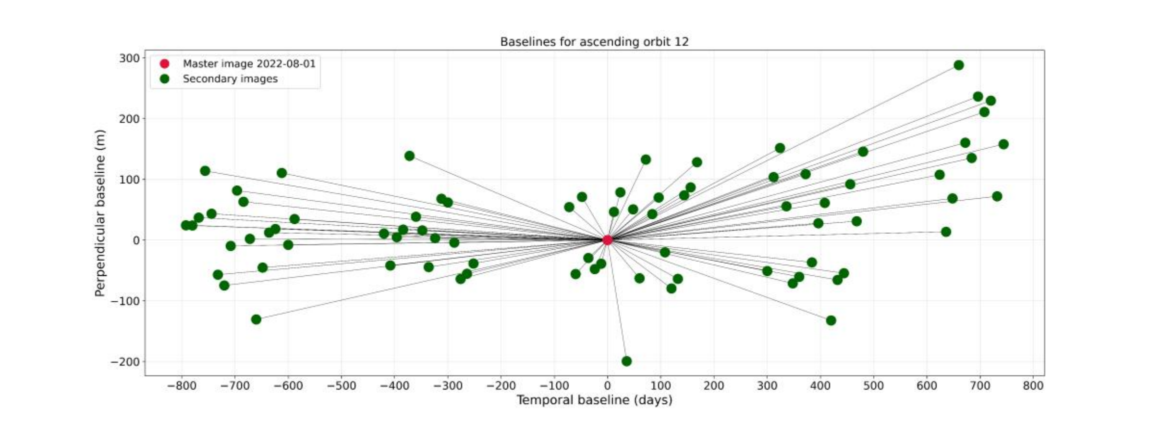

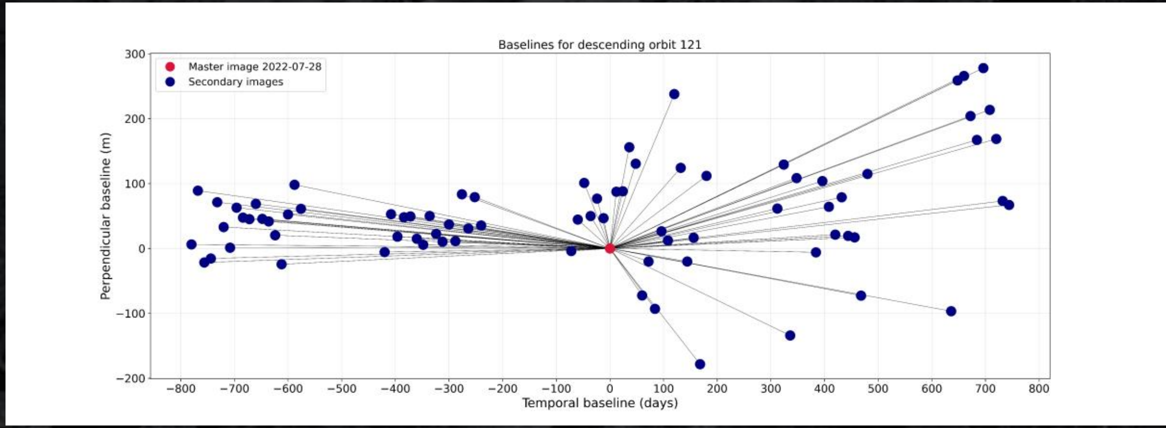

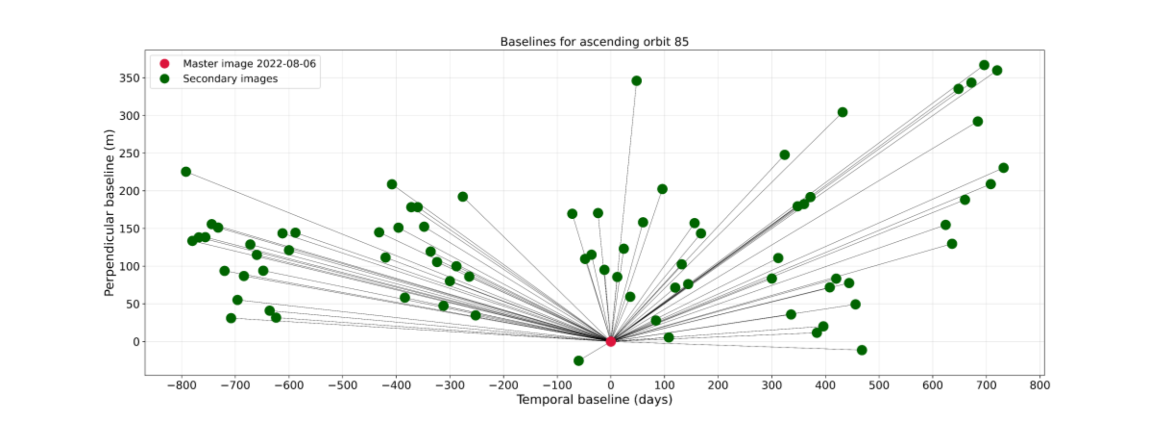

2.3 Postprocessing Displacements

Introduction

Data & Methods

Results

Discussion

Conclusion

1: LoS Preparation

2: LIA calculation
Local Incidence Angle of S1

3: Platform heading
between asc & dsc

4: Merge equal orbits
all asc & all dsc orbits

5: Spatial Merge
find point pair within 30m

6: Temporal merge
merge closes dates

7: Apply Formular[5]

$$\begin{bmatrix} \frac{d_v}{d_{h_{ald}^{dsc}}} \end{bmatrix} = \begin{bmatrix} \cos\theta^{asc} & \frac{\sin\theta^{asc}}{\cos\theta^{dsc}} \\ \cos\theta^{dec} & \sin\theta^{dsc} \end{bmatrix}^{-1} \begin{bmatrix} d_{LOS}^{asc} \\ d_{LOS}^{dsc} \end{bmatrix}$$

8: Final data export
vertical & ald displacements

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8: Final data export
vertical & ald displacements

"Wide" format

country	yr1960	yr1970	yr2010
x	10	13	15
y	20	23	25
z	30	33	35

"Long" format

country	year	metric
x	1960	10
x	1970	13
x	2010	15
y	1960	20
y	1970	23
y	2010	25
z	1960	30
z	1970	33
z	2010	35

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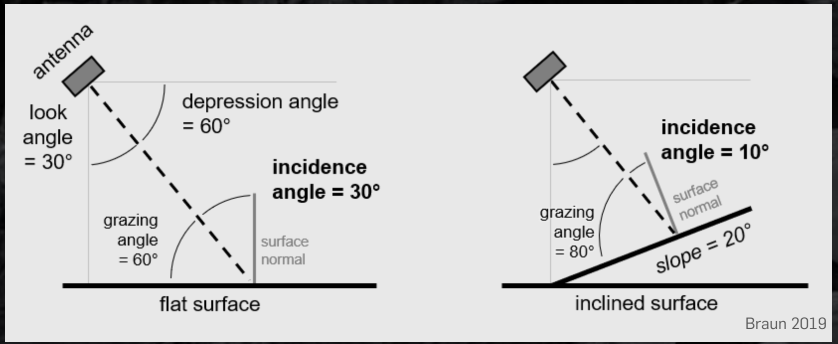
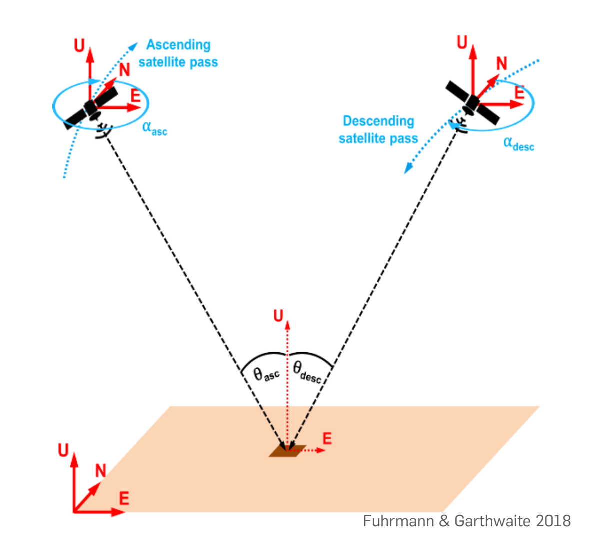
$$\begin{bmatrix} \frac{d_v}{d_{h^{dsc}_{ald}}} \end{bmatrix} = \begin{bmatrix} \cos\theta^{asc} & \frac{\sin\theta^{asc}}{\cos\theta^{dsc}} \\ \cos\theta^{dec} & \sin\theta^{dsc} \end{bmatrix}^{-1} \begin{bmatrix} d^{asc}_{LOS} \\ d^{dsc}_{LOS} \end{bmatrix}$$

8: Final data export
vertical & ald displacements



Braun 2019



Fuhrmann & Garthwaite 2018

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8: Final data export
vertical & ald displacements

1. Ascending orbit	ASC 12	1. Descending orbit	DSC 121
2. Ascending orbit	ASC 85	...	...
...	...	...	...
	merged ASC orbits		merged DSC orbits

2.3 Postprocessing Displacements

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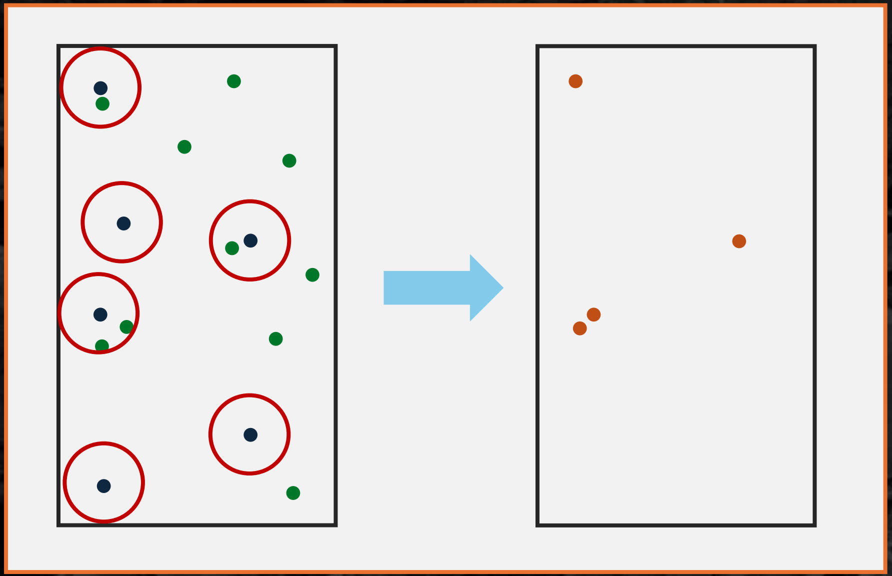
8: Final data export
vertical & ald displacements



ASC TS	DSC TS	Merged TS pair
01.01.2024	04.02.2024	01.02.2024 / 04.02.2024
15.01.2024	19.02.2024	15.02.2024 / 19.02.2024
01.02.2024	04.03.2024	01.03.2024 / 04.03.2024
15.02.2024	19.03.2024	15.03.2024 / 19.03.2024
01.03.2024	04.04.2024	01.04.2024 / 04.04.2024
15.03.2024	19.04.2024	15.04.2024 / 19.04.2024
01.04.2024	04.05.2024	01.05.2024 / 04.05.2024
15.04.2024	19.05.2024	15.05.2024 / 19.05.2024
01.05.2024	04.06.2024	01.06.2024 / 04.06.2024
15.05.2024	19.06.2024	15.06.2024 / 19.06.2024
01.06.2024	04.07.2024	01.07.2024 / 04.07.2024
15.06.2024	19.07.2024	15.07.2024 / 19.07.2024
01.07.2024	04.08.2024	01.08.2024 / 04.08.2024
15.07.2024	19.08.2024	15.08.2024 / 19.08.2024
01.08.2024	04.09.2024	01.09.2024 / 04.09.2024
15.08.2024	19.09.2024	15.09.2024 / 19.09.2024
01.09.2024	04.10.2024	
15.09.2024	19.10.2024	

2.3 Postprocessing Displacements

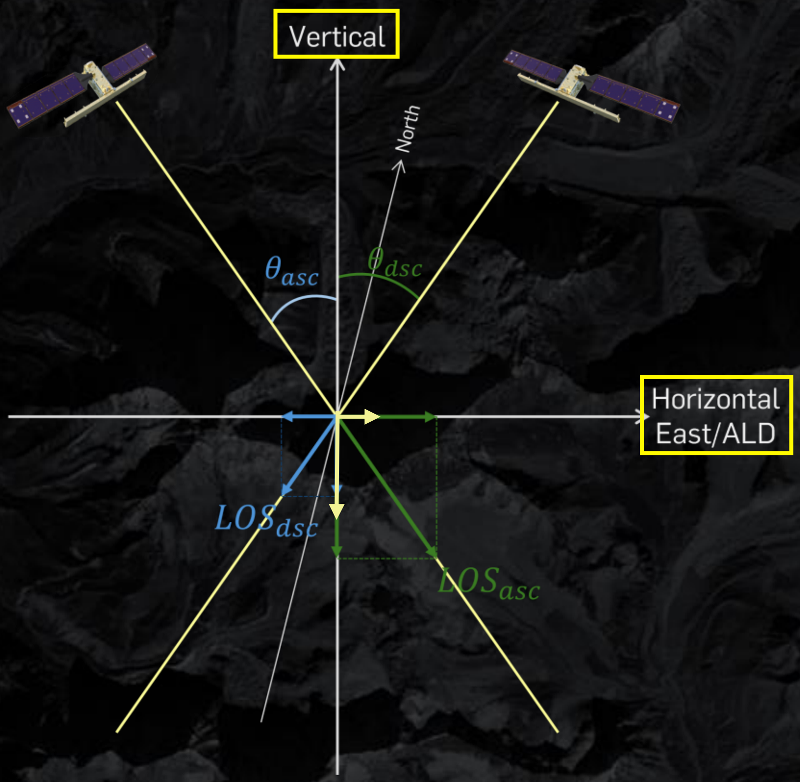
Vertical displacements
+uplift/-subsidence

Horizontal displacements
(along Azimuth Look Direction = ALD)
+east / -west

$$\begin{bmatrix} \boldsymbol{d_v} \\ \hline \boldsymbol{d_{h_{ald}^{dsc}}} \end{bmatrix}$$

2.3 Postprocessing Displacements

Vertical displacements
+uplift/-subsidence

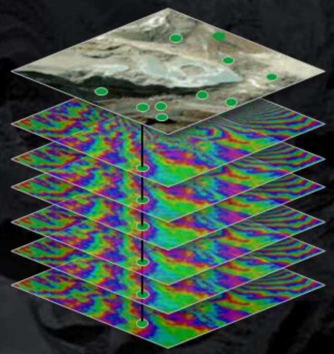


Horizontal displacements
(along Azimuth Look Direction = ALD)
+east / -west

$$\begin{bmatrix} d_v \\ d_{h_{ald}^{dsc}} \end{bmatrix} = \begin{bmatrix} d_{LOS}^{asc} \\ d_{LOS}^{dsc} \end{bmatrix}$$

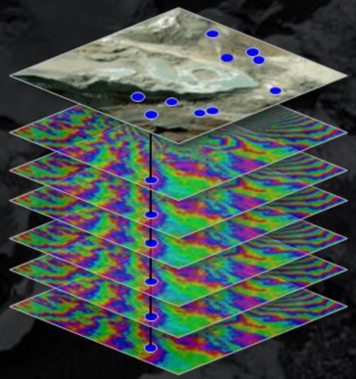
LoS displacements

ASC orbit



LoS displacements

DSC orbit



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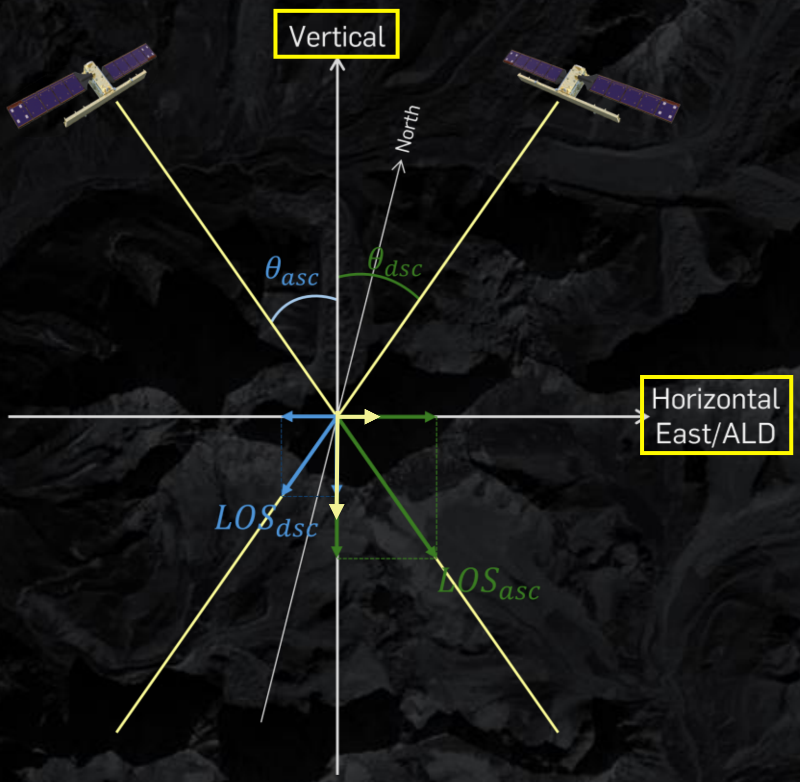
Institute of Geography
RUB

2.3 Postprocessing Displacements

Vertical displacements
+uplift/-subsidence



Horizontal displacements
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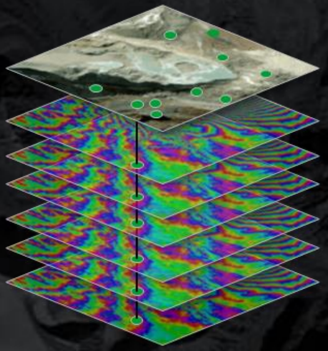
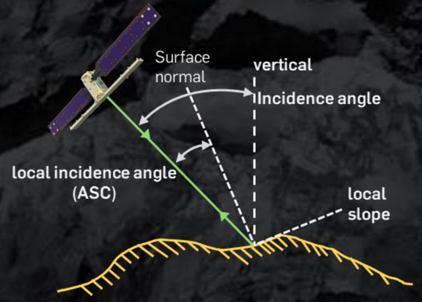
$$\left[\frac{d_v}{d_{h_{ald}^{dsc}}}\right] = \begin{bmatrix} d_{LOS}^{asc} \\ d_{LOS}^{dsc} \end{bmatrix} \begin{bmatrix} \cos\theta^{asc} & \\ \cos\theta^{dec} & \end{bmatrix}^{-1}$$

ASC orbit

LoS displacements

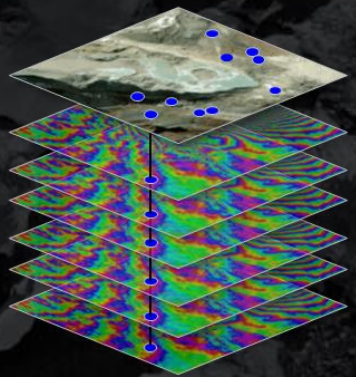


Local Incidence Angle

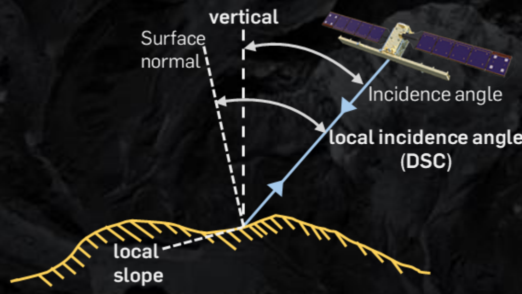


DSC orbit

LoS displacements



Local Incidence Angle

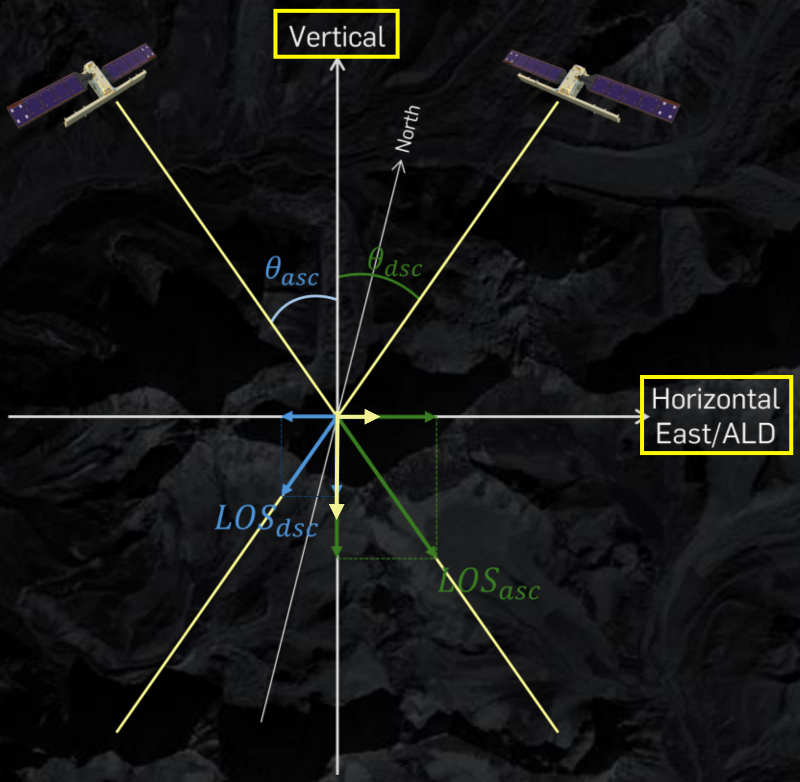


AK Fernerkundung | Esfahany et al. 2009; Delgado Blasco et al. 2023; Schlögl et al. 2021

2.3 Postprocessing Displacements

$$\begin{bmatrix} \dfrac{d_v}{d_{h_{ald}^{dsc}}} \end{bmatrix} = \begin{bmatrix} d_{LOS}^{asc} \\ d_{LOS}^{dsc} \end{bmatrix} \begin{bmatrix} \cos\theta^{asc} & \dfrac{\sin\theta^{asc}}{\cos\Delta\alpha} \\ \cos\theta^{dec} & \sin\theta^{dsc} \end{bmatrix}^{-1}$$

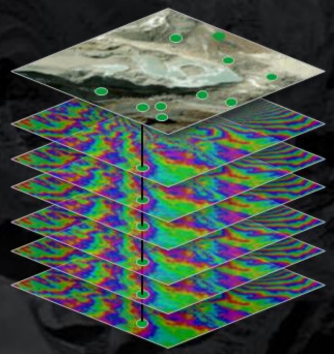
Vertical displacements
+uplift/-subsidence



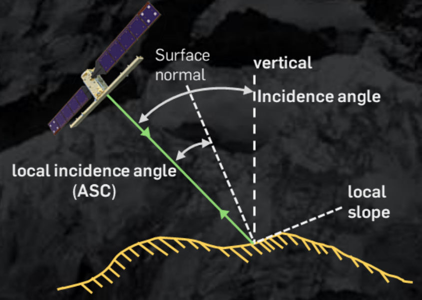
Horizontal displacements
(along Azimuth Look Direction = ALD)
+east / -west

ASC orbit

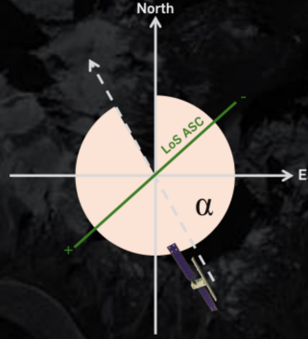
LoS displacements



Local Incidence Angle

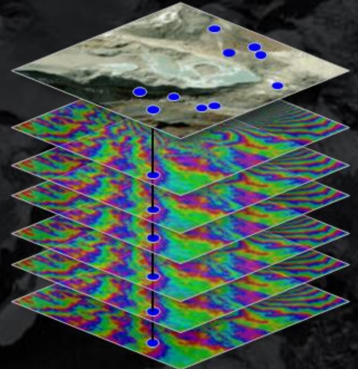


Heading of S1

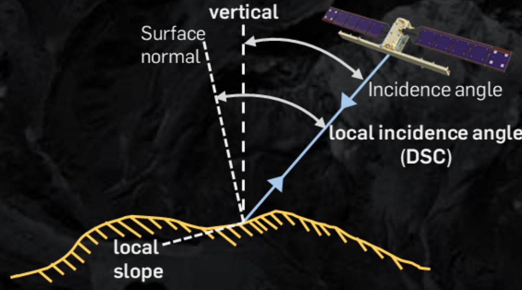


DSC orbit

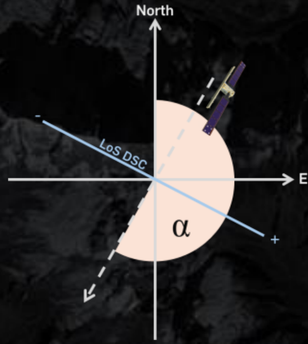
LoS displacements



Local Incidence Angle



Heading of S1



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Terminal moraine of upper Tso Mutse (1)