Satellite radar interferometry: state of the art and future directions

Recent developments in Europe

PALSAR workshop, Kyoto University, Japan

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2008年1月24日

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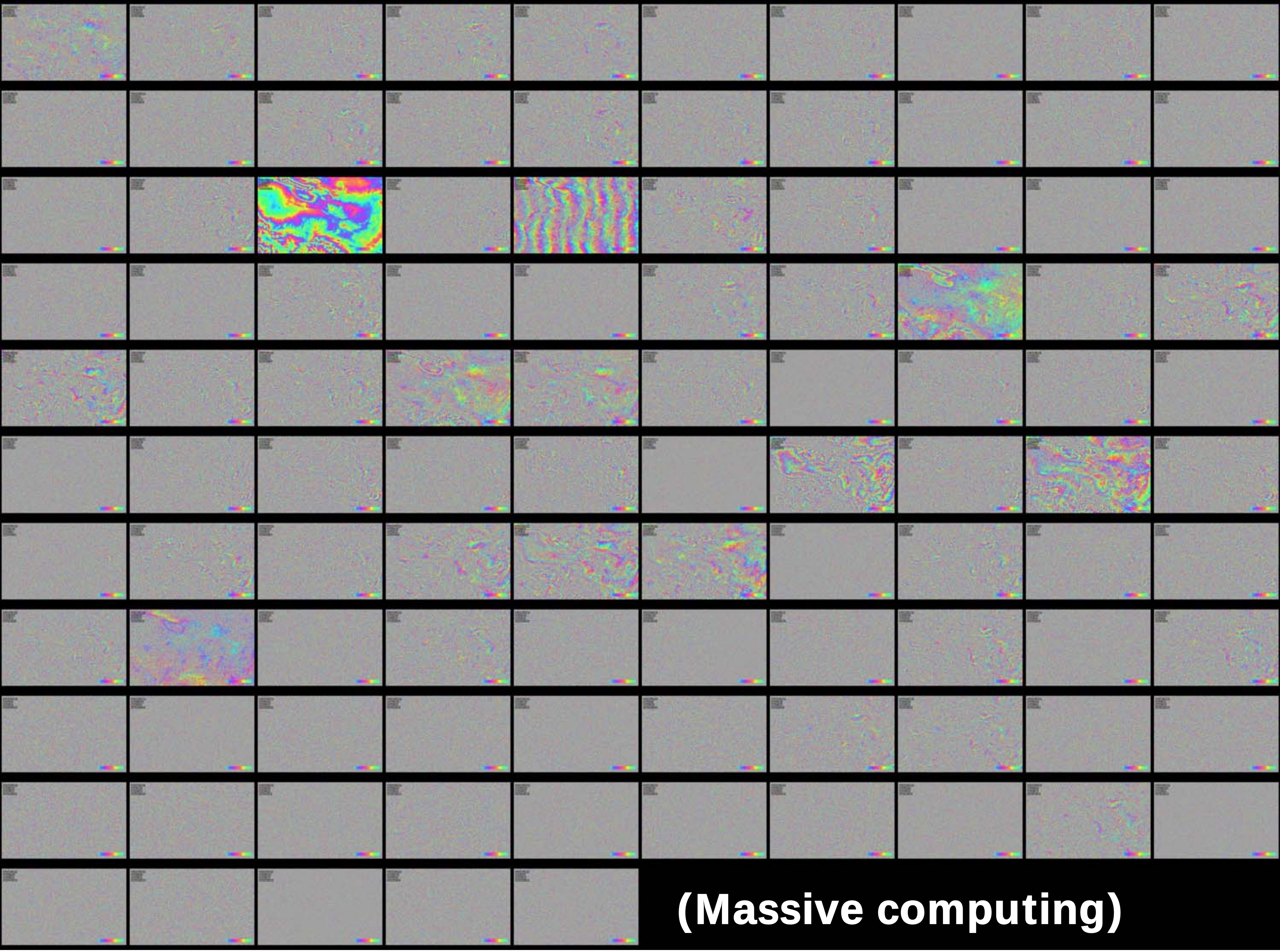
Contents

- INSAR: current limitations/problems
- Solutions to the limitations
  - New missions
  - Methodology developments
    - TOPS
    - PSI (SBAS, Hybrid)
  - Validation experiment (Terrafirma)
- Future directions



(Massive computing)

Model of observation equations (1)

Functional model:

$$\partial\phi_p = -\frac{4\pi}{\lambda}\left(D_p + \frac{B_\perp}{R_1 \sin\theta^\circ} H_p\right)$$

Observation

Unknowns

Rank deficiency!

Often treated opportunistically

Stochastic model:

$$Q_\phi = \sigma_\phi^2 I_n$$

Based on thermal (instrumental) noise

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Phase ambiguity

$$\partial\phi_p = -\frac{4\pi}{\lambda}\left(D_p + \frac{B_\perp}{R_1 \sin\theta^\circ} H_p\right)$$

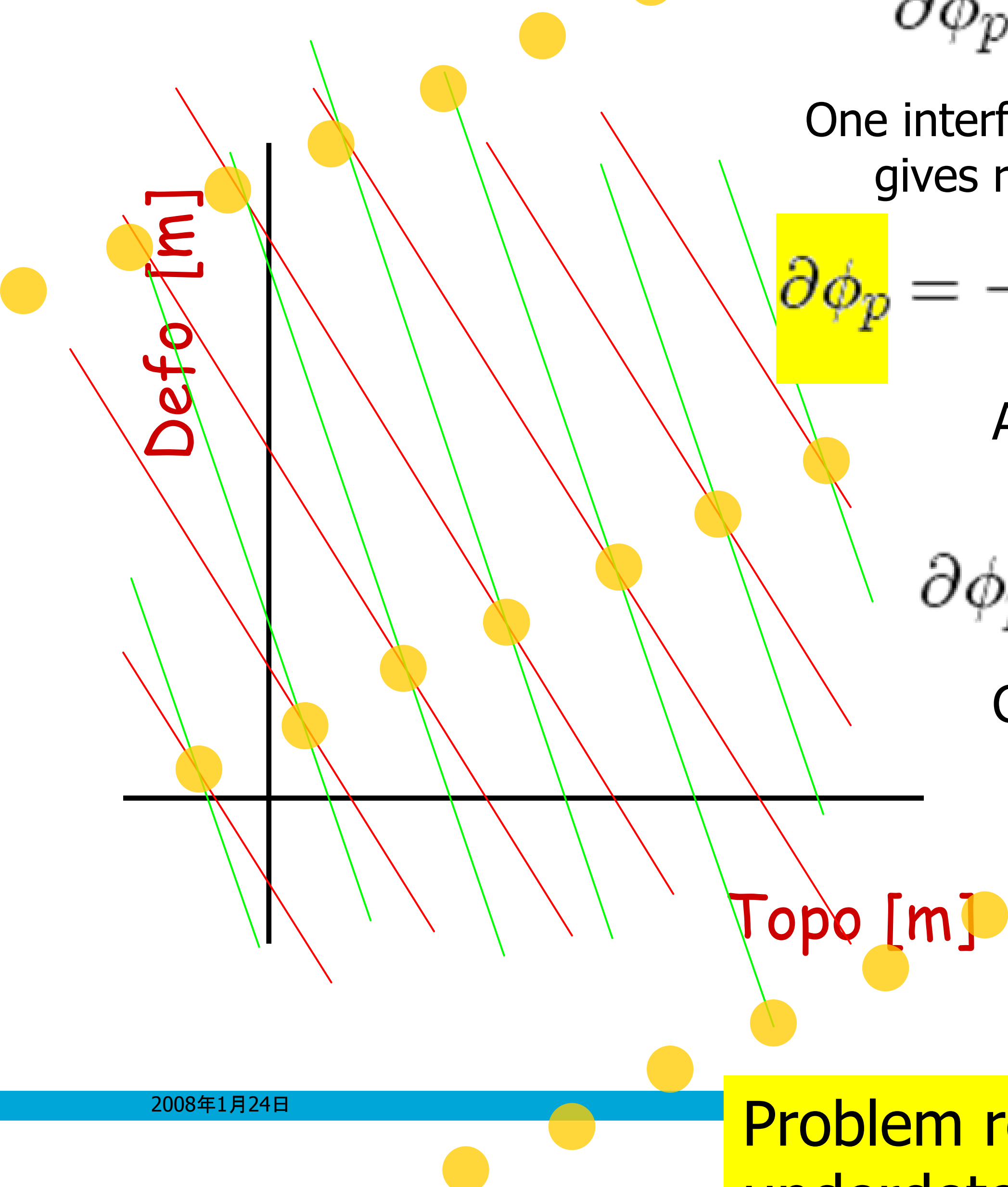
One interferogram, two unknowns + 1 ambiguity gives red pattern (solution space)

$$\partial\phi_p = -\frac{4\pi}{\lambda}\left(D_p + \frac{B_\perp}{R_1 \sin\theta^\circ} H_p + 2\pi k\right)$$

Adding a new ifg with different time and Bp

$$\partial\phi_p = -\frac{4\pi}{\lambda}\left(D_p + \frac{B_\perp}{R_1 \sin\theta^\circ} H_p\right)$$

Gives green pattern.



Solution space reduced to yellow dots. Now continue adding ifgs and formulate in probabilistic way

Problem remains underdetermined

Additional noise terms need to be added

Model of observation equations (2)

- **Add unknown parameter:**
  - Phase ambiguity

Integer valued unknown

$$\partial\phi_p = -\frac{4\pi}{\lambda}(D_p + \frac{B_\perp}{R_1 \sin\theta^\circ} H_p + 2\pi k$$

- **Add error signal to stochastic model:**
  - Atmosphere (troposphere, ionosphere)
  - Orbit errors
  - Decorrelation
    - Geometric
    - Temporal

Spatial varying disturbance

~trend

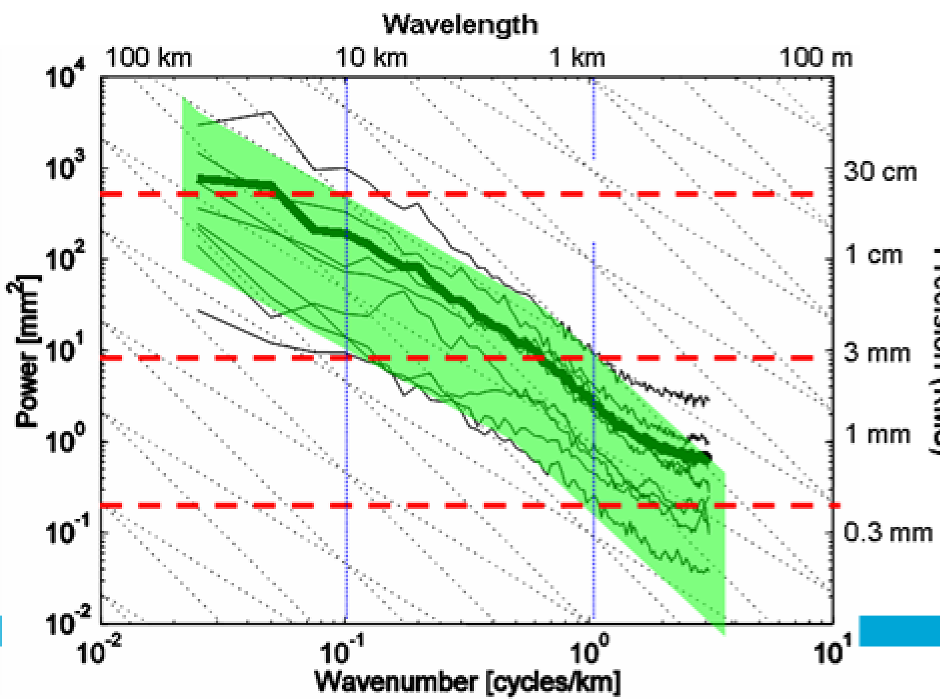
Pixel-based noise

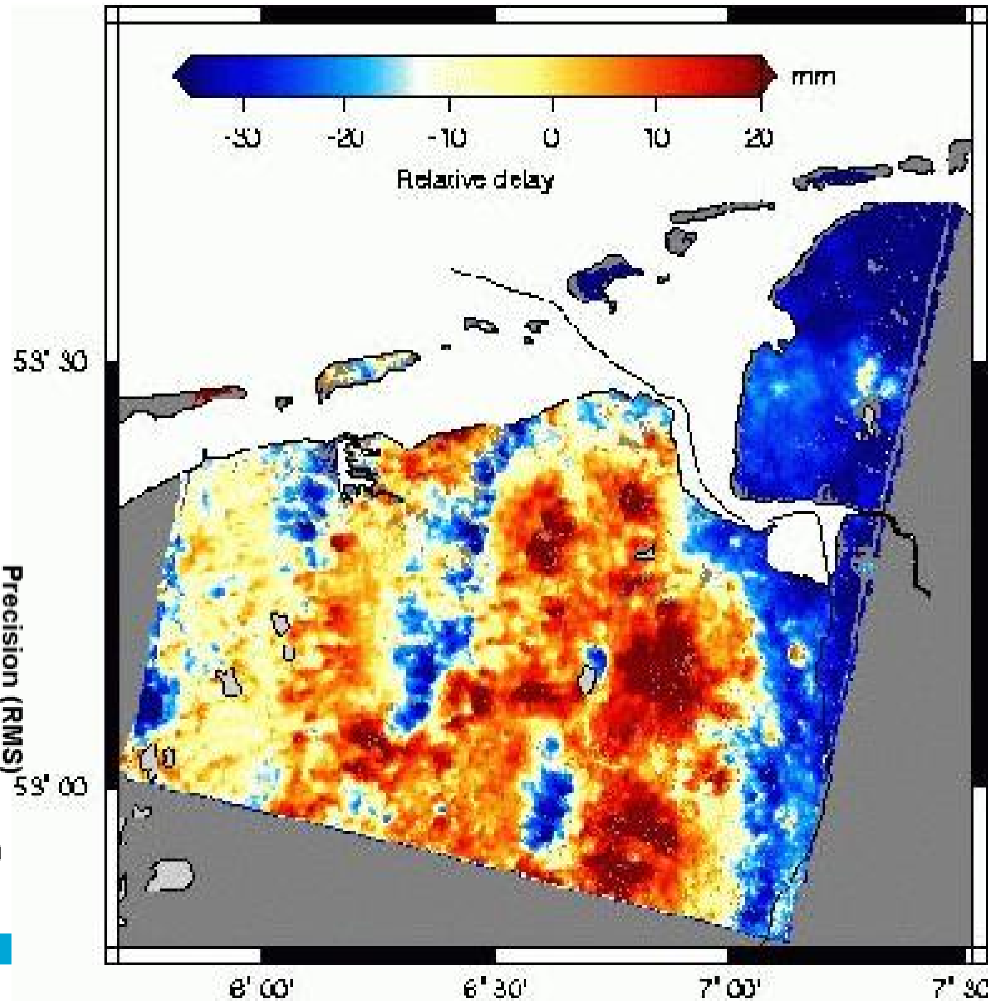
Spatially ~constant

Spatially varying

Atmospheric disturbance

- Spatially varying disturbance signal
- Can be ~5 cm over 20 km
- Spatially correlated but temporally uncorrelated (Δt>1 day)
- Introduces covariances in stochastic model





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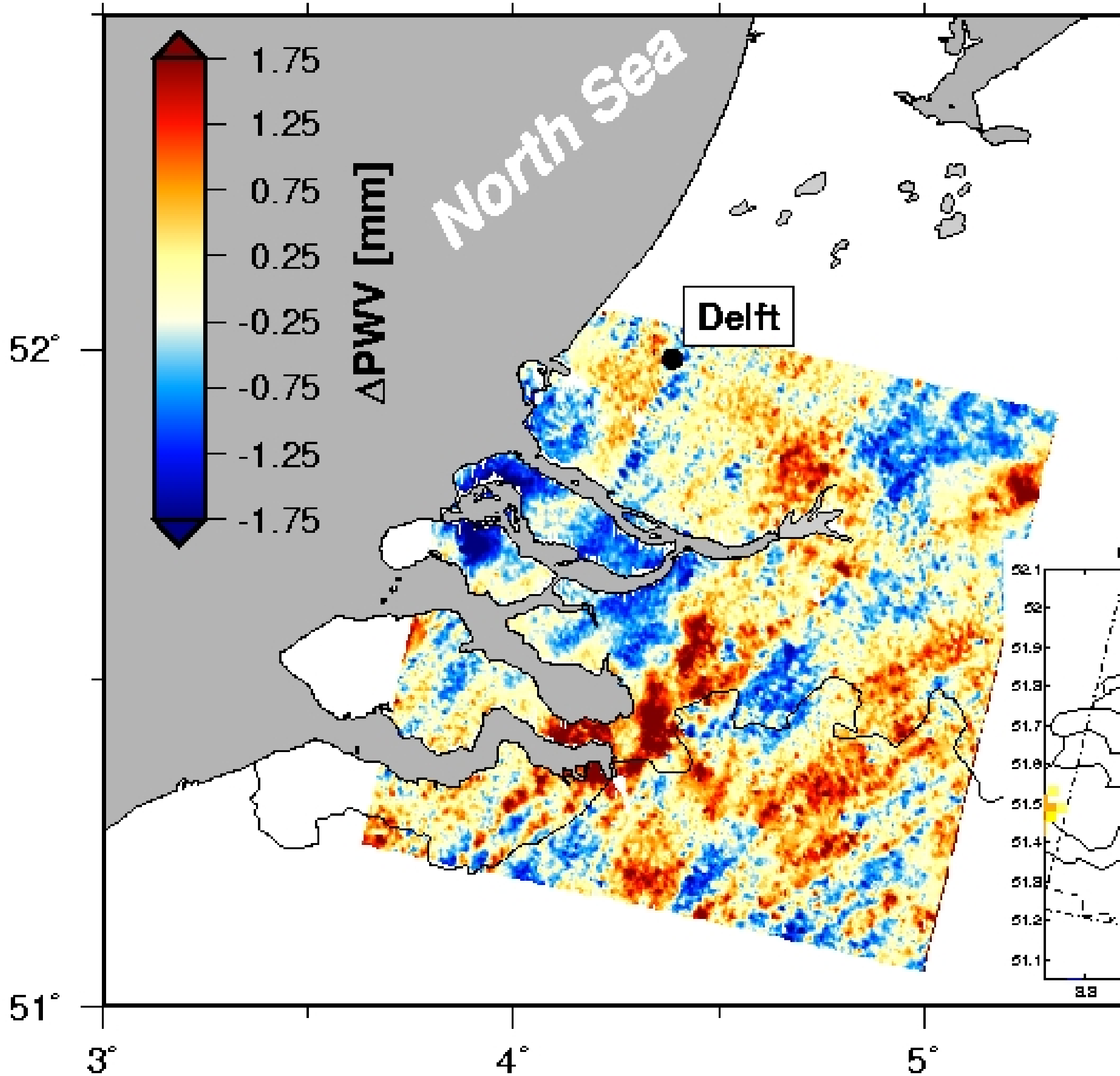
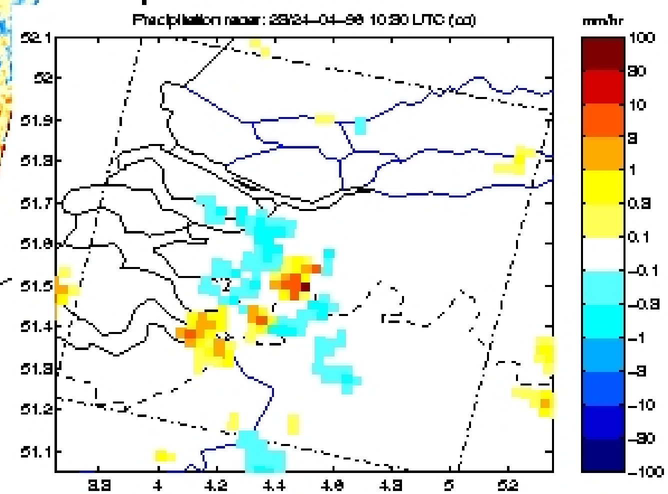
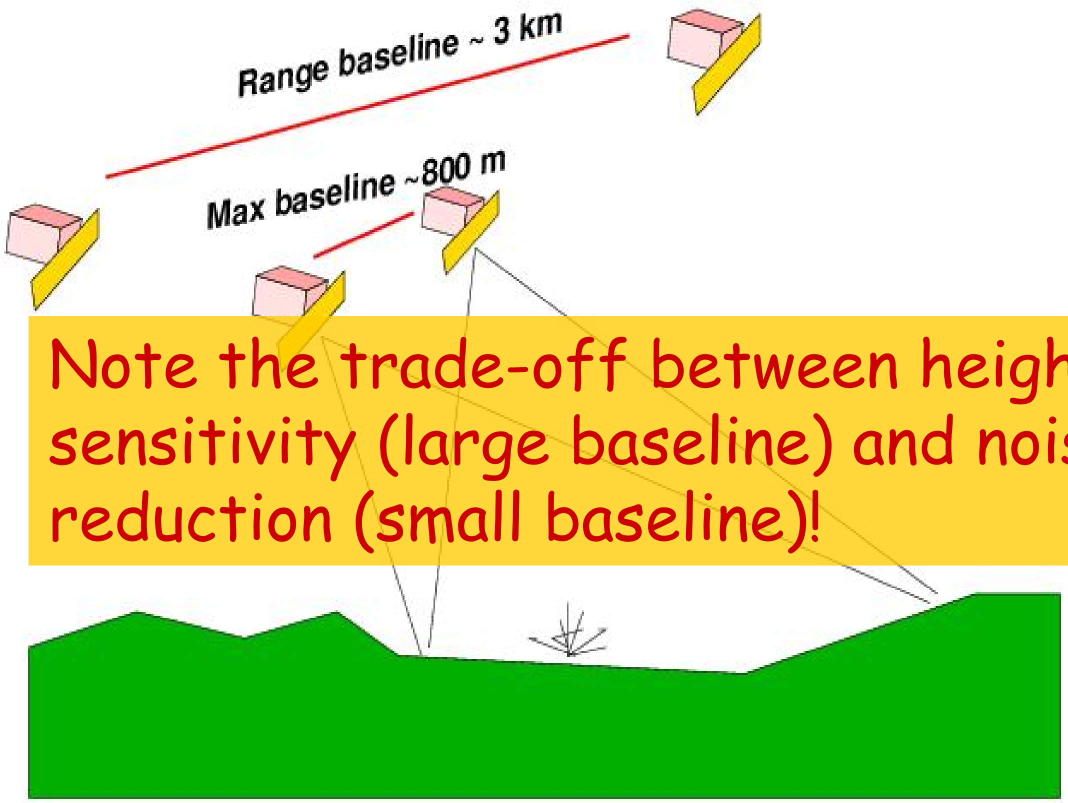
Example Interferometric Radar Meteorology





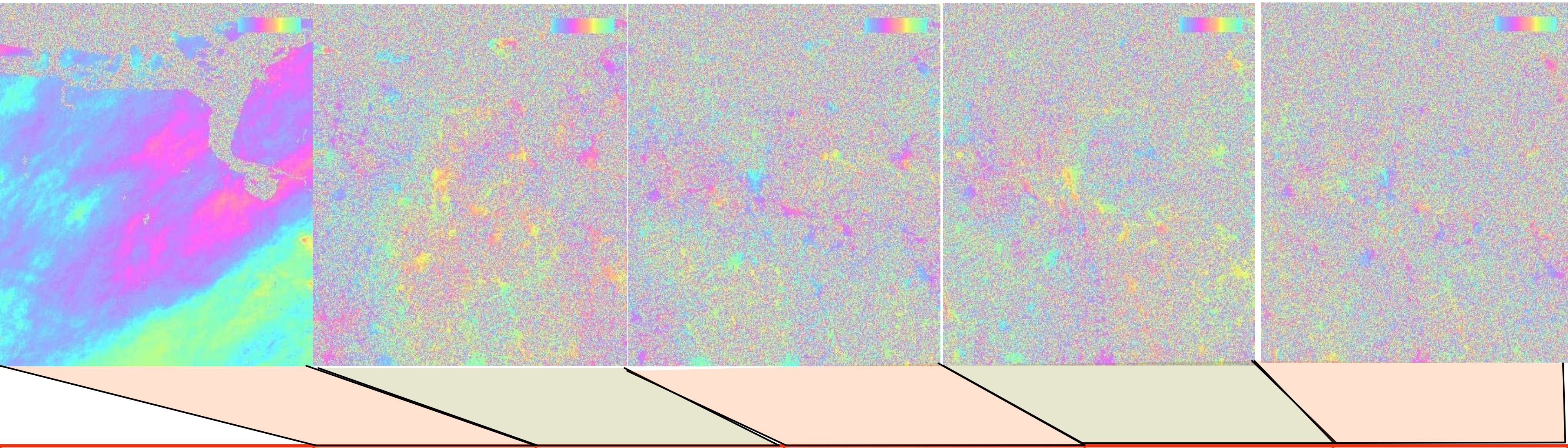
Geometric decorrelation



- Baselines vary
- Relative scattering mechanisms change
- Images become uncomparable
- Function of bandwidth, baseline, Doppler centroid, and terrain slope

Note the trade-off between height sensitivity (large baseline) and noise reduction (small baseline)!

Temporal decorrelation



Temporal baseline	1 day	1 year	2 years	3 years	6 years
Perpendicular baseline (m)	29	112	93	185	166

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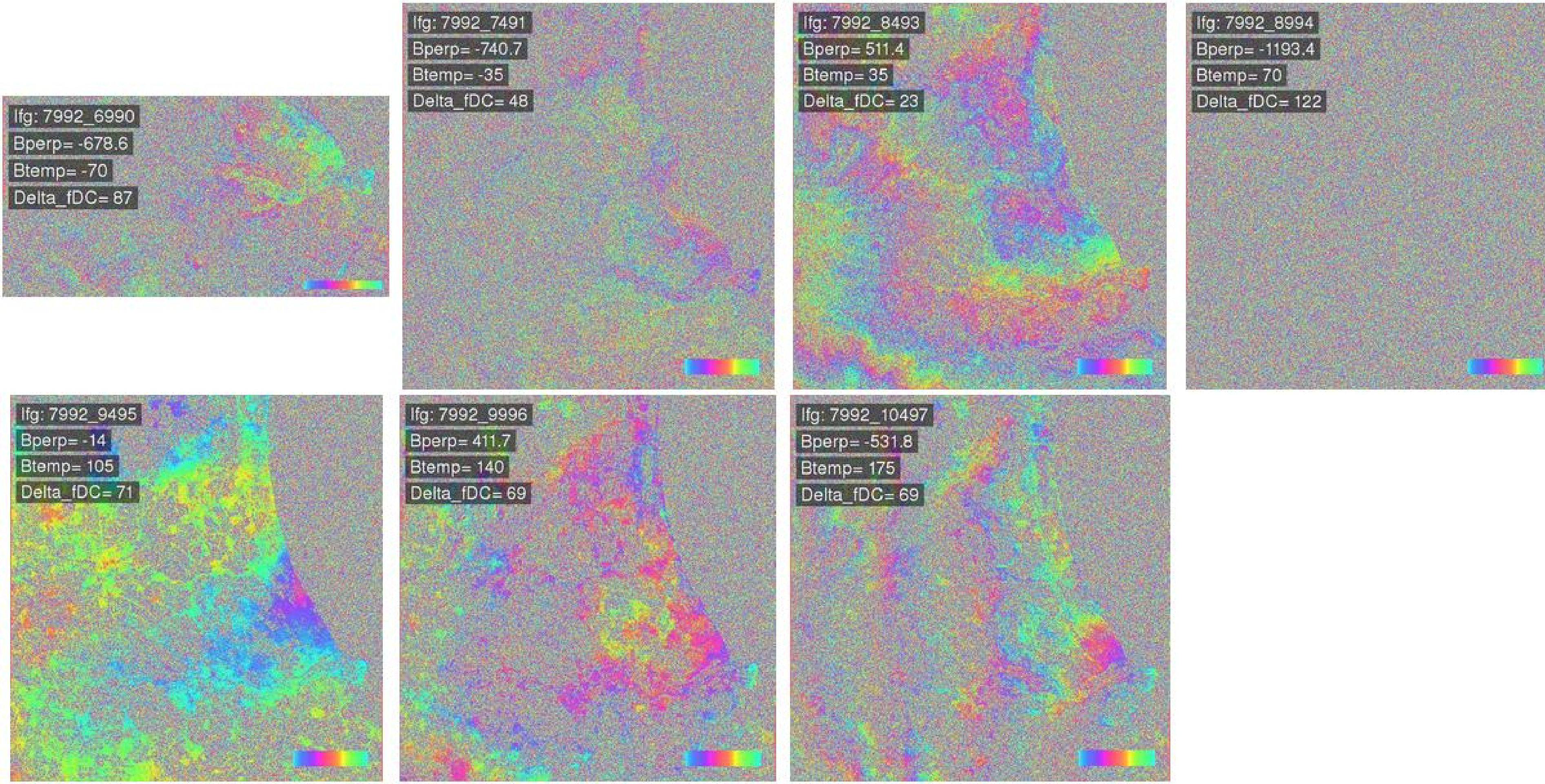
Envisat interferograms (single master)



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Current limitations

Problem/limitations	Consequence	Solution/mitigation (Hardware)	Solution/mitigation (Algorithmic)
Lack of data	Applications cannot be developed	More data, easier avail	Get the most from limited data
Temporal decorrelation	Noise, location dependent	Longer wavelength, Faster revisit (=wide swath)	Persistent scatterers, SBAS, hybrid
Geometric decorrelation	Noise/lower resolution	Wide bandwidth, orbit control	Selecting point scatterers only
Atmosphere	Phase screen	???	More data for averaging
Resolution	Small stable scatterers not used	Higher resolution	TOPS
Identification of time coherent scatterers	Few coherent points	Higher resolution, more data in time	Better PS algorithms, hybrid algorithms
Ambiguity resolution	Loss of phase lock	More data	Better algorithms (ILSQ)
Quality control and assessment	No redundancy, reliability hard to check, phase center not clear	Overlapping data takes, more data	Validation experiments, fundamental science, datum transformation, error propagation

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Developments in InSAR

1. To appreciate developments, we first need to consider the limitations of the current possibilities

2. Developments can be categorized in three groups

SENSORS and SYSTEMS

- ALOS
- GMES
- TSX
- RSAT
- Sentinel
- GEOSS

METHODOLOGY

- Time series processing
  - Psi (point selection)
  - Sbas
  - hybrid
- Spectral diversity

APPLICATIONS

- Solid earth geophysics
- Civil engineering (land slides, infrastructure)
- Atmosphere

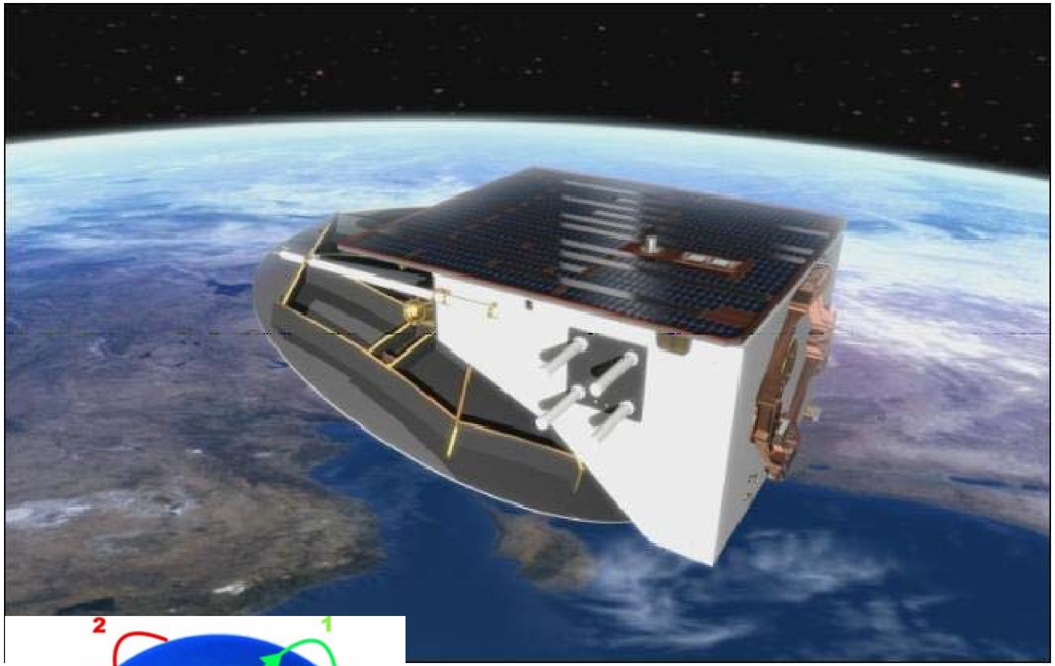
CONSEQUENCES

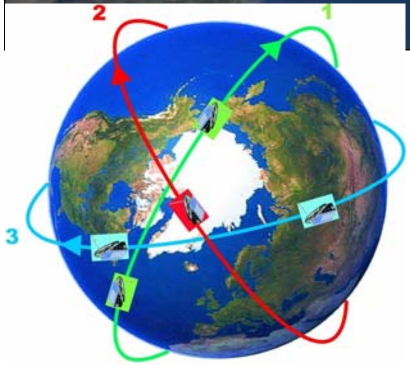
Missions

Future (X and C band)

Mission	From	Until	Band	Repeat orbit (days) (dagen)	Resolution (m)
ERS-1	1991	1999	C	35	4×20
ERS-2	1995	2011	C	35	4×20
Envisat	2003	2013	C	35	4×20
Radarsat-1	1995	2009	C	24	8×8
Radarsat-2	2007	2012	C	24	10×9
TerraSAR-X	2007	2012	X	11	1; 3
TanDEM-X	2009	2014	X	11	1;3
Cosmo-Skymed-1	2007	2012	X	16	1
Cosmo-Skymed-2	2007	2012	X	16	1
Cosmo-Skymed-3	2008	2013	X	16	1
Cosmo-Skymed-4	2009	2014	X	16	1
Sentinel-1a	2011	2030	C	12	5×10
Sentinel-1b	2012	2031	C	12	5×10
Radarsat-C1	2012	2019	C	12	10
Radarsat-C2	2013	2020	C	12	10
Radarsat-C3	2014	2021	C	12	10

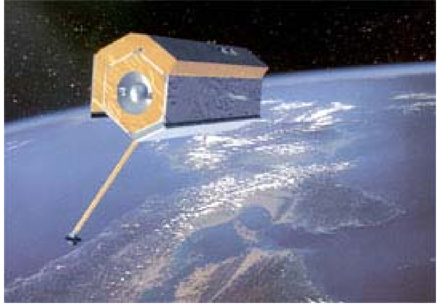
SAR-Lupe constellation





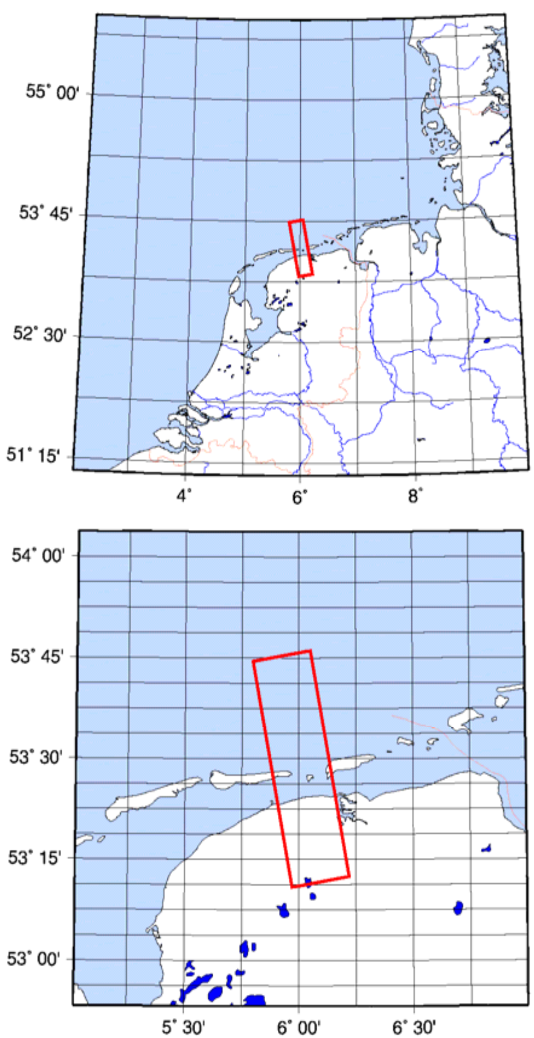
- German defense
- High resolution
- 5 sats
- 3 orbital planes
- 500 km
- Launches: Dec 2006-2008
- X-band (spotlight)

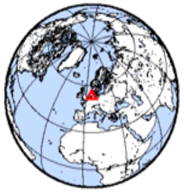
TerraSAR-X



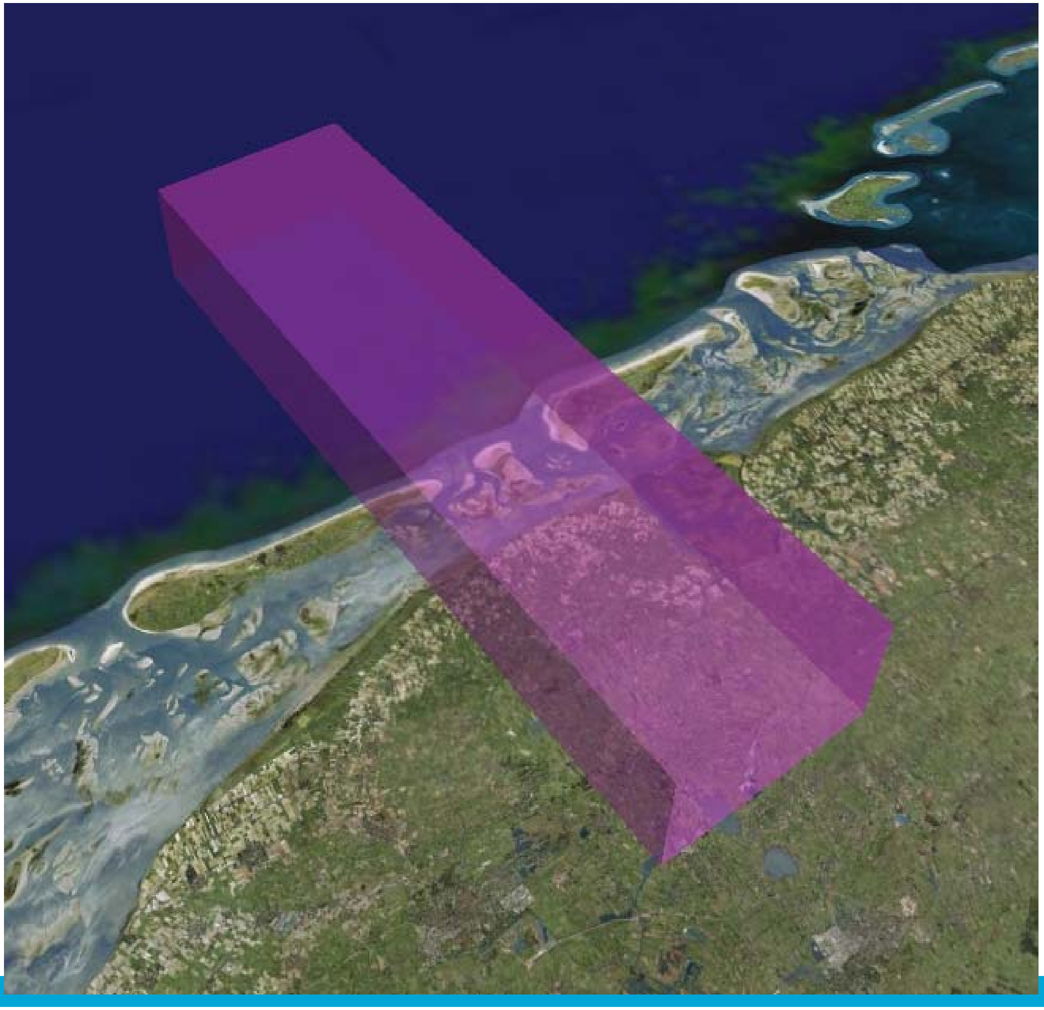
- Civil & Defense
- Resolution 3x3 (stripmap) (swath 30 km)
- Launch 15 June 2007
- TerraSAR-X-2
- TanDEM-X

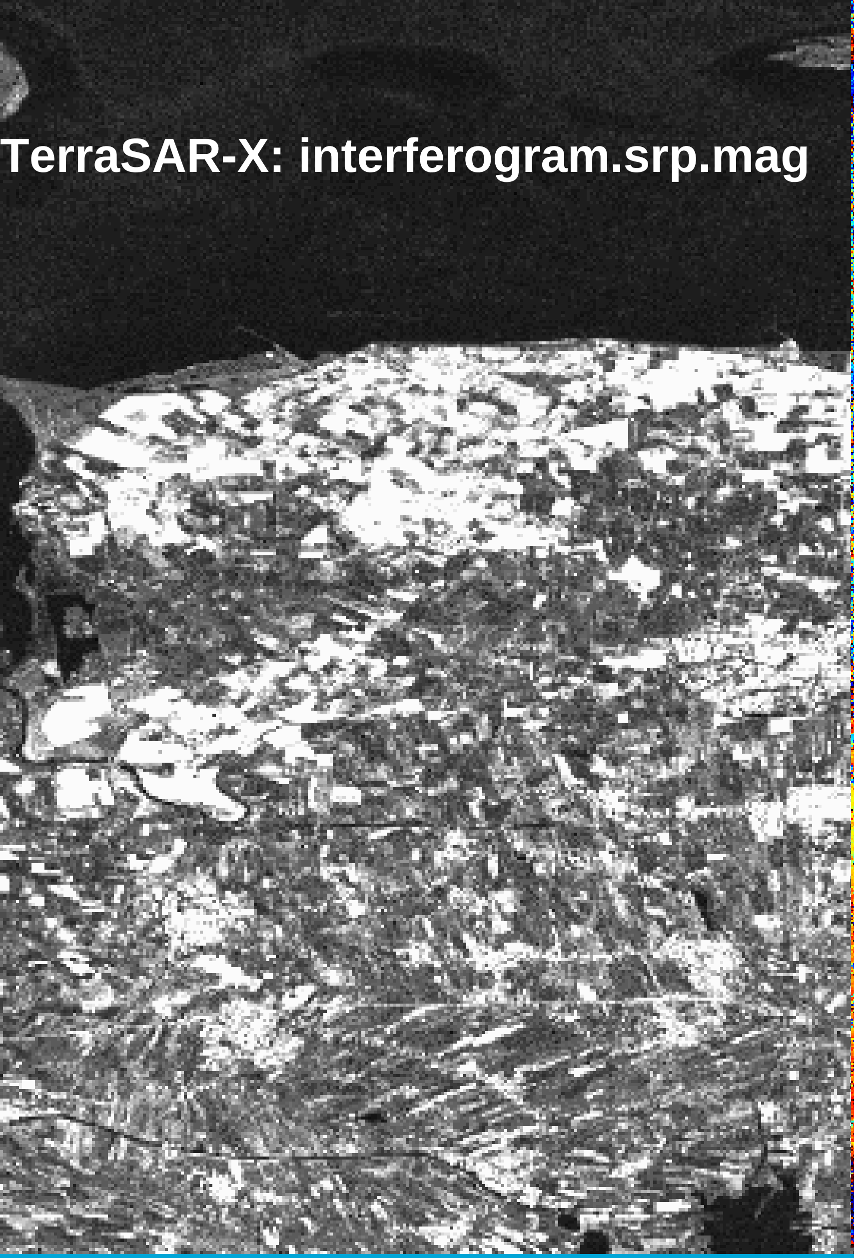
•TerraSAR-X: real data examples

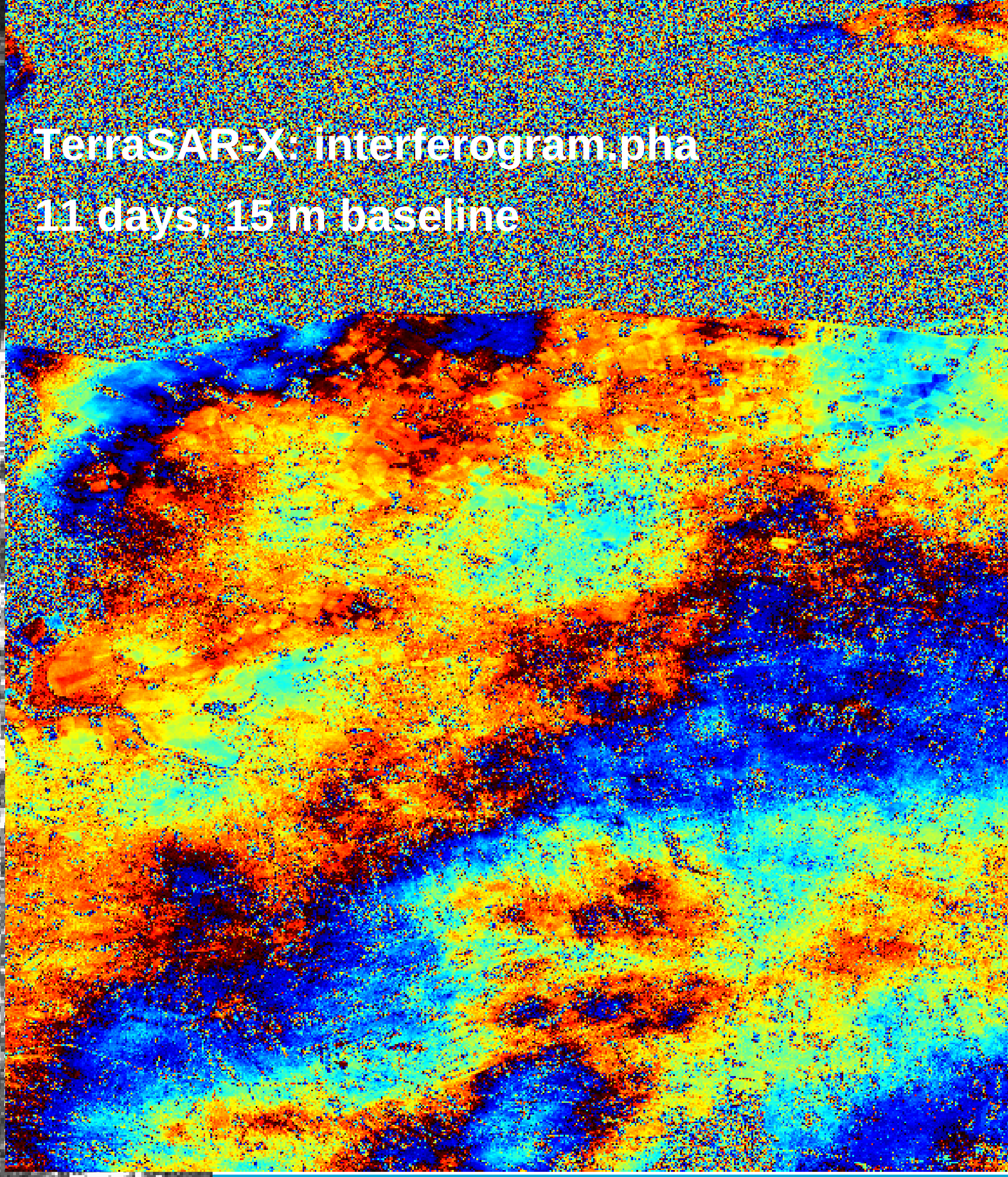




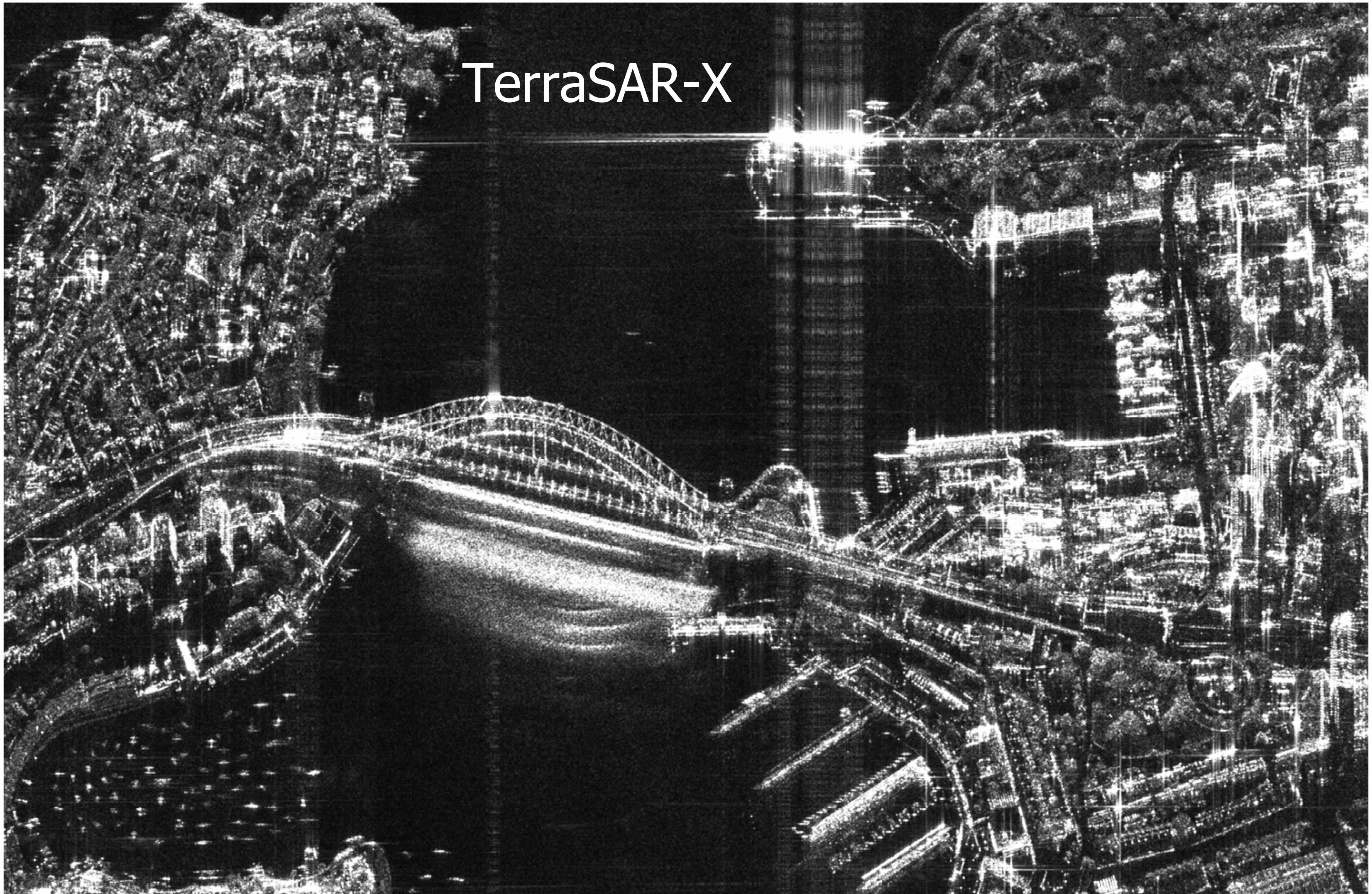
acquisition mode : "SM" / "stripNear_011" / "HH/VV" / "R"
product type : "SSC" /
start time UTC : "2007-11-23T17:18:26.867458"
stop time UTC : "2007-11-23T17:18:35.867463"
orbit cycle / no. / dir. : 15 / 2454 / 116 / "A"




TerraSAR-X: interferogram.srp.mag


TerraSAR-X: interferogram.pha
11 days, 15 m baseline

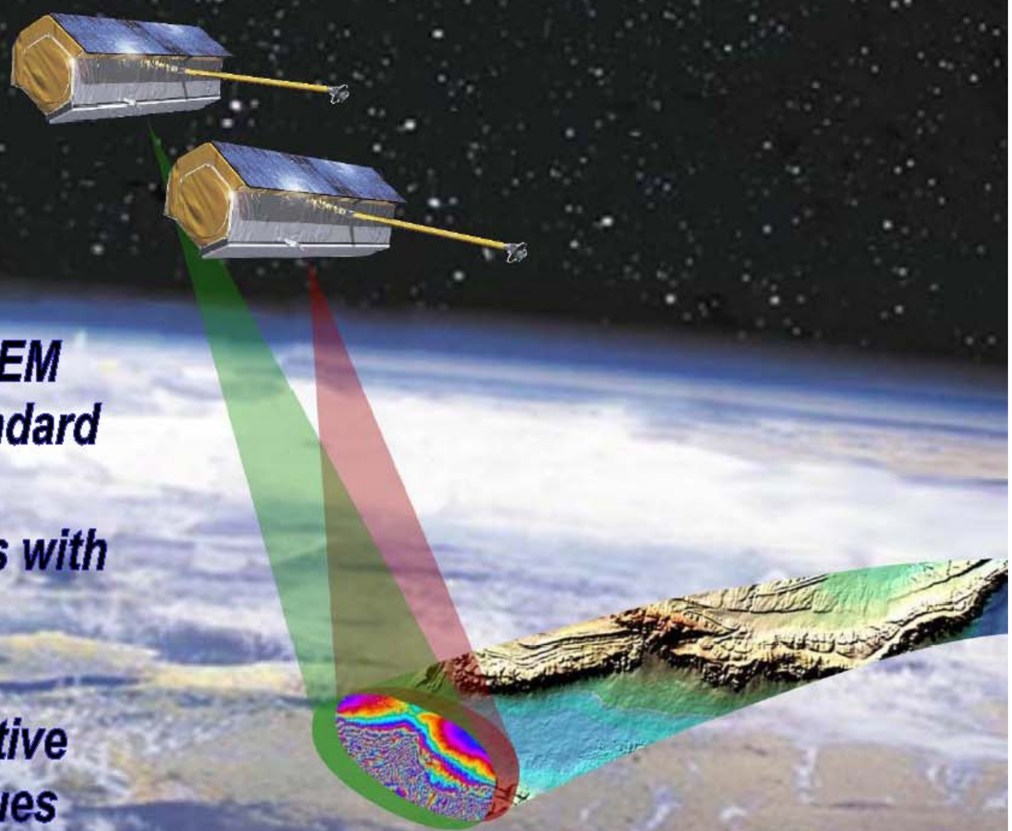
TerraSAR-X: resolution.dual.pole



High Resolution Spotlight – Sydney

HR Spotlight (VV), 150 MHz range bandwidth, $\theta_{incid} \approx 38.5°$, 5 km x 10 km

TanDEM-X Mission Goals

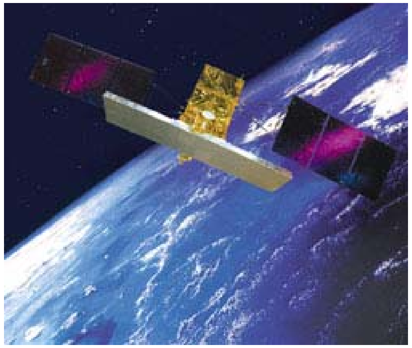


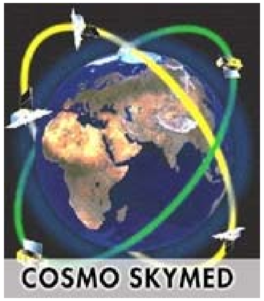
- acquisition of a global DEM according to HRTI-3 standard
- generation of local DEMs with HRTI-4 like quality
- demonstration of innovative bistatic imaging techniques and applications

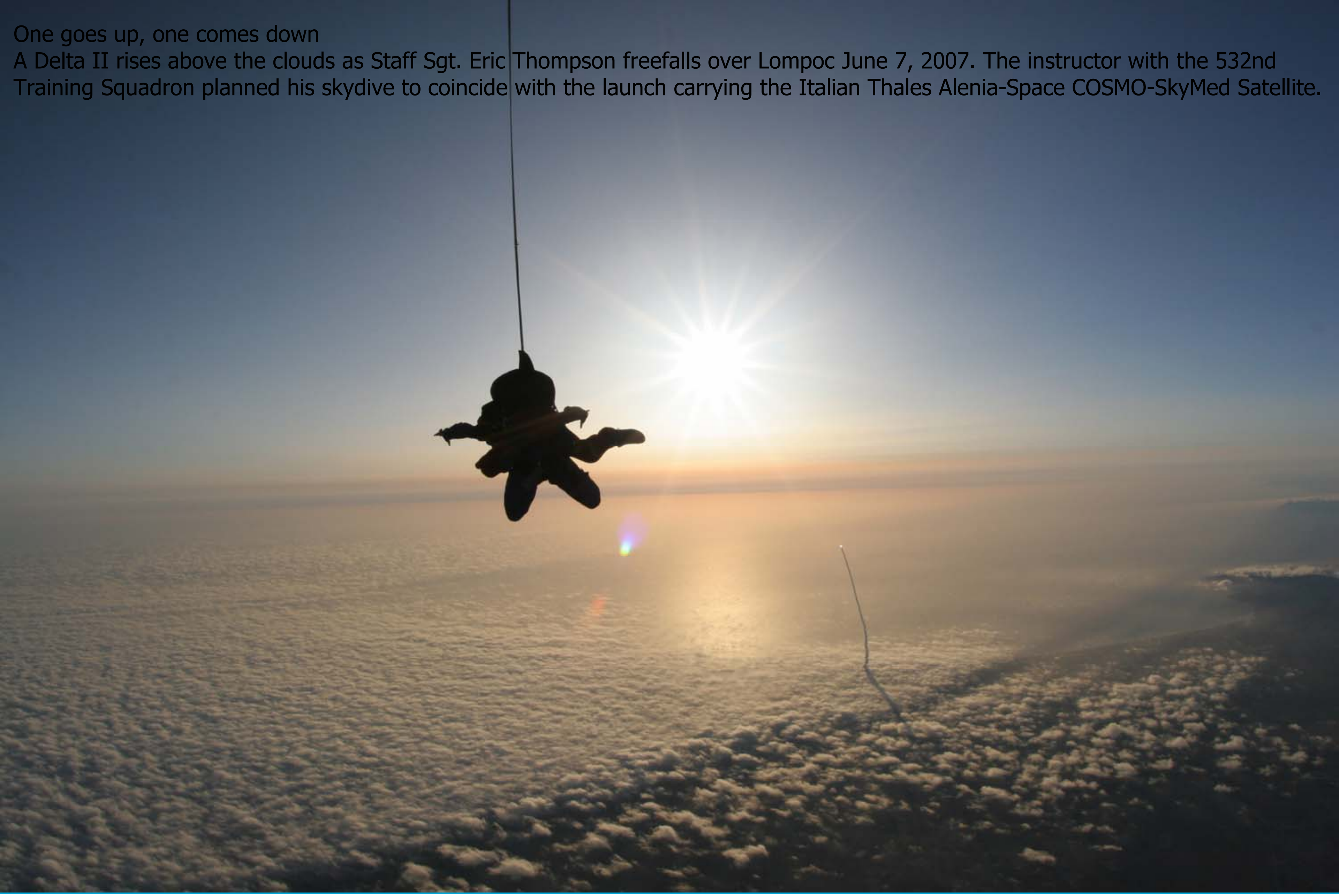
TerraSAR add-on for Digital Elevation Measurements

Source: H. Fiedler

Cosmo-Skymed 2 launch (9 Dec 2007)

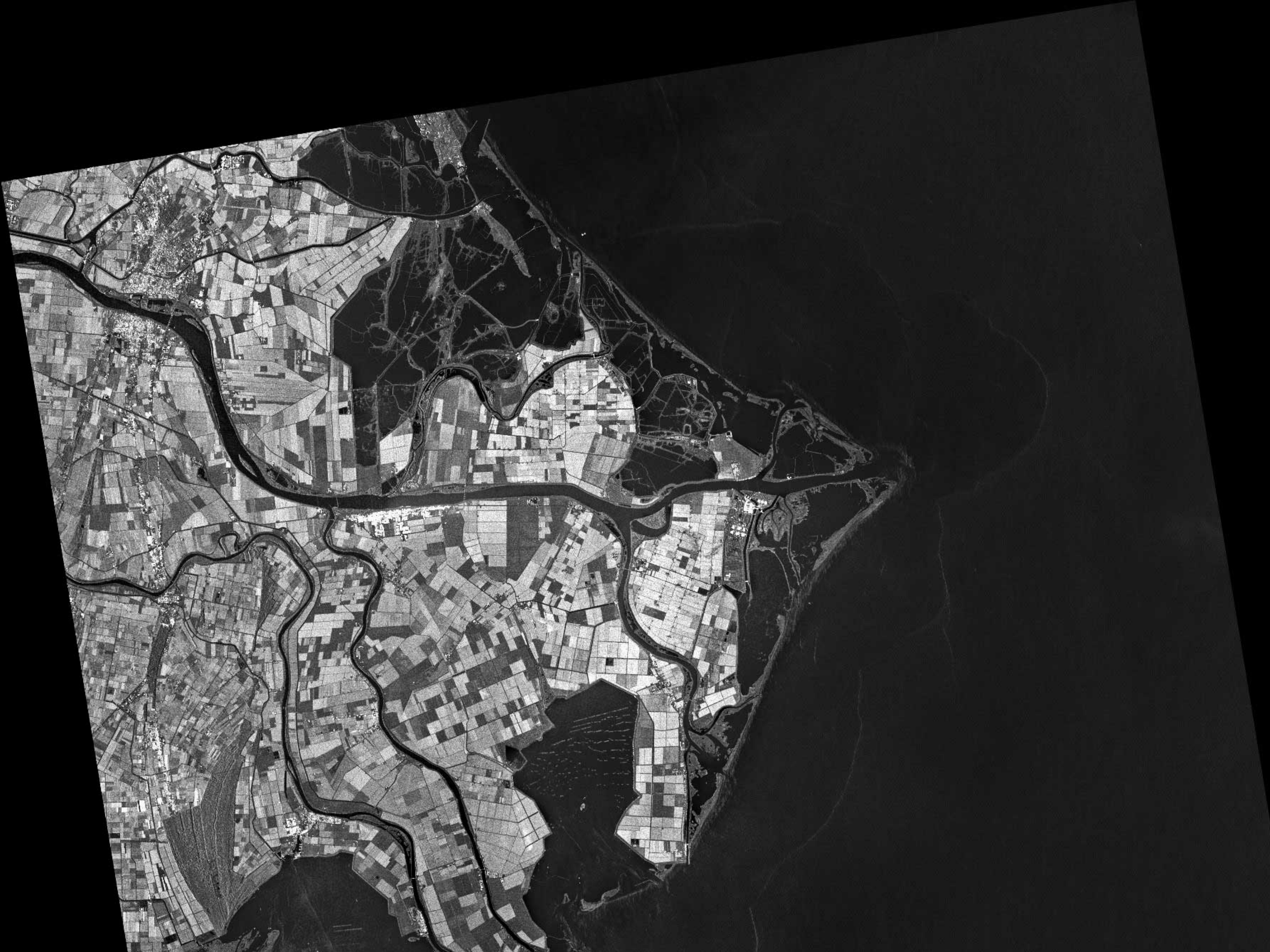






One goes up, one comes down
A Delta II rises above the clouds as Staff Sgt. Eric Thompson freefalls over Lompoc June 7, 2007. The instructor with the 532nd Training Squadron planned his skydive to coincide with the launch carrying the Italian Thales Alenia-Space COSMO-SkyMed Satellite.

Cosmo-Skymed Image

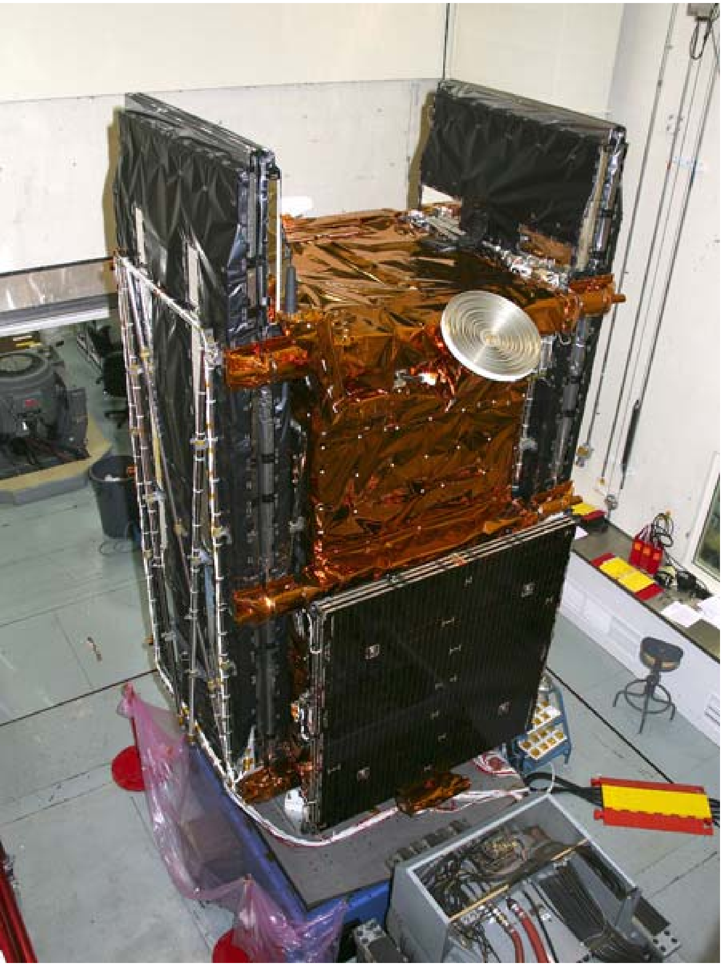


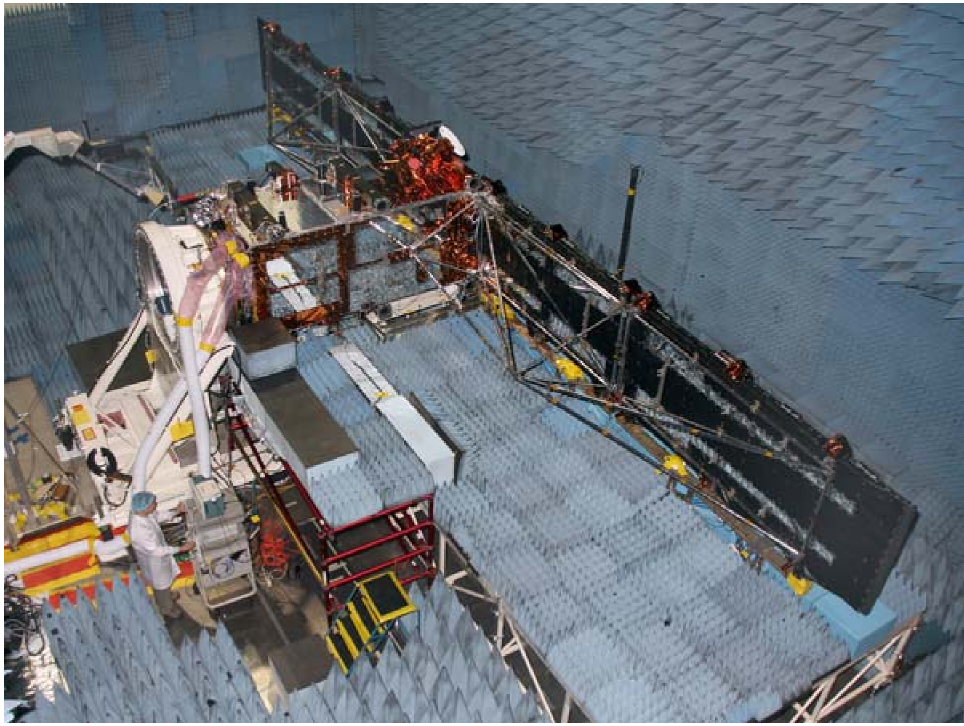
Radarsat 2 launch: 14 Dec 2007

RADARSAT-2 launch vehicle (Soyuz) at the launch pad. Credit: Roscosmos

RADARSAT-2 launch vehicle (Soyuz) at the launch pad. Credit: Roscosmos

RADARSAT-2 launch vehicle (Soyuz) at the launch pad. Credit: Roscosmos





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Radarsat Constellation

Small area excluded from 100% coverage requirement

Small area excluded from 100% coverage requirement

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Sentinel-1

Sentinel 1: an 'operational' mission

Designed for provision of 'guaranteed data services' for which liability can be accepted

Satisfy user needs consistent with GMES public institutional user model (cf. meteorological data provision

Most acquisitions pre-planned and routine operations normally uninterrupted

However, system designed to respond to emergency requests (support disaster management in crisis situations)

Source: E. Attema (ESA)

Sentinel-1 mission

- Following programmatic priorities and GMES pilot service requirements, Sentinel-1 gives
  - CONTINUITY of ERS Quality SAR data
  - RCT improvements
    - Revisit
    - Coverage
    - Timeliness

Source: E. Attema (ESA)

Conflict between orbit selection and service continuity?

GMES services require:

Better revisit w.r.t 35 days ERS/Envisat repeat cycle (based on altimetry)

Continuity: Same viewing geometry especially for differential interferometry

Potential conflict

Persistent scatterers insensitive to changes of frequency and viewing geometry?? (Yes/No)

Quick establishment of new archive

Source: E. Attema (ESA)

- Orbit
  - Near-Polar Sun-Synchronous
  - Mean Local Solar Time at Ascending Node 18:00 hours
  - Repeat Cycle 12 days
  - Cycle Length 175 orbits
- Swath Width
  - 80 km (SM)
  - 250 km (IW)
  - 400 km (EW)
  - 20 km x 20 km (WV)

Source: E. Attema (ESA)

- Polarisation
  - VV+VH or HH+HV (all modes)
- Spatial Resolution (Ground Range x Azimuth)
  - 5 x 5 m, single look (SM), 5 x 20 m single look (IW), 25 x 80 m 3-looks (EW), 20 x 5 single look (WV).
- Sensitivity
  - Noise Equivalent σ° -25 dB
- Radiometry
  - Stability 0.5 dB, Accuracy 1.0 dB
- Ambiguity Ratio
  - DTAR - 25 dB

Source: E. Attema (ESA)

Conclusions New Missions for interferometry

- **High bandwidth** → high resolutions
  - More persistent scatterers, better characterization
- **Short repeat orbit & wide swath interferometric mode**
  - Decreased temporal decorrelation, higher precision due to sampling
- **Constellations**
  - Higher repeat interval, more viewing geometries
- **Operational systems**
  - Guaranteed data provision
  - System of systems

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Methodology developments

- TOPS
- PSI

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New missions, frequent revisits: wide swath is necessary!

- Wide swath requires a wide *Slant Range Coverage ΔR*
- A wide slant range coverage requires a low PRF
- A low PRF requires a larger antenna length *L*
- Typical values for spaceborne SAR*:* *ΔR<Lx4800*

$$\Delta R \le \frac{c}{v_{sat}} \frac{L}{4} k$$

Example: ERS/ES/Sentinel: L=10m→ *ΔR < 48 km (=110km ground swath)*

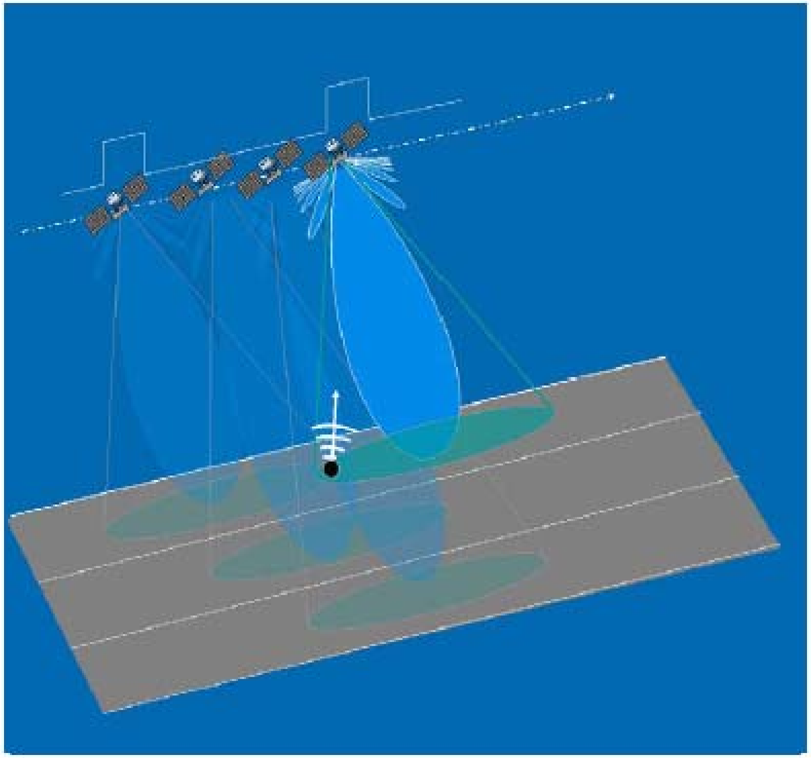
Consequence: a frequent revisit time (10 days) would demand a huge antenna

Source: A. Monti Guarnieri

Burst mode: ScanSAR

In ScanSAR mode, each target is revisited ≥ once in the azimuth footprint.

The Cycle Time should be lower than the footprint time:



$$T_C < T_F$$

Each target is observed for a Dwell Time:

$$T_D < T_F/N.$$

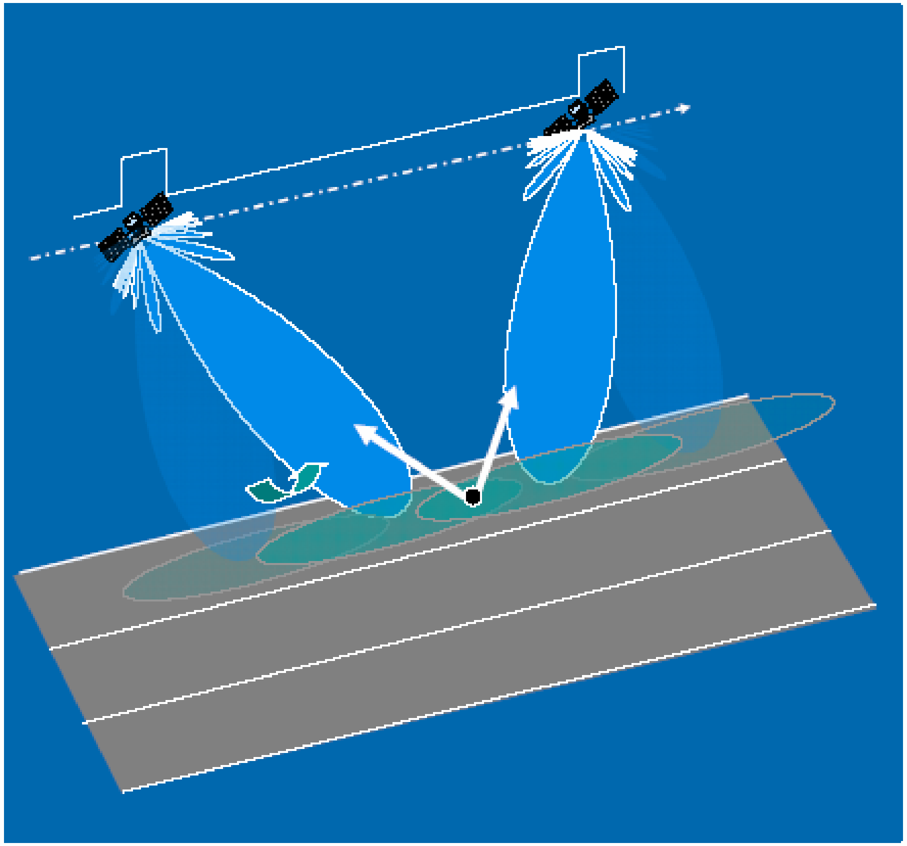
Its bandwidth is reduced of a factor > 1/N

Resolution is traded for coverage.

Source: A. Monti Guarnieri

Burst mode: TOPSAR

In TOPSAR mode, the cycle time is quite longer than the AAB time: $T_C >> T_F$



The continuous coverage is achieved by rotating the beam backward-to-forward.

The cycle time depends upon the beam angular velocity: there is a degree of freedom in that.

The rotation shrinks the AAP, simulating a longer antenna.

Resolution is traded for coverage.

Source: A. Monti Guarnieri

Methodologic solutions for problems: PSI

Deformation measurements: time-series approaches

- Evaluation per point: double-differences
- Opportunistic subsets

Purpose:

•Mitigate atmosphere signal

• resolve topography and deformation

•Resolve ambiguities

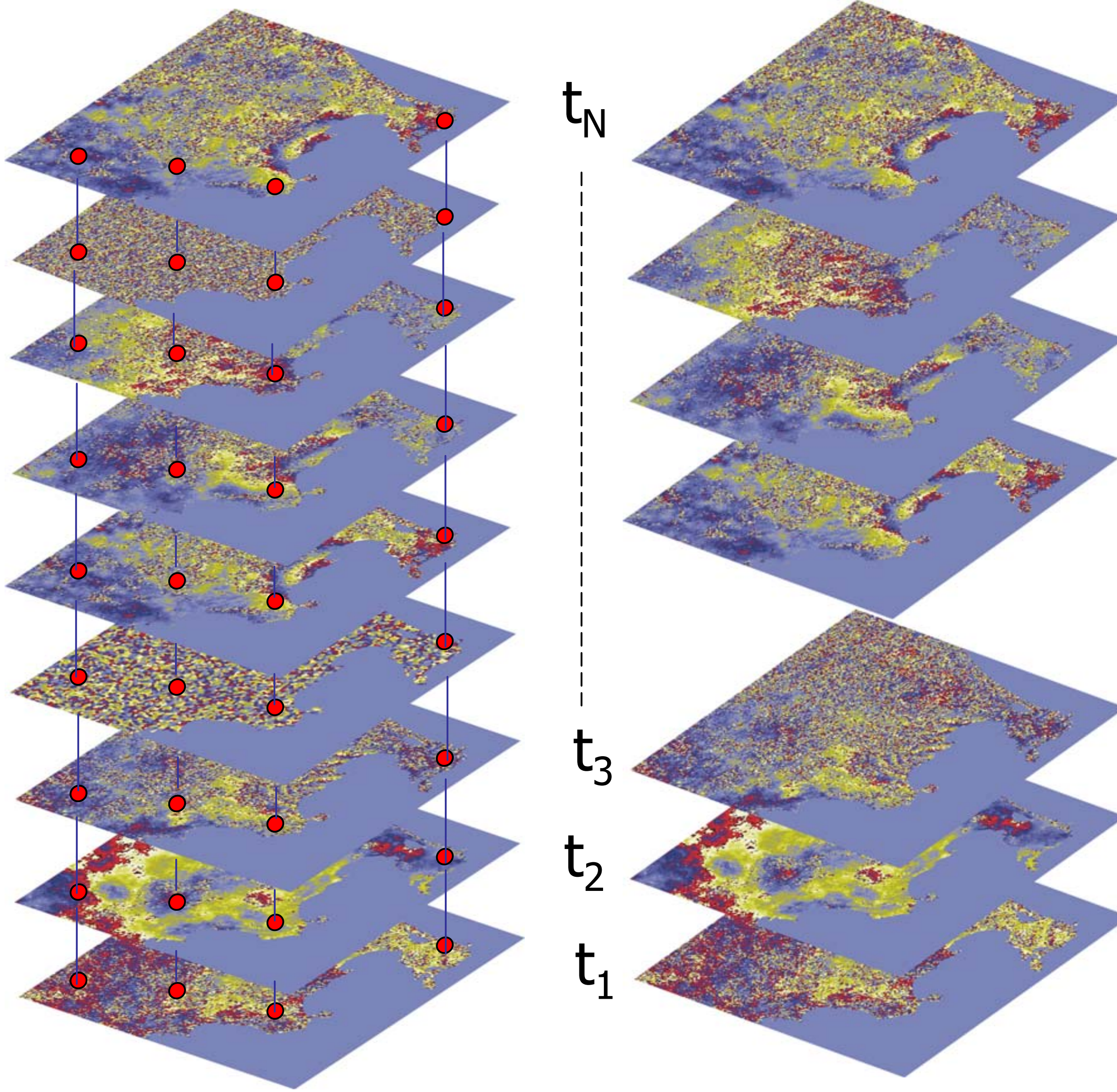
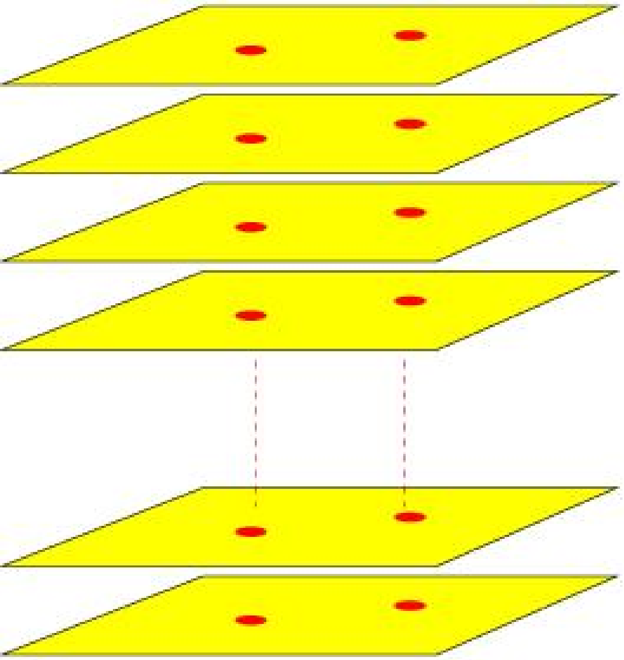
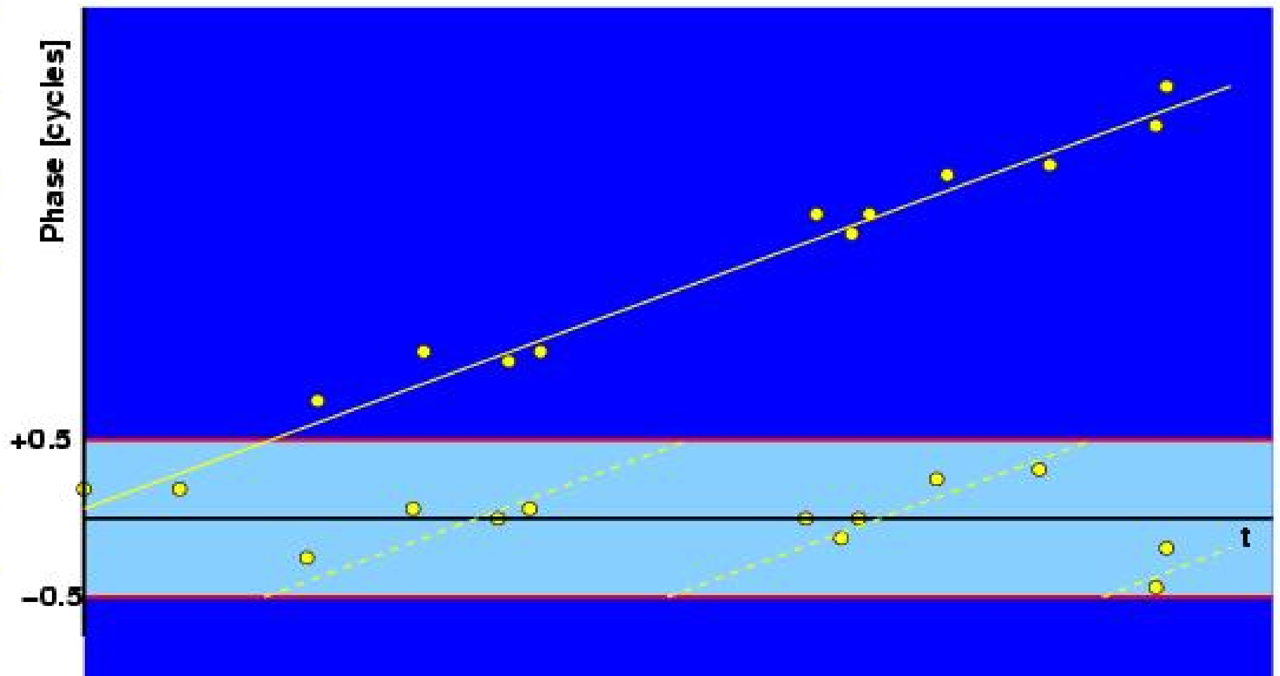


Image F. Serafino, Napels University

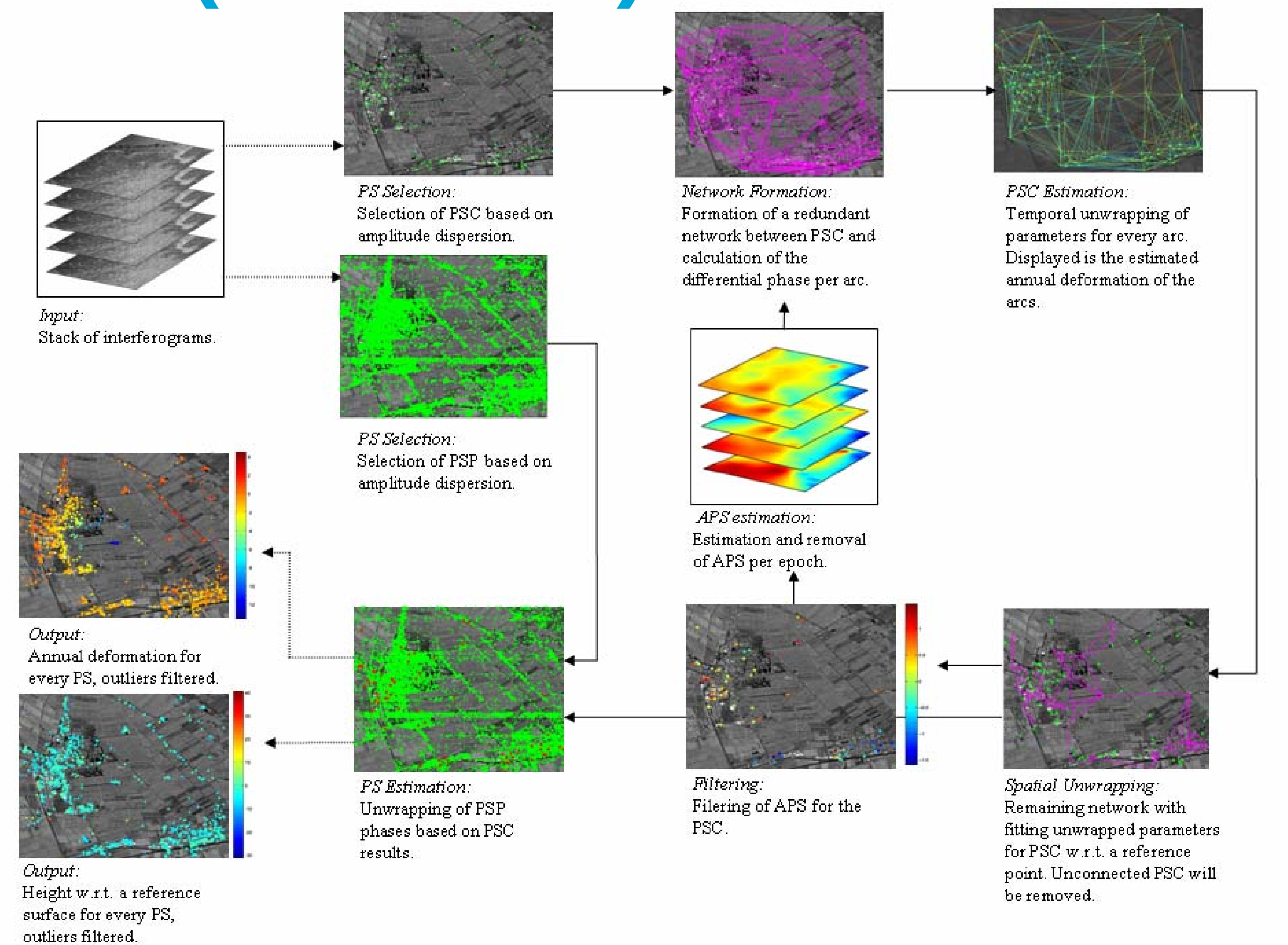
PS principle

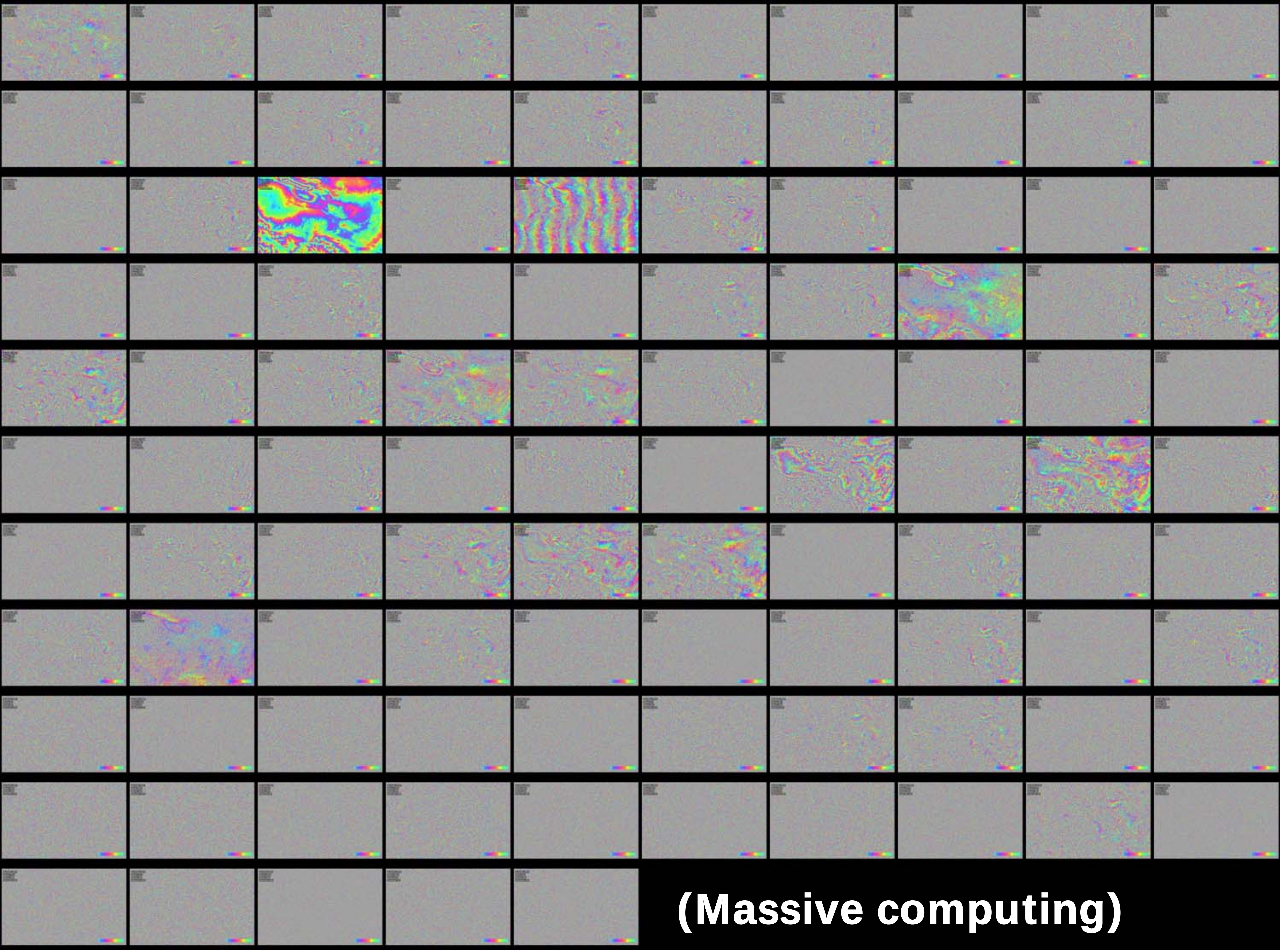
- Pixels with strong and consistent reflections in time.
- Multi-pass InSAR – time series necessary.
- Estimate atmospheric signal:
  - Spatially, not temporally correlated.
  - Independent of baseline. (topography is)





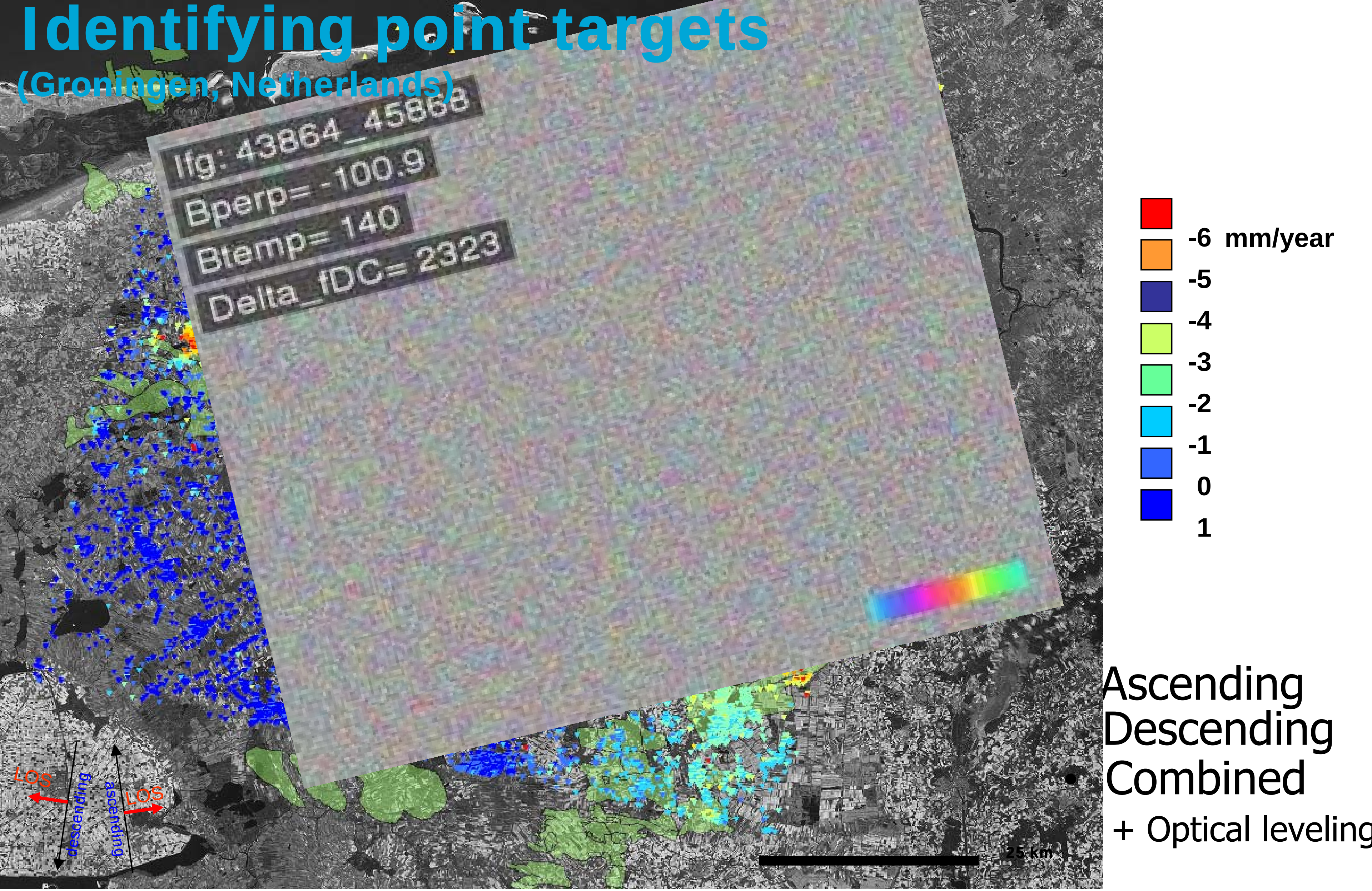
Principle of Persistent Scatterer InSAR (PS-InSAR)





(Massive computing)

Identifying point targets
(Groningen, Netherlands)



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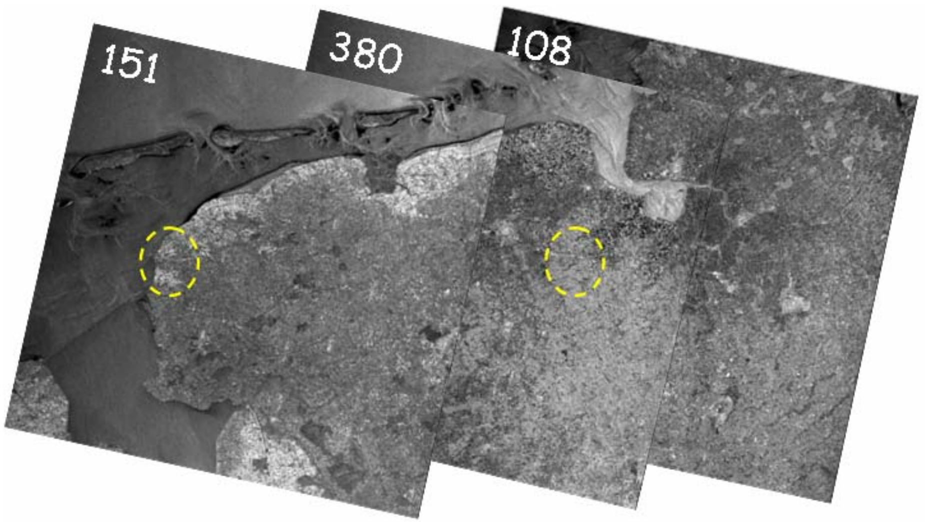
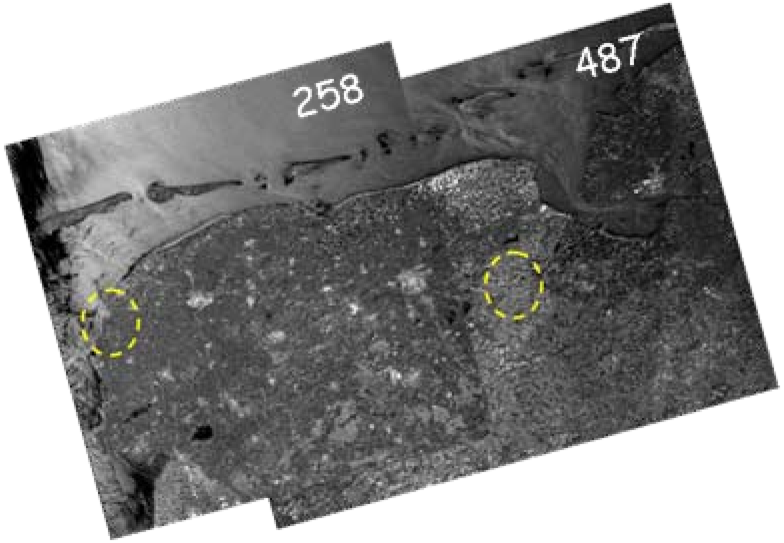
SAR Data North of the Netherlands





Track	No images	Master image	First image	Last image
108	68	05-Aug-97	09-May-92	27-Sep-05
380	75	20-Jul-97	02-Jul-92	21-Dec-03
151	75	21-May-97	12-May-92	13-May-05

Track	No images	Master image	First image	Last image
487	31	27-Jul-99	15-Apr-93	29-Sep-02
258	37	06-Jun-97	30-Mar-93	10-Feb-00

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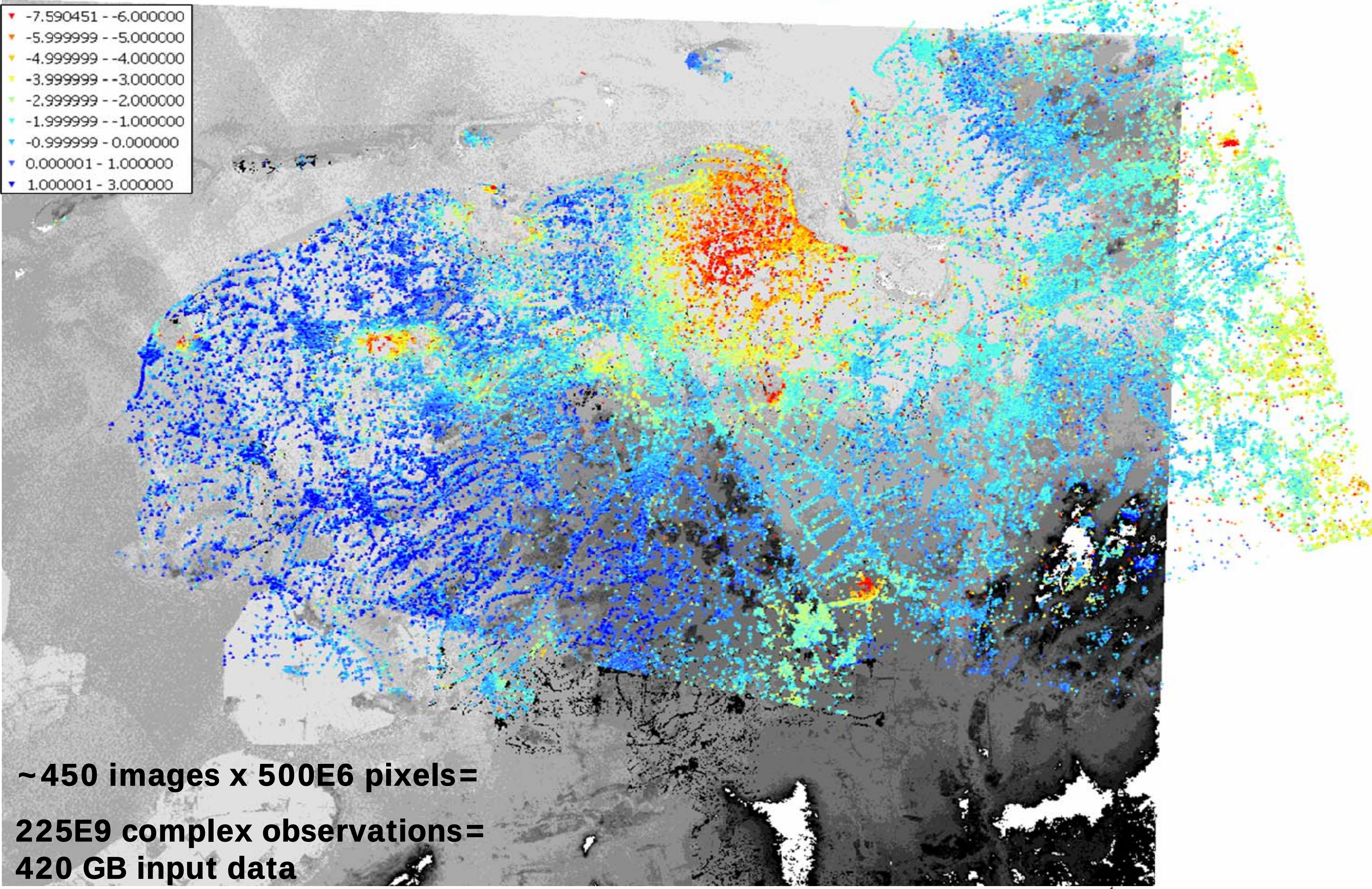
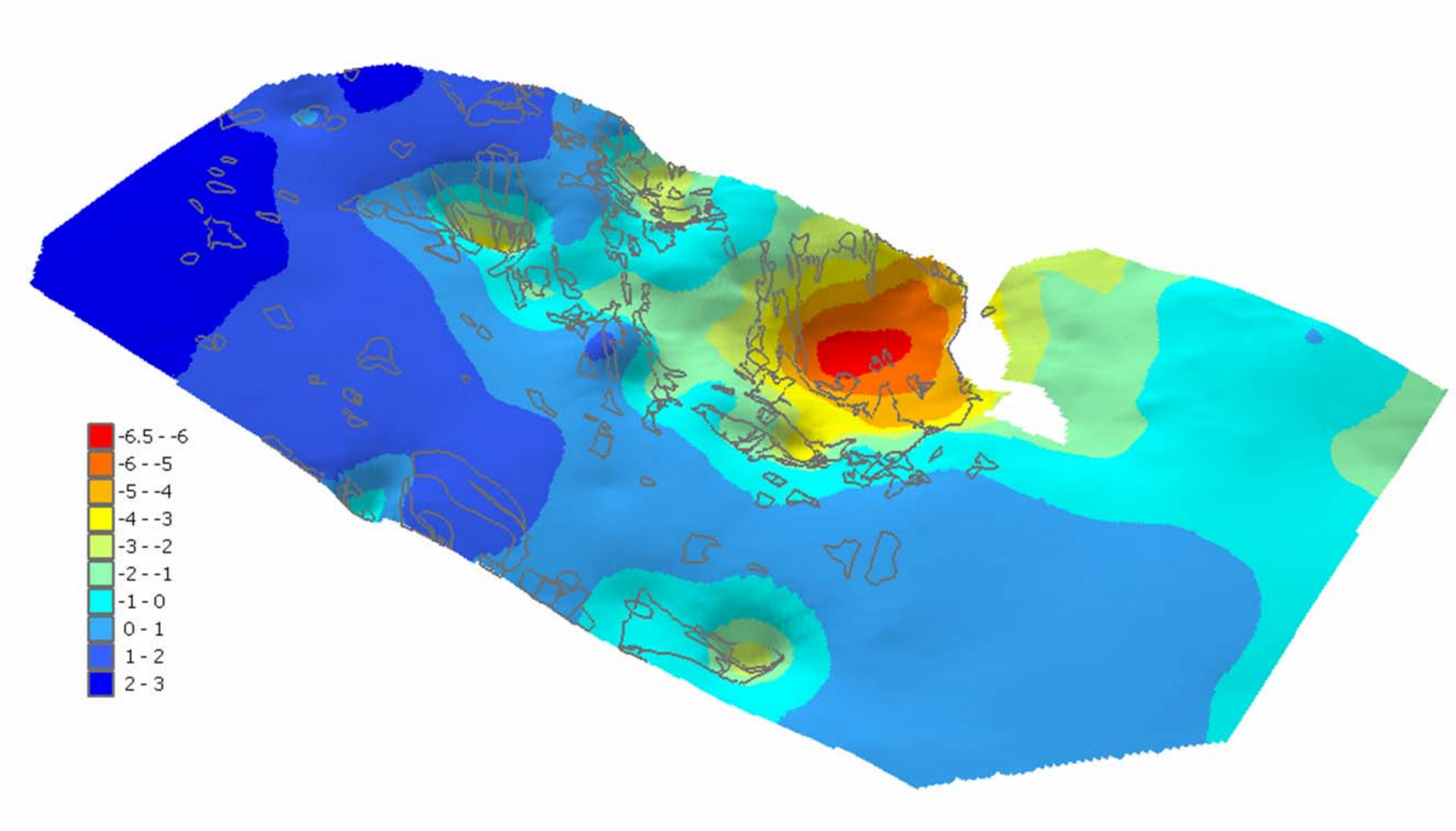
Six orbital tracks



~450 images x 500E6 pixels=

225E9 complex observations=
420 GB input data

Vertical PS velocities (mm / year)



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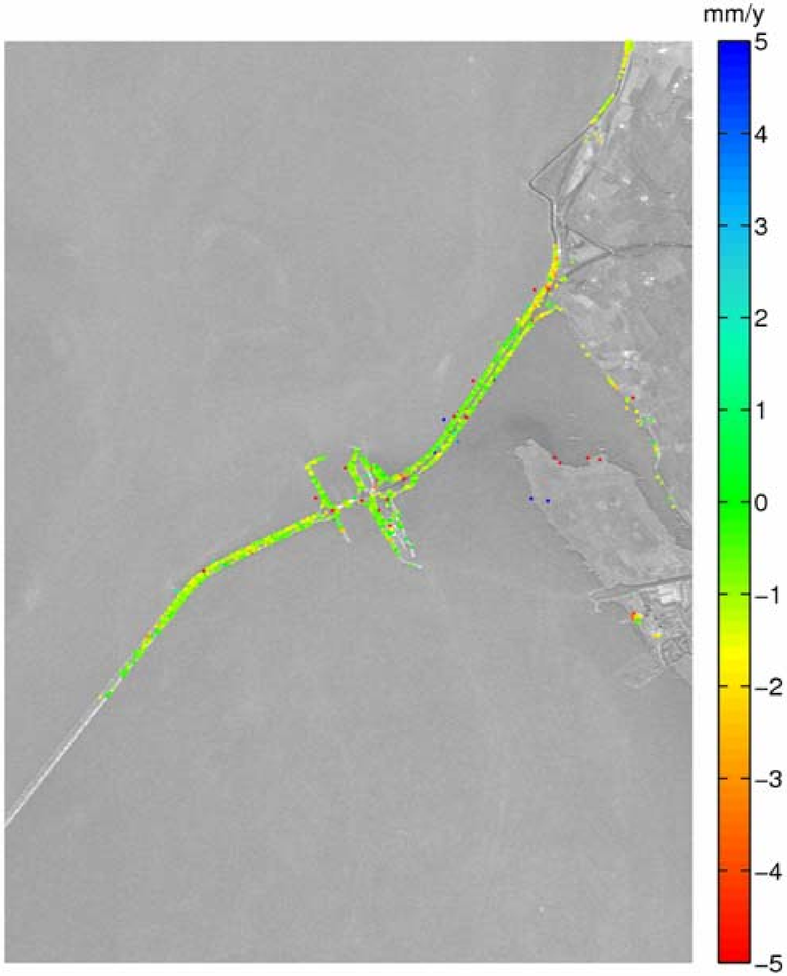
Infrastructure



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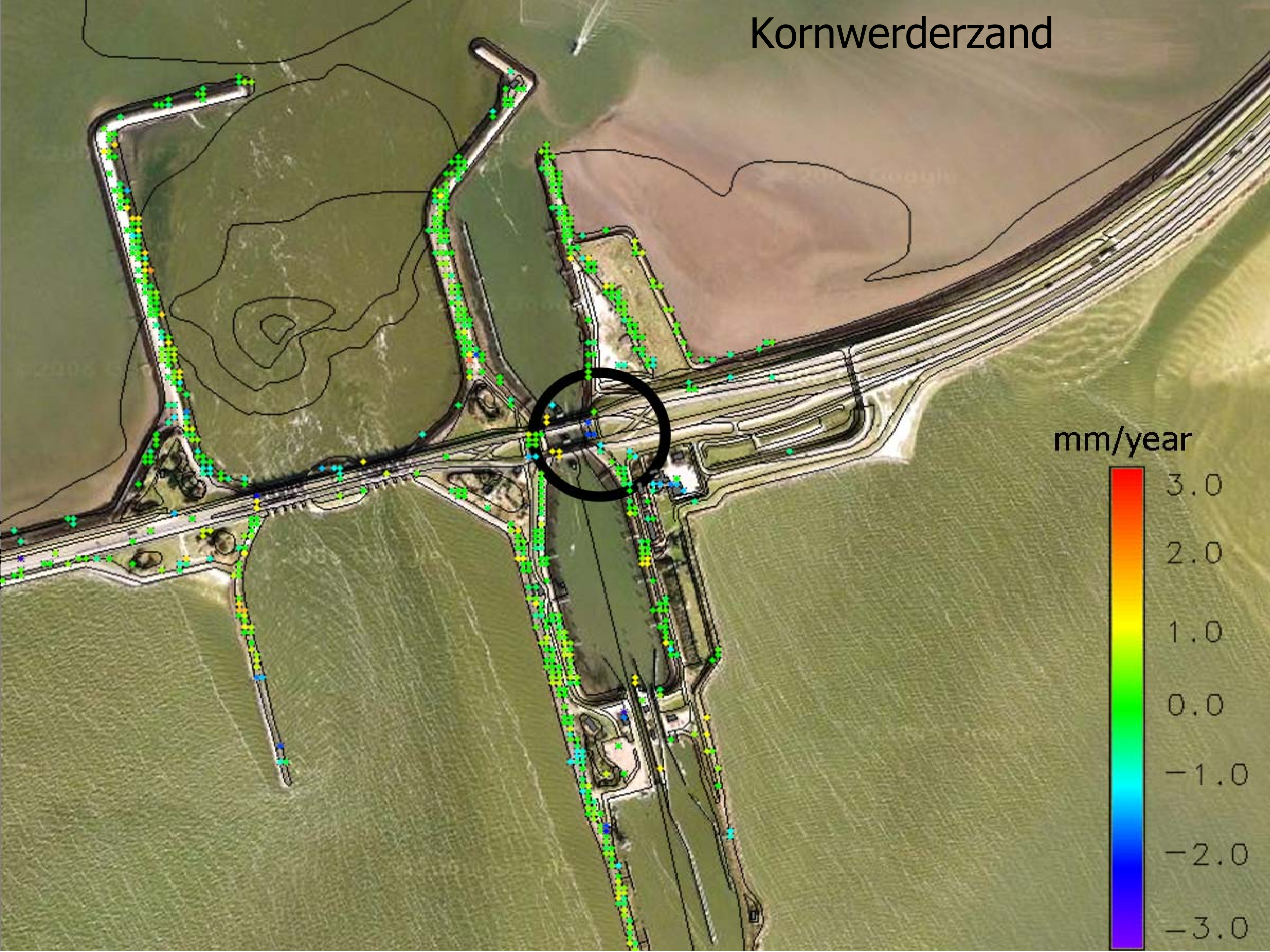
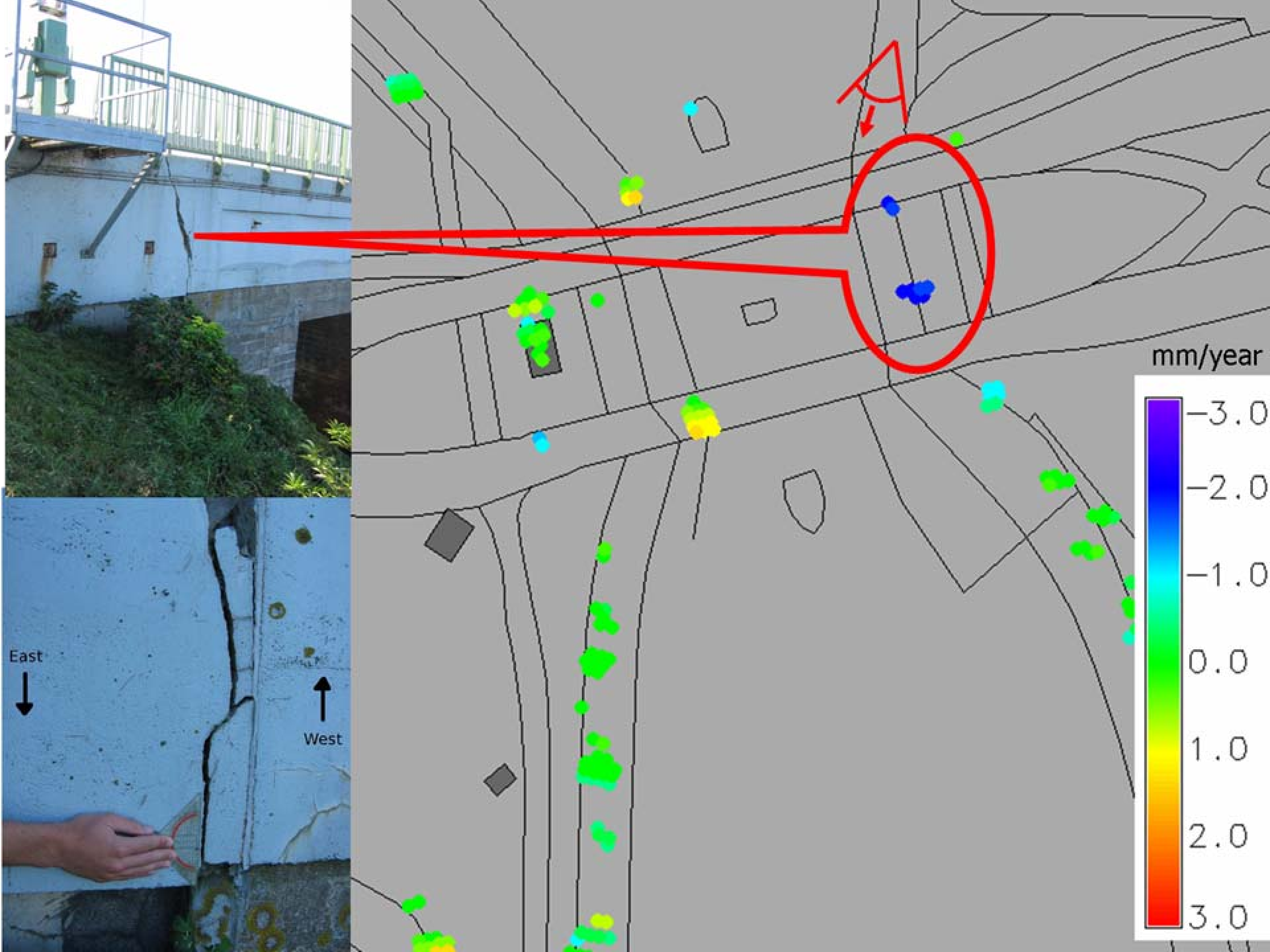
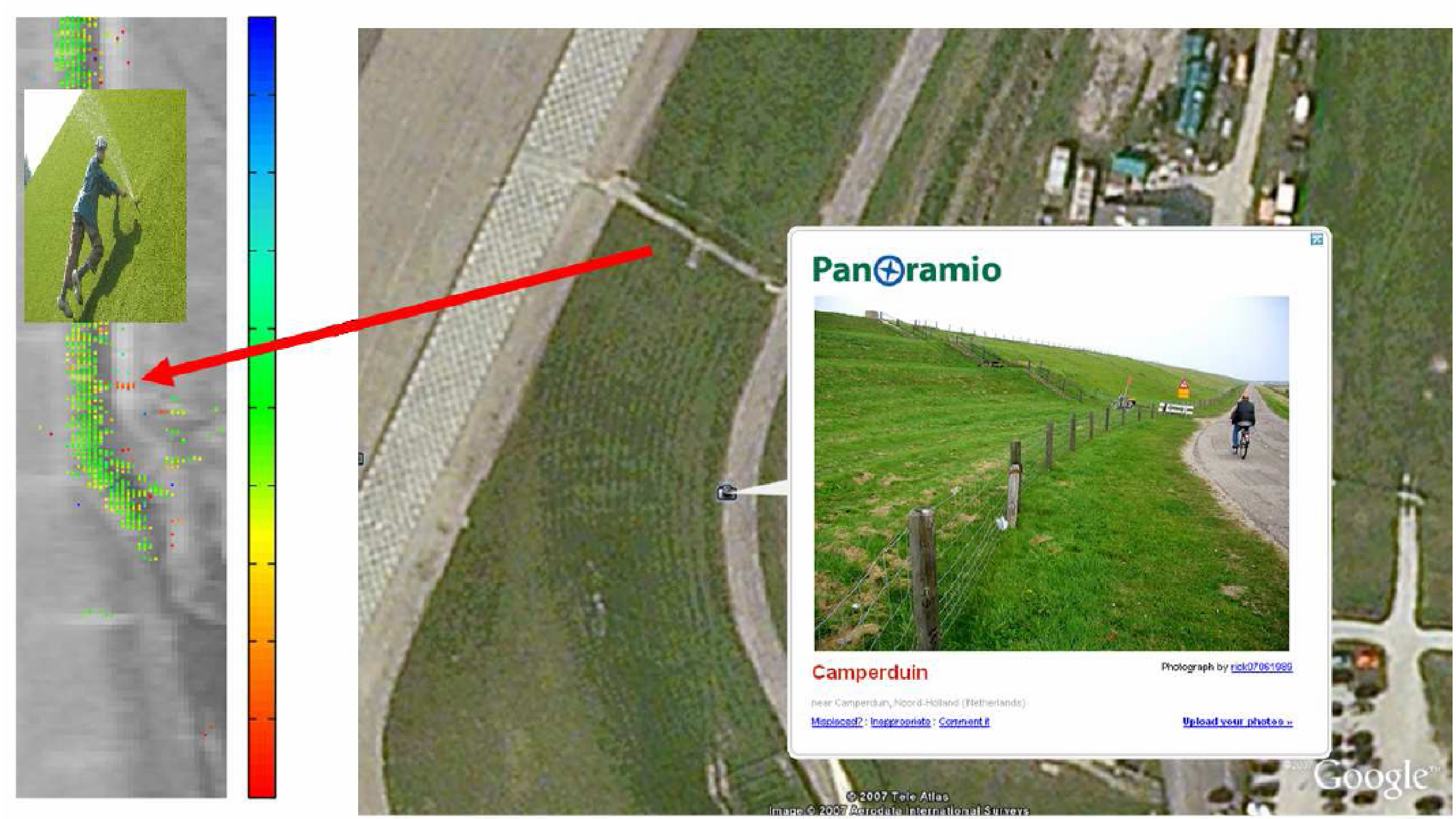

Kornwerderzand
mm/year
3.0
2.0
1.0
0.0
−1.0
−2.0
−3.0

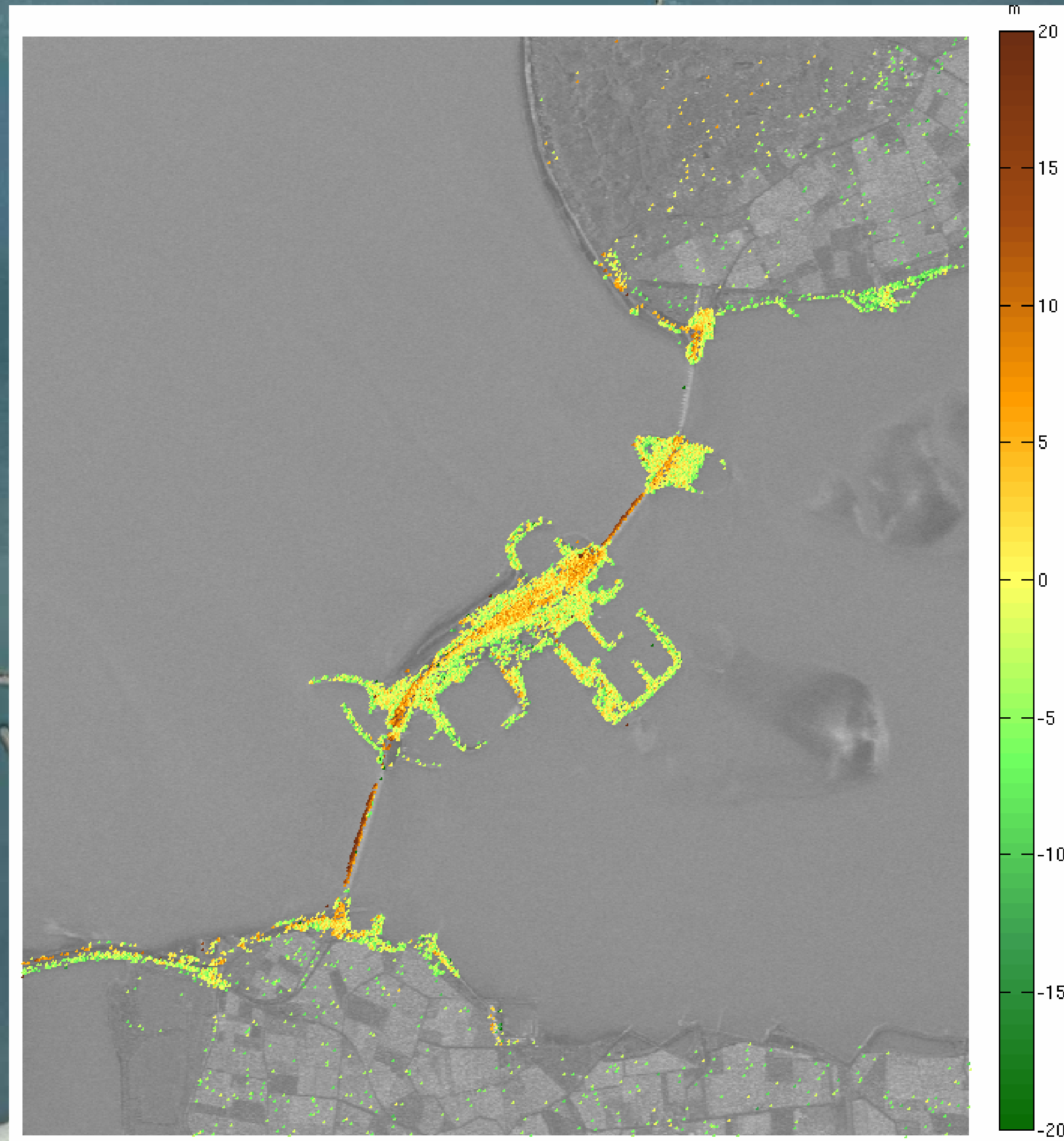
1000 ft
200 m
©2006 Google - Imagery ©2006 Aerodata International Su
mm/year
−3.0
−2.0
−1.0
−0.0
1.0
2.0
3.0


East
West
mm/year
−3.0
−2.0
−1.0
0.0
1.0
2.0
3.0

Hondsbossche Zeewering en Duinen



ERS-1 (3 day) en Sentinel-1



Validation Experiments

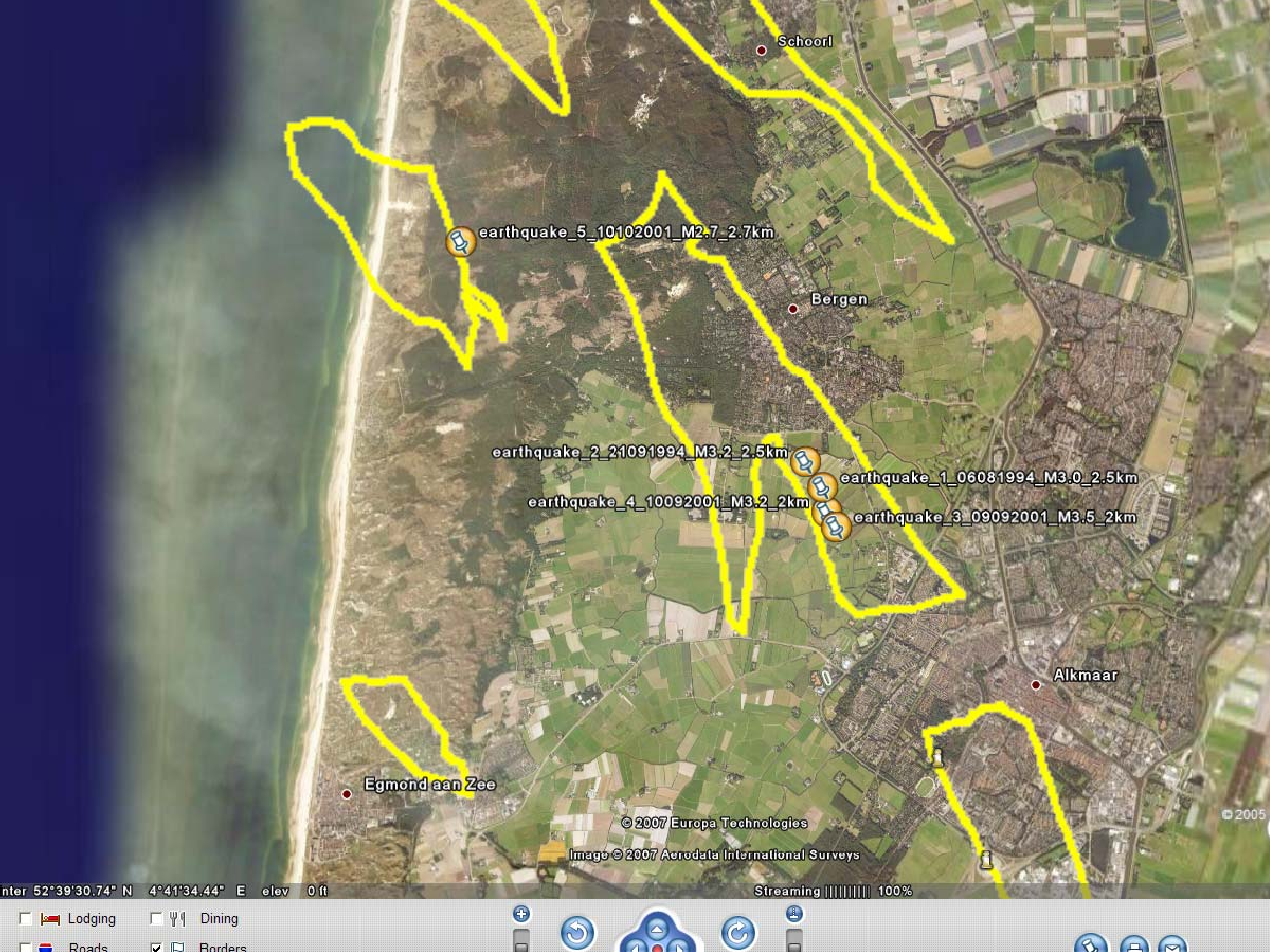
- Corner reflectors (see Petar Marinkovic’ presentation)
- Terrafirma validation experiment

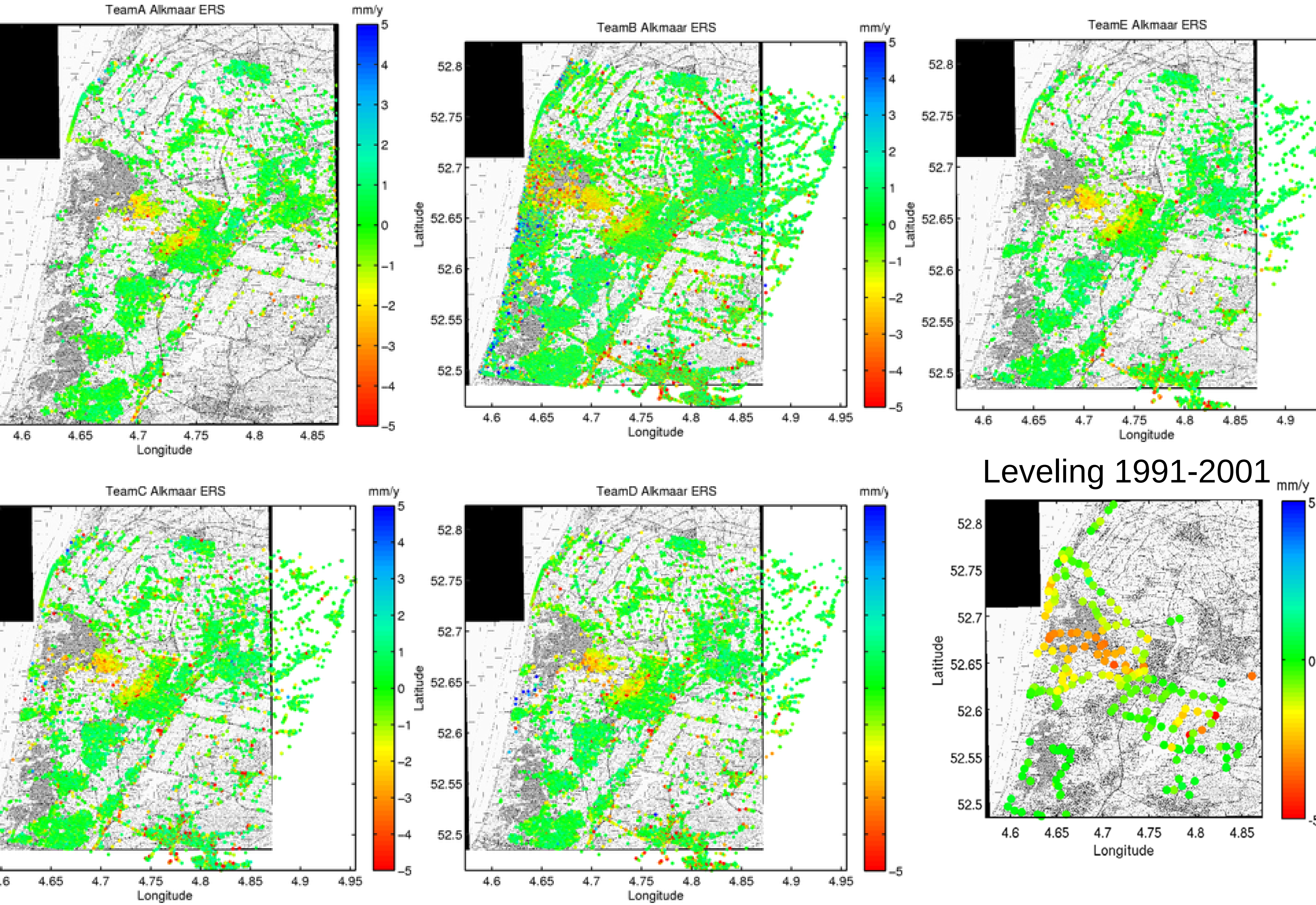
TU Delft

Case 'Alkmaar' - Background

- 16 gas fields
- Start gas production early 1970's
- Ongoing production, with expected end ~2010
- Production from depth > 2000m:
  - Rotliegend Slochteren Fm
  - Zechstein 3 Carbonate Mb (Platten)
  - Main Buntsandstein Subgr (Bunter).
- Max subsidence ~ 4mm/yr
- Expected maximum subsidence 2-8 cm over total prod. period.

TU Delft

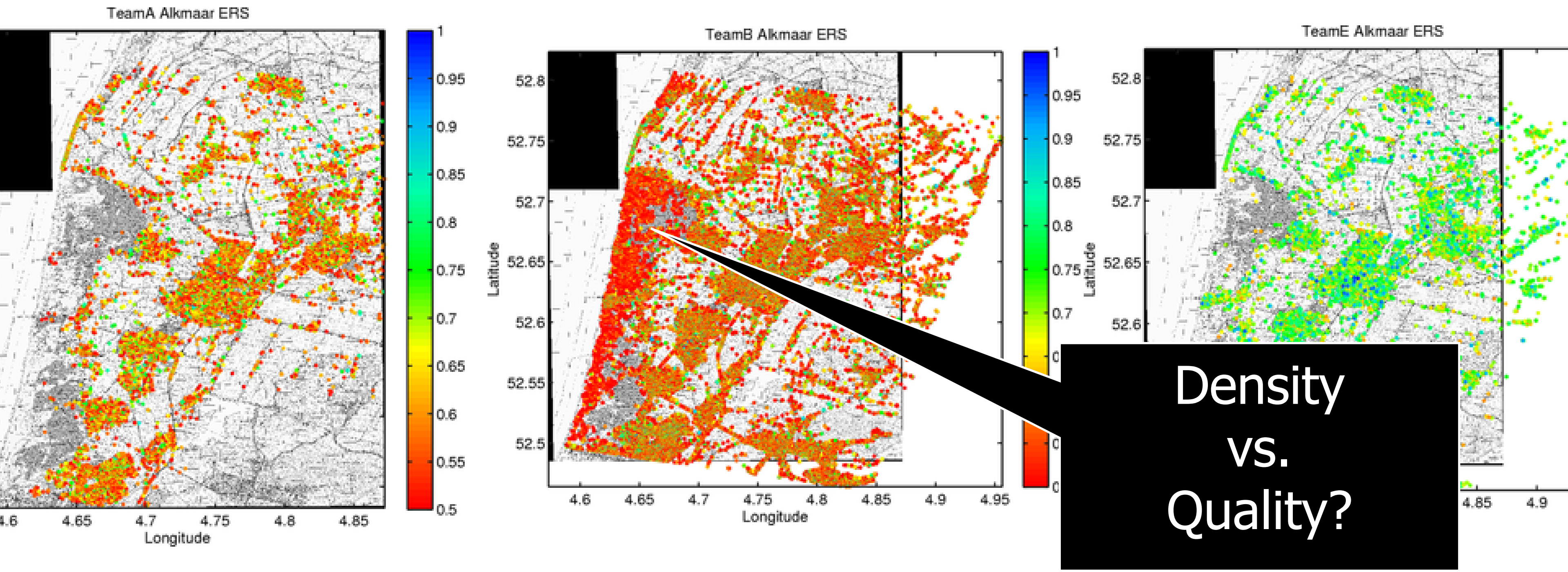

Schoorl
earthquake_5_10102001_M2.7_2.7km
Bergen
earthquake_2_21091994_M3.2_2.5km
earthquake_1_06081994_M3.0_2.5km
earthquake_4_10092001_M3.2_2km
earthquake_3_09092001_M3.5_2km
Alkmaar
Egmond aan Zee
© 2007 Europa Technologies
Image © 2007 Aerodata International Surveys
© 2005
inter 52°39'30.74" N 4°41'34.44" E elev 0 ft
Streaming |||||||||| 100%
Lodging
Dining
Roads
Borders

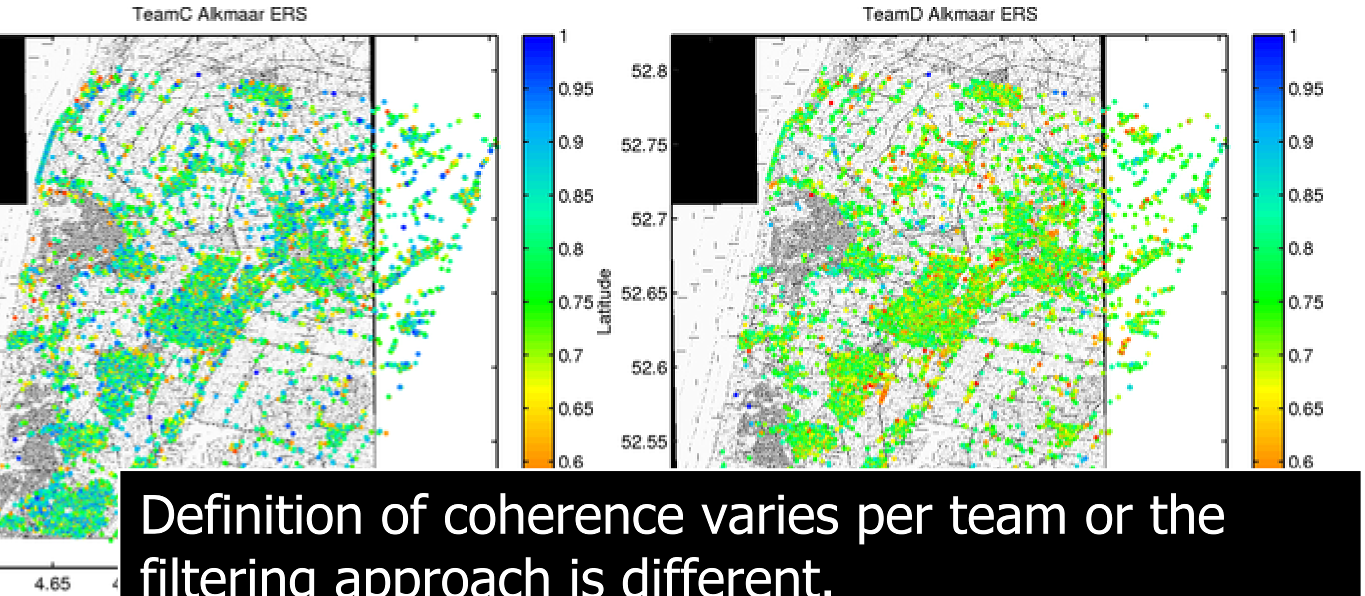

TeamA Alkmaar ERS
TeamB Alkmaar ERS
TeamE Alkmaar ERS
TeamC Alkmaar ERS
TeamD Alkmaar ERS
Leveling 1991-2001
mm/y
Latitude
Longitude

Plan view maps PS results

Alkmaar ERS

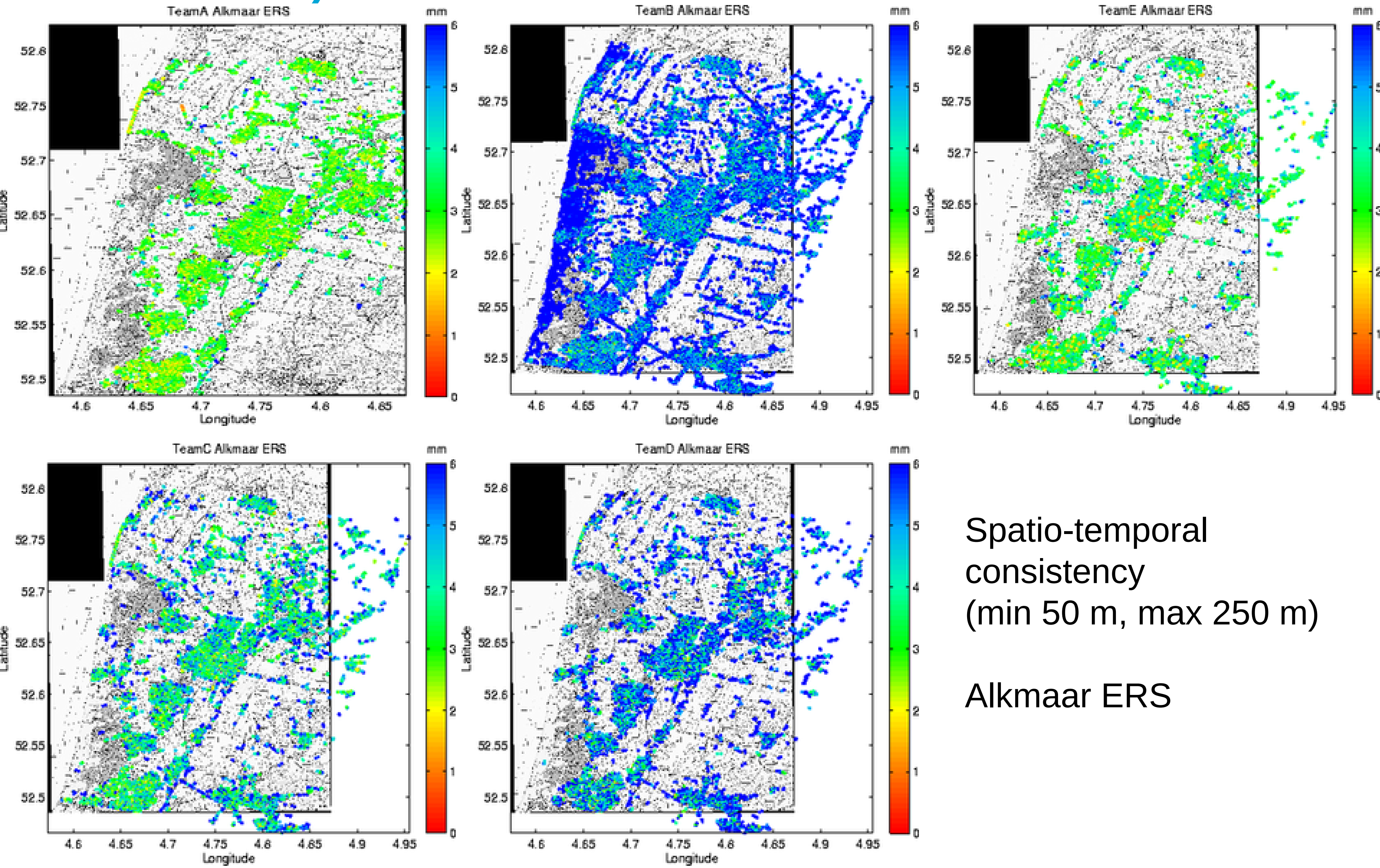
Coherence





Definition of coherence varies per team or the filtering approach is different.

An alternative measure: STC (Spatio-Temporal Consistency: Alkmaar ERS)

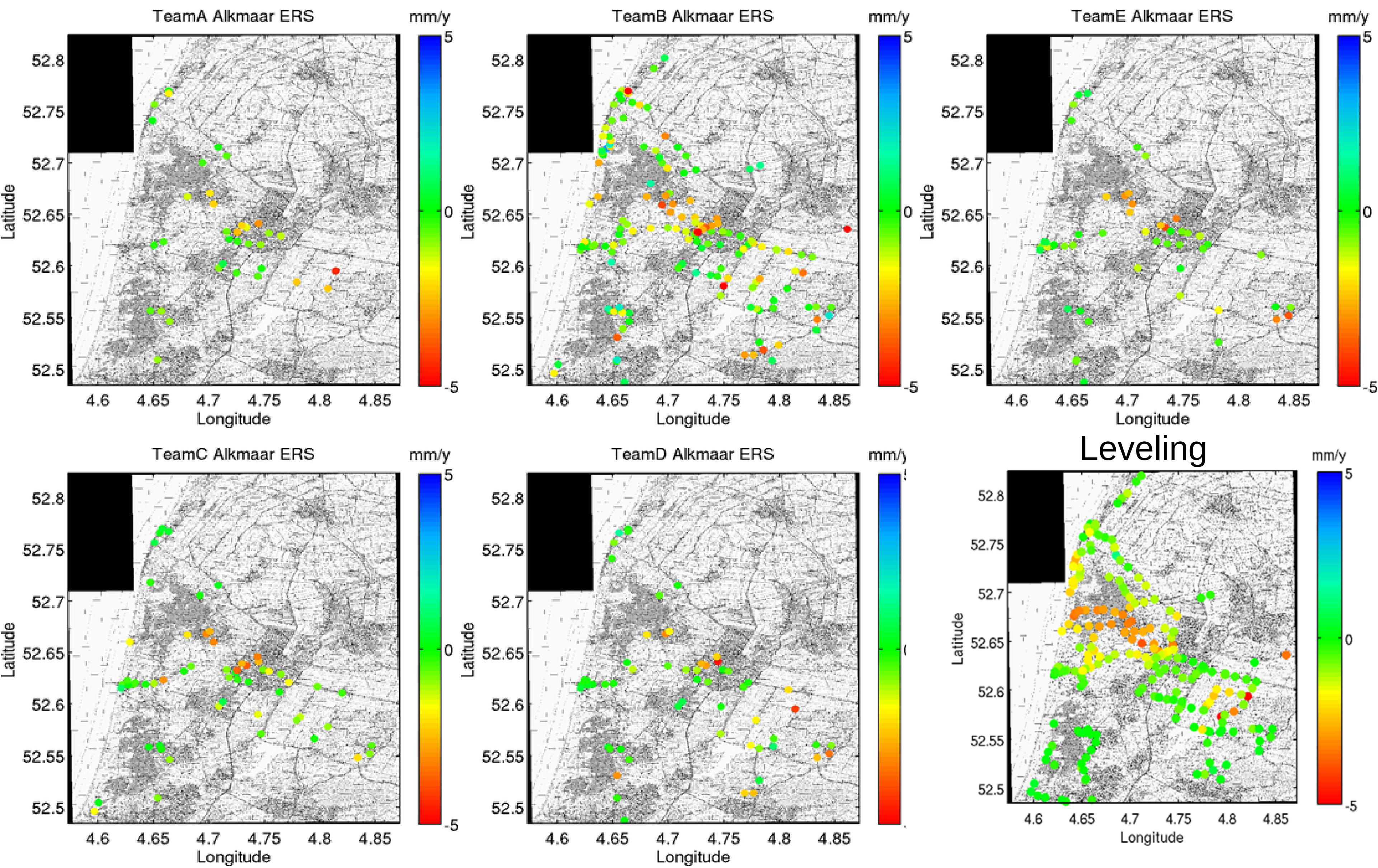


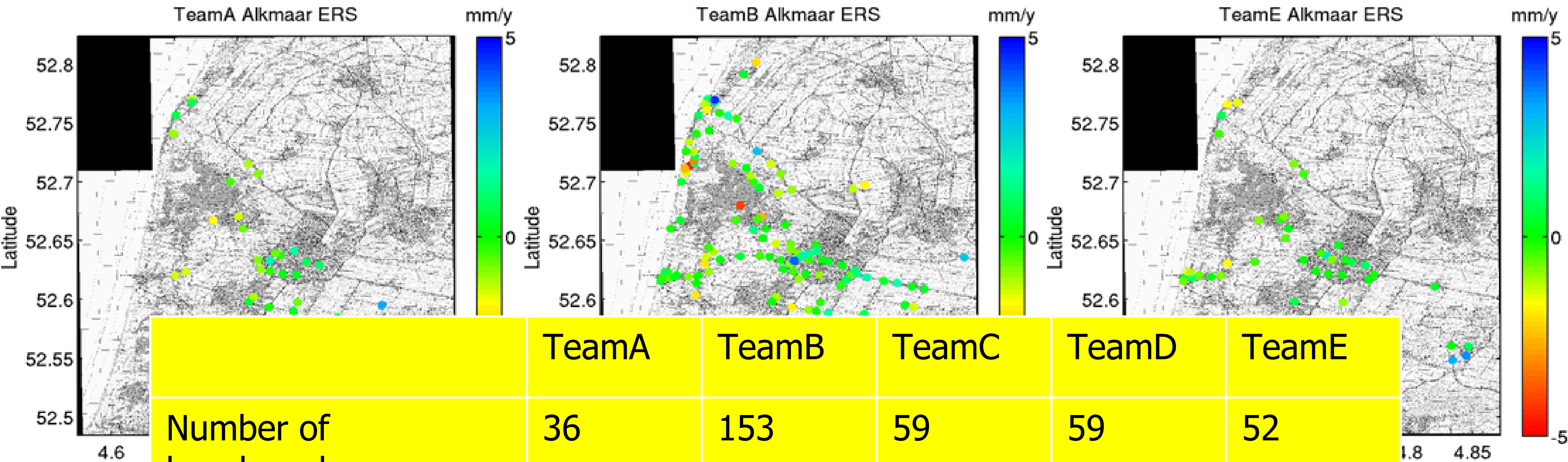
Spatio-temporal consistency
(min 50 m, max 250 m)

Alkmaar ERS

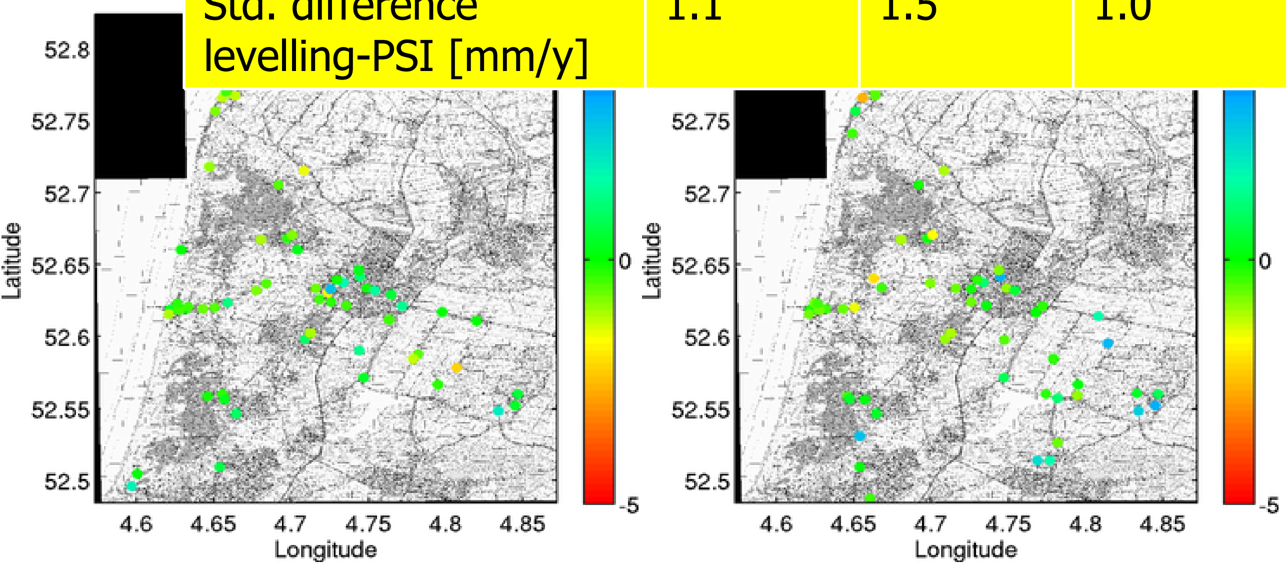
De-trended PSI velocities at leveling benchmarks

Alkmaar ERS





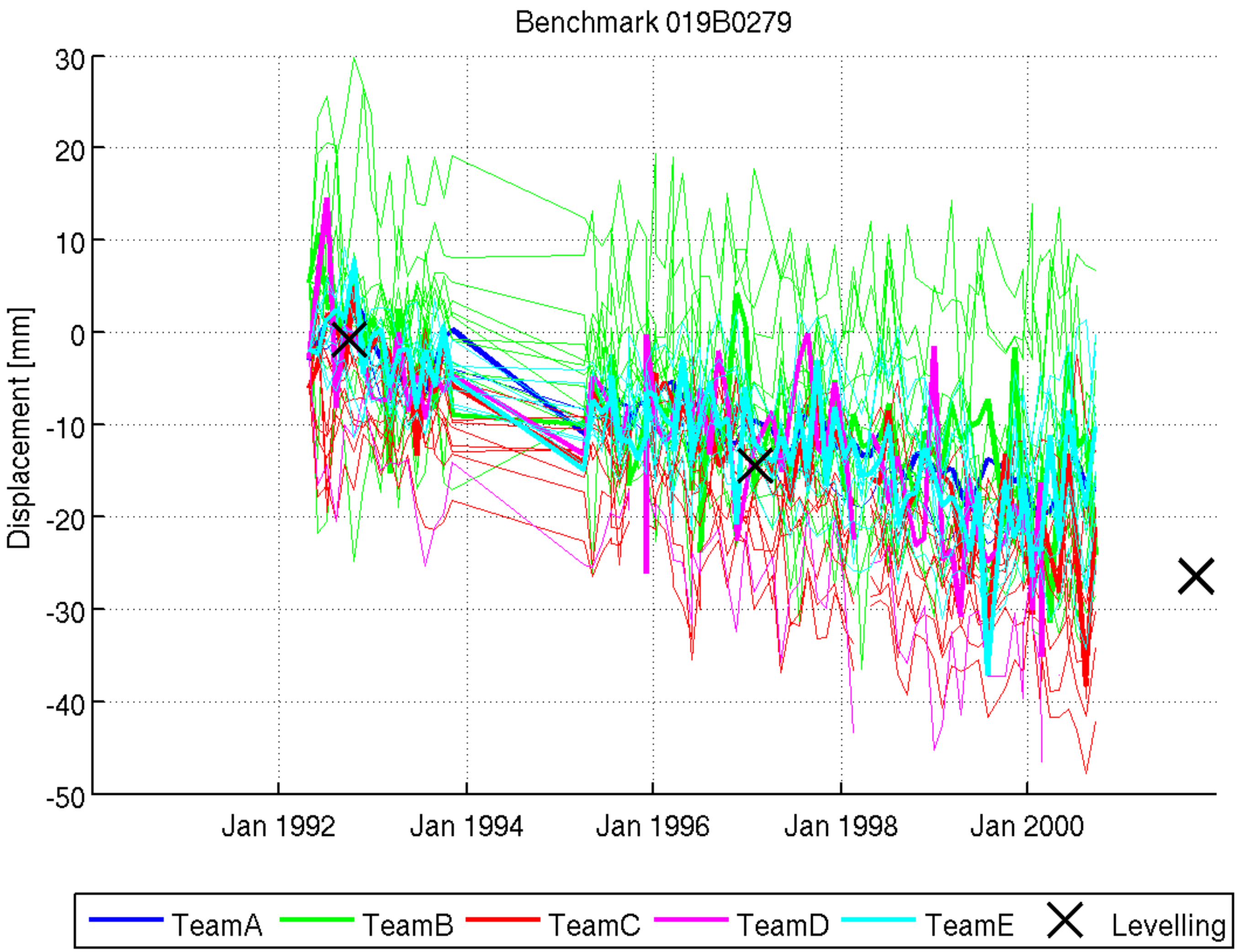
	TeamA	TeamB	TeamC	TeamD	TeamE
Number of benchmarks	36	153	59	59	52
Std. difference levelling-PSI [mm/y]	1.1	1.5	1.0	1.3	1.1



Difference between leveling and PSI (de-trended)
Alkmaar ERS

Example time series

Alkmaar ERS



Evaluation of individual displacements
Alkmaar ERS

- Based on temporal interpolation of the PSI time series at the time of leveling measurements (epochs)
- Temporal interpolation using square interpolation kernel of length 6

	TeamA	TeamB	TeamC	TeamD	TeamE
Number of benchmark epochs	328	3470	772	458	1265
Std. difference levelling-PSI [mm]	8.0	10.9	8.8	7.3	7.6

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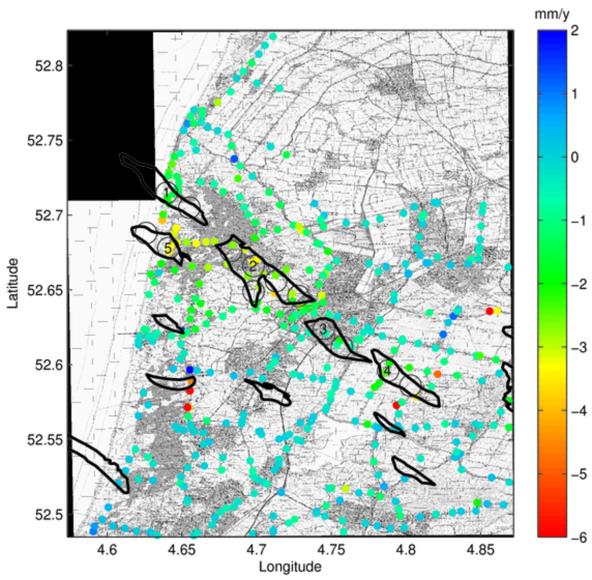
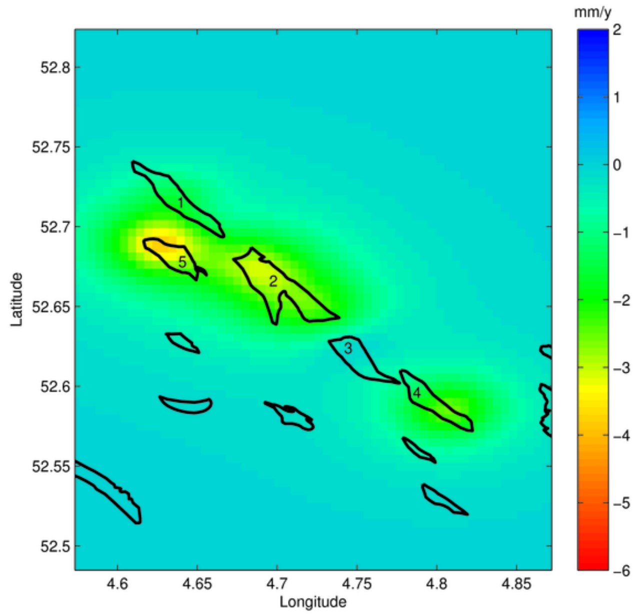
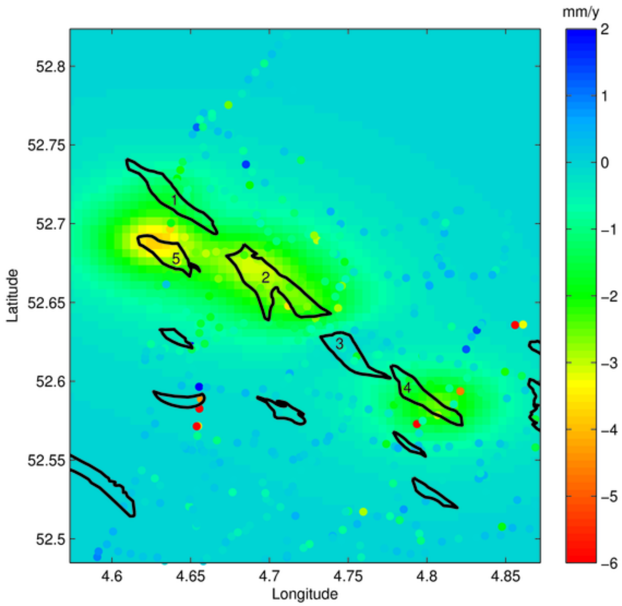
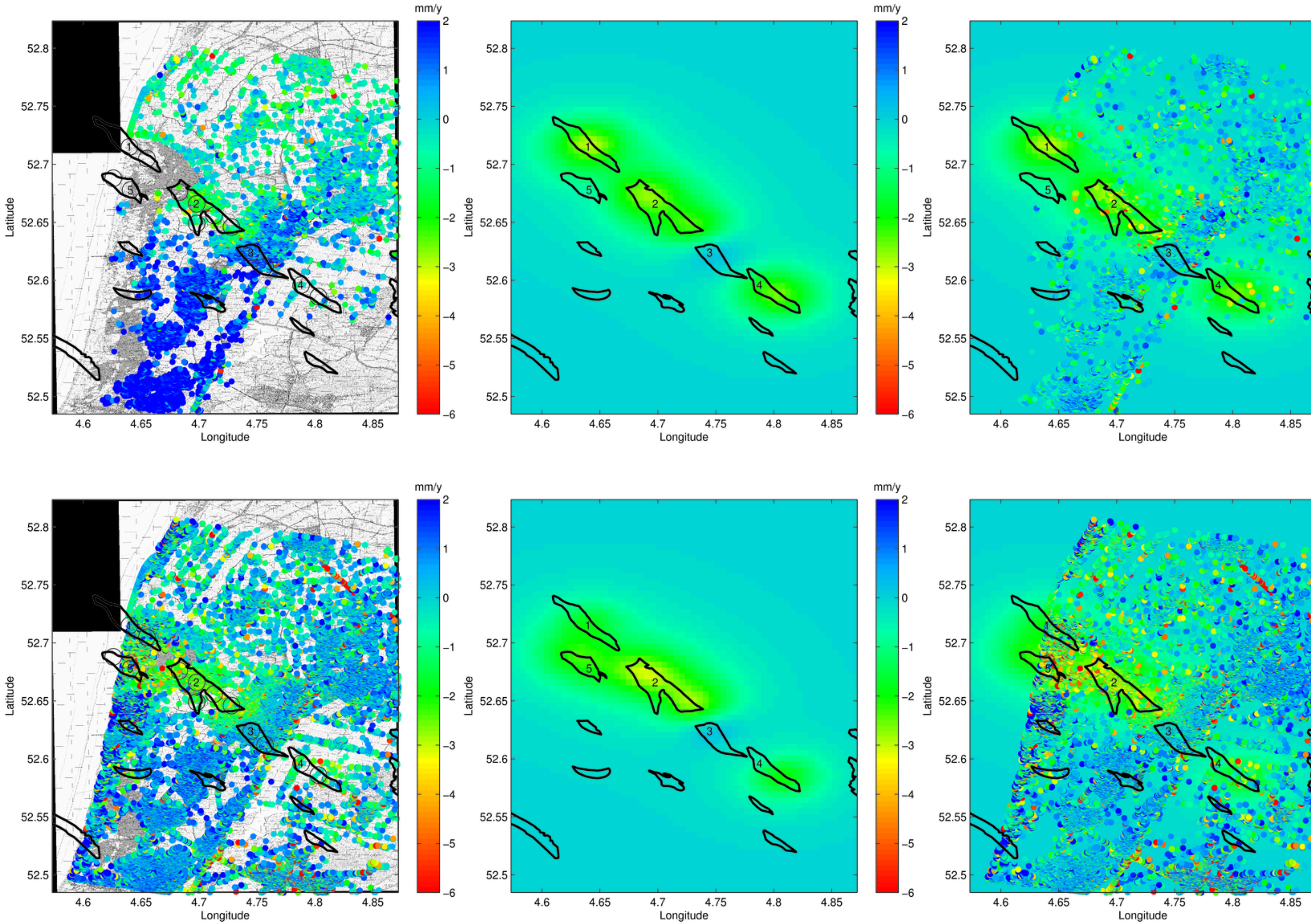
Comparison in the parameter space!

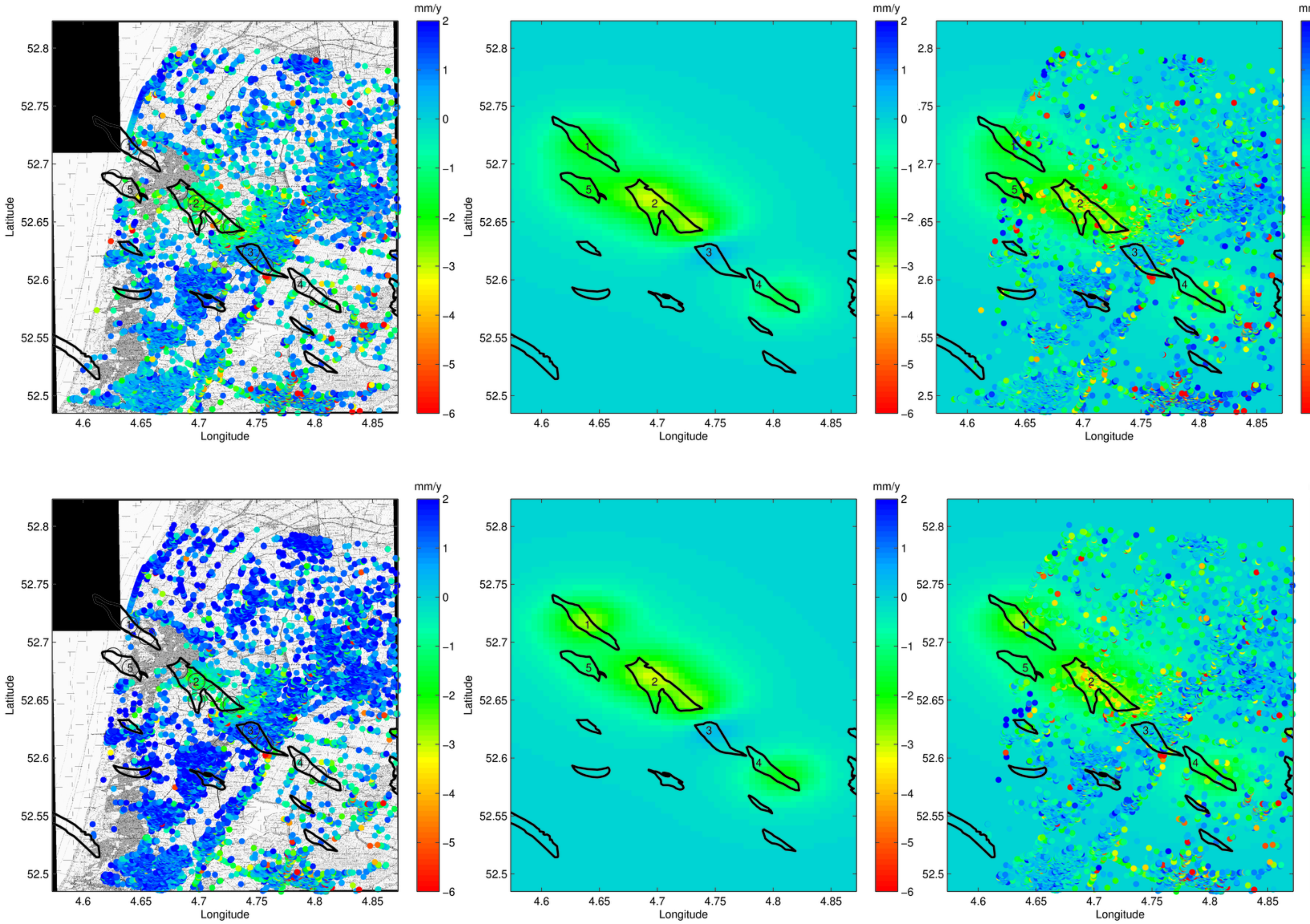
Mogi modeling



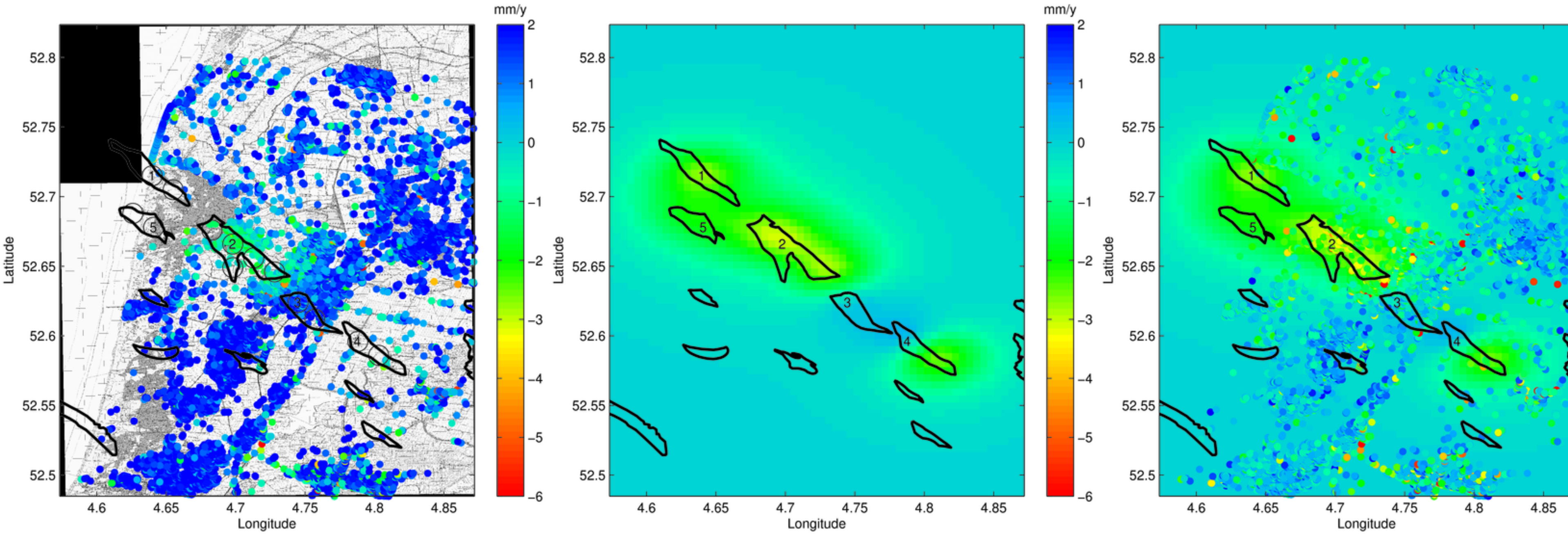




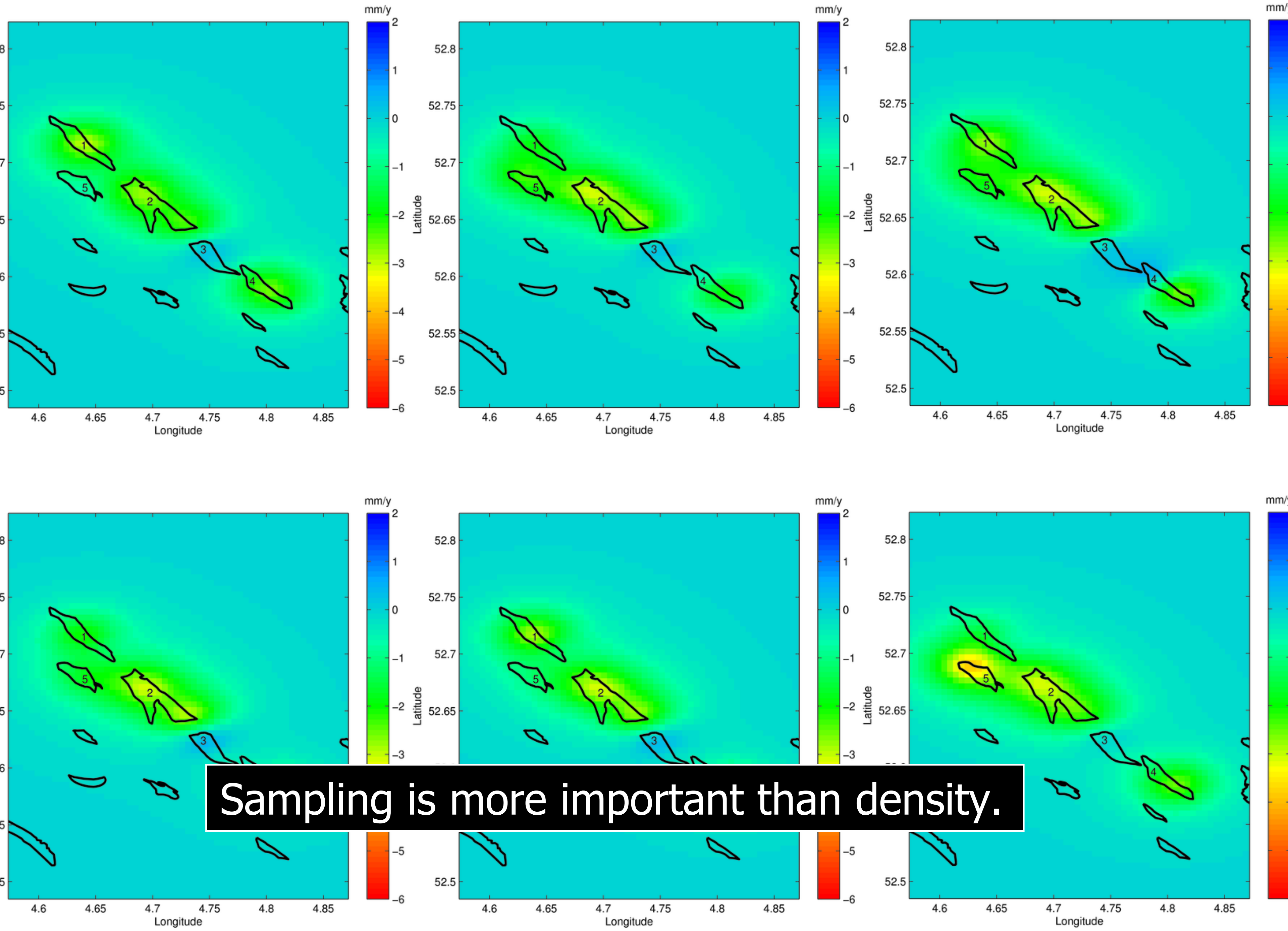

mm/y
Latitude
Longitude
2
1
0
−1
−2
−3
−4
−5
−6
52.8
52.75
52.7
52.65
52.6
52.55
52.5
4.6
4.65
4.7
4.75
4.8
4.85
1
2
3
4
5



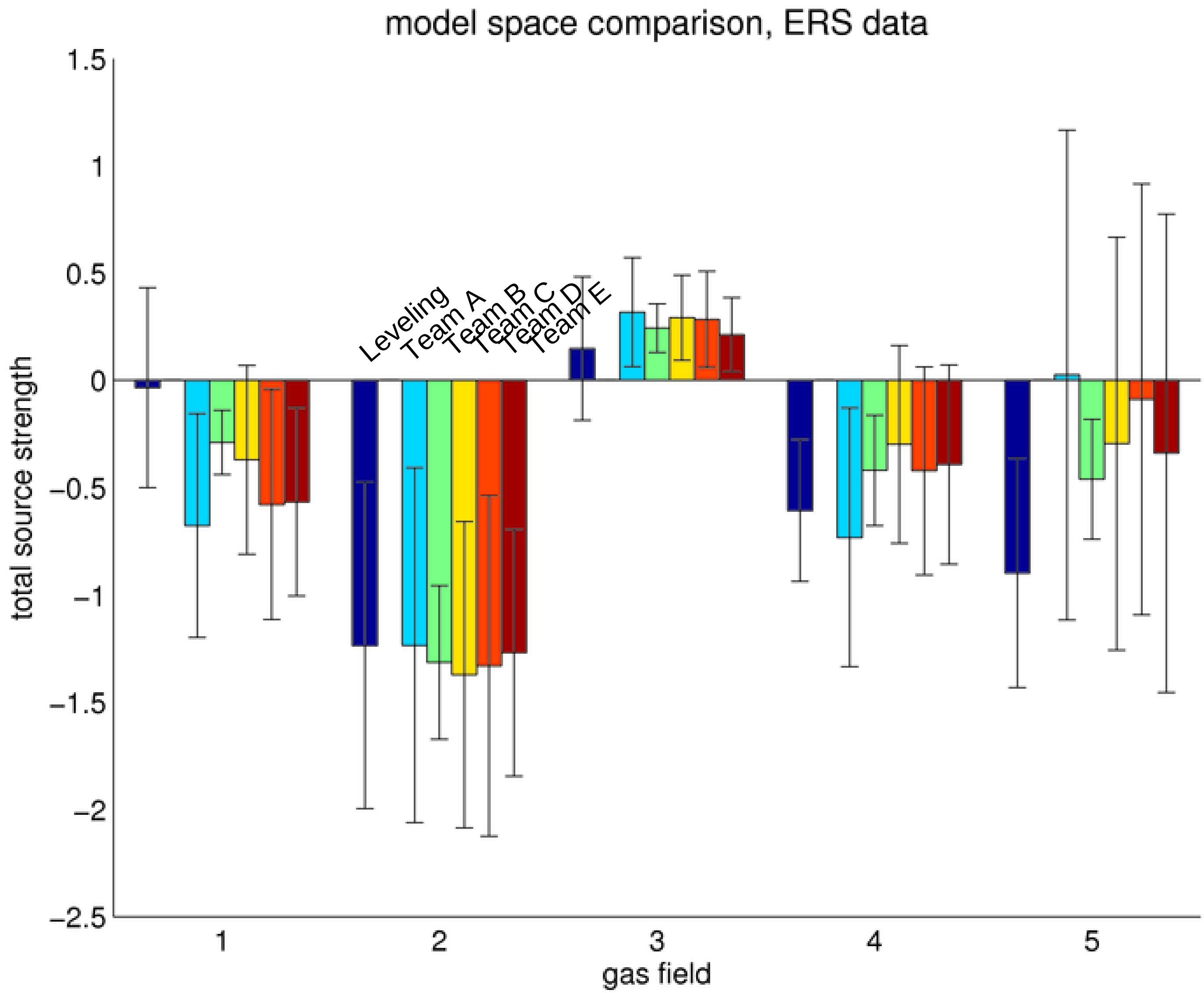
mm/y
Latitude
Longitude
52.8
52.75
52.7
52.65
52.6
52.55
52.5
4.6
4.65
4.7
4.75
4.8
4.85
2
1
0
−1
−2
−3
−4
−5
−6



mm/y
2
1
0
−1
−2
−3
−4
−5
−6
52.8
52.75
52.7
52.65
52.6
52.55
52.5
Latitude
4.6
4.65
4.7
4.75
4.8
4.85
Longitude
1
2
3
4
5



Sampling is more important than density.


model space comparison, ERS data
total source strength
gas field
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
1
2
3
4
5
Leveling
Team A
Team B
Team C
Team D
Team E

Conclusions case ‘Alkmaar’

- All teams were able to detect the signal of interest (irrespective of the spatial density and quality)
- Velocity precision (leveling-PSI): 1-2 mm/y
- Displacement precision (leveling-PSI): 8 mm

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Conclusions

- Large contribution to problems in radar interferometry based on
  - New missions
  - New methodology
  - Dedicated experiments