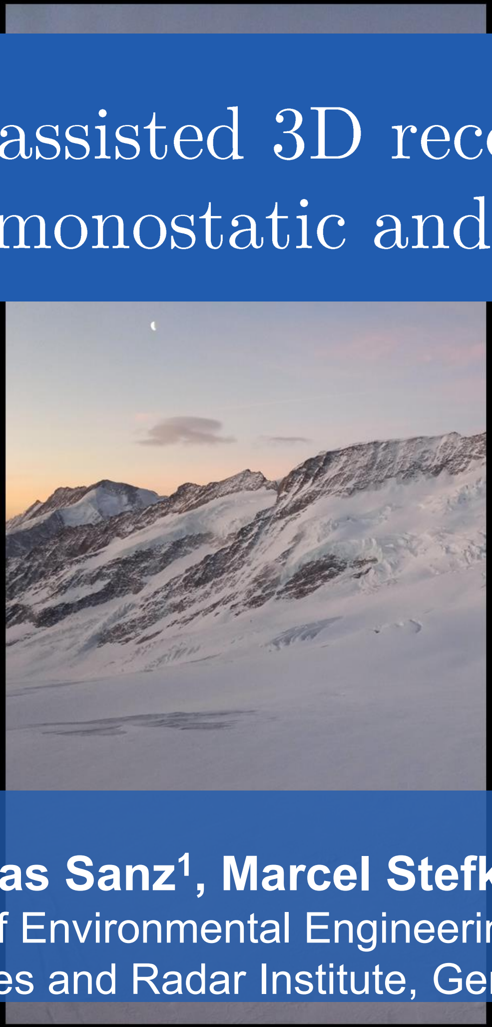
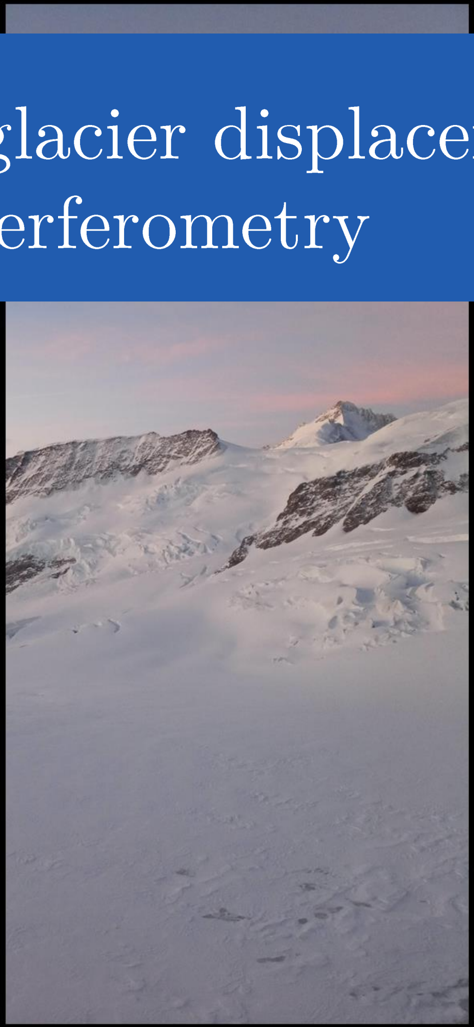
ETH zürich

DEM-assisted 3D reconstruction of Aletsch glacier displacements using monostatic and bistatic differential interferometry





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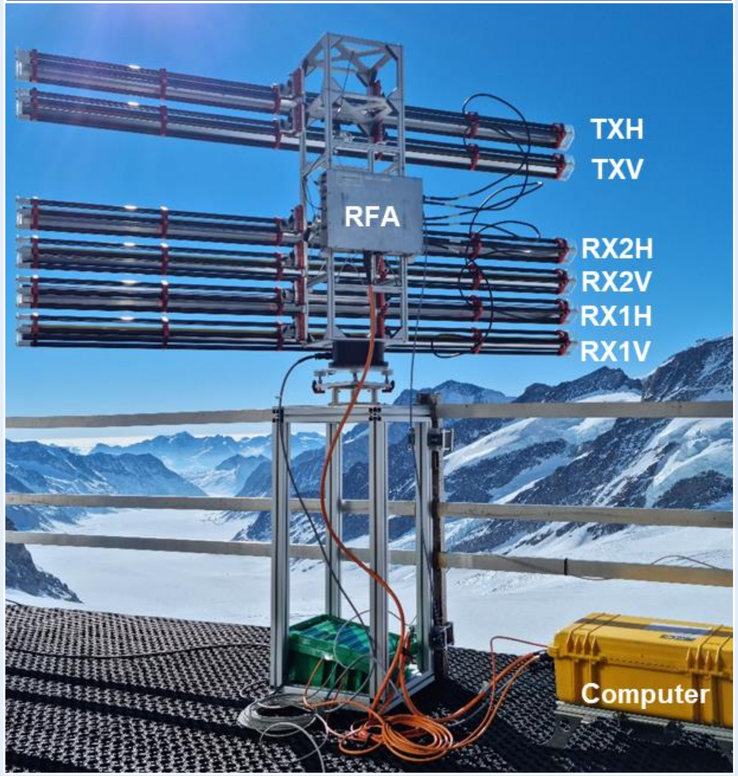
Earth Observation and Remote Sensing

Introduction to KAPRI

*Ku-Band **A**dvanced **P**olarimetric **R**adar **I**nterferometer*

Monostatic Unit

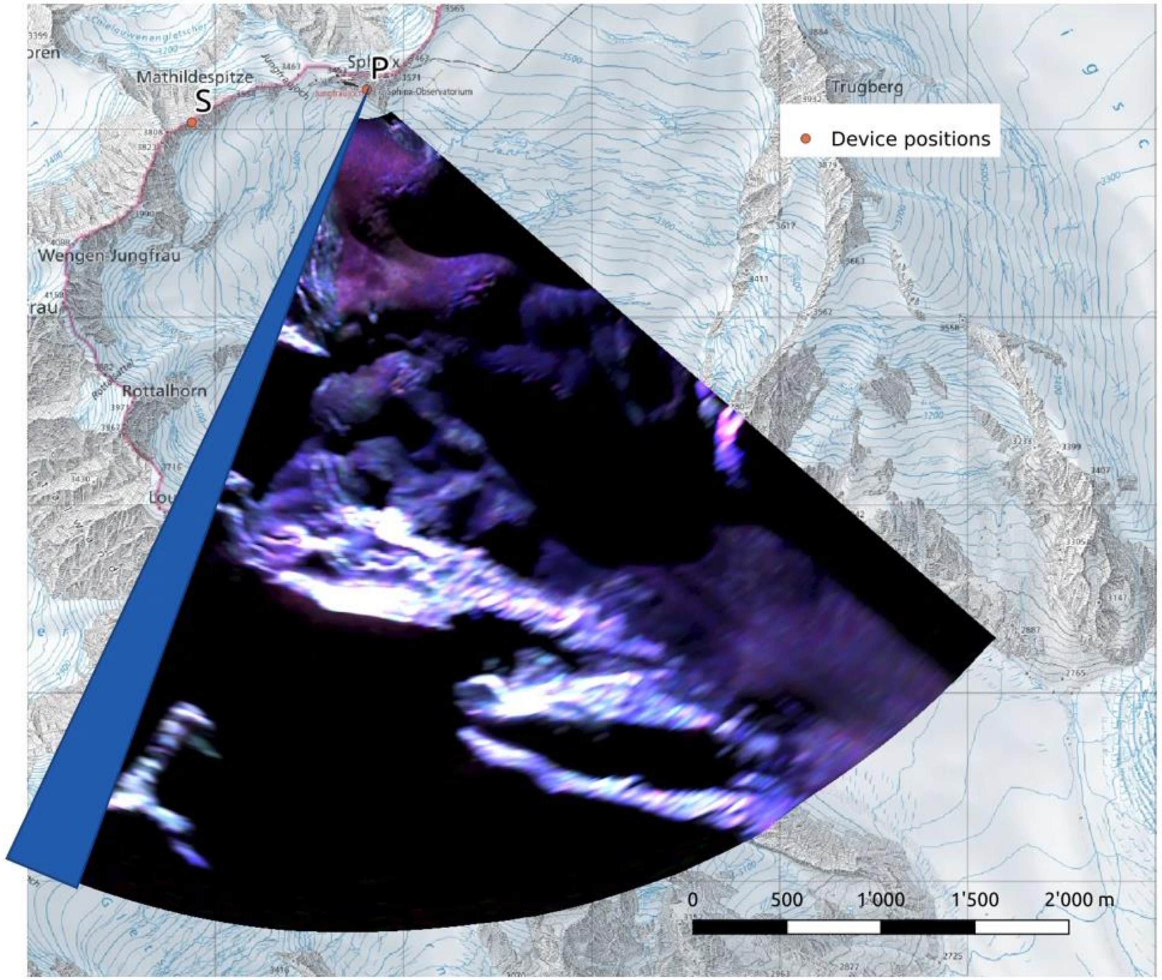


Bistatic Unit

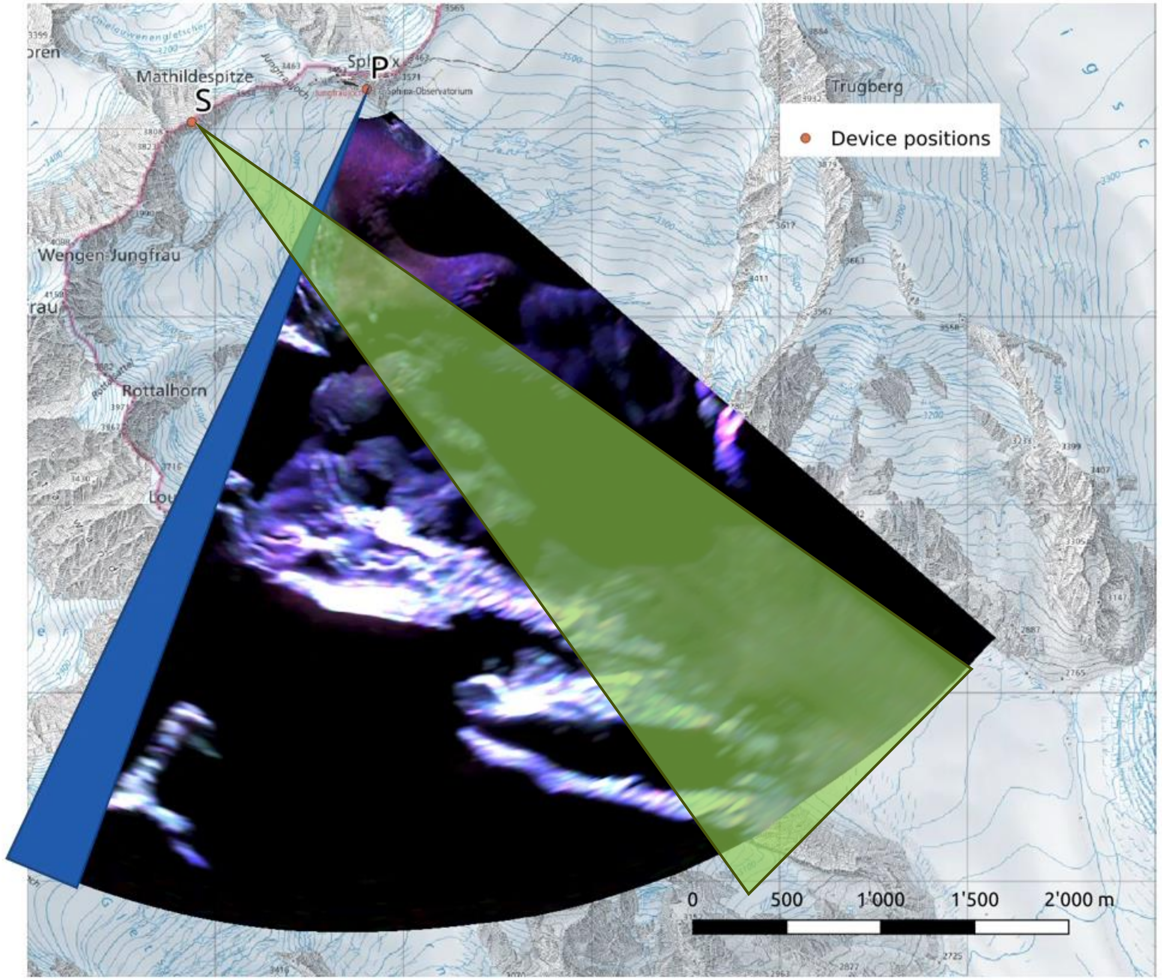
GAMMA REMOTE SENSING

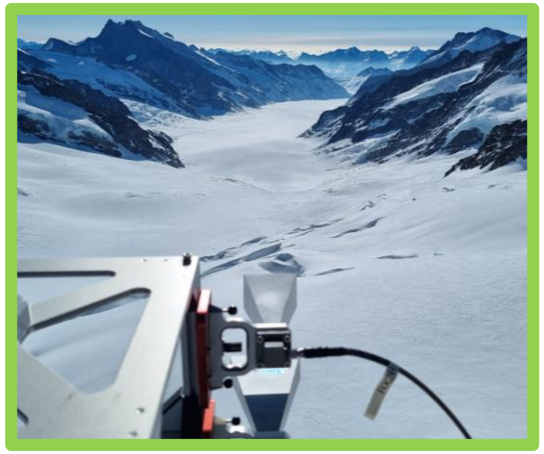
Specifications	
Frequency	17.2 GHz
Type	FMCW
Bandwidth	200 MHz
Polarization TX/RX	V, H
Range	50m – 10km
Operation modes	Monostatic, Bistatic
Other characteristics	Real Aperture

Introduction to KAPRI: Monostatic KAPRI operation



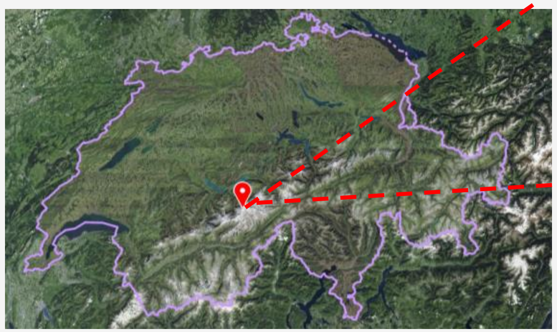
Introduction to KAPRI: Bistatic KAPRI operation

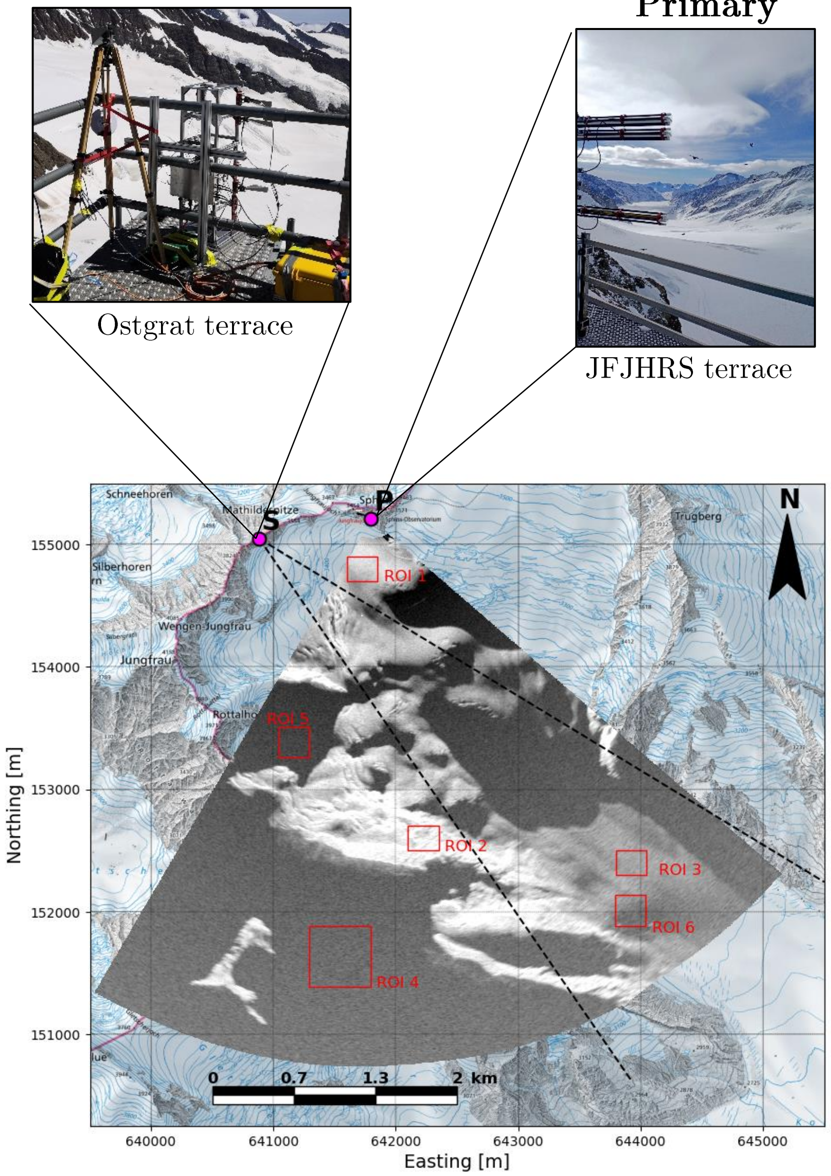




Description of the Dataset

Location





Specifications

Dataset Specs	
Date	2nd March 2022
Polarisation	Full-Pol (VV)
Repeat time	1.5 min
Time series	1h (9AM-10AM)
Min Range	200m
Max Range	4km

Regions of Interest (ROIs)

ROI Number	Description
1	Near Range
2	Mid Range
3	Far Range
4	Noise far range
5	Noise near range
6	Noise far range (only bistatic)

Displacement Calculation: Monostatic Case

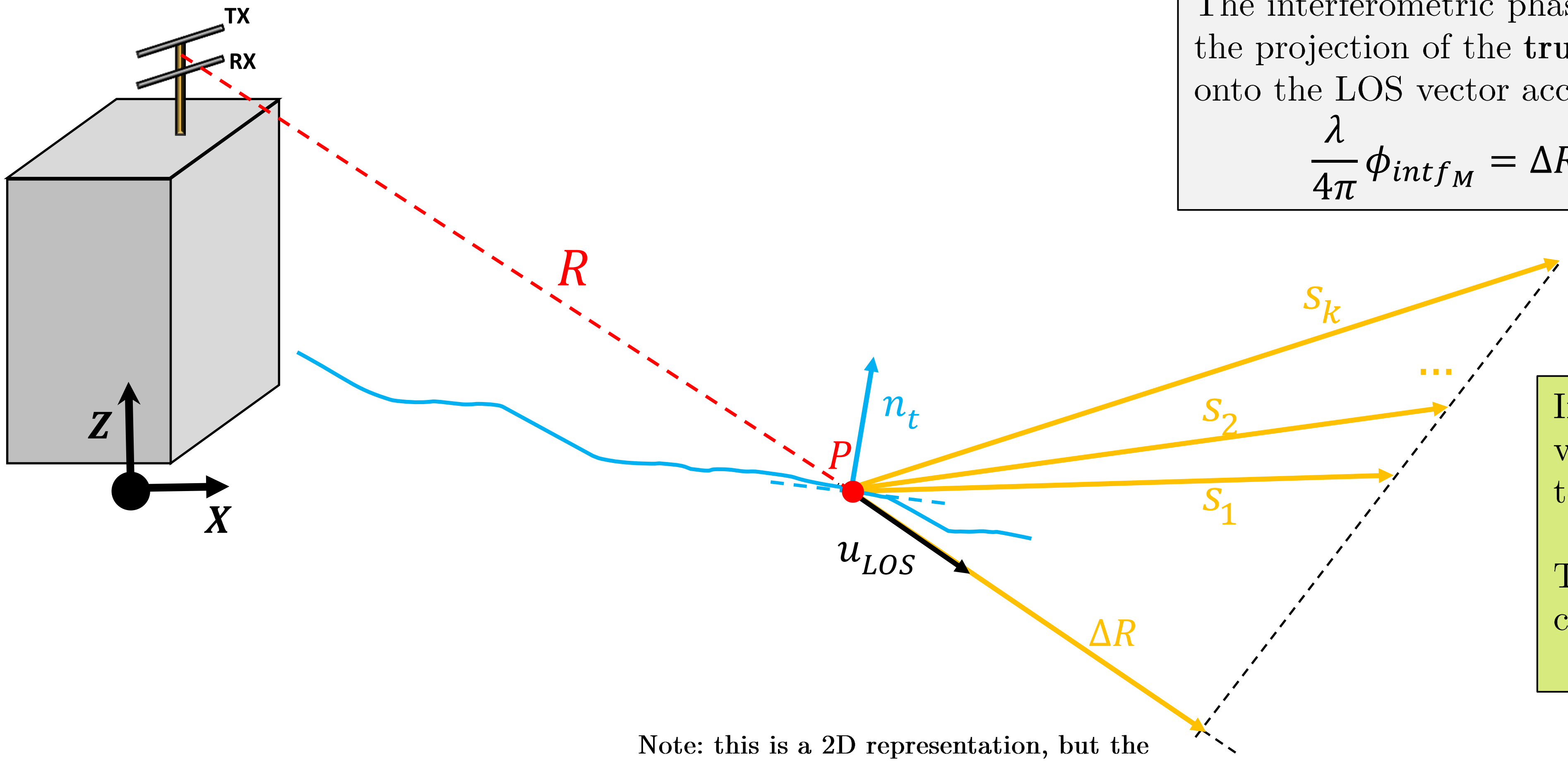
$R_{TX} = R_{RX}$

The TX leg is the same as the RX leg!

Interferogram [mono]: $\phi_{intf_M} = \frac{4\pi}{\lambda} \Delta R$

The interferometric phase is proportional to the projection of the **true displacements** onto the LOS vector according to:

$$\frac{\lambda}{4\pi} \phi_{intf_M} = \Delta R = \overrightarrow{s_k} \cdot \overrightarrow{u_{LOS}}$$



Imposing that displacement vector direction corresponds to the maximum gradient ∇f

$$\vec{s} = \nabla f \cdot |\vec{s}|$$

Then, there system is completely defined

$$\vec{s} \cdot \overrightarrow{u_{LOS}} = |\vec{s}| \nabla f \cdot \overrightarrow{u_{LOS}} = \Delta R$$

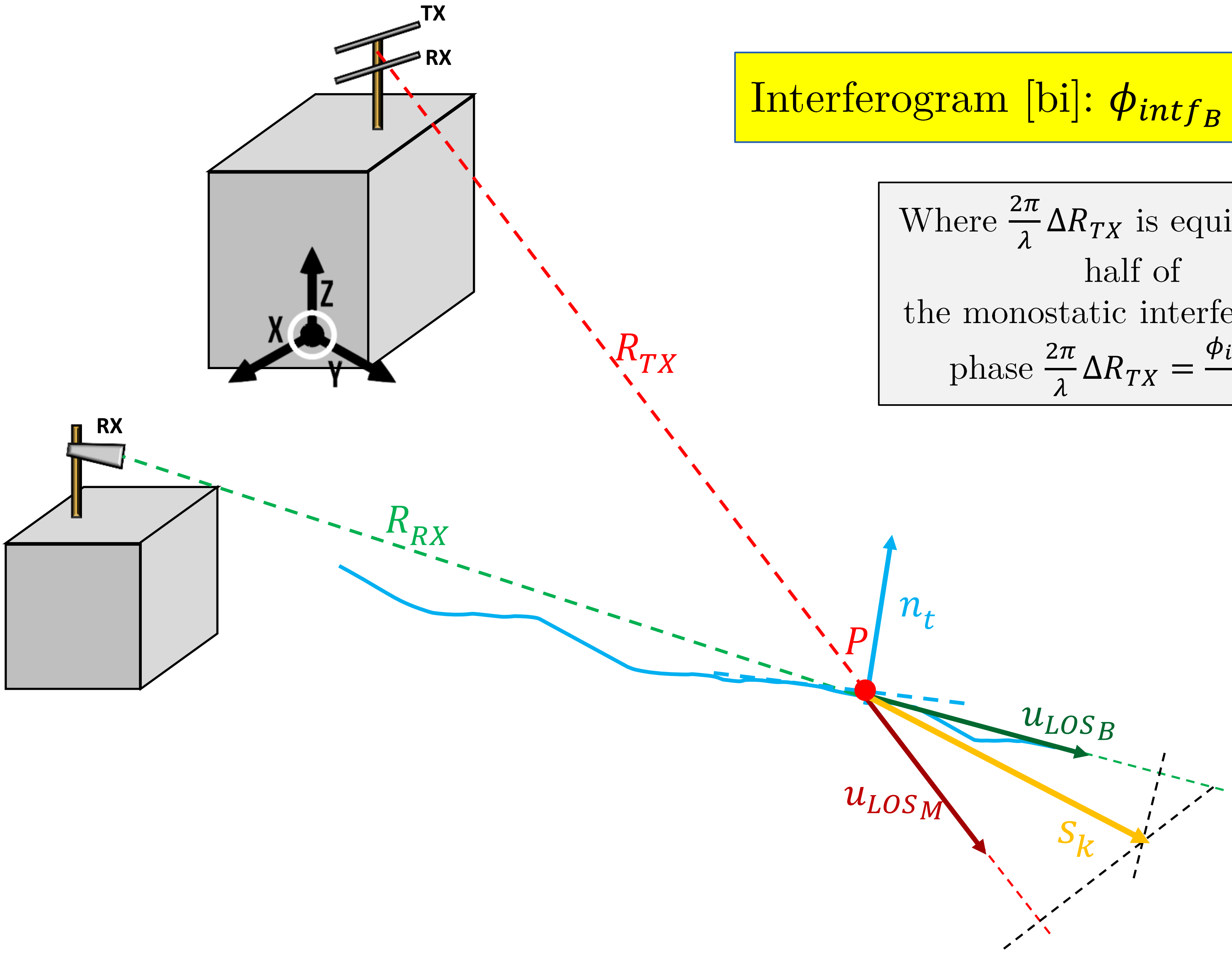
Note: this is a 2D representation, but the problem is 3D. In a general case $\boldsymbol{u_{LOS}}, \boldsymbol{n_t}, \boldsymbol{s}$ are not contained in the same plane

Displacement Calculation: Bistatic Case

The TX leg and RX leg have different look vectors!

Interferogram [bi]: $\phi_{intf_B} = \frac{2\pi}{\lambda}(\Delta R_{TX} + \Delta R_{RX})$

Where $\frac{2\pi}{\lambda}\Delta R_{TX}$ is equivalent to half of the monostatic interferometric phase $\frac{2\pi}{\lambda}\Delta R_{TX} = \frac{\phi_{interf_M}}{2}$



Each interferometric phase is proportional to the projection of the **true displacements** onto the respective LOS vector:

$$\frac{\lambda}{4\pi}\phi_{intf_M} = \Delta R_{TX} = \vec{s_k} \cdot \vec{u_{LOS\,M}}$$

$$\frac{\lambda}{2\pi}\phi_{intf_{RX\,leg}} = \Delta R_{RX} = \vec{s_k} \cdot \vec{u_{LOS\,B}}$$

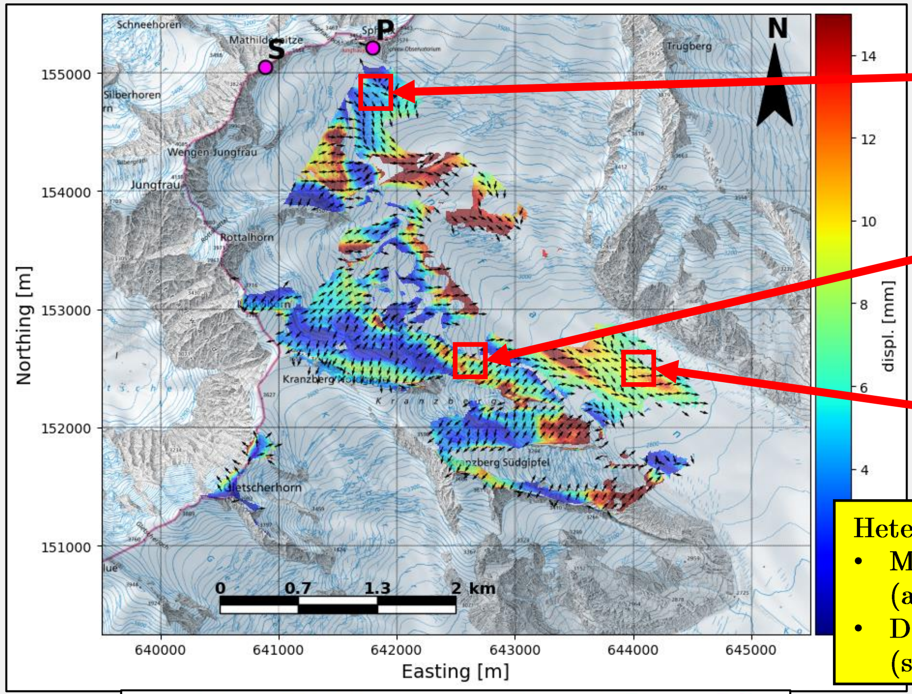
Imposing that displacement vector is contained in the plane tangential to the surface. In other words, that the dot-product between the normal of the surface and the true displacements is 0:

$$\vec{s} \cdot n_t = 0$$

Together with LOS equations, it forms an independent system with one solution

Displacements results: Displacement Vector Field

Monostatic

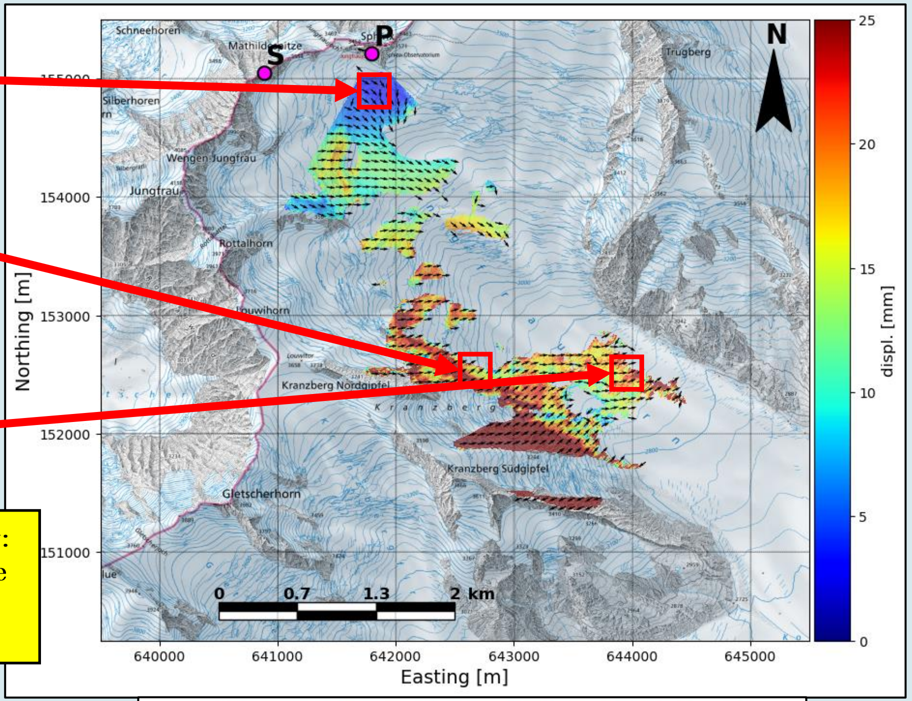


ROI 1

2D displacement map

ROI 2

ROI 3

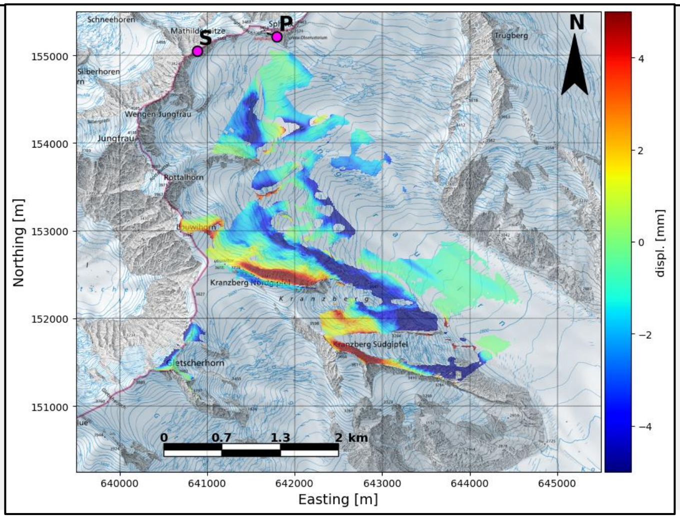


Heterogeneity:
- Magnitude (across scene)
- Direction (steep regions)

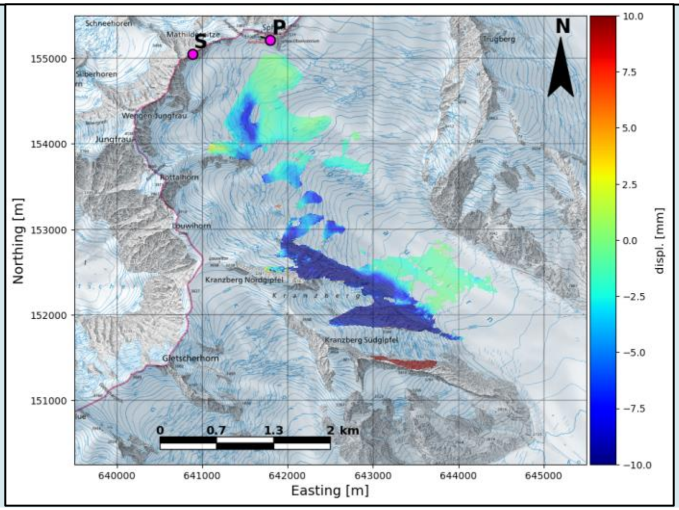
Homogeneity:
- Magnitude
- Direction

(near range)

Bistatic



Z-direction



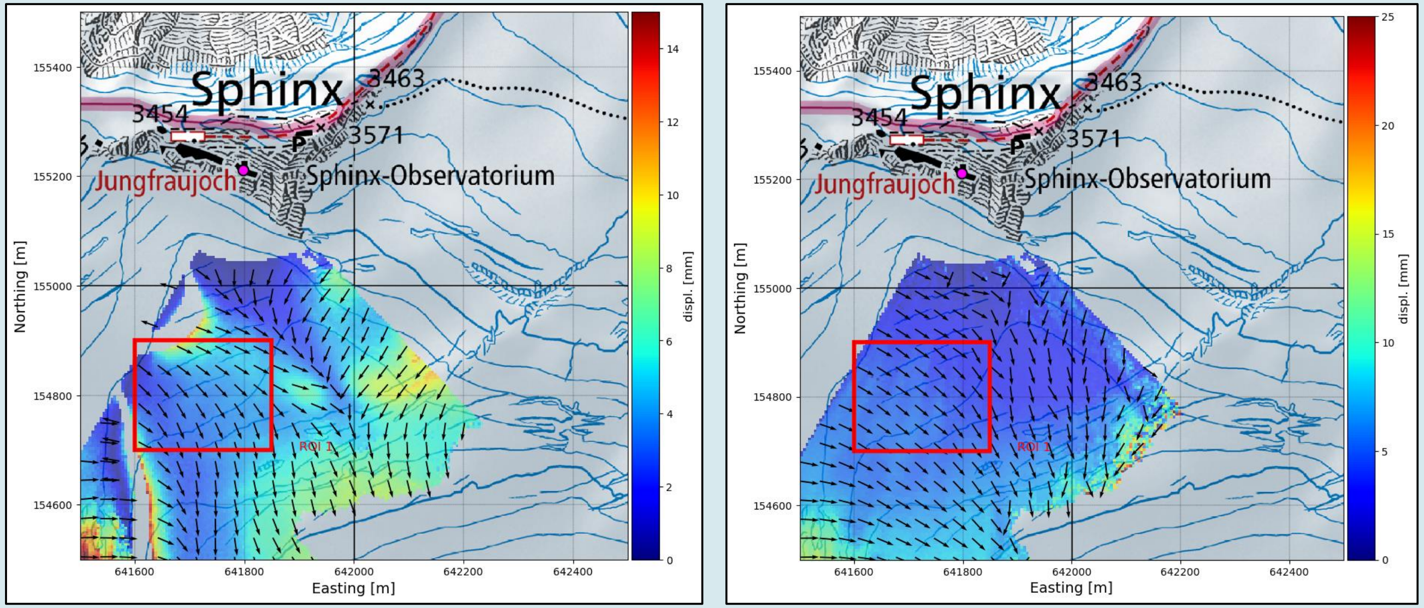
Glacier region
$\mathbf{\Delta_z} \approx \mathbf{0}$ m
Steep regions
($\mathbf{\Delta_z} \neq \mathbf{0}$ m)

Source: Mas Sanz et al., (under review)

Displacements results: Bearing, Elevation and Magnitude

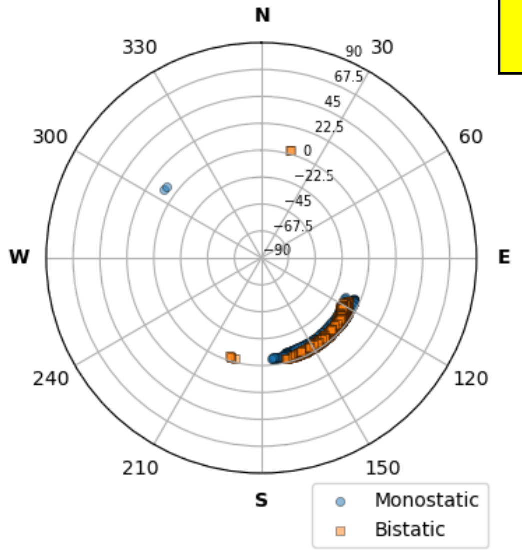
ROI 1 Zoom-In

Monostatic / Bistatic

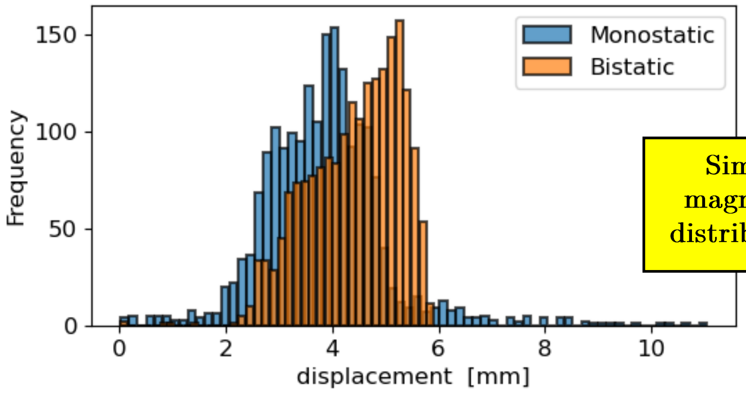


Estimation of very similar displacement field by the two methods

ROI 1 (near range glacier)



Same direction (3D)



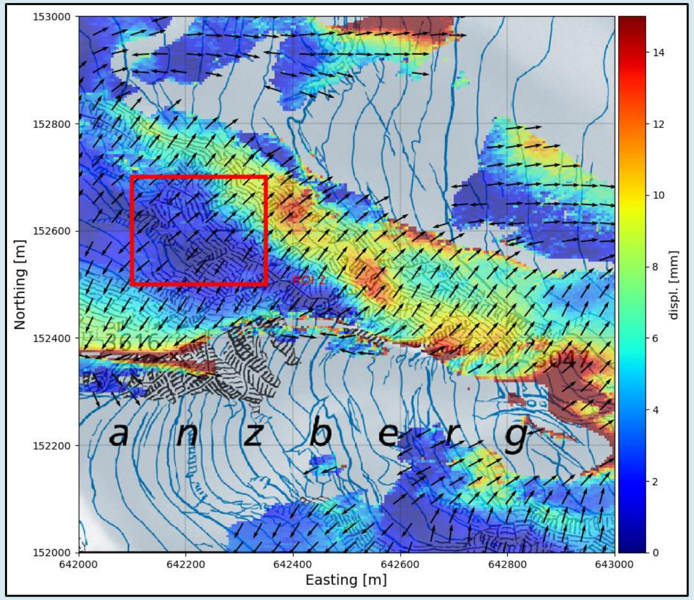
Similar magnitude distributions

Source: Mas Sanz et al., (under review)

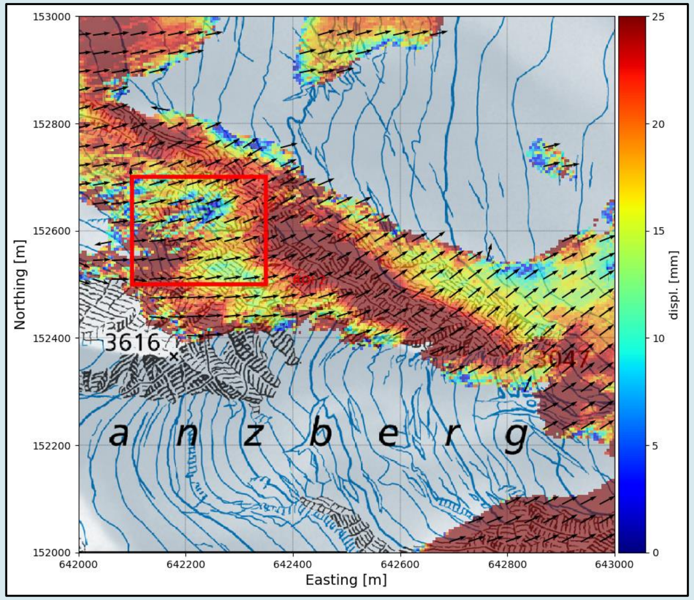
Displacements results: Bearing, Elevation and Magnitude

ROI 2 Zoom-In

Monostatic

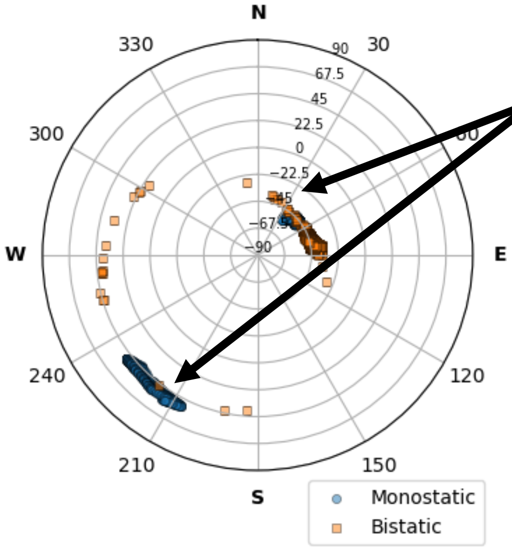


Bistatic

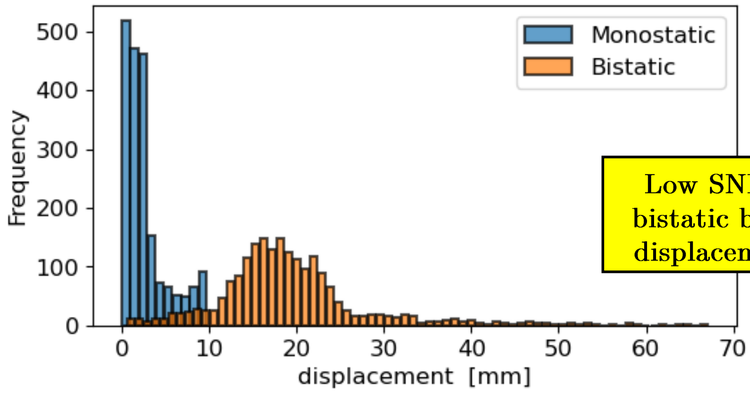


Unfavorable geometries in high steep regions + poor SNR (bistatic) lead to different displacement maps

ROI 2 (mid range, steep region)



- Monostatic: two data clusters in elevation (±∇f)
- Bistatic: bearing high std dev

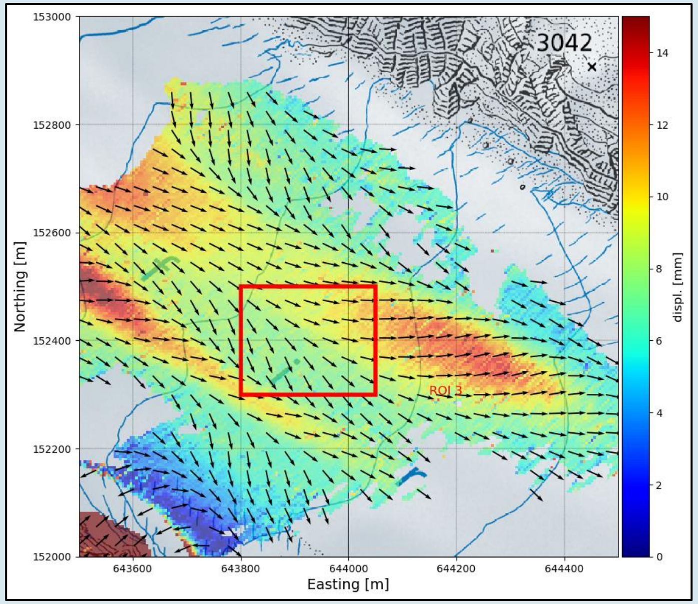


Low SNR in bistatic biases displacements

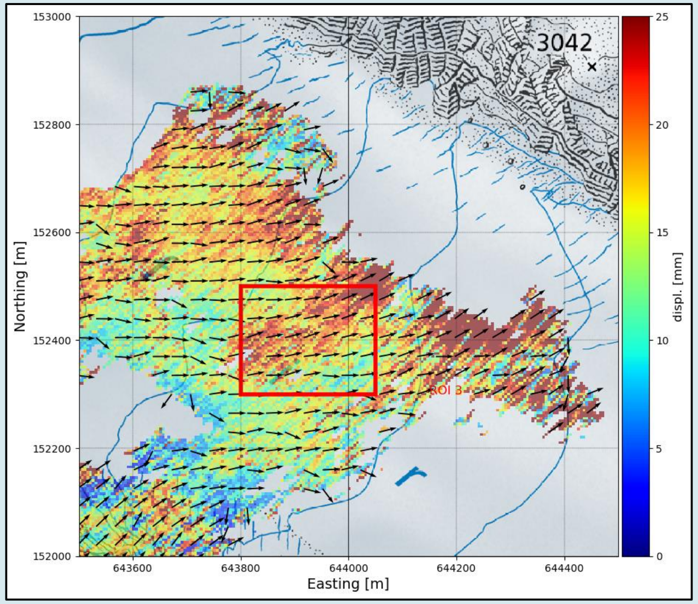
Displacements results: Bearing, Elevation and Magnitude

ROI 3 Zoom-In

Monostatic



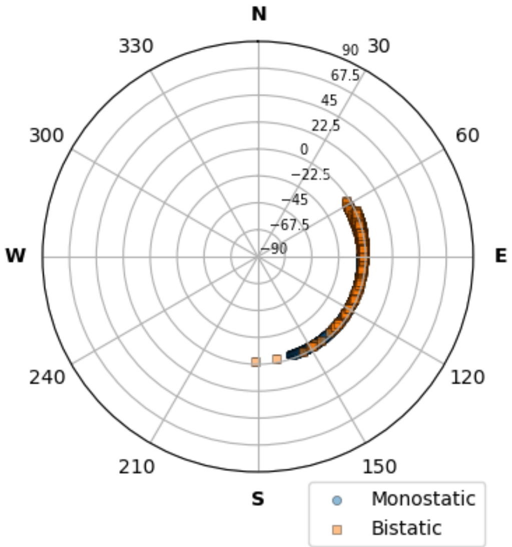
Bistatic



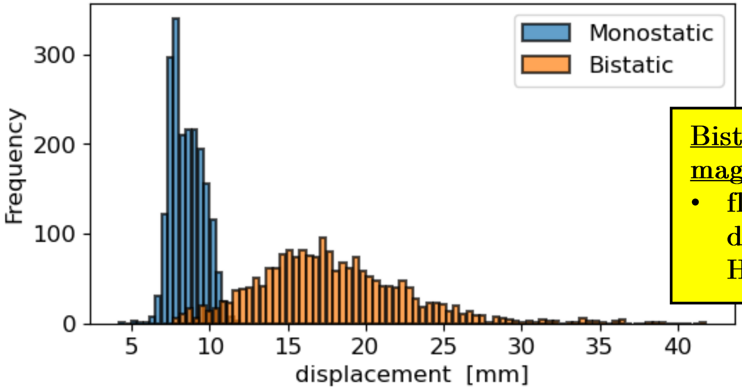
Monostatic:
- ***SNR* ≥ 10*dB*** in the far range
- Displacement direction fixed. Only magnitude affected

Bistatic:
- ***SNR* ≤ 10*dB*** in the far range
- Impact on magnitude and direction

ROI 3 (far range glacier)



Higher std dev on bearing (only DoF) → SNR lower



Bistatic magnitude:
- flattened distribution → Higher std dev

Source: Mas Sanz et al., (under review)

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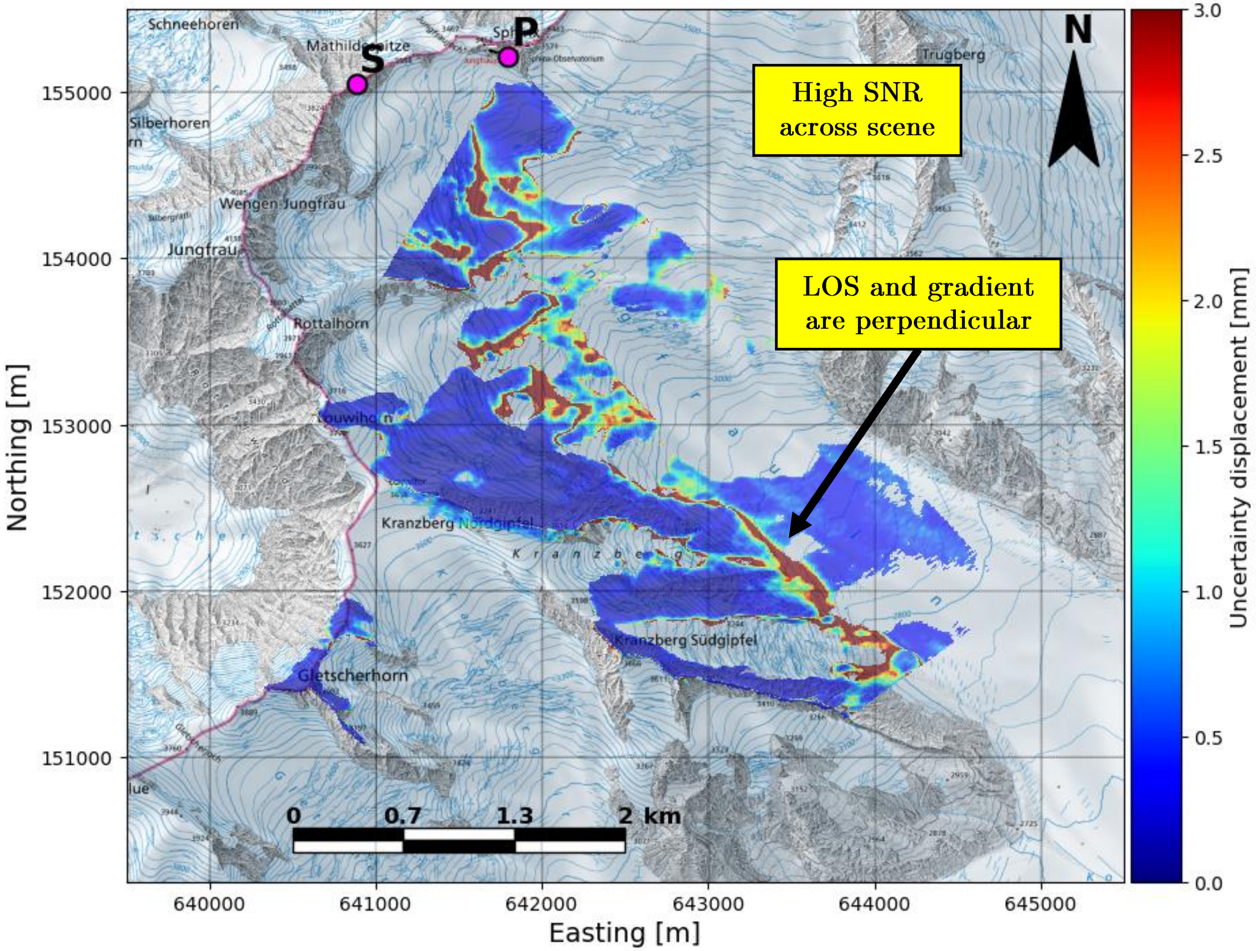
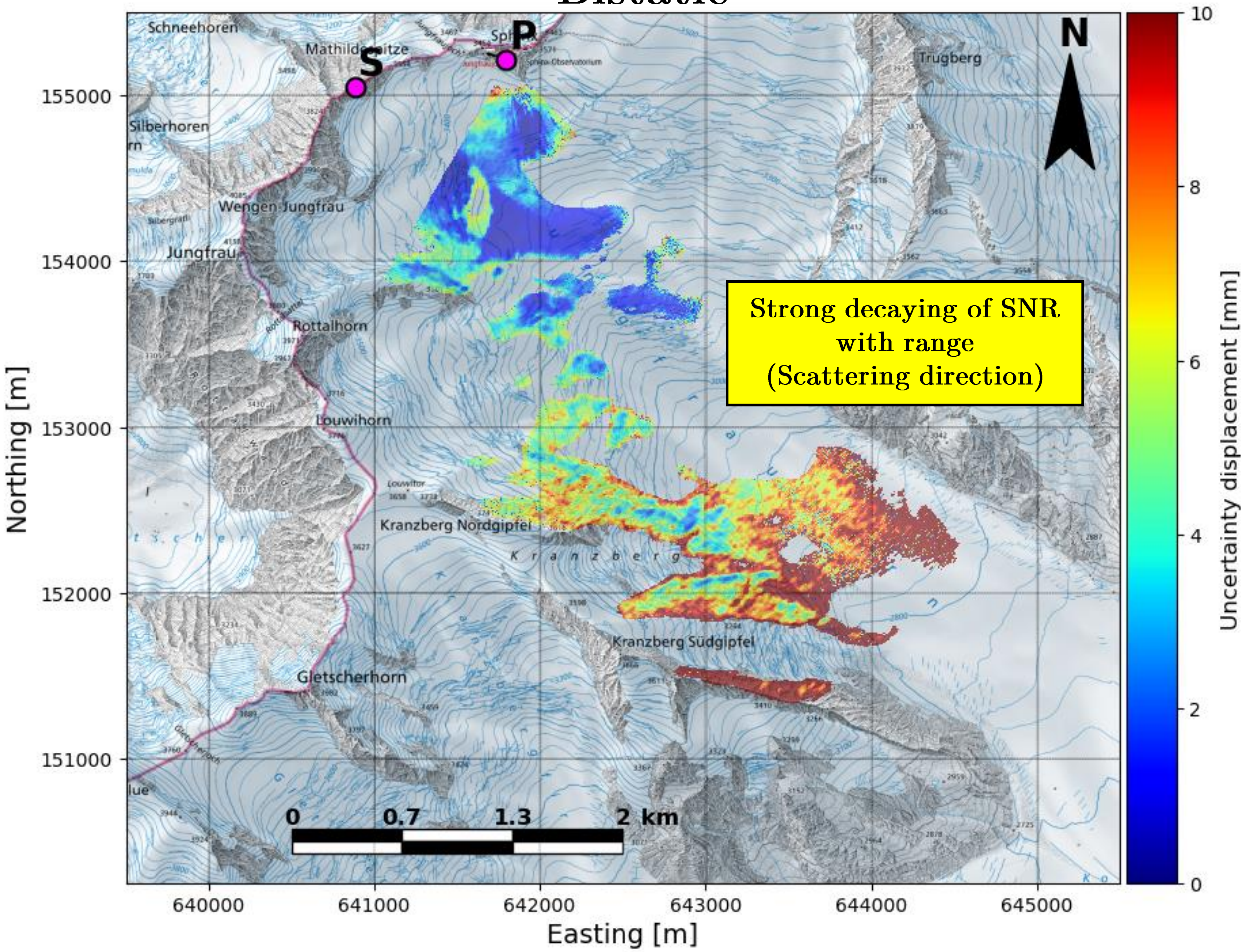
Displacements results: Displacement Uncertainty



$$\sigma_{||s||} = \frac{\lambda}{4\pi(\hat{g} \cdot \vec{u}_m)} \sigma_{\phi_m} \qquad \sigma_{\phi} = \frac{1}{\sqrt{SNR}}$$



$$\sigma_{||s||} = \sqrt{\left(\frac{\partial ||\vec{s}||}{\partial \phi_m}\right)^2 \sigma_{\phi_m}^2 + \left(\frac{\partial ||\vec{s}||}{\partial \phi_s}\right)^2 \sigma_{\phi_s}^2}$$

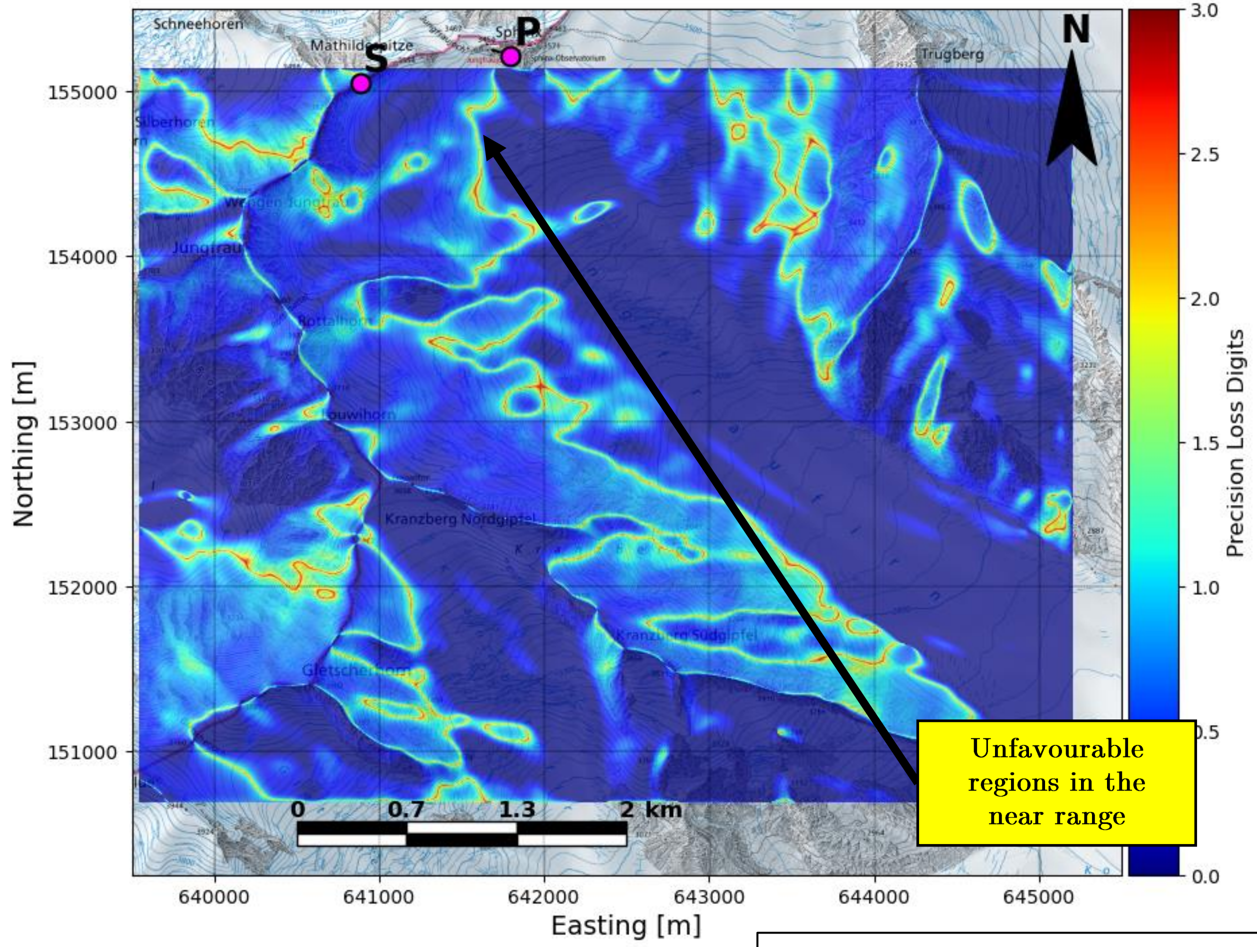
Source: Mas Sanz et al., (under review)

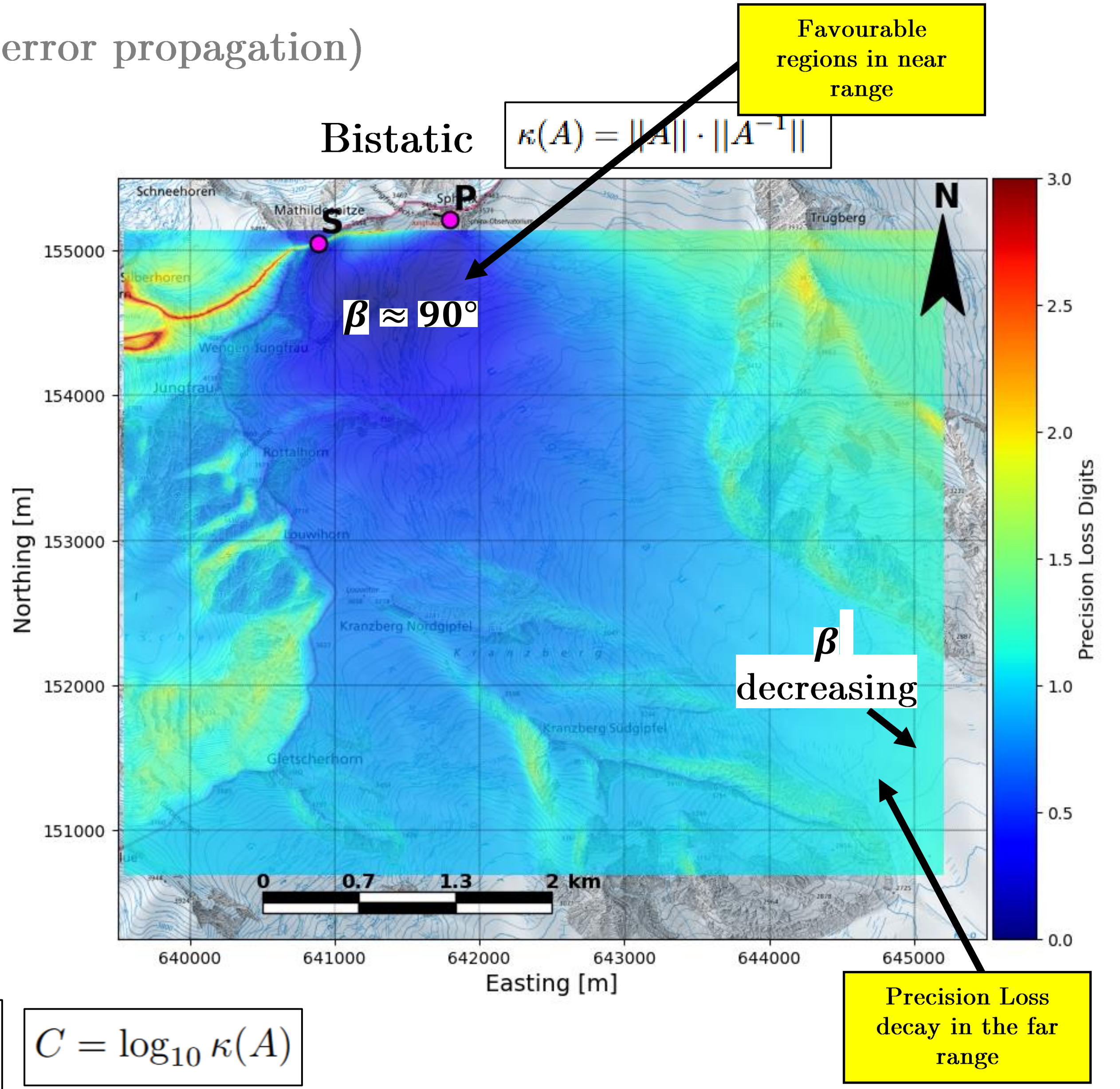
Displacements results: Digit Precission Loss

(factor for error propagation)

Monostatic $\kappa_m = ||\gamma \tan \gamma||$

Bistatic $\kappa(A) = ||A|| \cdot ||A^{-1}||$





$$\kappa = \lim_{\delta \to 0} \sup_{||\delta x|| \leq \delta} \left(\frac{||\delta f||}{||f||} \Big/ \frac{||\delta x||}{||x||} \right)$$

$$C = \log_{10} \kappa(A)$$

Source: Mas Sanz et al., (under review)

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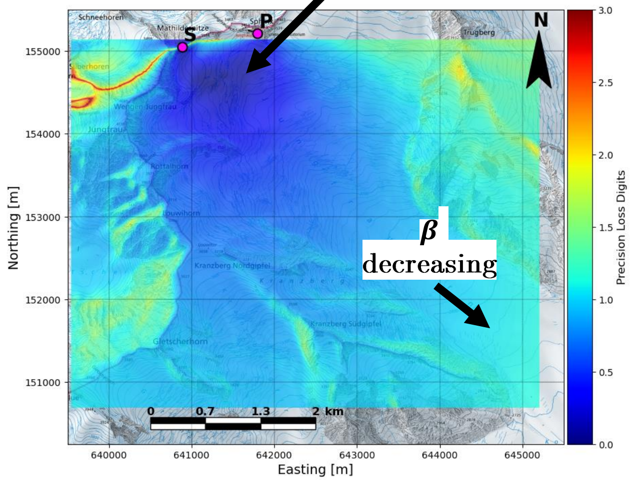
Displacements results: Digit Precission Loss

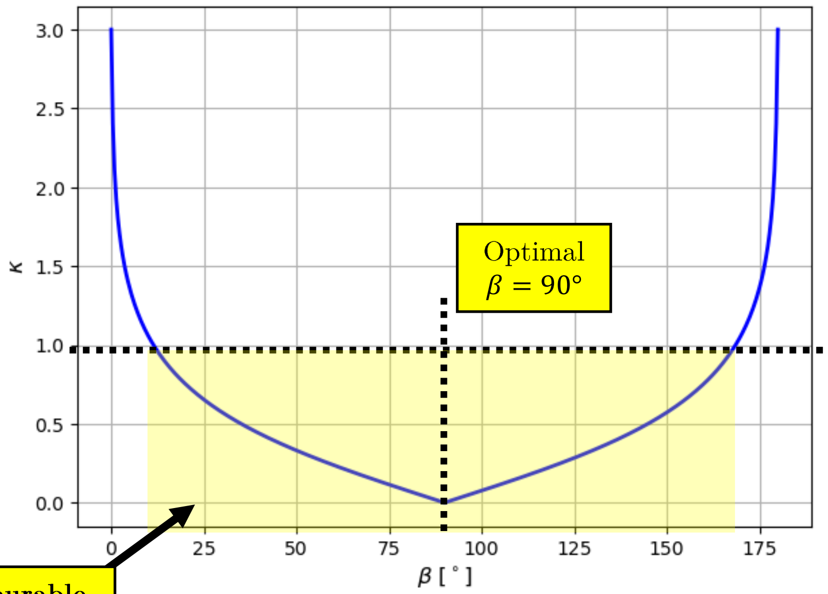
Favourable region

Bistatic



$$\kappa(A) = ||A|| \cdot ||A^{-1}||$$

Precision Loss 2D case

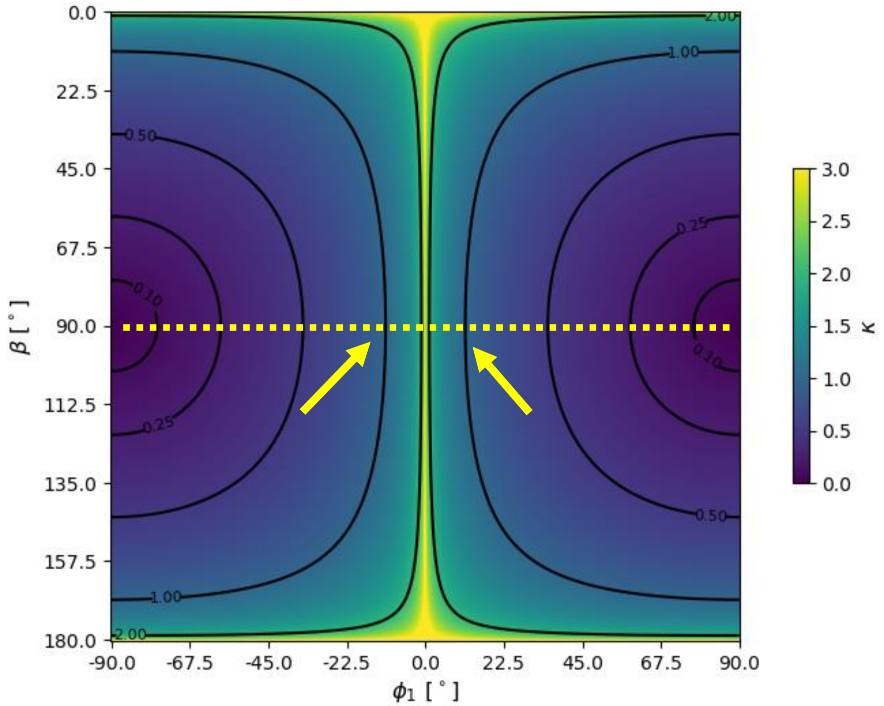


Favourable region

Displacement always conained in LOS plane

Only dependence with bistatic angle **β**. Limit value at **β**<=11.31 deg (**κ**>=1)

Precision Loss 3D case



2D case when $\boldsymbol{\varphi_1} = \mathbf{90°}$

Dependence on bistatic angle **β** and on local elevation angle $\boldsymbol{\varphi_1}$. Additional limit on **κ** when $\boldsymbol{\varphi_1} \rightarrow \mathbf{90}\ \boldsymbol{deg}$

Source: Mas Sanz et al., (under review)

Conclusions

Jungfraujoch Experiment Outcome

Monostatic-only Approach:

Displacement direction uncoupled from radar observations. Low SNR/geometry only affects magnitude

- Uncertainty low due to high SNR across the scene
- Low precision loss except challenging topography areas (LOS perpendicular to gradient)

Monostatic-bistatic Approach:

Displacement direction and magnitude presents robustness in the near range, both vulnerable to low SNR

- Uncertainty high due to low SNR (decay proportional to range)
- Precision loss map (specific configuration used) far range decay ($\beta \rightarrow 0°$) with favorable geometry in near range ($\beta \approx 90°$)

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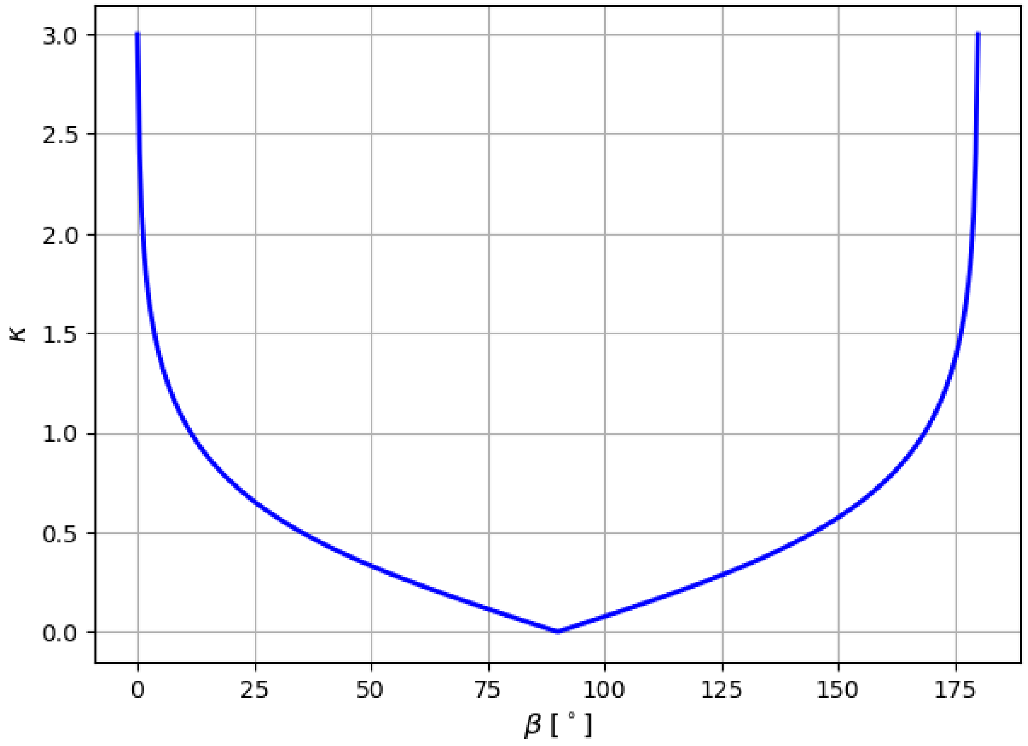
References

Mas Sanz, E., Stefko, M., Hajnsek, I., (under review) “DEM-assisted 3D reconstruction of Aletsch glacier displacements using monostatic and bistatic differential interferometry”. *Manuscript submitted for publication.*

Extra Slides

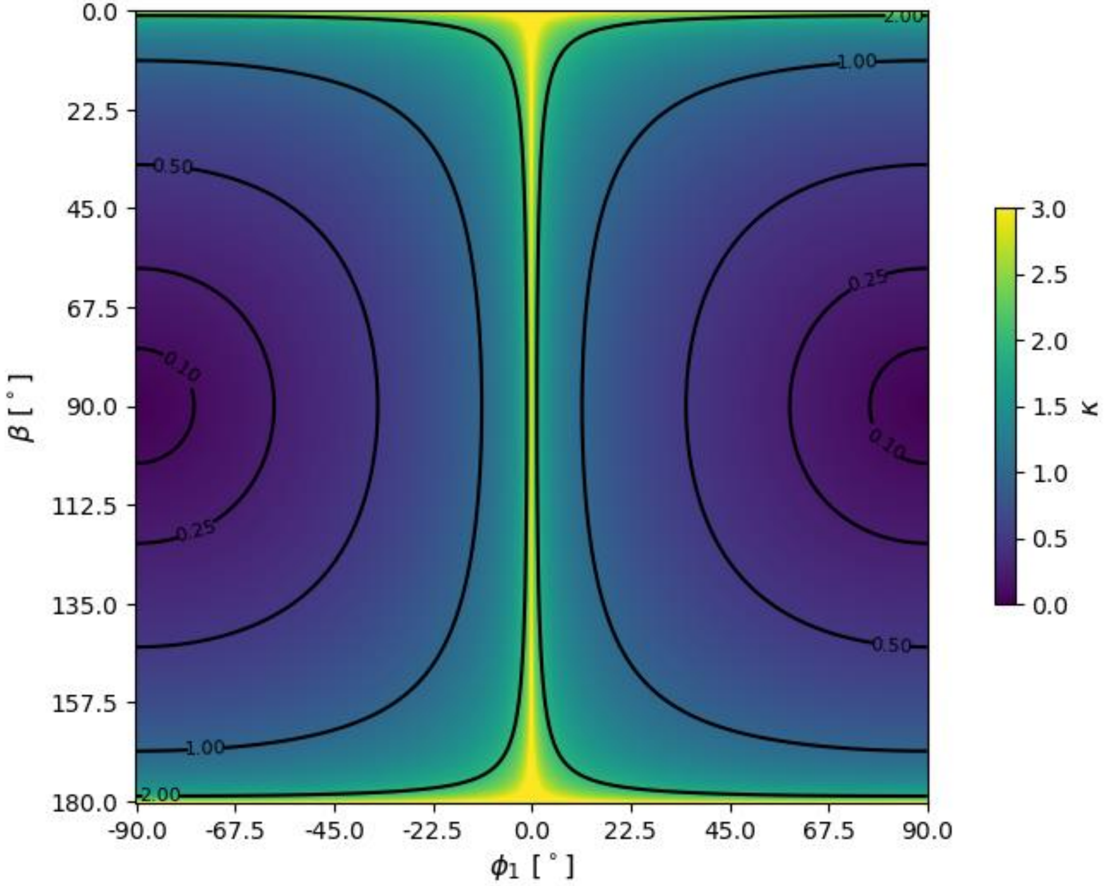
Displacements results: Digit Precission Loss

Precision Loss 2D case



Only dependence with bistatic angle β. Limit value at β<=11.31 deg (κ<=1)

Precision Loss 3D case



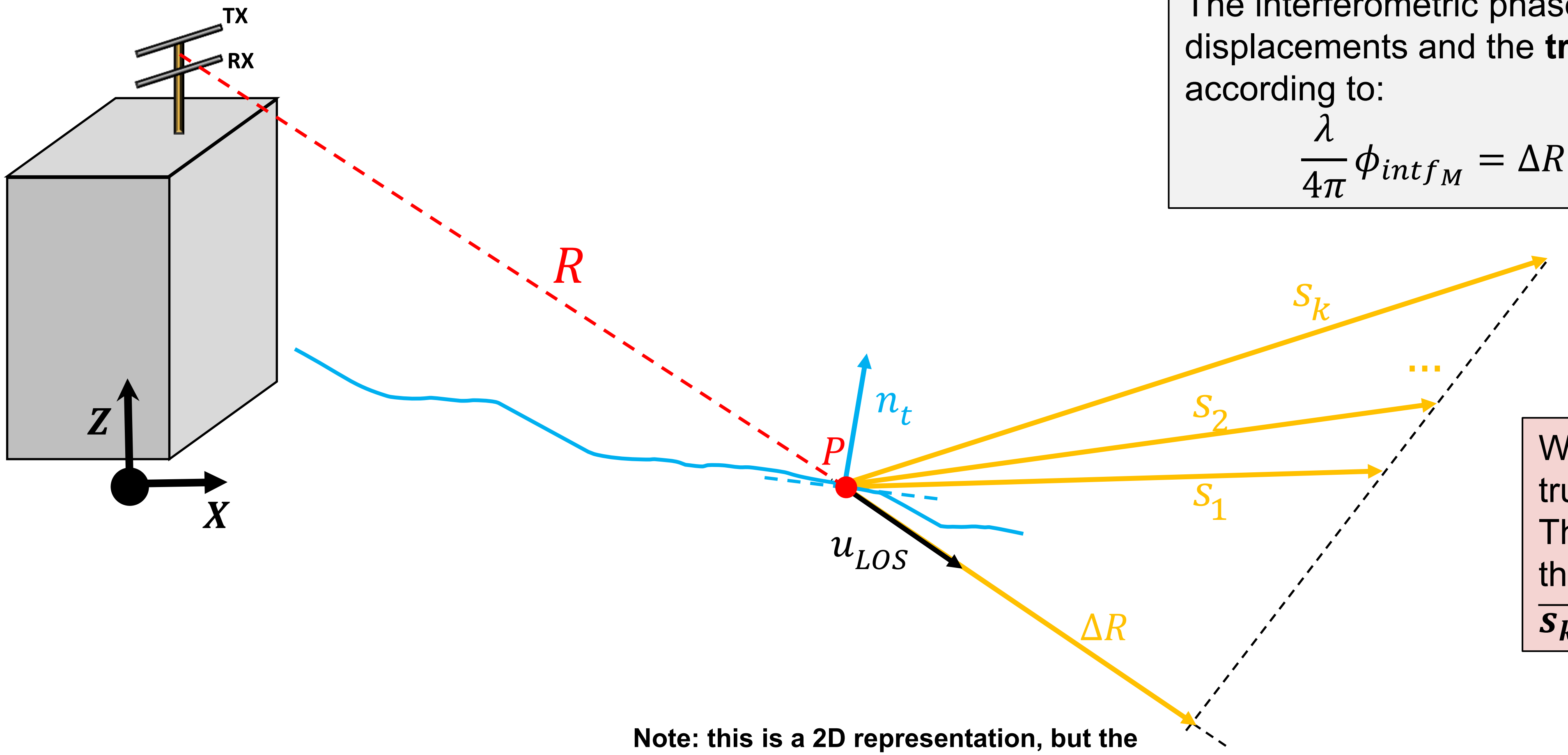
Dependence on bistatic angle β and on local elevation angle φ_1. Additional limit on κ when $\varphi_1 \rightarrow 90\ deg$

Displacement Calculation: Monostatic Case

$R_{TX} = R_{RX}$

The TX leg is the same as the RX leg!

Interferogram [mono]: $\phi_{intf_M} = \frac{4\pi}{\lambda}\Delta R$



The interferometric phase relates to the LOS displacements and the **true displacements** according to:

$$\frac{\lambda}{4\pi}\phi_{intf_M} = \Delta R = \overrightarrow{s_k} \cdot \overrightarrow{u_{LOS}}$$

Which is the value of the true displacements $\vec{s}$? There are infinite solutions that satisfy:
$\overrightarrow{\boldsymbol{s_k}} \cdot \overrightarrow{\boldsymbol{u_{LOS}}} = \boldsymbol{\Delta R}$

Note: this is a 2D representation, but the problem is 3D. In a general case u_{LOS}, n_t, s are not contained in the same plane

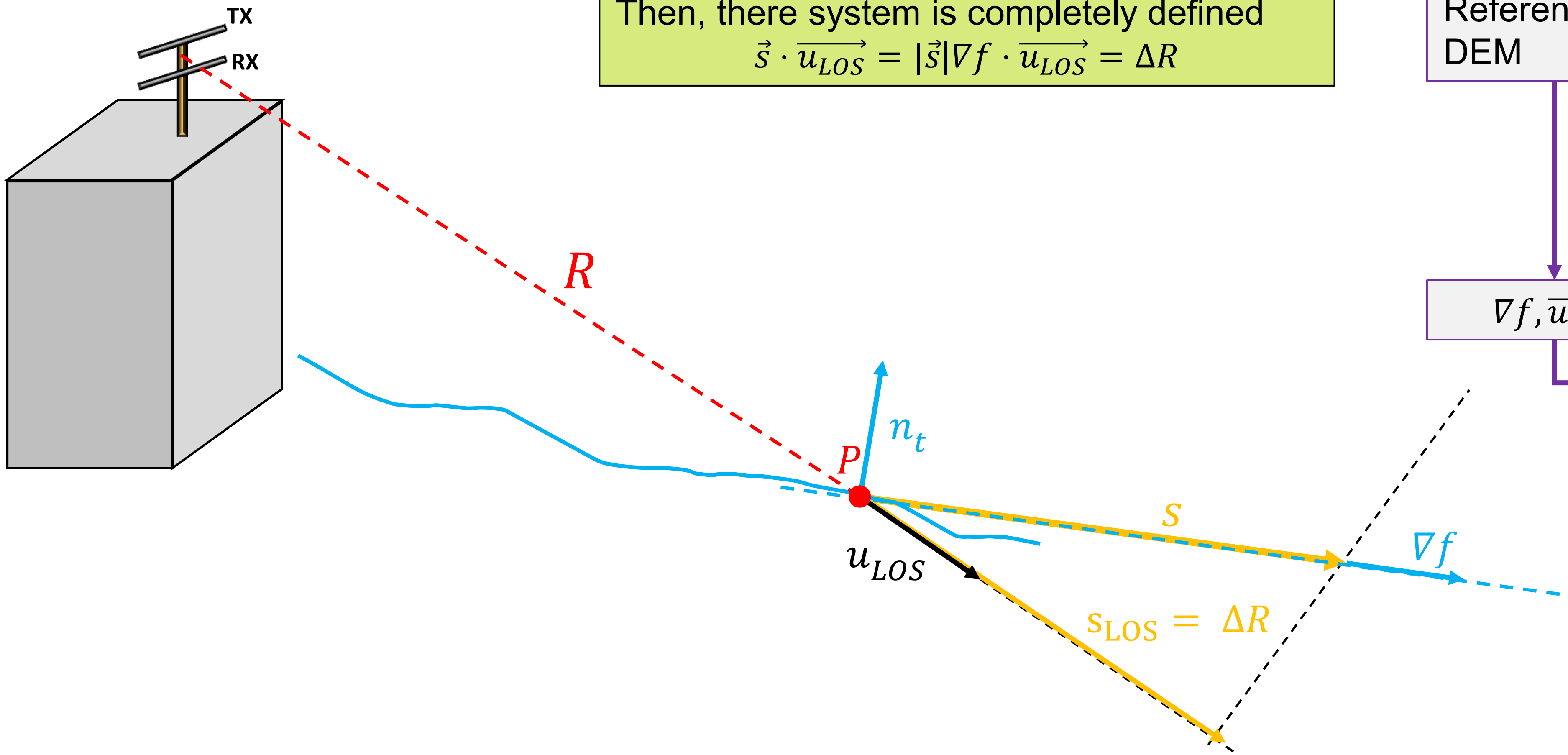
Displacement Calculation: Monostatic Case

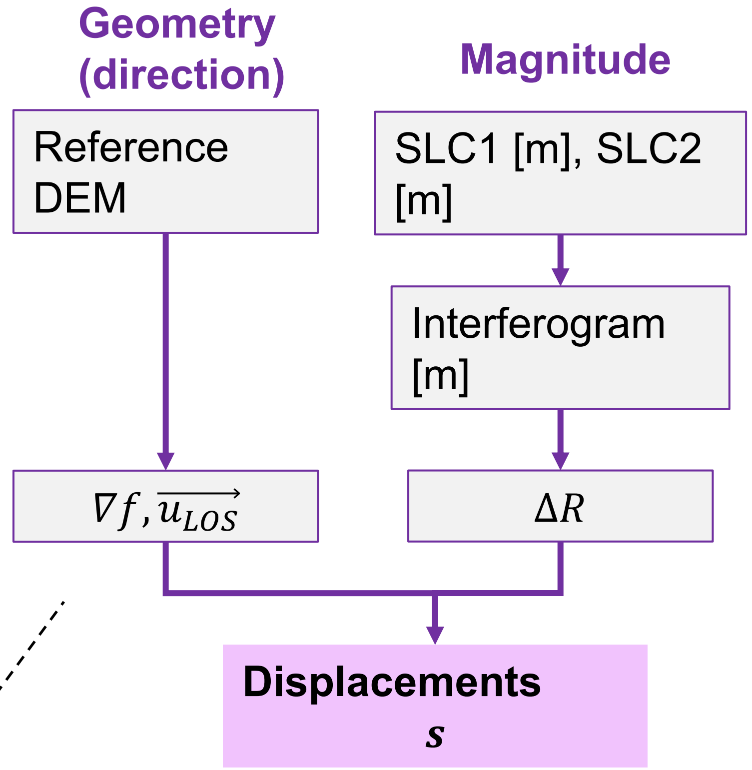
Imposing that displacement vector direction corresponds to the maximum gradient ∇f

$$\vec{s} = \nabla f \cdot |\vec{s}|$$

Then, there system is completely defined

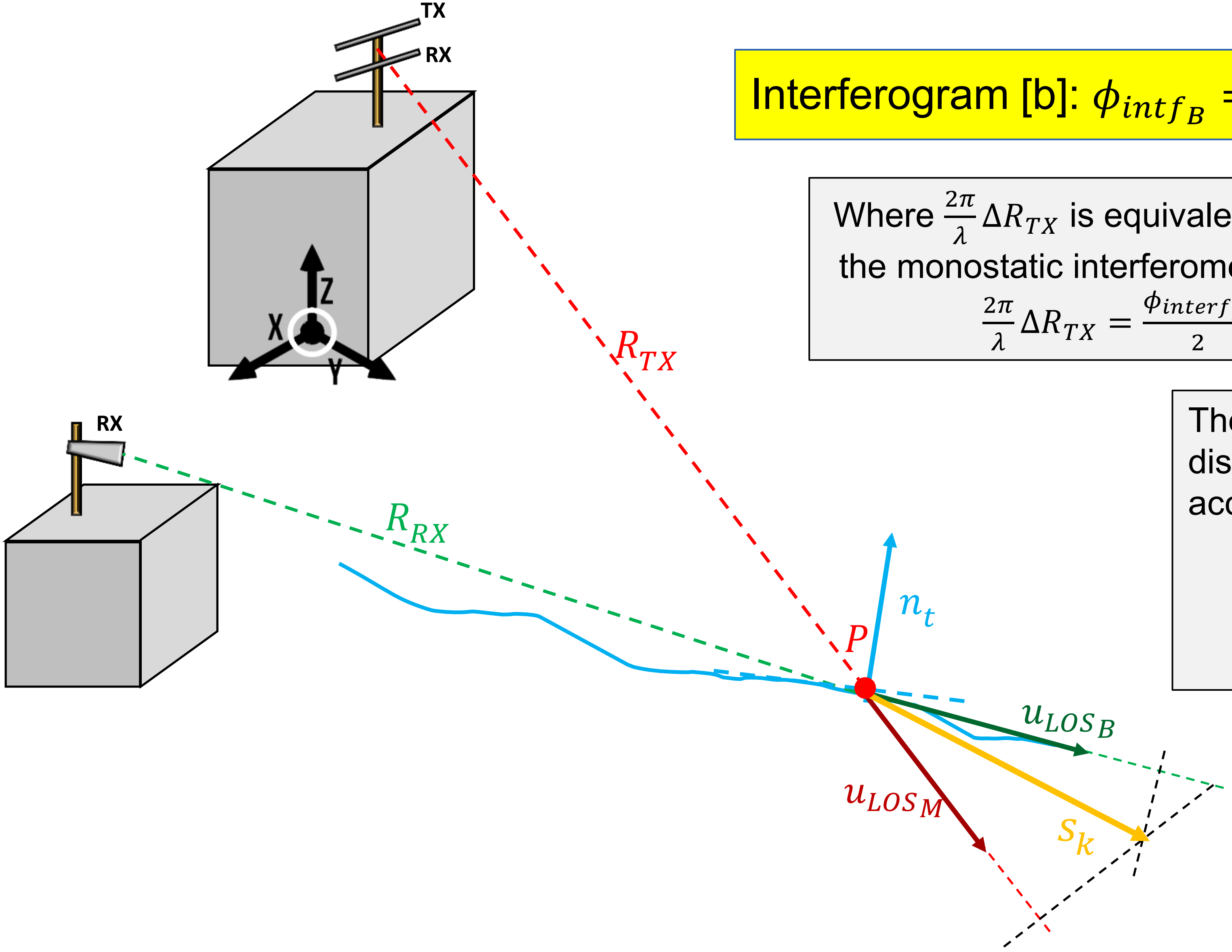
$$\vec{s} \cdot \overrightarrow{u_{LOS}} = |\vec{s}| \nabla f \cdot \overrightarrow{u_{LOS}} = \Delta R$$





Displacement Calculation: Bistatic Case

The TX leg and RX leg have different look vectors!



Interferogram [b]: $\phi_{intf_B} = \frac{2\pi}{\lambda}(\Delta R_{TX} + \Delta R_{RX})$

Where $\frac{2\pi}{\lambda}\Delta R_{TX}$ is equivalent to half of the monostatic interferometric phase

$$\frac{2\pi}{\lambda}\Delta R_{TX} = \frac{\phi_{interf_M}}{2}$$

And the LOS displacements seen from the RX leg are:

$$\phi_{intf_{RX\,leg}} = \phi_{intf_B} - \frac{\phi_{interf_M}}{2}$$

The interferometric phases relate to the LOS displacements and the **true displacements** according to:

$$\frac{\lambda}{4\pi}\phi_{intf_M} = \Delta R_{TX} = \vec{s_k}\cdot\overrightarrow{u_{LOS\,M}}$$

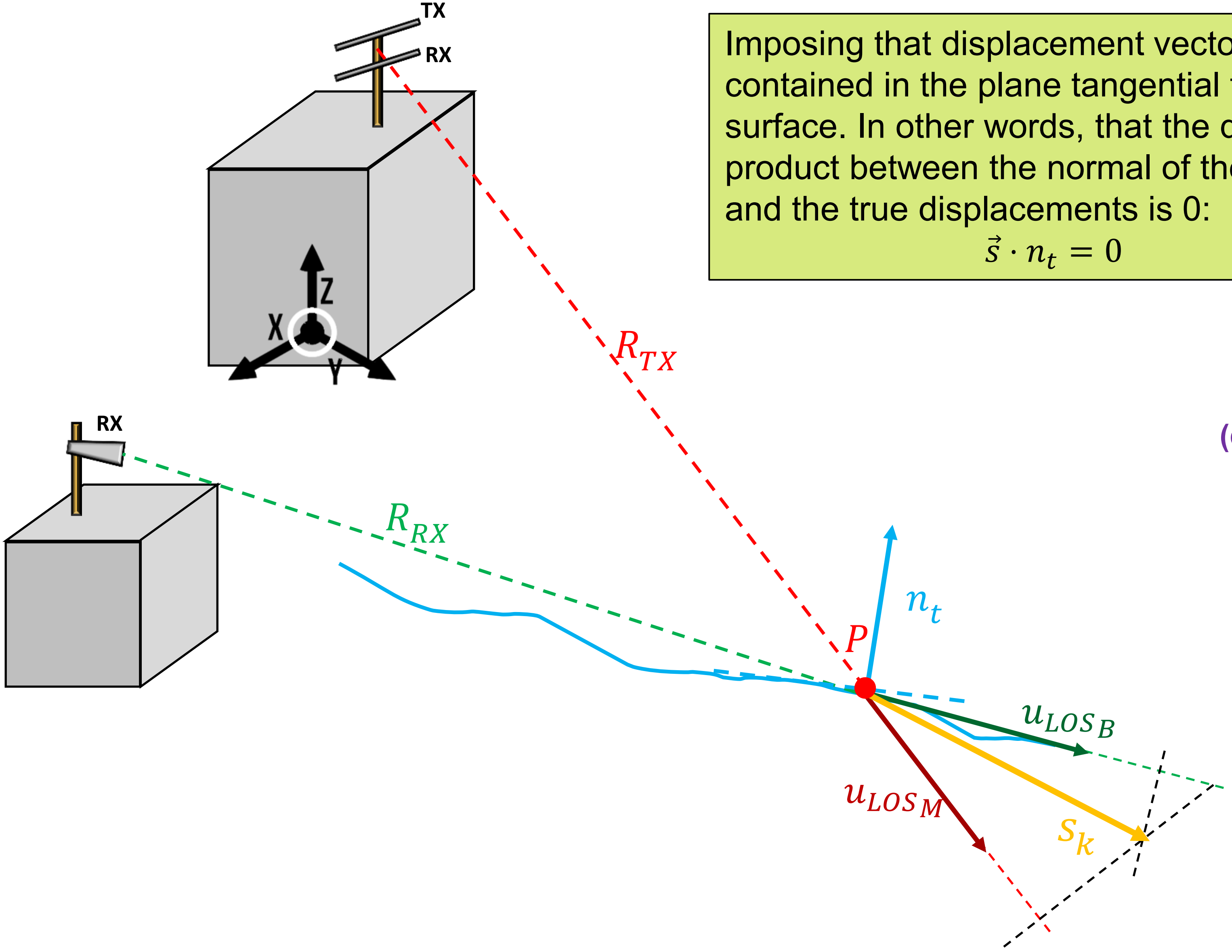
$$\frac{\lambda}{4\pi}\phi_{intf_{RX\,leg}} = \Delta R_{RX} = \vec{s_k}\cdot\overrightarrow{u_{LOS\,B}}$$

Which is the value of the true displacements $\vec{s}$? **?**

There are infinite solutions that satisfy:

$\boldsymbol{\Delta R_{TX} = \vec{s_k}\cdot\overrightarrow{u_{LOS\,M}}}$ **and** $\boldsymbol{\Delta R_{RX} = \vec{s_k}\cdot\overrightarrow{u_{LOS\,B}}}$

Displacement Calculation: Bistatic Case



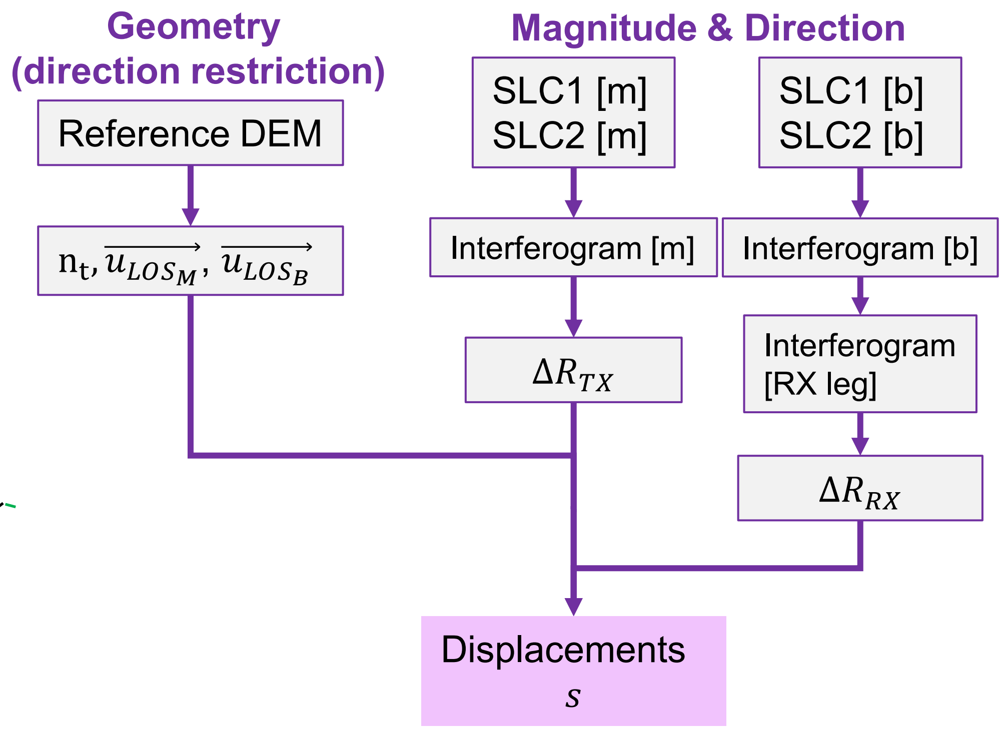
Imposing that displacement vector is contained in the plane tangential to the surface. In other words, that the dot-product between the normal of the surface and the true displacements is 0:

$$\vec{s} \cdot n_t = 0$$

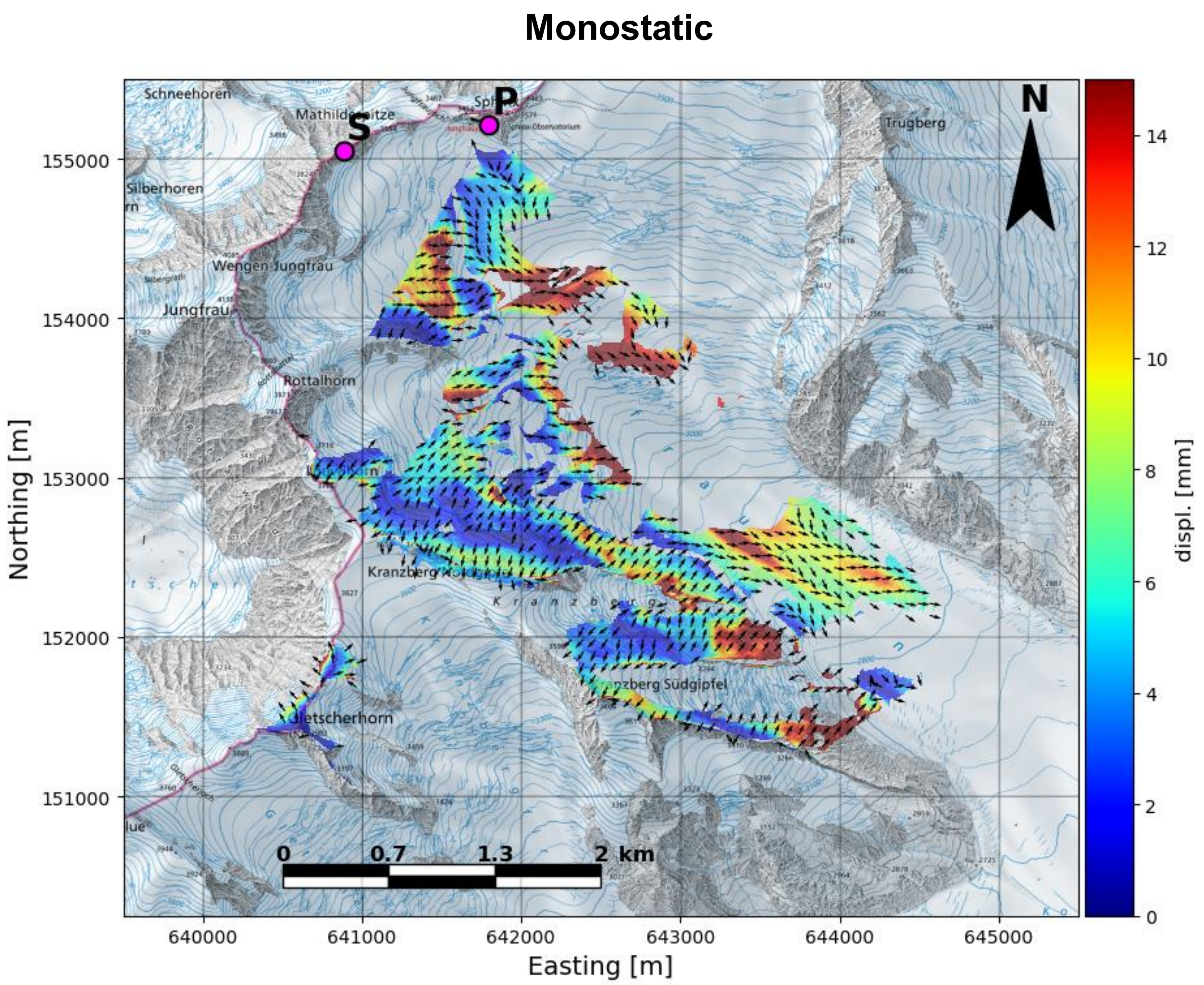
Together with equations:

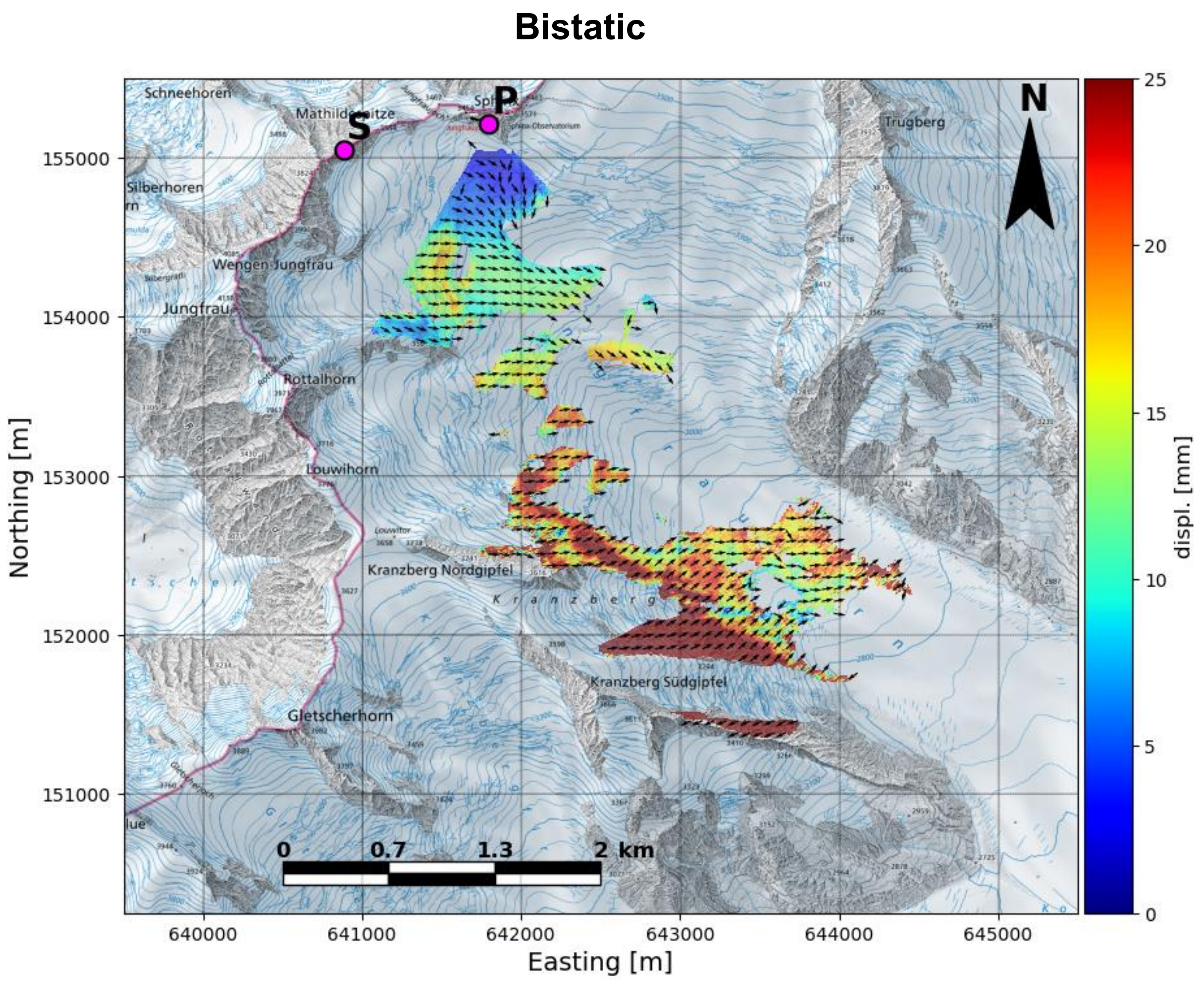
$$\Delta R_{TX} = \vec{s} \cdot \overrightarrow{u_{LOS\,M}}$$
$$\Delta R_{RX} = \vec{s} \cdot \overrightarrow{u_{LOS\,B}}$$

Forms an independent system with one solution



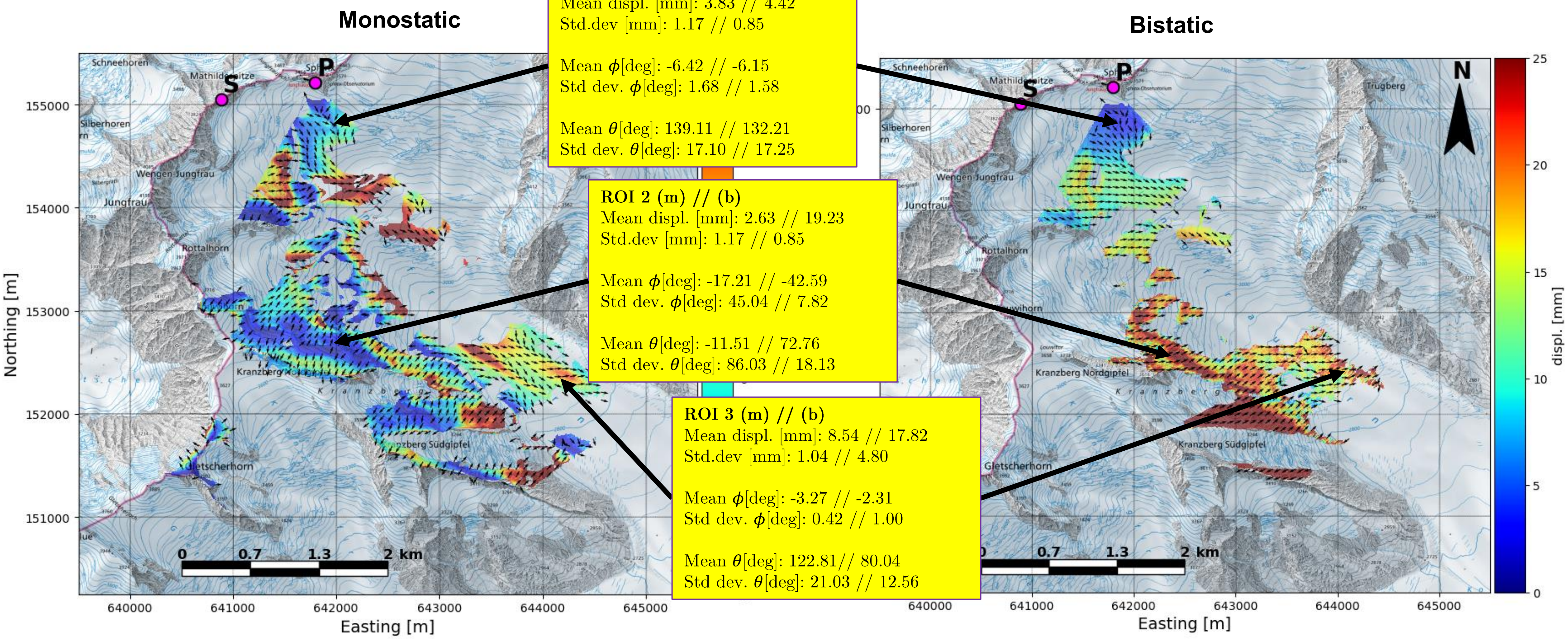
Displacements results: Displacement Vector Field





Source: Mas Sanz et al., (under review)

Displacements results: Displacement Vector Field



ROI 1 (m) // (b)
Mean displ. [mm]: 3.83 // 4.42
Std.dev [mm]: 1.17 // 0.85

Mean ϕ[deg]: -6.42 // -6.15
Std dev. ϕ[deg]: 1.68 // 1.58

Mean θ[deg]: 139.11 // 132.21
Std dev. θ[deg]: 17.10 // 17.25

ROI 2 (m) // (b)
Mean displ. [mm]: 2.63 // 19.23
Std.dev [mm]: 1.17 // 0.85

Mean ϕ[deg]: -17.21 // -42.59
Std dev. ϕ[deg]: 45.04 // 7.82

Mean θ[deg]: -11.51 // 72.76
Std dev. θ[deg]: 86.03 // 18.13

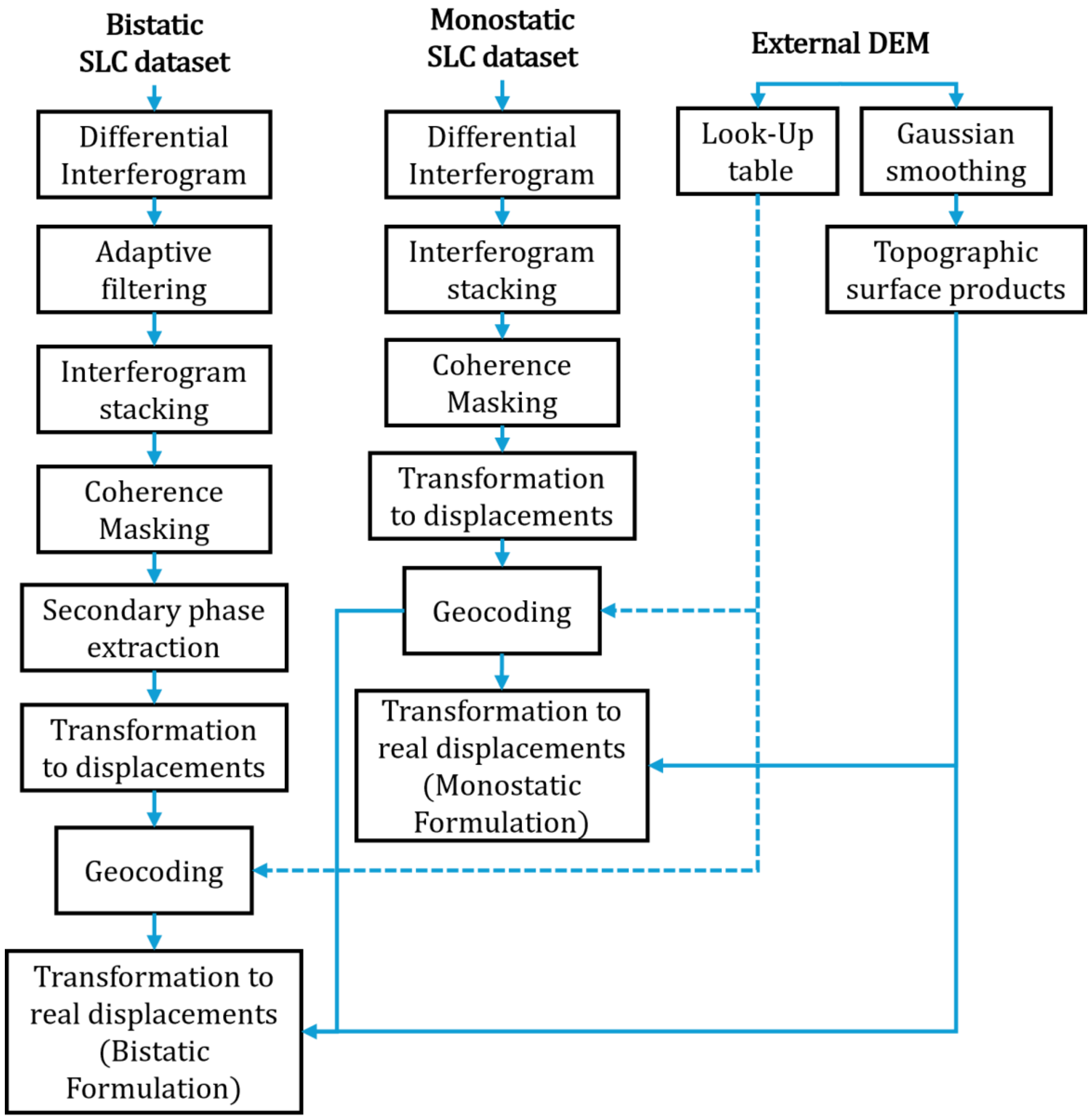
ROI 3 (m) // (b)
Mean displ. [mm]: 8.54 // 17.82
Std.dev [mm]: 1.04 // 4.80

Mean ϕ[deg]: -3.27 // -2.31
Std dev. ϕ[deg]: 0.42 // 1.00

Mean θ[deg]: 122.81// 80.04
Std dev. θ[deg]: 21.03 // 12.56

Source: Mas Sanz et al., (under review)

Processing Pipeline



Source: Mas Sanz et al., (under review)