Monitoring Surface Deformation of Slow-Moving Landslides Using Multi-Temporal InSAR Techniques

應用多時域雷達干涉技術監測慢滑移山崩地表變形

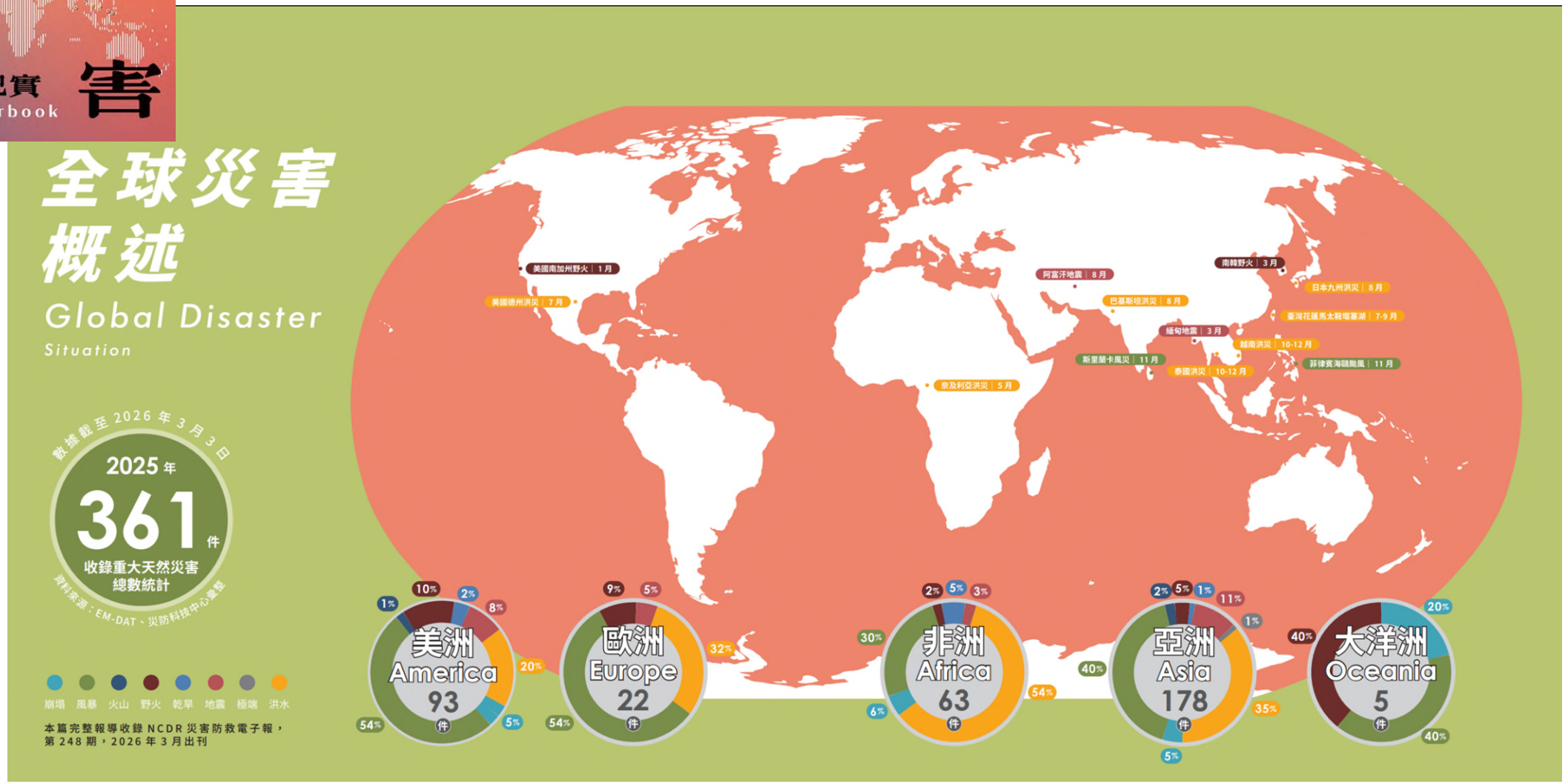
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Chun-Ying Chiu[3], Chung-Ray Chu[1], Chia-Han Tseng[4], Che-Hsin Liu[1],
Shih-Chiang Lee[1], Yu-Chung Hsieh[5], Chih-Hsin Chang[1]

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[3] Department of Geosciences, National Taiwan University, Taipei, Taiwan
[4] Department of Geology, Chinese Culture University, Taipei, Taiwan
[5] Geological Survey and Mining Management Agency, Taipei, Taiwan

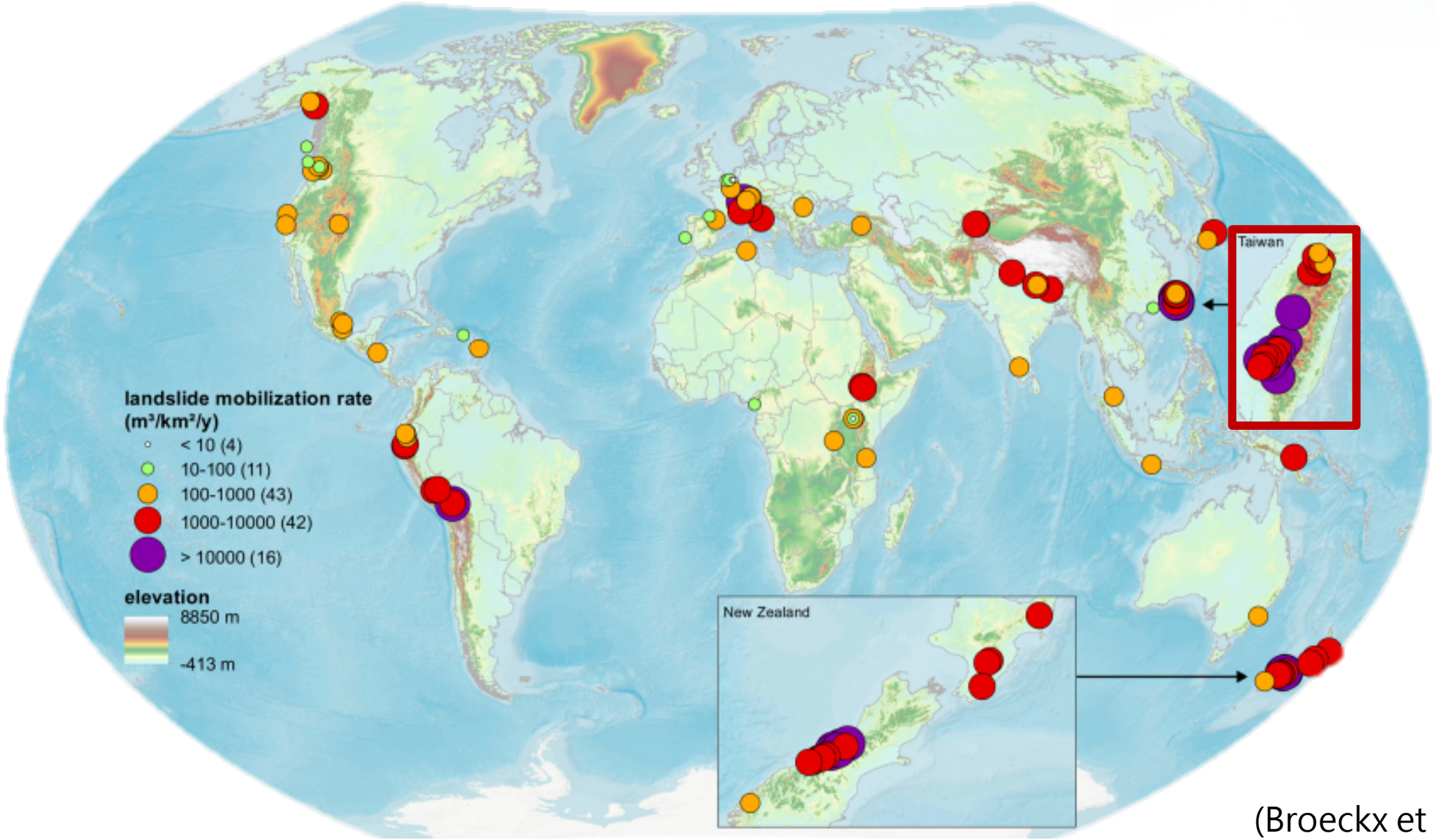
2026.11.11

2025 Global disaster situation





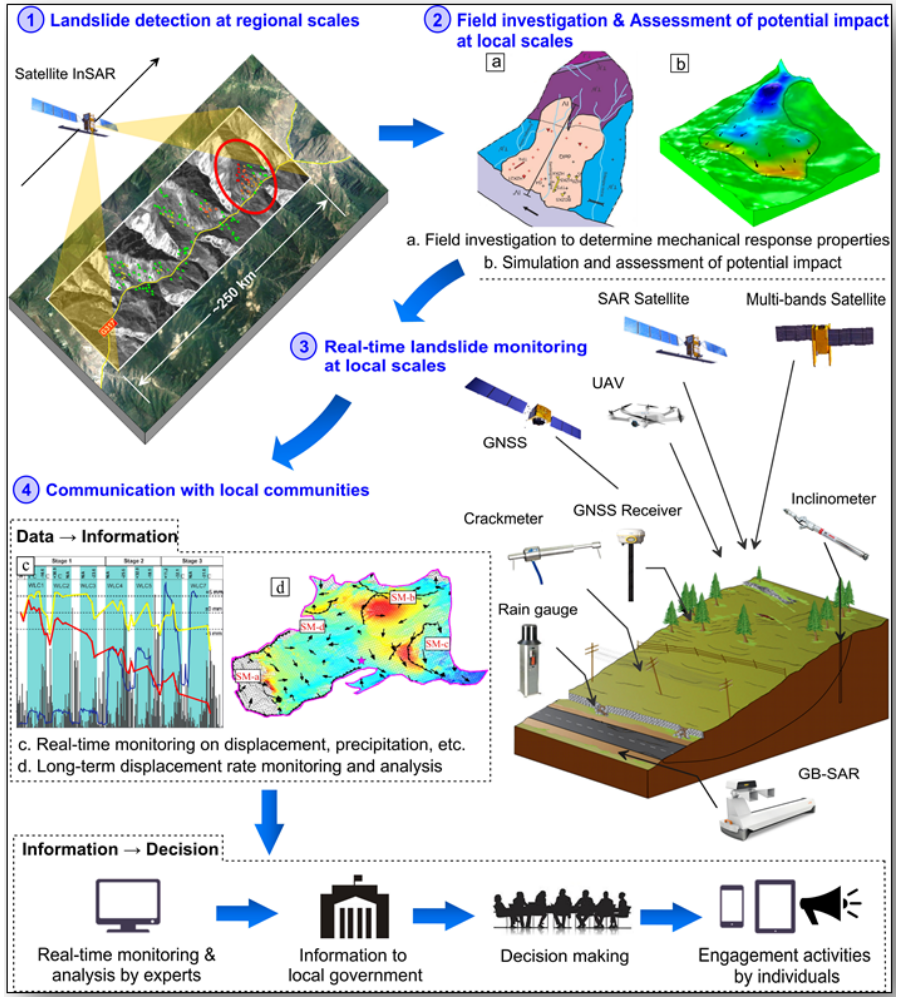
Global landslide mobilization rates



(Broeckx et al., 2020)

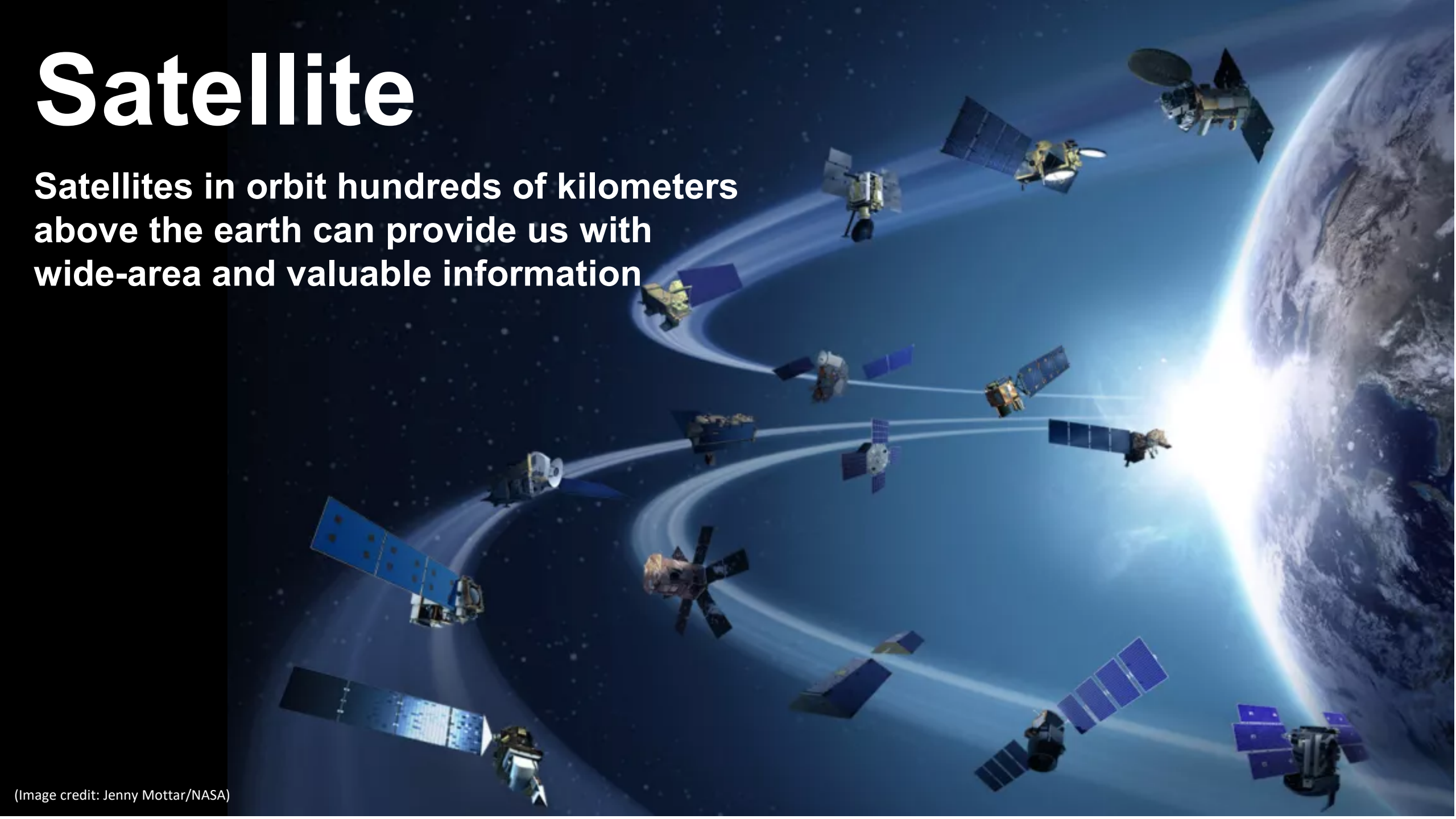
Outline

- Introduction of synthetic aperture radar (SAR)
- Multi-temporal InSAR techniques
- Applications of monitoring surface deformation of slow-moving landslides
- Summary



Satellite

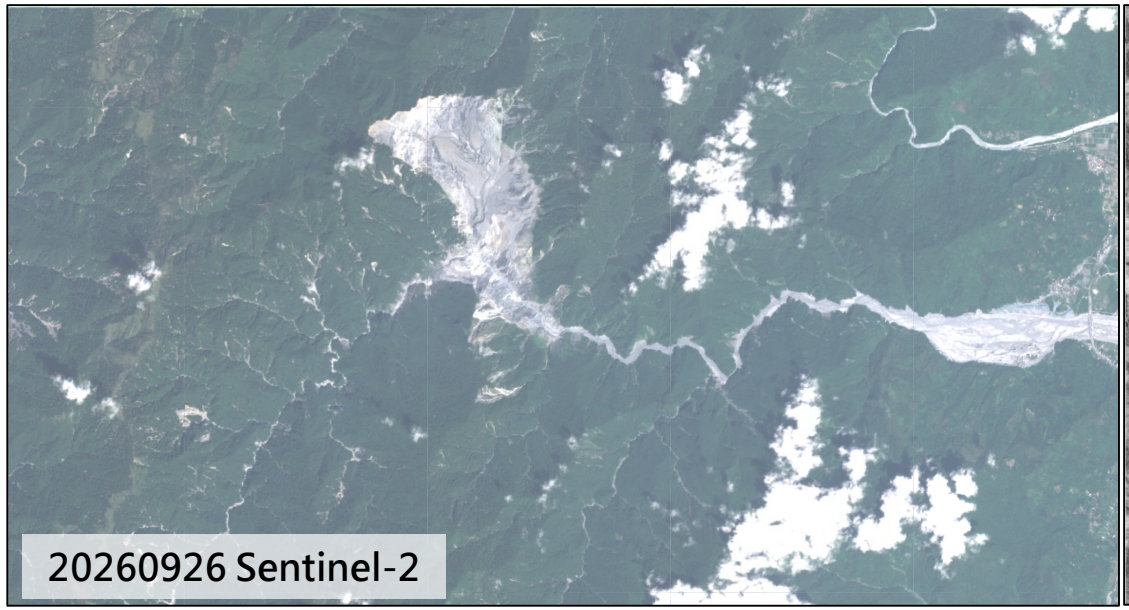
Satellites in orbit hundreds of kilometers above the earth can provide us with wide-area and valuable information

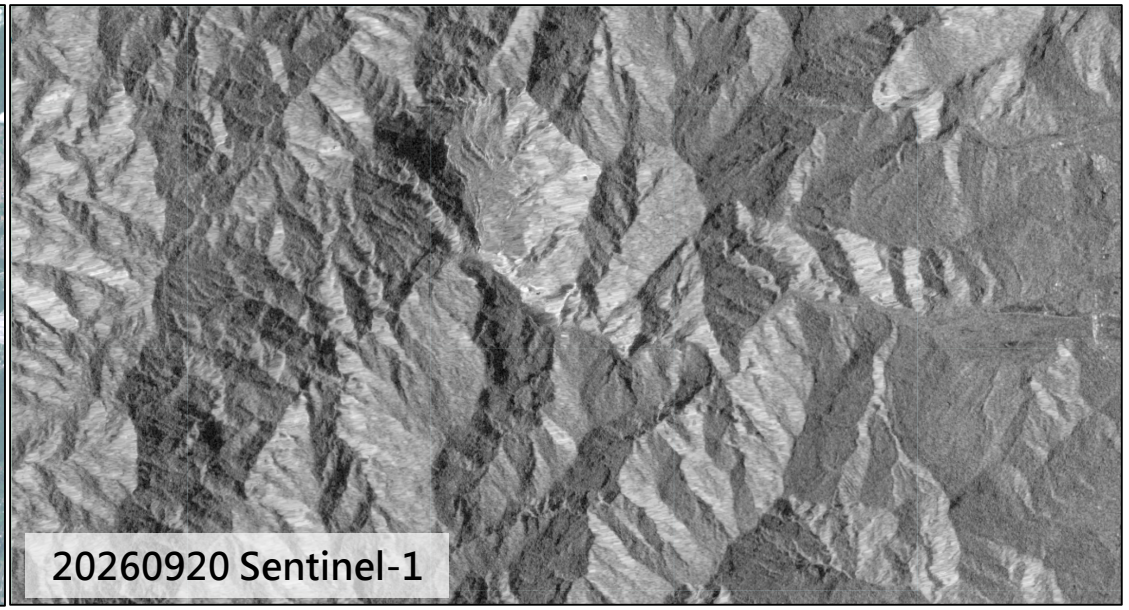


(Image credit: Jenny Mottar/NASA)

Satellite Image Classification

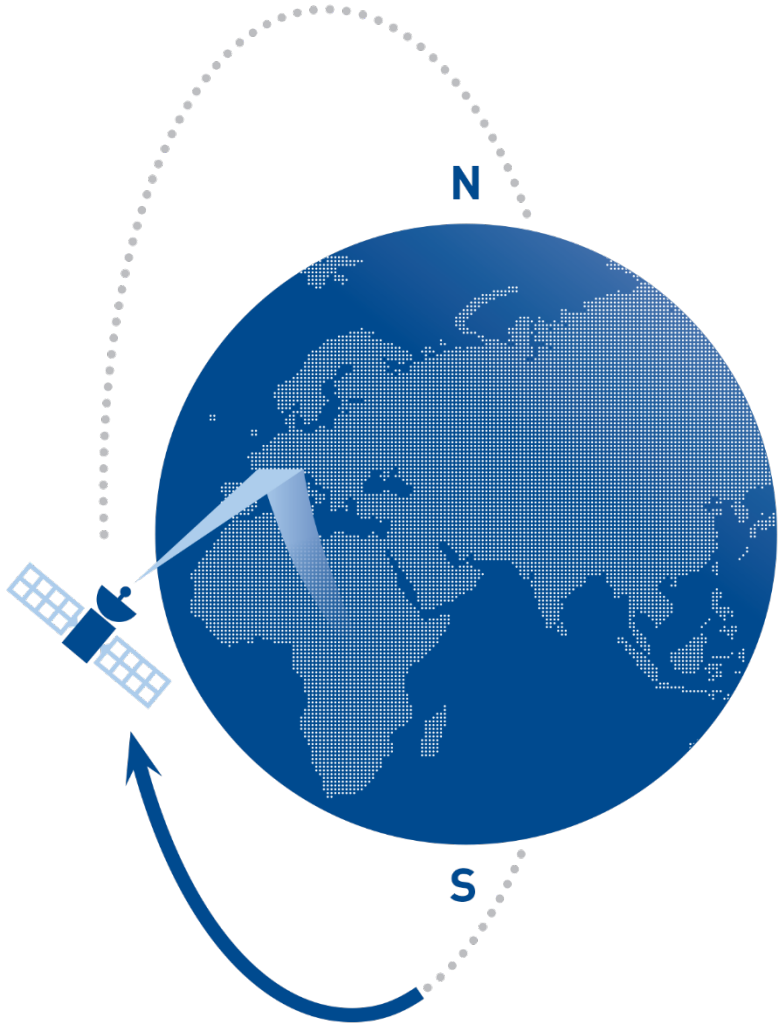
- **Optical Satellite Imagery**
  - Uses visible and infrared wavelengths; affected by sunlight and cloud cover; provides intuitive, easy-to-interpret images.
  - Sentinel-2, MODIS, Landsat-7/8, FORMOSAT-2/5/8
- **Synthetic Aperture Radar, SAR**
  - Uses active microwave sensing; enables day-and-night, all-weather observations; images are less intuitive to interpret.
  - Sentinel-1、ALOS PALSAR、ENVISAT、RADARSAT、ERS



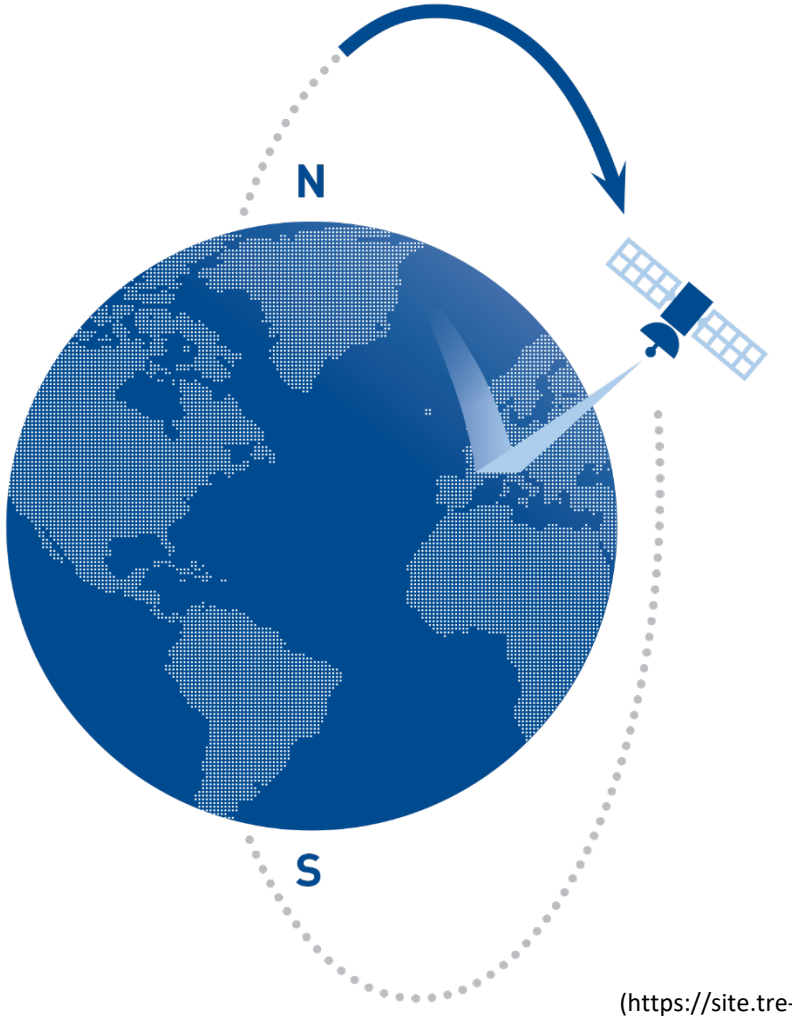


Satellite‘s orbit directions

(a) Ascending (升軌)

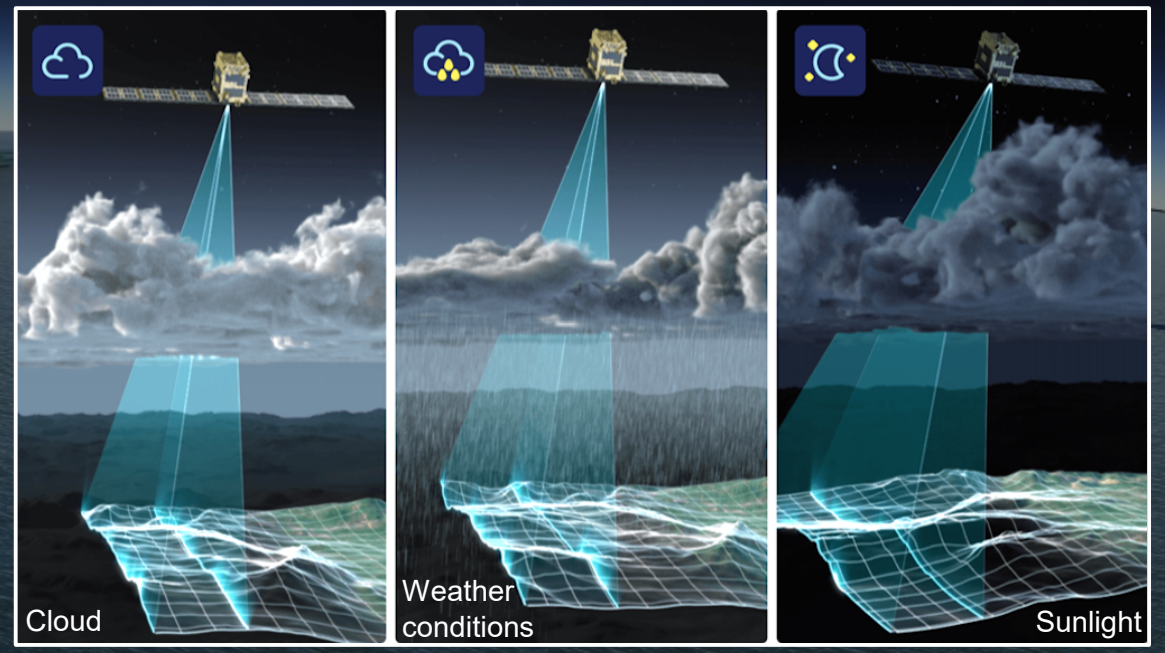


(b) Descending (降軌)



(https://site.tre-altamira.com/)

Observing surface information from Space



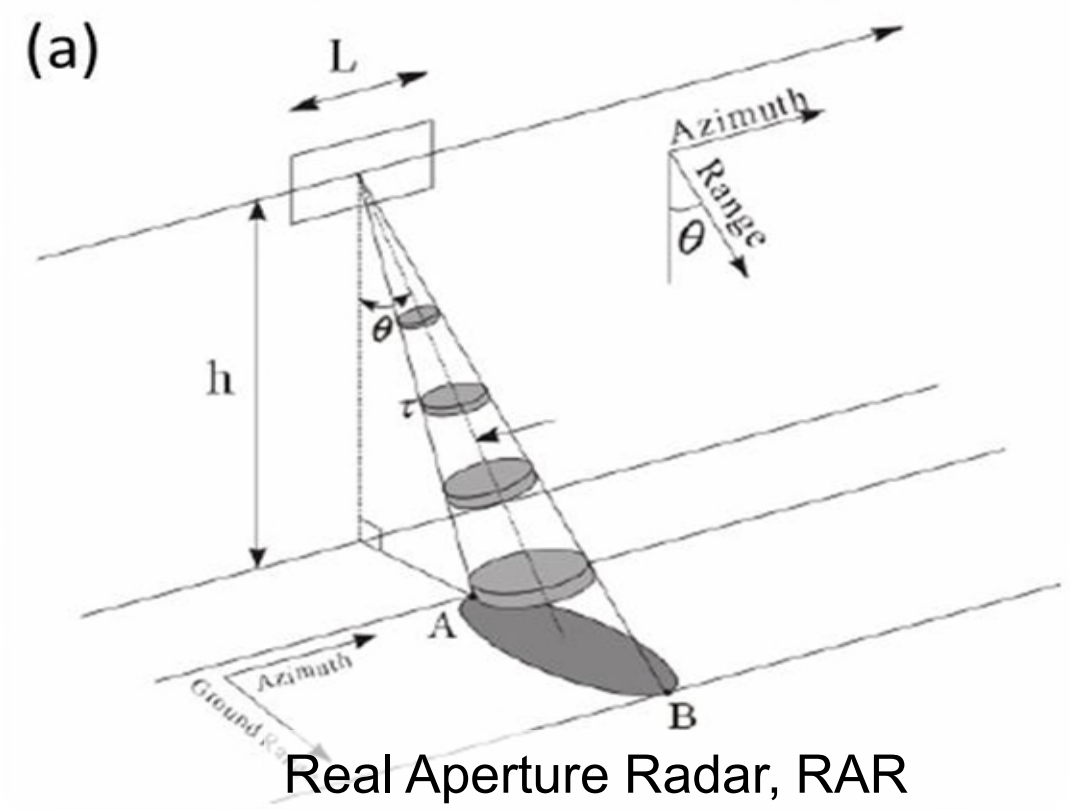
(Image credit: Synspective Inc.)

Synthetic Aperture Radar SAR

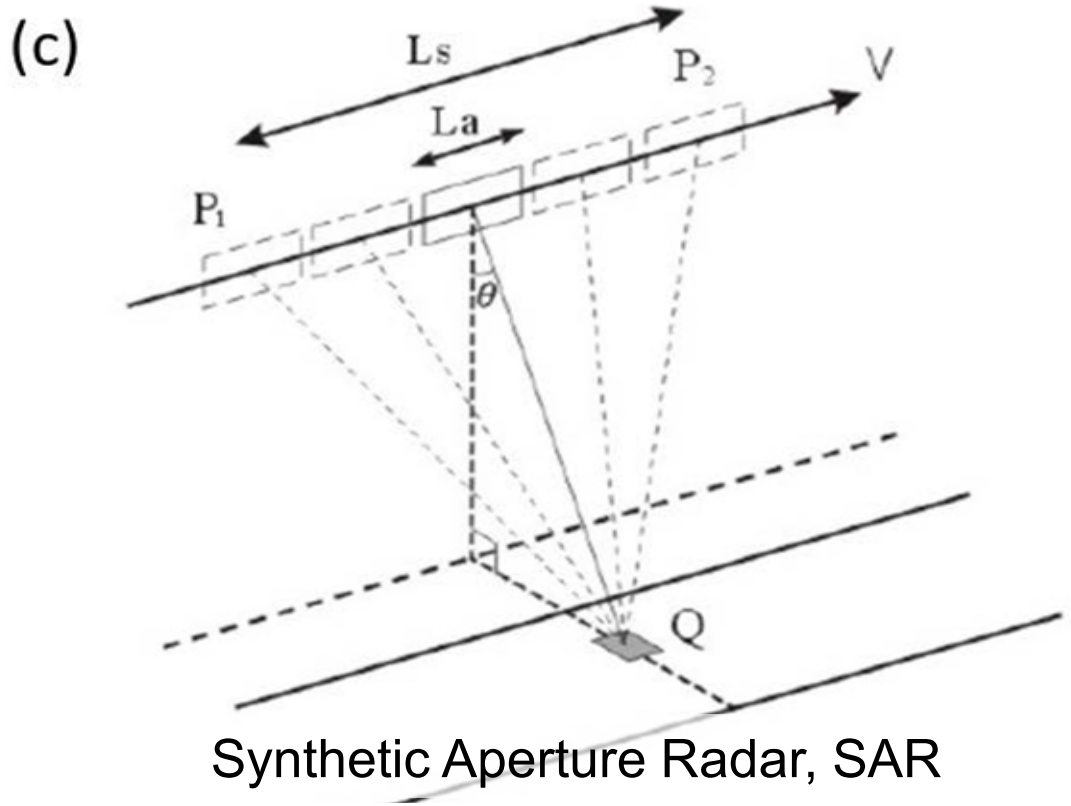
Synthetic Aperture Radar, SAR

Conventional radar obtains only once radar reflectivity from target.

SAR obtains multiple radar reflectivity by the motion of the radar antenna.



Real Aperture Radar, RAR

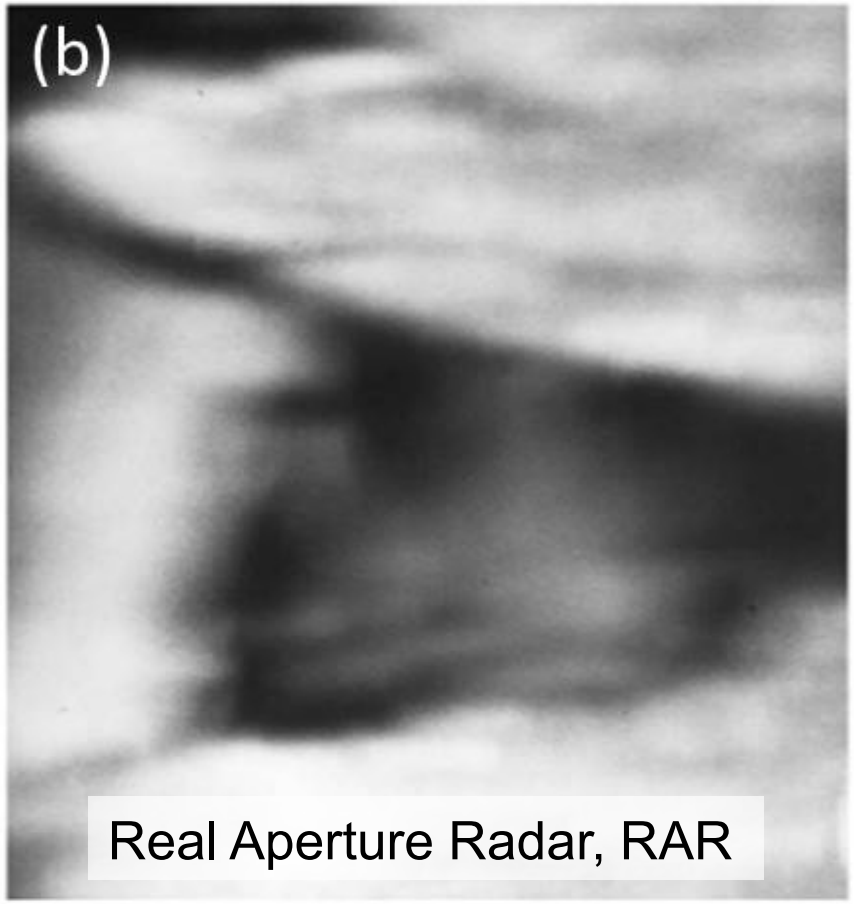


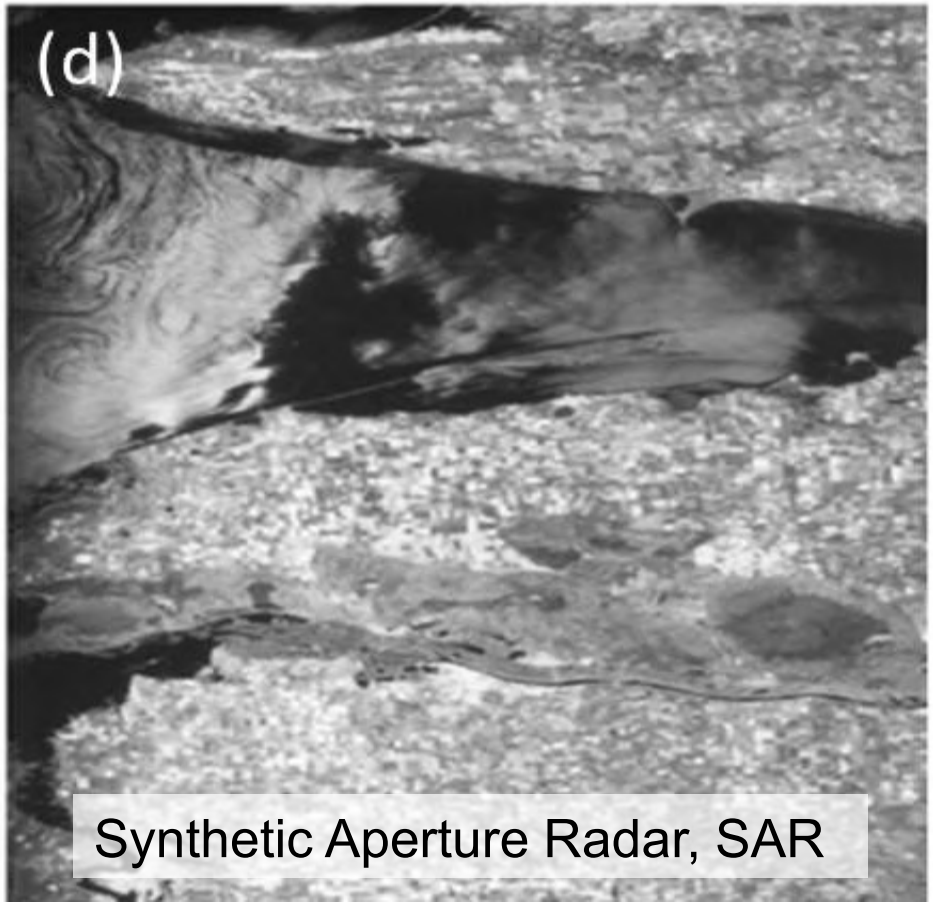
Synthetic Aperture Radar, SAR

(Masonnet and Feigl, 1998; Usai, 2001)

Synthetic Aperture Radar, SAR

SAR could provide finer spatial resolution than the conventional radar, especially from space.

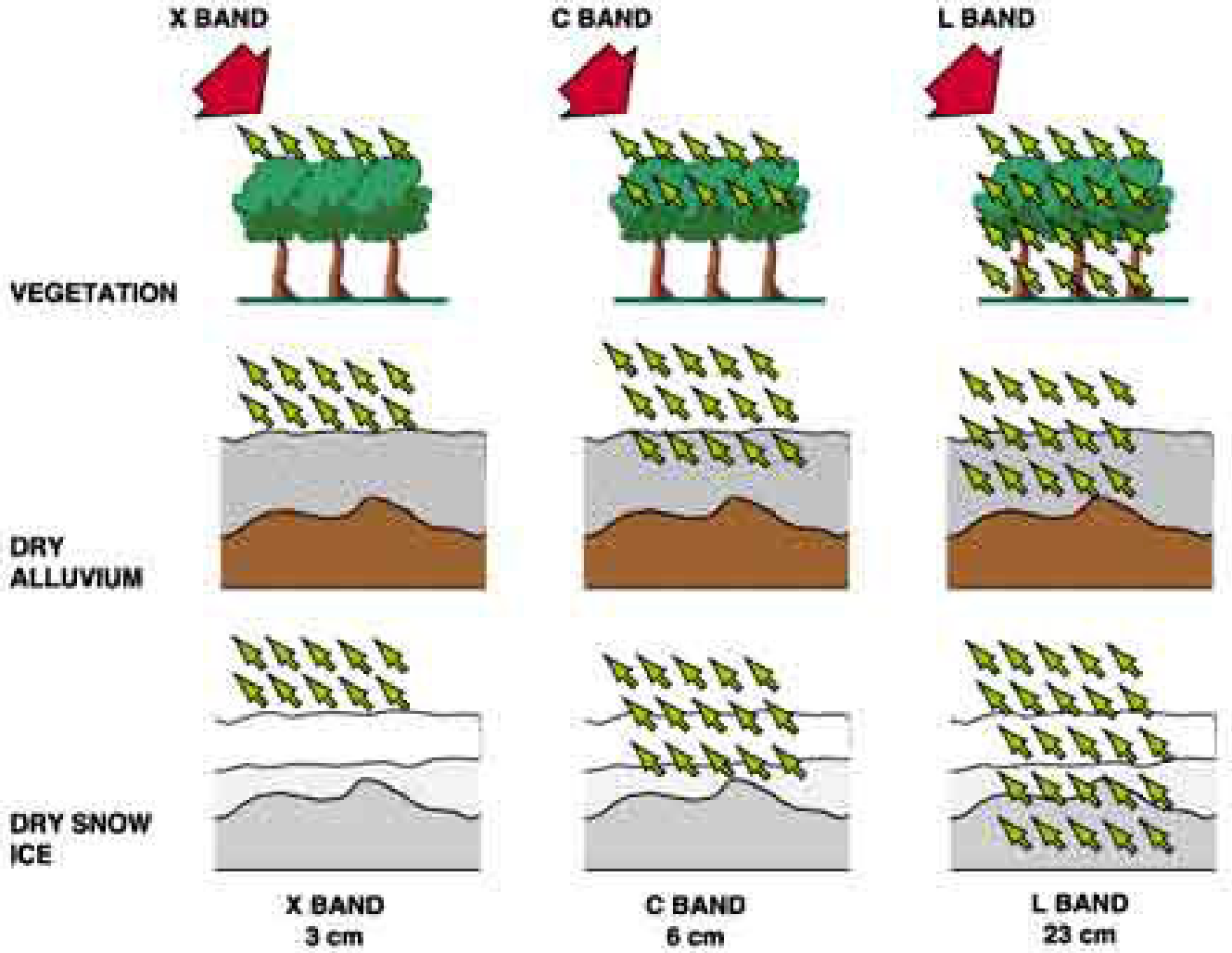




(Masonnet and Feigl, 1998; Usai, 2001)

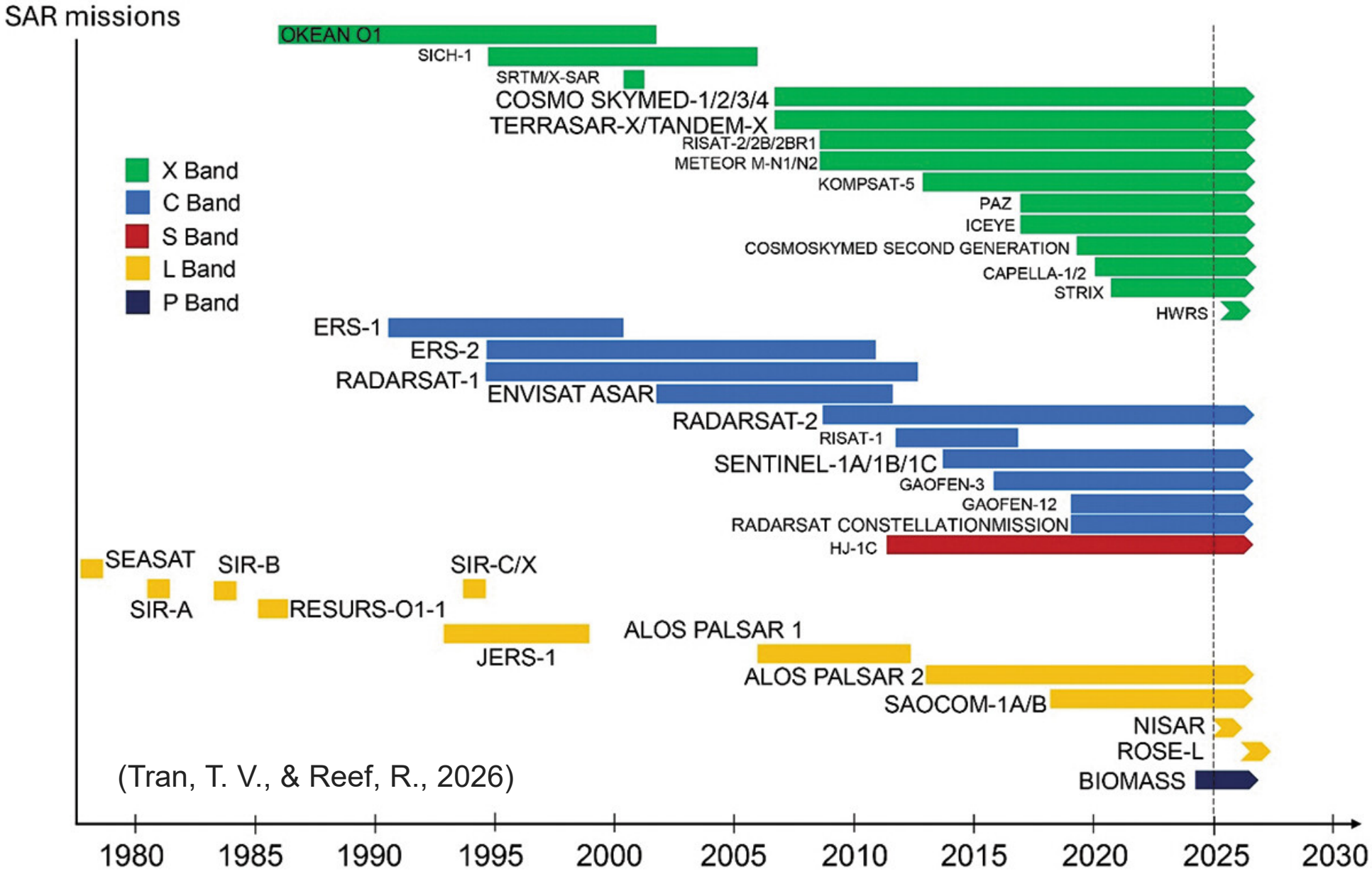
Synthetic Aperture Radar, SAR

- Different surface features exhibit different scattering characteristics:



(ESA earth online)

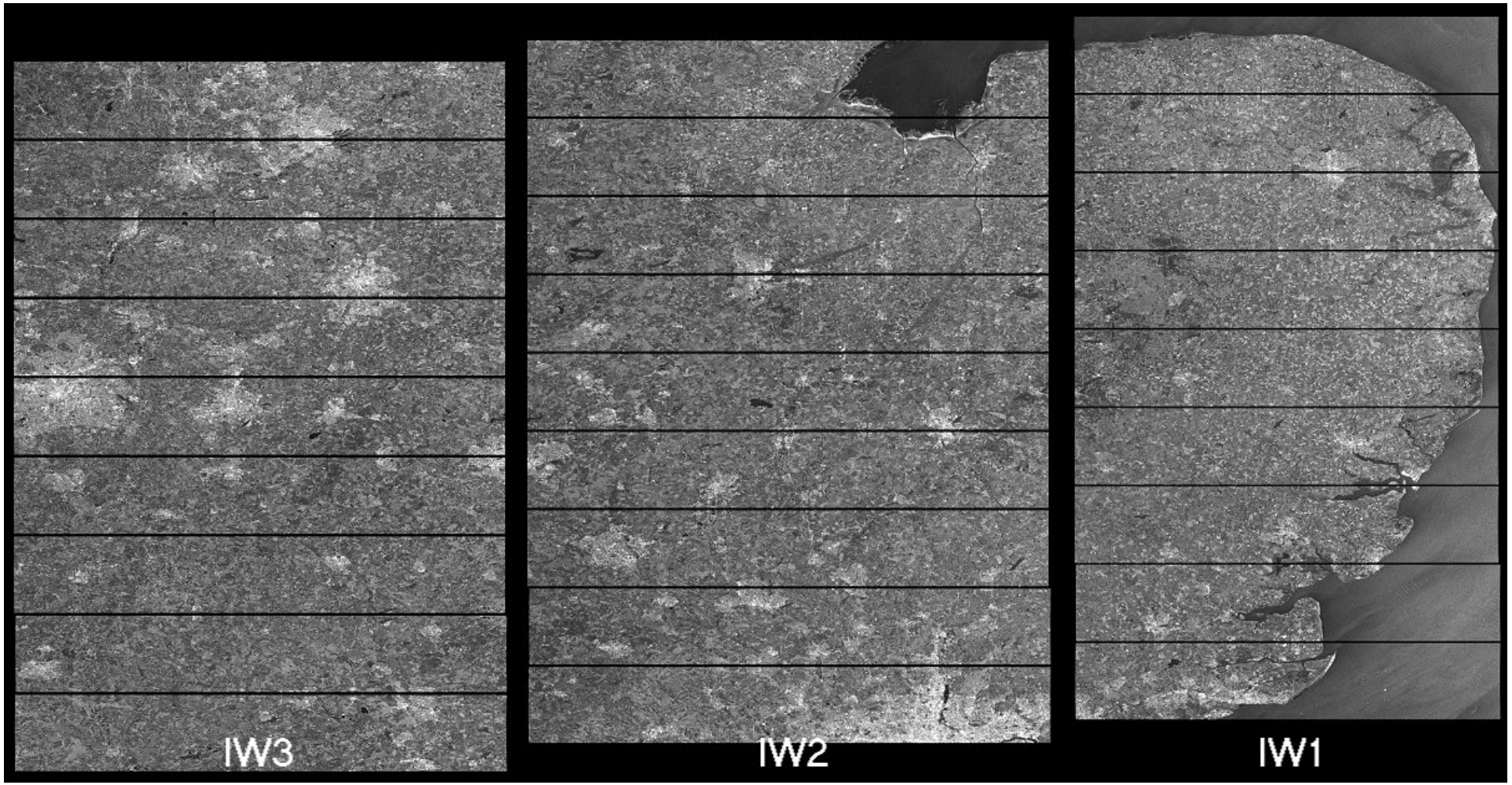
Synthetic Aperture Radar, SAR



(Tran, T. V., & Reef, R., 2026)

Synthetic Aperture Radar – Sentinel-1

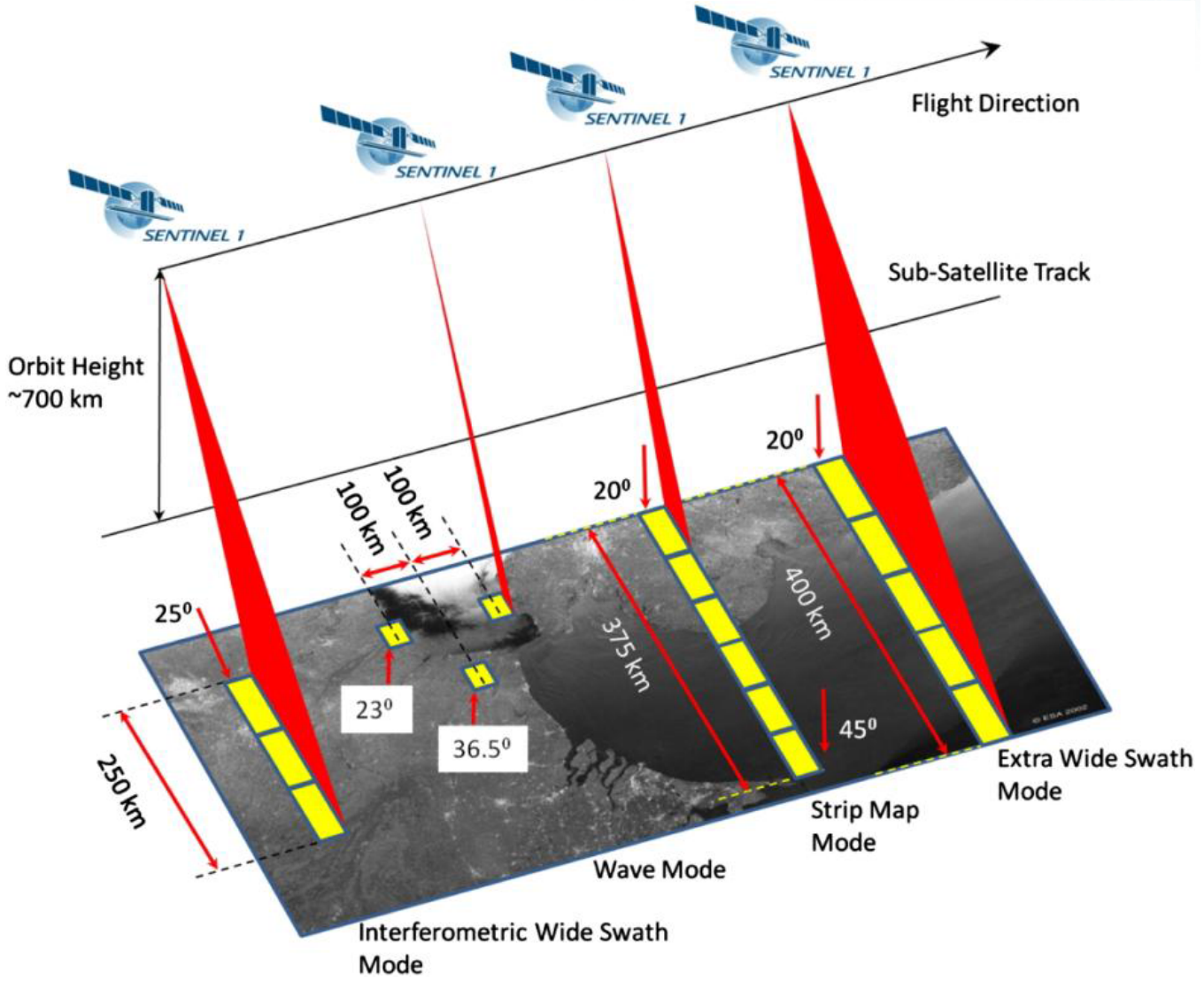
- Interferometric Wide swath (IW)



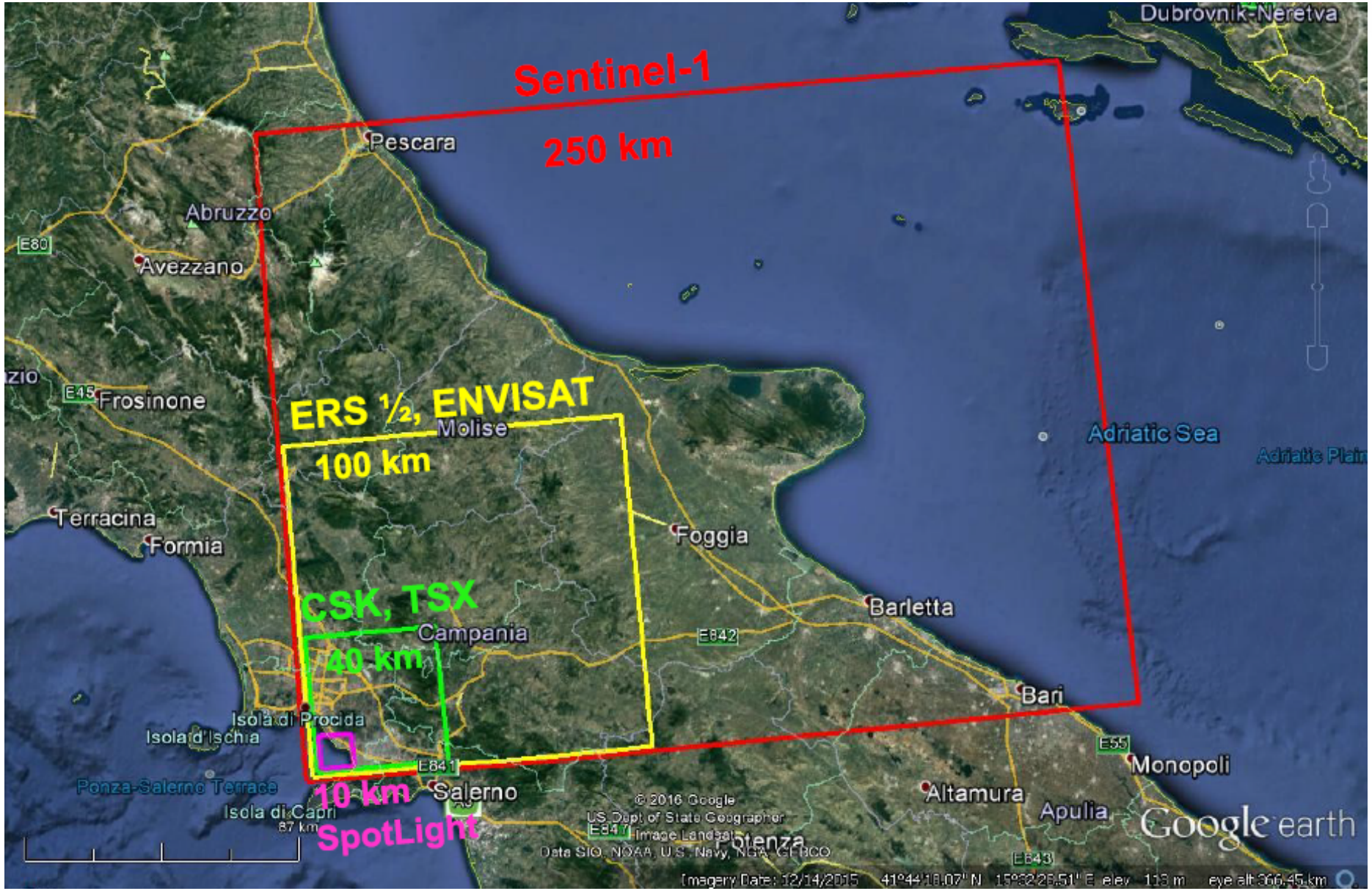
https://sentinel.esa.int/

Synthetic Aperture Radar – Sentinel-1

- **Acquisition modes**
  - **Stripmap (SM)**
    - used on request for extraordinary events
    - Swath: 80 km
    - Spatial resolution (single look): 5m*5m
  - **Interferometric Wide swath (IW)**
    - the majority of service requirements
    - Swath: 250 km
    - Spatial resolution (single look): 5m*20m
    - TOPSAR technique
  - **Extra-Wide swath (EW)**
    - used for wide area coastal monitoring (ship traffic, oil spill and sea-ice monitoring)
    - Swath: 400 km
    - Spatial resolution (single look): 20m*40m
    - TOPSAR technique
  - **Wave mode (WV)**
    - determine the direction, wavelength and heights of waves on the open oceans
    - 20 km by 20 km vignettes
    - Spatial resolution: 5m*5m

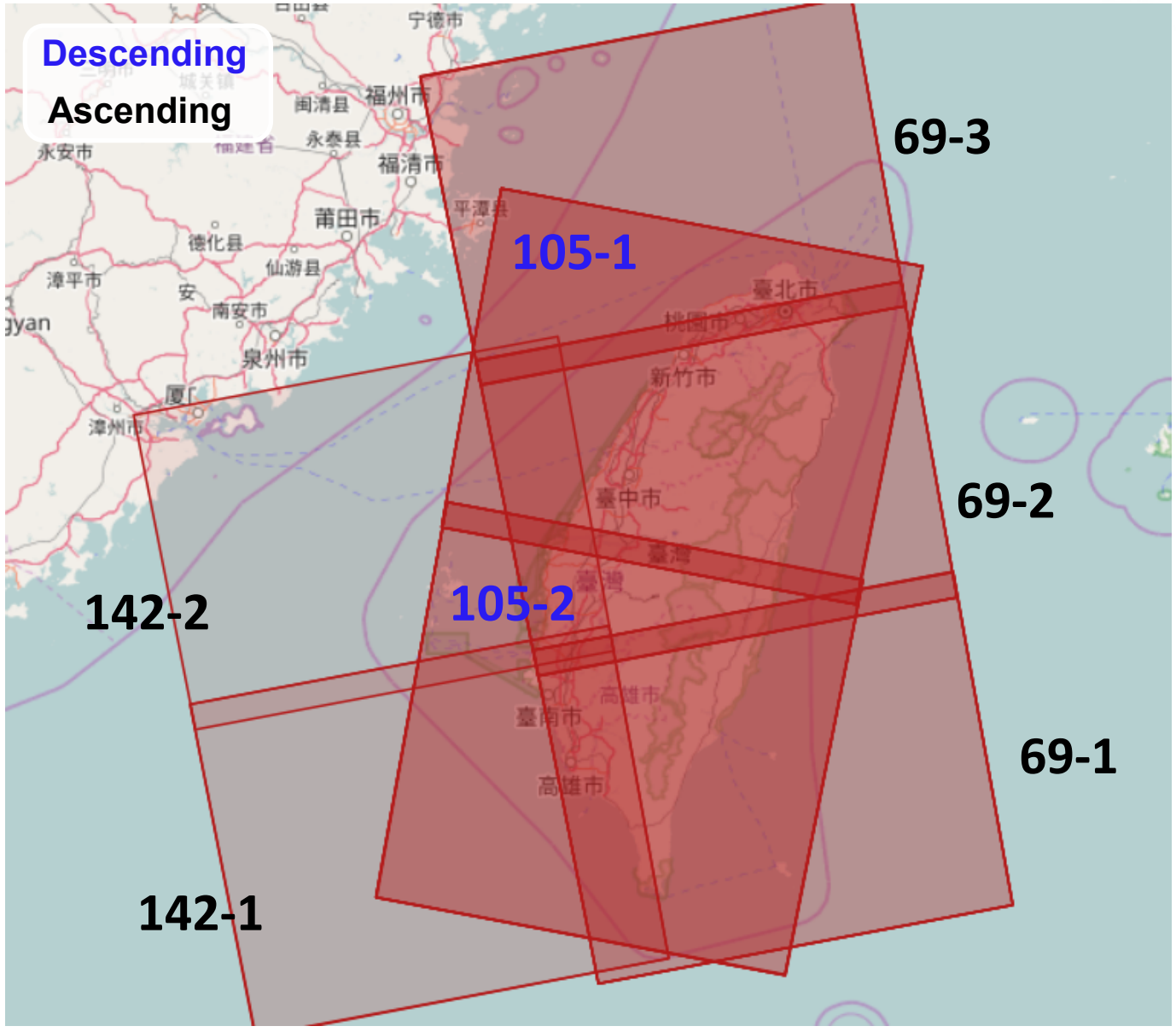


Synthetic Aperture Radar – Sentinel-1



(Wasowski, 2019)

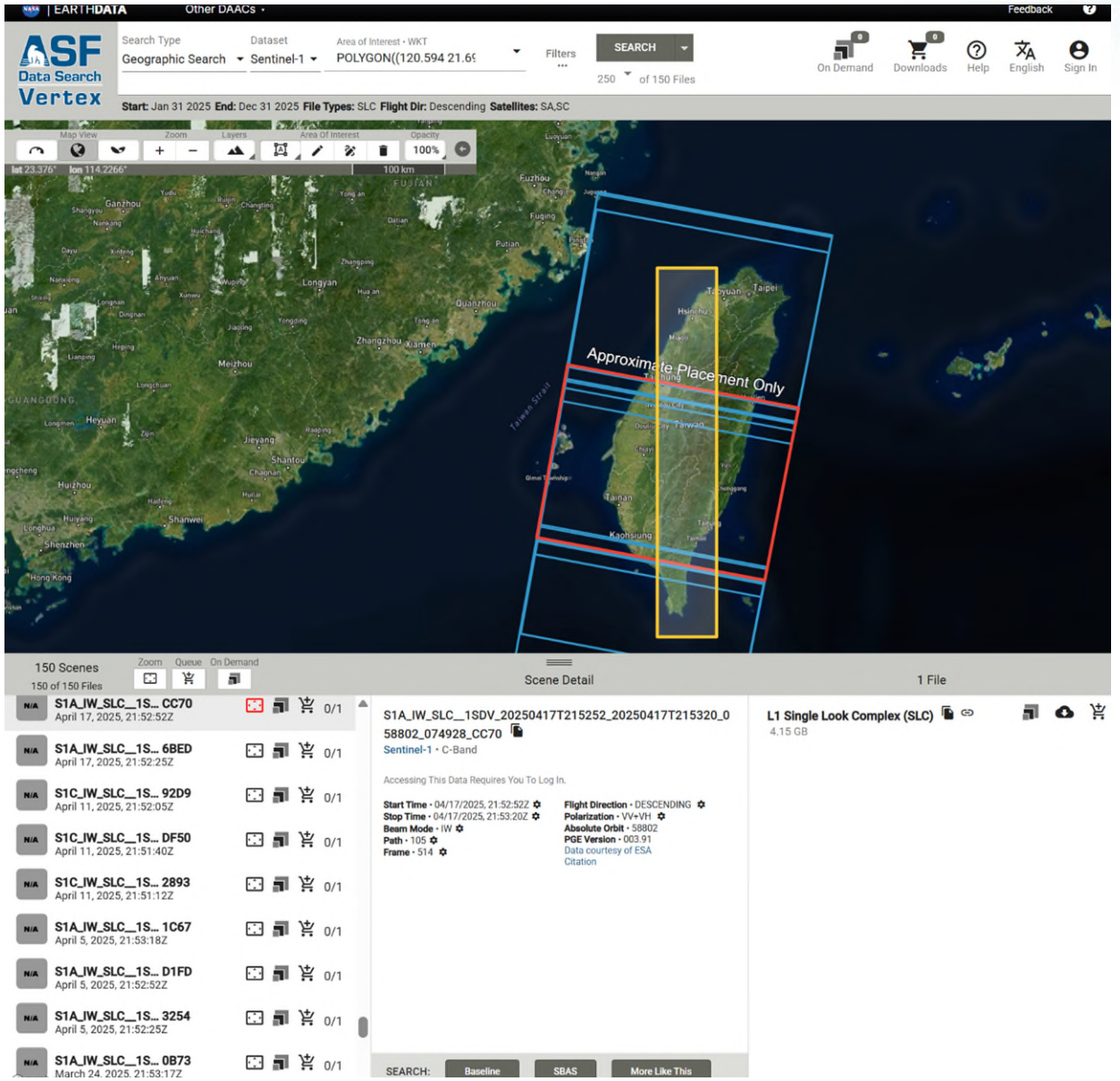
Synthetic Aperture Radar – Sentinel-1



Data Download Platforms and Analysis Software

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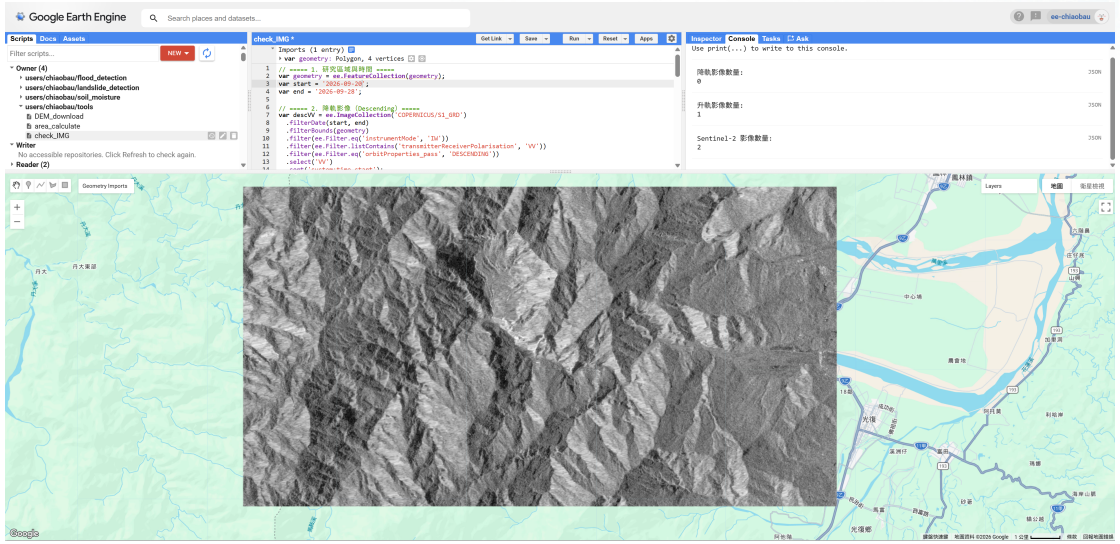
平台	主要衛星資料	特色與用途
Copernicus Data Space	Sentinel-1	免費下載 C-band SAR 影像，包含 SLC、GRD等產品
ASF Vertex	Sentinel-1、ALOS、NISAR	整合多種SAR資料適合長期監測與 InSAR 研究
JAXA G-Portal	ALOS、ALOS-2	提供日本SAR衛星部分開放資料及產品搜尋
NASA Earthdata Search	NISAR、NASA SAR 資料	整合NASA地球觀測資料，提供 SAR 影像搜尋與下載

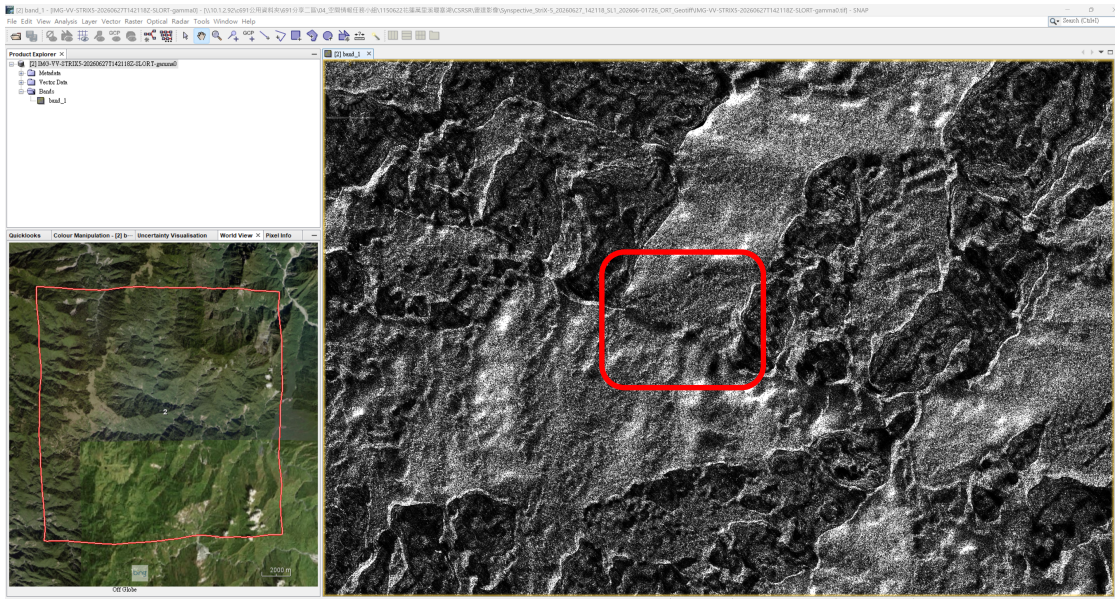


Data Download Platforms and Analysis Software

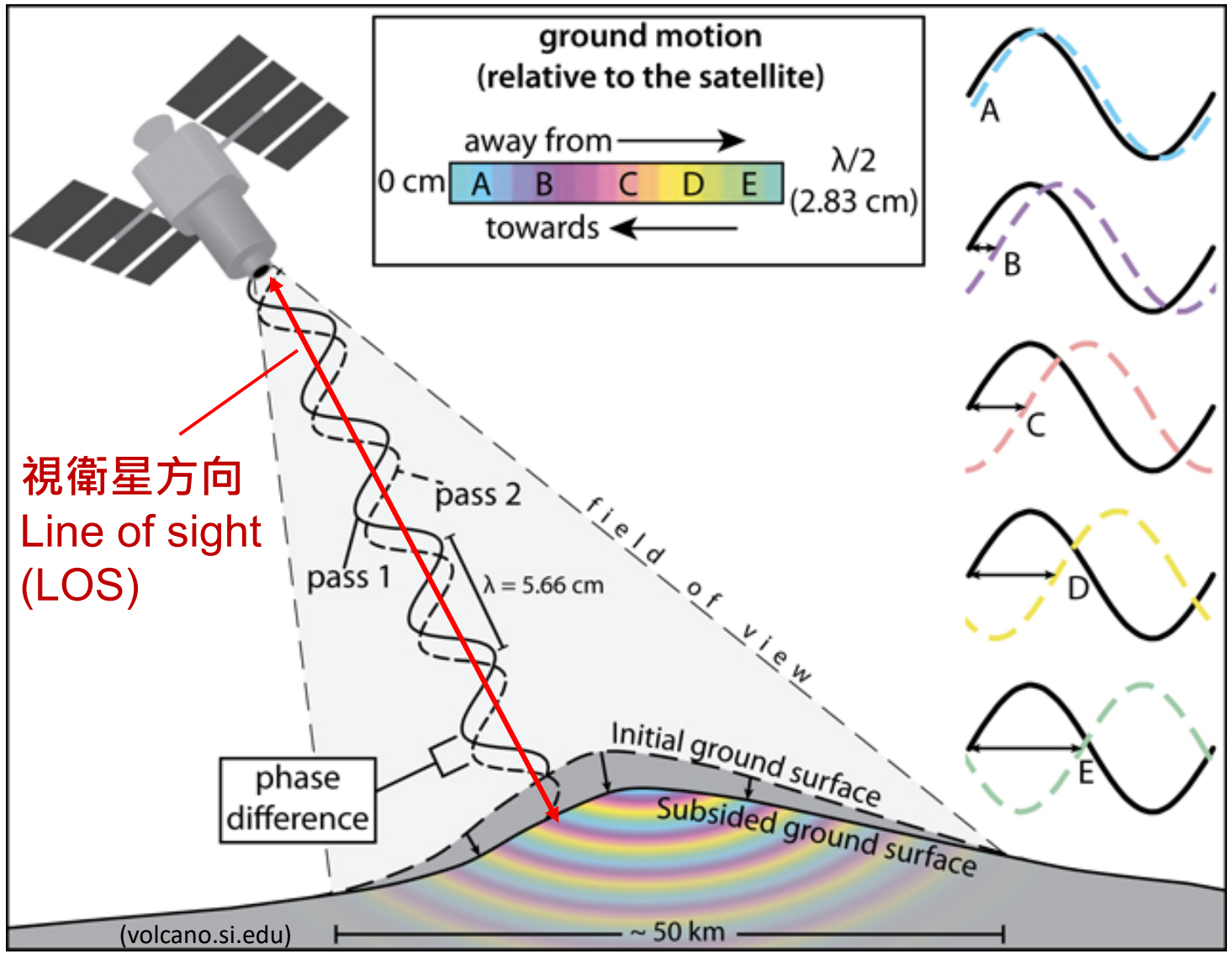
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軟體	主要功能	適合應用
Google Earth Engine (GEE)	雲端 SAR 影像處理與時序分析	水體、淹水、山崩及地表變遷判釋
ESA SNAP	SAR 影像前處理、影像配準與干涉分析	災害判釋、地表變形監測
ISCE	SAR 影像前處理、影像配準與干涉分析	災害判釋、地表變形監測
GMTSAR	SAR 影像前處理、影像配準與干涉分析、 SBAS 時序分析	地表變形監測、長期變形趨勢分析
StaMPS	PS-InSAR 與 SBAS 時間序列分析	長期地表變形監測
MintPy	SBAS 類型時間序列反演與誤差校正	長期地表變形監測





How to measure deformation from SAR?



Subtracting the phase

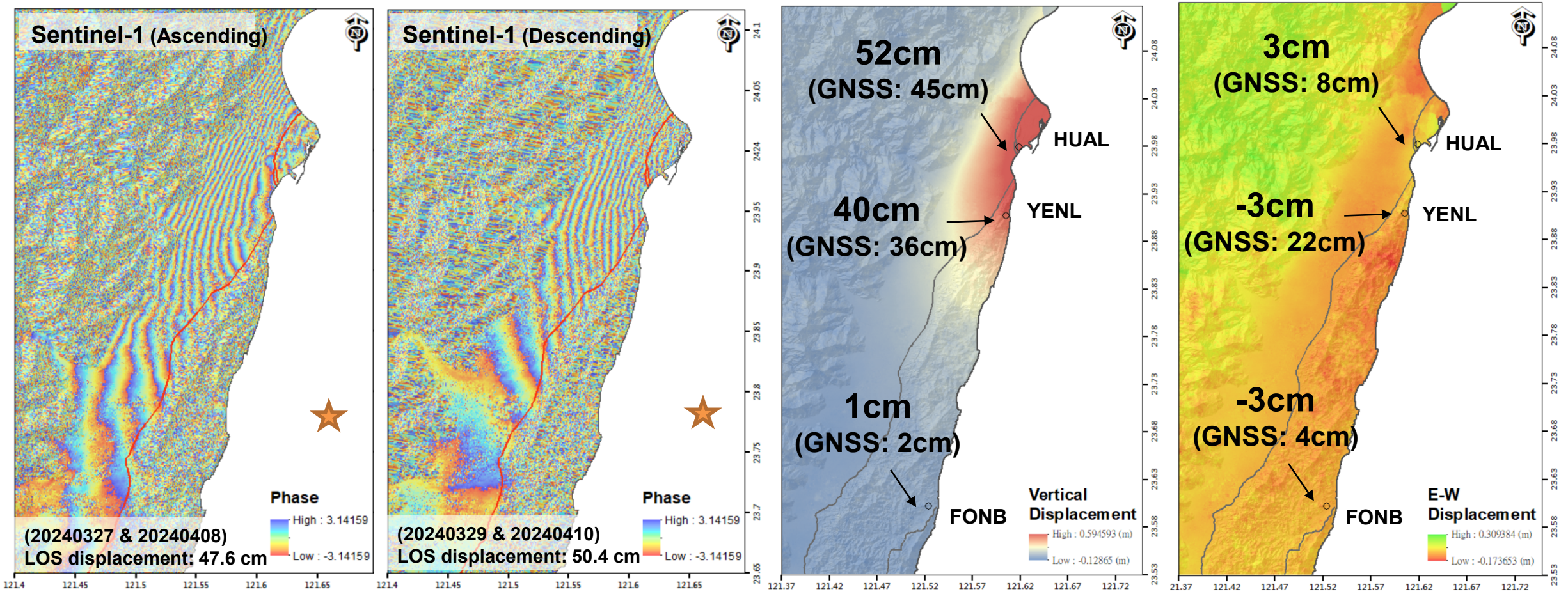
of radar waves from two SAR

images at different times.

Coseismic deformation: 0403 Hualien Earthquake

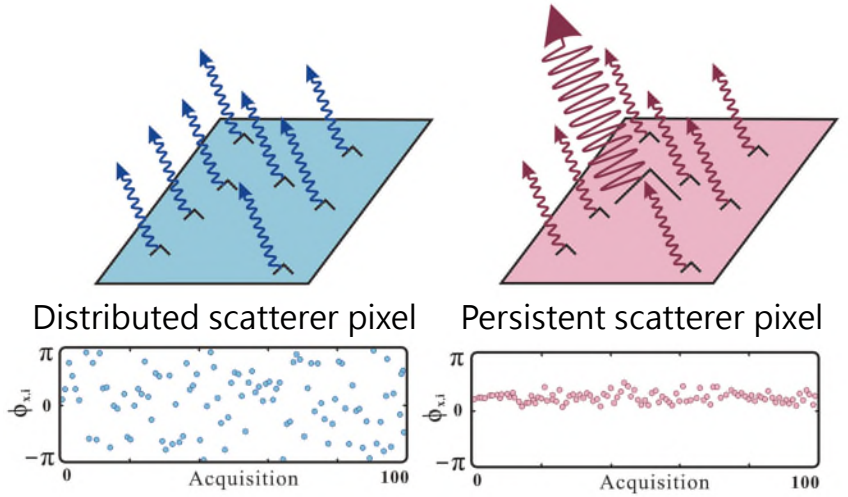
NCDR 國家災害防救科技中心

Satellite observations indicate that surface displacement ranged from about 47 cm to 50 cm along the LOS direction, with the displacement mainly occurring in Hualien City



Multi-Temporal InSAR Techniques

- **MTInSAR technique includes**
  - **PSInSAR** (Persistent Scatterer SAR Interferometric)
  - **SBAS-InSAR** (small baseline subset InSAR)
  - Other similar approaches
- **Concepts**
  - **PS: Stable and strong scatterer**, such as building, bridge and rock, which is brighter than the background scatterers
  - **DS:** involves a coherent sum of **many similarly bright scatterers** with no dominant scatterer in a resolution cell, which occur in nature environment such as lawn, fields and bare soil.

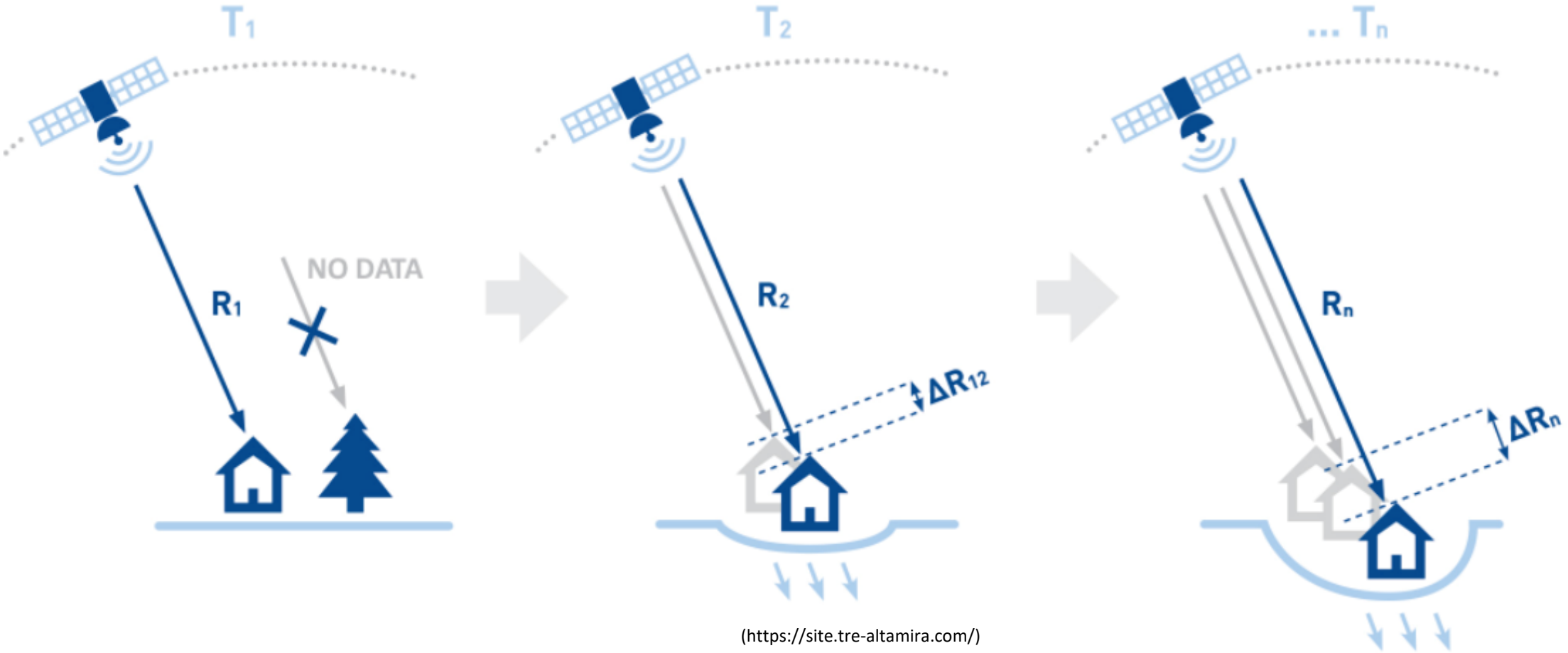


(Lu et al., 2020, Modified from Hopper et al., 2007)



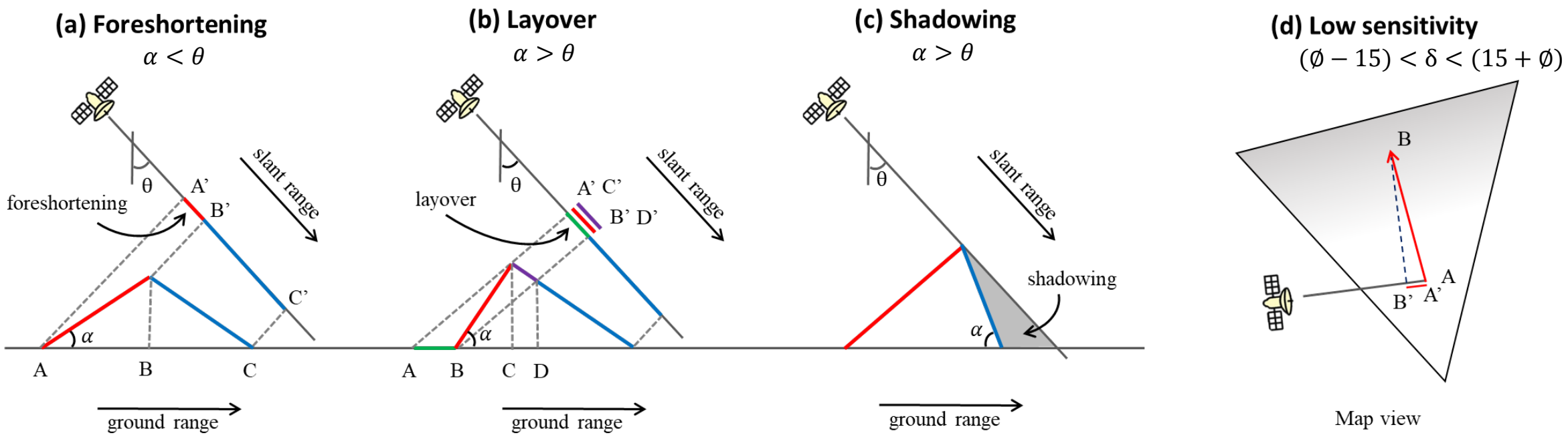
Multi-Temporal InSAR Techniques

The surface deformation could be obtained from space by measuring the phase difference of each PS/DS pixel over a period of time.



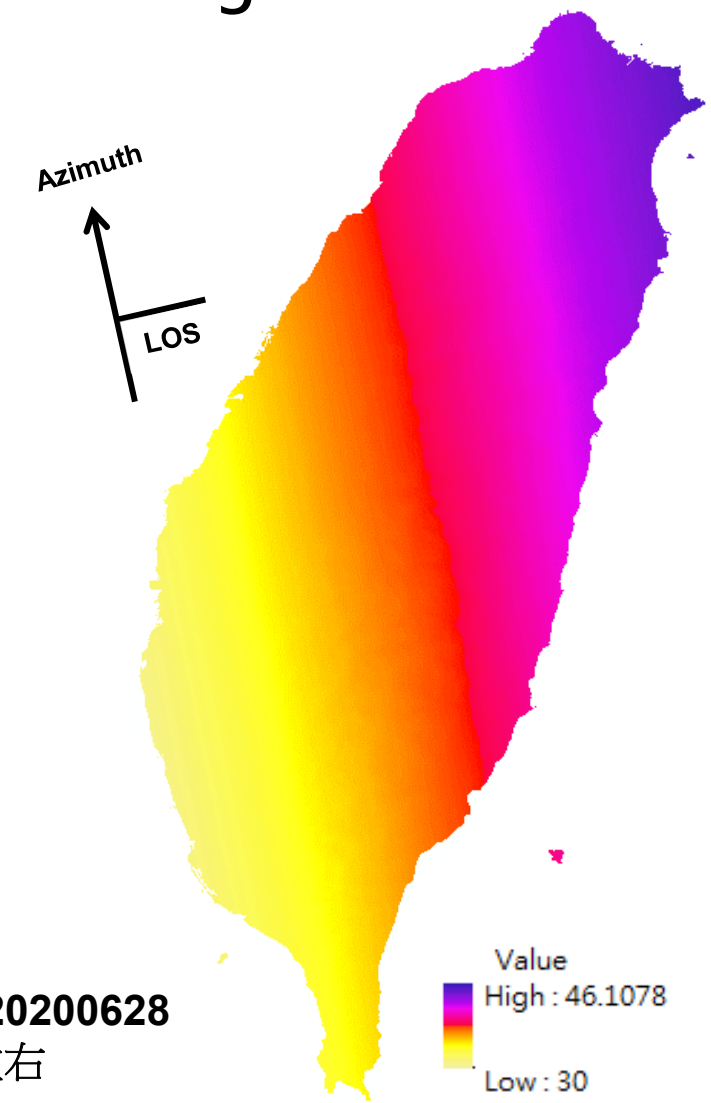
(https://site.tre-altamira.com/)

Feasibility analysis: geometrical visibility

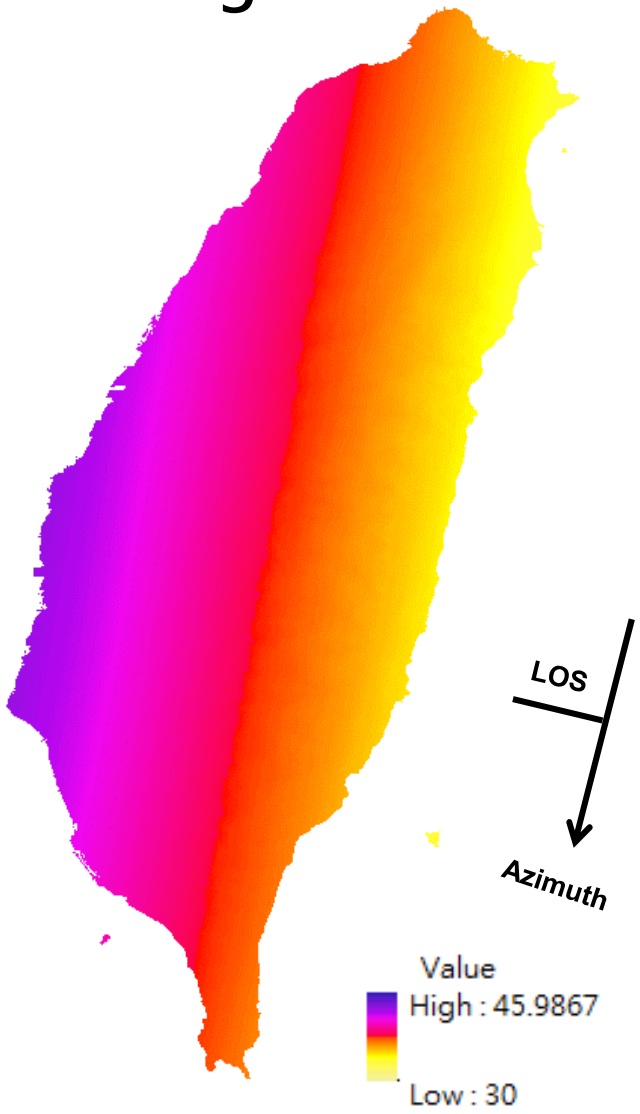


Feasibility analysis: geometrical visibility

- Ascending 20171030



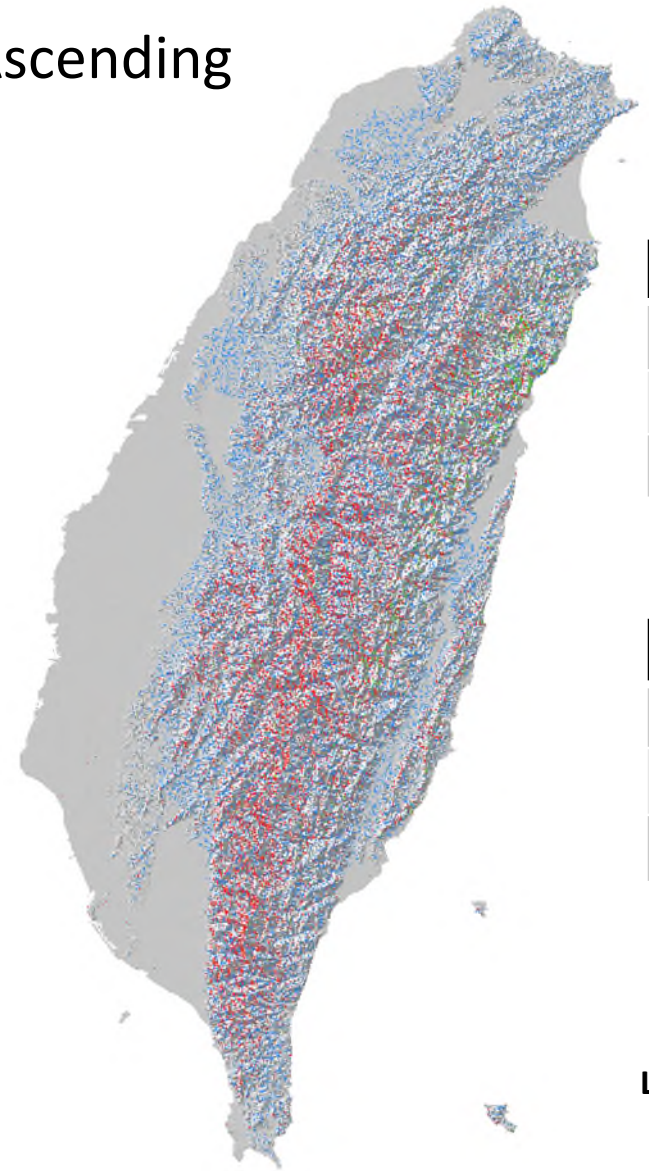
- Descending 20171030



20171030 v.s. 20200628
落在0.1-0.2度左右

Feasibility analysis: geometrical visibility

Ascending

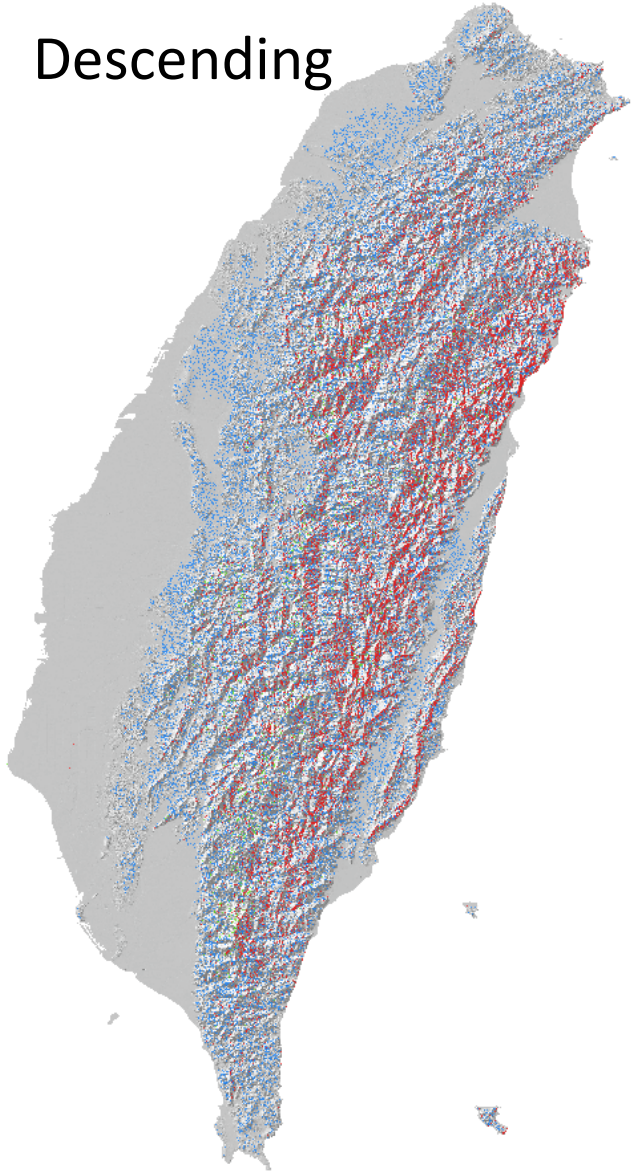


Ascending		
Layover	224707.95 (ha)	8.44%
Shadowing	27681.39 (ha)	1.04%
Low sensitivity	448,885 (ha)	16.85%

Descending		
Layover	242230.14 (ha)	9.09%
Shadowing	19354.05 (ha)	0.72%
Low sensitivity	437,814 (ha)	16.44%

Layover Shadowing Low Sensitivity

Descending

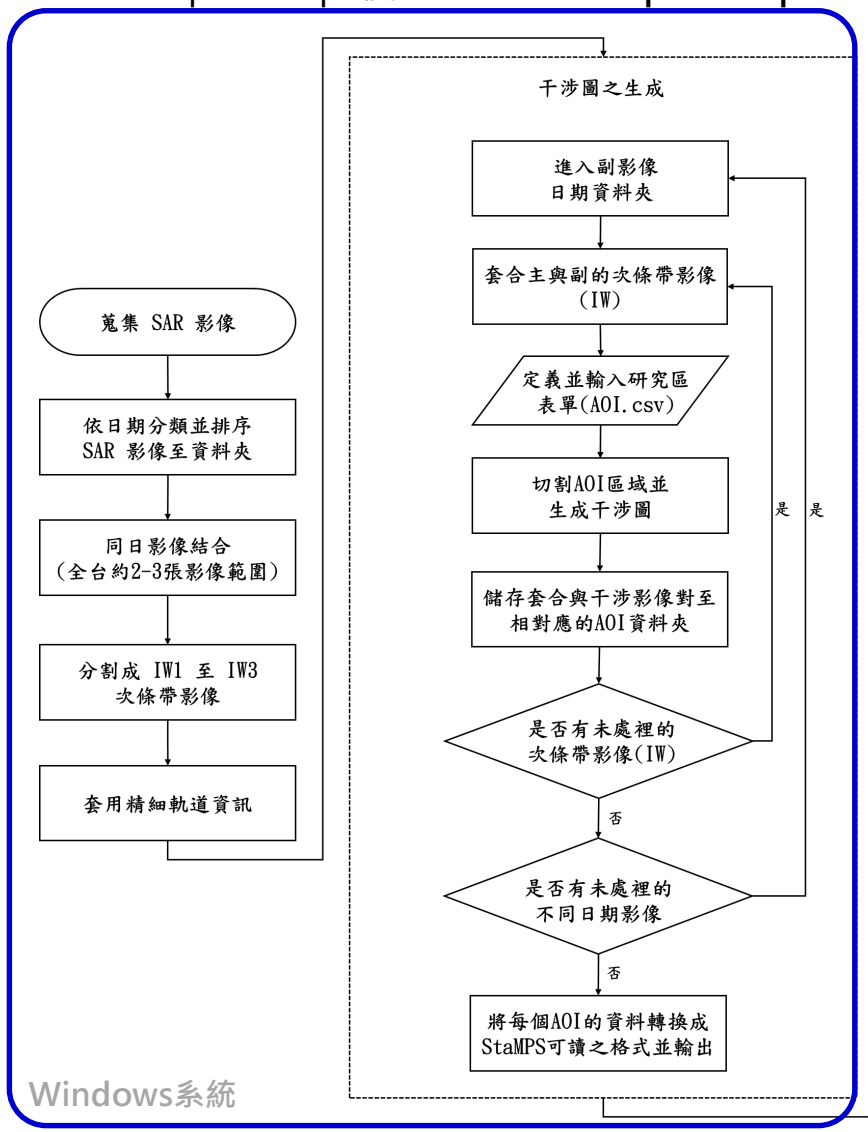


Optimization of MTInSAR Processing Workflow

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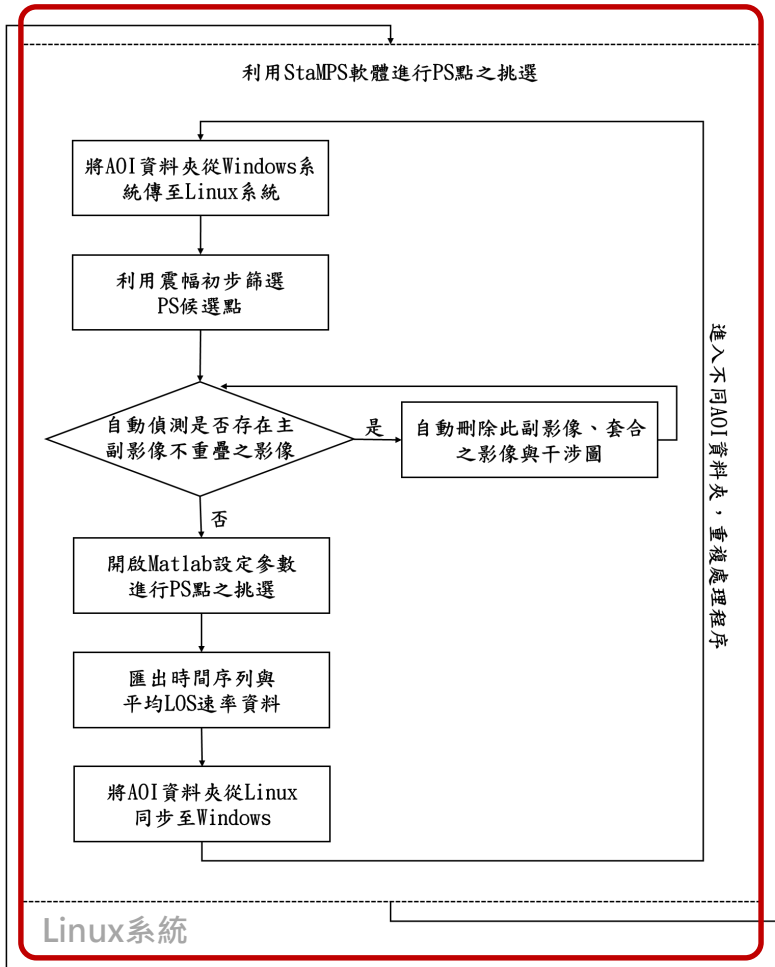
分區同步之干涉圖生成

將snap2stamps優化為**multi-snap2stamps**



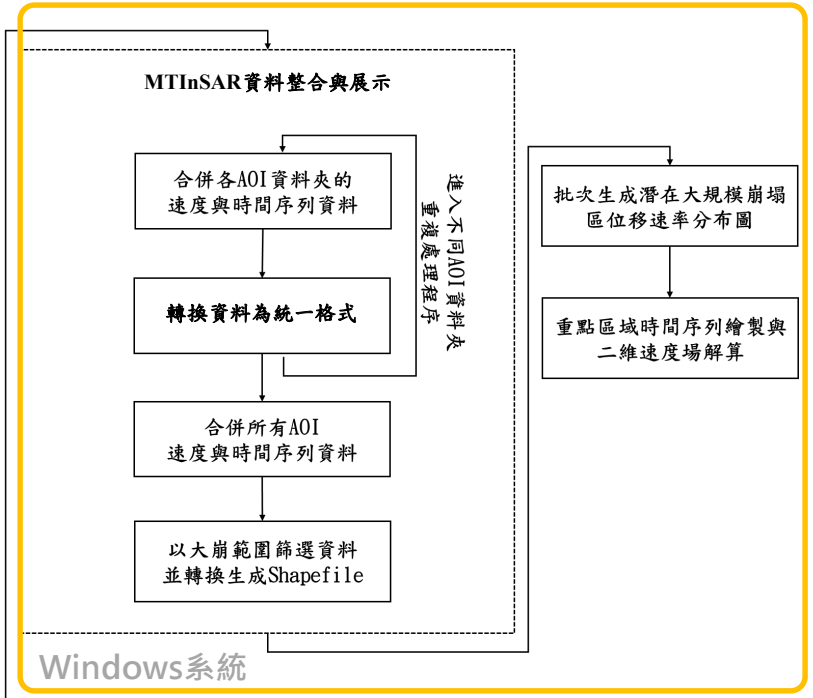
MTInSAR分析流程優化

自動化且批次: 資料傳輸、PS候選點篩選、偵測是否存在套合不完全之影像對、進入PS點篩選分析、速度與時間資料的輸出



資料整合與展示

InSAR 資 料 轉 換 與 整 合 、批次生成潛在大規模崩塌區位移速率分布圖

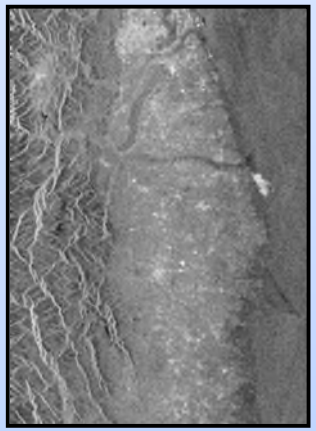


Optimization of MTInSAR Processing Workflow

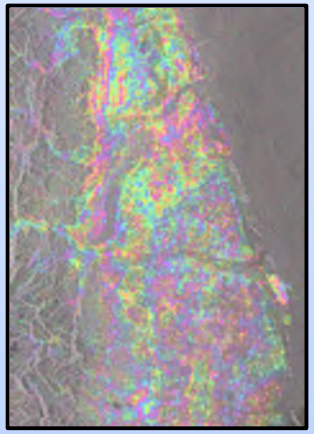
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DInSAR

SAR images



Interferograms

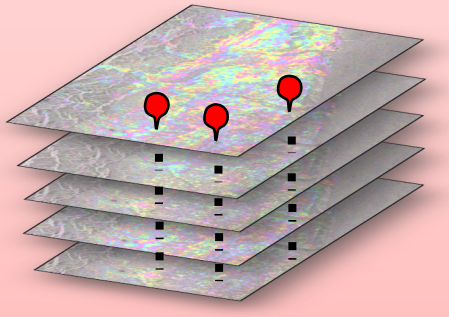


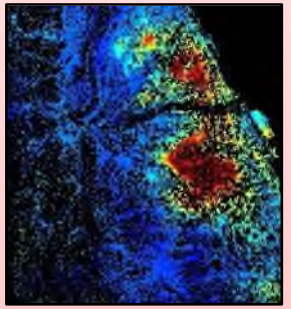
Sentinel Application Platform, SNAP

InSAR Scientific Computing Environment, ISCE

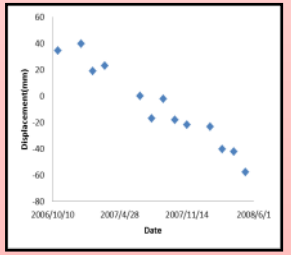
MTInSAR

Phase stability estimation and PS selection





Velocity field map



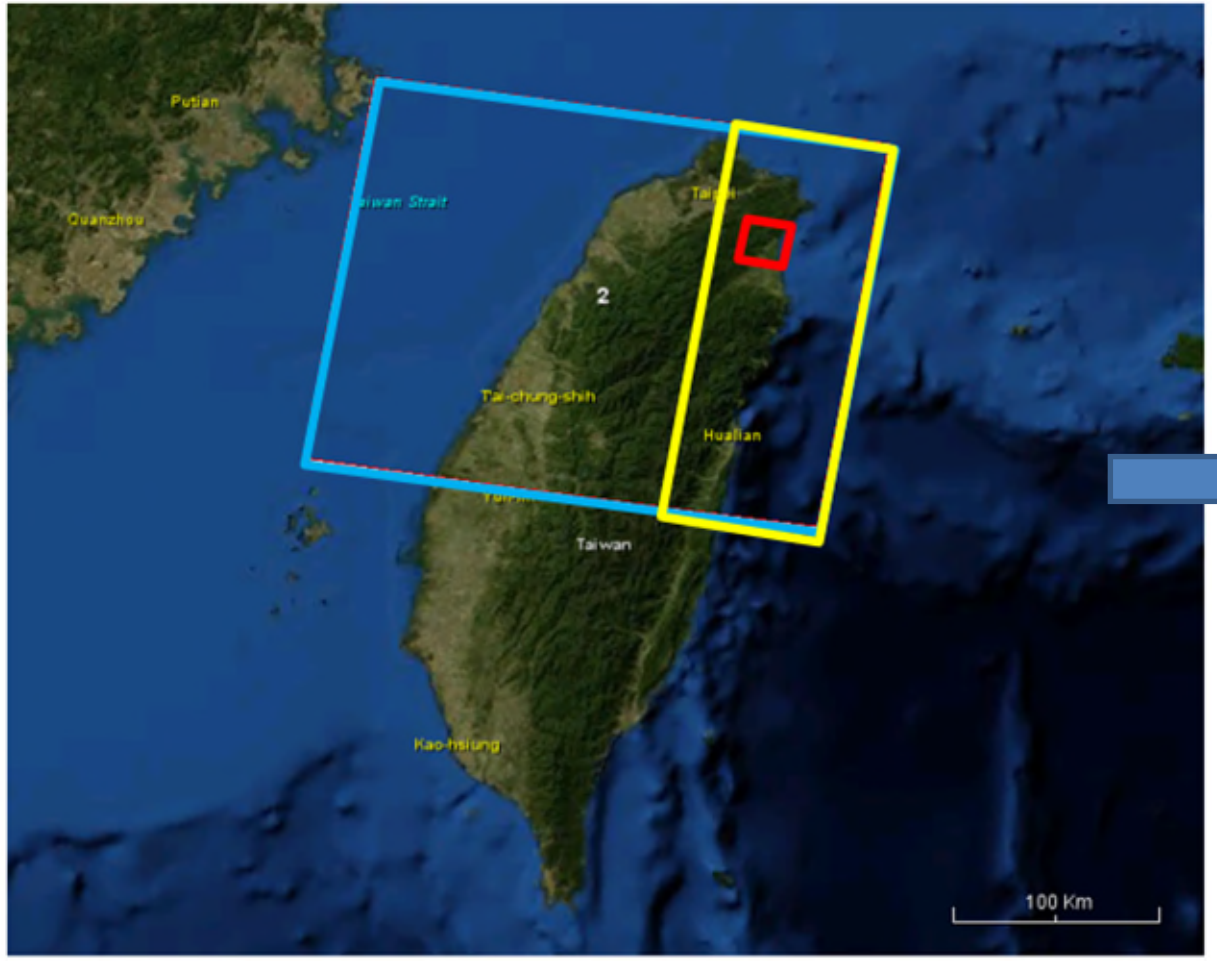
Displace-ment time series

Stanford Method for Persistent Scatterers, StaMPS

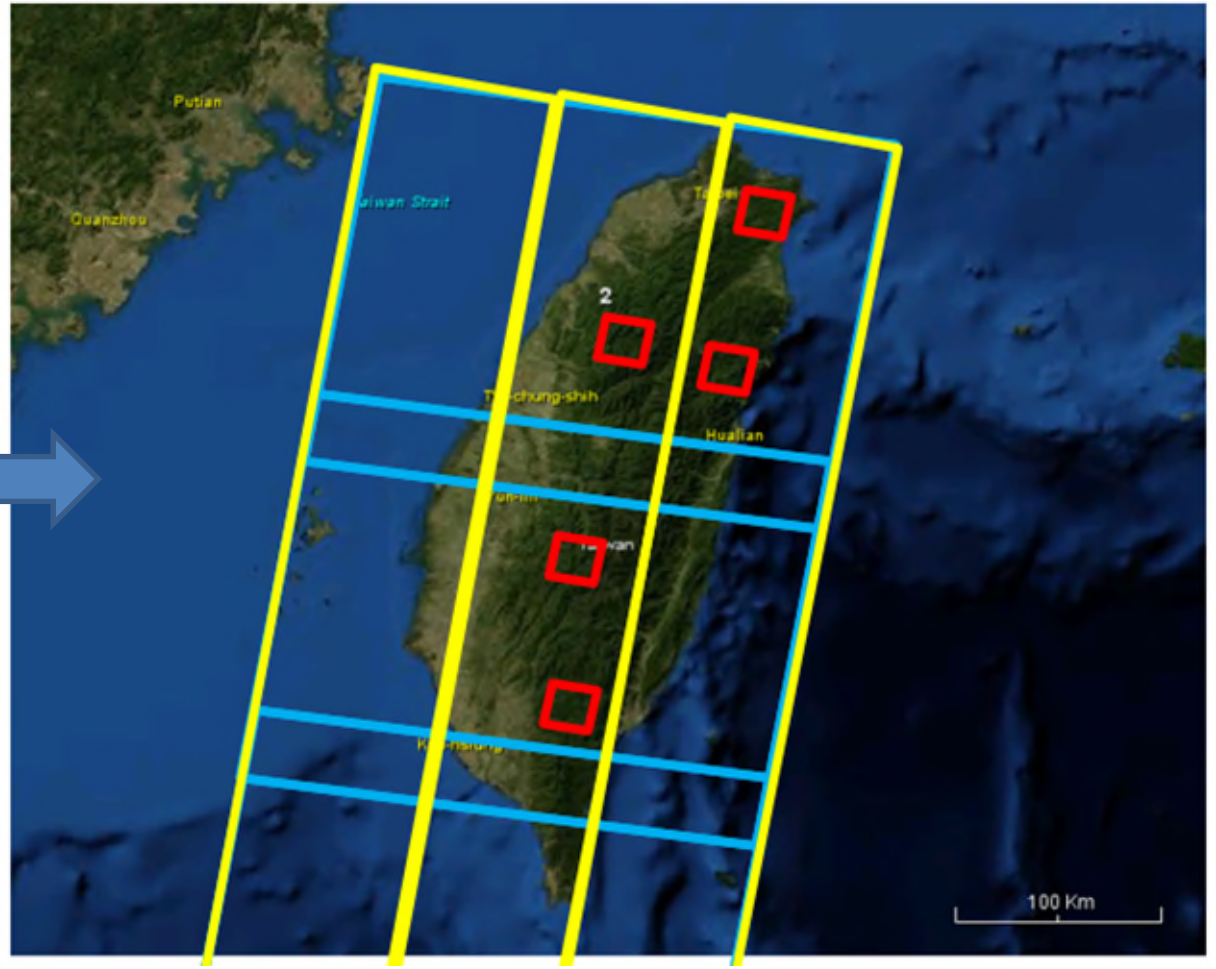
Optimization of MTInSAR Processing Workflow

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Processing interferograms of only **one** study area



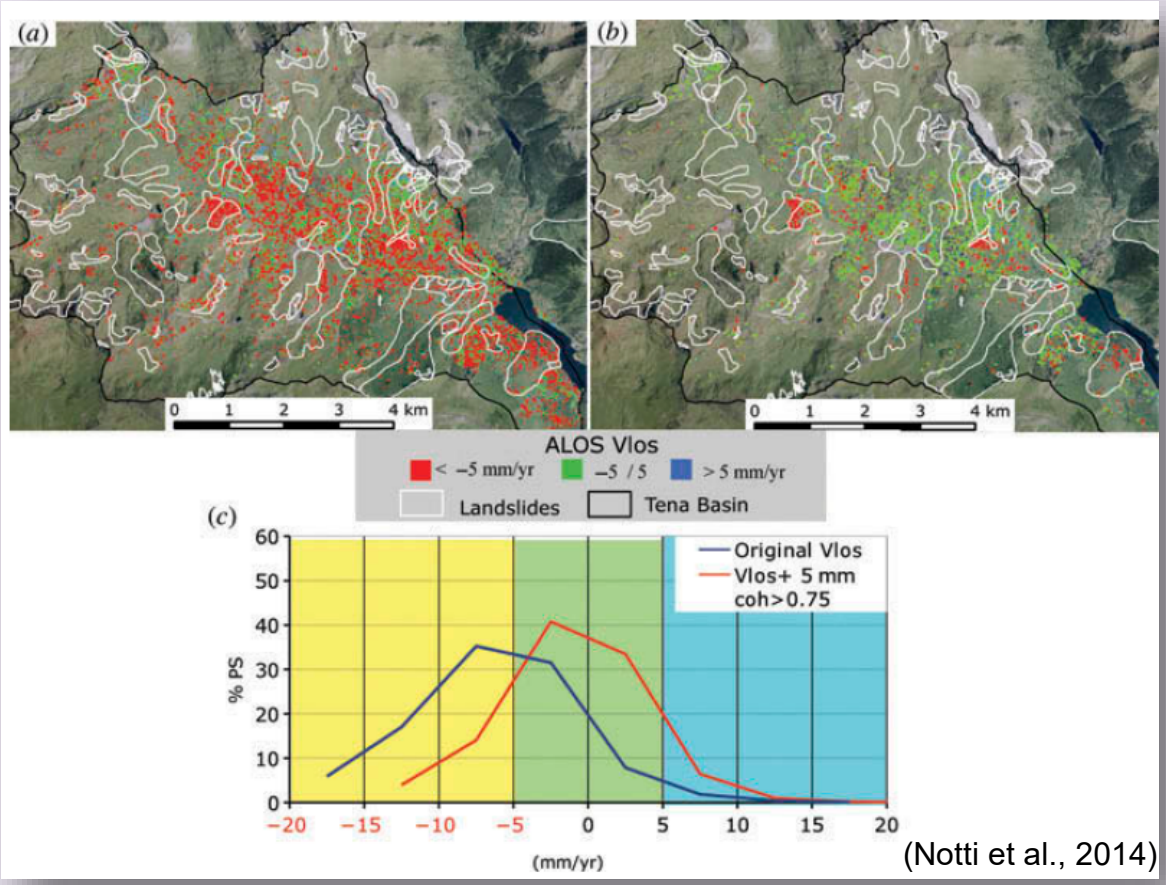
Processing interferograms of **multiple** study area



Optimization of MTInSAR Processing Workflow

Threshold of activity

- For C-band and X-band, the stability threshold could be ±**2 mm/yr**, and for L-band data the stability threshold could be ±5 mm/yr.



(Notti et al., 2014)

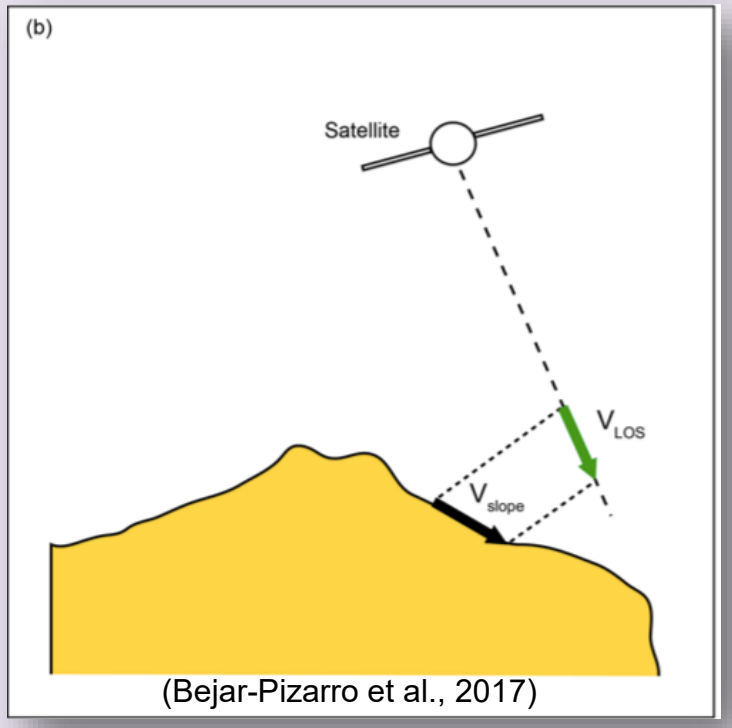
Data interpretation

- **Threshold of activity:** Determine a threshold velocity to assess the state of activity
- **Vslope**：Projection of the LOS velocity along the steepest slope
- **2D velocity field**：of two geometries allows the E–W and vertical velocity components to be resolved

Optimization of MTInSAR Processing Workflow

Projection of the LOS velocity along the steepest slope

- This projection was designed to **compare landslide velocities** with **different slope aspects**.
- The projection is assumed that the landslide movement is **parallel to the slope**.



(Bejar-Pizarro et al., 2017)

$$V_{SLOPE} = V_{LOS}/C$$

$$C = (nlos * \cos(S) * \sin(A - 1.571)) + (elos * (-1 * \cos(S) * \cos(A - 1.571)) + (hlos * \sin(S)))$$

$$hlos = \cos(\alpha)$$
$$nlos = -1 * \cos(1.571 - \alpha) * \cos(3.142 - \theta)$$
$$elos = -1 * \cos(1.571 - \alpha) * \cos(4.712 - \theta)$$

Parameters:
coefficient C、slope (S)、aspect (A)、LOS (nlos, hlos, and elos)、incidence angle (α)、LOS azimuth (θ)

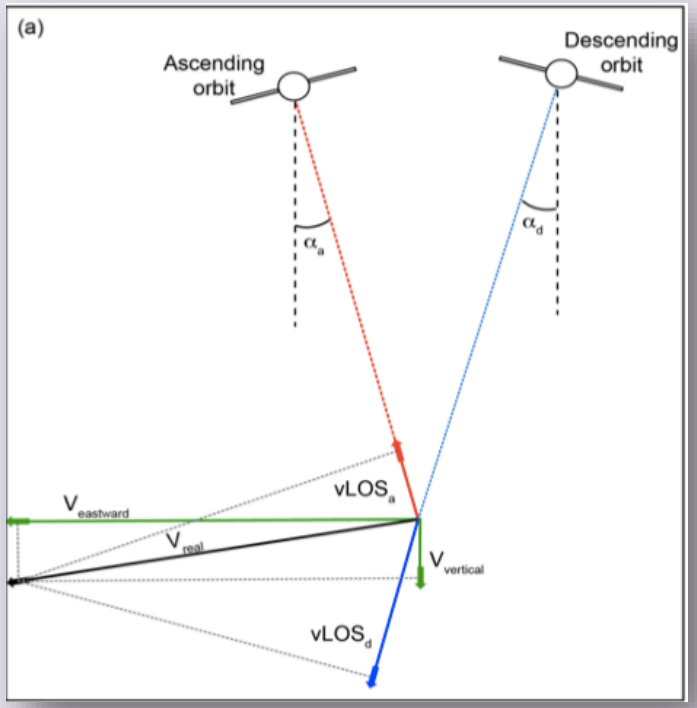
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Optimization of MTInSAR Processing Workflow

Component of the LOS velocity

- When the deformation field is obtained in two different viewing geometries, the **2-D deformation field** assuming that the north component is negligible could be obtained.



(Bejar-Pizarro et al., 2017)

$$VEL_{EW} = \frac{((Vel_d/hlos_d) - (Vel_a/hlos_a))}{(elos_d/hlos_d - elos_a/hlos_a)}$$

$$VEL_{VERT} = \frac{((Vel_d/elos_d) - (Vel_a/elos_a))}{(hlos_d/elos_d - hlos_a/elos_a)}$$

$$hlos = \cos(\alpha)$$
$$nlos = -1 * \cos(1.571 - \alpha) * \cos(3.142 - \theta)$$
$$elos = -1 * \cos(1.571 - \alpha) * \cos(4.712 - \theta)$$

Parameters:
ascending velocity(Vel_a)、descending velocity (Vel_d)、LOS (nlos, hlos, and elos)、incidence angle (α)、LOS azimuth (θ)

Data interpretation

- **Threshold of activity:** Determine a threshold velocity to assess the state of activity
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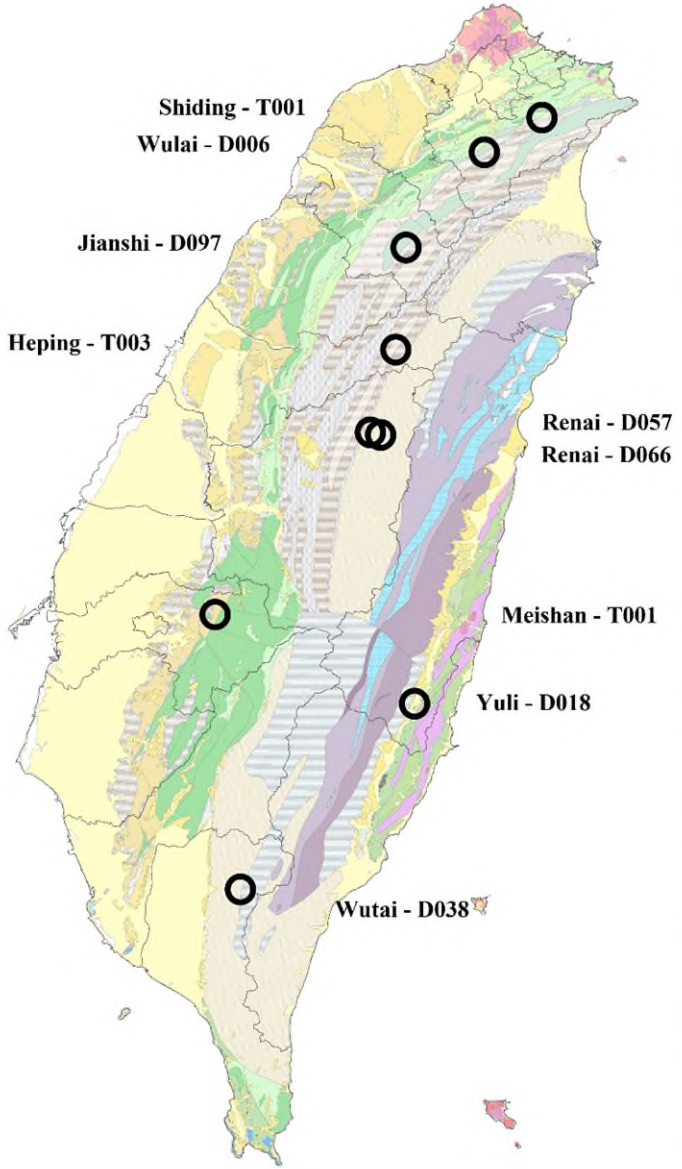
Slow-moving Landslides

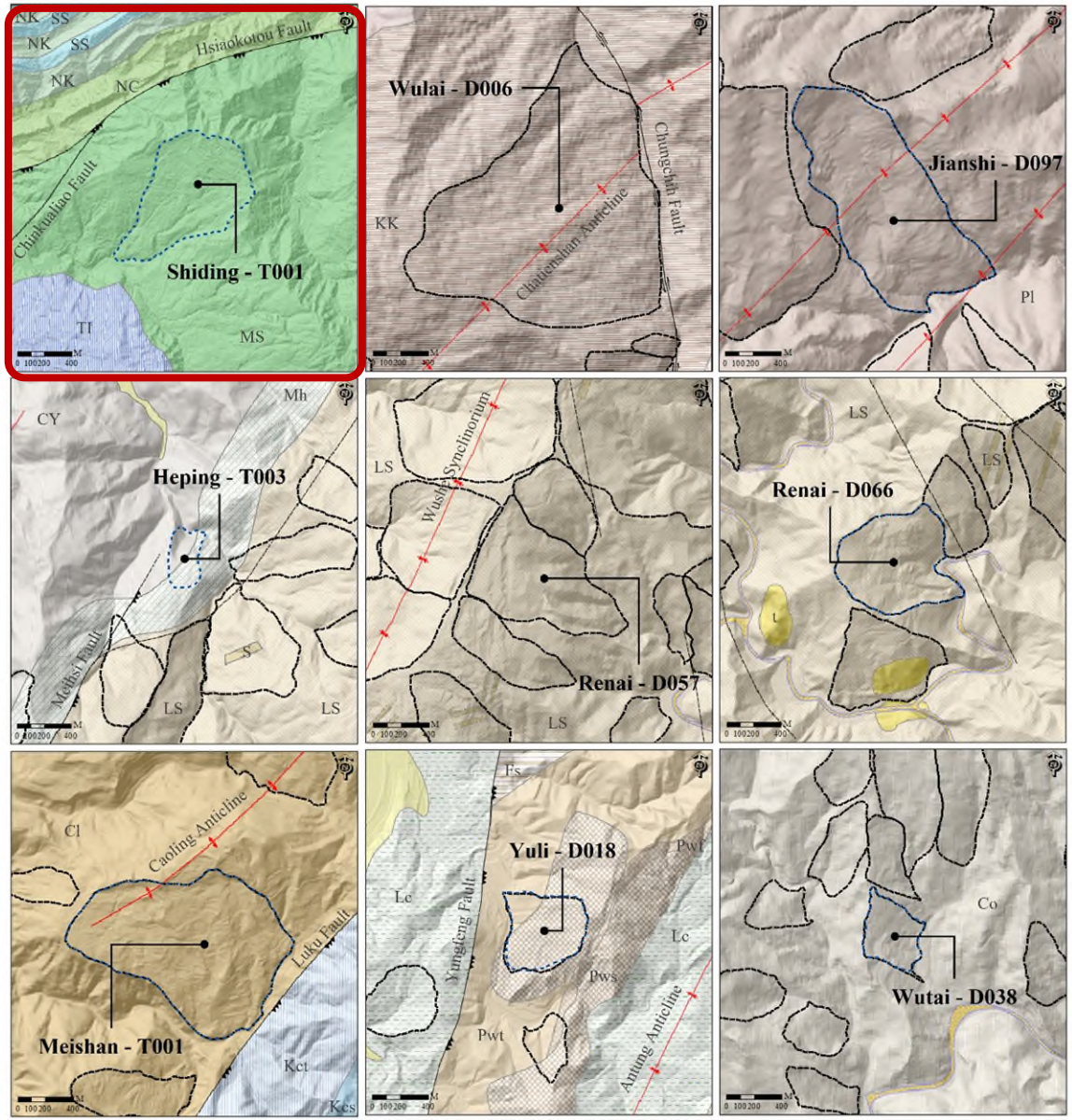
- The velocity of slow-moving landslides ranges from millimeters to meters per year
- Have the opportunity to transform to much more destructive rapid landslides
- Accelerated motion may be a precursor of a rapid landslide

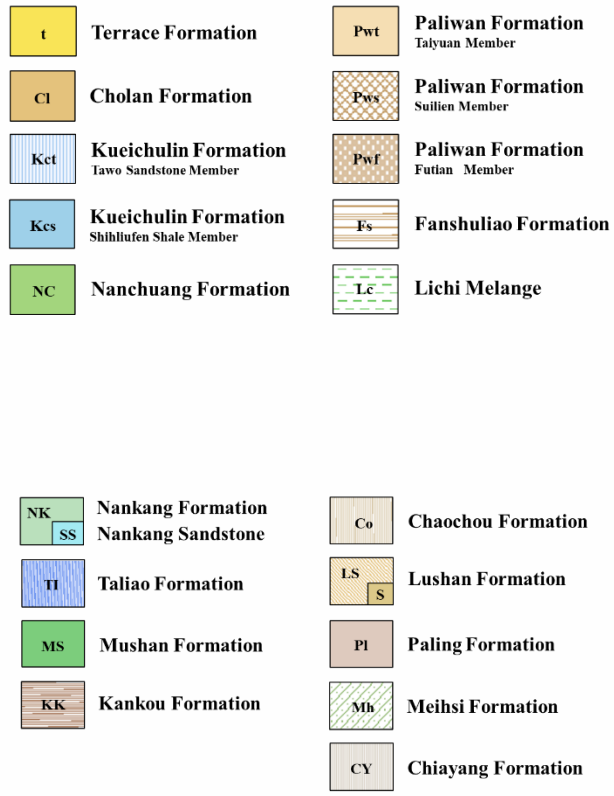


2018 Peru (By Galeria del Ministerio de Defensa del

Pre-existing slow-moving landslides





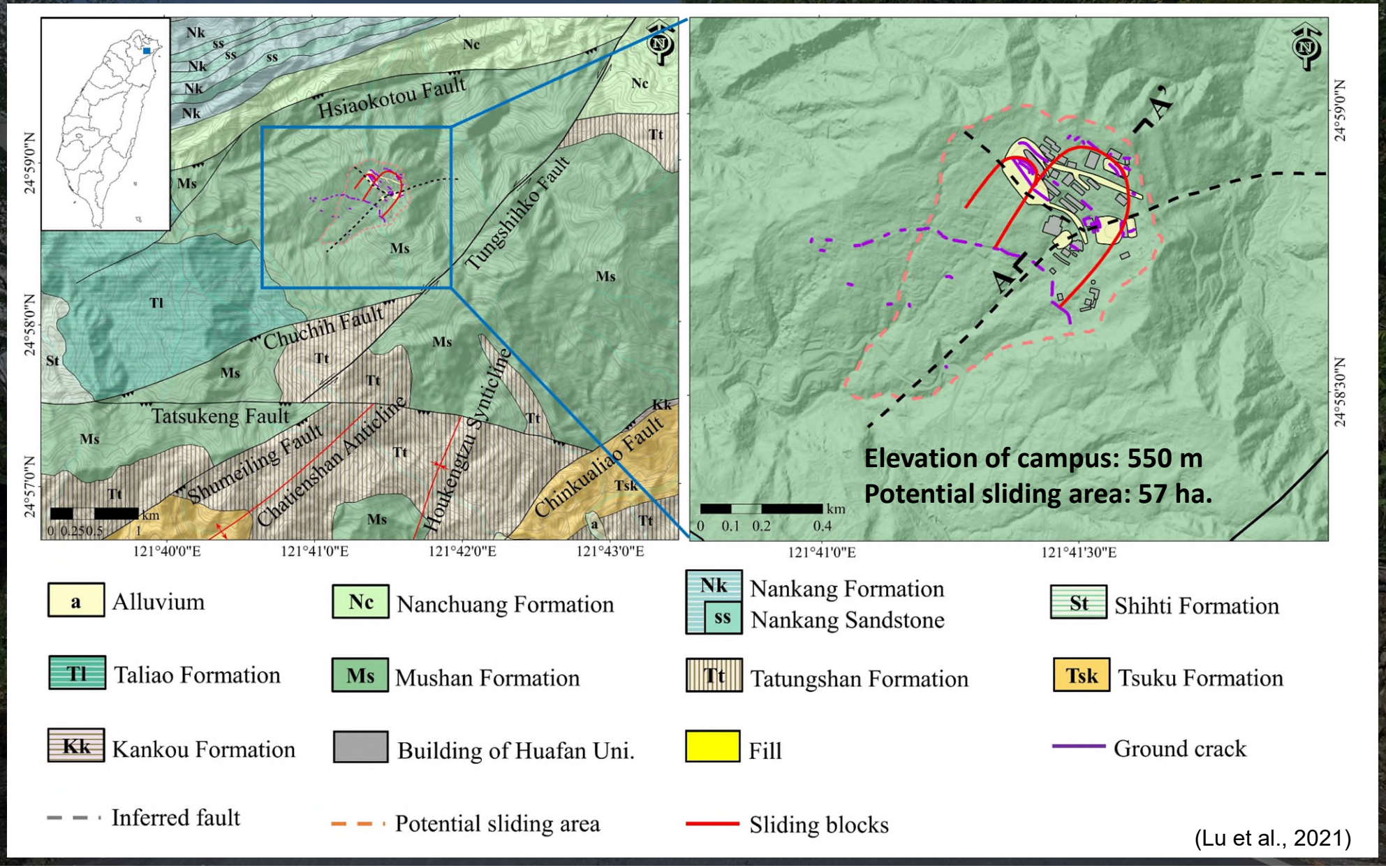


(Lu et al., 2023)



The HuaFan University is constructed on the upper part of this slope and the slow-moving phenomenon has been observed since 1990

Background of the Dalun Mountain area (Shiding-T001)

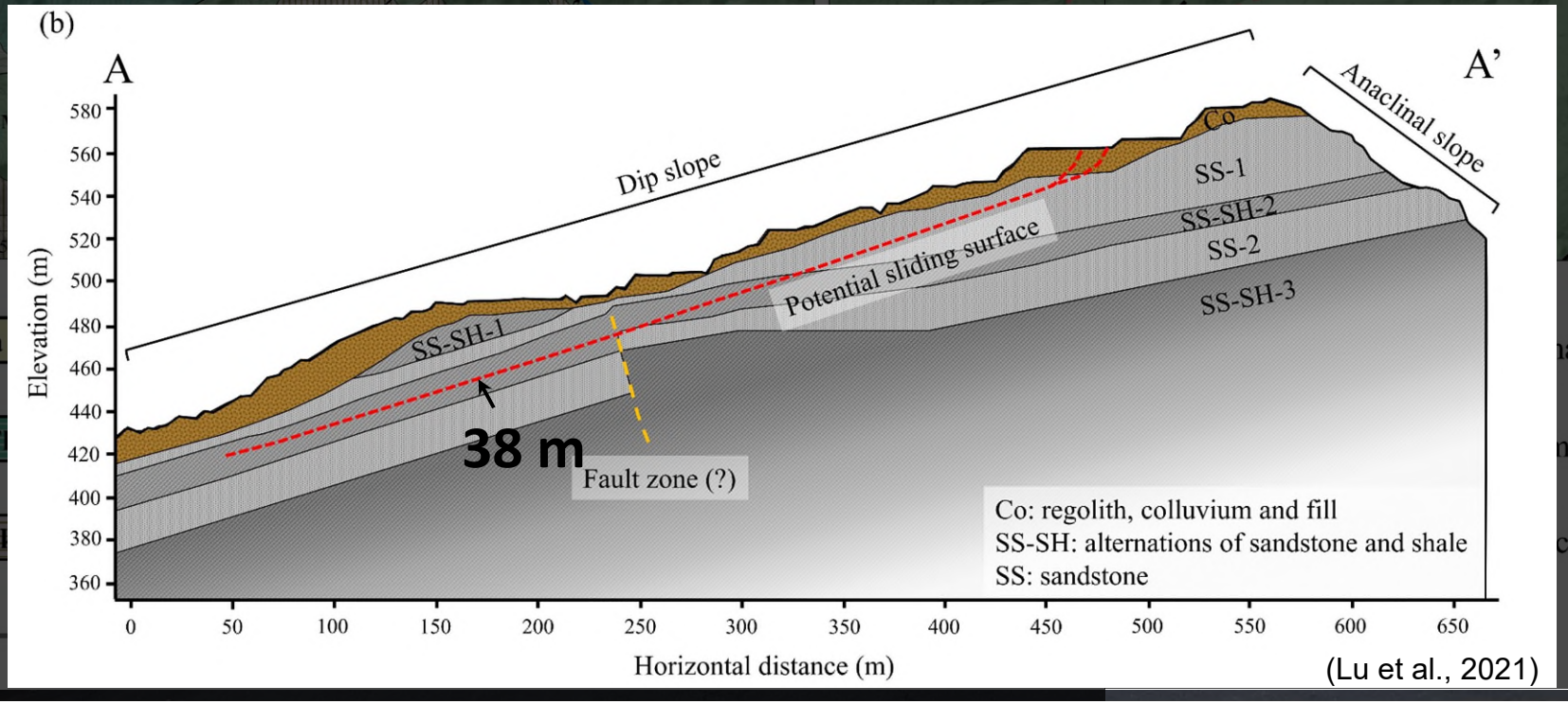


(Lu et al., 2021)

Background of the Dalun Mountain area (Shiding-T001)

- Alternations of sandstone and shale (N55°W/ 20°SW)
- Dip slope with average dip angle of about 20° toward the southwest





(Lu et al., 2021)

Background of the Dalun Mountain area (Shiding-T001)

- Average sliding velocity: about 2-3 cm/yr
- During heavy rainfall or typhoon events, the sliding velocity of this unstable slope increases significantly
- Many facilities on the campus have experienced noticeable damage

Background of the Dalun Mountain area (Shiding-T001)



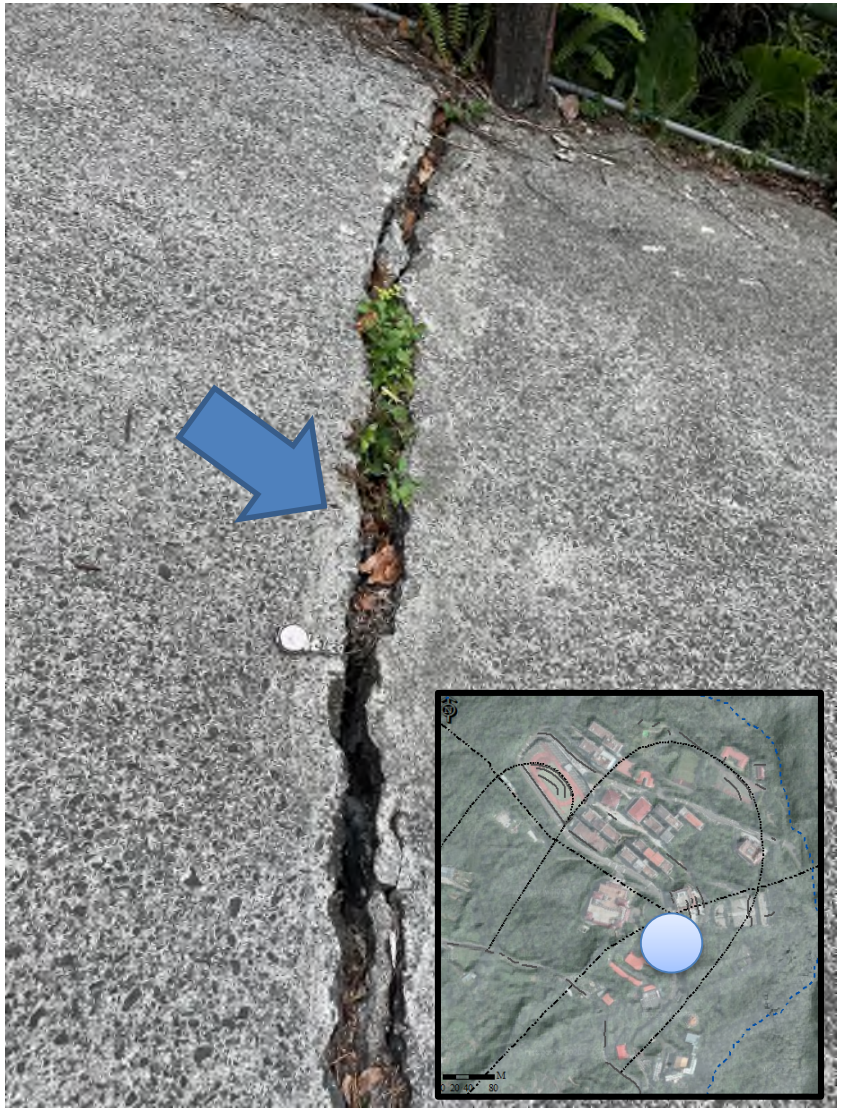


Basketball court



Background of the Dalun Mountain area (Shiding-T001)

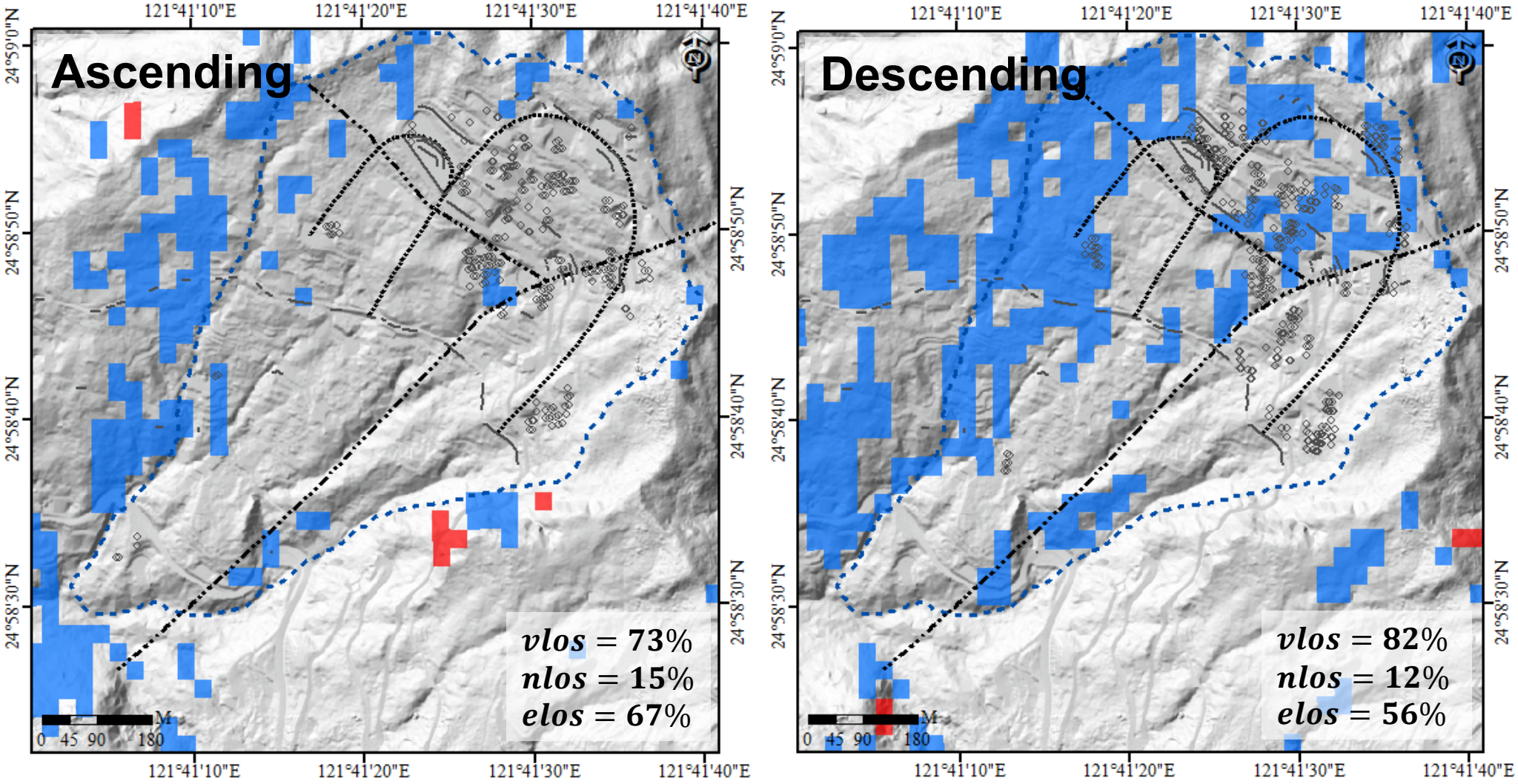
NCDR 國家災害防救科技中心







The results of geometrical visibility

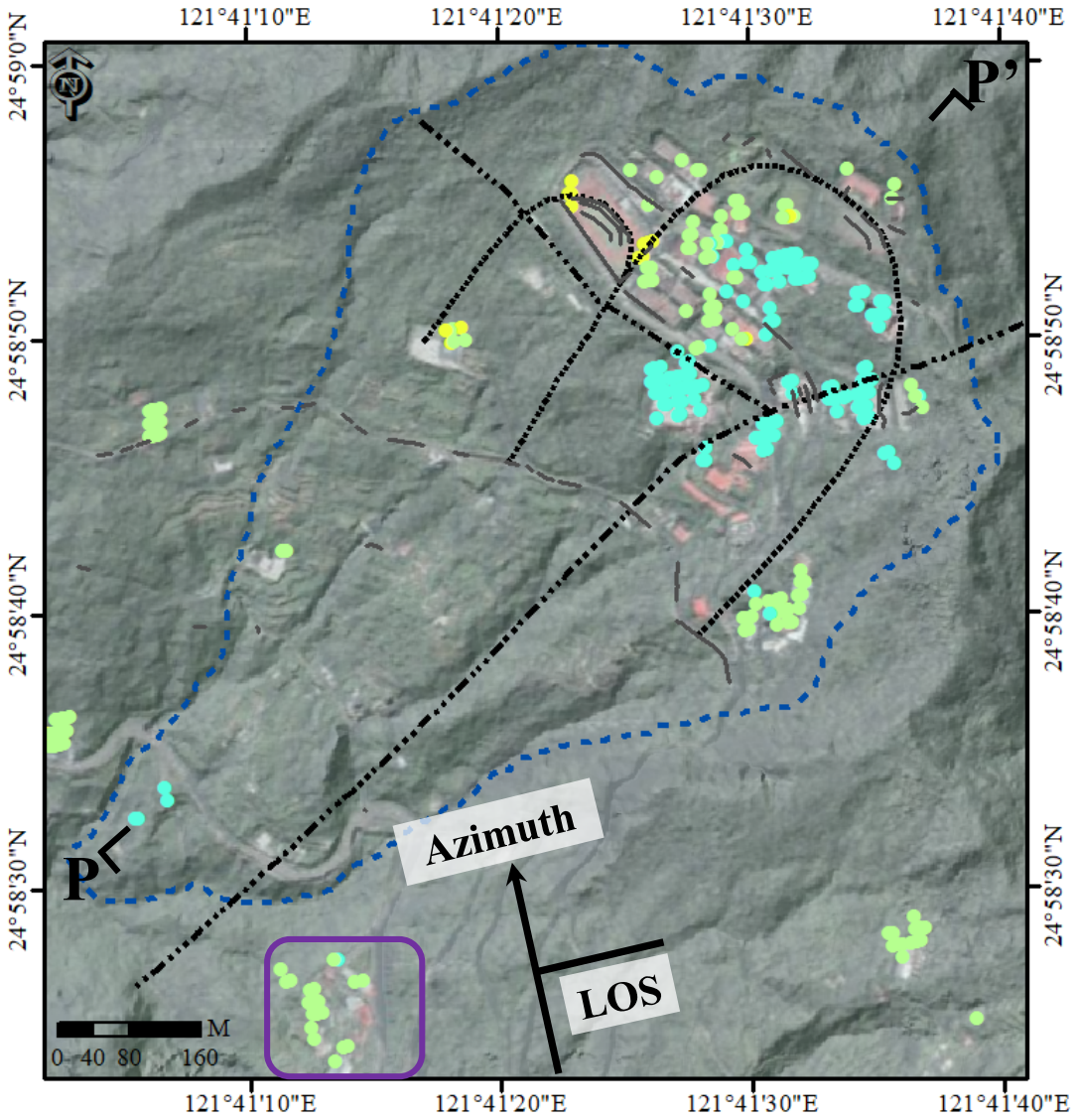


The activity of slow-moving landslide – Shiding-T001

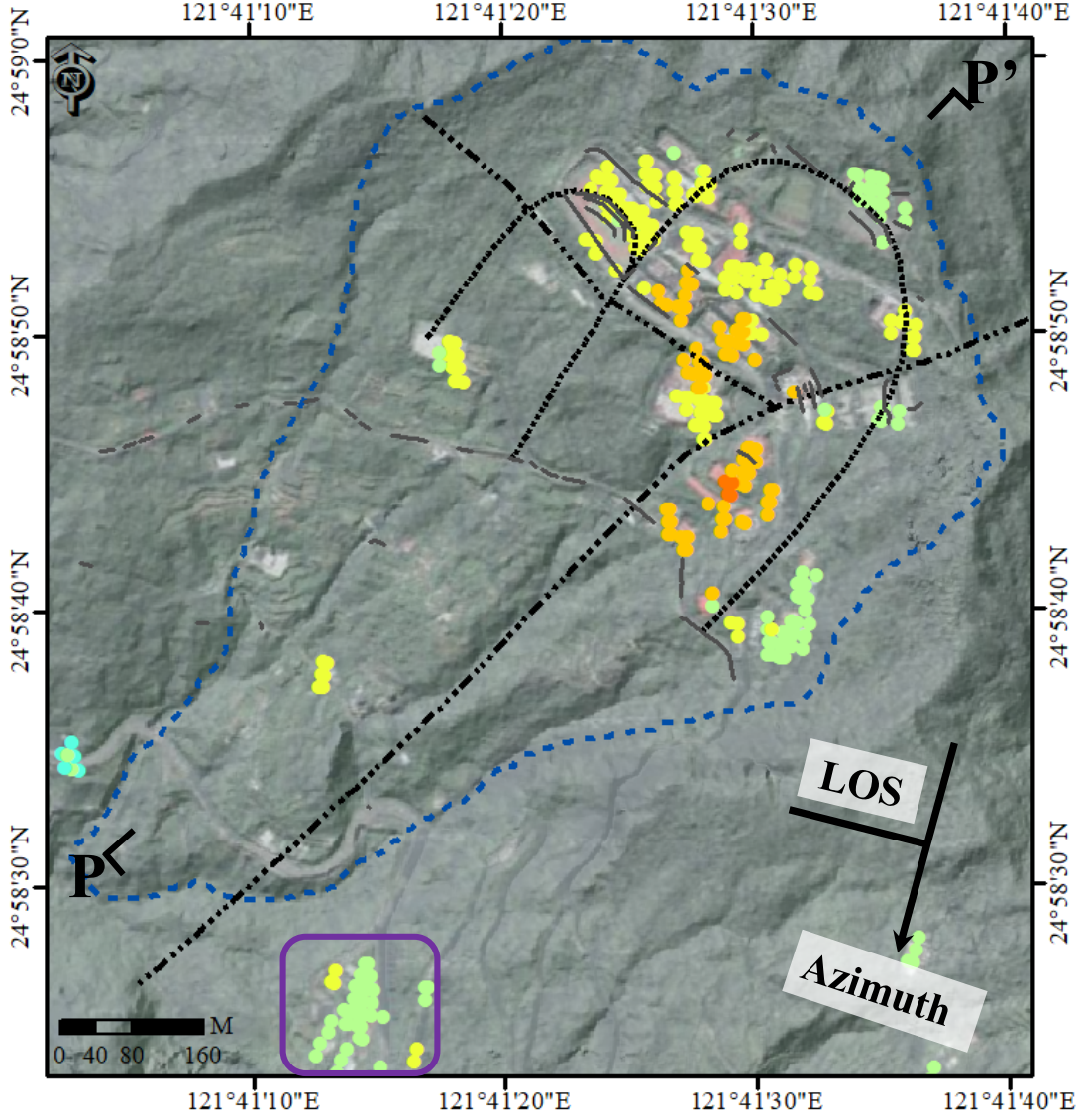
(2019-2021)

國家災害防救科技中心

(a) Ascending



(b) Descending



Tension crack

Fault

Sliding block

Potential sliding area

Reference area

LOS velocity (mm/yr)

- -35.1 - -30.0
- -29.9 - -20.0
- -19.9 - -10.0
- -9.9 - -2.0
- -1.9 - 2.0
- 2.1 - 10.0
- 10.1 - 20.0
- 20.1 - 30.0
- 30.1 - 35.0

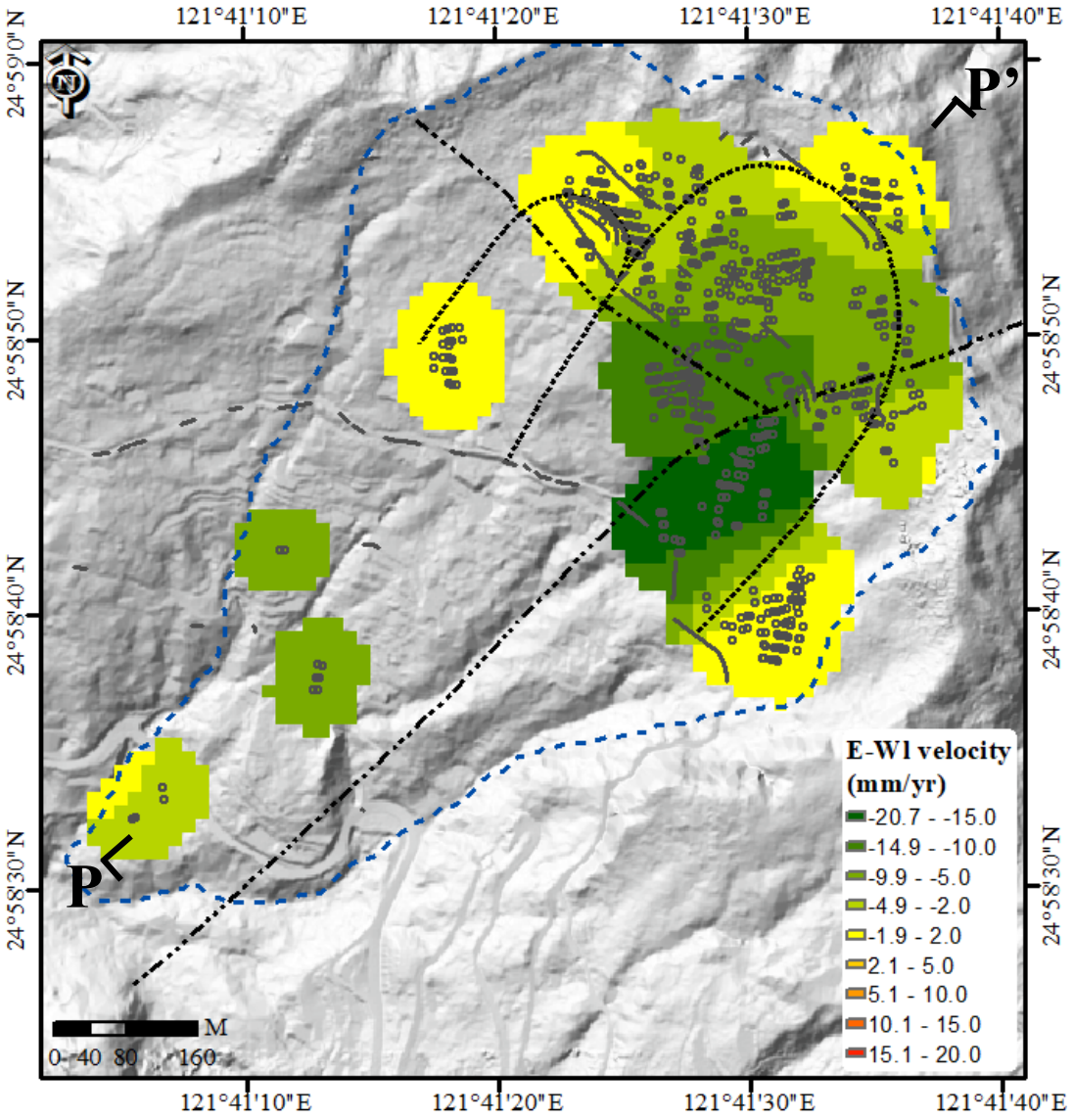
(Lu et al., 2023)

The activity of slow-moving landslide – Shiding-T001

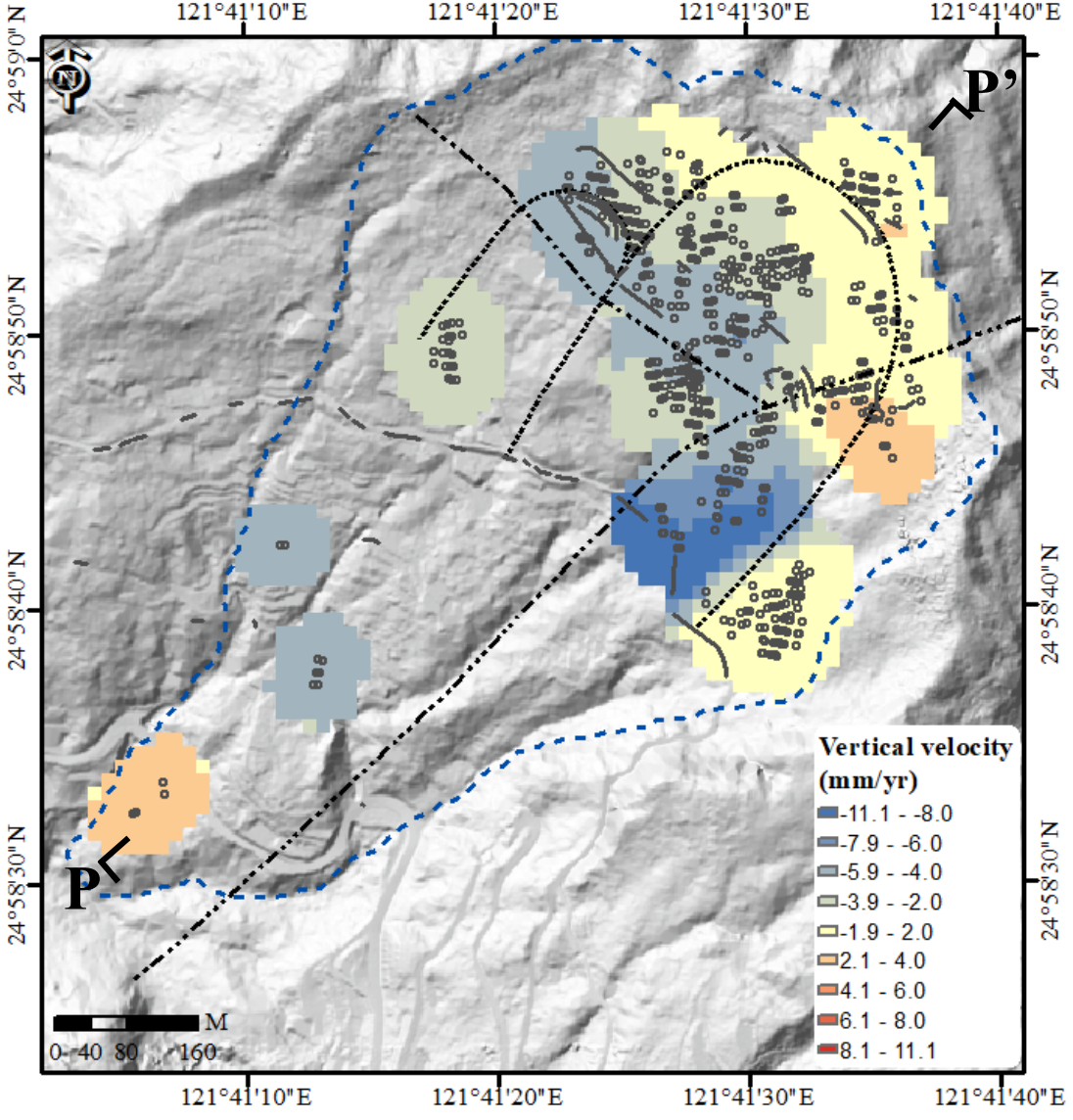
(2019-2021)

國家災害防救科技中心

(a) E-W velocity field



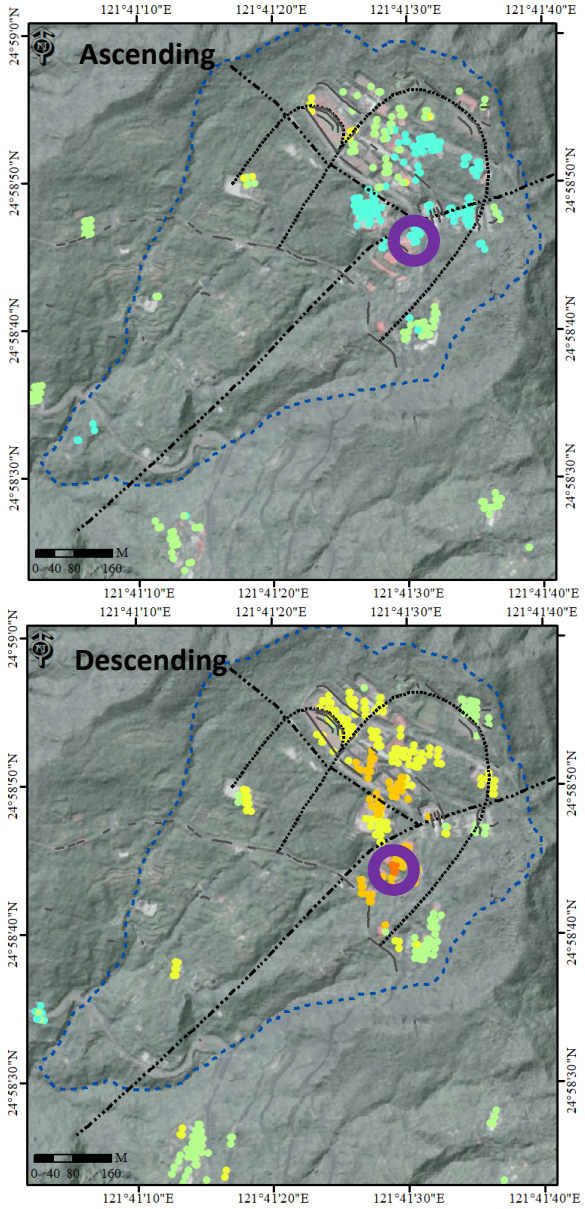
(b) Vertical velocity field

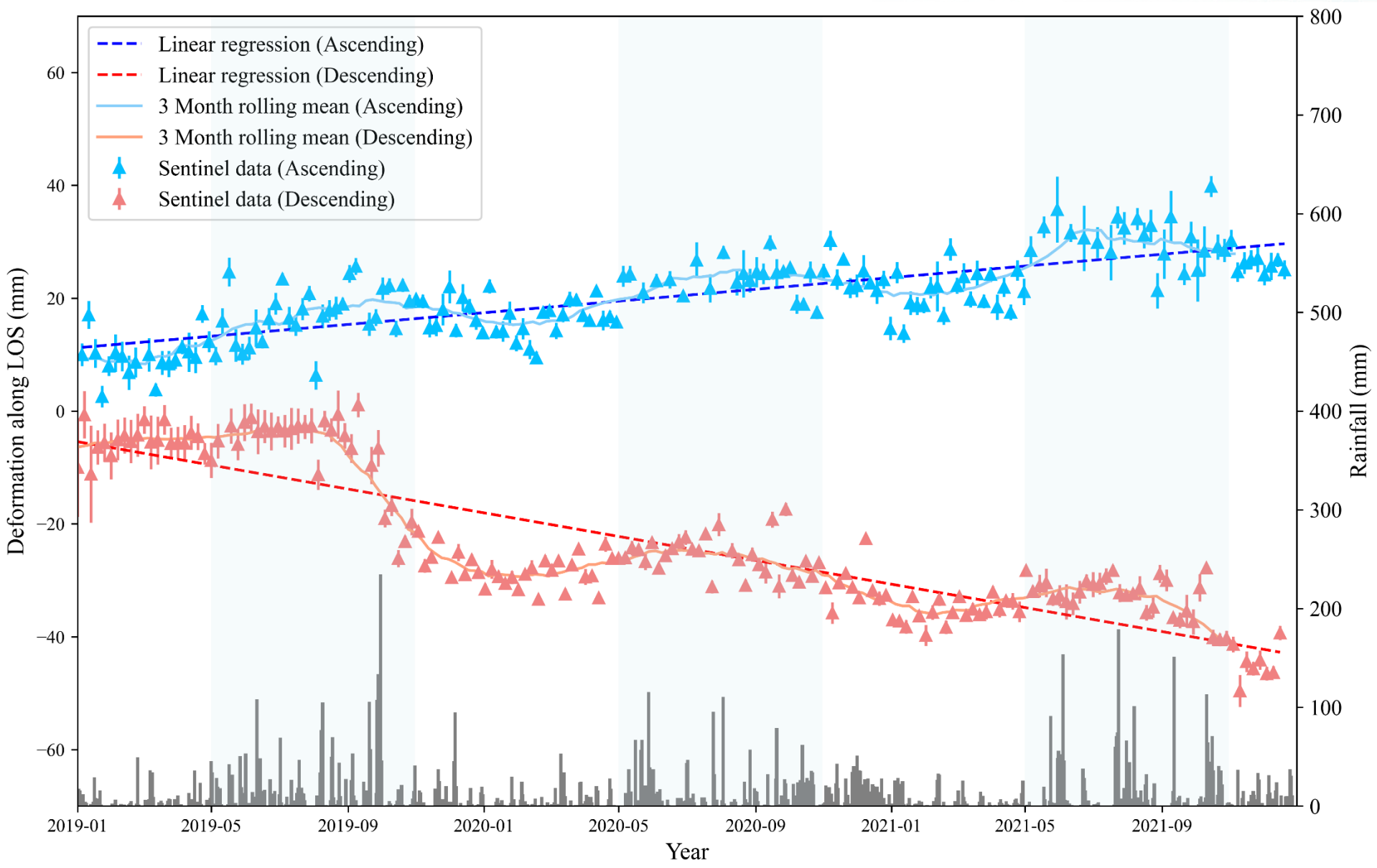


The activity of slow-moving landslide – Shiding-T001

(2019-2021)

國家災害防救科技中心

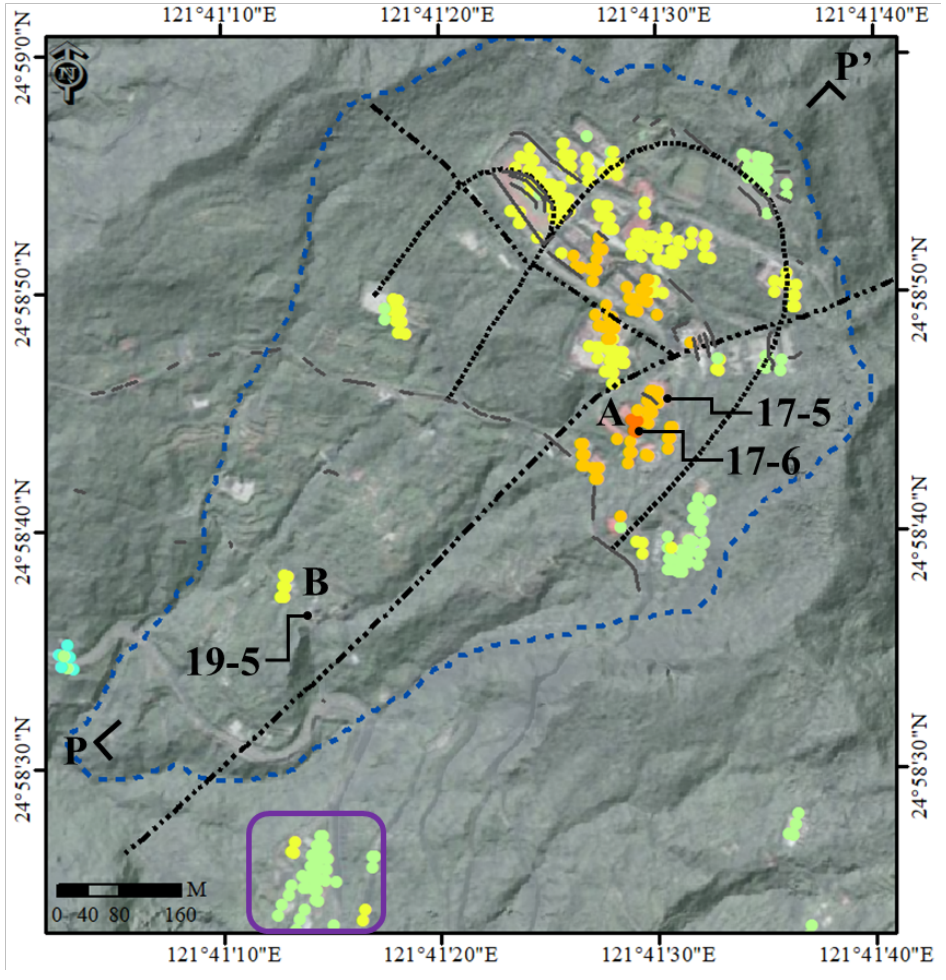


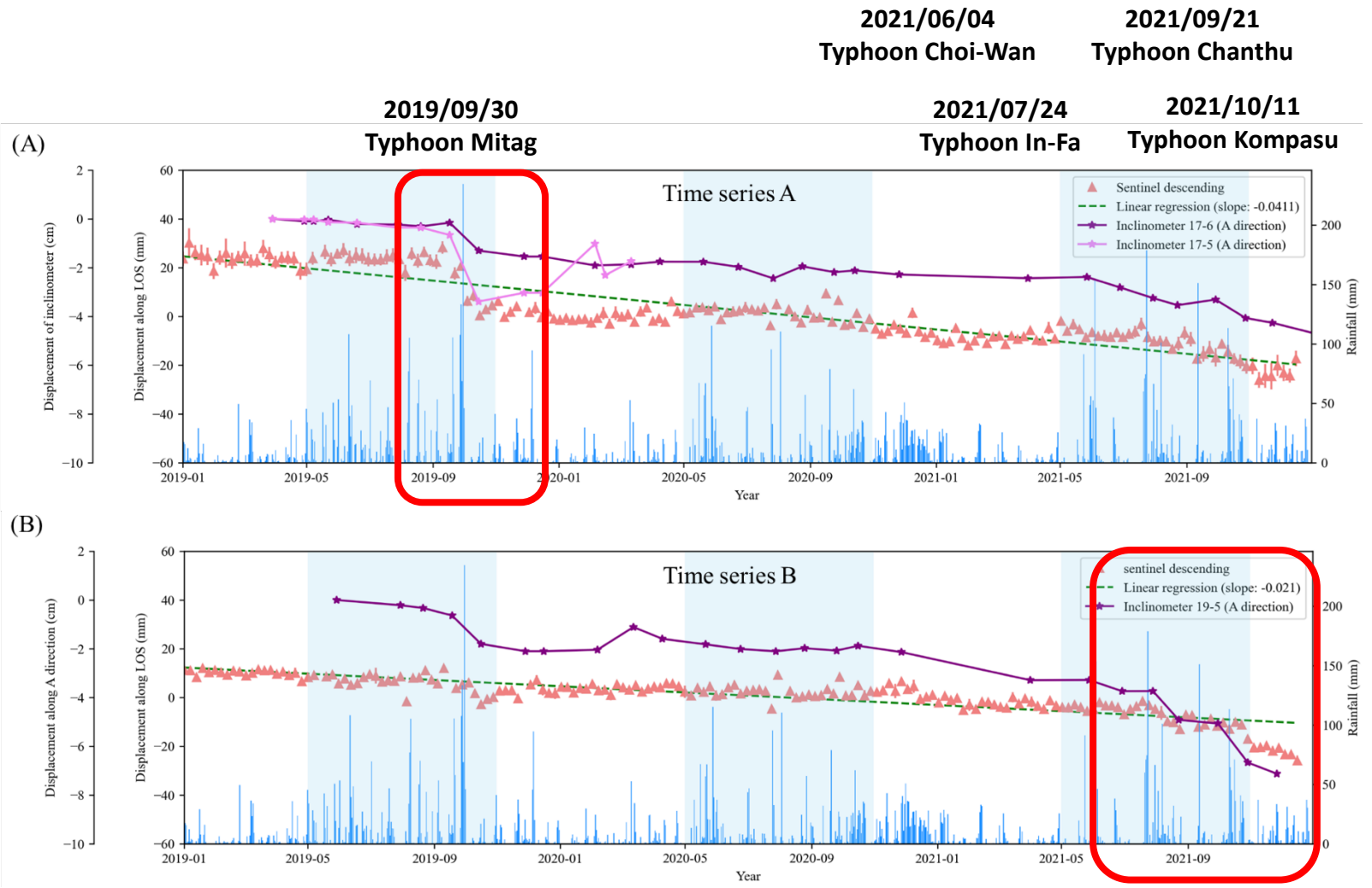


The activity of slow-moving landslide – Shiding-T001 (2019-2021)

國家災害防救科技中心

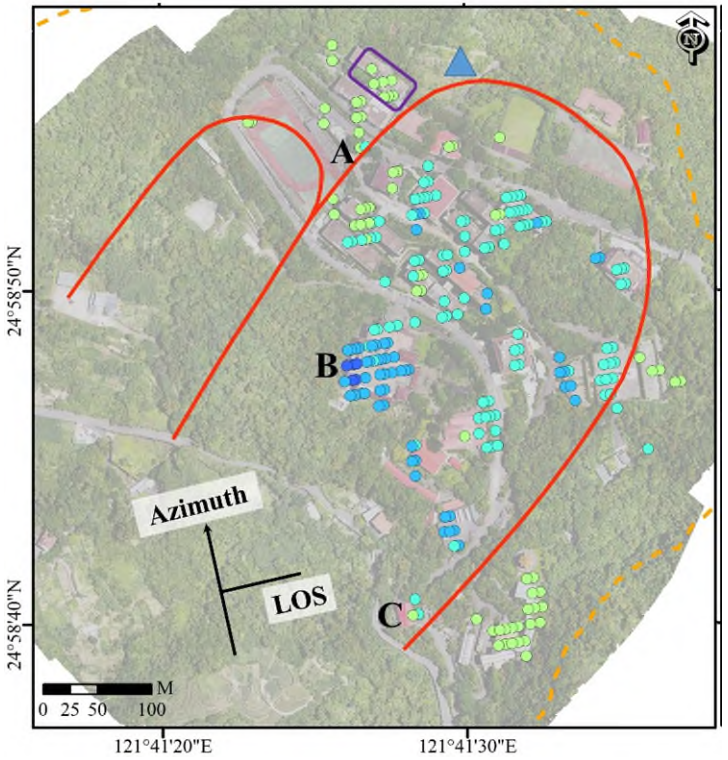
- The timing of accelerations detected by MTInSAR technique are agree with in situ monitoring data, which confirms the reliability of our analysis results

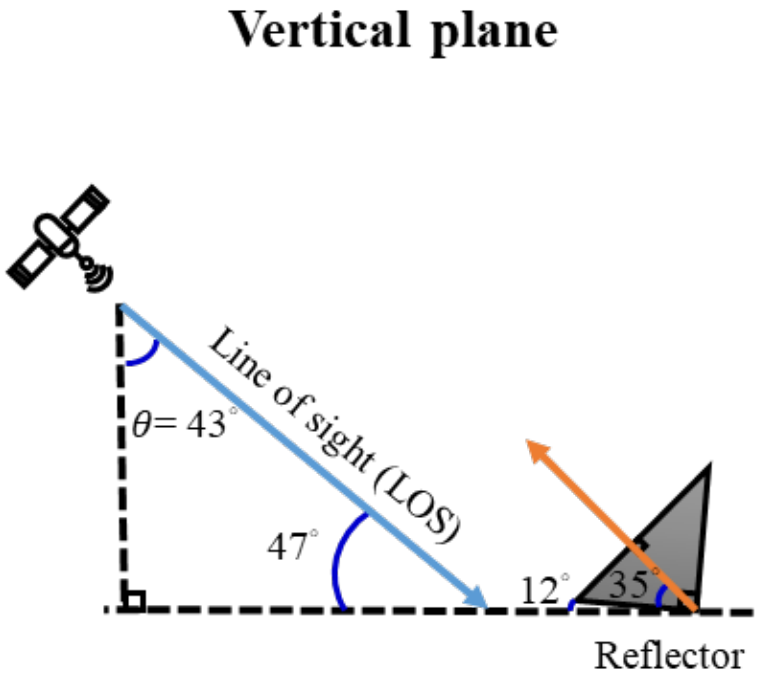


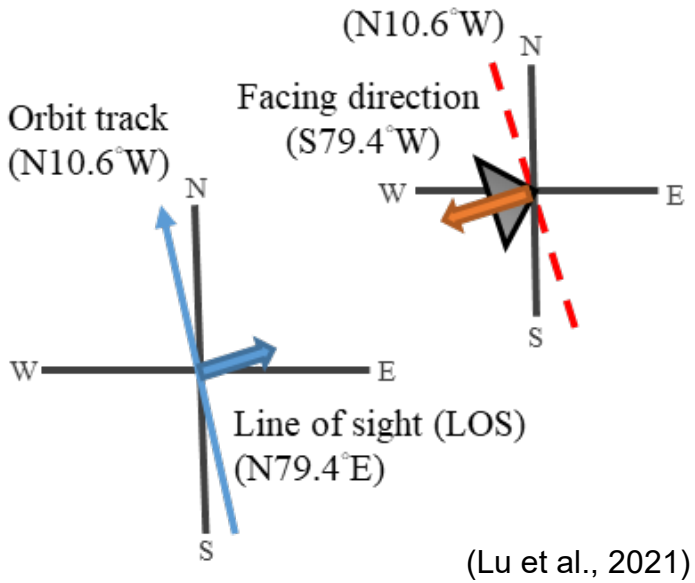


Corner reflector design and deployment

- The orientation of the corner reflector needs to be perpendicular to the orbit of the satellite.
- The minimum size of a corner reflector is a function based on the wavelength of the SAR sensor and the backscattering level of the surroundings.
  - Sentinel-1 satellites : 1 m



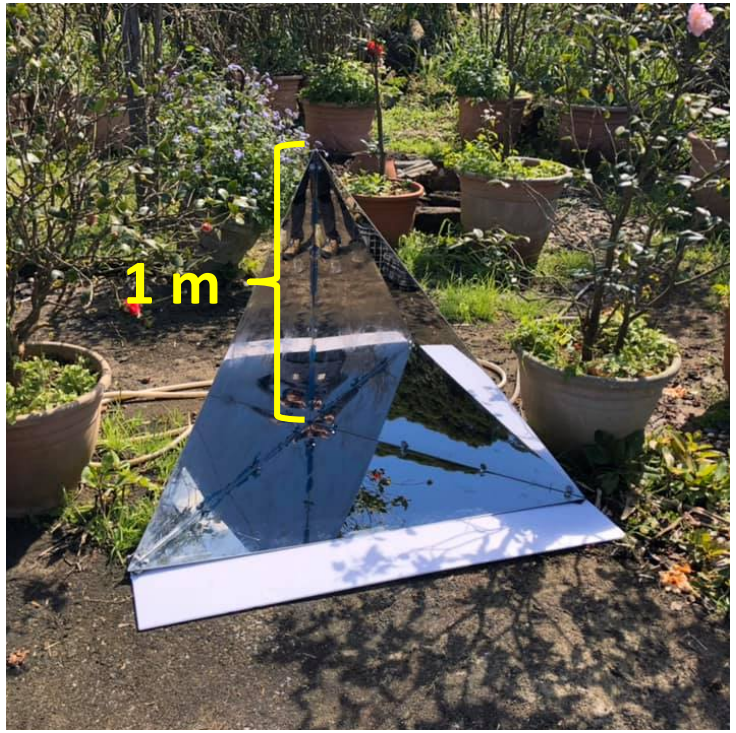


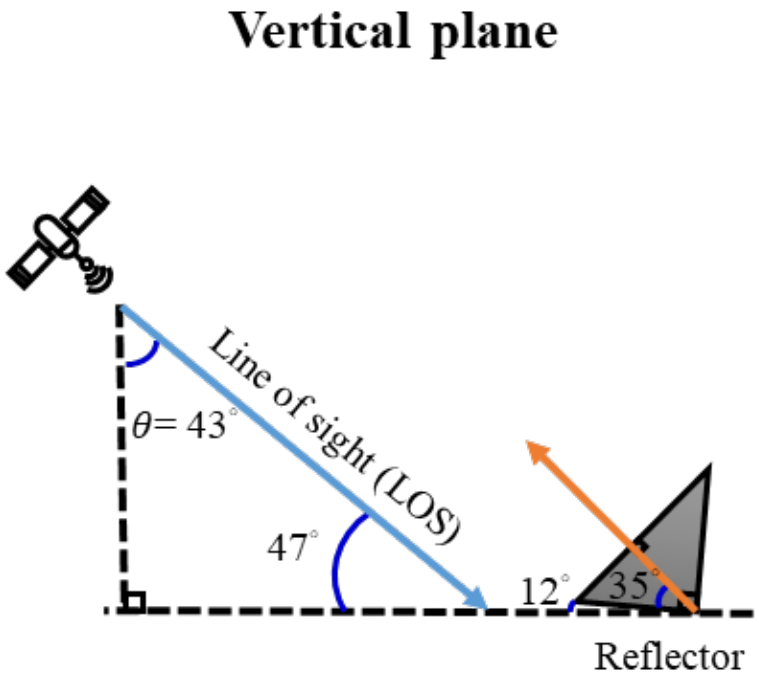


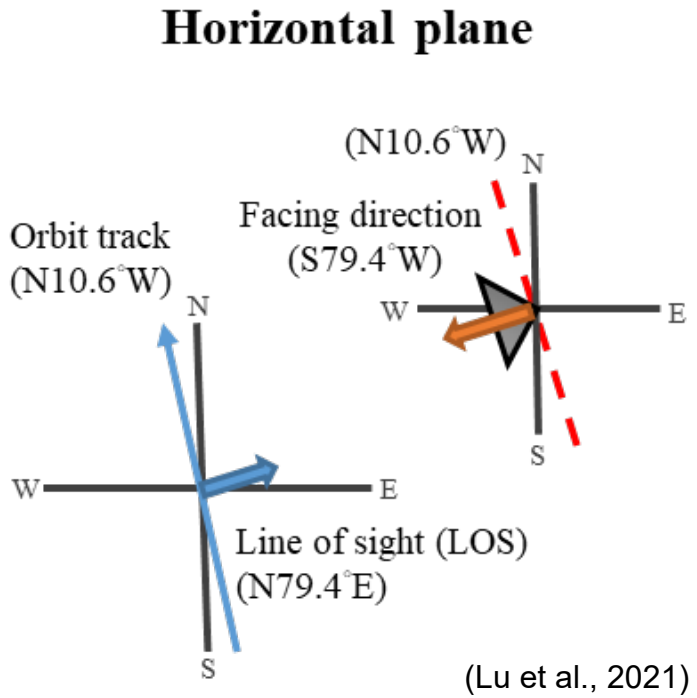
(Lu et al., 2021)

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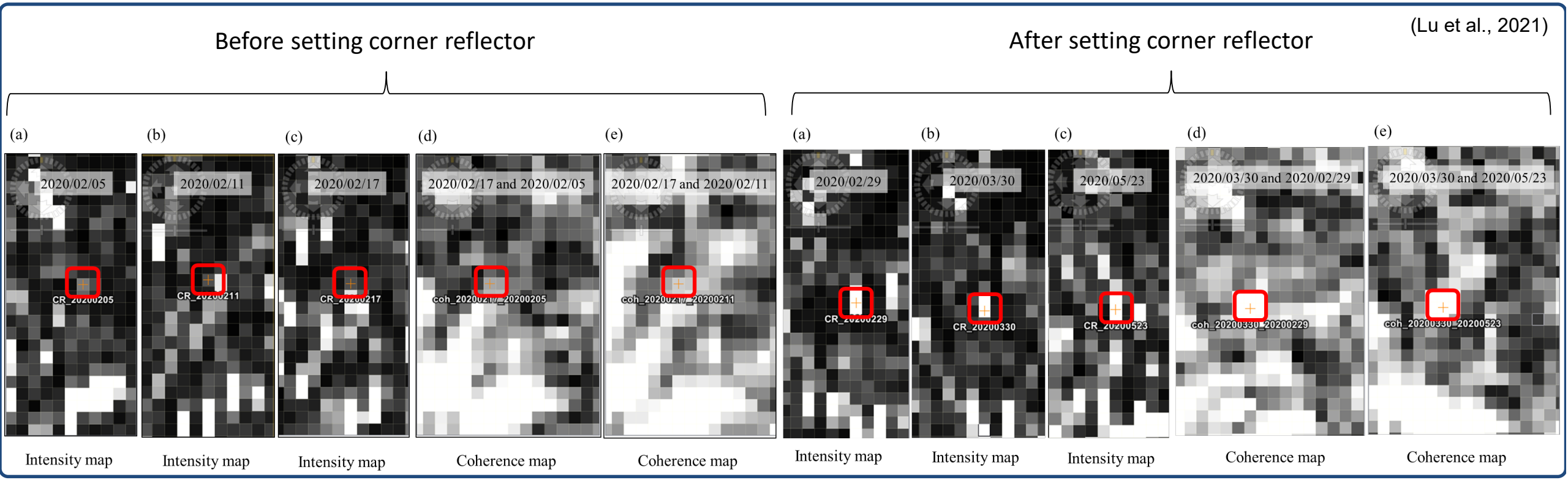




(Lu et al., 2021)

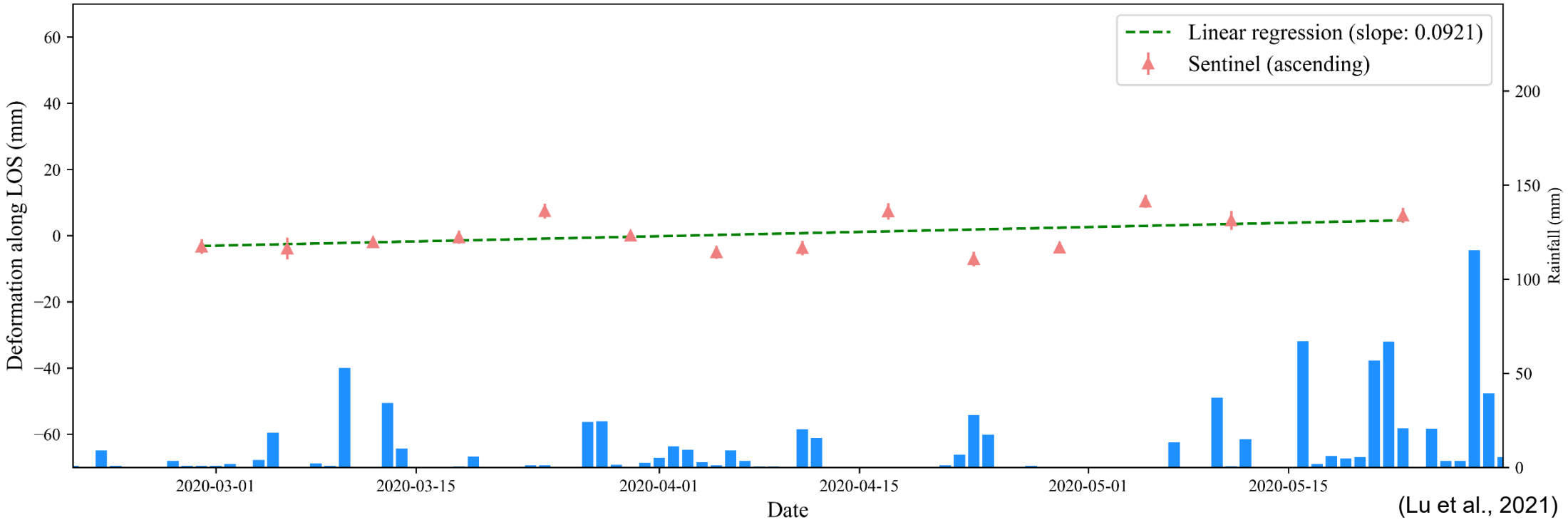
Corner reflector design and deployment

- The intensity and coherence maps of SAR images, were analyzed to confirm that the corner reflector could be detected by the SAR sensor of the satellite.
- The brighter color in the intensity map indicates the greater reflected energy of the pixel, and the brighter color in the coherence map indicates the higher coherence value between two SAR images of that pixel.



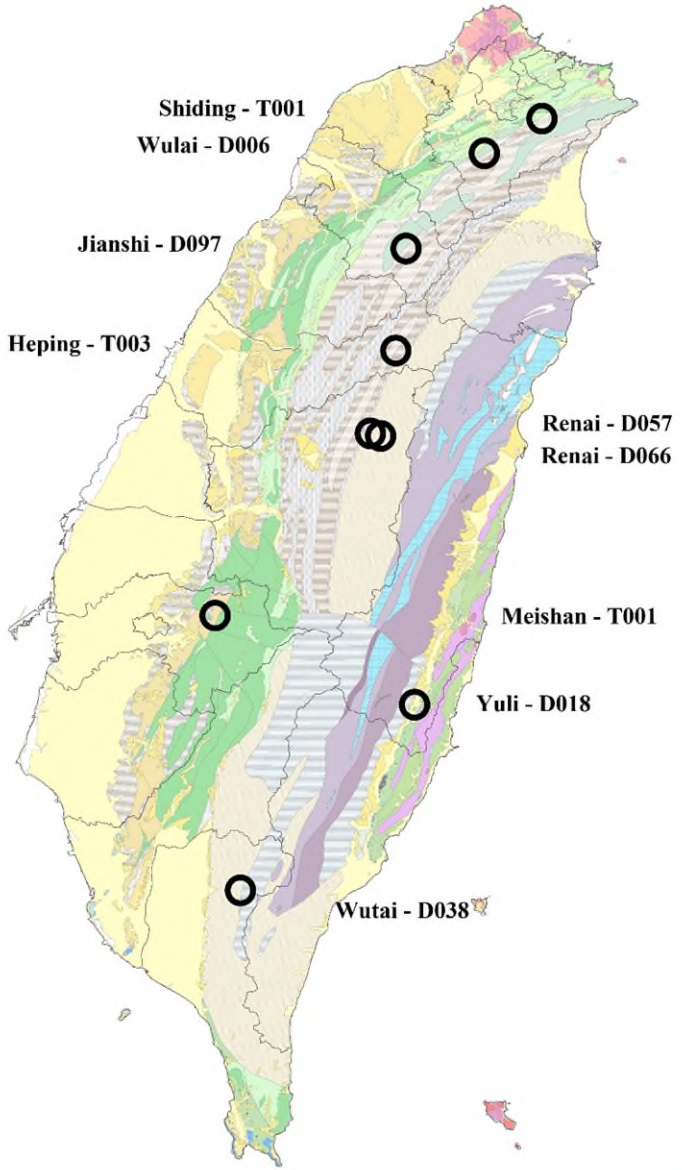
Corner reflector design and deployment

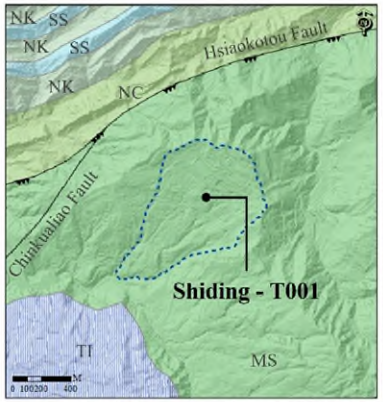
- **The preliminary time series result of corner reflector from 2020/02/27 to 2020/06/04.**

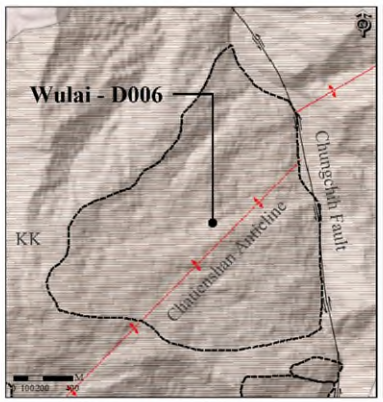


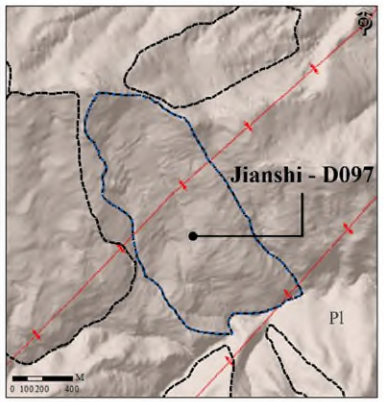
(Lu et al., 2021)

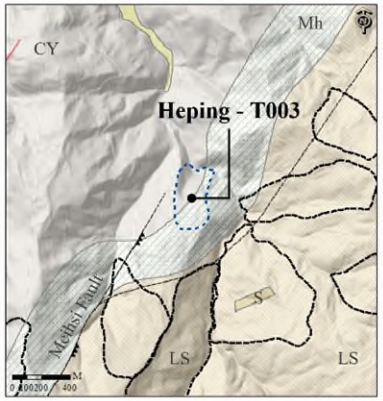
Pre-existing slow-moving landslides

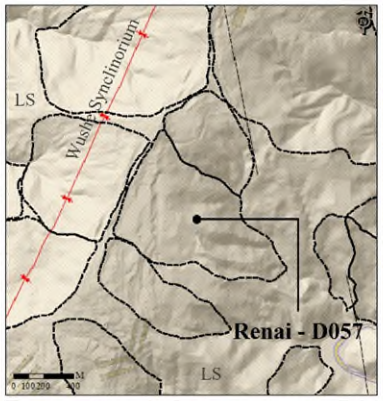


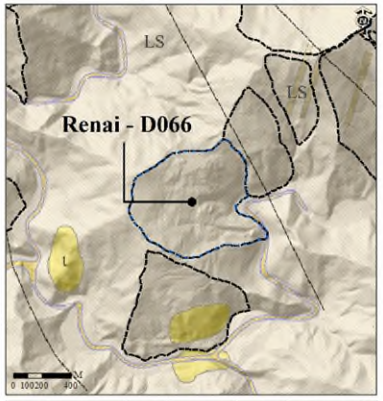


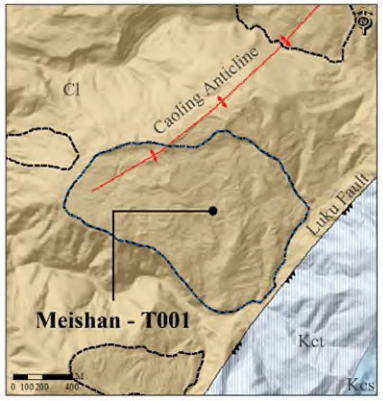


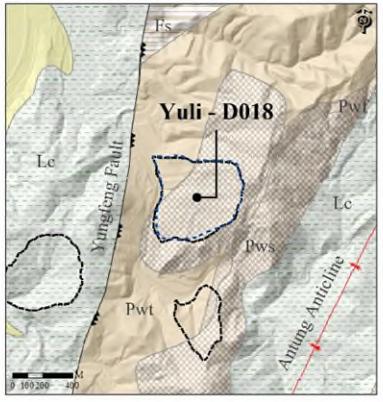


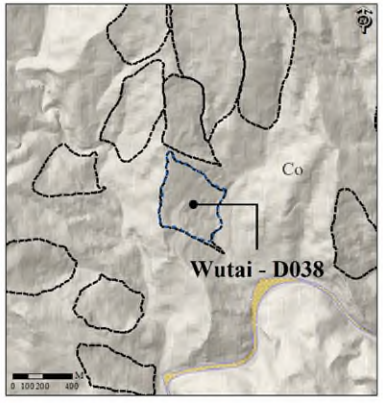










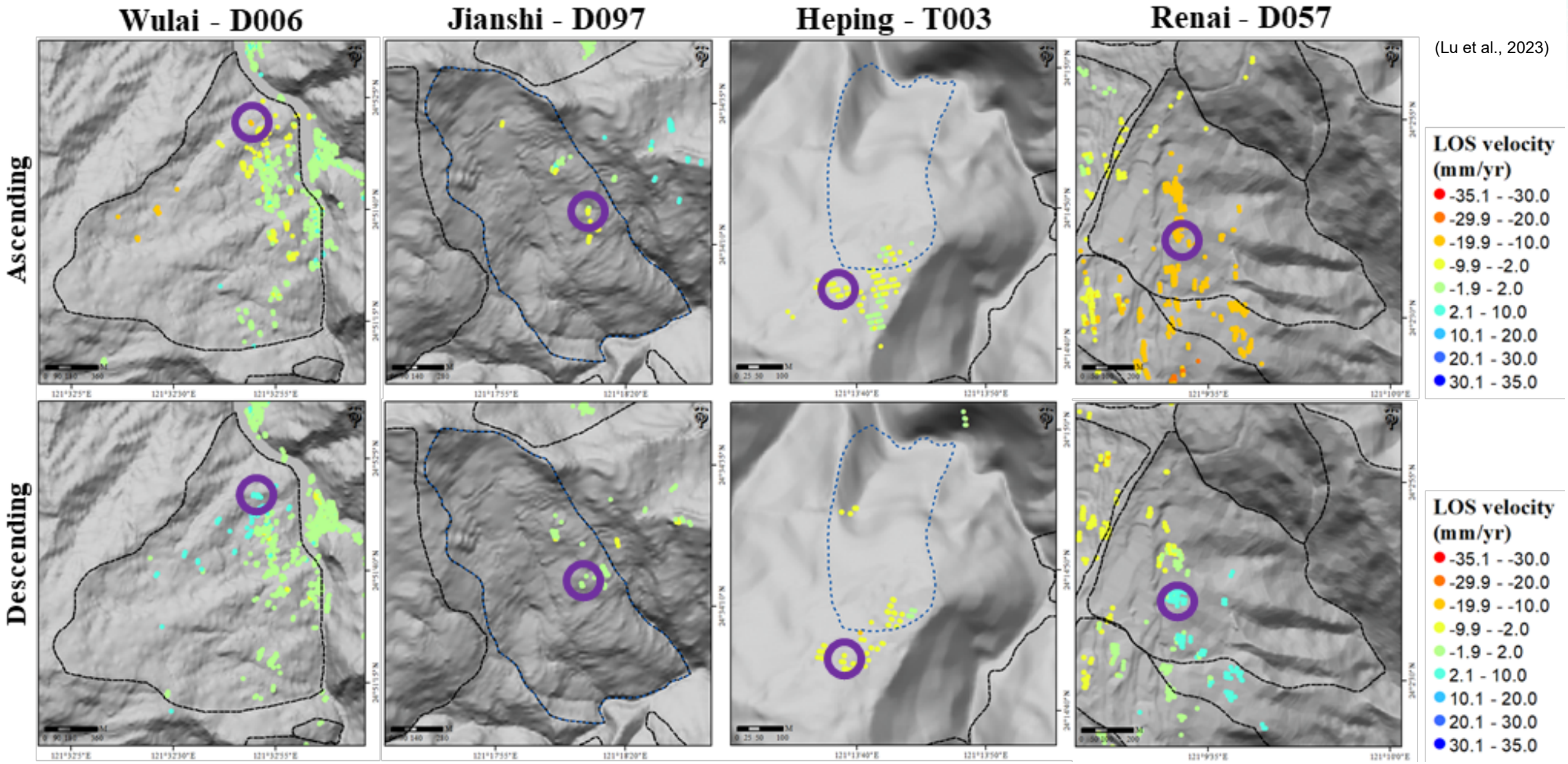


t	Terrace Formation
Cl	Cholan Formation
Kct	Kueichulin Formation Tawo Sandstone Member
Kcs	Kueichulin Formation Shihliufen Shale Member
NC	Nanchuang Formation
Pwt	Paliwan Formation Talyuan Member
Pws	Paliwan Formation Suilien Member
Pwf	Paliwan Formation Futian Member
Fs	Fanshuliao Formation
Lc	Lichi Melange

NK SS	Nankang Formation Nankang Sandstone
TI	Taliao Formation
MS	Mushan Formation
KK	Kankou Formation
Co	Chaochou Formation
LS S	Lushan Formation
Pl	Paling Formation
Mh	Meihsi Formation
CY	Chiayang Formation

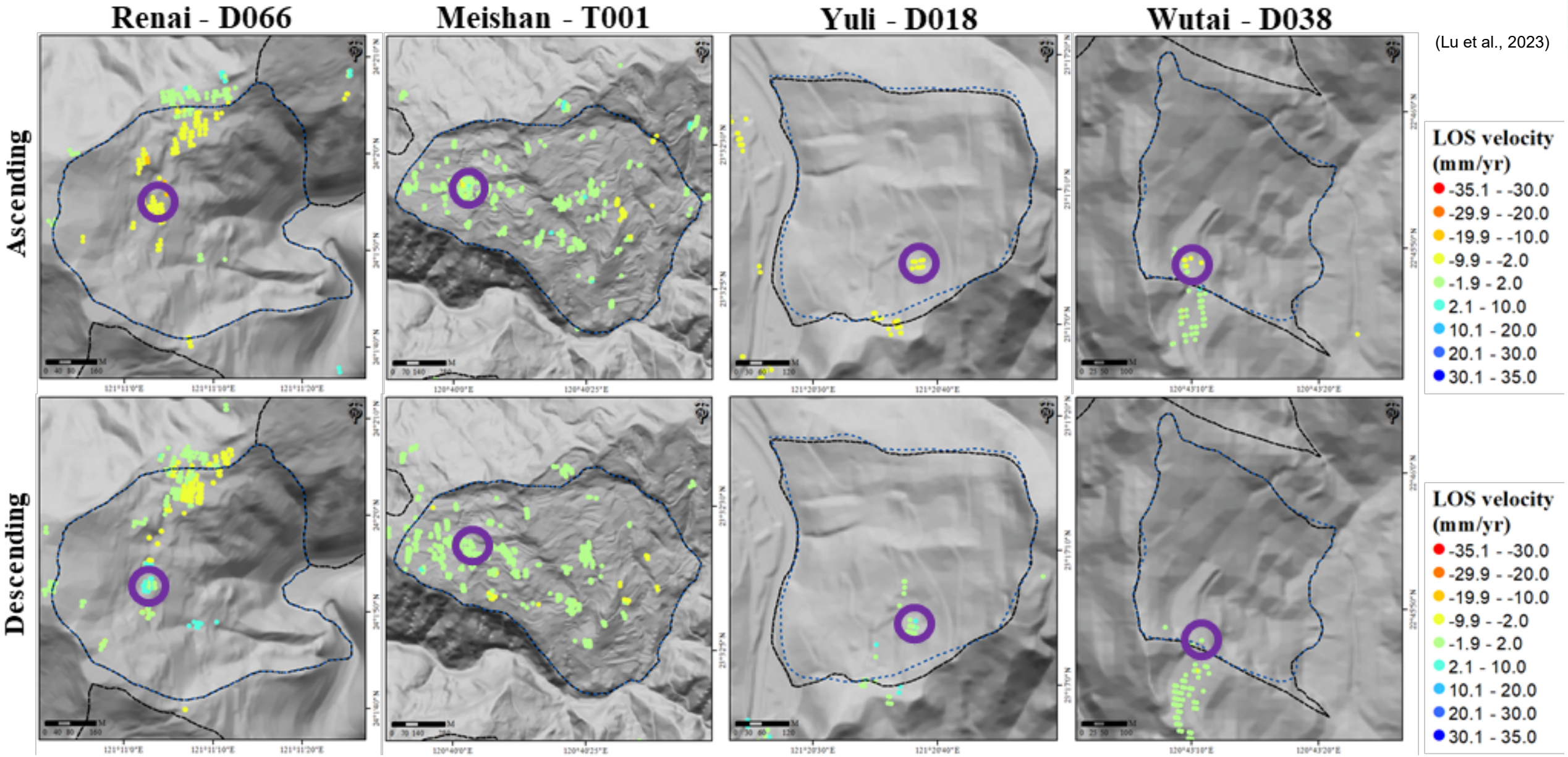
(Lu et al., 2023)

Monitoring activities of slow-moving landslide areas



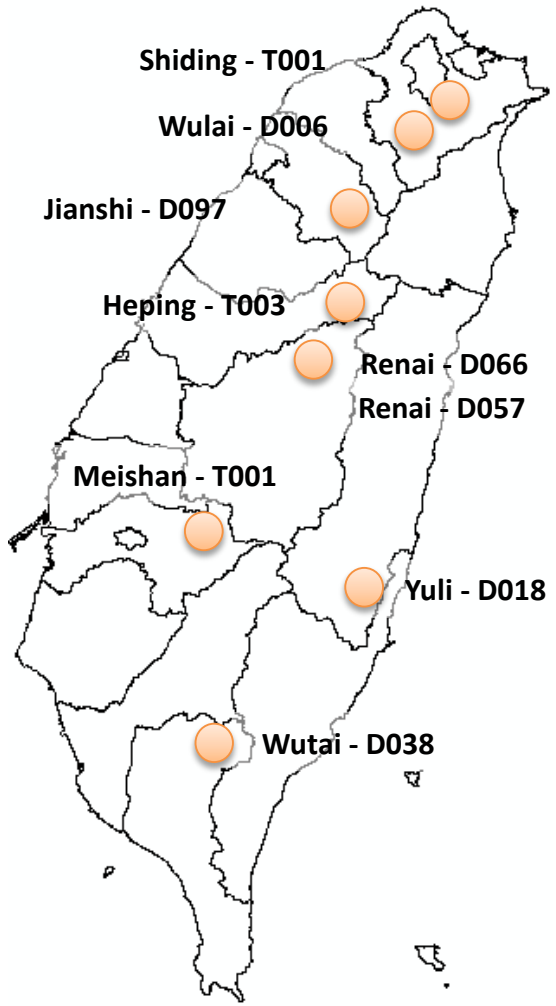
(Lu et al., 2023)

Monitoring activities of slow-moving landslide areas

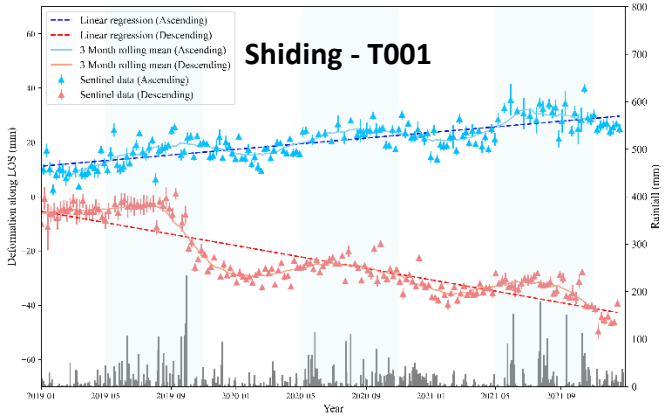


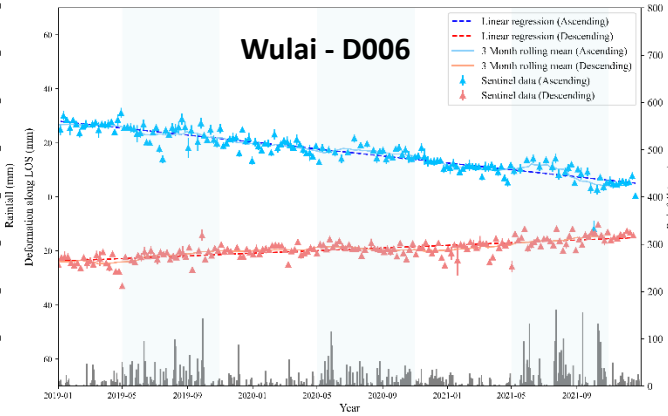
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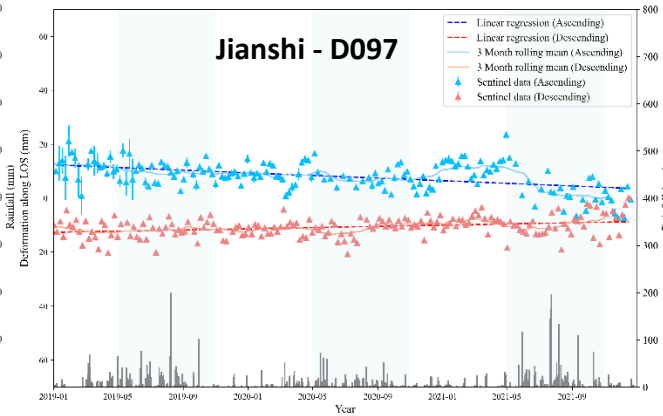
Monitoring activities of slow-moving landslide areas

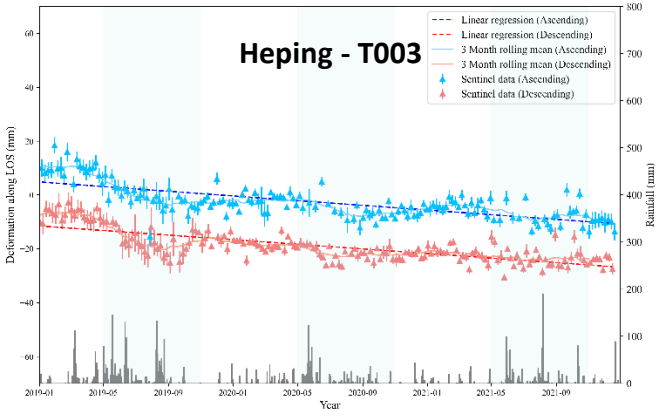


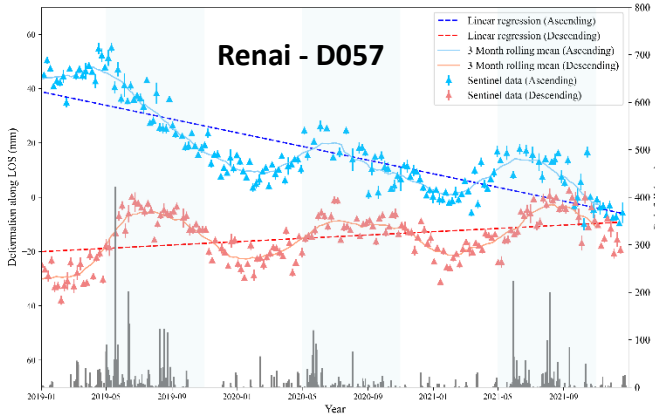
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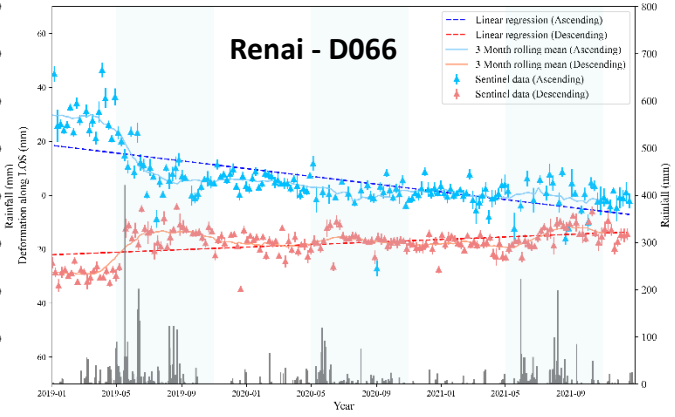


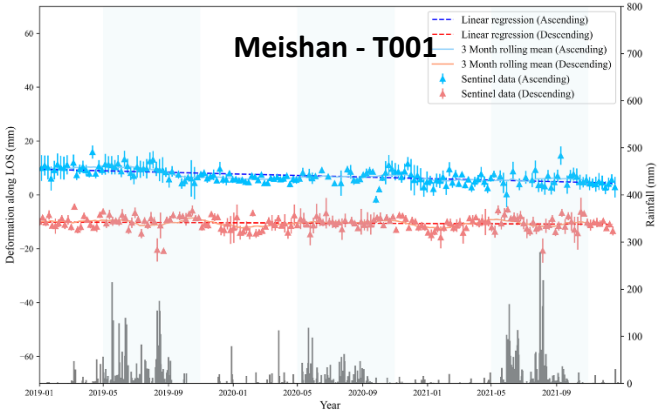


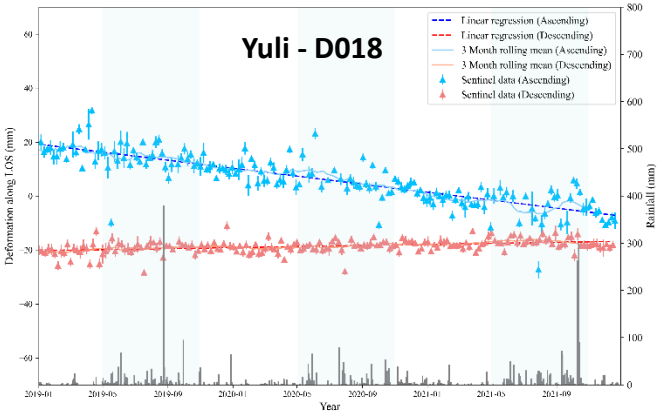


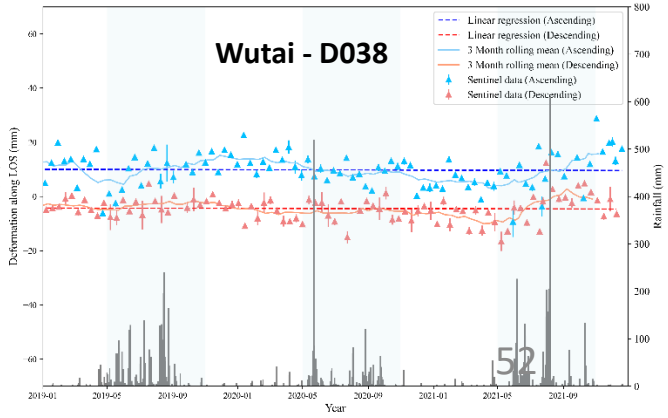




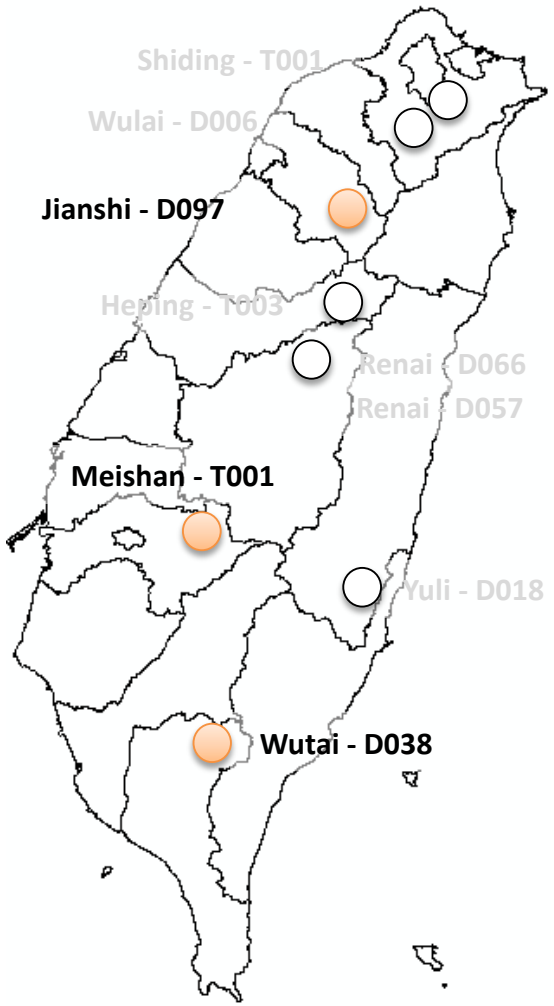




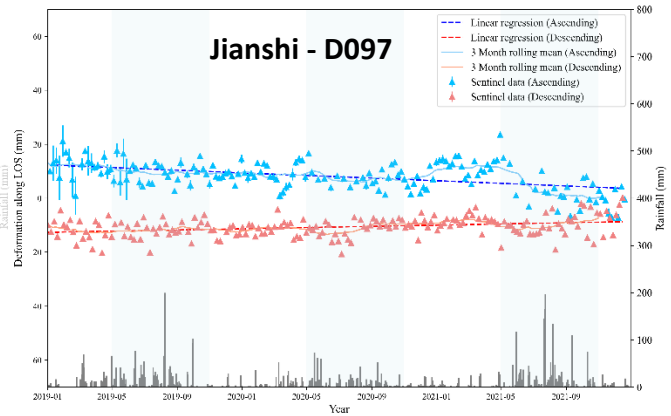


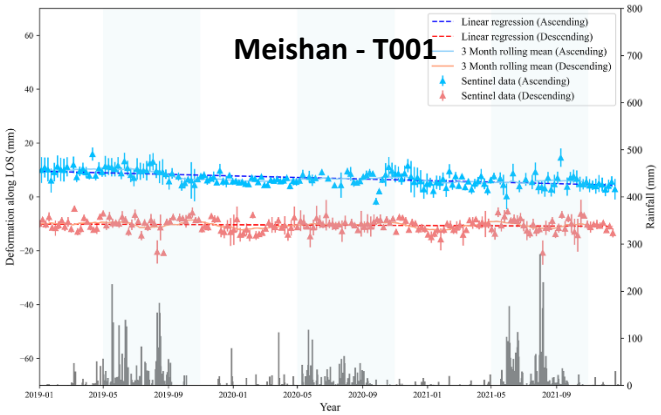


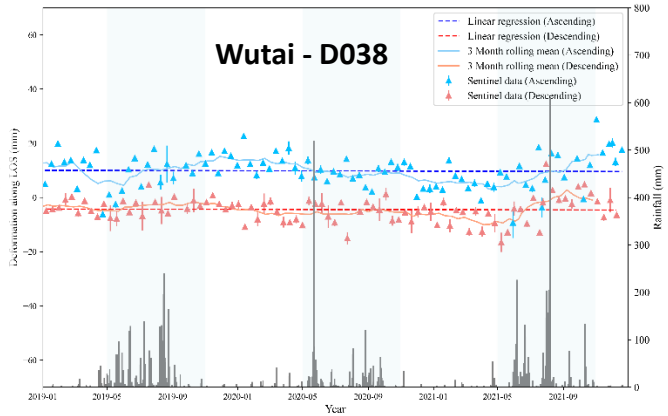
Monitoring activities of slow-moving landslide areas



(Lu et al., 2023)



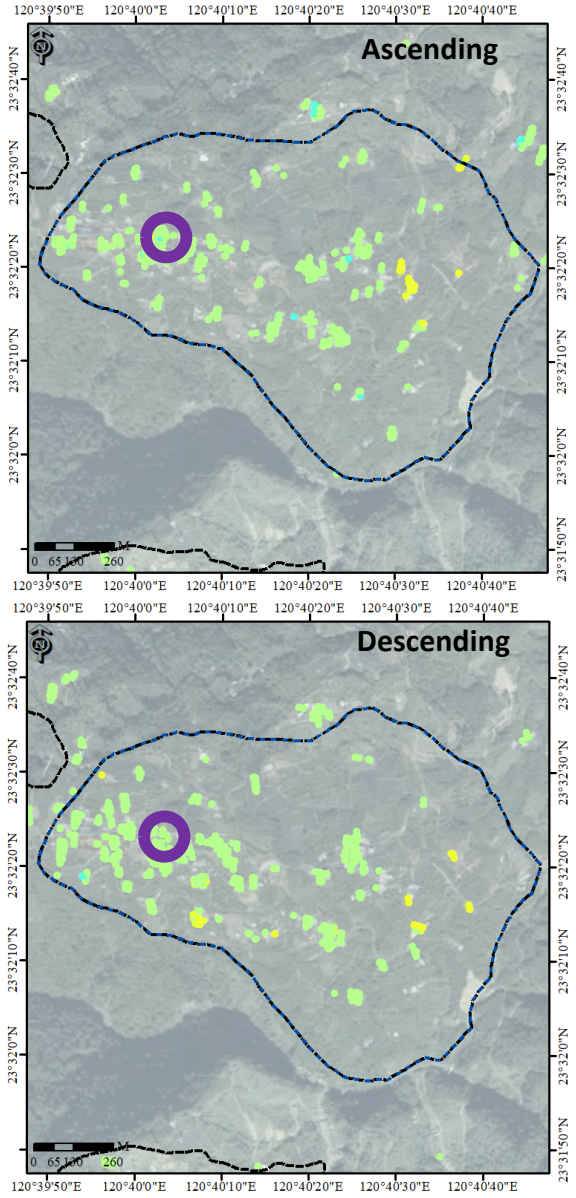


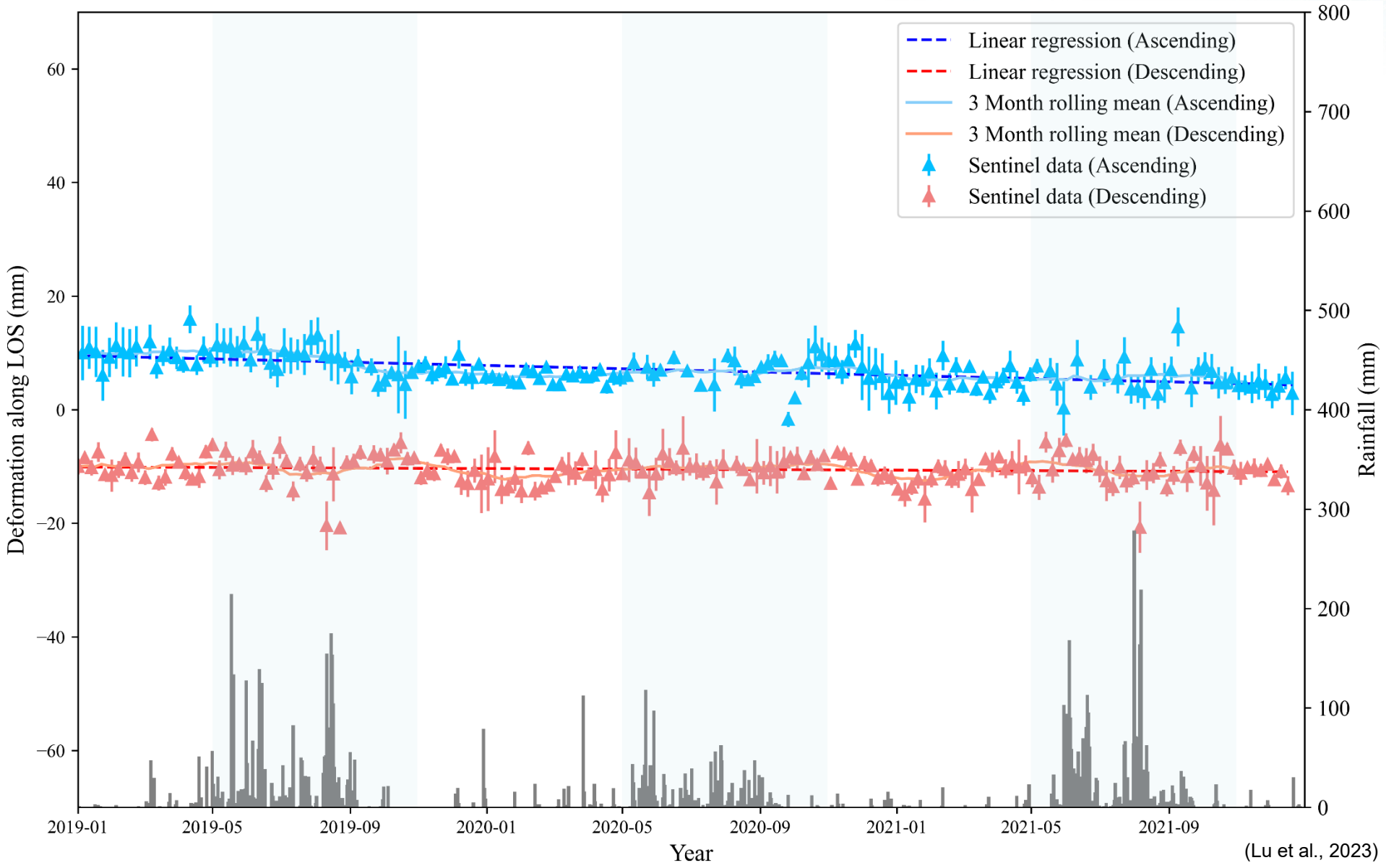


The activity of slow-moving landslide – Meishan-T001

(2019-2021)

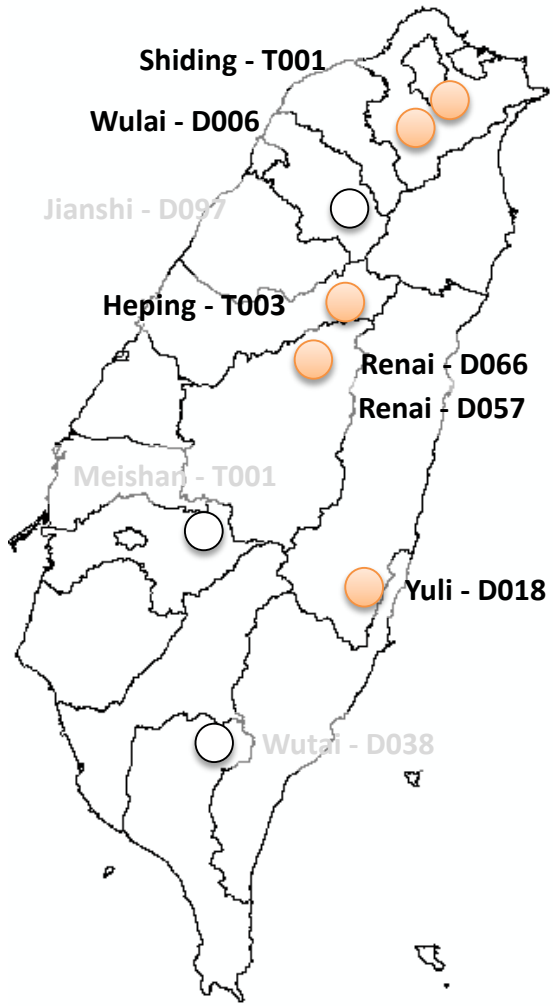
國家災害防救科技中心

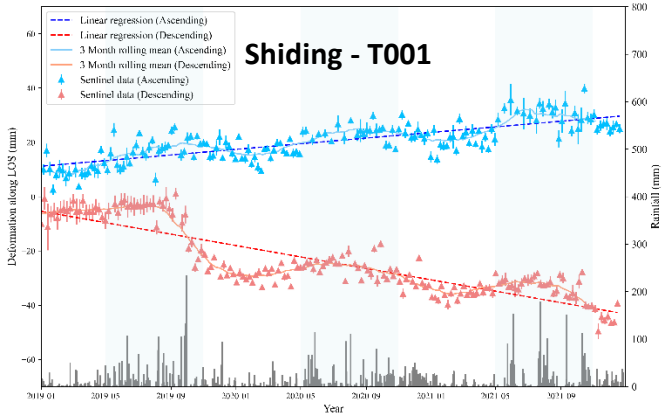


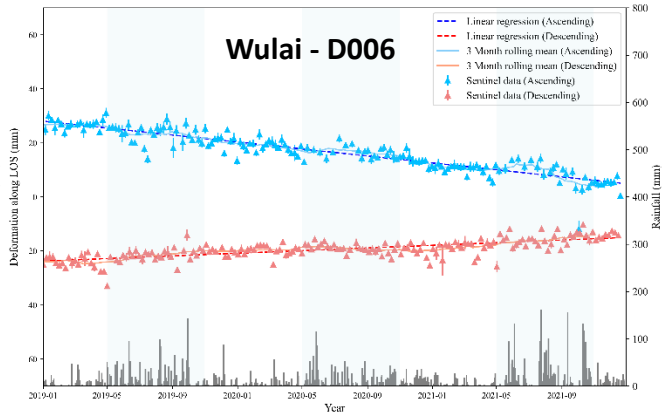


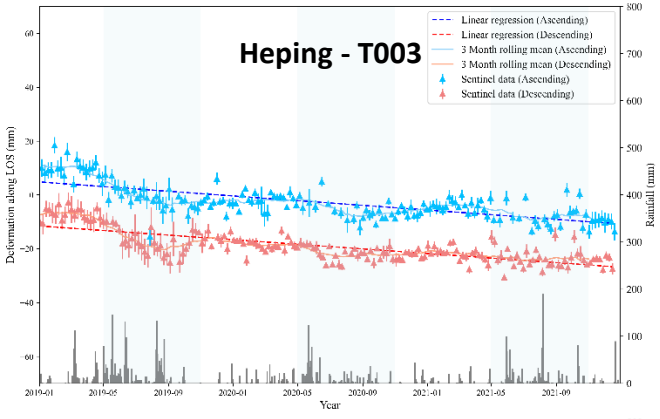
(Lu et al., 2023)

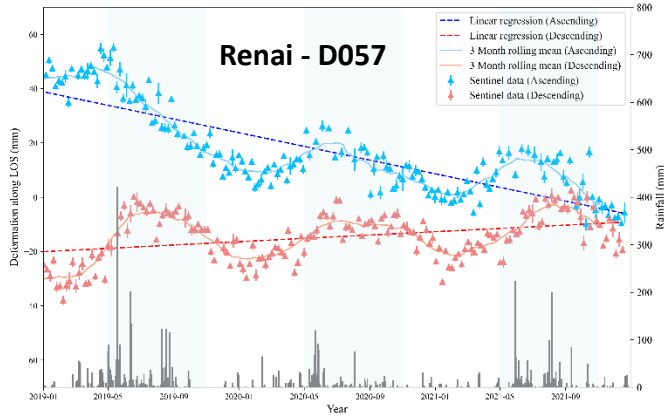
Monitoring activities of slow-moving landslide areas

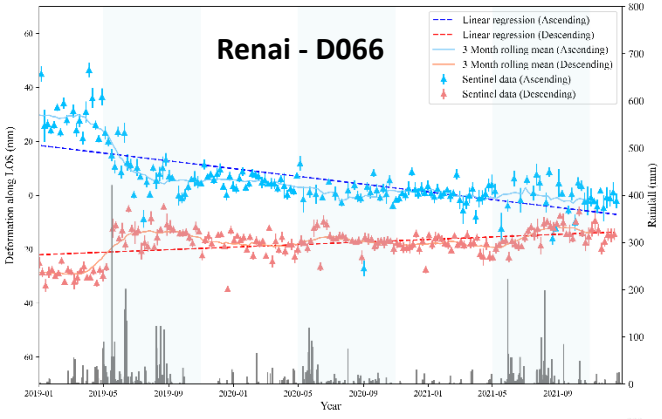


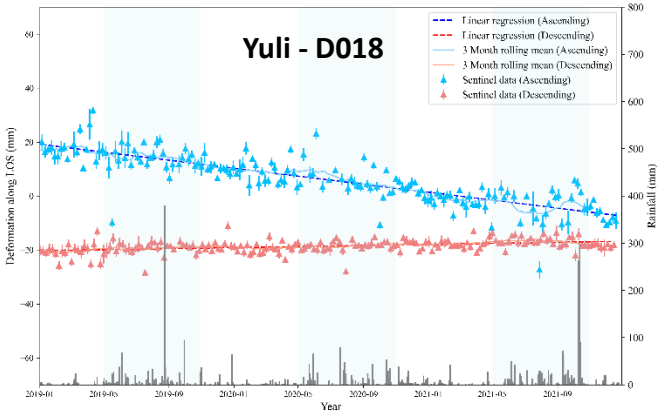




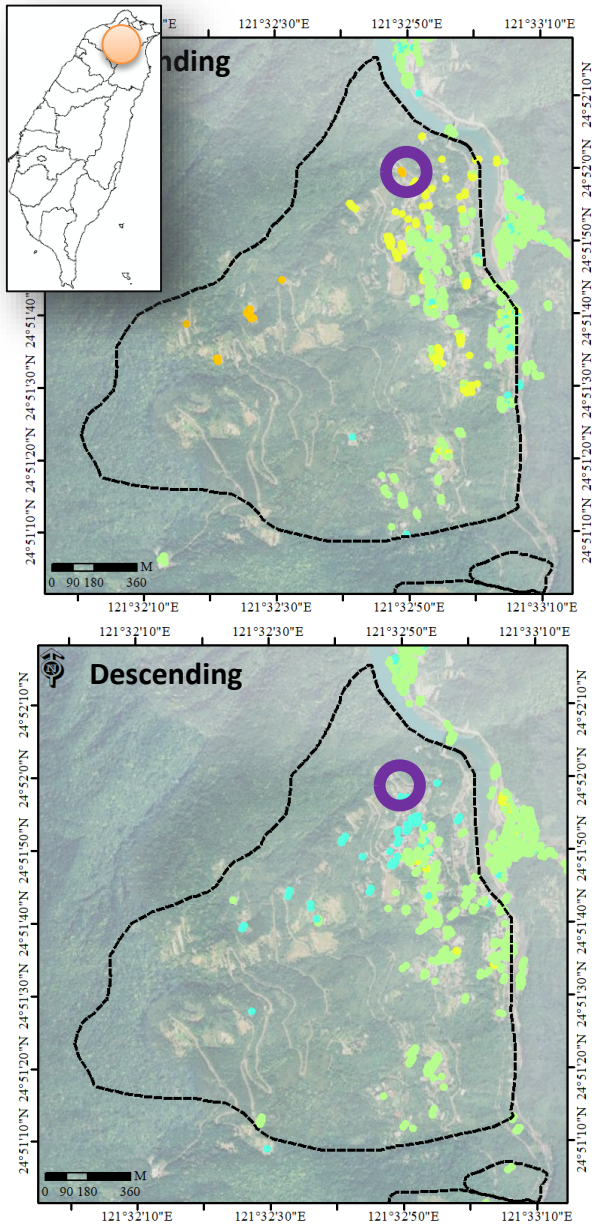


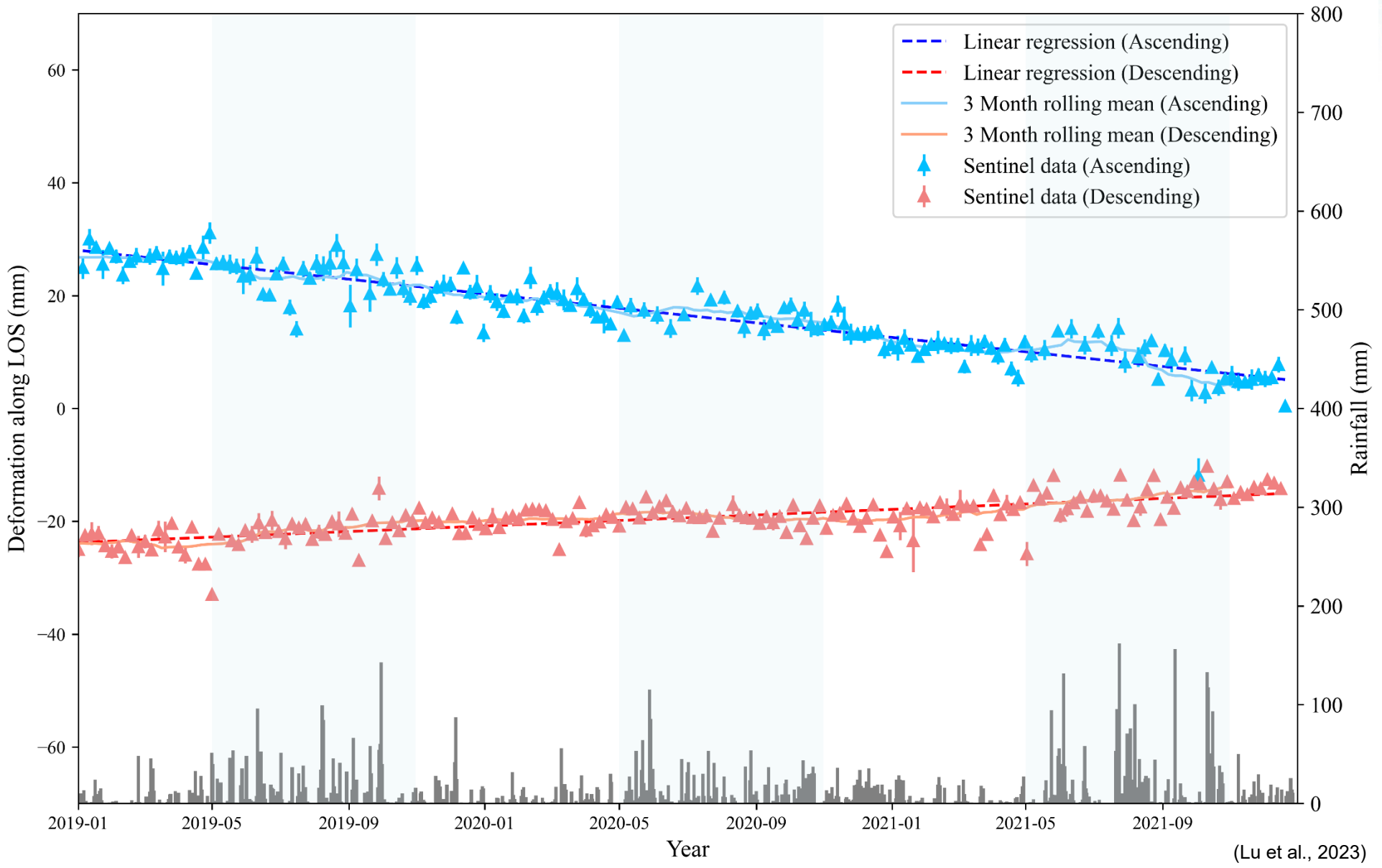






The activity of slow-moving landslide – Wulai-D006

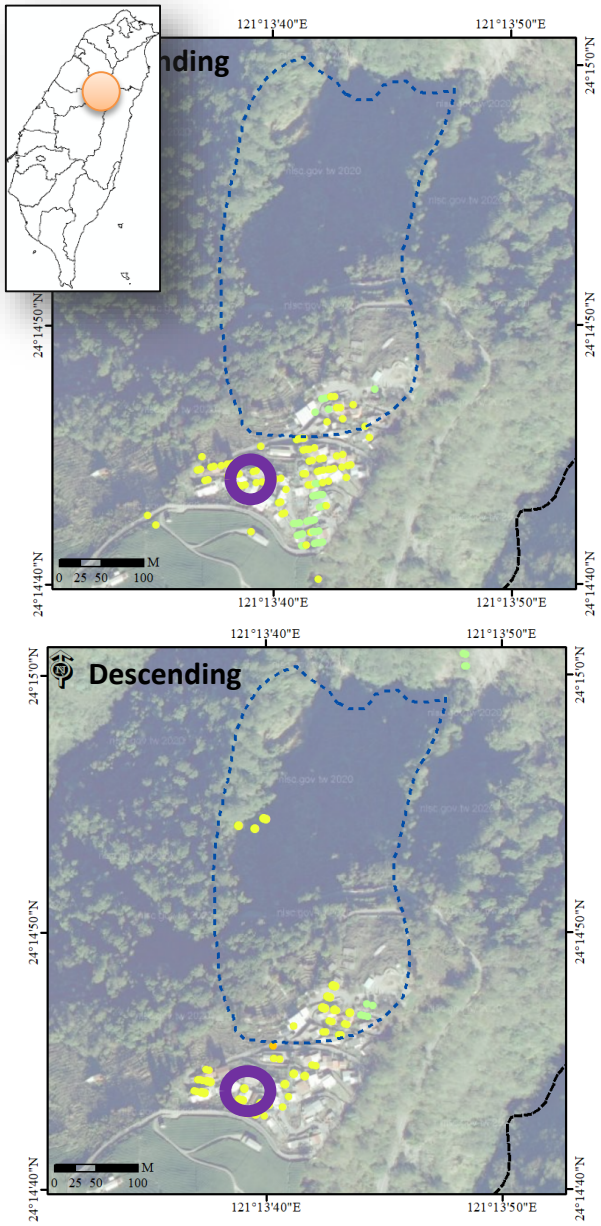


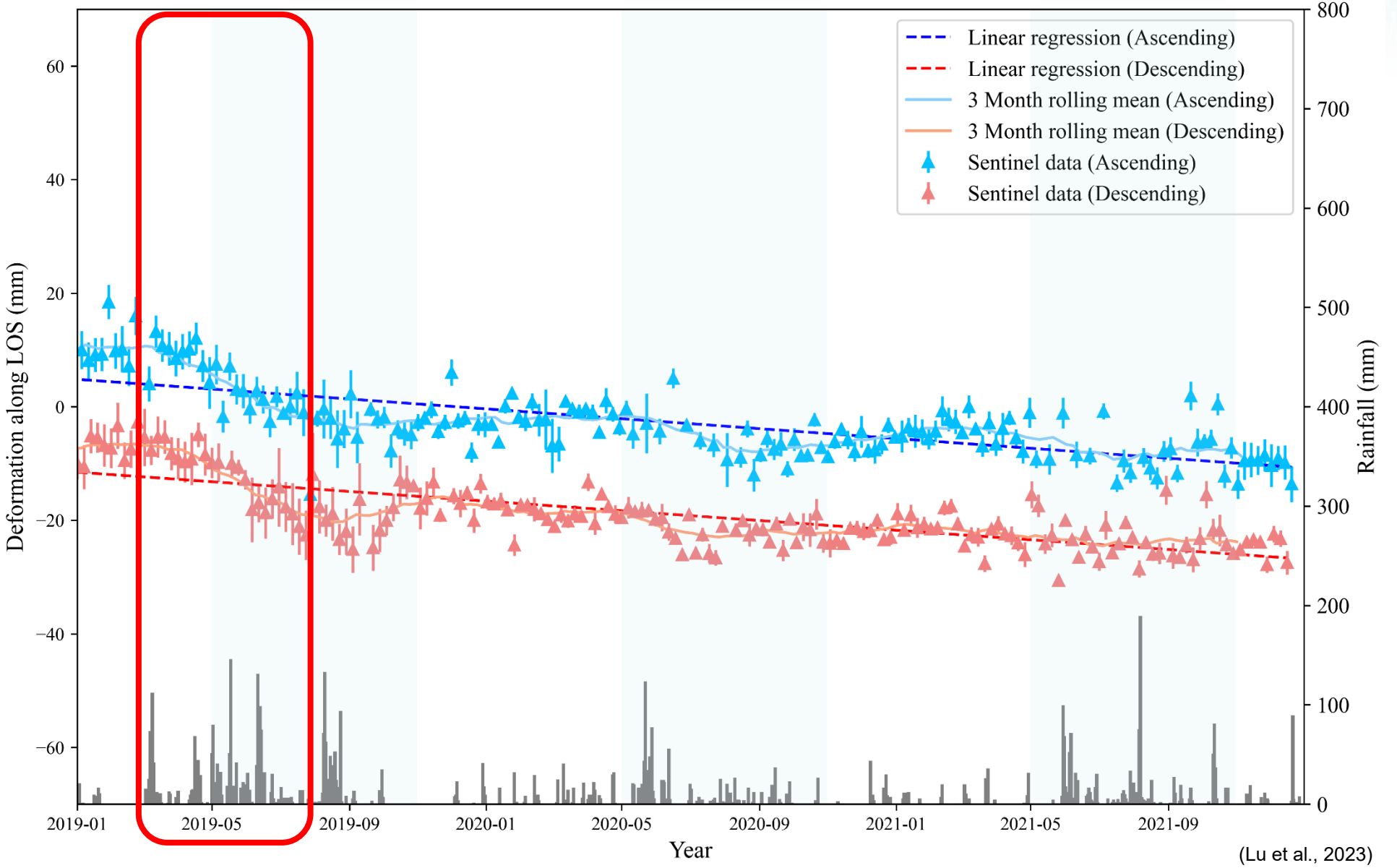


(Lu et al., 2023)

The activity of slow-moving landslide – Heping-T003

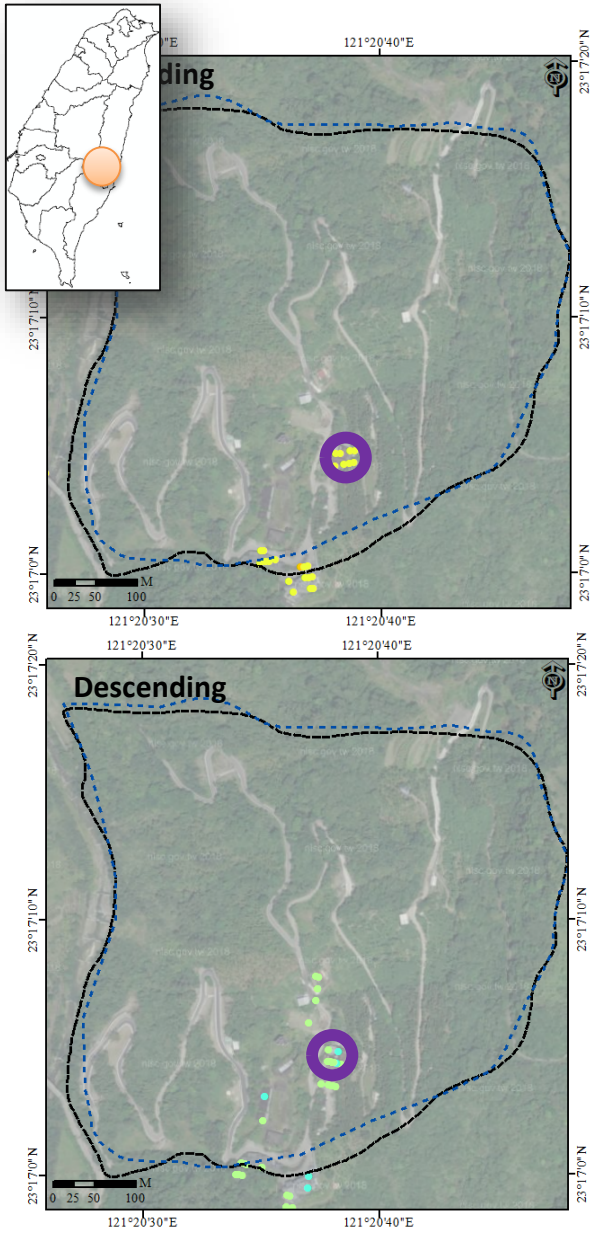
國家災害防救科技中心

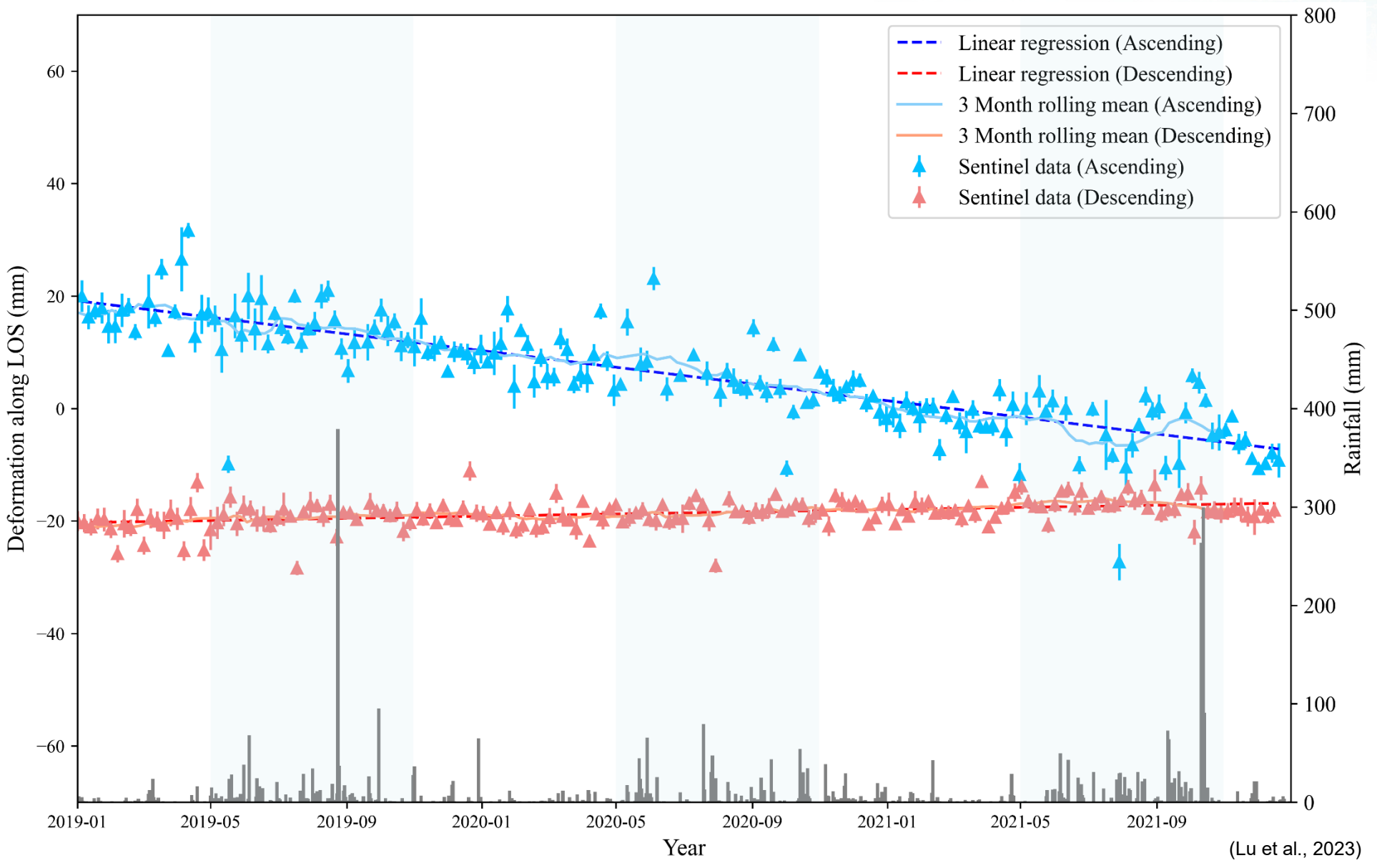




(Lu et al., 2023)

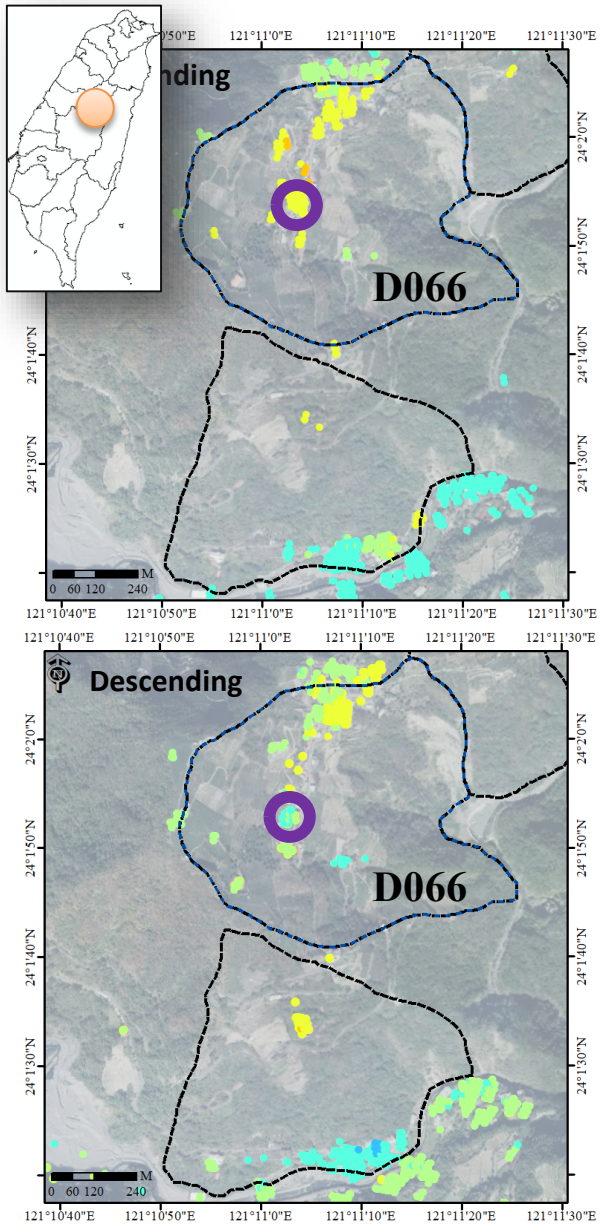
The activity of slow-moving landslide – Yuli-D018

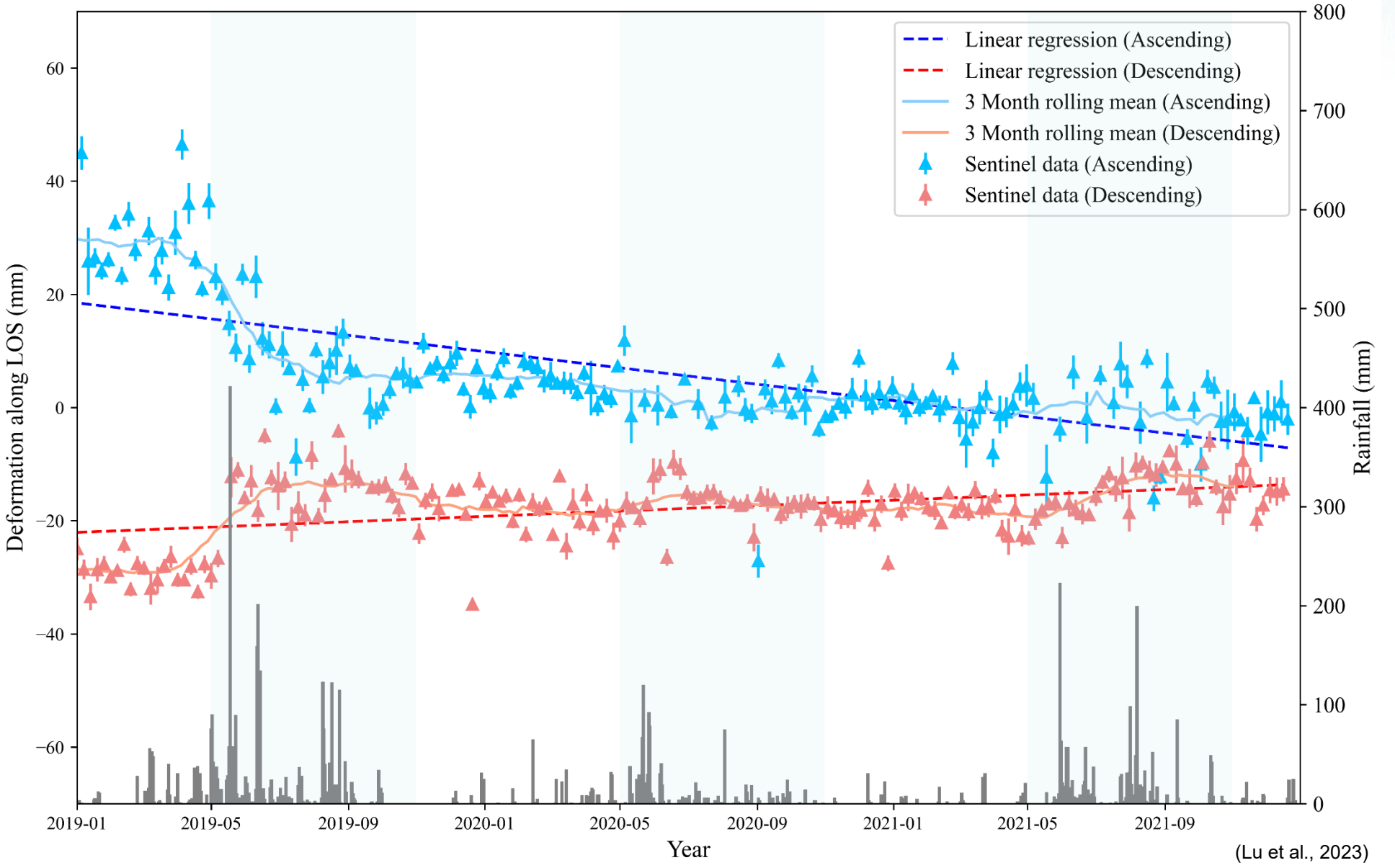




(Lu et al., 2023)

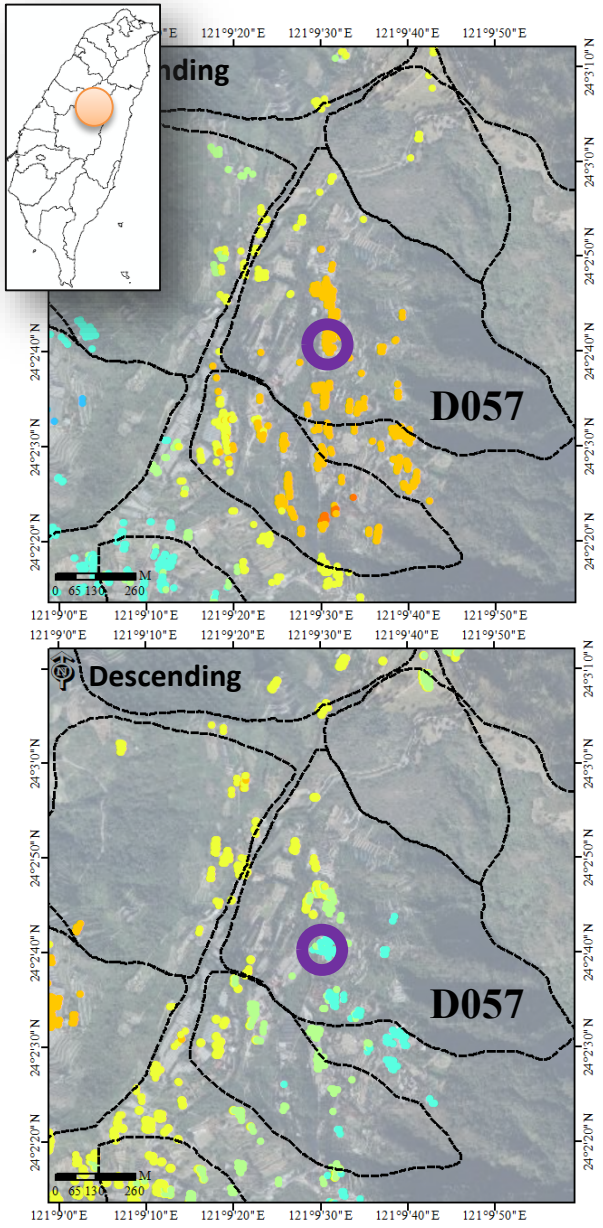
The activity of slow-moving landslide – Renai-D066

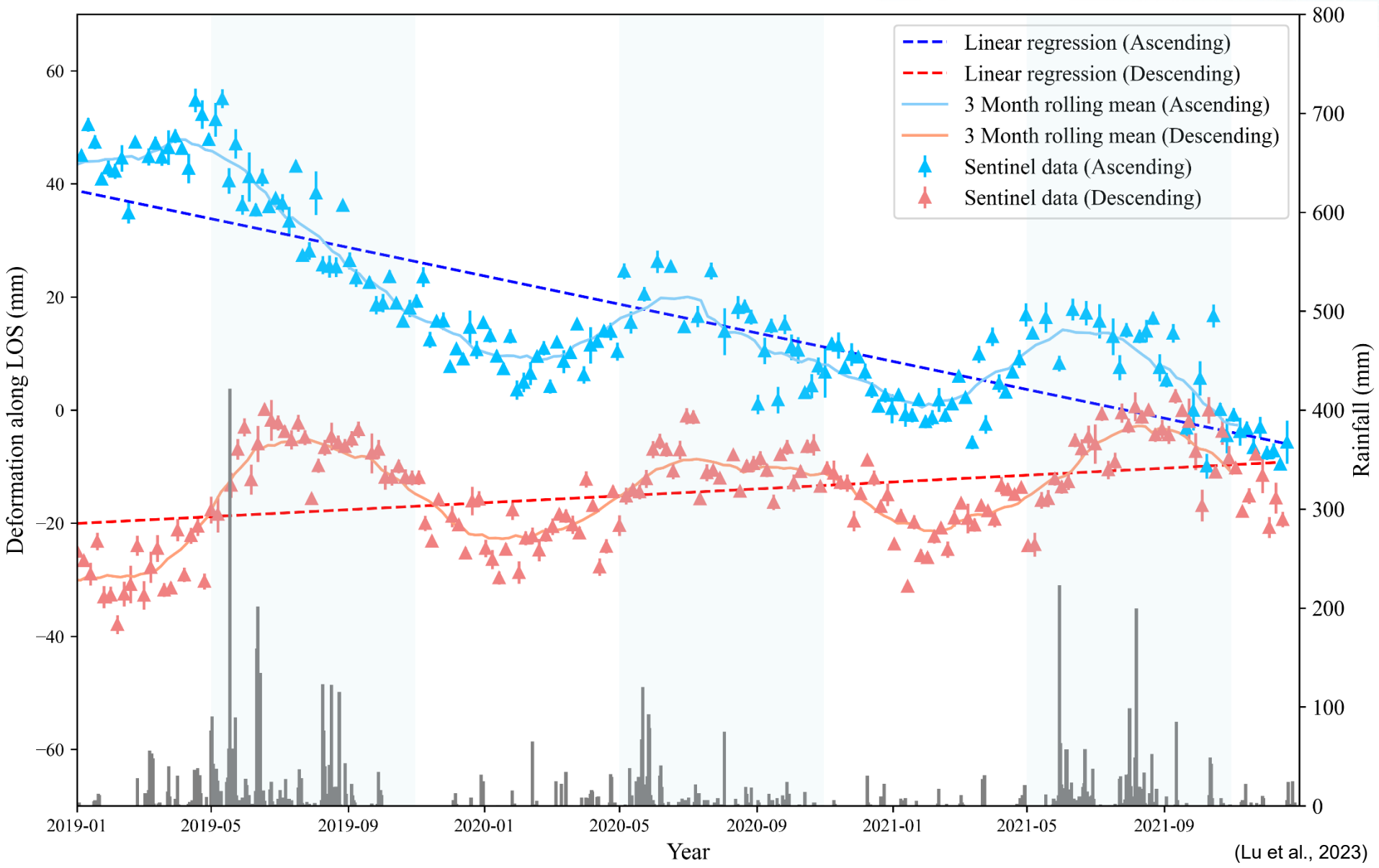




(Lu et al., 2023)

The activity of slow-moving landslide – Renai-D057

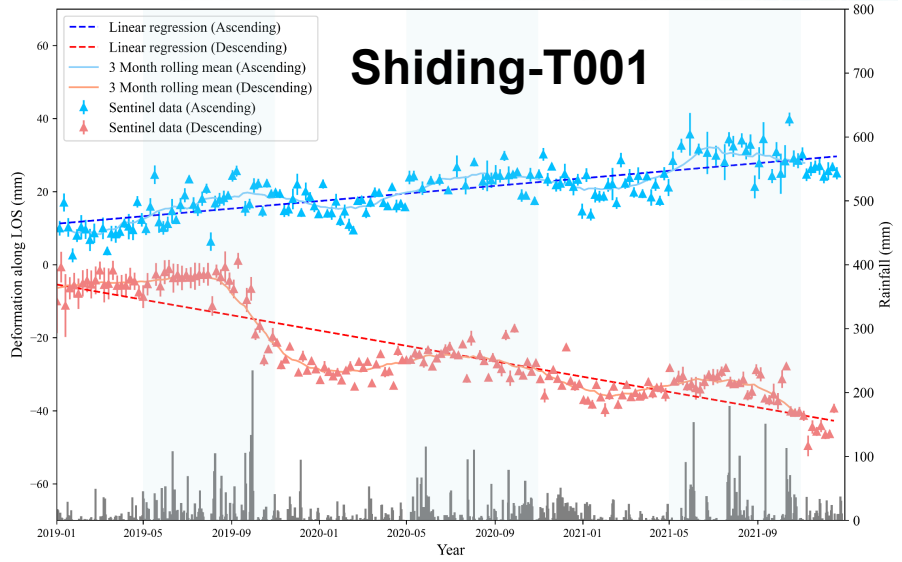


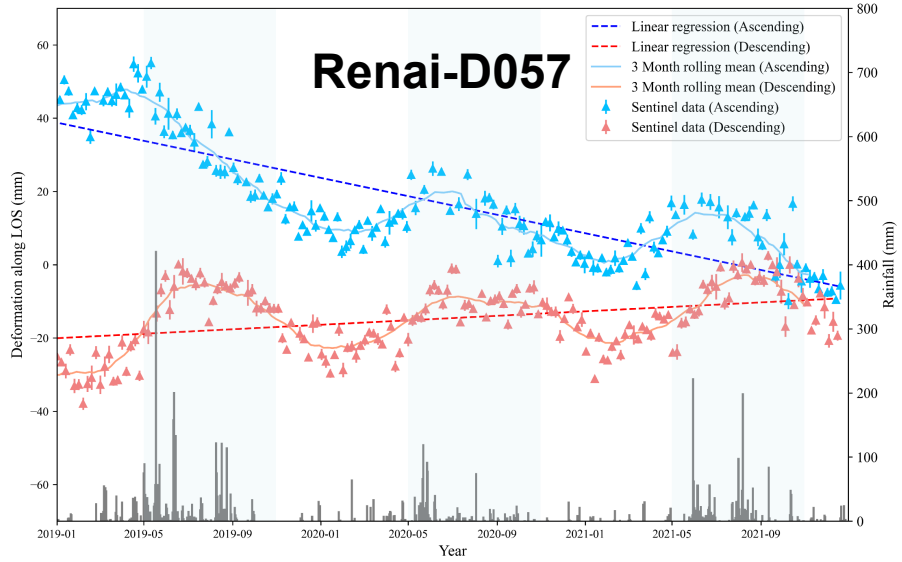


(Lu et al., 2023)

MTInSAR time series - Seasonal fluctuations

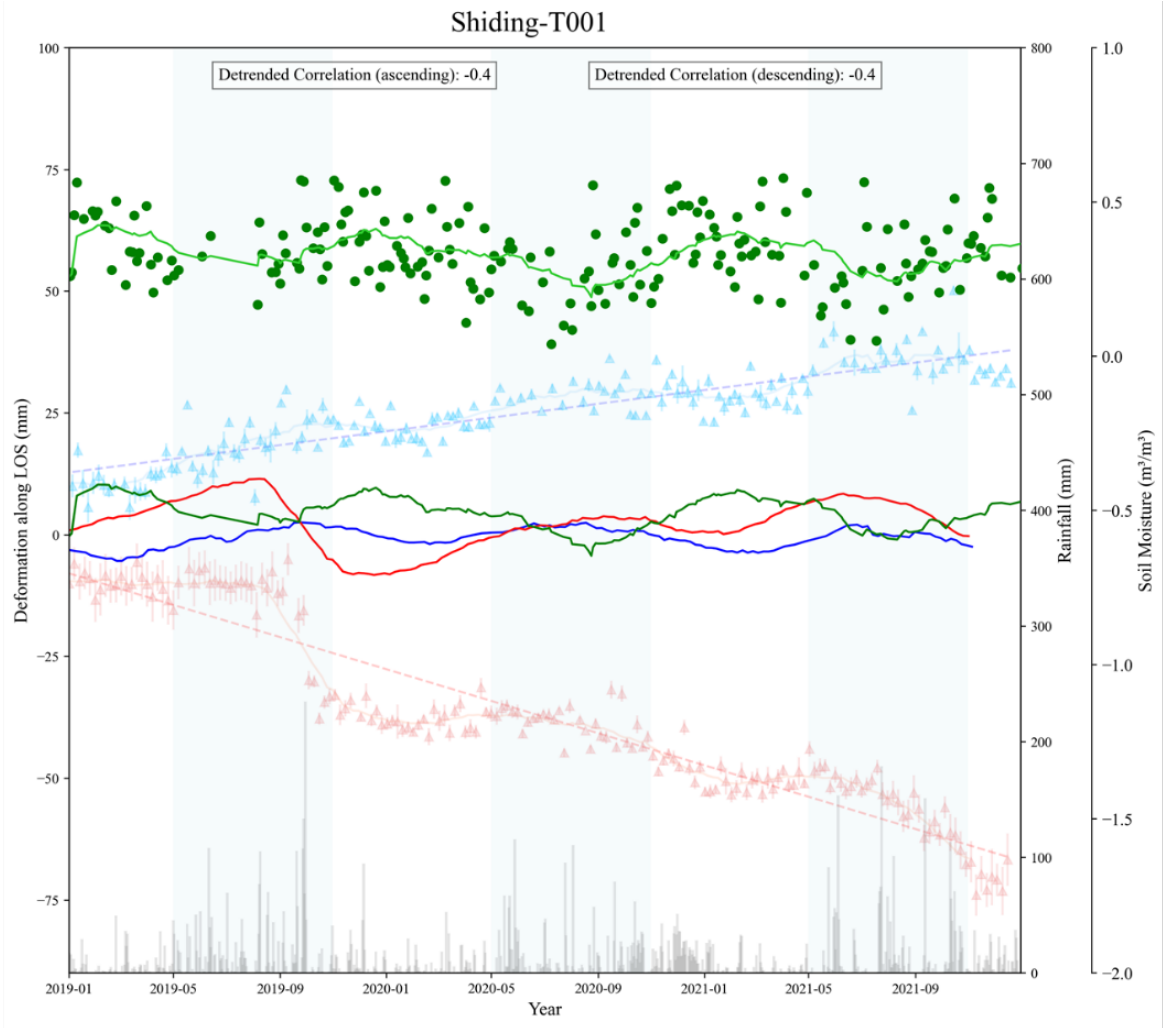
- **Seasonal Surface fluctuation**
  - **Seasonal fluctuations** in surface deformation can be observed at **global, regional, and local scales**
  - **Total tropospheric delay**
    - Turbulent delay ➔ **spatially correlated** but **temporally random**
    - Stratified tropospheric delay ➔ **steep gradients** or elevation changes exceeding 1000 meters
  - Variations of **hydrological condition**
    - soil moisture, surface water, snow accumulation, and groundwater levels
    - **Hydrological loading** ➔ vertical surface displacement
    - **Pore water pressure** ➔ vertical surface displacement, slope unstable

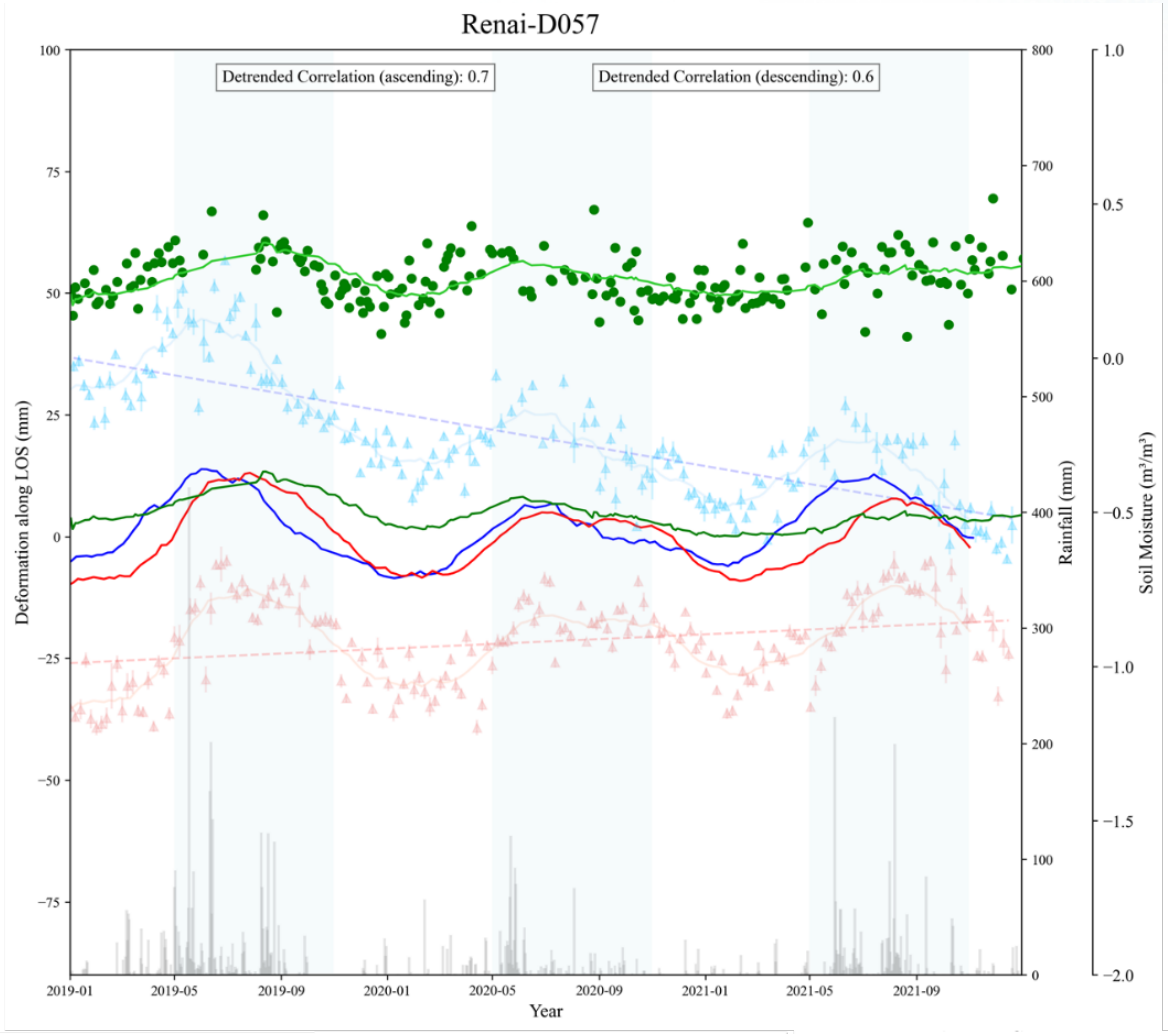




(Lu et al., 2023)

MTInSAR time series - Seasonal fluctuations





(Lu et al., 2026)

Summary

- Optimized analysis package multi-snap2stamps is proposed for processing interferograms in multiple regions more efficiently.
- Monitoring the activity of slow-moving landslide by MTInSAR technique
  - characterizing velocity distribution and movement
  - detecting accelerated motions
- MTInSAR technique can complement the lack of in situ monitoring data , provide important information for landslide hazard assessment and enhances the possibility of detecting landslide precursory motions in the future.
  - Still have some limitations：revisit time, persistent scatterers, effect of topography …...



(image credit: NISAR website)