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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[2] Institute of Earth Science, Academia Sinica, Taipei, Taiwan
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[5] Geological Survey and Mining Management Agency, Taipei, Taiwan

2026.11.11



Landslide in Yilan (PH-7 86.5K) during Typhoon Nesat (2022)
(Source: NCDR)



Flooding caused by Cyclone Gabrielle in New Zealand (2023)
(Source：NZDE)



Extreme heatwave struck Mecca, Saudi Arabia (2024)
(Source: AP / Dazhi Images (licensed))



Volcanic eruption in Iceland (Dec. 2023)
(Source: REUTERS / Dazhi Images (licensed))



0403 Hualien **earthquake** caused **landslides** (2024)
(Source: NCDR)



Noto **earthquake** in Japan triggered **tsunami** (2024)
(Source: EPA / Dazhi Images (licensed)



Winter storm struck Buffalo, New York (Dec. 2022)
(Source: REUTERS / Dazhi Images (licensed))

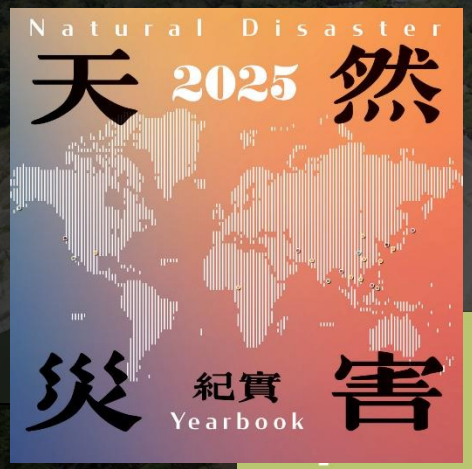


Wildfires in Southern California, USA (Jan. 2025)
(Source: AP / Dazhi Images (licensed))



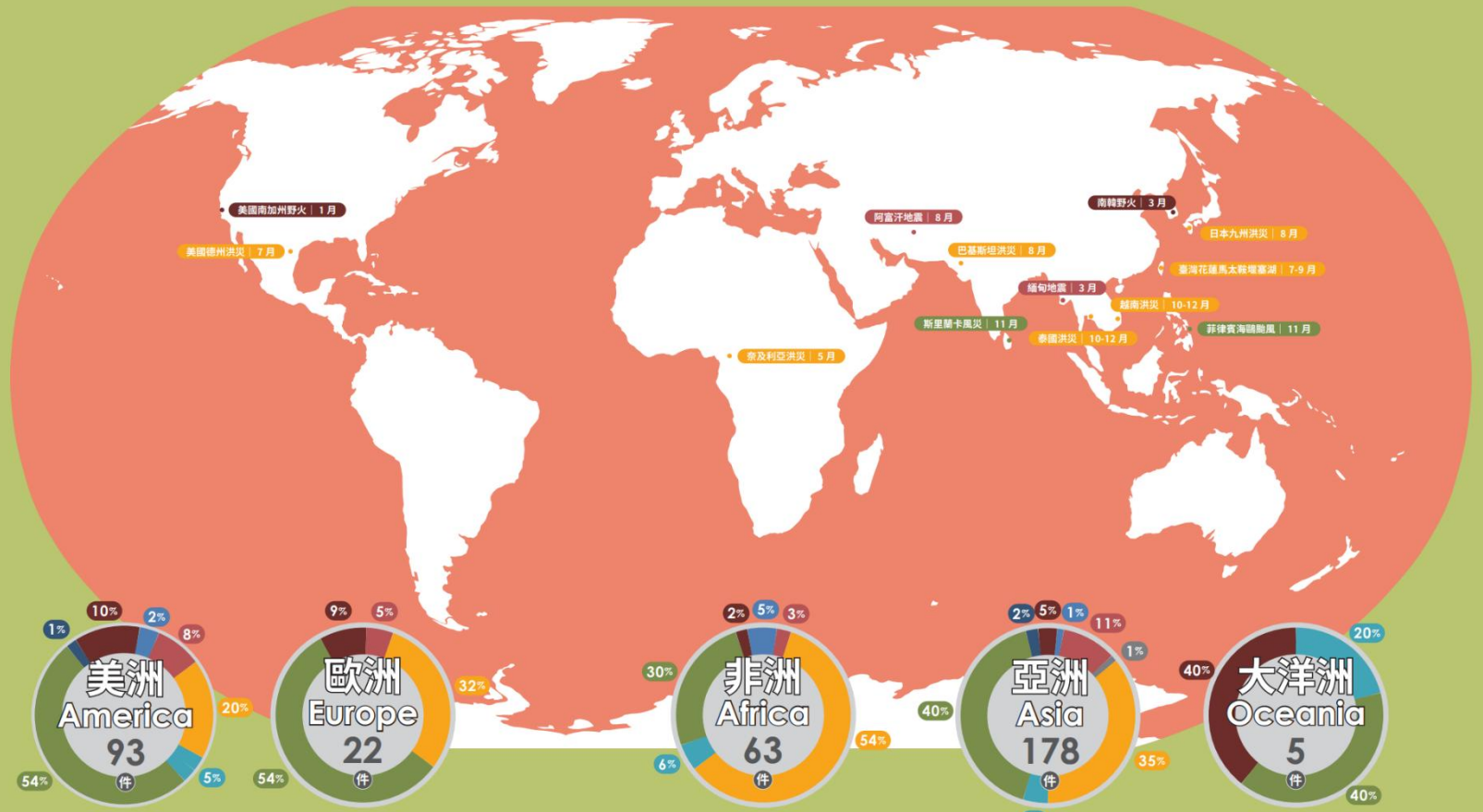
Noto **earthquake** caused **building damage** (2024)
(Source: REUTERS / Dazhi Images (licensed))

2025 Global disaster situation

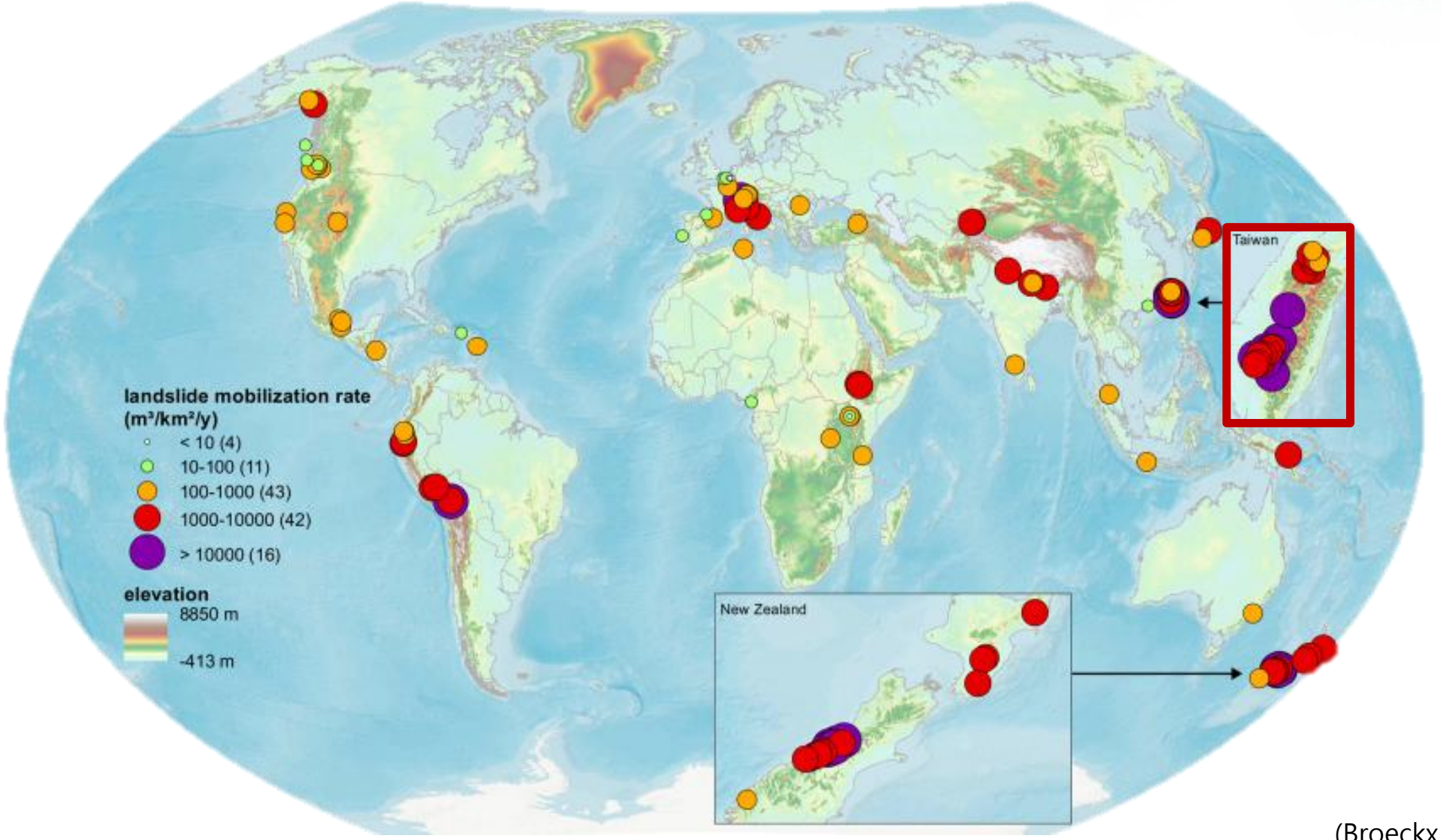


全球災害概述

Global Disaster Situation



Global landslide mobilization rates



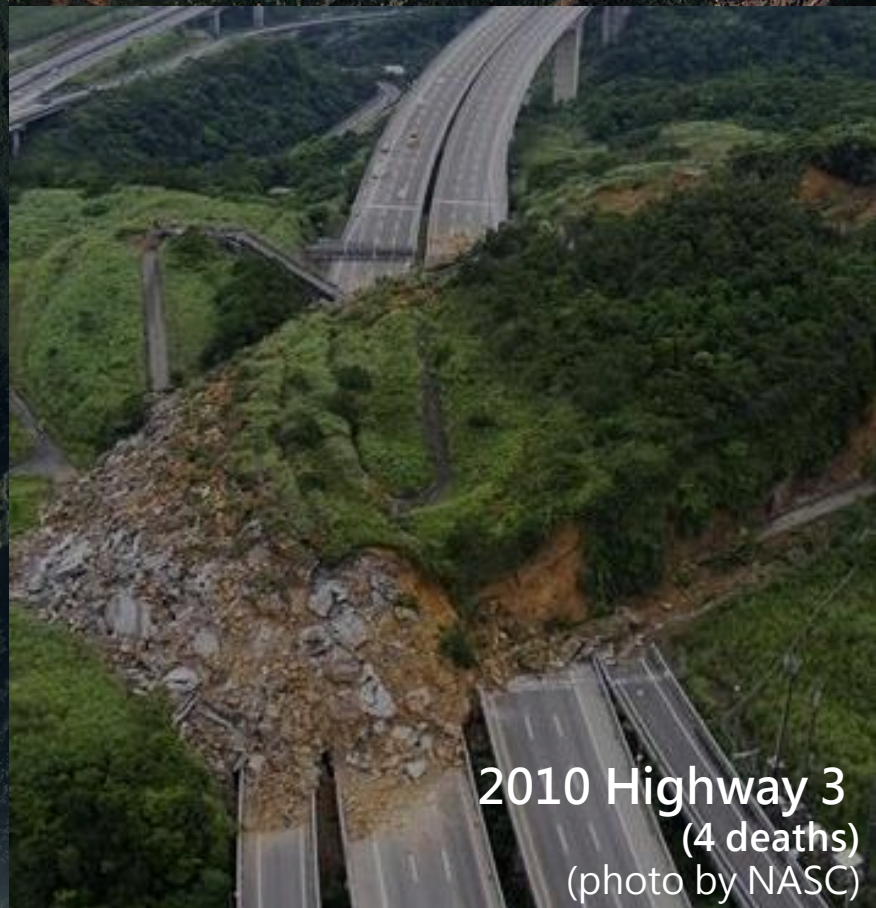
(Broeckx et al., 2020)

Over 328,583 slope failures and landslide happened, which caused about 1200 deaths during 2000-2025 in Taiwan.

Date: 2025/09/30
3D Terrain Model: NCDR
Source: Aerial Survey and Remote Sensing Branch,
Forestry and Nature Conservation Agency, MOA



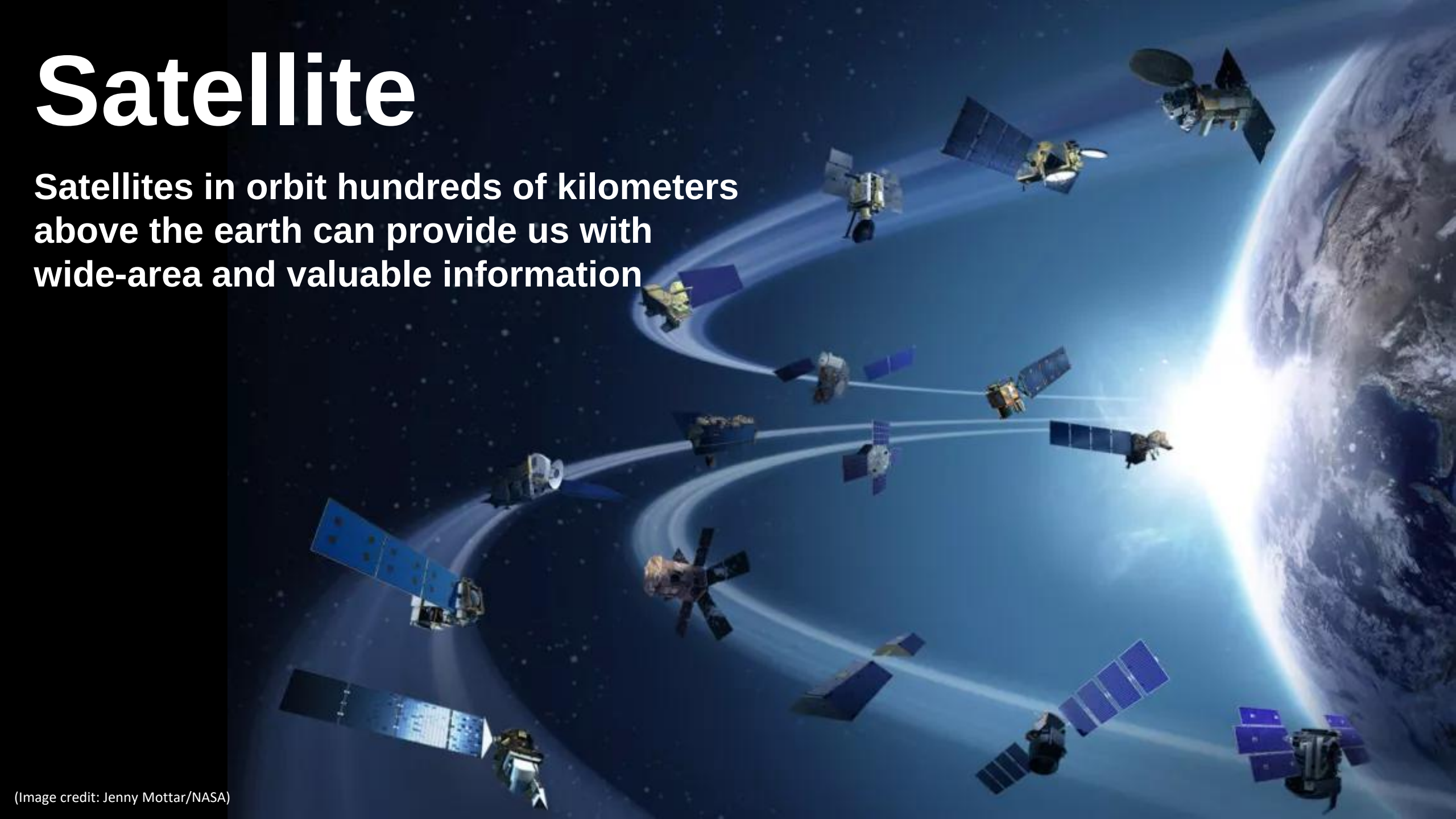
2009 Hsiaoling
(407 deaths)
(photo by Bo-Lin Chi)



2010 Highway 3
(4 deaths)
(photo by NASC)

Satellite

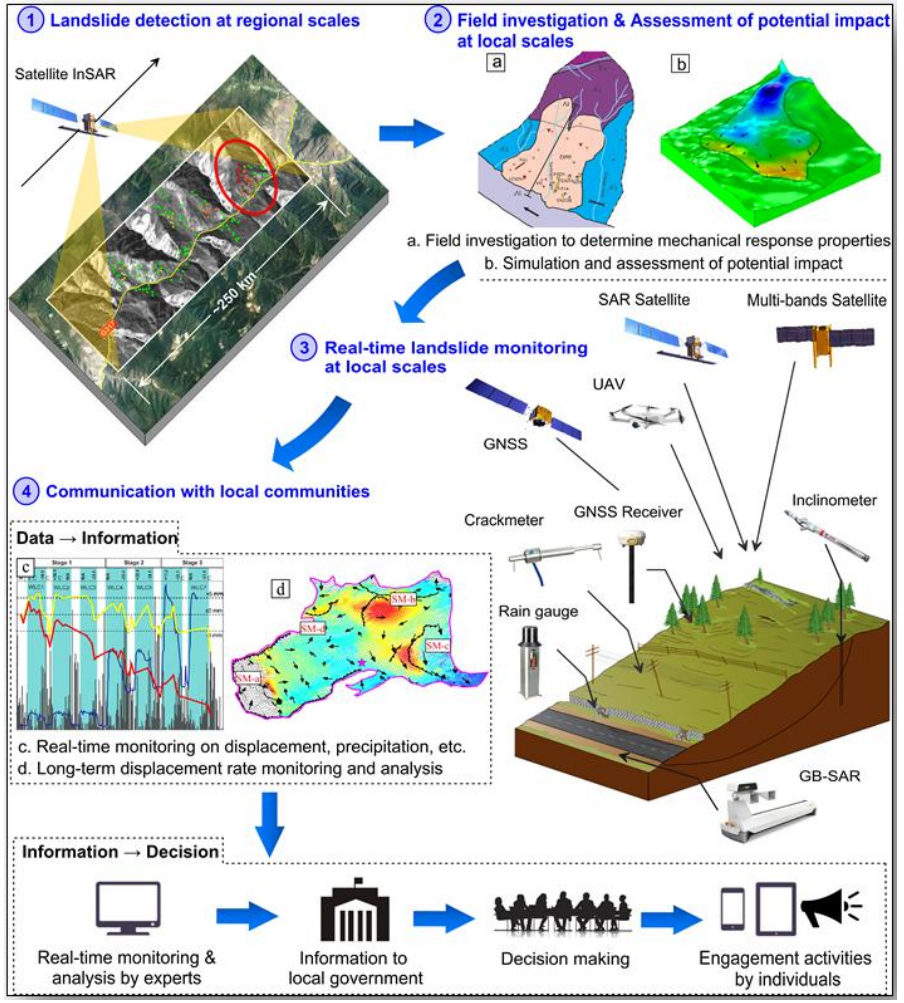
Satellites in orbit hundreds of kilometers above the earth can provide us with wide-area and valuable information



(Image credit: Jenny Mottar/NASA)

Outline

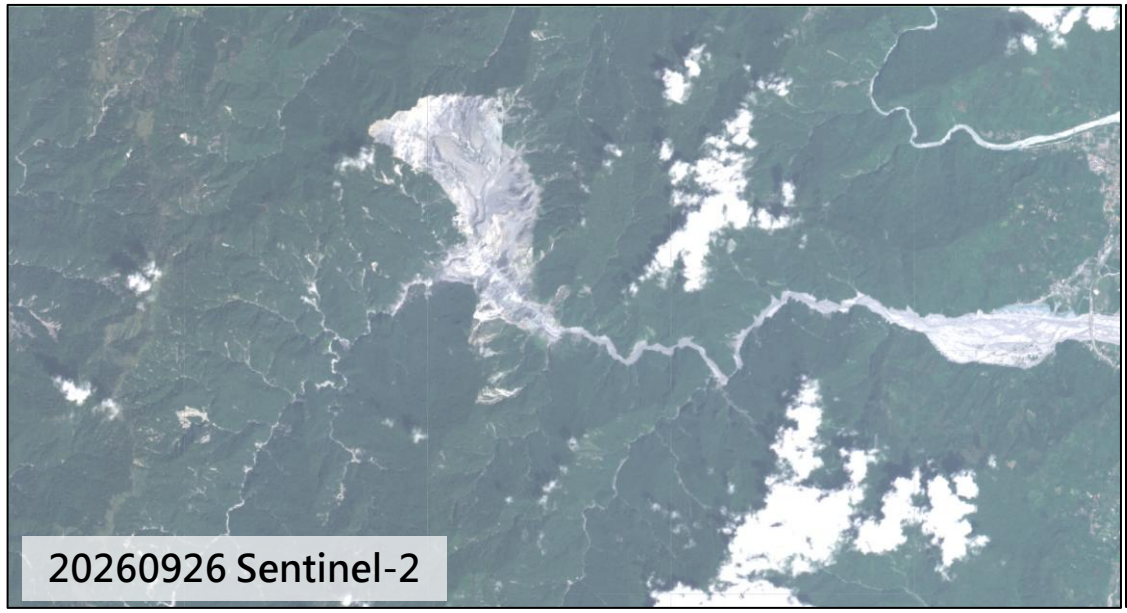
- Introduction of Synthetic Aperture Radar (SAR)
- Multi-Temporal InSAR Techniques
- Applications of Monitoring Surface Deformation of Slow-Moving Landslides
- Summary

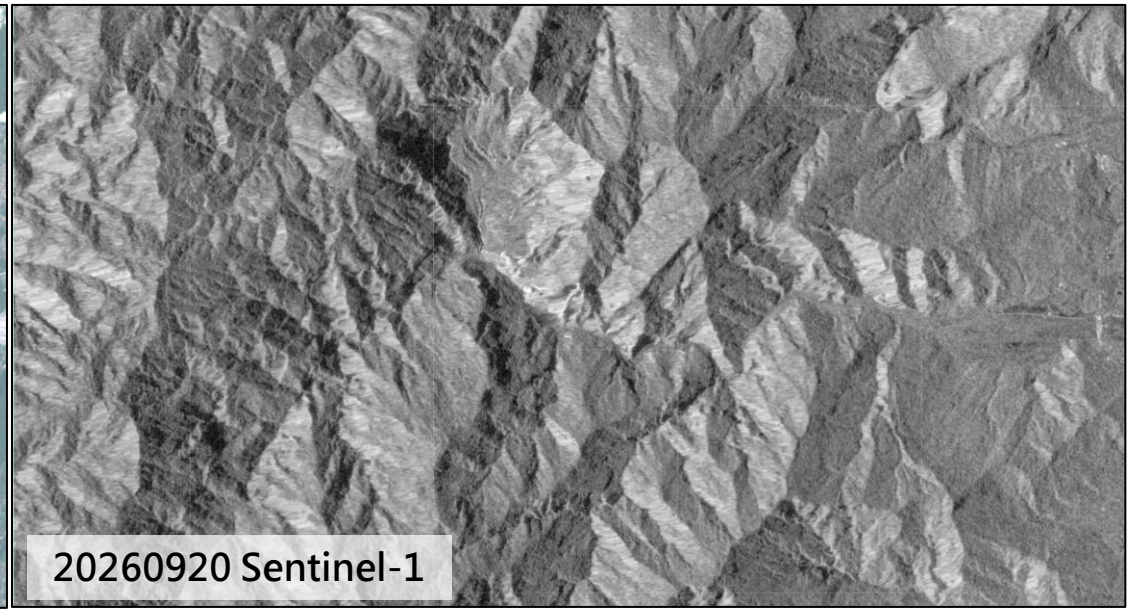


(Dai et al., 2020)

Satellite Image Classification

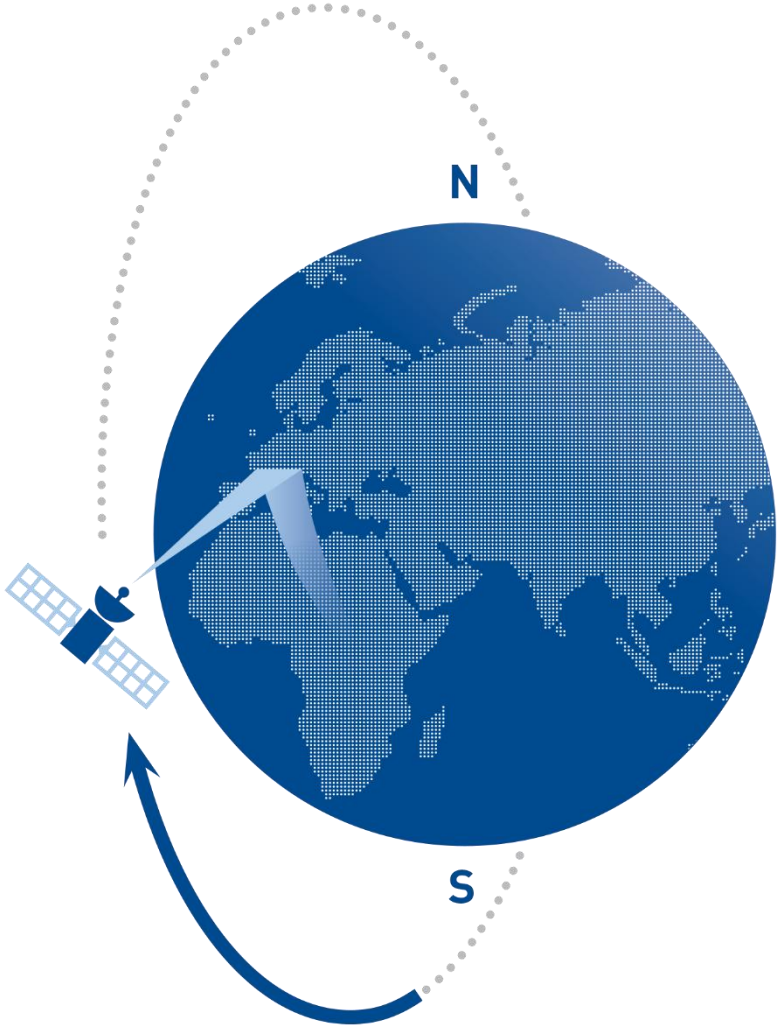
- **Optical Satellite Imagery**
  - Uses visible and infrared wavelengths; affected by sunlight and cloud cover; provides intuitive, easy-to-interpret images.
  - Sentinel-2, MODIS, Landsat-7/8, FORMOSAT-2/5/8
- **Synthetic Aperture Radar, SAR**
  - Uses active microwave sensing; enables day-and-night,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



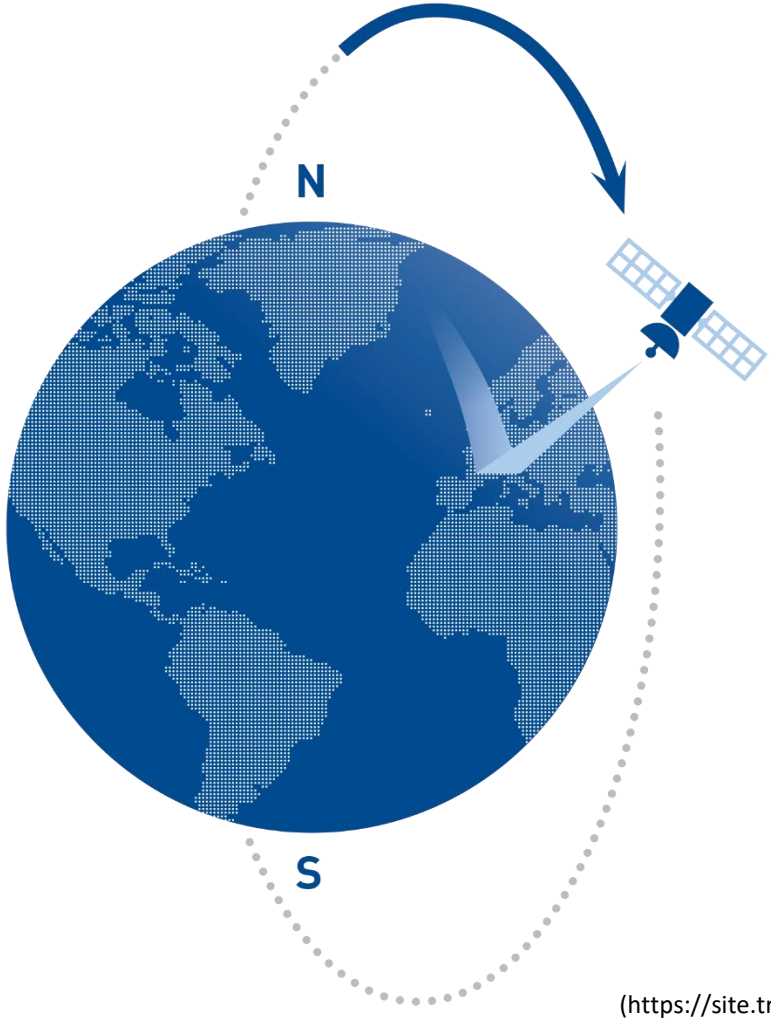


Satellite‘s orbit directions

(a) Ascending (升軌)

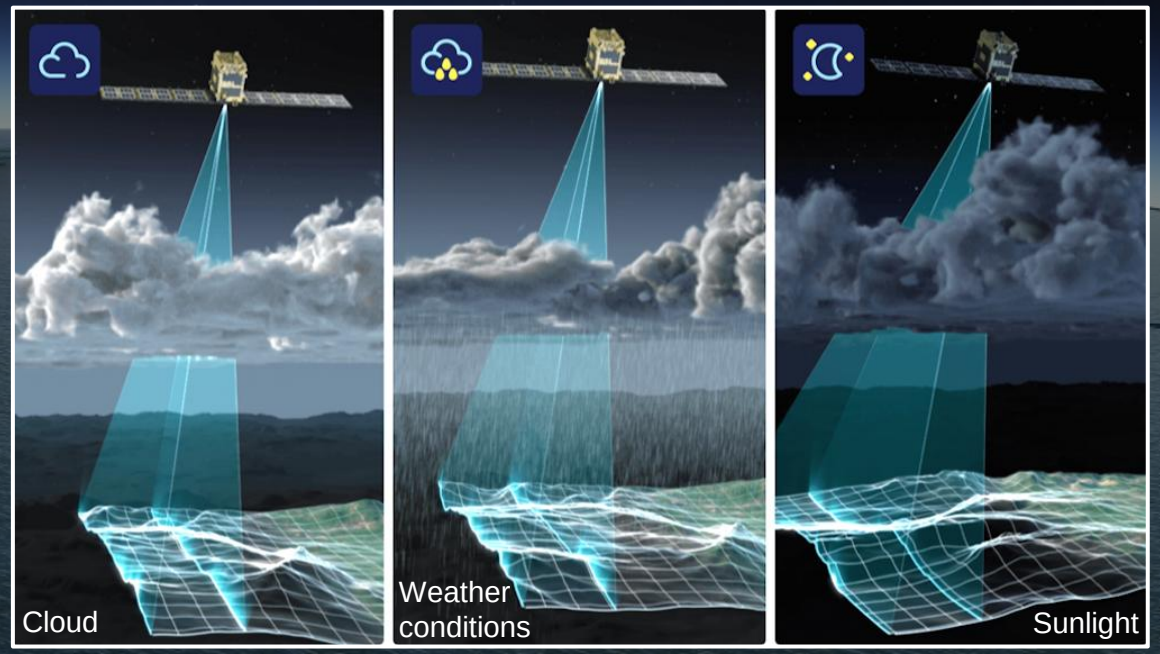


(b) Descending (降軌)



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

Observing surface information from Space



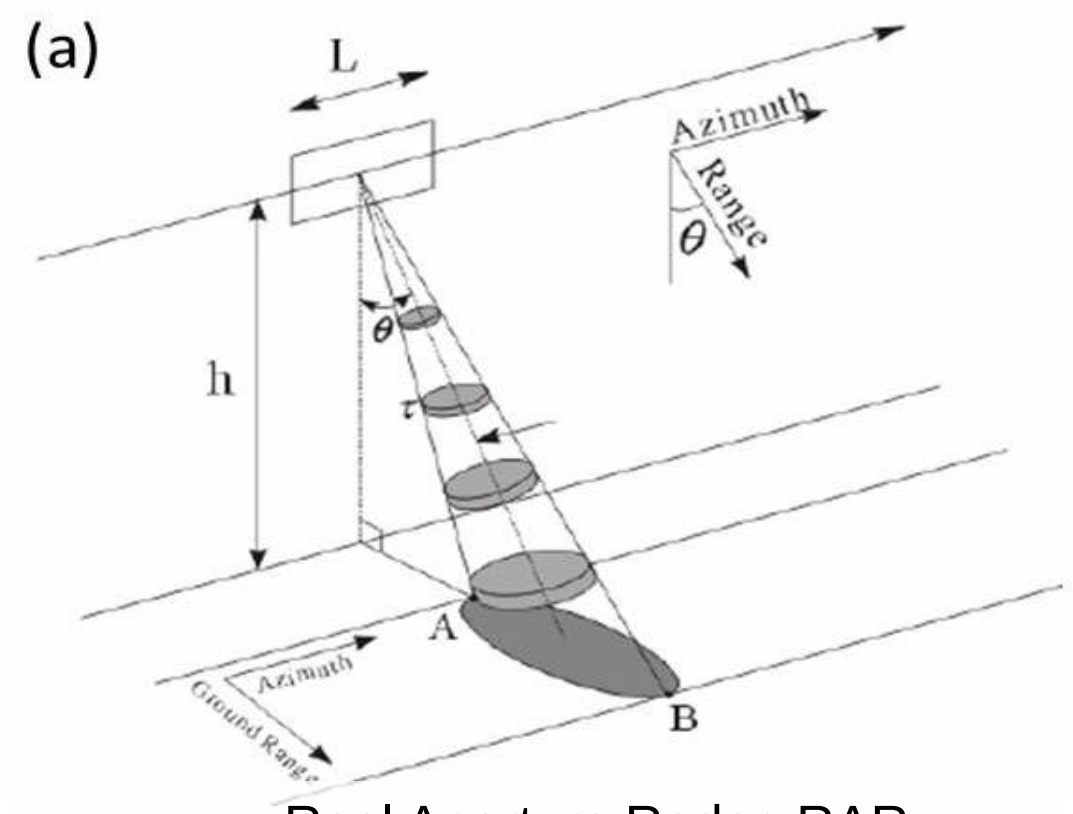
(Image credit: Synspective Inc.)

Synthetic Aperture Radar
SAR

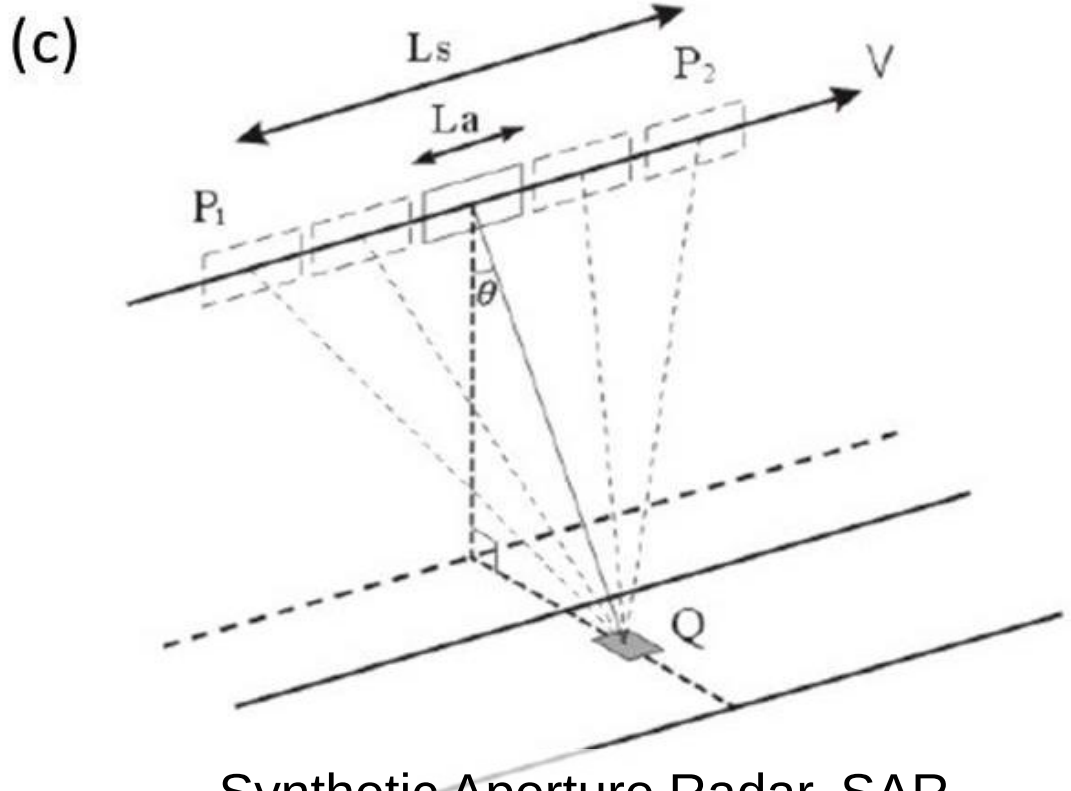
Synthetic Aperture Radar, SAR

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

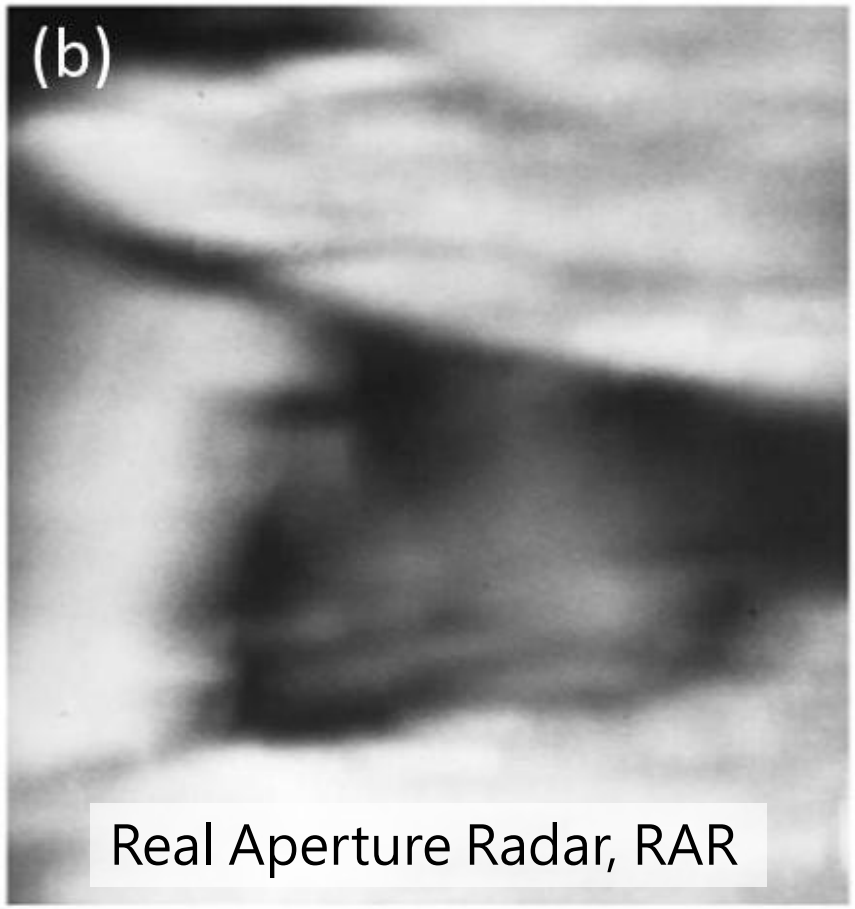


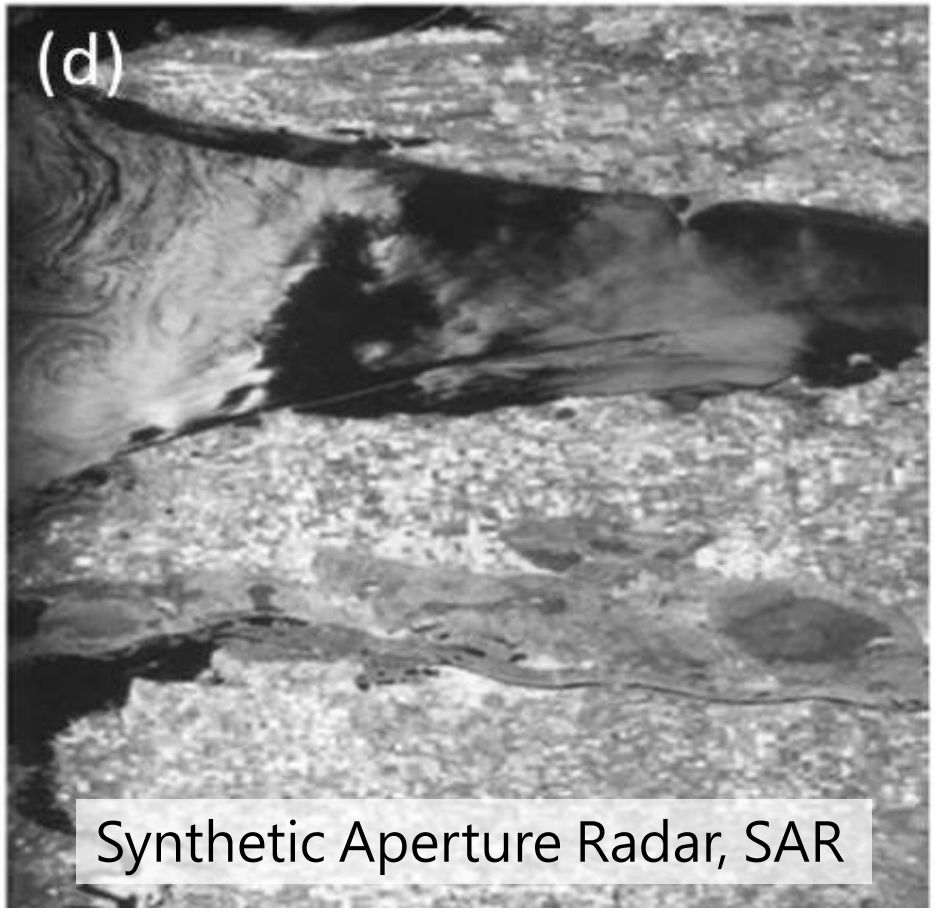
Synthetic Aperture Radar, SAR

(Masonnet and Feigl, 1998; Usai, 2001)

Synthetic Aperture Radar, SAR

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

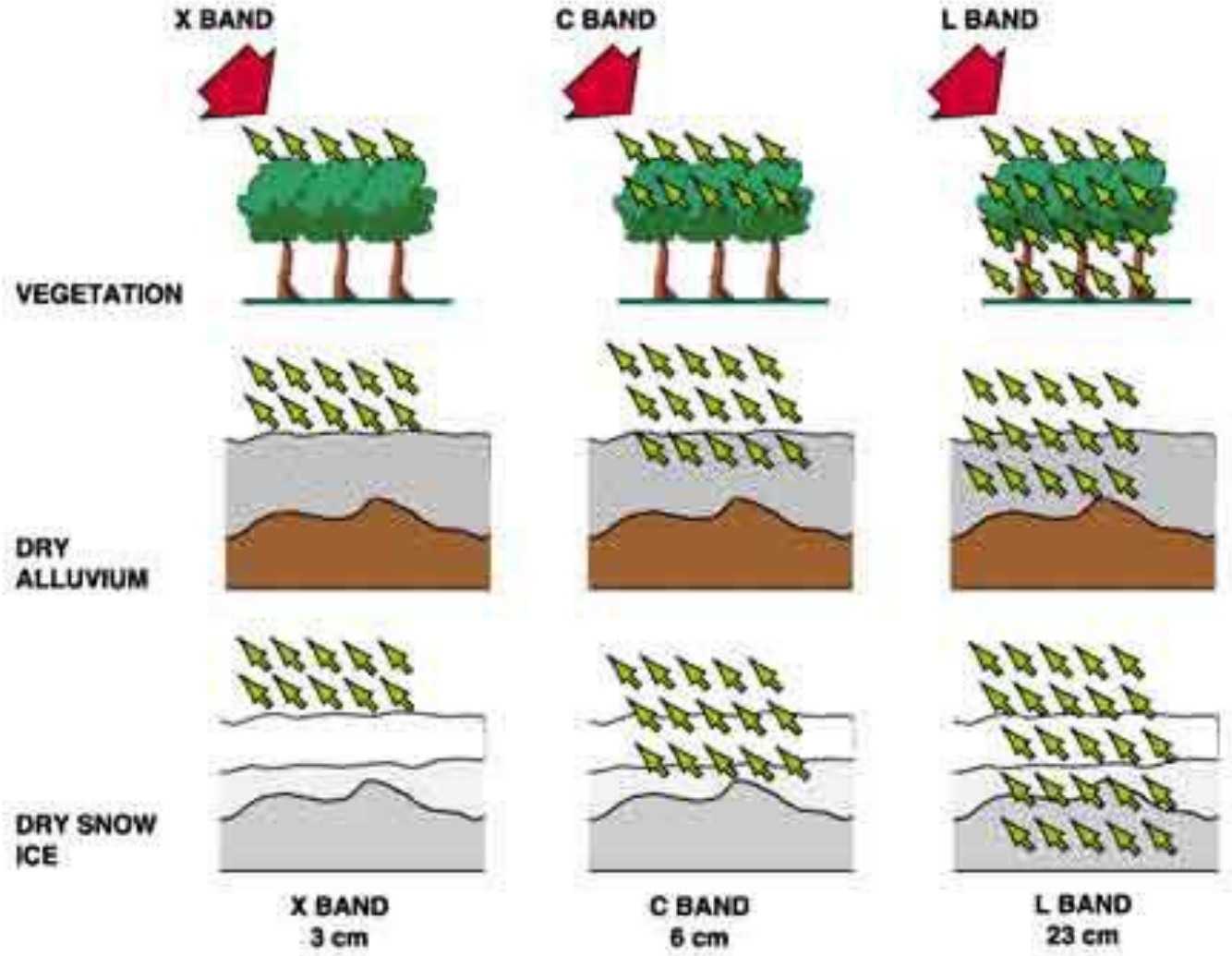




(Masonnet and Feigl, 1998; Usai, 2001)

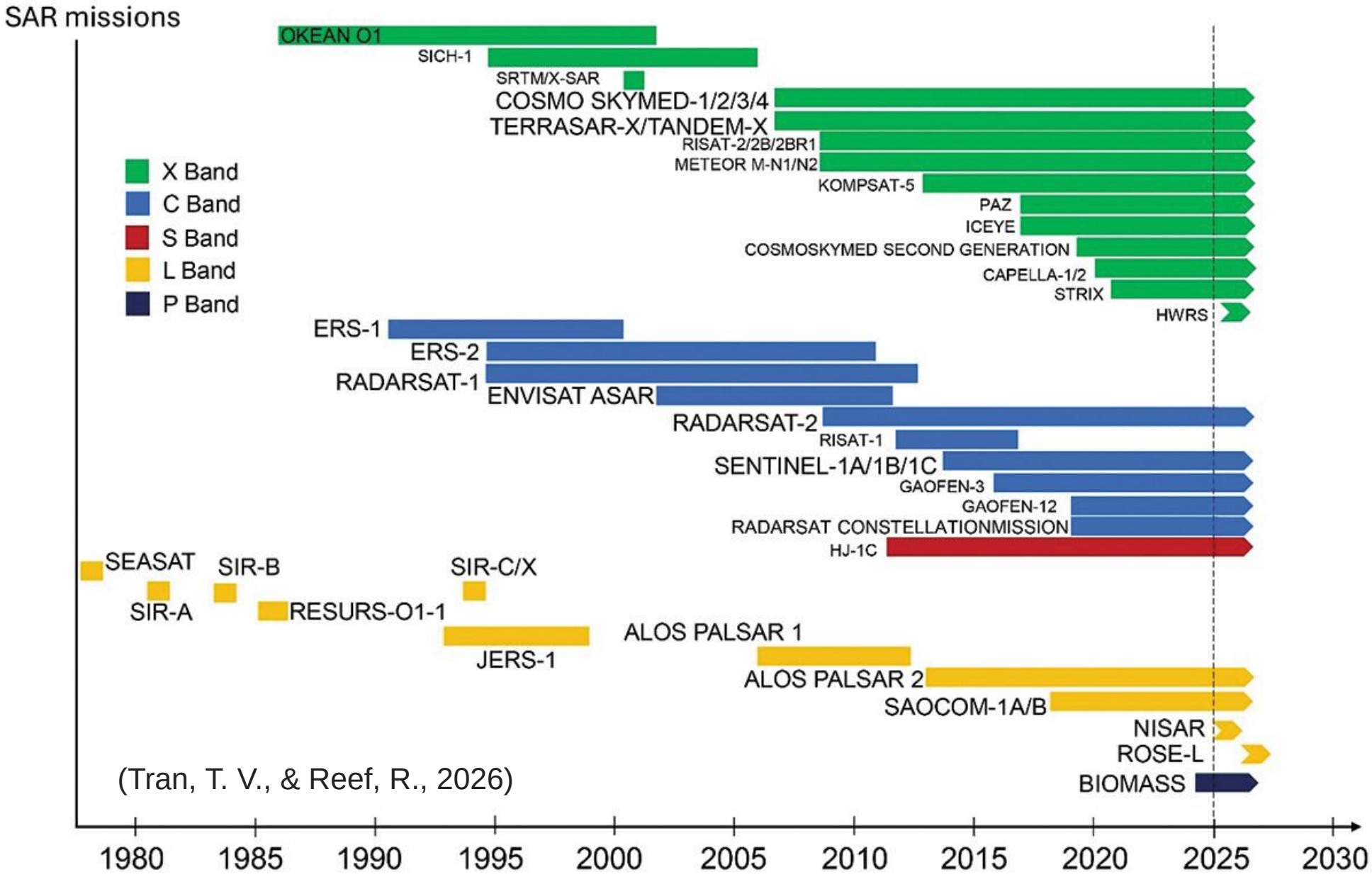
Synthetic Aperture Radar, SAR

- **Different surface features exhibit different scattering characteristics:**



(ESA earth online)

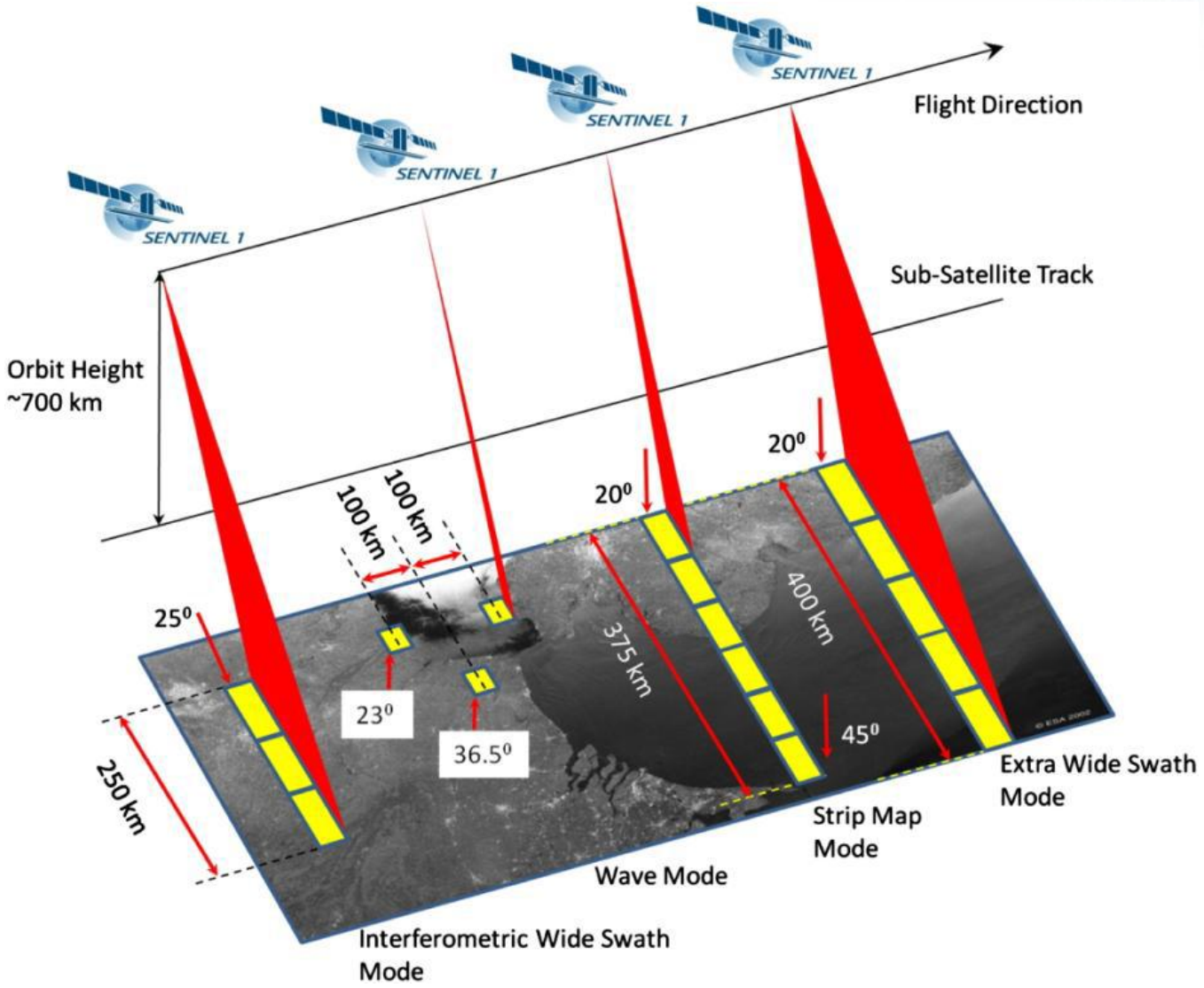
Synthetic Aperture Radar, SAR



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

Synthetic Aperture Radar – Sentinel-1

- **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

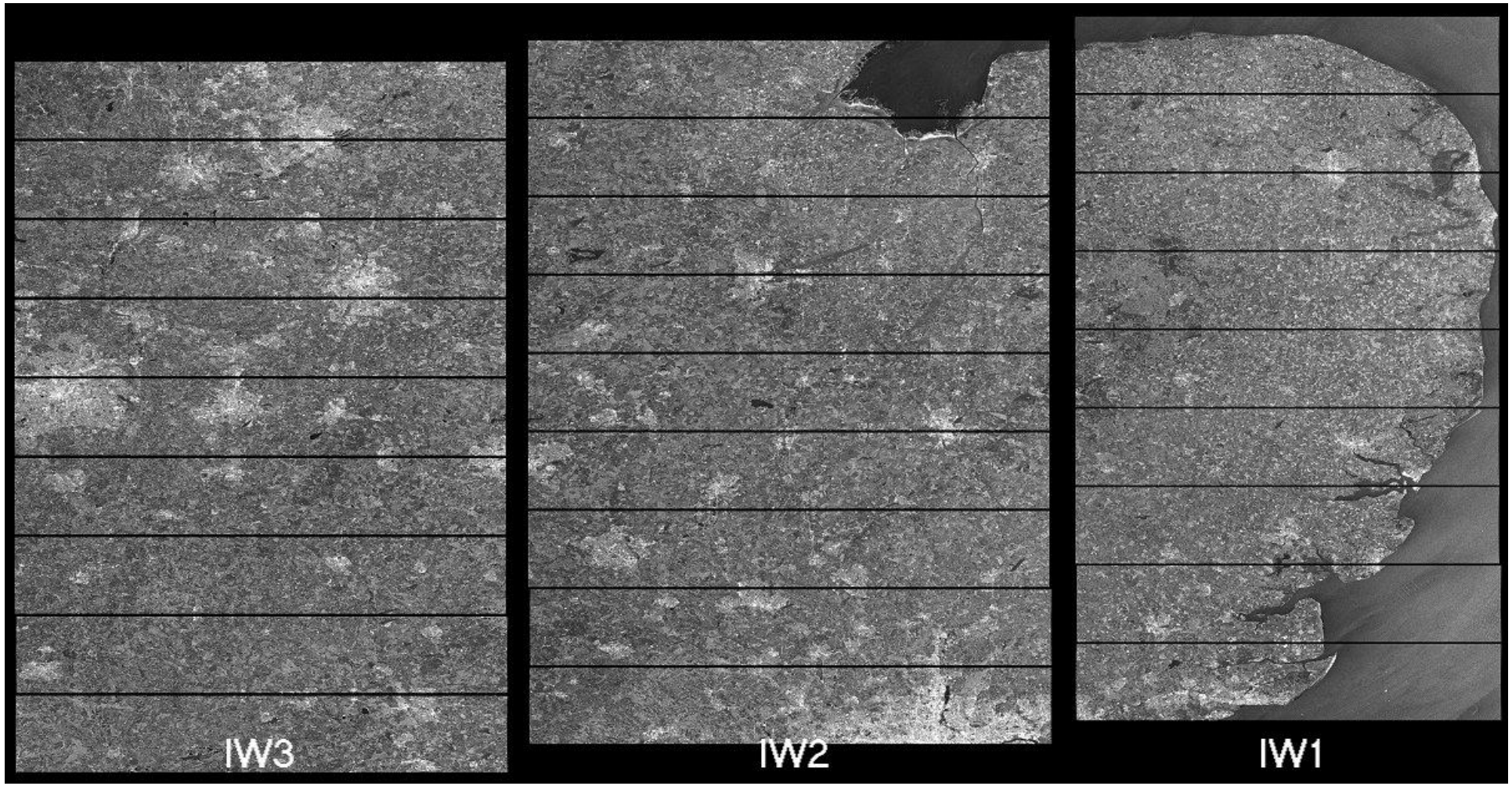


Synthetic Aperture Radar – Sentinel-1



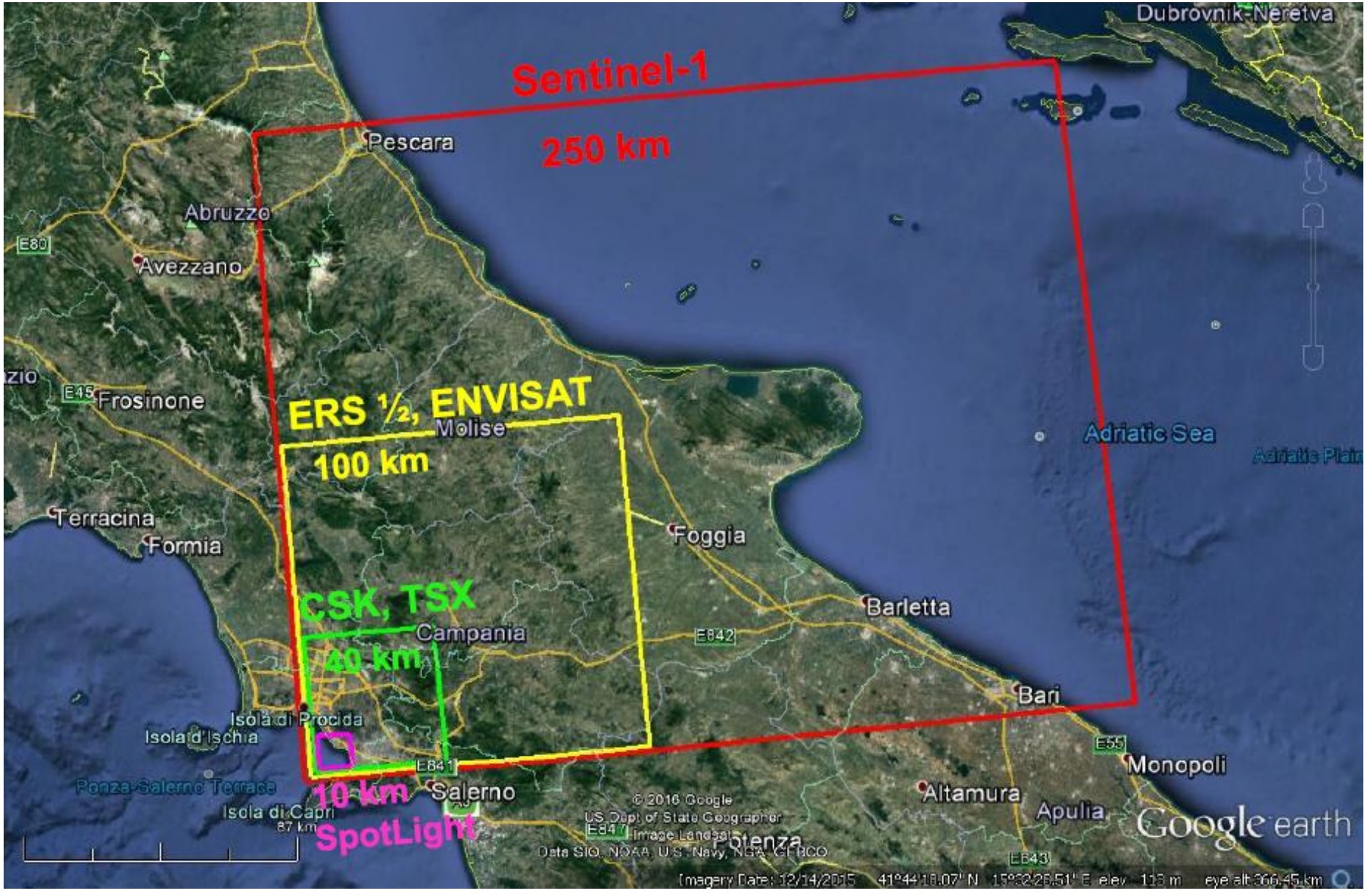
Synthetic Aperture Radar – Sentinel-1

- **Interferometric Wide swath (IW)**



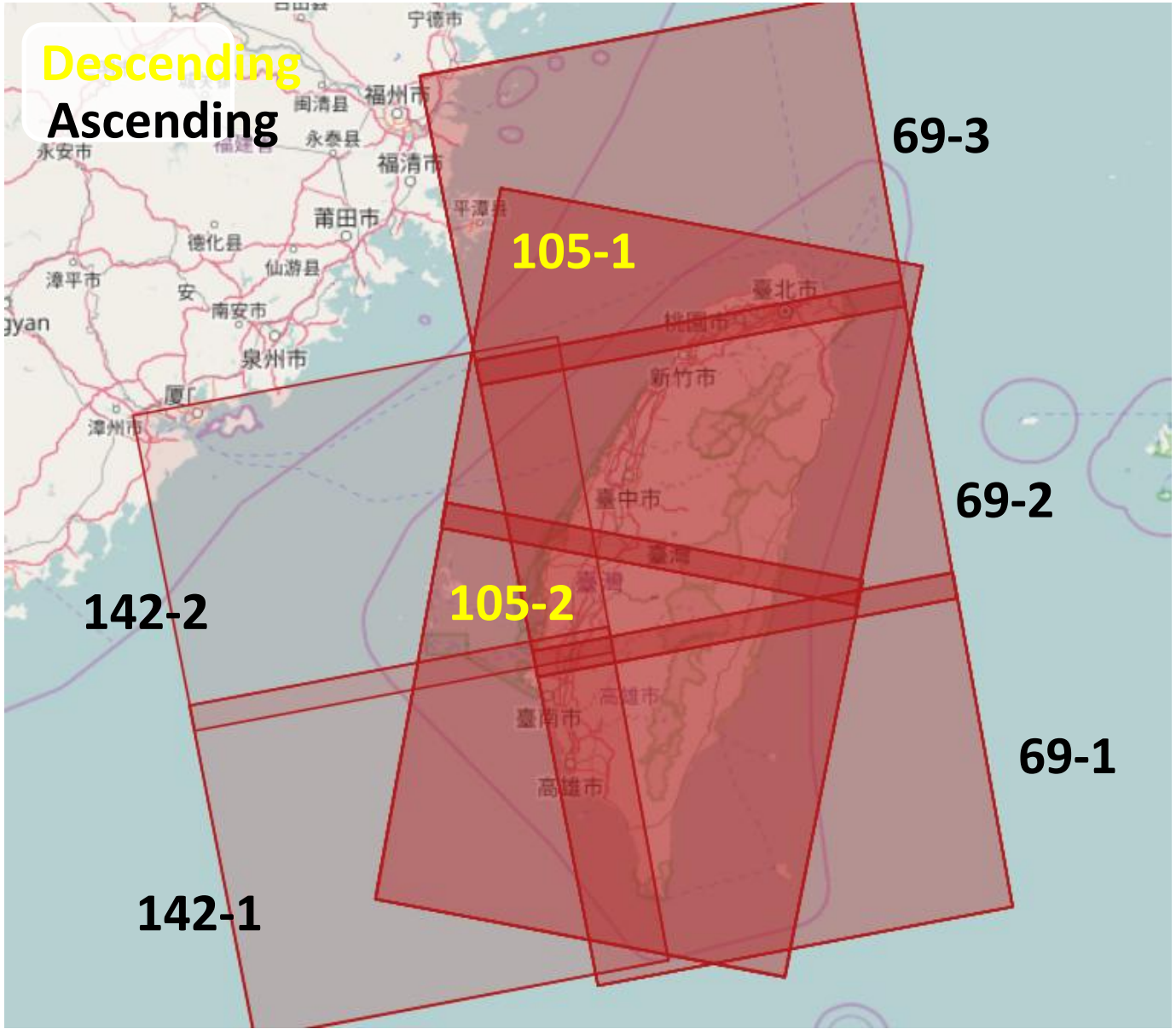
https://sentinel.esa.int/

Synthetic Aperture Radar – Sentinel-1



(Wasowski, 2019)

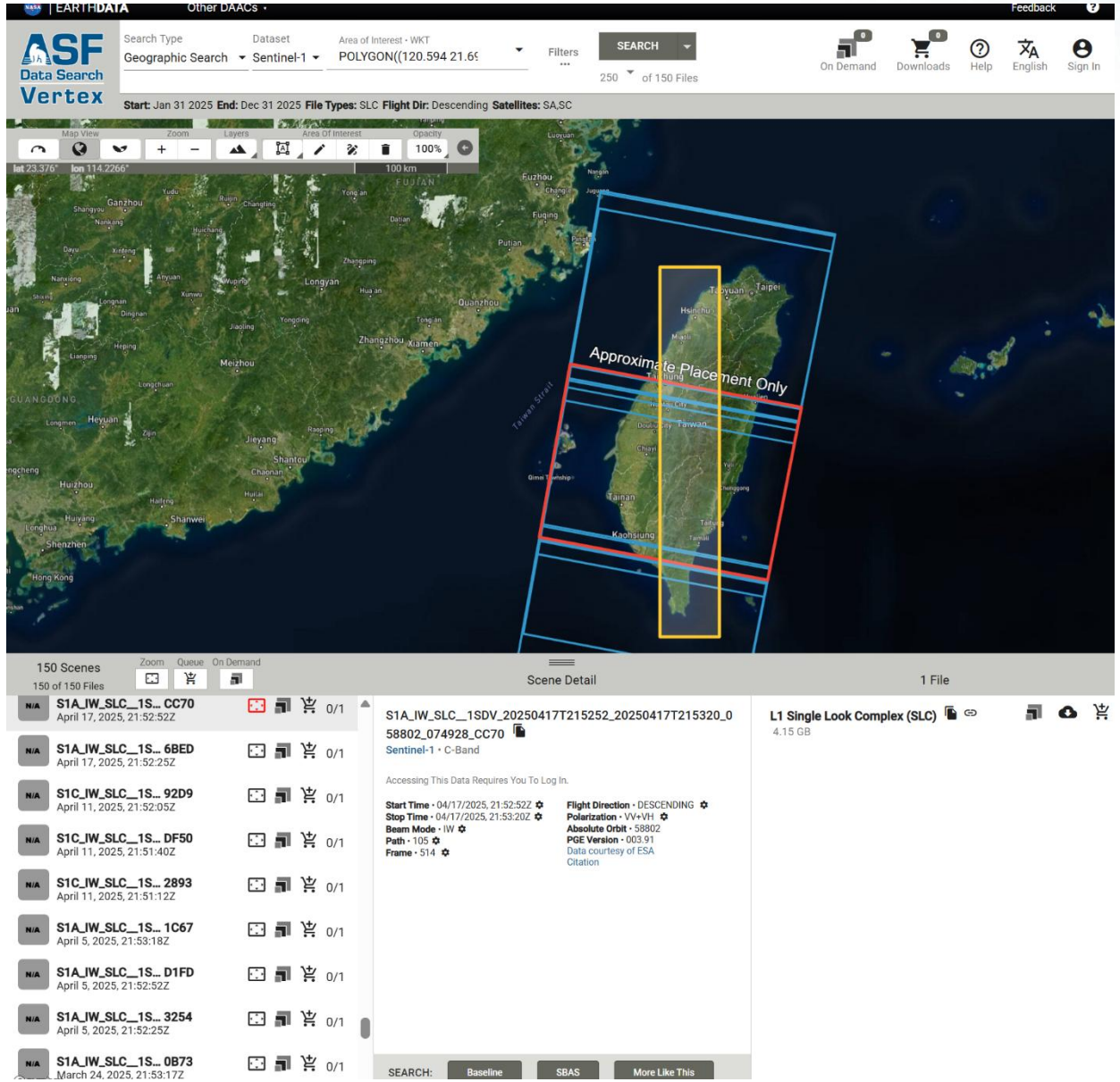
Synthetic Aperture Radar – Sentinel-1



Data Download Platforms and Analysis Software

國家災害防救科技中心

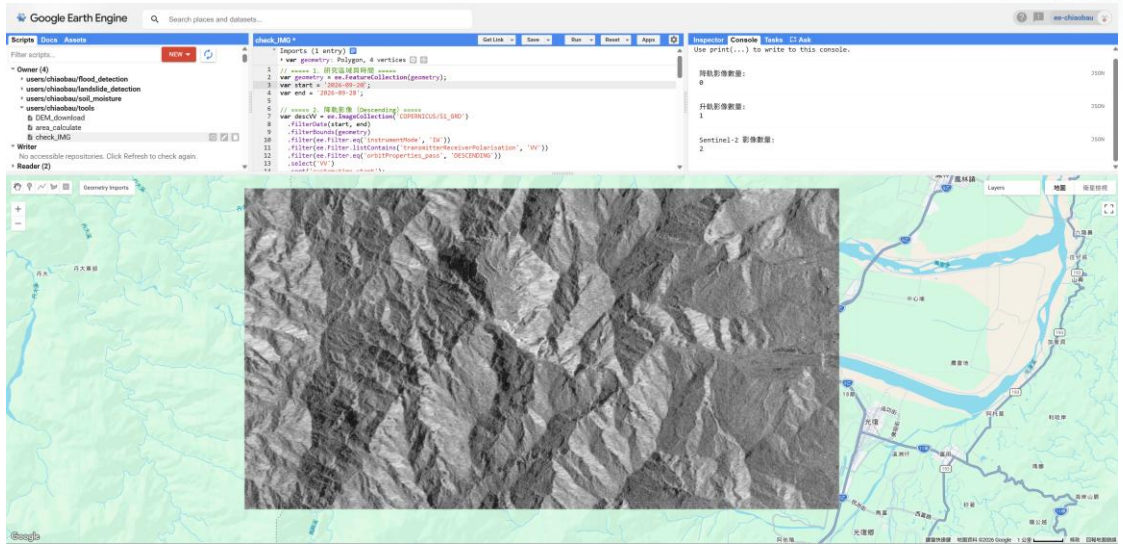
平台	SAR 衛星資料	特色與用途
ASF Vertex	Sentinel-1、NISAR、ERS ALOS-1等	專業雷達衛星資料平台，整合多國SAR衛星影像
Copernicus Data Space	Sentinel-1	歐洲衛星資料平台，主要提供Sentinel系列光學與雷達影像
NASA Earthdata Search	Sentinel-1、NISAR、ALOS-1	全球地球觀測資料平台，提供雷達、光學及多種環境觀測資料

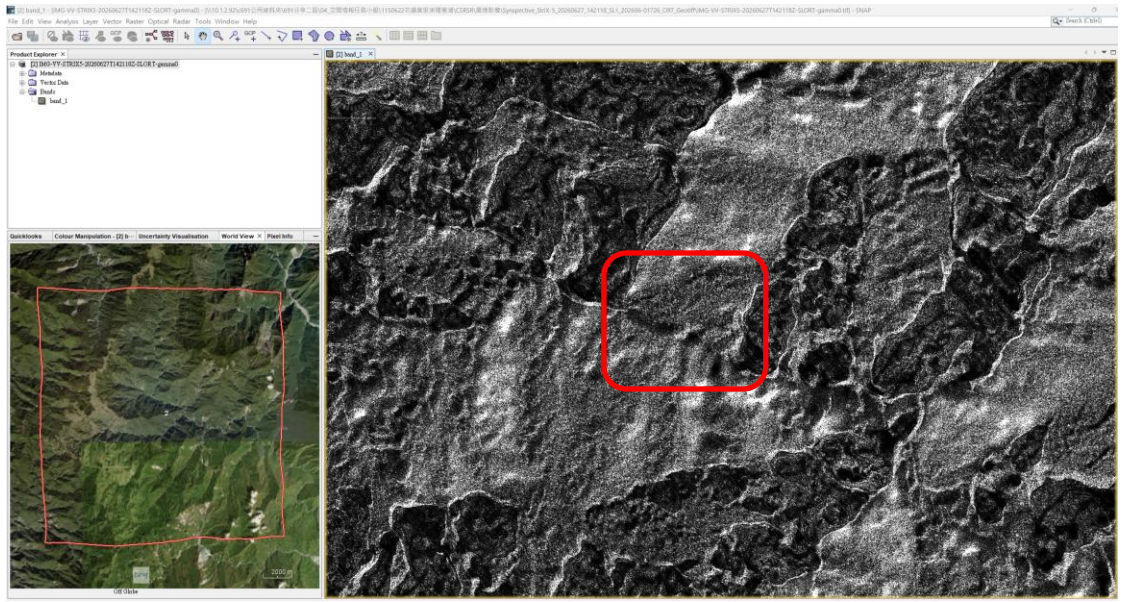


Data Download Platforms and Analysis Software

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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





SAR Image Components

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SAR 雷達觀測

衛星發射雷達波，接收地表回波訊號

雷達訊號處理

形成不同類型的 SAR 影像產品

SLC 影像 Single Look Complex

- **回波強弱（振幅 Amplitude）**

  呈現地表反射雷達波的強弱

- **雷達波相位（Phase）**

  可透過不同時間的相位比較，分析細微地表變形

主要應用：InSAR 地表變形監測

GRD 影像 Ground Range Detected

- **回波強弱（強度 Intensity）**

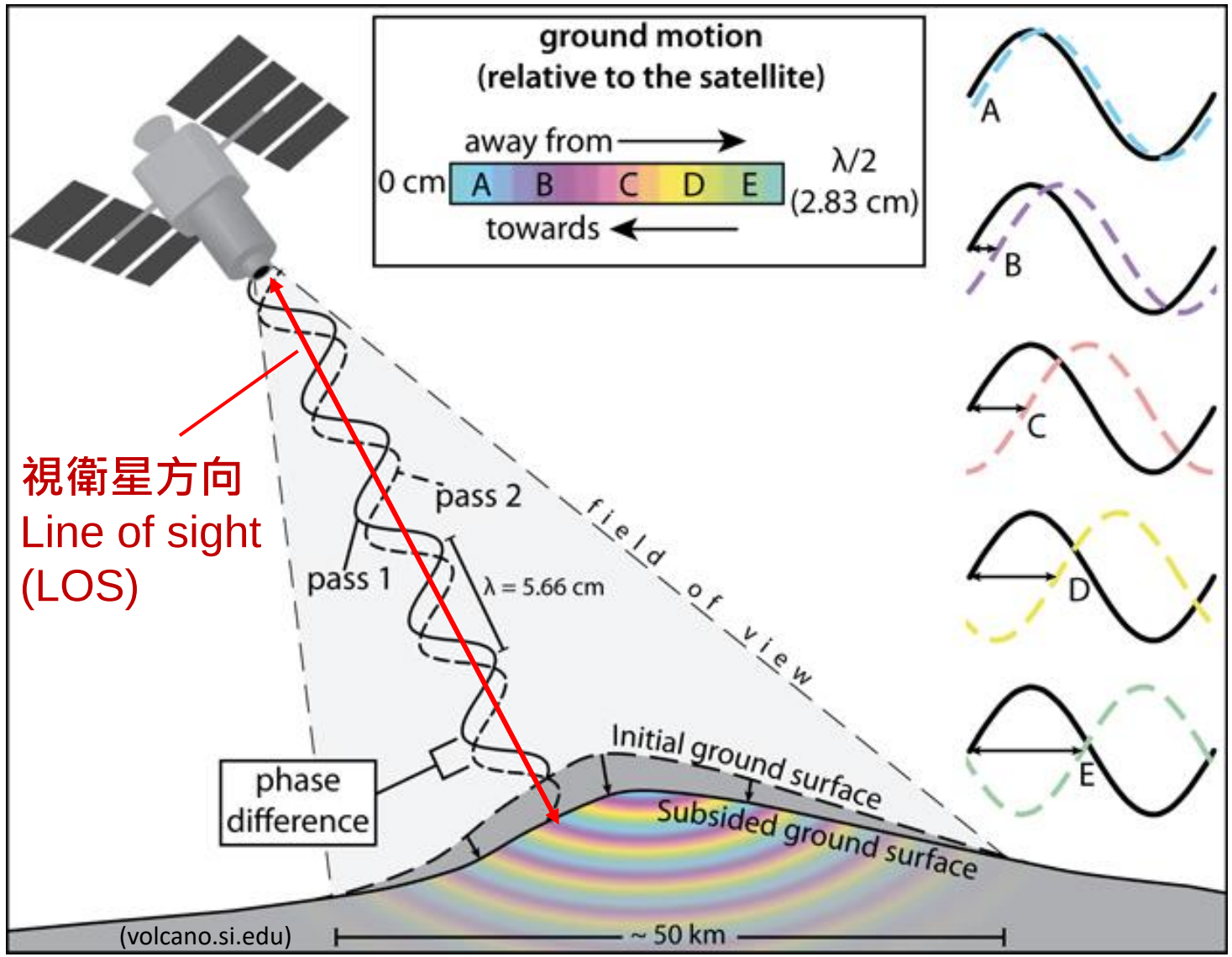
  將雷達回波的振幅平方轉換為強度，不保留相位資訊

- **地表特徵判釋**

  主要利用雷達回波強弱，辨識地表與災害變化

主要應用：水體、崩塌與淹水判釋

How to measure deformation from SAR?



Subtracting the phase

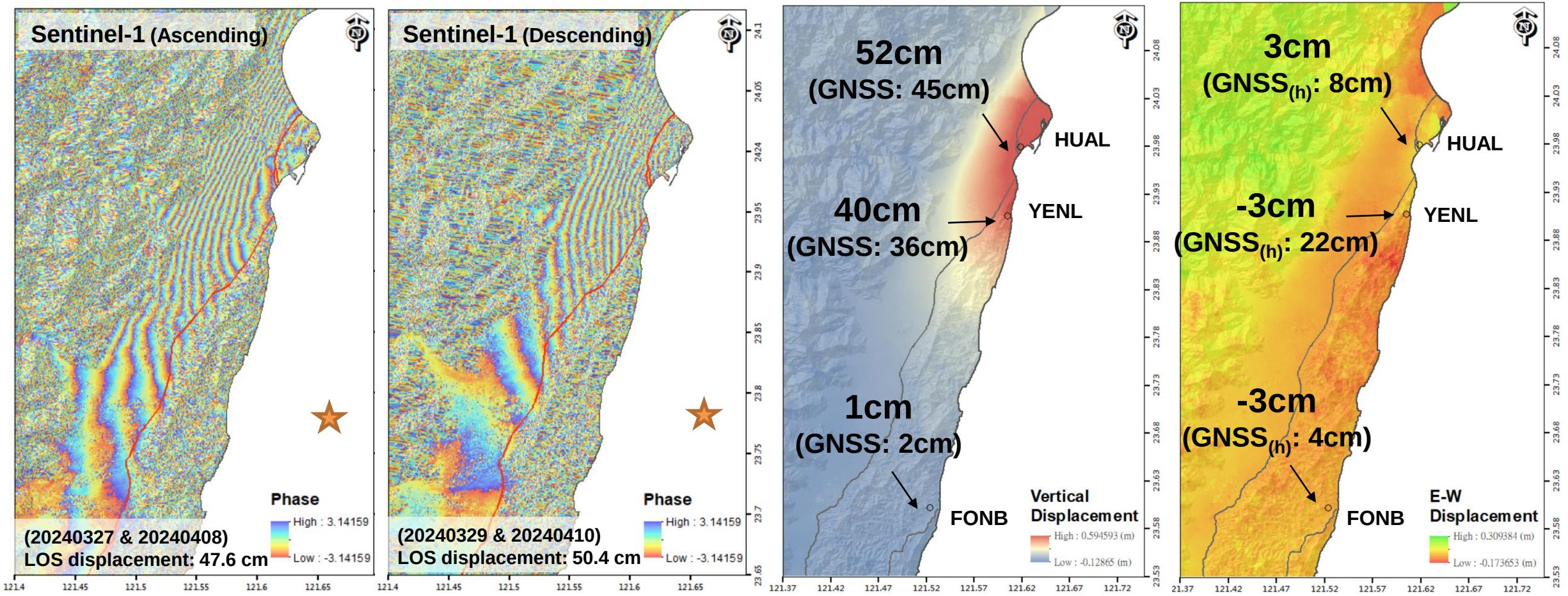
of radar waves from two SAR

images at different times.

Coseismic deformation: 0403 Hualien Earthquake

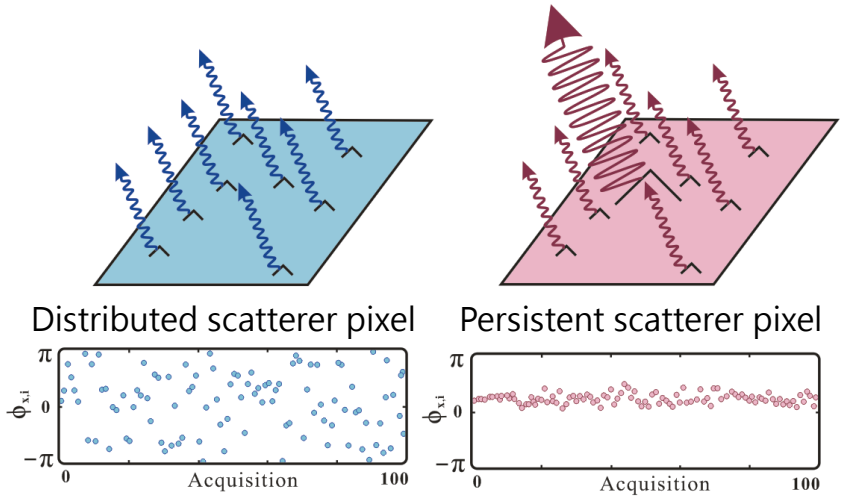
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Satellite observations indicate that surface displacement ranged from about 47 cm to 50 cm along the LOS direction, with the displacement mainly occurring in Hualien City



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.

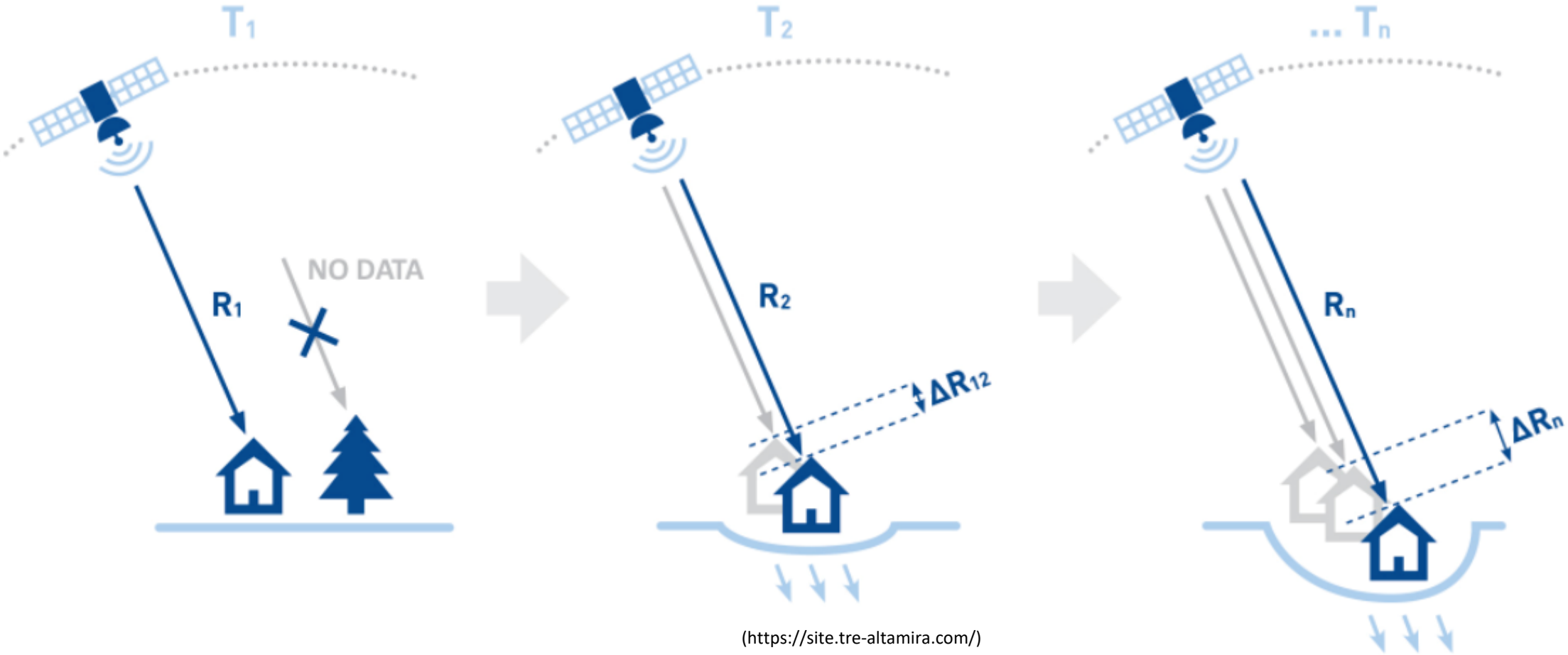


(Lu et al., 2020, Modified from Hopper et al., 2007)



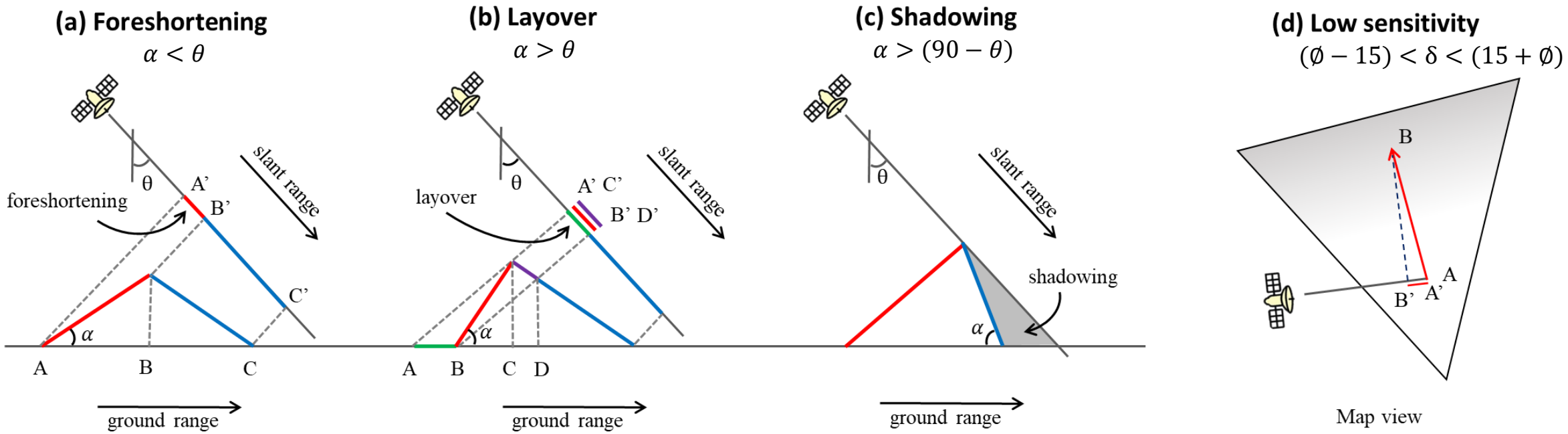
Multi-Temporal InSAR Techniques

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



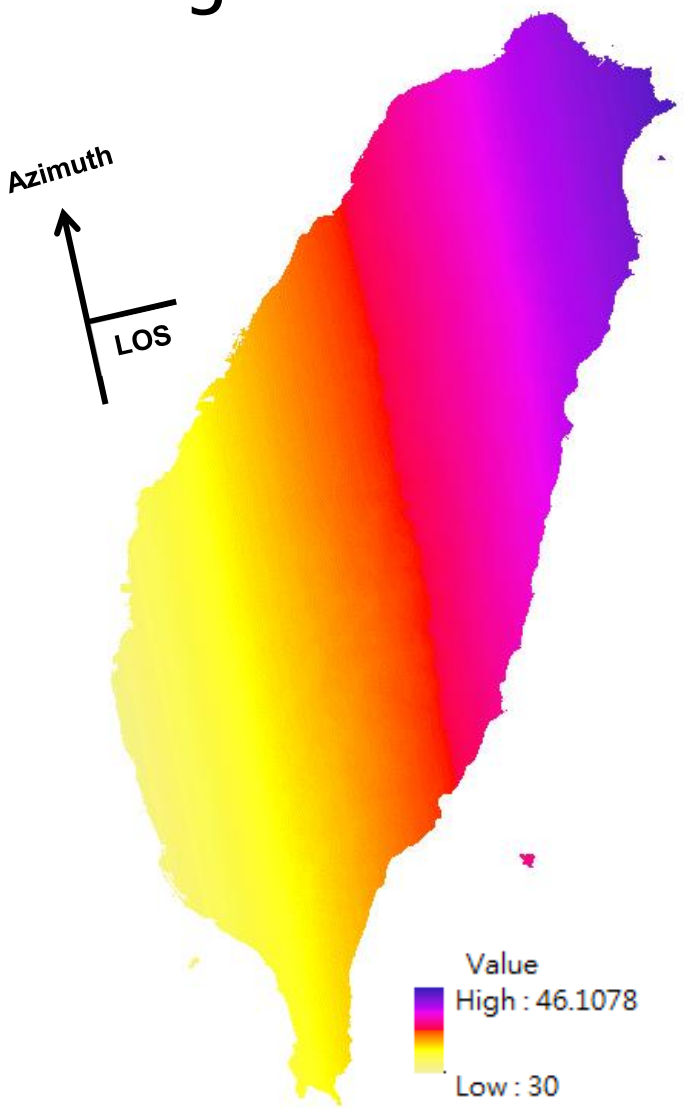
(https://site.tre-altamira.com/)

Feasibility analysis: geometrical visibility

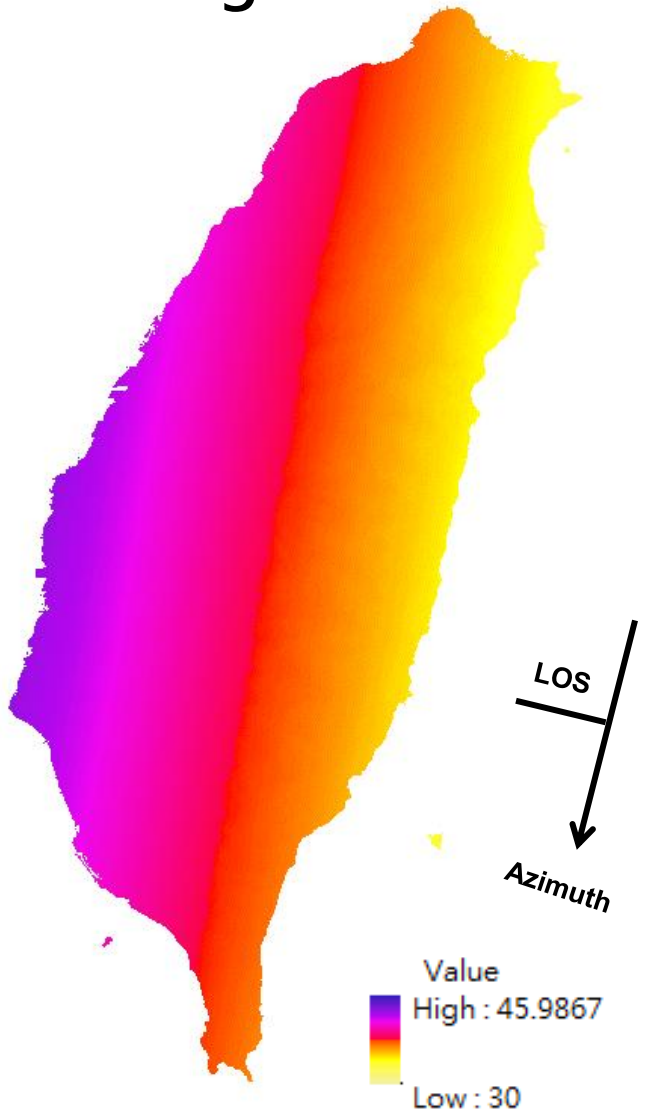


Feasibility analysis: geometrical visibility

- Ascending 20171030



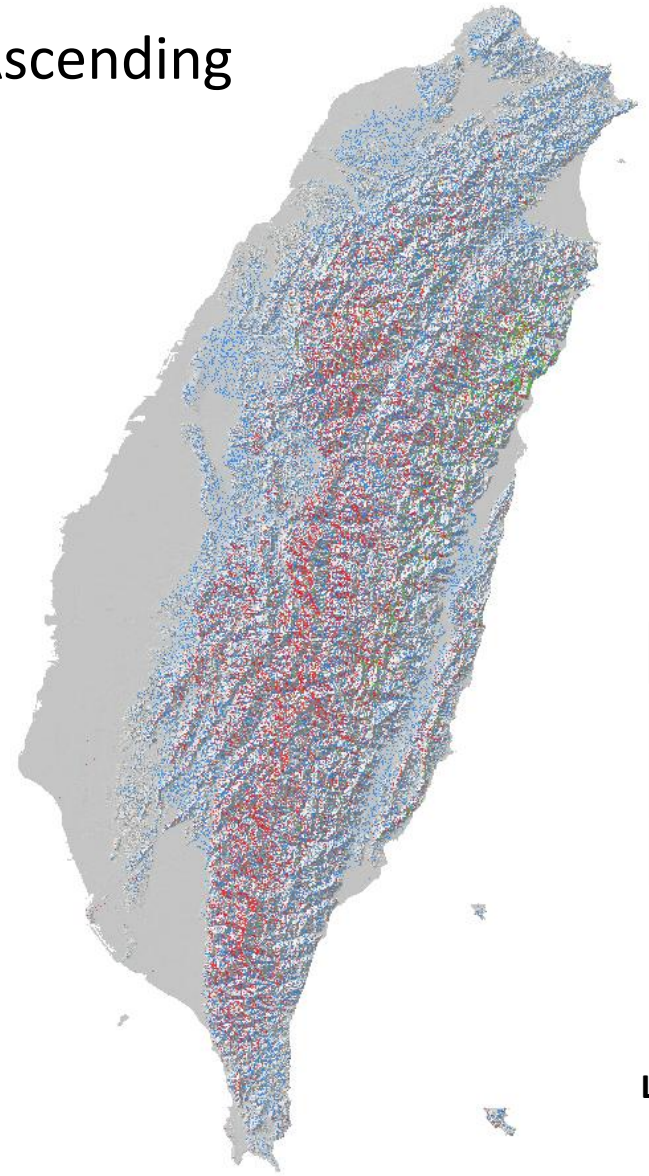
- Descending 20171030



Feasibility analysis: geometrical visibility

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Ascending

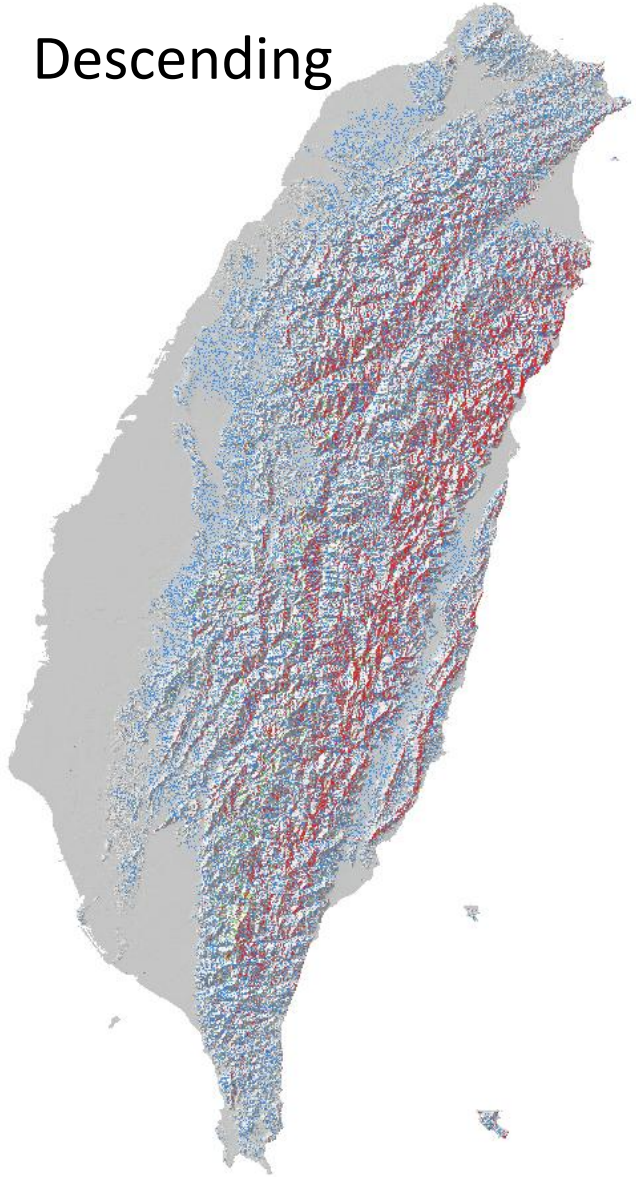


Ascending		
Layover	224707.95 (ha)	8.44%
Shadowing	27681.39 (ha)	1.04%
Low sensitivity	448,885 (ha)	16.85%

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

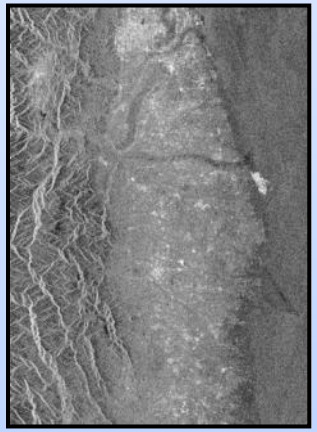


Optimization of MTInSAR Processing Workflow

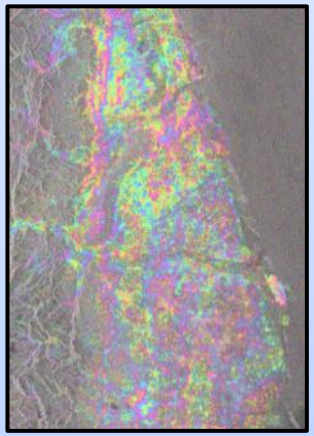
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DInSAR

SAR images



Interferograms

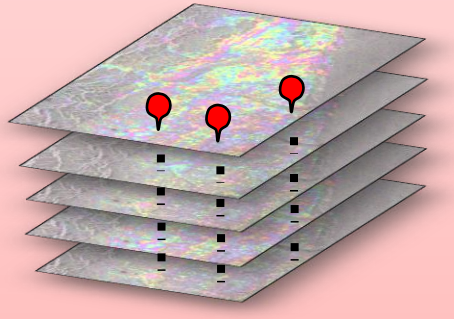


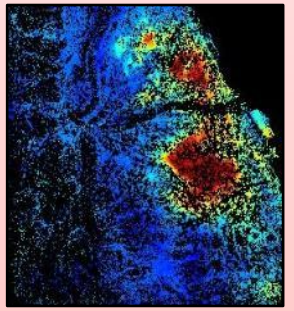
Sentinel Application Platform, SNAP

snap2stamps

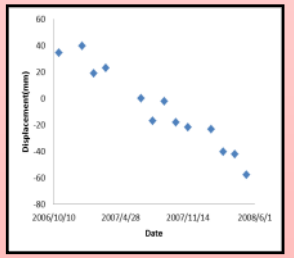
MTInSAR

Phase stability estimation and PS selection





Velocity field map



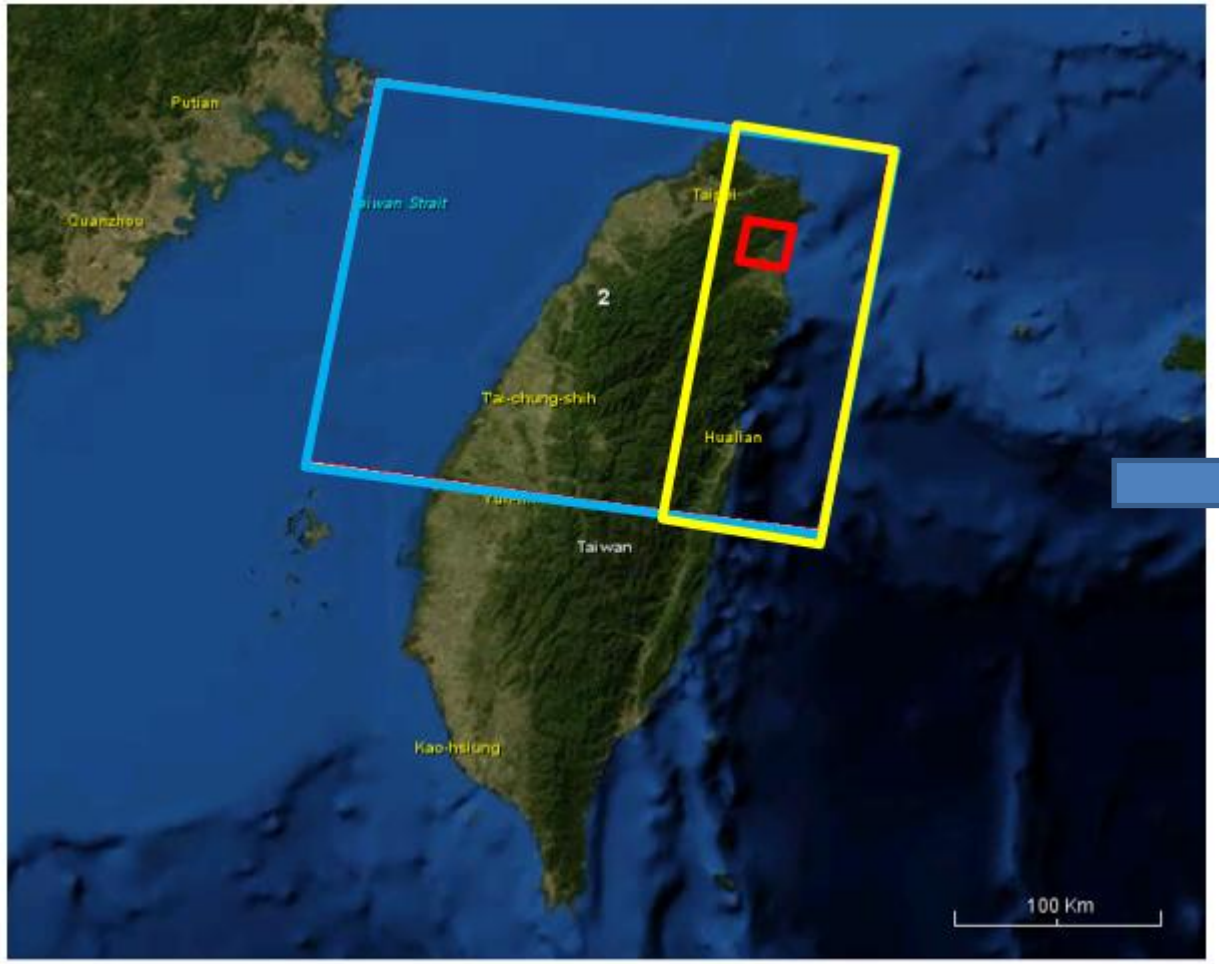
Displace-ment time series

Stanford Method for Persistent Scatterers, StaMPS

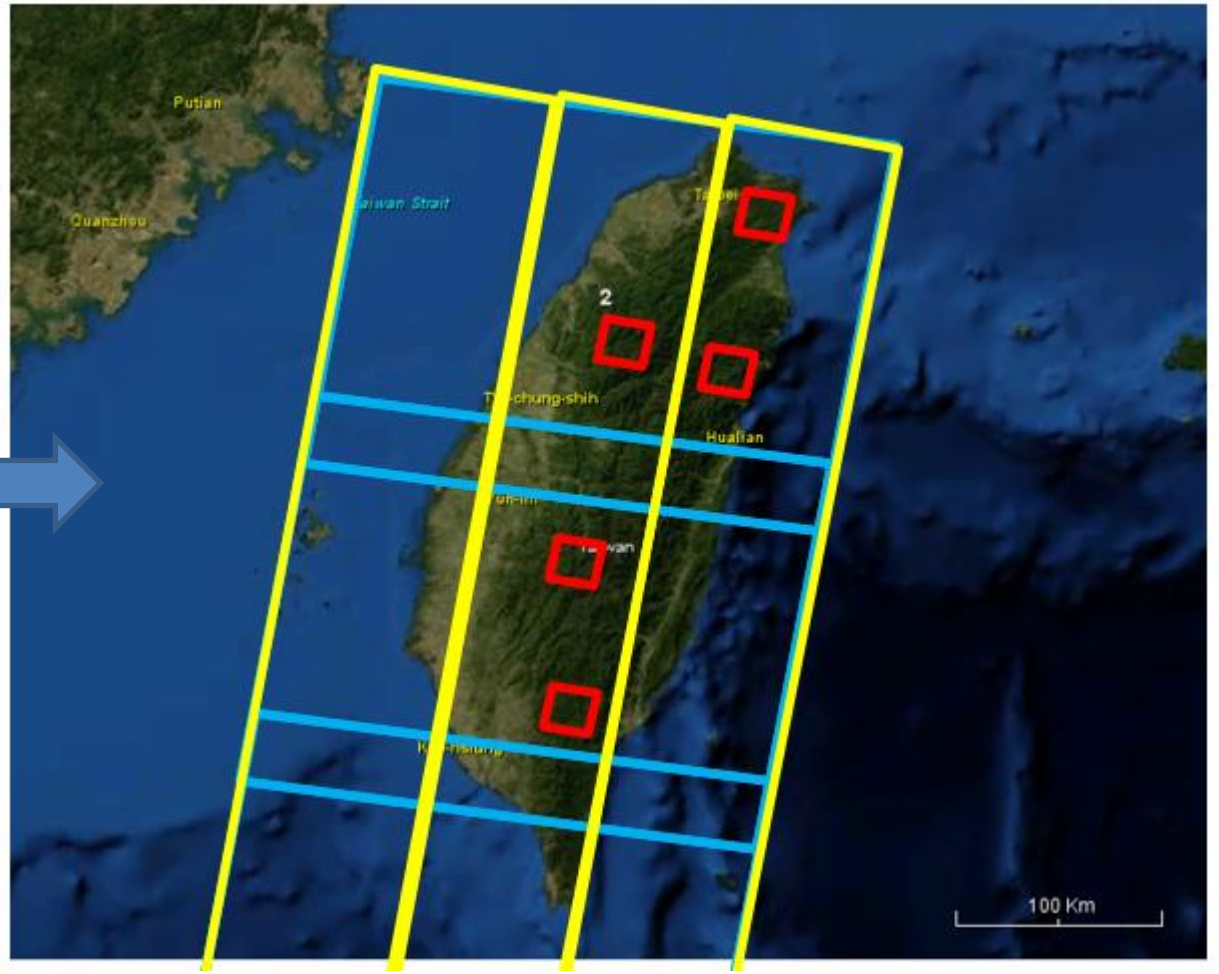
Optimization of MTInSAR Processing Workflow

NCDR 國家災害防救科技中心

Processing interferograms of only **one** study area



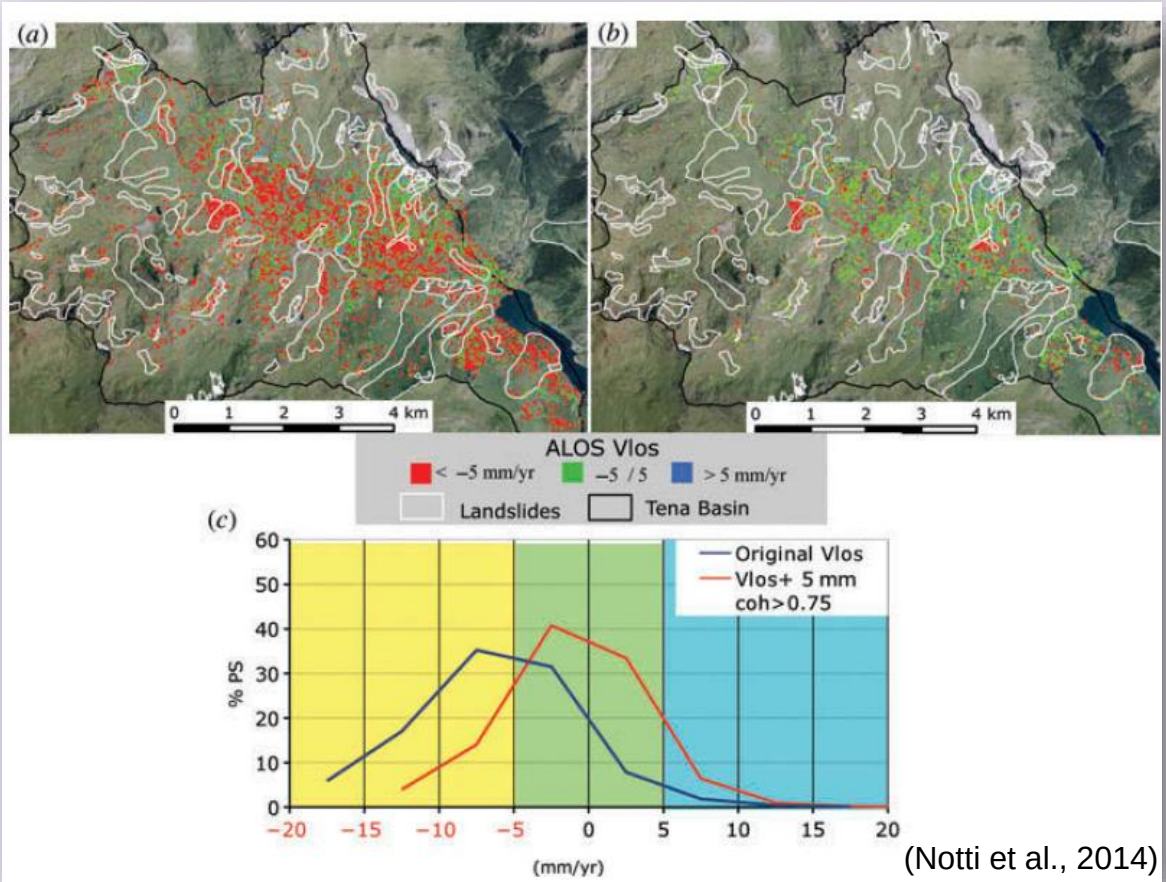
Processing interferograms of **multiple** study area



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)

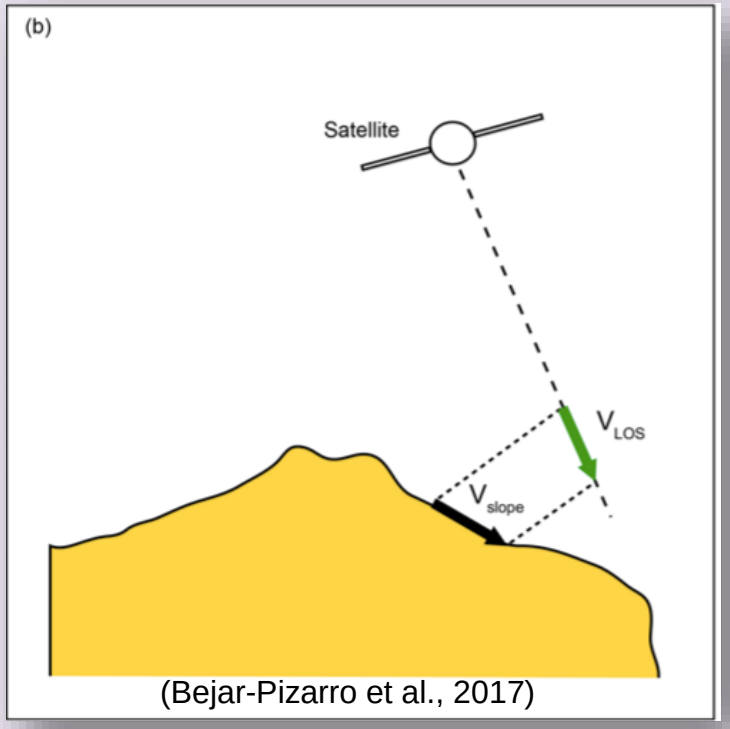
Data interpretation

- **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)

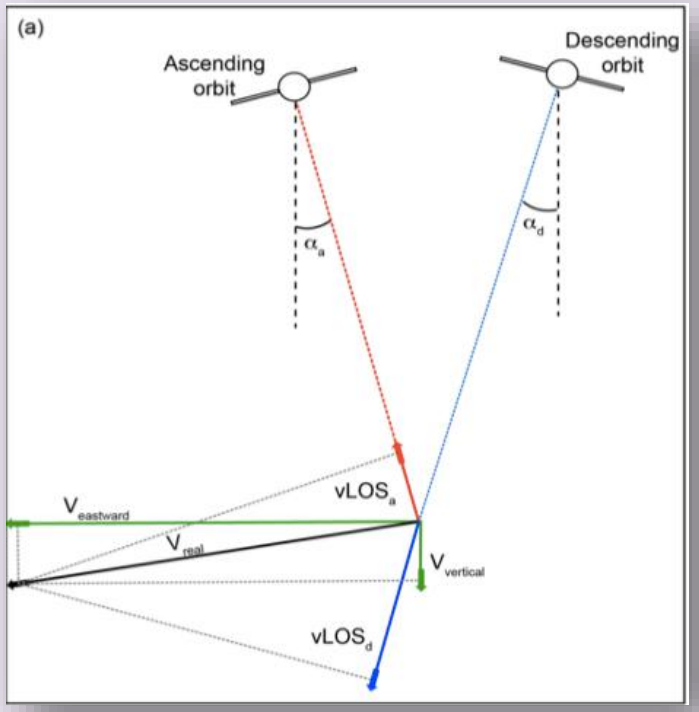
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Optimization of MTInSAR Processing Workflow

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)

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

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

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

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

Data interpretation

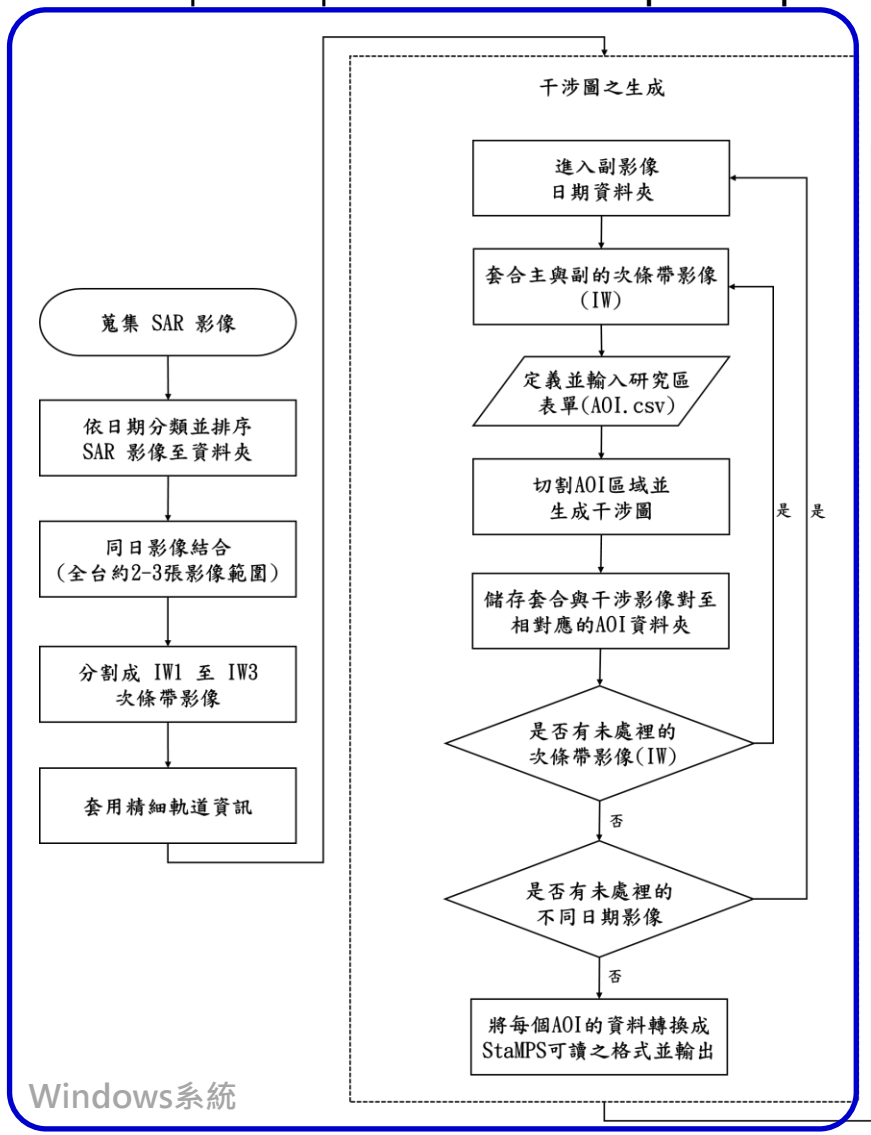
- **Threshold of activity:** Determine a threshold velocity to assess the state of activity
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Optimization of MTInSAR Processing Workflow

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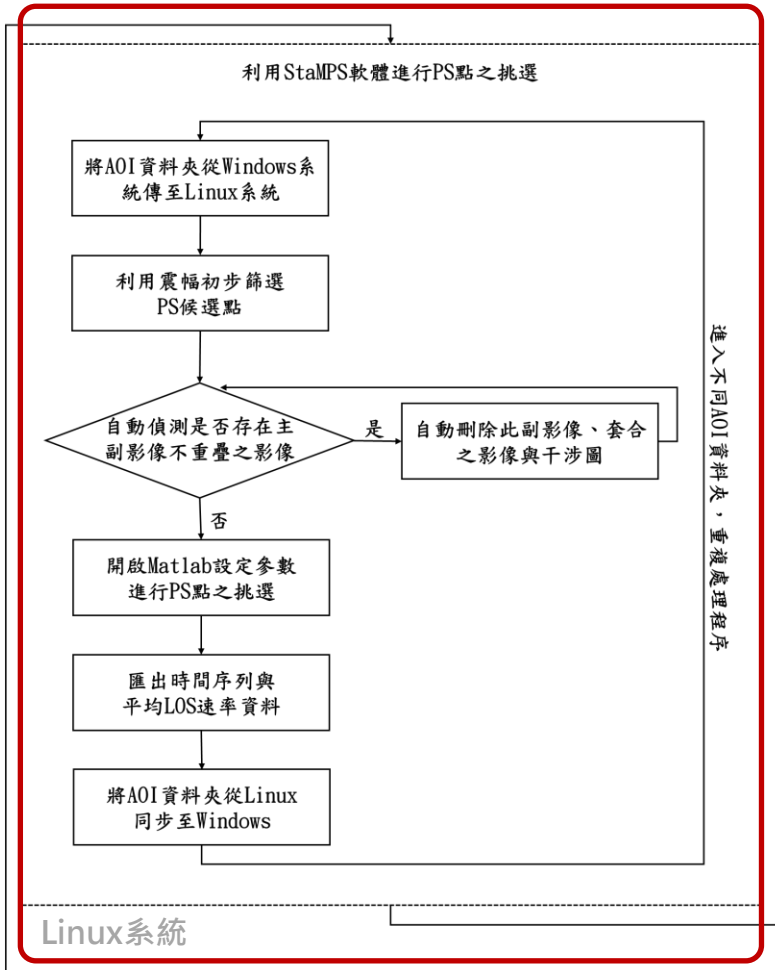
分區同步之干涉圖生成

將snap2stamps優化為**multi-snap2stamps**



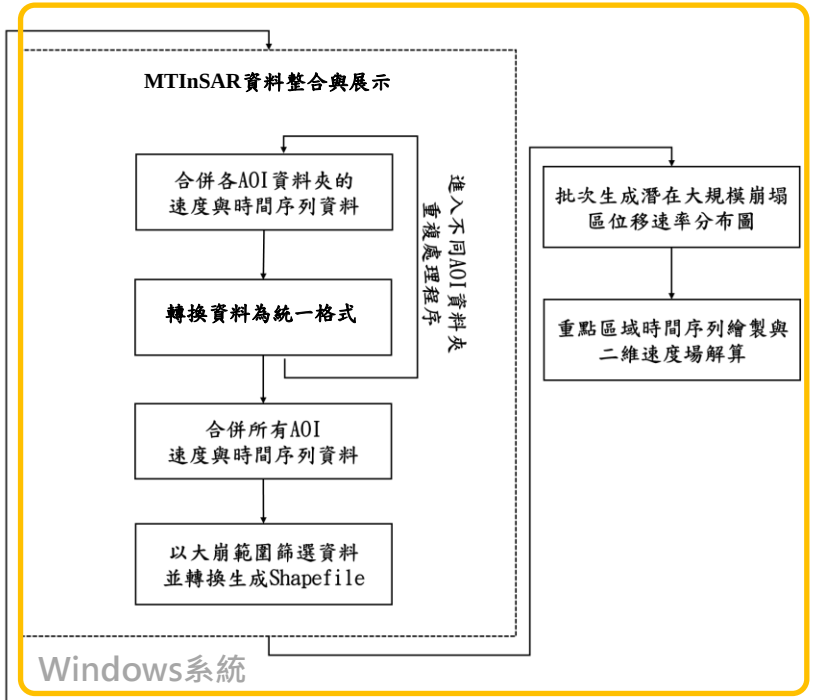
MTInSAR分析流程優化

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



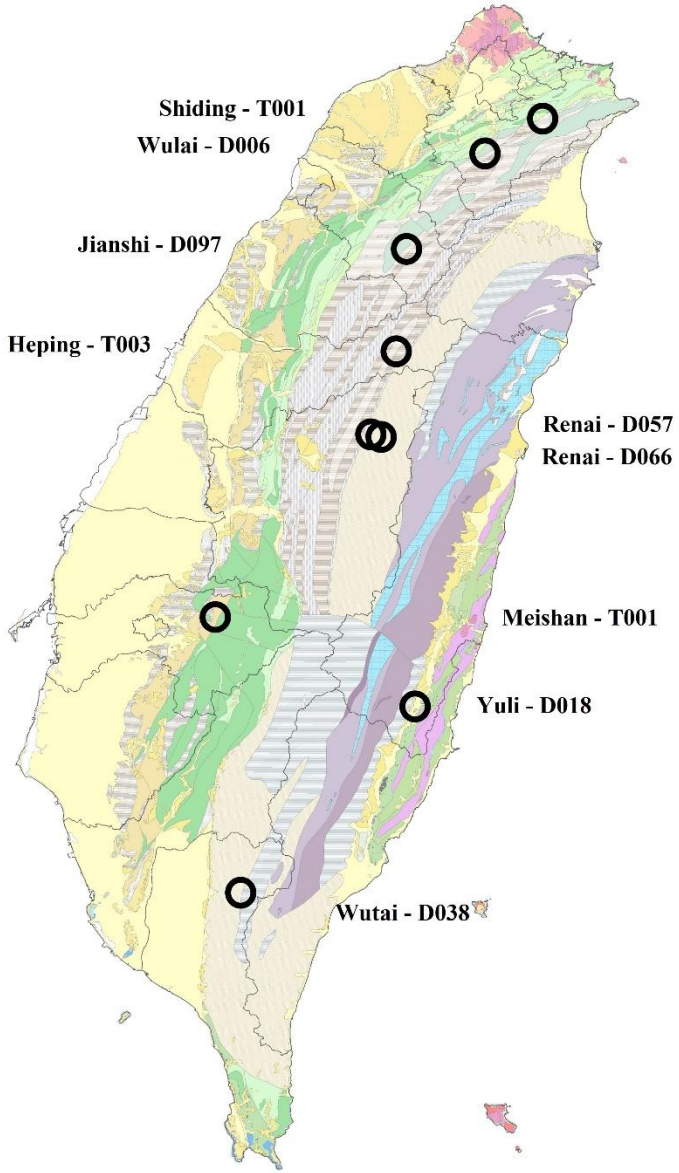
Slow-moving Landslides

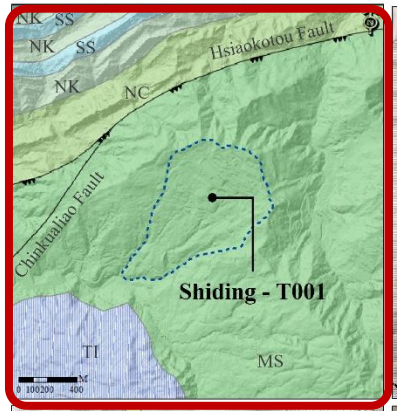
- The velocity of slow-moving landslides ranges from millimeters to meters per year
- Have the opportunity to transform to much more destructive rapid landslides
- Accelerated motion may be a precursor of a rapid landslide

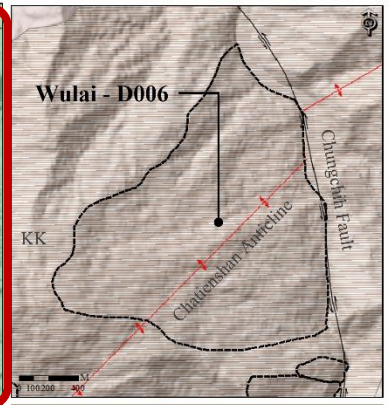


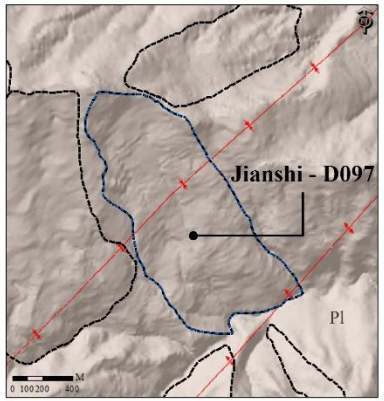
2018 Peru (By Galeria del Ministerio de Defensa del

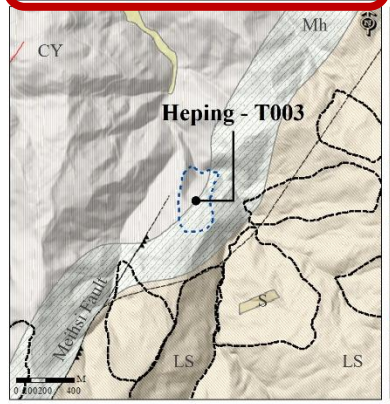
Pre-existing slow-moving landslides

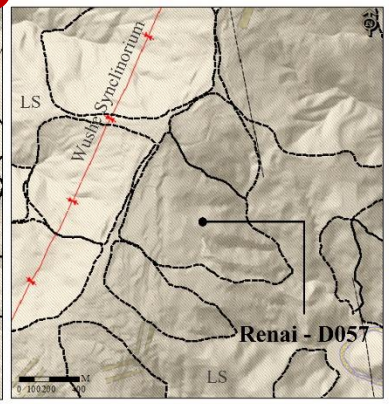


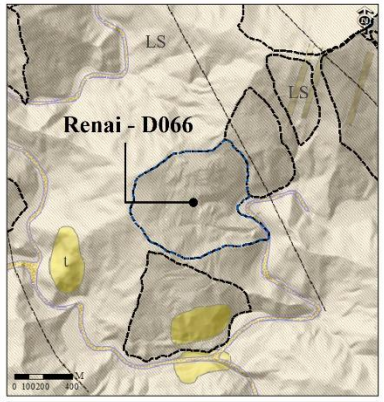


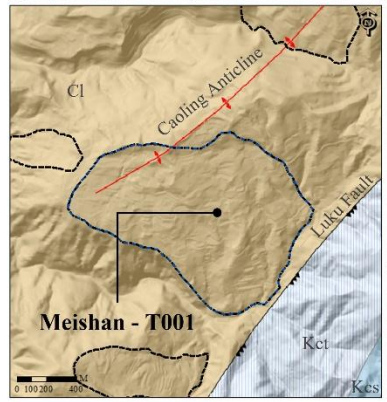


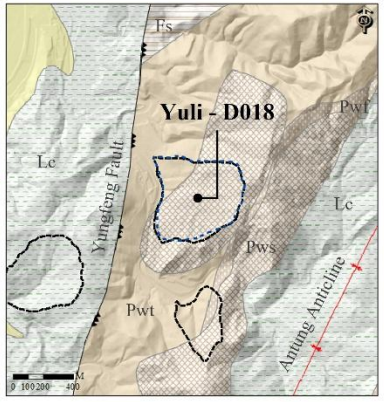


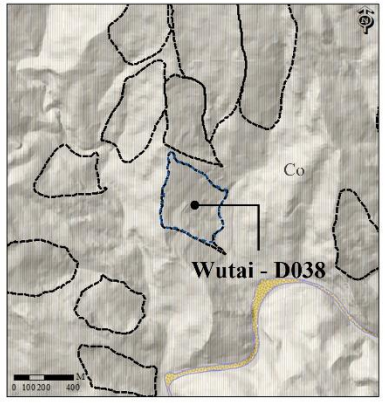












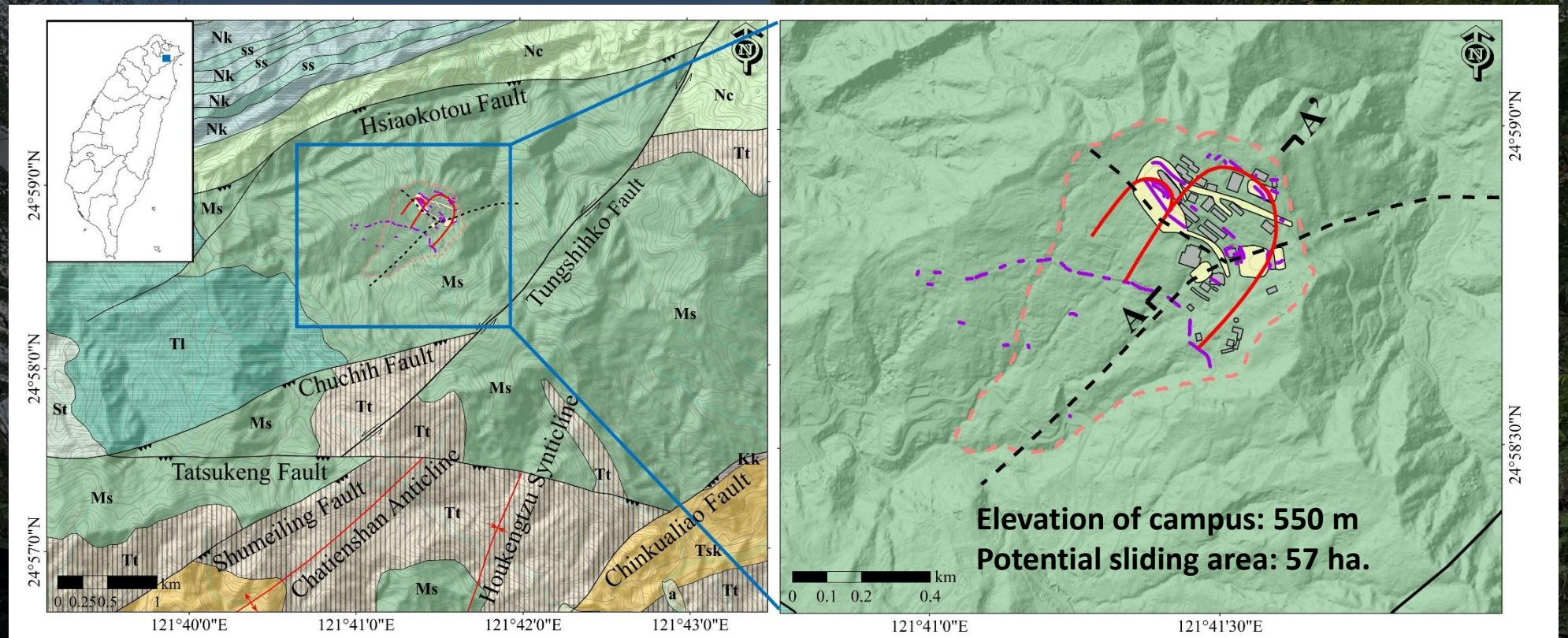
t Terrace Formation
Cl Cholan Formation
Kct Kueichulin Formation — Tawo Sandstone Member
Kcs Kueichulin Formation — Shihliufen Shale Member
NC Nanchuang Formation
Pwt Paliwan Formation — Taiyuan Member
Pws Paliwan Formation — Suilien Member
Pwf Paliwan Formation — Futian Member
Fs Fanshuliao Formation
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)


華梵大學
HUA FAN
UNIVERSITY

Background of the Dalun Mountain area (Shiding-T001)

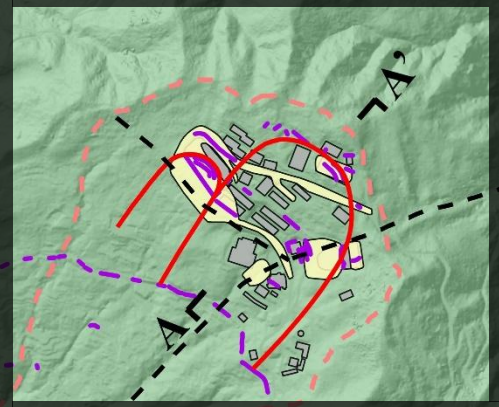


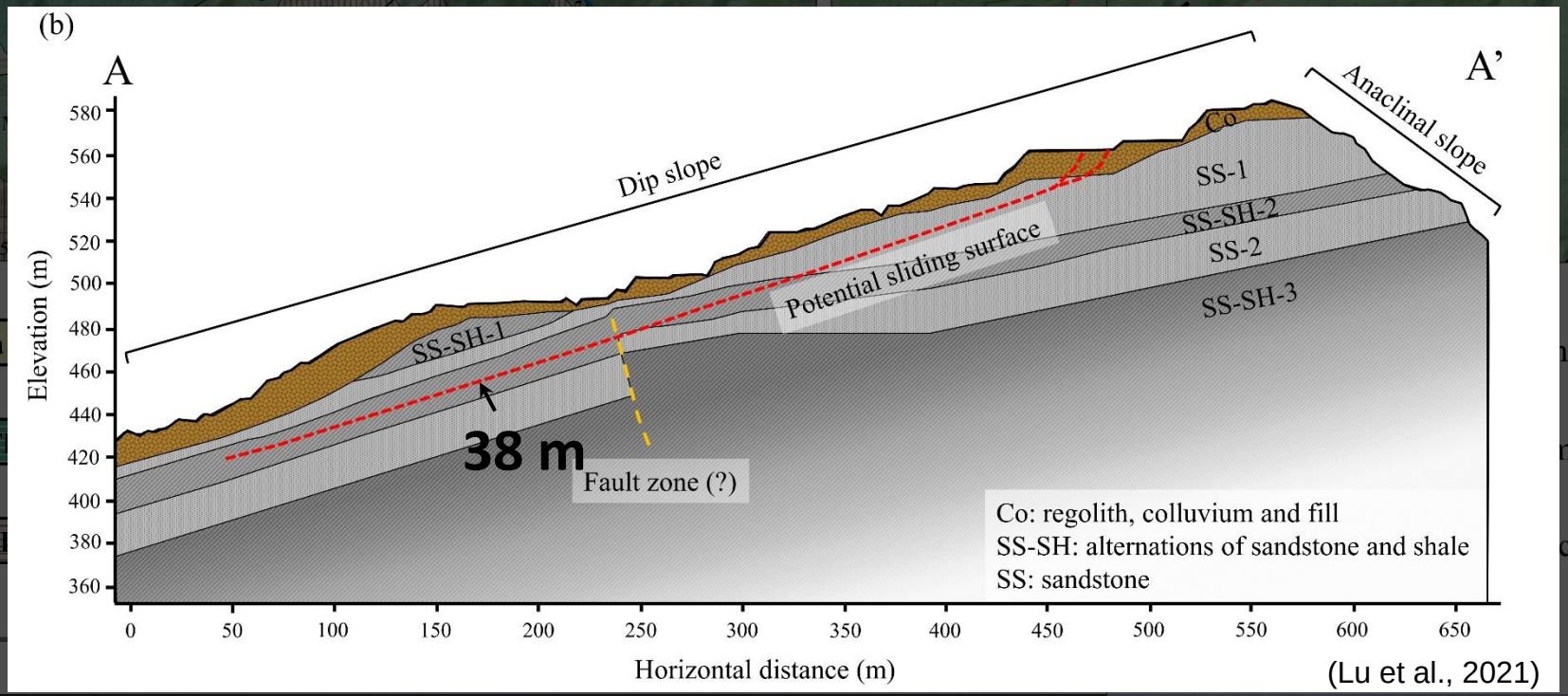
a Alluvium
Nc Nanchuang Formation
Nk Nankang Formation
ss Nankang Sandstone
St Shihti Formation
Tl Taliao Formation
Ms Mushan Formation
Tt Tatungshan Formation
Tsk Tsuku Formation
Kk Kankou Formation
Building of Huafan Uni.
Fill
Ground crack
Inferred fault
Potential sliding area
Sliding blocks

(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)



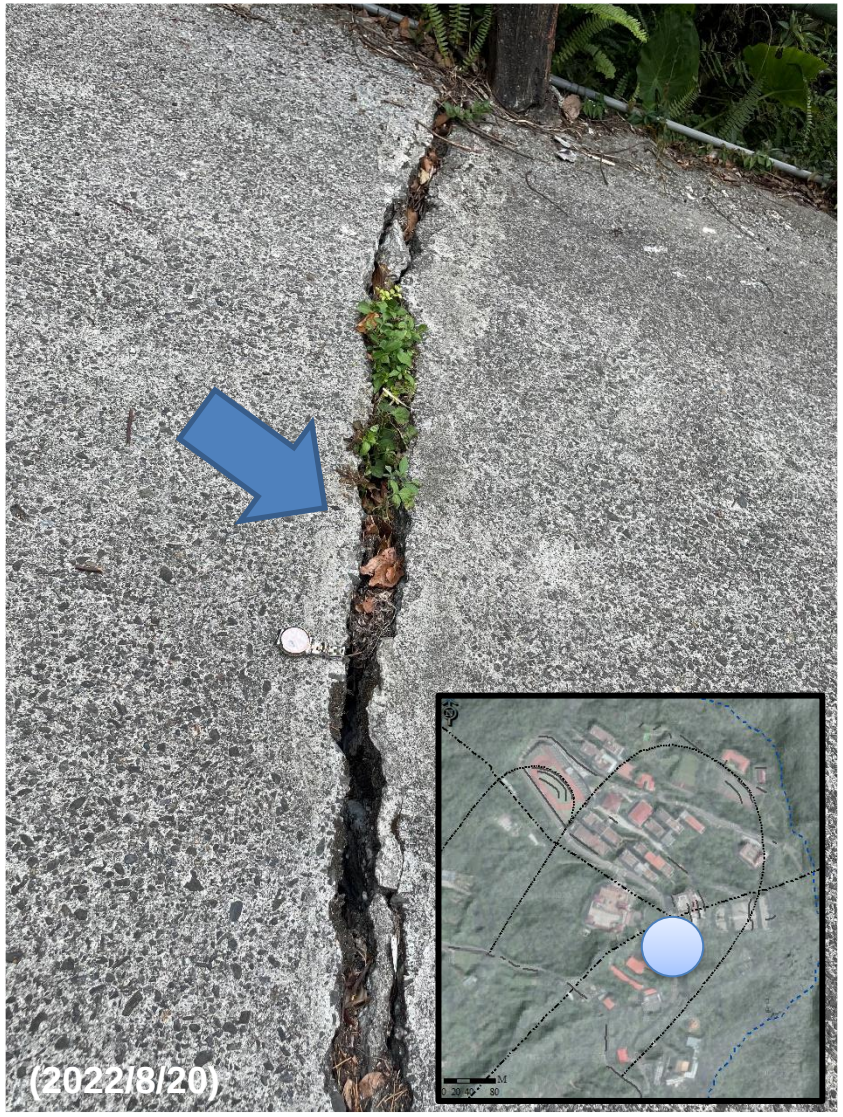


Basketball court



Background of the Dalun Mountain area (Shiding-T001)

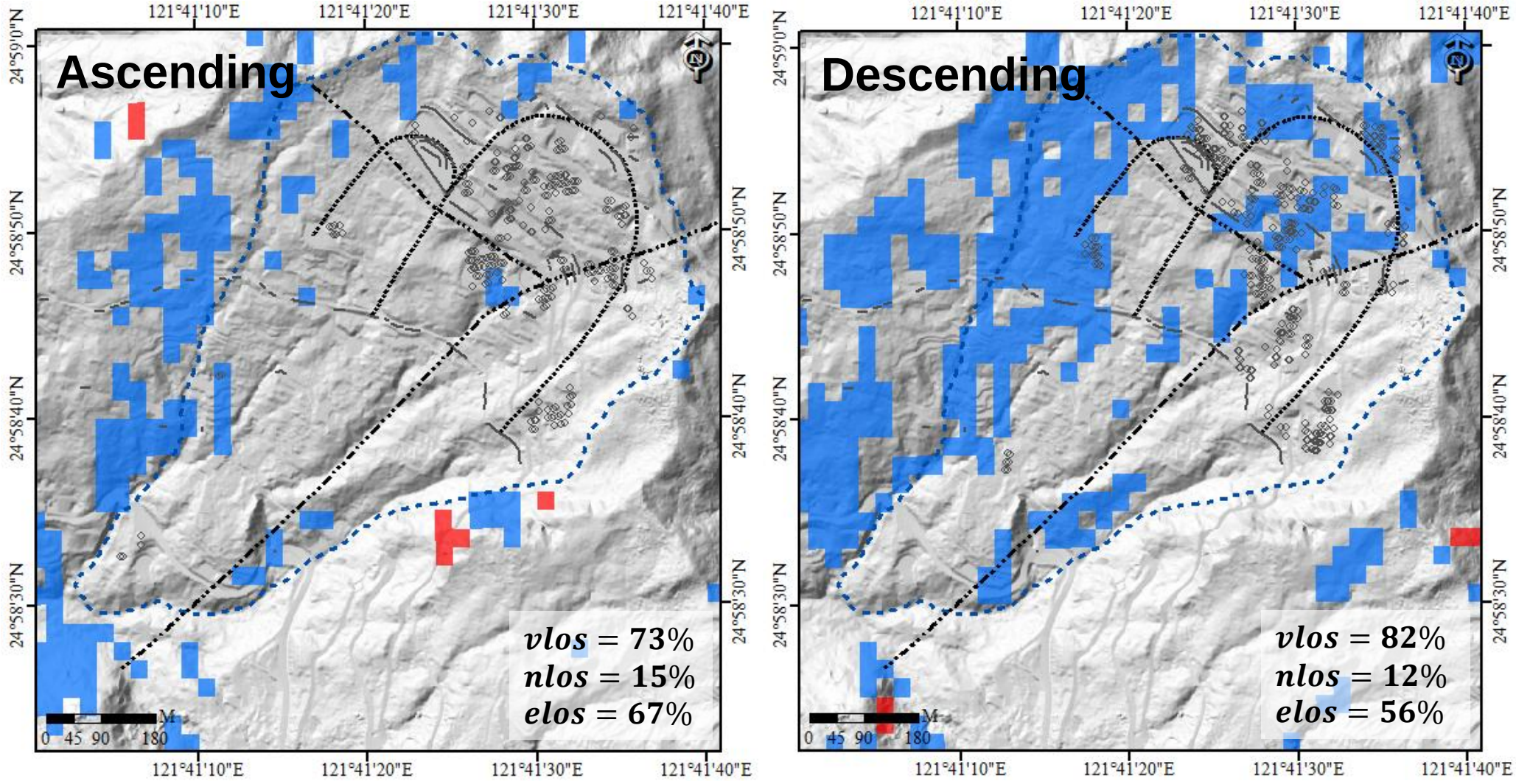
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The results of geometrical visibility



(Lu et al., 2023)

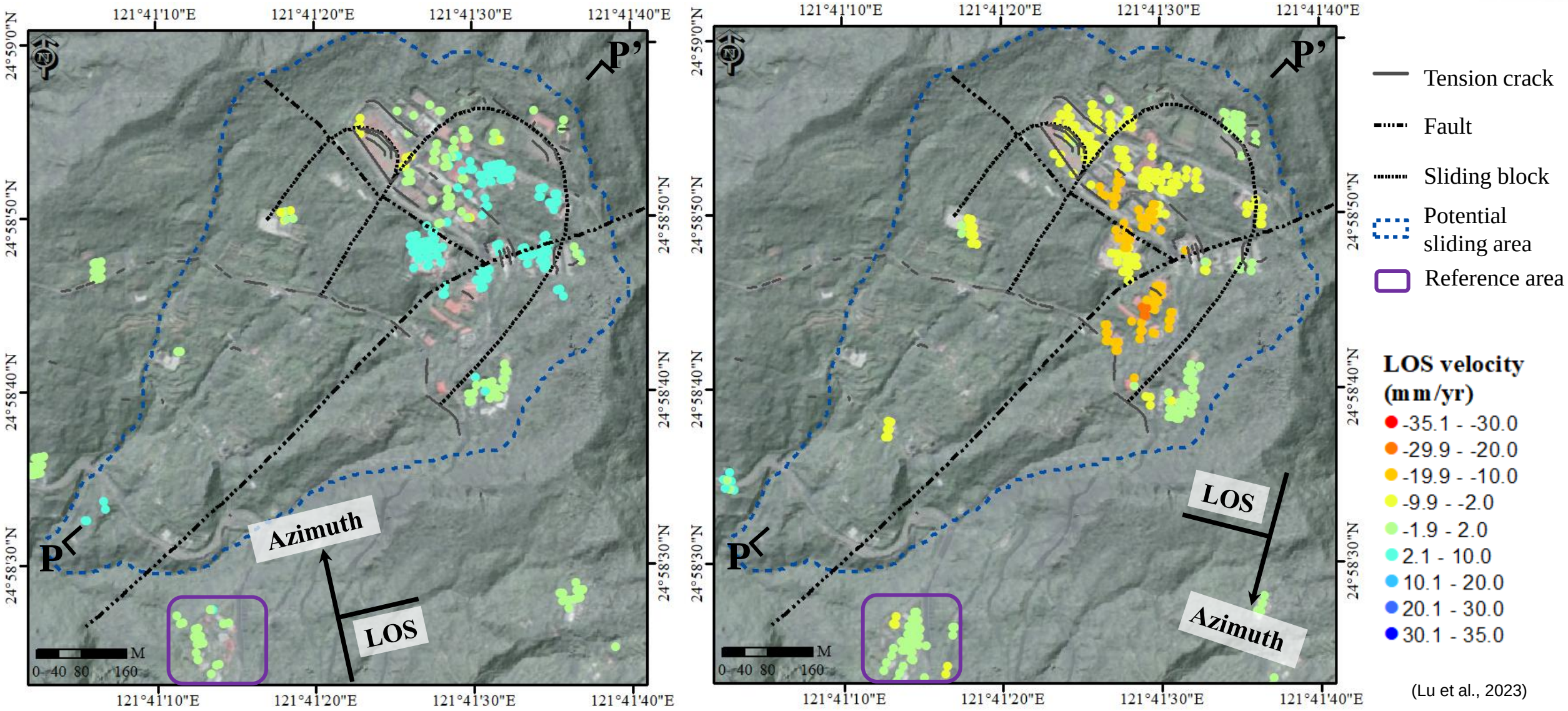
The activity of slow-moving landslide – Shiding-T001

(2019-2021)

國家災害防救科技中心

(a) Ascending

(b) Descending



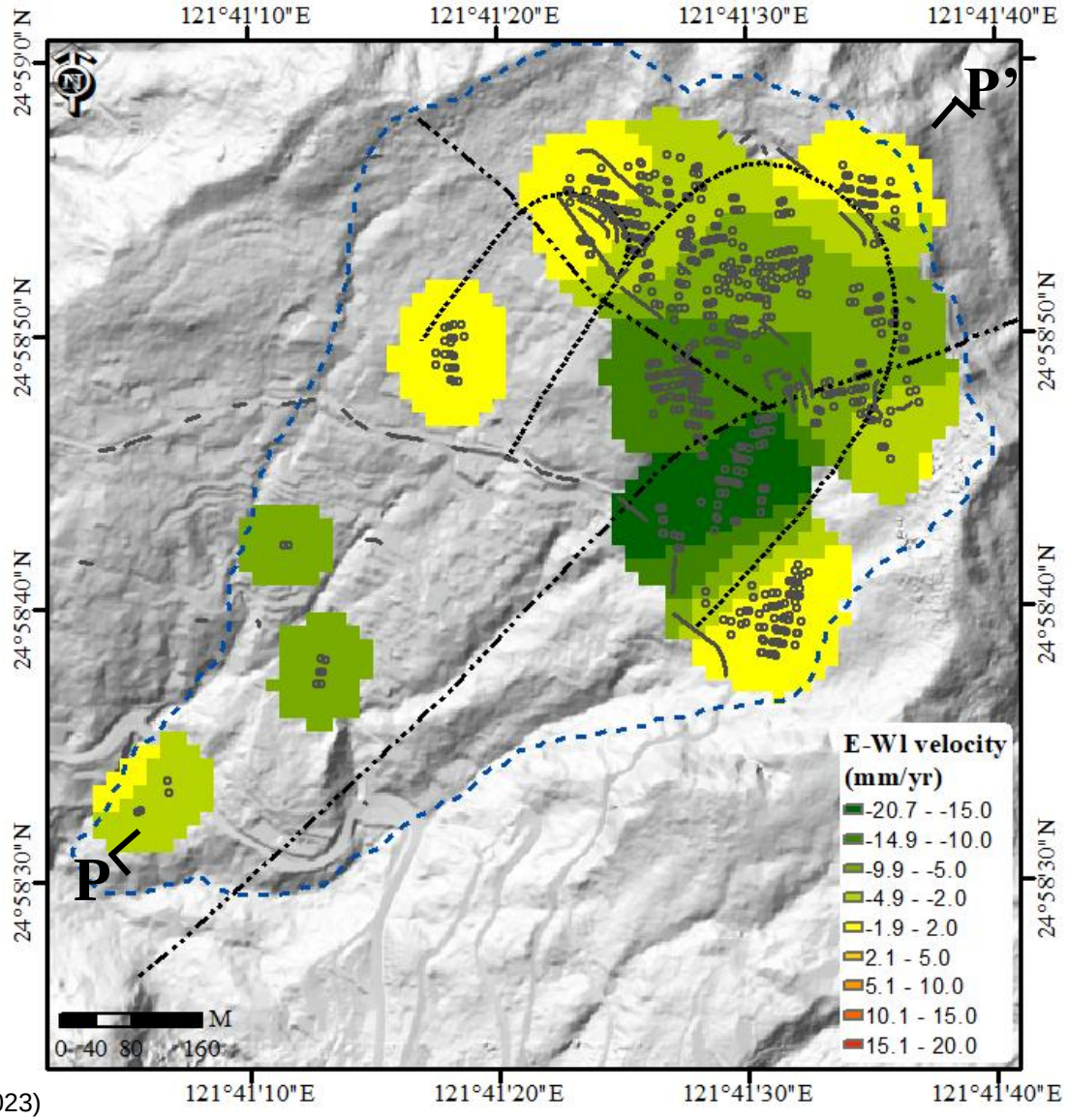
(Lu et al., 2023)

The activity of slow-moving landslide – Shiding-T001

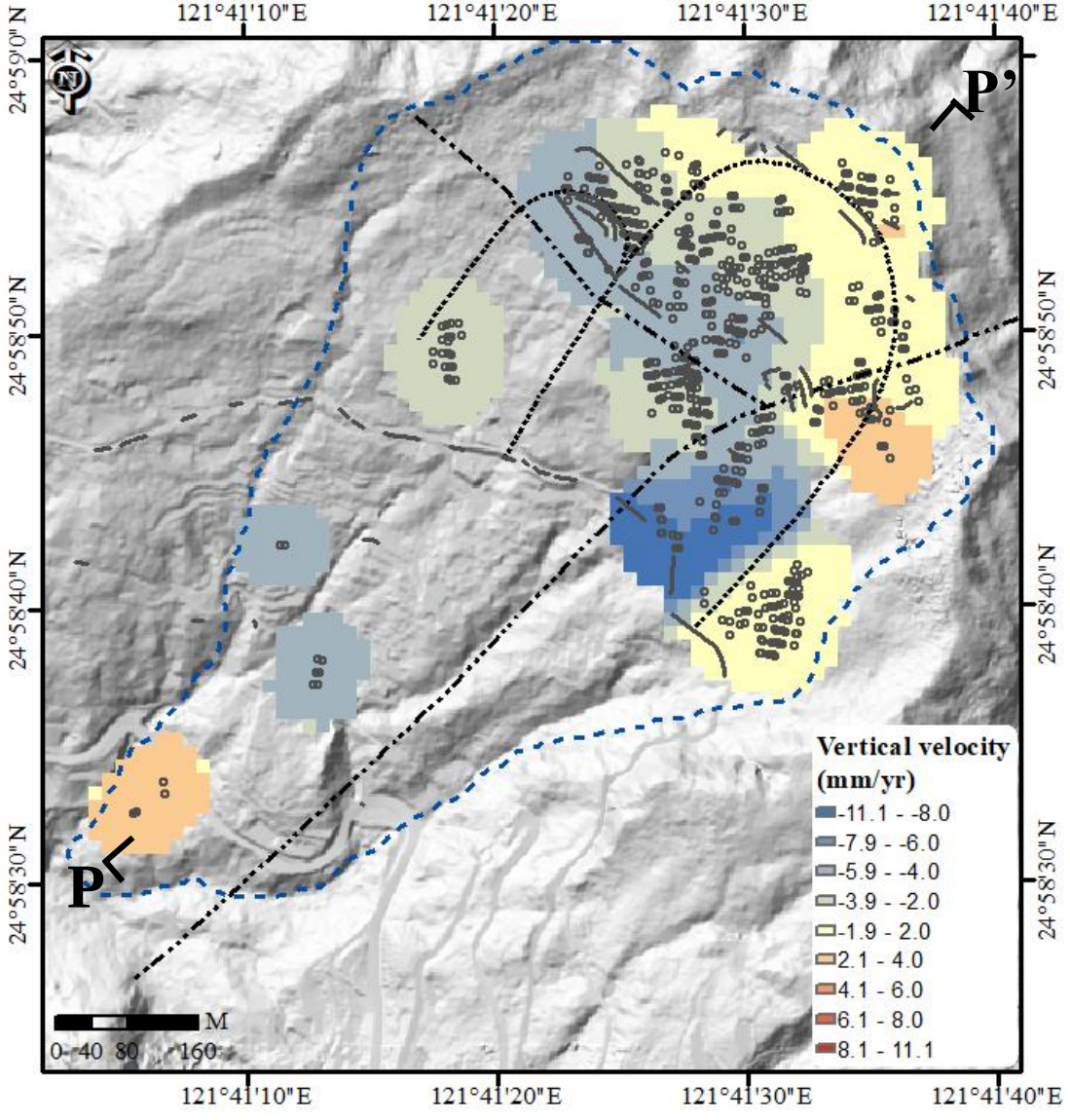
(2019-2021)

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(a) E-W velocity field



(b) Vertical velocity field

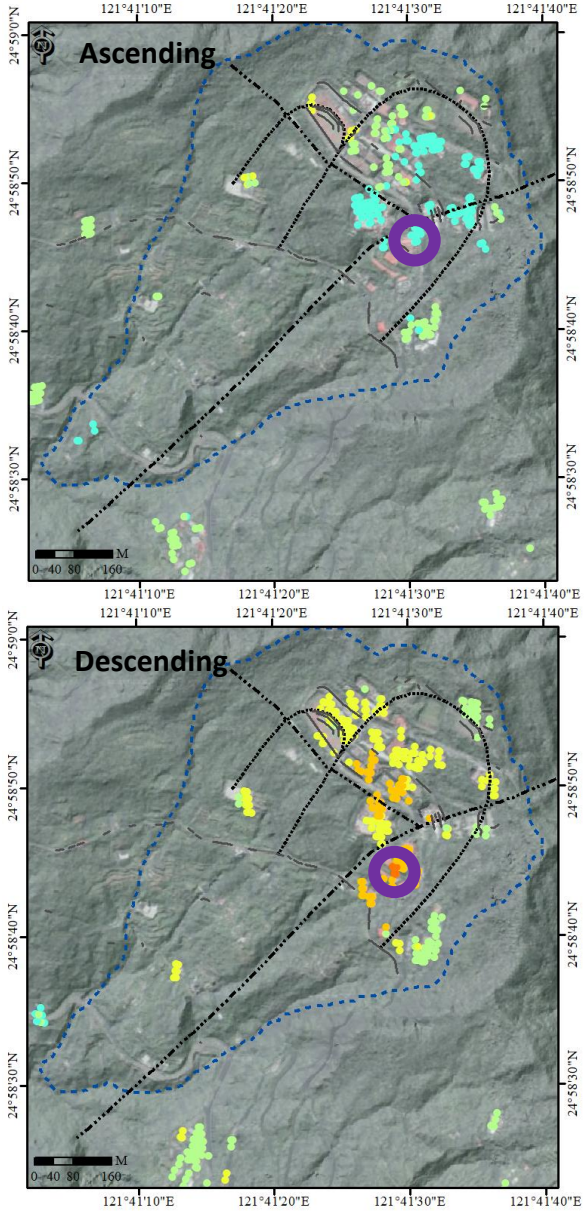


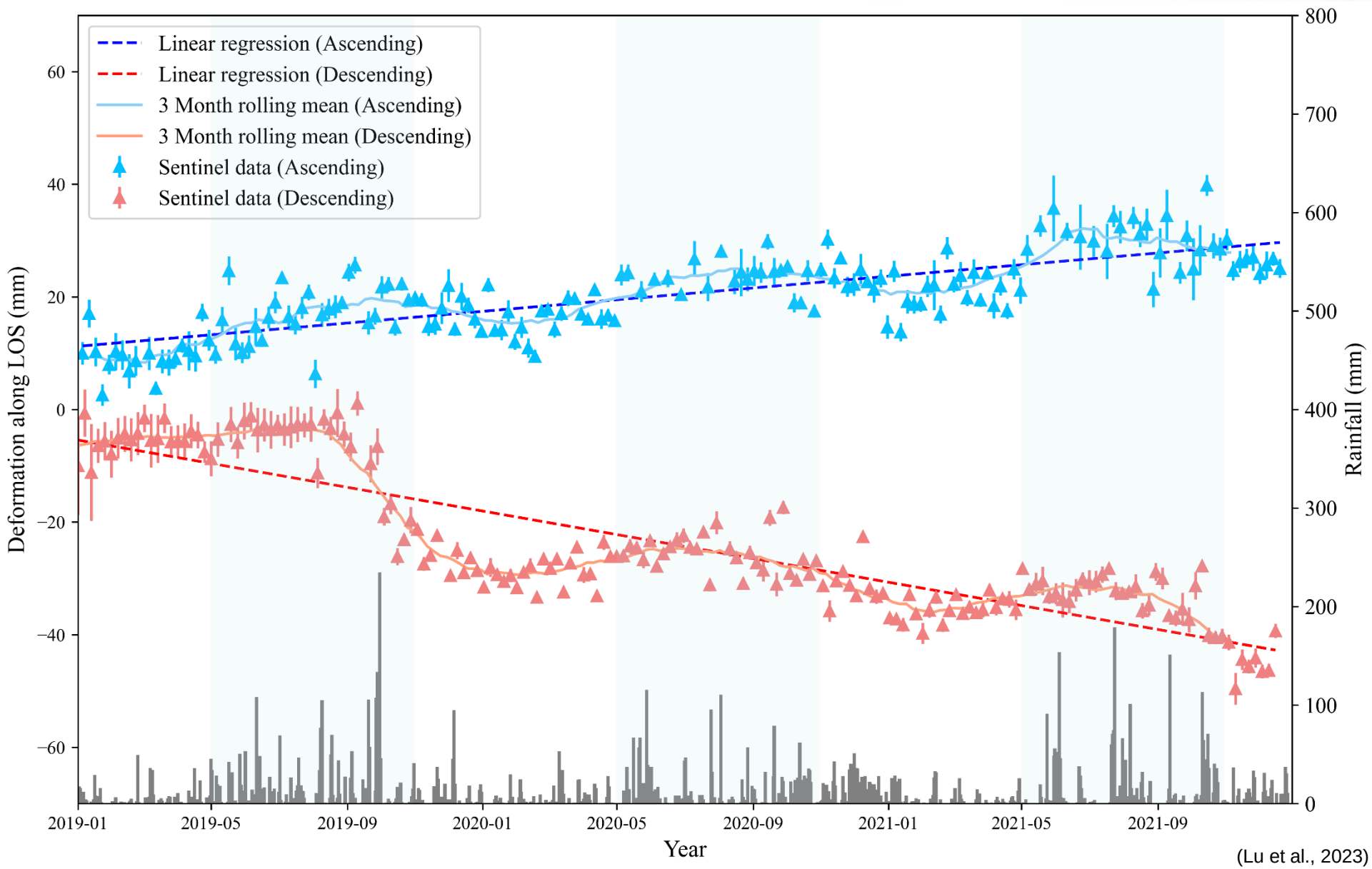
(Lu et al., 2023)

The activity of slow-moving landslide – Shiding-T001

(2019-2021)

國家災害防救科技中心

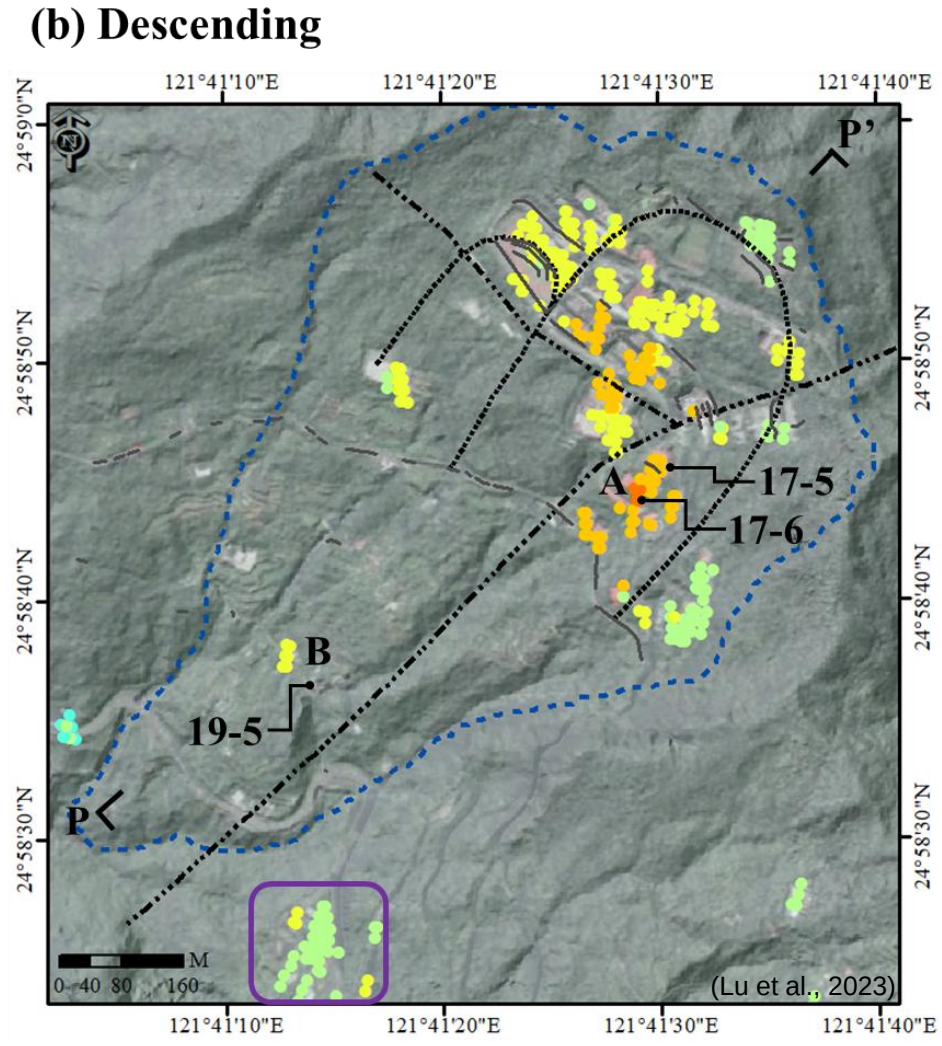


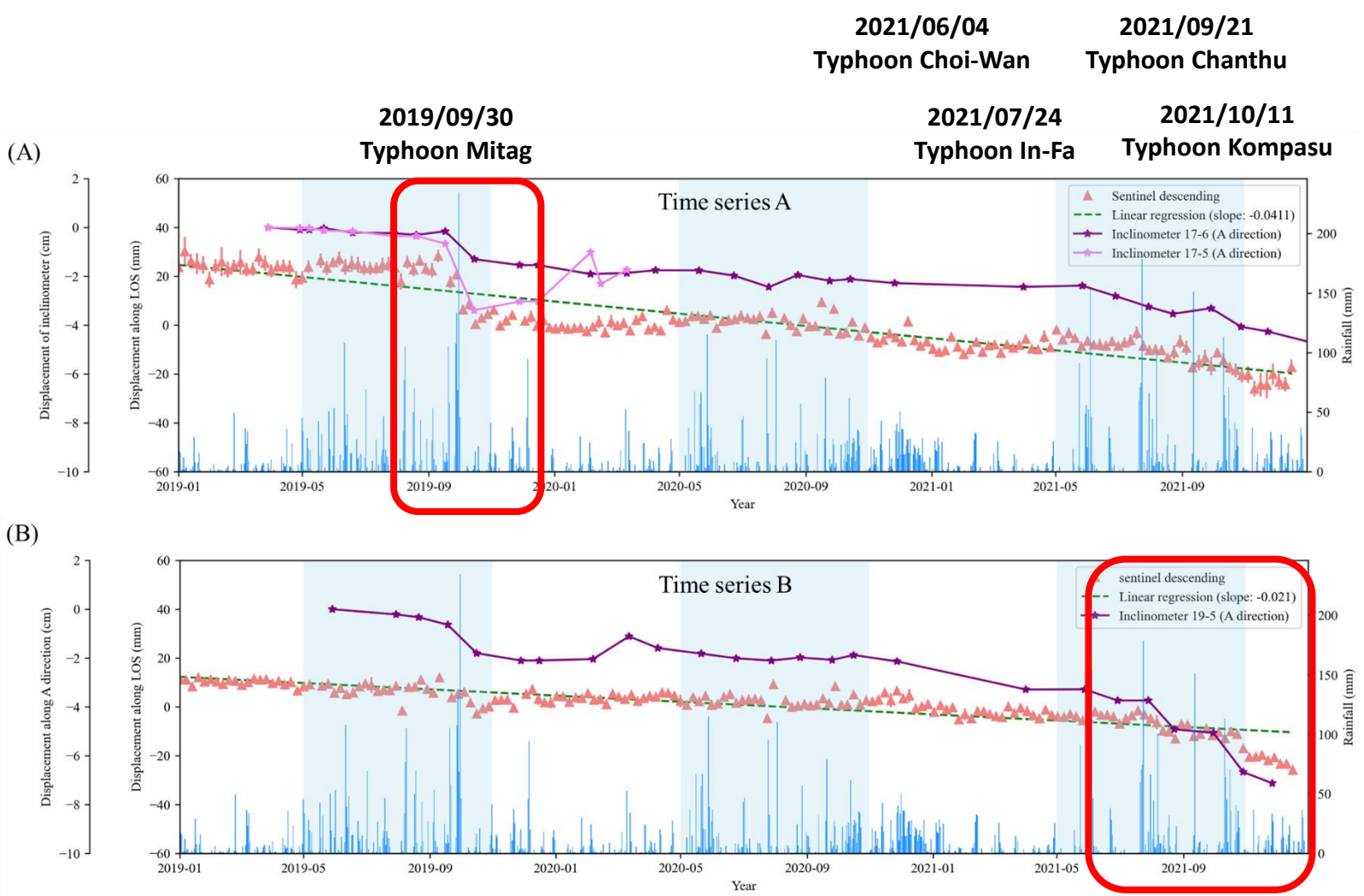


(Lu et al., 2023)

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

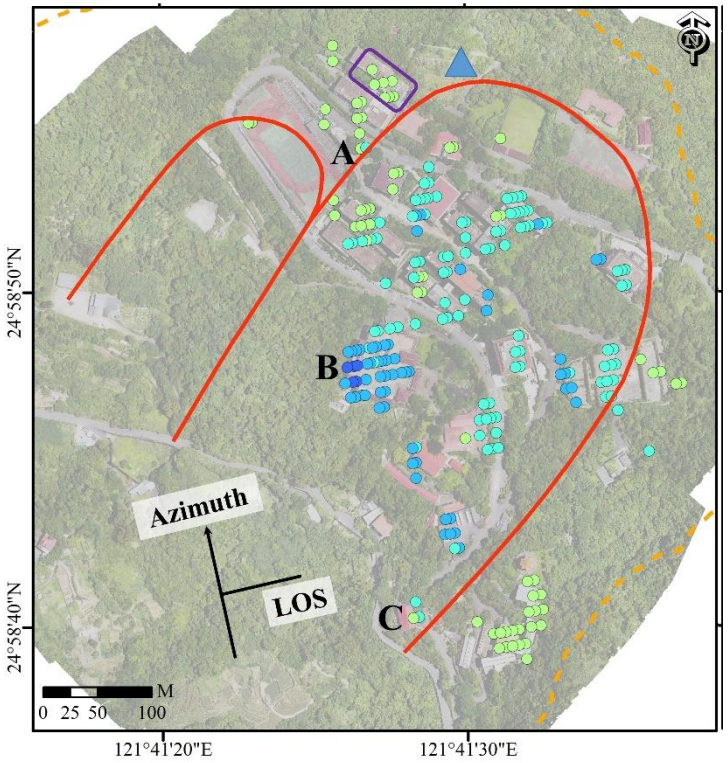
- **The timing of accelerations detected by MTInSAR technique are agree with in situ monitoring data, which confirms the reliability of our analysis results**

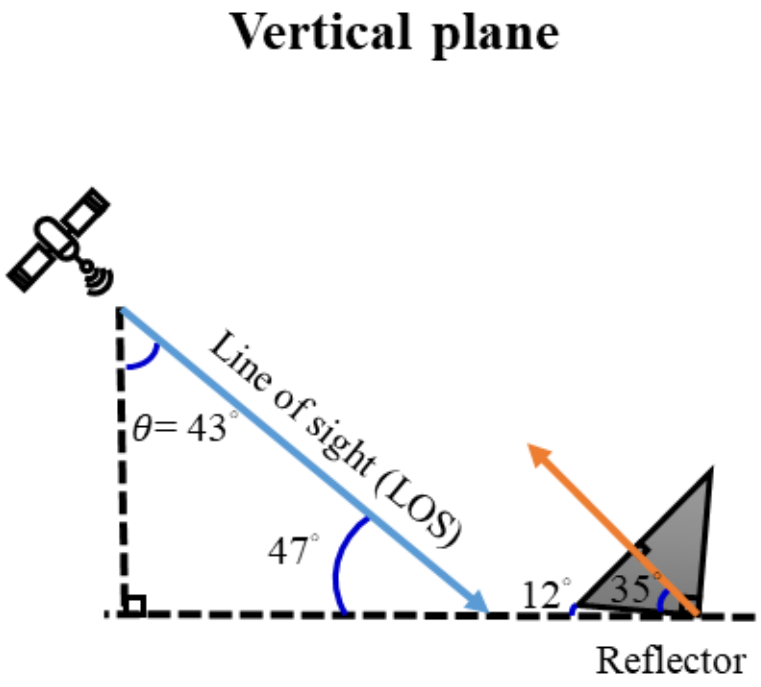


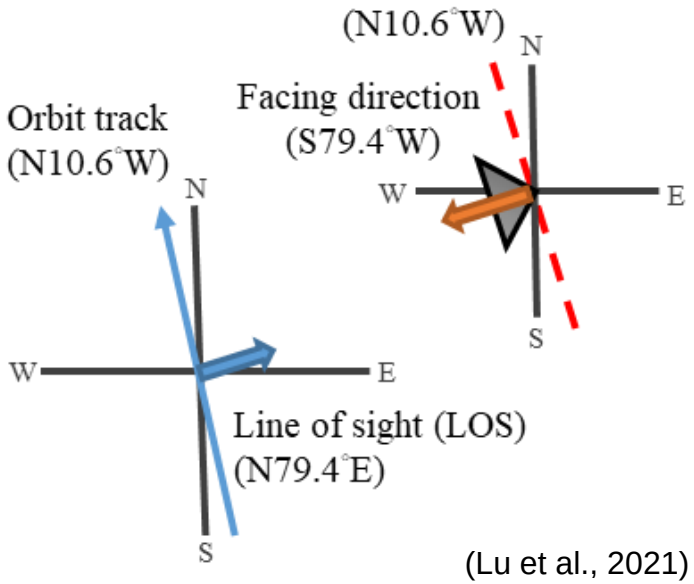


Corner reflector design and deployment

- 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





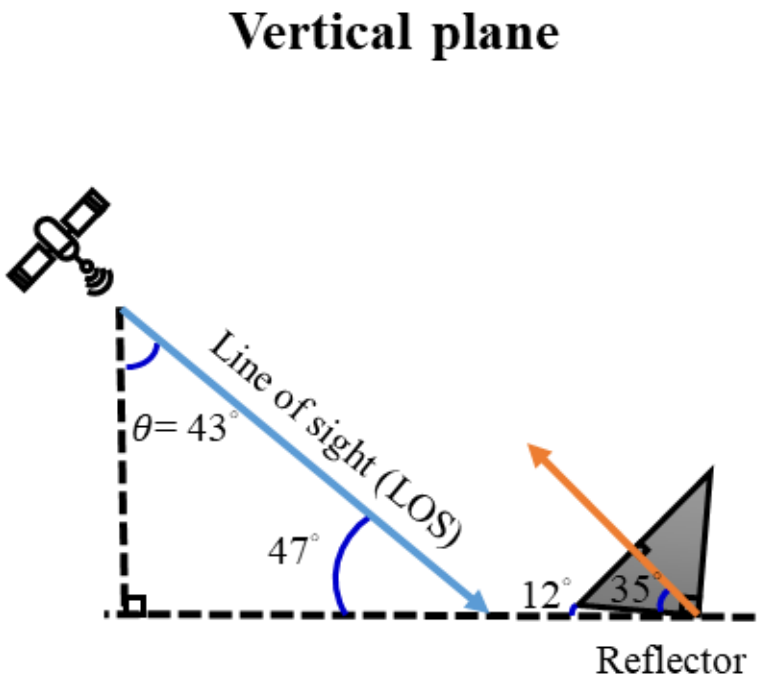


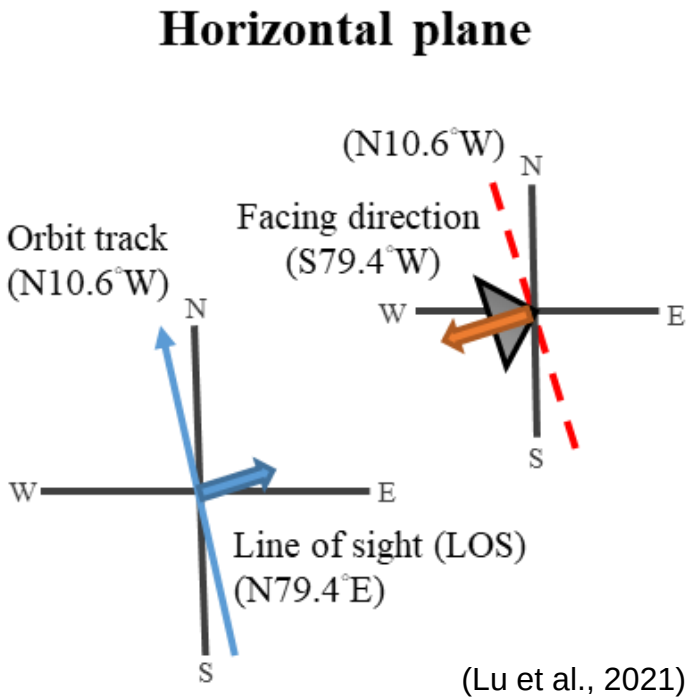
(Lu et al., 2021)

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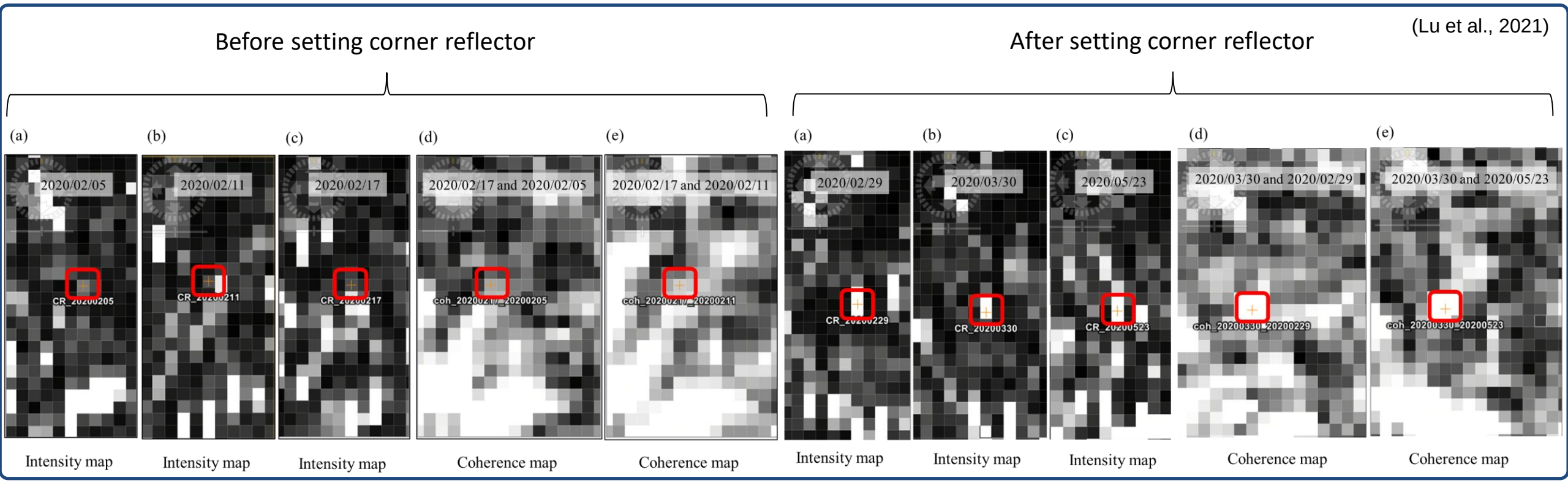


(Lu et al., 2021)

Corner reflector design and deployment

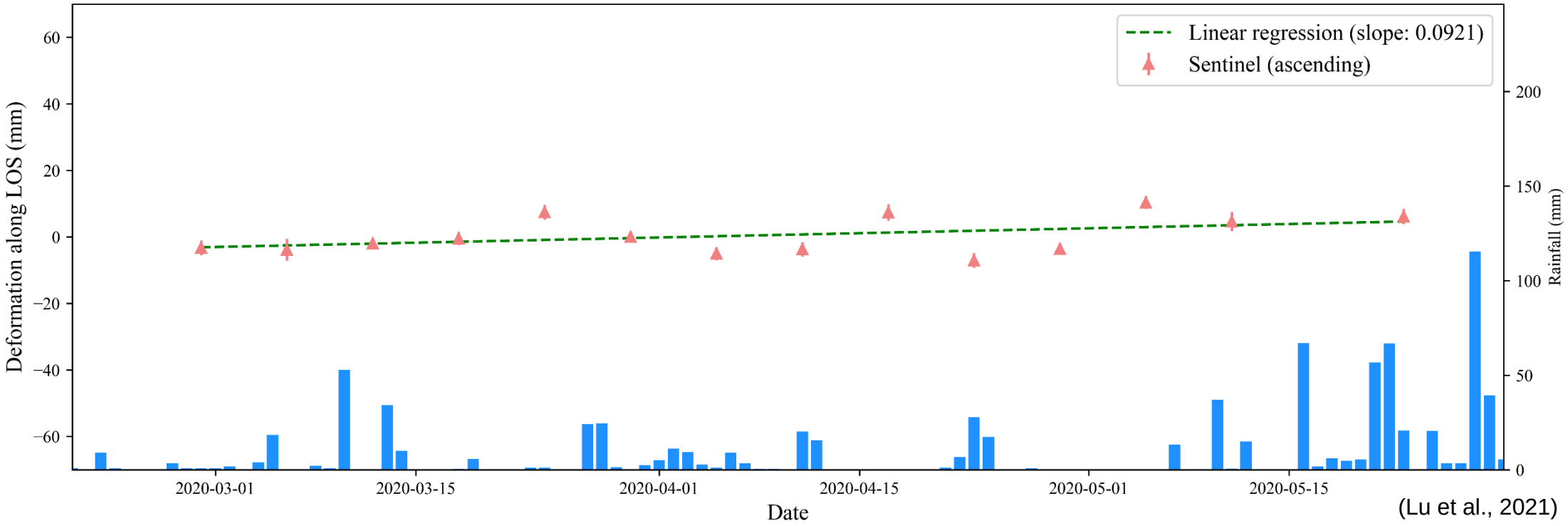
- **The intensity and coherence maps of SAR images, were analyzed to confirm that the corner reflector could be detected by the SAR sensor of the satellite.**
- **The brighter color in the intensity map indicates the greater reflected energy of the pixel, and the brighter color in the coherence map indicates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

(Lu et al., 2021)



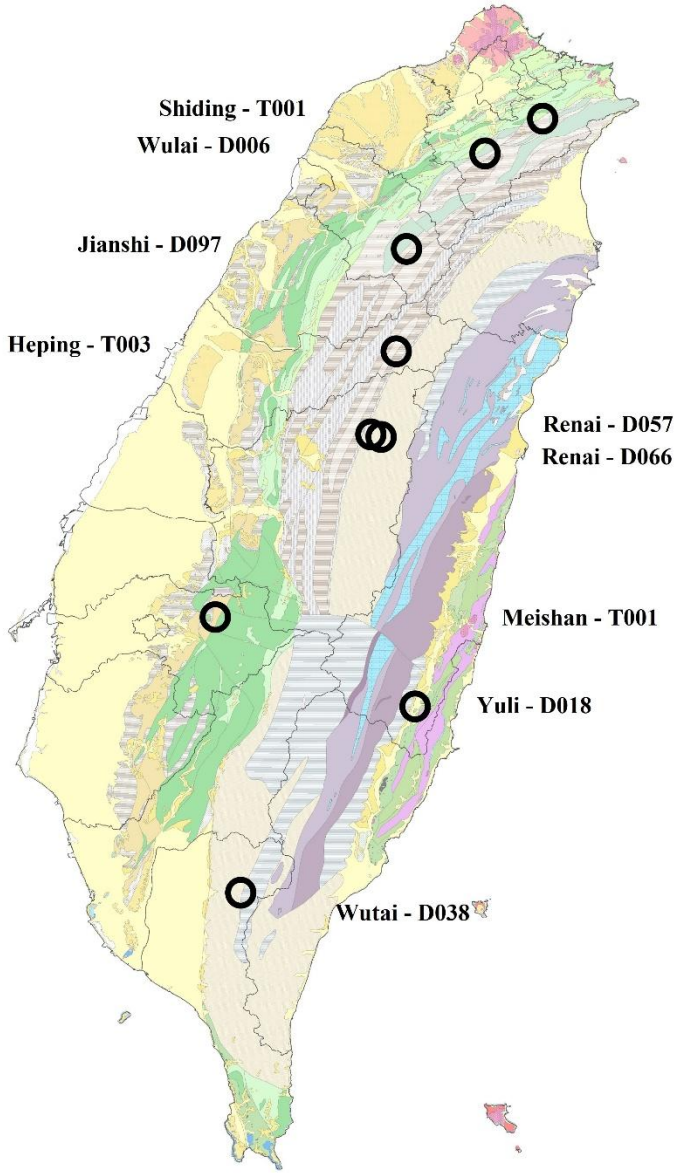
Corner reflector design and deployment

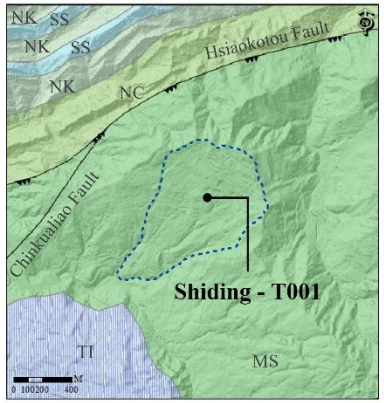
- **The preliminary time series result of corner reflector from 2020/02/27 to 2020/06/04.**

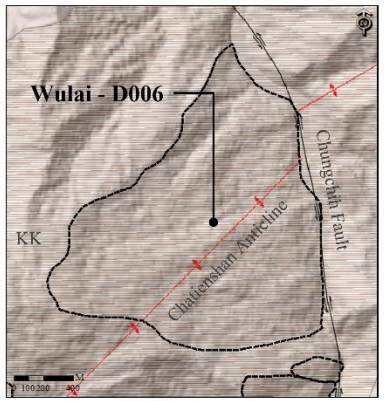


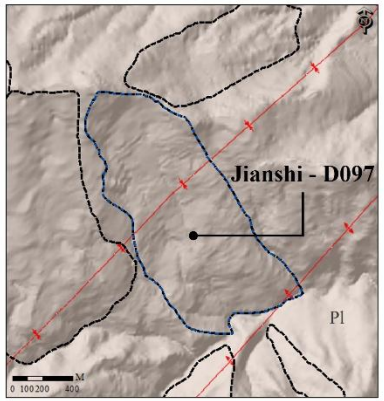
(Lu et al., 2021)

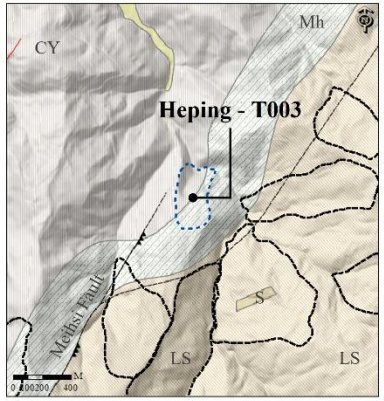
Pre-existing slow-moving landslides

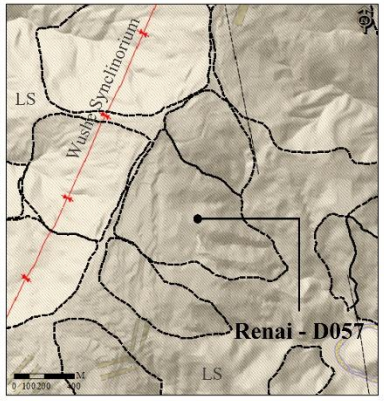


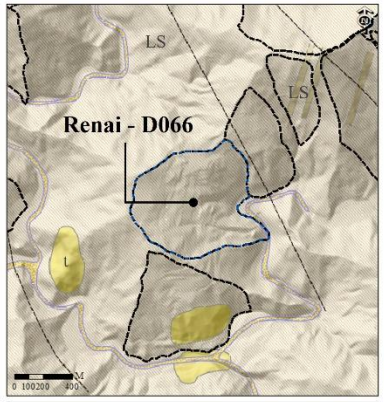


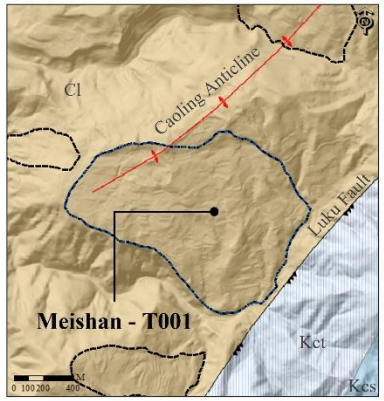


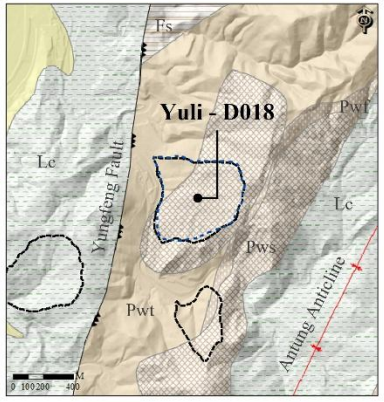


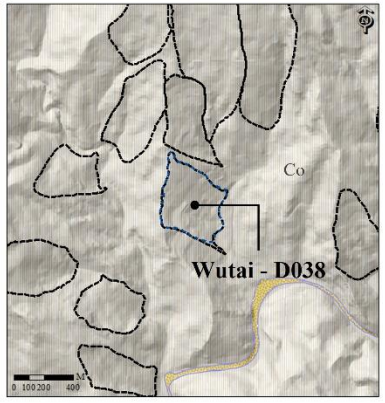


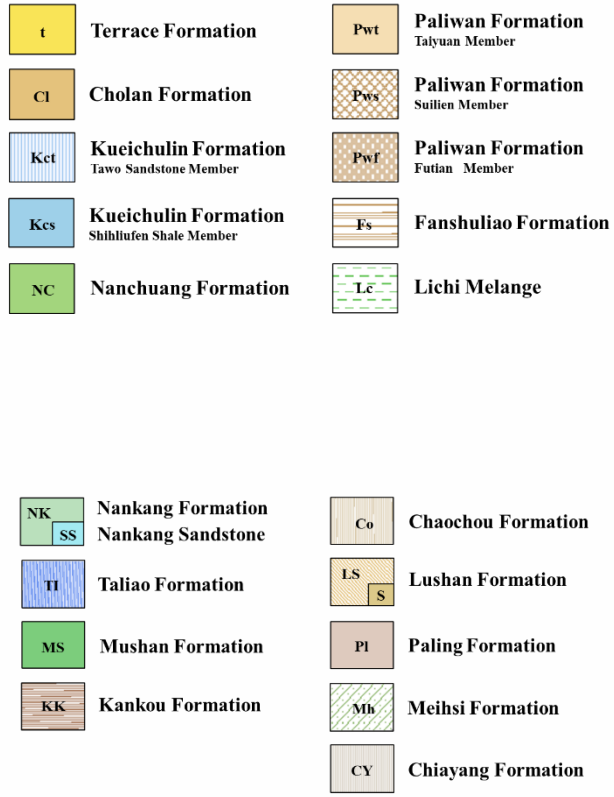








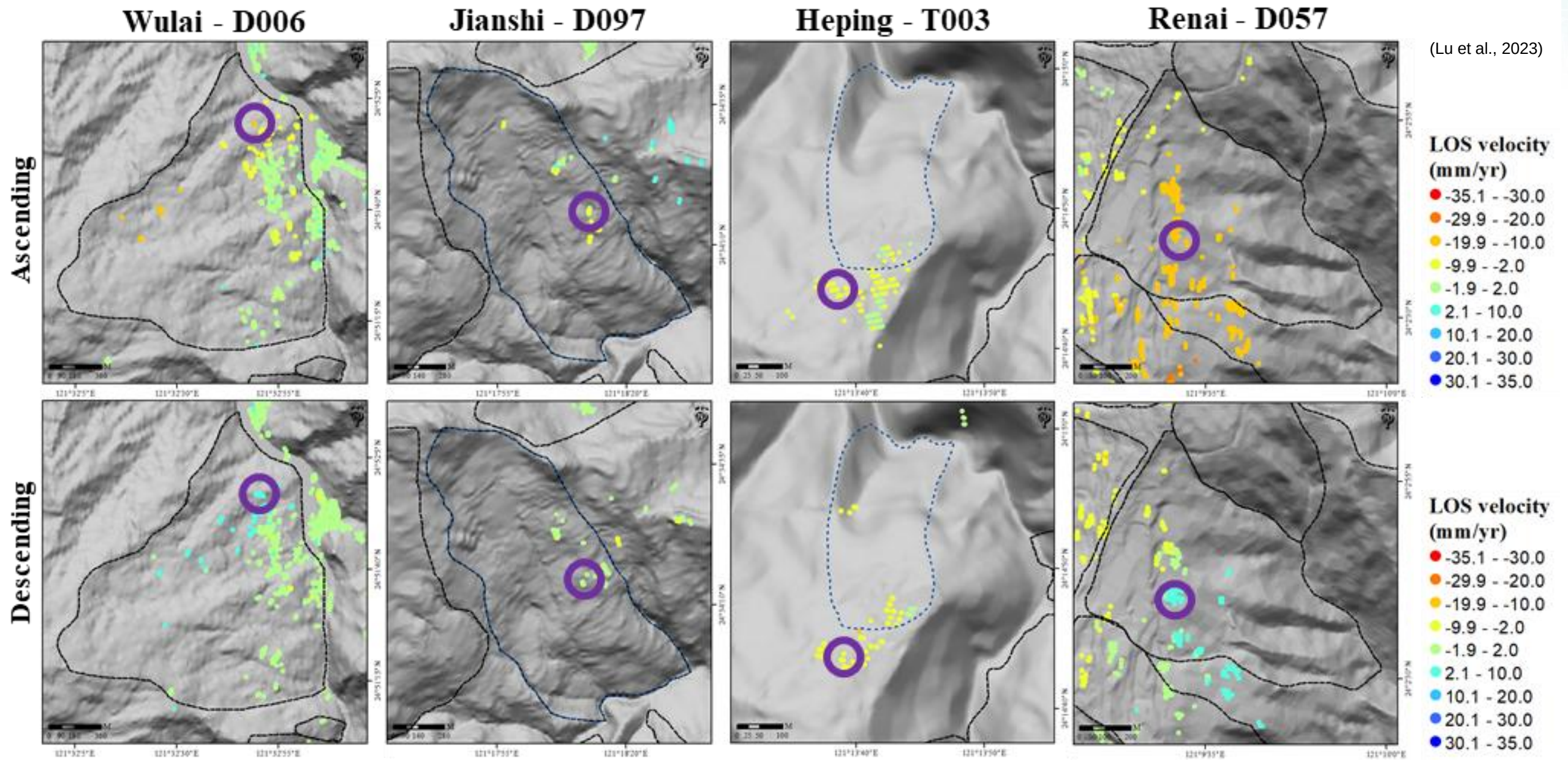




(Lu et al., 2023)

Monitoring activities of slow-moving landslide areas

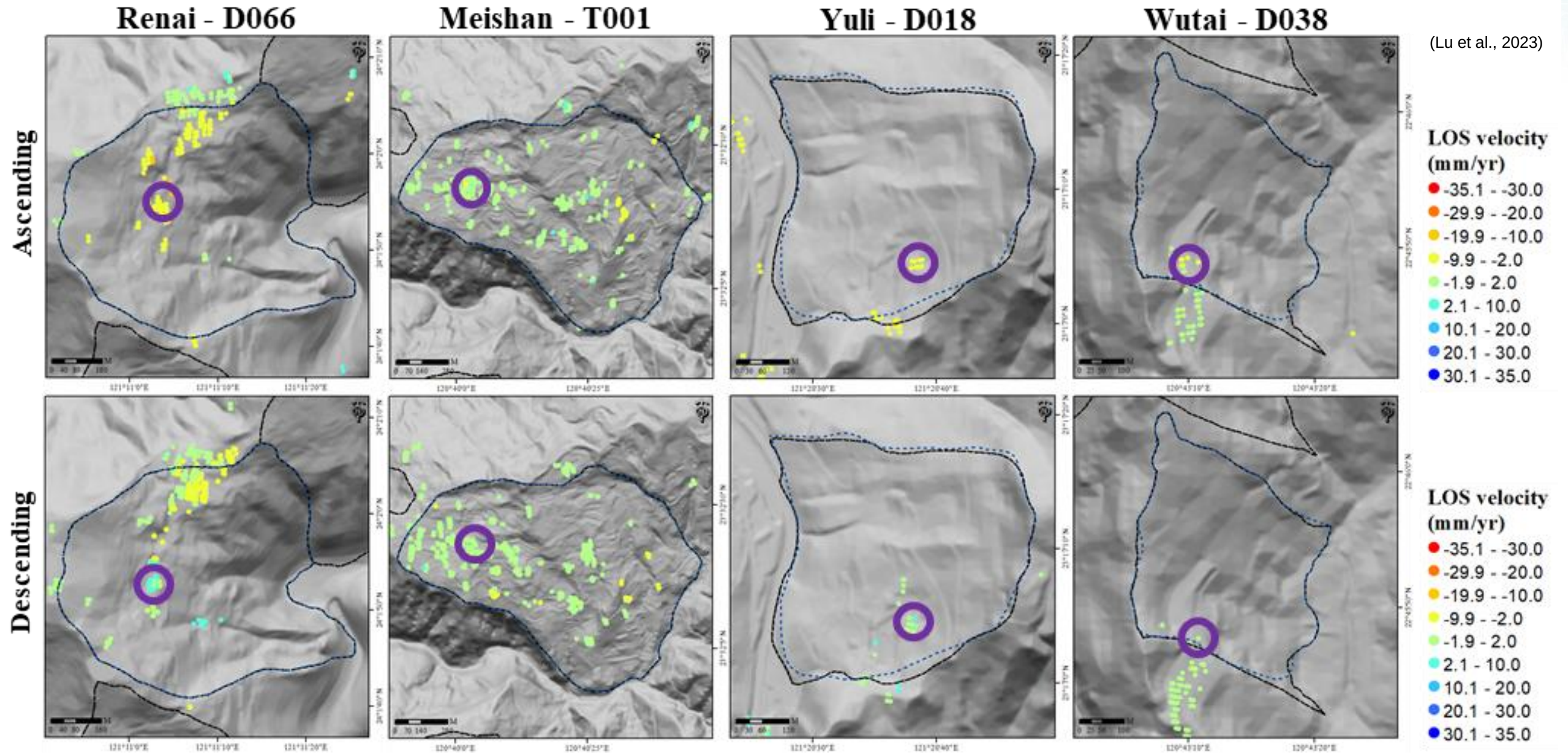
(2019-2021)



(Lu et al., 2023)

Monitoring activities of slow-moving landslide areas

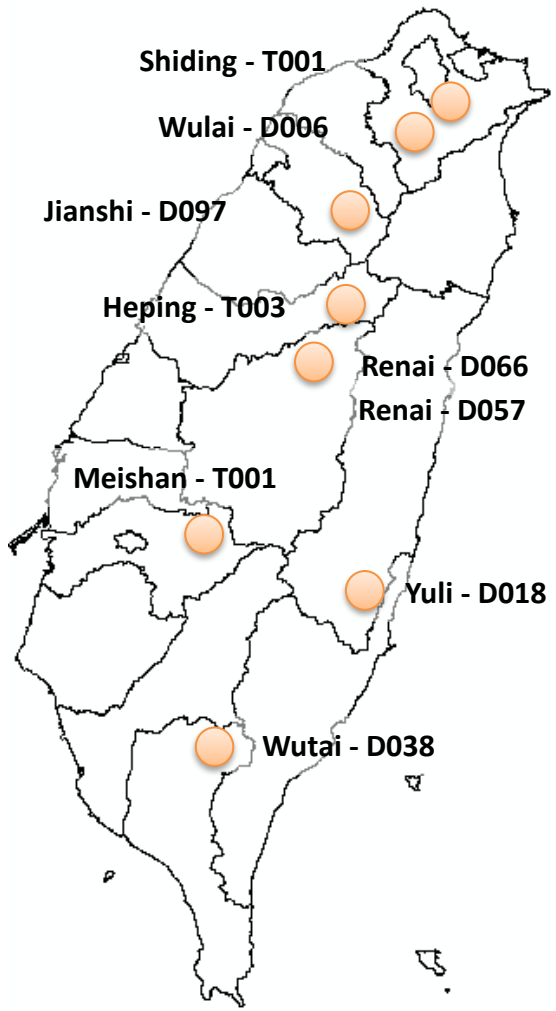
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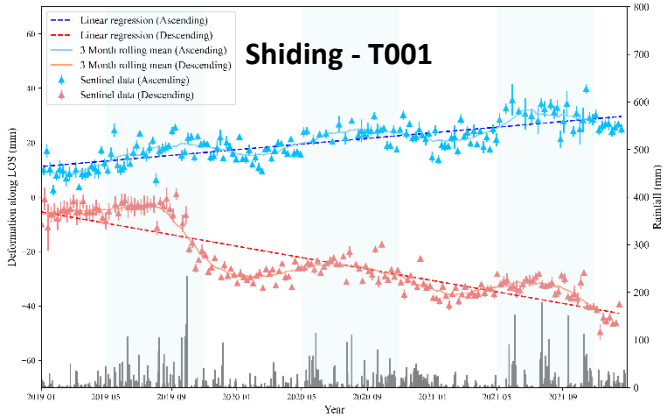
(Lu et al., 2023)

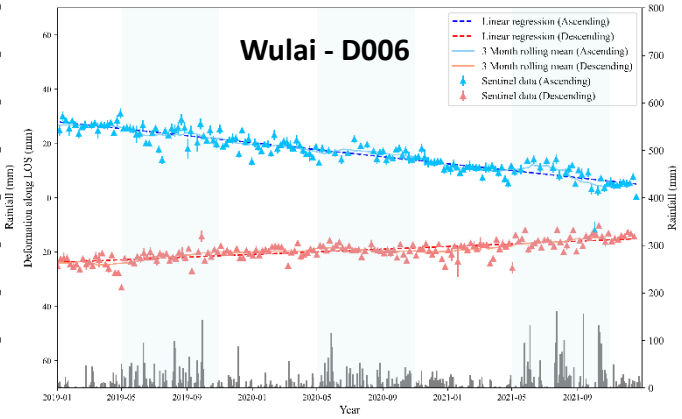
Monitoring activities of slow-moving landslide areas

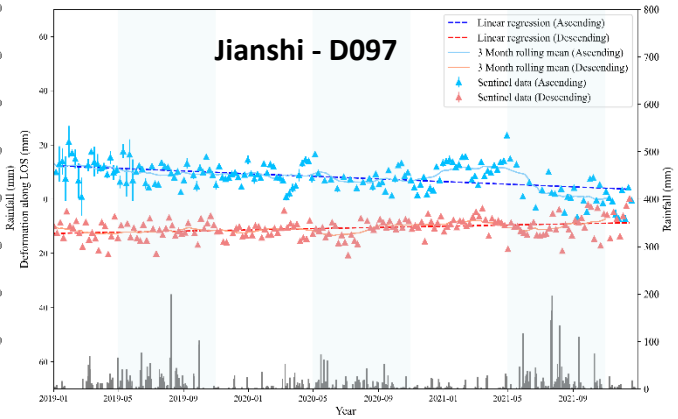
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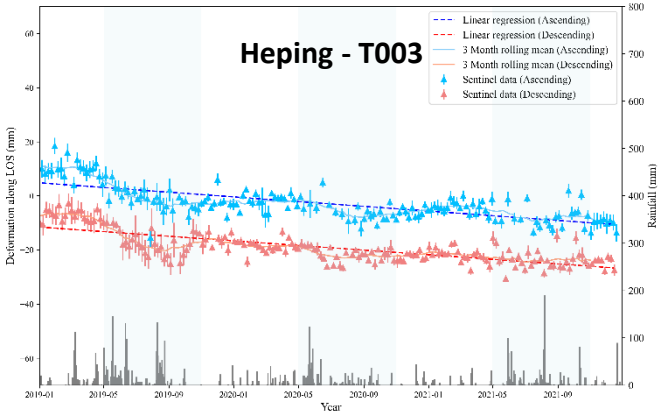


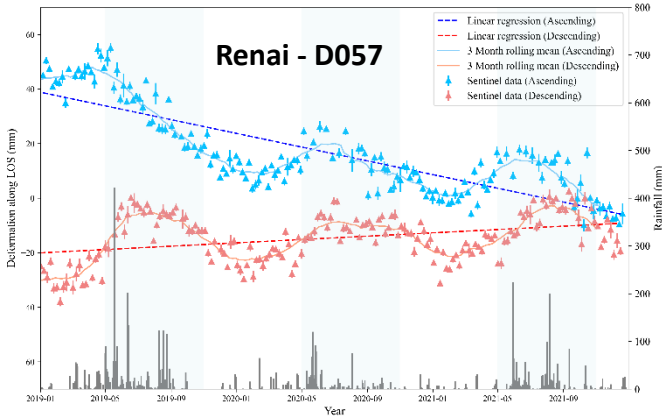
(Lu et al., 2023)

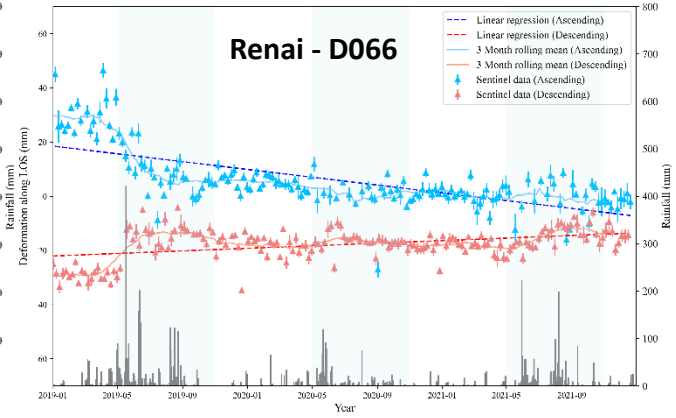


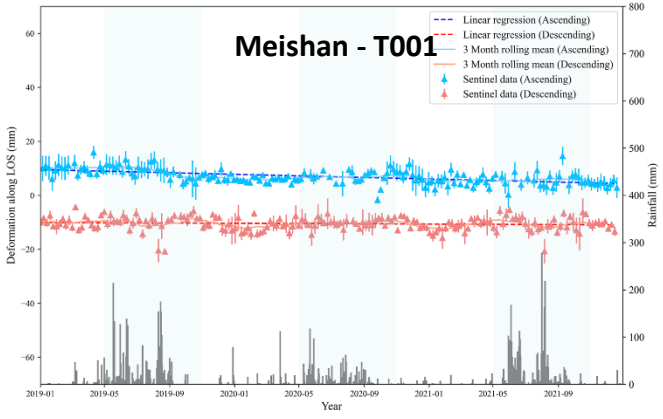


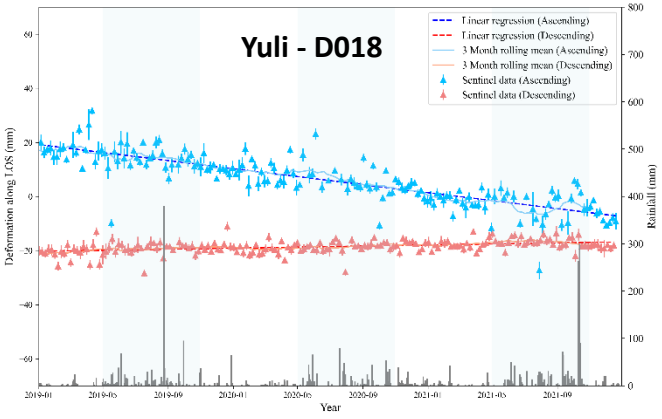


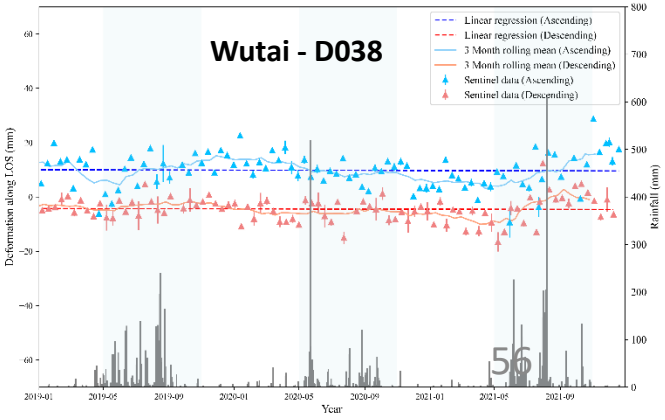






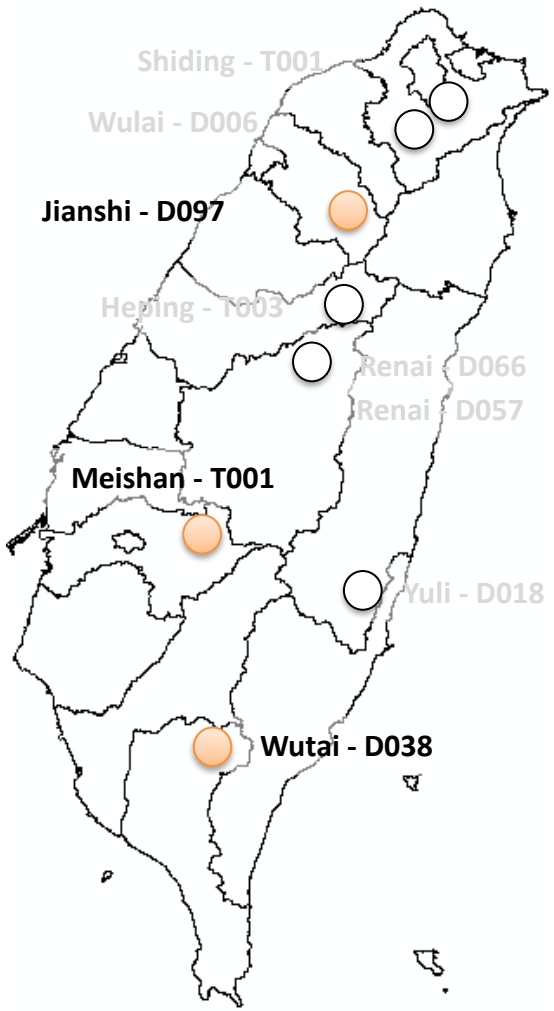




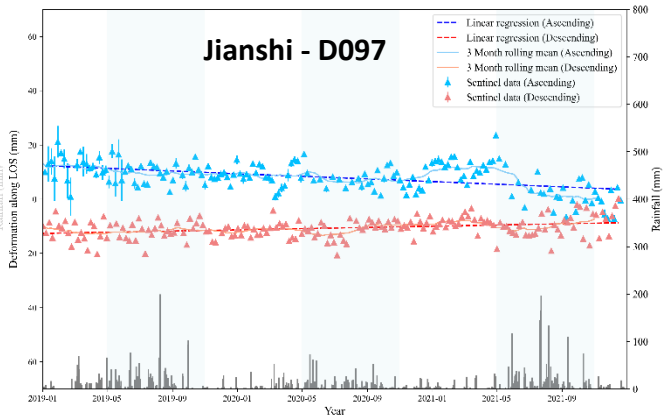


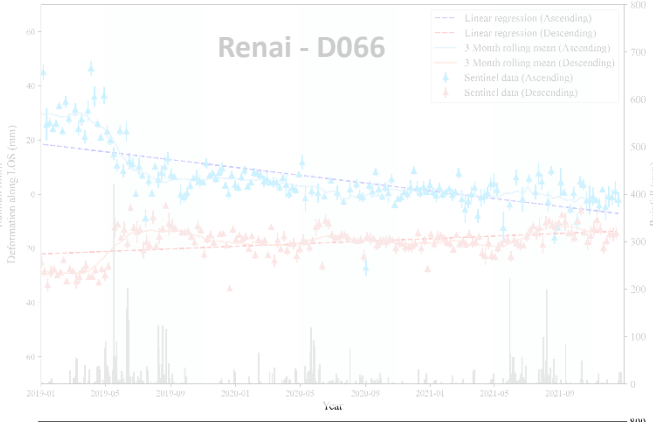
Monitoring activities of slow-moving landslide areas

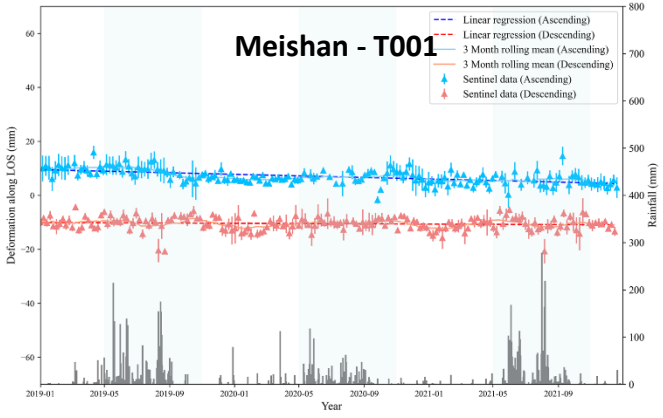
(2019-2021)

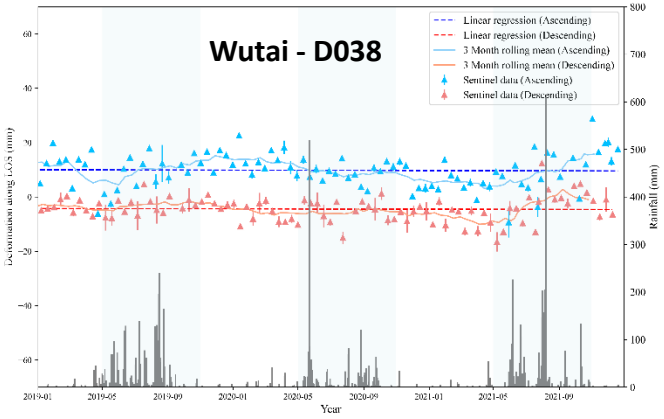


(Lu et al., 2023)





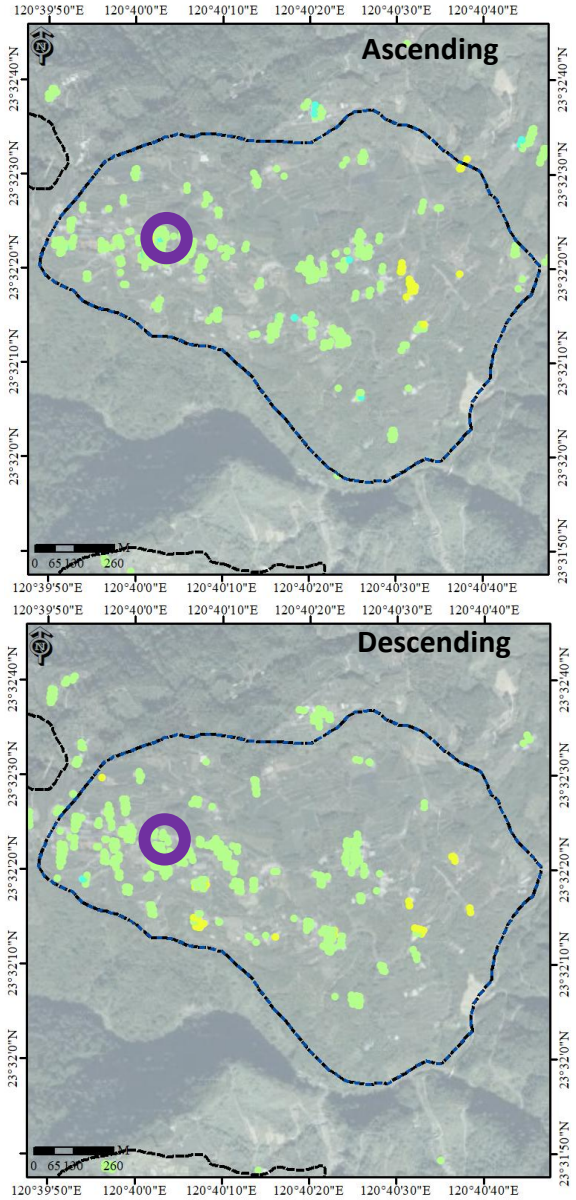


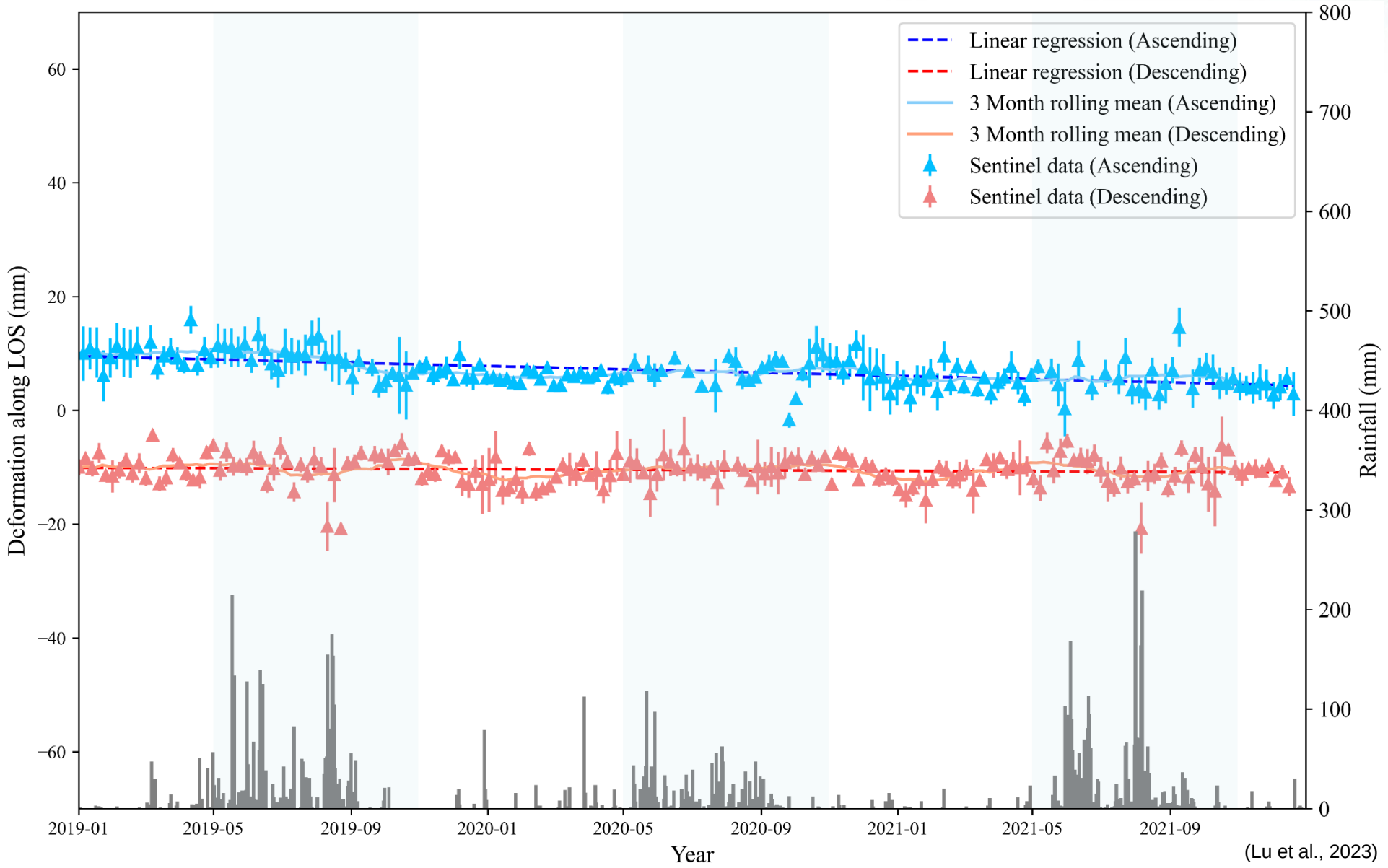


The activity of slow-moving landslide – Meishan-T001

(2019-2021)

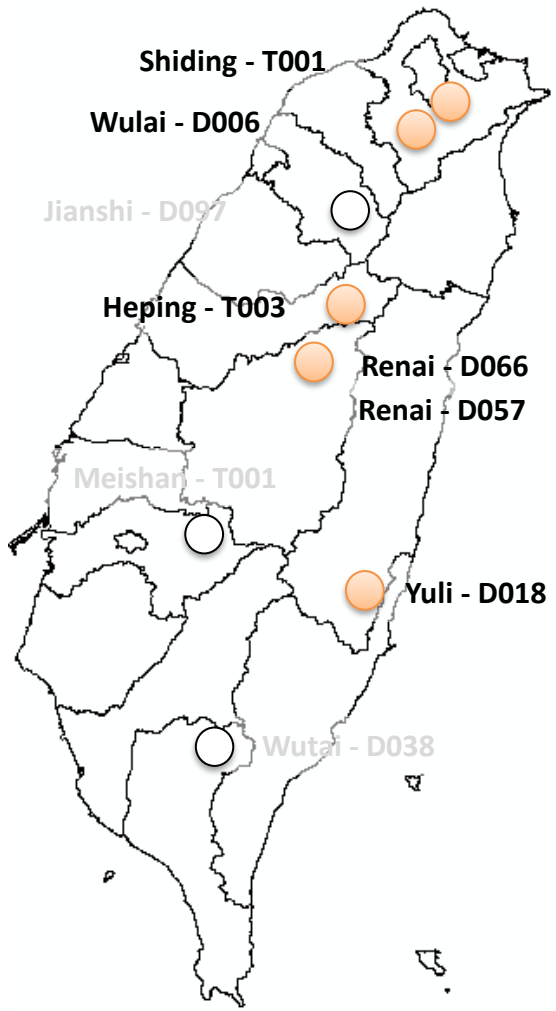
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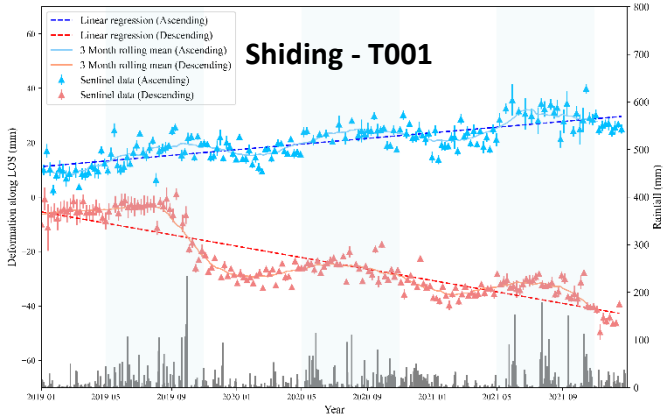


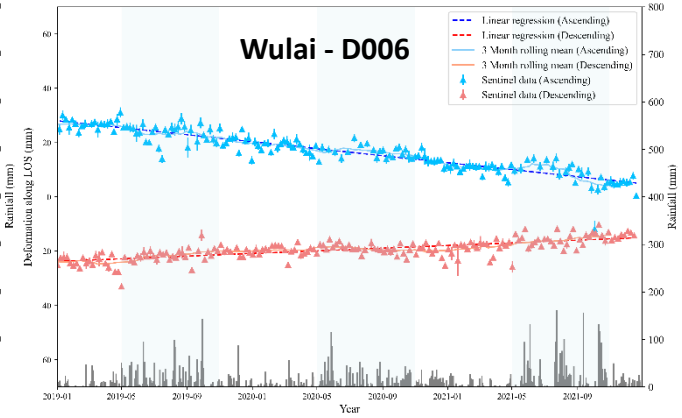


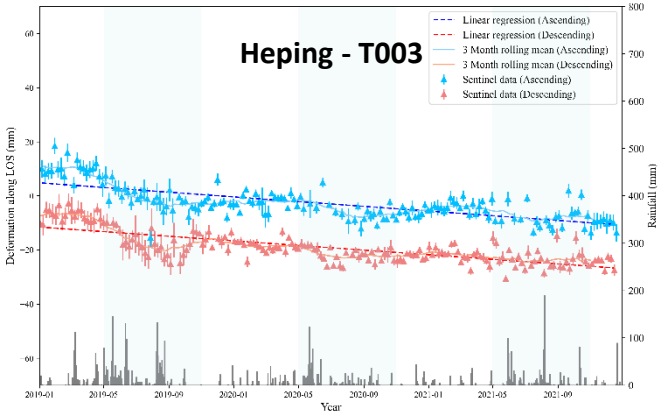
(Lu et al., 2023)

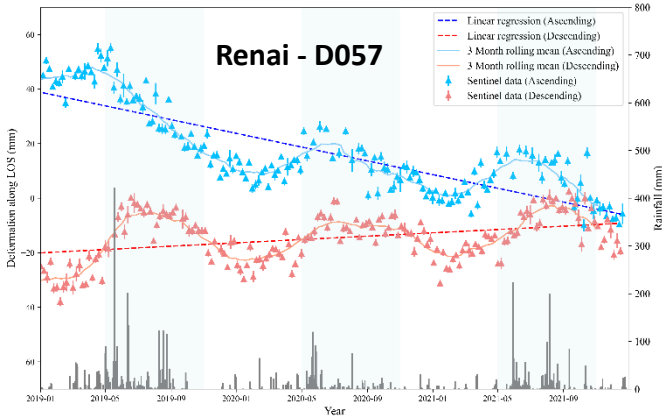
Monitoring activities of slow-moving landslide areas

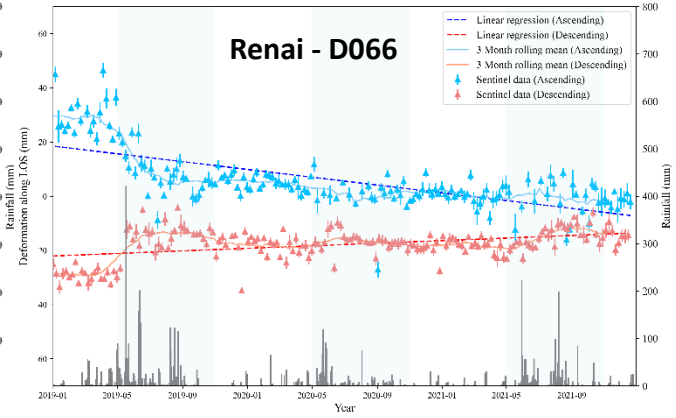


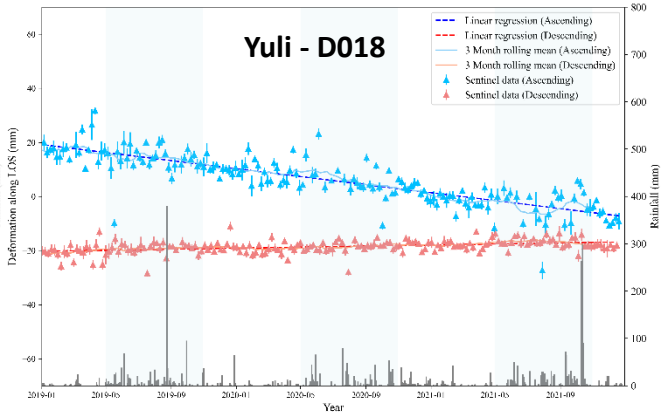




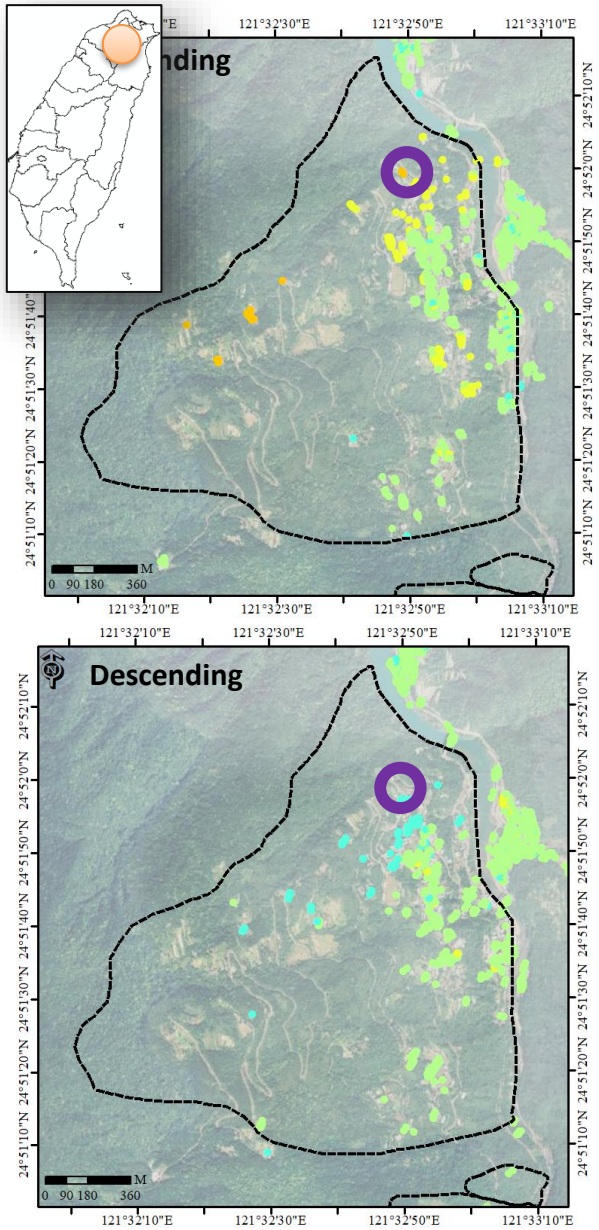


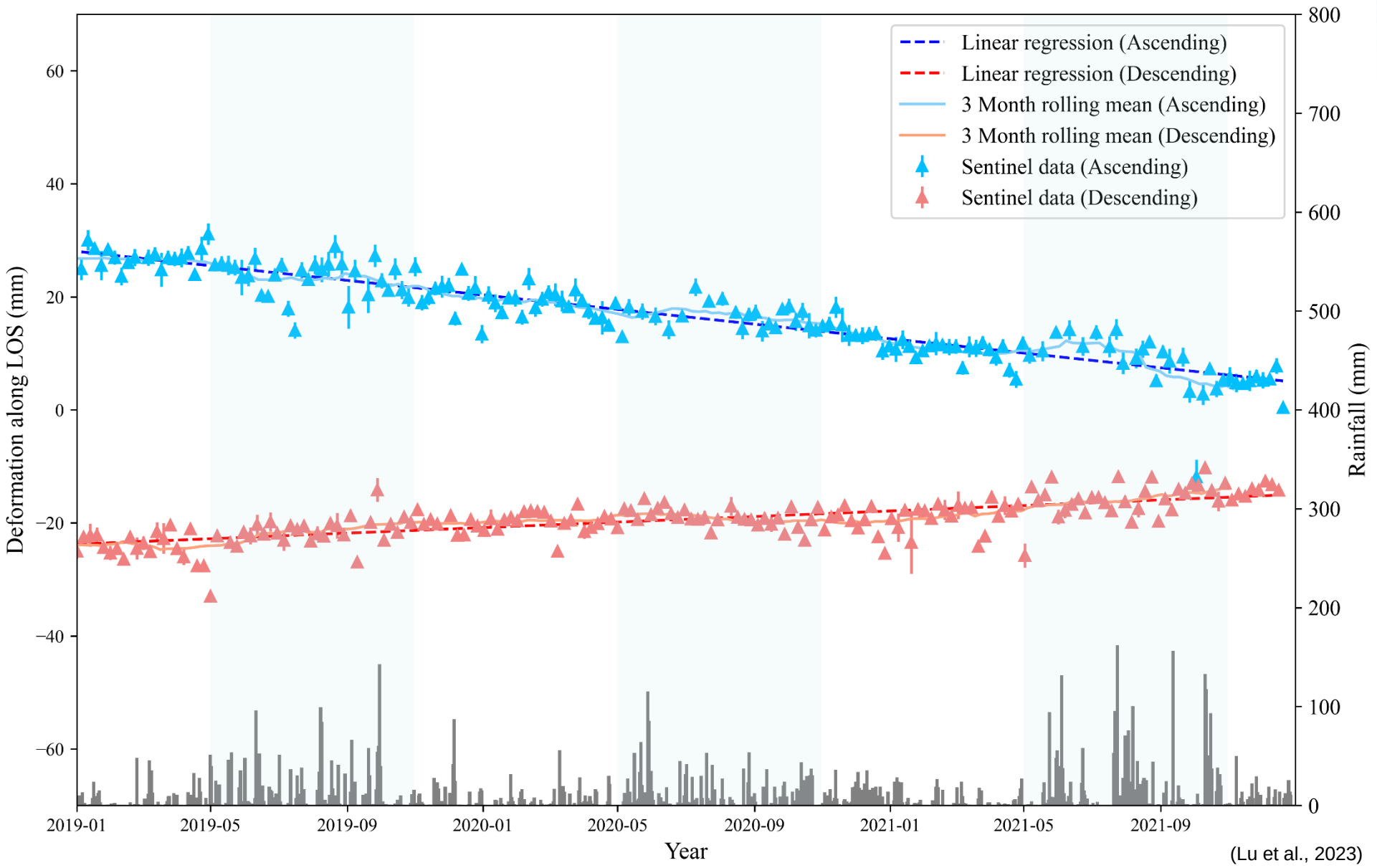






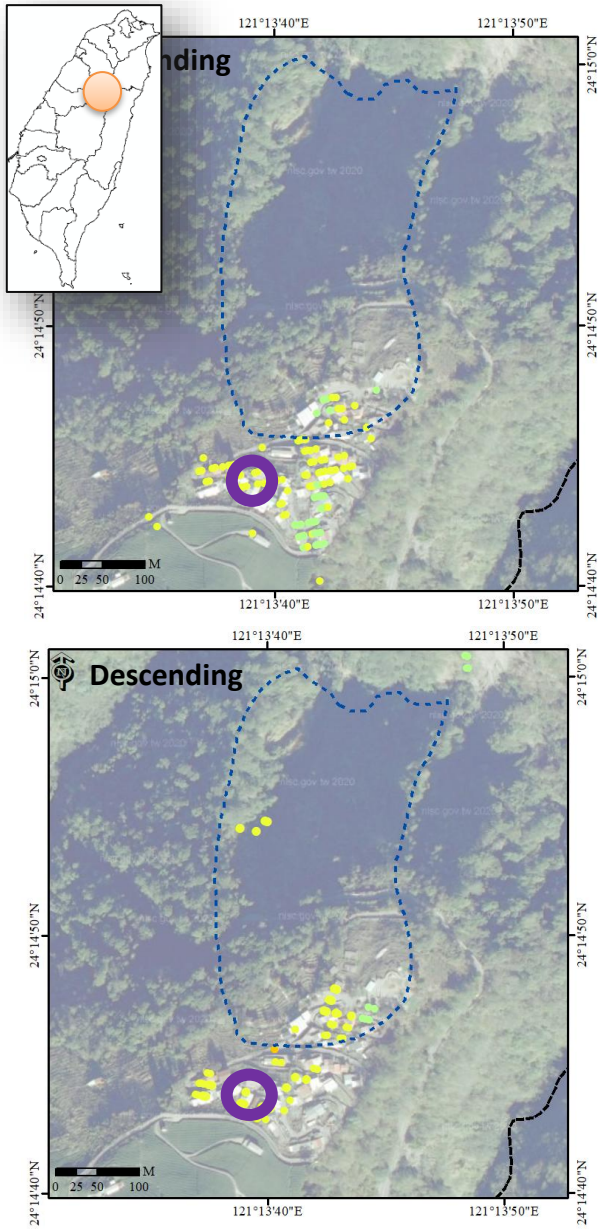
The activity of slow-moving landslide – Wulai-D006

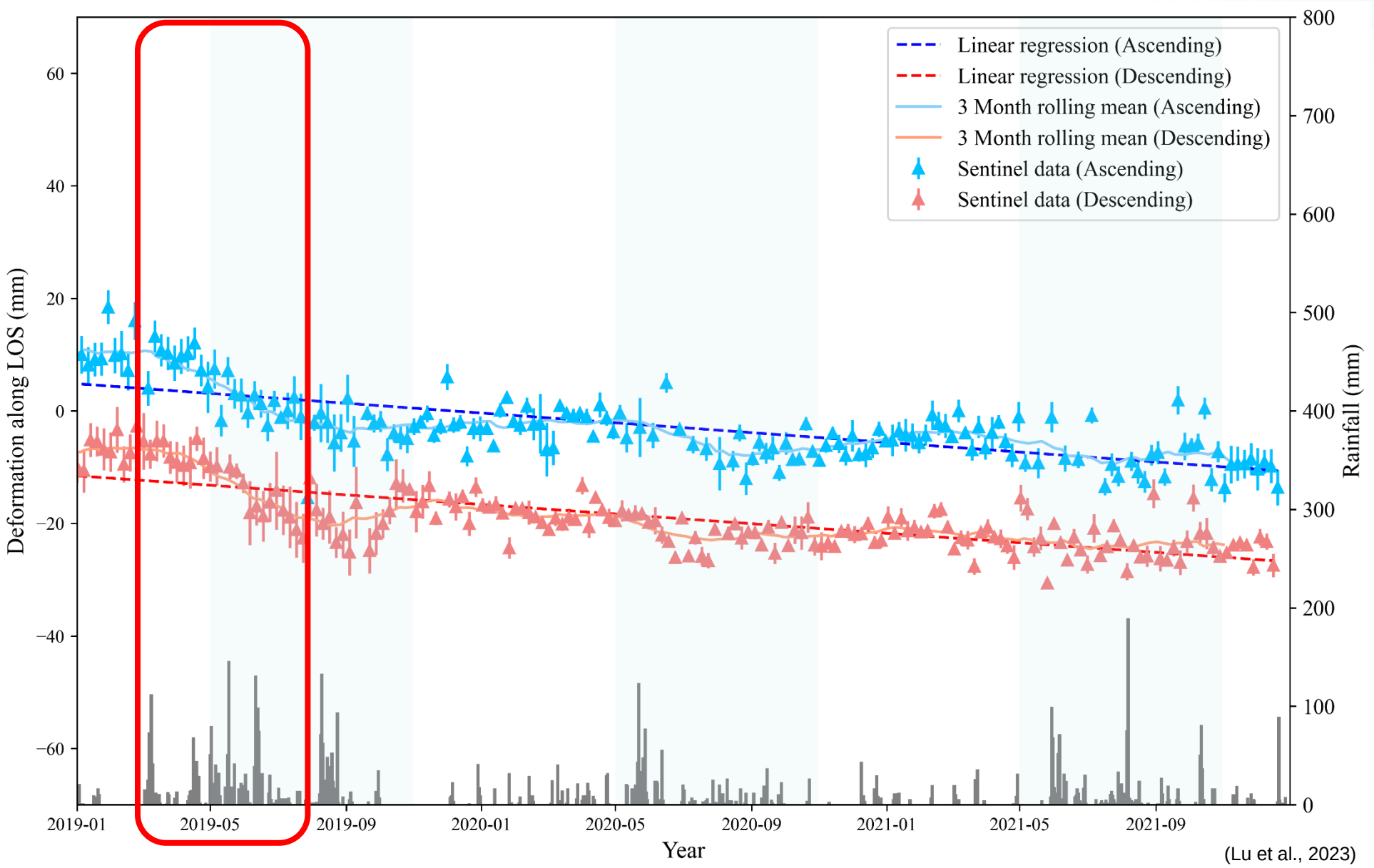




(Lu et al., 2023)

The activity of slow-moving landslide – Heping-T003

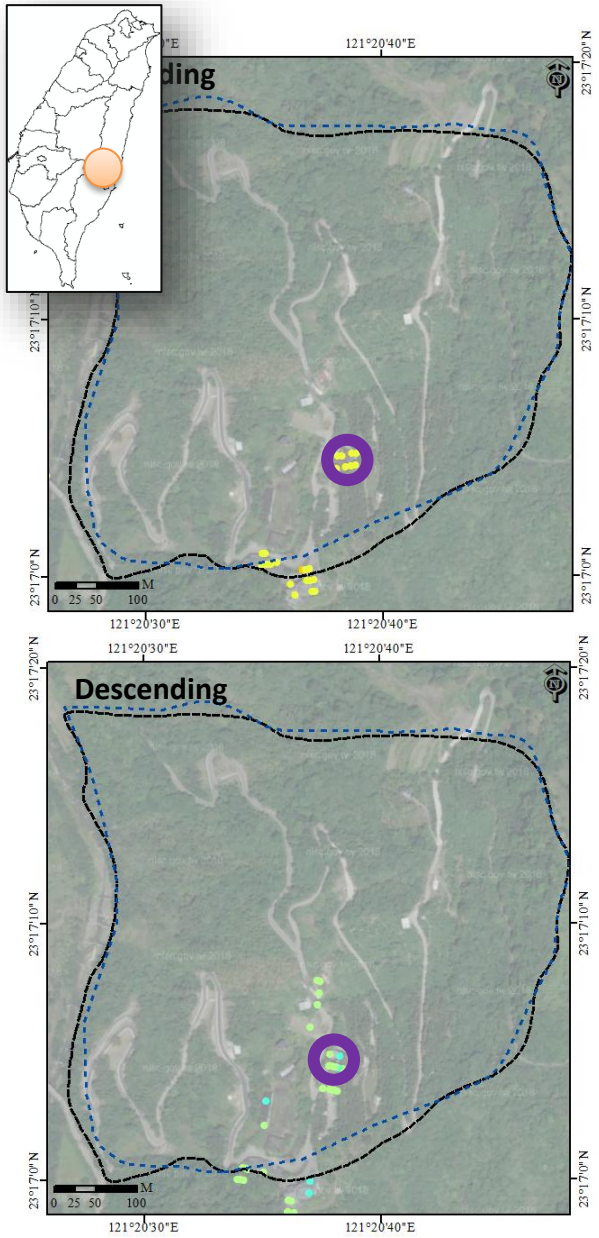


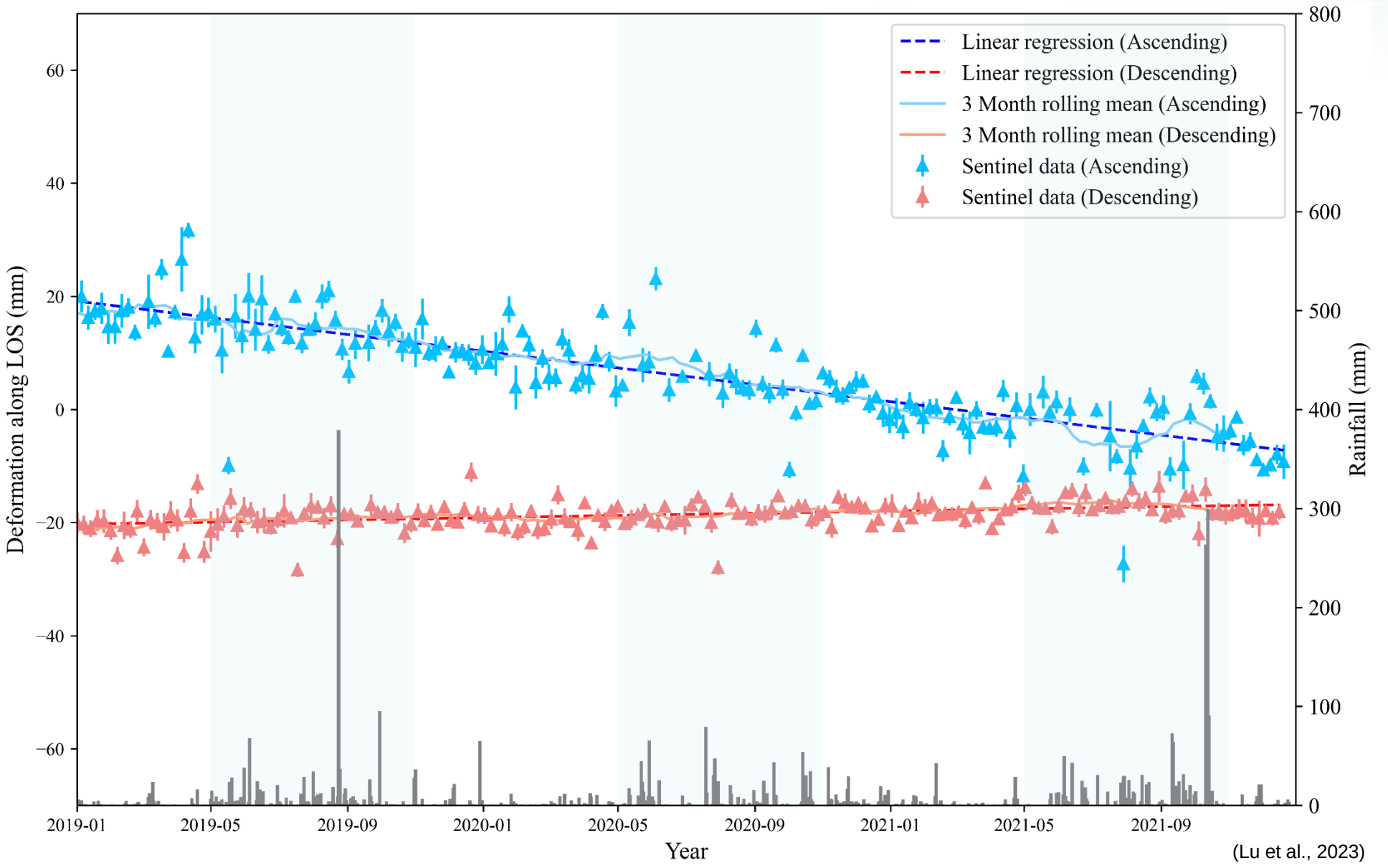


(Lu et al., 2023)

The activity of slow-moving landslide – Yuli-D018

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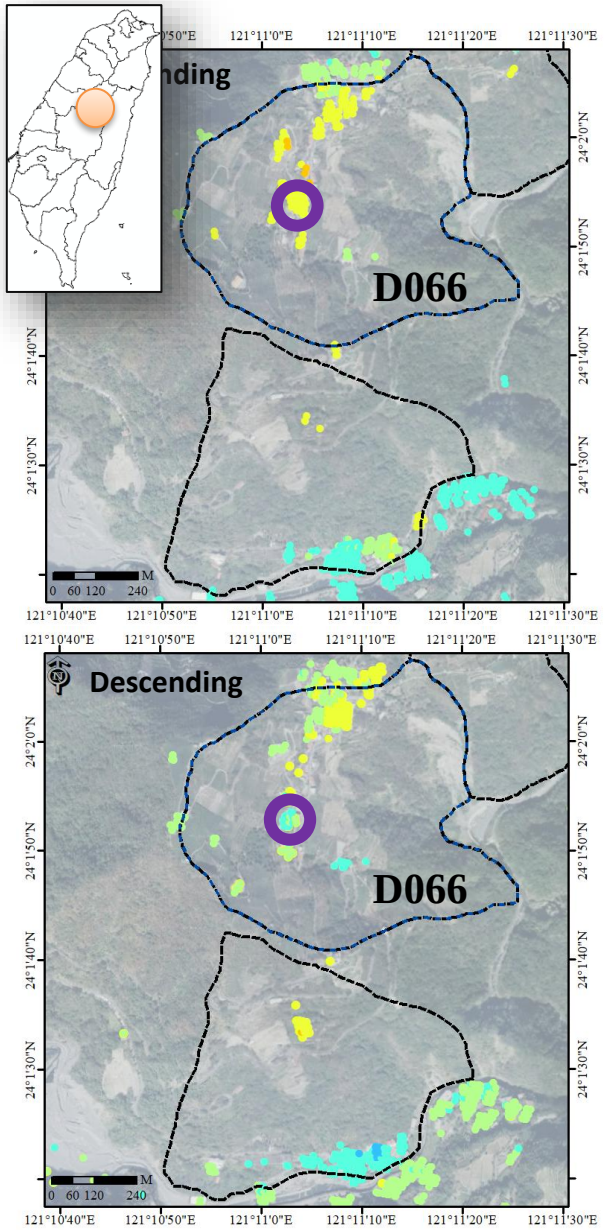


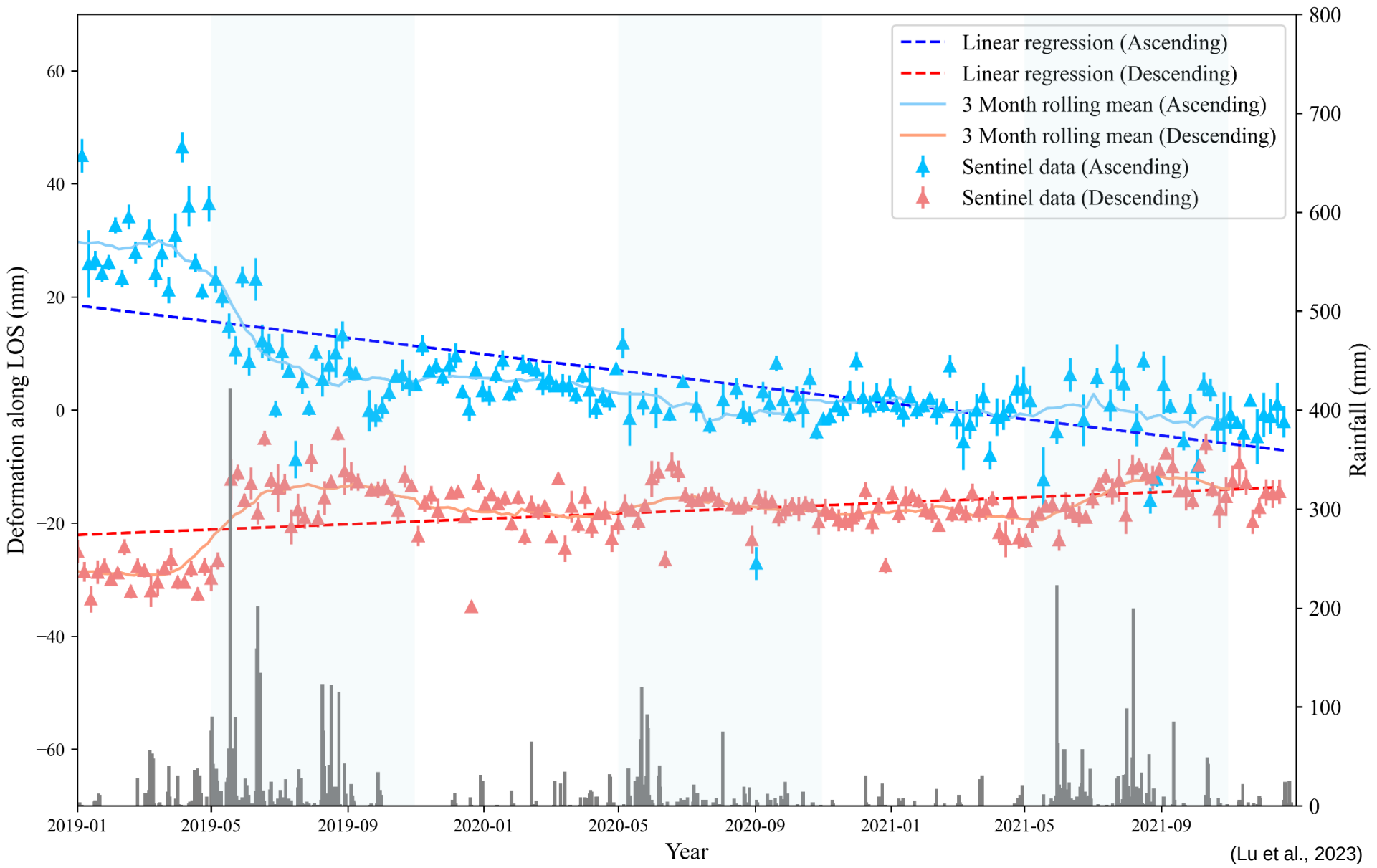


(Lu et al., 2023)

The activity of slow-moving landslide – Renai-D066

國家災害防救科技中心

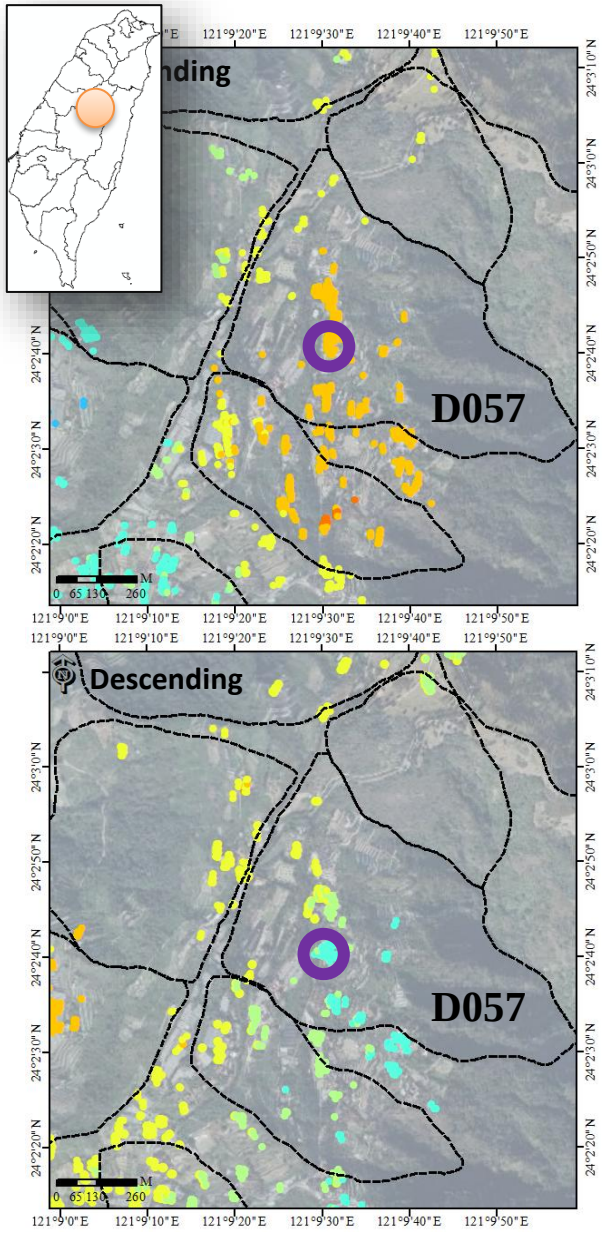


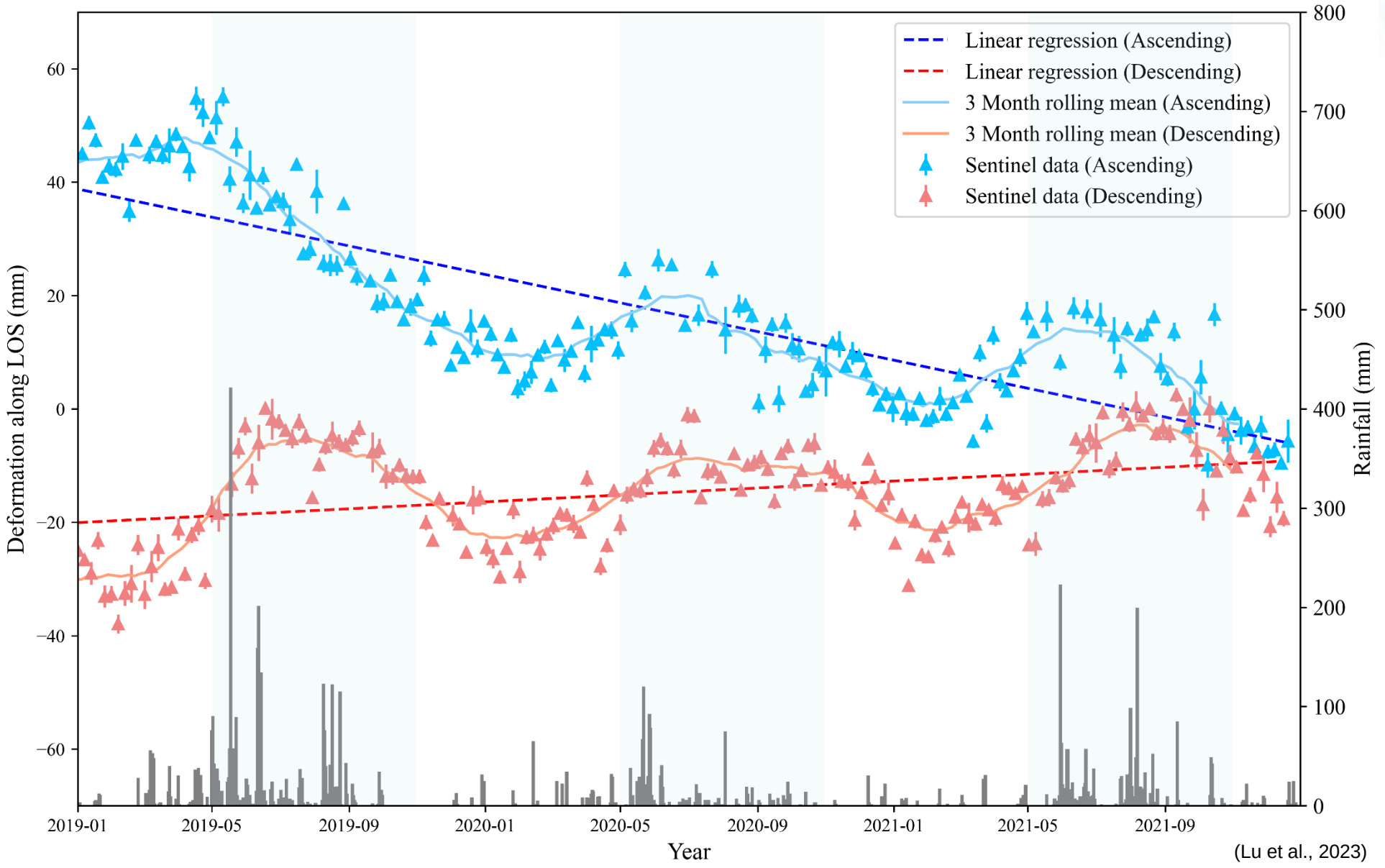


(Lu et al., 2023)

The activity of slow-moving landslide – Renai-D057

國家災害防救科技中心

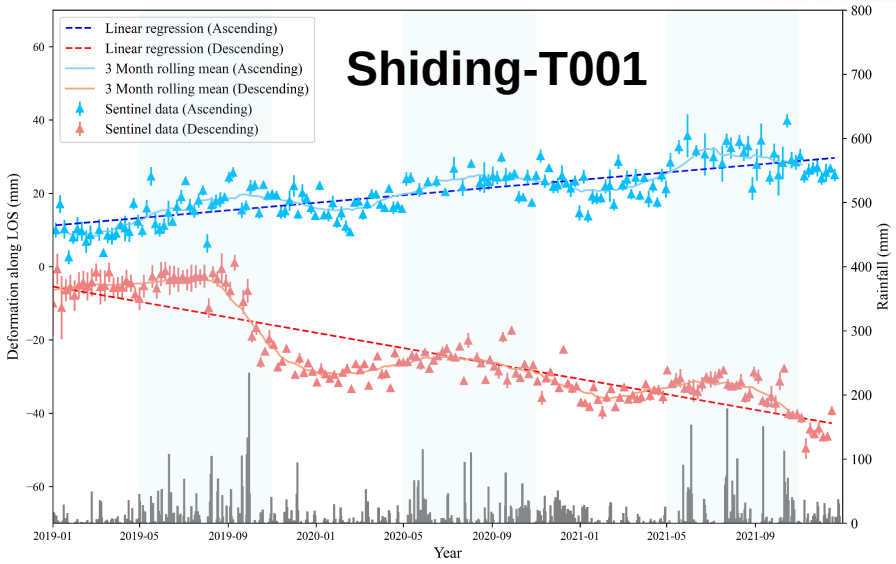


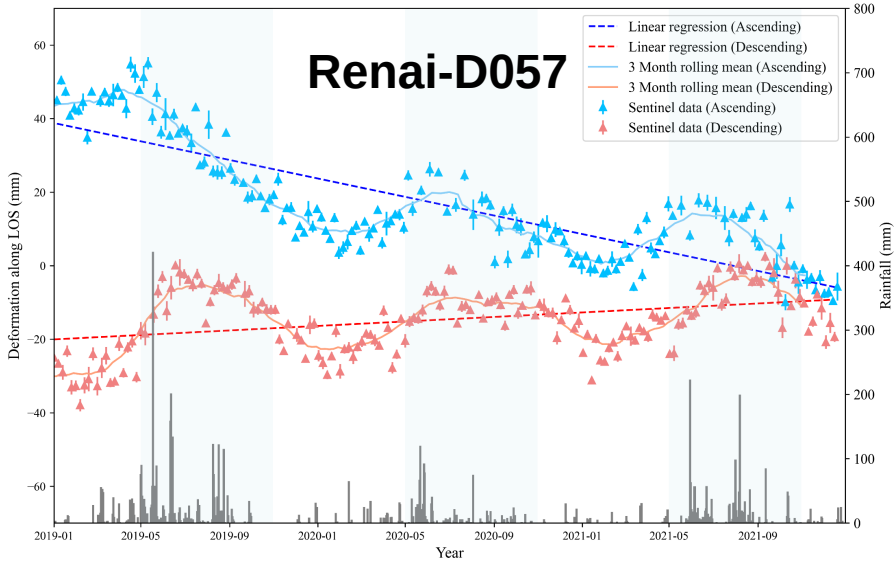


(Lu et al., 2023)

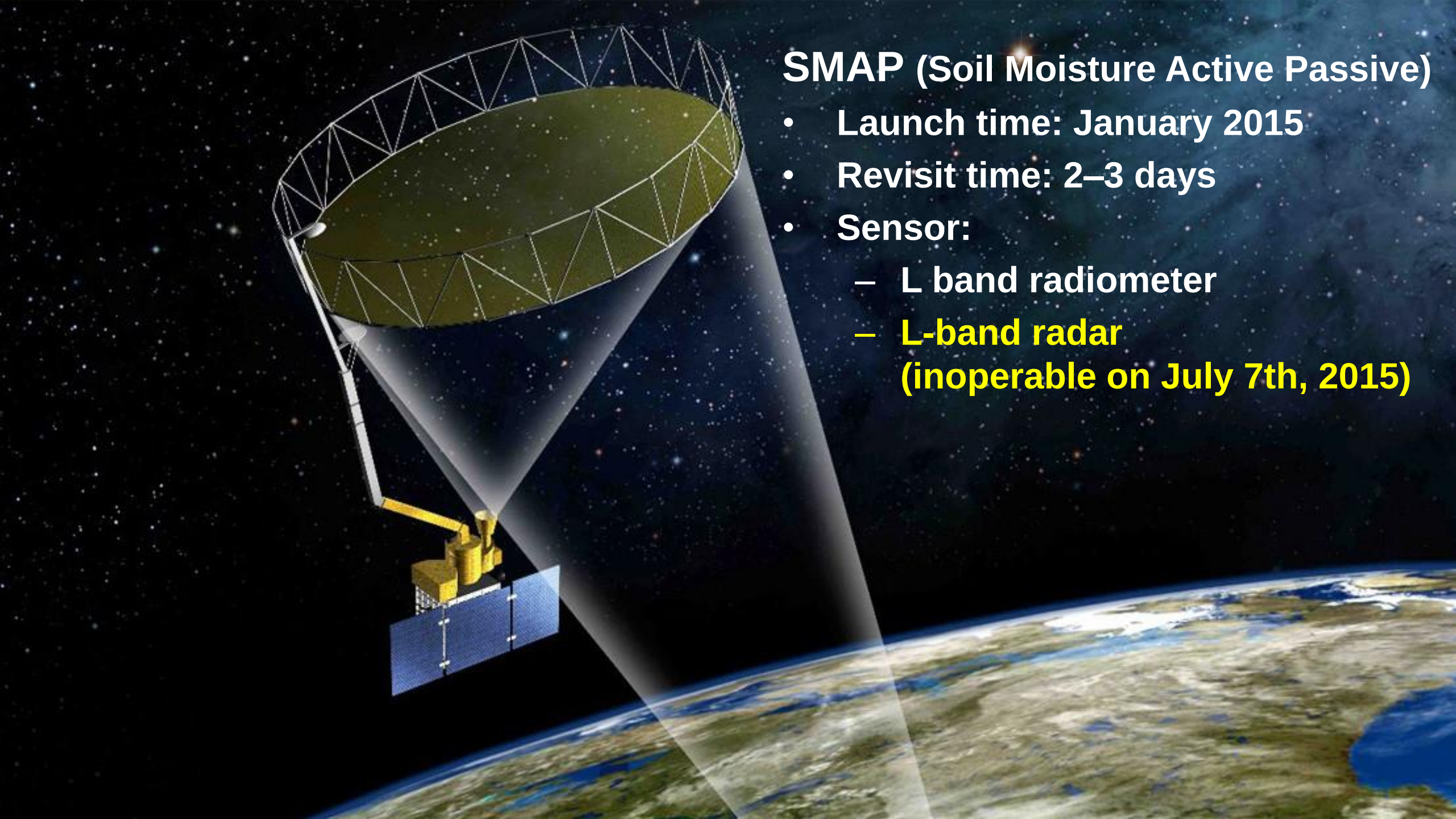
MTInSAR time series - Seasonal fluctuations

- **Seasonal Surface fluctuation**
  - **Total tropospheric delay**
    - Turbulent delay (湍流延遲) ➔ **spatially correlated** but **temporally random**
    - Stratified tropospheric delay (分層對流層延遲) ➔ **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





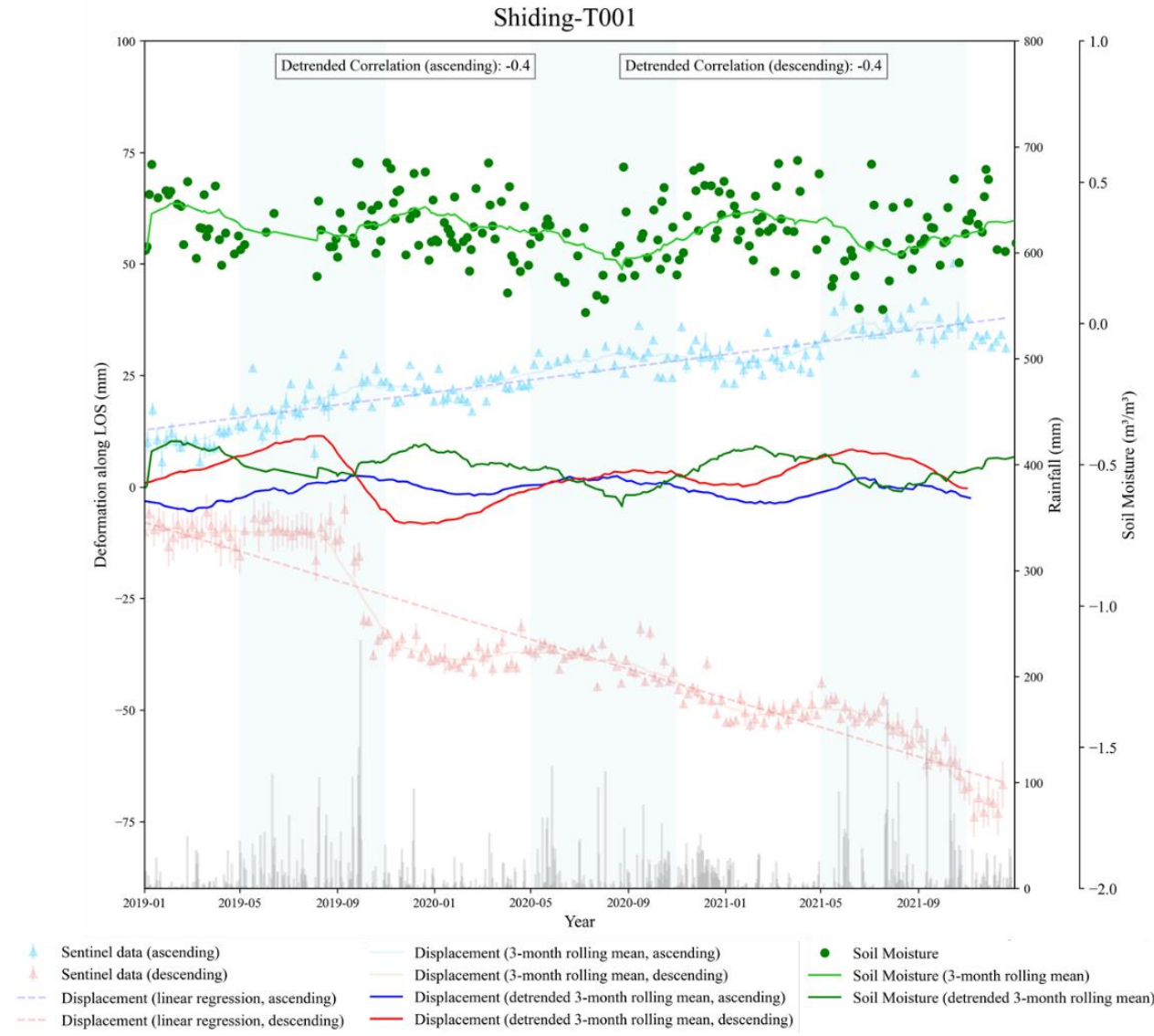
(Lu et al., 2026)

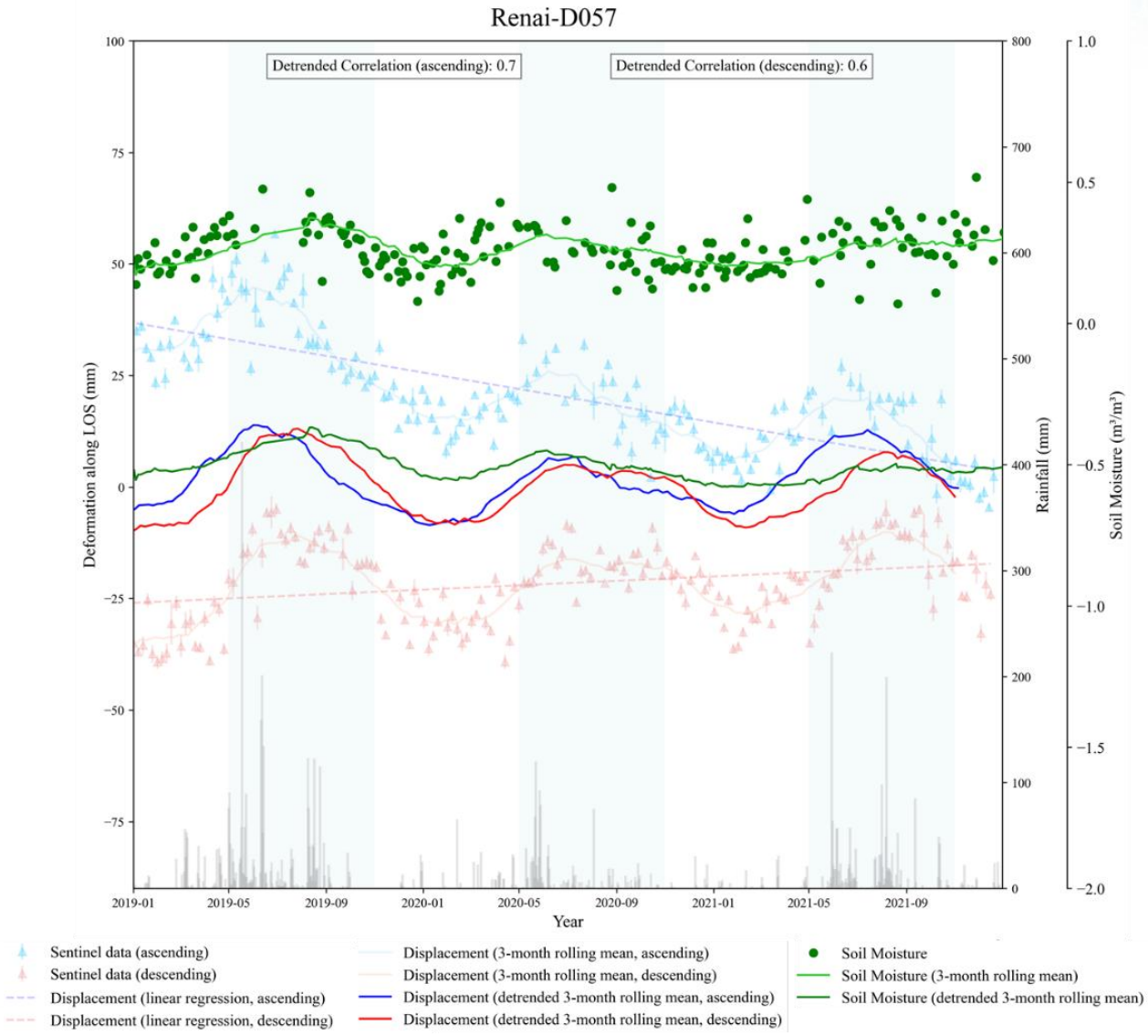


SMAP (Soil Moisture Active Passive)

- Launch time: January 2015
- Revisit time: 2–3 days
- Sensor:
  - L band radiometer
  - L-band radar (inoperable on July 7th, 2015)

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)