DRUŽICOVÉ METODY V GEODÉZII A KATASTRU 2020

InSAR geodézia súčasné možnosti a výzvy

InSAR geodesy current capabilities and challenges

Richard Czikhardt, Juraj Papčo, Matúš Bakoň, Branislav Droščák

Dept. of Theoretical Geodesy, Faculty of Civil Engineering, STU in Bratislava, Slovakia

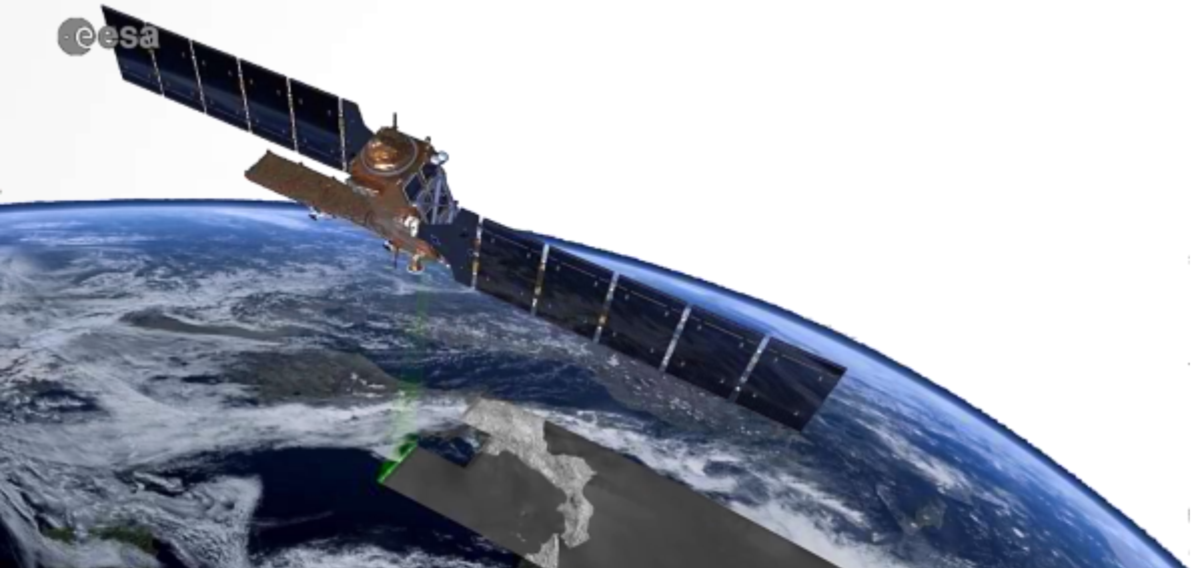
insar.sk s.r.o., Presov, Slovak Republic

Geodetic and Cartographic Institute (GKU), Bratislava, Slovakia

InSAR

InSAR (**I**nterferometric **S**ynthetic **A**perture **R**adar)

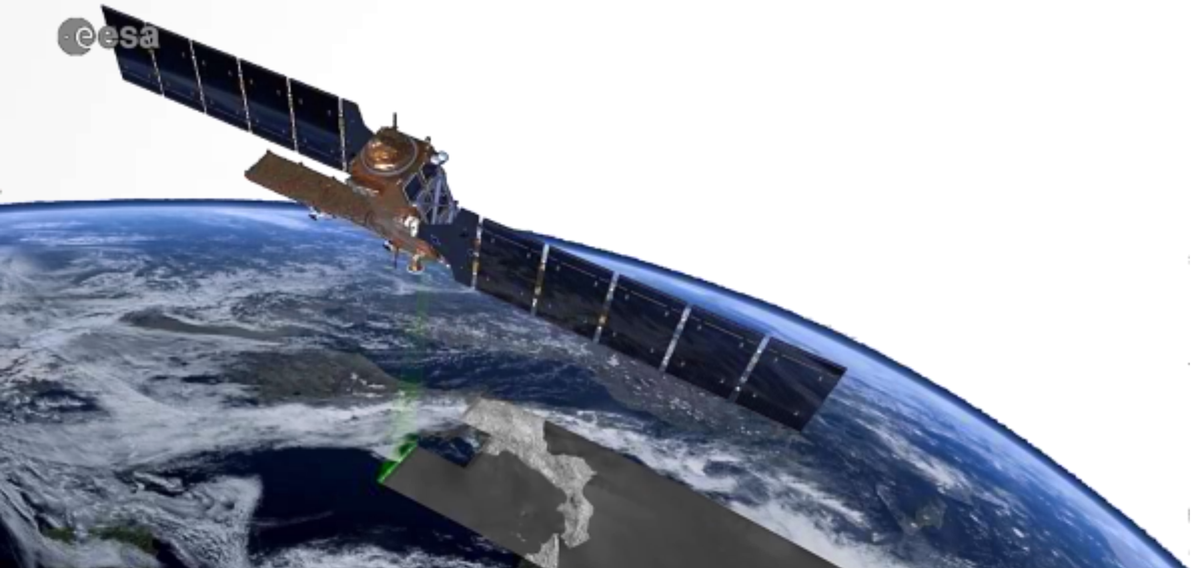
(In)SAR are measurements, not „nice images“



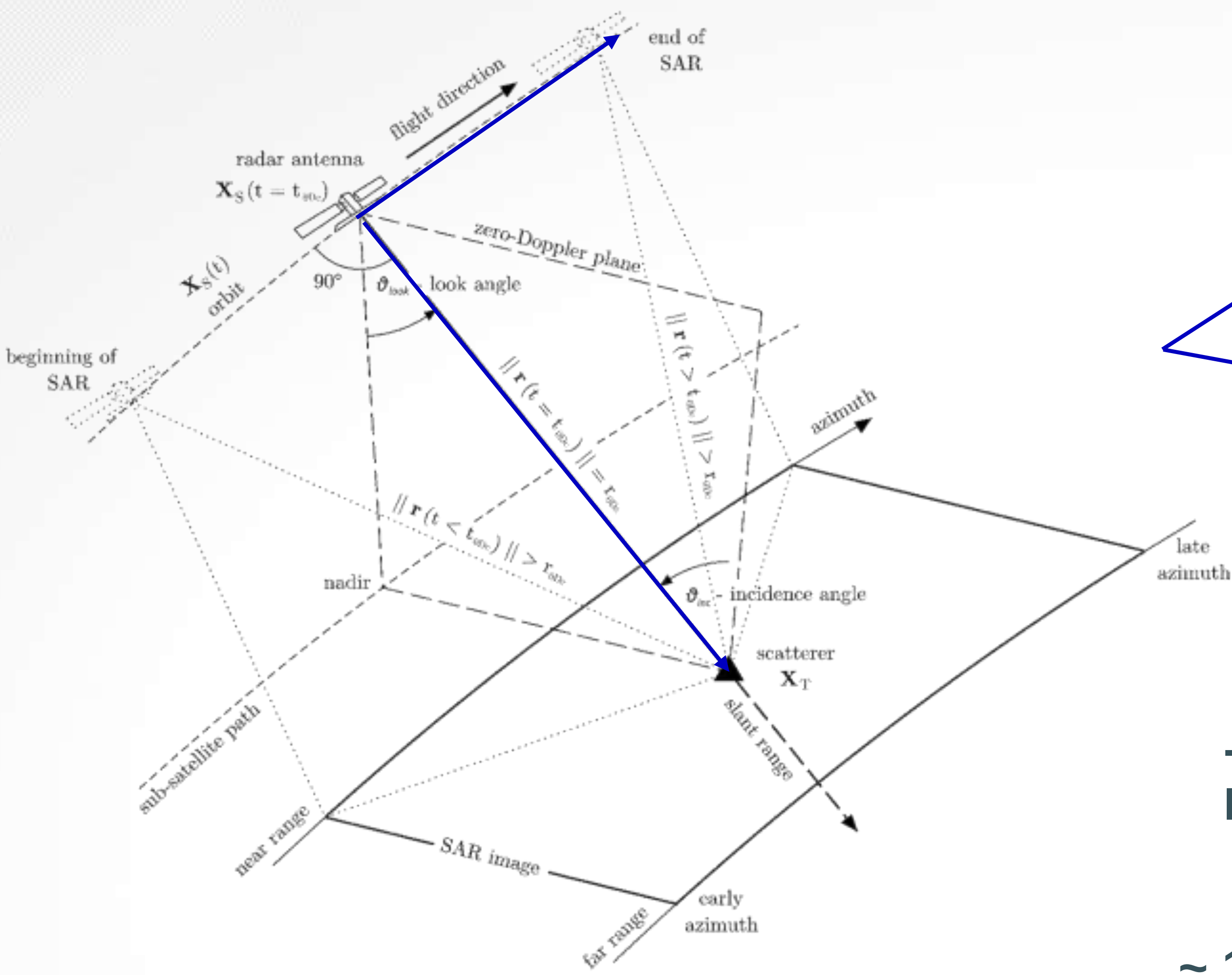
InSAR (**I**nterferometric **S**ynthetic **A**perture **R**adar)

- 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?

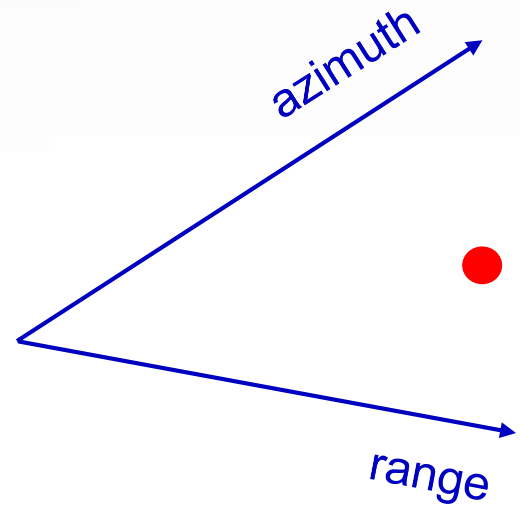
InSAR geodesy: theory



SAR point positioning



Radar coordinates:



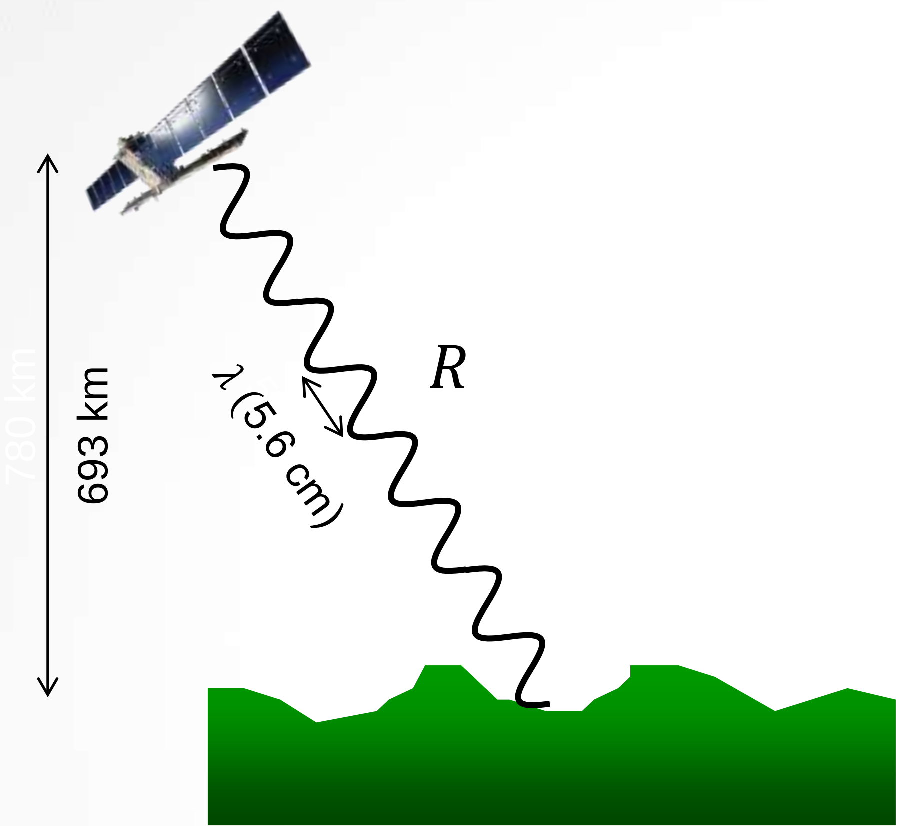
- transformed to ECEF coordinates

~ 1-10 m precision

SAR phase measurement

Complex phasor measurement per pixel:

$$y = \boldsymbol{A}\,\exp(i\boldsymbol{\psi})$$



Phase

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

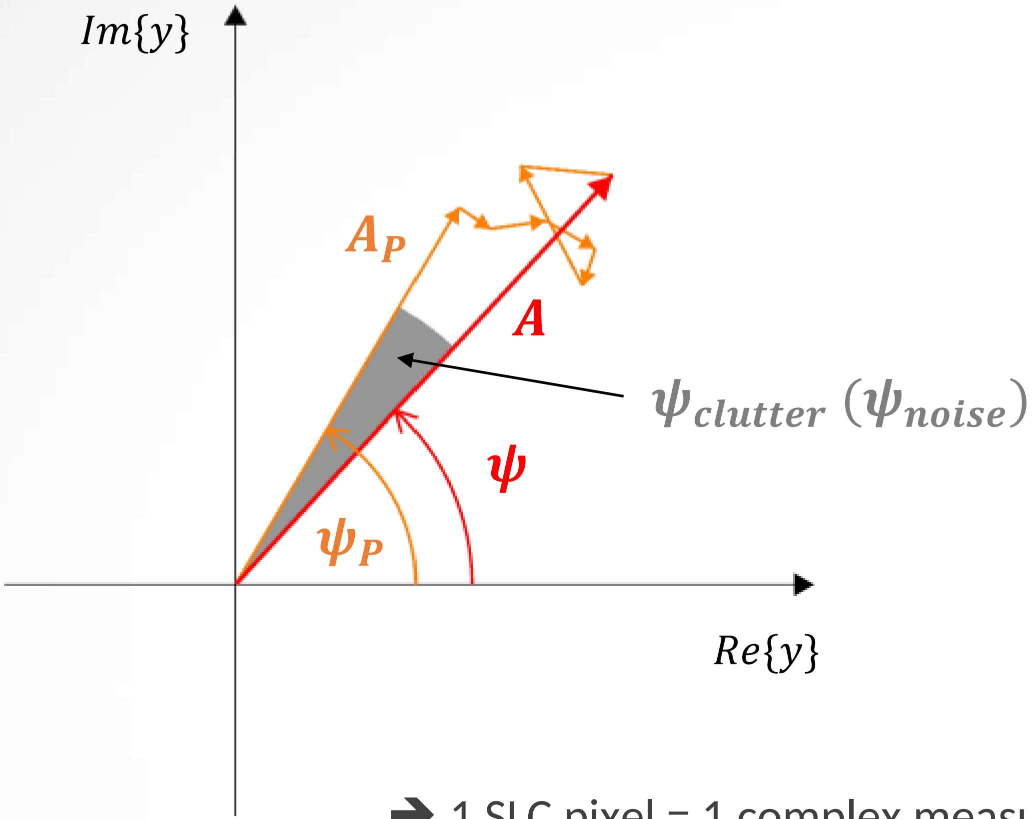
Round trip ~ 30 million wavelengths

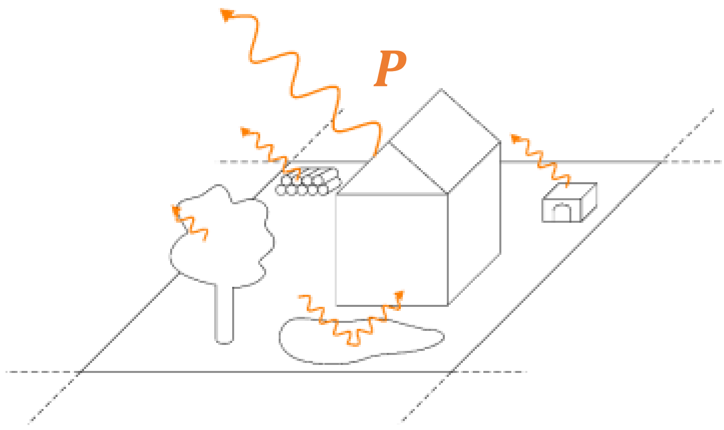
BUT we don’t know the exact number

(phase ambiguity)

Coherent scattering

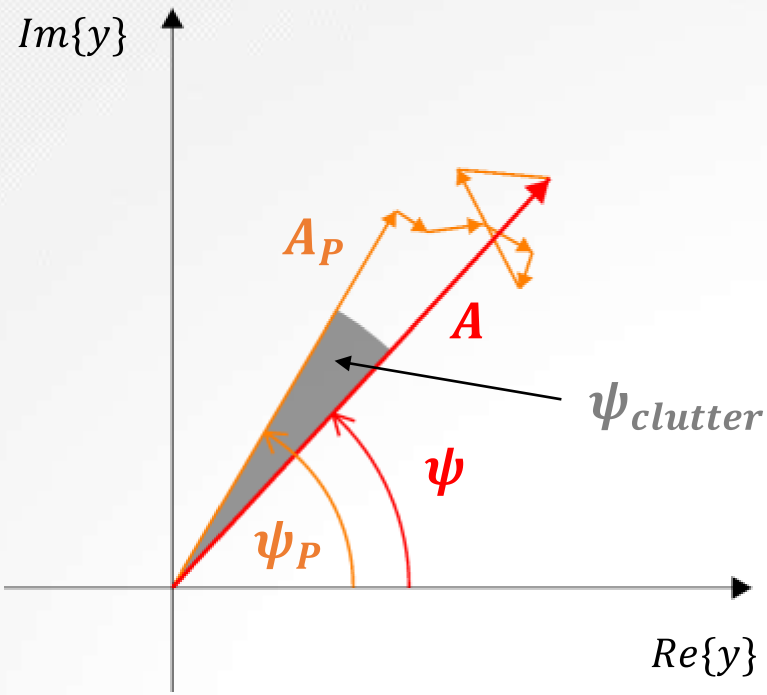
Complex phasor: $y = A \exp(i\psi)$ **per 1 pixel:**

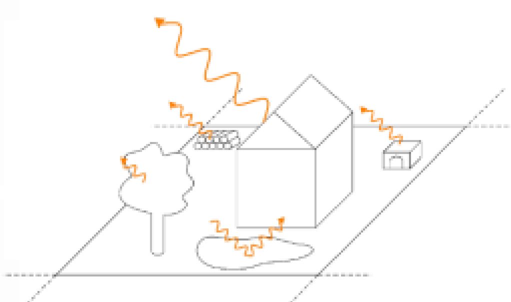




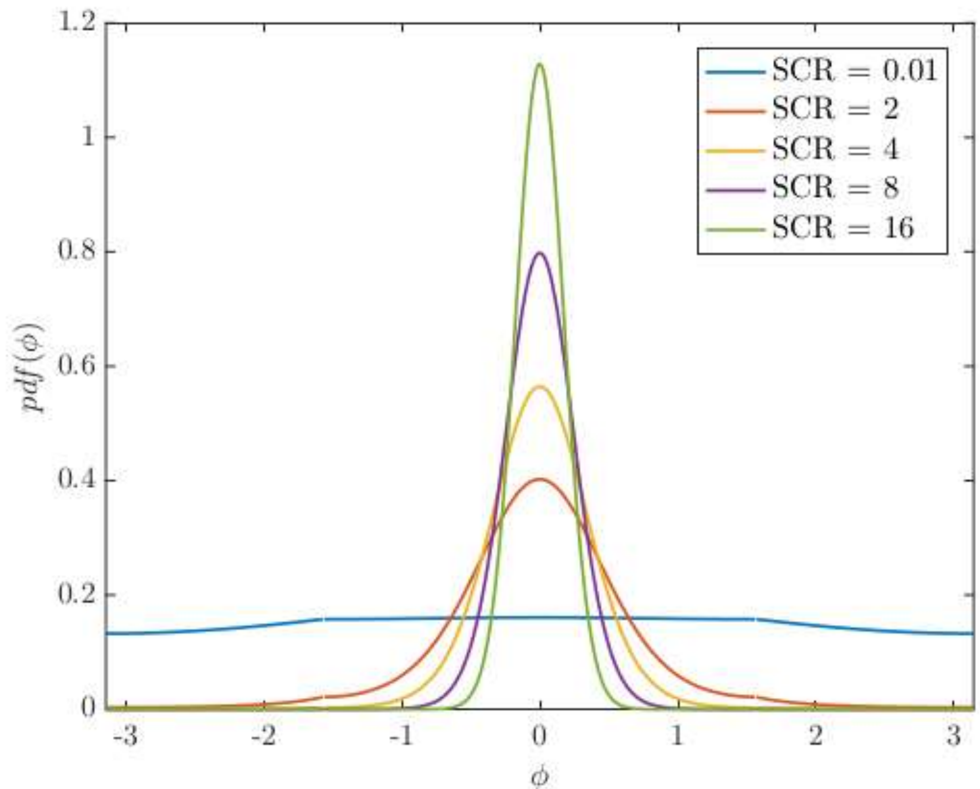
➔ 1 SLC pixel = 1 complex measurement

Signal-to-clutter ratio (SCR)



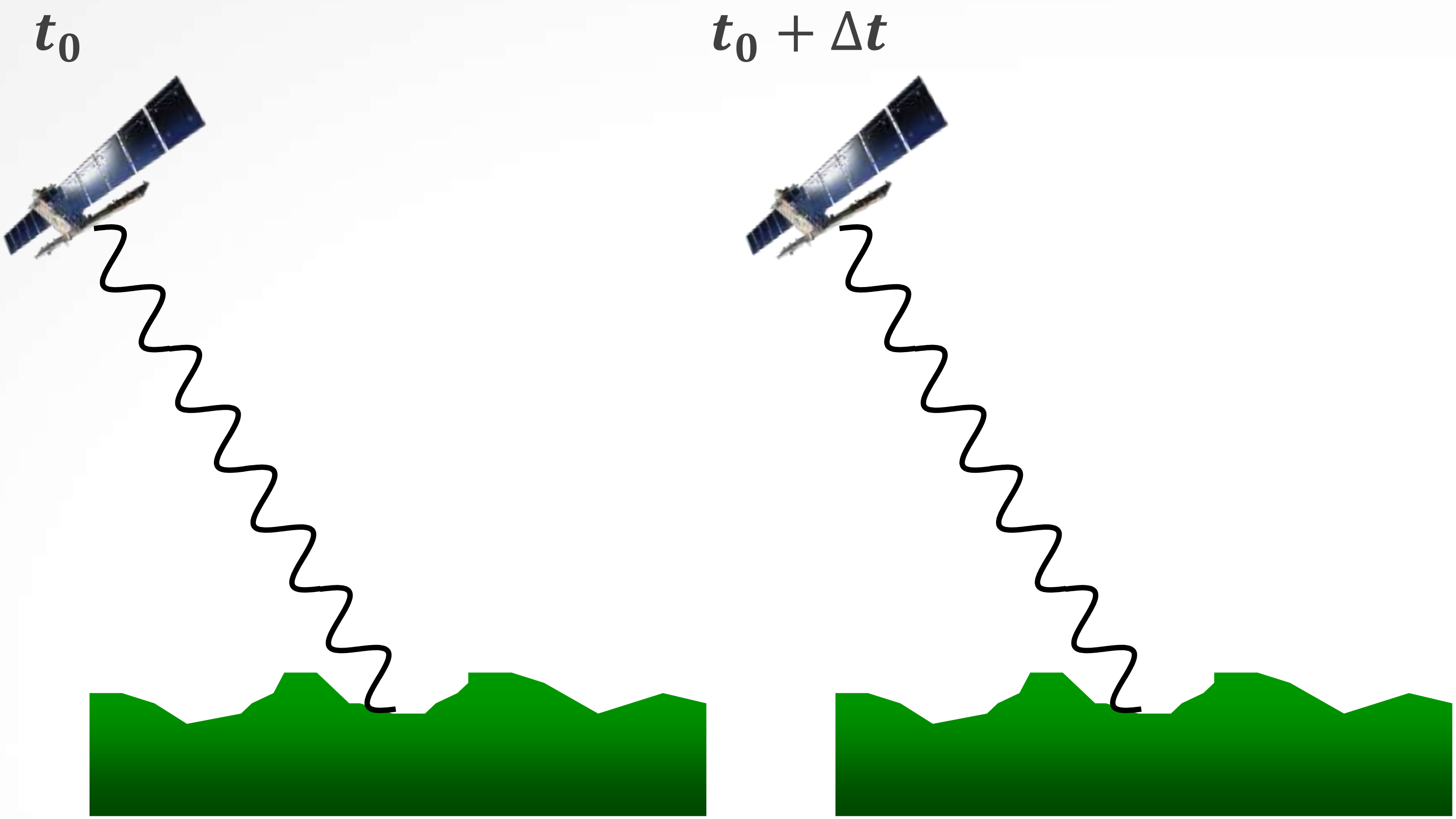


$$SCR = \frac{\text{signal}^2}{\text{clutter}^2} = \frac{\mathbb{E}(A)^2}{2\sigma_n^2}$$



SAR Interferometry (InSAR)

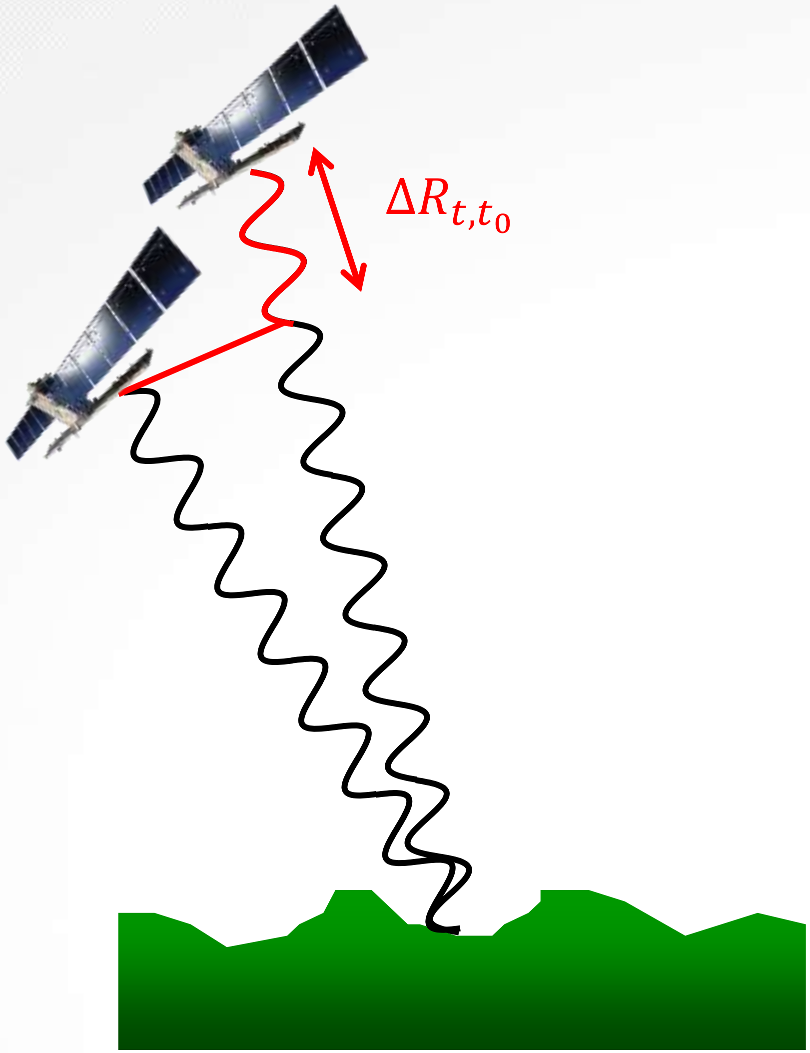
$$y_1 y_2^* = |y_1||y_2| \exp\left(j\left(\psi_1 - \psi_2\right)\right)$$



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 (paralax)
- position of scatterer (deformation)
- atmospheric signal delay

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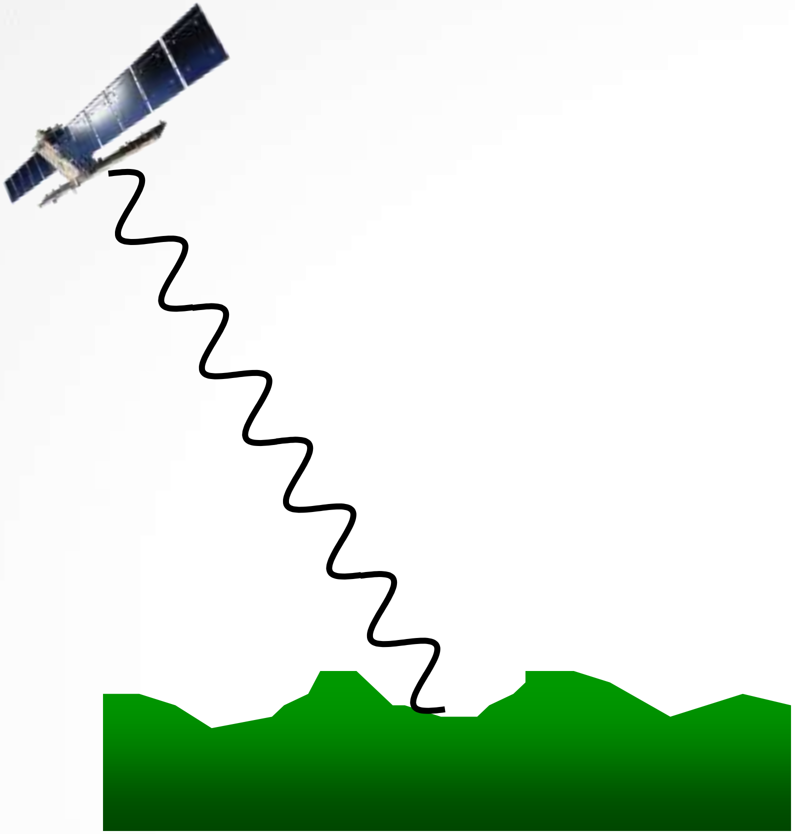

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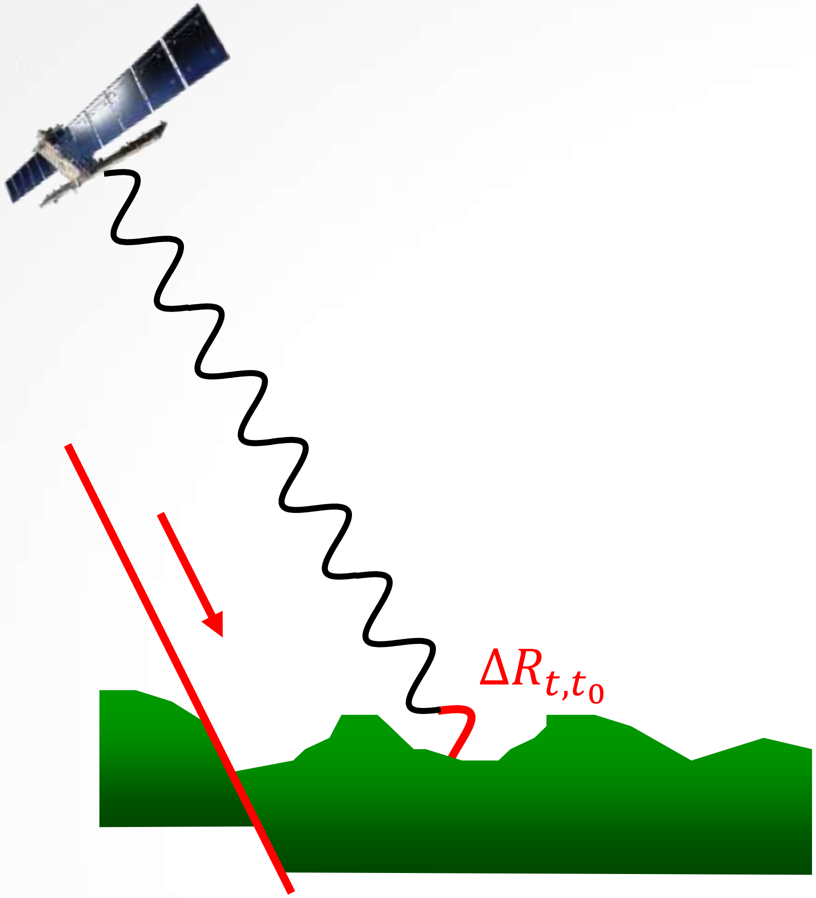

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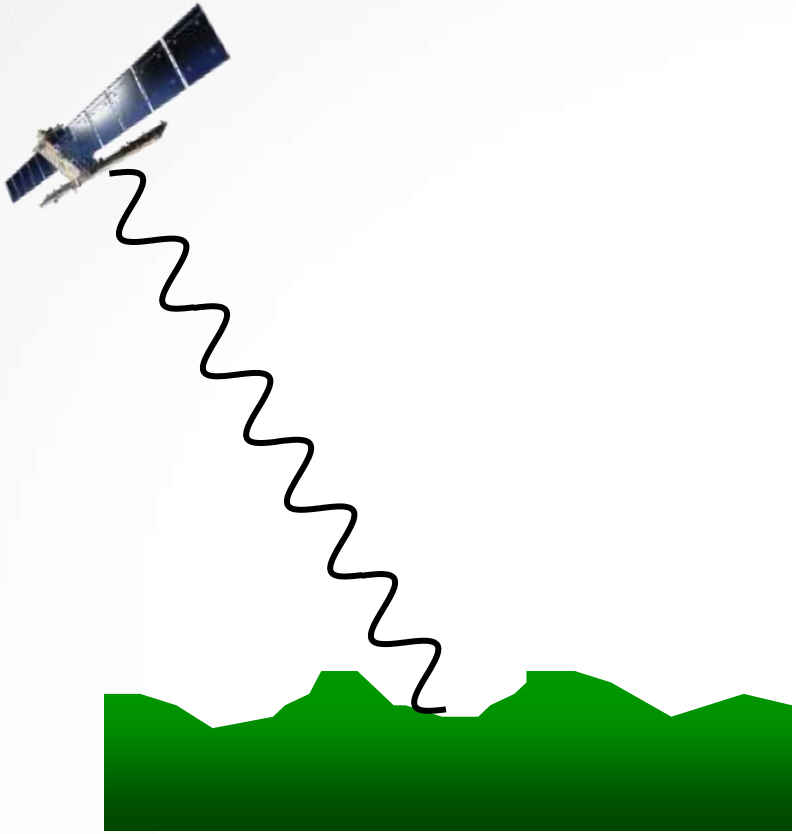

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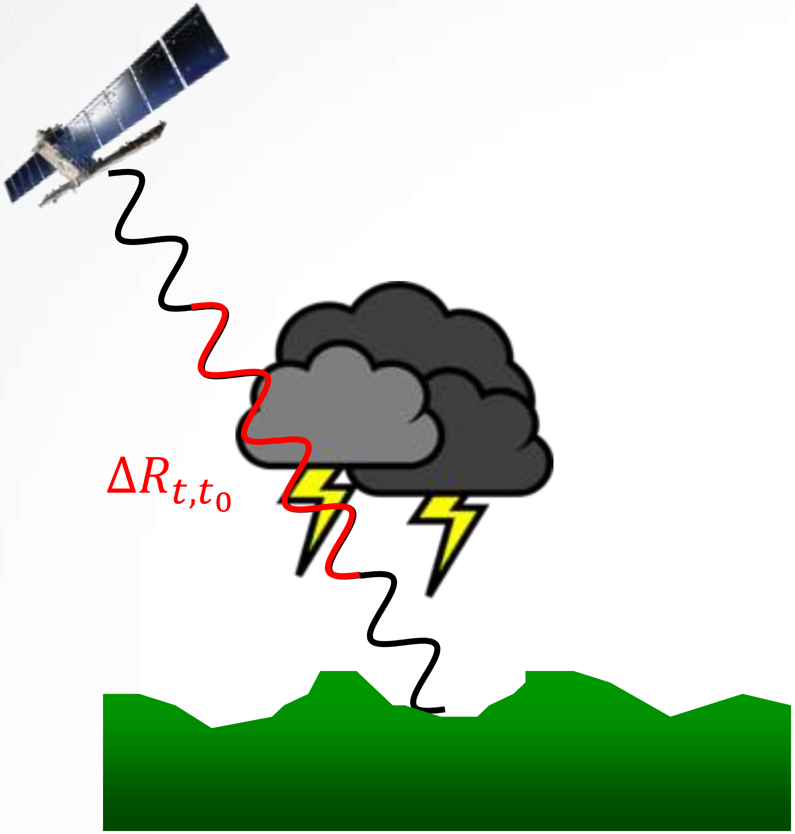

$\Delta R_{t,t_0}$ caused by different:

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InSAR observation equation

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

Geometry phase
ϕ_{geom}

- Reference phase
  ϕ_{ref}
  - Ref. body phase
    $\phi_{refBody}$
    $\phi_{orbitErr}$
    ϕ_{subPix}
    **if compensated*
  - Topography phase
    ϕ_{topo}
    $\phi_{resTopo}$
    **if compensated*
- Displacement phase
  ϕ_{defo}

Atmospheric phase
ϕ_{atmo}

- Ionospheric phase
  ϕ_{iono}
- Tropospheric phase
  ϕ_{tropo}
  - Turbulent component
    $\phi_{turbulent}$
  - Stratified component
    $\phi_{stratified}$

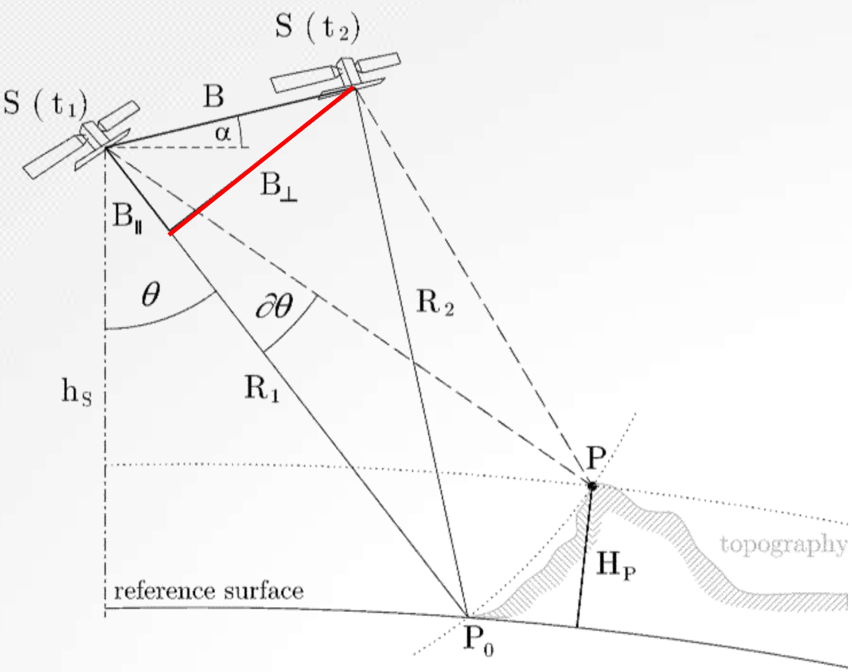
Scattering (Clutter) phase
ϕ_{scatt}

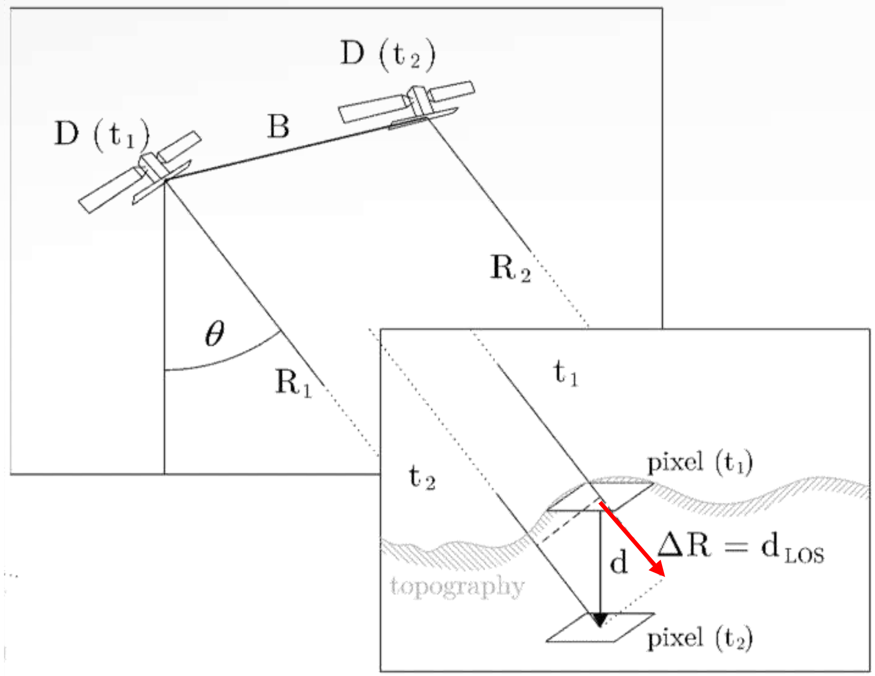
- Clutter phase
  ϕ_{clutt}
- Decorrelation phase (change of clutter = loss of coherence γ)
  $\phi_{decorel}$
  - Temporal
  - Geometric

Phase noise
ϕ_{noise}

- Sensor & Processing noise

Topography & Displacement (LOS) phase





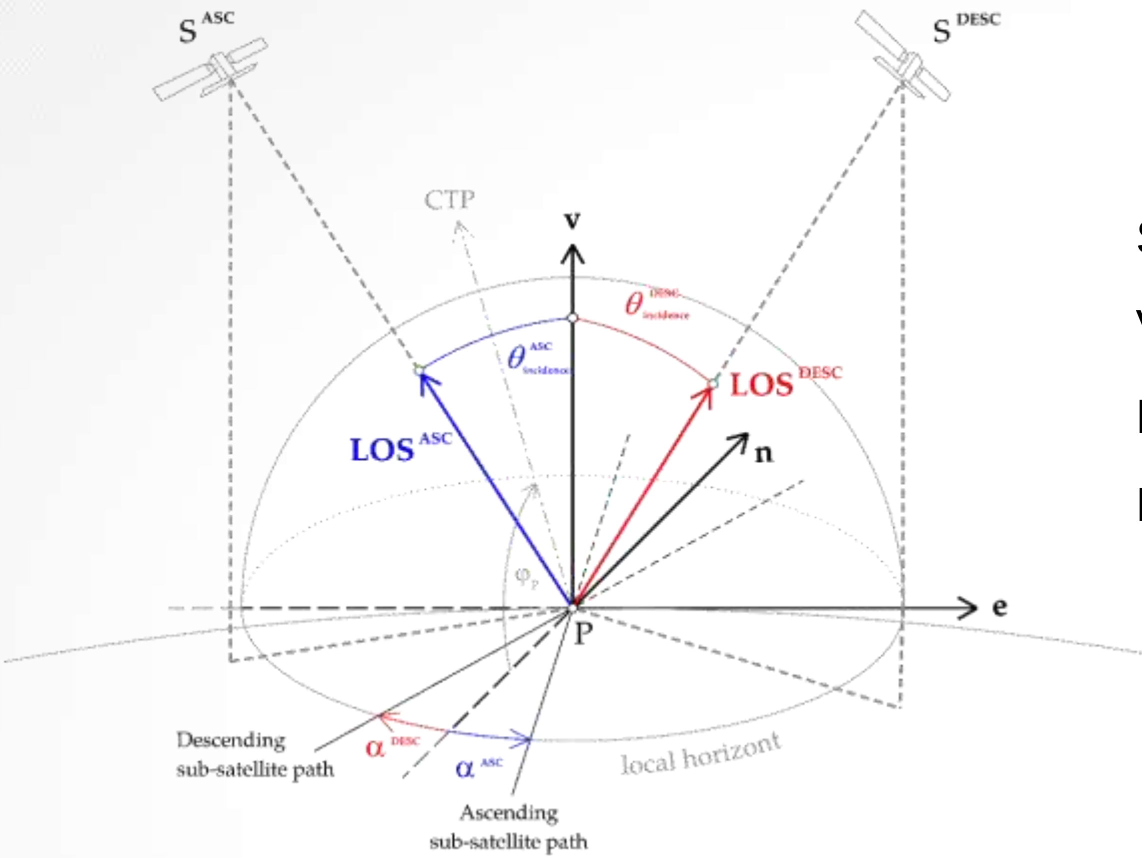
$$\phi_{topo} = \frac{4\pi}{\lambda}\frac{B_{\perp}}{R\sin\theta}H_P$$

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

“residual” topography (linearized by DEM)

Displacement sensitivity

$$d_{LOS} = d_v \cos(\theta) - \sin(\theta)\,[d_n \cos(\alpha_h - 3\pi/2) + d_e \sin(\alpha_h - 3\pi/2)]$$



Sentinel-1:

VERTICAL = **76%** ,

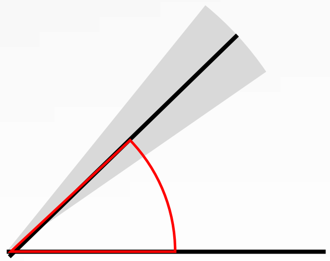
EAST-WEST = **63%**,

NORTH-SOUTH = **17%**

A-priori precision

Scatterer with SCR = 20 :

$$\sigma_\phi = \sim 6°$$



Relative height precision

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

theoretically →

$$\sigma_H = \sim 1\, m$$

Displacement precision

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

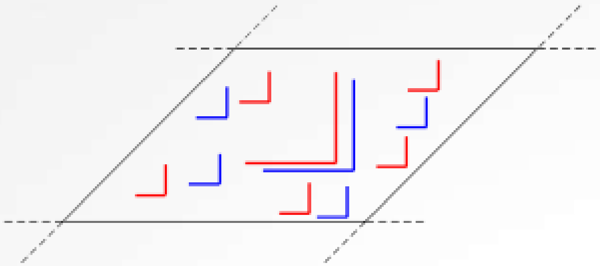
theoretically →

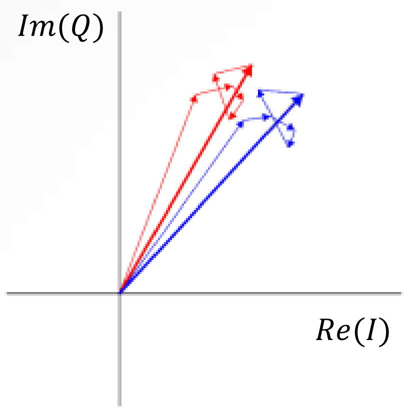
$$\sigma_{d_{LOS}} = \sim 0.5\, mm$$

Persistent Scatterers (PS)

Point scattering

a.) coherent

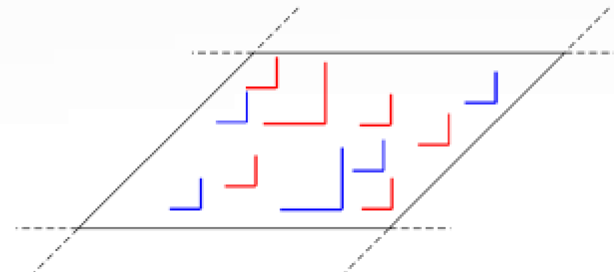


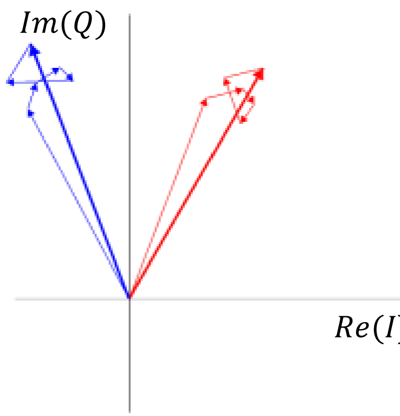


T_0

$T_0 + \Delta T$

b.) incoherent

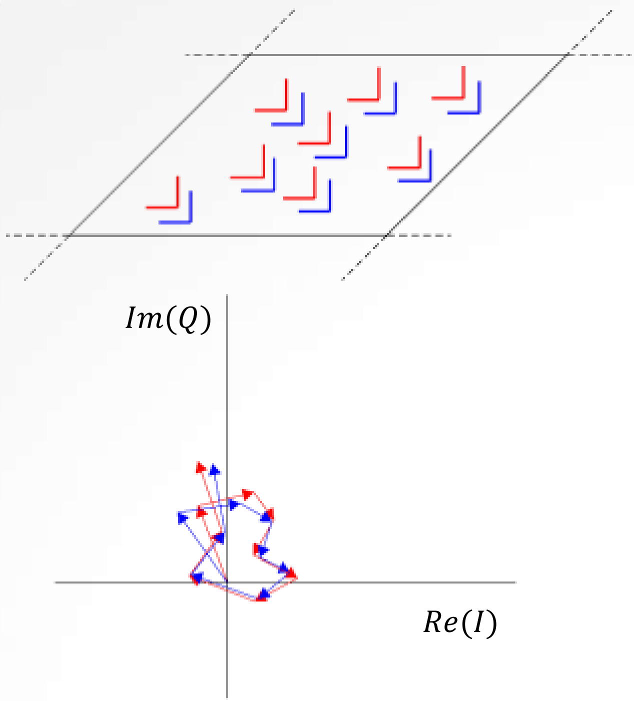




Persistent Scatterers (PS)

Distributed scattering

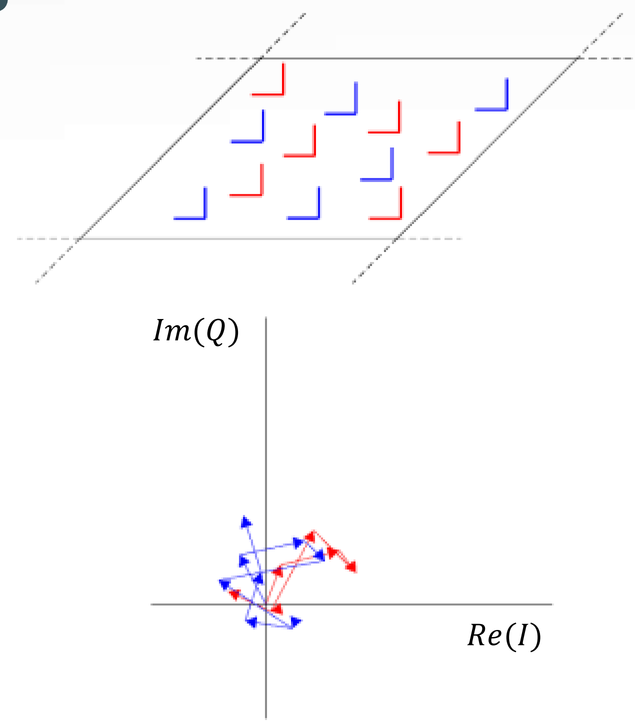
a.) coherent



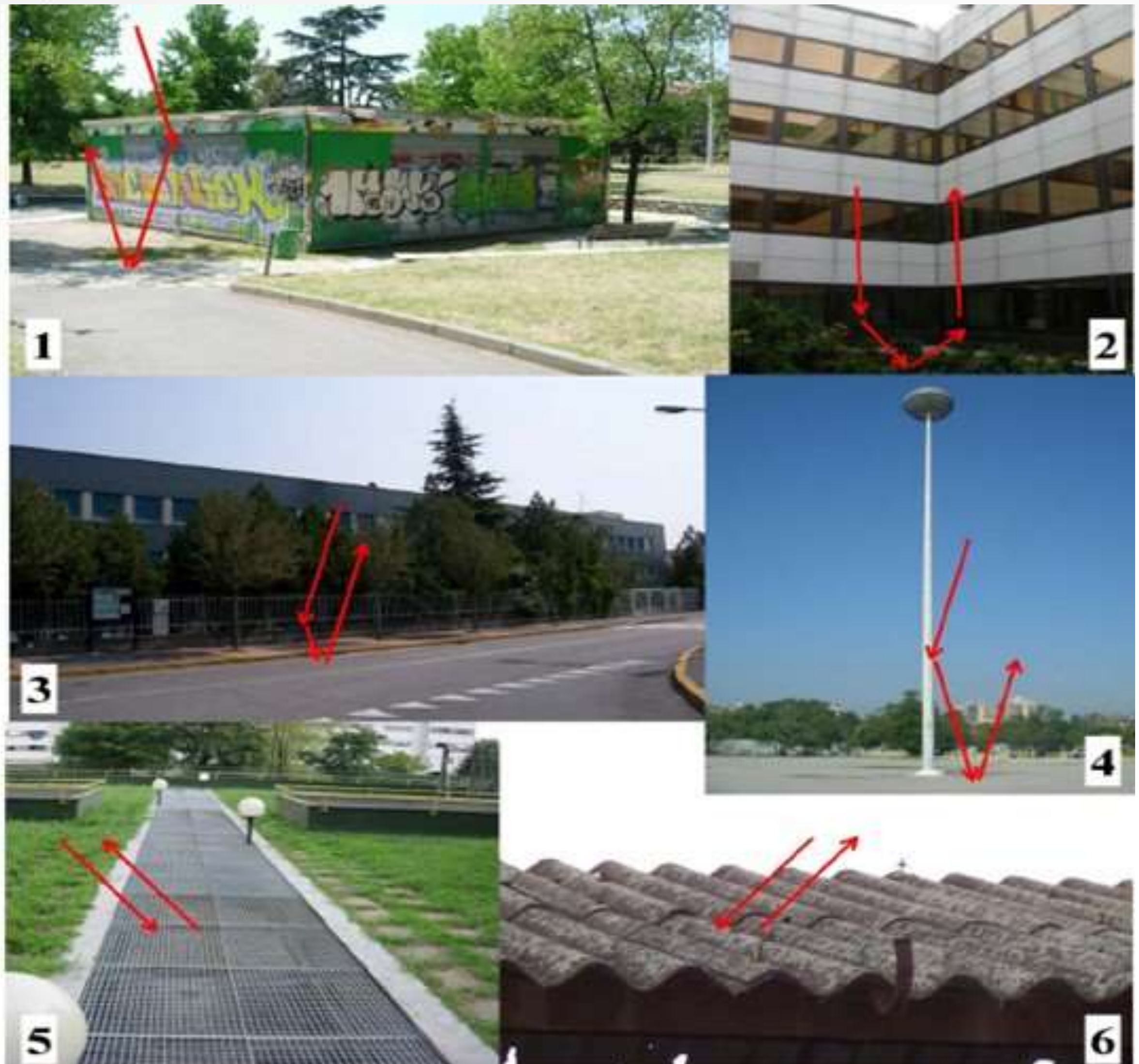
T_0

$T_0 + \Delta T$

b.) incoherent

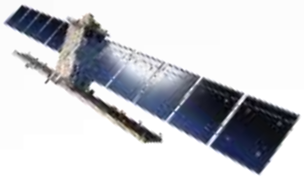


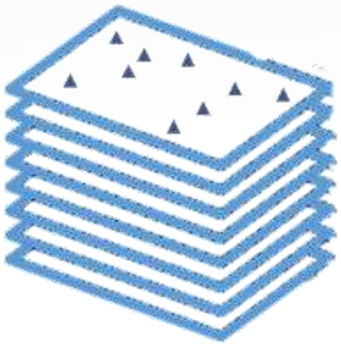
Persistent Scatterers (PS)



Time-series (Multi-temporal InSAR)

- **New acquisition = new measurement every 6 days**





SAR image time series

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

t_0	"Master" epoch
$t_{1,2,3\ldots N}$	"Slave" epochs

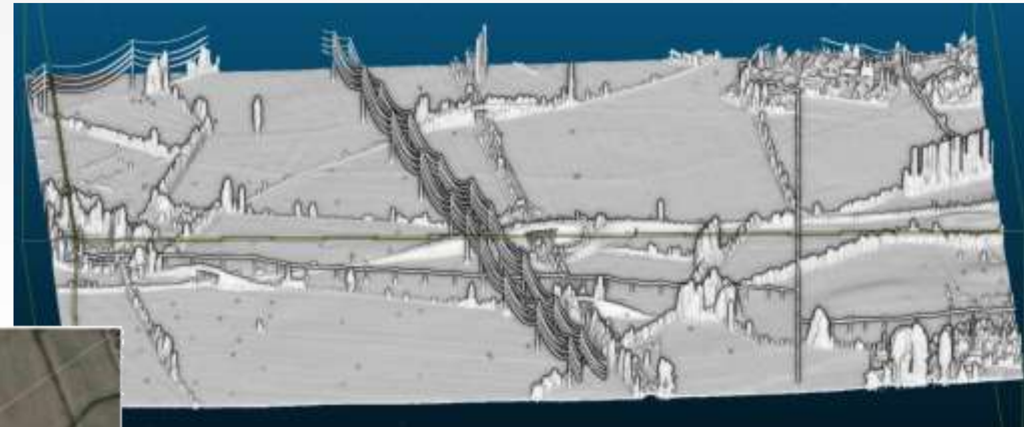
Outcome:

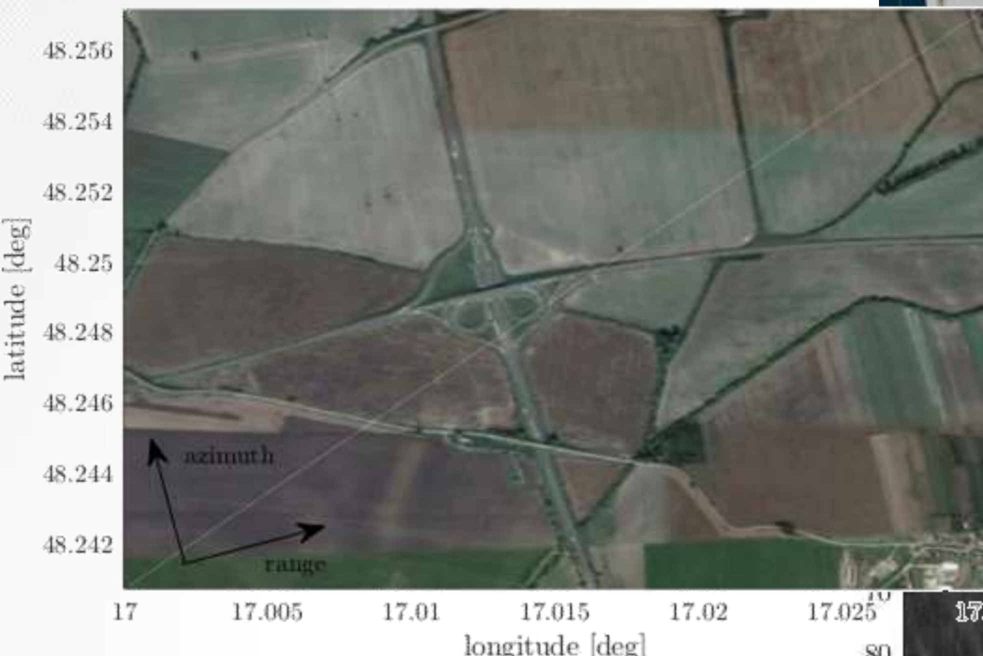
$\phi_{1,2,3\ldots N}$	Interferometric phase time series in every pixel

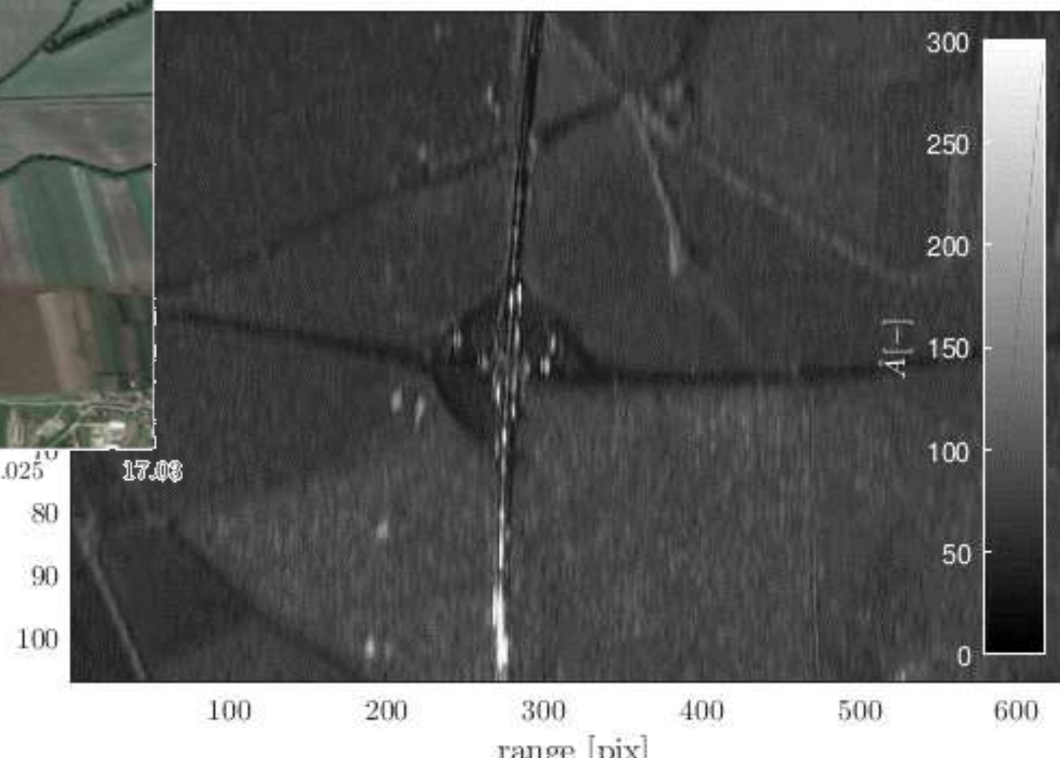
- **Network of Persistent Scatterers – geodetic estimation theory**

Demonstrative case

D2/D4 Záhorská Bystrica

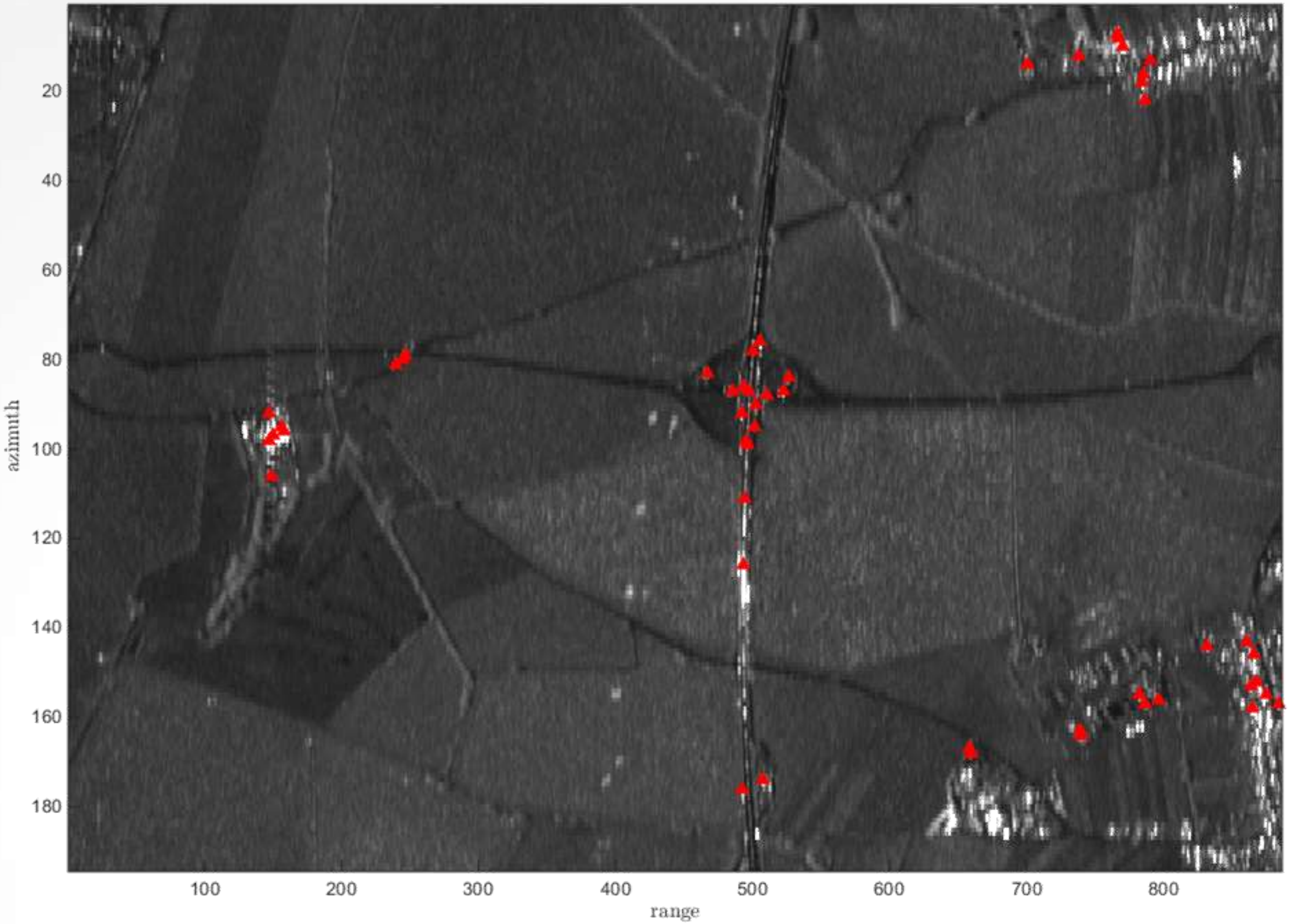






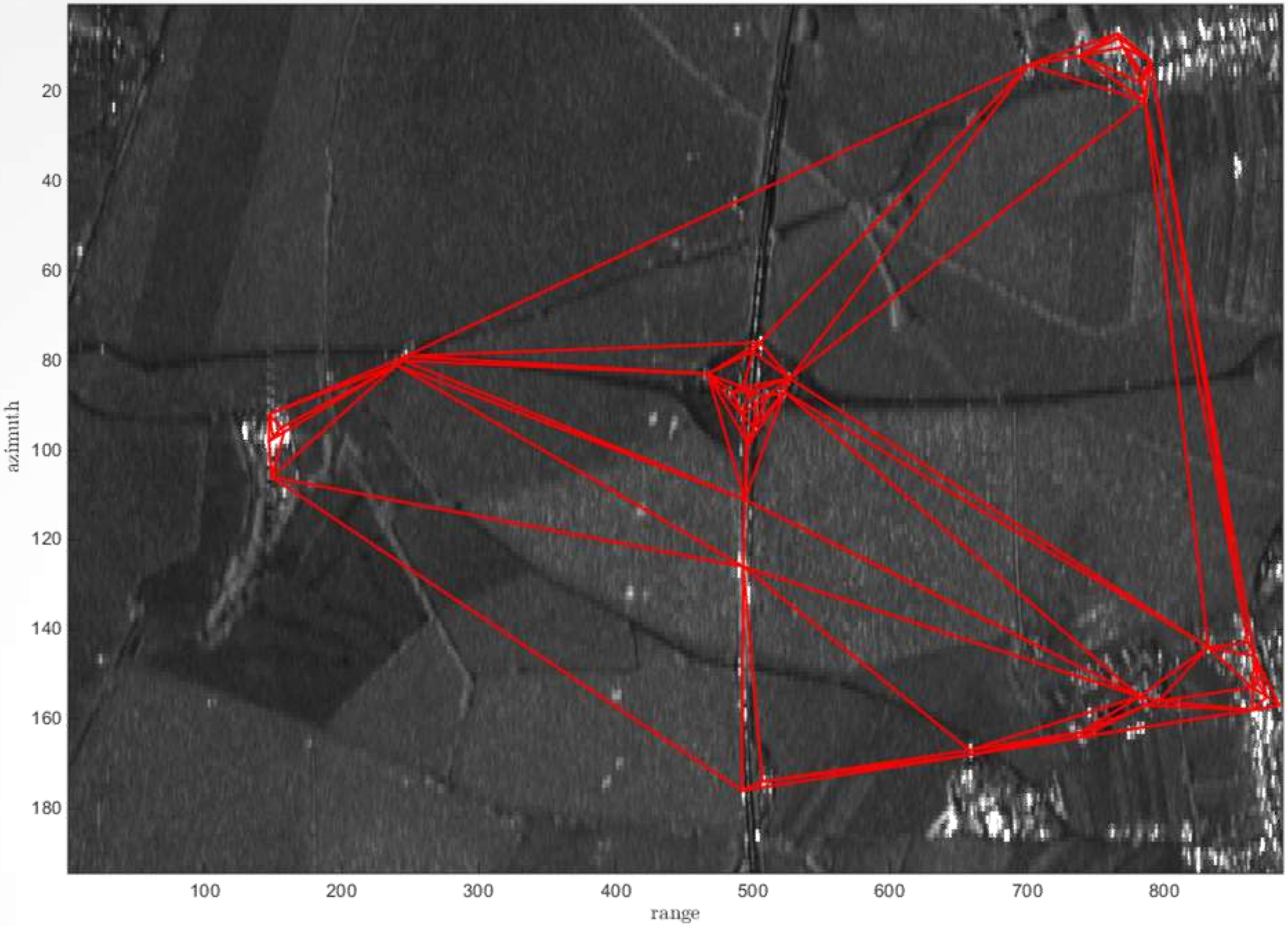
Detection & estimation problem

Persistent Scatterer Candidates (PSC)



1st order estimation network

Phase double-differences

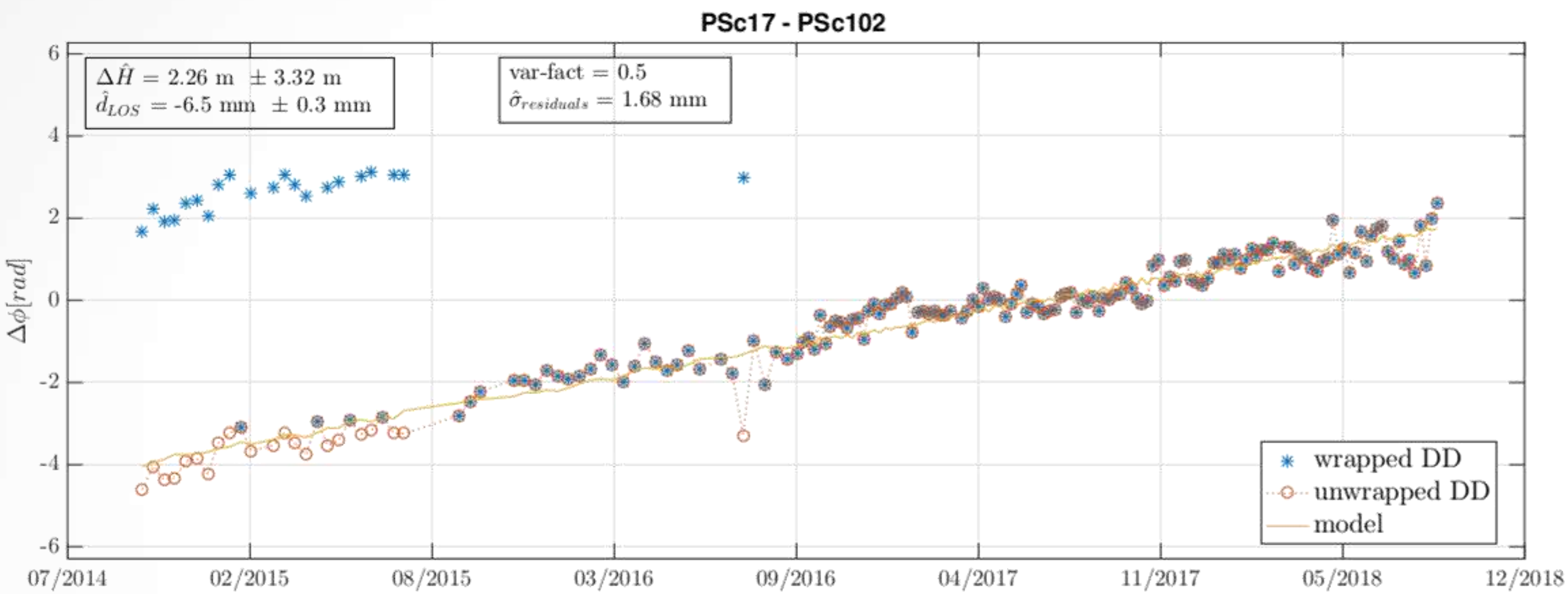


Ambiguity resolution

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

$$\boldsymbol{\Delta\phi}_{i,j} = \boldsymbol{\alpha}\, \Delta h_{i,j} + \boldsymbol{\beta}\, \Delta d_{i,j} + 2\pi \boldsymbol{a}_{i,j}$$ <- ambiguity vector

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



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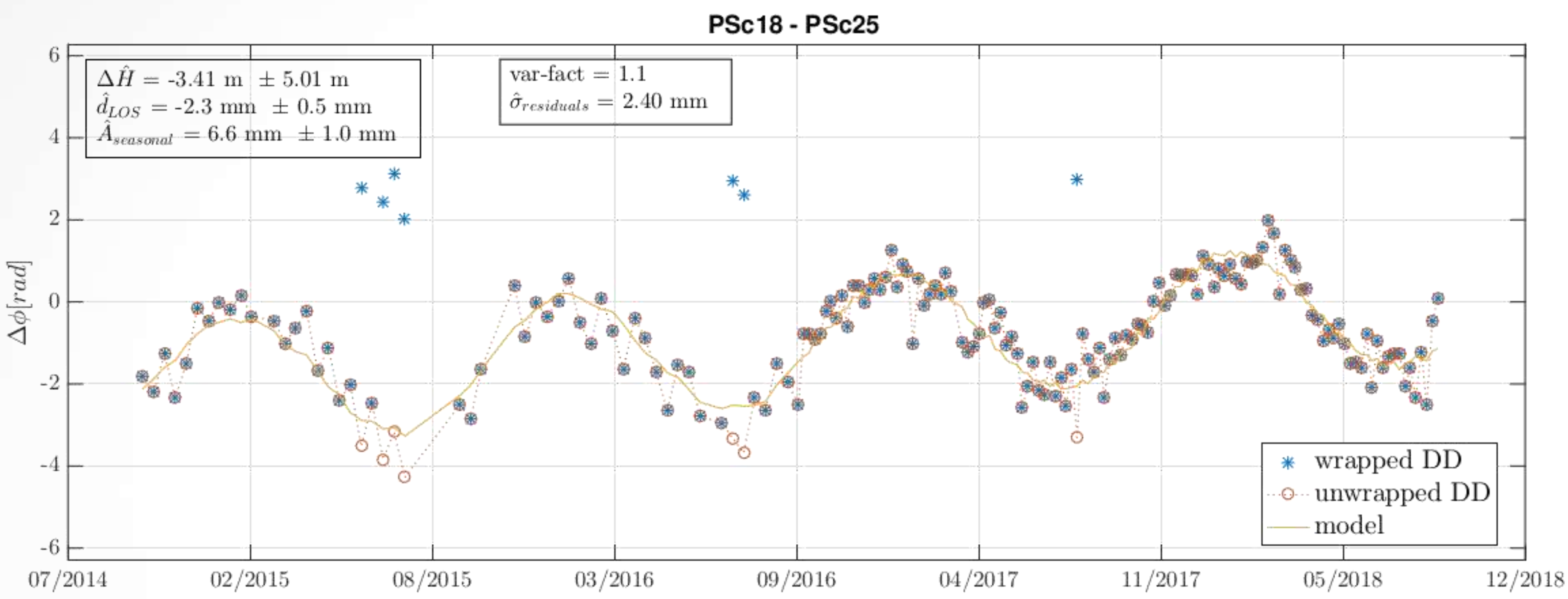


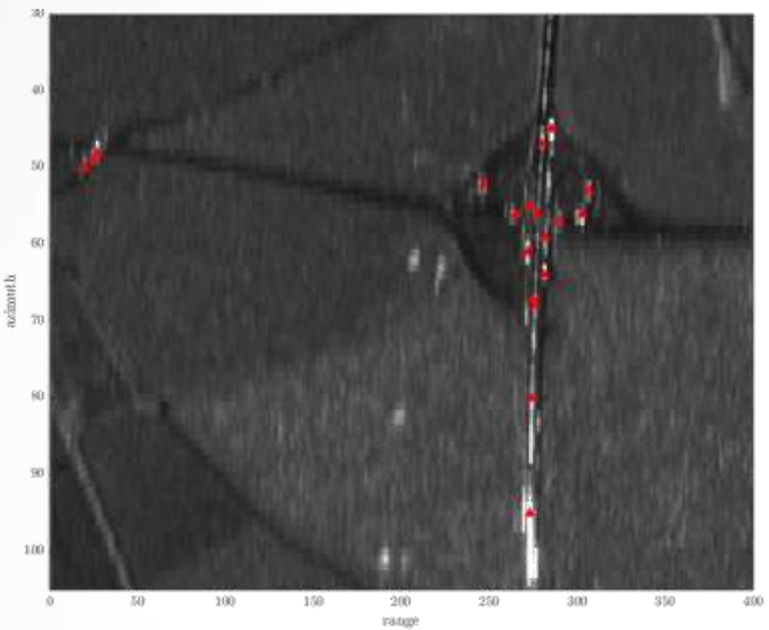
Network integration

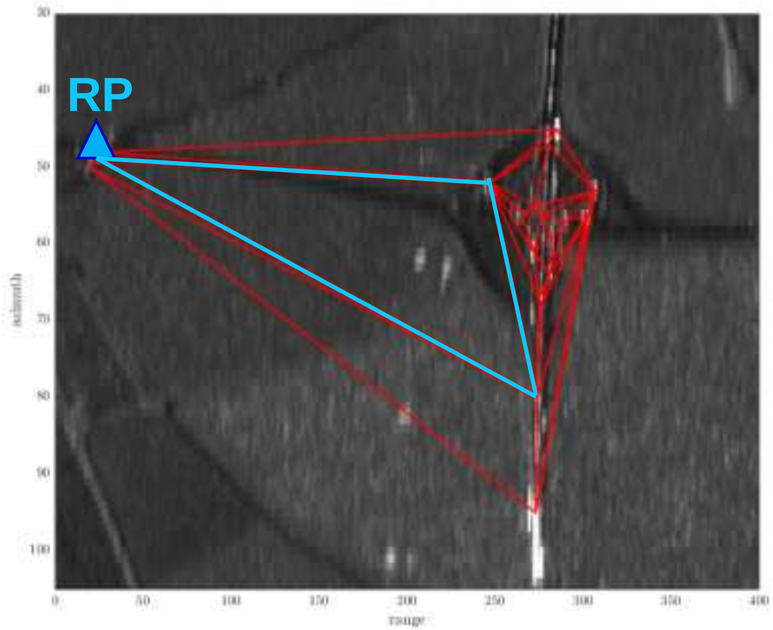
- all relative to one arbitrary reference point (RP)

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“)

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

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“)

$$\boldsymbol{\Sigma}_{\widehat{\boldsymbol{h}}_i,\widehat{\boldsymbol{d}}_i}$$

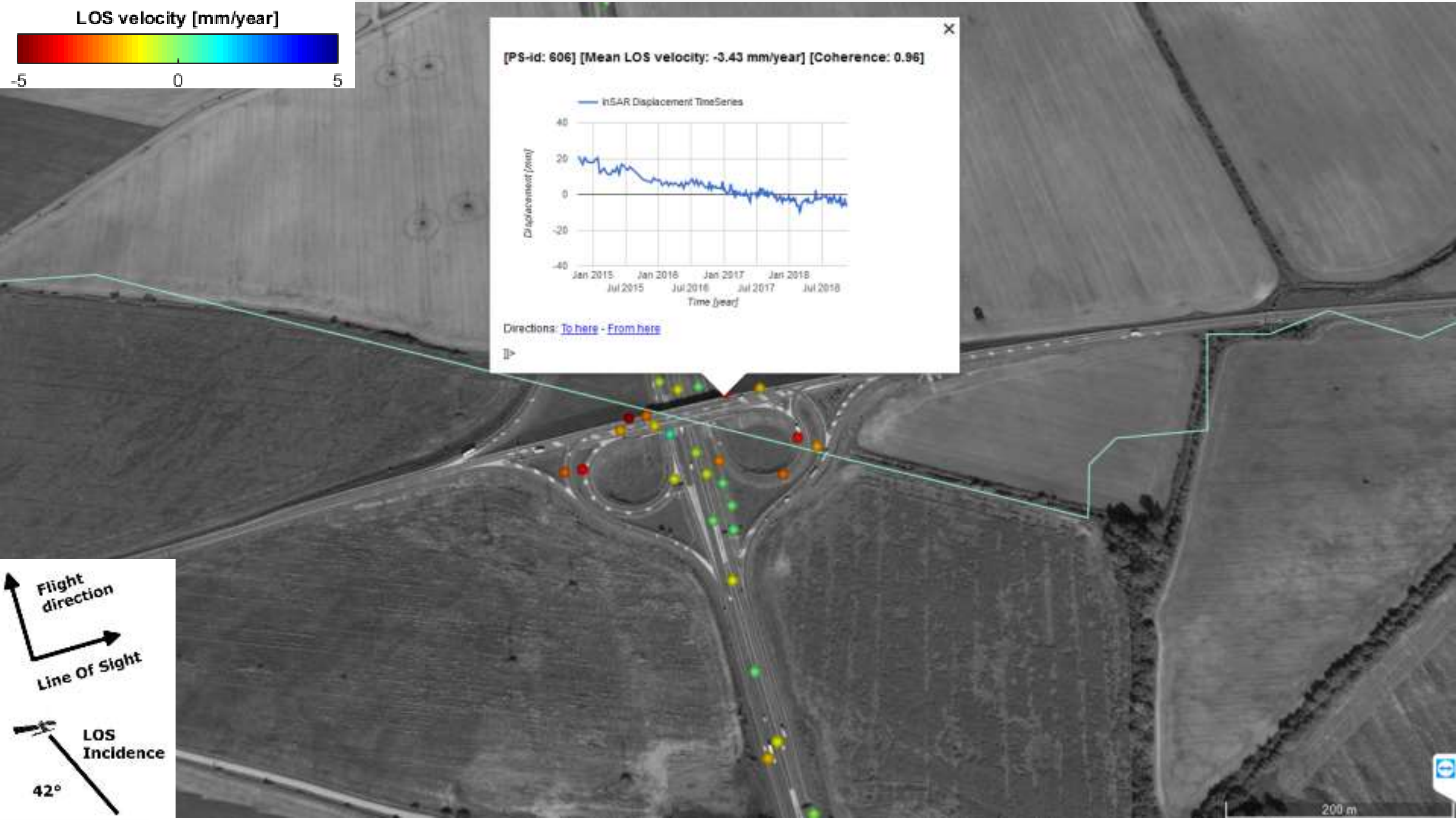
Correctness of functional model & redundancy & ambiguity errors

PS network

PS network

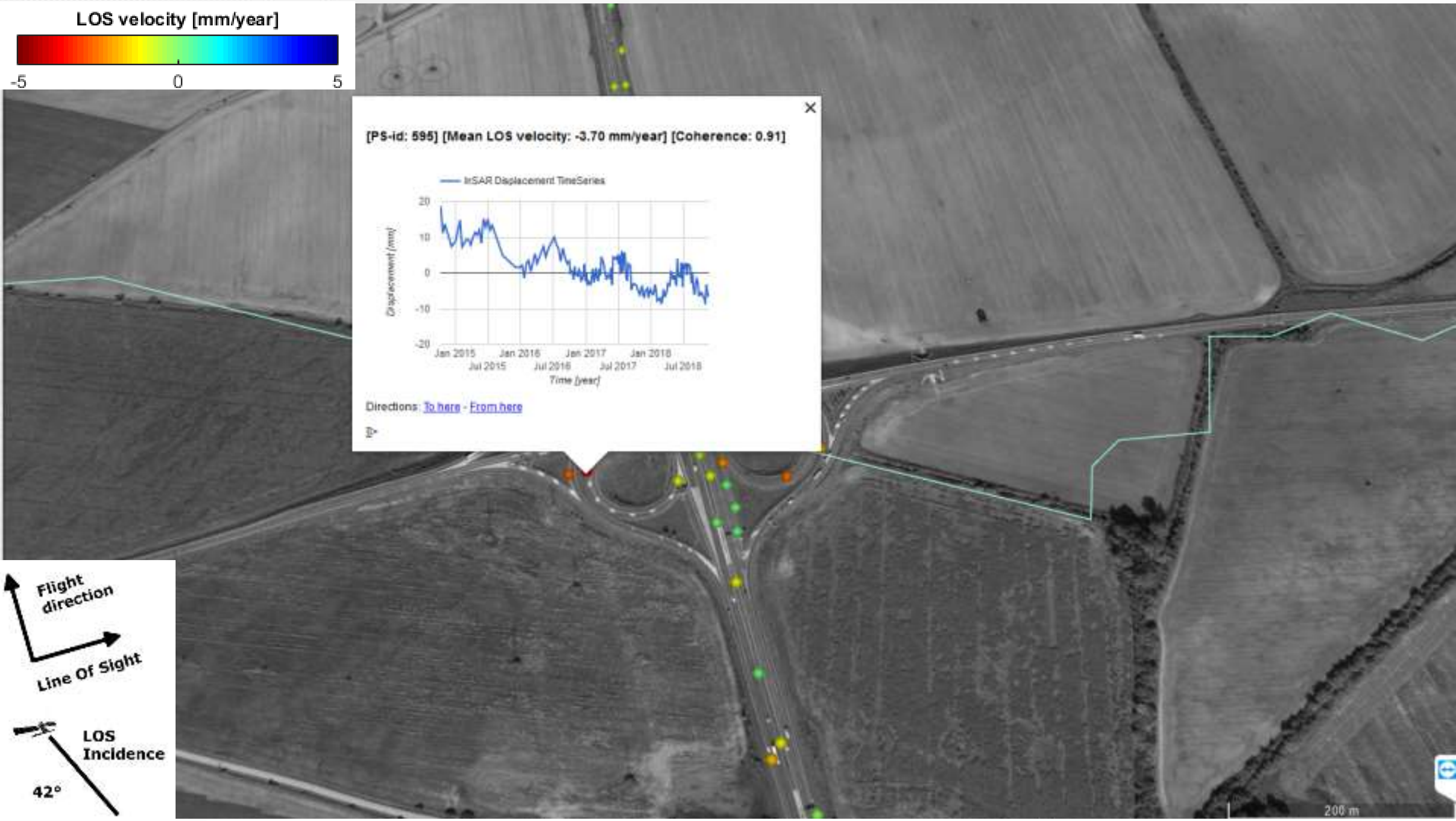

LOS velocity [mm/year]
-5
0
5
Flight direction
Line Of Sight
LOS Incidence
42°
200 m

PS network

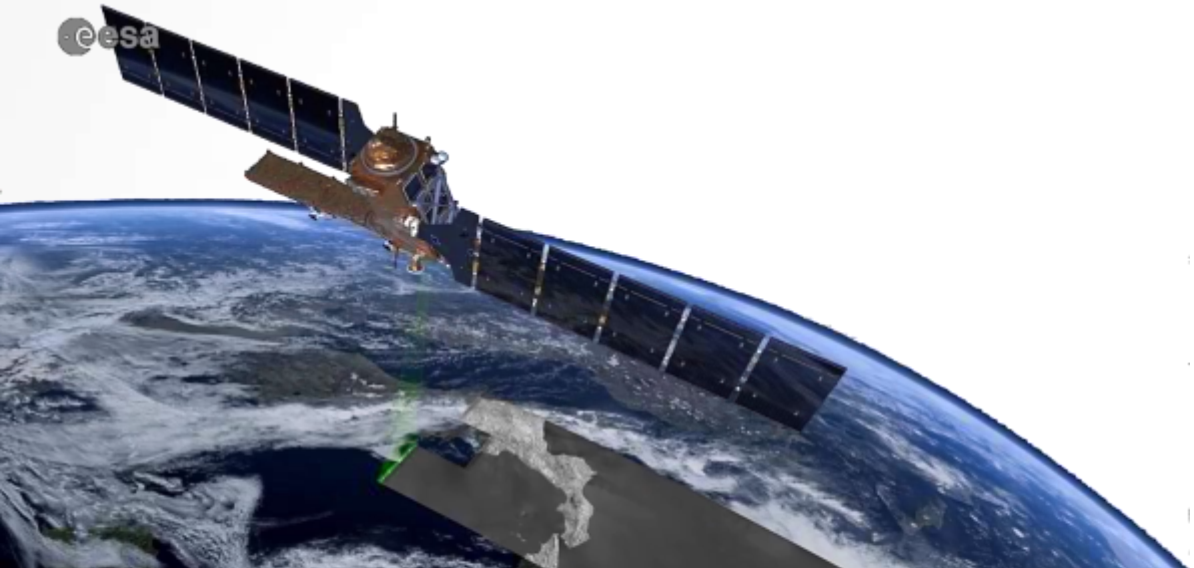


LOS velocity [mm/year]
-5
0
5
[PS-id: 606] [Mean LOS velocity: -3.43 mm/year] [Coherence: 0.96]
InSAR Displacement TimeSeries
Displacement [mm]
Time [year]
Jan 2015
Jul 2015
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Directions: To here - From here
Flight direction
Line Of Sight
LOS Incidence
42°
200 m

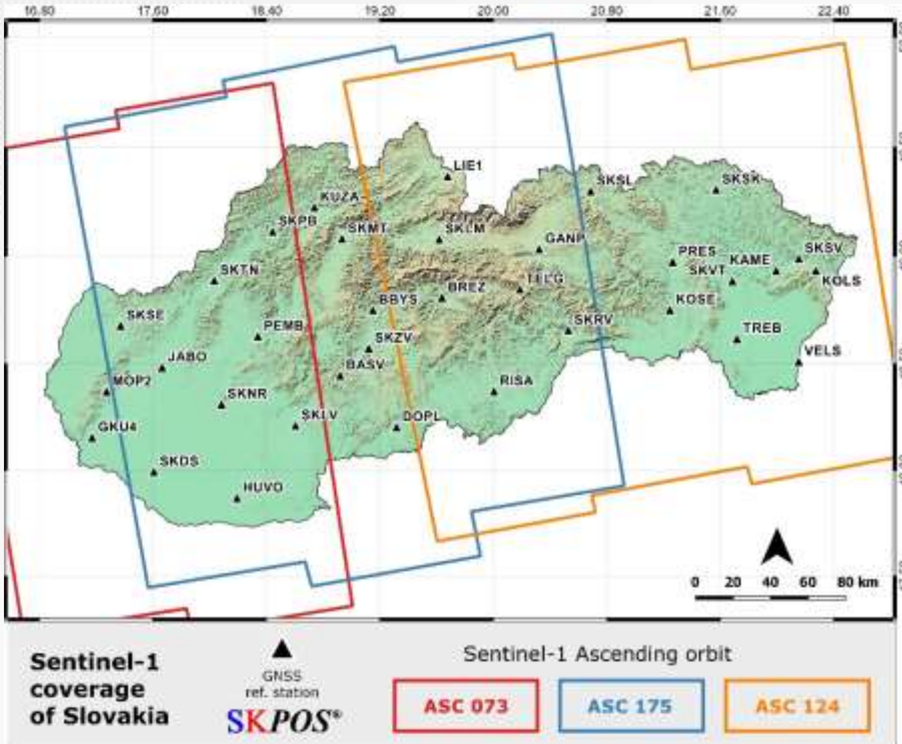
PS network

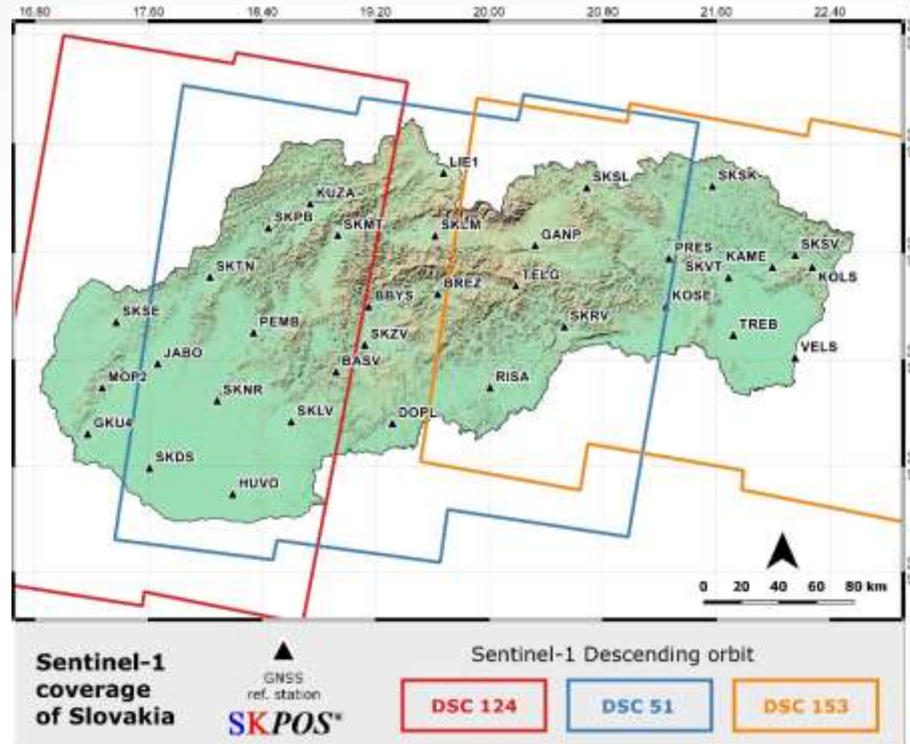

LOS velocity [mm/year]
-5
0
5
[PS-id: 595] [Mean LOS velocity: -3.70 mm/year] [Coherence: 0.91]
InSAR Displacement TimeSeries
Displacement [mm]
20
10
0
-10
-20
Jan 2015
Jul 2015
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Time [year]
Directions: To here - From here
Flight direction
Line Of Sight
LOS Incidence
42°
200 m

Case studies from Slovakia



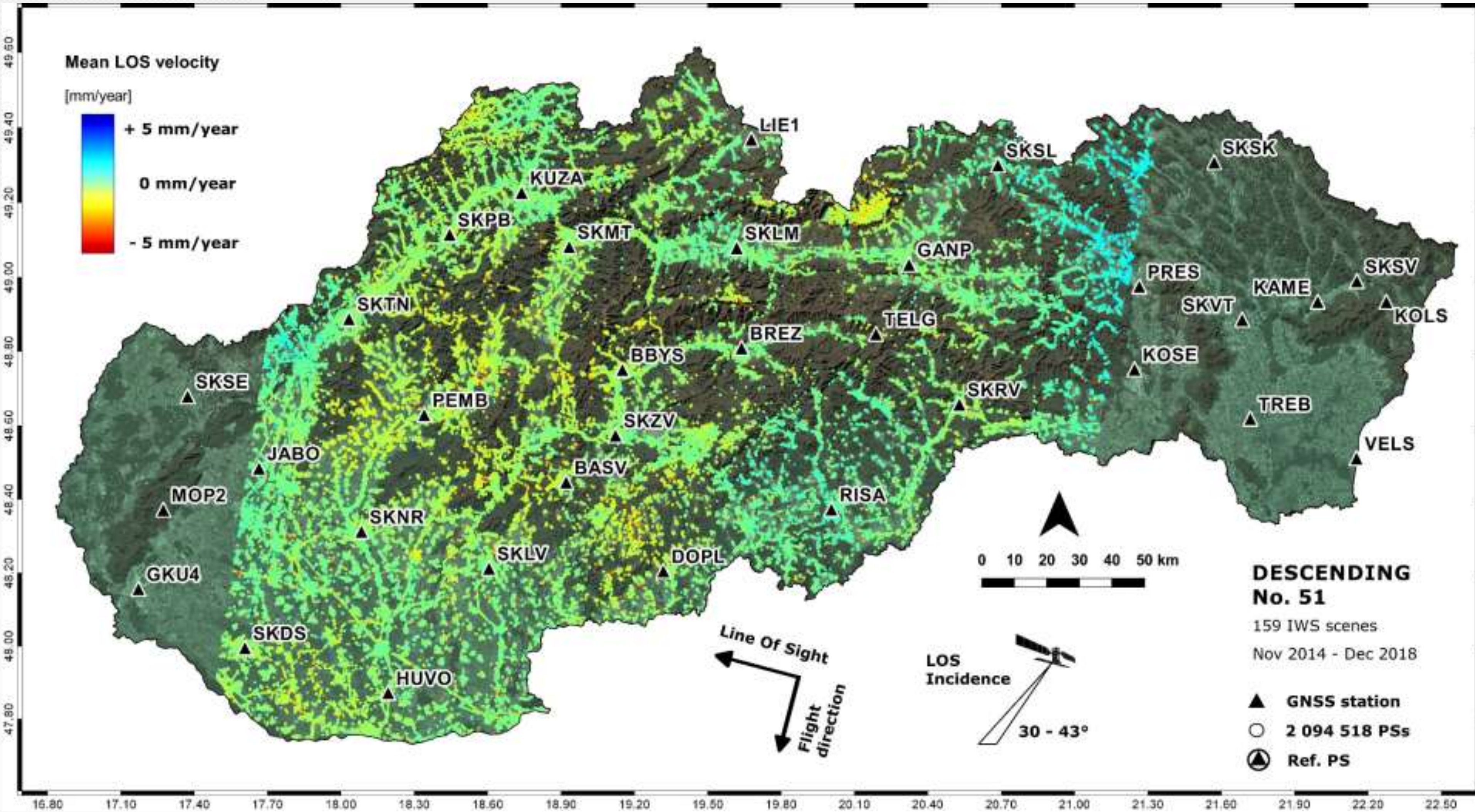
Sentinel-1 coverage of Slovakia



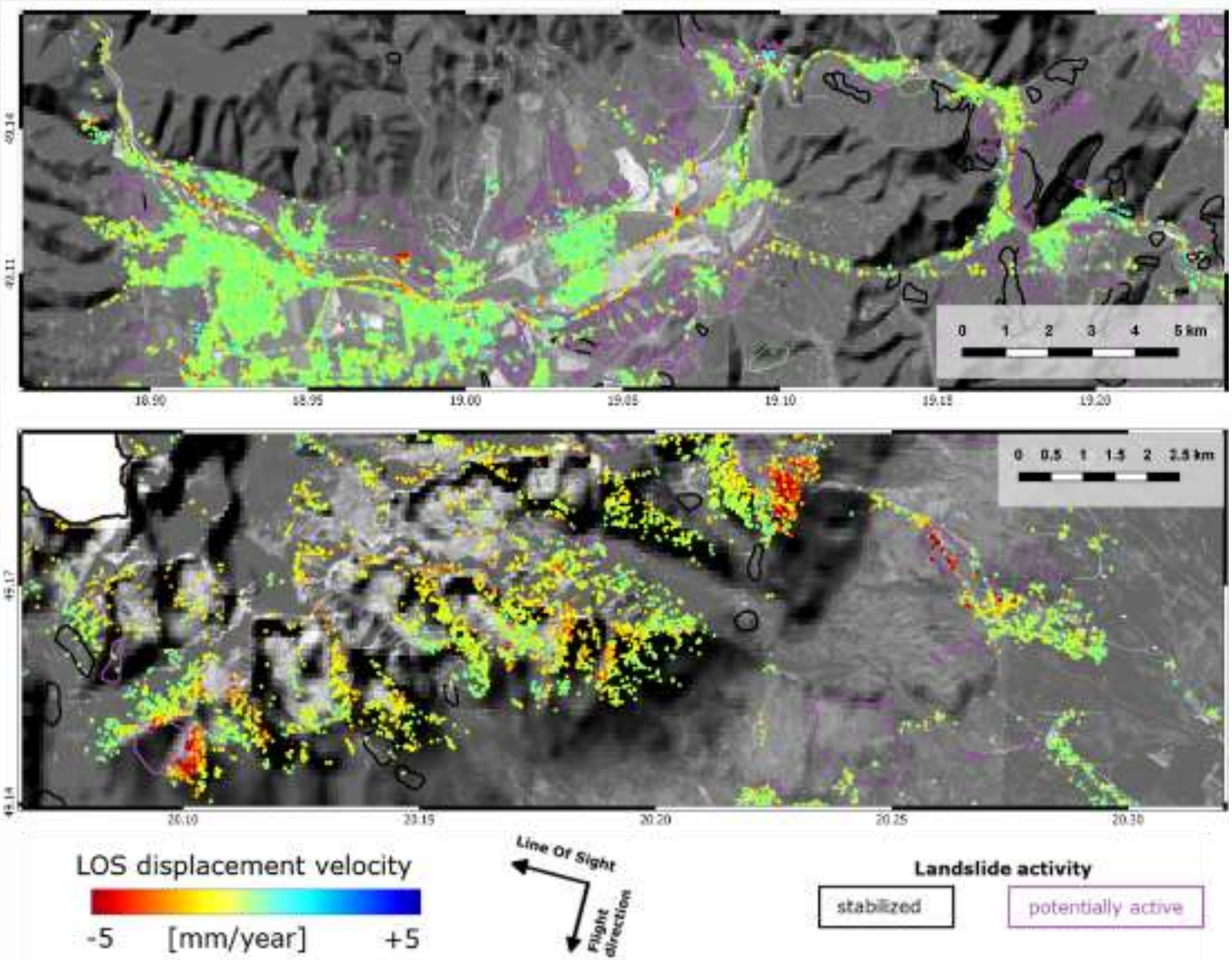


orbit	Ascending			Descending		
	ASC 175	ASC 102	ASC 073	DSC 153	DSC 124	DSC 051
Number of acquisitions	208	228	225	211	221	210
First usable acquisition	20150226	20141129	20141209	20141203	20141014	20141201
Acquisition interval	Currently every 6 days, 12 days prior to Sentinel-1B (20160920)					

State-wide monitoring

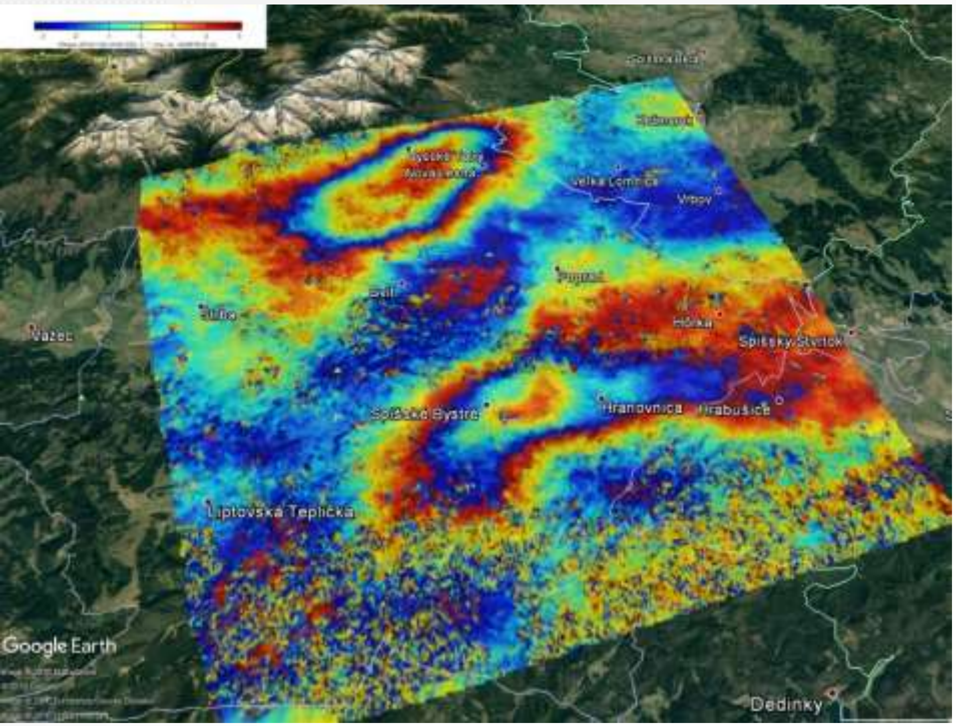


Regional monitoring capability

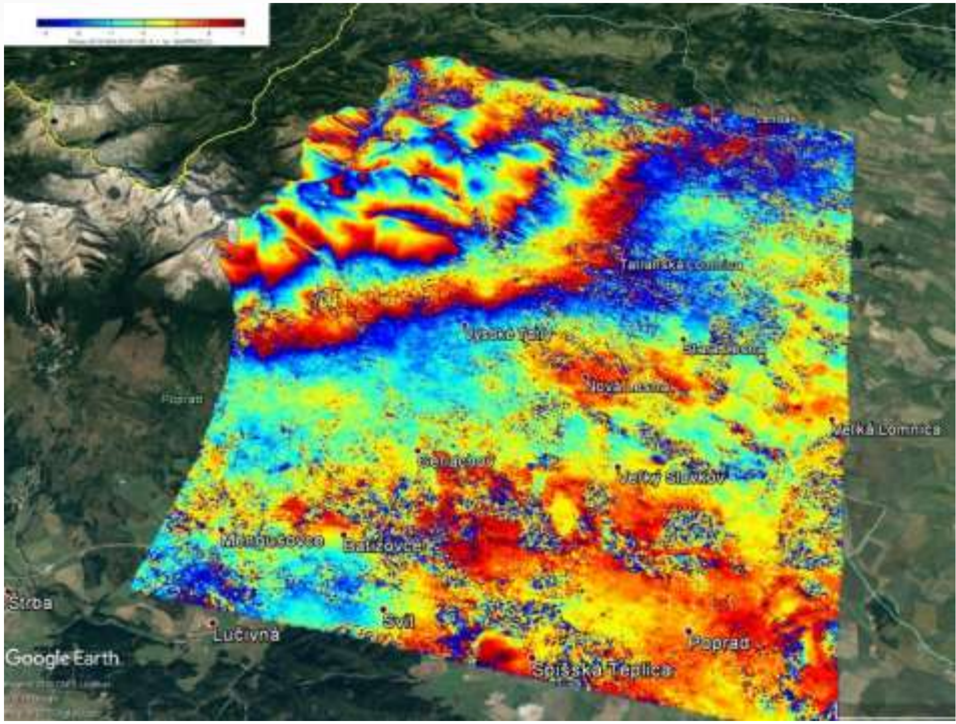


Problem: Atmospheric Phase Screen (APS)

20170619 - 20170712

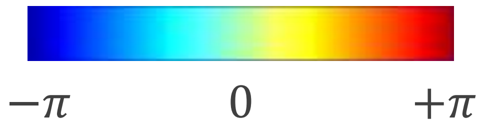


20170619 - 20170607

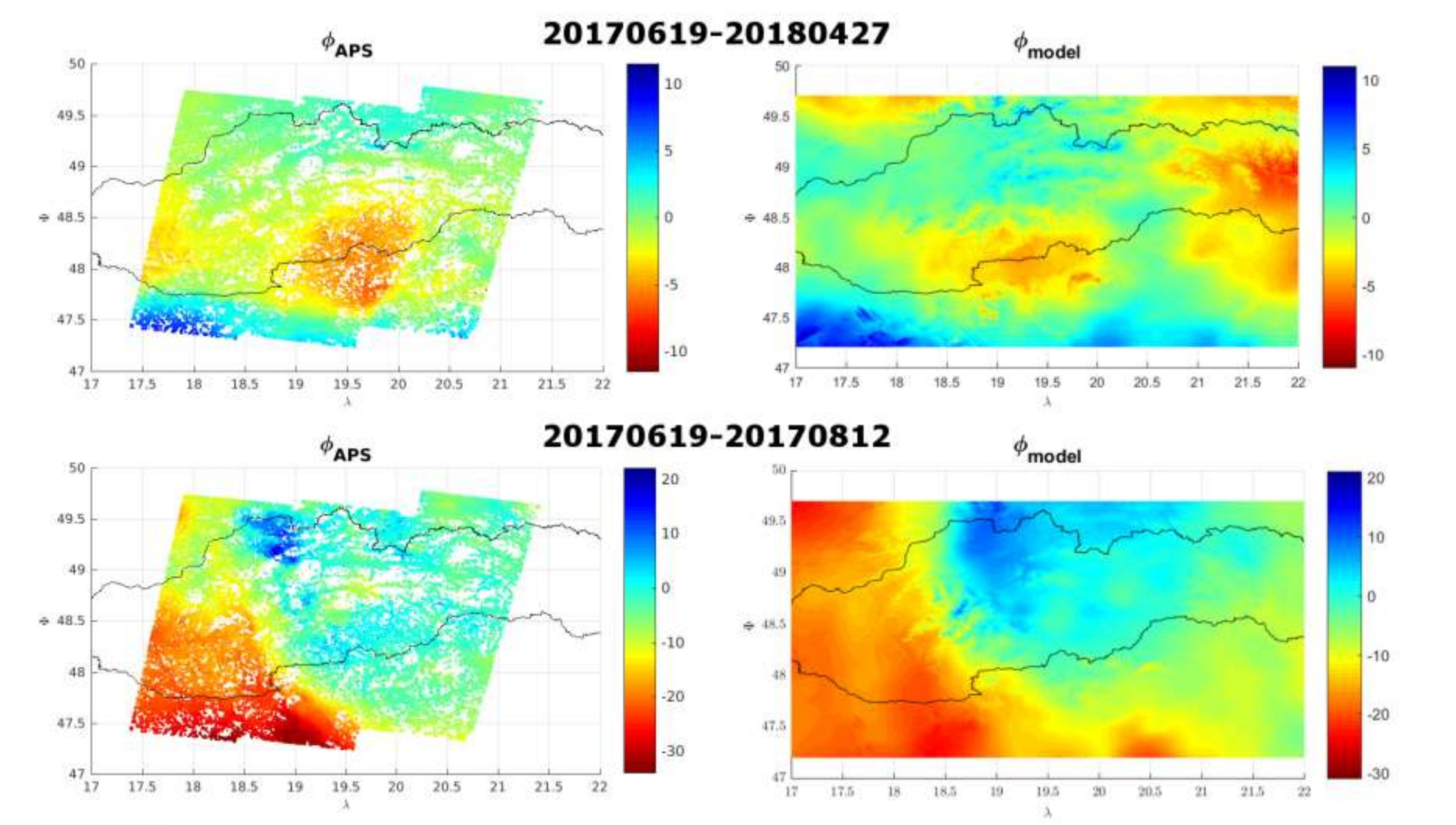


➔ turbulence

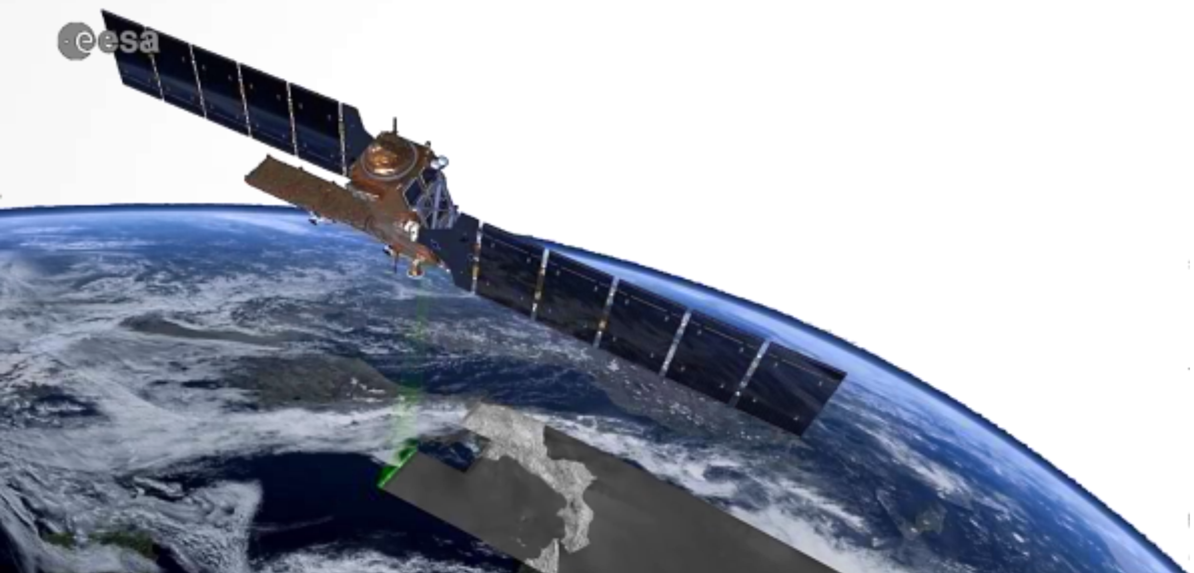
➔ stratification



APS – InSAR estimation / Numerical weather model



InSAR limitations and challanges



Limitations & challenges for InSAR geodesy

1. InSAR network = “free network/datum”

- 1 spatial + 1 temporal reference required
- 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

InSAR & GNSS/levelling collocation

Collocation of InSAR measurements with other technique in:

a.) parameter space

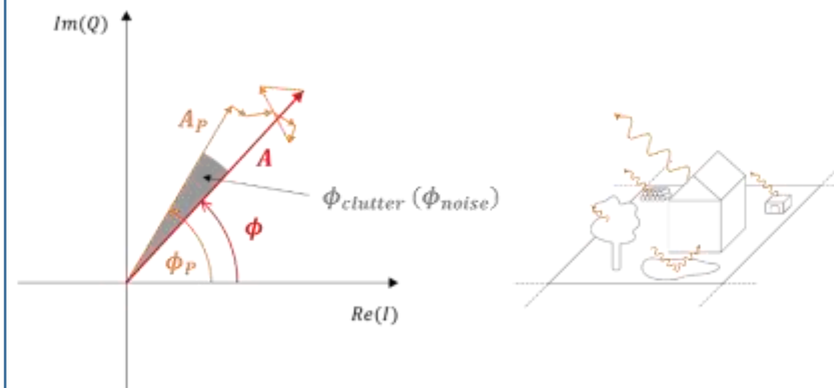
$$\Delta_p \Delta_t u = [u(p_1, t_1) - u(p_1, t_0)] - [u(p_0, t_1) - u(p_0, t_0)]$$

b.) observation space

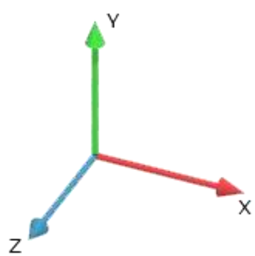
"Conventional" geodetic techniques vs. InSAR

Geodetic benchmark

Complex sum of scatterers per pixel

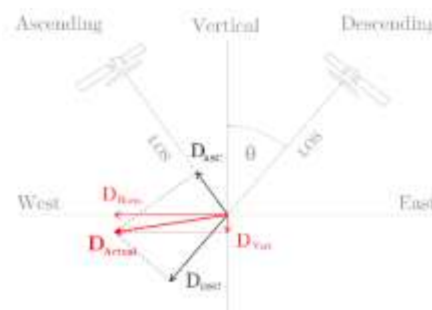


3D / 1D (vertical) vector



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

Line-of-sight (LOS) vector



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

InSAR & GNSS/levelling collocation

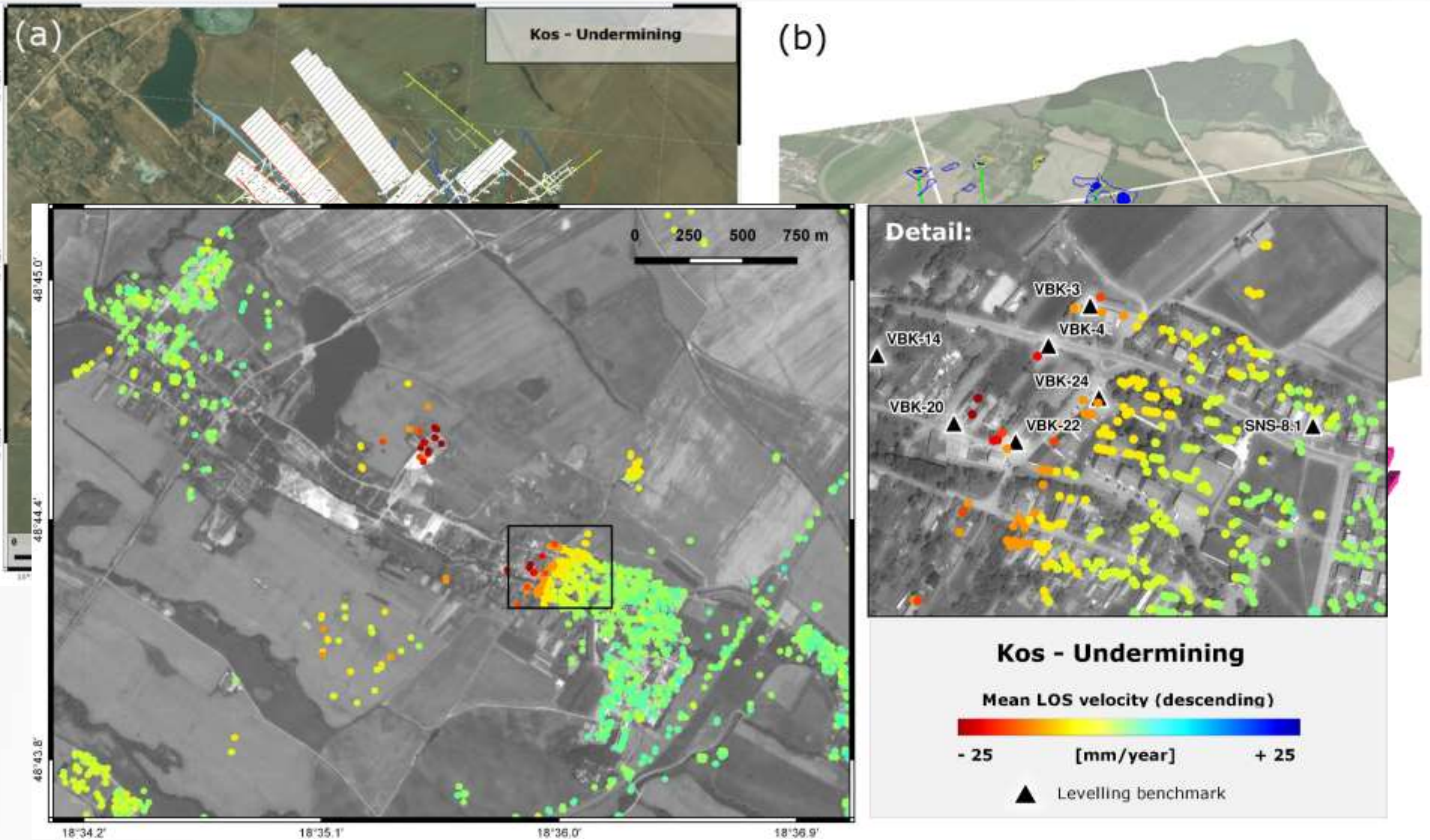
Collocation of InSAR measurements with other technique in:

a.) parameter space

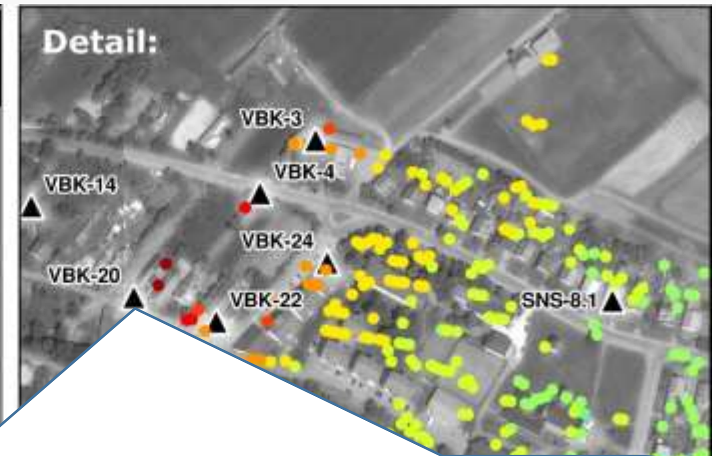
$$\Delta_p \Delta_t u = [u(p_1, t_1) - u(p_1, t_0)] - [u(p_0, t_1) - u(p_0, t_0)]$$

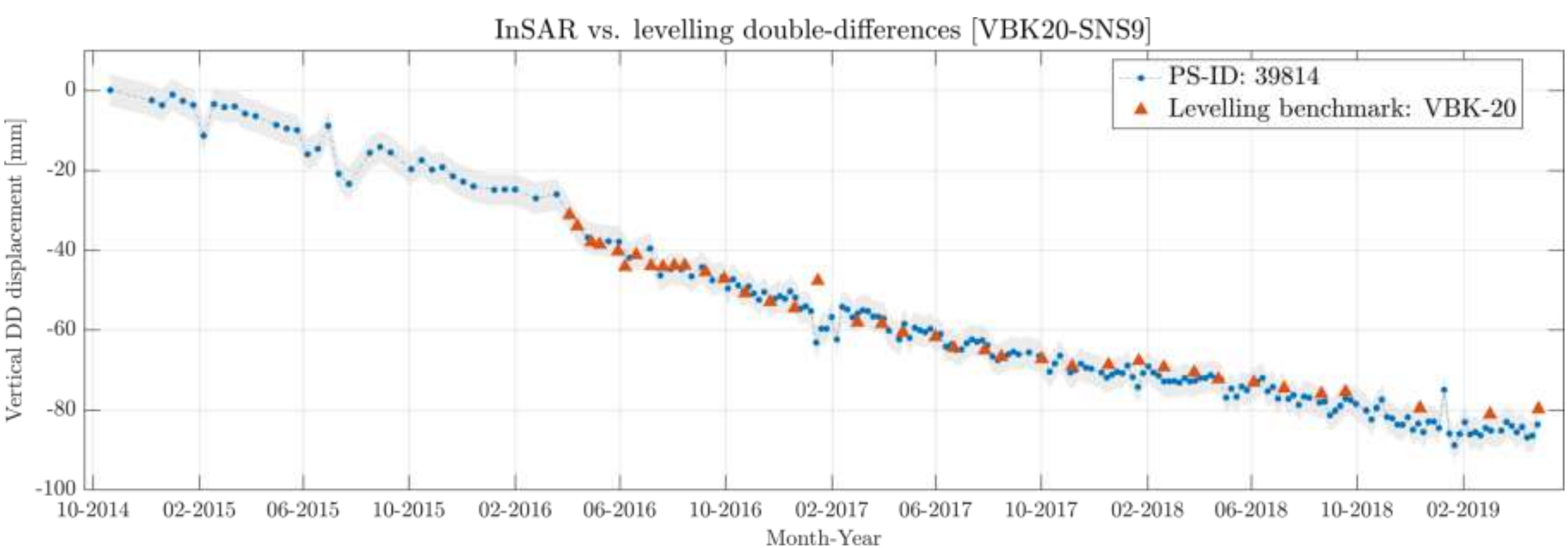
b.) observation space

InSAR & Levelling: Undermining subsidence



InSAR & Levelling

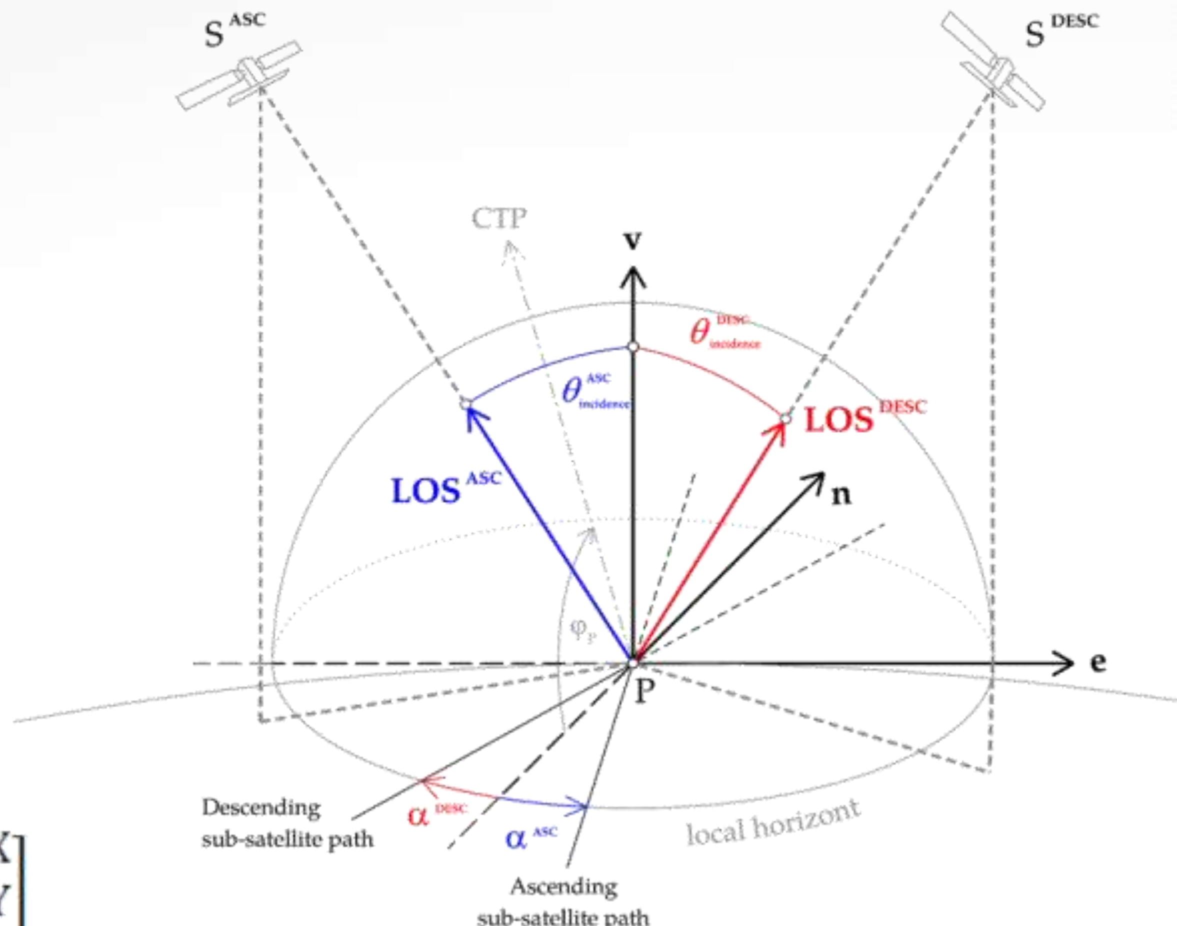




InSAR & GNSS

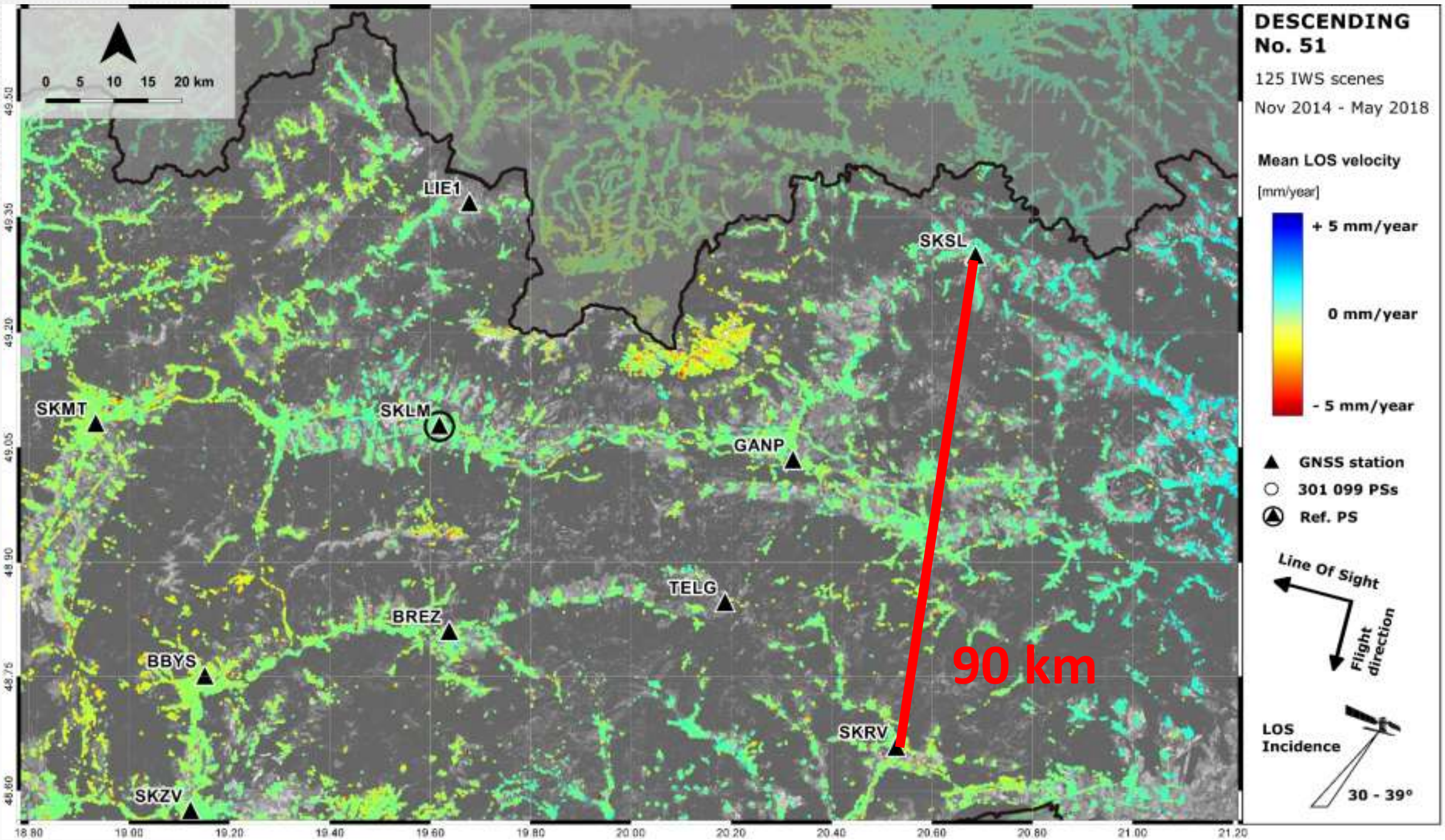
GNSS baselines:

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



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

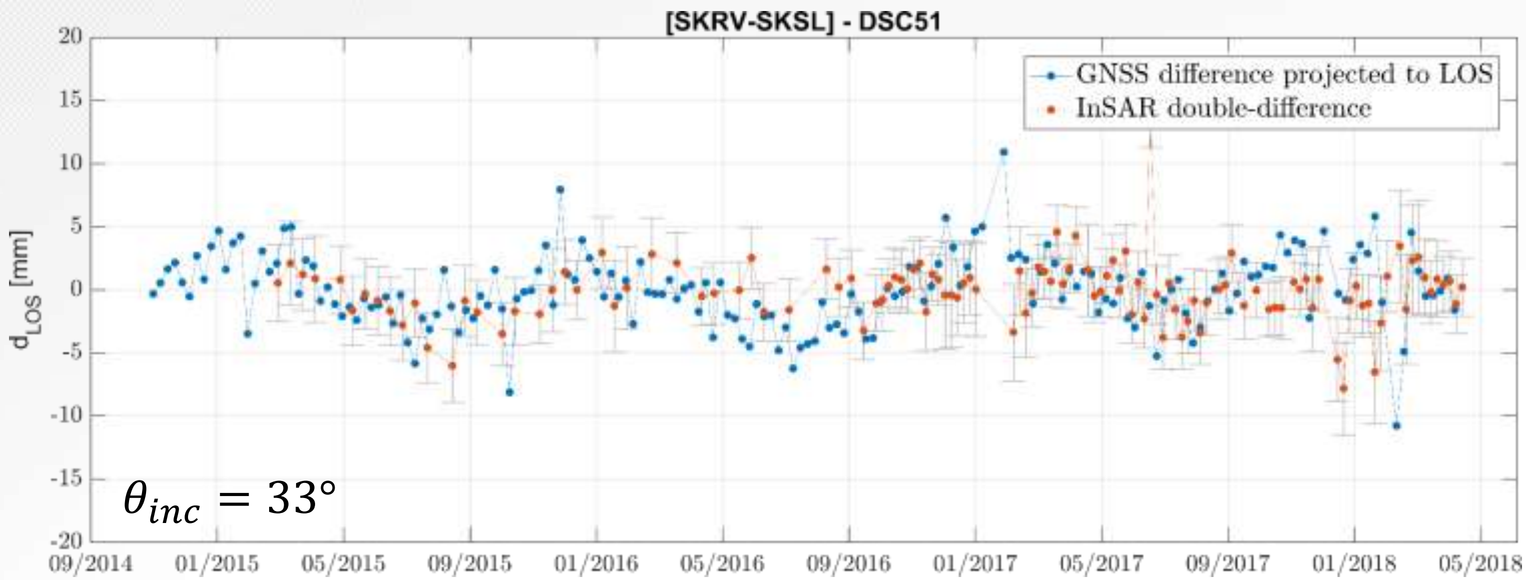
InSAR & GNSS



0 5 10 15 20 km
DESCENDING
No. 51
125 IWS scenes
Nov 2014 - May 2018
Mean LOS velocity
[mm/year]
+ 5 mm/year
0 mm/year
- 5 mm/year
GNSS station
301 099 PSs
Ref. PS
Line Of Sight
Flight direction
LOS Incidence
30 - 39°
LIE1
SKSL
SKMT
SKLM
GANP
TELG
BREZ
BBYS
SKRV
SKZV
90 km

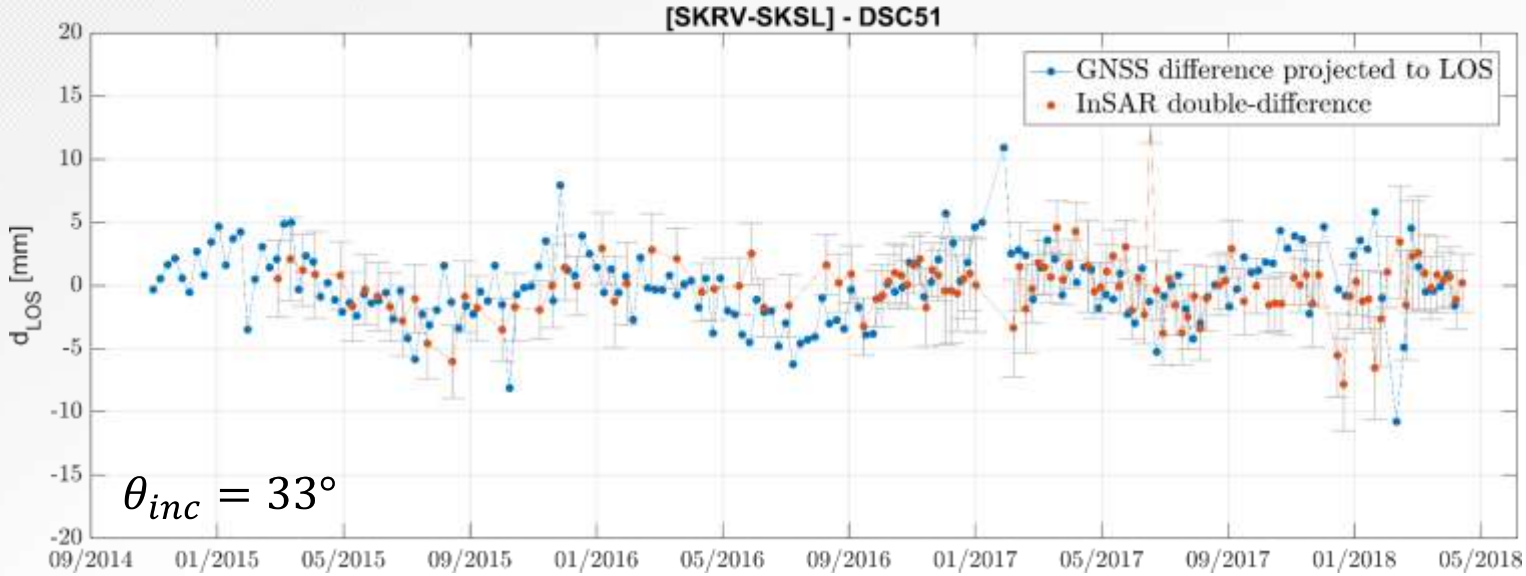
InSAR & GNSS

Descending 51

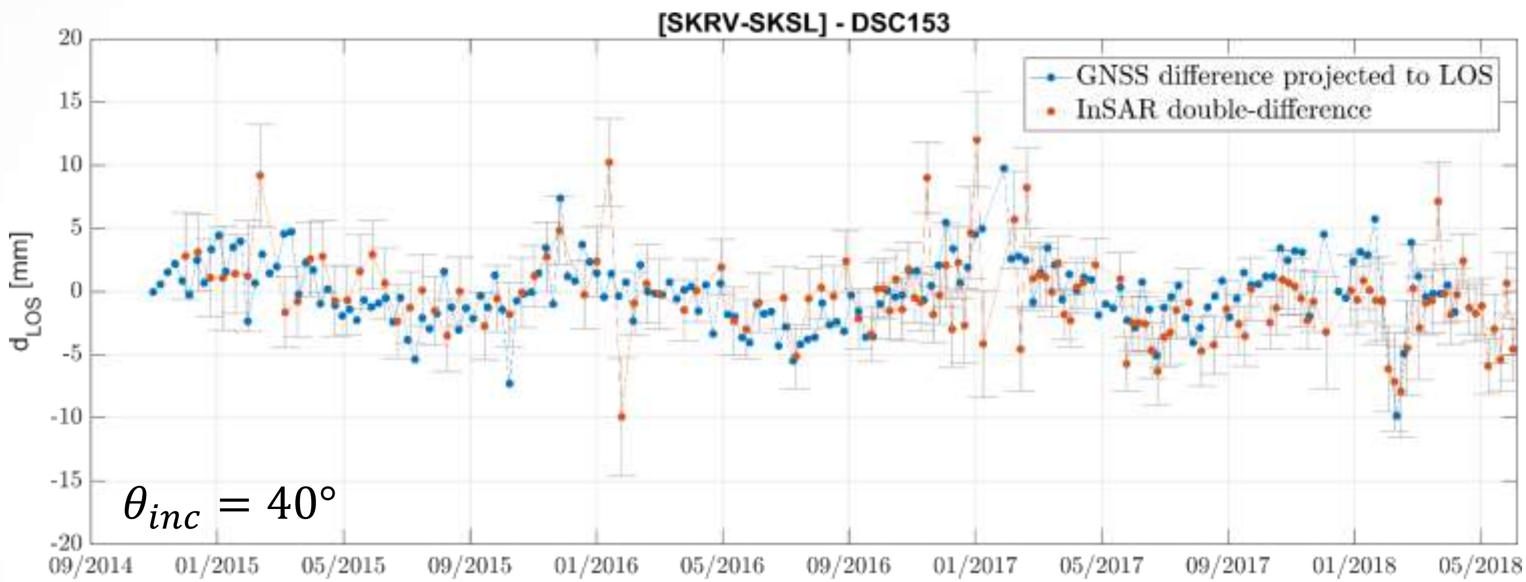


InSAR & GNSS

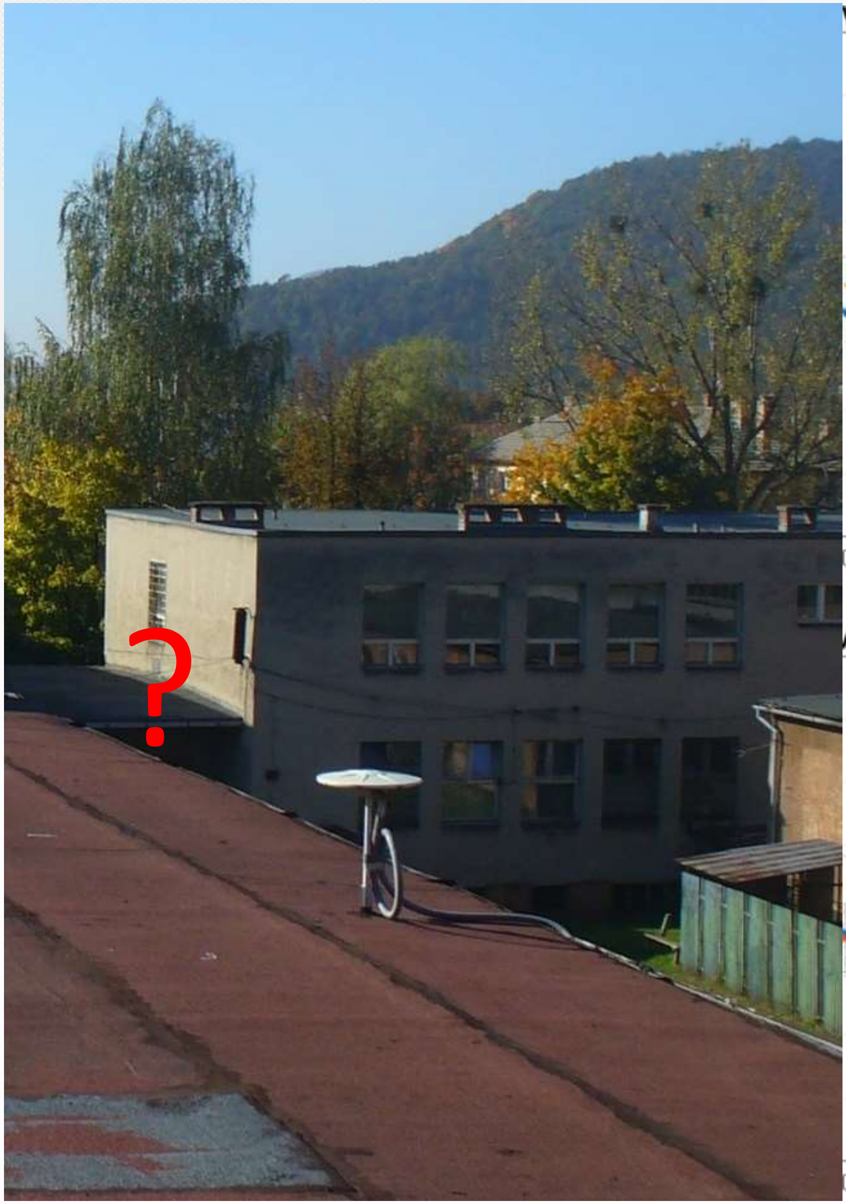
Descending 51



Descending 153



InSAR & GNSS



InSAR & GNSS/levelling 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

InSAR & GNSS/levelling collocation

Corner reflectors

Compact active transponders (CAT)

InSAR artificial reflectors

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

InSAR & GNSS collocation

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

METASENSING
Radar Solutions

Integrated geodetic reference station – IGRS

InSAR

GNSS

Levelling

Tachymetry

LiDAR

Gravimetry

Design:

TU Delft

Type:
DBF90T-GNSS

First InSAR & GNSS collocation site in SR

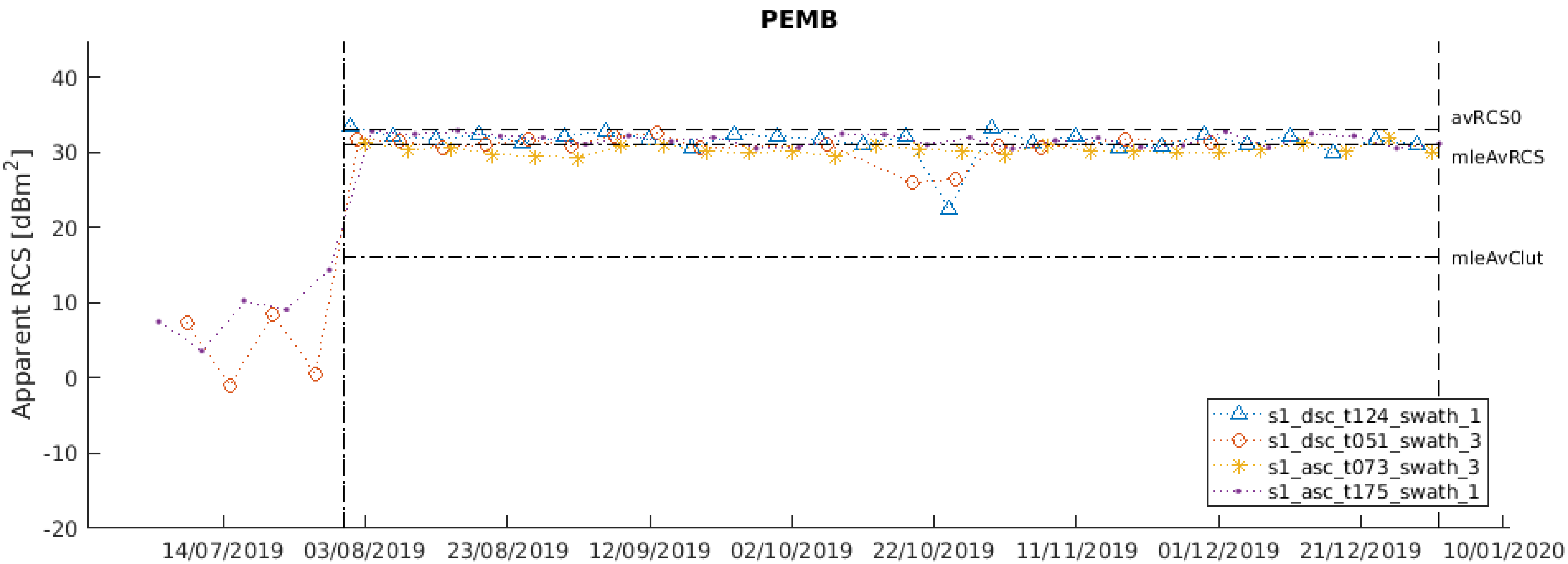
Date installed:

31.7.2019

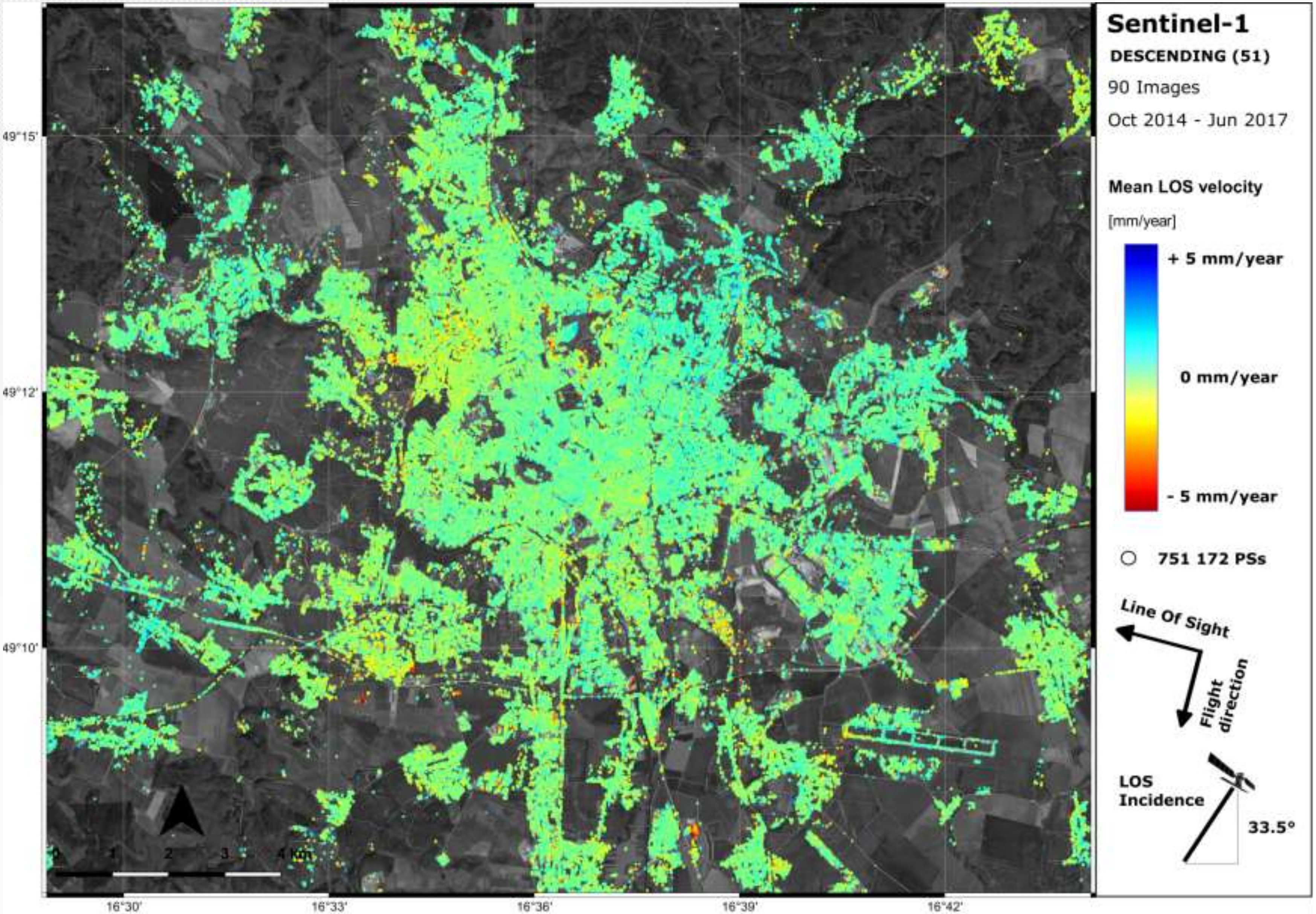
Hvezdáreň Partizánske

PEMB (PEM2)

First InSAR & GNSS collocation site in SR



Questions?


Sentinel-1
DESCENDING (51)
90 Images
Oct 2014 - Jun 2017
Mean LOS velocity
[mm/year]
+ 5 mm/year
0 mm/year
- 5 mm/year
751 172 PSs
Line Of Sight
Flight direction
LOS Incidence
33.5°
49°15'
49°12'
49°10'
16°30'
16°33'
16°36'
16°39'
16°42'
0
1
2
3
4 km

BACKUP SLIDES

Future

„InSAR measurements in a geodetic reference frame“

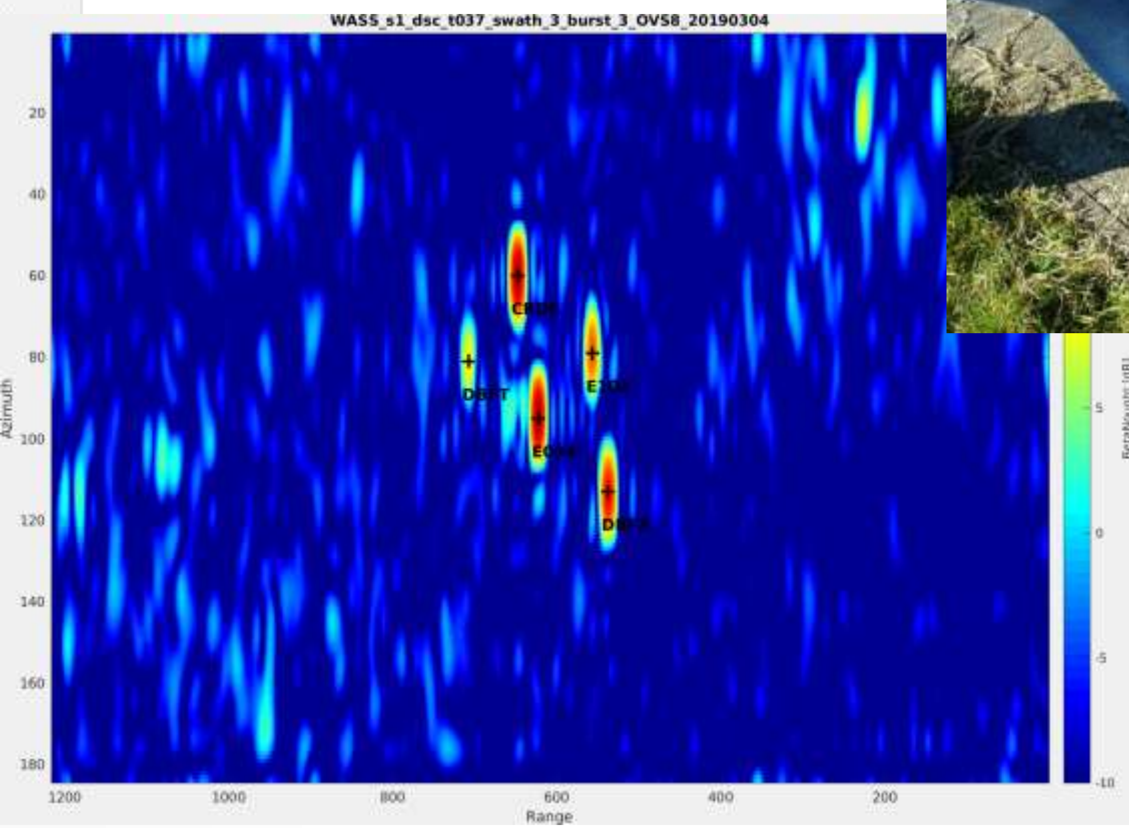
A.) Transformation of InSAR “datum-free networks” into a standard coordinate reference system (frame) via deployment of artificial SAR reflectors (passive/active) and their collocation with permanent GNSS measurements

B.) Standardization of InSAR quality control (precision/accuracy indicators) via further development of own time series processing chain (G-MaPIT)

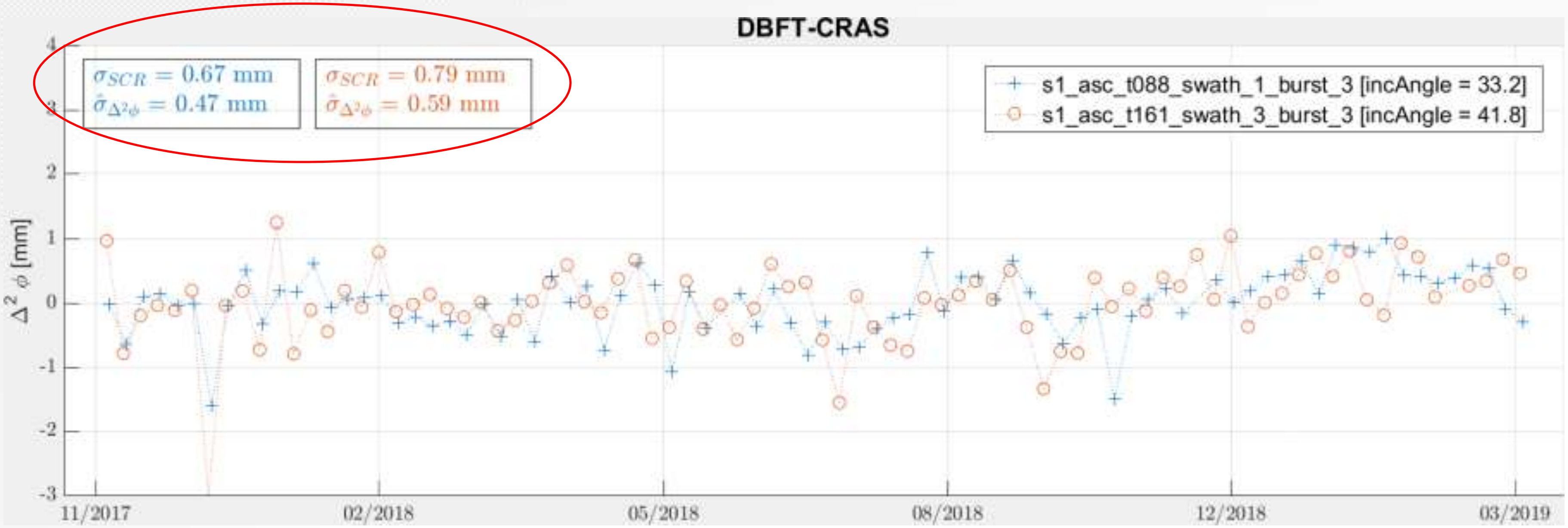
C.) Mitigation of atmospheric systematic effects via utilization of auxiliary data (GNSS-derived tropospheric products and numerical weather models)

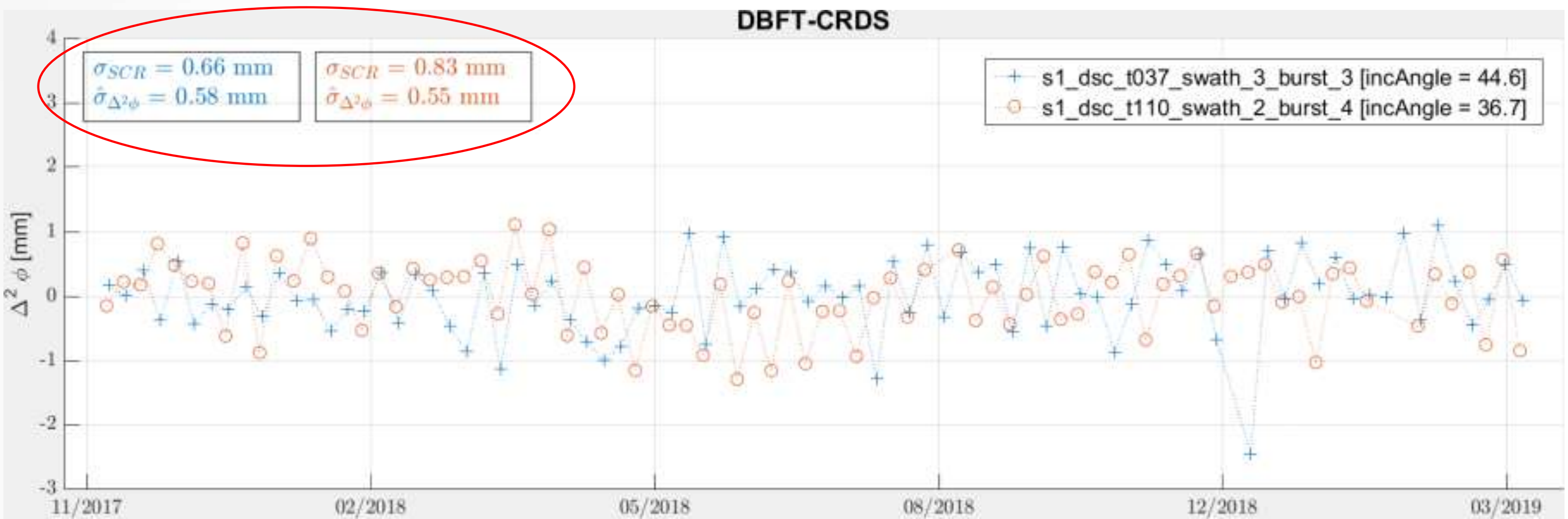
ECR-Cs testing

	E094 [RCS]	E104 [RCS]
asc_t088_swath1 (incAngle = 33.2deg, azAngle = 258.8deg)		
20190301	40.56	–
20190307	40.43	42.48
20190313	–	–
20190319	–	–
asc_t161_swath3 (incAngle = 41.8deg, azAngle = 260.5deg)		
20190228	38.37	39.14
20190306	–	–
20190312	–	–
20190318	–	–



InSAR analysis – Wassenaar test site





1st order network solution

Functional model for PS „i“:

$$E\{\boldsymbol{\phi}_i\} = \frac{4\pi}{\lambda R \sin\theta} \boldsymbol{B}_\perp h_i + \frac{4\pi}{\lambda} f(\boldsymbol{t} - t_0)\ d_{LOS,i} + 2\pi\ \boldsymbol{a} \qquad D\{\boldsymbol{\phi}_i\} = \boldsymbol{\Sigma}_{\phi_i}$$

function of geometry — function of time — vector of ambiguities

- Transition to phase double-differences

1st order network solution – ambiguity resolution

Functional model for PS „i“:

$$\mathrm{E}\{\boldsymbol{\phi}_i\} = \frac{4\pi}{\lambda R \sin\theta} \boldsymbol{B}_\perp h_i + \frac{4\pi}{\lambda} f(\boldsymbol{t} - t_0)\ d_{LOS,i} + 2\pi\ \boldsymbol{a}$$

Functional model for “arc” between PS „i“ and PS „j“:

$$\boldsymbol{\Delta\phi}_{i,j} = \boldsymbol{\alpha}\ \Delta h_{i,j} + \boldsymbol{\beta}\ \Delta d_{i,j} + 2\pi\ \boldsymbol{a}_{\boldsymbol{i},\boldsymbol{j}}$$

BLUE solution: **Integer least-squares** (e.g. LAMBDA method)

Remark:
Atmospheric phase cannot be included within functional model –
its just partially reduced by solving short “arcs” - inc. in stochastic model

APS estimation

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

- 1st order PS network residuals:

$$\boldsymbol{\phi}_i - \widehat{\boldsymbol{\phi}}_{i,model} = \boldsymbol{\phi}_{unmodeled\,Defo} + \boldsymbol{\phi}_{atmo,t_i} + \boldsymbol{\phi}_{noise}$$

- isolated from residuals by spatio-temporal filtering:

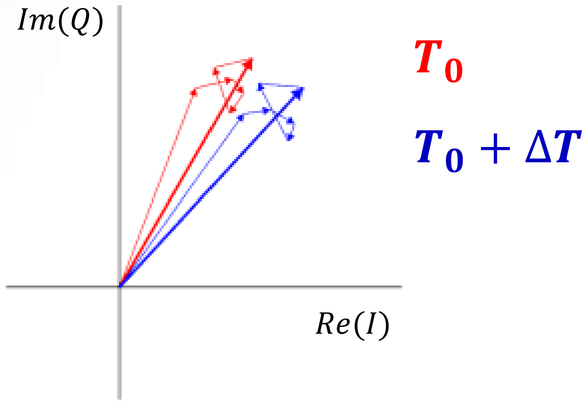
$$\widehat{\boldsymbol{\phi}}_{atmo,t_i} = \left[\left[\boldsymbol{\phi}_i - \widehat{\boldsymbol{\phi}}_{i,model}\right]_{\mathrm{HP\_time}}\right]_{\mathrm{LP\_space}}$$

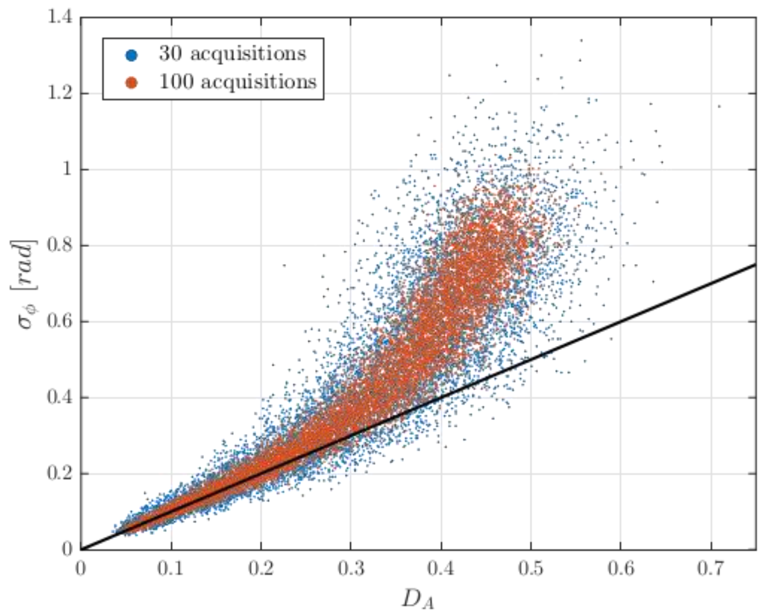
- significant spatial wavelengths of APS estimated within 1st order network by variogram (empirical covariance function of atmo.)

Detection & estimation problem

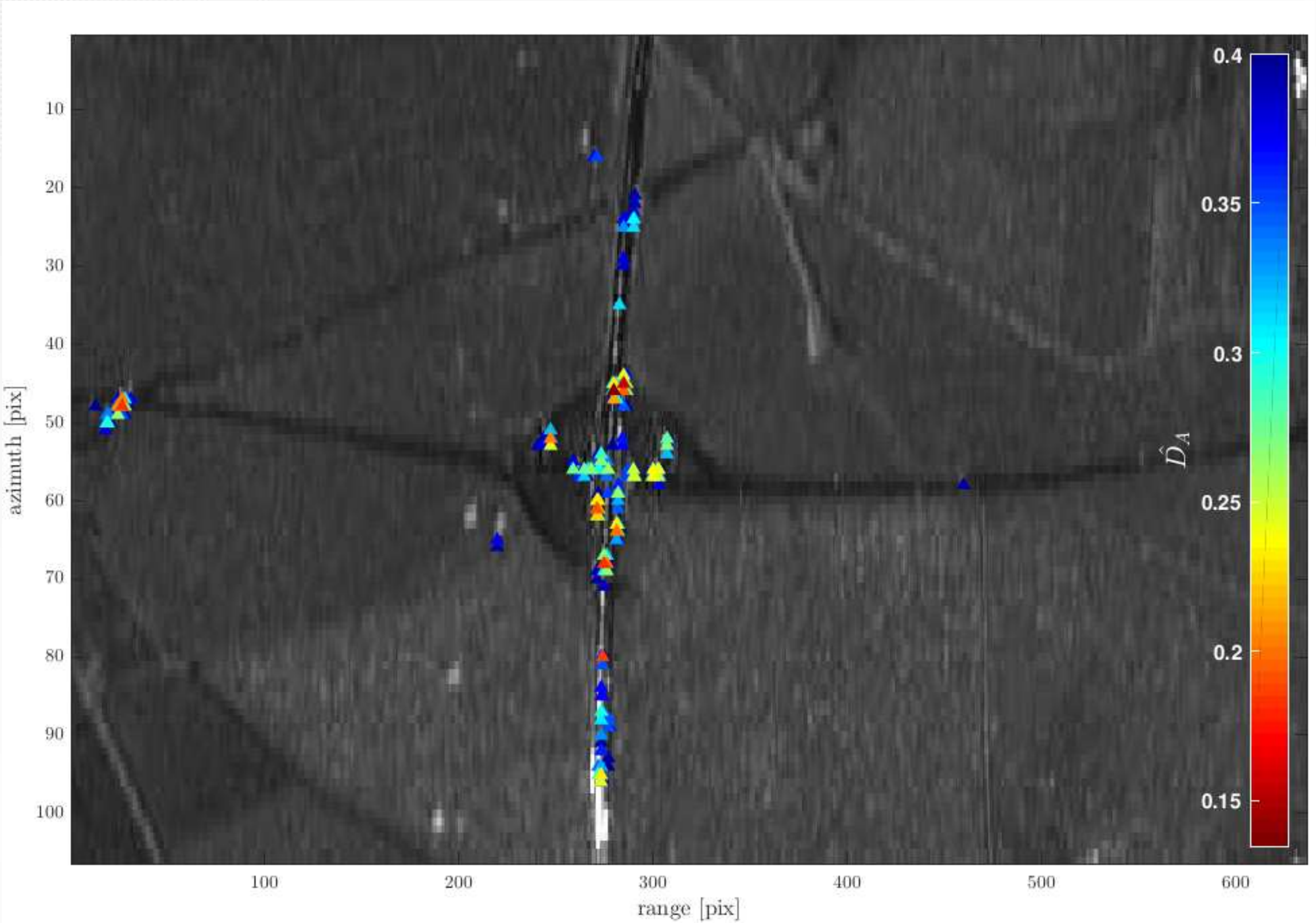
Persistent Scatterer Candidates (PSC)

- Cannot use coherence (“phase dispersion”) for PS selection because phase contains ambiguity (is wrapped) $(0,2\pi)$!
- Amplitude dispersion as a proxy for coherence

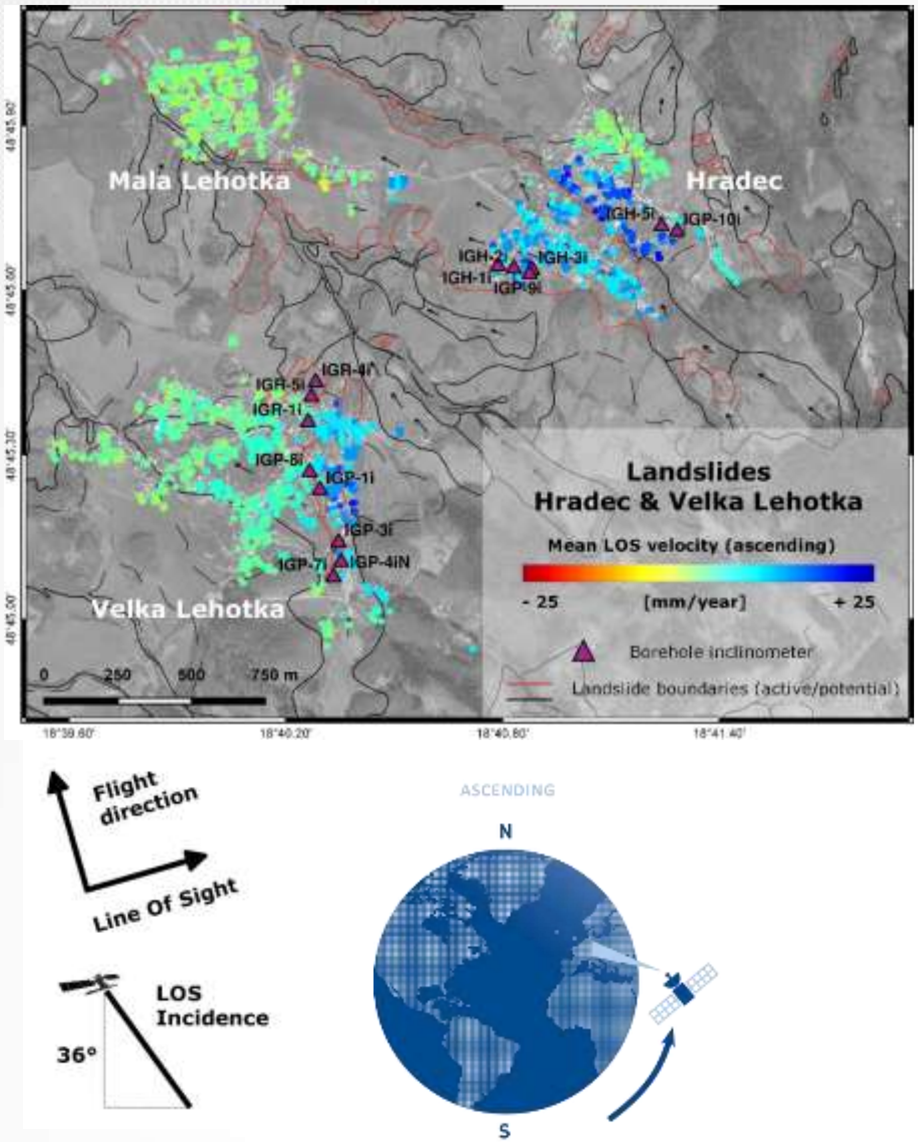


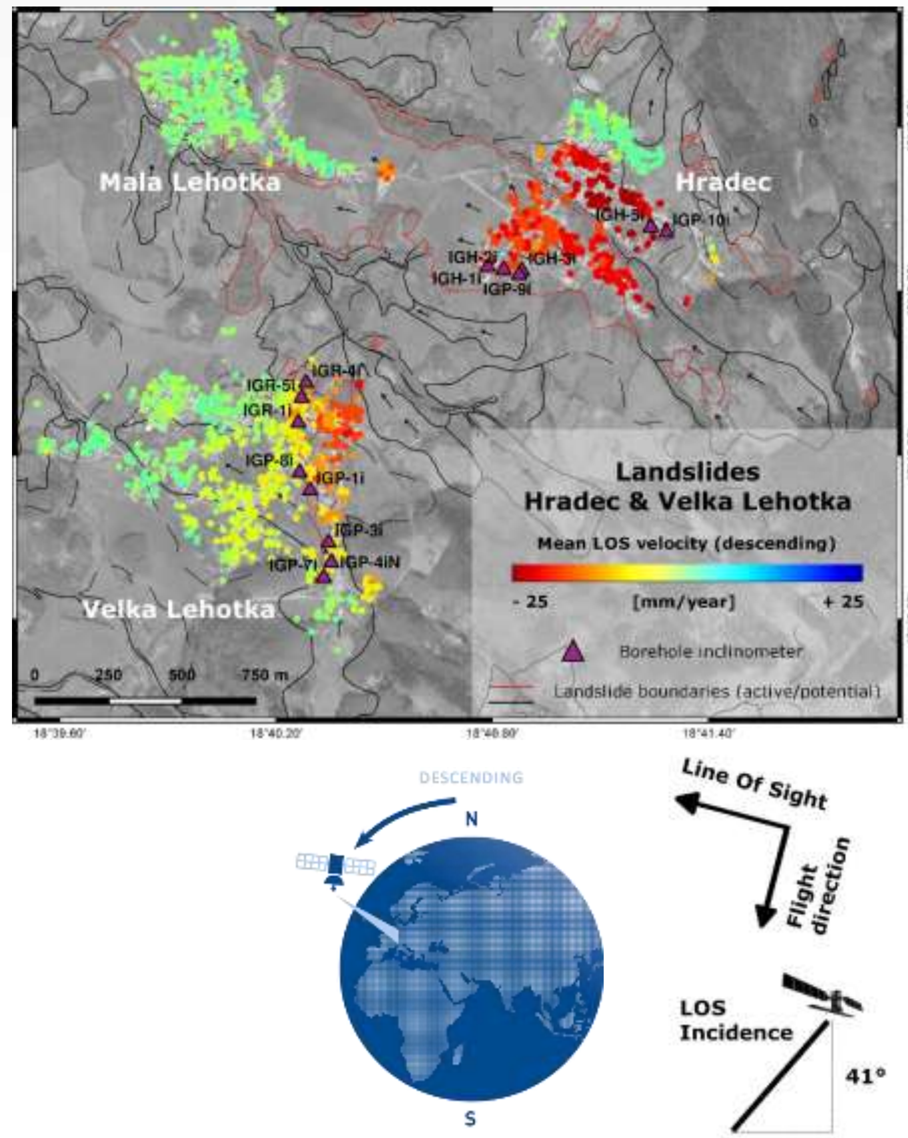


Persistent Scatter Candidates (PSC)

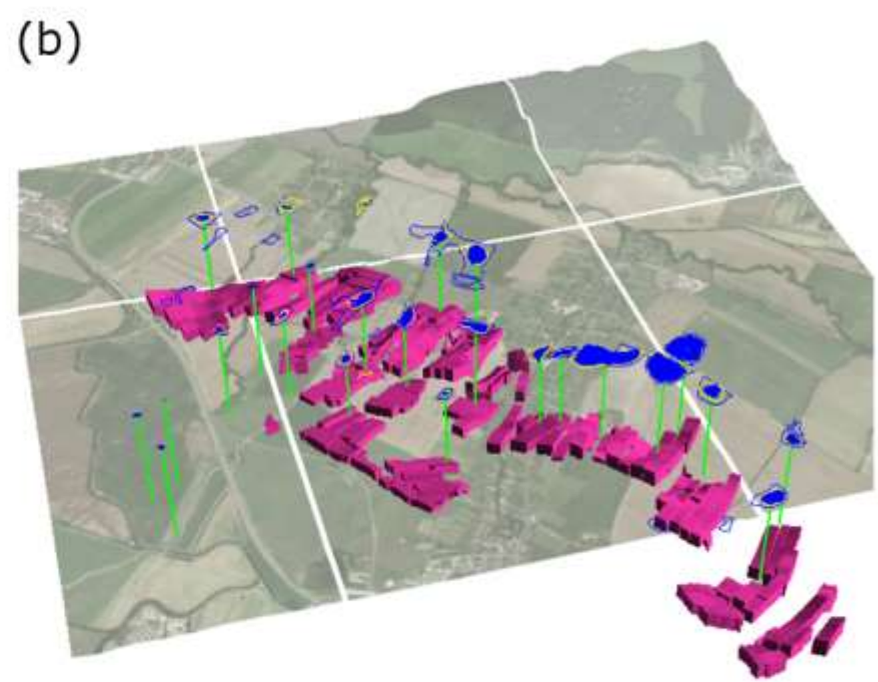


Local monitoring: Landslides





Local monitoring: Undermining subsidence



Atmospheric phase

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

$$\phi_{atmo} = \psi_{atmo,t_0} - \psi_{atmo,t_i}$$

$$\phi_{atmo} = \phi_{iono} + \phi_{tropo}$$

Ionosphere

C-band (5.6 cm) sparingly affected

Long spatial wavelengths
(~ 100s of km)

Troposphere

Dry + wet component

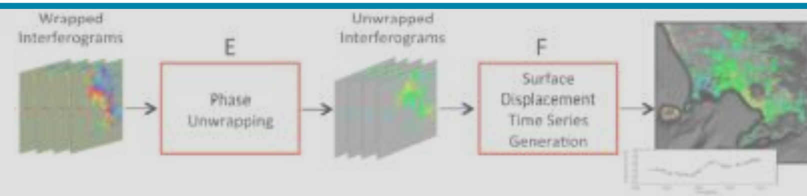
- turbulence
- stratification

Relatively short spatial wavelengths (~ 10s of km)

Time-series (Multi-temporal) InSAR

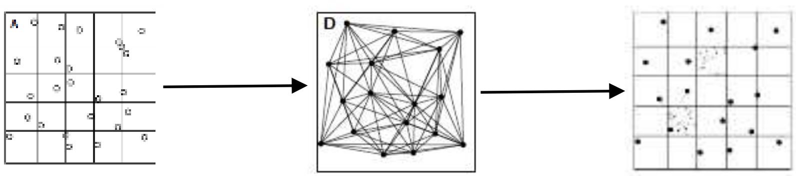
How to extract displacement time series from wrapped phase time series of PS?

a.) „Geophysical“ approach



- questionable assumptions, model-oriented approach
- image processing / signal processing
- lack of relevant quality indicators

b.) „Geodetic“ approach

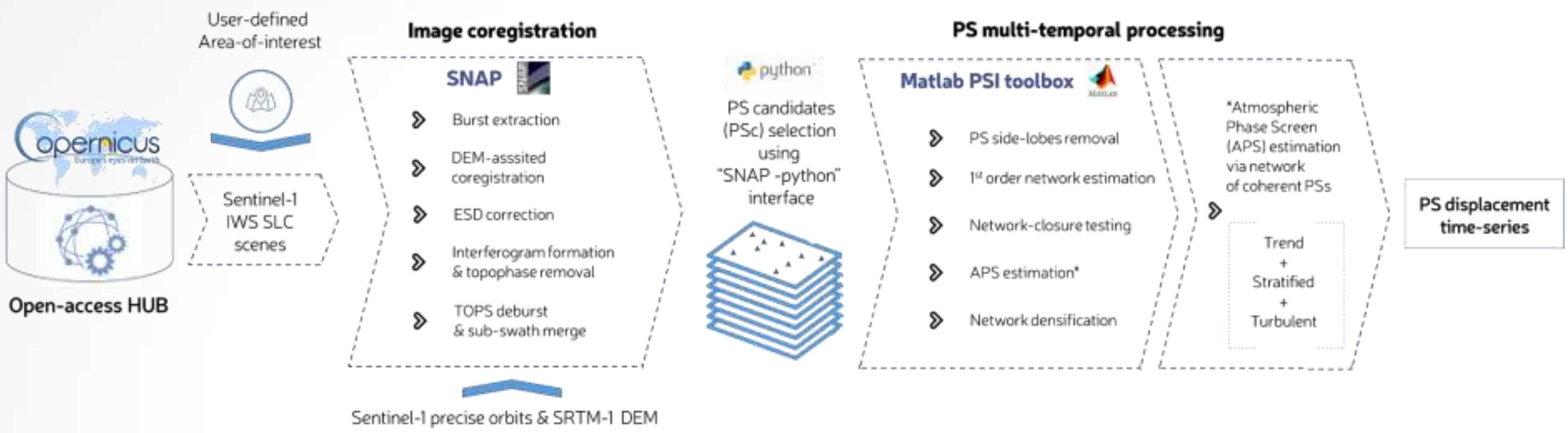


- „Delft school“
- geodetic estimation theory
  (propagation of stochastic properties - VC matrices)

TU Delft

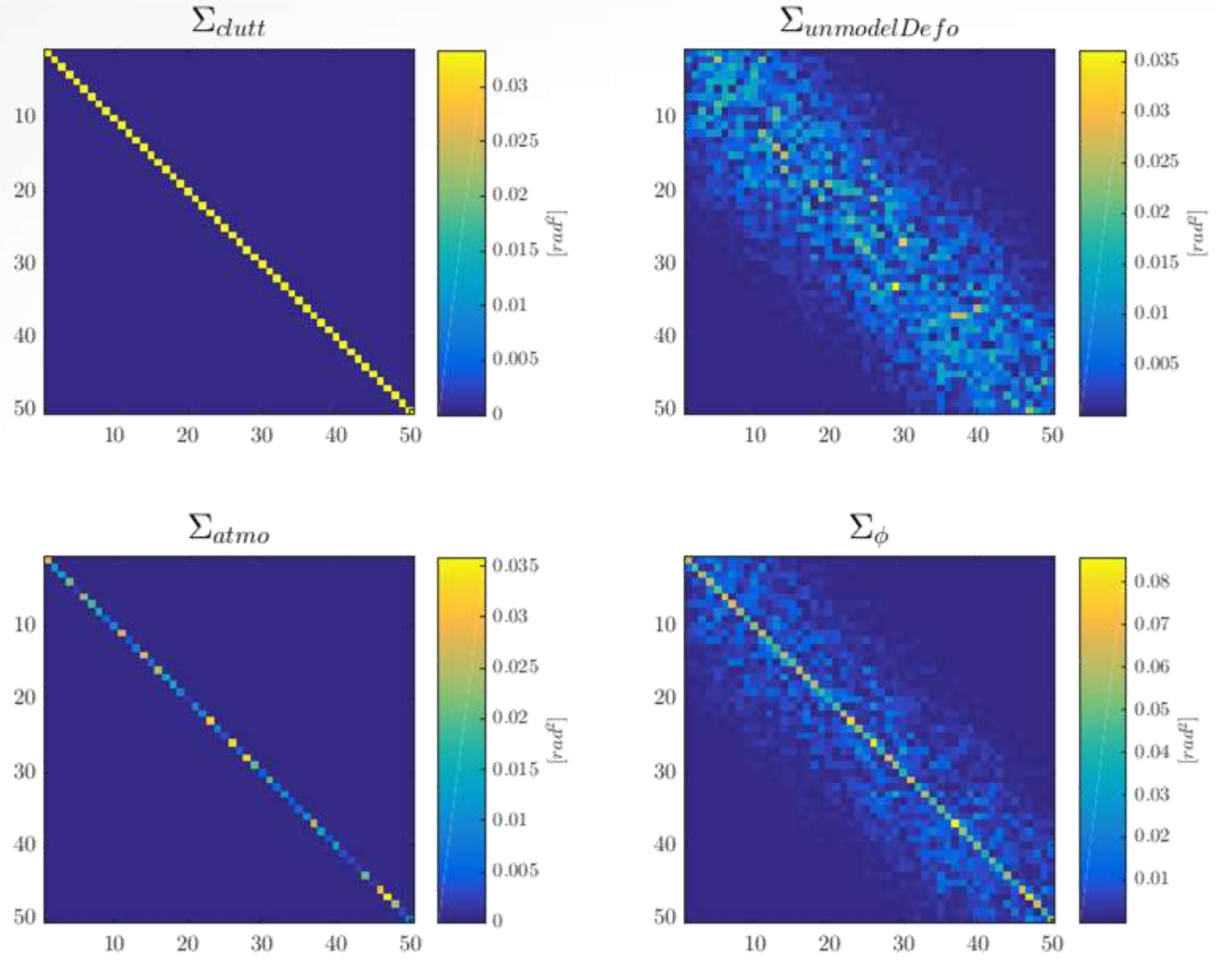
Own software implementation

Geodetic MATLAB & Python-based InSAR toolbox (**G-MaPIT**)

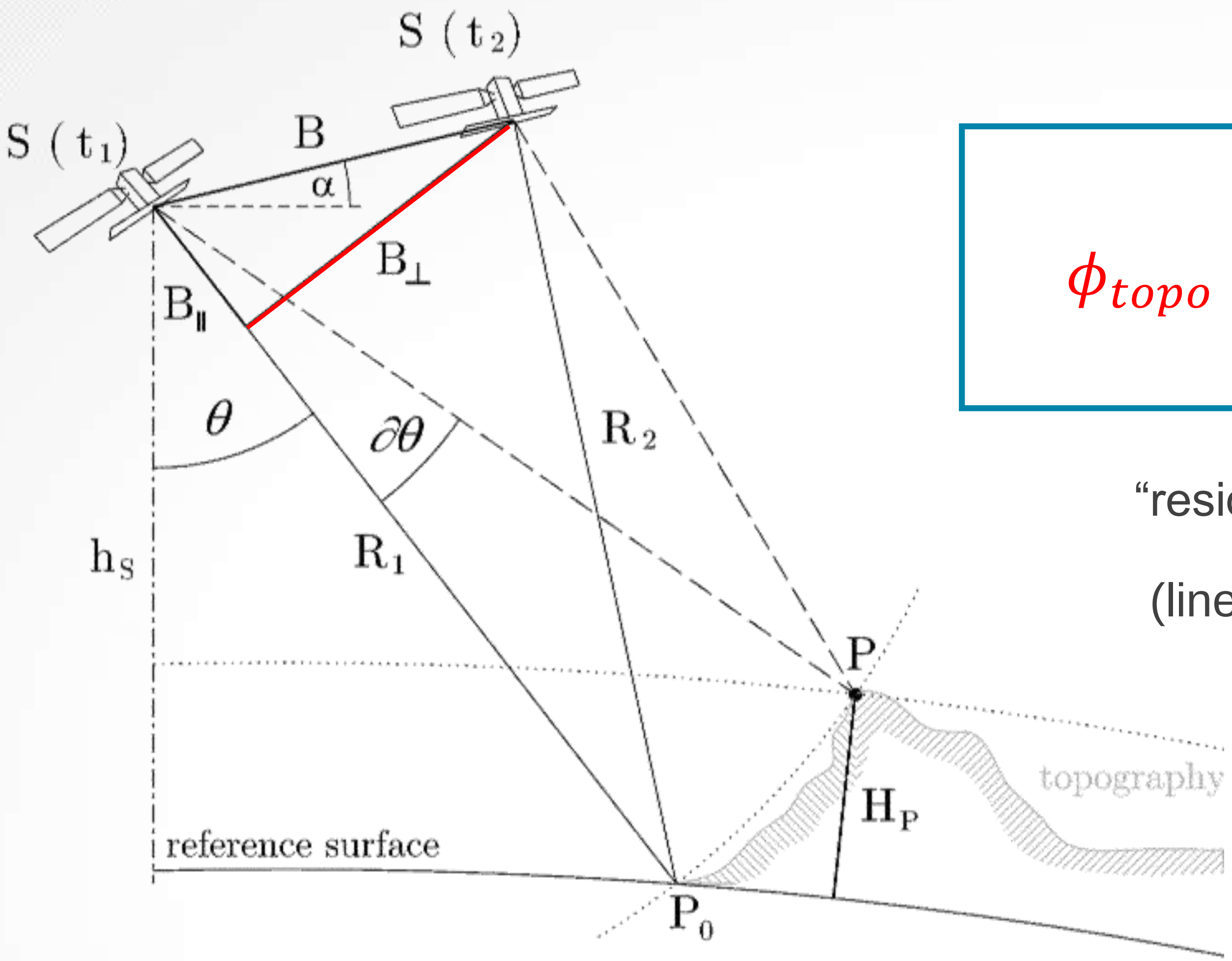


APS estimation

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



Reference (Topography) phase

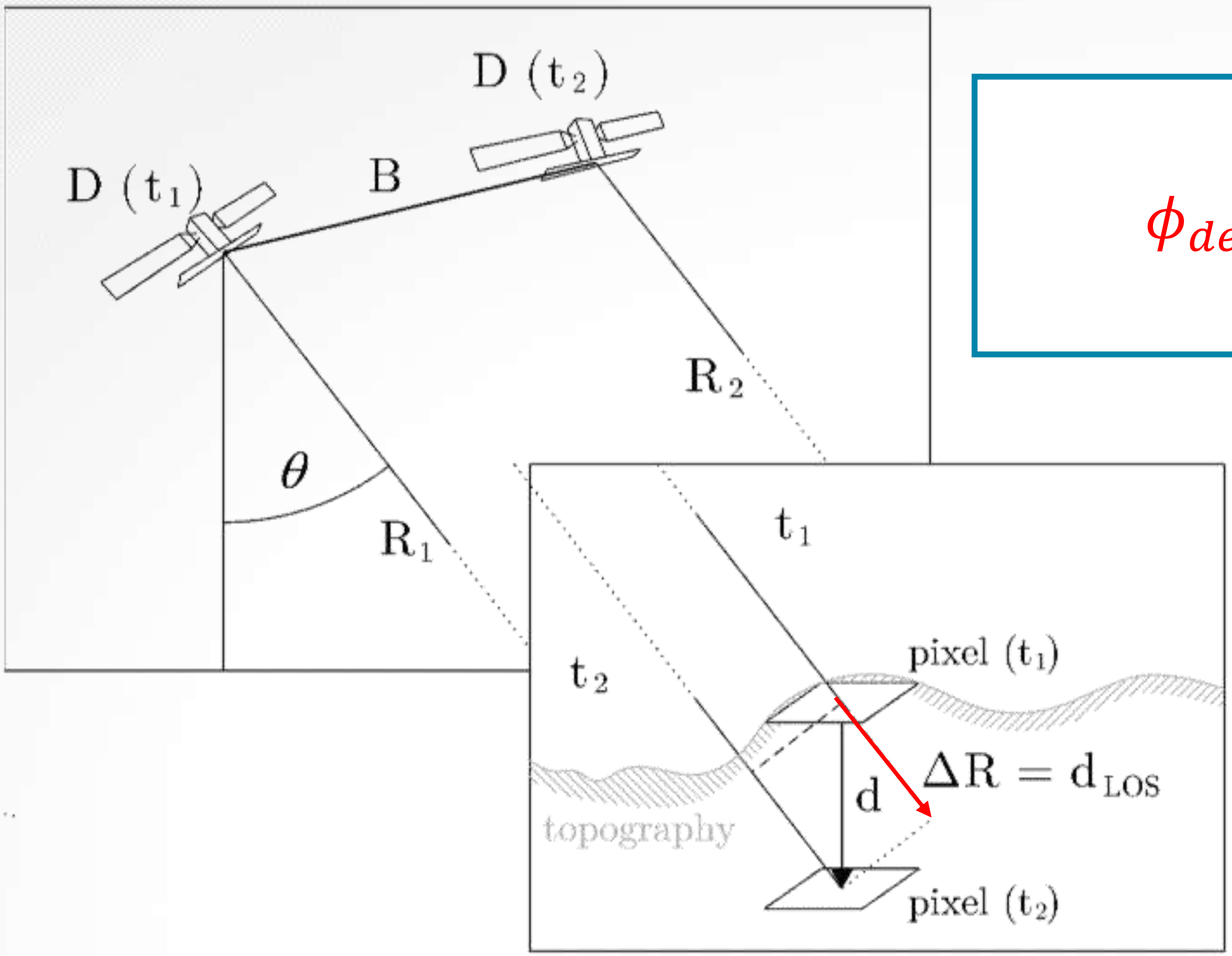


$$\phi_{topo} = \frac{4\pi}{\lambda}\frac{B_{\perp}}{R\sin\theta}H_P$$

"residual" topography

(linearized by DEM)

Displacement phase (LOS geometry)



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