Health Assessment of Levees Using Remote Sensing and Field Monitoring

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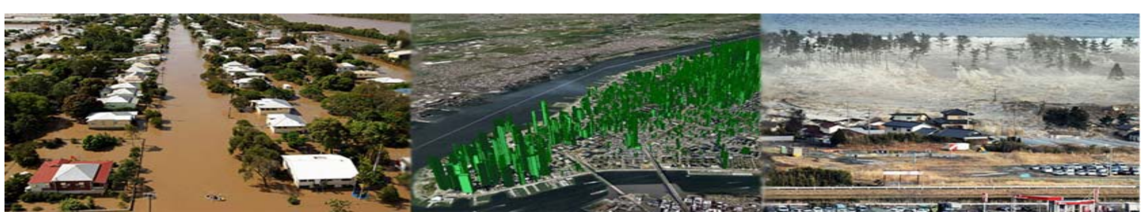


Acknowledgements

Four-Year Project: Development of a Multiscale Monitoring and Health Assessment Framework for Effective Management of Levees and Flood-Control Infrastructure Systems-TIP supported

Joint Venture

Rensselaer Polytechnic Institute (M. Zeghal, T. Abdoun, B. Yazici)

Geocomp (A. Marr)

Overview

- Introduction
- Vision and project overview
- Remote sensing (InSAR)
- Field Monitoring
- Multi-scale identification and health assessment
- Concluding remarks

Introduction

- Integrity and reliability of flood-control infrastructure (levees, earthen dams, etc.) essential components of homeland safety

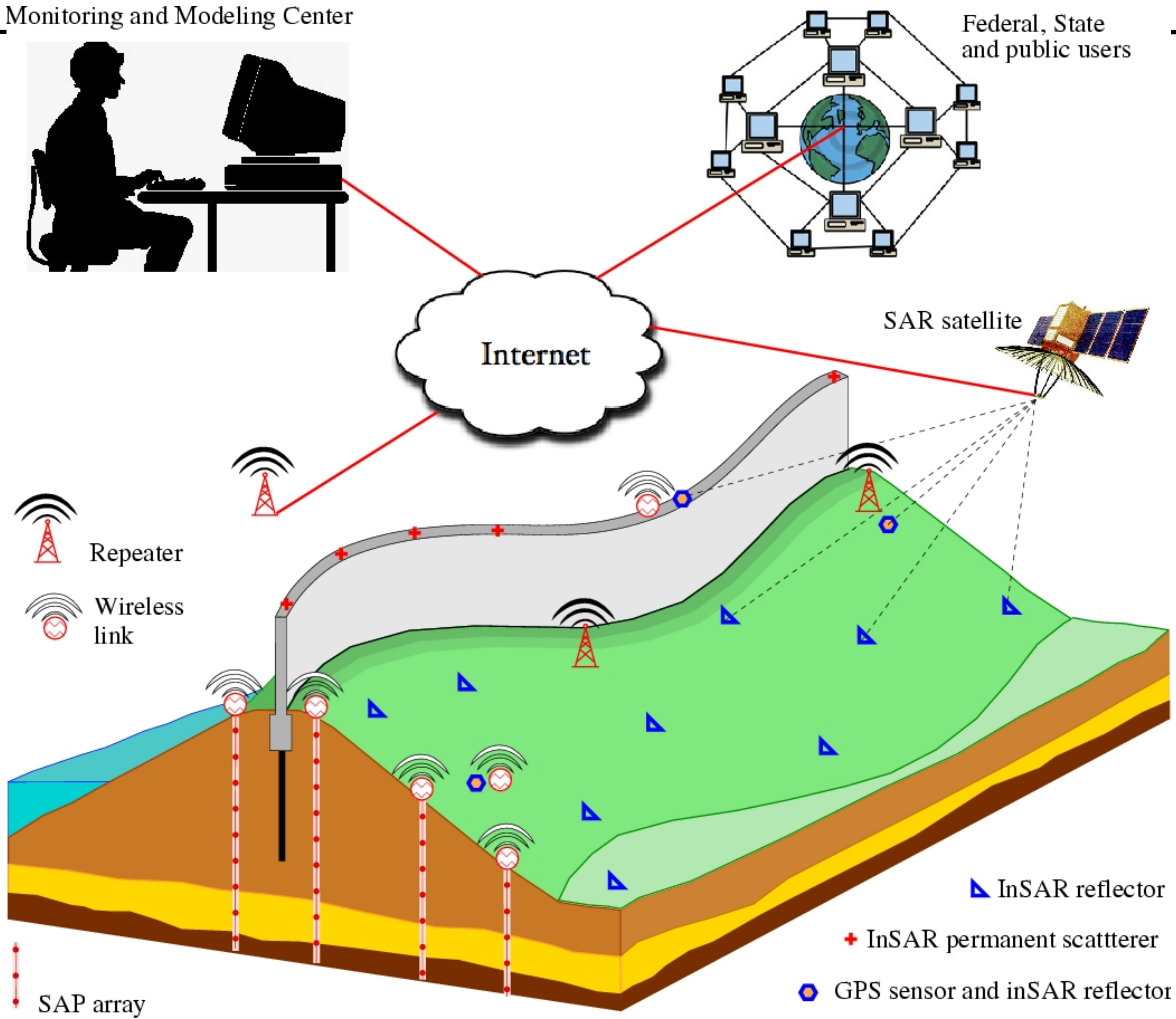
- Aging and deteriorating flood-control infrastructure:
  - ASCE's 2009 Report Card: a grade of D to dams and a grade of D^- to levees

Motivation

Health Assessment: Current State-of-the-Practice

- Levee health assessed based on visual inspection
  - Primarily periodic site visits (monthly to annually and more)
  - Surface information (incomplete and mostly qualitative
  - Focus on components
- Provides
  - Limited damage or weakness detection capability
  - Inconclusive health assessment
  - Limited predictability of overall system performance

Vision



Monitoring and Modeling Center
Federal, State and public users
Internet
SAR satellite
Repeater
Wireless link
InSAR reflector
InSAR permanent scattterer
GPS sensor and inSAR reflector
SAP array

Vision

Sensor-Aided Model-Based Approach:

- Monitoring:
  - Global: Remote sensing (InSAR)
  - Local: Shape-Acceleration-Pore Pressure Array
  - Bridging: GPS
- Health Assessment
  - Multi-scale (global, intermediate and local) **model-based** framework

Remote Sensing

Objectives:

- Monitor large areas of levee system (10s of sq. kms)
  - Obtain few meters/pixel resolution for observed area
- Estimate deformation in levee structures with millimeter accuracy
  - Interferometric Synthetic Aperture Radar (InSAR)
- Estimate near surface moisture content
  - Polarimetric Synthetic Aperture Radar (PolSAR)

SAR: **S**ynthetic **A**perture **R**adar

- Large **Synthetic** antenna obtained using history of radar echoes generated during spacecraft forward motion

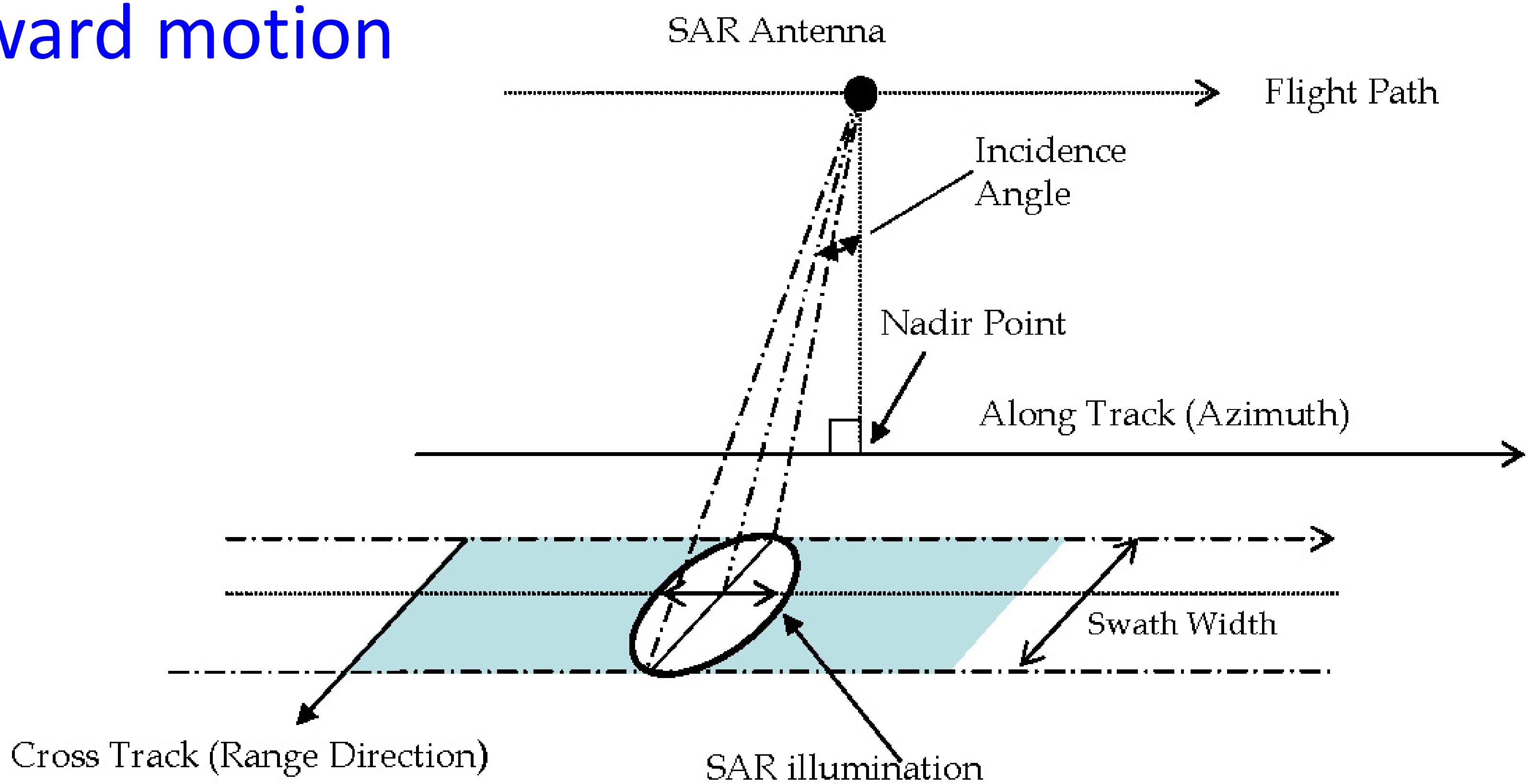


Image courtesy of Power et al. (2006)

Differenctial InSAR: DInSAR

Generates (using 2 or more SAR Interference images):

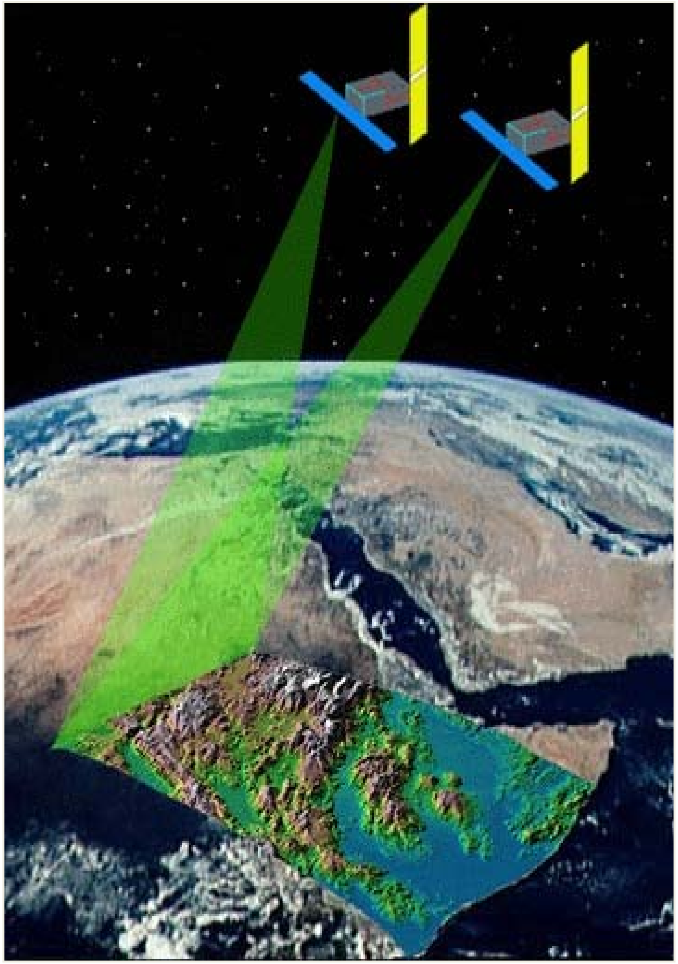


Image courtesy H. Zebker

- digital elevation maps
- surface deformation

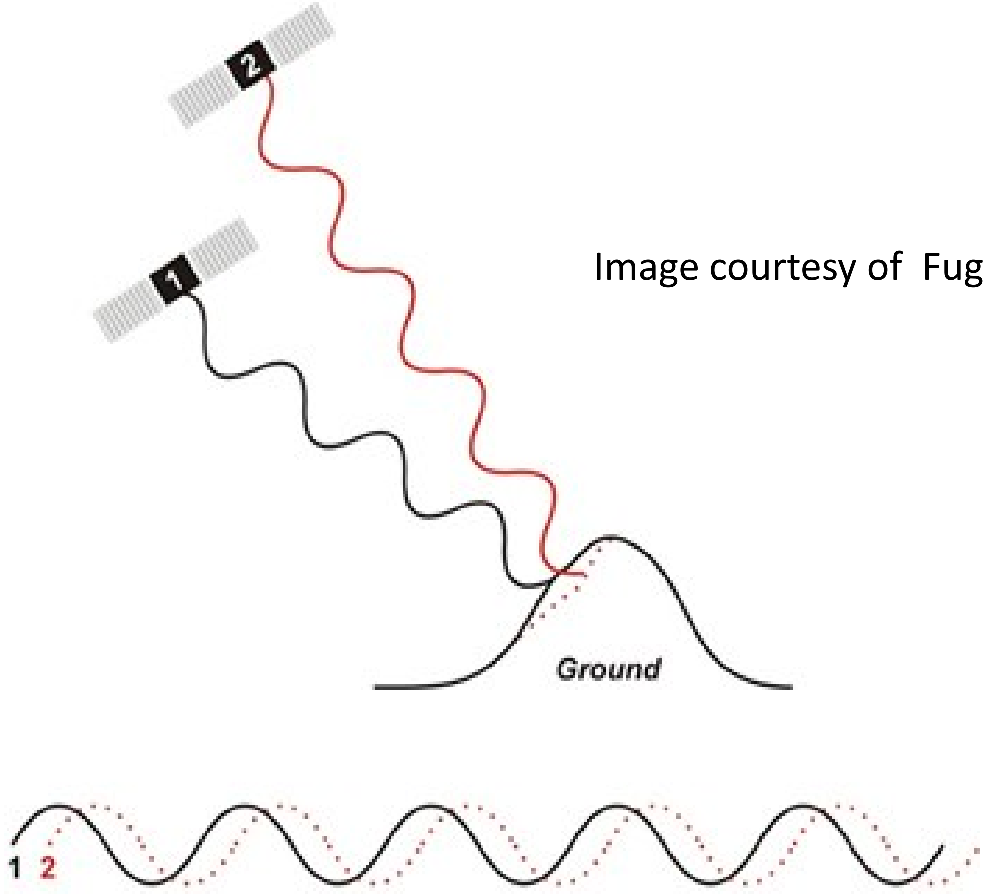
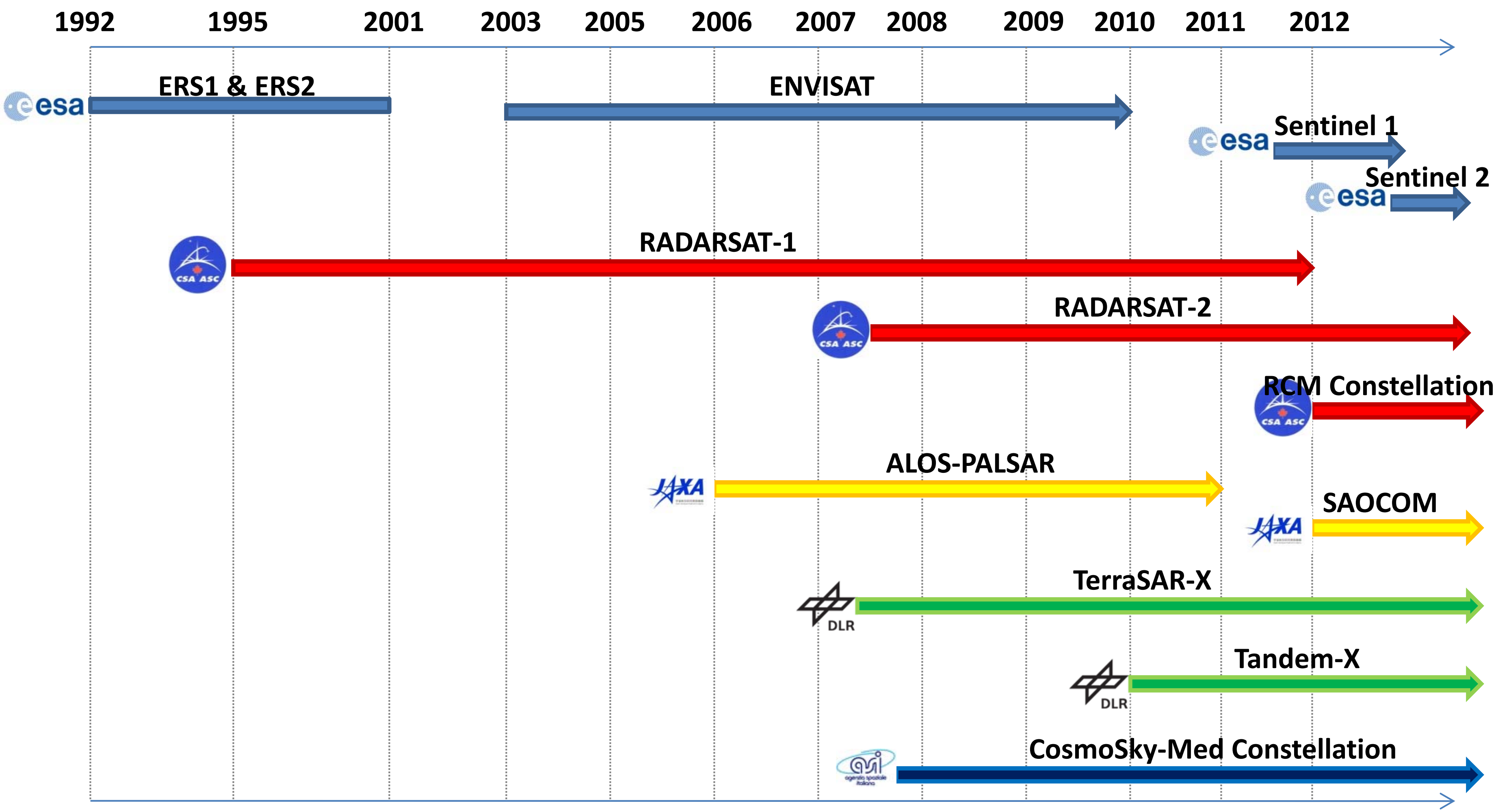


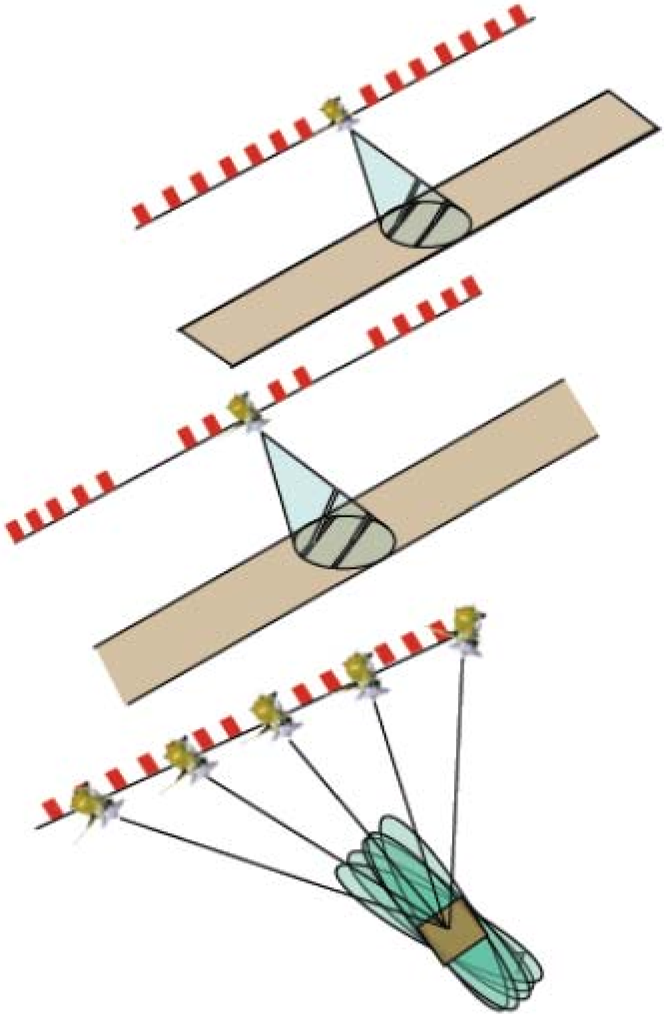
Image courtesy of Fugro

Radar Satellites

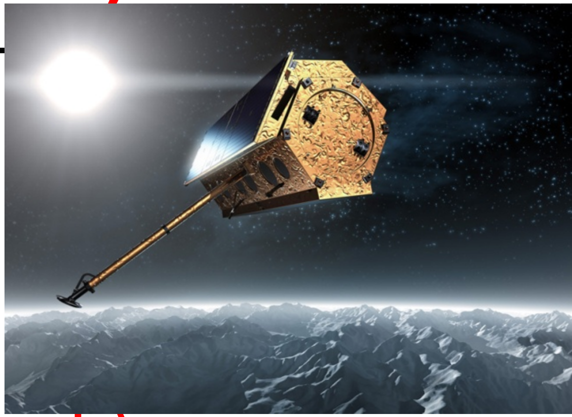


SAR Imaging Modes

- Strip map
  - “Average” coverage area
- Scan SAR
  - **Increased** swath width
  - **Reduced** resolution and signal-to-noise ratio
- Spotlight
  - **Reduced** swath **width**
  - **Increased** resolution



TerraSAR-X (9.67 GHz)



- **SpotLight**:
  1.8m x 3.4m resolution
  scene size 10 km (width) x 5 km (length)
- **StripMap**:
  3.5m x 8.0m resolution
  scene size 30 km (width) x 50 km (length)
- **ScanSAR**:
  18m x 18m resolution
  scene size 100 km (width) x 150 km (length)

"Sampling rate" every 11 days

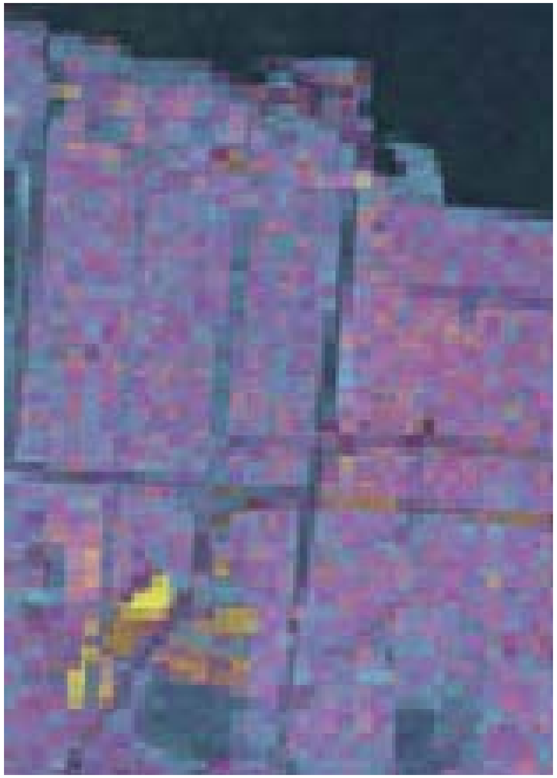
PSInSAR to address Challenges in DInSAR

PSInSAR (persistent scatter) used to address lack of coherence due to:

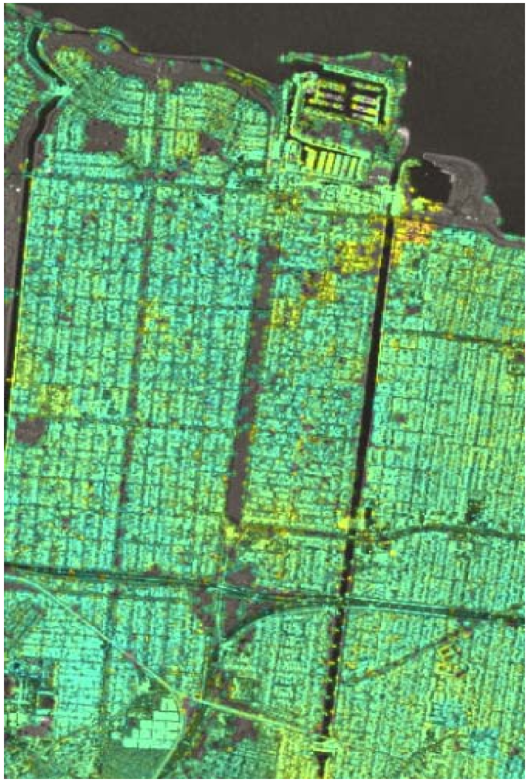
- **Geometric decorrelation** – Satellite must be as close as possible to the same orbital position when images are acquired over time
- **Temporal decorrelation** – Movement of scatterers or temporal change in the dielectric properties
  - Vegetation growth
  - Change in soil moisture, snow cover, etc.
- **Atmospheric effects** –dispersion
  - Change in temperature, pressure, water vapor
- **Sparsity of temporal data**

Coherence

DInSAR



PSInSAR



Average value 0.5~0.6

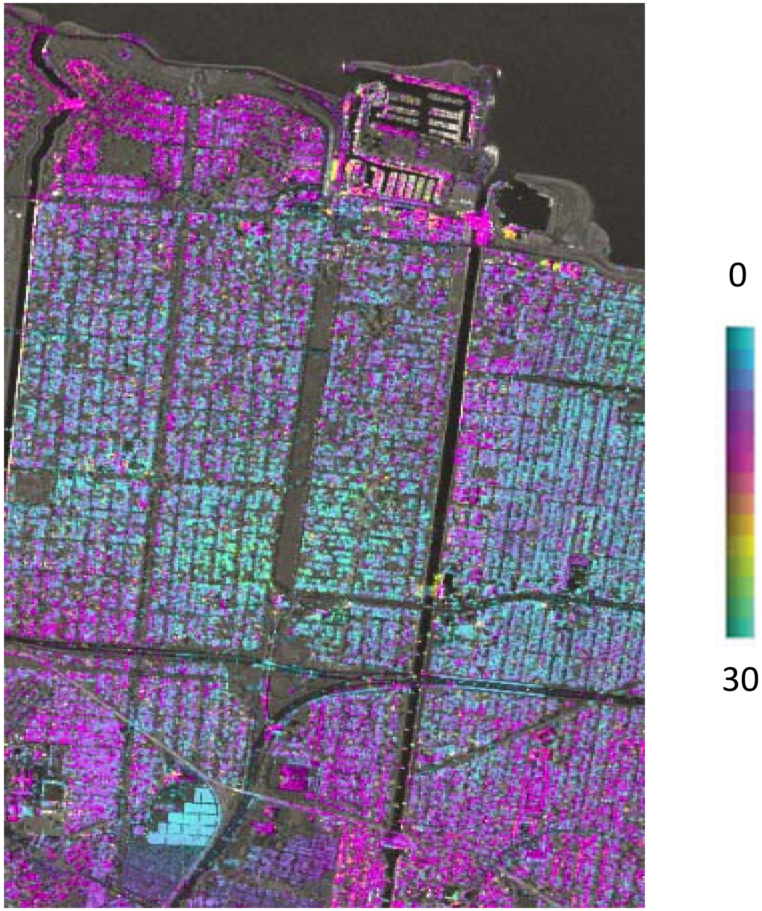
0.2 0.9

0.7 1

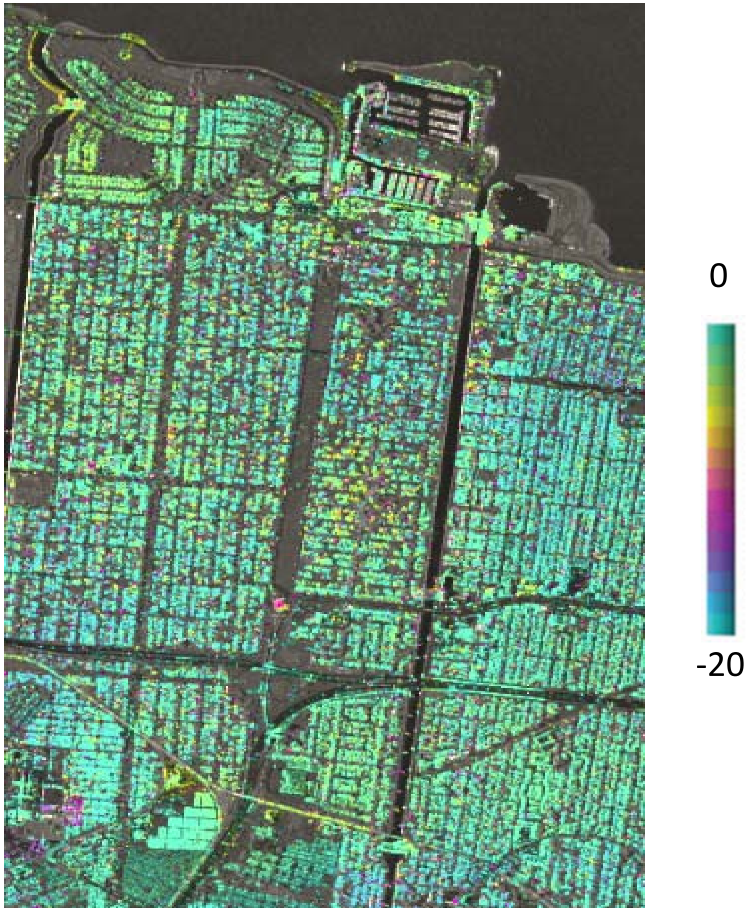
Average value 0.85~0.9

Coherence map: TSX data

Elevation and Displacement Rate

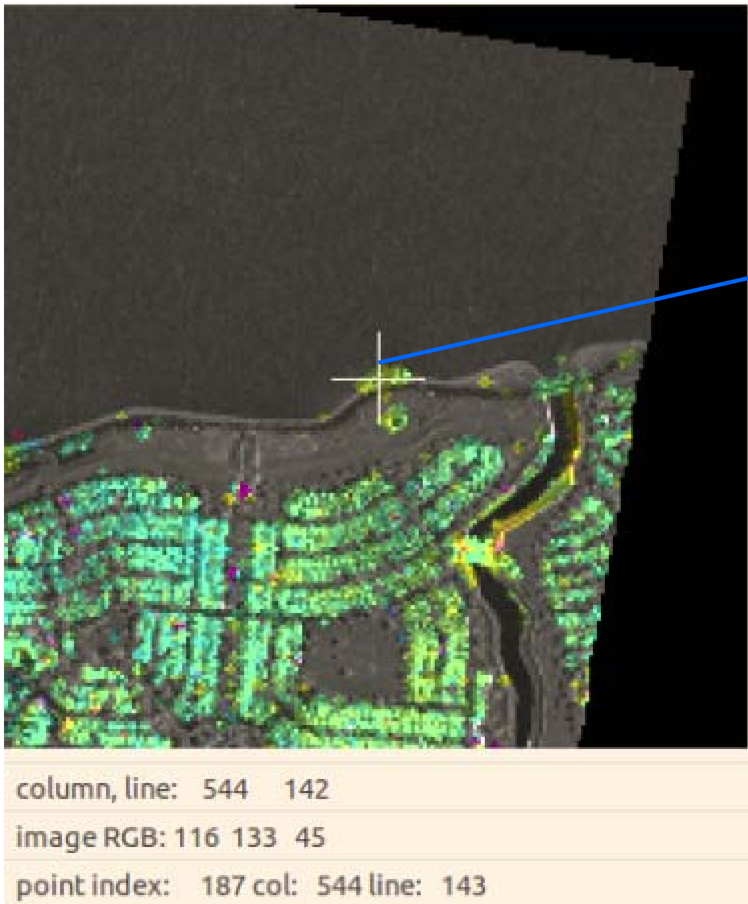


Elevation (m)



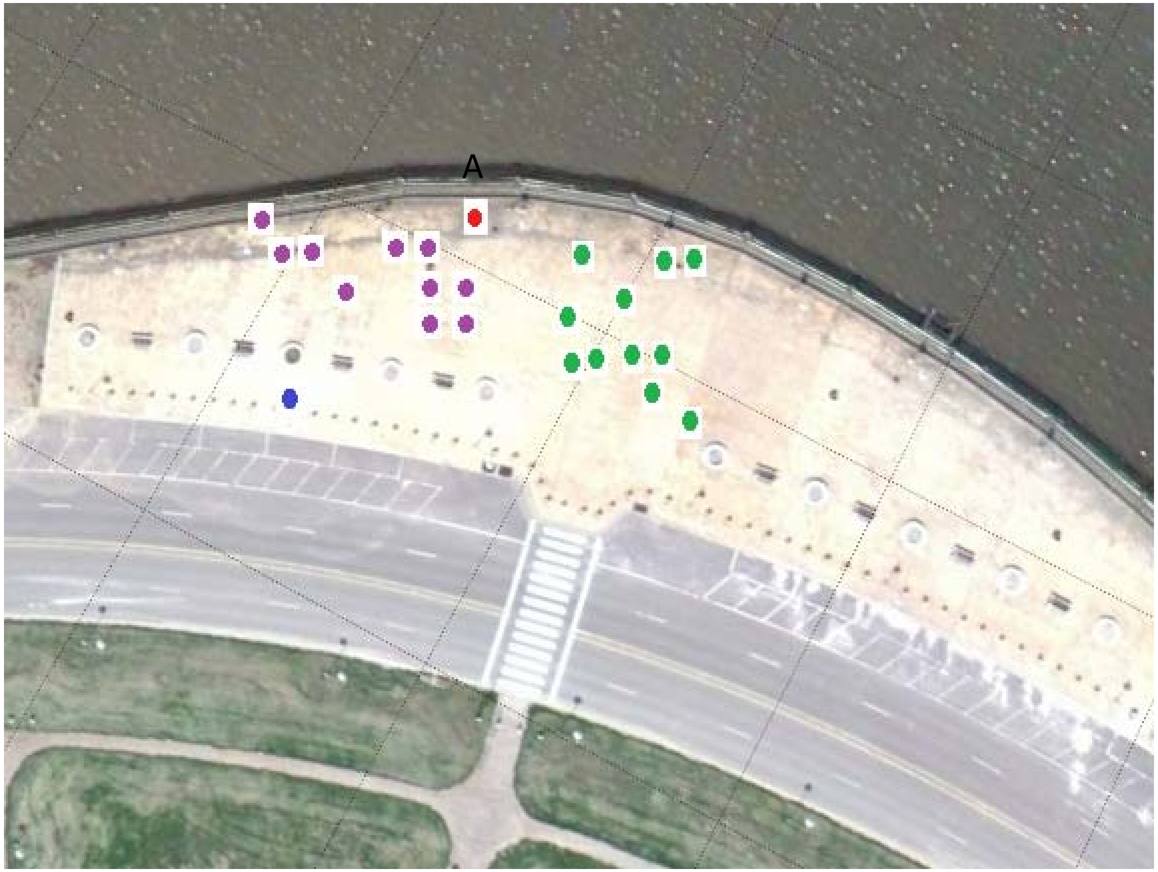
Rate of subsidence (mm/year)

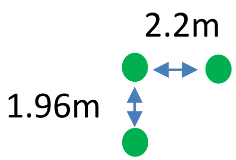
Settlement Rate



height (m): 7.636
deformation rate (mm/y): -5.674
deformation rate uncertainty (mm/y): 0.681

Settlement Rate





Deformation Rate

- -8.2 (Point A)
- -7.6
- -5.0 ~ -6.2
- -3.5 ~ -4.9

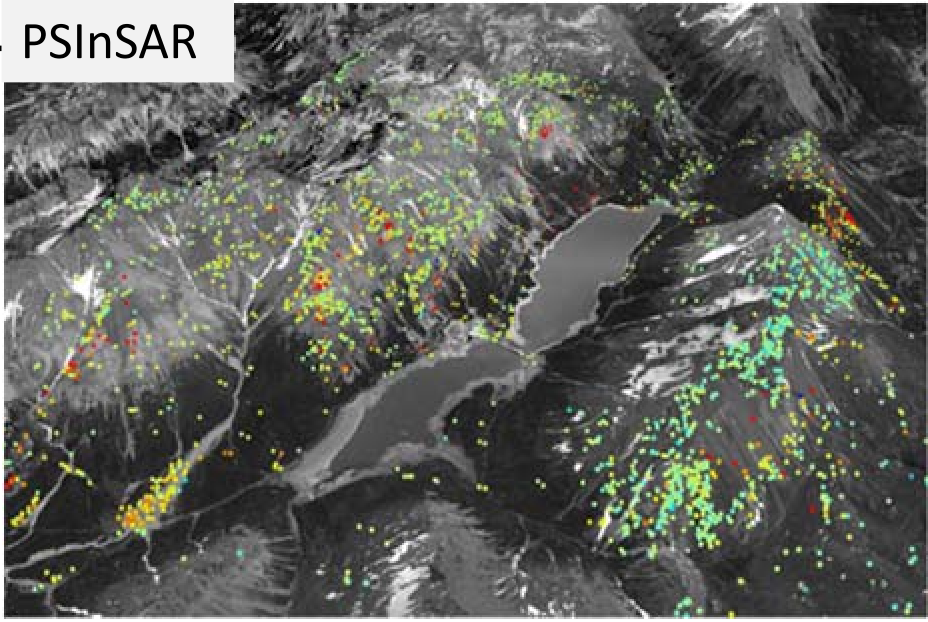
mm/year

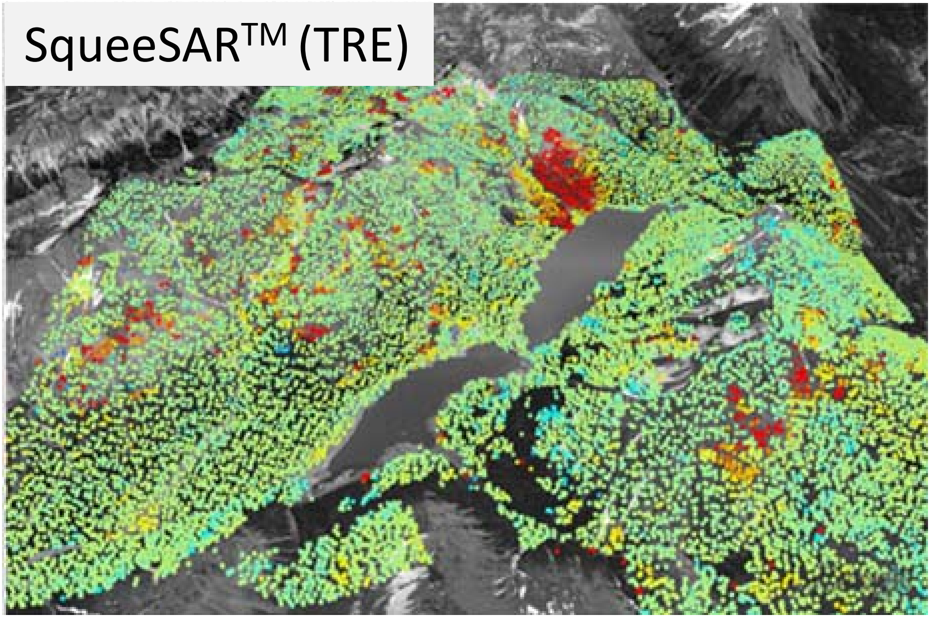
TerraSAR-XStripmap
2009March13 - 2010October28
19 images

Improving Accuracy and Space Resolution

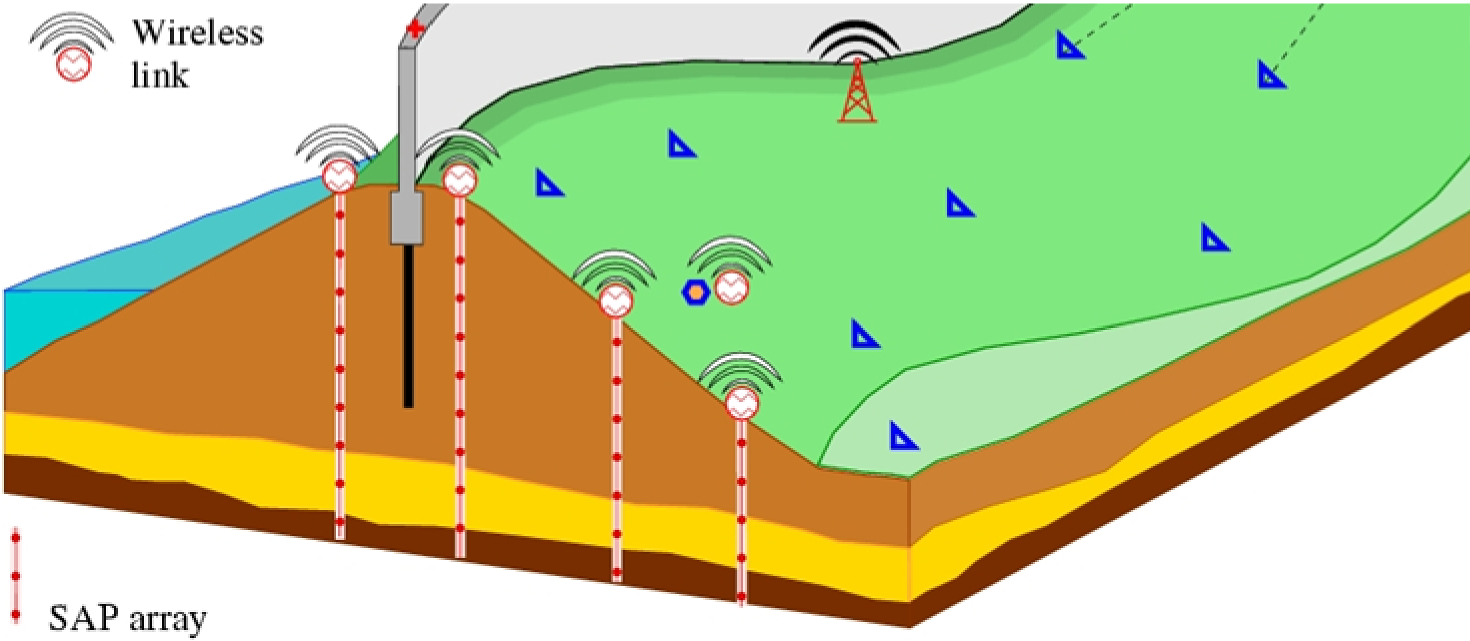
Reflectors:

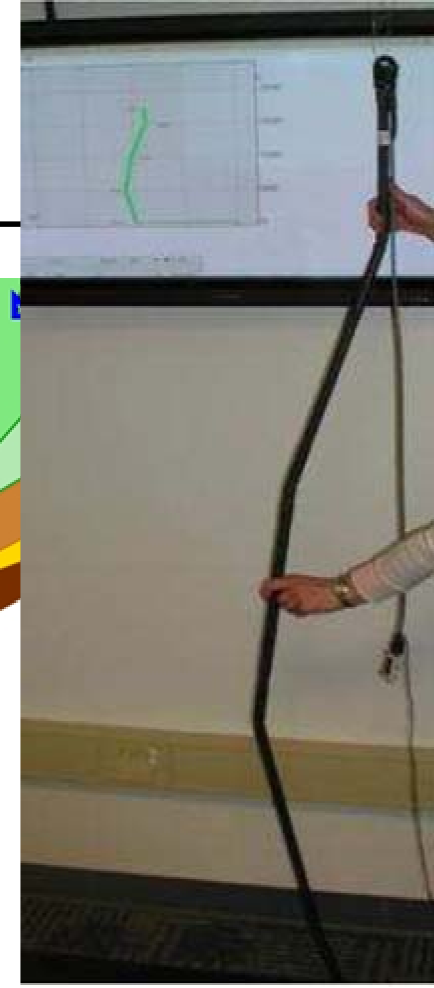
improves signal intensity





Field Instrumentation



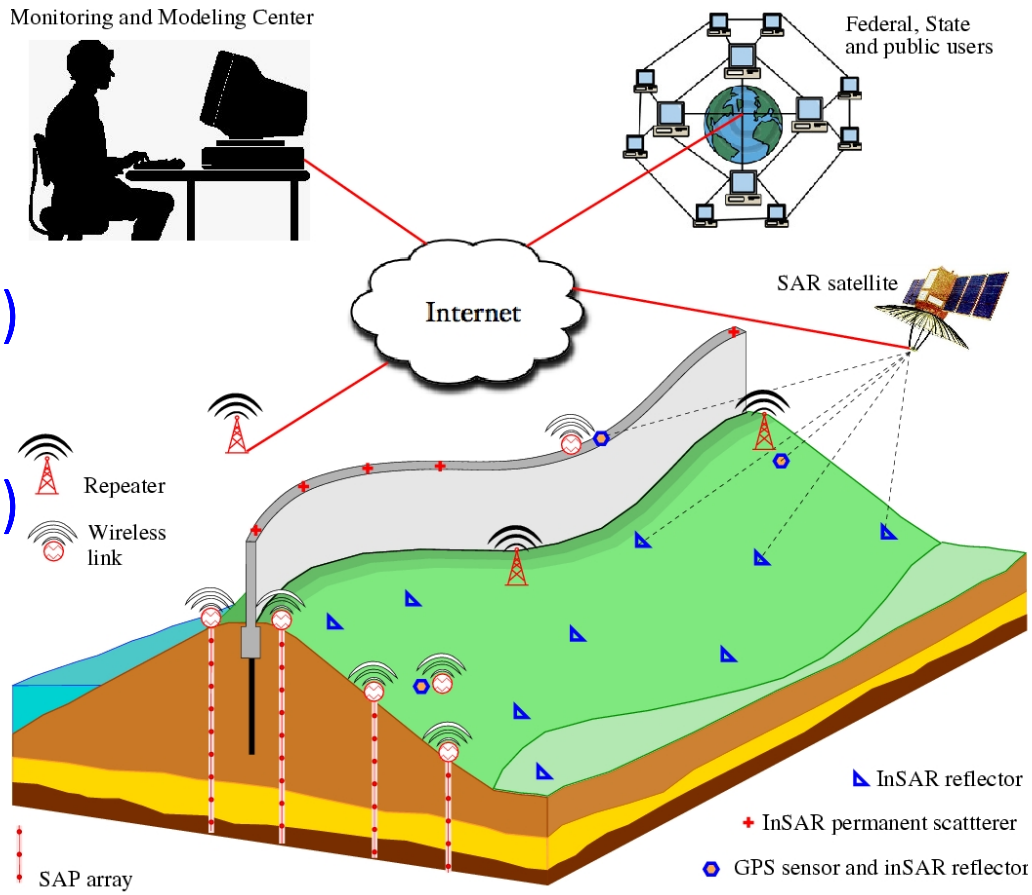


- Shape acceleration pore pressure (SAP) array
  - -- Higher resolution
  - -- Higher sampling rate (seconds to minutes)
- GPS array
  - -- Higher sampling rate (daily to few hours)
  - -- cost effective (~ $1500)

Health Assessment

Adaptive multi-scale:

- Global
  - InSAR data (strip mode)
  - InSAR data (spotlight mode)
- <u>Intermediate</u>
  - InSAR data (spotlight mode)
  - GPS data
- Local
  - Shape-acceleration-Pore Pressure data
  - GPS data

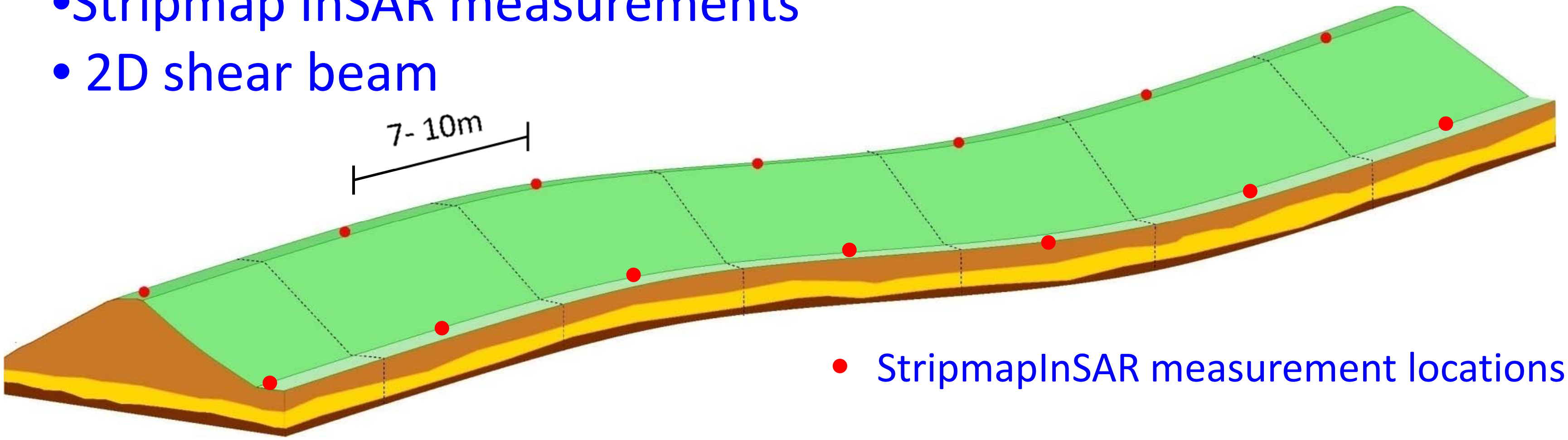


Health Assessment Rationale

- Calibrated baseline levee **model**
  - a priori information
- Updated levee **models**
  - baseline model
  - new measurements
- Evaluation of **health status** and identification of damage (if any)
  - **discrepancies** between baseline and updated models
  - other information

Global-Scale Health Assessment

Coarse global analysis:
- Stripmap InSAR measurements
- 2D shear beam



$$\frac{\partial \boldsymbol{\tau}}{\partial s} - \mathbf{q}^{\mathrm{ext}} = \mathbf{0}$$

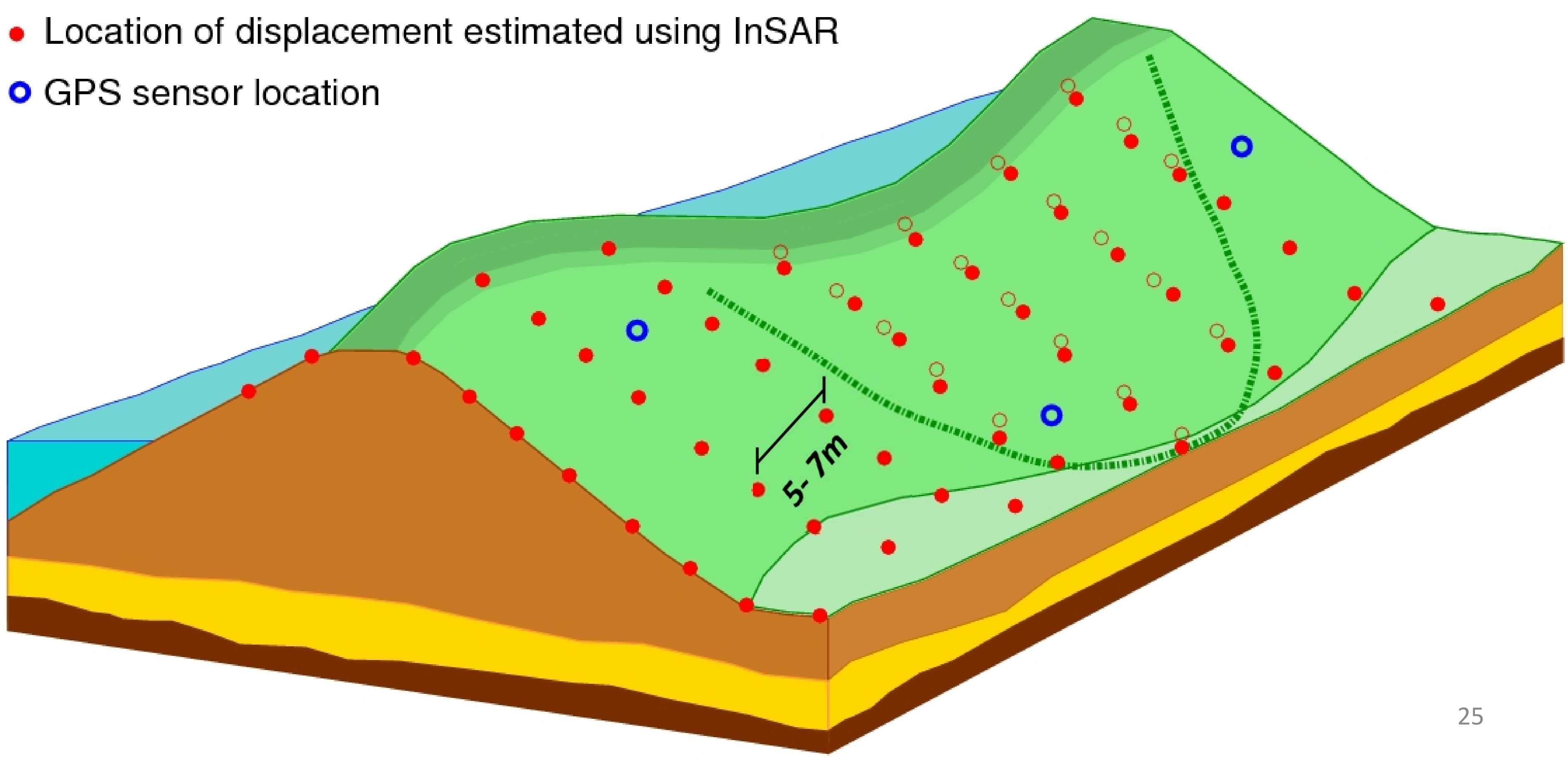
$$\boldsymbol{\tau} = \boldsymbol{\tau}(\tau_1, \tau_2)$$

$\mathbf{q}^{\mathrm{ext}}$: All external loads

Intermediate-Scale Health Assessment

Fine global analysis:

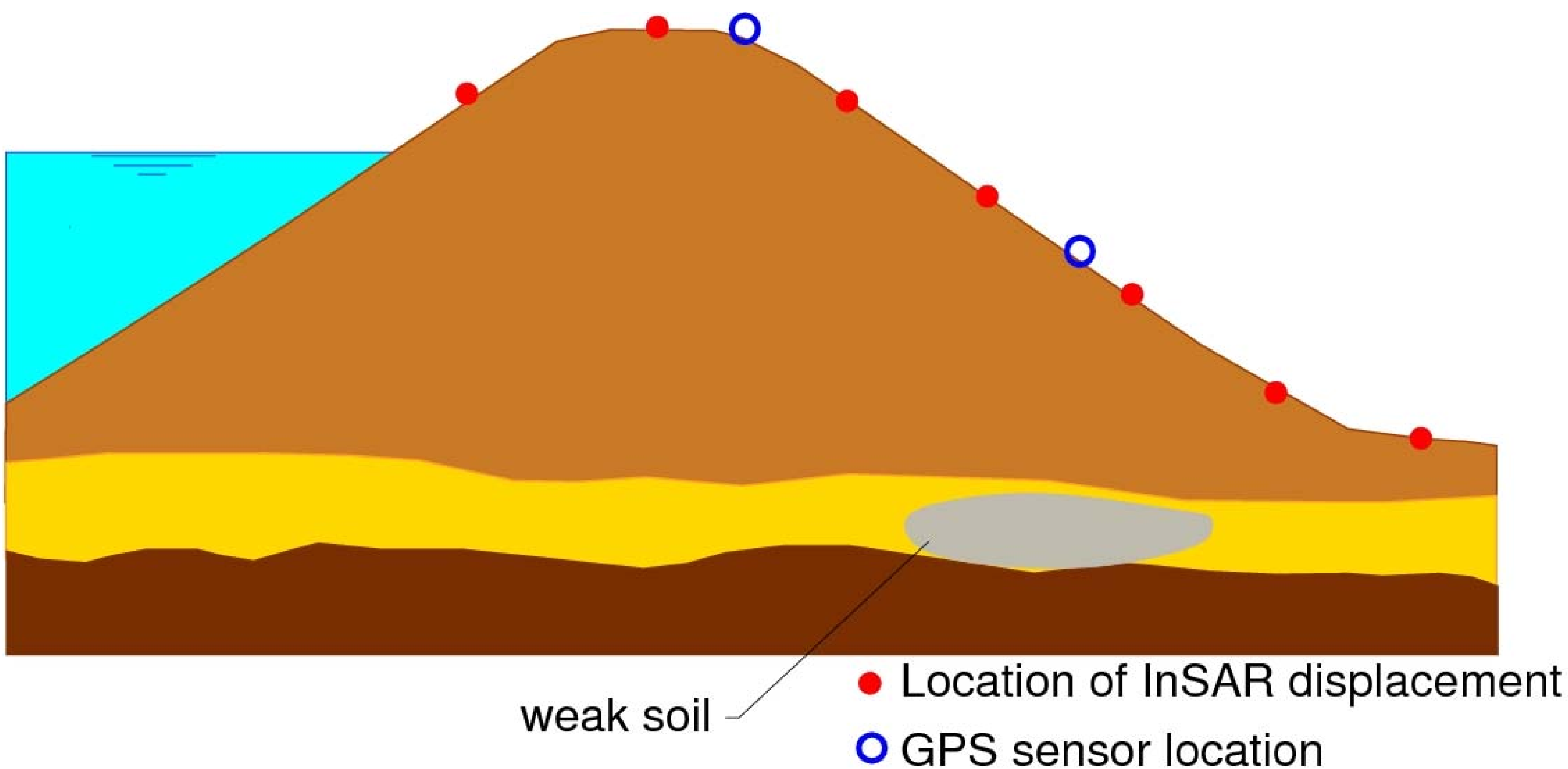
- Spotlight InSAR measurements
- Neural network and 3D simple models



Intermediate-Scale Health Assessment

Intermediate Analysis:

- Spotlight mode InSAR measurements
- GPS measurements (higher sampling rate)
- 2D refined model of critical section



Intermediate-Scale Health Assessment

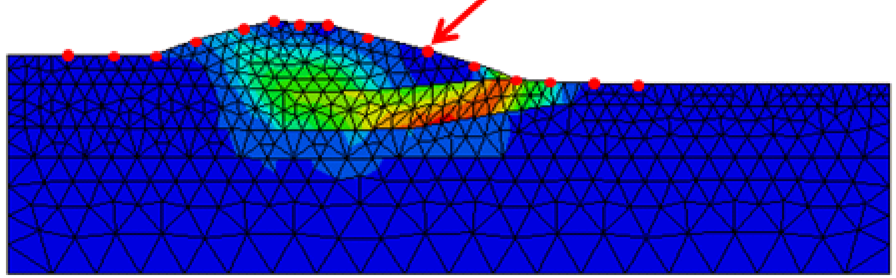
- Localization
  - Neural networks
- Parameter Identification
  - Localization used to constrain geometry of possible weak zones.
  - Optimization algorithms used to identify “geometry” of weak zones and to quantify associated stiffness properties.
- Health assessment
  - Based on in internal (strain) energy of weak zone(s)

Intermediate-Scale Health Assessment

Localization

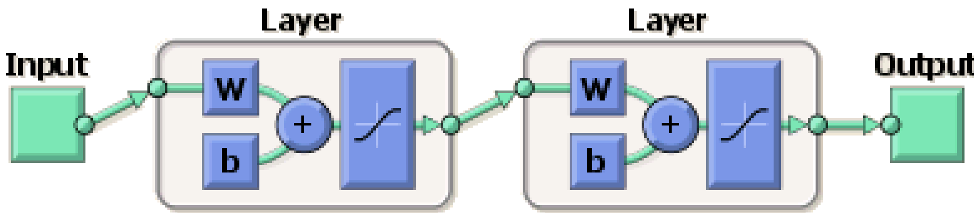
Neural networks trained to identify possible locations of weak zones given surface displacements/deformation

Monitoring point



Observed displacements

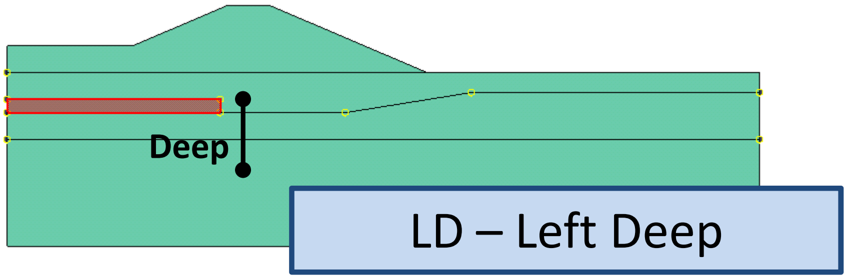
Location of weak zone

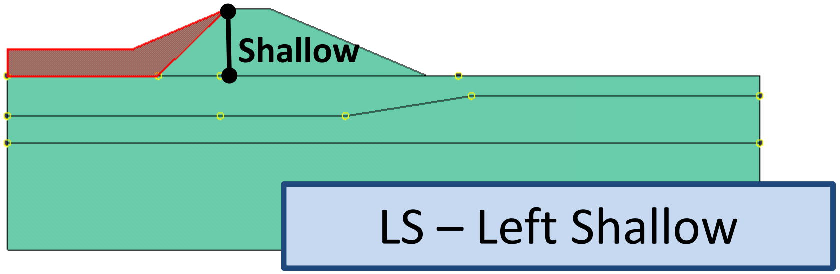


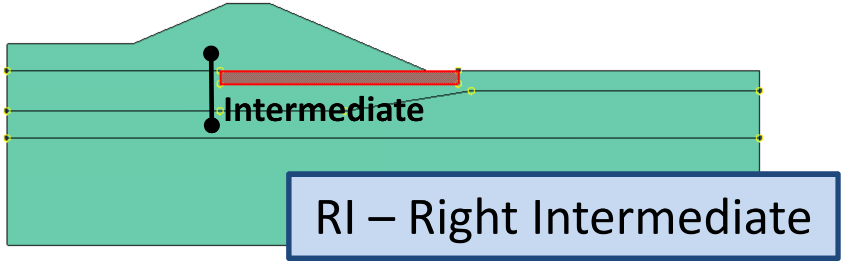
Neural Network

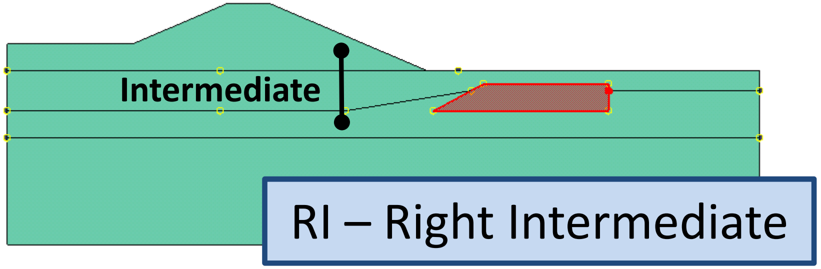
Intermediate-Scale Health Assessment

Localization Results (Example)









Localization Results

0.5 mm uncertainty in displacement readings

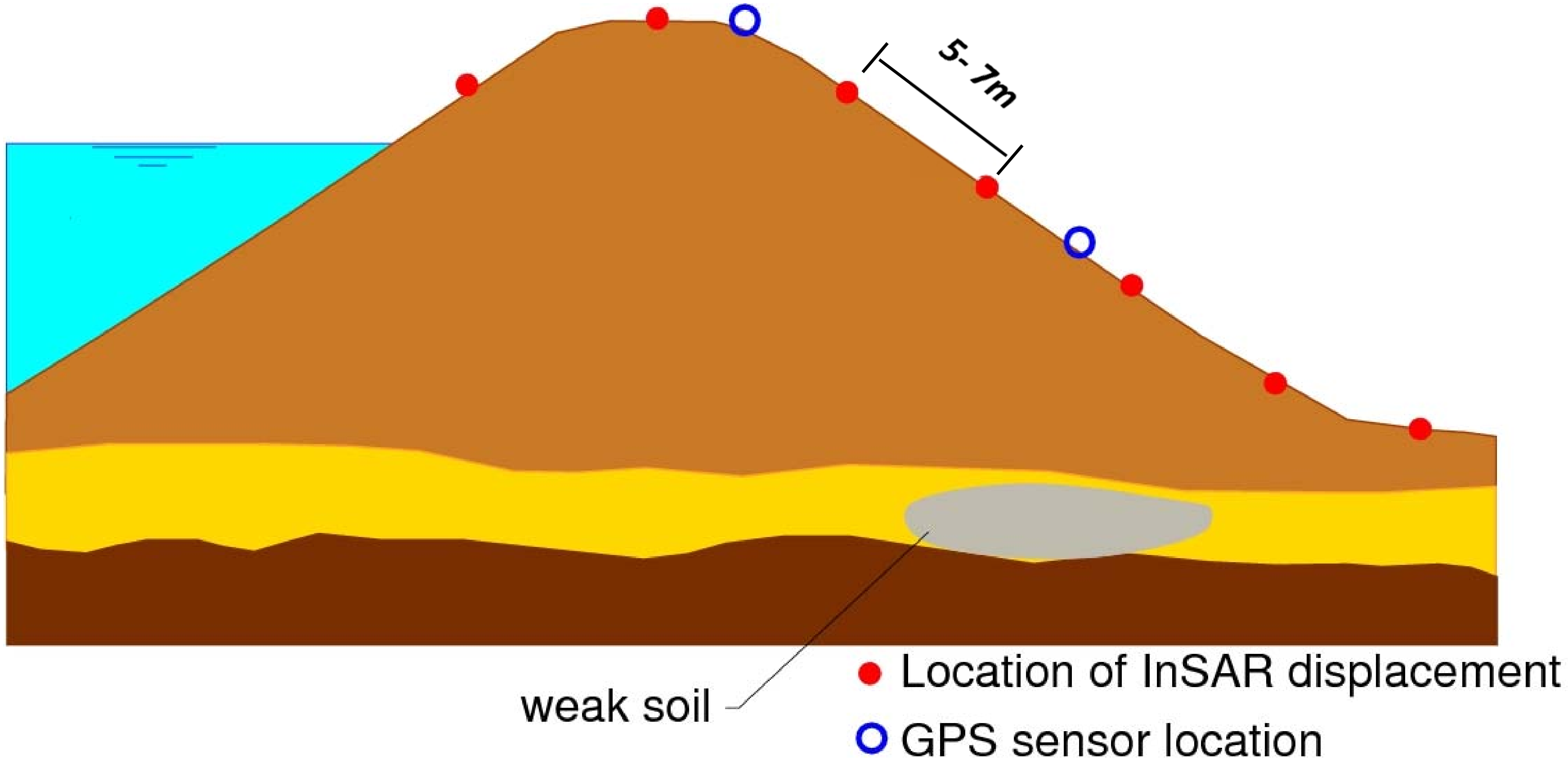
Correct classifications for Independent Test: 86%

correct classifications for displacements > 2 mm: 93.5%

Identified Category \ Actual Category	1	2	3	4	5	6	
1	**94** 13.1%	**2** 0.3%	**2** 0.3%	**1** 0.1%	**0** 0.0%	**0** 0.0%	94.9% 5.1%
2	**8** 1.1%	**109** 15.1%	**22** 3.1%	**0** 0.0%	**0** 0.0%	**3** 0.4%	76.8% 23.2%
3	**10** 1.4%	**9** 1.3%	**91** 12.6%	**8** 1.1%	**6** 0.8%	**1** 0.1%	72.8% 27.2%
4	**7** 1.0%	**0** 0.0%	**3** 0.4%	**107** 14.9%	**2** 0.3%	**1** 0.1%	89.2% 10.8%
5	**0** 0.0%	**0** 0.0%	**0** 0.0%	**4** 0.6%	**111** 15.4%	**2** 0.3%	94.9% 5.1%
6	**1** 0.1%	**0** 0.0%	**2** 0.3%	**0** 0.0%	**1** 0.1%	**113** 15.7%	96.6% 3.4%
	78.3% 21.7%	90.8% 9.2%	75.8% 24.2%	89.2% 10.8%	92.5% 7.5%	94.2% 5.8%	**86.8% 13.2%**

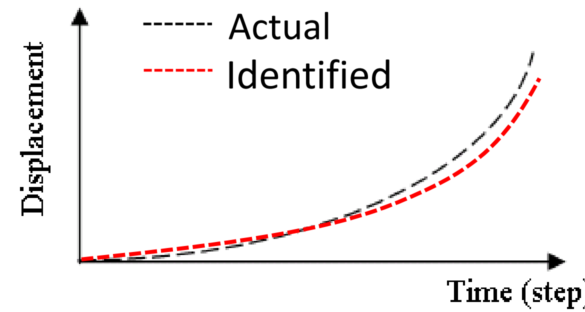
Intermediate-Scale Health Assessment

Identification of stiffness parameters



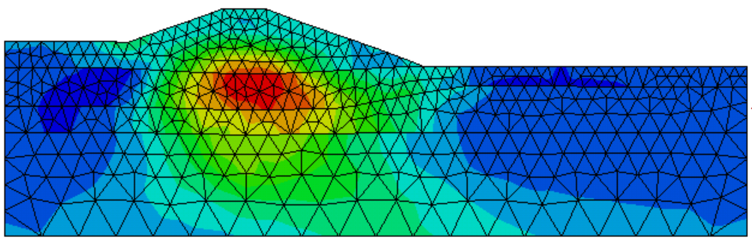
Intermediate-Scale Health Assessment

Identification Algorithm

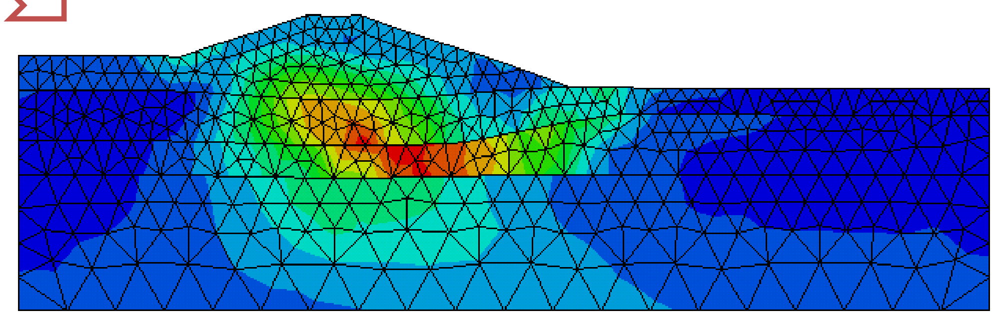


$$\mathbf{p}^{\mathrm{optm}} \rightarrow \min_{\mathbf{P}} \left\|\Delta \mathbf{d}\right\|$$

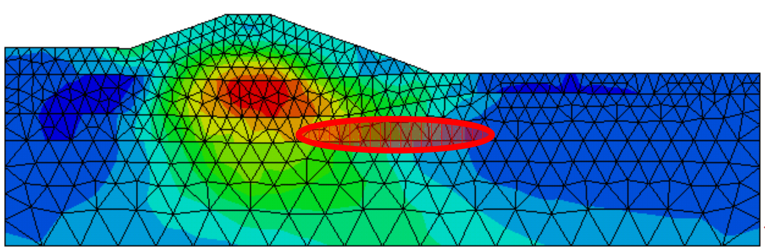
Parameter Identification



Initial Model

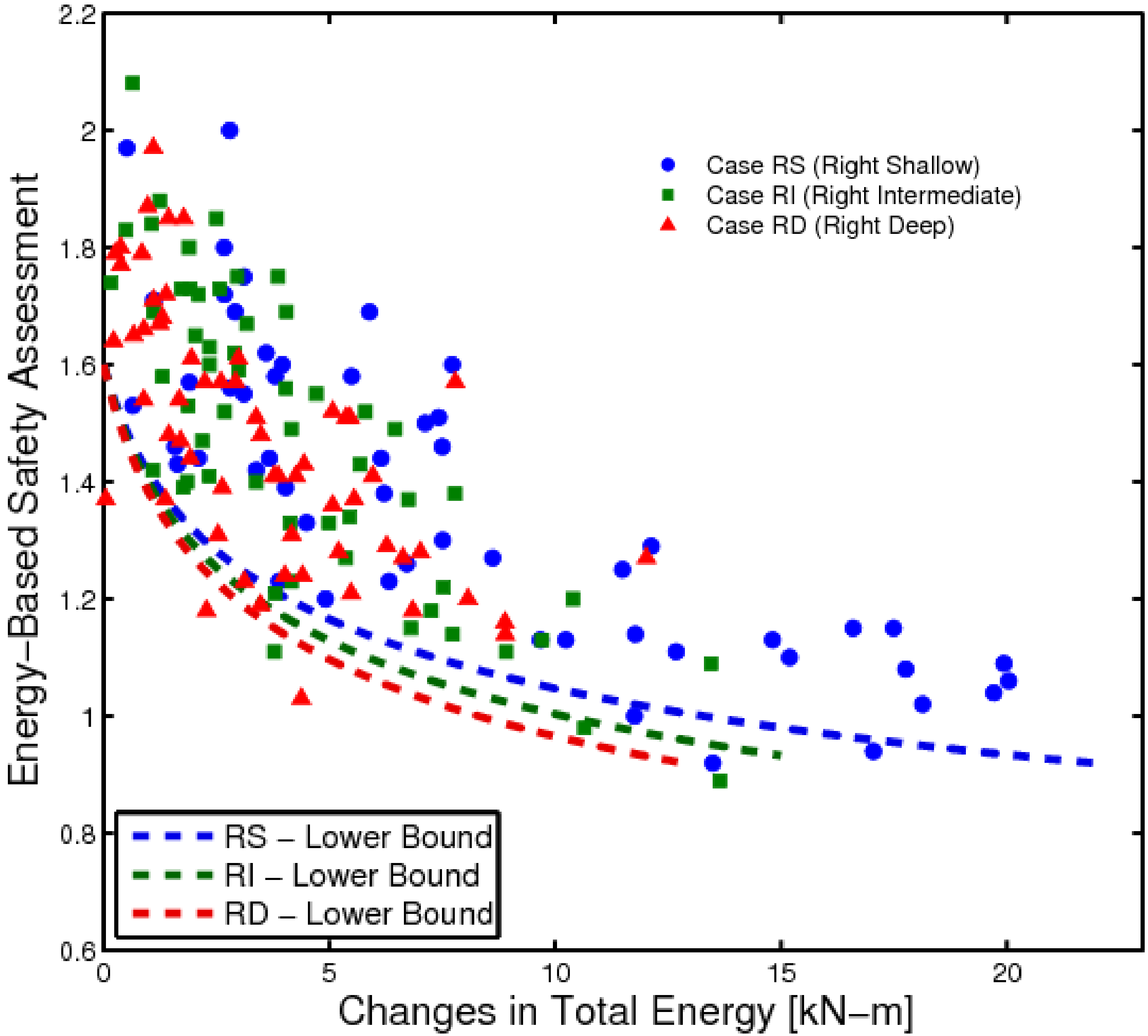


Model after weakening



Weakening scenario:

Energy-based Safety Assessment



Health Assessment: Quantification

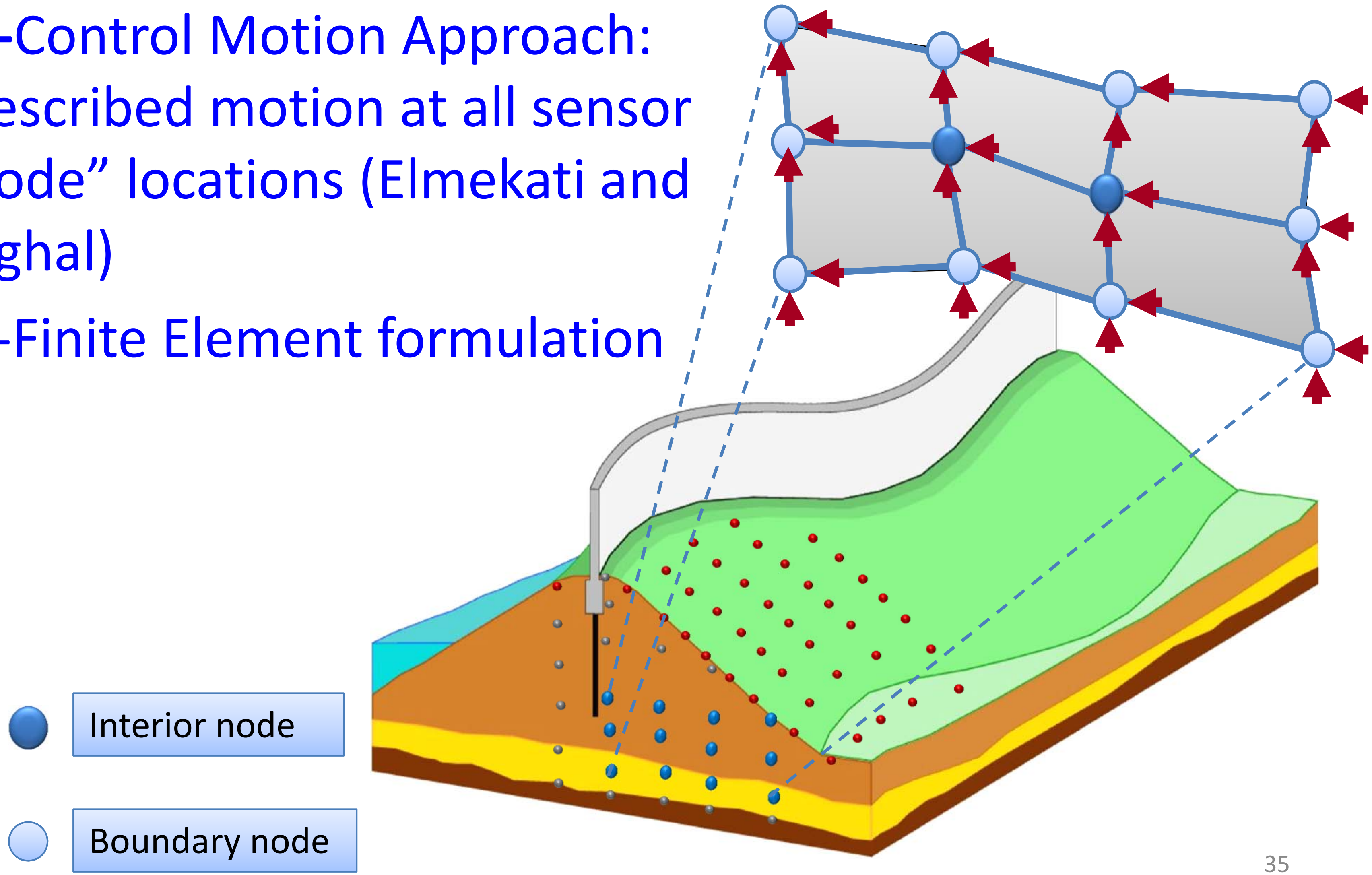
Quantification based on progression of:

- Degradation of stiffness and strength parameters
- Weakened zones and associated energy

Local-Scale Health Assessment

CMP-Control Motion Approach: prescribed motion at all sensor “node” locations (Elmekati and Zeghal)

CMP-Finite Element formulation



Concluding Remarks

Health assessment framework:

- Sensing tools
  - Remote sensing
  - SAP
  - GPS
- Local-Intermediate-Global health assessment
  - Provides an evaluation of levee condition
  - Provides amble time to implement required repairs before major events (hurricanes, floods, …)
  - Enables resilient of flood control levee systems (lower risk of having a catastrophic failure)
- Provides an automated monitoring and data collection program that could be used to organize and implement a rehabilitation program.

Questions?