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# InSAR geodesy: current capabilities, challenges and why we need GNSS?

EUPOS 2019

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Richard Czikhardt, Juraj Papčo



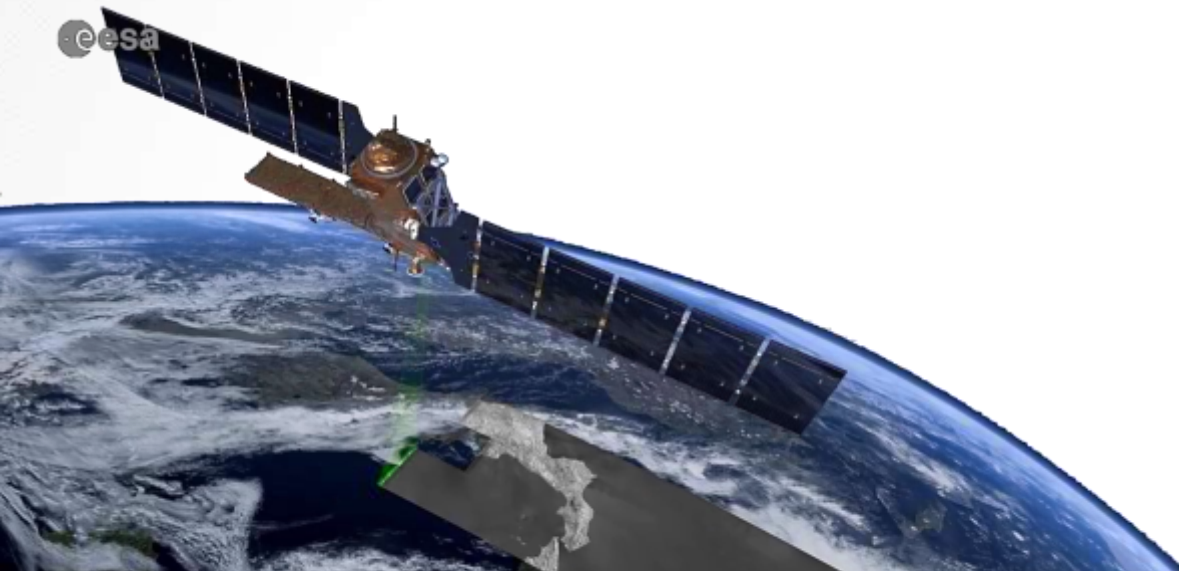
Dept. of Theoretical Geodesy

Faculty of Civil Engineering

Slovak University of Technology in Bratislava, Slovakia

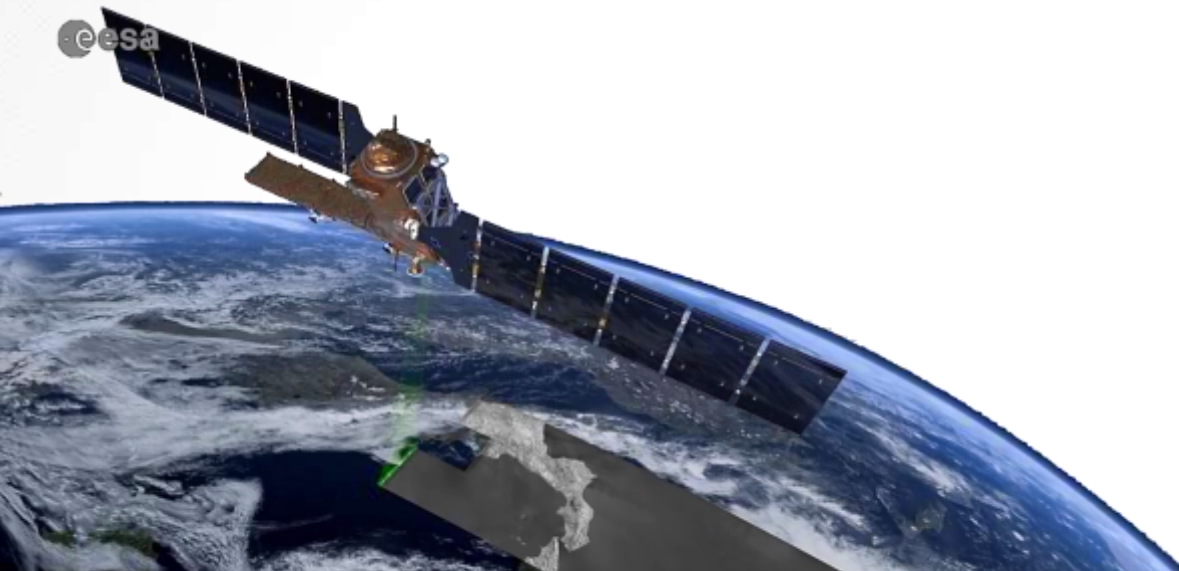
## InSAR (Interferometric Synthetic Aperture Radar)

**“Geodetic remote sensing technique for effective monitoring of large-scale ground deformation phenomena or even stability of individual buildings and structures.”**



## InSAR (Interferometric Synthetic Aperture Radar)

**(In)SAR are measurements, not „nice images“**

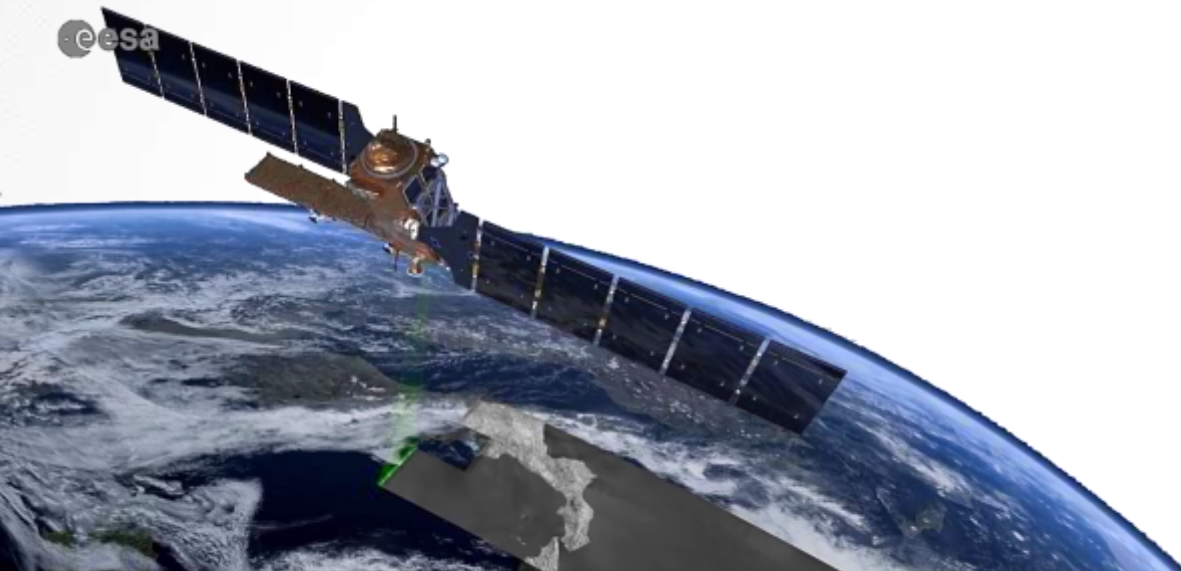


## InSAR (Interferometric Synthetic Aperture Radar)

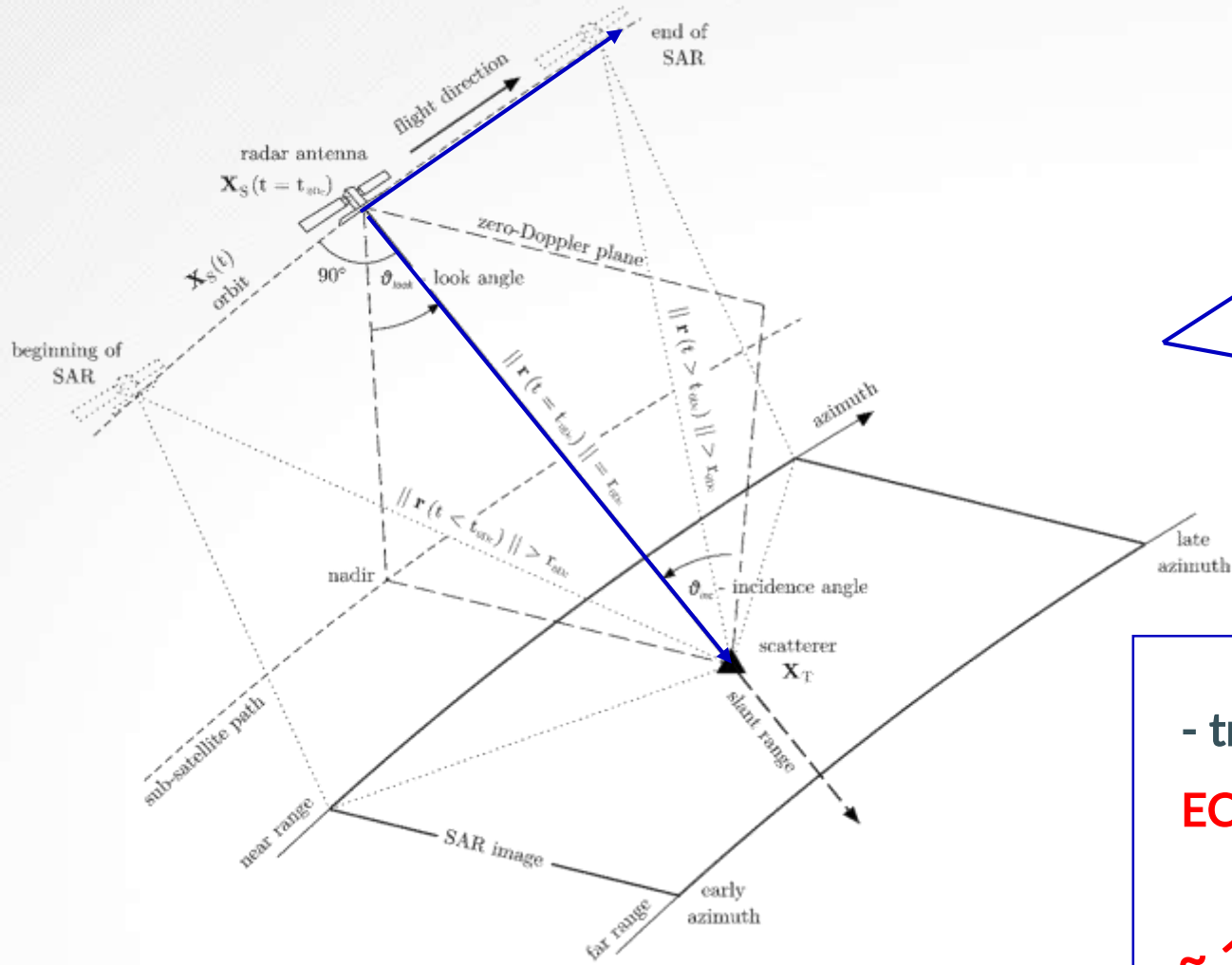
- What do we measure (directly & indirectly)?
- What are the benchmarks?
- What is its reference system (frame)?
- What is the precision and accuracy (stochastic properties)?
- What are the capabilities, limitations and challenges?



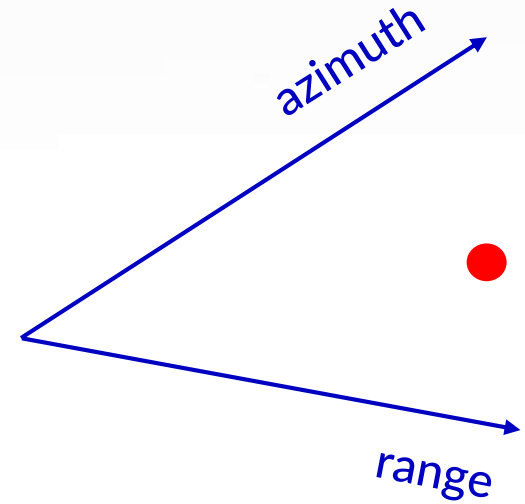
# InSAR geodesy: theory

The ESA logo is located in the bottom left corner of the image. It consists of the letters 'esa' in a lowercase, sans-serif font, with a small circular icon to its left containing a stylized satellite or space-related symbol.

# SAR point positioning



Radar coordinates:



- transformed to  
**ECEF (TRF) coordinates**  
**~ 1-10 m precision**

# SAR phase measurement

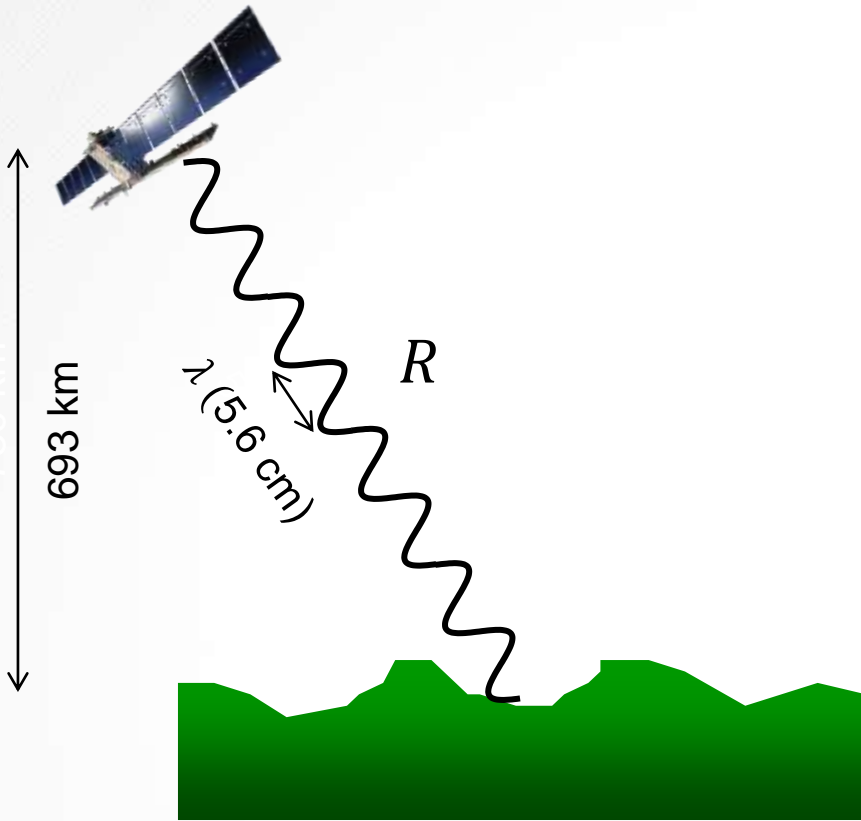
Complex phasor  
measurement per pixel:

$$y = A \exp(i\psi)$$

Phase

$$\psi = \frac{2\pi}{\lambda} 2R = n2\pi + \Delta\psi$$

Round trip ~ 30 million wavelengths  
BUT we don't know the exact number  
(phase ambiguity)

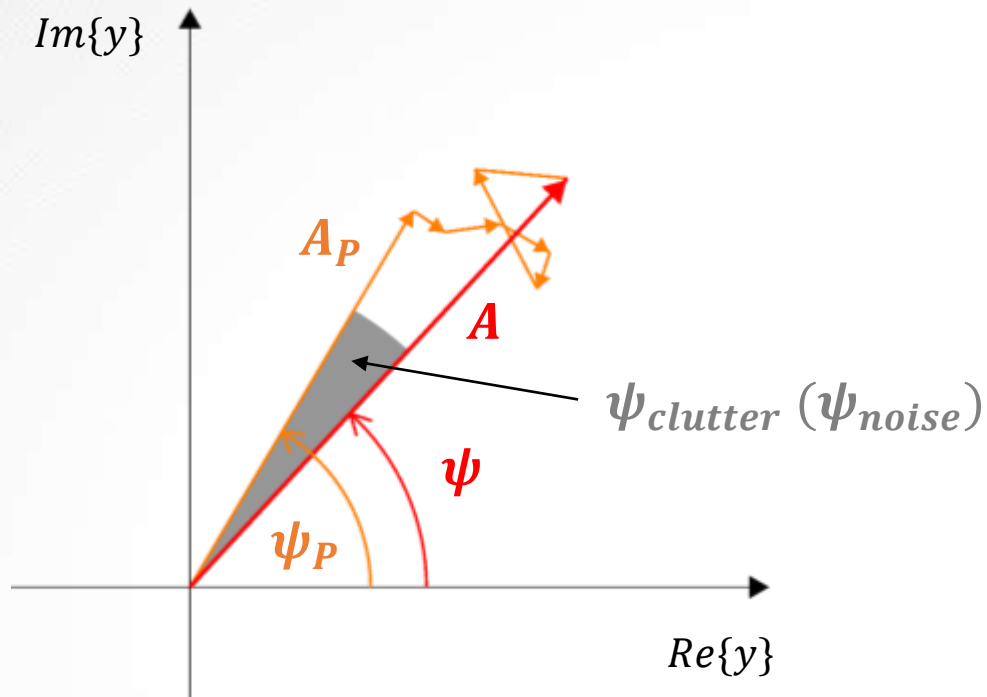


# Coherent scattering

Complex phasor  
measurement:

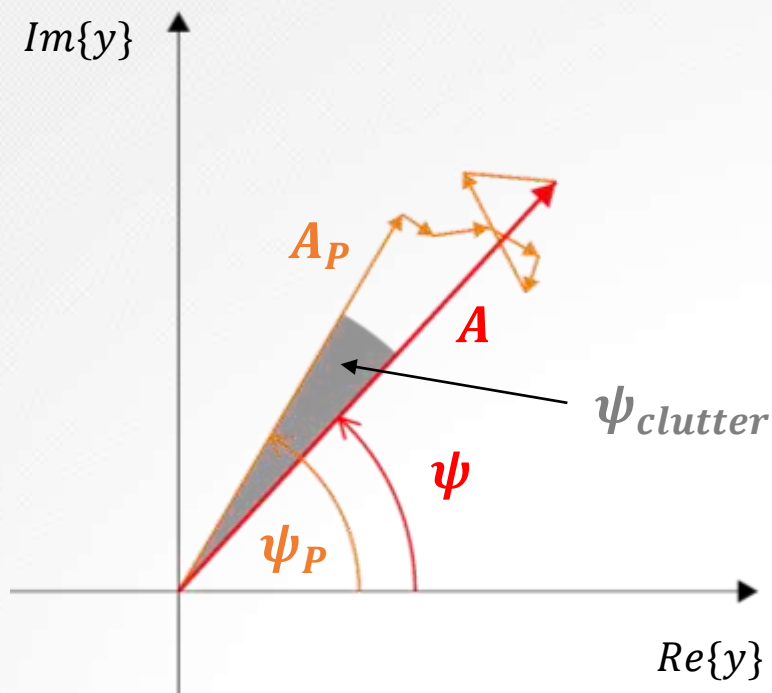
$$y = A \exp(i\psi)$$

per 1 pixel:



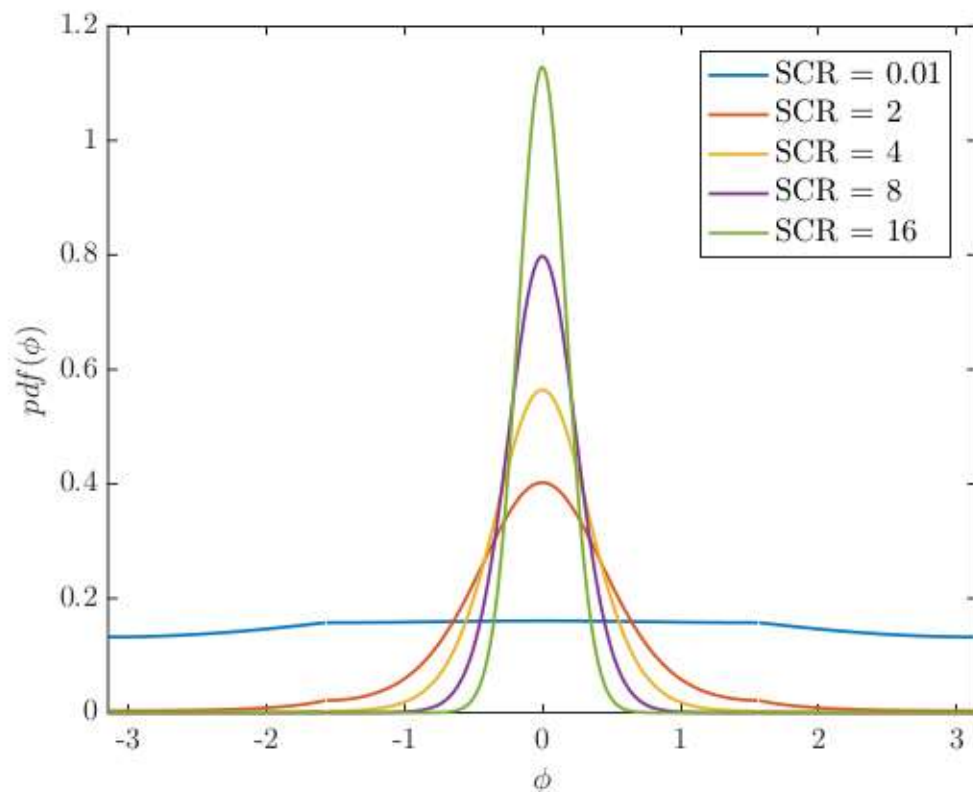
→ dominant (point) scatterer + clutter

# Signal-to-clutter ratio (SCR)



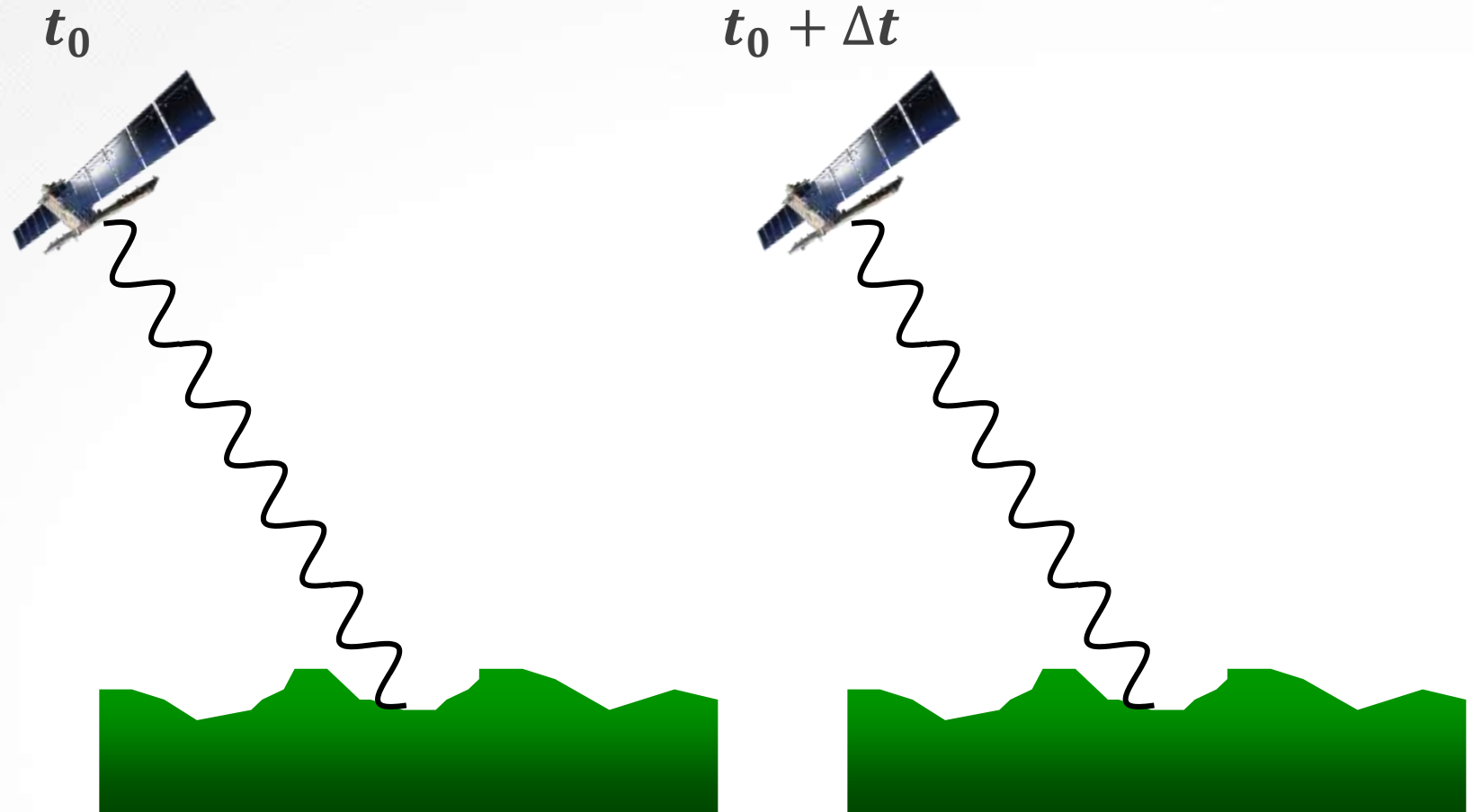
$$\sigma_{\psi}^{\text{a-priori}} \approx \frac{1}{\sqrt{2SCR}}$$

$$SCR = \frac{\text{signal}^2}{\text{clutter}^2} = \frac{\mathbb{E}(A)^2}{2\sigma_n^2}$$



# SAR Interferometry (InSAR)

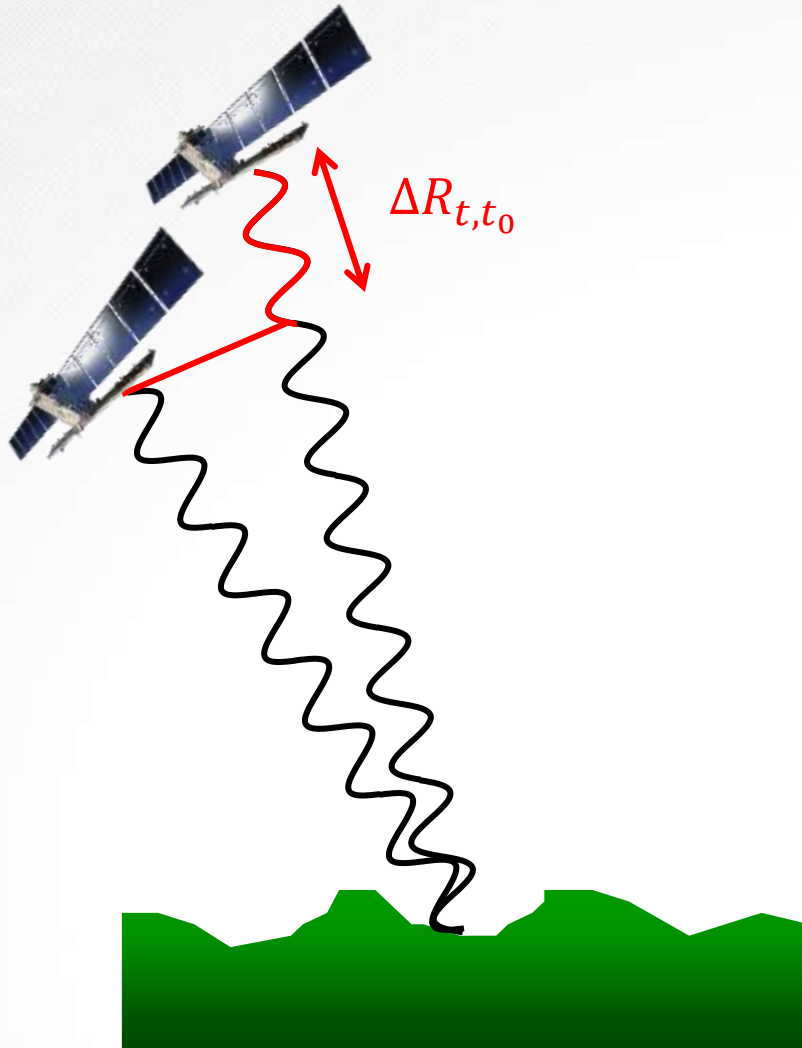
$$y_1 y_2^* = |y_1| |y_2| \exp(j(\psi_1 - \psi_2))$$



# SAR Interferometry

## Interferometric phase (interferogram)

$$\psi_t - \psi_{t_0} = \frac{4\pi}{\lambda} \Delta R_{t,t_0}$$



$\Delta R_{t,t_0}$  caused by different:

- position of sensor (parallax)
- position of scatterer (deformation)
- atmospheric signal delay

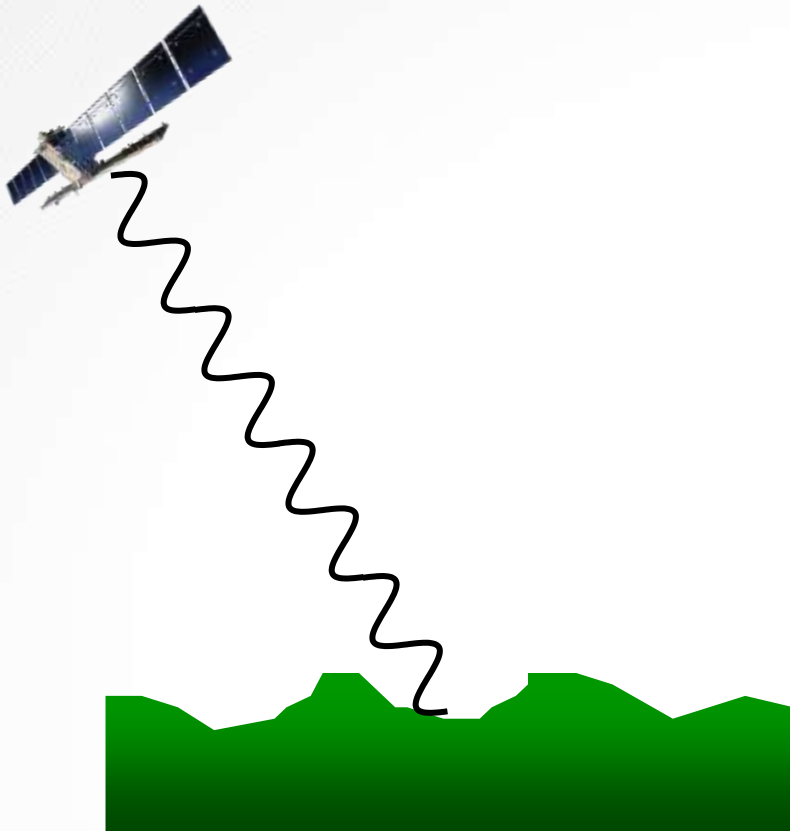
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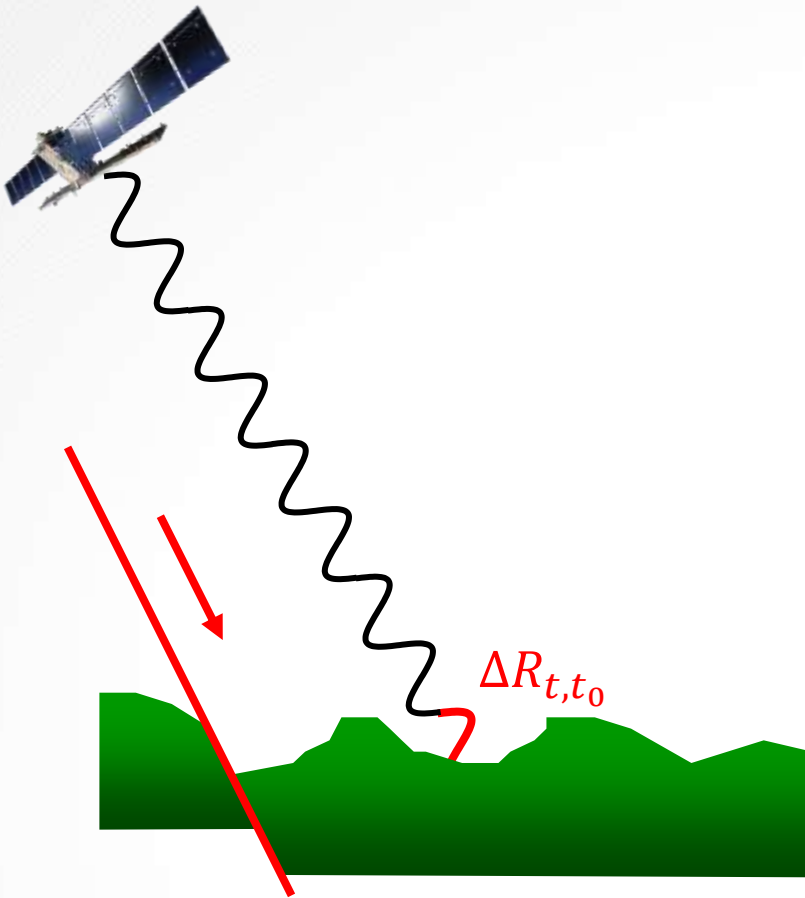
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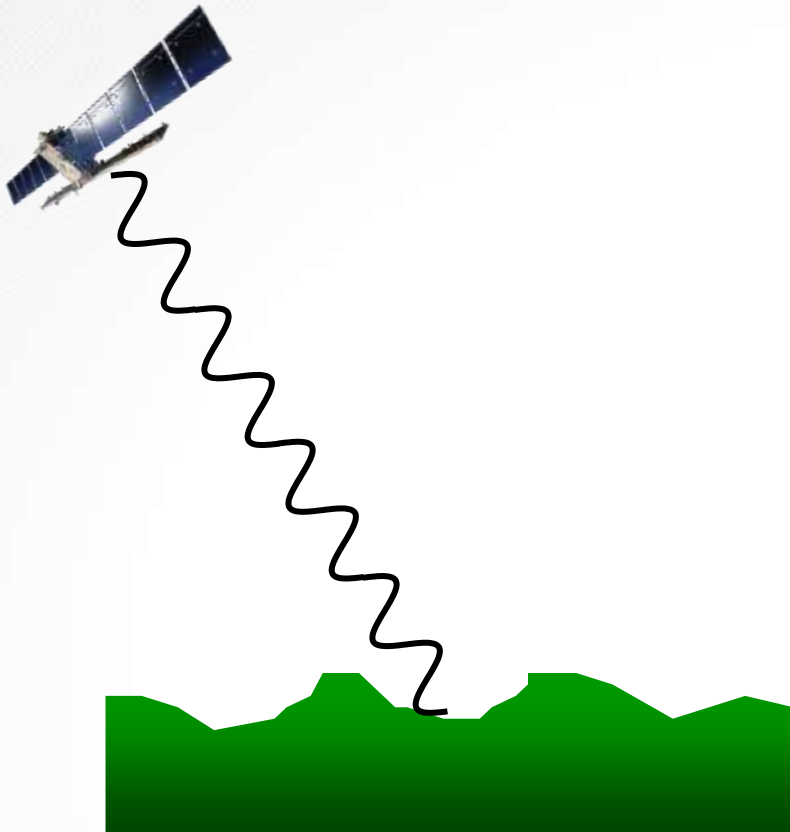
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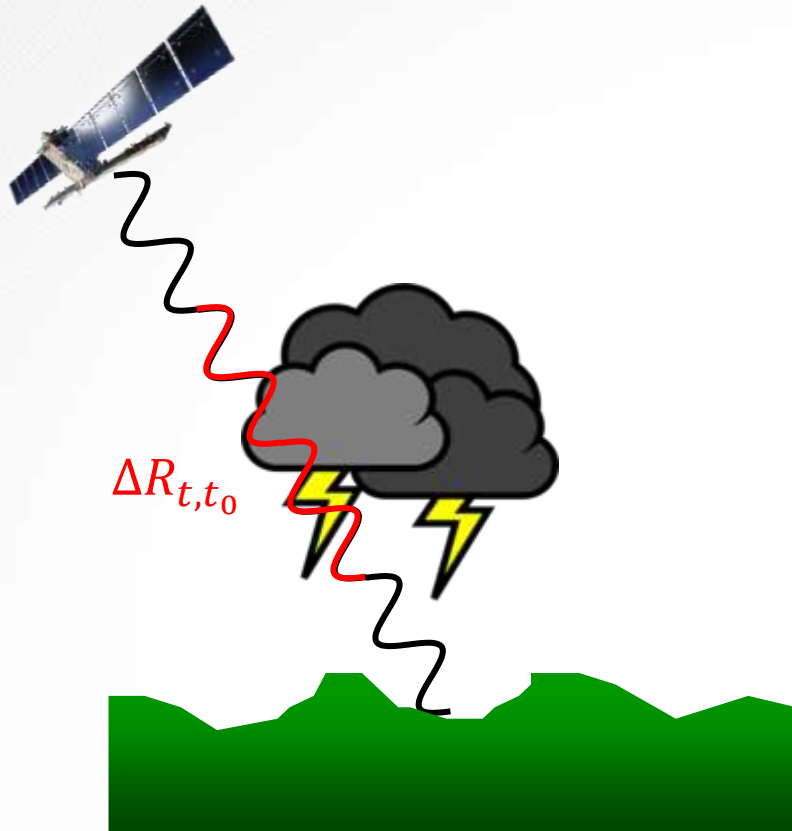
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# SAR Interferometry

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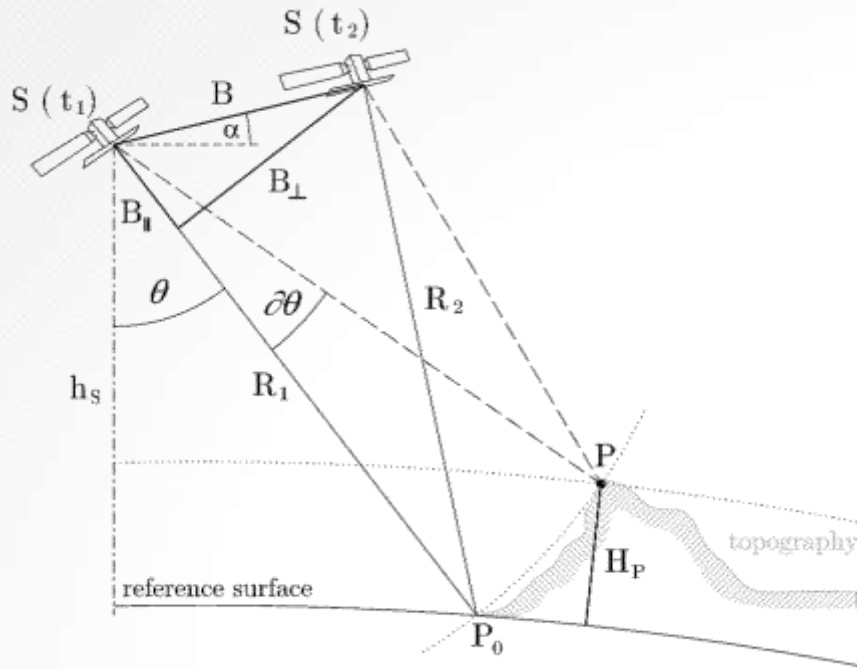


$\Delta R_{t,t_0}$  caused by different:

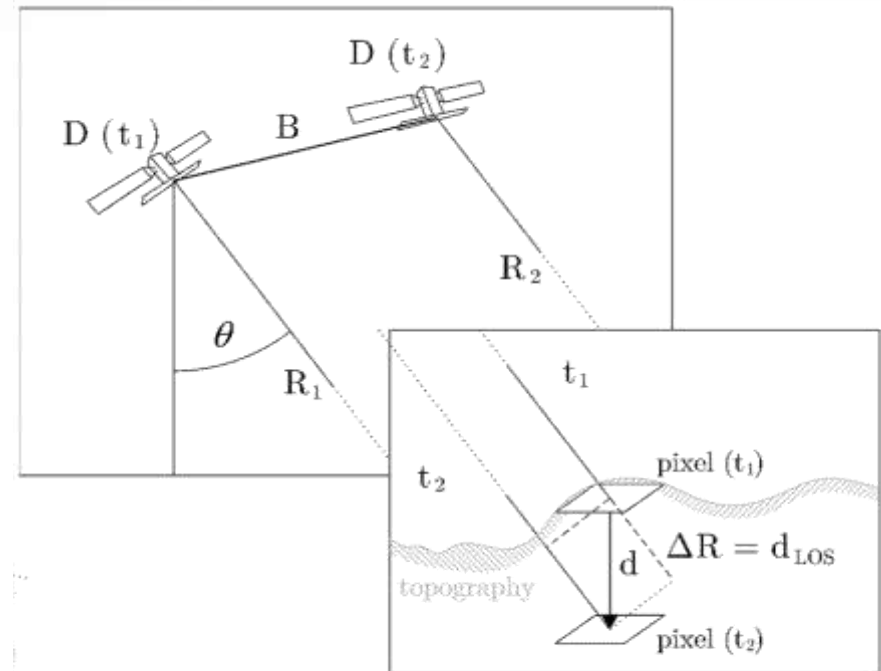
- position of sensor (parallax)
- position of scatterer (deformation)
- atmospheric signal delay

# InSAR observation equation

$$\phi = -2\pi a + \phi_{ref} + \phi_{defo} + \phi_{atmo} + \phi_{scatt(clutt)} + \phi_{noise}$$



$$\phi_{topo} = \frac{4\pi}{\lambda} \frac{B_{\perp}}{R \sin \theta} H_P$$



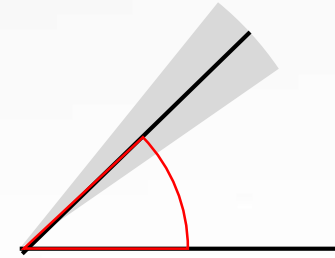
$$\phi_{defo} = \frac{4\pi}{\lambda} d_{LOS}$$



# A-priori precision

Scatterer with SCR = 20 :

$$\sigma_{\phi} = \sim 6^{\circ}$$



Relative height precision

$$\phi_{topo} = \frac{4\pi}{\lambda} \frac{B_{\perp}}{R \sin \theta} H_P$$

theoretically



$$\sigma_H = \sim 1 \text{ m}$$

Displacement precision

$$\phi_{defo} = \frac{4\pi}{\lambda} d_{LOS}$$

theoretically

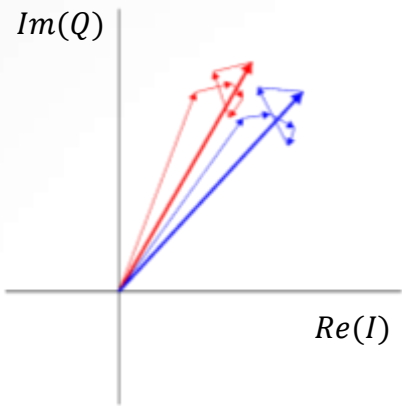
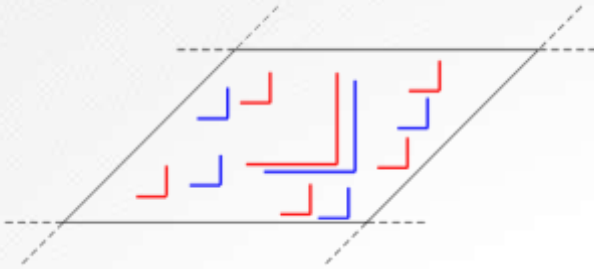


$$\sigma_{d_{LOS}} = \sim 0.5 \text{ mm}$$

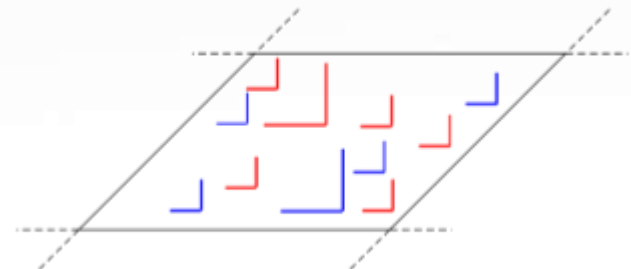
# Persistent Scatterers (PS)

## Point scattering

a.) coherent

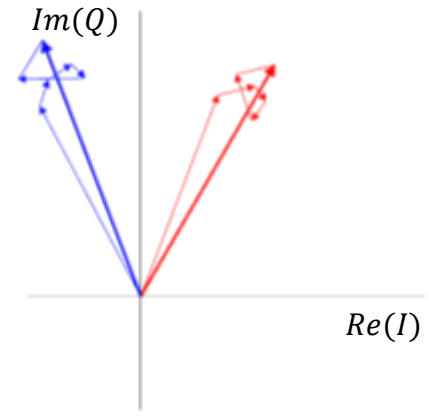


b.) incoherent



$$T_0$$

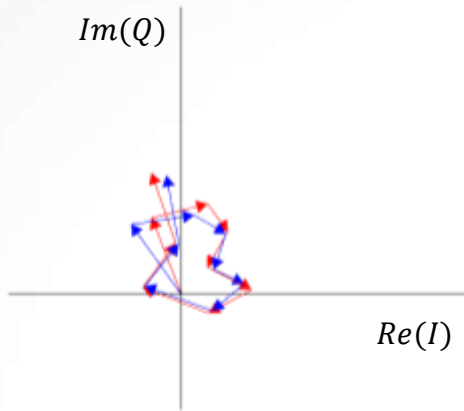
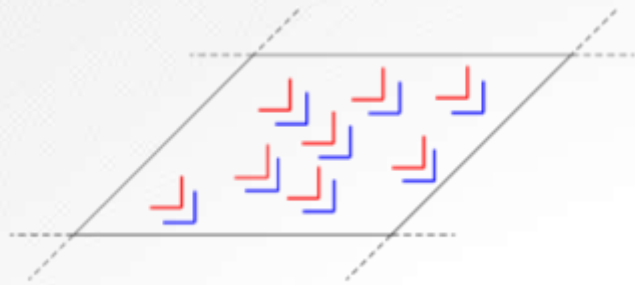
$$T_0 + \Delta T$$



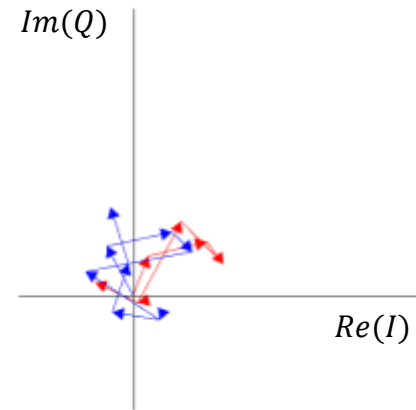
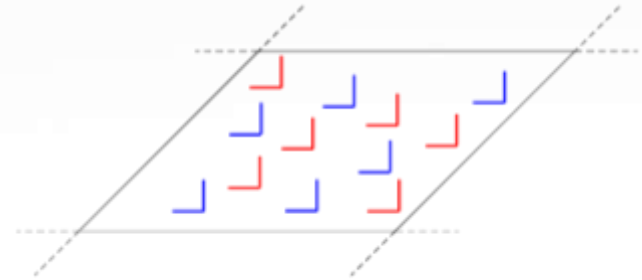
# Persistent Scatterers (PS)

## Distributed scattering

a.) coherent



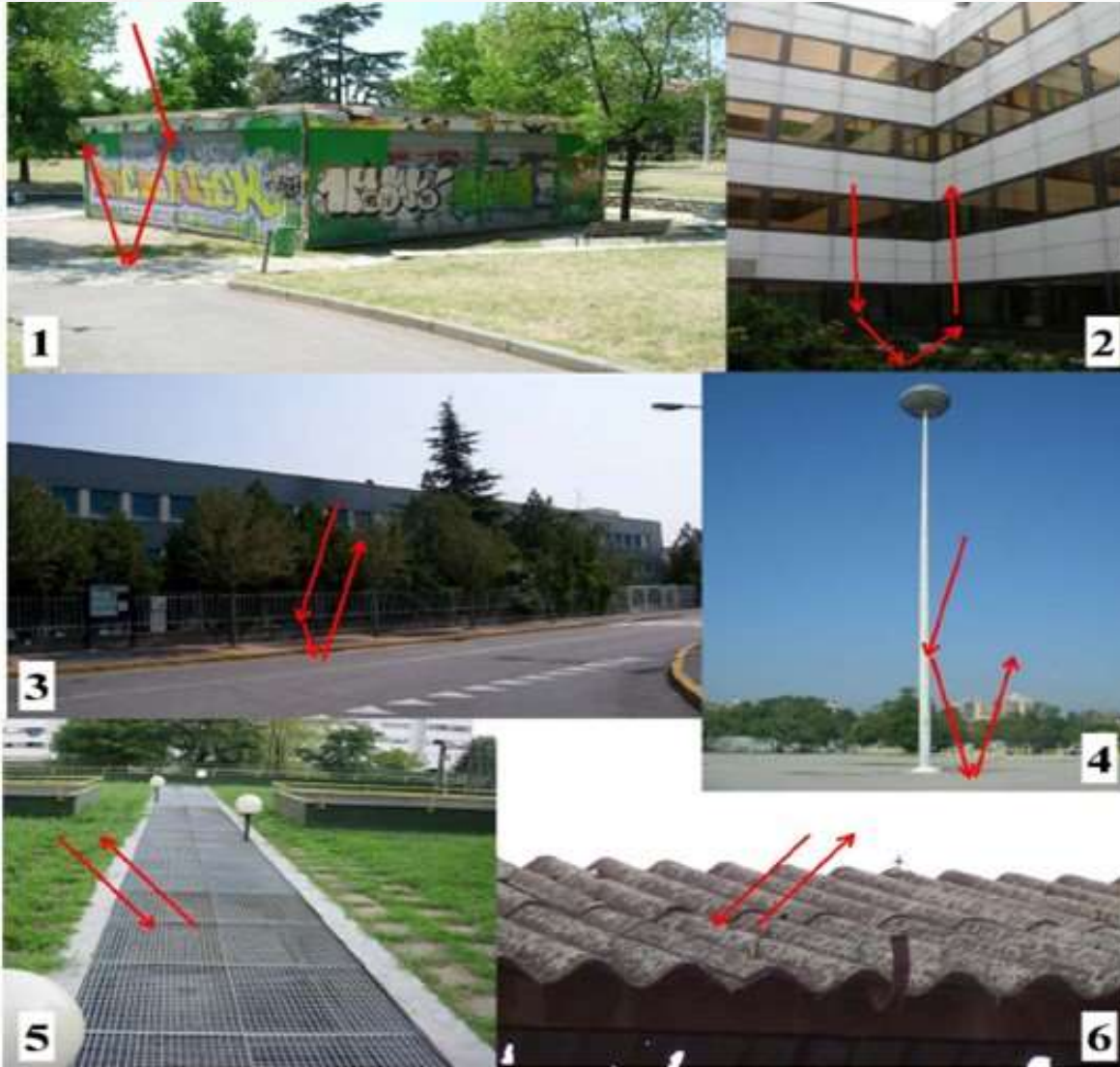
b.) incoherent



$T_0$

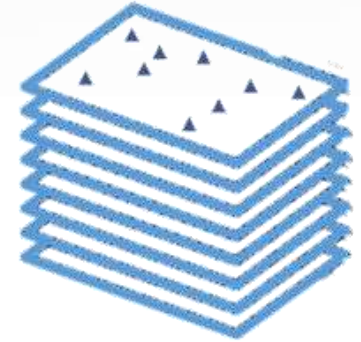
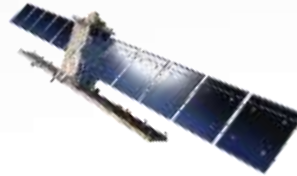
$T_0 + \Delta T$

# Persistent Scatterers (PS)



# Time-series InSAR

- New acquisition = new measurement every 6 days



- freely available, whole Earth's landmass, {October 2014 – ongoing}

SAR image time series

$t_0$

“Master” epoch  
(reference datum)

$t_{1,2,3...N}$

“Slave” epochs

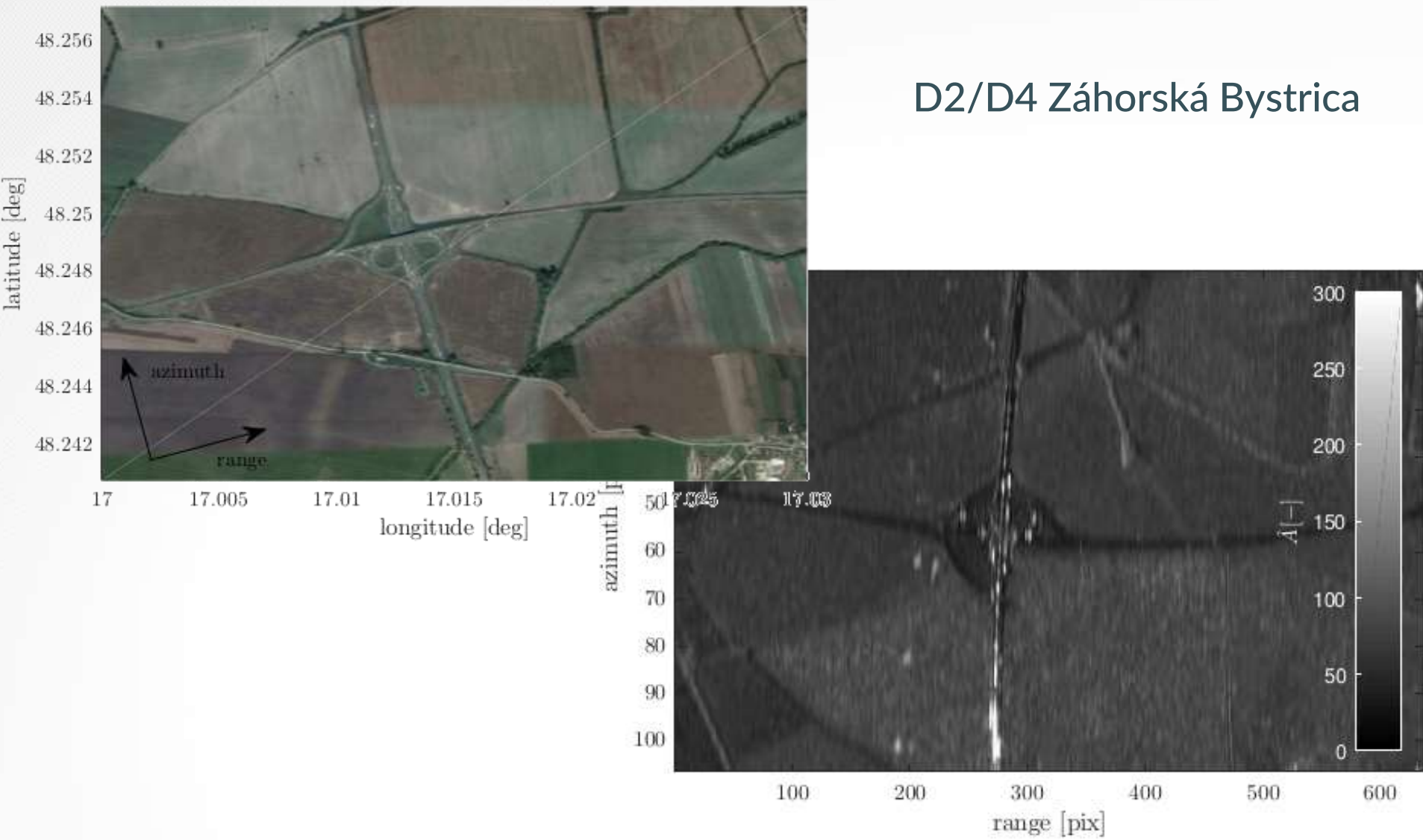
Outcome:

$\phi_{1,2,3...N}$

Interferometric phase  
time series in every pixel

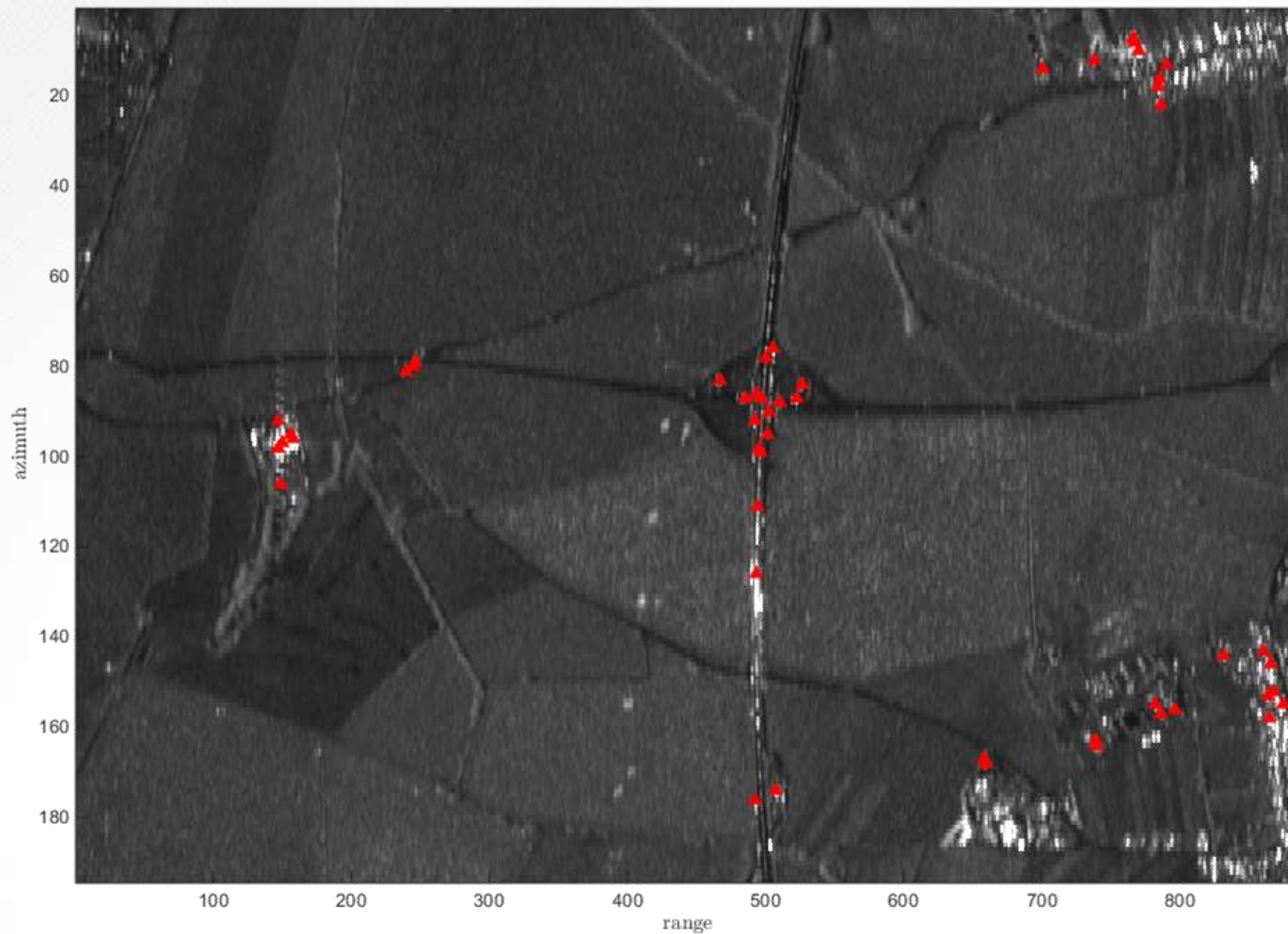
# Demonstrative case of time-series InSAR

D2/D4 Záhorská Bystrica



# Detection & estimation problem

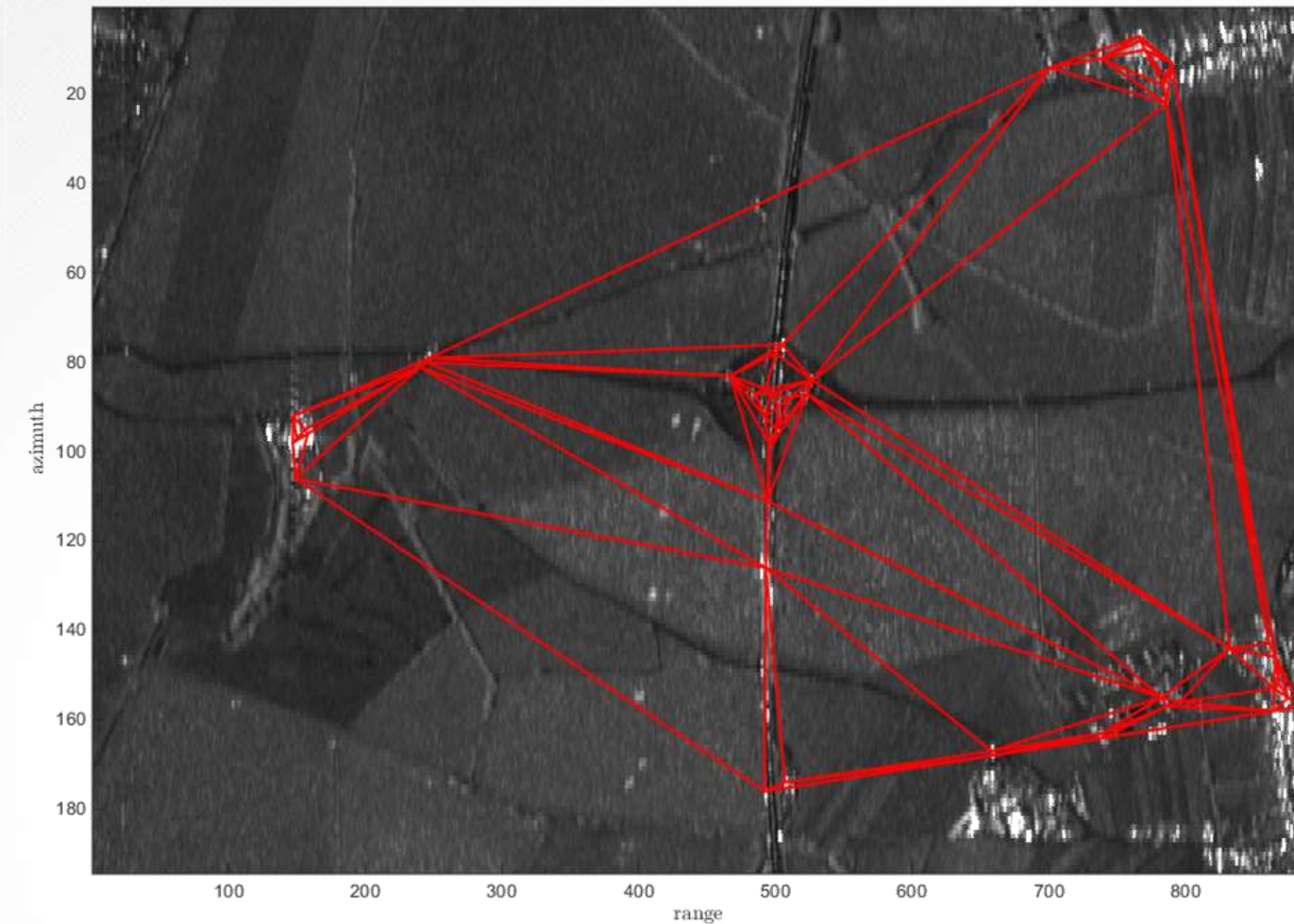
## Persistent Scatterer Candidates (PSC)



“opportunistic geodetic network”

# 1st order estimation network

## Phase double-differences

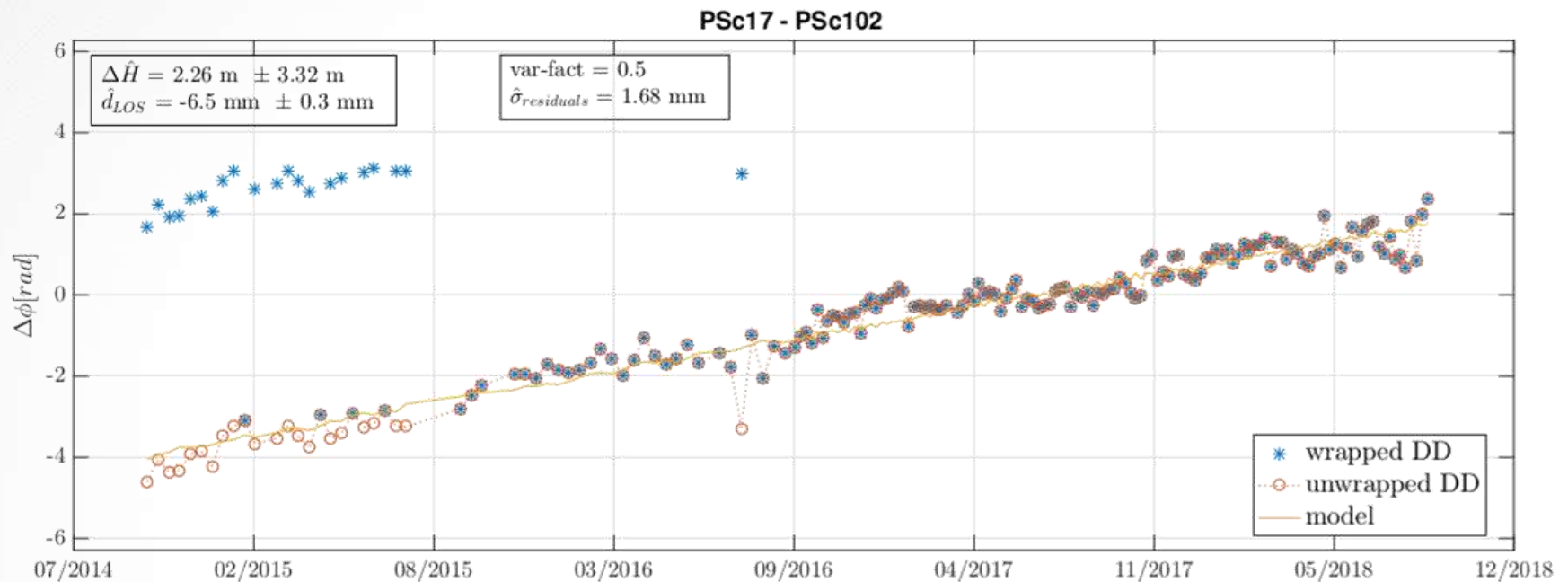


# Ambiguity resolution

Functional model for arc between PS „i“ a PS „j“:

$$\Delta\phi_{i,j} = \alpha \Delta h_{i,j} + \beta \Delta d_{i,j} + 2\pi \mathbf{a}_{i,j} \quad \leftarrow \text{ambiguity vector}$$

Ambiguity resolution examples (Integer least-squares, LAMBDA method):

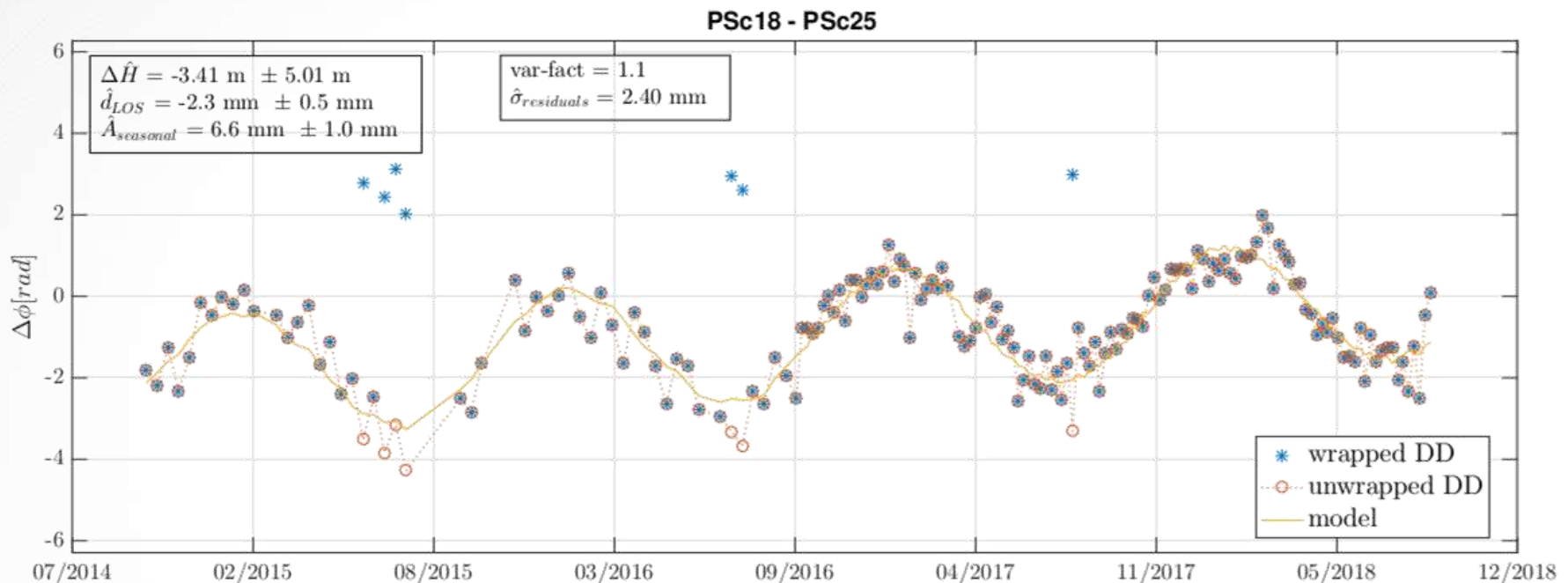


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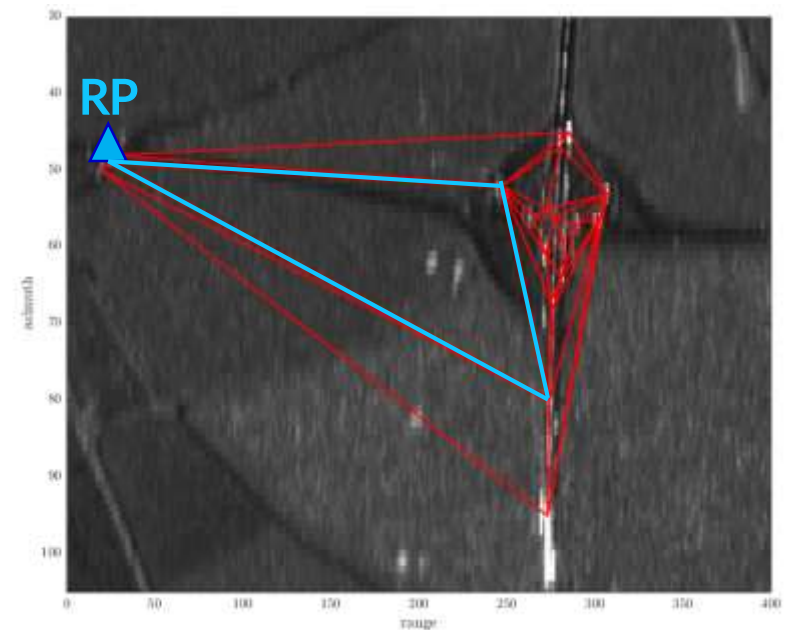
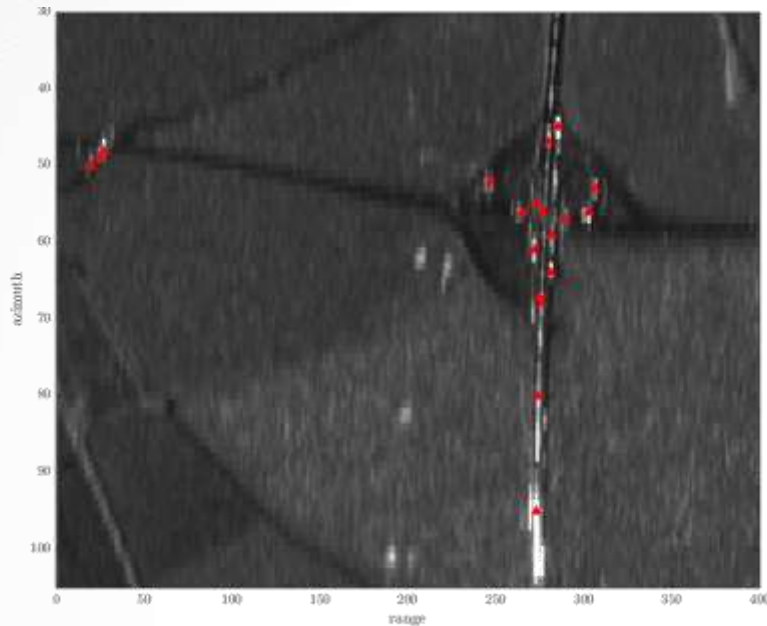
# Network integration

- all relative to one arbitrary reference point (RP)

I.) Variance component estimation (VCE) for new VC matrices

II.) Ambiguity testing in triangle closures

$$\Delta\phi_{i,j} + \Delta\phi_{j,k} + \Delta\phi_{k,i} = 0$$



# InSAR quality indicators

## I. A-posteriori variance factor (for PS „i“)

$$\hat{\sigma}_i^2 = \frac{(\boldsymbol{\phi}_i - \hat{\boldsymbol{\phi}}_{model}) \boldsymbol{\Sigma}_{\hat{\boldsymbol{\phi}}} (\boldsymbol{\phi}_i - \hat{\boldsymbol{\phi}}_{model})^T}{N - k}$$

Correctness of functional model & a-priori variances

## II. Ensemble coherence (for PS „i“)

$$|\hat{\gamma}_i| = \frac{1}{N} \sum_{k=1}^N \exp \left[ j(\phi_i - \hat{\phi}_{model})_k \right]$$

Correctness of functional model & degree of phase noise

## III. VC matrix of estimated parameters (for PS „i“)

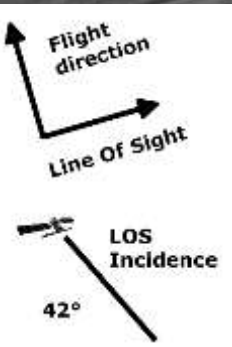
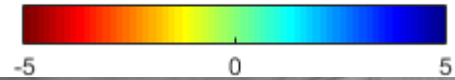
$$\boldsymbol{\Sigma}_{\hat{\mathbf{h}}_i, \hat{\mathbf{d}}_i}$$

Correctness of functional model & redundancy & ambiguity errors

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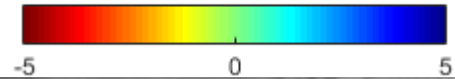
# PS network

LOS velocity [mm/year]

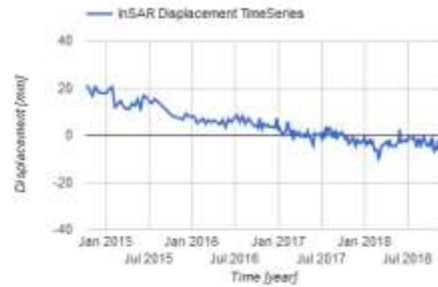


# PS network

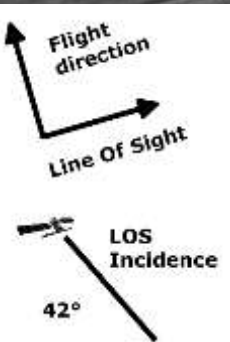
LOS velocity [mm/year]



[PS-id: 606] [Mean LOS velocity: -3.43 mm/year] [Coherence: 0.96]

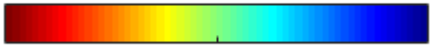


Directions: [To here](#) - [From here](#)



# PS network

LOS velocity [mm/year]



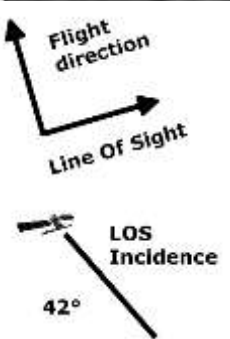
-5 0 5



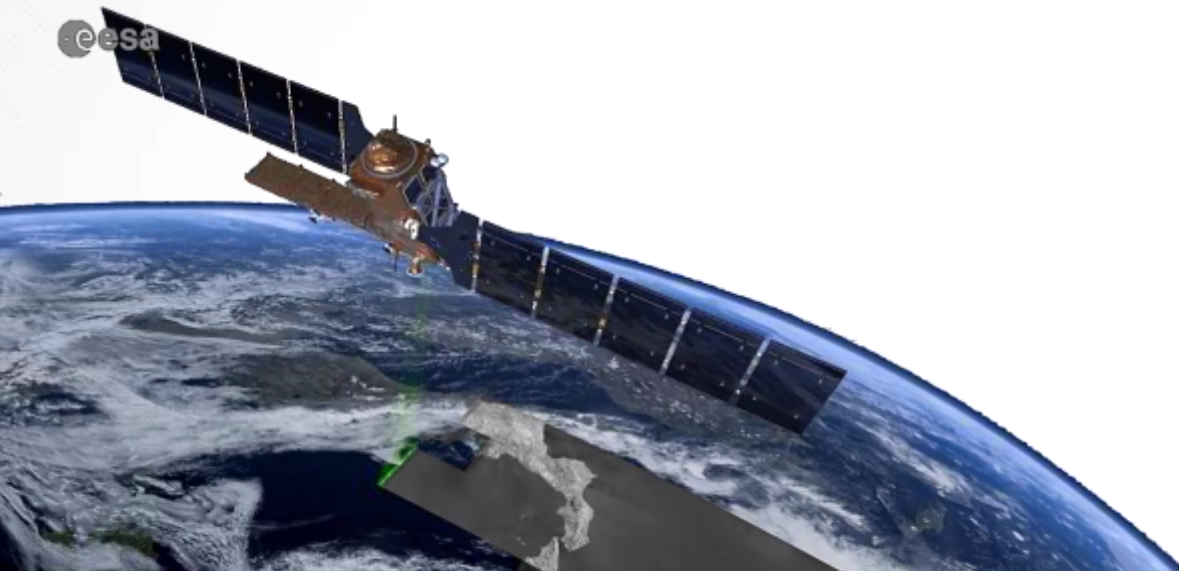
[PS-id: 595] [Mean LOS velocity: -3.70 mm/year] [Coherence: 0.91]



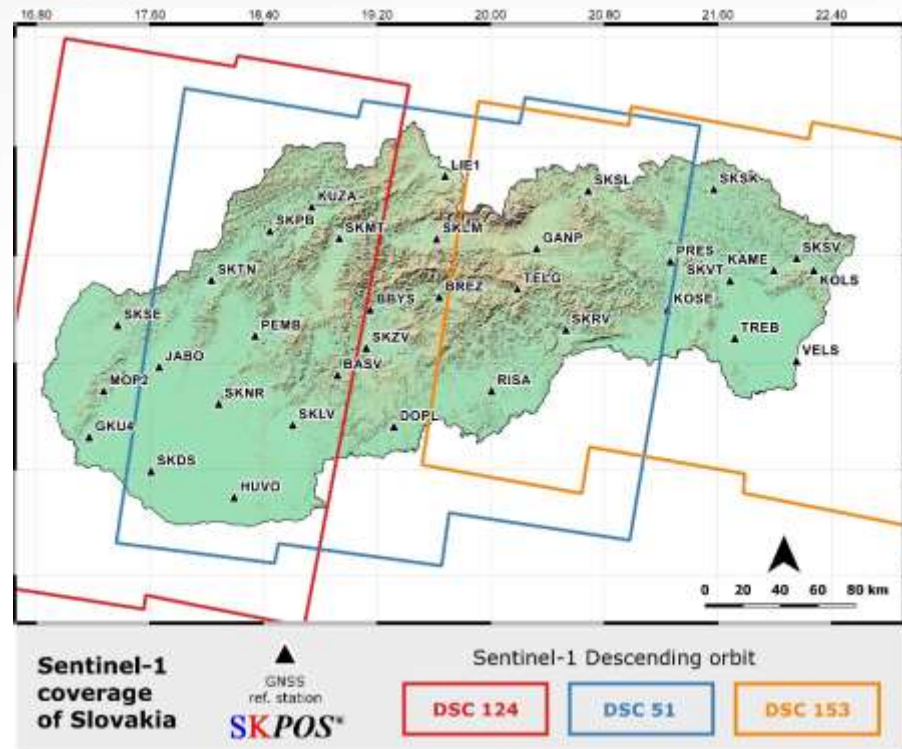
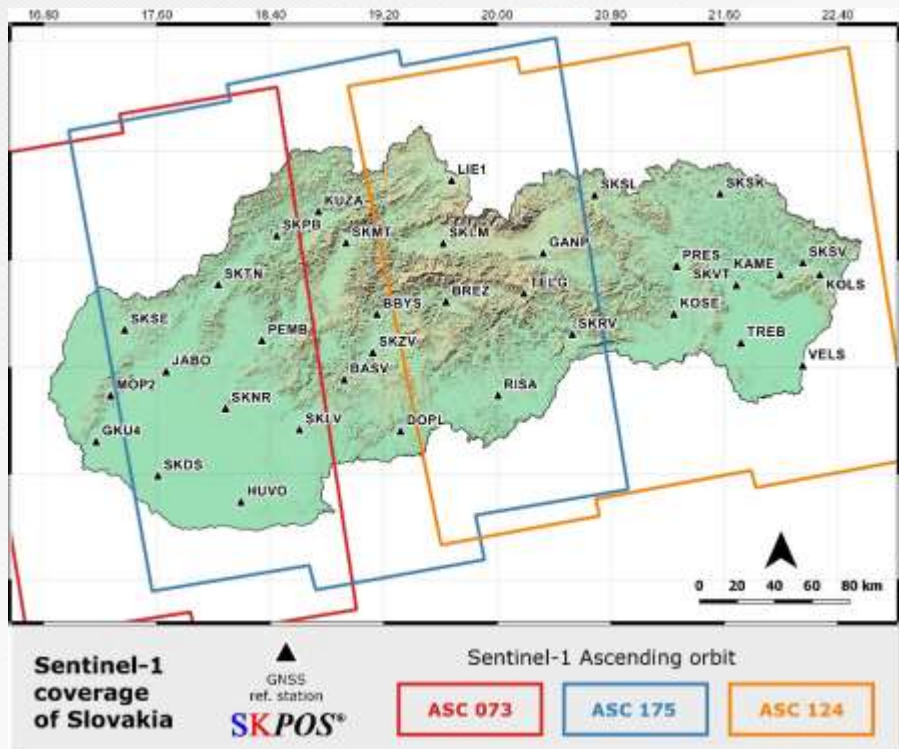
Directions: [To here](#) - [From here](#)



# Case studies from Slovakia



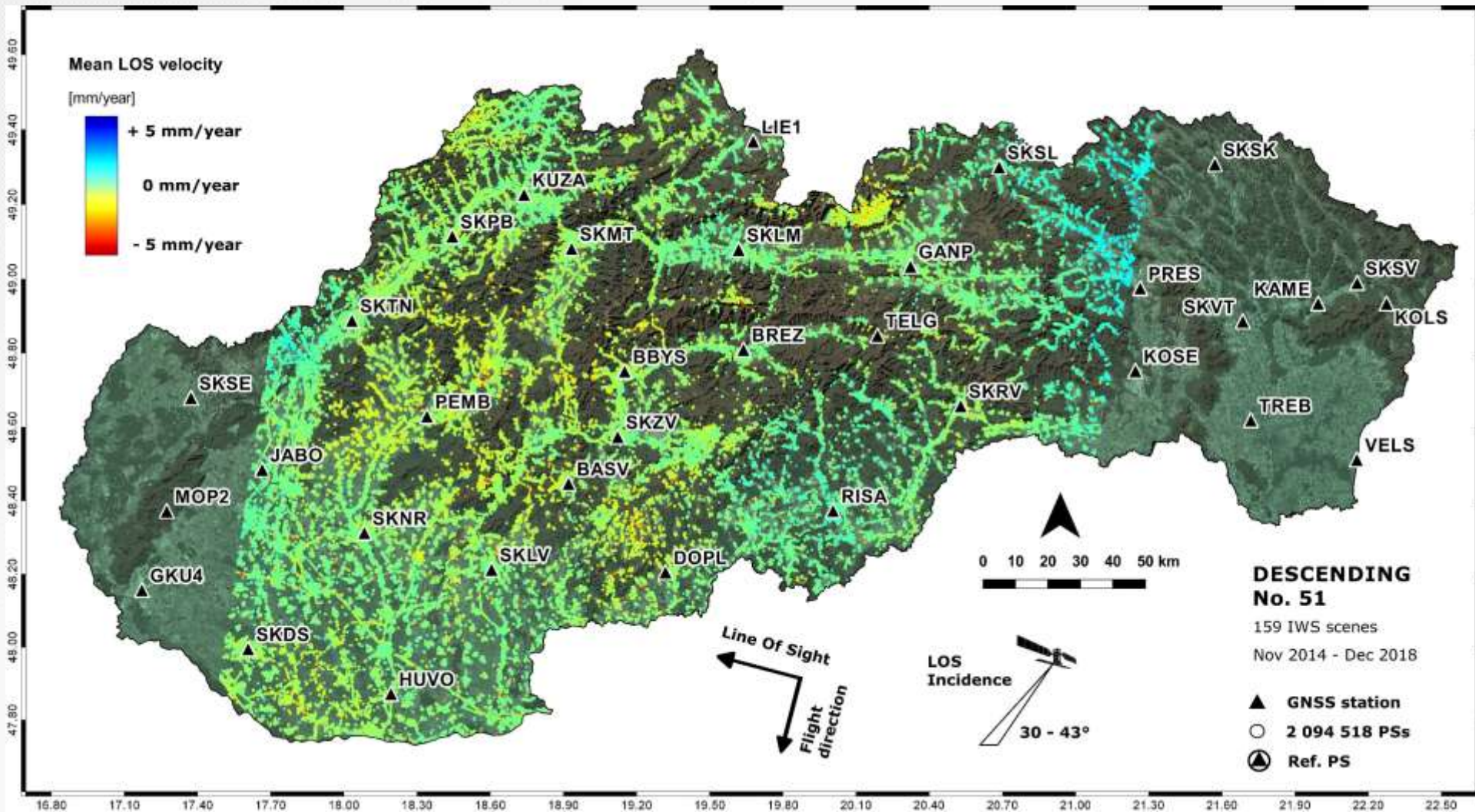
# Sentinel-1 coverage of Slovakia



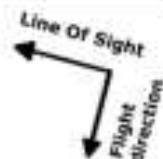
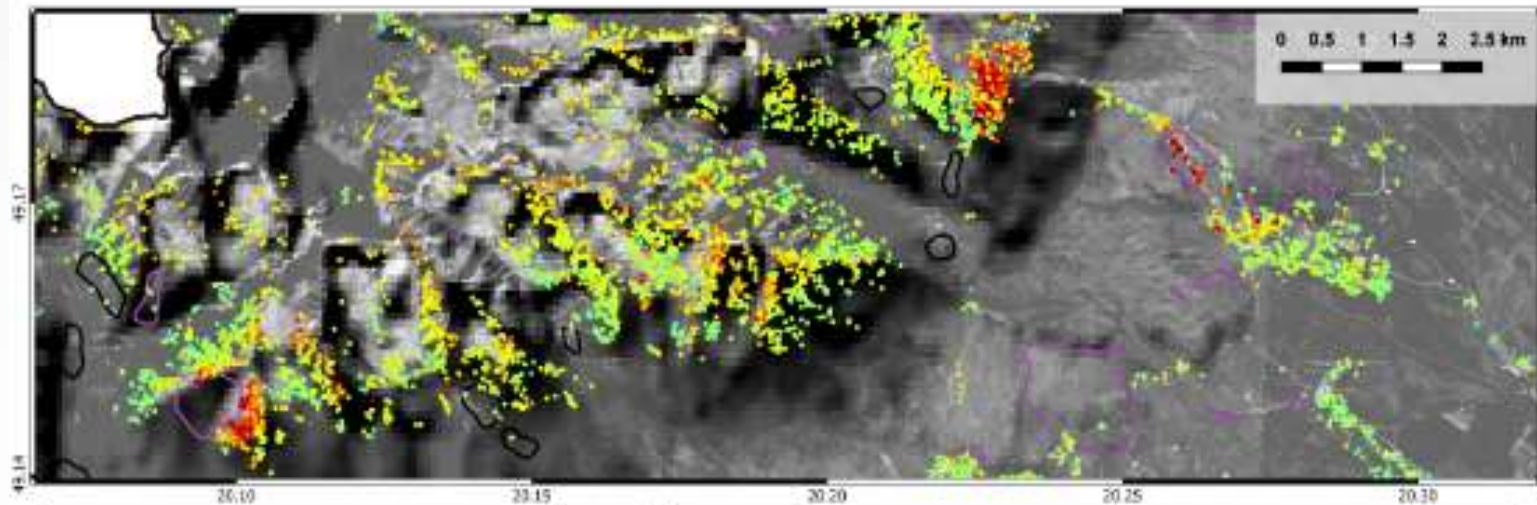
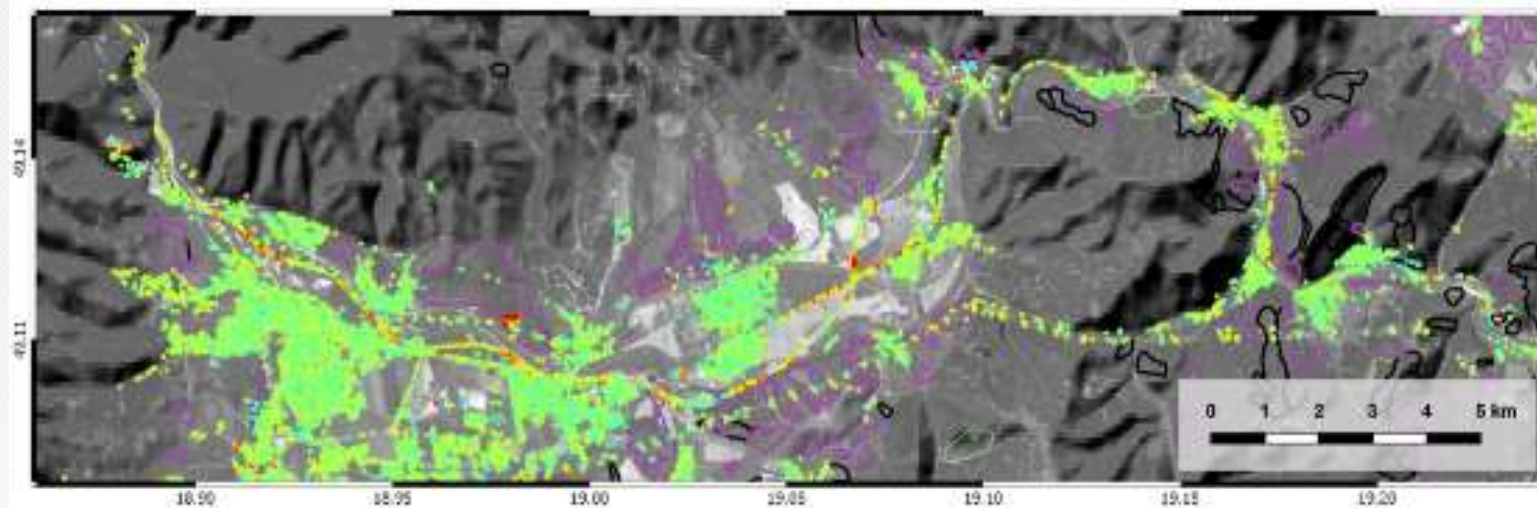
**Operational monitoring (under ESA PECS project):**

- **Landslides (Upper Nitra region)**
- **Undermining subsidence (Nováky and surroundings)**
- **Waterworks (Gabčíkovo, Čuňovo)**

# State-wide monitoring



# Regional monitoring capability

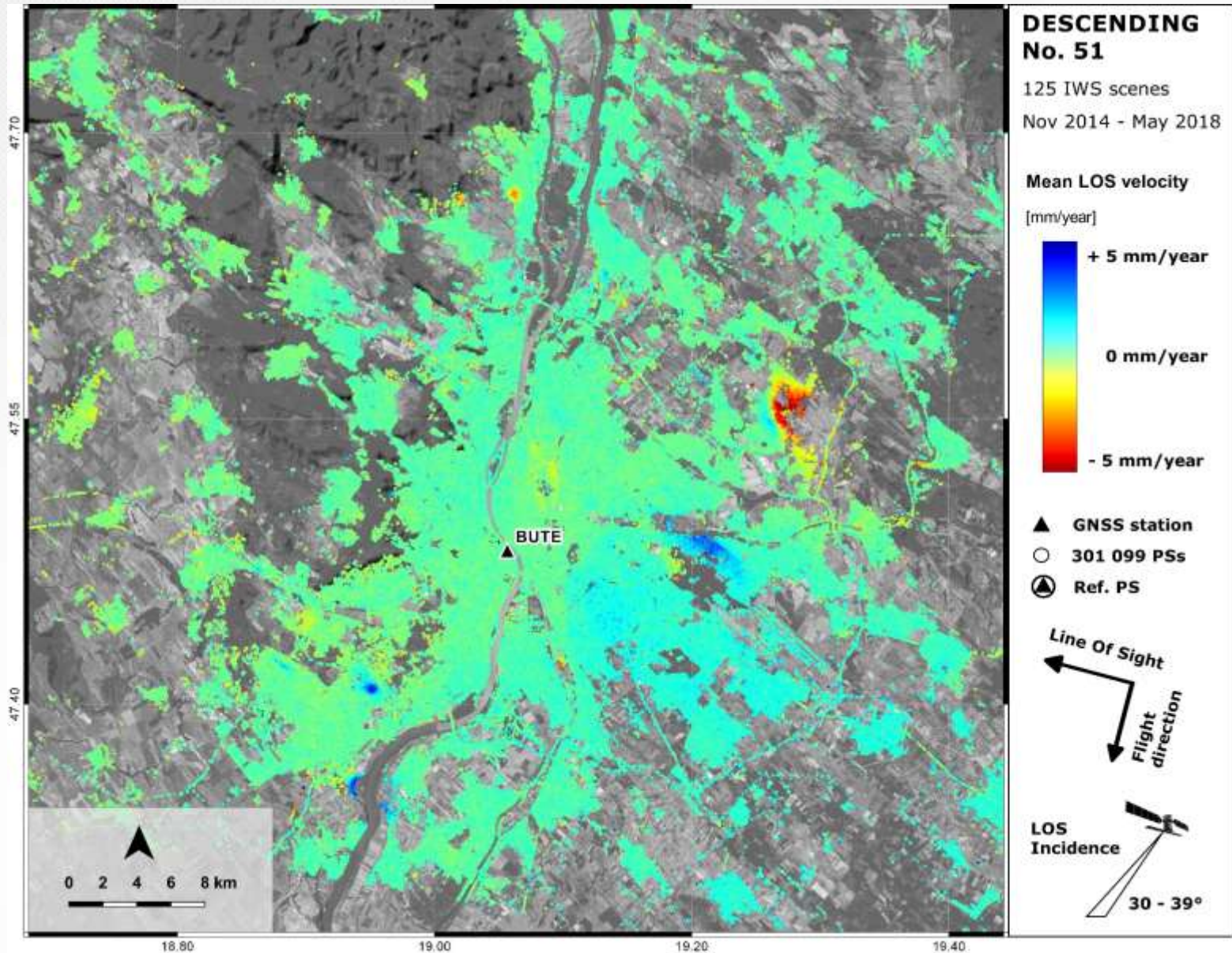


### Landslide activity

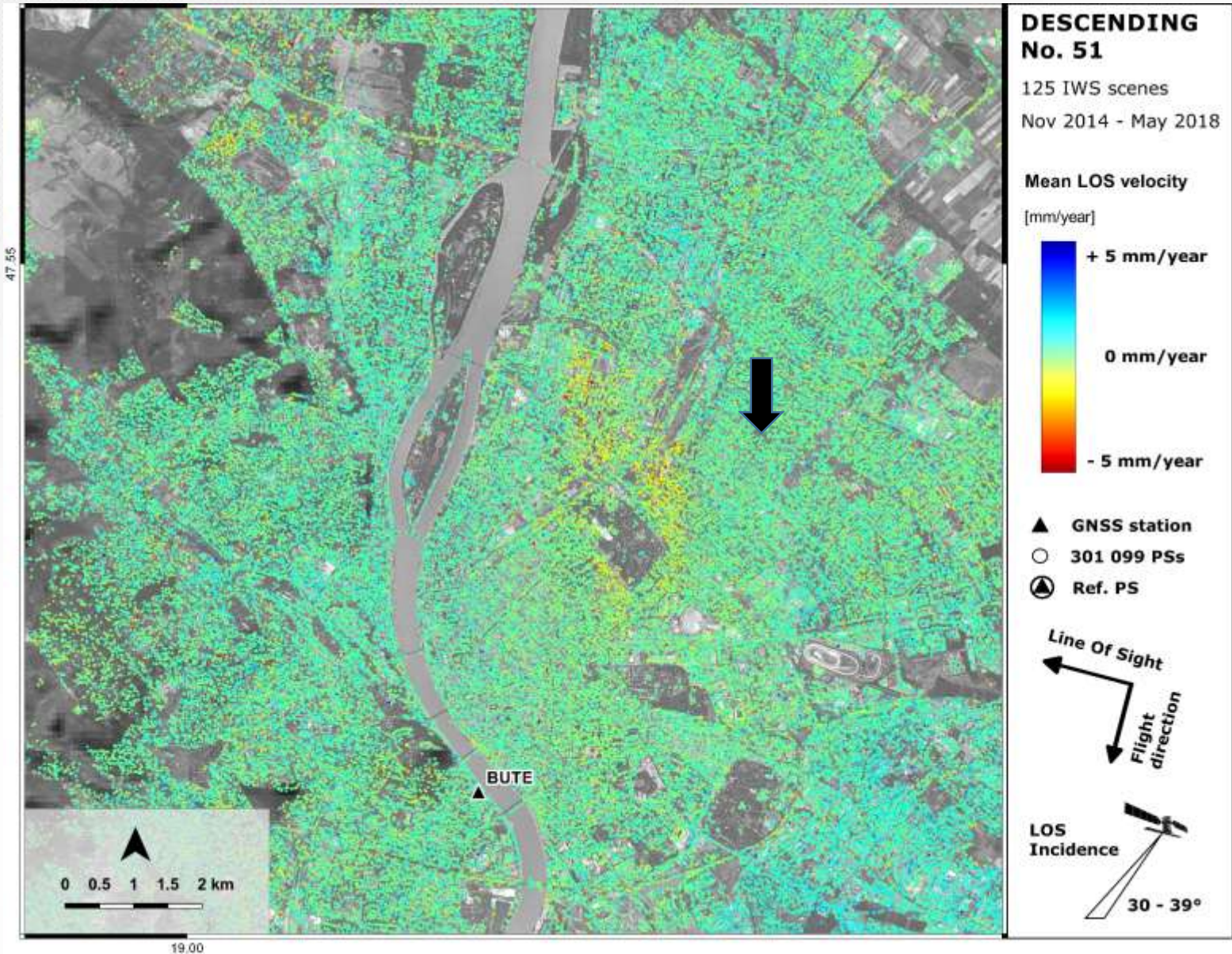
stabilized

potentially active

# Budapest as seen by Sentinel-1 InSAR



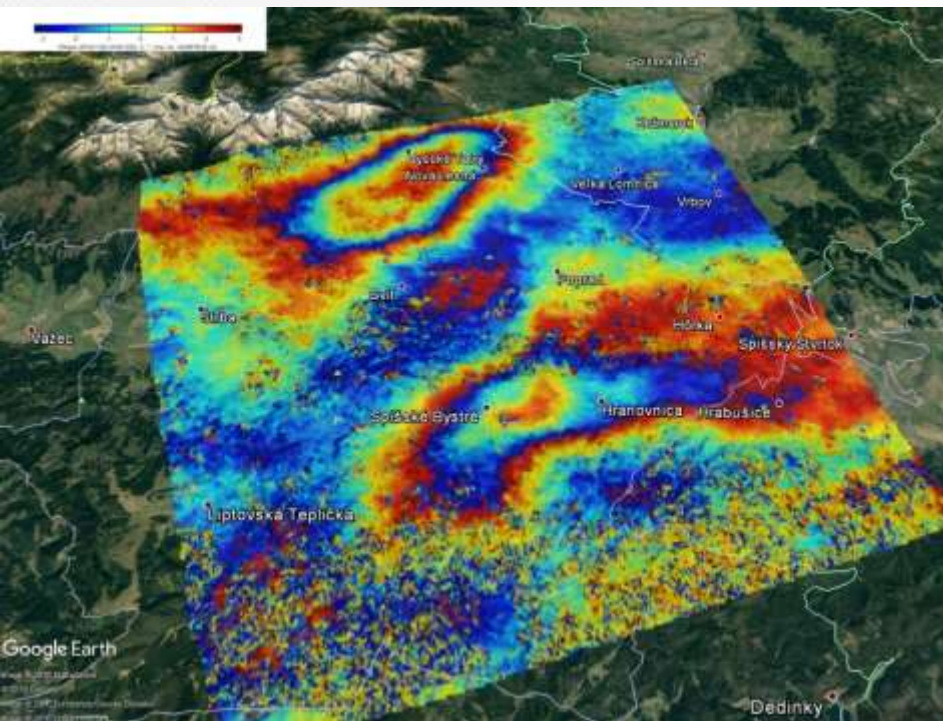
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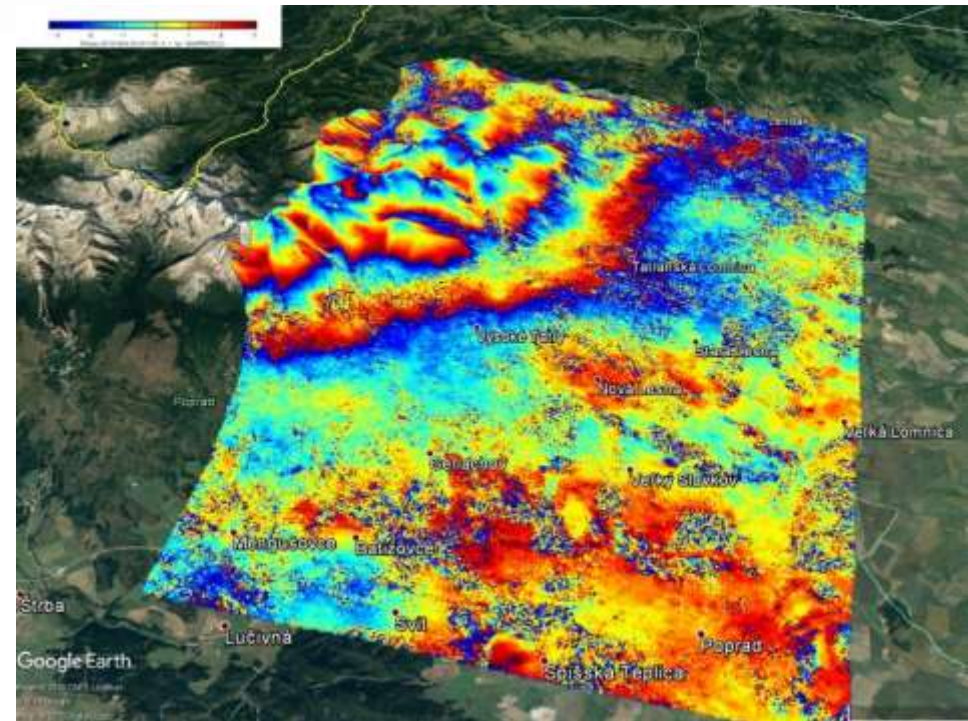
# Problem: Atmospheric Phase Screen (APS)

InSAR: differential atmospheric phase ( $t_0 - t_i$ ):

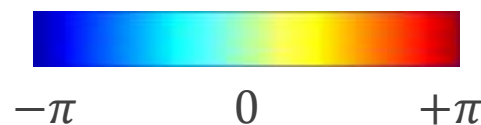
20170619 - 20170712



20170619 - 20170607



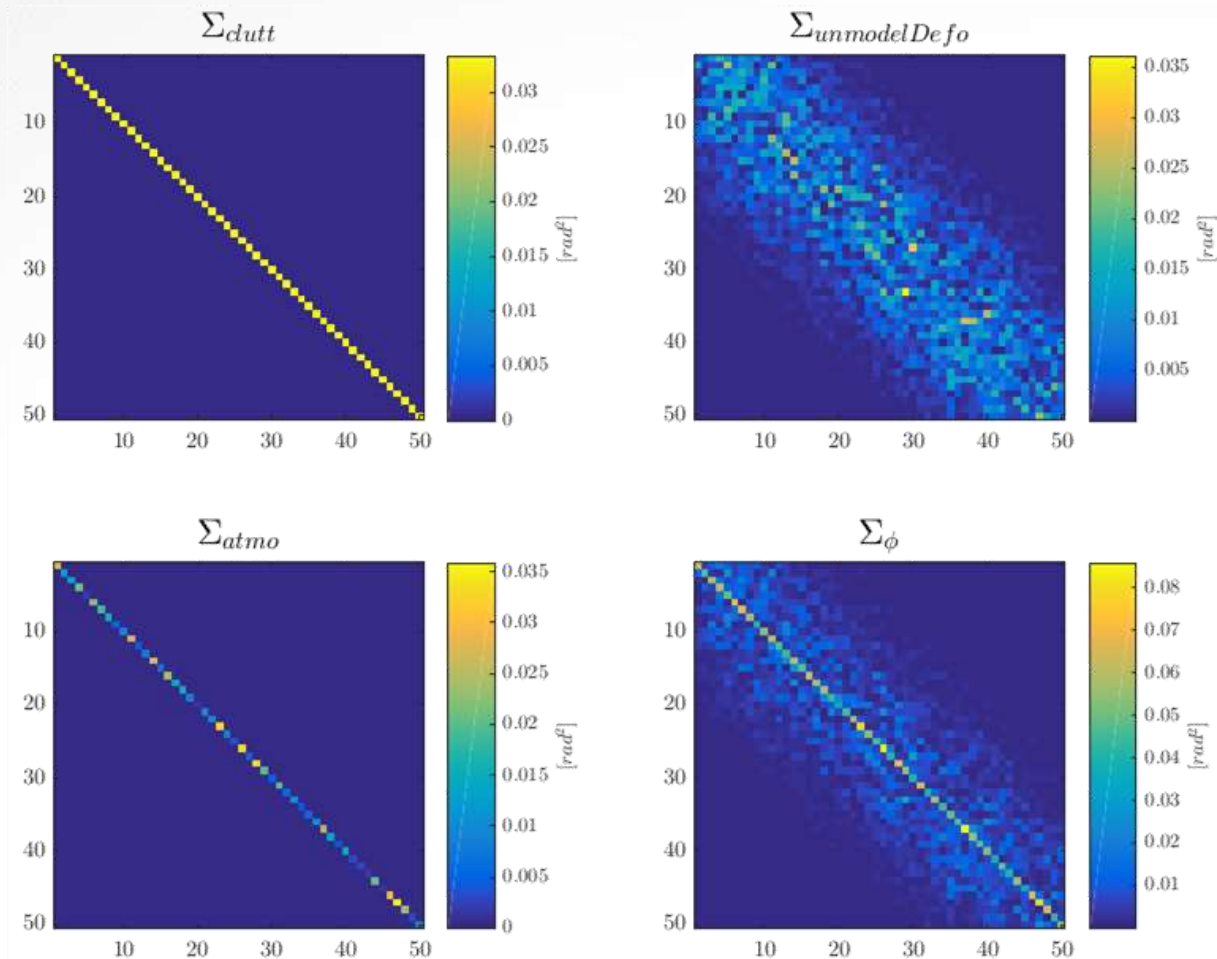
→ turbulence



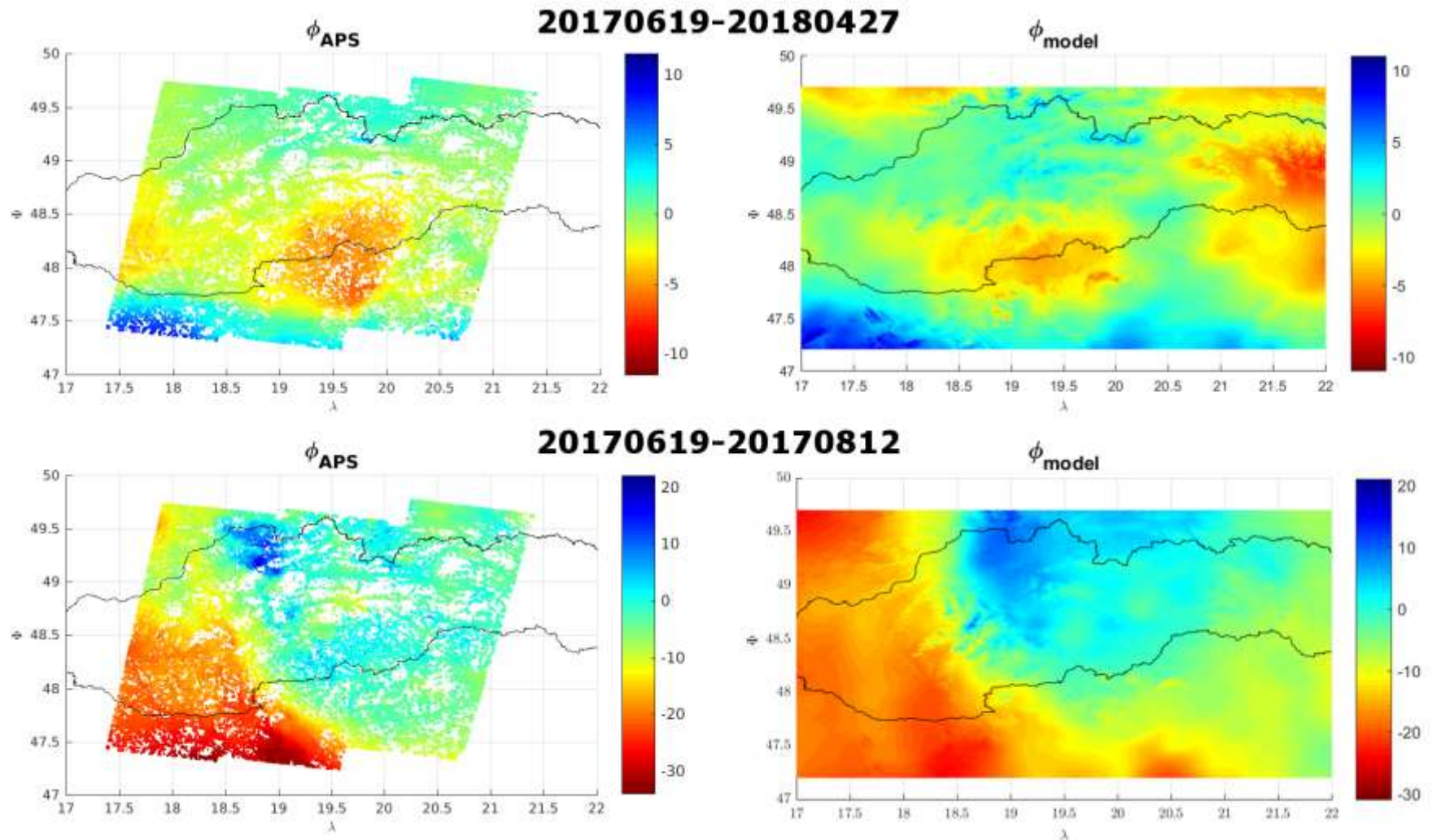
→ stratification

# APS estimation

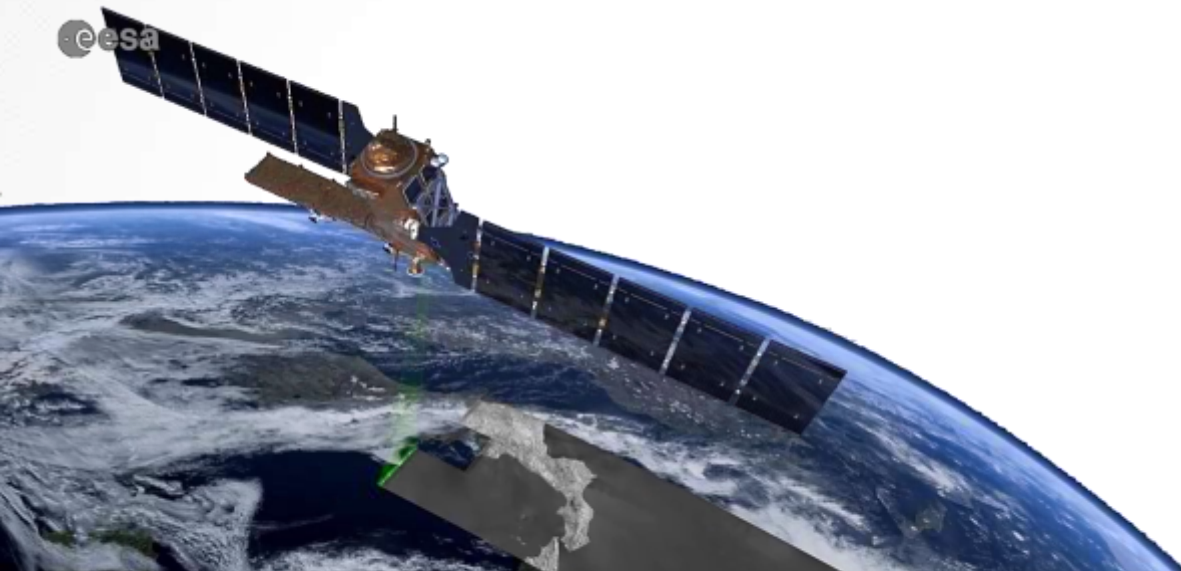
Assumption: APS is correlated in space, while decorrelated in time (of individual satellite acquisitions)



# APS – InSAR estimation / Numerical weather model



# InSAR limitations and challenges

The ESA logo is located in the bottom left corner of the image. It consists of the letters 'esa' in a lowercase, sans-serif font, with a small circular icon to its left containing a stylized satellite or probe.

# Limitations & challenges for InSAR geodesy

## 1. InSAR network = “free network/datum”

- 1 spatial (ref. point) + 1 temporal (ref. epoch) reference required
- **low geolocation accuracy** ~ several metres

## 2. Accuracy, although $< 1$ mm, significantly decreases over large arc lengths

- esp. due to **systematic effects**, e.g. **troposphere**

## 3. No standardized and generally accepted:

- **algorithm**, software;
- exchange format;
- **quality indicators**

# Limitations & challenges for InSAR geodesy

The challenge:

**„InSAR measurements in a geodetic reference frame“**

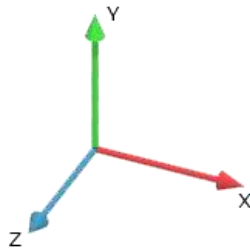
Transformation of InSAR “datum-free networks” into a standard coordinate reference system (frame) via deployment of artificial SAR reflectors (passive/active) and their **collocation with permanent GNSS measurements**

# “Conventional” geodetic techniques vs. InSAR

## Geodetic benchmark

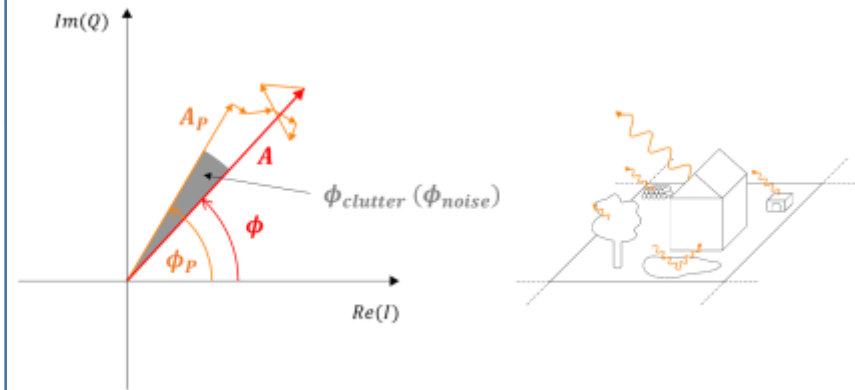


## 3D / 1D (vertical) vector

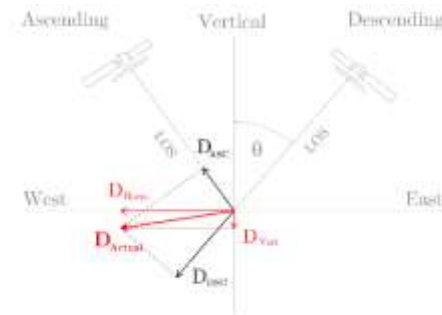


$$\{\Delta X, \Delta Y, \Delta Z\}; \{\Delta h\}$$

## Complex sum of scatterers per pixel



## Line-of-sight (LOS) vector



$$\{\Delta LOS\}_{ASC}; \{\Delta LOS\}_{DSC}$$

# InSAR & GNSS collocation

Collocation of InSAR measurements with other technique in:

a.) parameter space

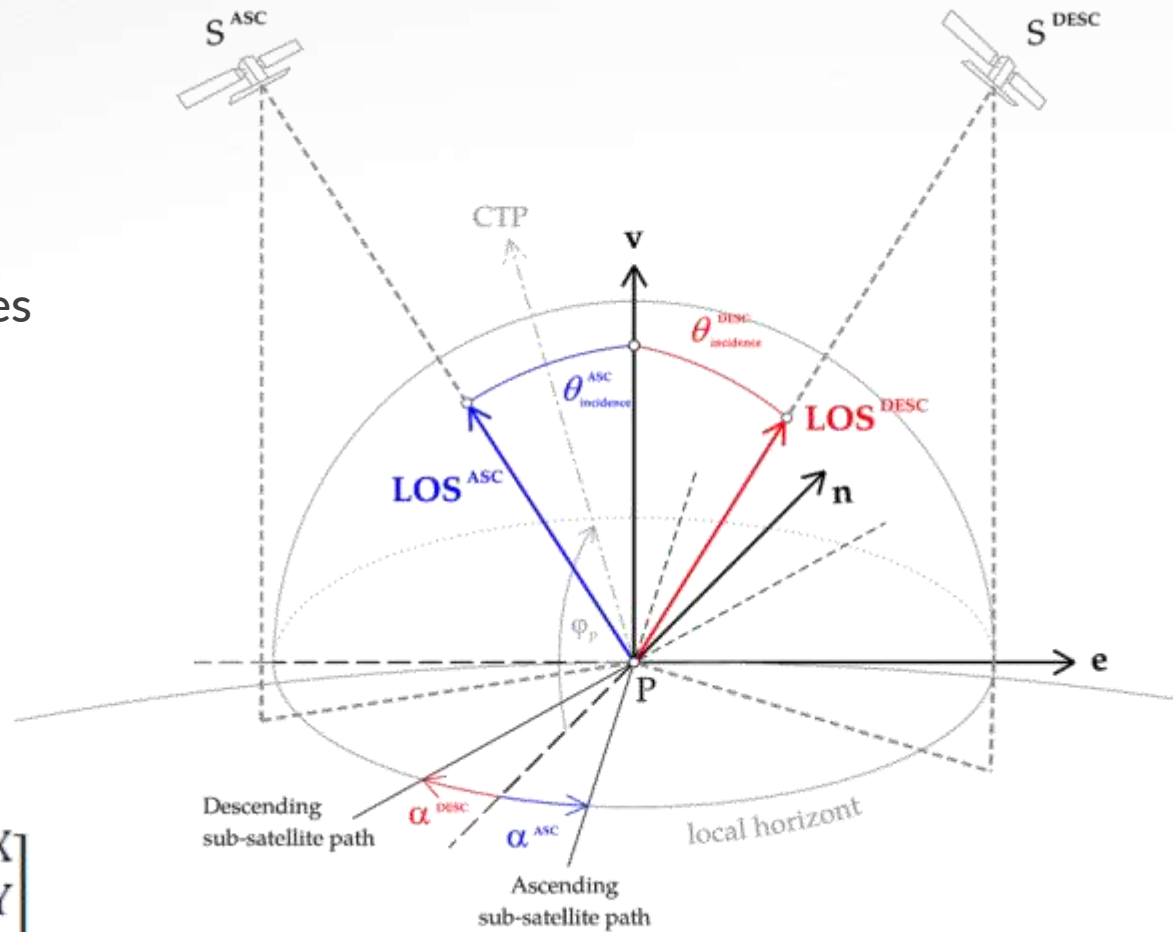
$$\Delta_p \Delta_t u = [u(p_1, t_1) - u(p_1, t_0)] - [u(p_0, t_1) - u(p_0, t_0)]$$

b.) observation space



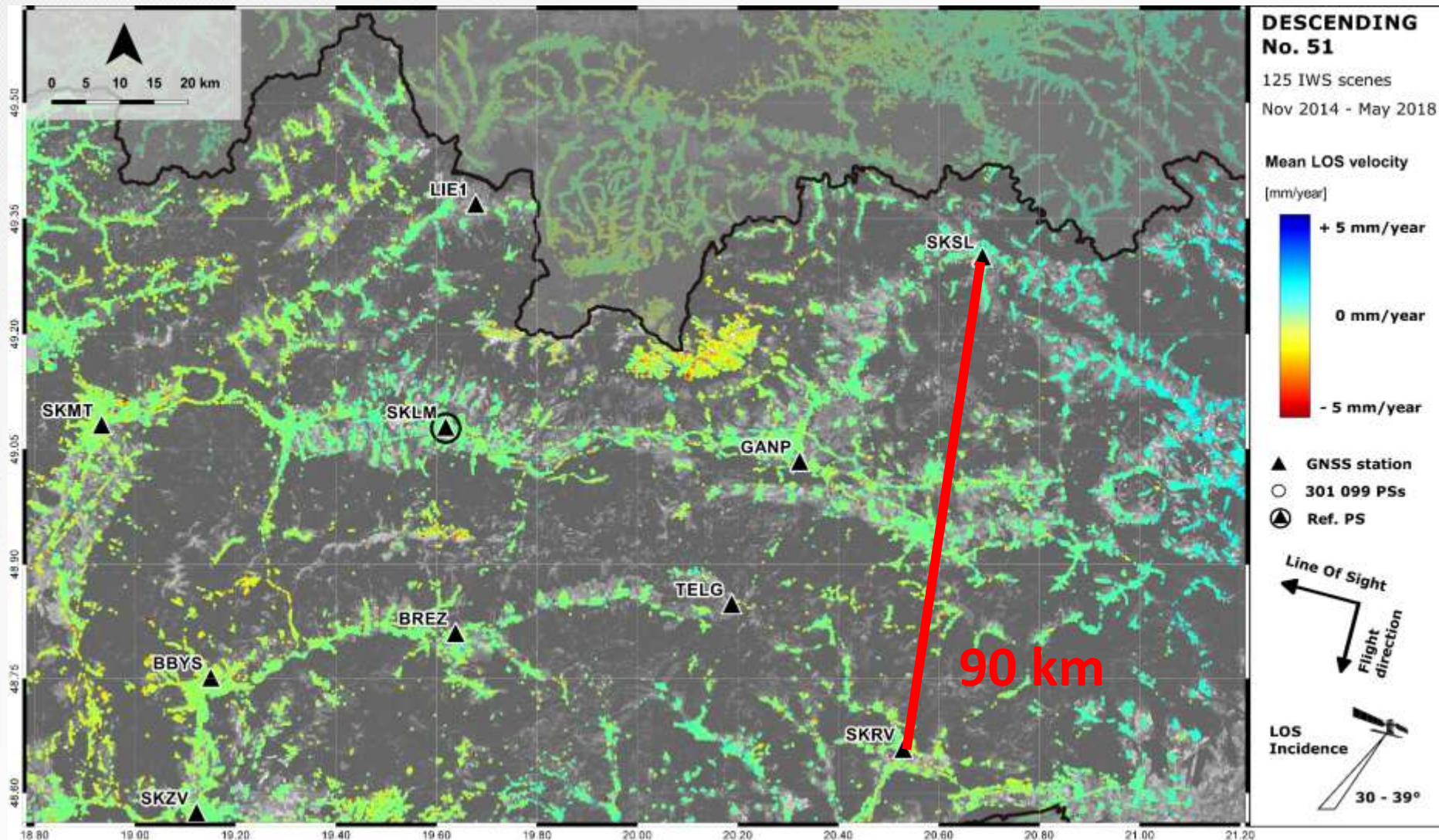
**GNSS baselines:**

0. reference epoch
1. cartesian double-differences (weekly solutions)
2. topocentric differences
3. LOS differences



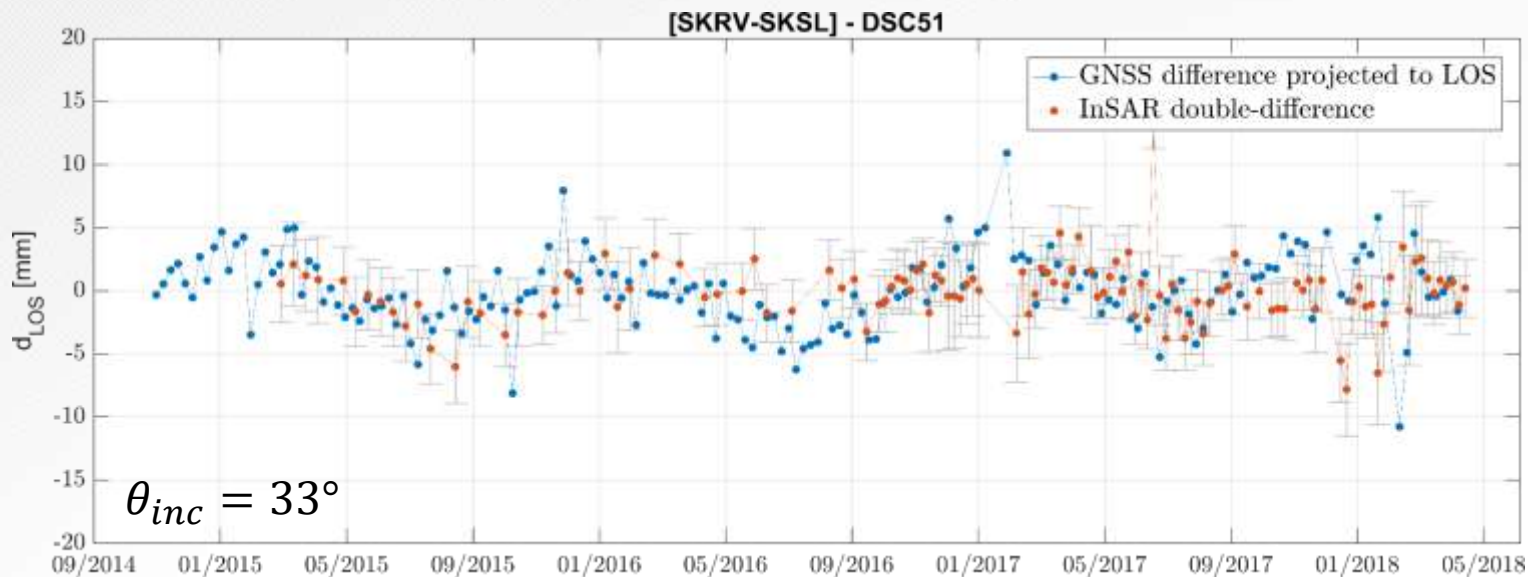
$$\Delta d_{LOS,GNSS} = R(\theta, \alpha) R(\varphi, \lambda) \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}_{GNSS}$$

# InSAR & GNSS

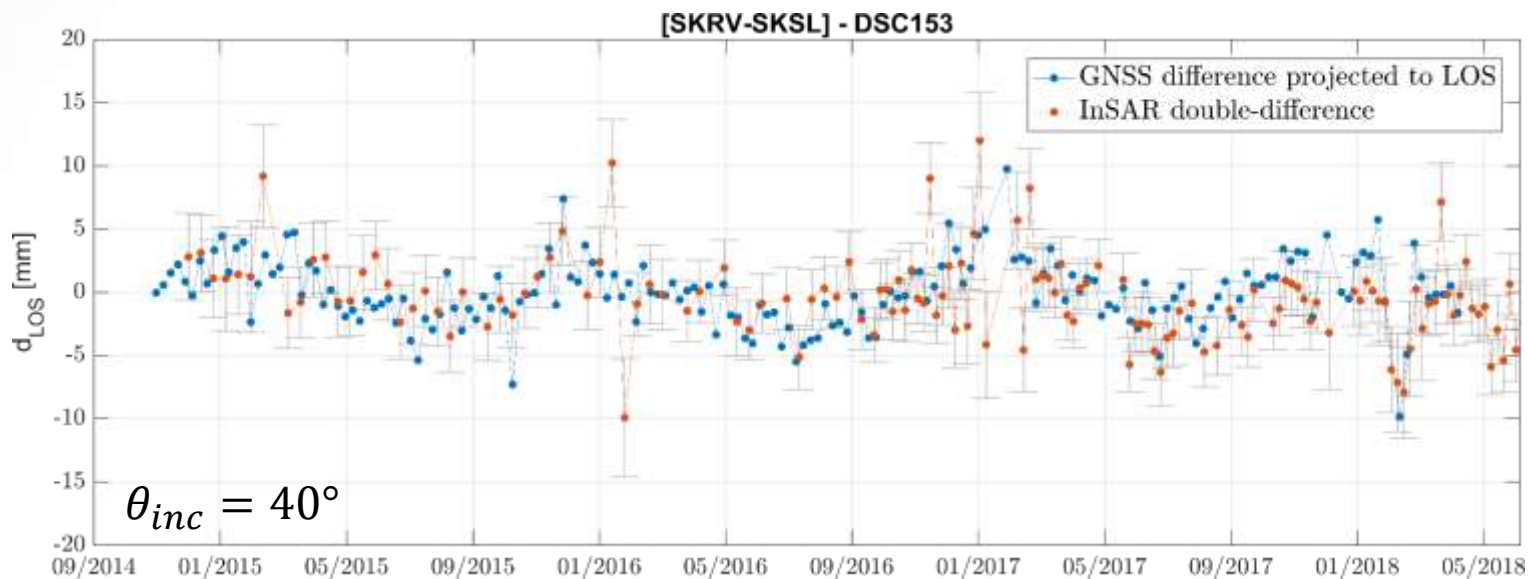


# InSAR & GNSS

Descending 51



Descending 153



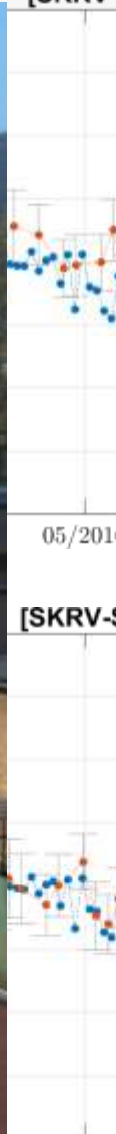
# InSAR & GNSS

[SKRV-SKSL1] - DSC51

**GNSS antenna phase centre**



**SAR scatterer phase centre**



09/2014 01/2015 05/2015 09/2015 01/2016 05/2016 09/2016 01/2017 05/2017 09/2017 01/2018 05/2018

# InSAR & GNSS collocation

Collocation of InSAR measurements with other technique in:

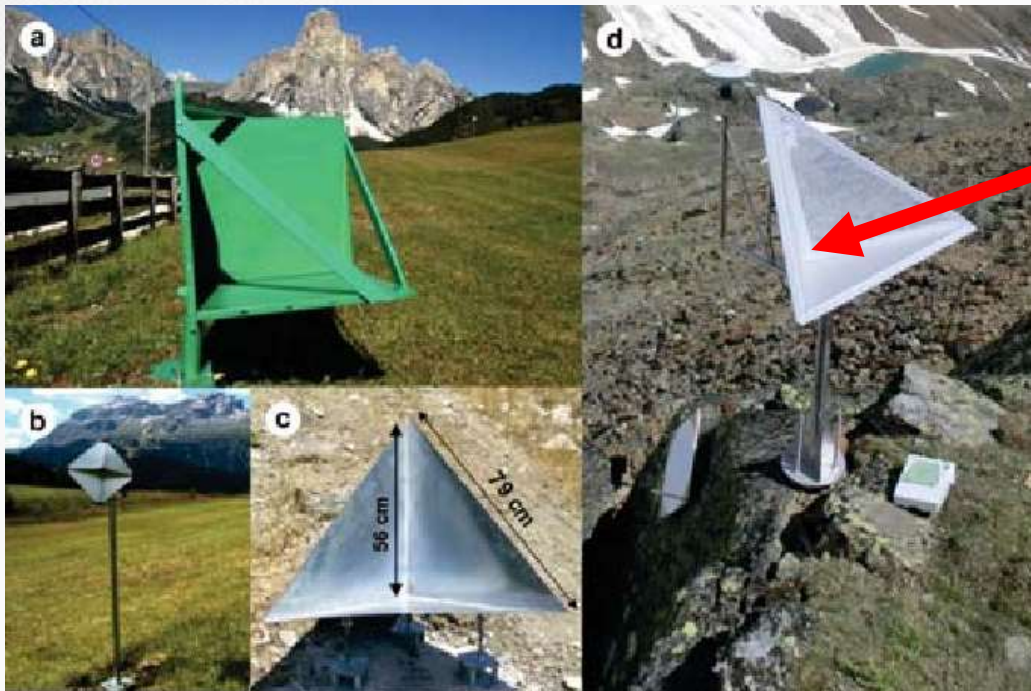
a.) parameter space 
$$\Delta_p \Delta_t u = [u(p_1, t_1) - u(p_1, t_0)] - [u(p_0, t_1) - u(p_0, t_0)]$$

b.) observation space



# Artificial SAR reflectors

## A.) Corner reflectors (Passive artificial radar point scatterer)



Exactly known phase centre! (apex)



# InSAR & GNSS collocation

## B.) Radar transponders (Active artificial radar point scatterer)



# First InSAR & GNSS collocation site in Slovakia



Date installed:

**31.7.2019**

**Hvezdáreň Partizánske**

**PEMB (PEM2)**



# First InSAR & GNSS collocation site in Slovakia



PEM2 (Double back-flipped square trihedral) – SCR performance

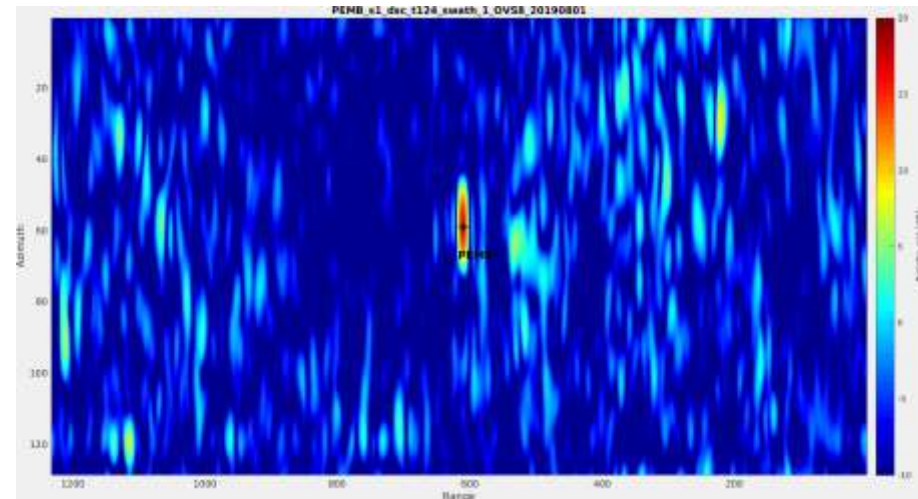
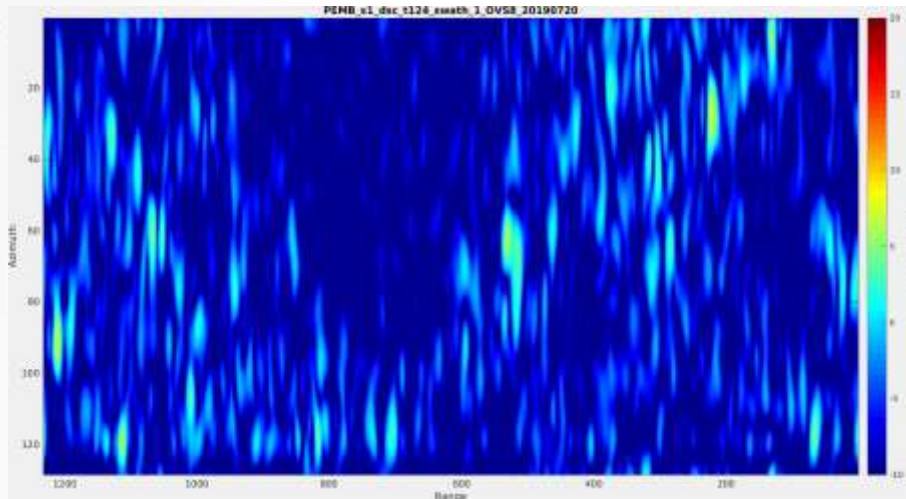
Sentinel-1 track	$\widehat{RCS}$ [ $dBm^2$ ]	$\widehat{RCS}_{clutter,before}$ [ $dBm^2$ ]	$\widehat{RCS}_{clutter,after}$ [ $dBm^2$ ]	$\widehat{SCR}$ [dB]	$\widehat{\sigma}_\psi$ [mm]
ASC073	29.26	9.1	11.9	17.3	<b>0.9</b>
ASC175	29.96	9.3	14.7	15.3	<b>1.1</b>
DSC051	31.3	5.9	11.7	19.6	<b>0.7</b>
DSC124	31.9	7.0	13.9	17.9	<b>0.8</b>

# What to consider when deploying CRs?

## Suitability of ref. station for CR installation:

### Evaluation of expected Signal-to-Clutter (SCR) ratio:

- I. Simulation of reflector's RCS,
- II. Estimation of the clutter power (RCS) at deployment site.



# Thank you. Questions?

