Institute of Remote Sensing and Digital Earth
Chinese Academy of Sciences

Space-eye of radar interferometry promote the sustainable conservation of Angkor World Heritage site

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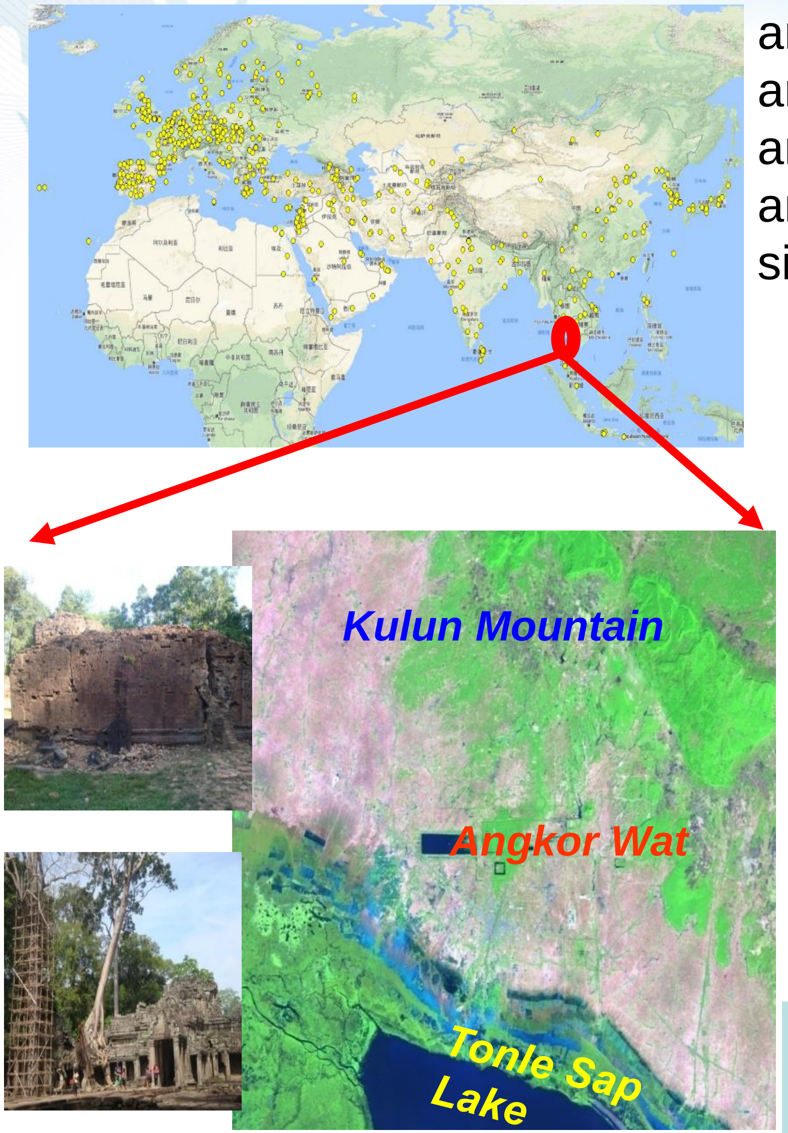
Outline

- Motivation: Raised problems
- Methodology: Two-scale MT-InSAR solution
- Angkor World Heritage site monitoring and assessment
- Summary and recommendations

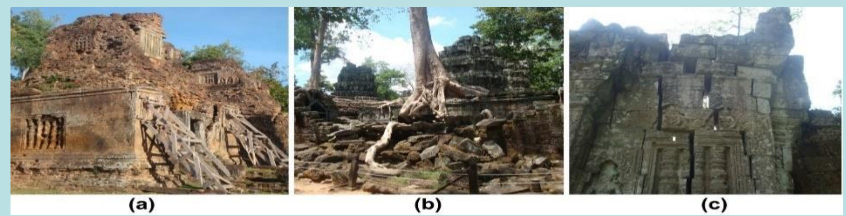
1. Motivation: Raised problems

Silk Road



The witness of the Chinese prosperous civilization and the friendship between East and West. There are 529 world cultural heritage sites along the Belt and Road, including categories of cultural relics, ancient architectural complex and archaeological sites----Cultural Road

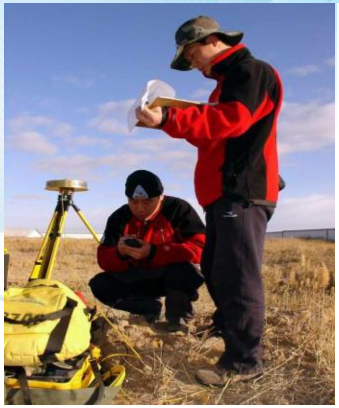
◆ Challenges and raised problems



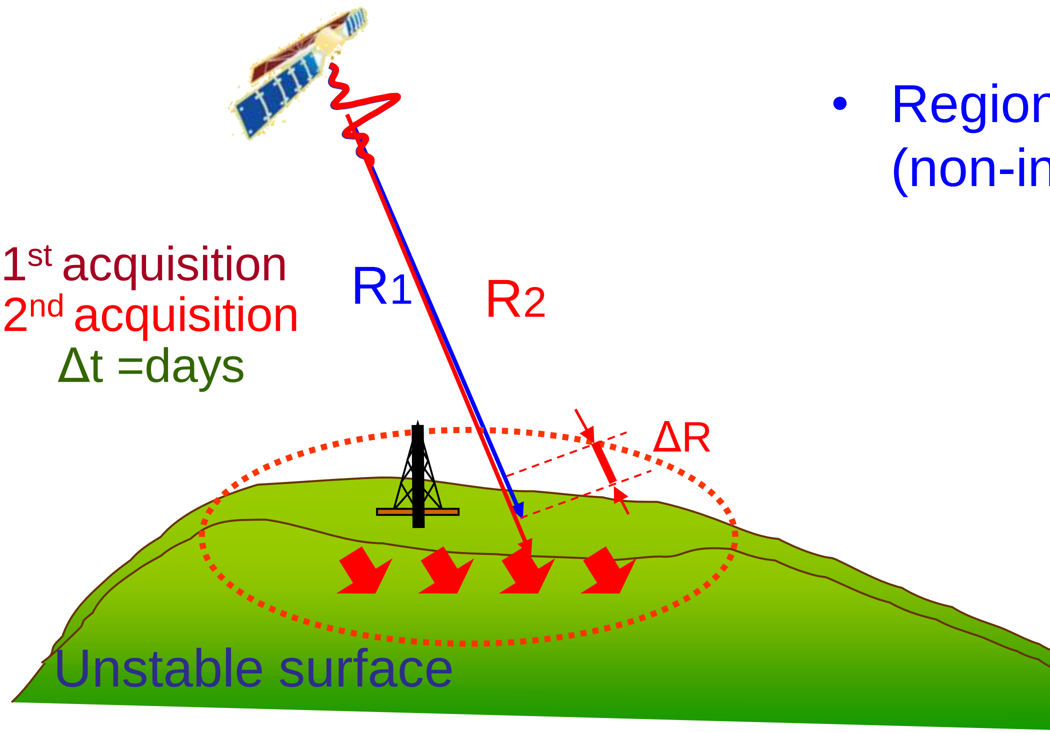
Collapse of temple complex

An impending water crisis due to over-tourism

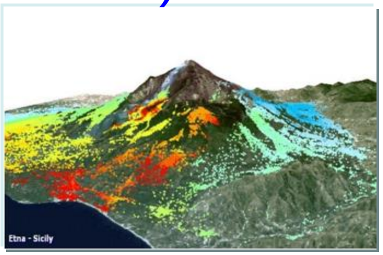
Measureable motion indicators either in cultural landscape or monument structural scale



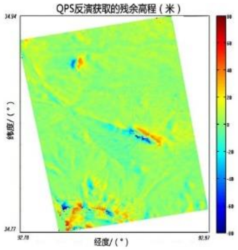
- Point-based measurements, such as leveling and network sensors (invasive)



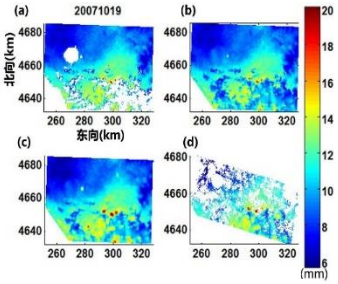
- Regional-based measurements, (non-invasive)



Spatial-temporal decorrelations



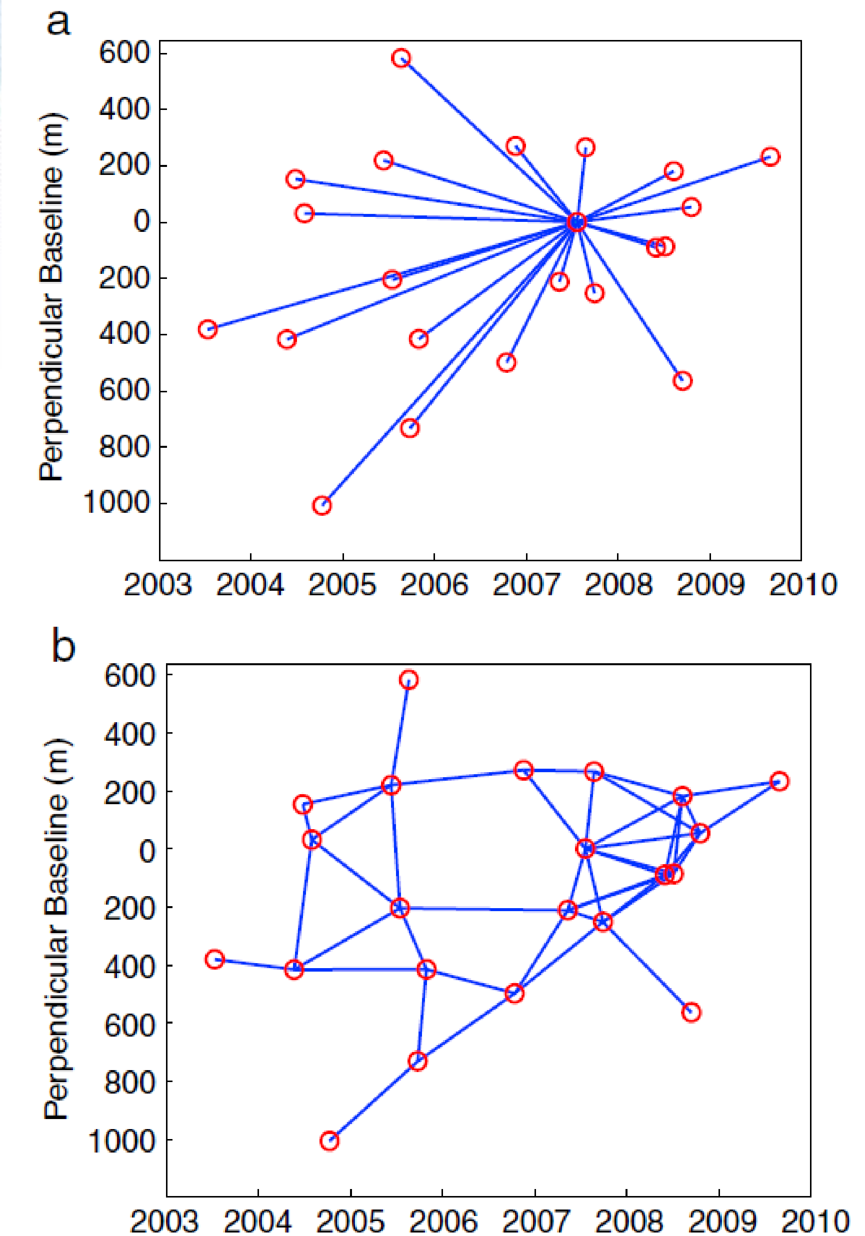
inaccurate reference DEM



APS errors (cm)

Radar interferometry: an innovative space technology and effectual tool to measure subtle motion from space

Multi-temporal SAR interferometry



PSI

$$\begin{cases} \delta\phi_{\text{dif}} = \delta\phi_{\text{mov}} + \delta\phi_{\text{error topo}} + \delta\phi_{\text{atm}} + \delta\phi_{\text{noise}} \\ \delta\phi_{\text{mov}} = \delta\phi_{\text{linear}} + \delta\phi_{\text{nonlinear}} = \dfrac{4\pi}{\lambda} \cdot \Delta v \cdot T + \delta\phi_{\text{nonlinear}} \end{cases}$$

SBAS

$$\phi(t_i) = \bar{v} \cdot (t_i - t_0) + \frac{1}{2} \bar{a} \cdot (t_i - t_0)^2 + \frac{1}{6} \Delta \bar{a} (t_i - t_0)^3$$

$$[\mathbf{AM}, \mathbf{c}]\mathbf{x} = \boldsymbol{\delta\Phi}$$

$$\mathbf{Bv} = \boldsymbol{\delta\Phi}'$$

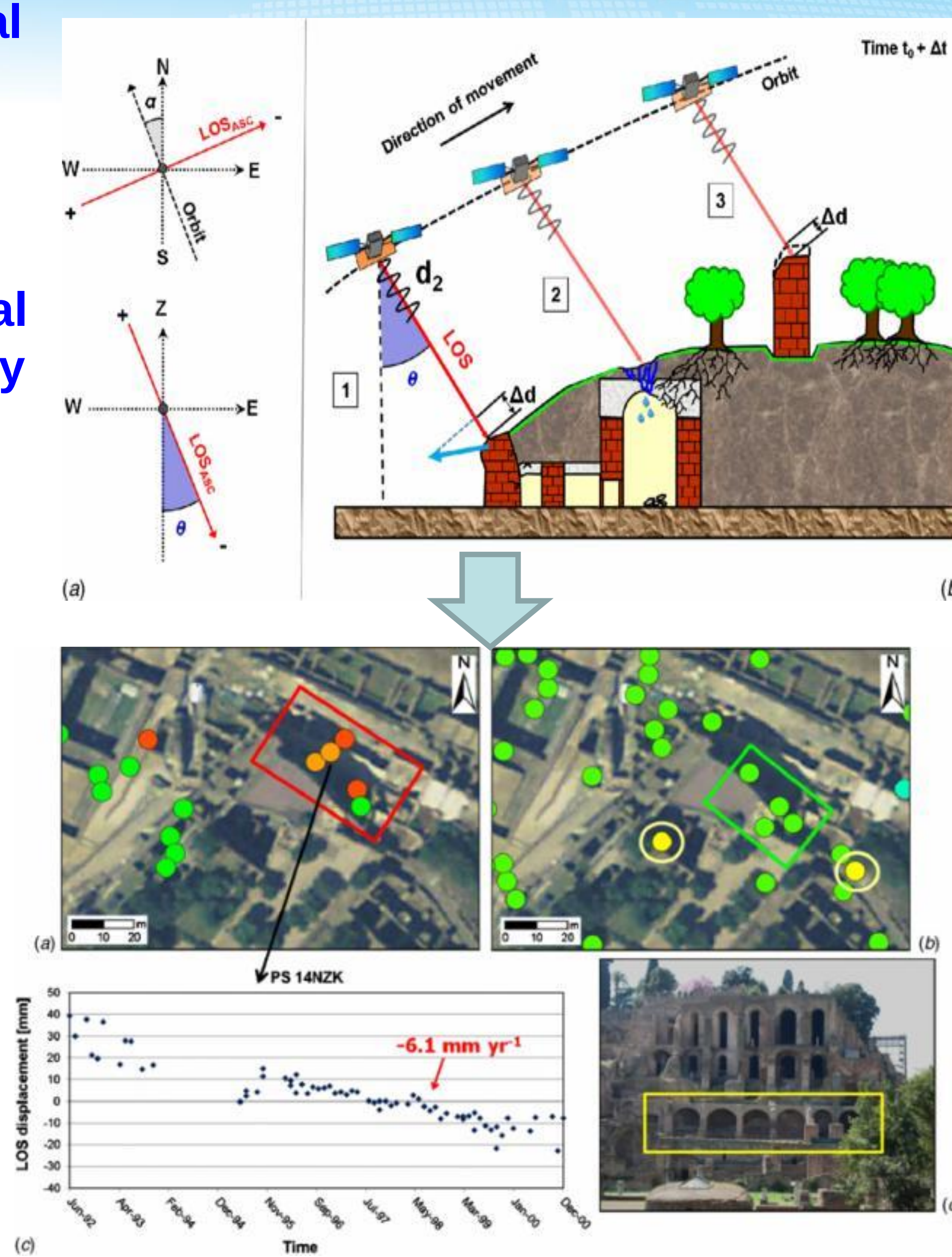
Millimeter accuracy of velocity rates with motion time series can be derived

Feasibility analysis

Motion anomaly in spatio-temporal either on monuments or hosting landscapes is one significant indicator for the occurrence of potential risks. Thus, monitoring the motion phenomena is essential for safeguarding and sustainability of heritage sites

- Archeological sites
- Ancient architecture complex

In particular when the spatial dimension of cultural heritage sites is several sq,km at least in order to taking advantage of synoptic observation capability of the space-eye, such as Angkor Heritage site.



2. Methodology: Two-scale MT-InSAR solution

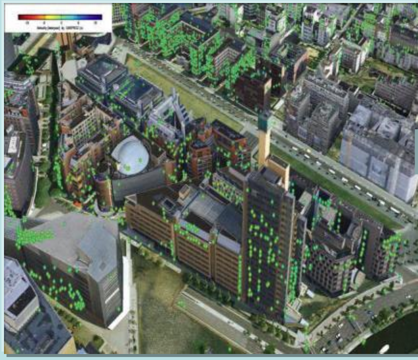
A two-scale monitoring solution

PS-InSAR for the cultural landscape monitoring (motion velocity and time series)

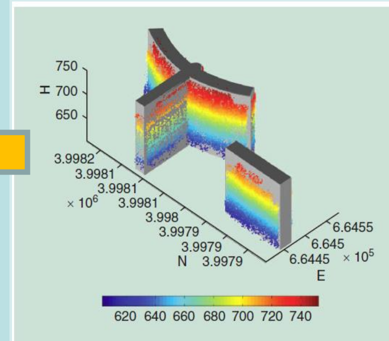
D-TomoSAR for the monument structural instability monitoring and health diagnosis (motion velocity, time series, and thermodynamics of materials

PS-InSAR and D-TomoSAR

PS-InSAR



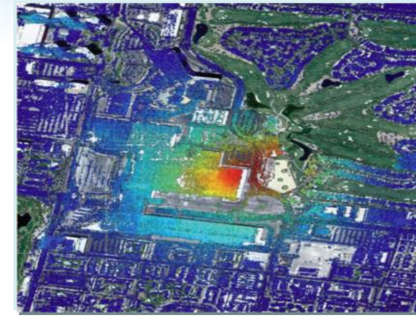
SAR Tomography



Powerful in motion inversion with millimeters accuracy, which is achieved by selecting stable point targets from time series SAR images over the same scene and analyzing their phases

Resolve unfavorable imaging, such as layover

D-TomoSAR



- Phase and amplitude are jointly used for the temporal coherence calculation
- Resolve the layover effects

Enhance the PS measurement for the structural instability monitoring & evaluation

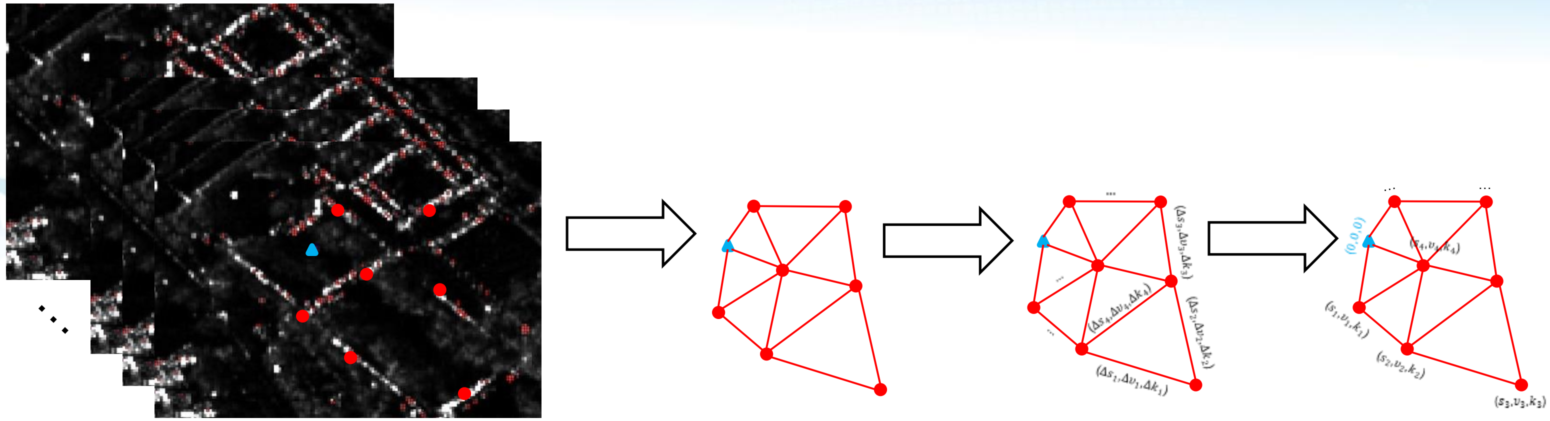
$$\boldsymbol{a}(s,v,k) = \begin{bmatrix} \exp\big(j2\pi(\varepsilon_1 s + \eta_1 v + \zeta_1 k)\big) \\ \dots \\ \exp\big(j2\pi(\varepsilon_N s + \eta_N v + \zeta_N k)\big) \end{bmatrix}$$

$$\hat{\gamma}(s,v,k) = \frac{\left|\boldsymbol{a}(s,v,k)^H \langle \boldsymbol{y} \rangle\right|}{N} \quad \xLeftrightarrow[\text{D-TomoSAR}]{\text{PSInSAR}} \quad \hat{\gamma}(s,v,k) = \frac{\left|\boldsymbol{a}(s,v,k)^H \langle \boldsymbol{y} \rangle\right|}{N}$$

RADI

Procedures of MT-InSAR with two-tier networking

First-tier network



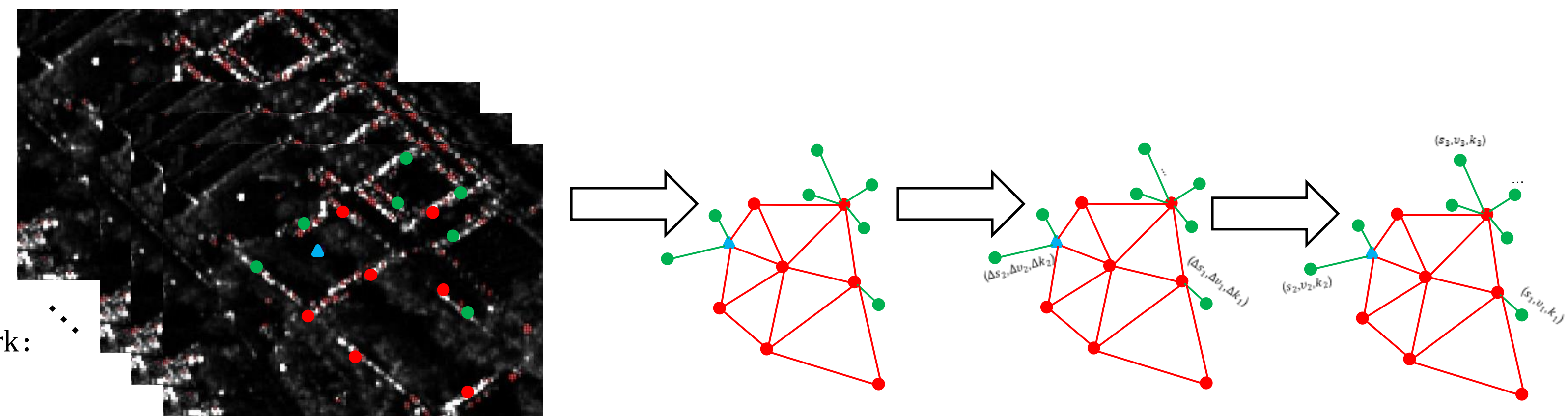
PSs in the first network

Delaunay network

Multi-dimensional Beamforming

Network adjustment

Second-tier network：

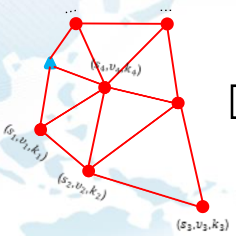


Extracted remain PSs（green）

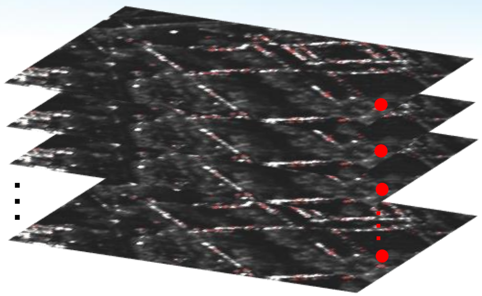
Star-network based on the PSs on the first-tier network

Multi-dimensional Beamforming

Parameter estimation



Linear motion and heights



$$\begin{bmatrix} \varphi_{resi\_1} \\ \varphi_{resi\_2} \\ \vdots \\ \vdots \\ \varphi_{resi\_N} \end{bmatrix}$$

Residual phase

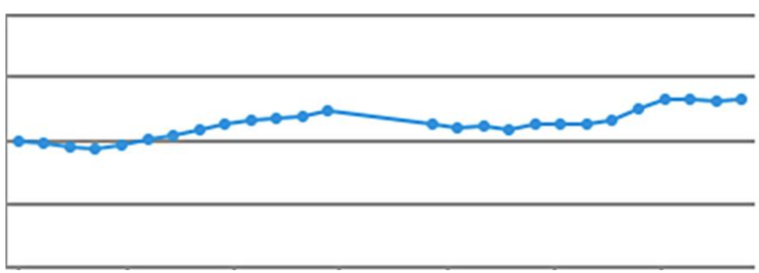
$$\begin{bmatrix} \varphi_{resi\_nonl\_1} \\ \varphi_{resi\_nonl\_2} \\ \vdots \\ \vdots \\ \varphi_{resi\_nonl\_N} \end{bmatrix}$$

Nonlinear motions

$$\varphi_{def\,resi\_nonl} = \varphi_{resi} - [\varphi_{resi}]_{HP\_time}$$

$$(\boldsymbol{D}_{def})_i = (\varphi_{def})_{i\_all} \lambda / 4\pi$$

$$(\varphi_{def})_i = 2\pi(\eta_i v + \zeta_i k)$$



Motion time series

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3. Angkor World Heritage site monitoring and assessment

We investigate the impacts of hitherto imperceptible and poorly understood factors of groundwater and temperature variations on the monuments in Angkor World Heritage site by InSAR tools.

We interpret findings from satellite radar interferometry (InSAR) motion fields for the period 2007-2017 to derive new insights into the dynamics of the relationship between over-tourism and cultural landscape sustainability

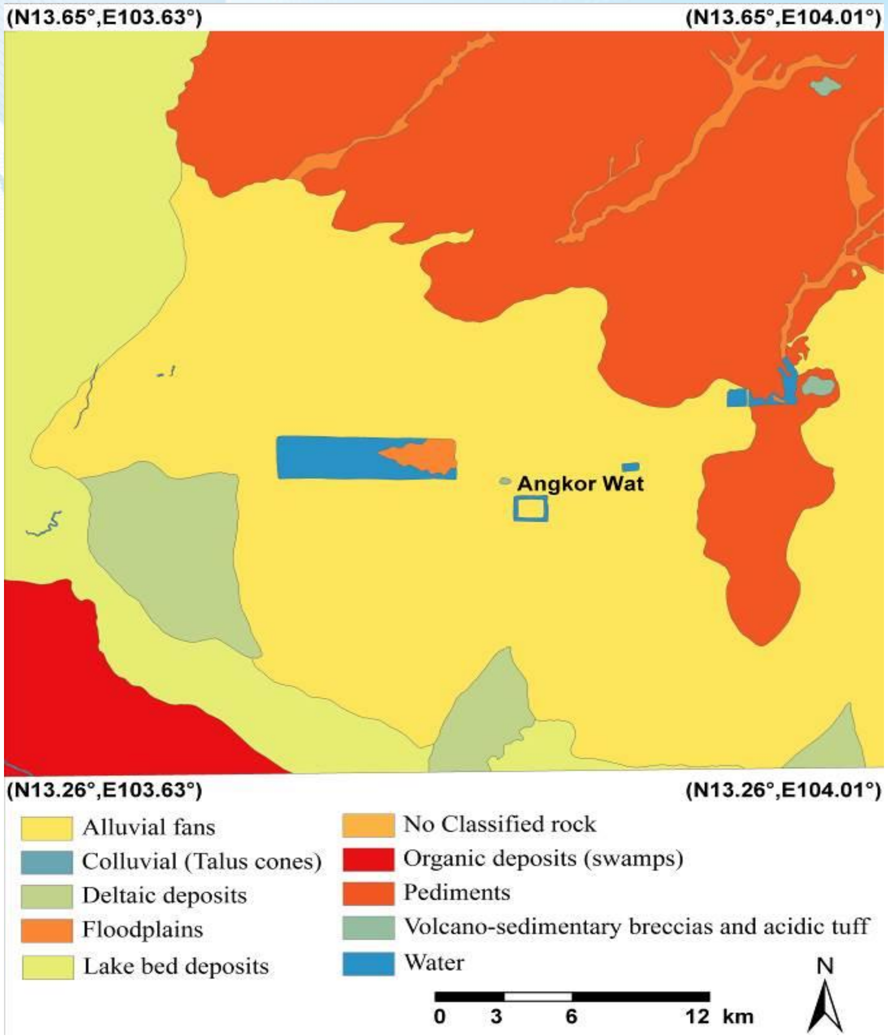
46 scenes of Stripmap TerraSAR data (3 m ground resolution) acquired in the span of February, 2011 to December, 2013 were used for the flood hazard evaluation and deformation time series analysis

One hundred and one scenes of multi-band SAR data, including twenty-four scenes of L-band ALOS PALSAR-1 (2007-2011), forty-five scenes of X-band TerraSAR (2011-2013) and thirty-two scenes of C-band Sentinel-1 A/B data (2016-2017).

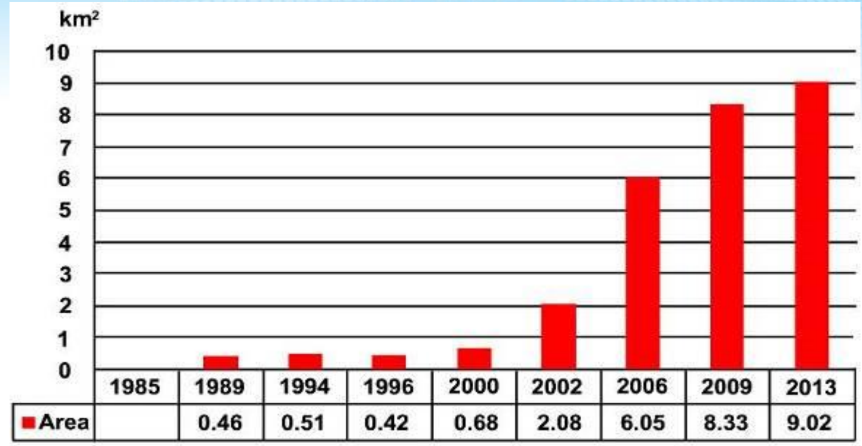
First-phase

Second-phase

➢ First phase study



Geology map of Angkor site



Urbanization in recent 30 years

(a) (b)

Field campaigns conducted

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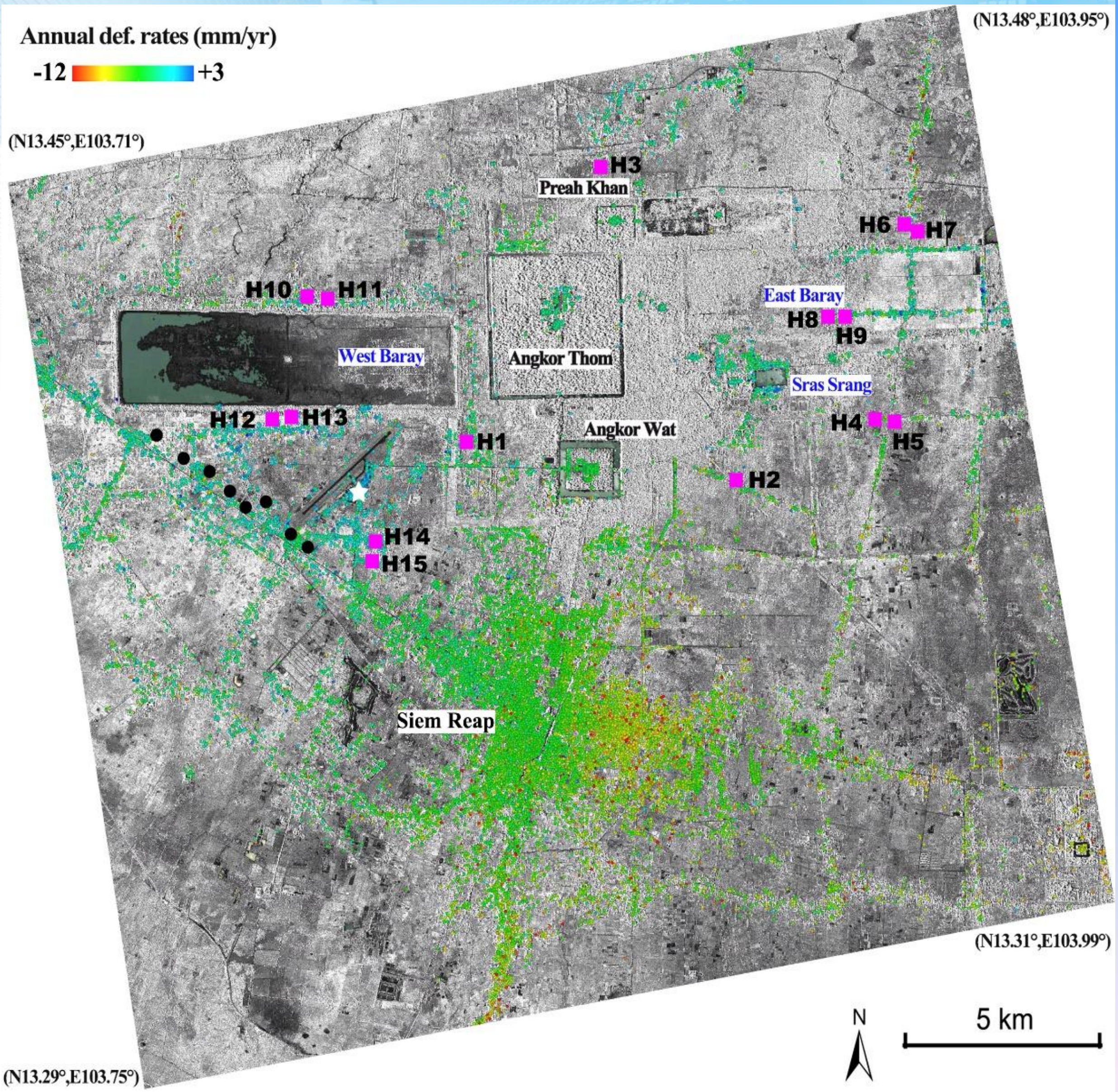


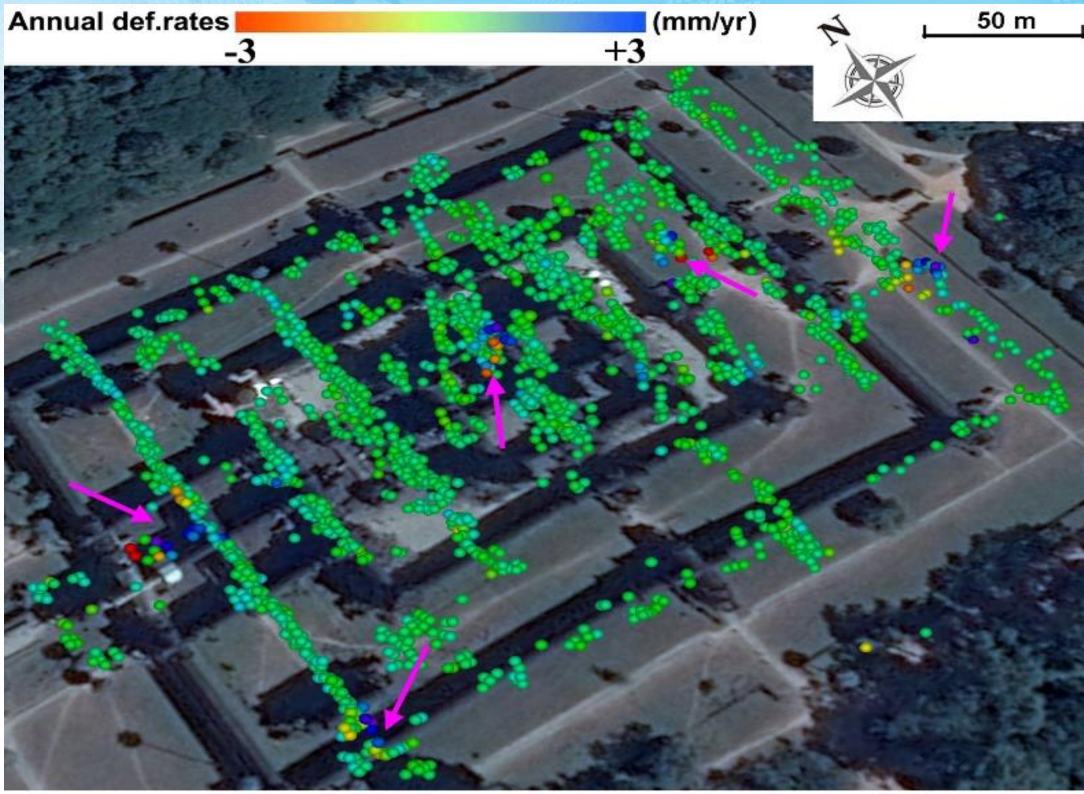
Regional-scale PSInSAR derived annual motion rates

✓Surface stability and/or mild subsidence were observed surrounding the central archaeological zone, due to restoration of the ancient hydraulic system as well as maintaining or raising the water-level of reservoirs.

✓Urbanization was rapid, leading in a mild-to-moderate surface subsidence in the Siem Reap city region.

✓Local government and APSARA made an optimal site selection for the public pumping wells (a safe distance away from the heritage core area)

Motion heterogeneity



(a)

(b)

Monument-scale D-TomoSAR derived results in Angkor Wat for the observation period 2011-2013

Particularly on junction points or locations of different structural components

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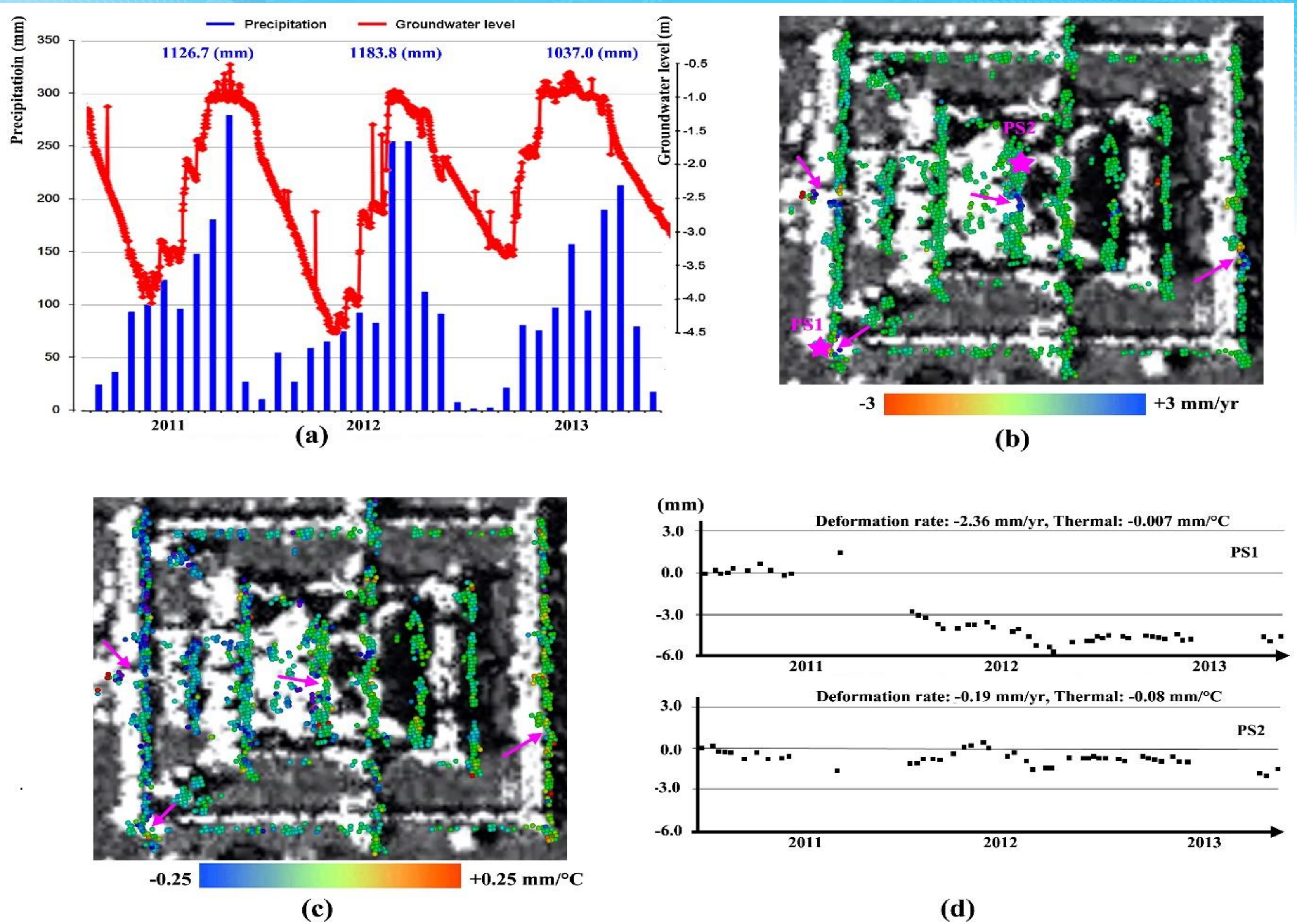
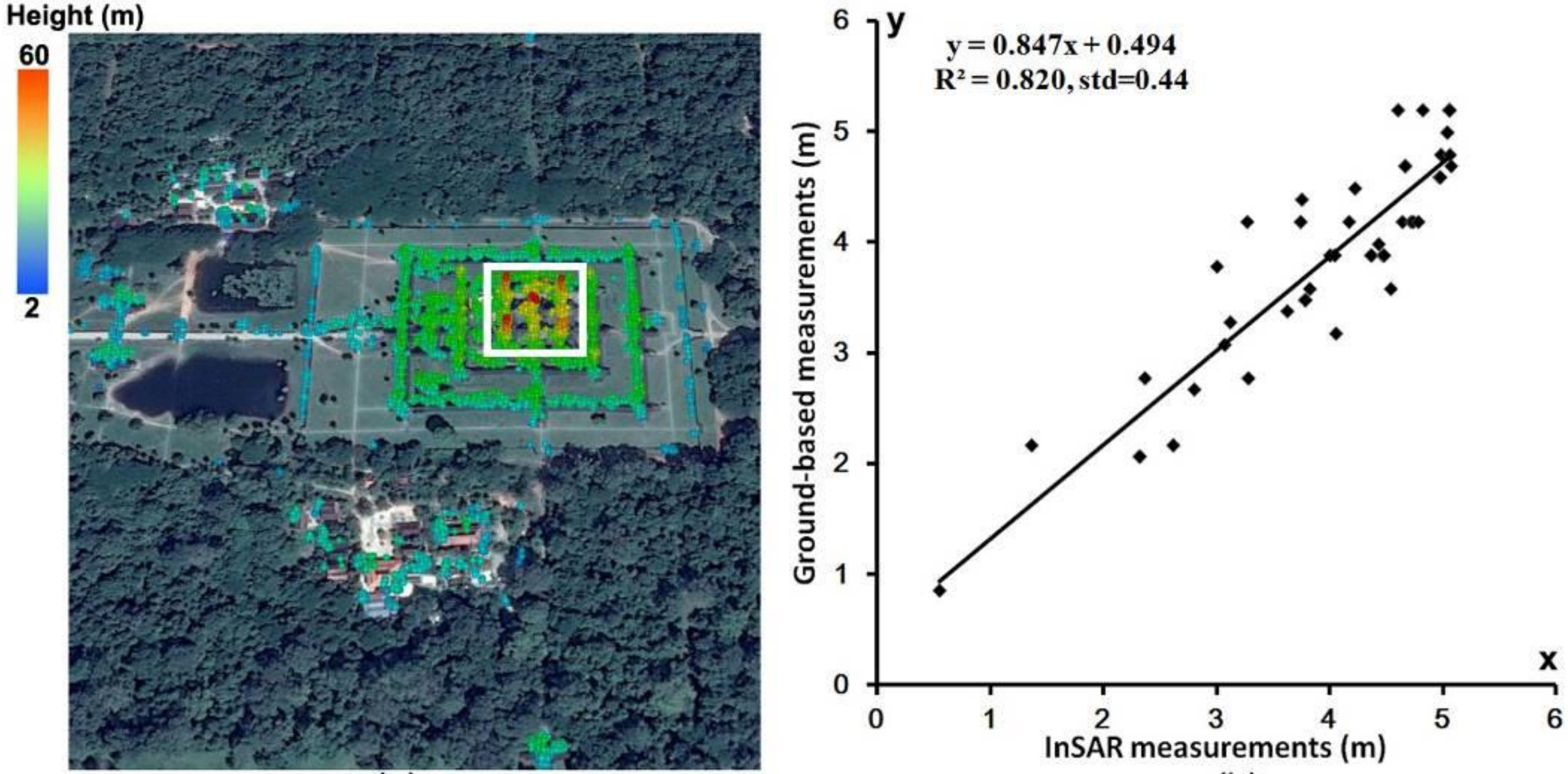


Pumping of groundwater does not cause an immediate region-wide surface subsidence threatening the sustainability of monuments. But imperceptible influence from seasonal variations of the groundwater table in conjunction with the thermal expansion of temple materials are newly-recognized contributory factors to the long-term deterioration of monuments which are normally driven by other natural causes such as the sandstone weathering and biological alteration.

From statistical analysis, an accuracy of motion up to 1 mm/a was derived

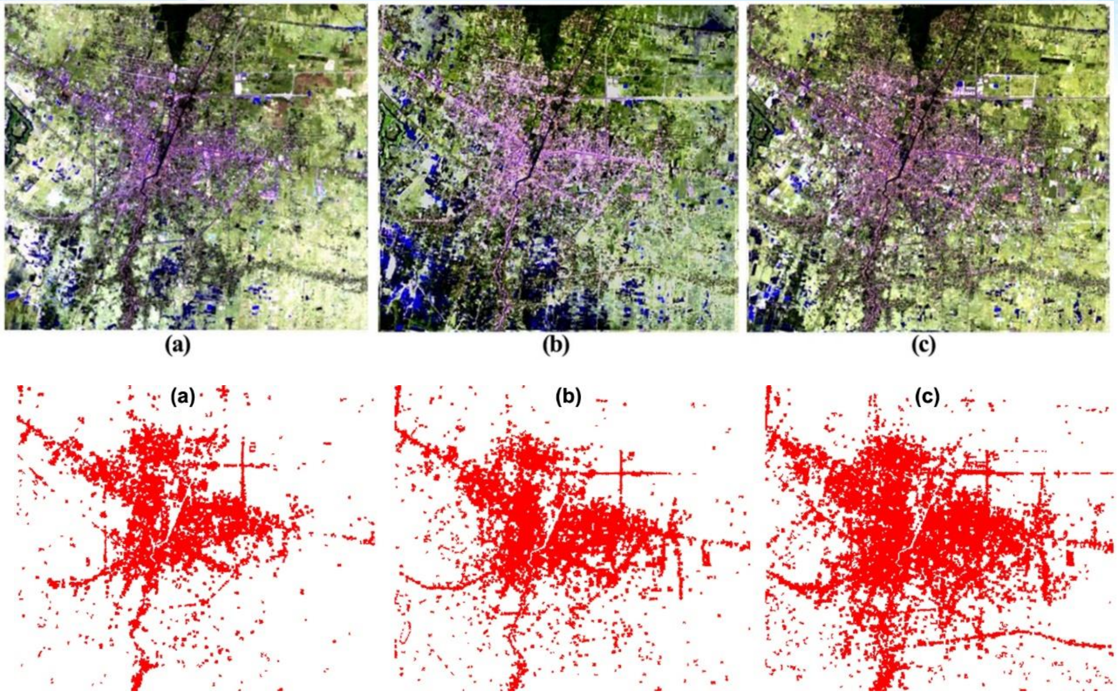


(a) (b)

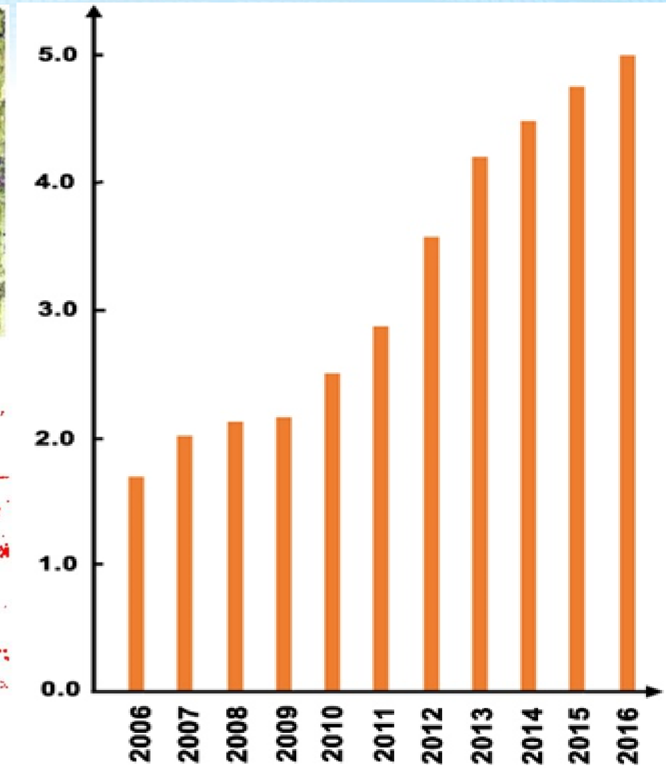
Validation of Tomo-PSInSAR derived motions:

1) Utilizing the PS heights confirmed by the field verifications undertaken in 2014; scatter-plot of estimated heights compared with the ground-truth on the terrace gallery, indicating a consistent trend supported by a significant correlation coefficient of 0.820 with a standard deviation of 0.44 m.
2) Linear thermal expansion coefficients of temple materials (for example, sandstone with values around 5.0 × 10−5 to 6.0 × 10−5)

➢ Second phase study

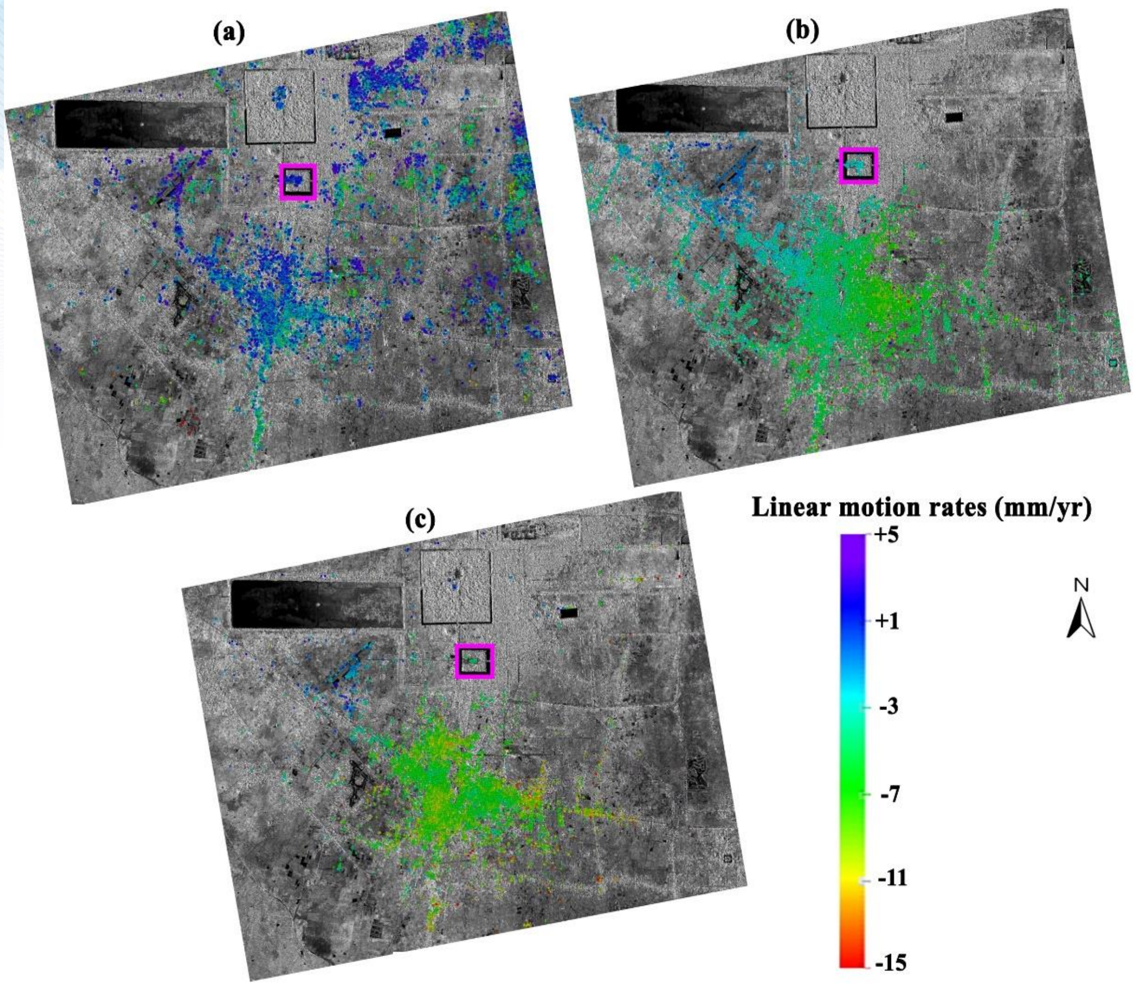


Urbanization of Siem Reap City for the period from 2010 to 2017 extracted from the Landsat multispectral images. Urbanization map of (a) 2010, (b) 2014 and (c) 2017, respectively



Explosive tourism in 2006-2017

An 11-12% increase in annual urbanization closely tracking the 12% annual rate of increase of visitor numbers for the observation period of 2010-2016.

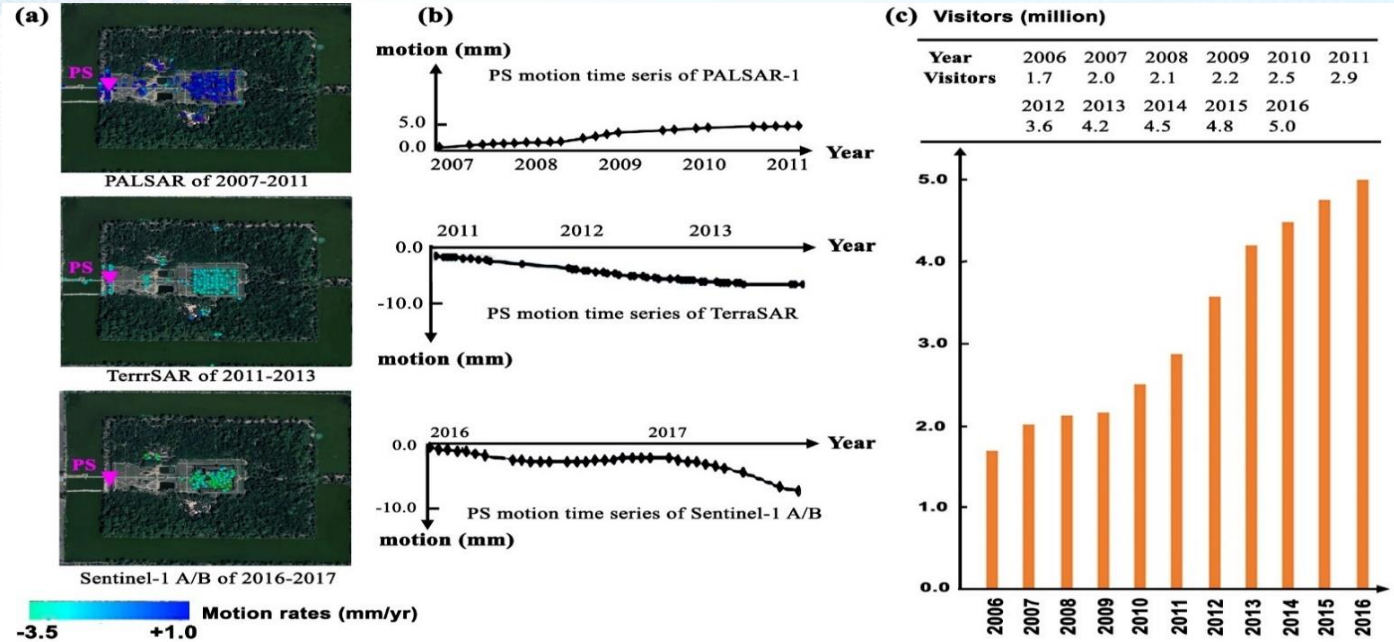


Vertical projected linear motion rates in the heritage landscape of Angkor site.

(**a**) PALSAR-1 2007-2011,
(**b**) TerraSAR-X 2011-2013 and
(**c**) Sentinel-1 A/B 2016-2017,
(the red-blue color bar indicates subsidence-uplift motions)

- ✓ **The surface of urban regions is stable up to 2011; but spatially heterogeneous for subsequent period of 2011-2017.**
- ✓ **Subsidence had aggravated for the period 2011-2017. Subsidence was located only in the northeast up to 2013 but extended to the entire downtown by 2017.**

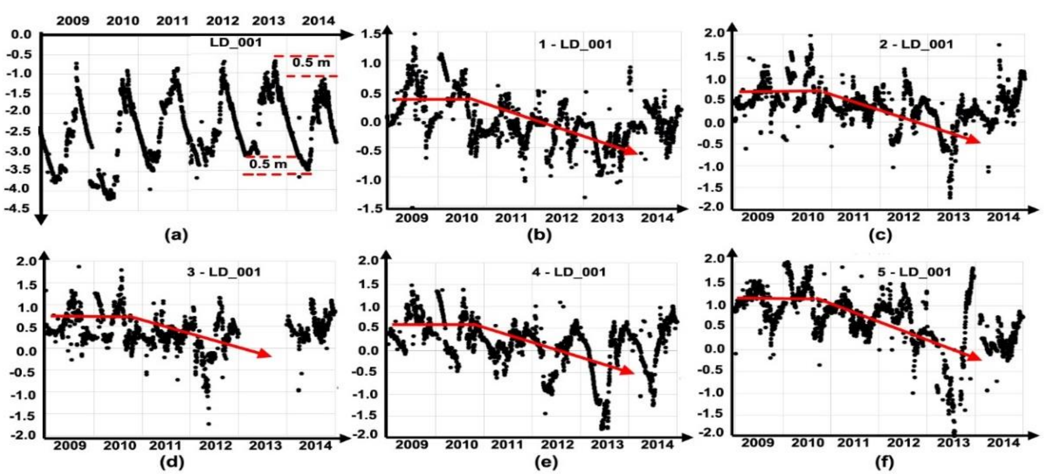
Interaction investigation of hydrology, tourism, InSAR-derived motions implying the an impending water crisis due to over-tourism



+0.5 mm/a

-1.5 mm/a

-3.5 mm/a



Scientific findings: Over-tourism impacts the sustainability of the cultural heritage, 1) the land subsidence is on-going and aggravated; 2) the decline of groundwater table is confirmed.

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Big Earth data

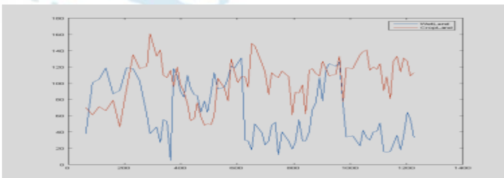
Social-economic

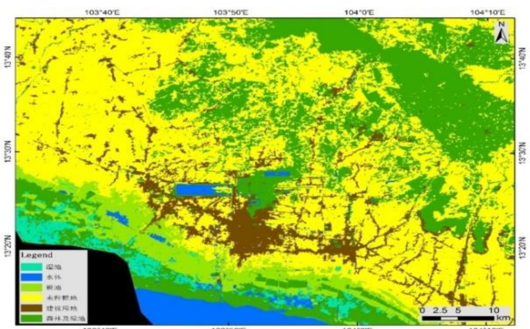
Remote sensing

Urbanization

geology

hydrology





Land cover and land change in the Angkor cultural landscape in 2017

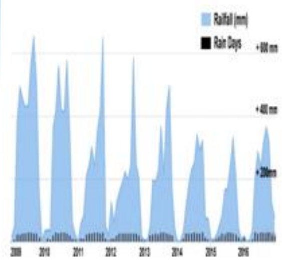
Tourism industry

Ground water pumping

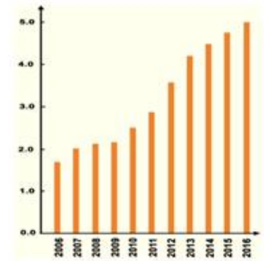
Surface subsidence

Temple collapse

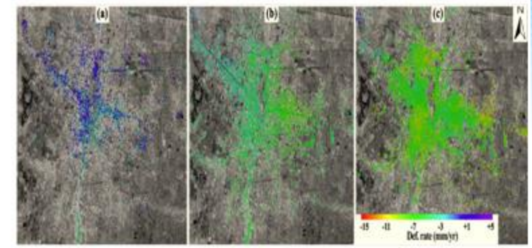
Precipitation



tourism numbers



surface subsidence



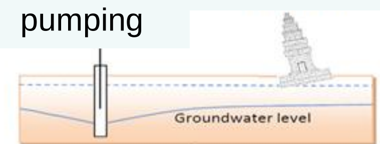
InSAR-derived Land subsidence in 2007-2017

Future prediction

Prediction model

Groundwater pumping

Ancient temple



The surface subsidence can be up to -4.7 to -5.0 mm/a in 2021

Except for the fund inputs, space technology promote the sustainable conservation of world heritage sites, such as for the Angkor site, the technology integration and interdisciplinary analysis of remote sensing, geology, hydrology, social-economic and urbanization provides new insights and scientific data for the smart management of the site.

4. Summary and recommendations

Summary

- The need to take into consideration the environmental and sustainable development of the Angkor heritage landscape for the long-term conservation of the Angkor Archaeological Park and World heritage site.

- Dynamics of motion trends indicated that the central archaeological zone shifted from a surface stability to a mild subsidence, in particular for the regions along its southern border, e.g. Angkor Wat Temple. Hydraulic head comparison between southern and northern parts of the central archaeological park implied the decline of groundwater table in the last ten years.

- Subsidence phenomena was jointly induced by the decline of annual precipitation by the impacts of climate change and increased extraction of groundwater linked to rapid growth in tourism. However, in our prediction model the latter accounted for a more significant contribution to subsidence.

Recommendations:

Our recommendations for its sustainable conservation from a scientific perspective are as follows:

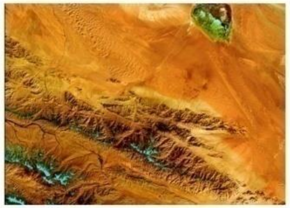
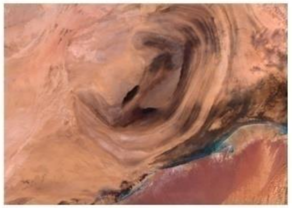
- Groundwater exploitation from thousands of private wells have to be controlled in order to limit the volume of waters extracted.

- the growth in visitor numbers and their demand for water needs to be regularly monitored and controlled; our estimated upper limit of tourists, i.e. 2.5 million per year, has already been exceeded in 2016 when the number of visitors have doubled this upper limit, reaching 5 million.

- Alternative solutions to tapping ground water for development needs, such as obtaining water from the Tonle Sap Lake (Southeast Asia's largest fresh water lake), need to be urgently explored.

Note that: Enrich the UN SDGs 11.4 (Strengthen efforts to protect and safeguard the world's cultural and natural heritage) by the contribution of scientific and technology development and pilot applications.

Thanks!

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