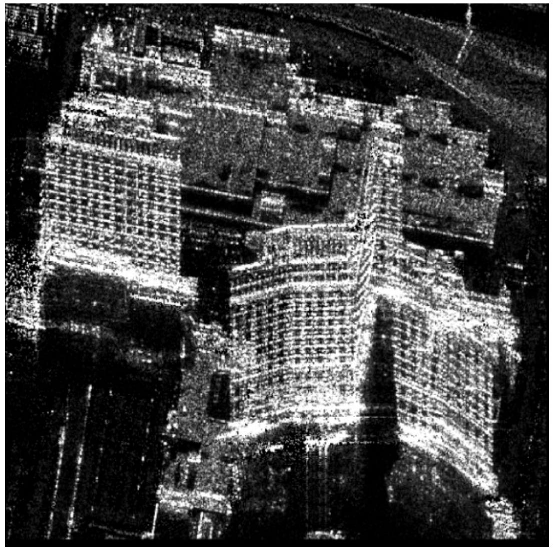
Deformation Monitoring of Urban Infrastructure by Tomographic SAR Using Multi-View TerraSAR-X Data Stacks

Sina Montazeri[1], Xiao Xiang Zhu[1,2], Michael Eineder[1,2], Ramon F. Hanssen[3], Richard Bamler[1,2]

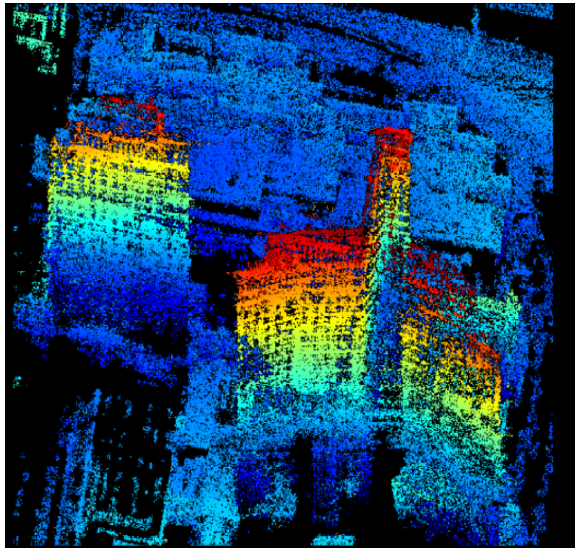
(1) German Aerospace Center (DLR)
(2) Technical University of Munich (TUM)
(3) Delft University of Technology (TU Delft)

TomoSAR Urban Imaging

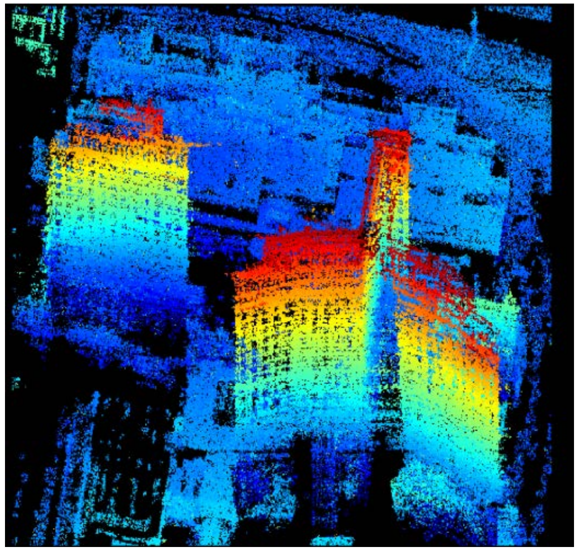
- Multi-baseline InSAR approach
- Layover separation capability
- Up to 10^6 points/km^2 achievable with meter-resolution SAR data
- Non-linear and multi-component motion (e.g. linear subsidence and thermal seasonal deformation) can be accounted for → LOS deformation



Mean intensity map



Single scatterers map



Single and double scatterers map

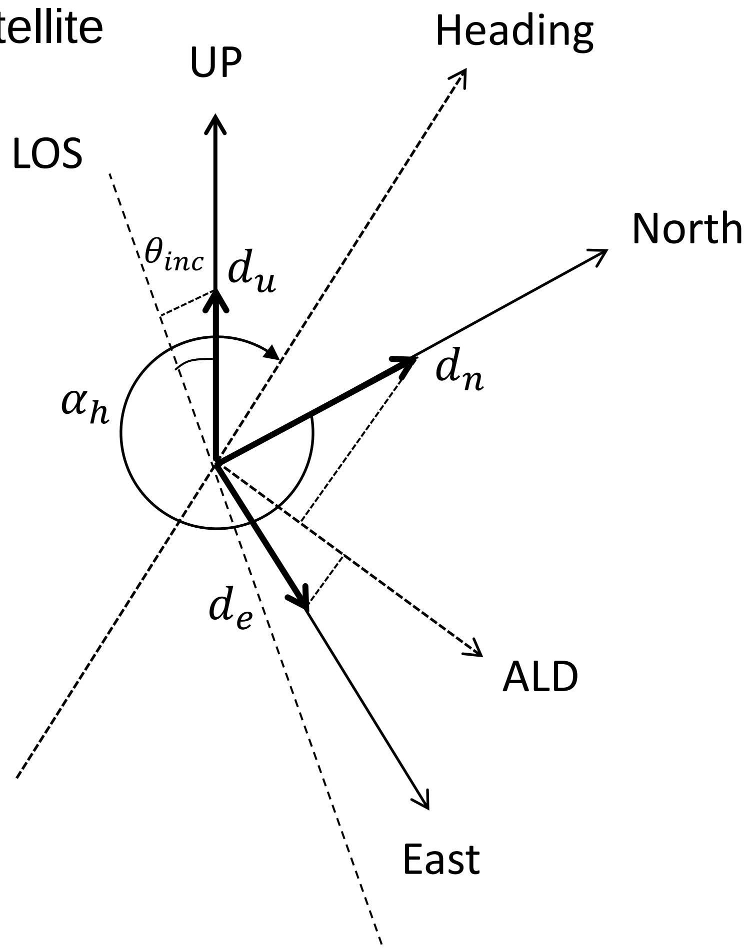
Source: Zhu, 2011

InSAR LOS Deformation

- InSAR provides deformation estimates projected onto the LOS of the satellite (One-dimensional deformation)

$$d_{LOS} = d_u \cos(\theta_{inc}) - d_e \cos(\alpha_h) \sin(\theta_{inc}) + d_n \sin(\alpha_h) \sin(\theta_{inc})$$

d_{LOS}	LOS deformation
d_u	Motion component in vertical direction
d_e	Motion component in east-west direction
d_n	Motion component in north-south direction
θ_{inc}	Local incidence angle of satellite beam
α_h	Azimuth angle of the satellite



LOS deformation estimates from, at least, three geometries → Retreival of d_u, d_e, d_n

InSAR LOS Deformation

- Considering near-polar orbits of TerraSAR-X, for instance:
  - Heading angle ($\alpha_h = 190.6°$)
  - Incidence angle ($\theta_{inc} = 36.1°$)

$$[0.8\ 0.58\ -0.1][\ d_u\ d_e\ d_n]^T$$

- Should not lead to ignorance of d_n in the functional model of 3D motion retrieval

$$\Delta_e = d_n \cdot \tan(\alpha_h) \approx 18\ \%\ d_n$$

Bias in estimated d_e

Why motion decomposition?

Tomographic data available from **one** viewing geometry:

- One-dimensional LOS deformation
- No information on the shadowed part

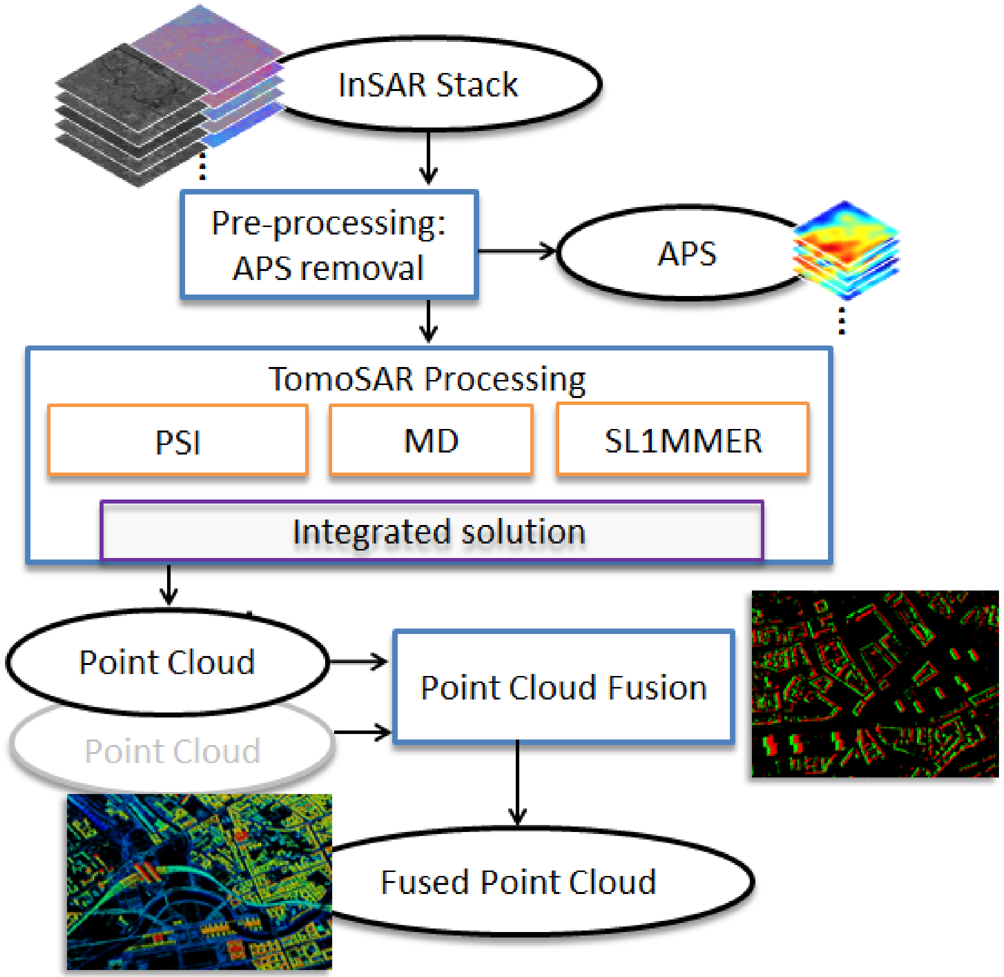
Tomographic data available from **Multiple** viewing geometries:

- Decomposed horizontal and vertical motion
- Shadow-free deformation monitoring
- Higher number of scatterers on each building

Workflow

- Required data: Stacks available from cross-heading tracks
- TomoSAR processing of each SAR image stack and geocoding
- Geodetic point cloud fusion
- Motion decomposition from the available LOS measurements

Tomo-GENESIS Processing System



New features:

- SL1MMER for SR
- Time Warp method
- Integrated solution
- Point clouds fusion

PSI-GENESIS: Adam et.al 2005

Tomo-GENESIS: Zhu et.al 2013

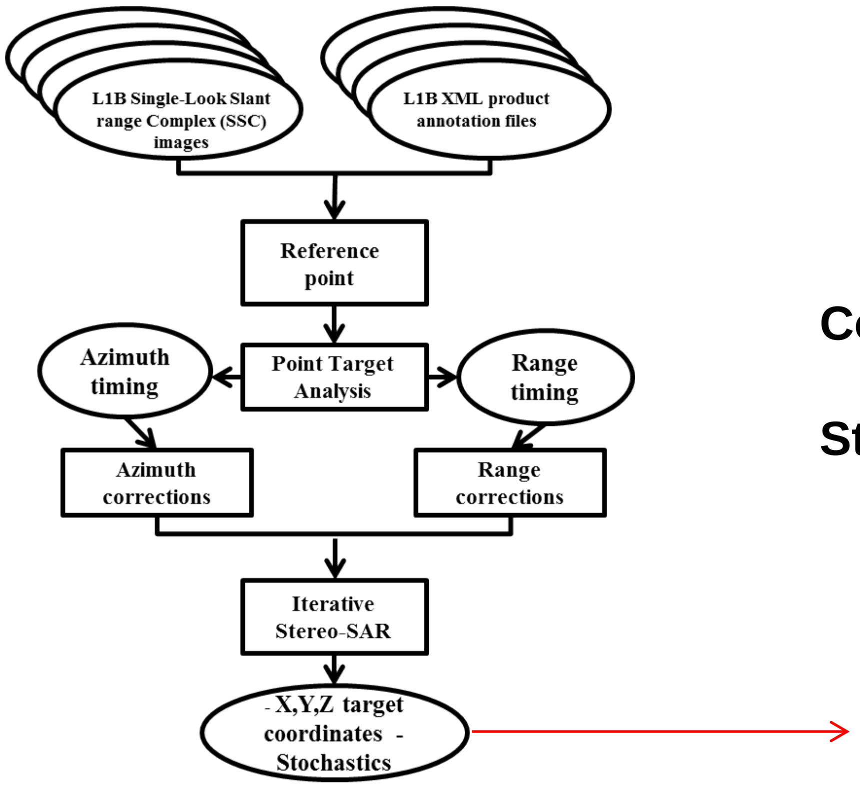
Point Cloud Fusion

- TomoSAR point clouds from different acquisition geometries cannot be directly merged:
  - Unknown height of the reference point in each stack
- Available *geometrical* fusion algorithms
  - Least squares identical point matching (**Gernhardt et.al, 2012**)
  - Feature-based building end-point matching (**Wang and Zhu, 2014**)

How about geodetic point cloud fusion?

Geodetic Point Cloud Fusion

- Based on an **absolutely localized identical reference point** for all the TomoSAR stacks



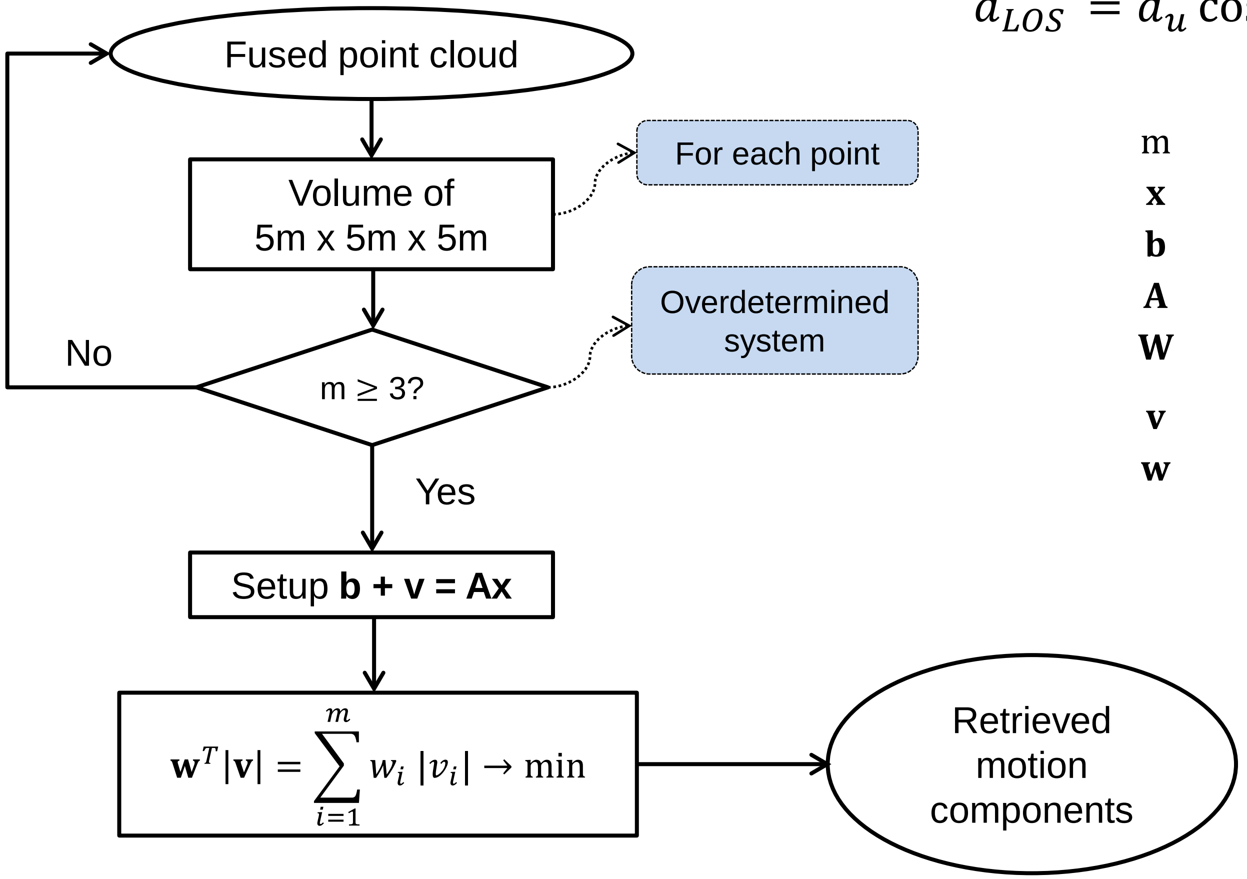
Corrections: Atmospheric and geodynamic effects

Stereo-SAR: Combination of absolute SAR measurements

Elevation and deformation estimates of all the stacks are w.r.t this point

Source: Eineder et.al, TGRS 2011
Source: Zhu et.al, IGARSS 2014
Source: Gisinger et.al, TGRS 2015

Motion Decomposition



$$d_{LOS} = d_u \cos(\theta_{inc}) - d_e \cos(\alpha_h) \sin(\theta_{inc}) + d_n \sin(\alpha_h) \sin(\theta_{inc})$$

m	Number of points inside the cube
$\mathbf{x}$	Unknown vector consist of (d_u, d_e, d_n)
$\mathbf{b}$	Observation vector consist of TomoSAR LOS deformations
$\mathbf{A}$	Design matrix based on (θ_{inc}, α_h)
$\mathbf{W}$	Weight matrix proportional to inversed squared distances
$\mathbf{v}$	Vector of residuals
$\mathbf{w}$	Vector consists of diagonal elements of $\mathbf{W}$

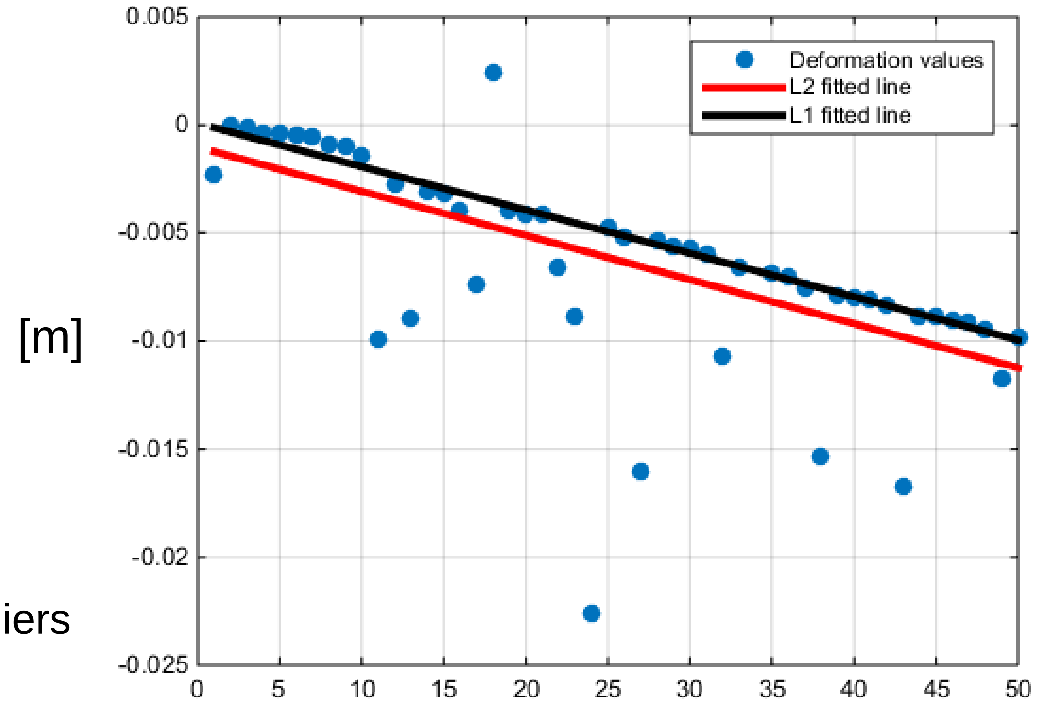
Why L1 Norm Instead of L2?

- L2 norm minimization (Least squares):

$$\mathbf{v}^{\mathrm{T}}\,\mathbf{W}\,\mathbf{v} = \sum_{i=1}^{m} v_i\,\mathbf{W}_{i,i}\,{v_i}^{\mathrm{T}} \rightarrow \min$$

- L1 norm minimization

$$\mathbf{w}^{T}|\mathbf{v}| = \sum_{i=1}^{m} w_i\,|v_i| \rightarrow \min$$ → Robust against outliers

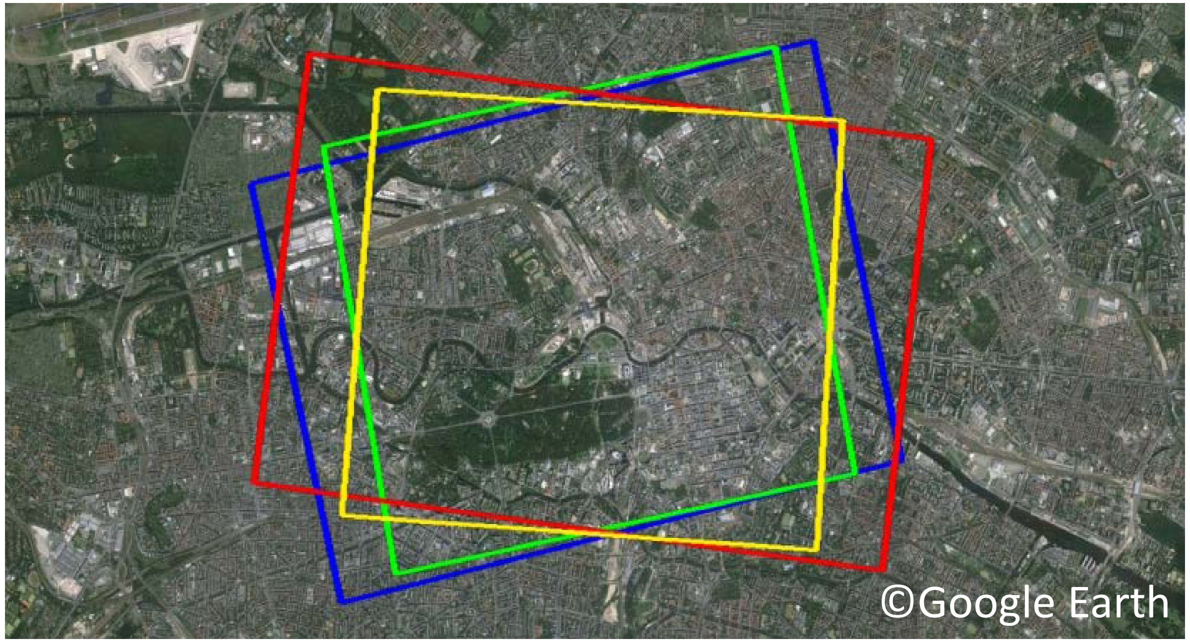


Experimental Results

Dataset and Test Area

- Central area of Berlin, Germany
- Four stacks of TerraSAR-X VHR spotlight images (300MHz)
- Period: March 2008 to March 2013

Scene coverage

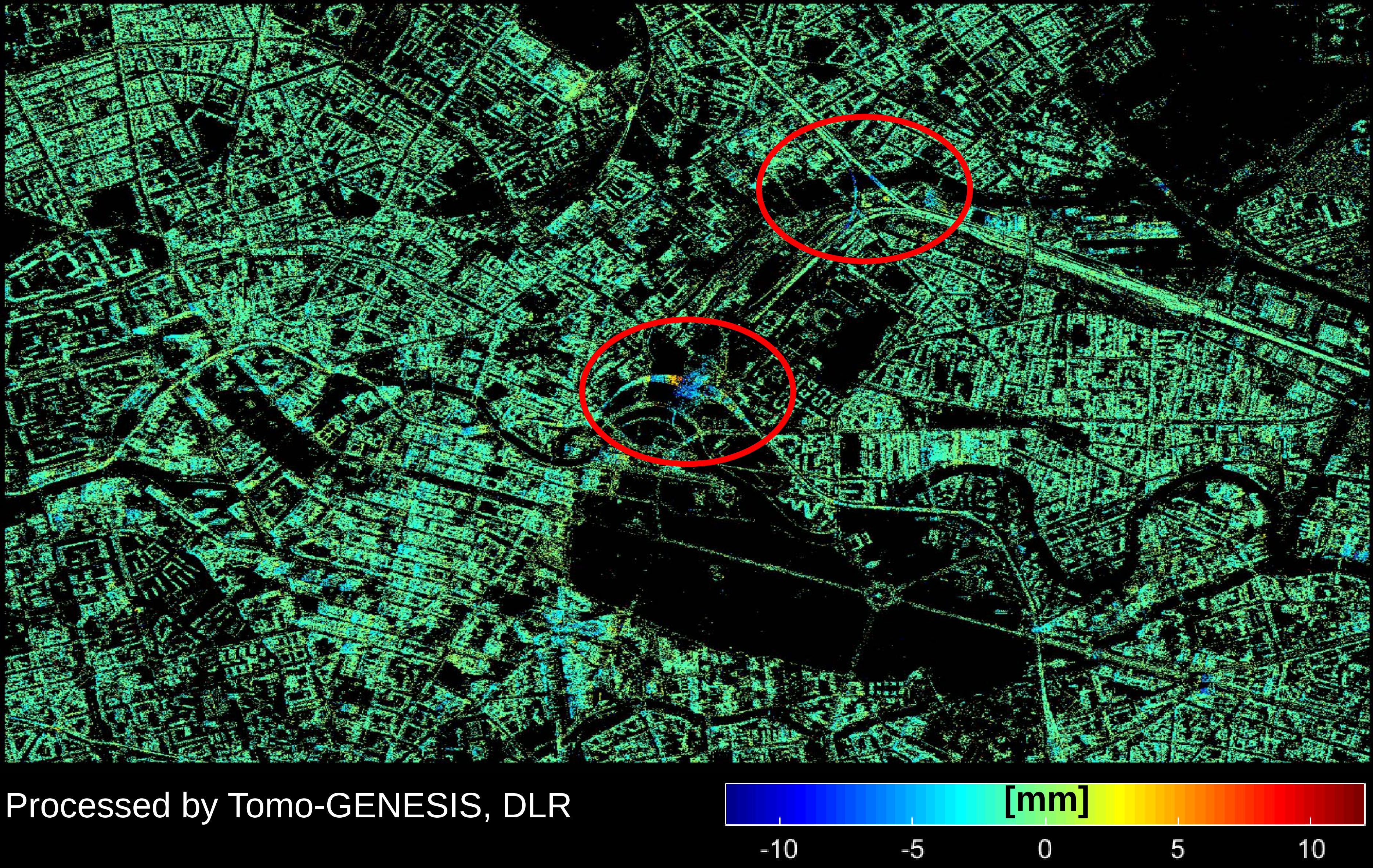


SAR data

Beam	Incidence angle	Heading angle	Track type	Nr. of Images
57	41.9°	350.3°	Ascending	102
85	51.1°	352°	Ascending	111
42	36.1°	190.6°	Descending	109
99	54.7°	187.2°	Descending	138

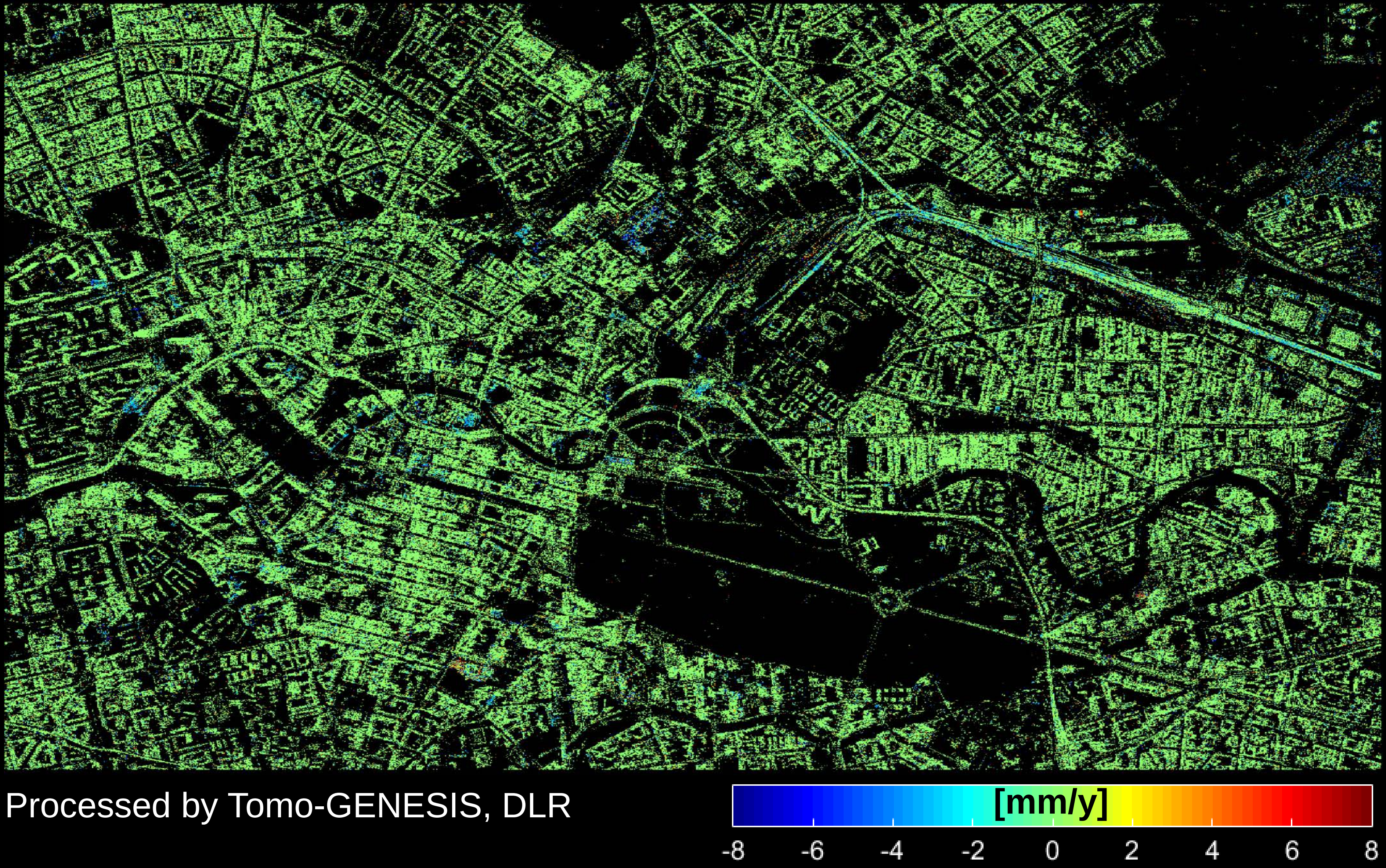
TomoSAR Deformation Results

Seasonal deformation map (Descending)



Processed by Tomo-GENESIS, DLR

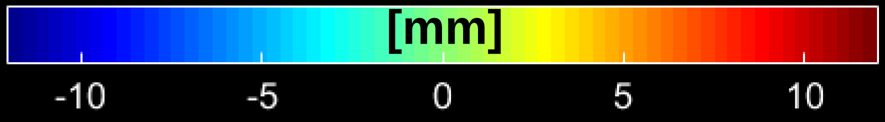
Linear deformation map (Descending)



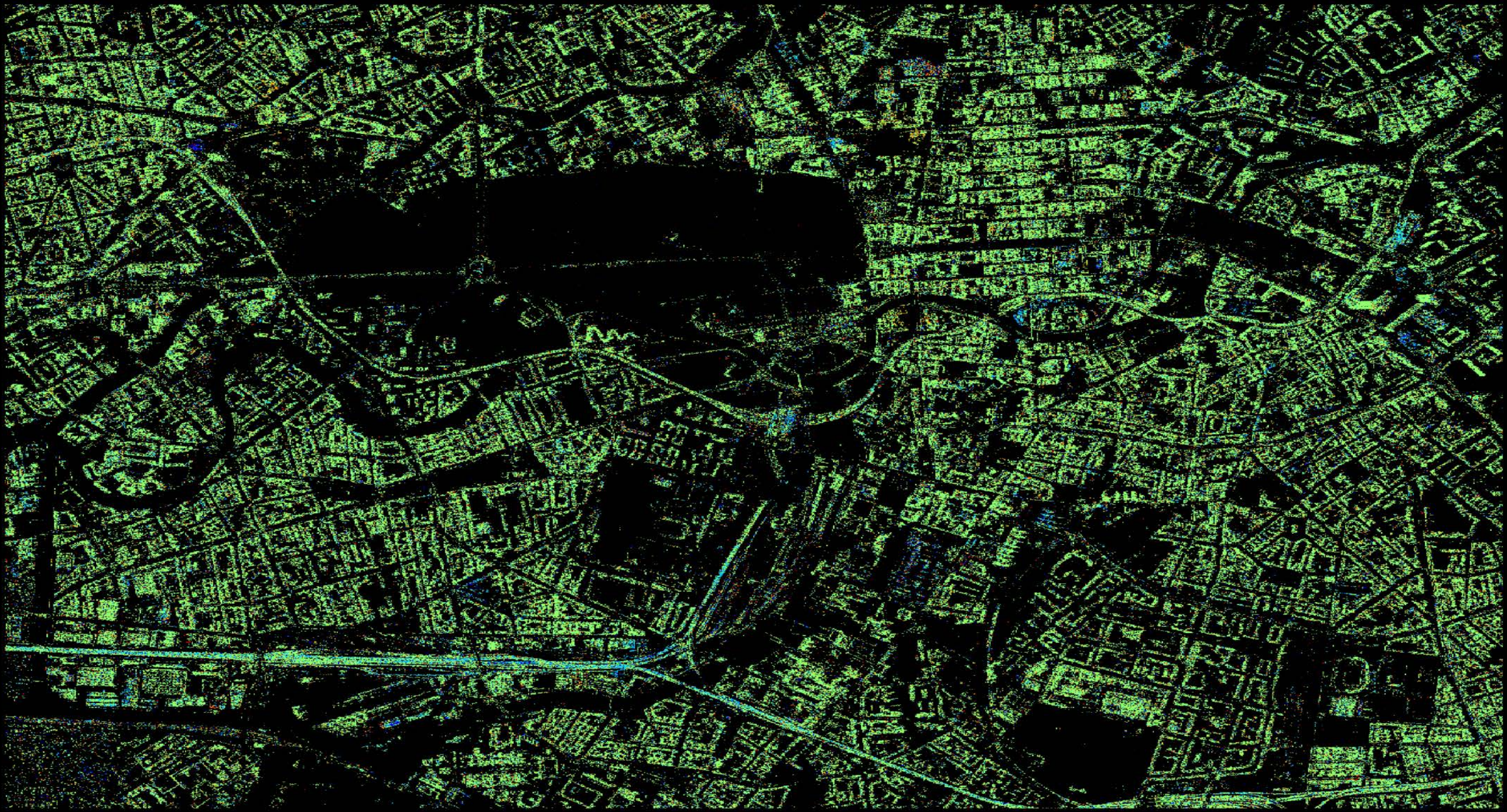
Processed by Tomo-GENESIS, DLR

Seasonal deformation map (Ascending)

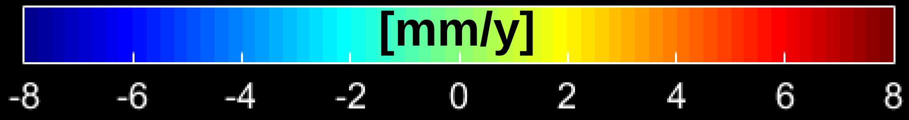
Processed by Tomo-GENESIS, DLR



Linear deformation map (Ascending)



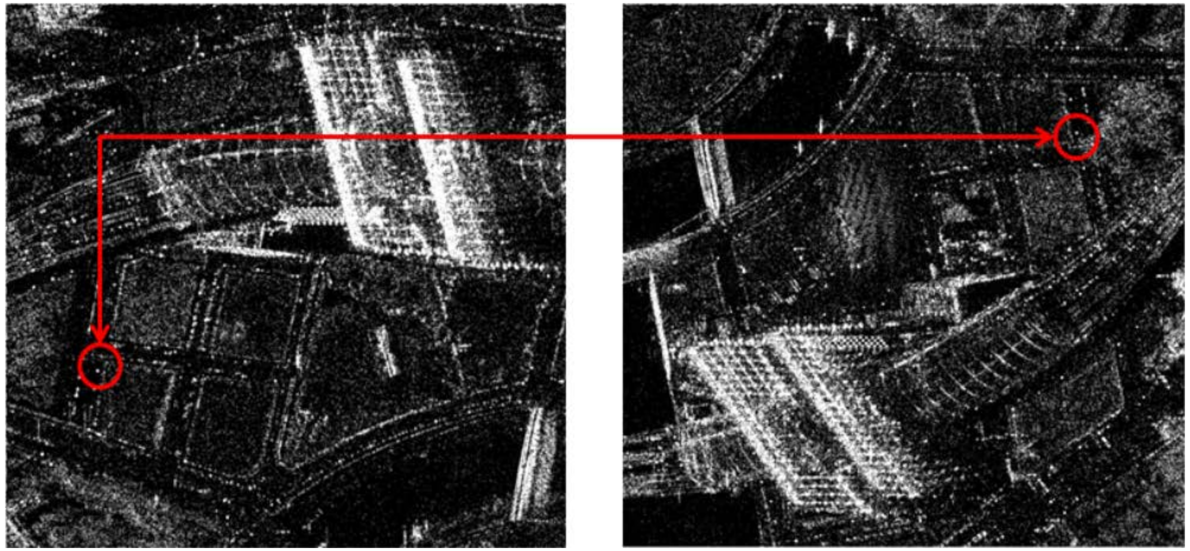
Processed by Tomo-GENESIS, DLR



Geodetic Point Cloud Fusion

Geodetic Point Cloud Fusion

Selected reference point: Base of a lamp post near central railway station



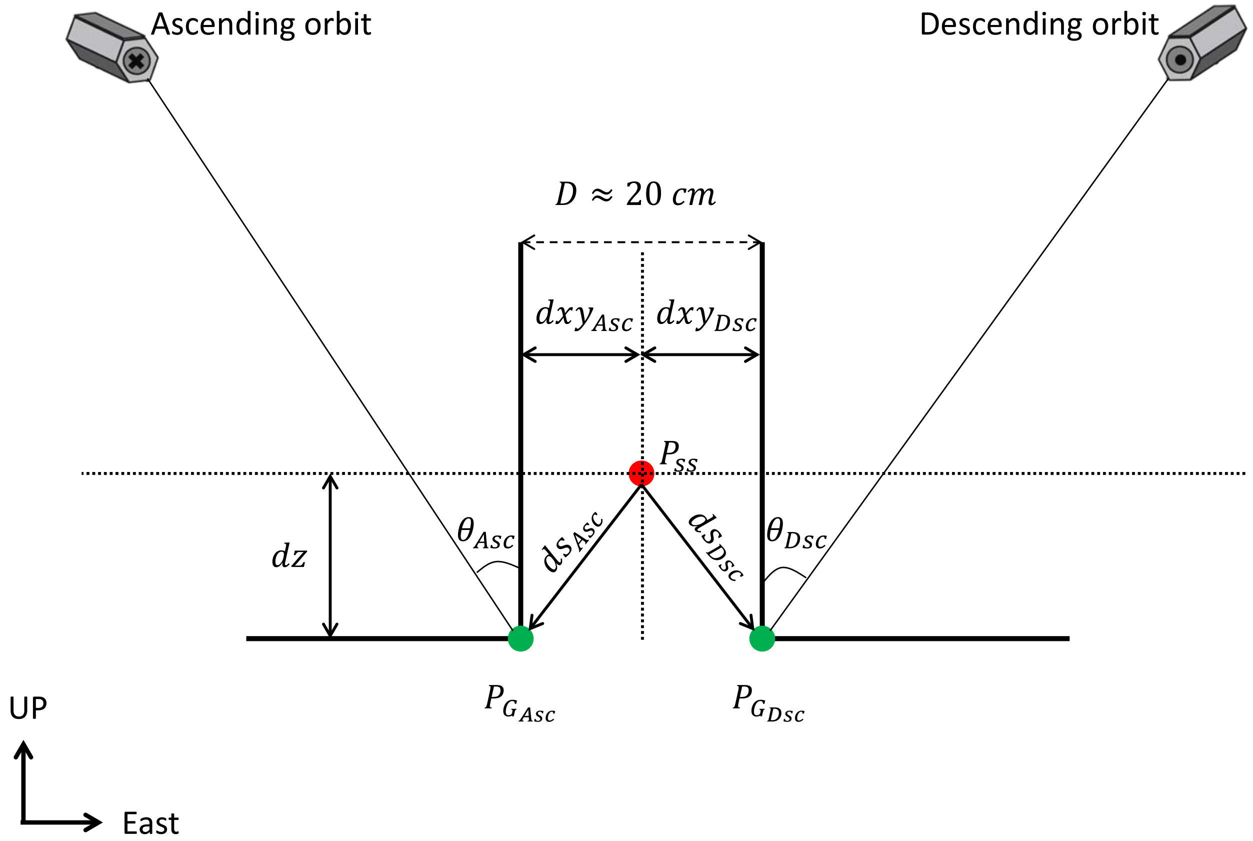
ITRF 2008:

$$X = 3783630.014 \pm 0.010 \text{ m}$$
$$Y = 899035.0040 \pm 0.010 \text{ m}$$
$$Z = 5038487.589 \pm 0.011 \text{ m}$$

We expect a bias of approximately 20 cm due to the diameter of the lamp post

→ RT - InSAR theory and techniques (24.03)

Geodetic Point Cloud Fusion



$$dz = \frac{D \cdot \tan(\theta_{Asc}) \cdot \tan(\theta_{Dsc})}{\tan(\theta_{Asc}) + \tan(\theta_{Dsc})}$$

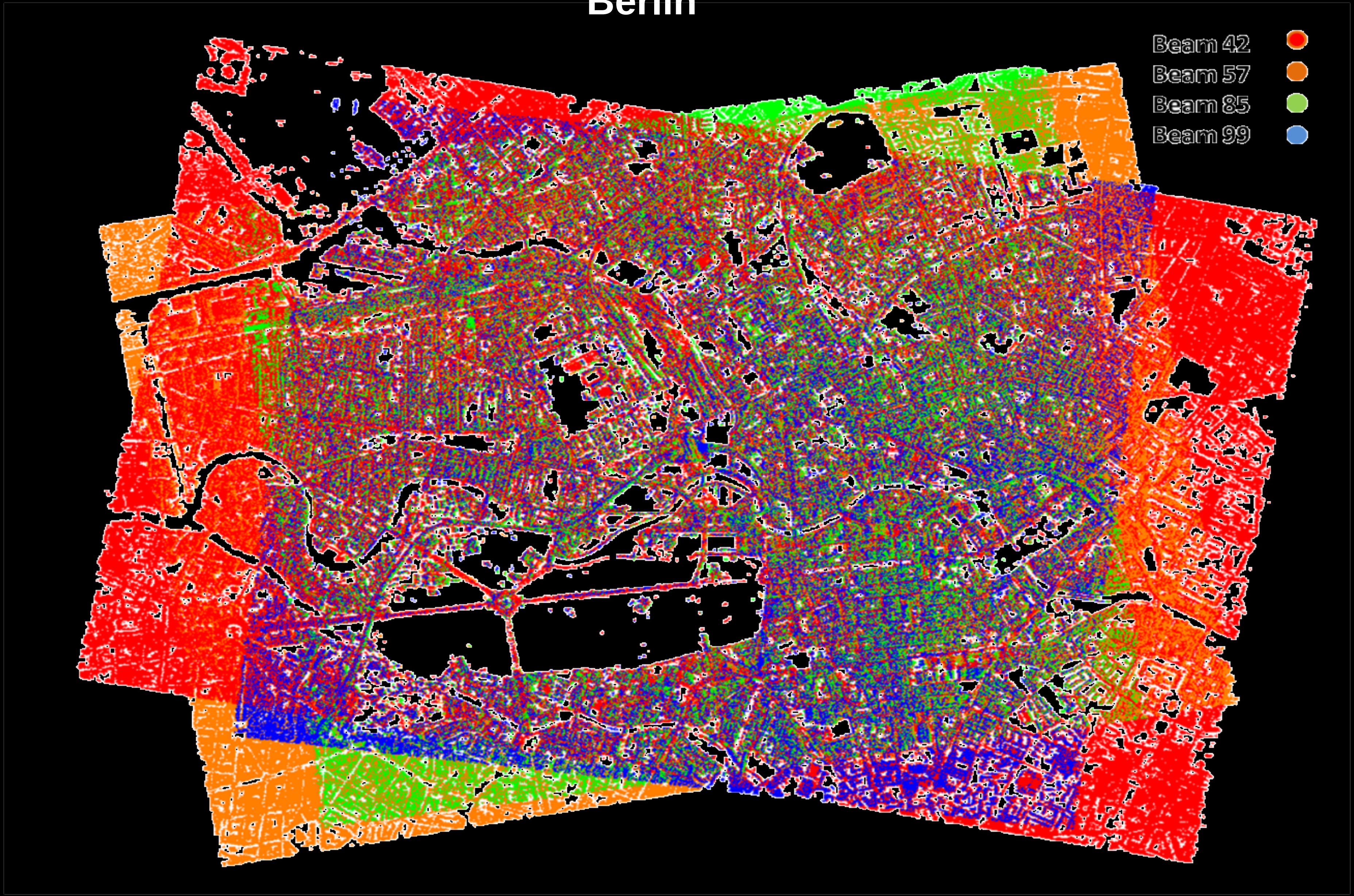
$$dx_{Asc} = dxy_{Asc} \cdot \cos(\alpha_{Asc})$$

$$dy_{Asc} = -dxy_{Asc} \cdot \sin(\alpha_{Asc})$$

$$dx_{Dsc} = dxy_{Dsc} \cdot \cos(\alpha_{Dsc})$$

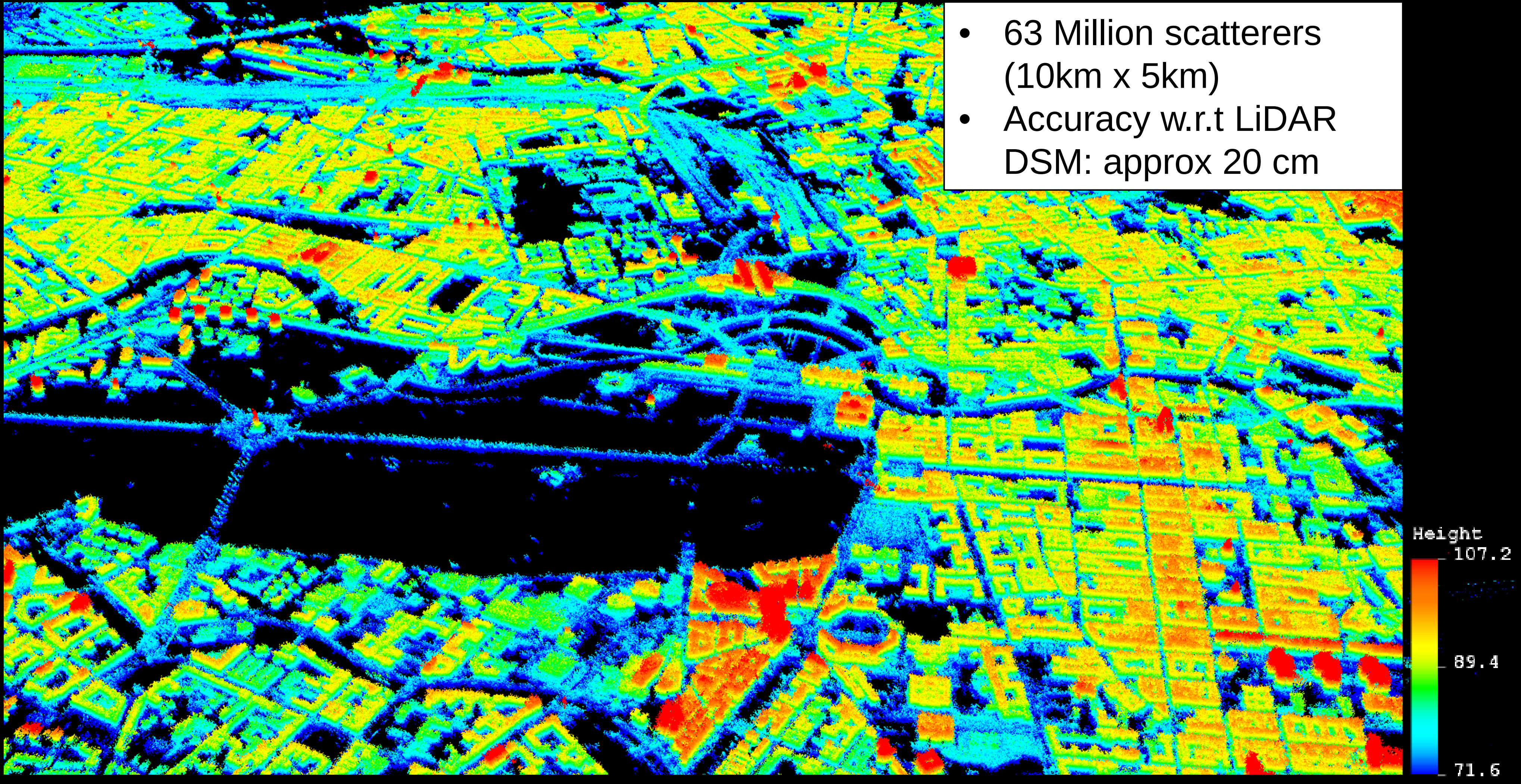
$$dy_{Dsc} = -dxy_{Dsc} \cdot \sin(\alpha_{Dsc})$$

Geodetically Fused TomoSAR point cloud of Berlin



Berlin in 3D

- 63 Million scatterers (10km x 5km)
- Accuracy w.r.t LiDAR DSM: approx 20 cm



Processed by Tomo-GENESIS, DLR

Motion Decomposition

Motion Decomposition (Geometry Assessment)

- Assuming a single scatterer is visible in all the four stacks
- A concept similar to Dilution of Precision (DOP) in GPS:
  - $\mathbf{A}$: Design matrix (based on α_h, θ_{inc})
  - $\sigma = 1$

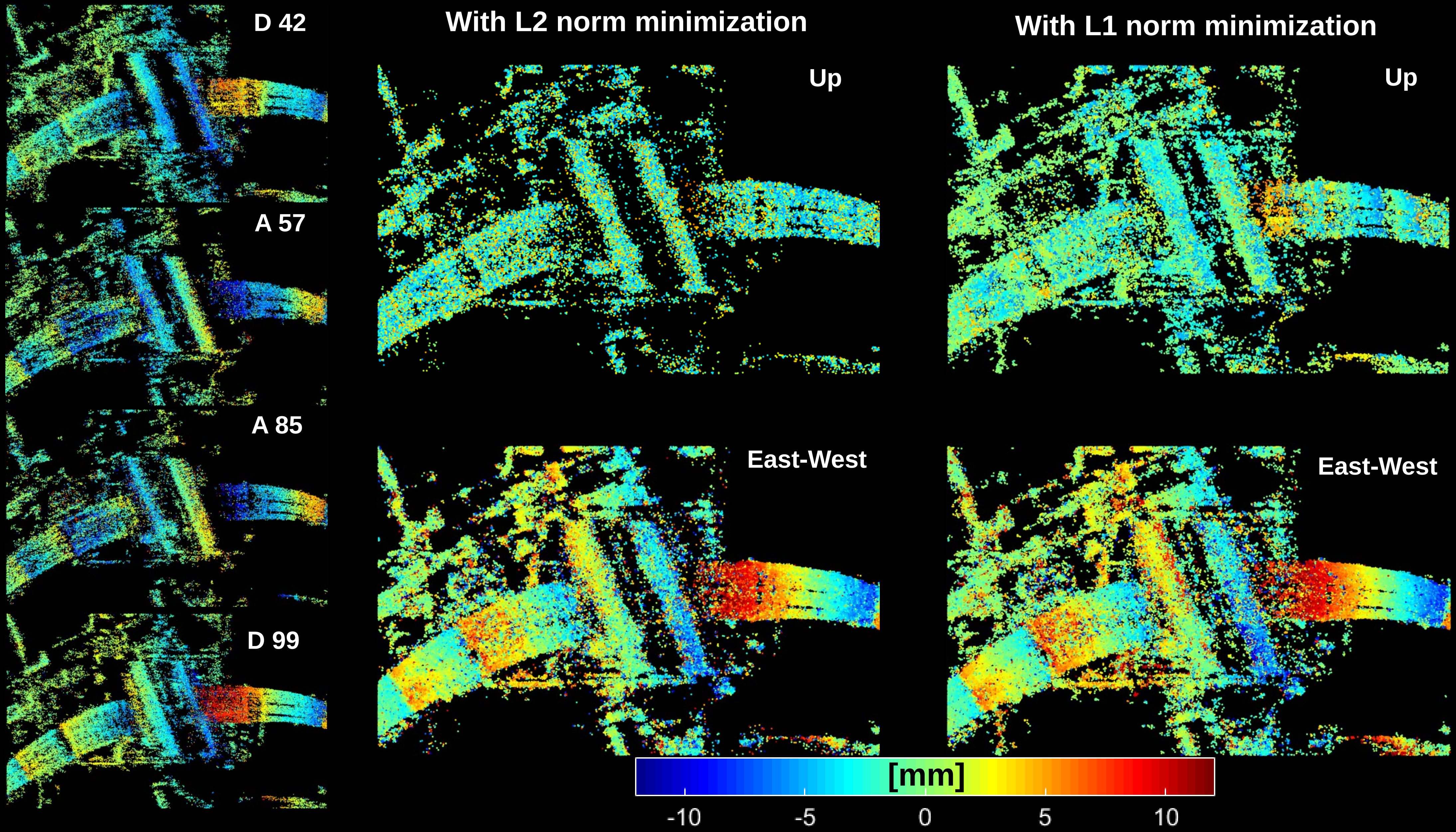
$$G = \sigma^2 \cdot (A^T A)^{-1}$$

Up East North

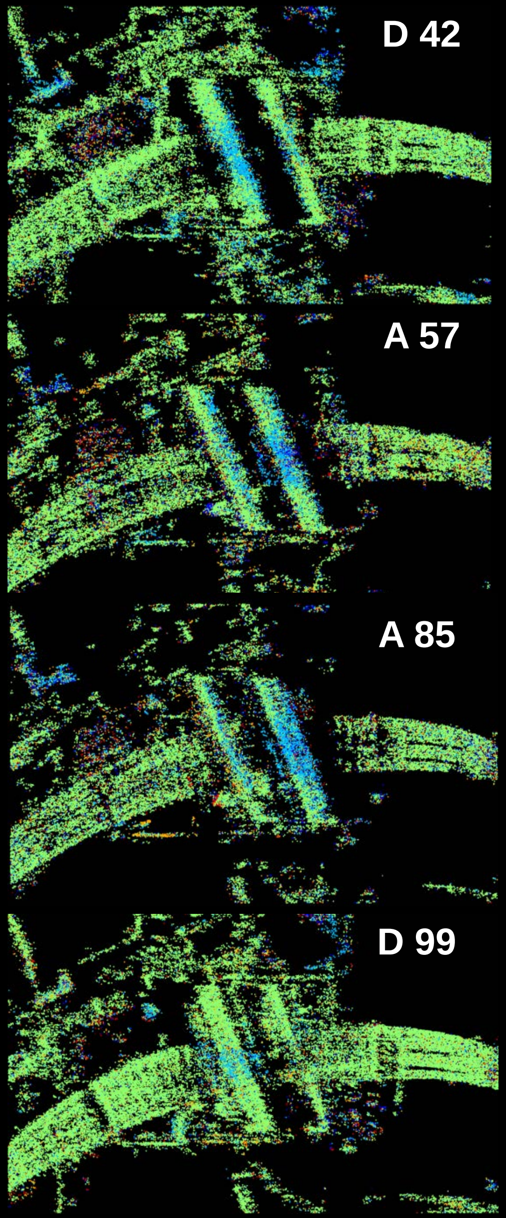
$$\begin{bmatrix} 43.3 & -0.8 & 277.8 \\ -0.8 & 0.51 & -5.4 \\ 277.8 & -5.4 & 1801.7 \end{bmatrix}$$

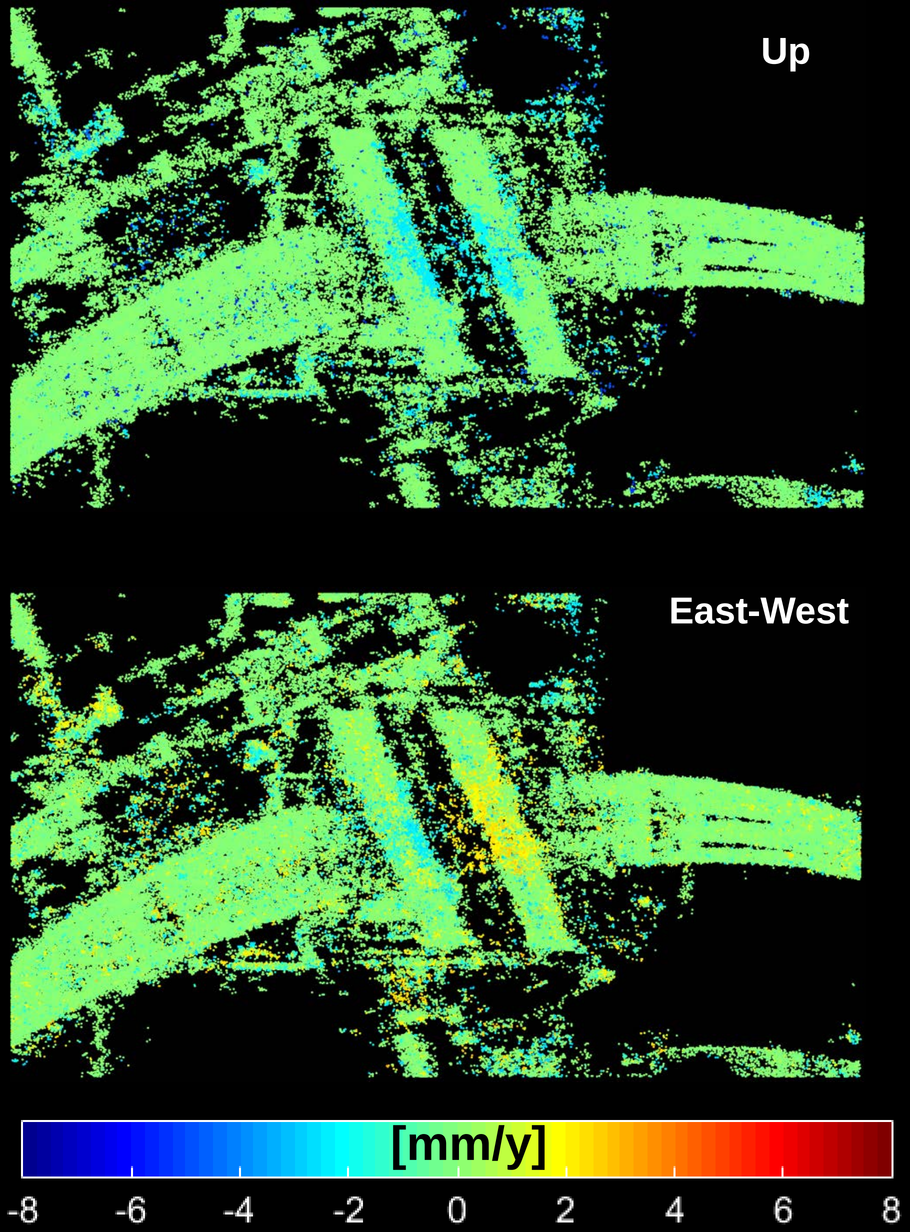
- [6.6 0.7 42.5]
- Correlation between components

Seasonal Motion Decomposition (Berlin Central Station)

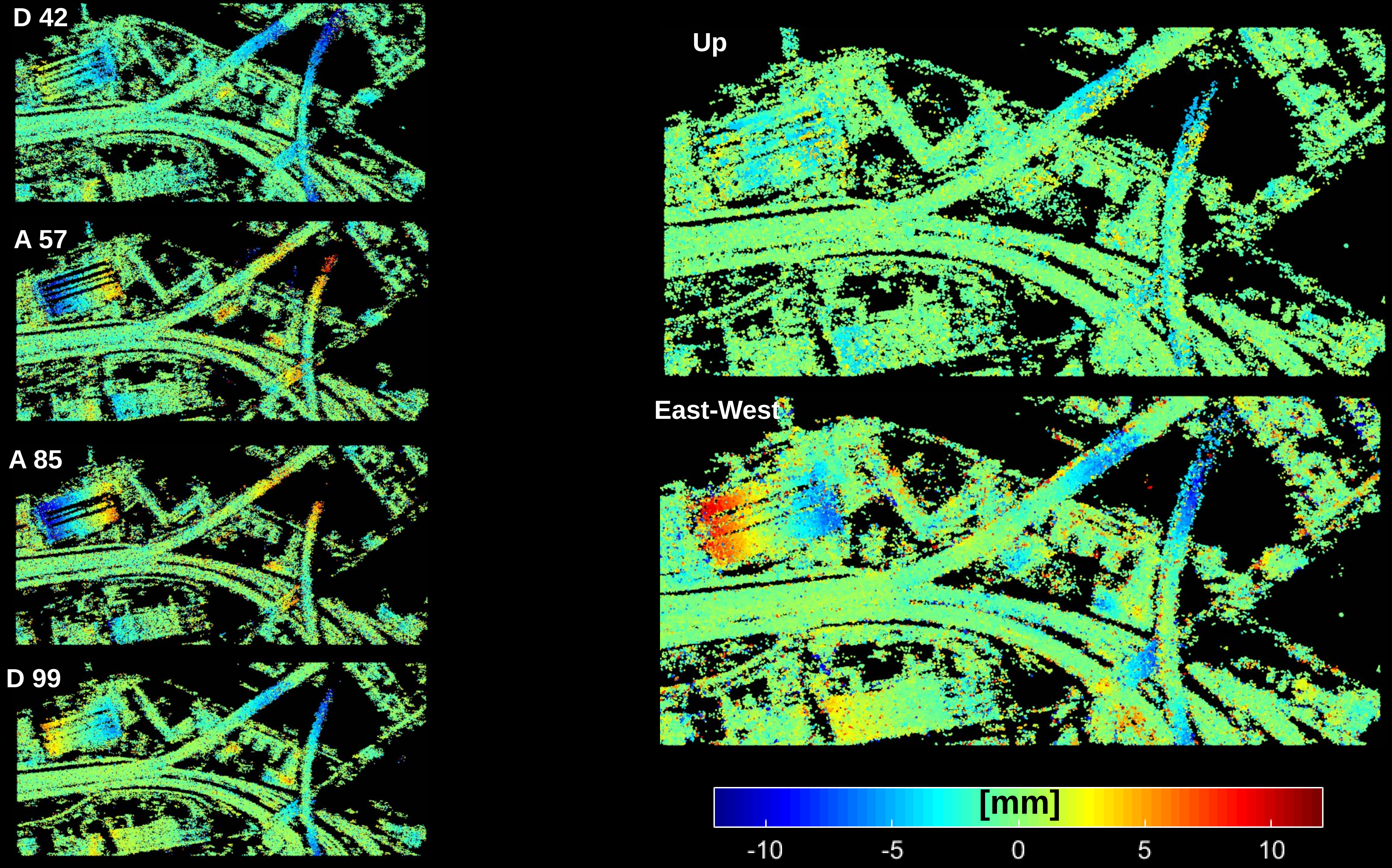


Linear Motion Decomposition (Berlin Central station)





Seasonal Motion Decomposition (Eisenbahn Bridge)



Conclusions and Outlook

- Motion decomposition based on multiple-viewing angles:
  - The functional model of deformation should contain the three components in order to prevent biased deformation estimates.
  - In urban area monitoring using X-band data the seasonal deformation should be considered.
  - Seasonal deformation in the order of 12 mm (between summer and winter 24 mm) in the east-west direction were observed in Berlin central station.
- Retrieval of the motion components by L1 norm preserves more information than L2.
- GPS deformation observations can be corporated to provide absolute deformations.

Thank you for your attention!