Recent Subsidence of the Venice Lagoon from Continuous GPS and Interferometric Synthetic Aperture Radar

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(Bock et al. G-cubed, 2012)

Venice

Subsidence and sea level rise occasionally flood the city
“Aqua Alta”

Presentation content

- Introduction
  - Venice and its subsidence
- Subsidence monitoring techniques
  - GPS
  - InSAR
- Venice subsidence
  - Observations
  - Implications
- Other study areas
  - Mexico
  - Indonesia
- Summary

History

- Venice is a historical city founded in 750
- For 1000 years it was a great power in southern Europe and its Influence extended from Spain to the Byzantine empire

An 18th century view of Venice by Venetian artist Canaletto.

Location

- The city is located within the Venice Lagoon.
- It is located on an archipelago of 128 small islands

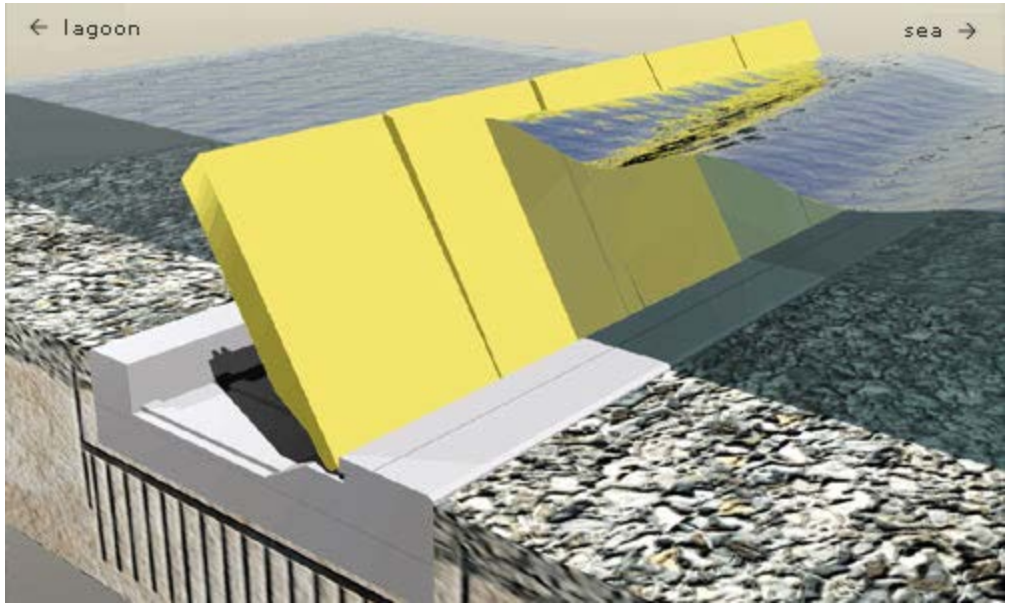
Introduction

- Venice is subsiding, sea levels are rising…
- Water movements inside the lagoon is highly related to the tides.
- Groundwater extraction (discontinued since 1970) caused non-uniform subsidence.
- Tide gauge record at Punta de Salute indicates 23 cm sea level rise in 20th century.
- This consists of:
- 9 cm land subsidence (3 cm natural, 6 cm anthropogenic)
- 11 cm sea level rise in upper Adriatic
- Most severe flooding in 1966, water levels reaching ~ 2 m
- Sea water ruins limestone and marble buildings.
- Fresh water ecosystems have been lost at an alarming rate (-50% over the last century)

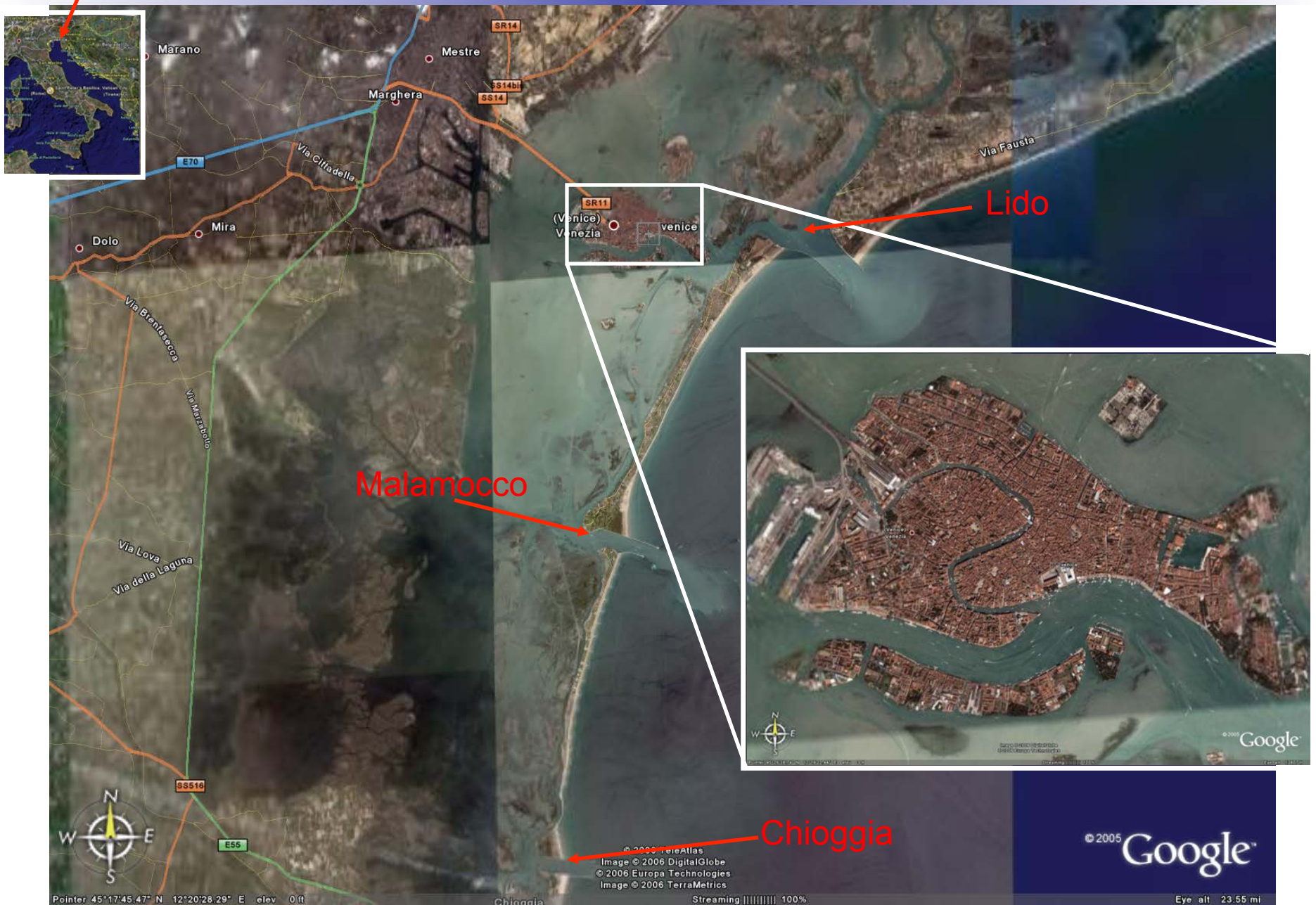
Alta Aqua

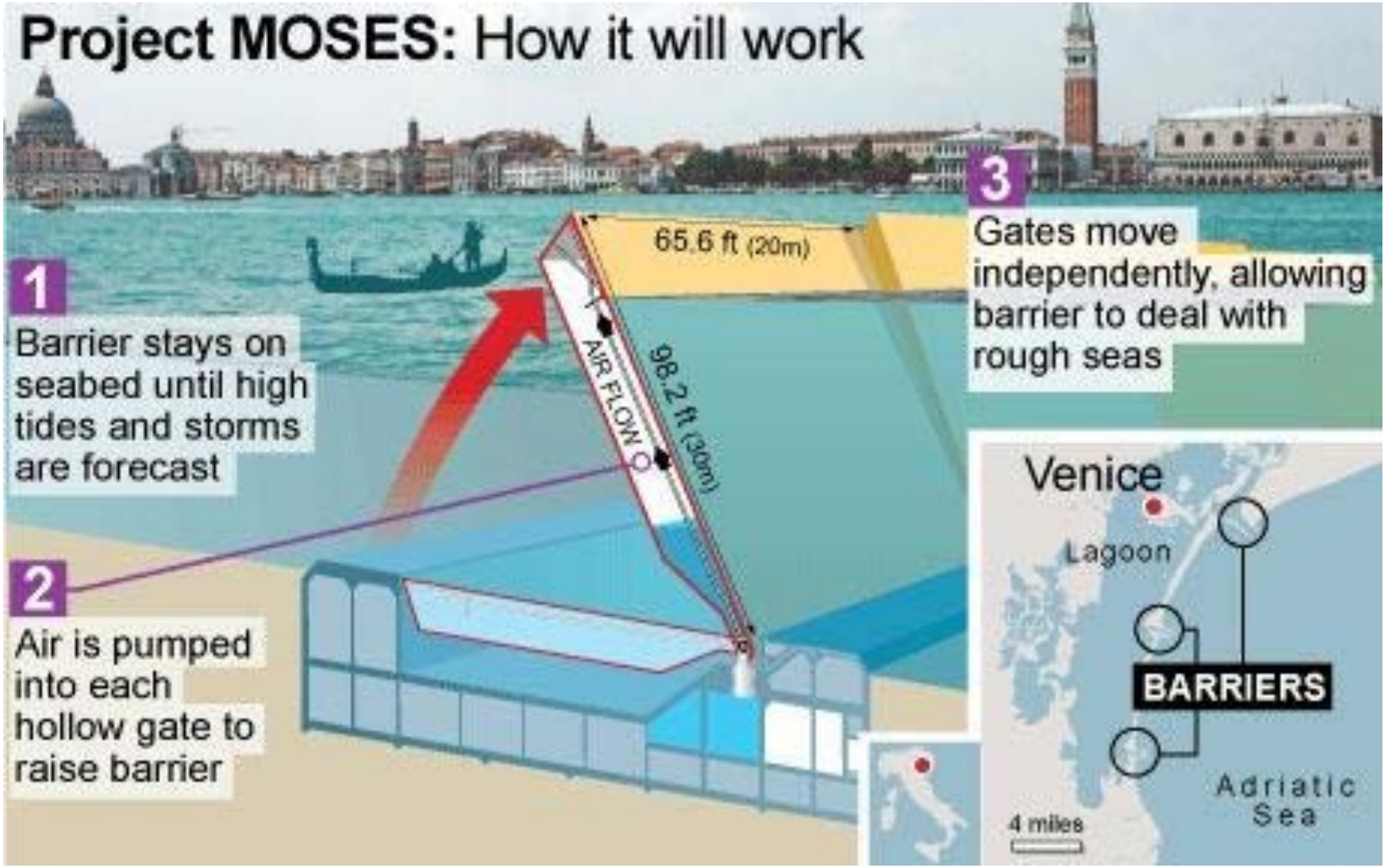
Project MOSE

- Latest studies indicate ground stability at the central parts, but 3-5 mm/yr at the northern and southern regions.
- Italian government took several steps to protect Venice – Project MOSE (MOdulo Sperimentale Elettromeccanico, *Experimental Electromechanical Module)*
- Artificial beach nourishments
- Wetland Reconstruction
- Raising the banks of the city
- Mobile Barriers (2003)



Venice Lagoon



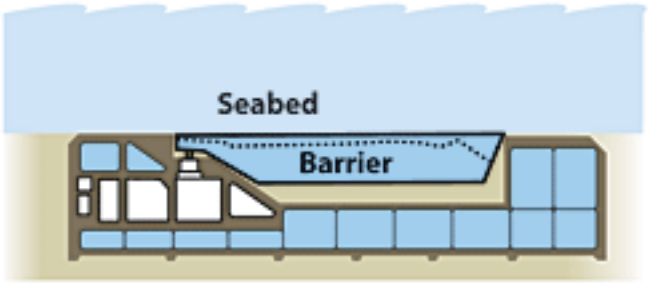

Project MOSES: How it will work
1
Barrier stays on seabed until high tides and storms are forecast
2
Air is pumped into each hollow gate to raise barrier
3
Gates move independently, allowing barrier to deal with rough seas
65.6 ft (20m)
98.2 ft (30m)
AIR FLOW
Venice
Lagoon
BARRIERS
Adriatic Sea
4 miles

Venice flood barriers

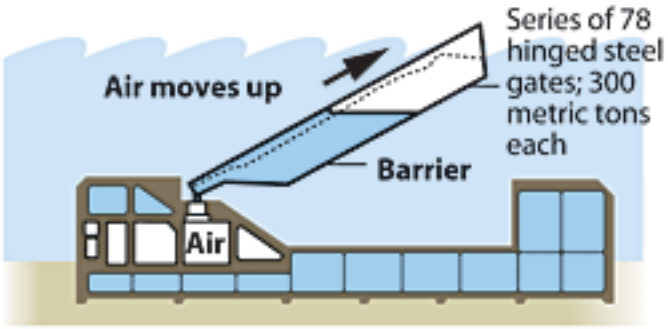
Venice is building a system of movable barriers that would rise from the seabed to ease the effect of high tides.

How it works

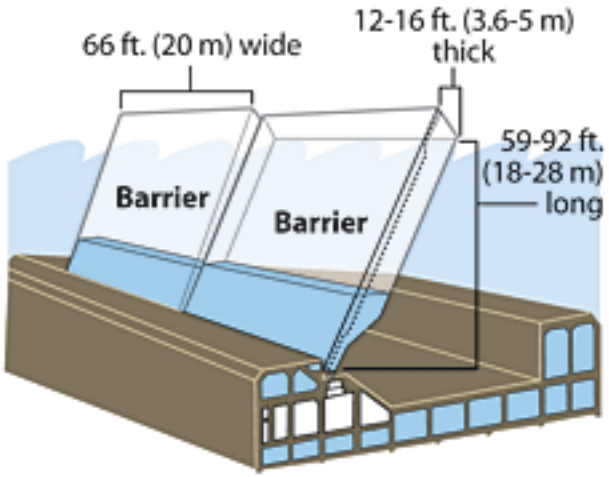
1 Barrier will stay on the seabed until high tides and storms are forecast.



2 Air is pumped into each hollow gate causing it to rise to the surface; it takes 30 minutes to rise and only 15 minutes to return.



3 Each gate moves independently, allowing the barrier to deal with rough seas; Lagoon level can be up to 4 ft. (1.4 m) below sea level.



- **Project name:** MOSE
- **Cost:** $5.5-10.4 billion (€3.5-4.2 billion)
- **In operation:** By 2014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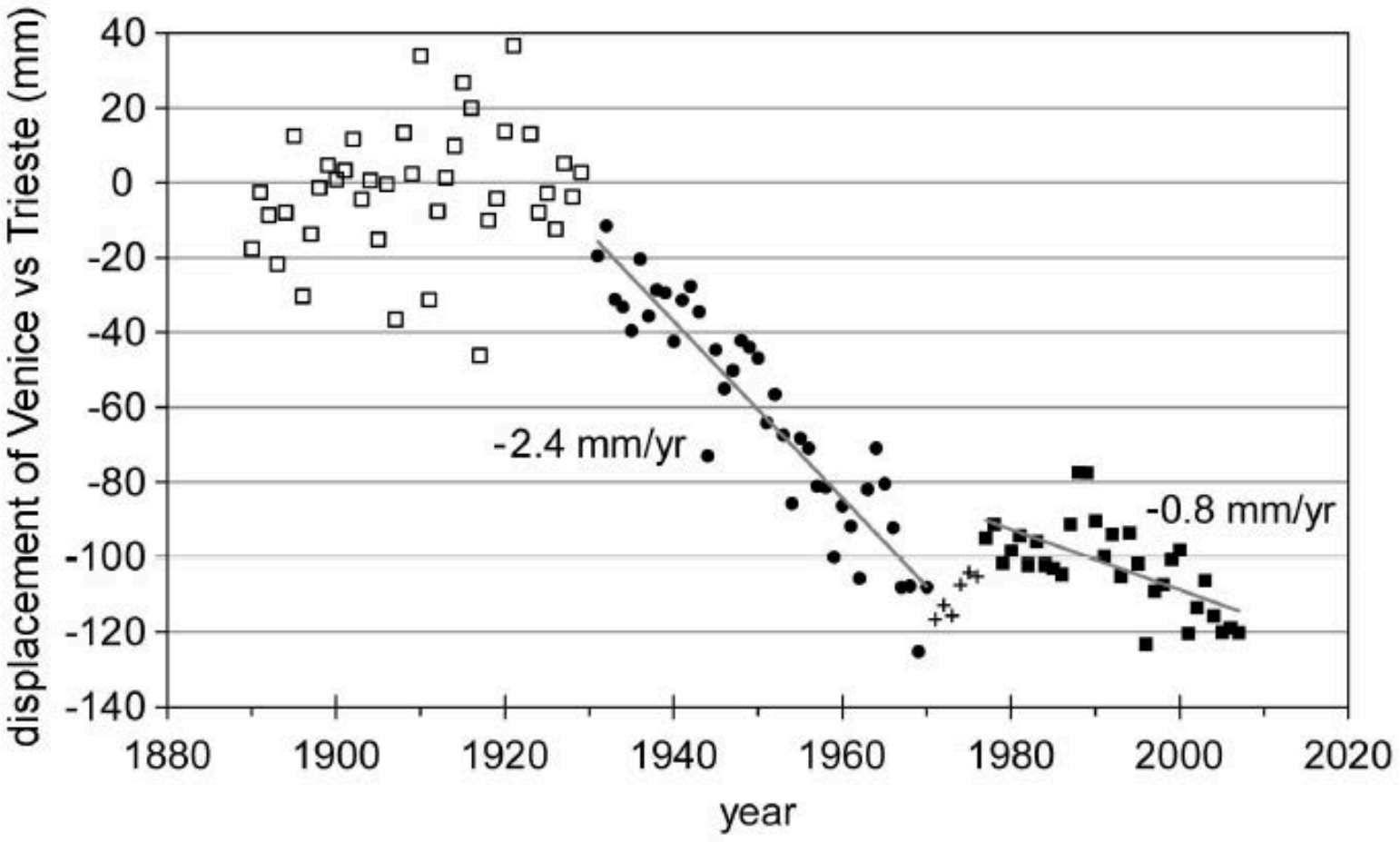
Venice subsidence



Teatini et al (2012)

Eustacy and land subsidence in the Venice Lagoon at the beginning of the new millennium

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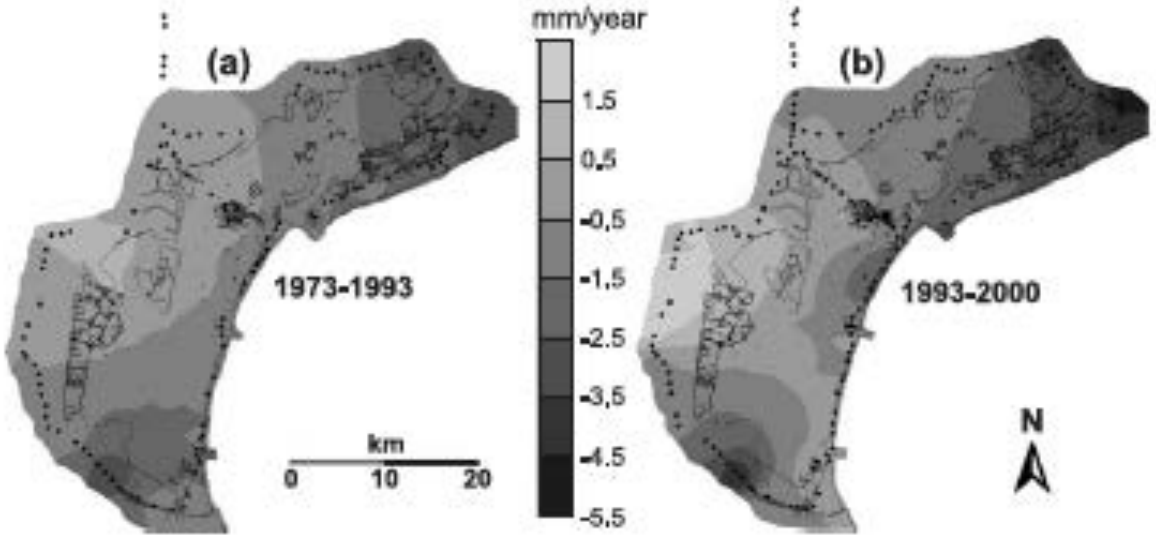

Fig. 2. Rates of vertical displacement (in mm/year) during the periods 1973–1993 (a) and 1993–2000 (b). These contour maps are obtained through the interpolation of the point measurements using the Kriging stochastic method. Positive values mean uplift, negative land subsidence.

Mapping regional land displacements in the Venice coastland by an integrated monitoring system

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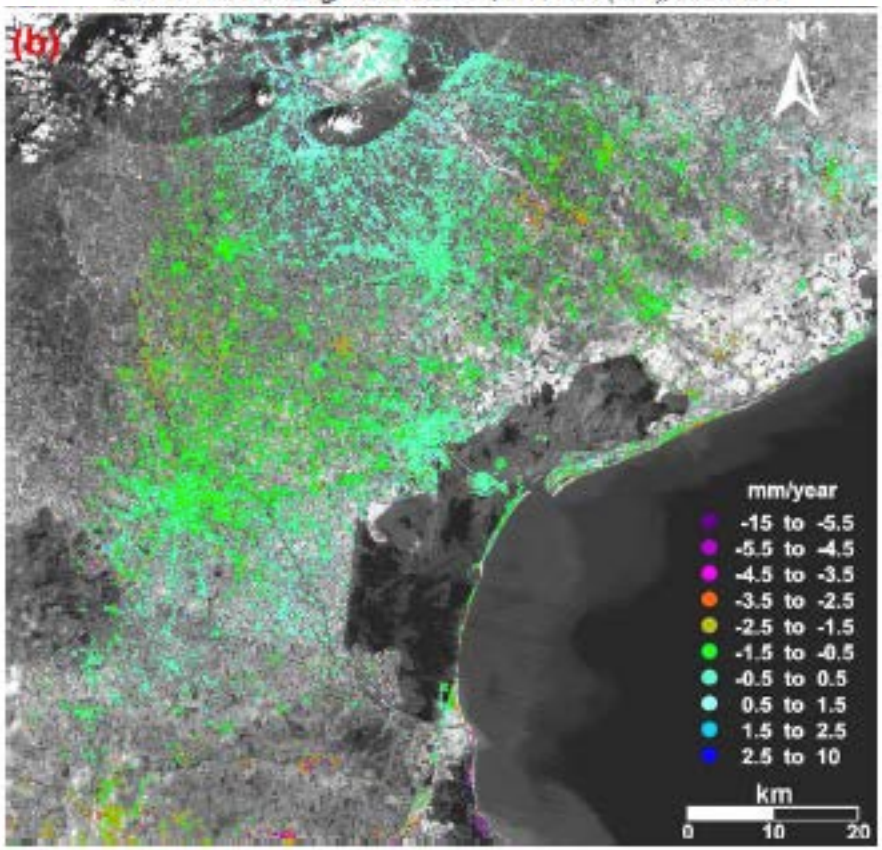
[c] *Gamma Remote Sensing, Thunstrasse 130, 3074 Muri (Bern), Switzerland*



TerraSAR-X reveals the impact of the mobile barrier works on Venice coastland stability

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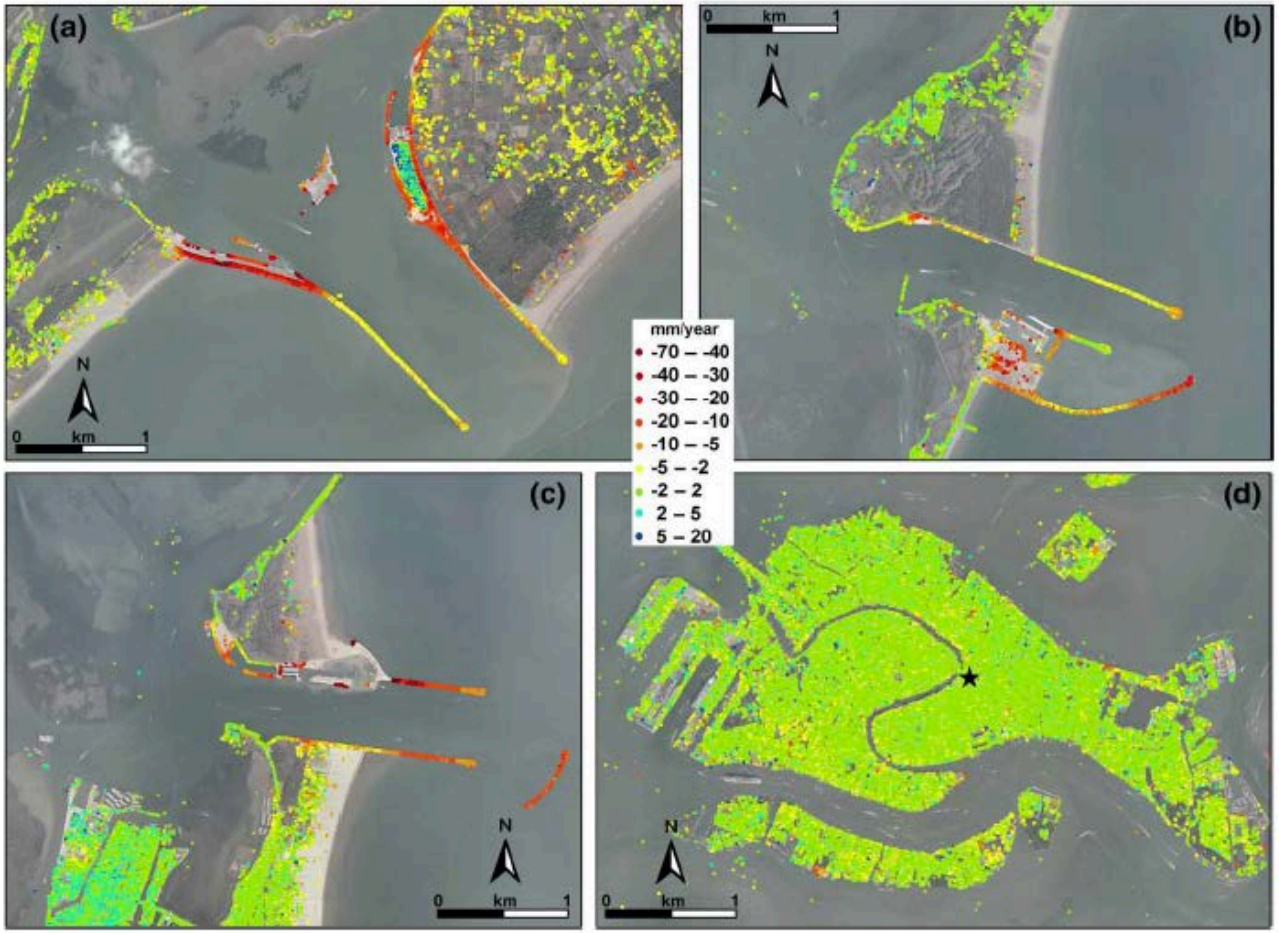
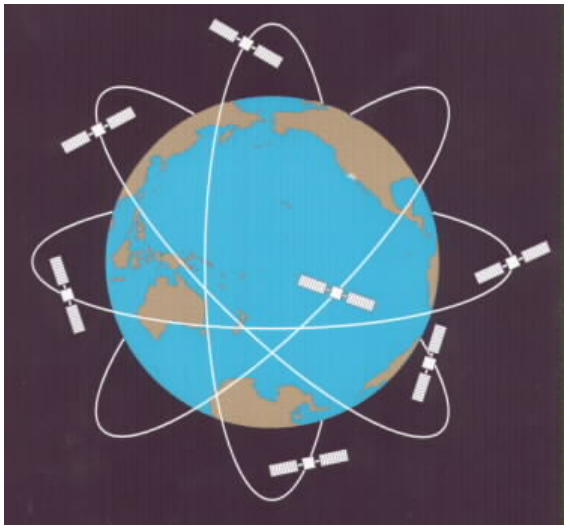
[c] Institute of Marine Sciences, National Research Council, Castello 1364/a, 30122, Venice, Italy



Space geodetic measurements

Measurements of current crustal movements

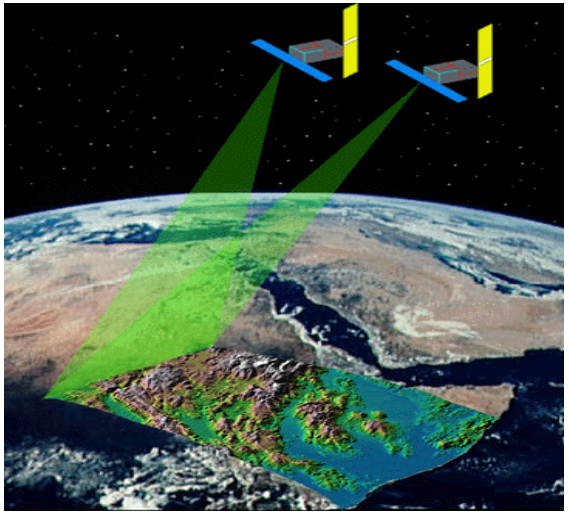
The very slow movement of the Earth's solid surface (mm/yr – cm/yr) can be measured nowadays using space geodetic technologies (VLBI, SLR, GPS, InSAR).



GPS

The measurements reflects:

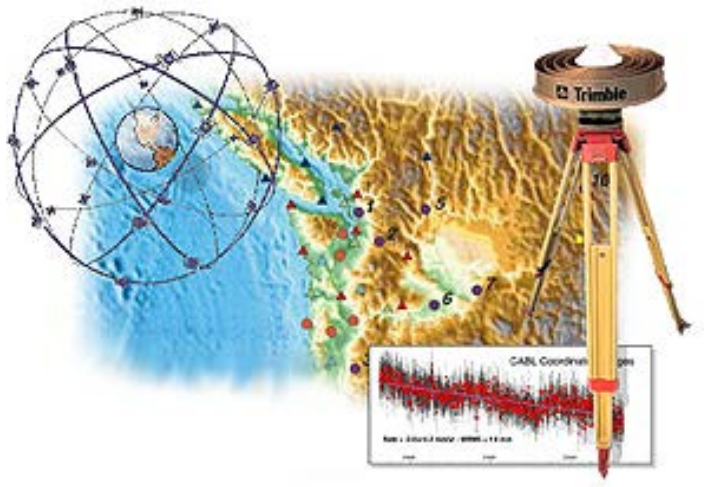
- Tectonic plate motion
- Earthquake induced surface (co-seismic) displacements
- Crustal deformation between earthquake (inter-seismic)
- Surface subsidence



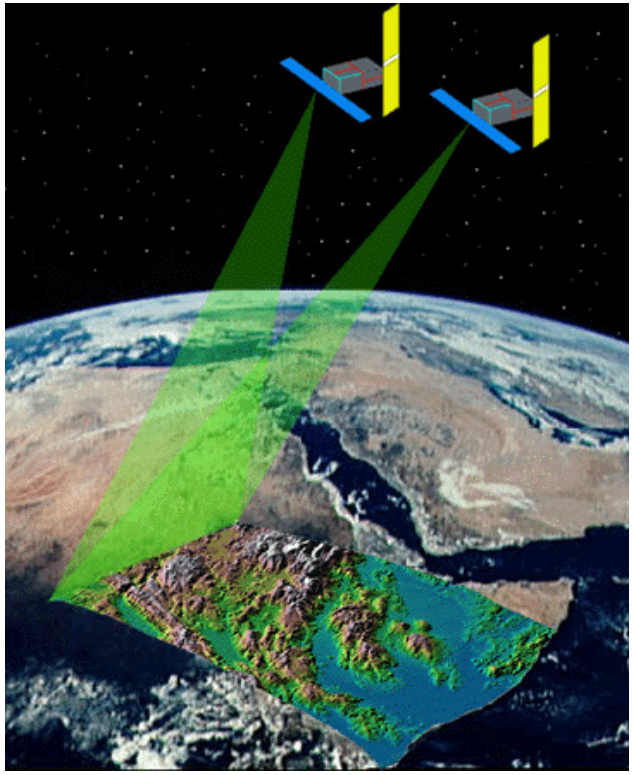
In-SAR

Global Positioning System - GPS

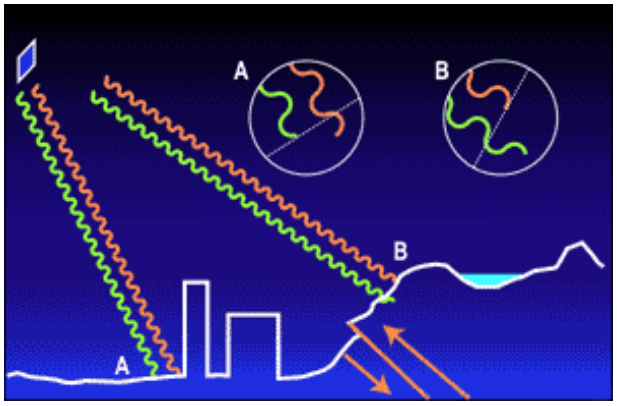
- The Global Positioning System (GPS) is a satellite-based navigation system.
- GPS was originally intended for military applications, but in the 1980s, the government made the system available for civilian use.
- GPS works in any weather conditions, anywhere in the world, 24 hours a day. There are no subscription fees or setup charges to use GPS
- Some civilian uses:
  - Navigation on land, sea, air and space
  - Geophysics research
  - Guidance systems
  - Geodetic network densification
  - Hydrographic surveys



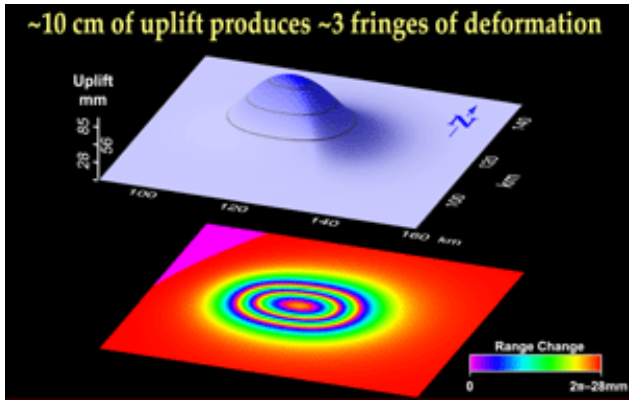
Interferometric SAR - InSAR



Two or more data acquisition of the same area from nearby location (< 1000 m)



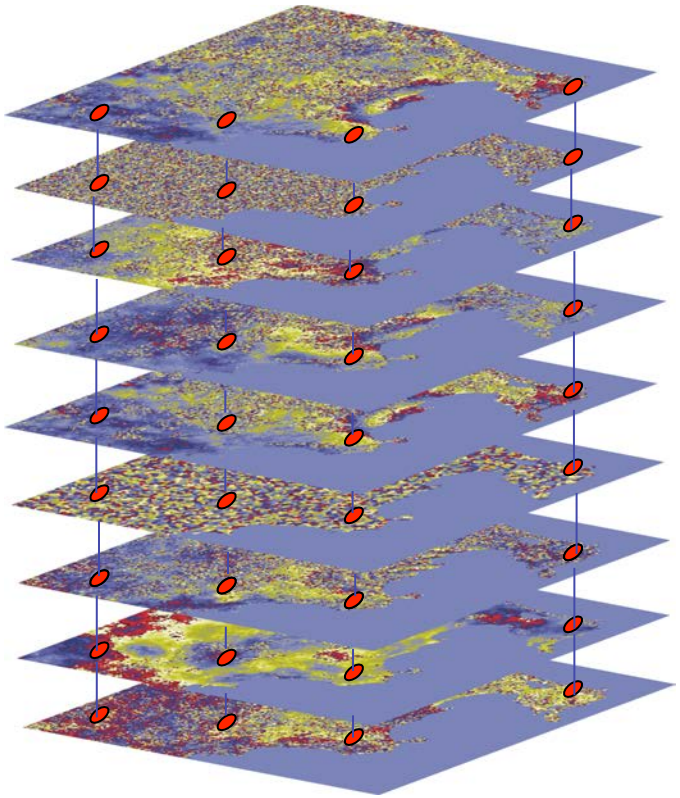
Changes in surface location result in detectable phase changes

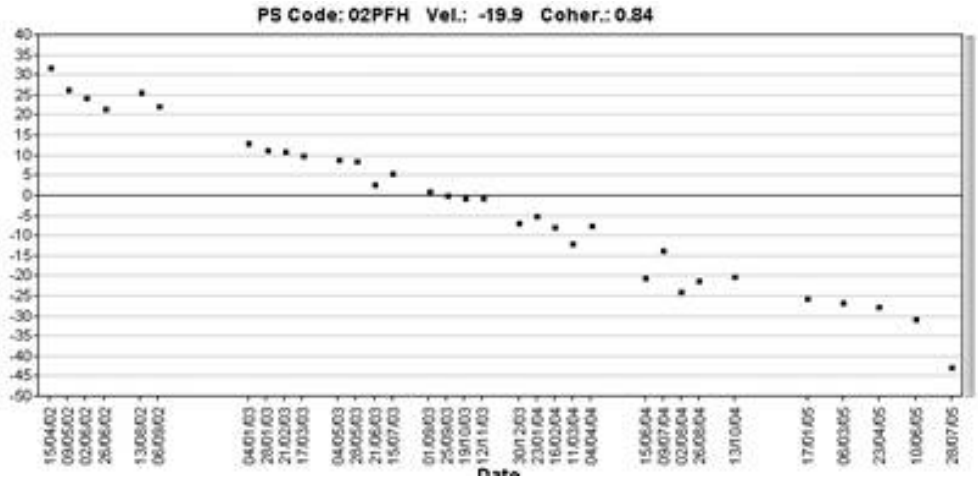


Fringes – 1 cycle (2π) = ½ λ

InSAR time series

- Subset of reliable scatterers
- InSAR time series
- Low pass filter for removing atmospheric noise

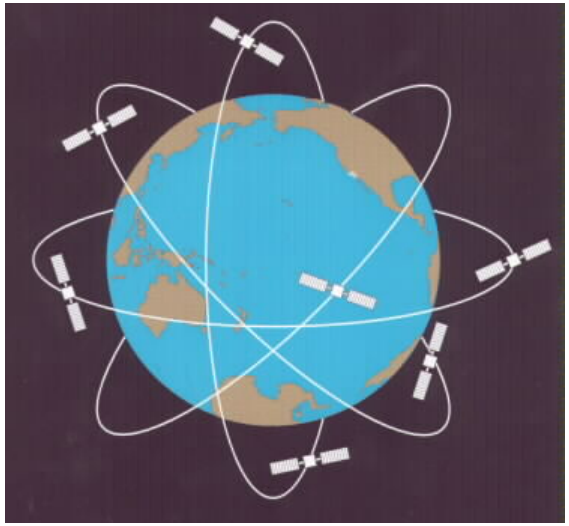




GPS

Absolute (3D) displacements
Continuous measurements
Almost no artifact

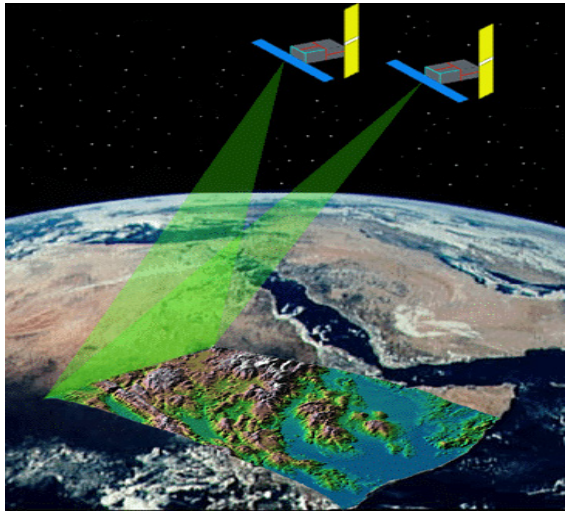
Horizontal resolution - 1mm
Vertical resolution - ~ 3mm
Restricted to receiver sites
Requires stable monuments



InSAR

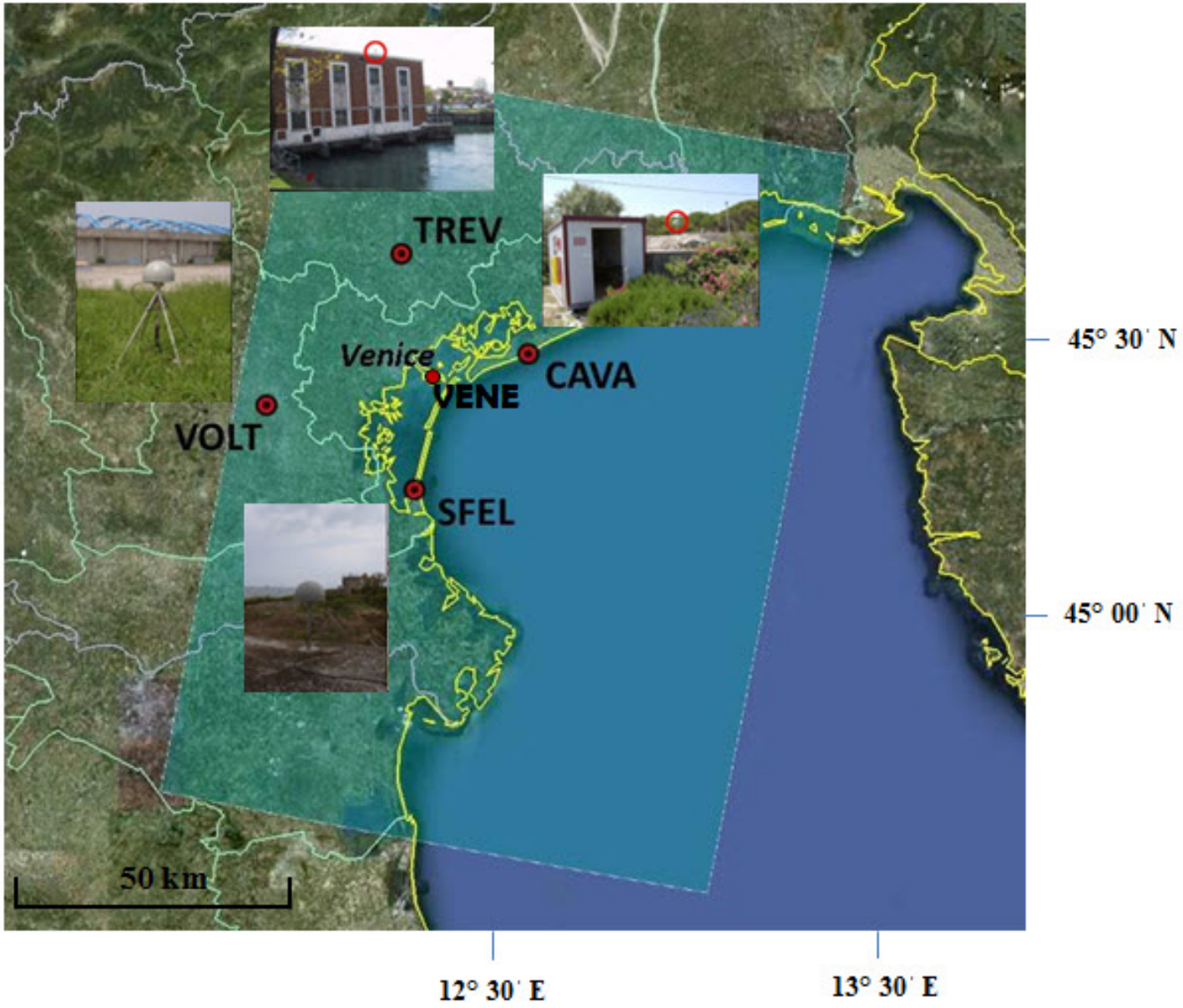
Line of sight displacements
Periodic measurements
Orbital & atmospheric artifacts

Horizontal resolution - 15mm
Vertical resolution - 2mm
Complete spatial coverage
Requires no monuments



Space geodetic measurements of the Venice Lagoon

Continuous GPS station



CGPS Observations

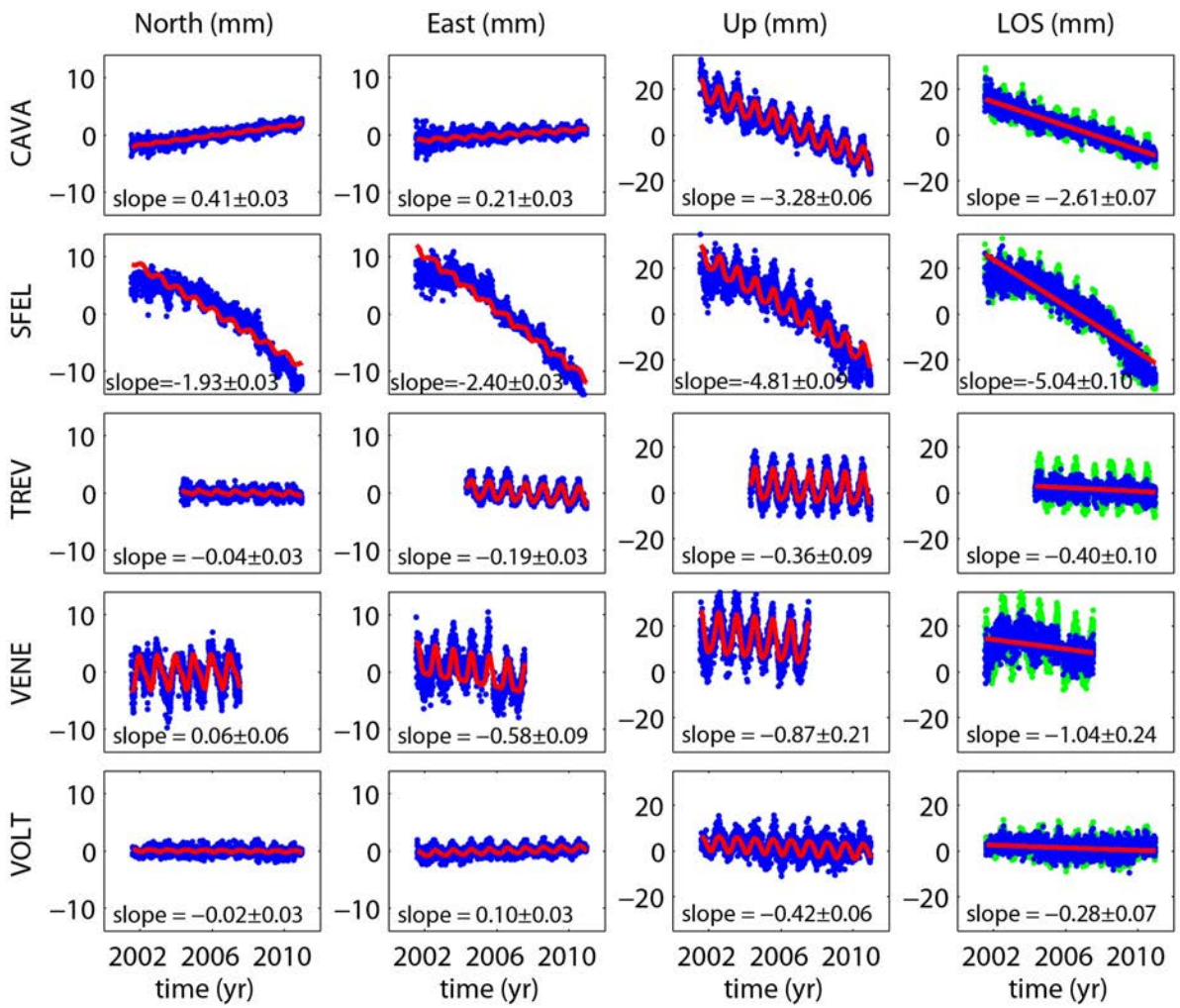
- These three stations are donated by remote data transmission systems.
- 24 hr Rinex files from SOPAC website
- ITRF2000

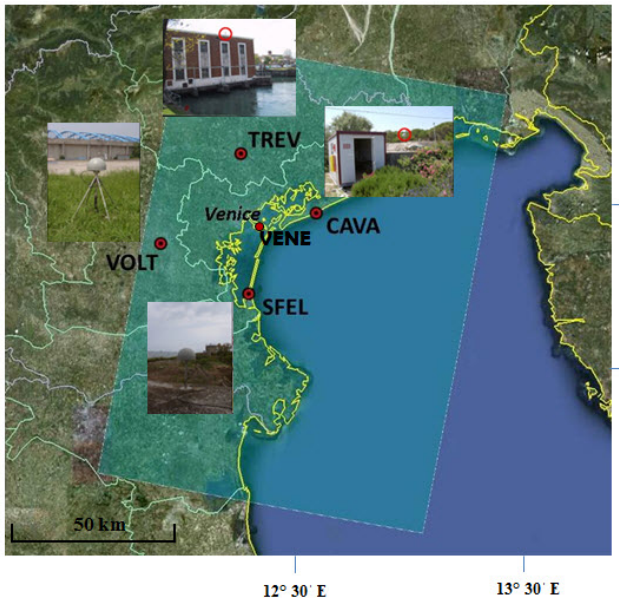
- No detectable seismic deformation except plate motion
- No instrumental or seismic offsets

- Observed motion modeled as:

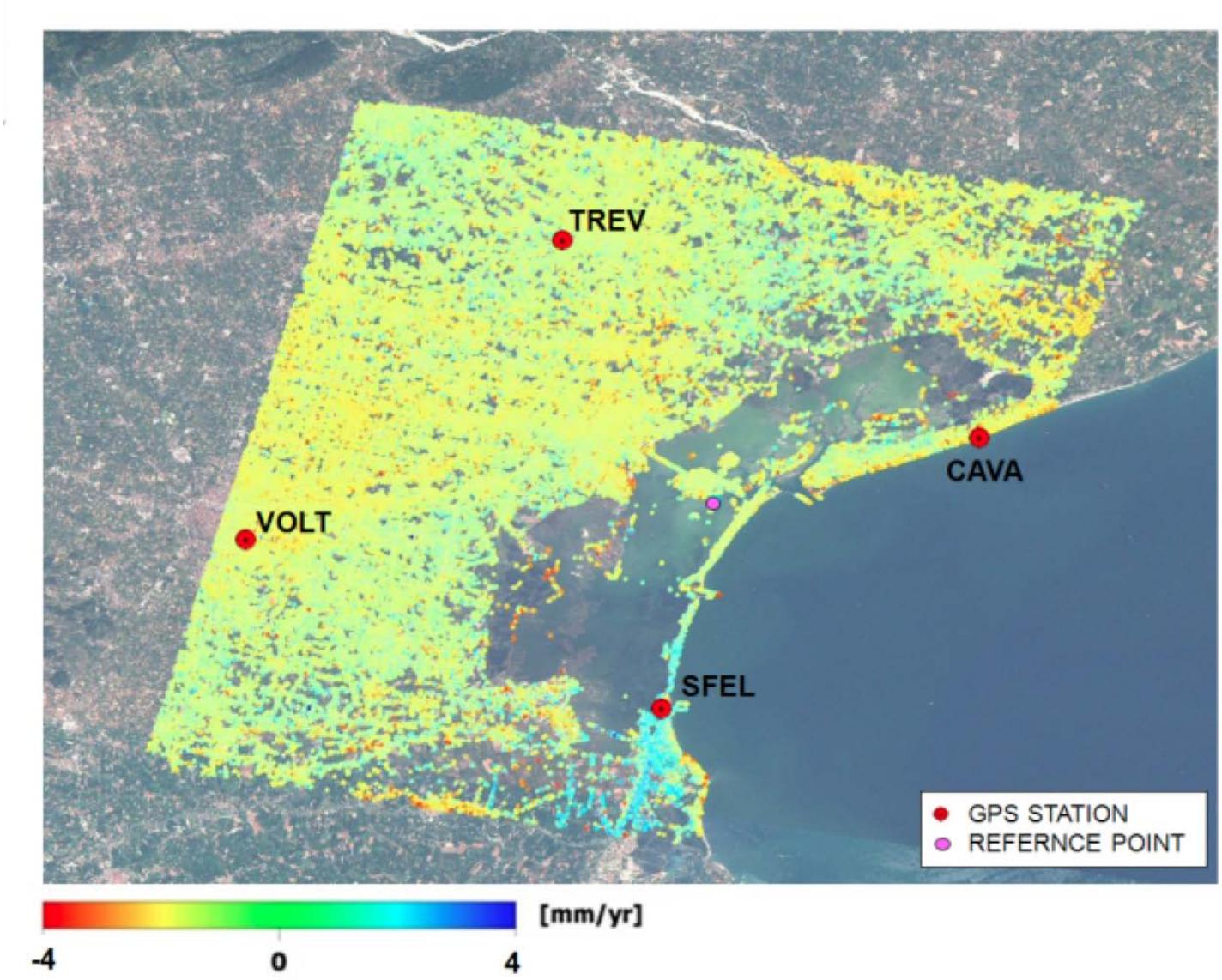
$$y(t_i) = a + bt_i + c\sin(2\pi t_i) + d\cos(2\pi t_i) + e\sin(4\pi t_i) + f\cos(4\pi t_i) + v(t_i)$$

CGPS Observations

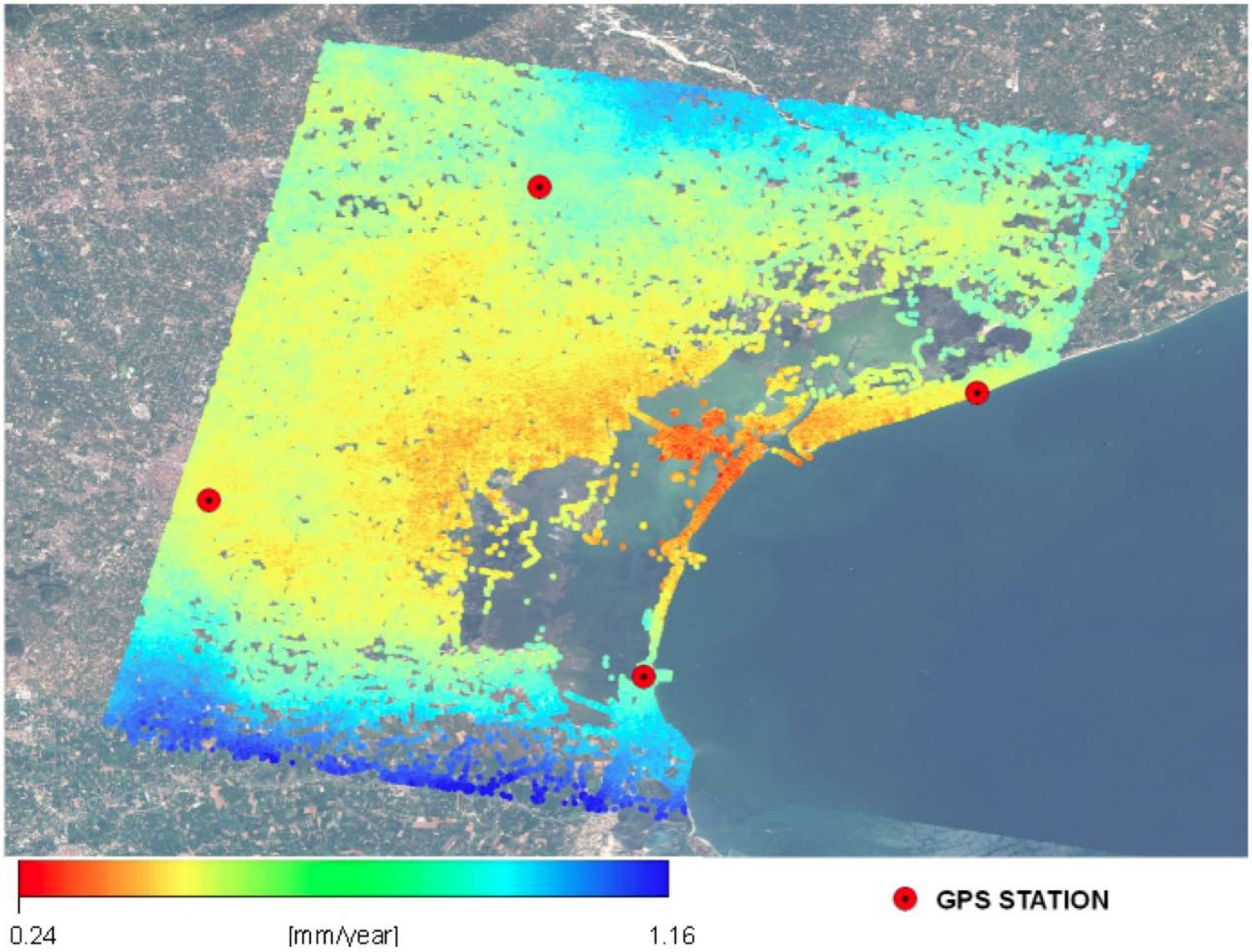




PSInSAR Observations



PSInSAR Observations - accuracy



PSInSAR Observations

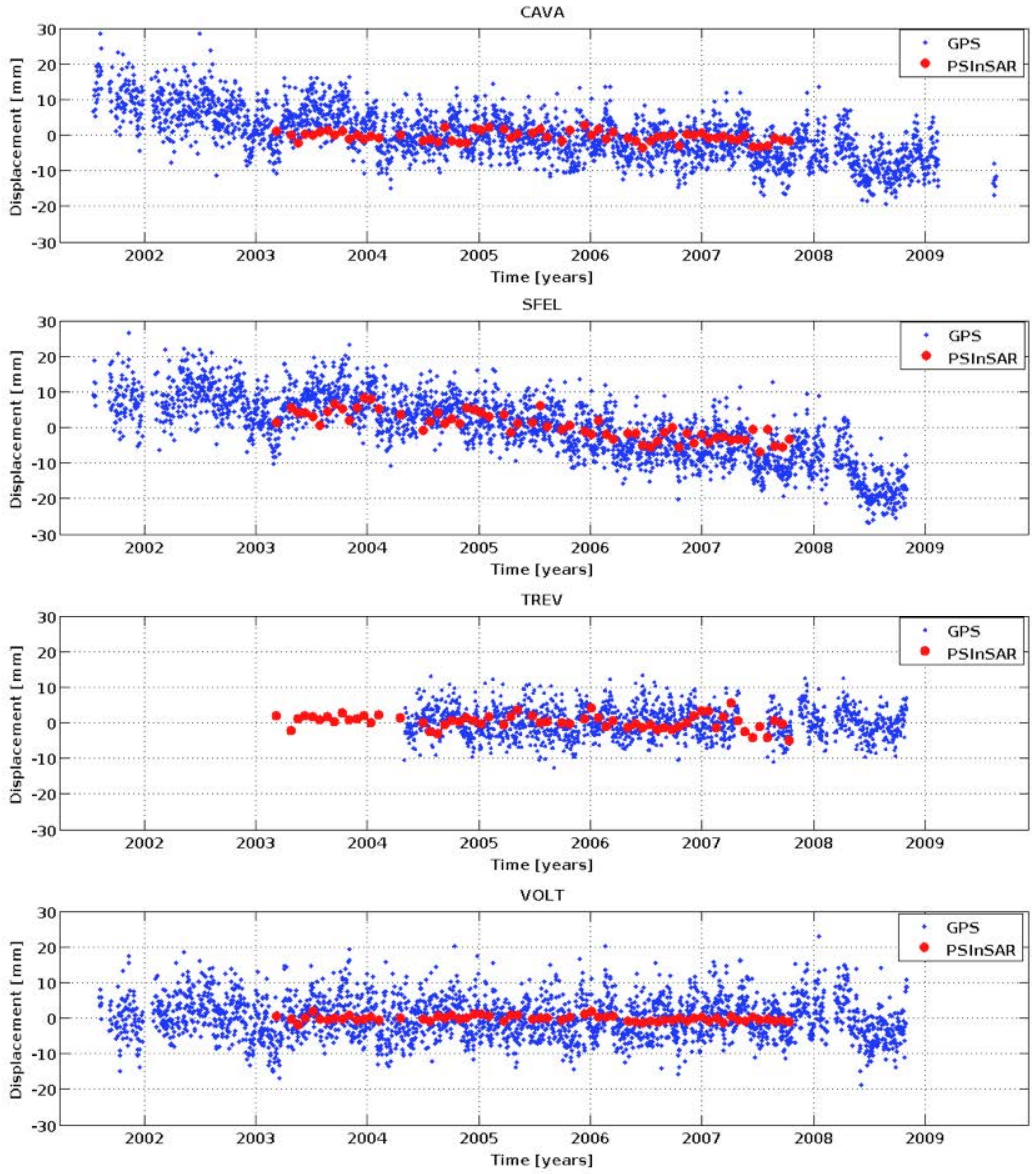
a) CAVA

b) SFEL

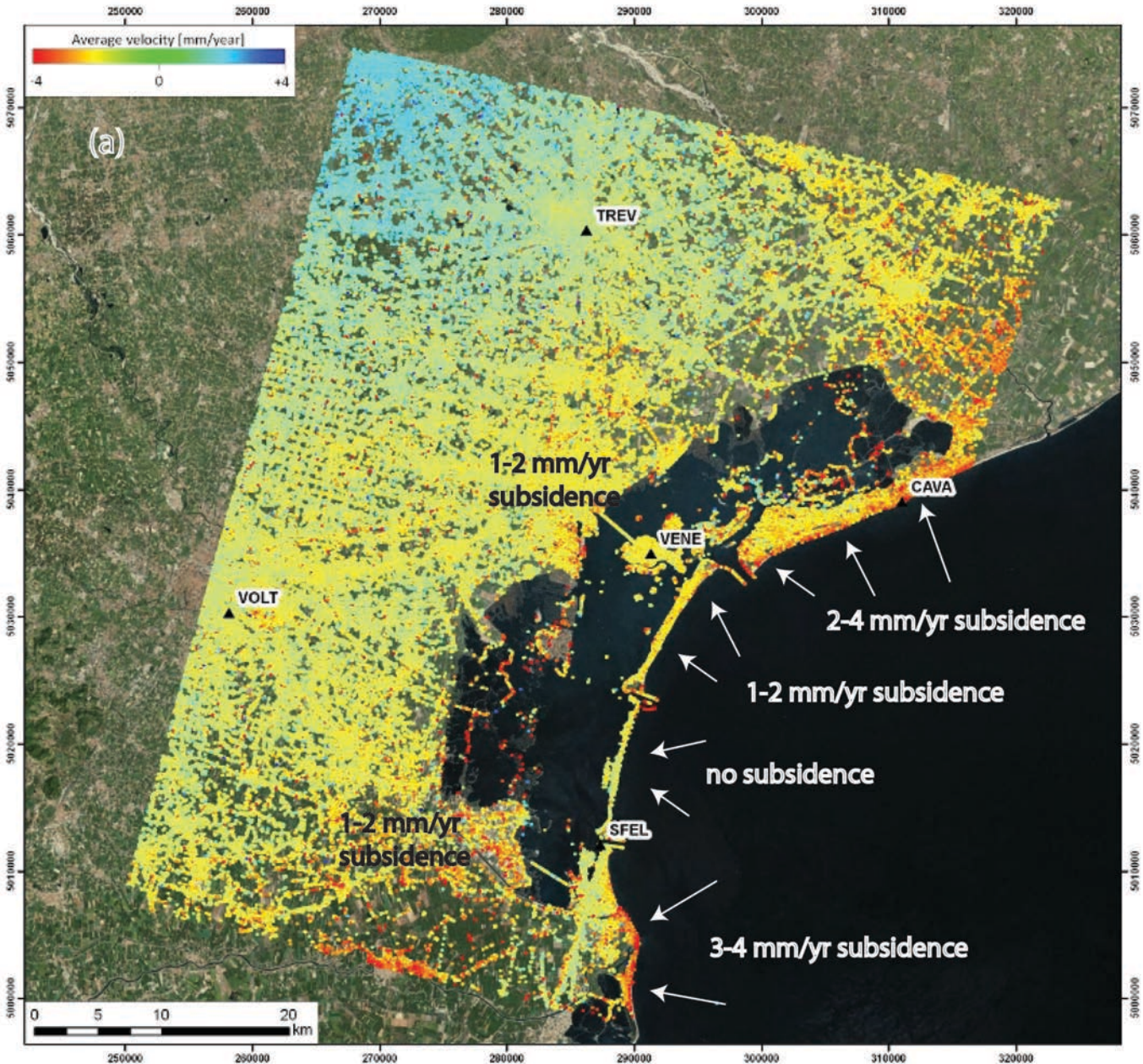
c) TREV

d) VOLT

Comparison between GPS and PSInSAR

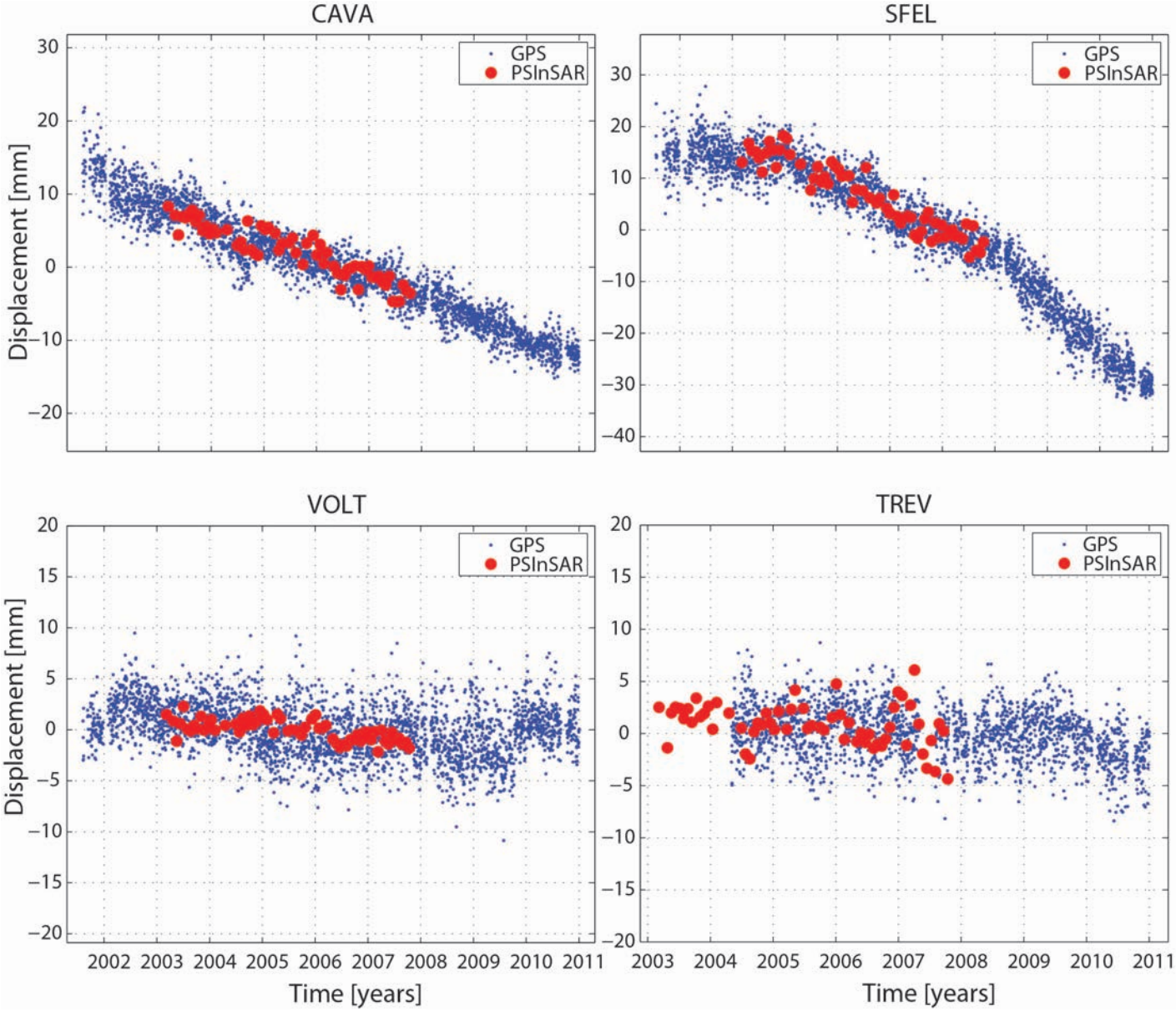


PSInSAR Observations



PSInSAR Observations

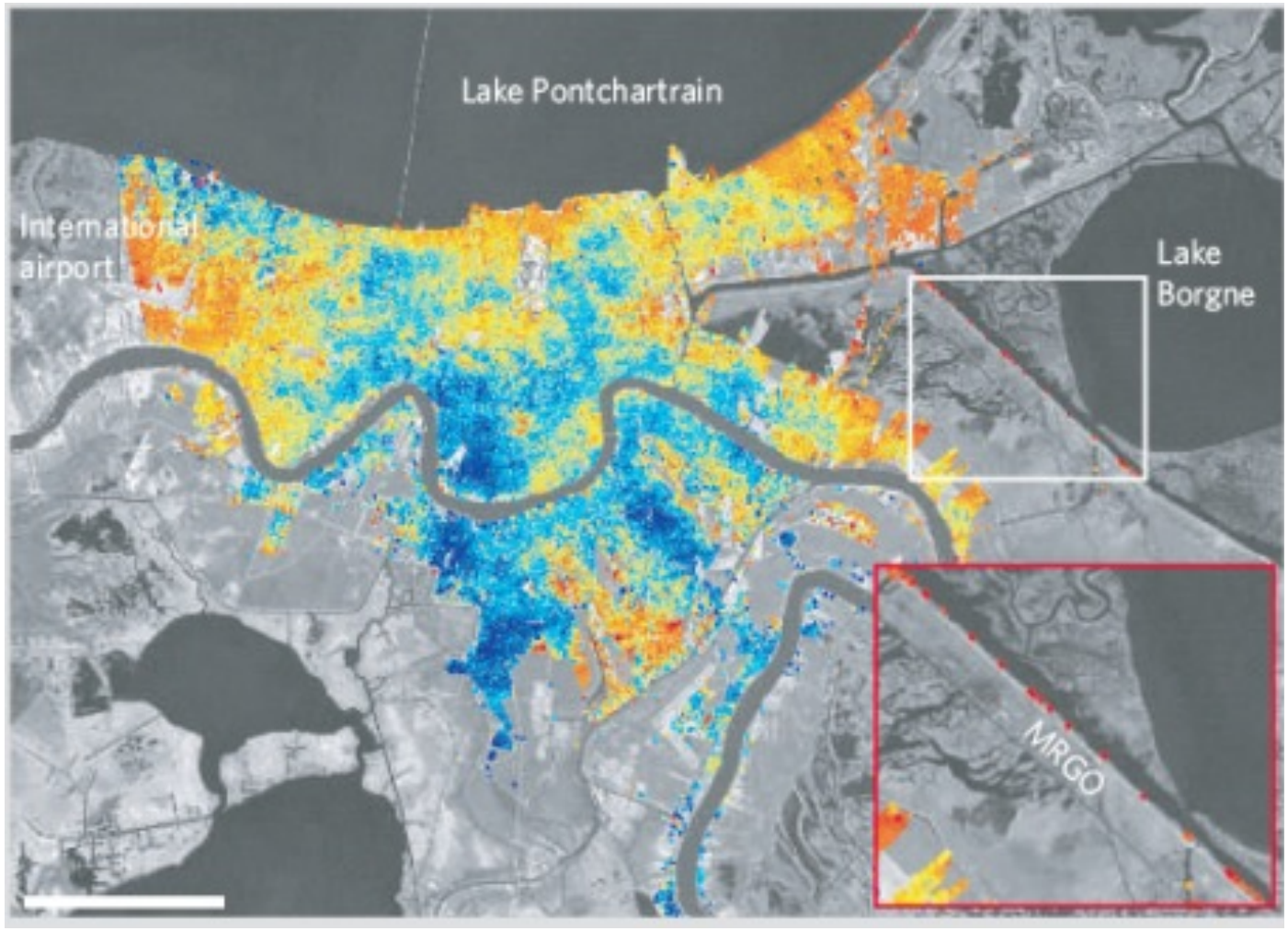
Comparison between GPS and PSInSAR



PSInSAR Observations

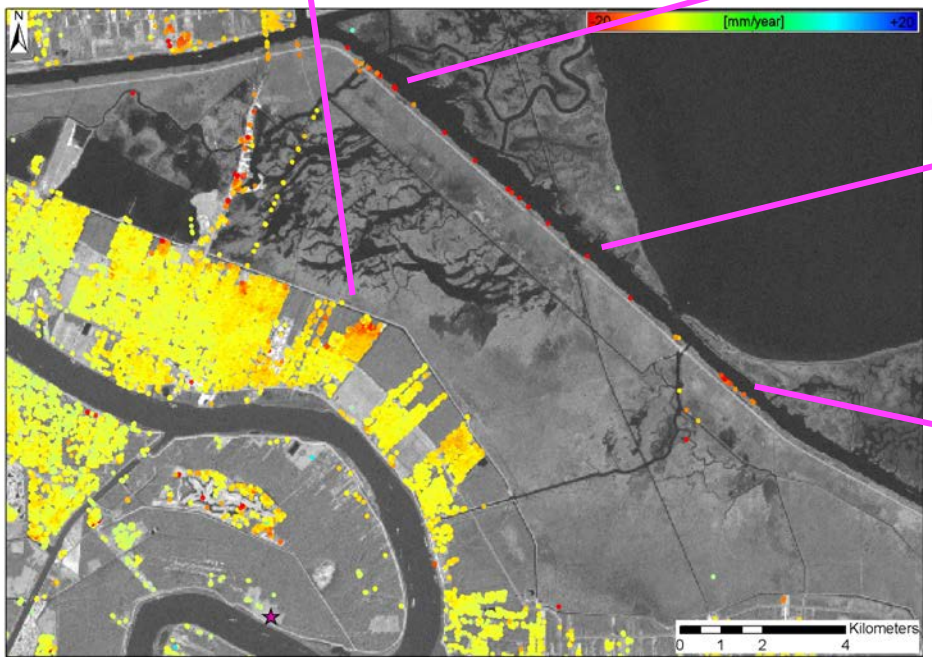
Other studies

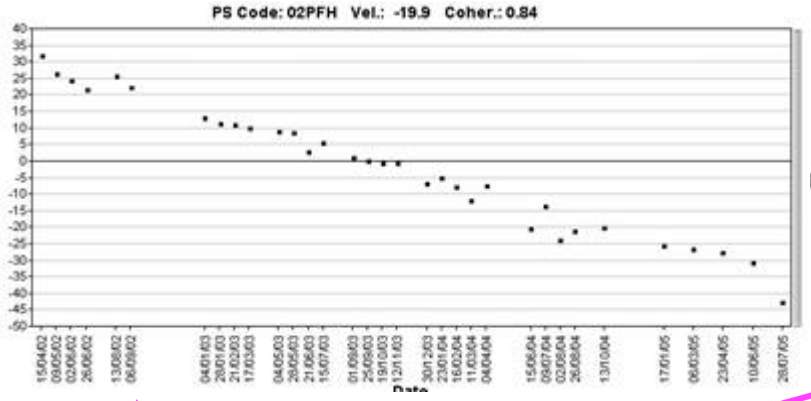
New Orleans Flooding & Subsidence

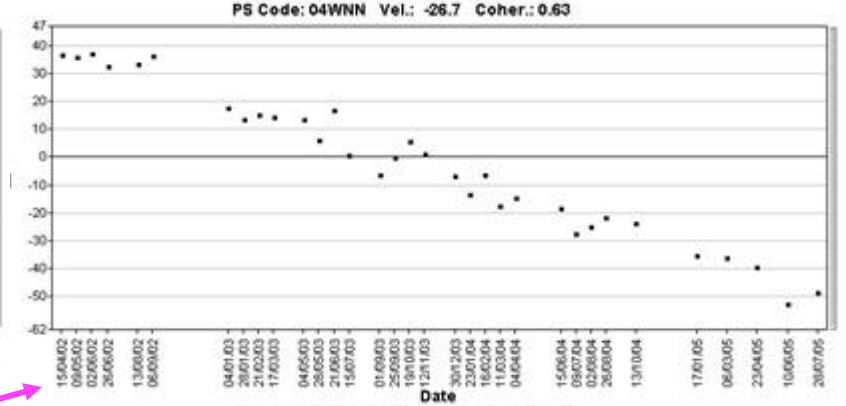


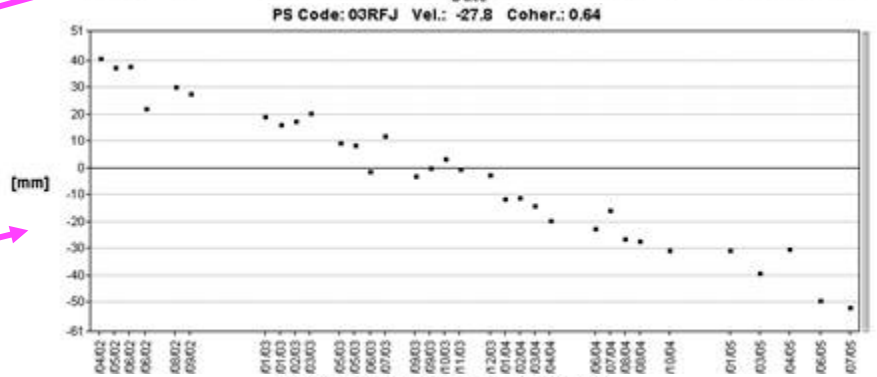
Dixon et al. (2006)

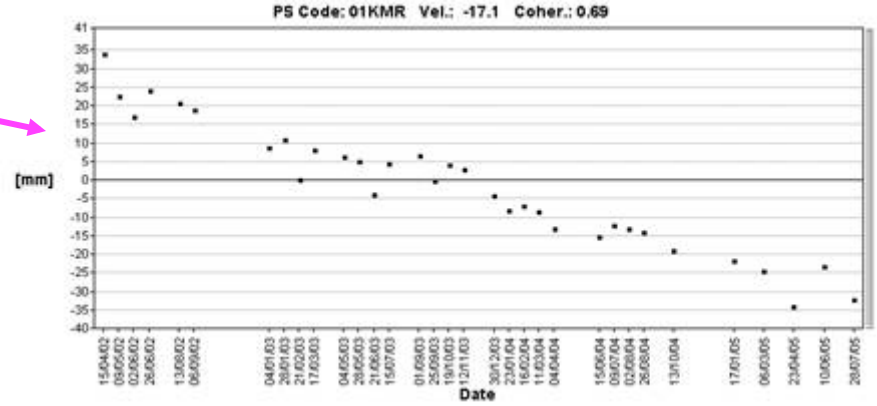
St. Bernards Parish:
PS displacement time series in LOS





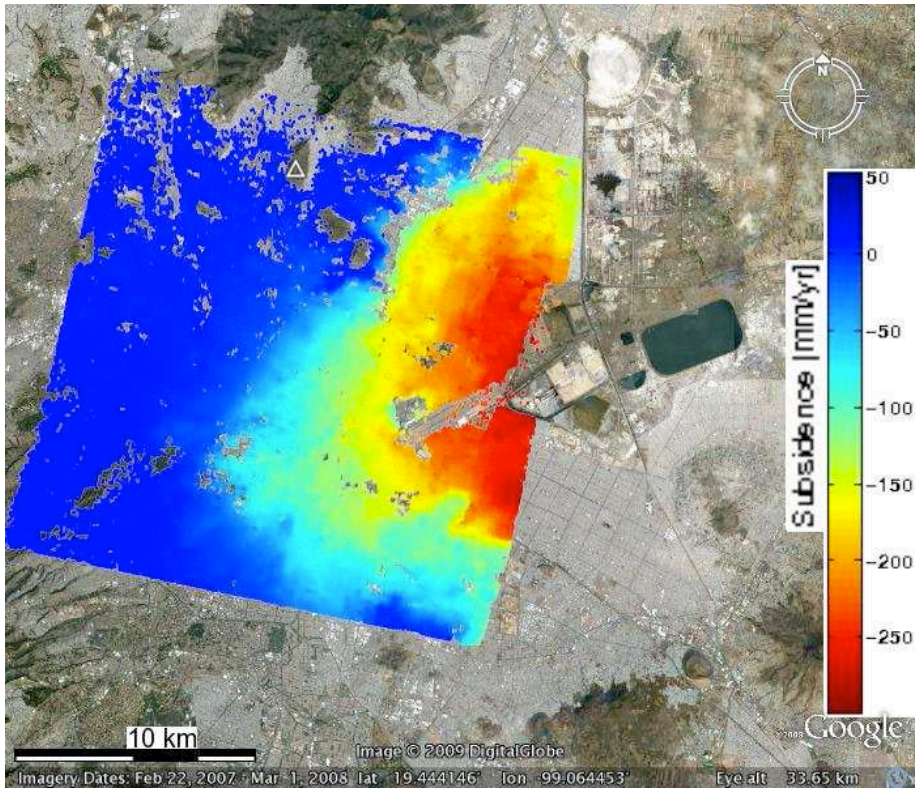






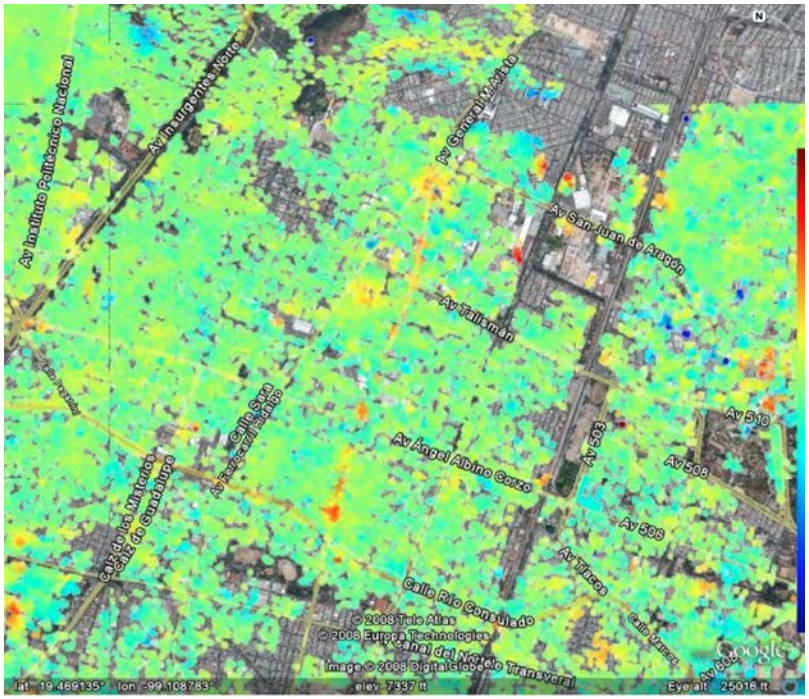
Mexico City

- Mexico City is built on lake deposits
- It subsides at very high rate, up to 25 cm/yr
- The subsidence causes structural damage in many buildings and to the infrastructure



Osmanoglu et al. (2011)

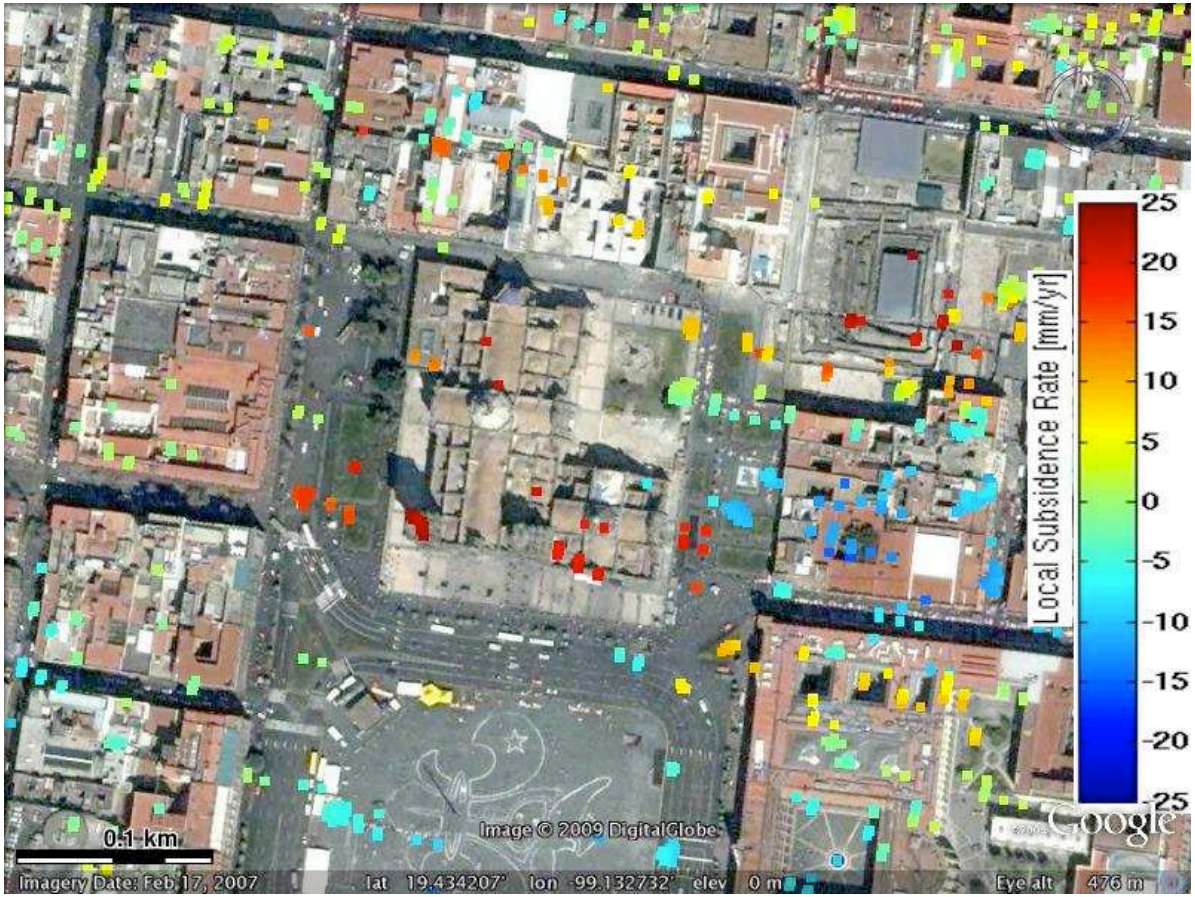
Mexico City



Differential subsidence in Mexico City causes structural damage to building and infrastructure

Osmanoglu et al. (2011)

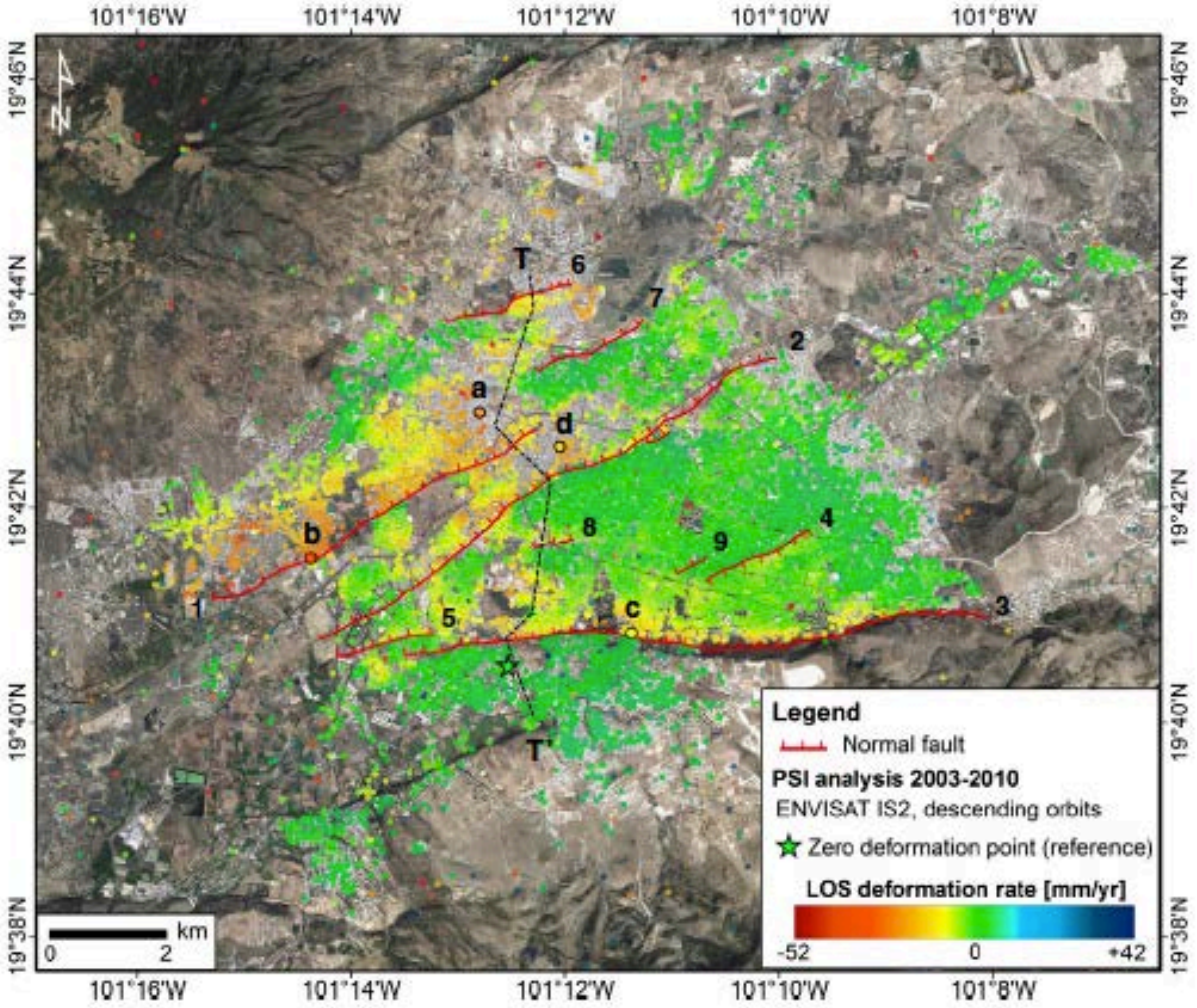
Mexico City



Differential subsidence at the building scale (main Cathedral)

Osmanoglu et al. (2011)

Morelia (Mexico)



Subsidence is controlled by geological fault

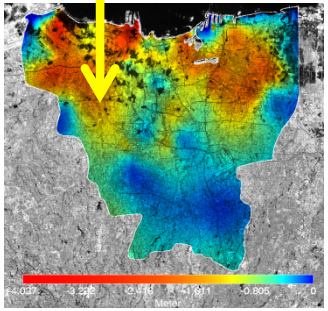
Cigna et al. (2011)

A new NASA project

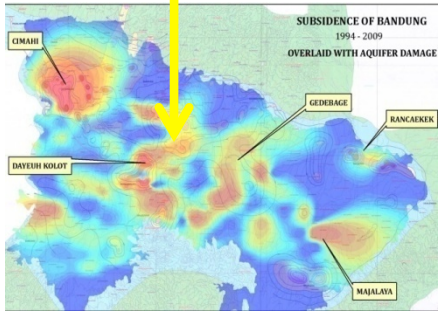
Applications of InSAR time series imagery for subsidence hazards and water resources exploitation in four Mexican metropolitans

Land Subsidence around Java Island

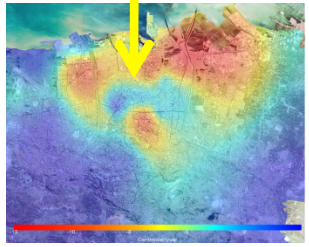
Where are the places of subsidence around Java?



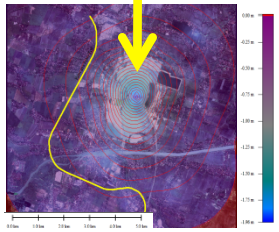
Jakarta area



Bandung area



Semarang area



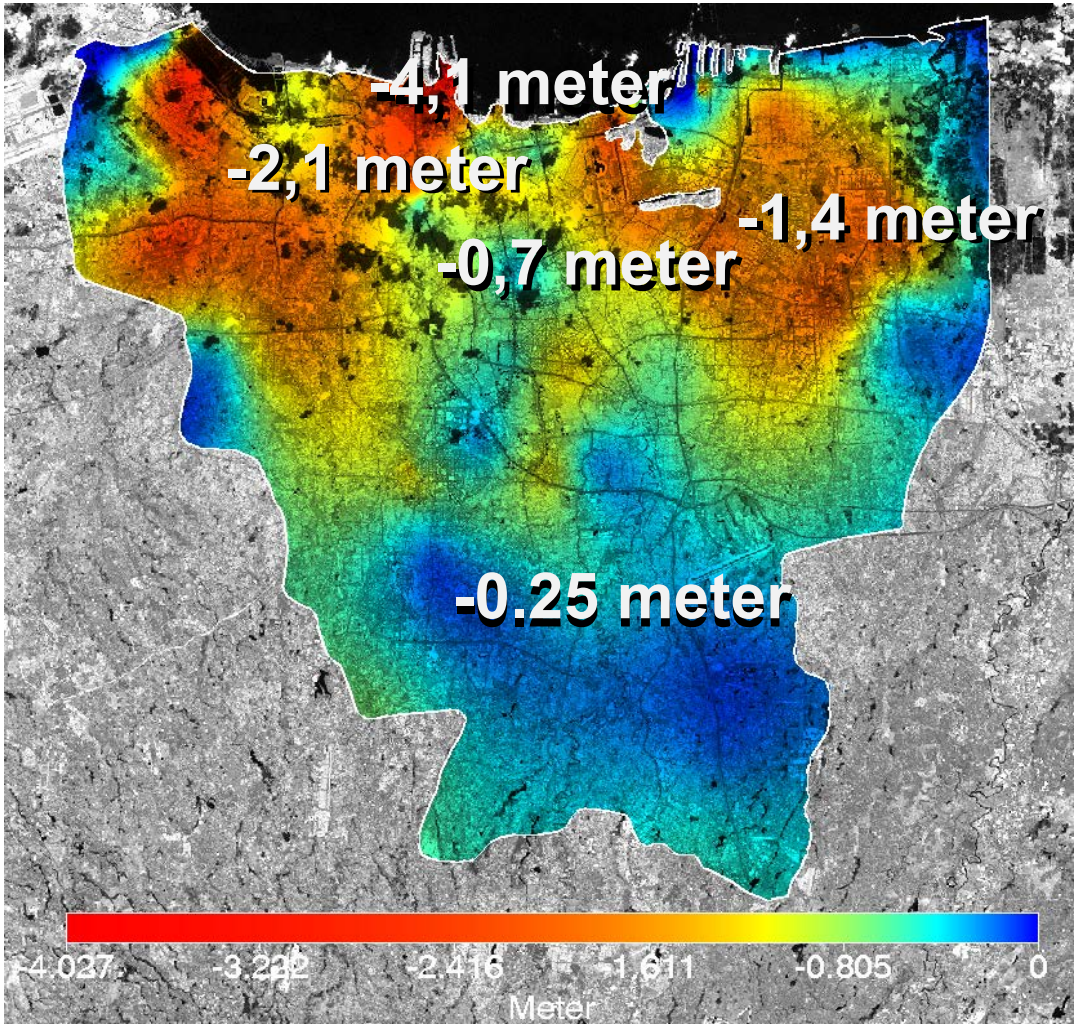
LUSI area

Chaussard et.al 2012

University of Miami

Land Subsidence around Jakarta area

In period of 1974-2010 a significant subsidence happened in Jakarta area. Four meter recorded in the north of Jakarta, two meter in west area, and one and a half in the east. Seventy cm recorded for central part while 25 cm for southern area



Consequences of Jakarta subsidence

“ROB” in northern Part of Jakarta

Rob in Kamal Muara

Rob in Muara Baru

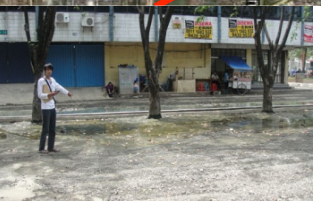
Rob in Muara Baru

Rob in Rukindo Priok

Rob in PLTGU Priok

Rob in Priok Harbor

Rob in Pluit



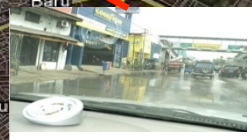
Rob in Pluit

Rob in Tongkol Ps Ikan

Rob in P.Jayakarta

Rob in P. Jayakarta

Rob in G.Sahari



Rob in G. Sahari

Rob in Kel Ancol

Conclusions

- InSAR and GPS are very powerful techniques for monitoring small surface movements
- Venice is subsiding at a rate of 1-2 mm/yr.
- The Lagoon's barrier is subsiding at a rate of 2-4 mm/yr.
- Due to the increasing rate of sea level rise (2-3 mm/yr during the 20th century, possibly higher in the 21st century) project Mose will provide flooding protection only for a limited time period.

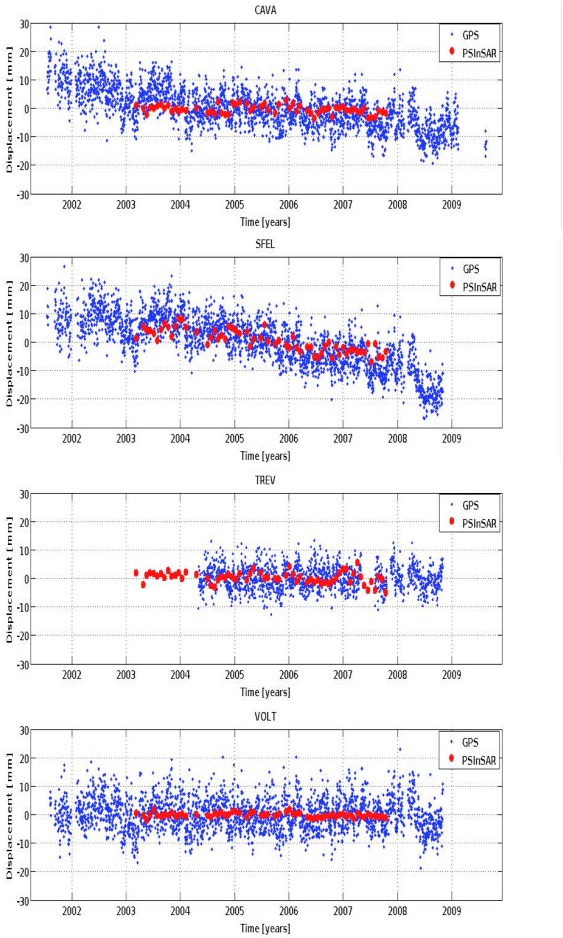
Take home lessons

Limitations

- **InSAR measurements cannot detect long wavelength subsidence signal.**
- **GPS measurements can be biased due to local deformation.**

Joint GPS-InSAR solution can overcome the limitation of each technique.

Trust your data. If two independent datasets don't agree with one another, may be there is a good reason for that.



Subsidence of Venice Lagoon

… and subsidence