Ground deformations monitoring by persistent scatterer pairs (PSP) SAR interferometry

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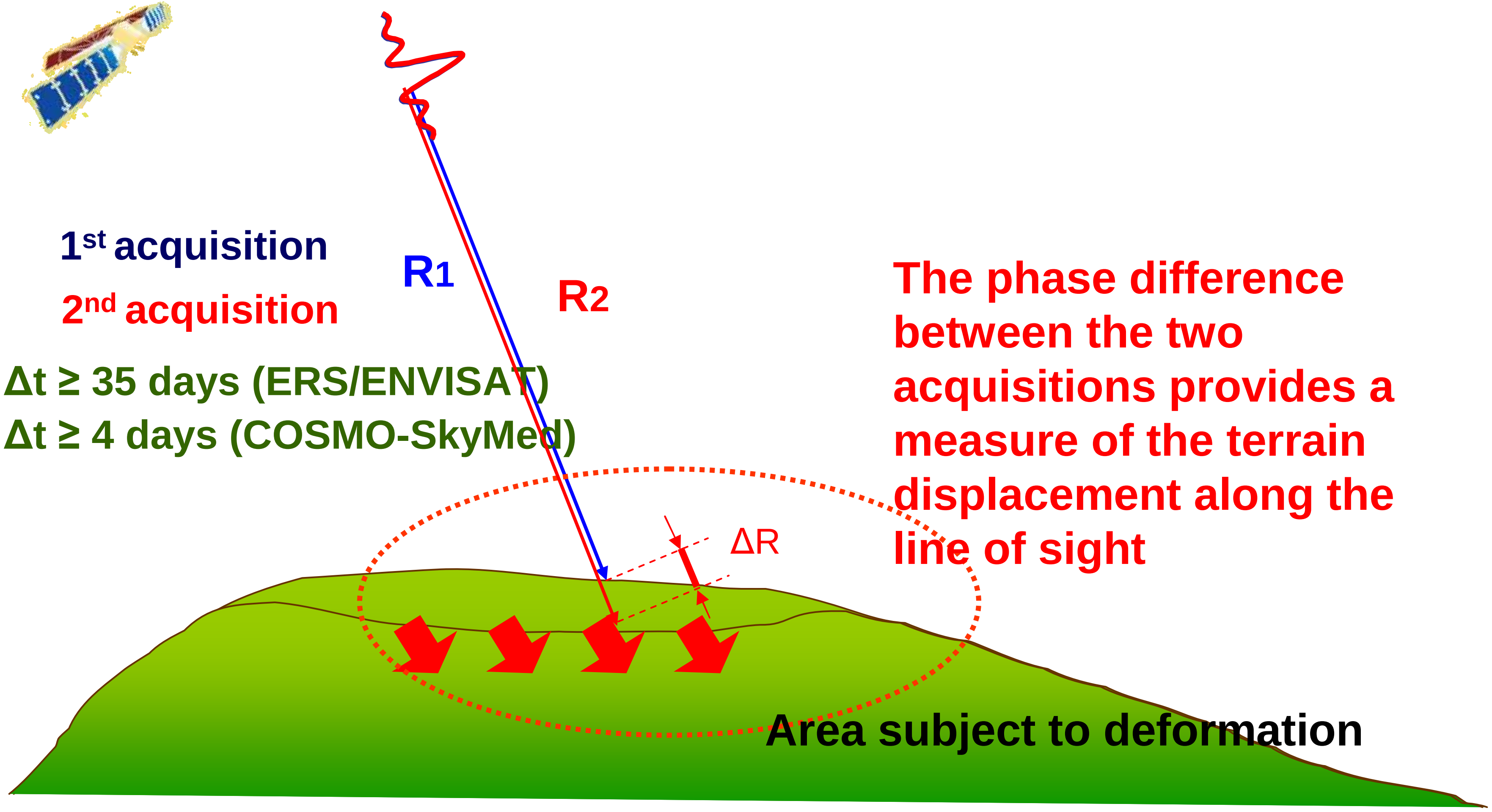
Summary

- Repeat-pass differential SAR interferometry
- E-GEOS PSP-IFSAR processing technology:
  - Persistent scatterer pair (PSP) technique
  - Redundant LP finite difference integration and phase unwrapping
  - High performance parallel processing system
- PSP-IFSAR analysis of high resolution COSMO-SkyMed SAR data
  - Beijing, China
  - Shanghai subway lines, China
  - Tuapse-Adler railway track, Russia
- A national scale project: analysis of the whole Italian territory with ERS/Envisat SAR data
- Conclusions

Repeat-pass SAR interferometry

Repeat-pass differential SAR interferometry principle

Differential SAR interferometry is a powerful technique to measure from satellite slow surface deformations due to subsidence, landslides, seismic and volcanic phenomena



Repeat-pass differential SAR interferometry potential and problems

- Repeat-pass SAR interferometry allows determining terrain displacements due to subsidence, landslides, earthquakes and volcanic phenomena with millimetric accuracy

- Extraction of this information is complex. The interferometric phase is:

  - Wrapped modulo 2π (need for unwrapping)

  - Affected by decorrelation noise
    - Only few sparse points (to be found) with a coherent signal (typically corresponding to buildings, rocks, bare soil)

  - Characterized by additional signals (to be separated from the displacement signal)
    - Topographic phase contributions
    - Atmospheric and orbital phase contributions

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E-GEOS PSP-IFSAR Technology

- E-GEOS has developed an advanced processing technology (PSP-IFSAR) with original algorithms, among which:
  - Persistent scatterer pair (PSP) method for selection and analysis of coherent points
  - Redundant LP finite difference integration and phase unwrapping
- The processing chain runs on a parallel HPC system
- Successfully validated and used in massive productions, with ERS/Envisat and high resolution COSMO-SkyMed SAR data

High performance production chain

- We have developed a high performance processing chain running on a high performance computing (HPC) system in order to provide PSI measurements over large areas. Key elements of the system are:
  - High quality terrain displacement measurements, both in terms of accuracy and density of the measurements, also in areas where radiometrically stable structures are very sparse or displacements that evolve non-linearly with the time are present.
  - Robustness: the algorithm is designed to exploit redundant information in order to obtain very reliable results
  - Automatism: the robustness of the algorithm and the processing chain based on a workflow system minimize the need for human intervention
  - Parallelism: the implemented sw is parallel and runs on a HPC system in order to reduce the processing time

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Persistent scatterer pair (PSP) approach

Persistent scatterer pairs (PSP)

- *Persistent scatterer pair* (PSP) method [Costantini et al., *Proc.* IGARSS, 2008, 2009] is a new approach to persistent scatterer interferometry (PSI).
- PSP method exploits only the relative properties of the signals between pairs of nearby points, both for identifying and analyzing the persistent scatterers:
  - Nearby points are similarly affected by atmospheric, orbital and, in general, spatially correlated phase contributions (also non linear movements)
- The PSP method:
  - does not require data calibration and model-based fits (in order to remove, in particular, atmosphere and orbital phase contributions)
  - is less sensitive to the density of PS
  - allows better identifying PS in natural terrains and PS characterized by non linear movements
  - can straightforwardly include identification of distributed scatterers
  - is computationally efficient and highly parallelizable

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PSP main idea and computational issues

- Points that contain information are identified by the fact that they can be paired (with nearby points) according to a given test (e.g. the temporal coherence, but other tests can be used).

- Working with pairs of points (arcs), rather than with single points, can be computationally very expensive.

- There are N(N-1)/2 arcs connecting N points.

- Considering only the M nearest points of each point reduces the number of arcs to MN; still too many because the PS to be found are sparse and M >> 1.

- Need for a strategy to explore a minimal graph.

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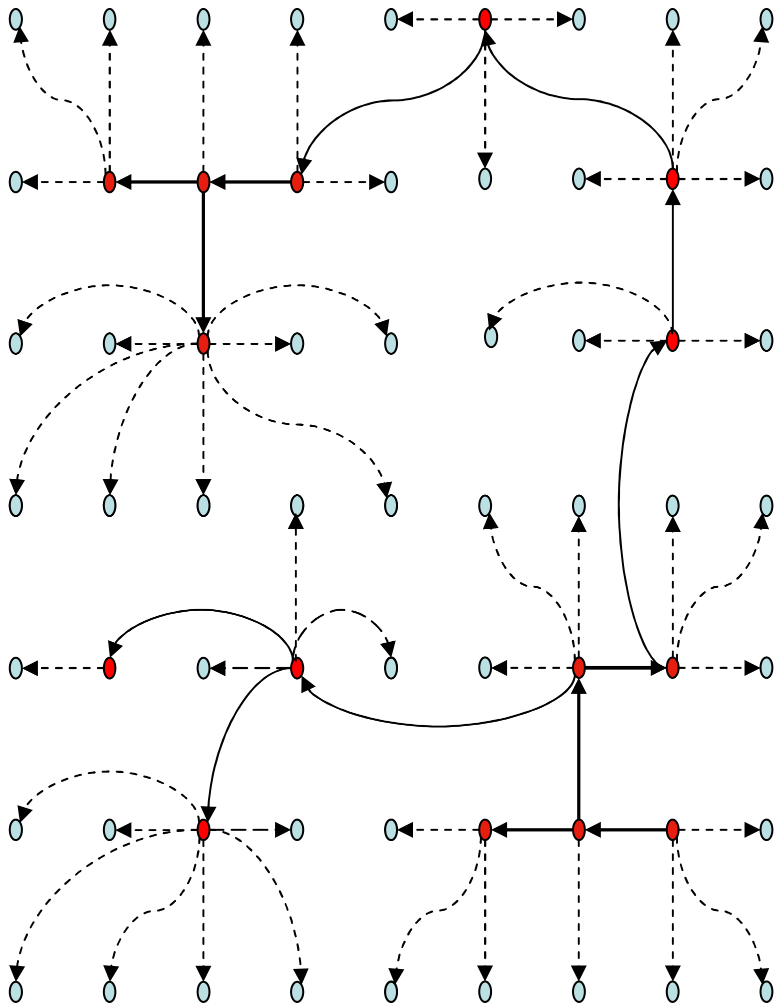
Minimal graph

- The minimal graph necessary to identify the PS is formed by the:
  - Arcs connecting each PS with a few (at least one) nearby PS
  - Arcs connecting each "bad" point with a few (at least one) nearby PS
- When only one connection per point is considered, the minimal graph is a tree connecting all points, and has N arcs; in general a few connections are used, and the no. of arcs is LM, with L ~ 1

- Building such a minimal graph is not immediate, because the PS positions are not known but are rather the purpose of the search.
- We have developed an efficient algorithm, which reduces the computational complexity of the pair-of-points approach

- Details in [Costantini et al., *Proc.* IGARSS, 2008, 2009]
  Long paper in preparation



Robust phase unwrapping and finite difference integration

Details in [Costantini et al., *Proc.* IGARSS, 2008, 2009]

Long paper submitted to TGRS

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Robust phase unwrapping and finite difference integration

- We recently presented a robust finite difference integration and phase unwrapping approach [Costantini et al., *Proc.* ESA Fringe 2009, *Proc.* IGARSS 2010].
- The reconstruction problem is formulated as the inversion of an overdetermined linear system of equations
- Standard phase unwrapping techniques are comprised as particular cases
- The proposed general formulation allows exploiting more information for a more robust solution:
  - Highly redundant phase unwrapping and finite difference integration
  - Multitemporal phase unwrapping
  - Multi-baseline / multi-frequency phase unwrapping
  - Integration of external information (e.g. GPS)
- Linear programming (LP) or quadratic programming (QP) problems with with L1 or L2 norm, respectively
- Computationally efficient, even though slower than minimum cost flow [Costantini, 1996-1997] –[Costantini and Rosen, 1999]

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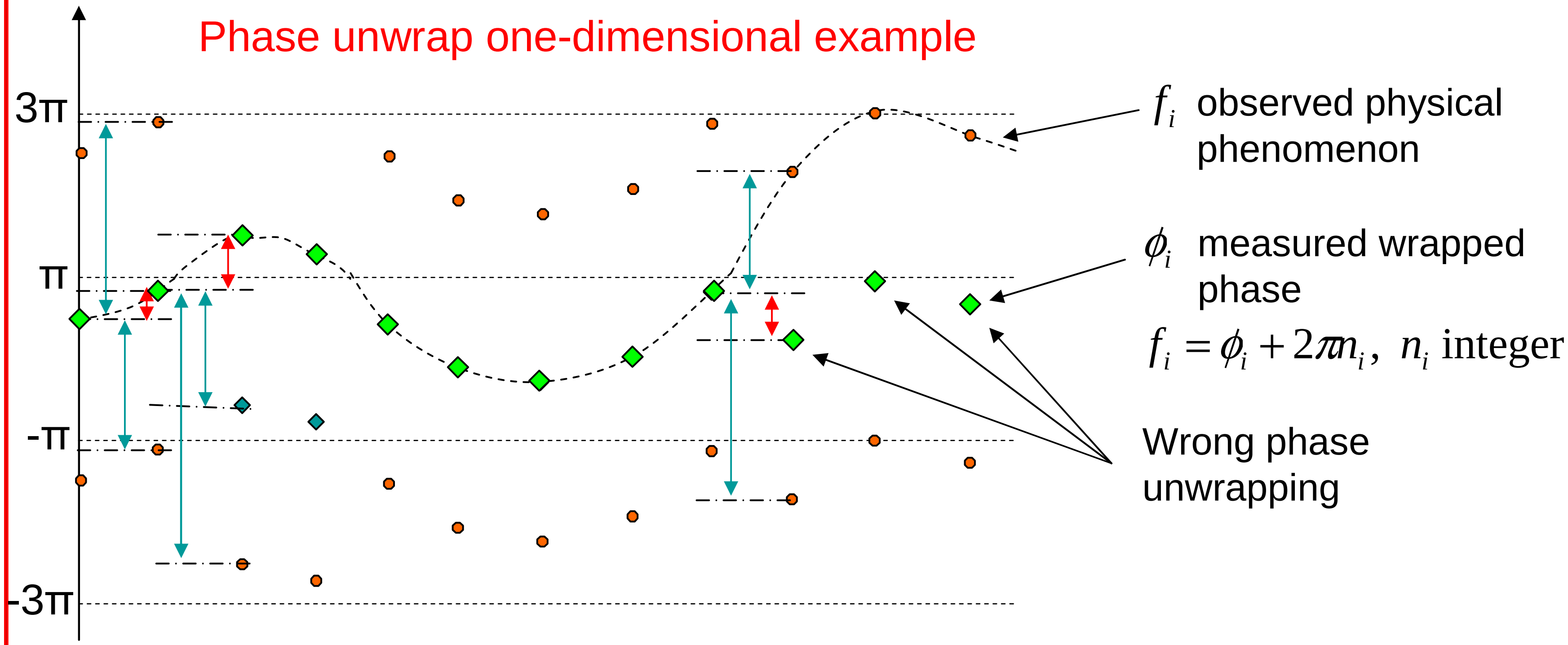
Phase unwrapping and finite difference integration problems



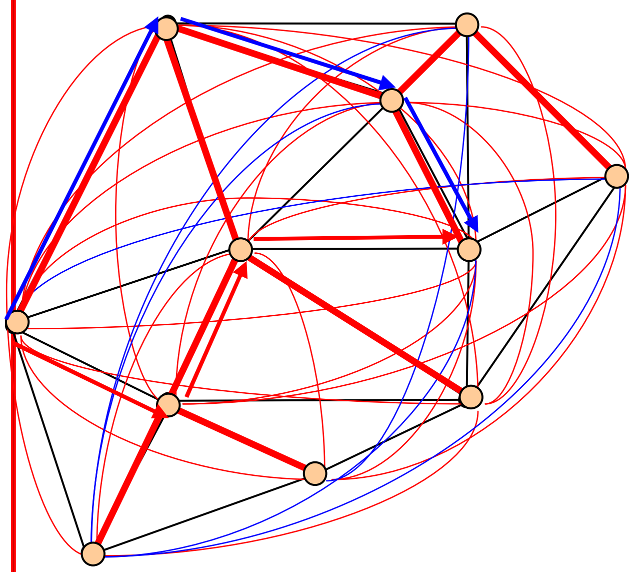
Assuming “smoothness” of the function to be reconstruded, its gradient f_{ij}' can be estimated

The solution can be obtained by integration of the gradient f_{ij}'

$$f_i - f_j + \delta_{ij} = f_{ij}' \longrightarrow \begin{cases} \delta_{ij} = 2\pi n_{ij},\ n_{ij} \text{ integer: phase unwrapping} \\ \delta_{ij} \text{ generic: integration of finite differences} \end{cases}$$

Exploitation of highly redundant information for accuracy and robustness

Phase unwrap and finite difference integration:
two dimensional/multi-dimensional example



- 1st level neighbors
- 2nd level neighbors
- 3rd level neighbors

The integration along a spanning tree is equivalent to the one-dimensional case.

The standard technique solve the phase unwrap (and the finite difference integration) problem starting from a set of differences between nearest neighbors.

Connecting nearest neighbors allows exploiting a new condition: the integration along any cycle must be zero.

The proposed novel approach includes standard techniques as special case, but allows obtaining a solution more robust to noise and outliers by exploiting redundant information obtained working with more pairs of close points (not only nearest neighbors).

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Mathematical formulation

$$\min_{\delta_{ij}} \sum_{(i,j)\in A} c_{ij} \left|\delta_{ij}\right|^{p}, \quad \text{subject to:}$$

weights

equation residuals

$$f_i - f_j + \delta_{ij} = f'_{ij}, \quad (i,j) \in A$$

reconstructed values on the graph nodes

estimated differences on the graph arcs

arcs (pairs of points)

- Quadratic programming (QP) problem with the L2 norm (p = 2)
- Linear programming (LP) problem with the L1 norm (p = 1)
  - more robust to error spreading
  - integer multiples of 2π in phase unwrapping (easily proved using results of graph theory)

A first advantage of this formulation is the possibility of easily integrating external information (e.g. from GPS measurements)

[This part of the proposed approach was contemporarily but independently presented also by Agram and Zebker at the same conference, ESA Fringe 2009]

Equivalent formulation based on "irrotationality constraints"

- By choosing a basis of the cycle space (i.e. the space spanned by all closed paths) and summing the equations of each cycle (for a planar graph the Delaunay triangles constitute a cycle basis):

$$\min_{\delta_{ij}} \sum_{(i,j)\in A} c_{ij} \left|\delta_{ij}\right|^p$$

subject to :

$$f_i - f_j + \delta_{ij} = f'_{ij}$$

$$f_j - f_k + \delta_{jk} = f'_{jk}$$

$$f_k - f_i + \delta_{ki} = f'_{ki}$$

⇔

$$\min_{\delta_{ij}} \sum_{(i,j)\in S} c_{ij} \left|\delta_{ij}\right|^p$$

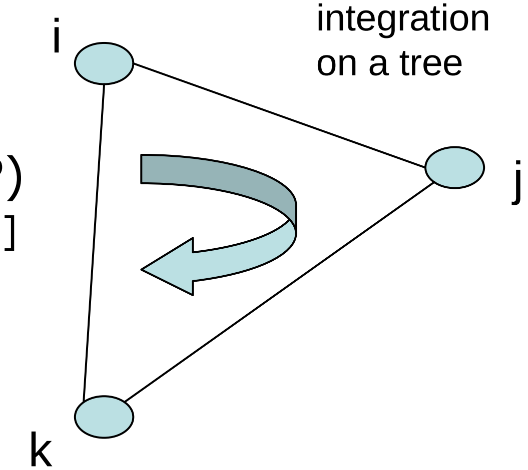
subject to :

$$\delta_{ij} + \delta_{jk} + \delta_{ki} = f'_{ij} + f'_{jk} + f'_{ki}$$

$$\left.\begin{aligned} f_i - f_j + \delta_{ij} &= f'_{ij} \\ f_j - f_k + \delta_{jk} &= f'_{jk} \end{aligned}\right\}$$

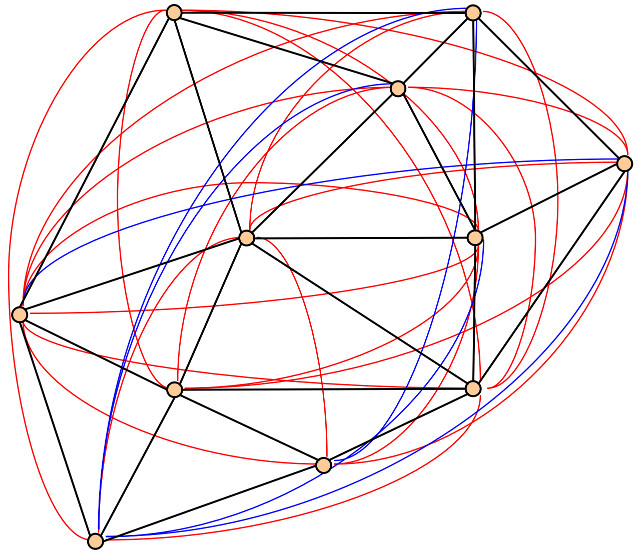
irrotationality conditions

integration on a tree



- With the L_1 norm, linear programming (LP) problem [Costantini, 1996-98; Costantini et al., '02]
- With the L_1 norm and planar graphs, minimum cost flow problem on a network [Costantini, '96-'98; Costantini and Rosen, '99]

Highly redundant phase unwrapping and finite difference integration



- 1st level neighbors
- 2nd level neighbors
- 3rd level neighbors

- Not a planar graph
- Easy to add redundant arcs in the proposed formulation:
  - one equation (and corresponding residual) for each arc
- Represented in the standard (irrotationality) formulation, using a cycle basis that is not the Delaunay triangulation
- PERSISTENT SCATTERE PAIR (PSP) ARCS GIVE THE BEST RESULTS: arcs are chosen based on their coherence

Multi-temporal/multi-layer and multi-baseline/multi-frequency phase unwrap

- The redundant finite difference integration and phase unwrapping method previously discussed is valid for generally sparse data on multidimensional domains (also 3D). But it is not suitable for non-isotropic multi-dimensional spaces.

- Multi-temporal phase unwrap in SAR interferometry (anisotropy due to atmospheric and orbital artifacts)
- The general formulation we propose makes possible to overcome the problem by considering double differences (in time and space)

$$\min_{\delta_{ijkl}} \sum_{(i,j)\in A_1,(k,l)\in A_2} c_{ijkl}\left|\delta_{ijkl}\right|^p, \quad \text{subject to:}$$

$$f_{ik} - f_{il} - f_{jk} + f_{jl} + \delta_{ijkl} = f''_{ijkl}, \quad (i,j)\in A_1, (k,l)\in A_2$$

Joint unwrapping of multitemporal interferograms (zero residue both in space and time cycles)

- Multiple interferometric pairs can be available with slightly different baselines (multi-baseline interferometry) or at different frequencies (wide-band interferometry)
- Same formulation as multitemporal phase unwrapping, but an additional property holds (the interferometric phase is proportional to the baseline or the frequency):
- A unique function g to be reconstructed for all frequencies/baselines: $f_{ik} - f_{il} = \alpha_{kl} g_i$

$$\min_{\delta_{ijkl}} \sum_{(i,j)\in A_1,(k,l)\in A_2} c_{ijkl}\left|\delta_{ijkl}\right|^p, \quad \text{subject to:}$$

$$\alpha_{k,l}\left(g_i - g_j\right) + \delta_{ijkl} = f''_{ijkl}, \quad (i,j)\in A_1, (k,l)\in A_2$$

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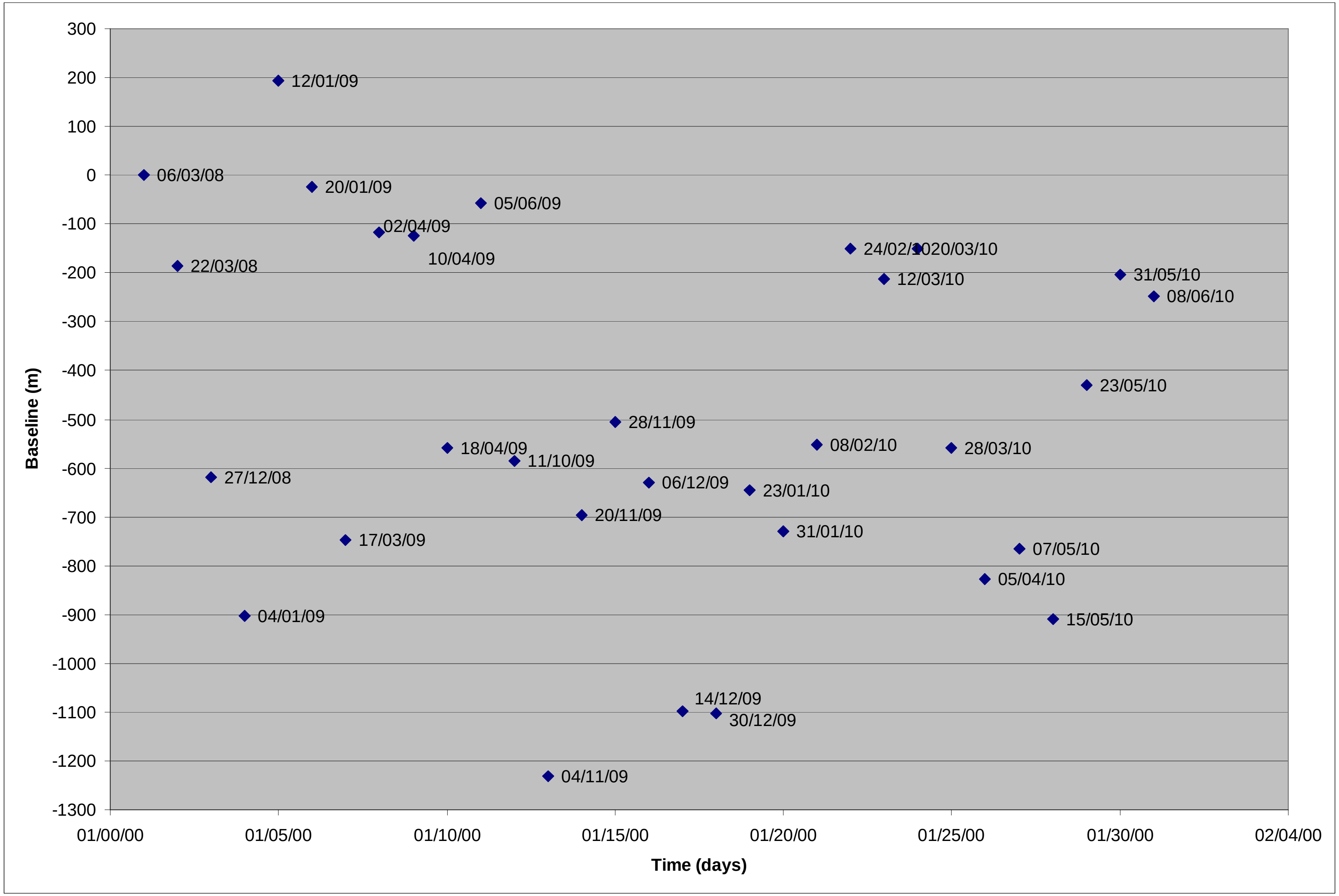
Validation & application examples

PSP IFSAR analysis
of COSMO-SkyMed data
over Beijing, China

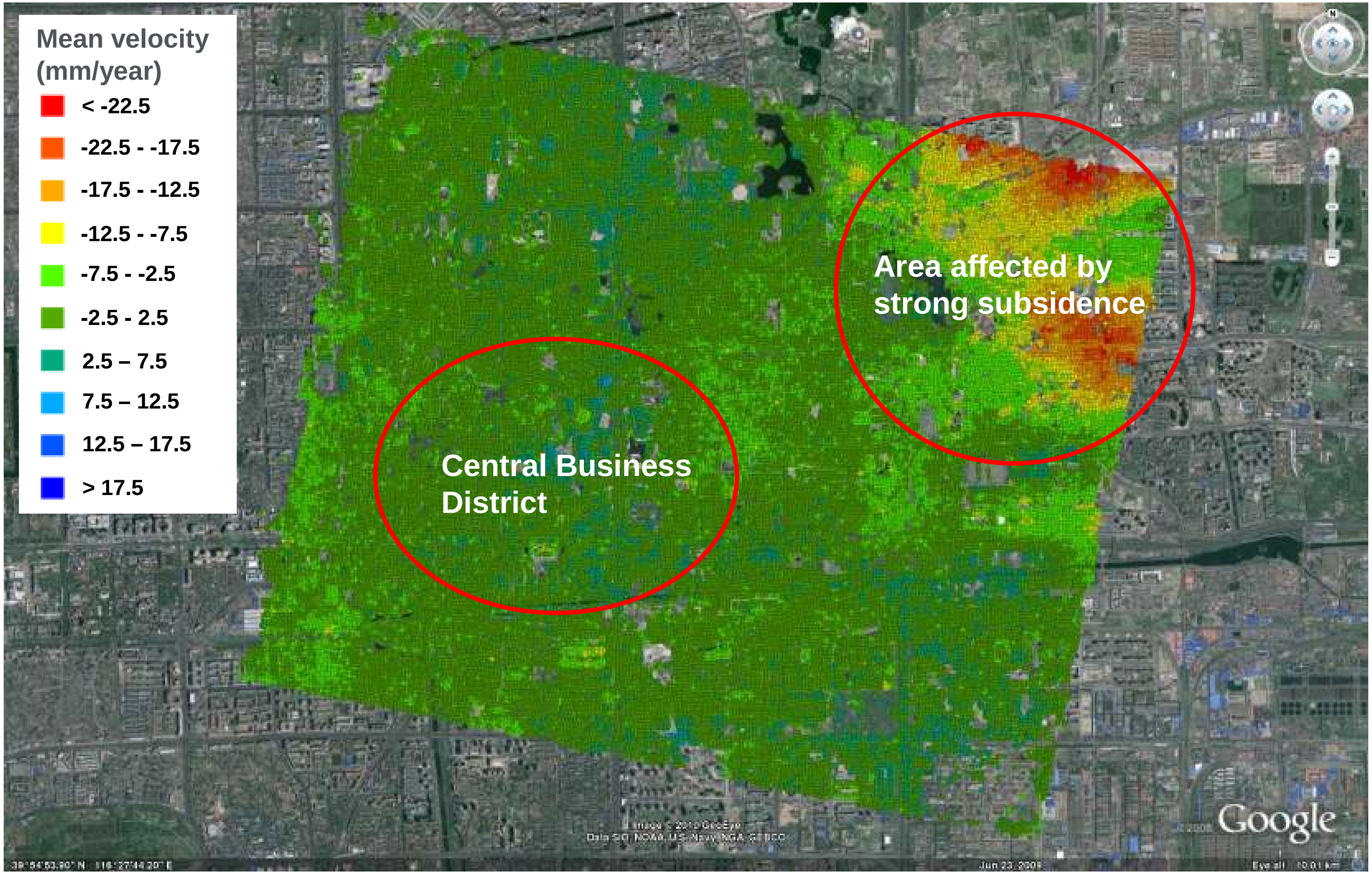
COSMO-SkyMed acquisitions used for PSP-IFSAR analysis

- Stripmap H4-0A acquisition mode
- Ground resolution 3 m x 3 m
- Polarization HH
- Incidence angle 20.06°
- Right looking, descending pass
- Analyzed period: Mar. 2008 – Jun. 2010
- Number of acquisitions: 31

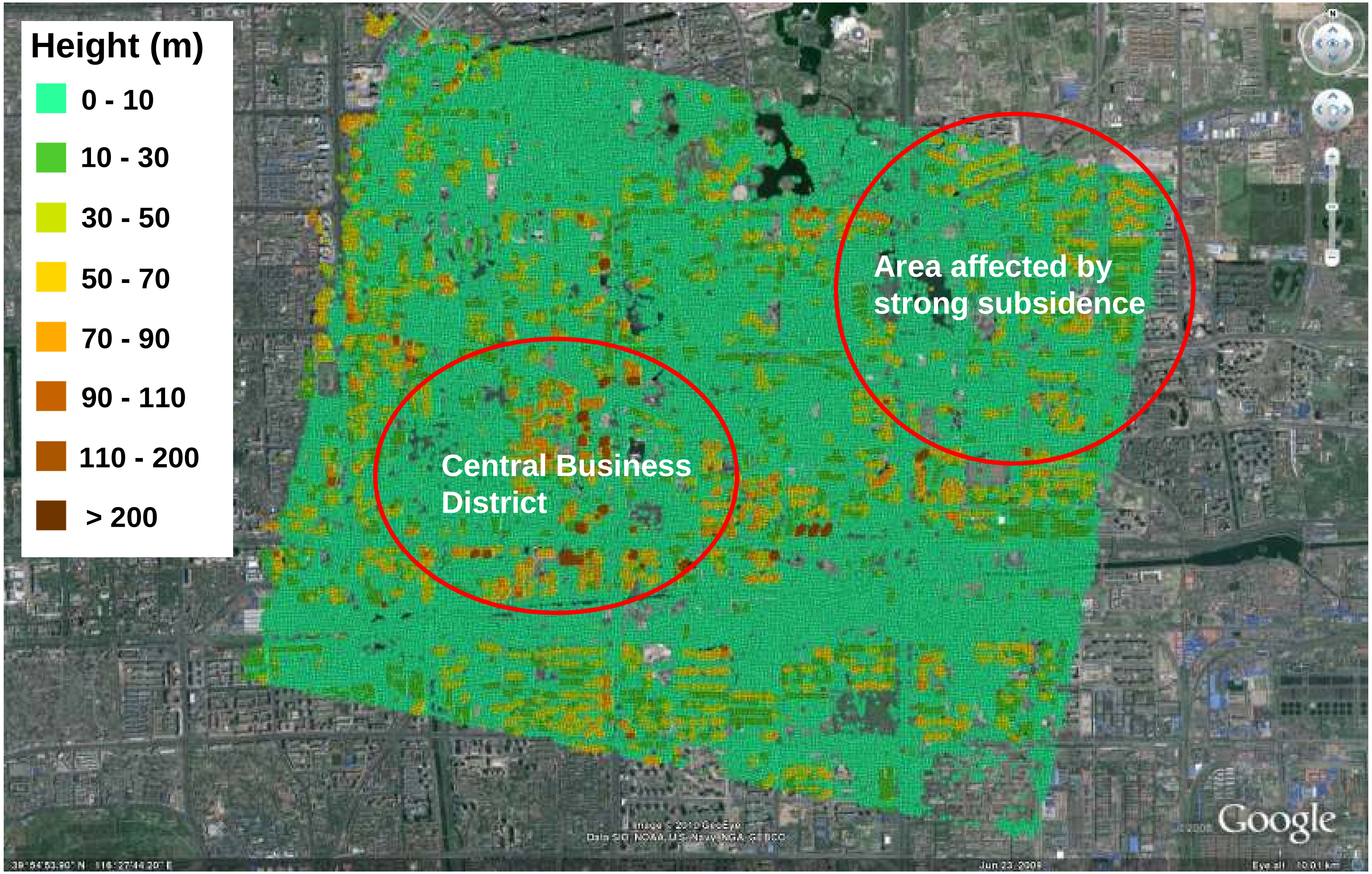
Spatial and temporal distribution of the COSMO-SkyMed acquisitions



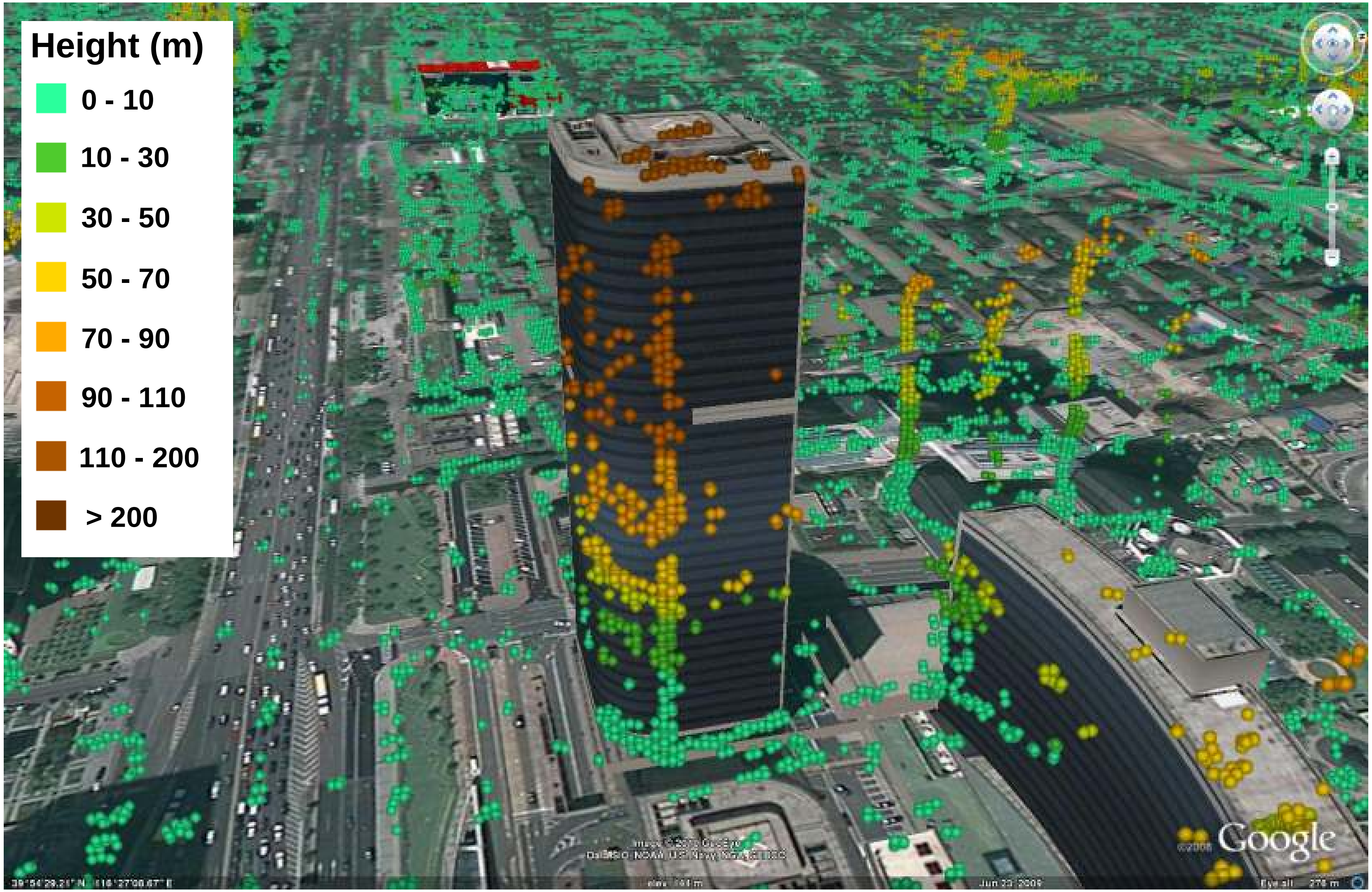
Chaoyang District
PS mean velocities



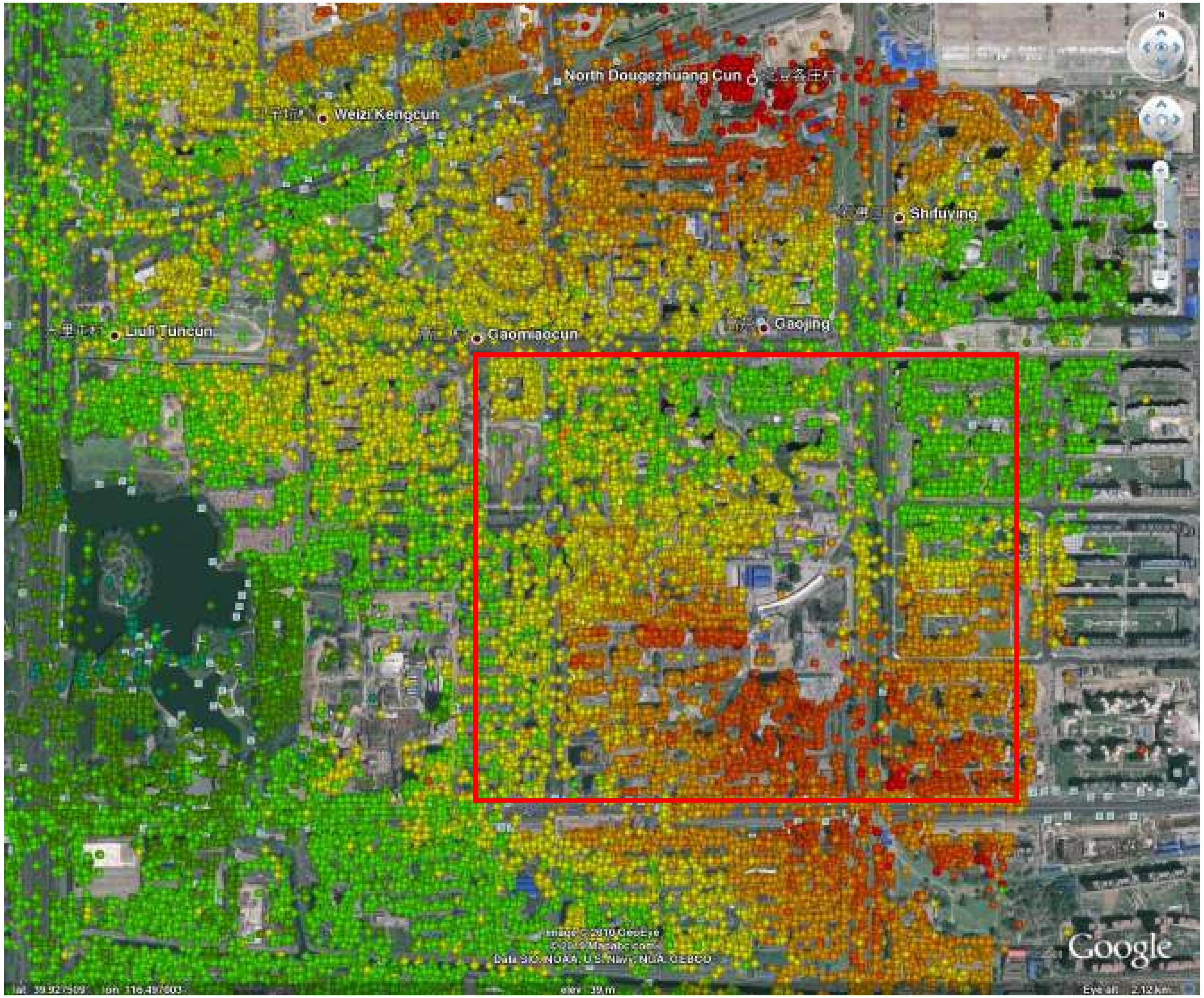
Chaoyang District
PS heights



The China World Trade Center
PS heights 3D view



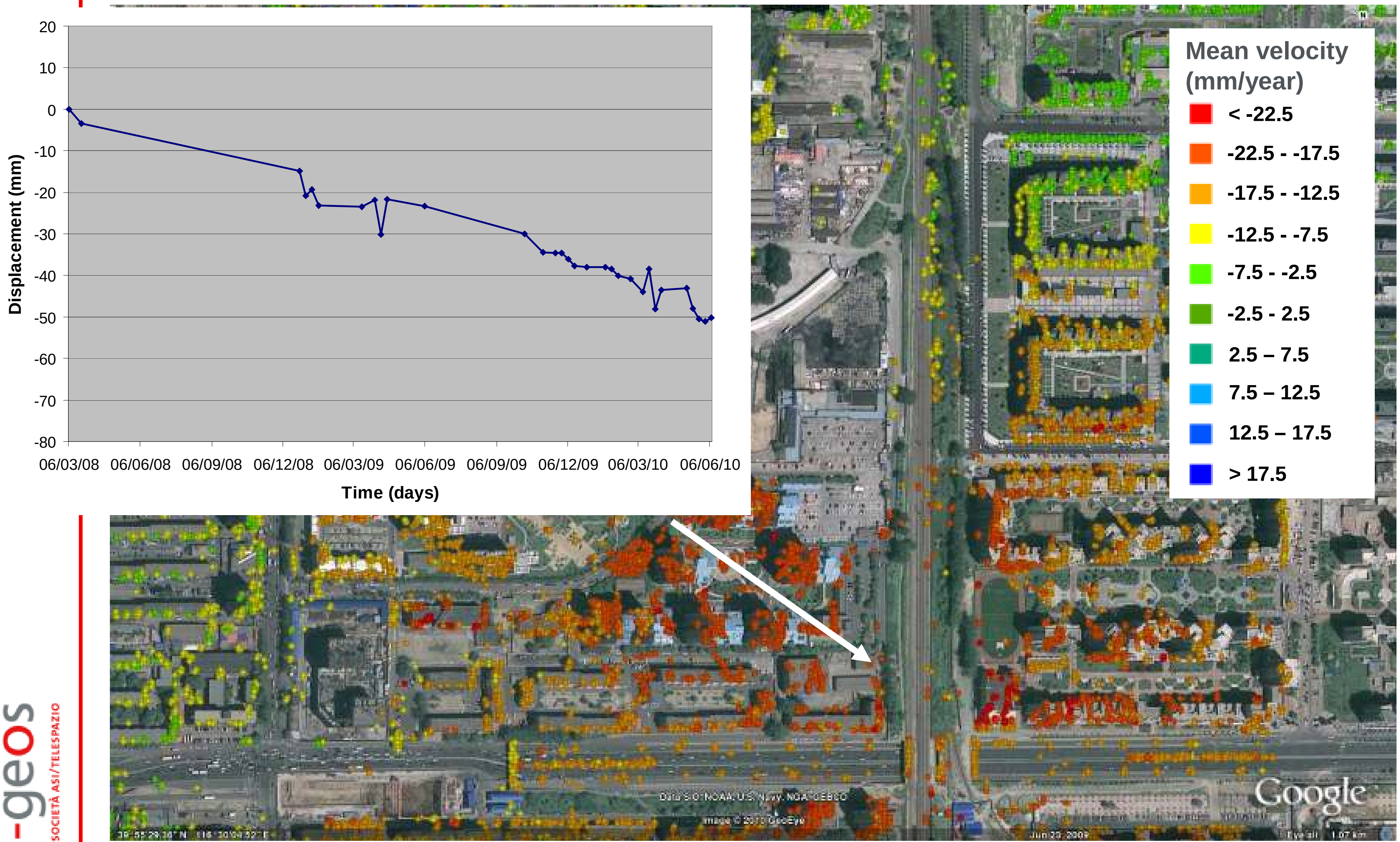
AREA AFFECTED BY STRONG SUBSIDENCE



Mean velocity (mm/year)

- < -22.5
- -22.5 - -17.5
- -17.5 - -12.5
- -12.5 - -7.5
- -7.5 - -2.5
- -2.5 - 2.5
- 2.5 – 7.5
- 7.5 – 12.5
- 12.5 – 17.5
- > 17.5

PS mean velocities

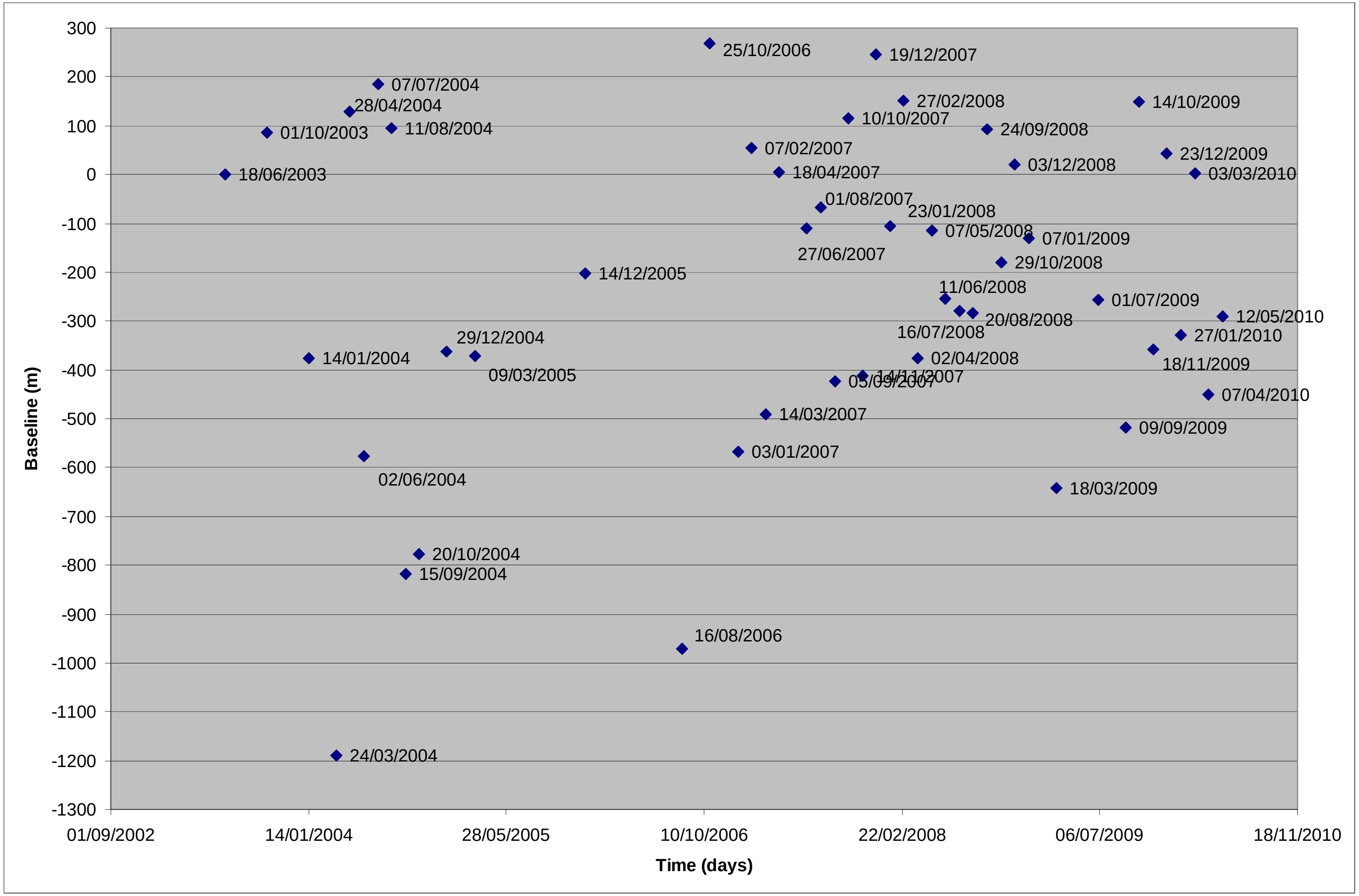


PSP IFSAR analysis of ENVISAT data over Beijing, China

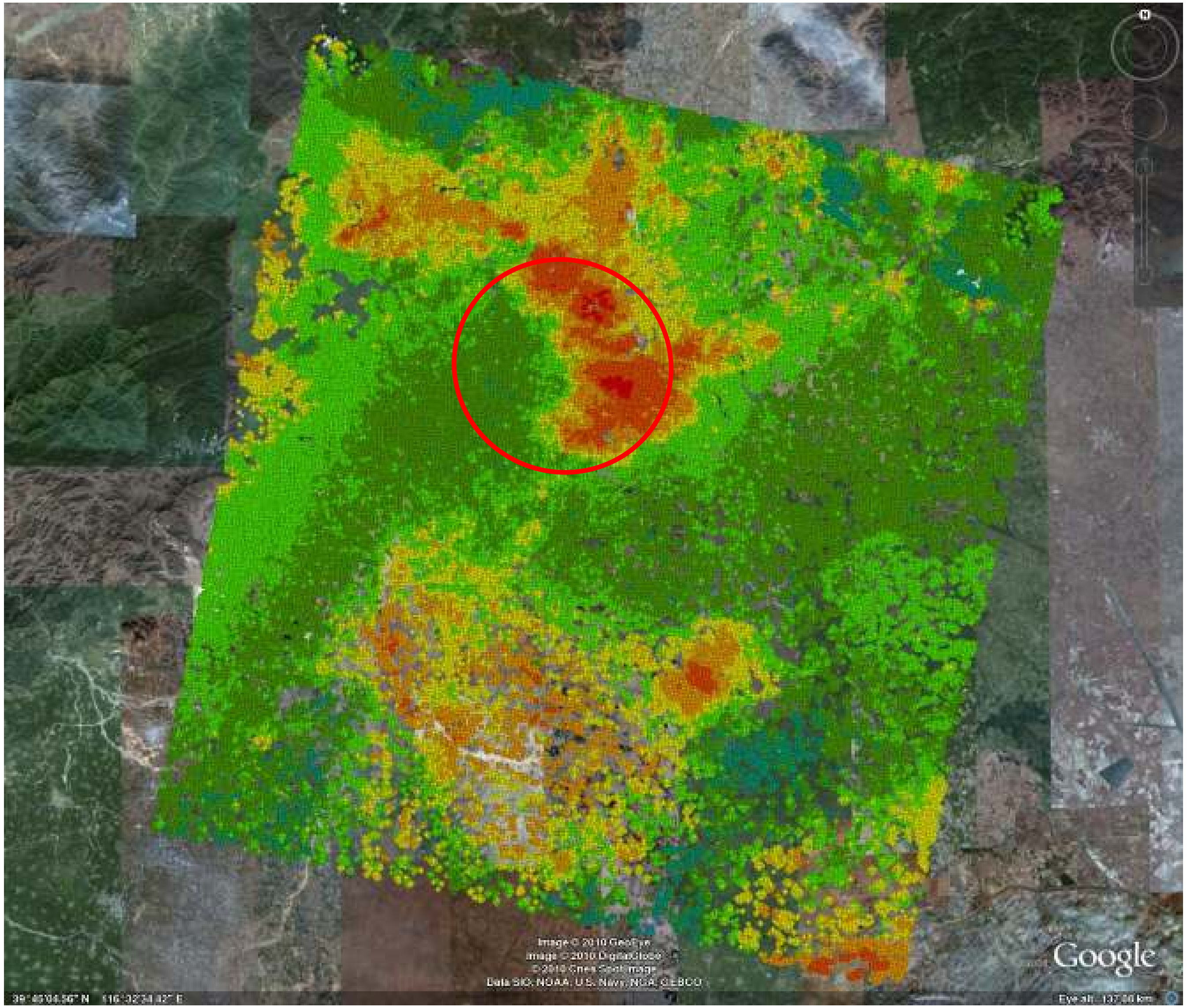
ENVISAT acquisitionson Beijing used for PSP-IFSAR analysis

- Track 2218 Frame 2805
- Ground resolution 5 m x 25 m
- Polarization VV
- Incidence angle ~23°
- Descending pass
- Analyzed period:
  June 2003 – May 2010
- Number of acquisitions: 49

Spatial and temporal distribution of the ENVISAT acquisitions



PS mean velocities
(ENVISAT 2003-2010)



Mean velocity (mm/year)

red	< -80
dark orange	-80 - -40
orange	-40 - -20
yellow	-20 - -10
light green	-10 - -2.5
green	-2.5 - 2.5
teal	2.5 - 10
light blue	10 - 20
blue	20 - 40
dark blue	> 40

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COSMO-SkyMed vs ENVISAT PSP-IFSAR comparison

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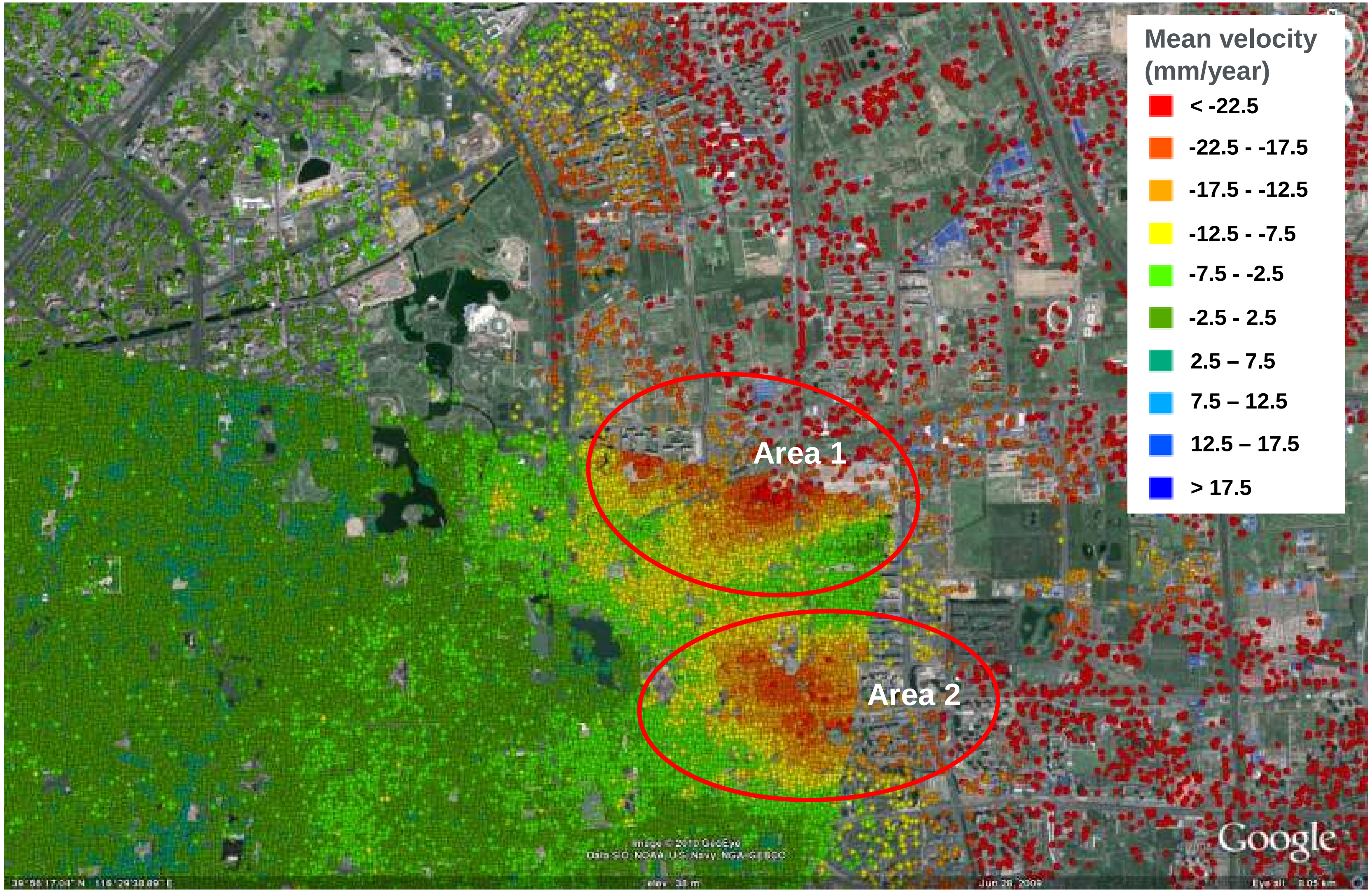
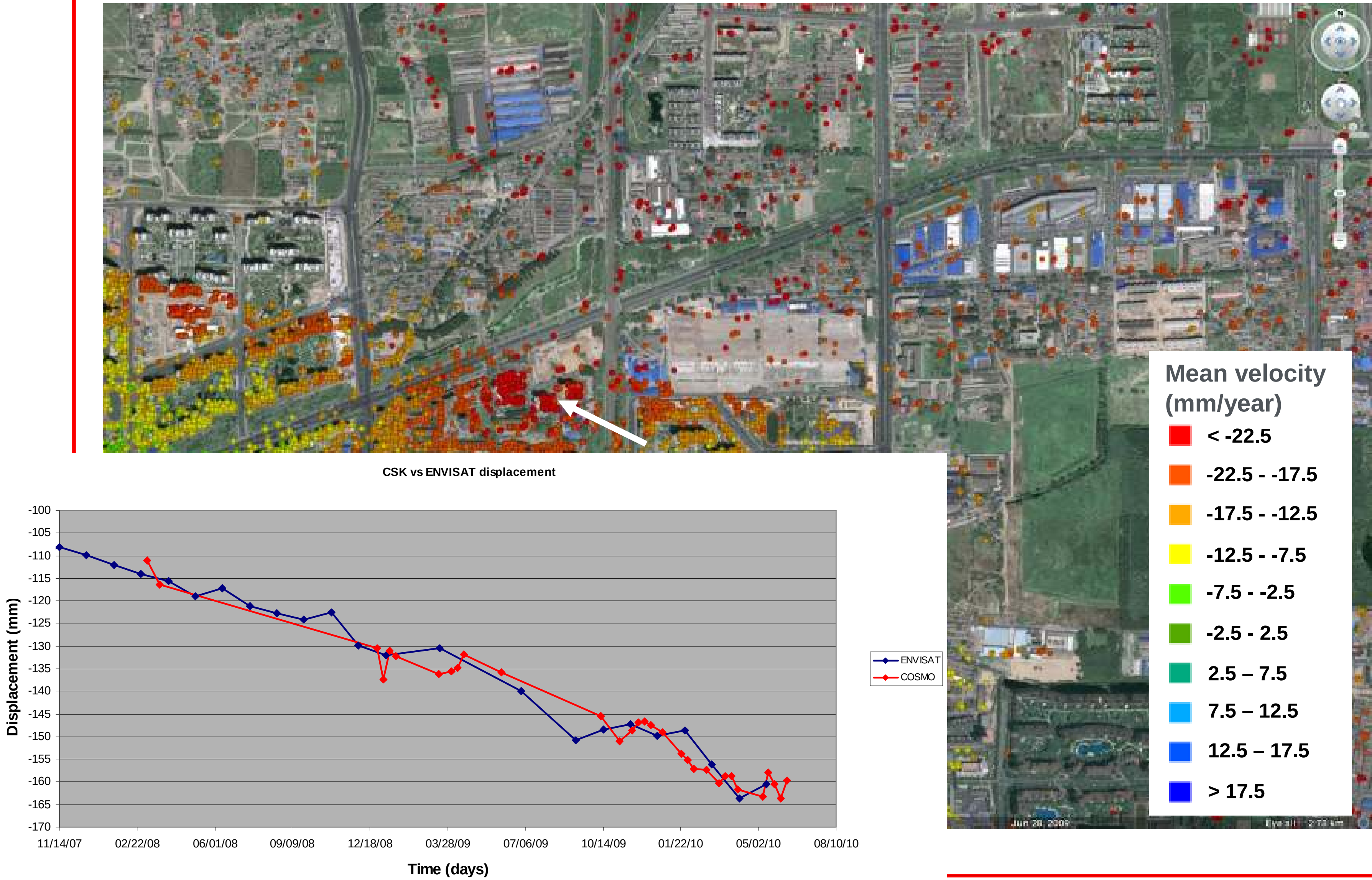
COSMO-SkyMed vs ENVISAT
PS mean velocities



COSMO-SkyMed vs ENVISAT
PS mean velocities: area 1



COSMO SkyMed for persistent scatterers interferometry

- High resolution X-band SAR proved to be very good for persistent scatterer interferometry:
  - Very high density of persistent scatterers (tens of thousands per km^2 in urban areas already with stripmap images)
    - Measurement of differential displacements within the same structure (i.e. a building, a bridge, a dam)
  - High sensitivity to displacements (short wavelength)
  - Very good PS localization (COSMO-SkyMed baselines are kept large, although well below the critical baseline)

- COSMO-SkyMed constellation of 4 satellites has some unique capabilities:
  - Very good revisit time (up to 8 acquisitions per month with the same look angle)
    - Measurement of fast movements
    - Long series of acquisitions in a short time
  - High acquisition capabilities (up to 2000 images per day)
    - Coverage of large areas

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Examples of COSMO-SkyMed PSP IFSAR analysis of subsidence along Shanghai subway, China

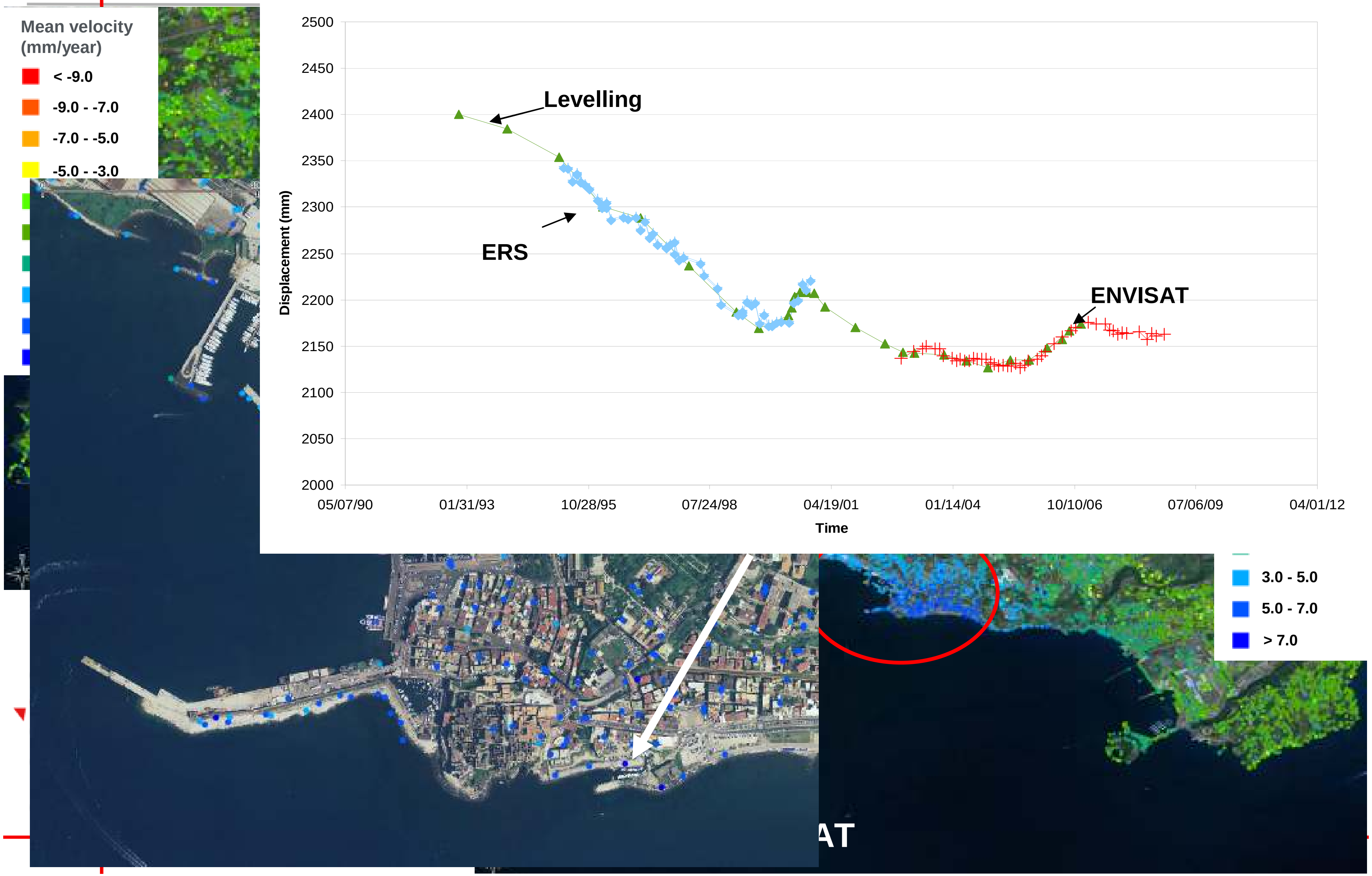
PSP-IFSAR
Shanghai subway tracks

- Stripmap H4-0B acquisition mode
- Ground resolution 3 m x 3 m
- Polarization HH
- Incidence angle 23.96°
- Right looking, descending pass
- Analyzed period:
  May. 2008 – Jun. 2010
- Number of acquisitions: 52 (about 2 acq./month)

PSP-IFSAR Mean velocity
Shanghai subway line 9 detail
COSMO-SkyMed May 2008 – Jun 2010

PSP-IFSAR analysis:
validation and massive productions

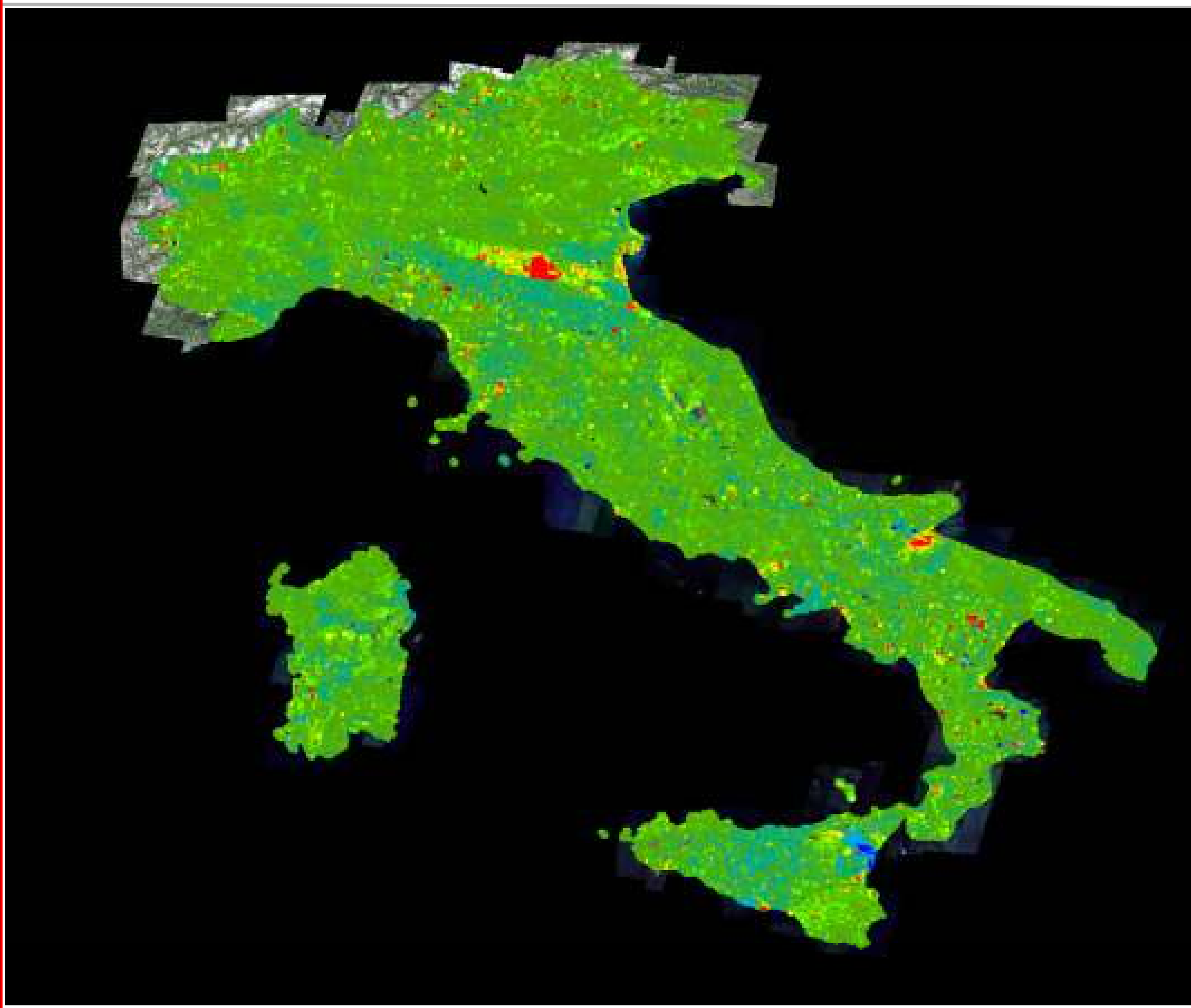
Volcanic bradyseism, Naples region, Italy
PSP-IFSAR analysis and validation



Some examples from a nation-wide PSI analysis project

- The PST-A/2 project, commissioned by the Italian Ministry of the Environment, is a huge project aimed at providing terrain displacement measurements by SAR interferometry over an entire national territory (Italy, 300,000 Km^2)
- Analysis of the whole period covered by data available for interferometry: 1992–2000 (ERS) and 2003–2010 (Envisat)
- Processing of the whole ESA ERS/Envisat archive over Italy (about 15,000 images), by TRE and e-GEOS
- TO BE PROBABLY EXTENDED WITH COSMO-SKYMED DATA

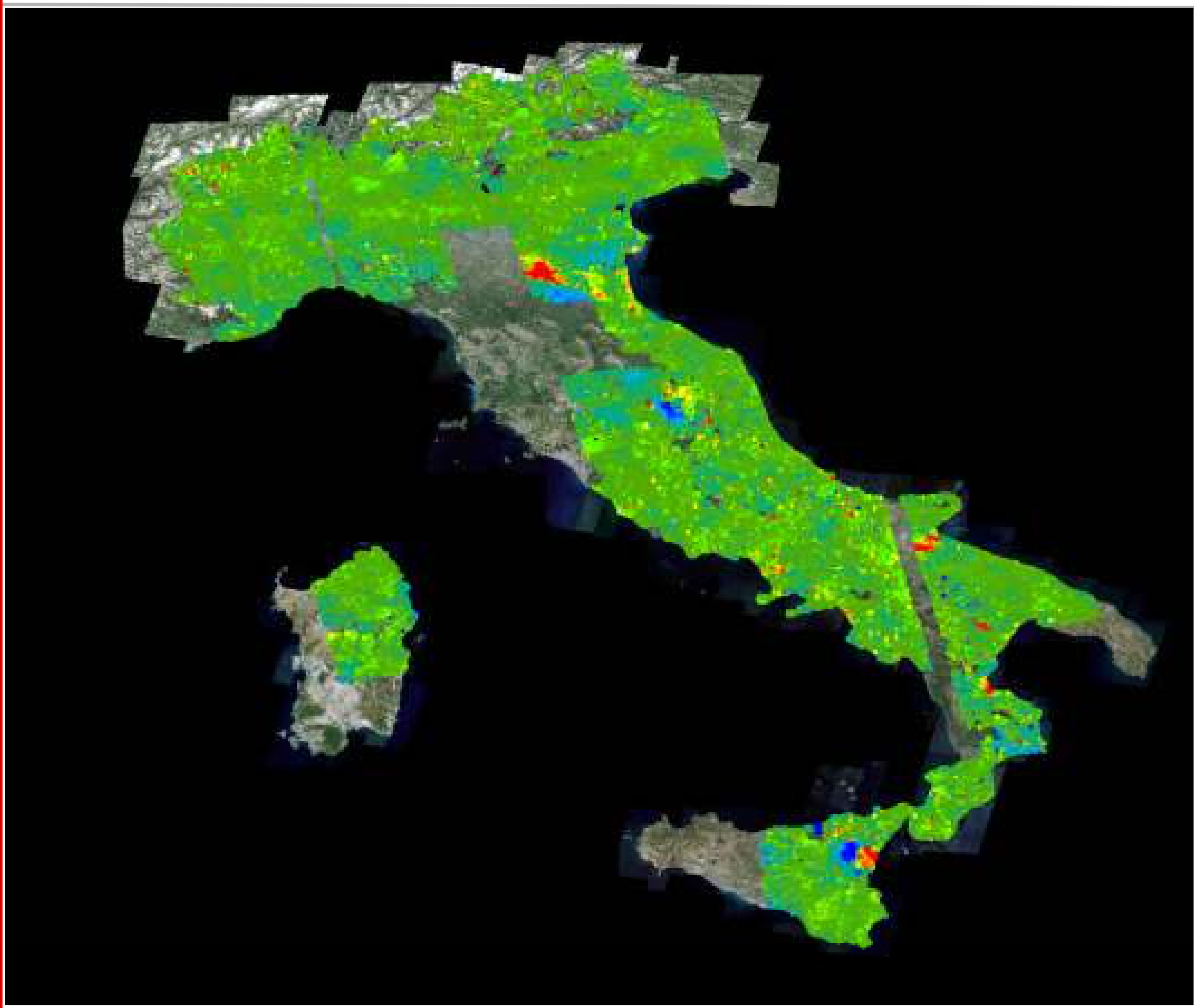
Processed area:
1992-2000 ERS descending data



Mean velocity (mm/year)

- < -9.0
- -9.0 - -7.0
- -7.0 - -5.0
- -5.0 - -3.0
- -3.0 - -1.0
- -1.0 - 10
- 1.0 - 3.0
- 3.0 - 5.0
- 5.0 - 7.0
- > 7.0

Processed area:
1992-2000 ERS ascending data



Mean velocity (mm/year)

- < -9.0
- -9.0 - -7.0
- -7.0 - -5.0
- -5.0 - -3.0
- -3.0 - -1.0
- -1.0 - 10
- 1.0 - 3.0
- 3.0 - 5.0
- 5.0 - 7.0
- > 7.0

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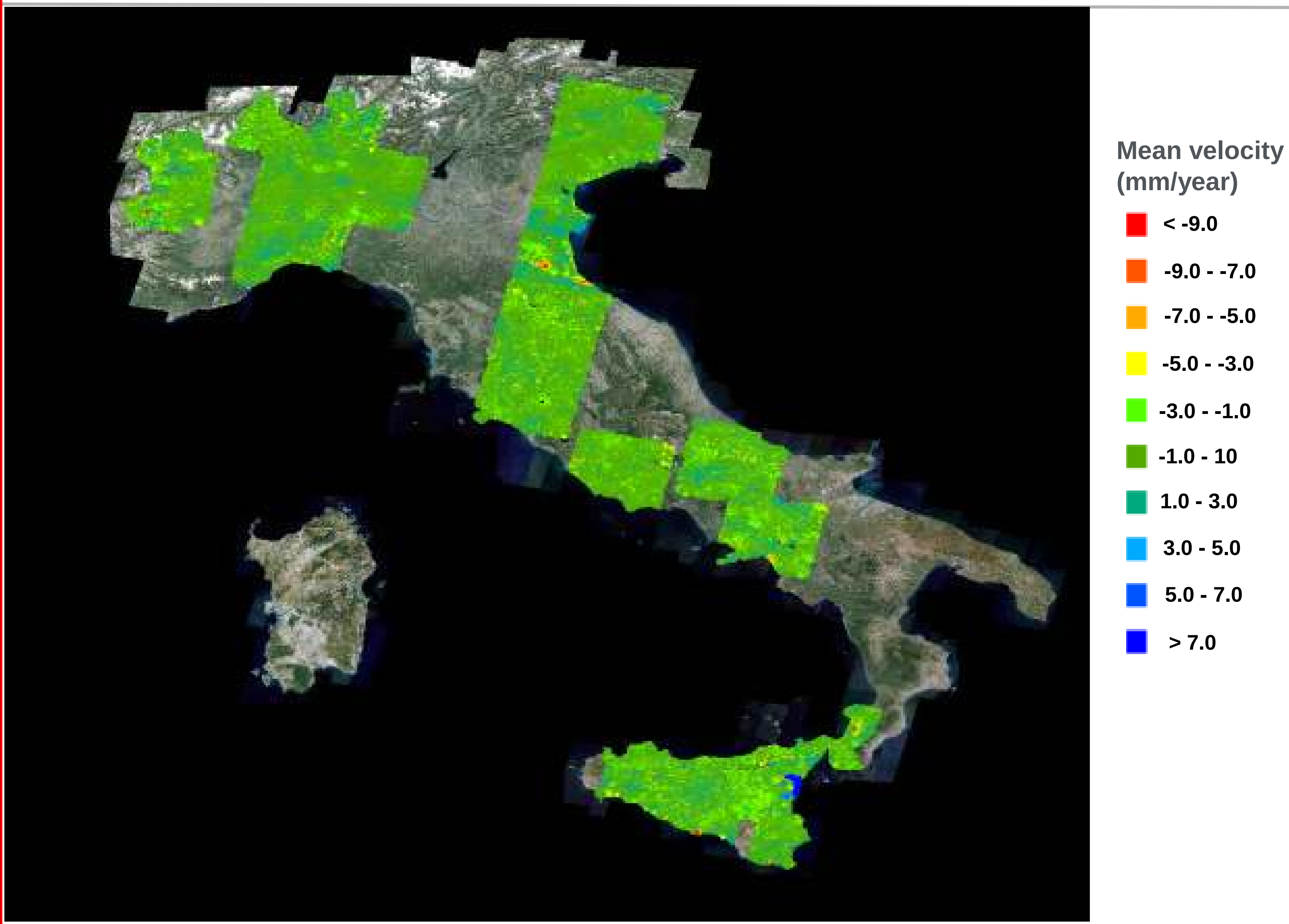
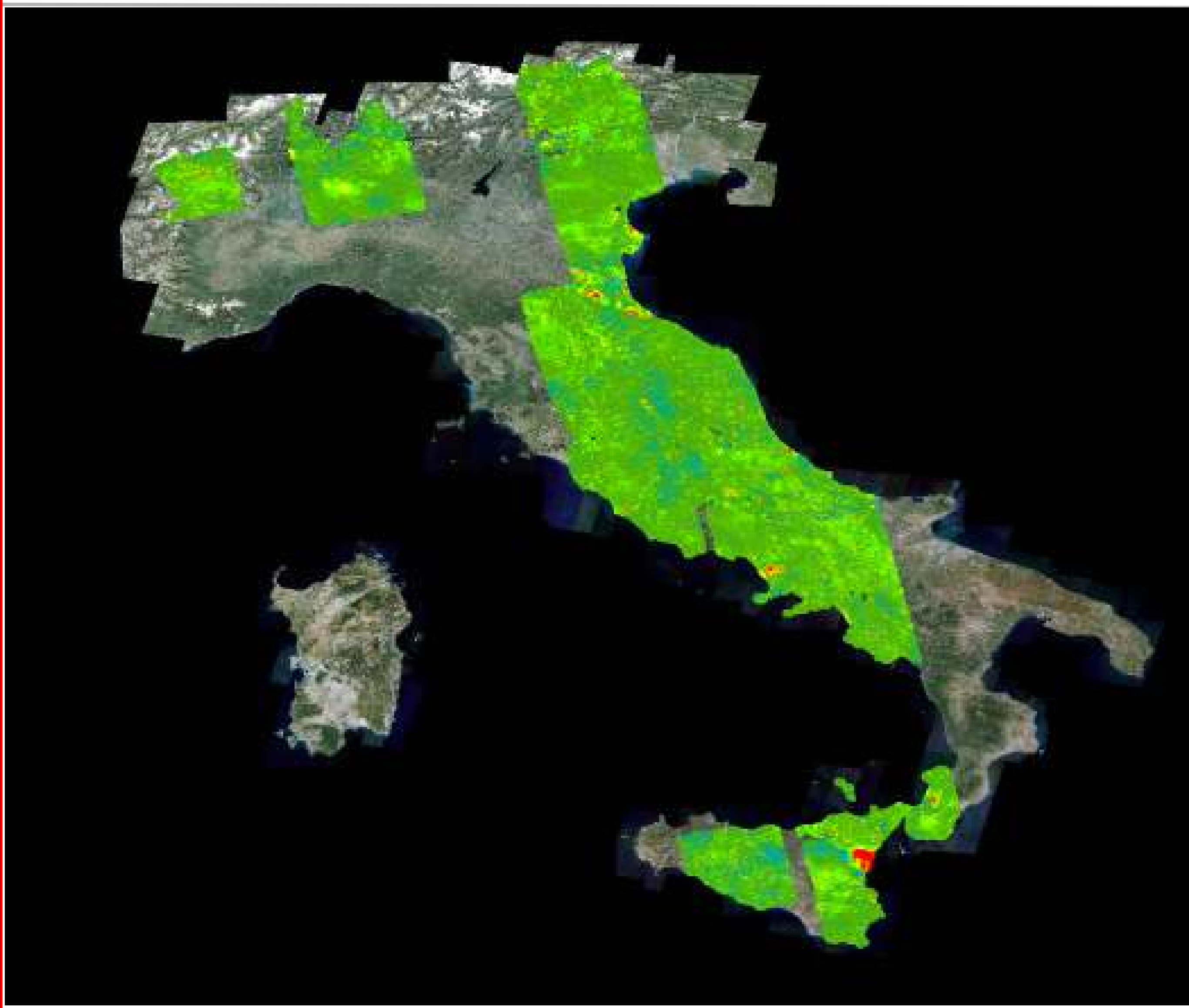
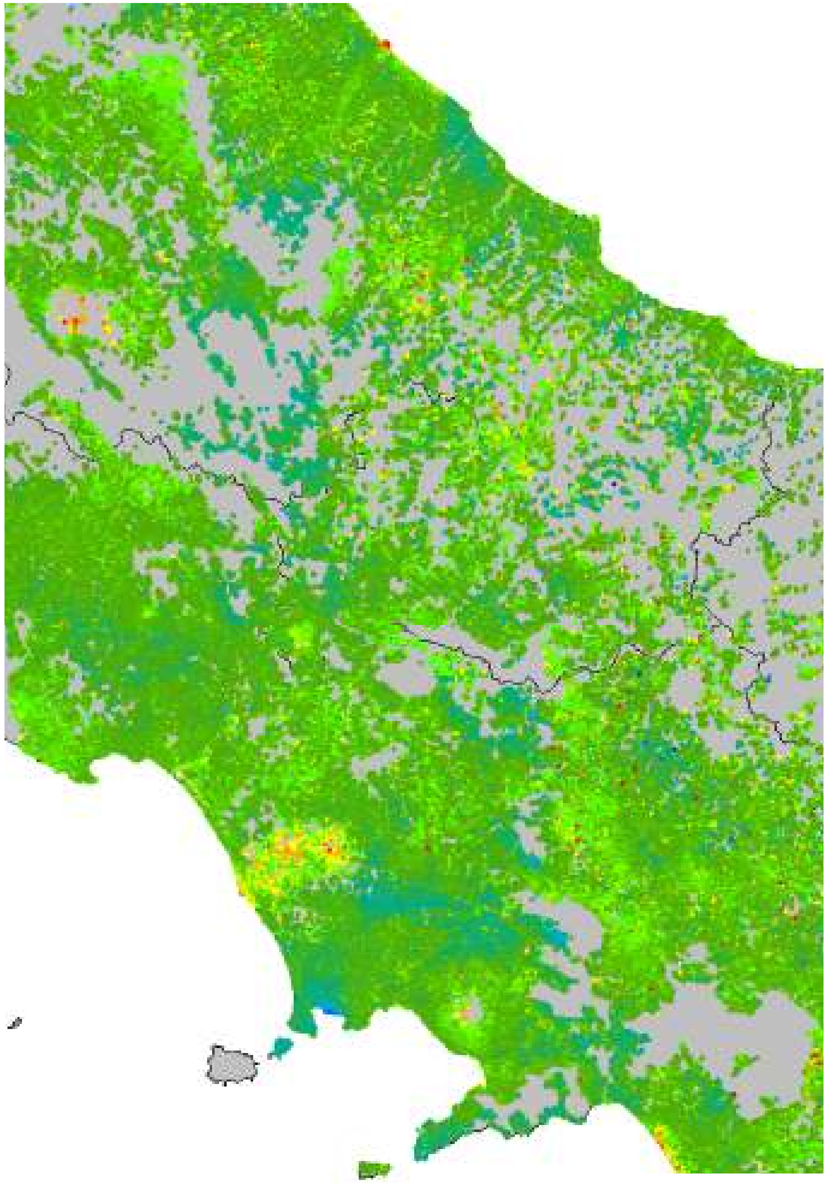
Processed area:
2003-2008 ENVISAT descending data



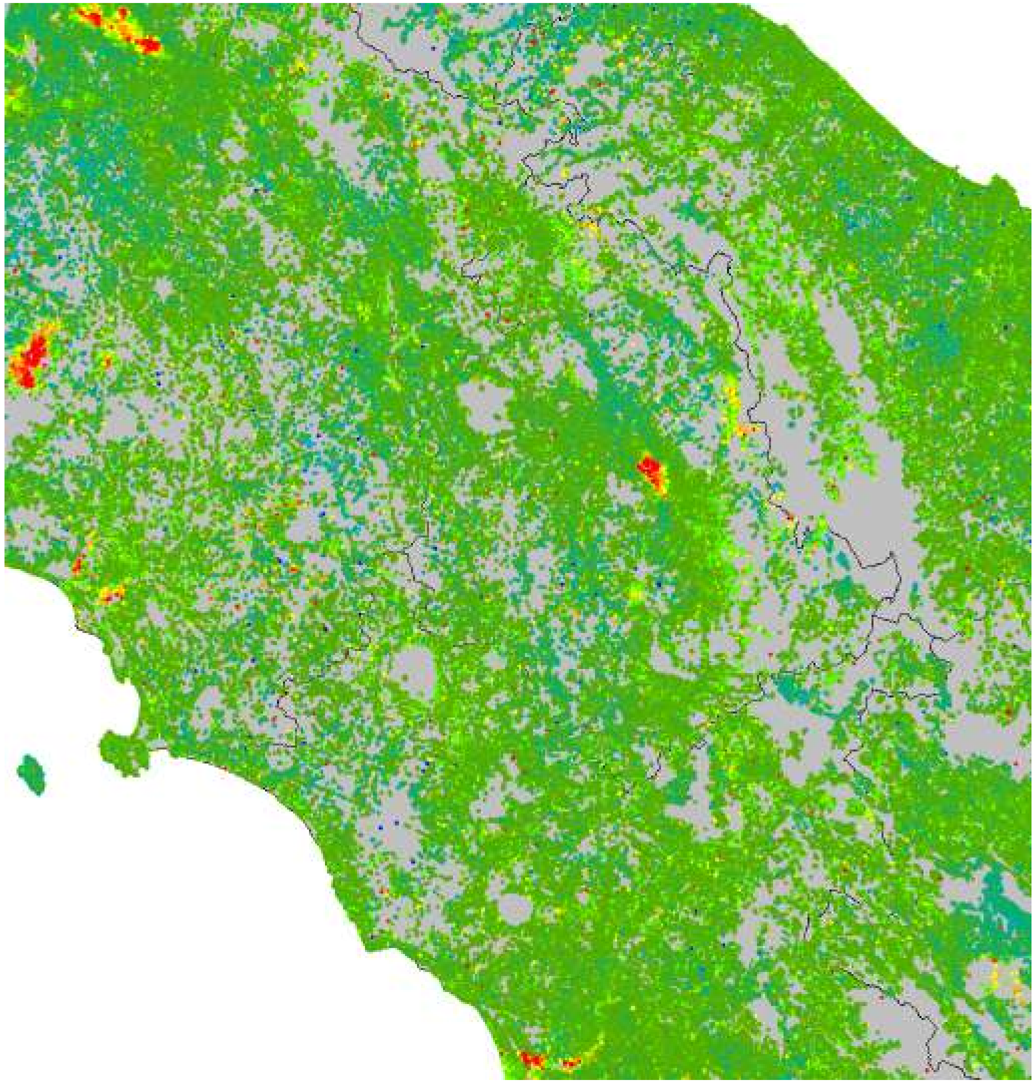
Processed area:
2003-2008 ENVISAT ascending data



Centre-South Italy mean velocity: 2003-2008 ENVISAT ascending data



Centre Italy mean velocity: 1992-2000 ERS descending data



Mean velocity (mm/year)

- < -9.0
- -8.99 - -7.00
- -6.99 - -5.00
- -4.99 - -3.00
- -2.99 - -1.00
- -0.99 - 1.00
- 1.01 - 3.00
- 3.01 - 5.00
- 5.01 - 7.00
- > 7.0

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COSMO-SkyMed PSP IFSAR analysis of railway tracks in Russia

PSP-IFSAR application examples

- E-Geos completed a pilot project for the Russian Railway company (NIIAS/RZD) to assess the capabilities of SAR differential interferometry in monitoring the railway track Adler-Tuapse
  - See next presentation by Alexander Vasileisky

- An operational monitoring service is in progress
  - Thanks to the higher no. of acquisition and to a more favorable acquisition geometry a higher density of measurements have been obtained w.r.t. the pilot project
  - Some preliminary results (not yet fully analyzed) will be shown in the next slides

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COSMO-SkyMed acquisitions used for PSP-IFSAR analysis

- Stripmap HI-01 acquisition mode
- Ground resolution 3 m x 3 m
- Polarization HH
- Incidence angle 26.65°
- Right looking, descending pass
- Analyzed period: Dec. 2008 – Sept. 2010
- Number of acquisitions: 52

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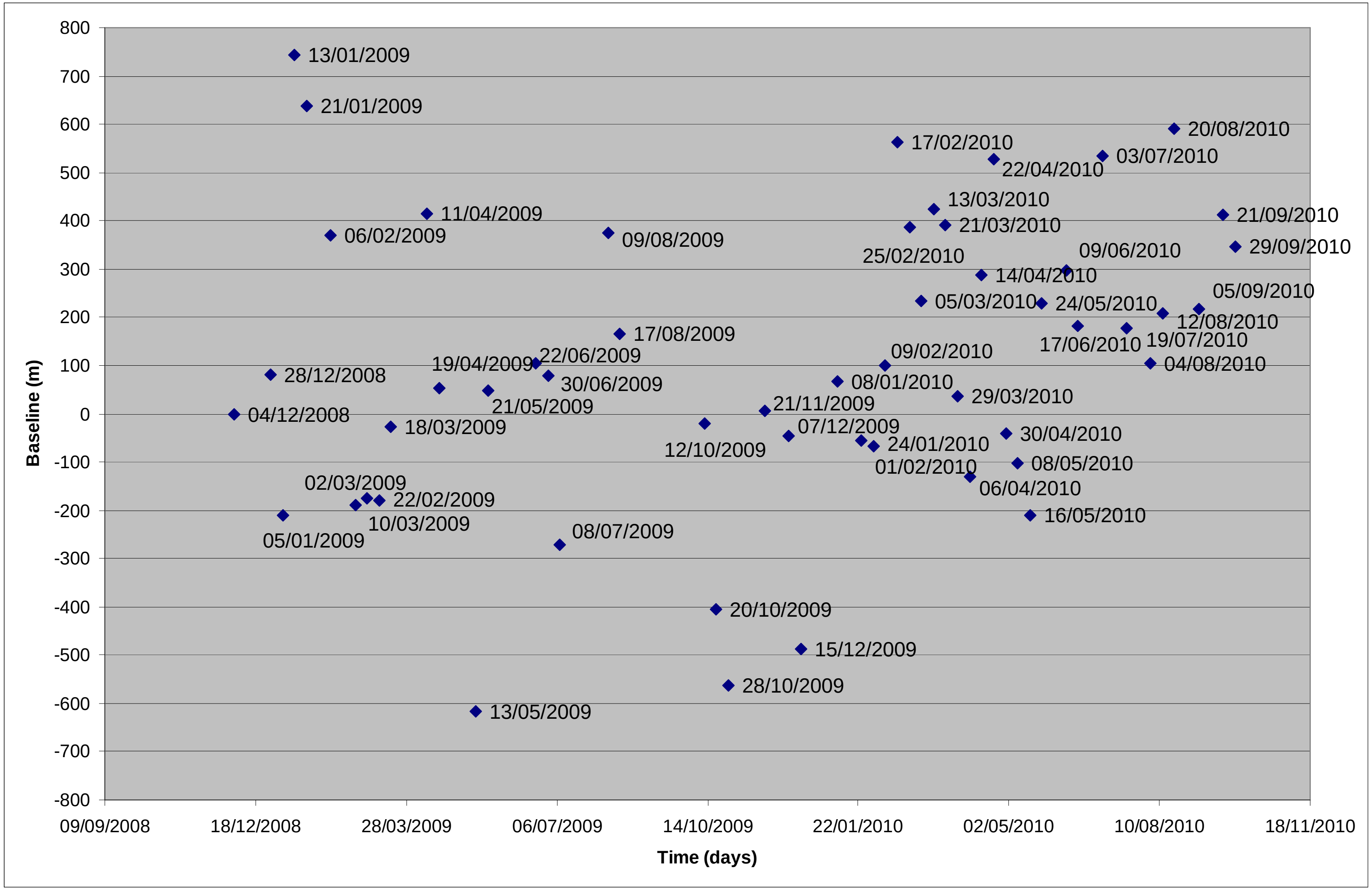
Spatial and temporal distribution of the COSMO-SkyMed acquisitions



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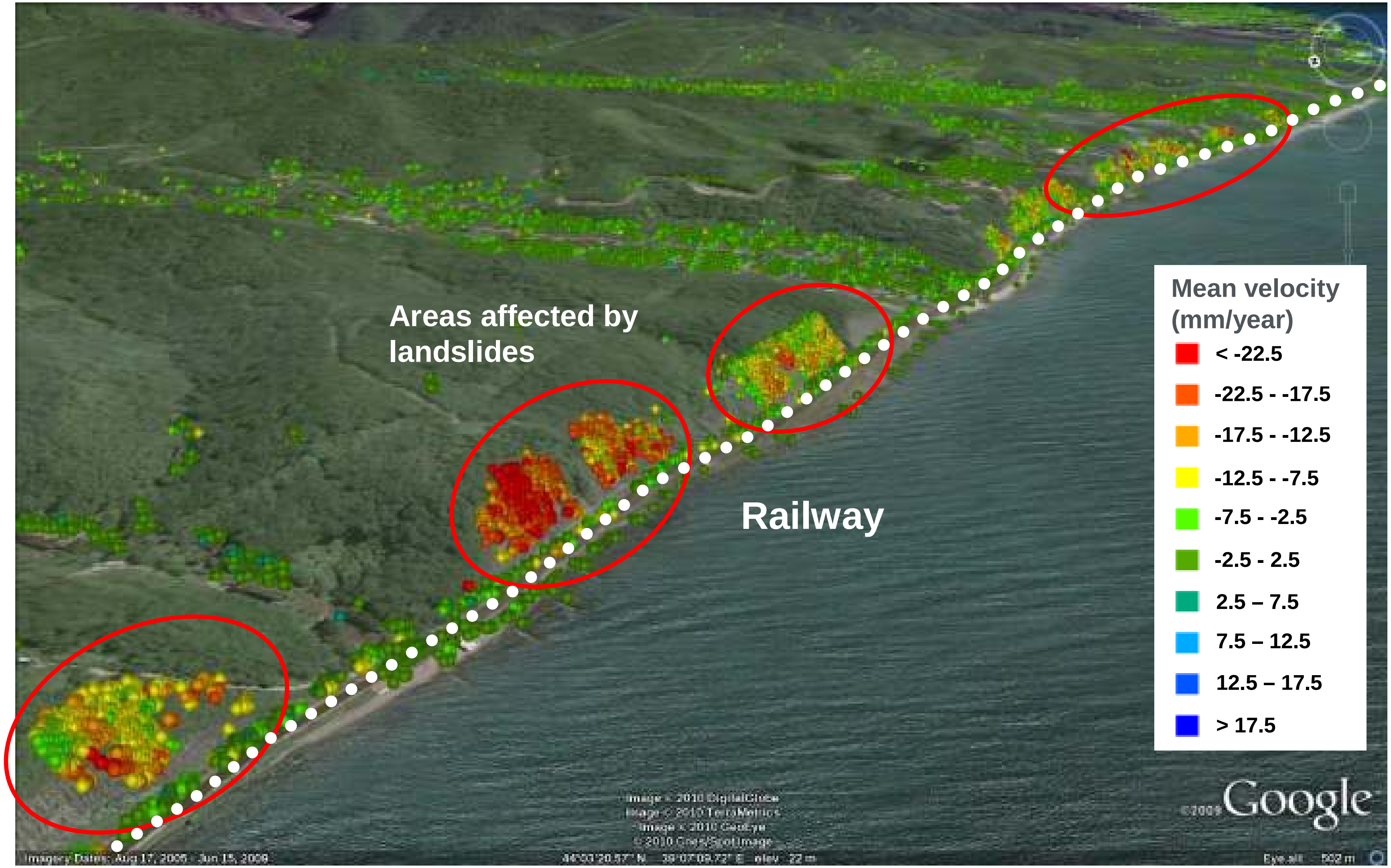
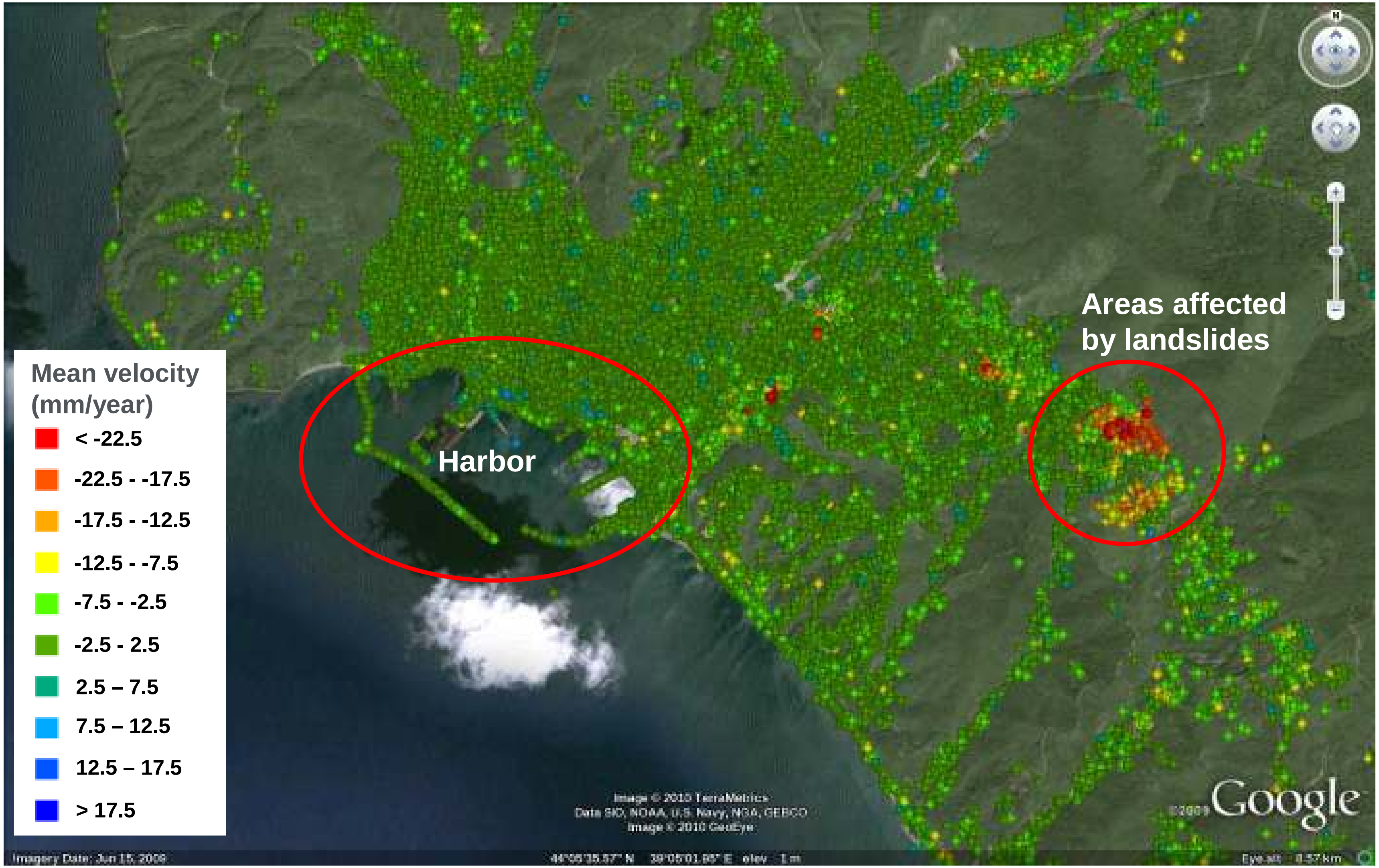
Railway line
PS mean velocities 3D view



Landslides
PS mean velocities 3D view

Tuapse
PS mean velocities



Tuapse Harbor
PS mean velocities

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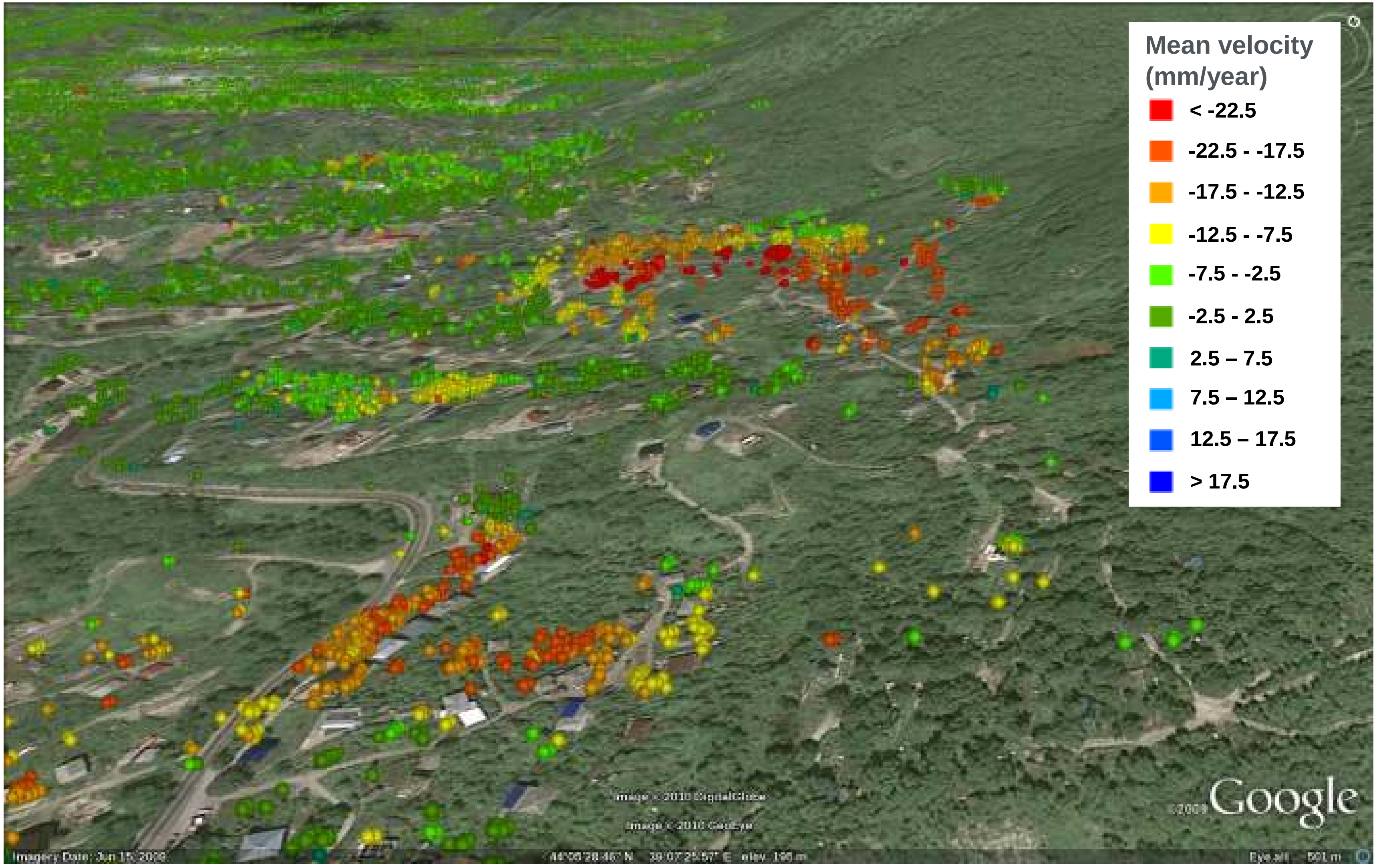
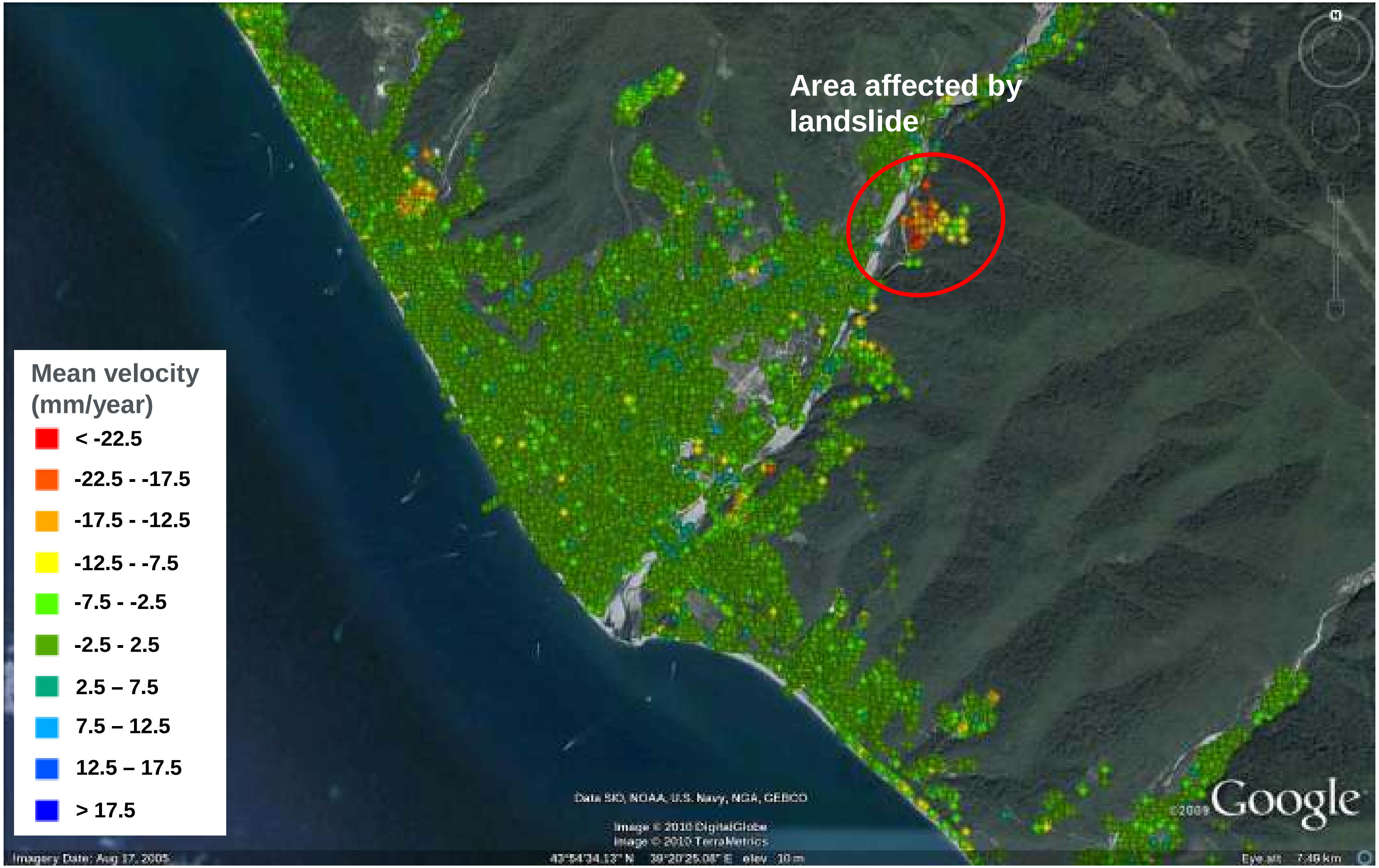
Tuapse landslide
PS mean velocities 3D view



Lazarevdkoye
PS mean velocities



Lazarevdkoye landslide
PS mean velocities 3D view

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Conclusions (1 of 2)

- E-GEOS PSP-IFSAR processing technology:
  - Persistent scatterer pair (PSP) technique: an advanced approach to persistent scatterer pair interferometry
  - Redundant LP finite difference integration and phase unwrapping: improved accuracy and reliability of results
  - High performance parallel processing system: large scale productions

- PSP-IFSAR analysis of high resolution COSMO-SkyMed SAR data
  - Beijing, China
  - Shanghai subway lines, China
  - Tuapse-Adler railway track, Russia

- A national scale project: analysis of the whole Italian territory with ERS/Envisat SAR data

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Conclusions (2 of 2)

- SAR interferometry enables ground deformations measurements with:
  - High temporal frequency
    - up to 8 measurements per months with COSMO-SkyMed constellation
  - Unprecedented spatial density
    - tens of thousand measurements per km^2 with stripmap CSK data and up to one million per km^2 with spotlight

- PSP-IFSAR technology proved to guarantee:
  - Accurate deformation measurements
  - Accurate 3D localization of the measurements
  - High density of measurements
  - Reliability and robustness to noise and outliers
  - Massive automatic productions

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Thank you

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