

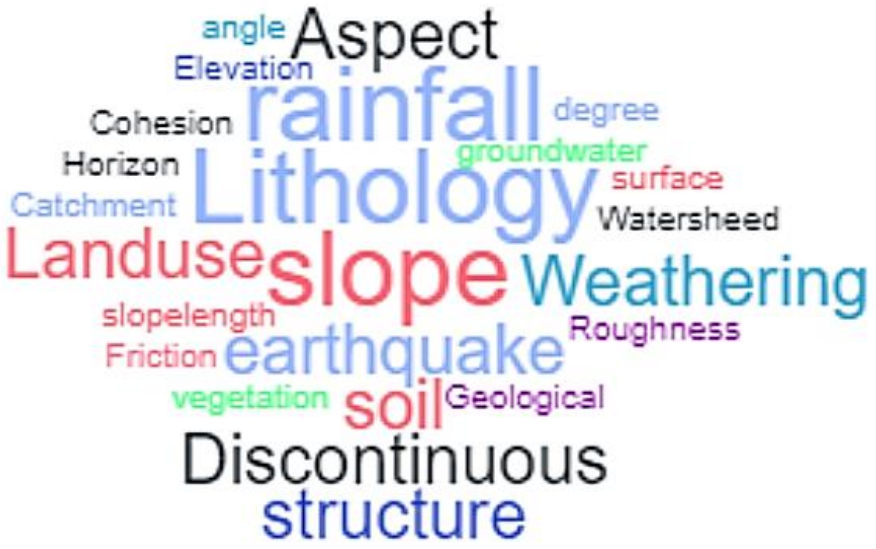
# 精進邊坡安全監測方法
# Ku波段地基合成孔徑雷達干涉


## 水保局技研小組
### 國立成功大學 衛星資訊研究中心

余騰鐸 主任　楊宇恩 博士生　蘇昱瑄碩士生　林彥均博士生

# 研究問題






**Intrinsic Factor**

- Soil
- Groundwater
- Vegetation
- Slope gradient
- Lithology, etc.

**Triggering Factor**

- Rainfall
- Volcanic eruptions
- Earthquakes, etc.

(Lu and Godt, 2013)



# 既有邊坡安全監測

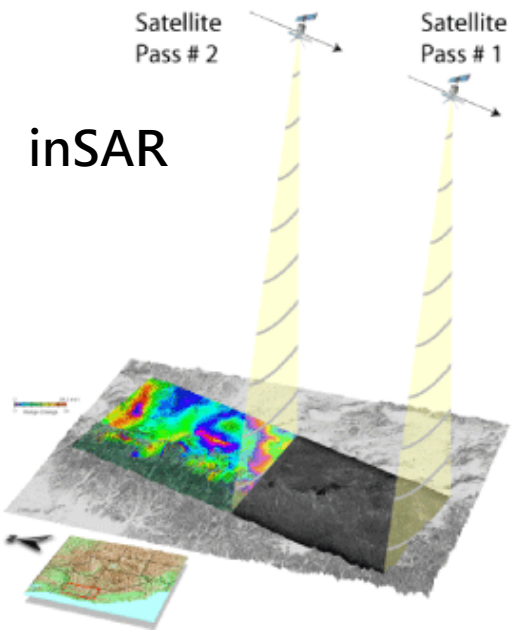
| 地表 | 地下 |
| --- | --- |
| 裂縫計 | 鑽探 |
| 地表伸張計 | 傾斜管 |
| 傾度盤 | 孔內伸縮計 |
| GPS | 傾斜儀 |
| Lidar | 地中變位儀 |
| inSAR | |





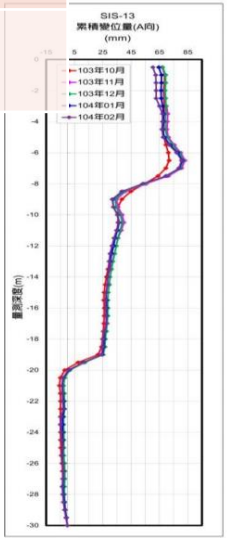


inSAR





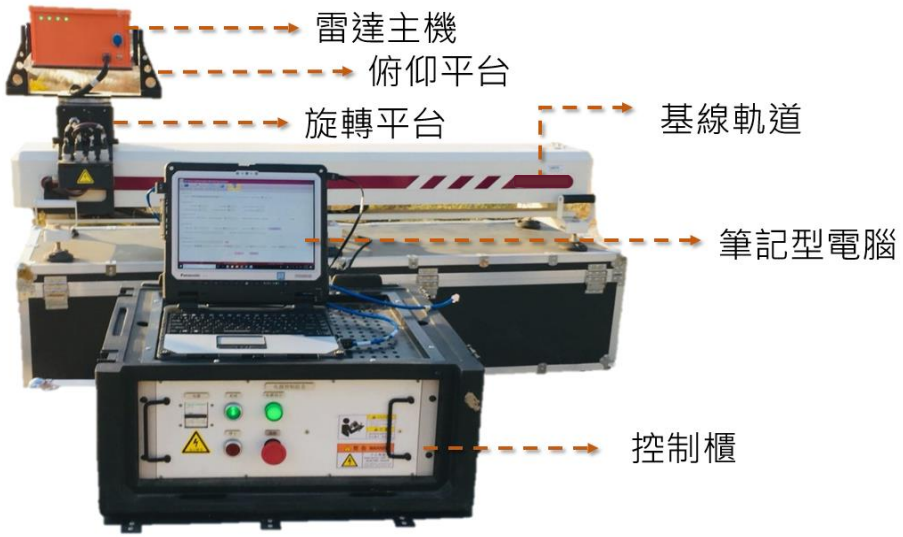







# GB SAR System

- Ground-Base SAR 地基合成孔徑雷達系統



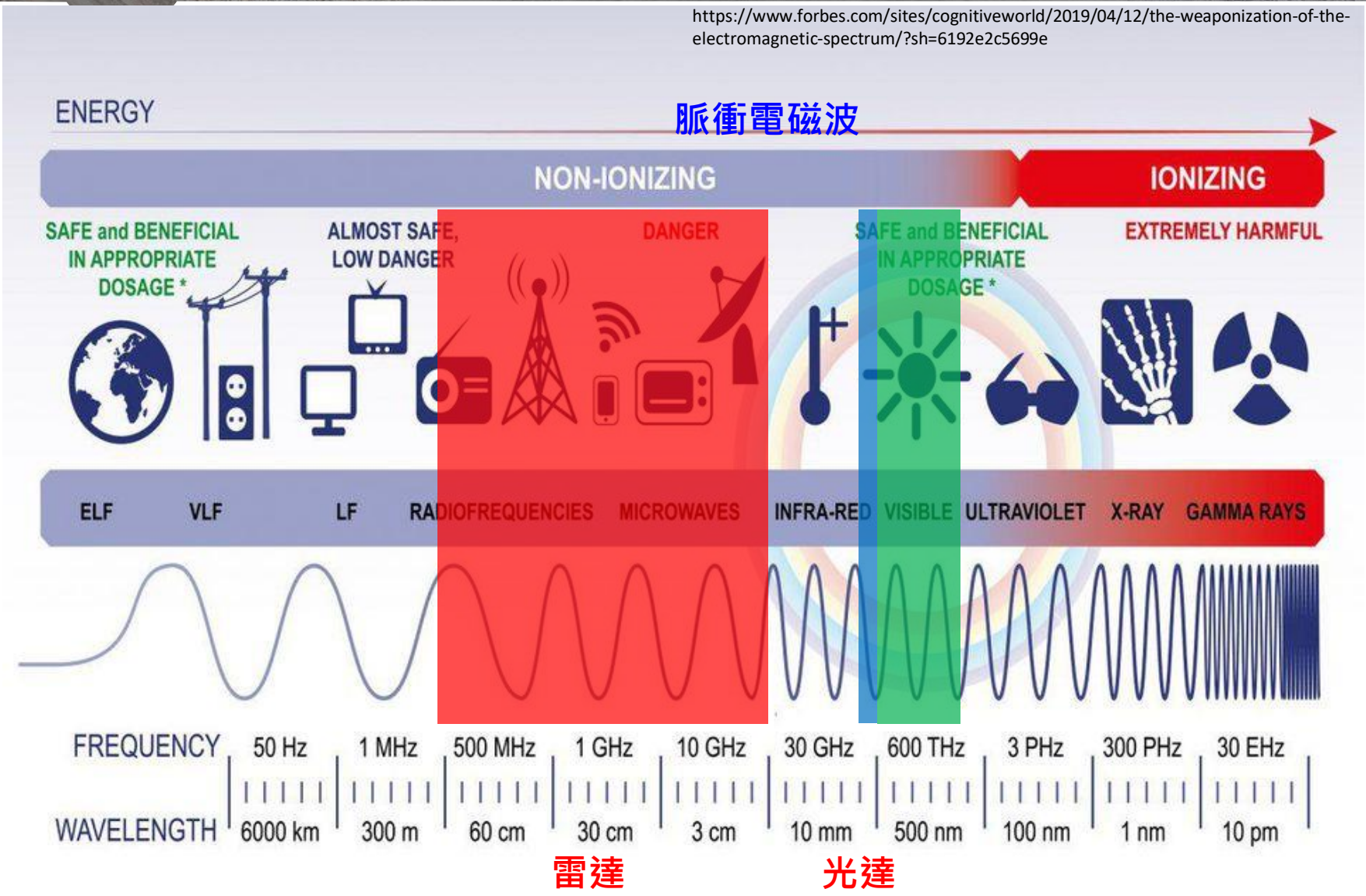

| 儀器參數 | |
|---|---|
| **Operating Frequency** | 17000-18000MHz (17.0 GHz-18.0 GHz) |
| **Bandwidth (Bw)** | 0 ~ 1000 (MHz) |
| **Pulse-width (Pw)** | 1 - 1000 (ms) |
| **Waveform** | FMCW |
| **Radar Rotation Angle** | 360° |
| **Polarization** | None |
| **Transmit Power** | 2 mW ~ 1 W |
| **Antenna Gain** | 0 - 30 dB |
| **Antenna Scanning Angle** | 18°(azimuth), 40°(elevation)<br>28°(azimuth), 18°(elevation) |
| **Radar Scanning Angle** | -30° ~ 30° |
| **Synthetic Length** | 1.6 m |
| **Scanning Distance** | 70 m - 4000 m |
| **Range Resolution** | 0.75 m - 0.15 m |
| **Cross Range Resolution** | 5.36 mrad |

| | |
|---|---|
| 波長 | Ku-band(約1.7cm) |
| 掃描距離 | 70m ~ 4,000m |
| 掃描週期 | <1 min |
| 掃描角度 | 360度 |
| 水平解析度 | 距離 70m 0.37m |
| | 距離2000m 10.72m |



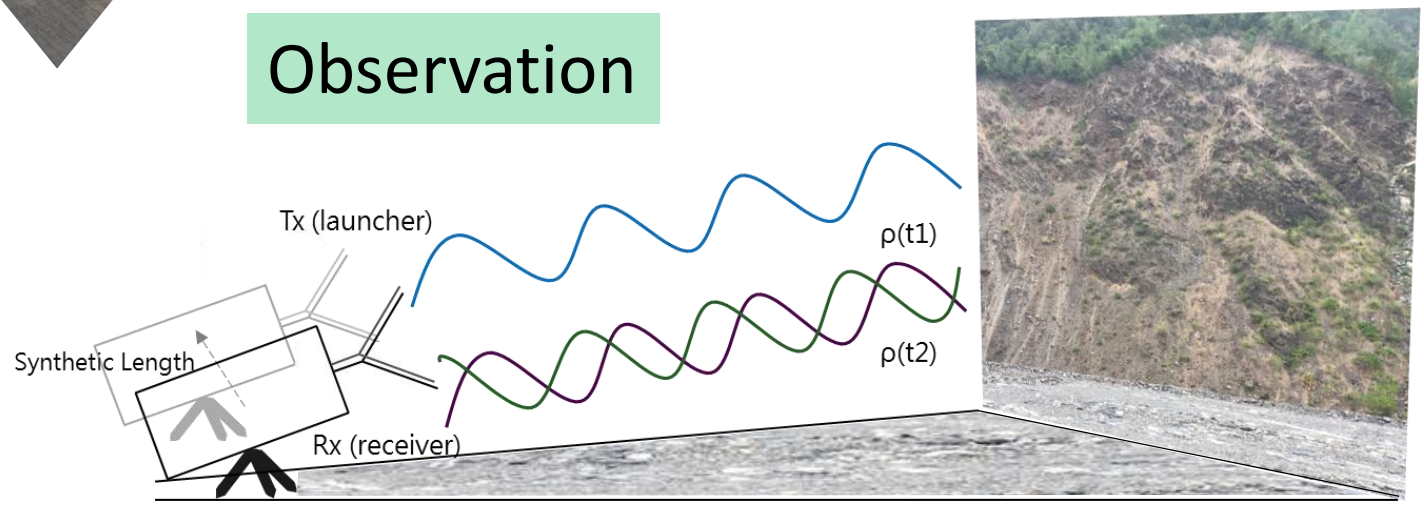
# Spectrum 光譜

https://www.forbes.com/sites/cognitiveworld/2019/04/12/the-weaponization-of-the-electromagnetic-spectrum/?sh=6192e2c5699e

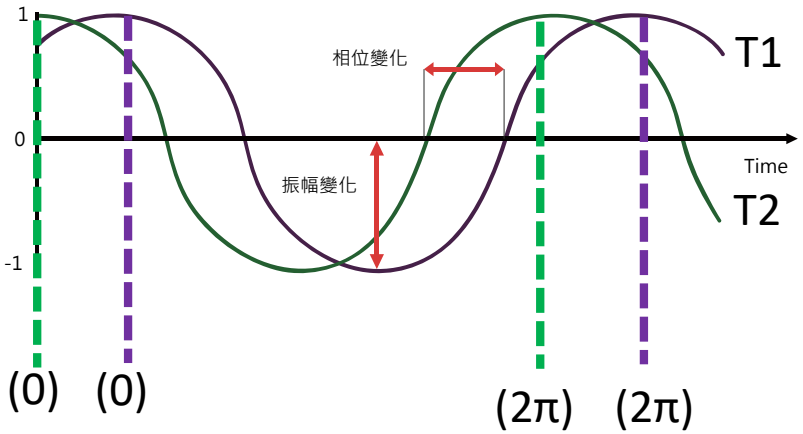


# DInSAR

## Observation




## Difference of phase




本研究採用Ku band (1.7cm)

## Displacement

$$\Delta\gamma = \frac{\Delta\varphi}{4\pi}\lambda$$

$\Delta\gamma$ = 變形量
$\Delta\varphi$ = 觀測相位差
$\lambda$ = 儀器波長

# Synthetic Aperture Radar

## Synthetic Aperture Radar ,SAR (合成孔徑雷達)

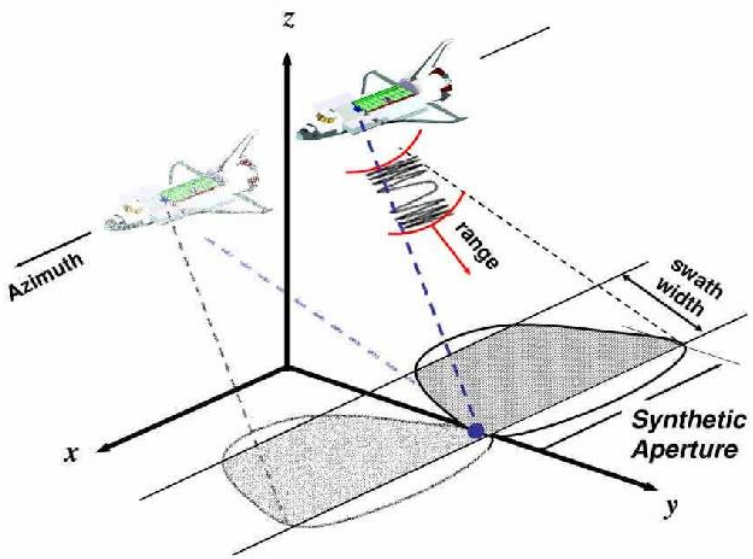
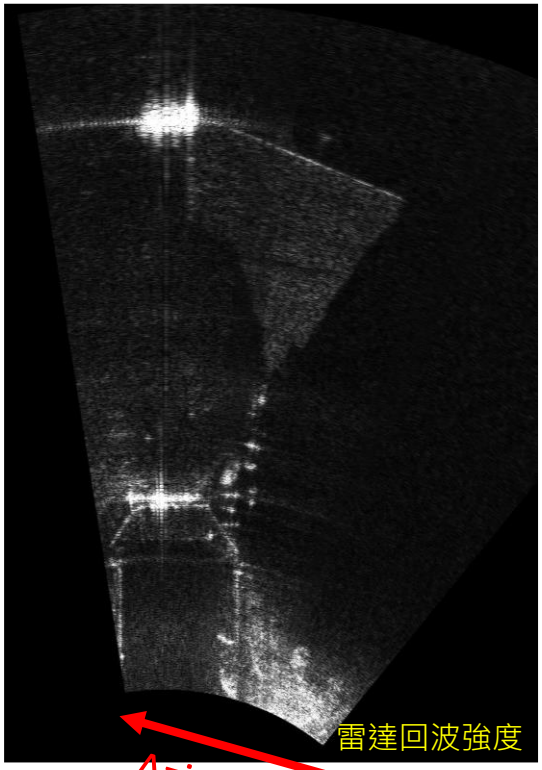



*Fig. 1 - Basic geometry for a Synthetic Aperture Radar*

Moreira, A., & Krieger, G. (2003, October).







曾文水庫大壩

# GB SAR




- **Range Resolution**
  視距方向解析度

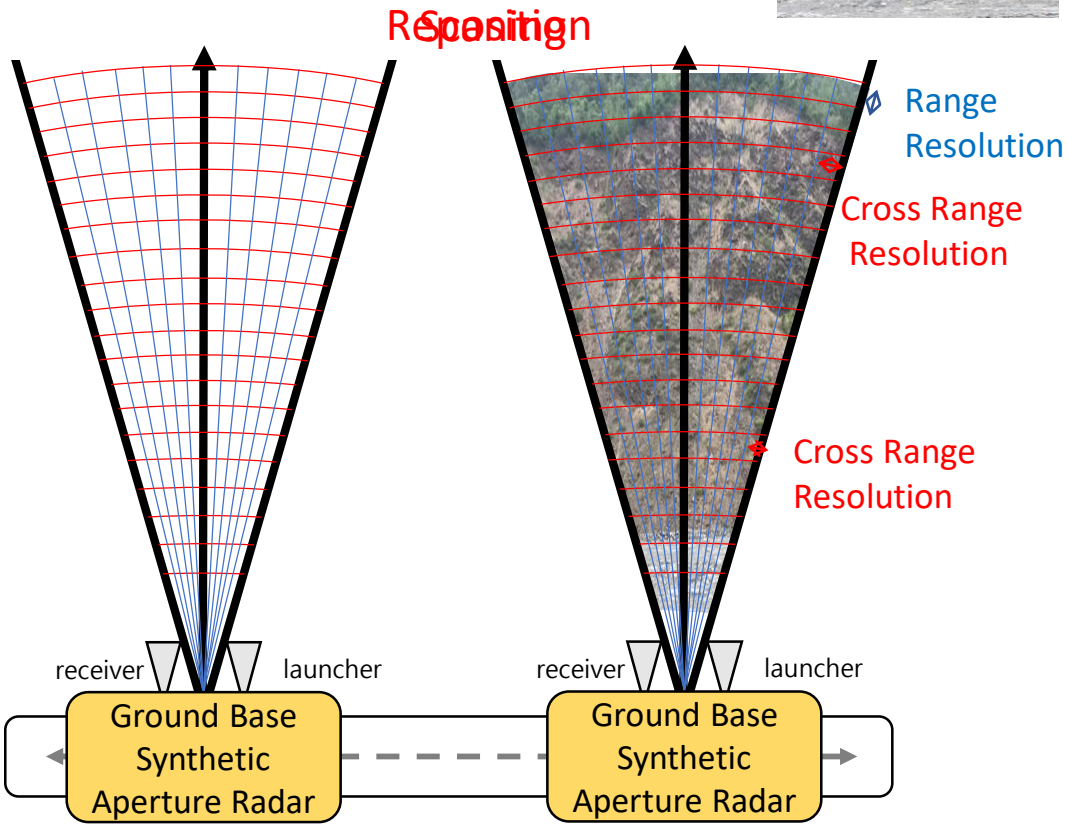
$$\Delta R = c/2Bw$$

C=光速 (299,792,458 m/s)
Bw=帶寬 (400 MHz、1000 MHz)
(調幅寬度)

- **Cross Range Resolution**
  水平方向解析度

$$\Delta CR = R\lambda/2L$$

R=目標物距離
λ=雷達波長 (0.017m)
L=基線軌道長度 (1.6m)




| | |
|---|---|
| 視距解析度 | 0.37m (帶寬400MHz) |
| 水平解析度 | 0.37m (目標距離 70m ) |
| | 10.72m (目標距離2000m ) |

# Coherence 同調性

## 計算方式

① 選取主影像(M)與副影像(S)

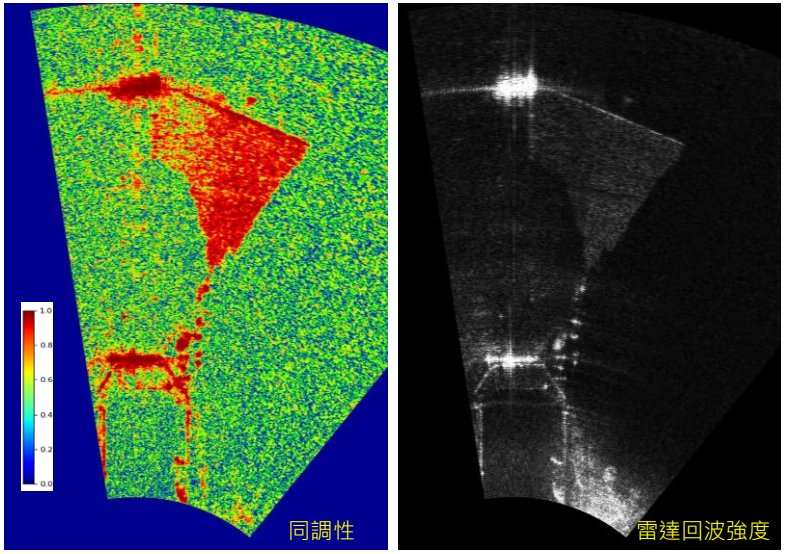
② 設定移動罩窗

③ 評估主/副影像同調性(相關分析)

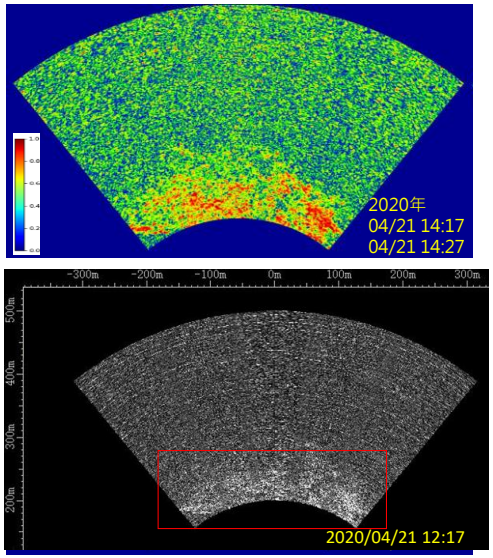
$$\gamma = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} M(i,j)S^{*}(i,j)}{\sqrt{\sum_{i=1}^{m}\sum_{j=1}^{n}\left|M(i,j)\right|^{2}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|S(i,j)\right|^{2}}}$$

M(i,j), S(i,j) 主/副影像局部像素

**曾文水庫大壩**




**來義崩塌地**



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Engineering Geology 68 (2003) 15–30

ENGINEERING GEOLOGY

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## Landslide monitoring by using ground-based SAR interferometry an example of application to the Tessina landslide in Italy

Dario Tarchi [a], Nicola Casagli [b,*], Riccardo Fanti [b], David D. Leva [a], Guido Luzi [c], Alessandro Pasuto [d], Massimiliano Pieraccini [c], Sandro Silvano [d]

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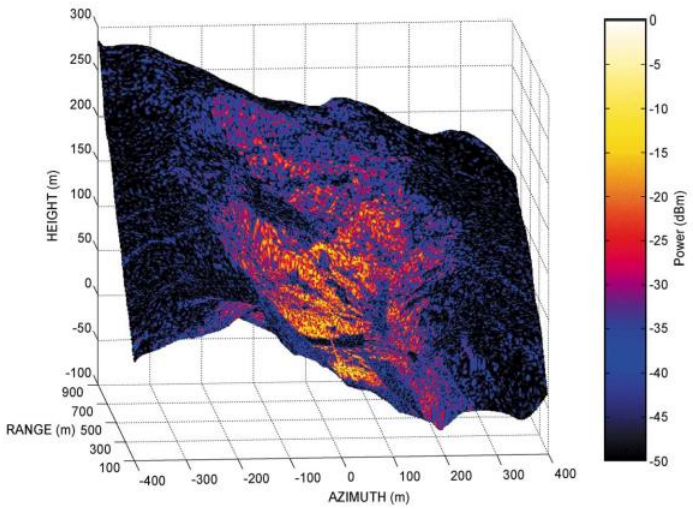
[d] *National Research Council, Institute for Hydro-geological Protection, Padua, Italy*

Received 7 January 2002; received in revised form 29 May 2002; accepted 8 July 2002





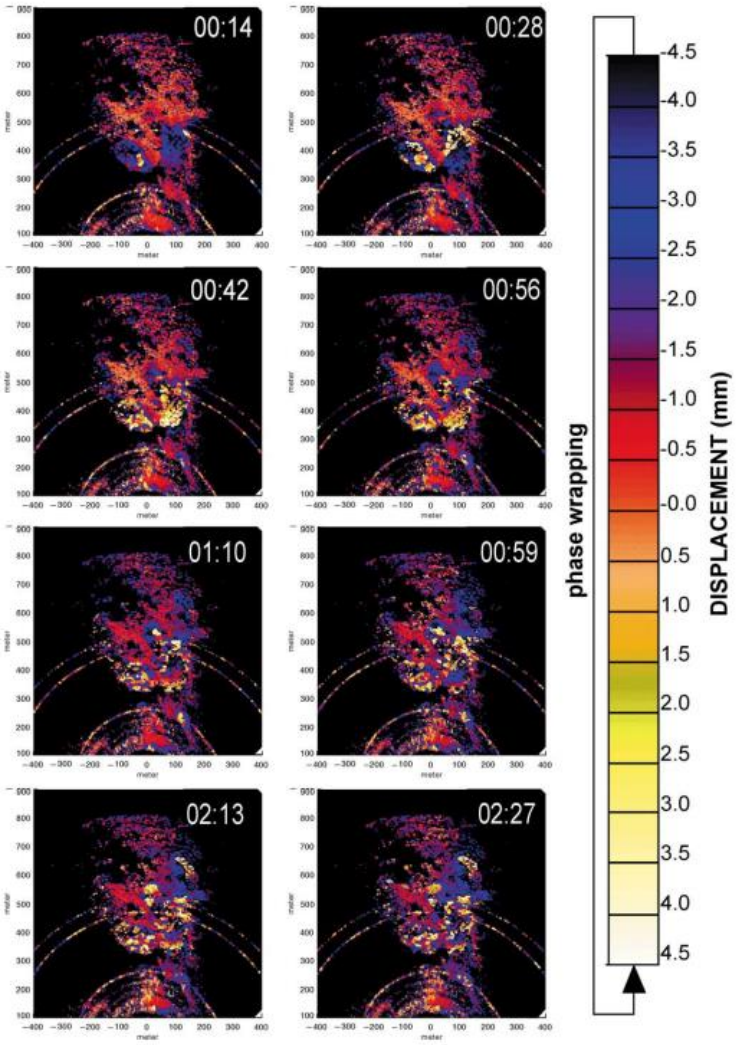




Fig. 7. Sequence of interferograms between the 00:00 and the 02:27 of the 05/10/2000. The time elapsed from the start of the se (reference image) is shown on the topright of each interferogram.

# 文獻回顧2

Nat. Hazards Earth Syst. Sci., 17, 845–860, 2017
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Natural Hazards and Earth System Sciences
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EGU

## GB-InSAR monitoring and observational method for landslide emergency management: the Montaguto earthflow (AV, Italy)

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Received: 23 October 2015 – Discussion started: 7 December 2015
Revised: 14 April 2017 – Accepted: 4 May 2017 – Published: 9 June 2017

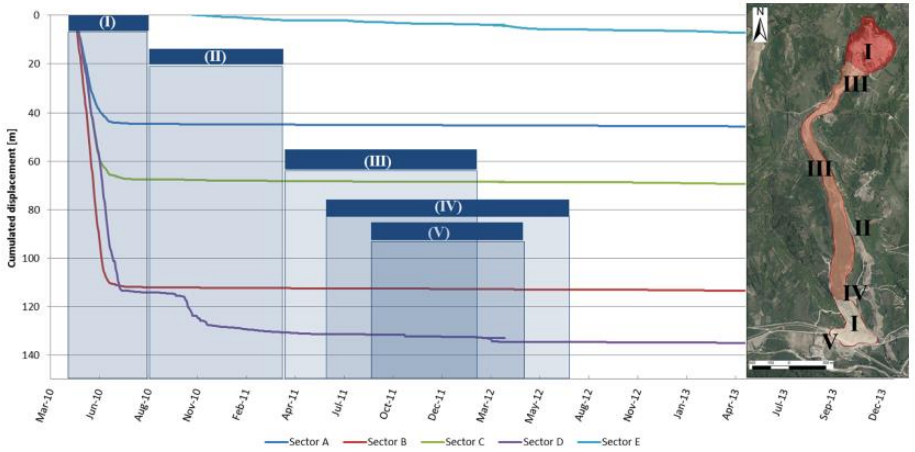



**Figure 10.** Displacement time series of representative points within the monitored sectors and verification of the efficiency of works with the time history of the velocity recorded at critical points: (I) drainage of the upstream and lower sector; (II) Rio Nocelle water channeling (Fig. 11, no. 7–10); (III) upper-medium sector works; (IV) medium-low sector works; and (V) toe sector works. See Fig. 11 for the stabilization works details and location.

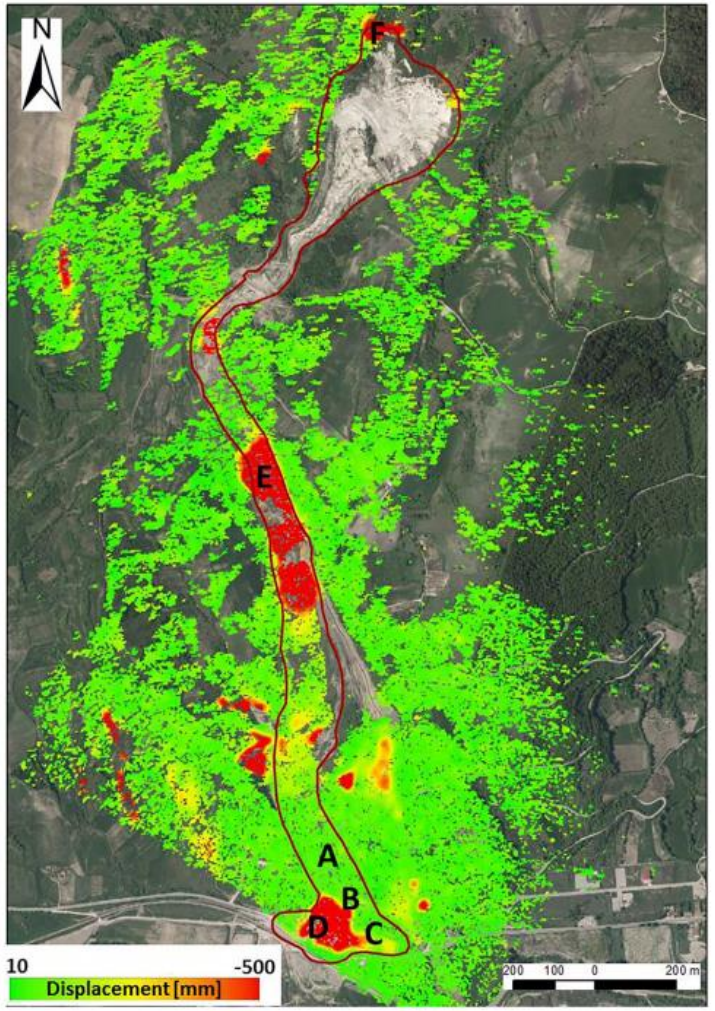
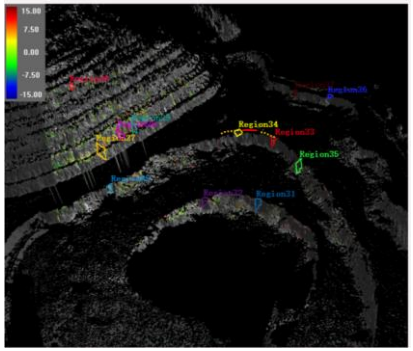
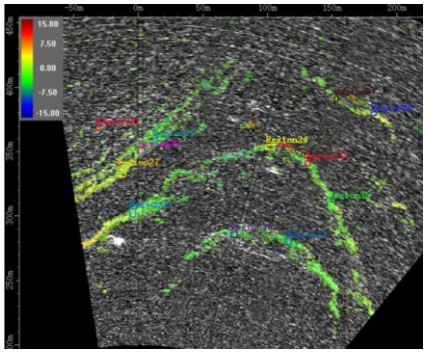



**Figure 7.** Monthly cumulated displacements (mm) map recorded between 1 and 31 March 2011. Negative values indicate movement towards the instrument.

# Method

| | |
|---|---|
| **Date &Time** | 2020 / 04 / 07　09:05 - 14:38 |
| **Number of observations** | 24 times |
| **Coherence Threshold** | 0.75 |
| **Blasting time** | 11:38 |
| **Operating Frequency** | 17000 MHz – 17400Mhz |
| **Bandwidth (Bw)** | 400MHz |
| **Pulse-width (Pw)** | 50 ms |
| **Antenna** | 18°(azimuth) |
| **Synthetic Length** | 1.6 m |
| **Radar Rotation Angle** | 90°、105°、120° |
| **Target distant** | 210 m – 500 m |
| **Observation Area** | About 10.5 ha |
| **Theoretical Maximum target distance** | 562 m |
| **spatial resolution (Cross Range)** | 200 m：1.07m；500 m：2.68m |
| **spatial resolution (Range)** | 0.37m |









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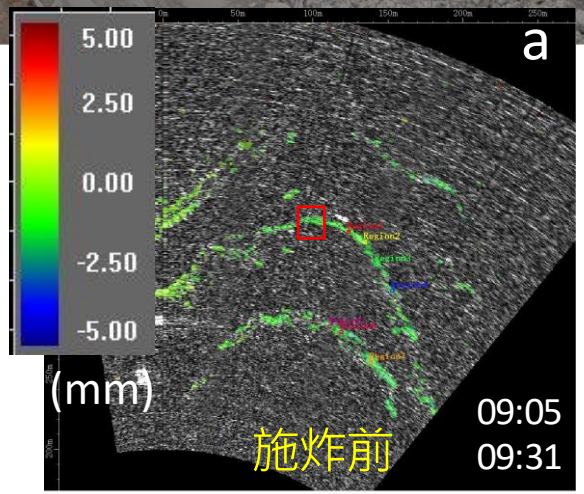
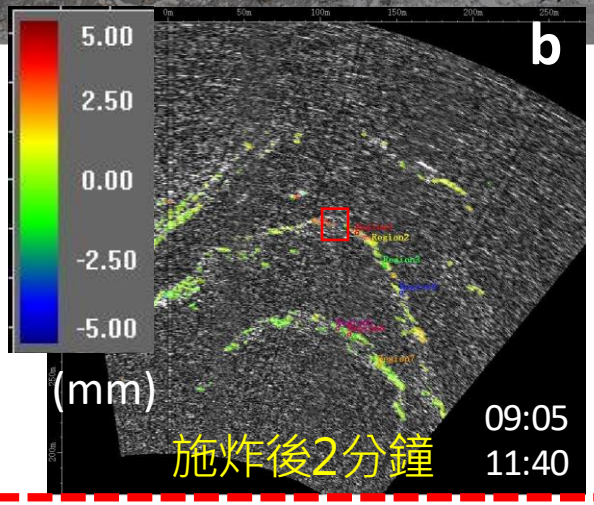
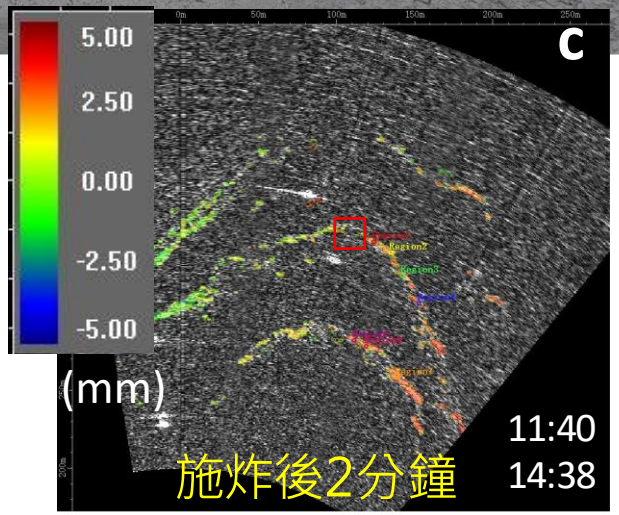
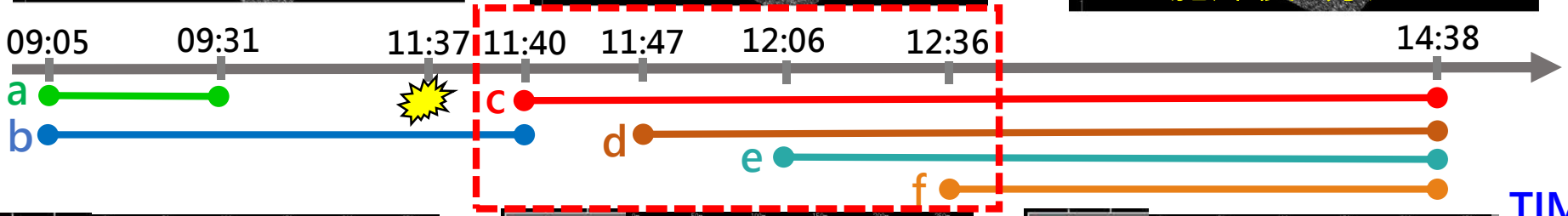
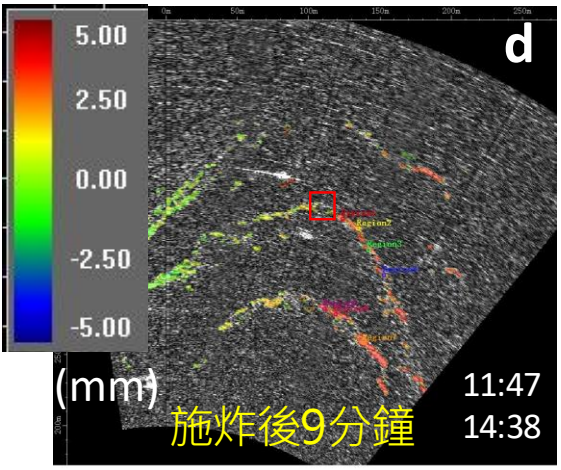
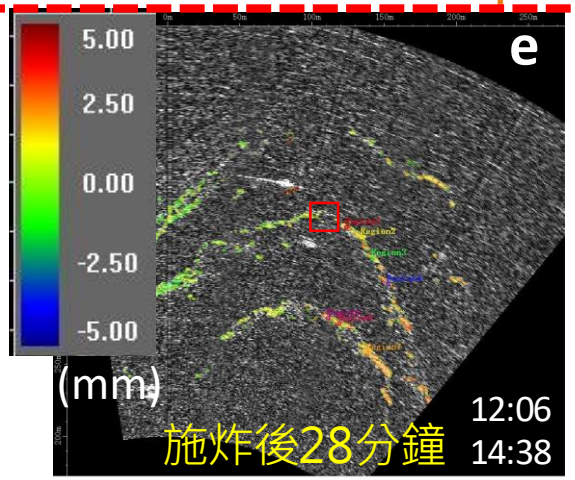

a
5.00
2.50
0.00
-2.50
-5.00
(mm)
施炸前
09:05
09:31

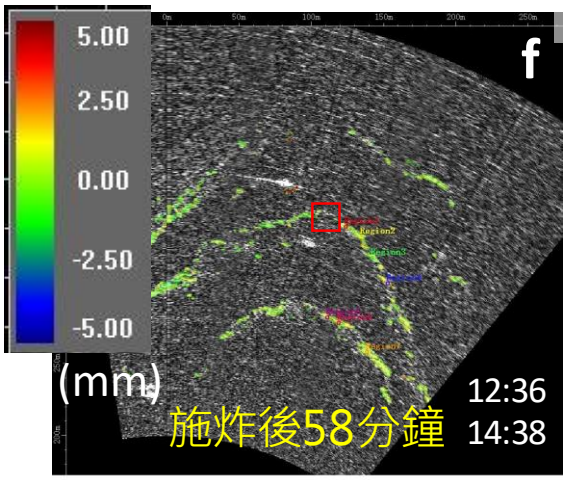

b
5.00
2.50
0.00
-2.50
-5.00
(mm)
施炸後2分鐘
09:05
11:40


c
5.00
2.50
0.00
-2.50
-5.00
(mm)
施炸後2分鐘
11:40
14:38

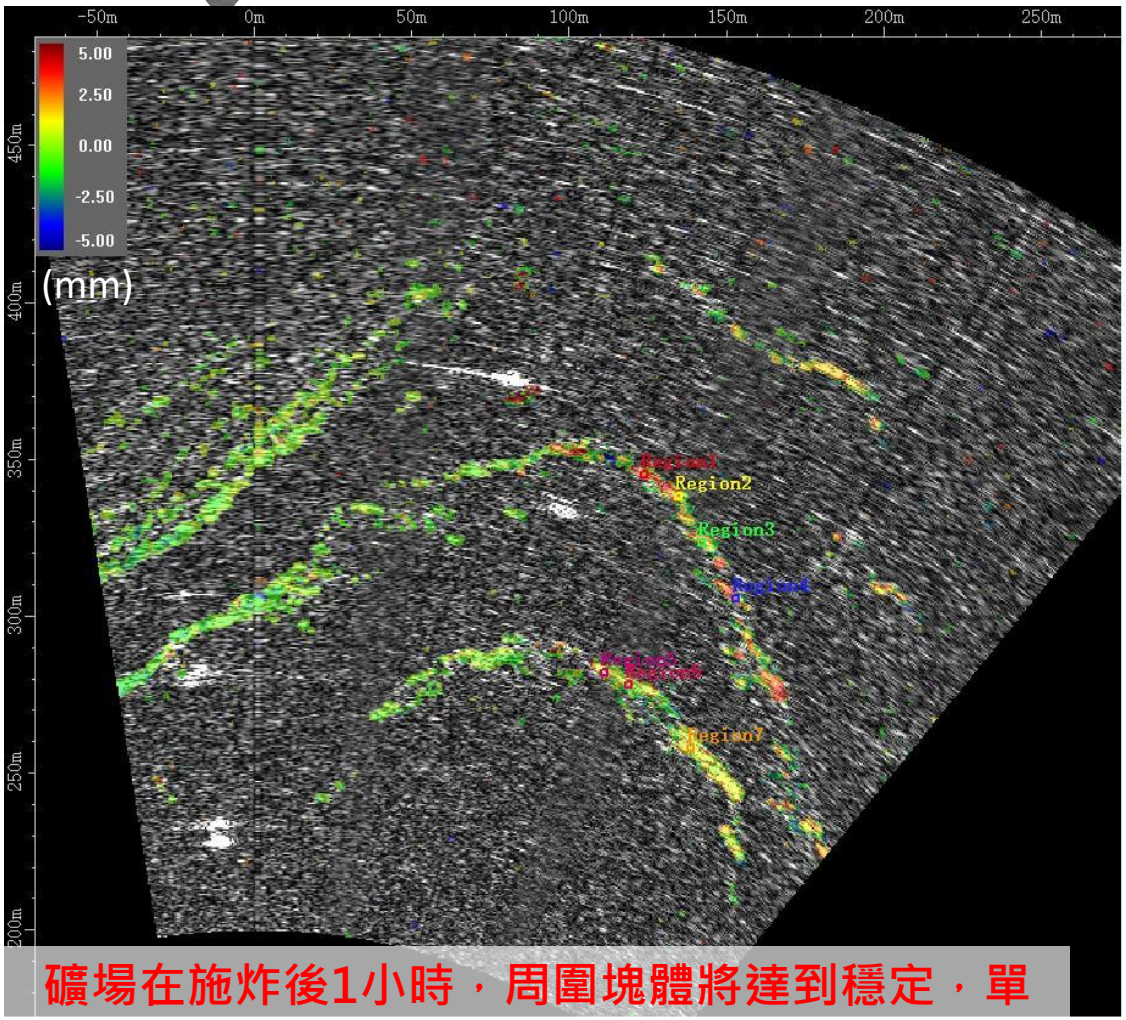

09:05
09:31
11:37
11:40
11:47
12:06
12:36
14:38
a
b
c
d
e
f
TIME


d
5.00
2.50
0.00
-2.50
-5.00
(mm)
施炸後9分鐘
11:47
14:38

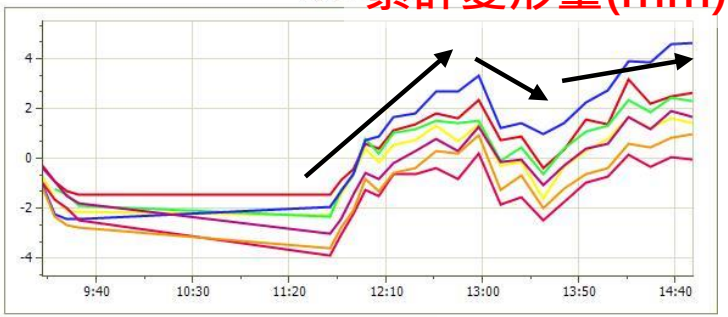

e
5.00
2.50
0.00
-2.50
-5.00
(mm)
施炸後28分鐘
12:06
14:38


f
5.00
2.50
0.00
-2.50
-5.00
(mm)
施炸後58分鐘
12:36
14:38

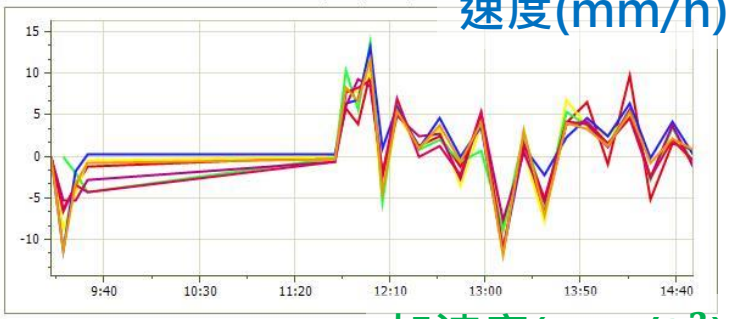
# Result




累計變形量(mm)




速度(mm/h)

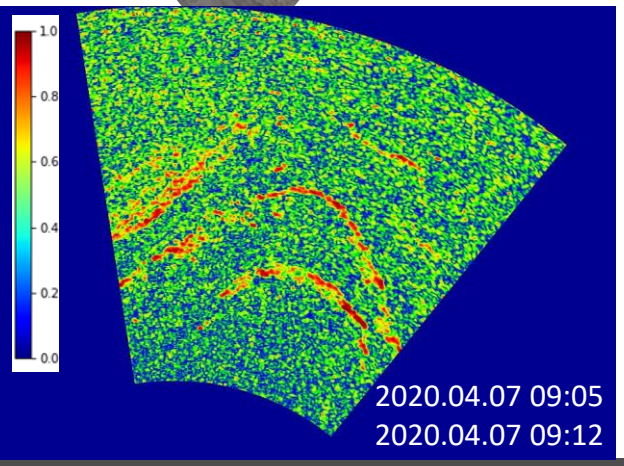


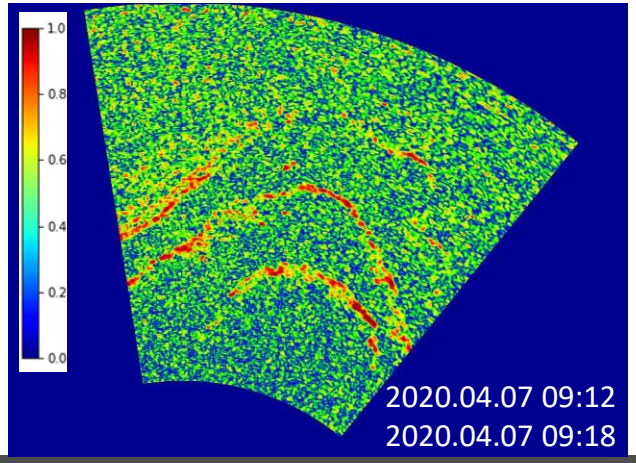

加速度(mm/$h^2$)

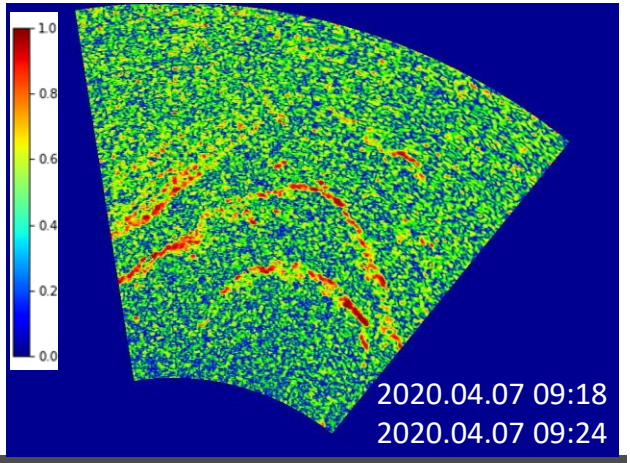



礦場在施炸後1小時，周圍塊體將達到穩定，單次施炸使得周圍累積位移量達2~4mm

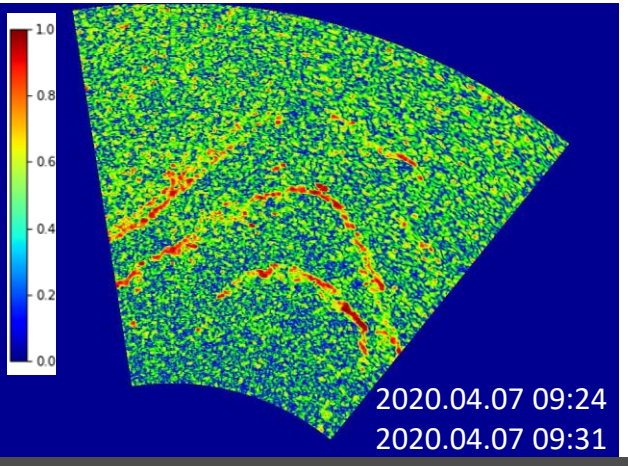
# Result

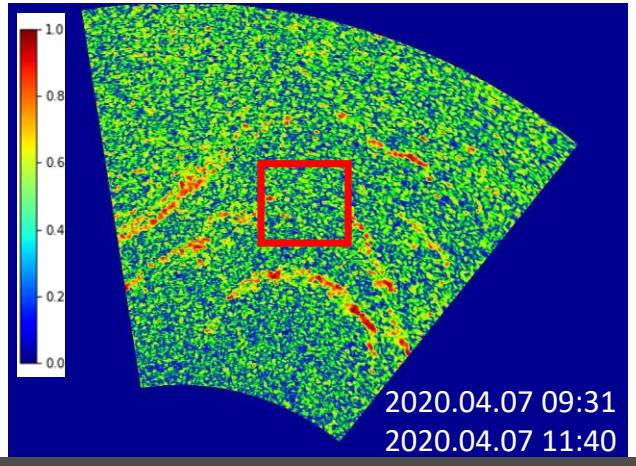


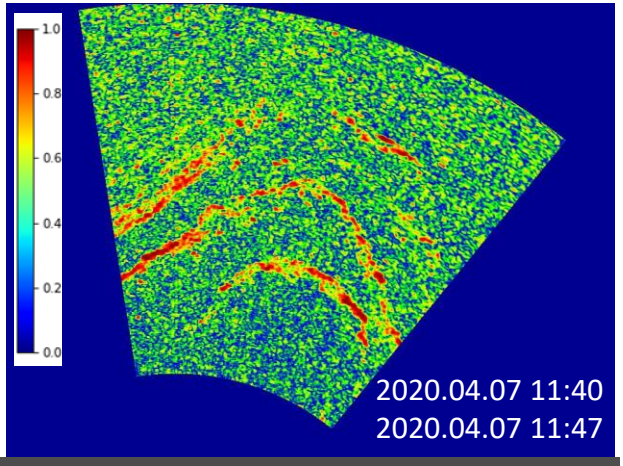




## 時序性同調性



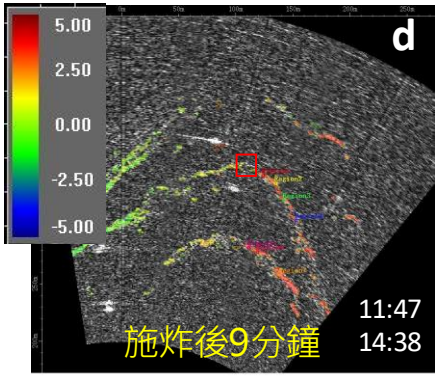

## 施炸前後同調性變化

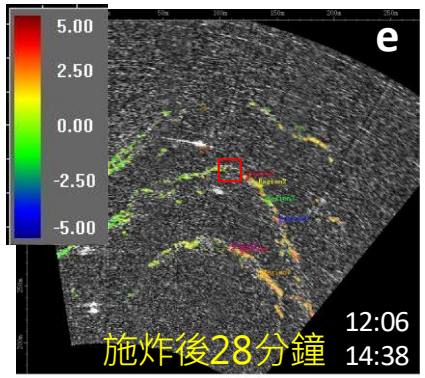
# Conclusions

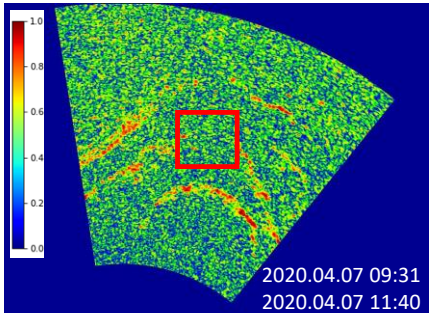
① 崩塌周圍累積**微變動**約在**4mm**。

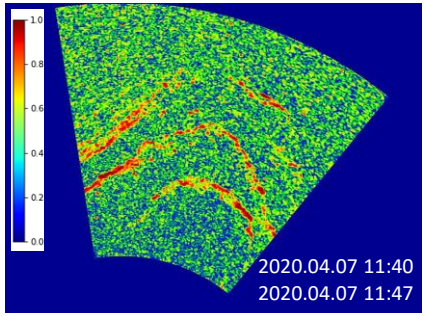
② 邊坡於施炸**30分鐘**後趨向穩定。

③ 既有研究於**微幅變動量計算**，但可以**時序同調性**作為即時監測參考。



# Limitation

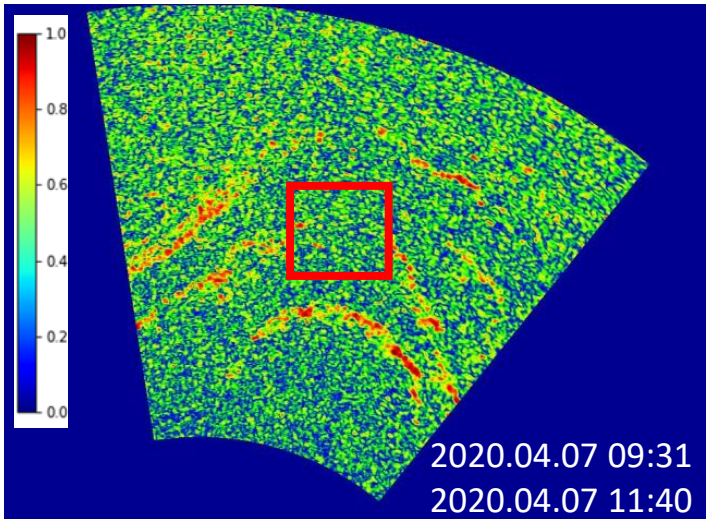
① 同調性低區域則無法計算微變形。 >>增加同調性

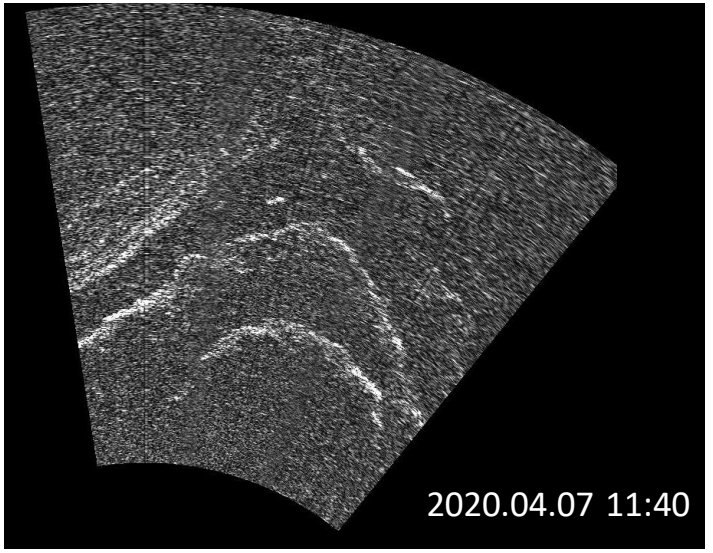
② 雷達與目標交角過小，回波強度不足。 >>增加發射強度

③ 目標物材質反射率低，回波強度不足 。 >>增加回波強度



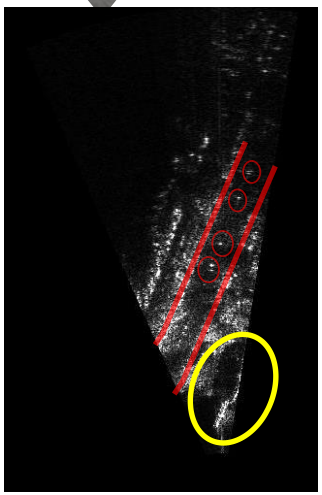

Threshold > 75

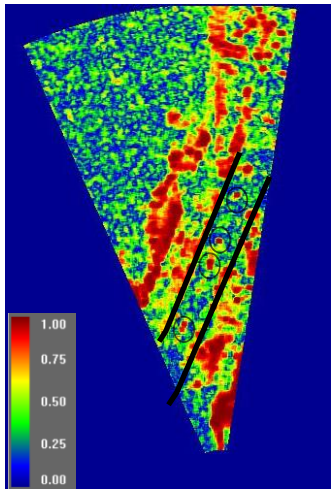


# Farther

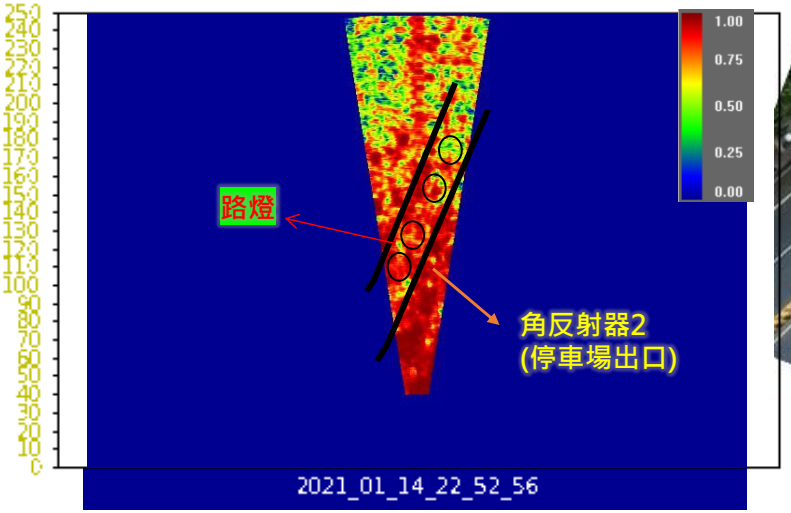
## 路面沈陷監測

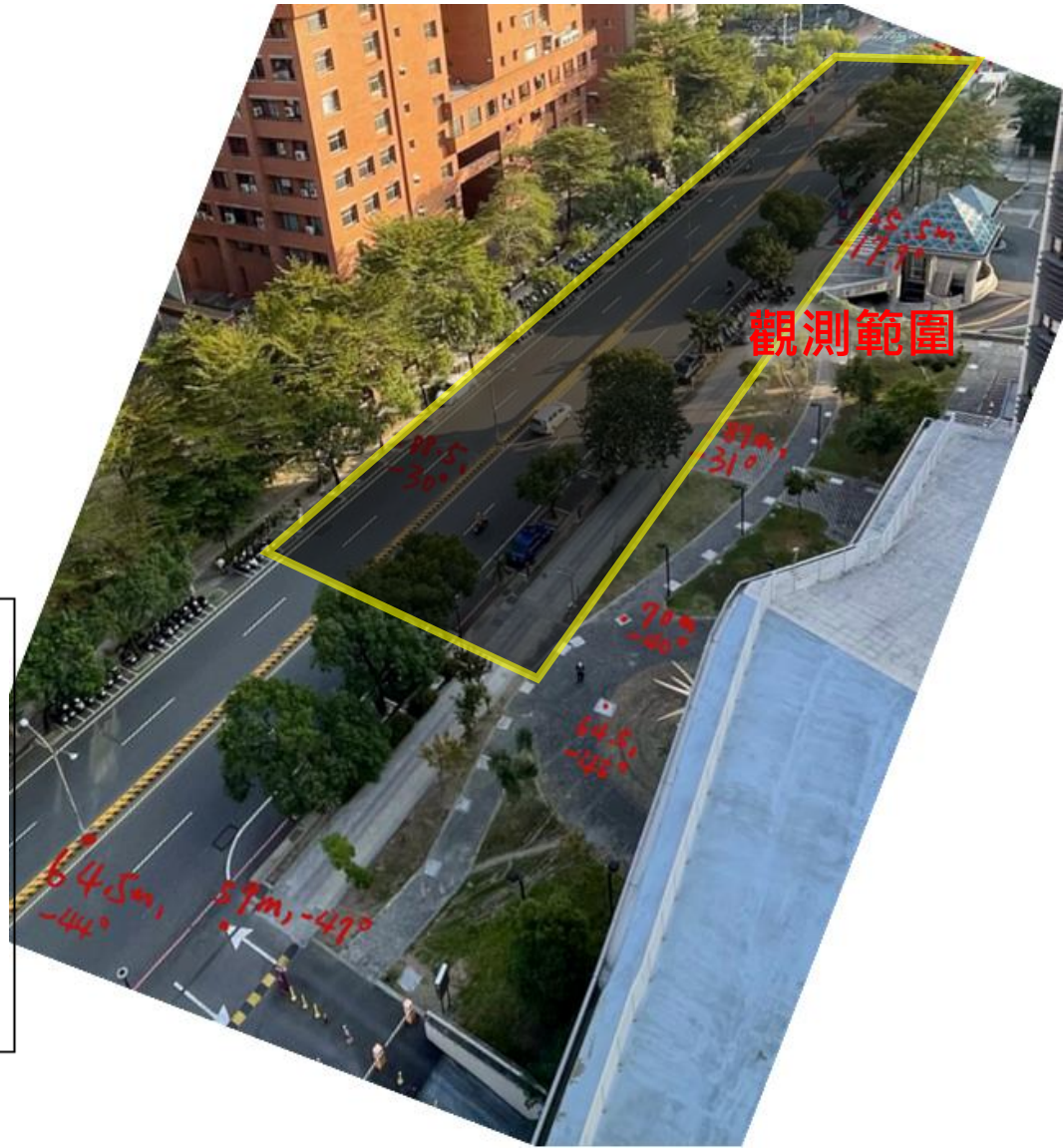




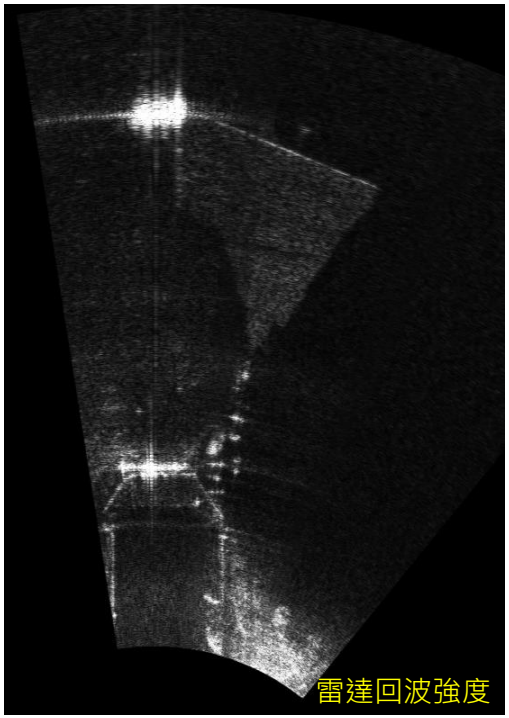

狀況：掃描過程持續有車經過

過濾無車的情況



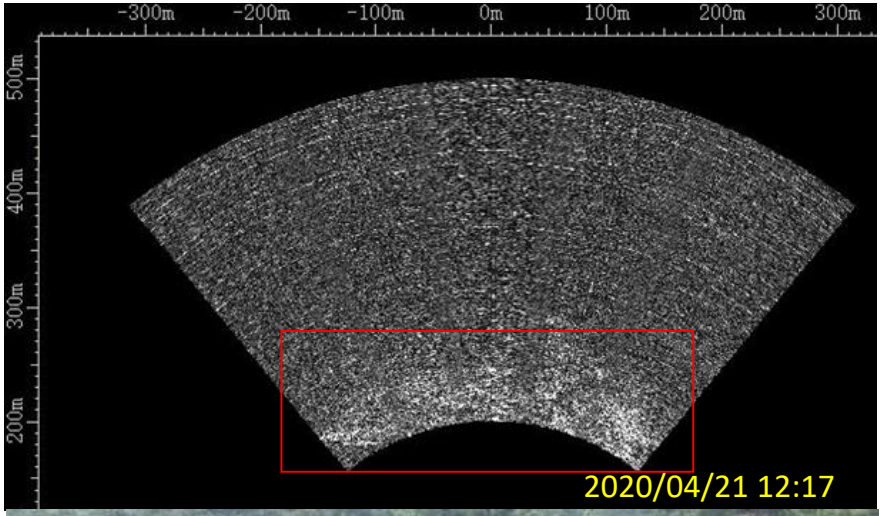



# Farther











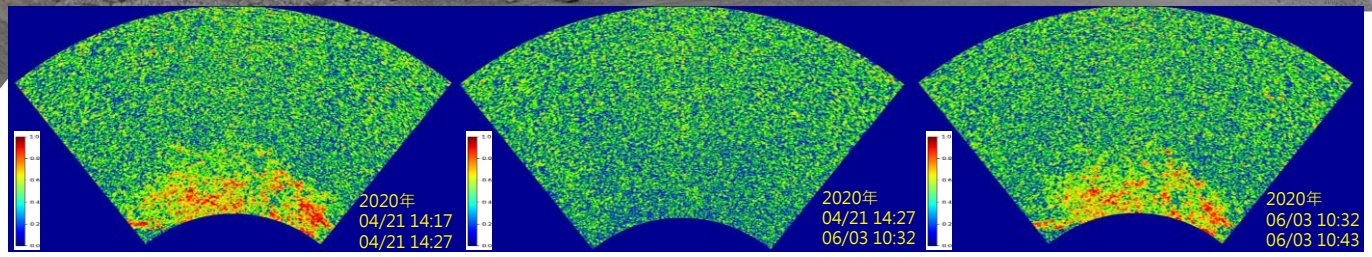


人工構造物

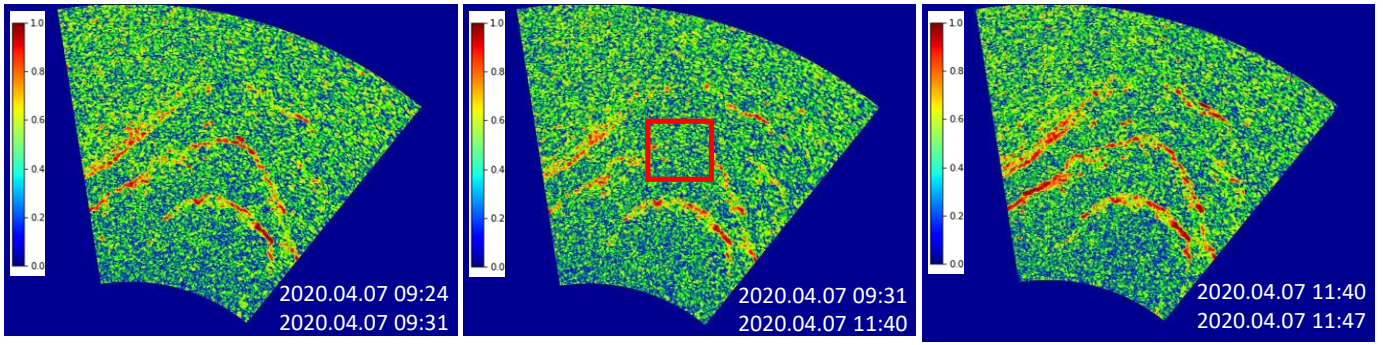
自然邊坡

地表覆蓋物(材質)、角度(天線與目標物)影響為主!

# Farther



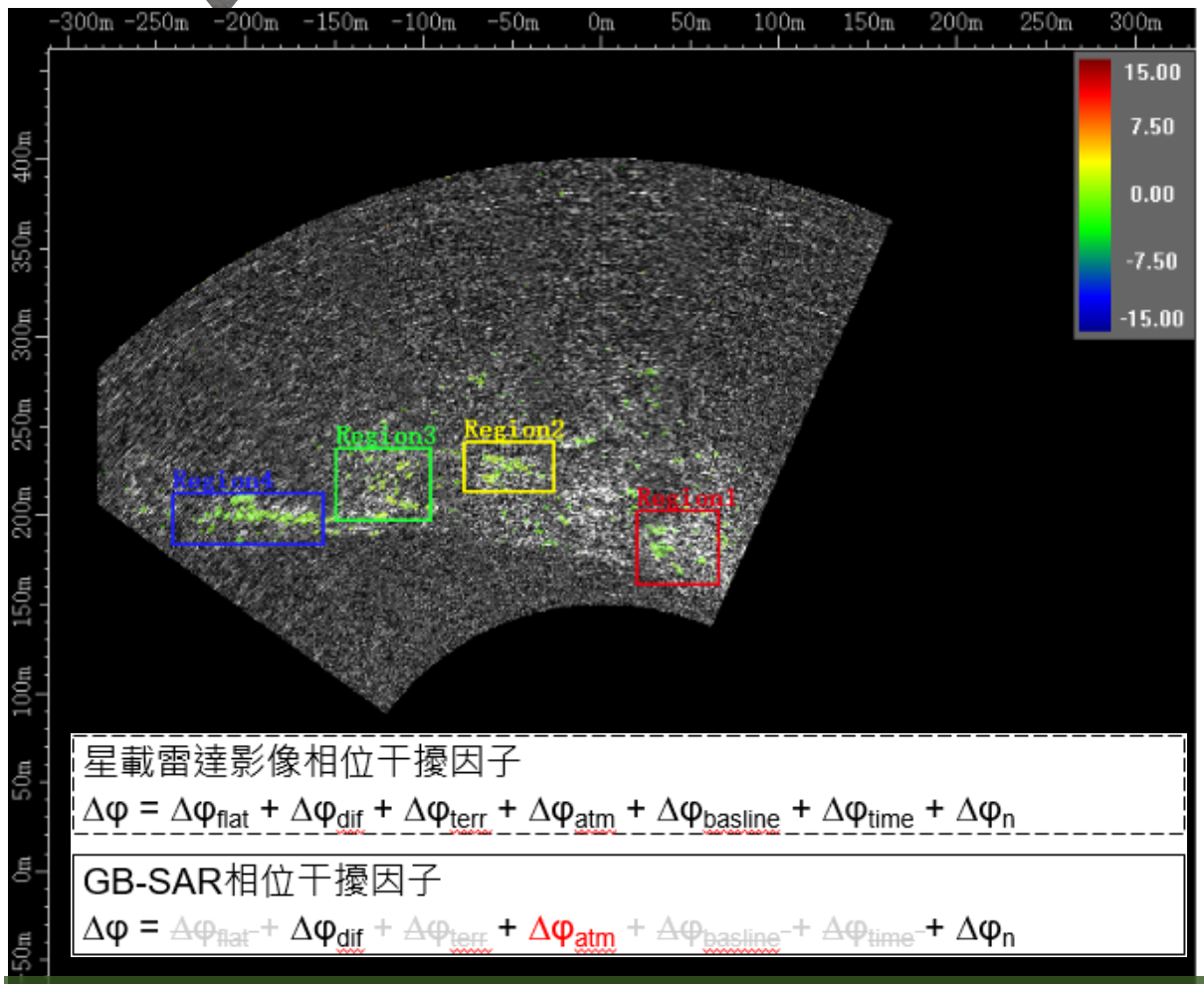

非連續性觀測同調性成果(來義)




連續性觀測失去同調性成果(某礦場)

## 時序同調性分析

# Farther

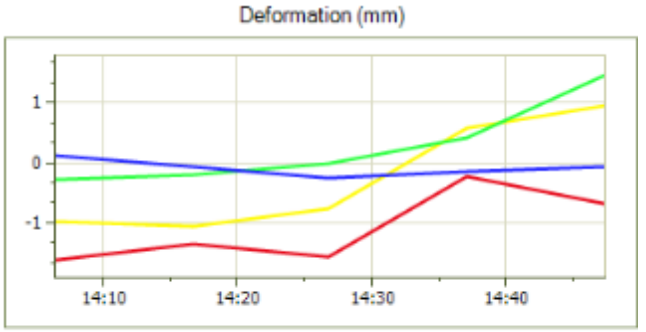


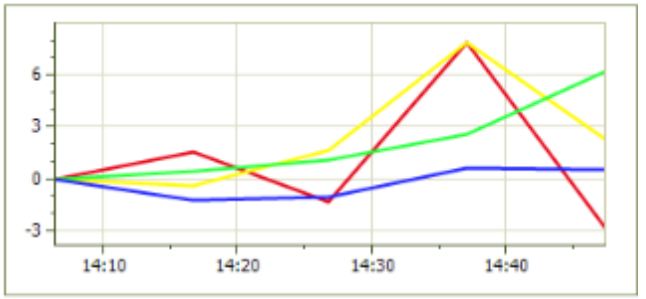

星載雷達影像相位干擾因子

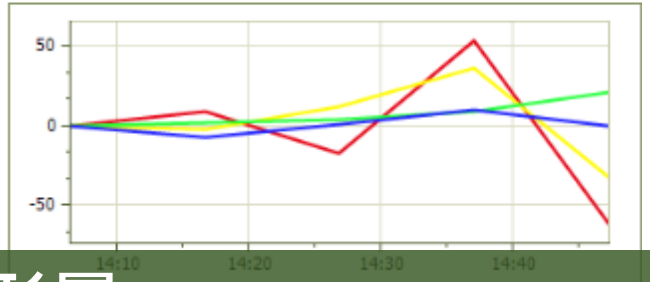
$\Delta\varphi = \Delta\varphi_{flat} + \Delta\varphi_{dif} + \Delta\varphi_{terr} + \Delta\varphi_{atm} + \Delta\varphi_{basline} + \Delta\varphi_{time} + \Delta\varphi_{n}$

GB-SAR相位干擾因子

$\Delta\varphi = \Delta\varphi_{flat} + \Delta\varphi_{dif} + \Delta\varphi_{terr} + \Delta\varphi_{atm} + \Delta\varphi_{basline} + \Delta\varphi_{time} + \Delta\varphi_{n}$



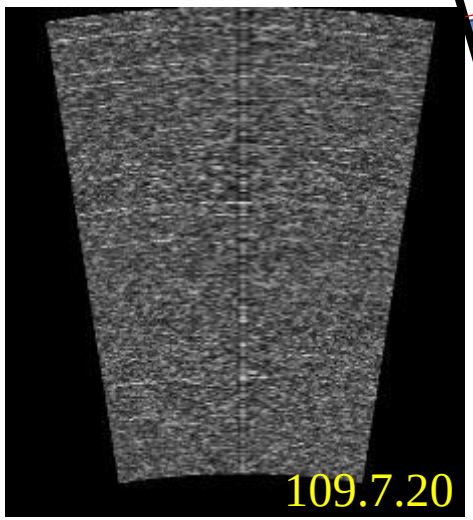




## 大氣誤差影響之微變形量

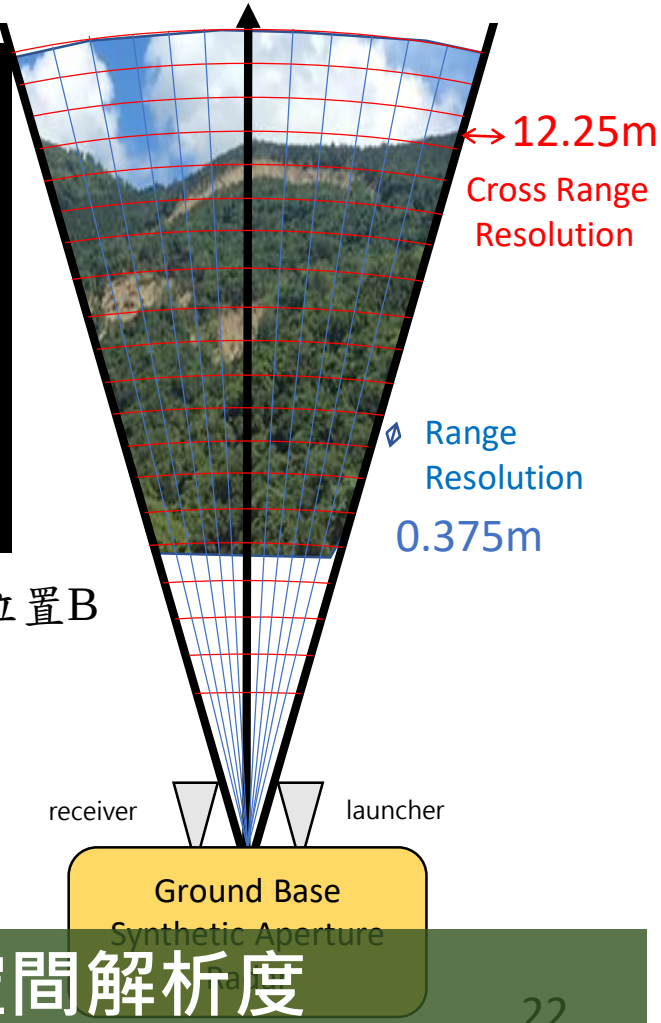
# Farther




Google Map (2020)




舞鶴研究區儀器擺設位置B




**強反射範圍需要至少大於空間解析度**

# 1.2 動機

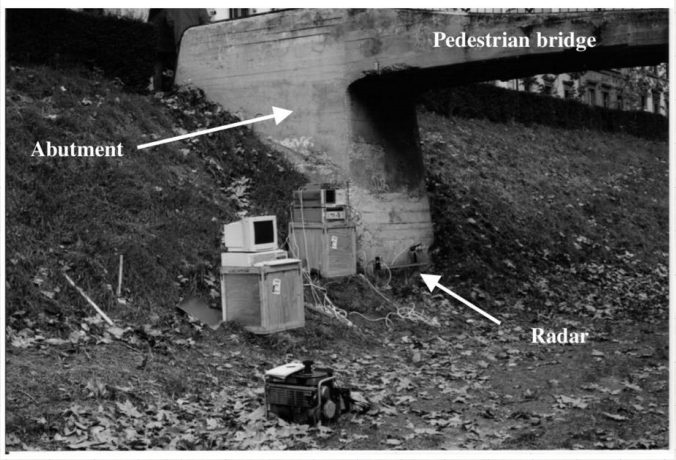
- GBSAR所使用的波長不只影響位移精度，還對植生區域的穿透率影響甚大。
- Ku band精度達毫米等級，但在台灣山區植生廣泛，限制其應用。

# 2 文獻回顧

## 2.1 地基合成孔徑雷達發展及應用

Tarchi, et al.，2000
首次提出利用地基干涉技術來監測建築物，這種非侵入式且大規模的變形監測技術，在義大利當地文化遺產古蹟眾多之下，其發展令人期待。





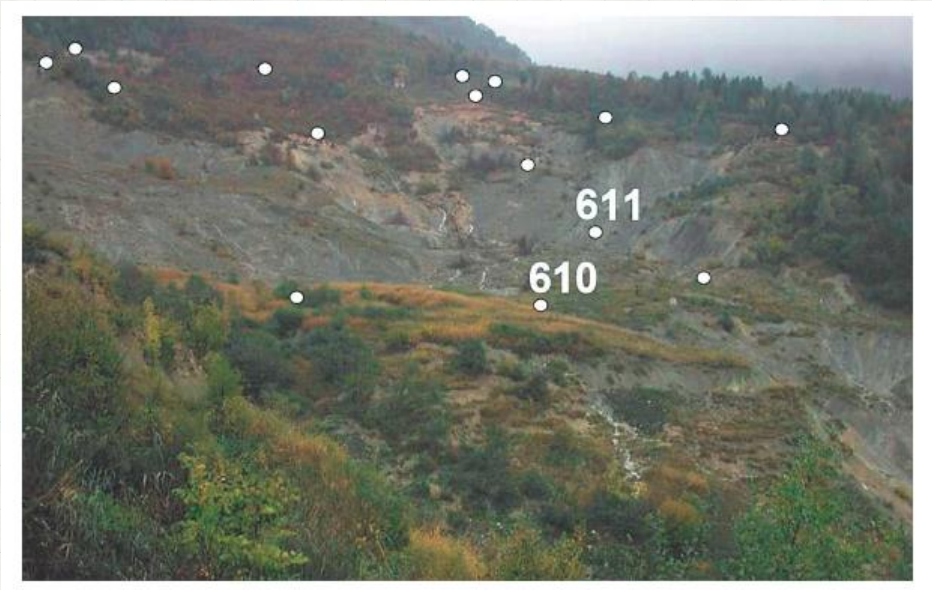

Pieraccini,et al.，2000
對橋樑進行靜態測試。推動政府對此項技術注重。

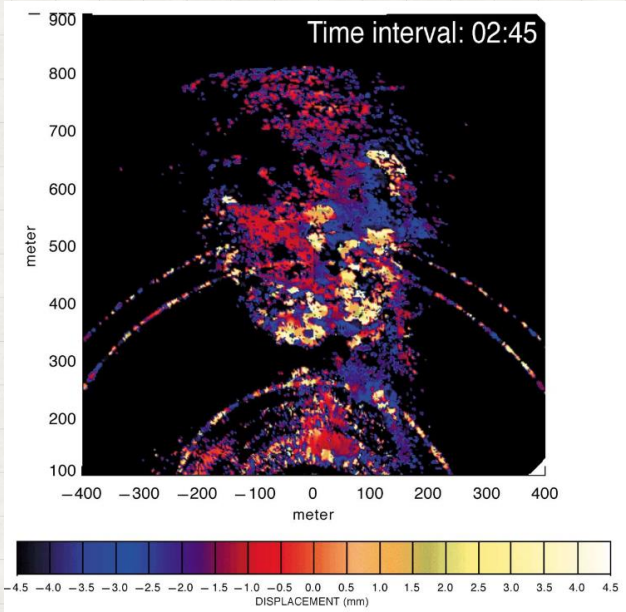
# 2 文獻回顧

## 2.1 地基合成孔徑雷達發展及應用

Tarchi, et al.，2003

首次對於滑坡進行監測，也比較地基合成孔徑雷達與當時常規的變形測量工具結果，驗證GBSAR對於滑波監測是有效的工具。

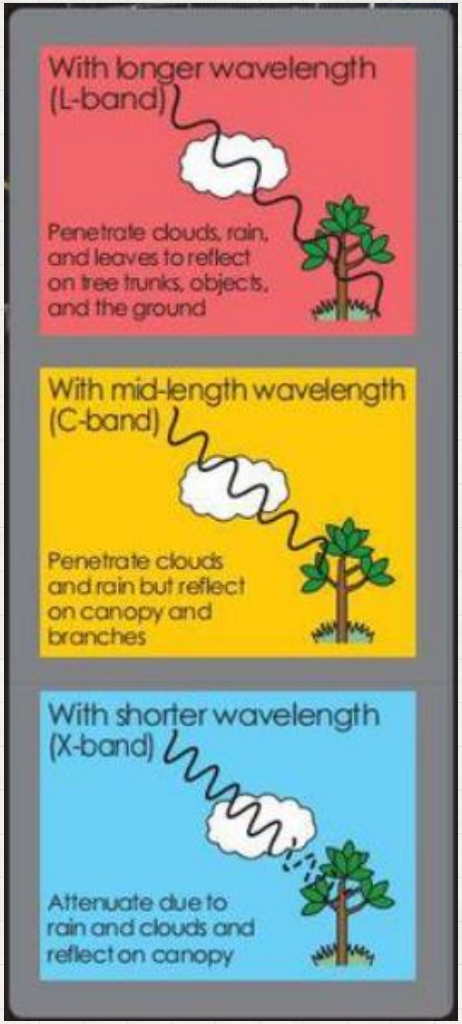


# 2.2 植生區域對各波段之影響

| 頻段 | 頻率(GHz) | 波長(cm) |
|---|---|---|
| Ka | 27-40 | 1.1-0.8 |
| K | 18-27 | 1.7-1.1 |
| Ku | 12-18 | 2.4-1.7 |
| X | 8-12 | 3.8-2.4 |
| C | 4-8 | 7.5-3.8 |
| L | 1-2 | 30-15 |
| P | 0.3-1 | 100-30 |

- 各頻率波段波長列表

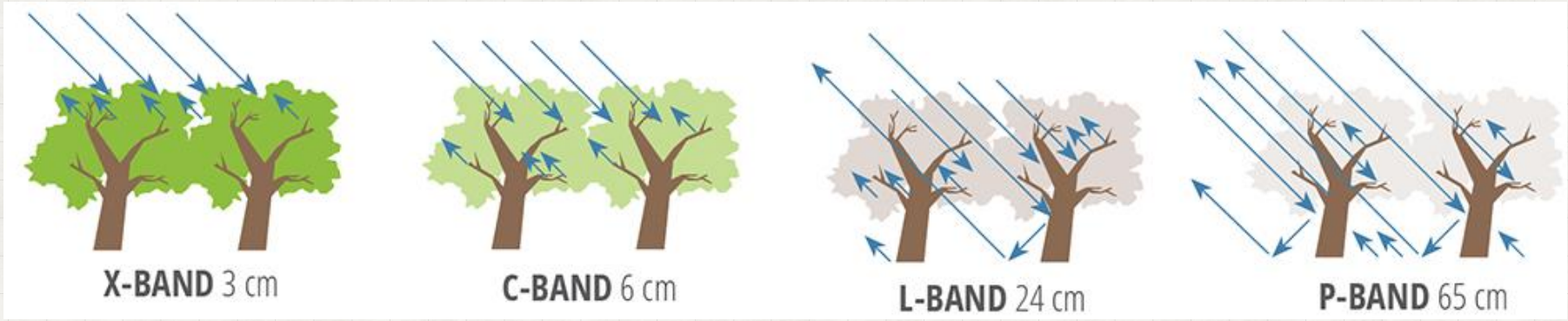


# 2 文獻回顧

## 2.2 植生區域對各波段之影響

Askne, et al.,1997

- 雷達系統中不同波段的雷達波束，其對目標物的穿透程度也不一樣。
- X 或 K 等短波波段穿透力較弱，在植物頂層就會被反射回去，較適合用來對樹梢或樹葉的探測上。
- L 或 P 等長波波段穿透力較強，可穿透樹林濃密的樹葉而探測到樹枝或樹幹。
- 介於中間波段 C 波段，則可提供到目標物表面或目標物下的資訊。

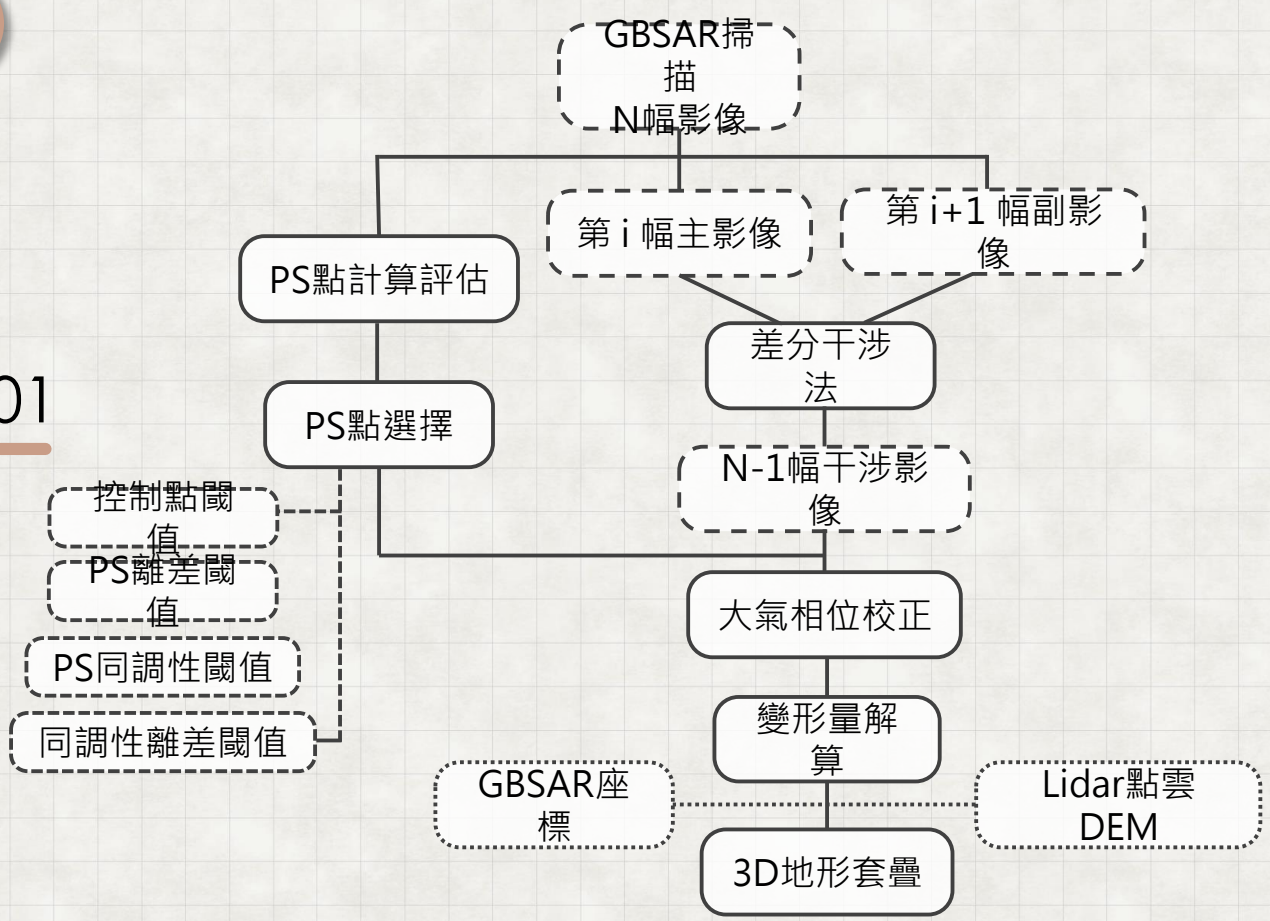



- NASA Earth Data

# 3 研究區域與方法

## 3.1研究工具

GBInSAR_chsck01




• GBInSAR_chsck01工作流程圖

# 3 研究區域與方法

## 3.2實驗流程與結果



• 資源系館五樓儀器擺放位置視野







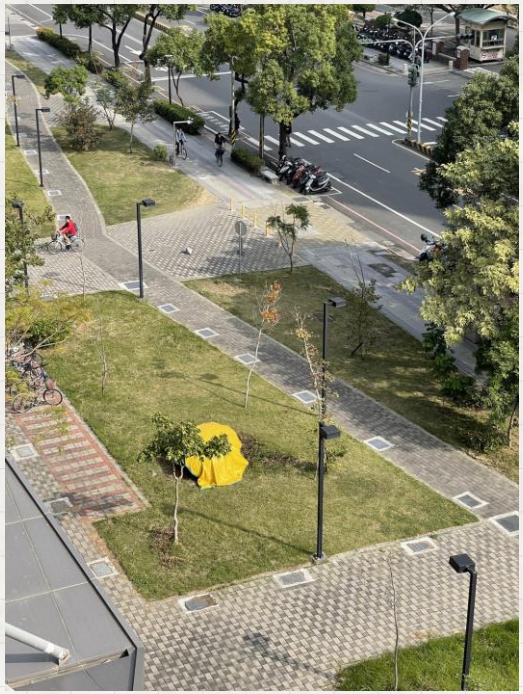

• 實驗流程圖

# 3 研究區域與方法

## 1、帆布鋪於花叢



• 原始場景 (角反射器於十字路口)



• 帆布鋪於花叢

距離:花叢37m





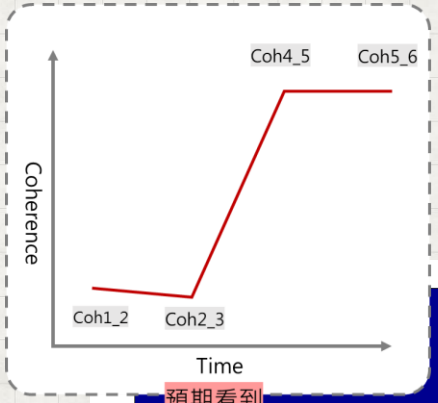
• 花叢帆布覆蓋前後現場照

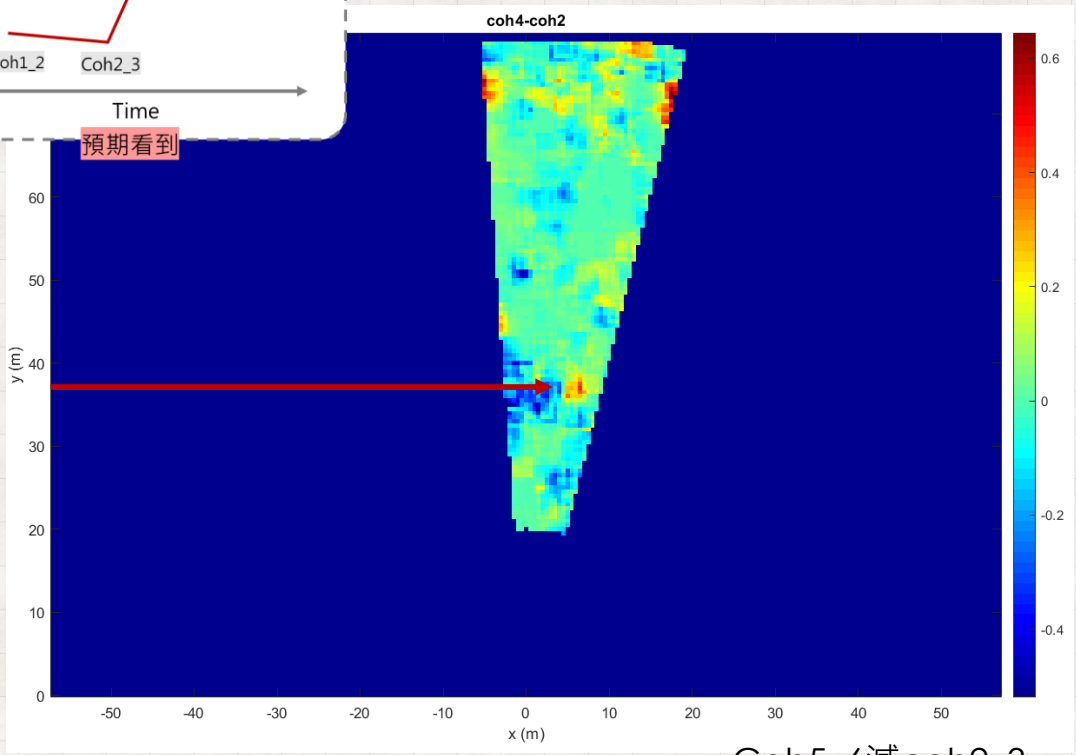
# 3 研究區域與方法

## 1、帆布鋪於花叢

| | | |
|---|---|---|
| 1 | 10:10_原始場景 | - |
| 2 | 10:13_原始場景 | Coh1_2 |
| 3 | 10:15_原始場景 | Coh2_3 |
| 4 | 10:18_帆布於花叢 | Coh3_4 |
| 5 | 10:20_帆布於花叢 | Coh4_5 |
| 6 | 10:23_帆布於花叢 | Coh5_6 |

相減



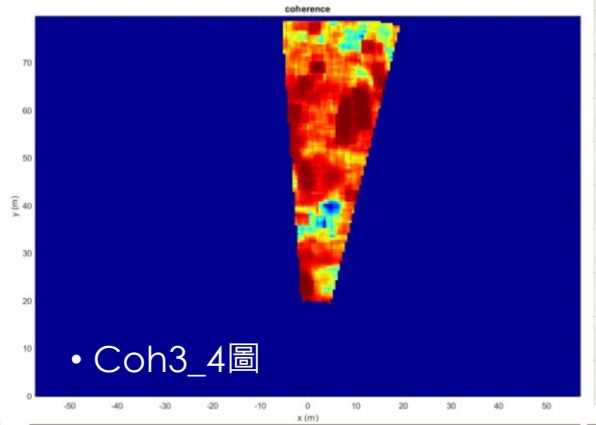




相減後數值大的區域表示coherence有明顯變高的跡象，對應距離，判斷為在花叢上鋪帆布影響。

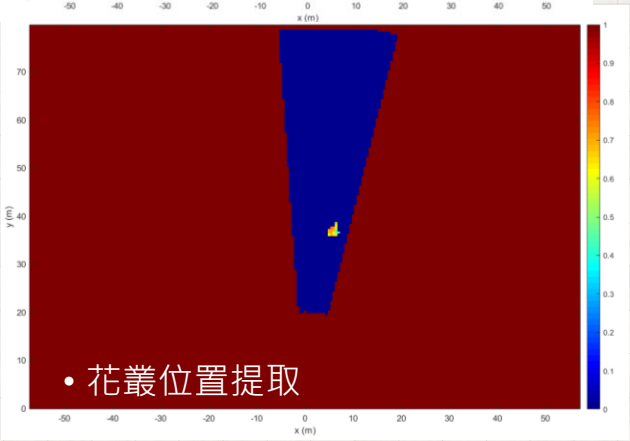
• Coh5_6減coh2_3圖

# 3 研究區域與方法

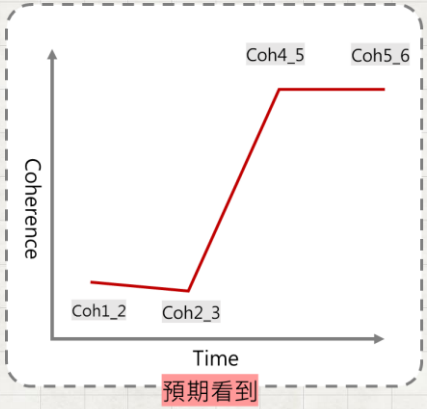
## 1、帆布鋪於花叢



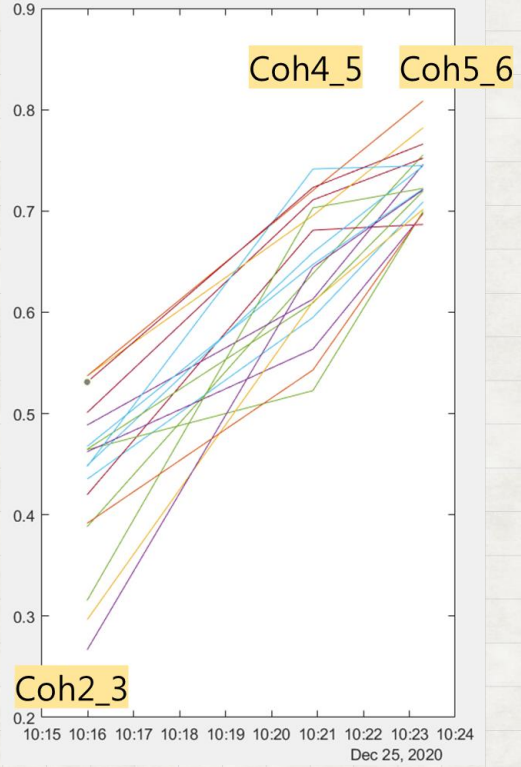

• Coh3_4圖




• 花叢位置提取




| | | |
|---|---|---|
| 1 | 10:10_原始場景 | - |
| 2 | 10:13_原始場景 | Coh1_2 |
| 3 | 10:15_原始場景 | Coh2_3 |
| 4 | 10:18_帆布於花叢 | ~~Coh3_4~~ |
| 5 | 10:20_帆布於花叢 | Coh4_5 |
| 6 | 10:23_帆布於花叢 | Coh5_6 |




• coherence花叢位置時序圖

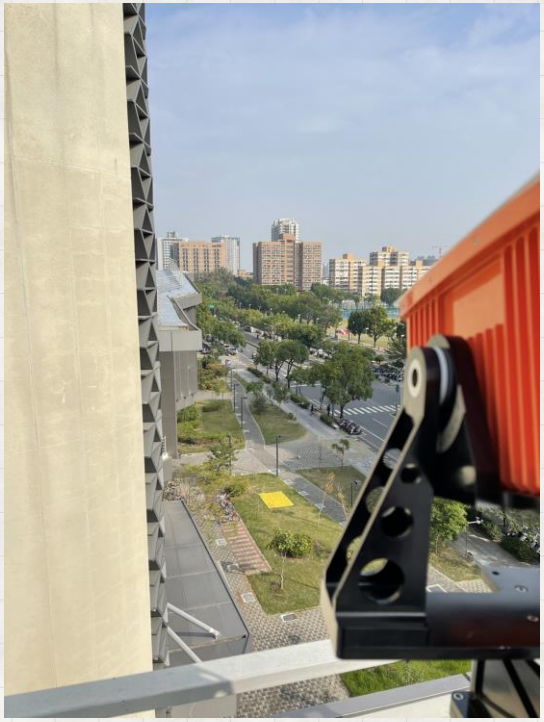
coherence的時序與預期想法一致，

**在花叢區域之coherence因帆布的放置而提高。**

# 3 研究區域與方法

## 2、帆布鋪於草地

距離:帆布49m



• 5樓視野



• 帆布、角反射器設置中



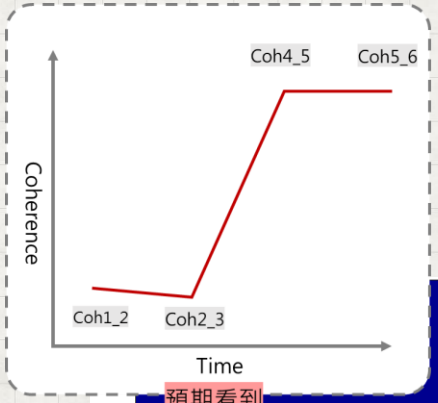
• 帆布鋪於草地照

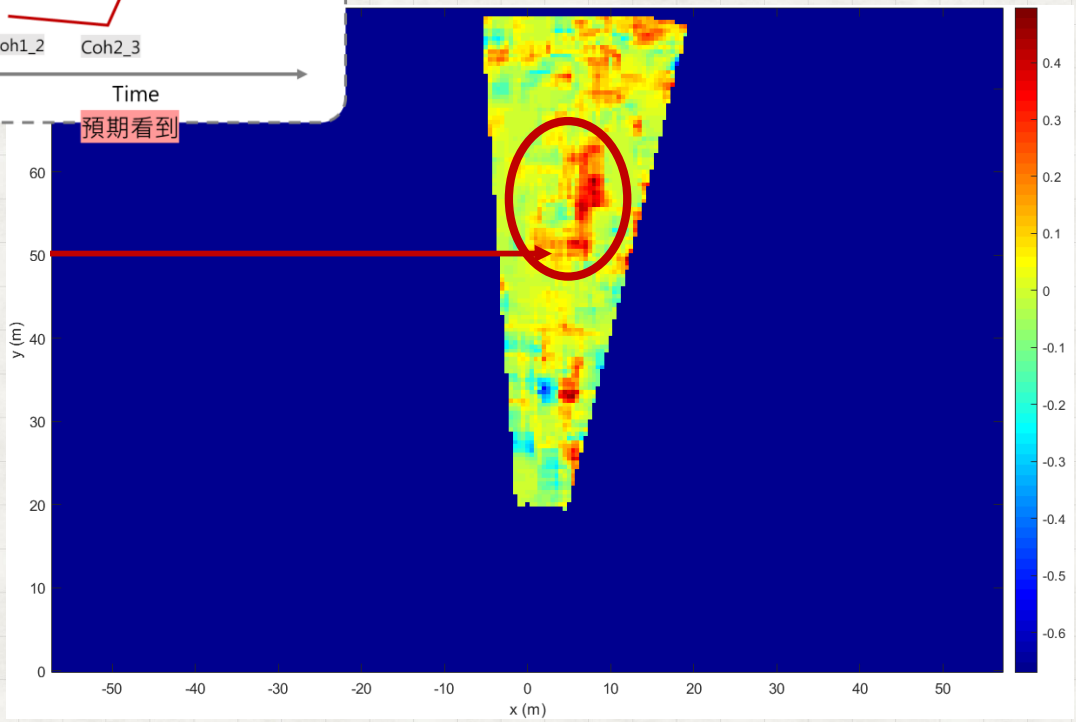
# 3 研究區域與方法

## 2、帆布鋪於草地

| | | |
|---|---|---|
| 1 | 09:17_原始場景 | - |
| 2 | 09:20_原始場景 | Coh1_2 |
| 3 | 09:22_原始場景 | Coh2_3 |
| 4 | 09:26_帆布於草地，十字路口角反射器 | Coh3_4 |
| 5 | 09:29_帆布於草地，十字路口角反射器 | Coh4_5 |
| 6 | 09:31_帆布於草地，十字路口角反射器 | Coh5_6 |

相減



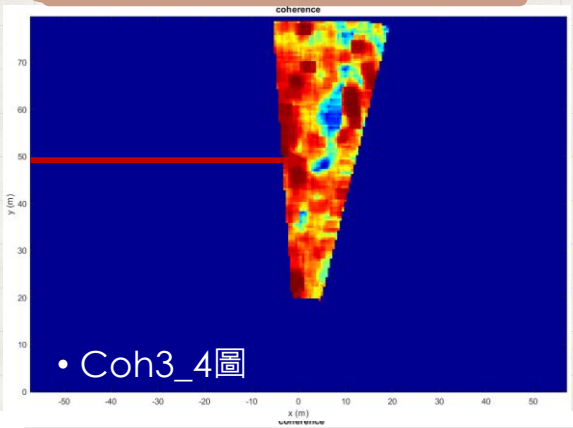




相減後數值大的區域表示coherence有明顯變高的跡象，對應距離，判斷為角反射器放置處與草地上鋪帆布。

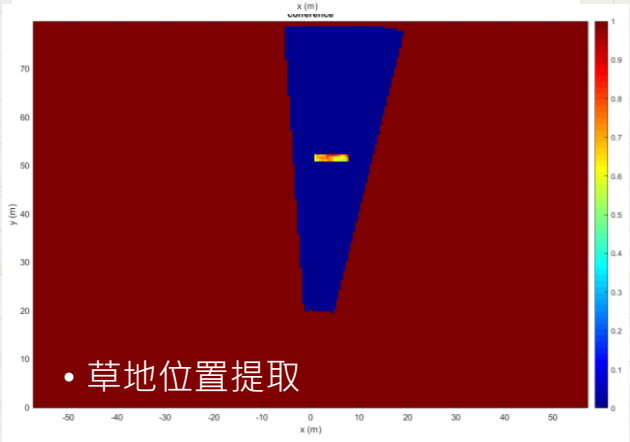
• Coh5_6減coh2_3圖

# 3 研究區域與方法

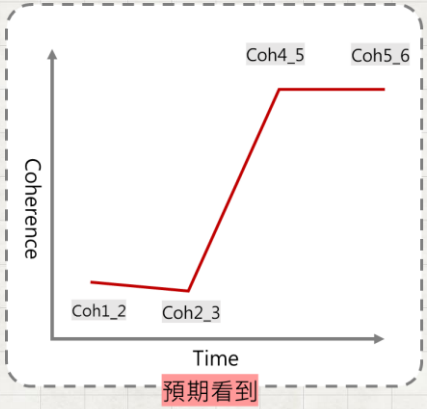
## 2、帆布鋪於草地




• Coh3_4圖

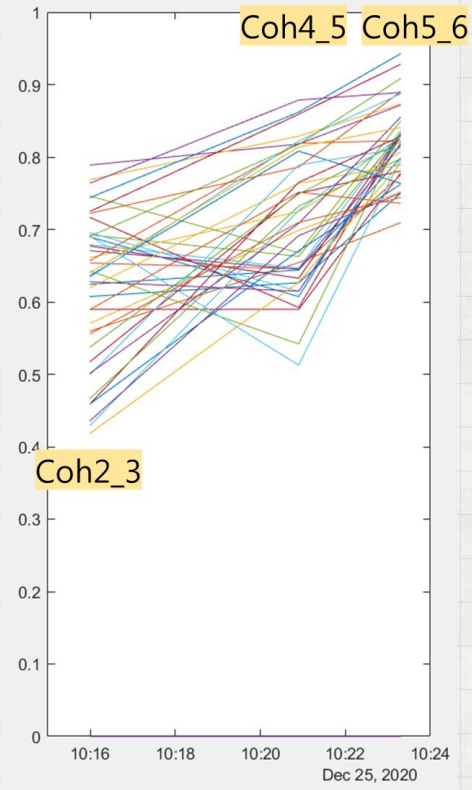



• 草地位置提取




預期看到

| | | |
|---|---|---|
| 1 | 09:17_原始場景 | - |
| 2 | 09:20_原始場景 | Coh1_2 |
| 3 | 09:22_原始場景 | Coh2_3 |
| 4 | 09:26_帆布於草地，十字路口角反射器 | ~~Coh3_4~~ |
| 5 | 09:29_帆布於草地，十字路口角反射器 | Coh4_5 |
| 6 | 09:31_帆布於草地，十字路口角反射器 | Coh5_6 |



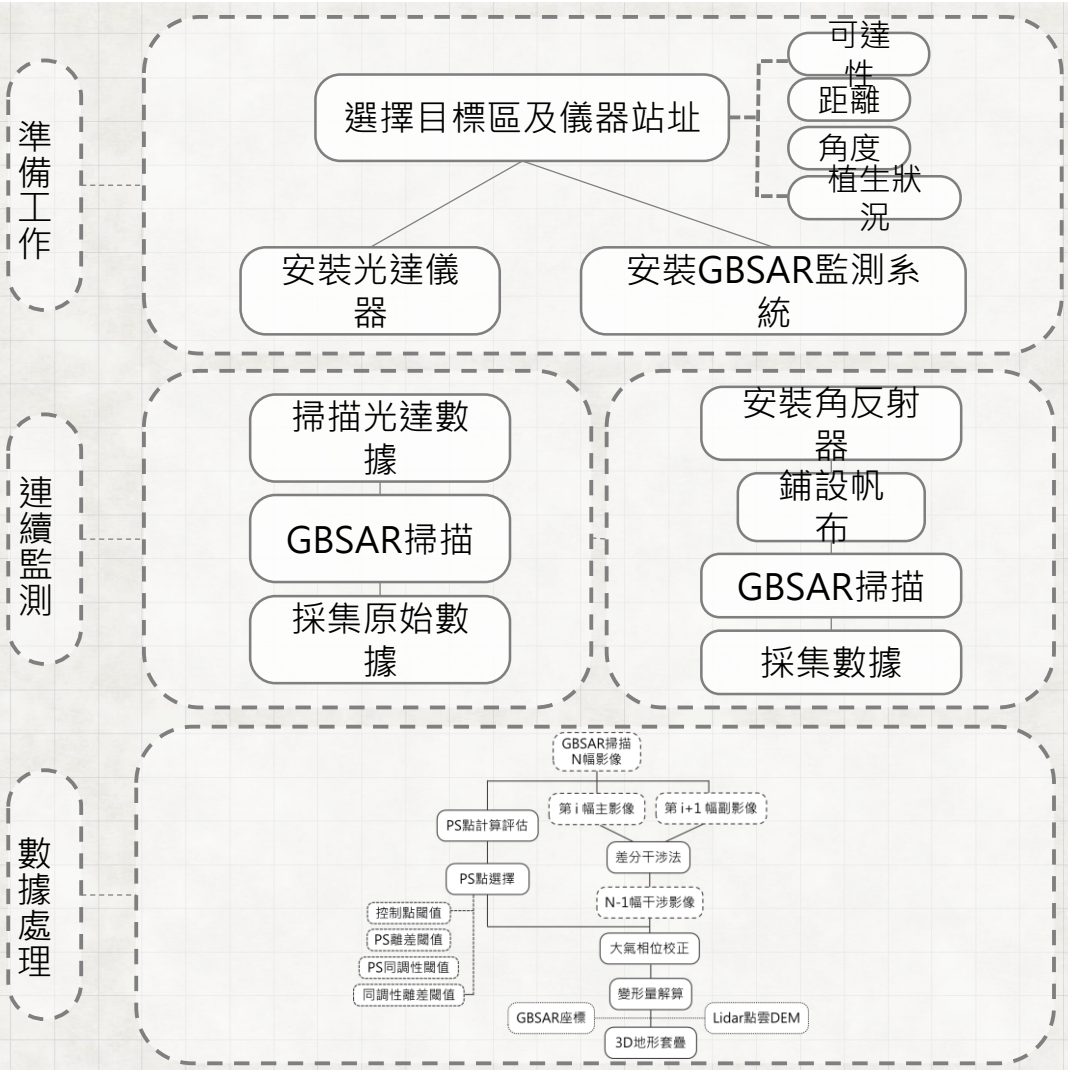

• coherence草地位置時序圖

coherence的時序蠻符合預期，

**草地的coherence因鋪上帆布而提高。**

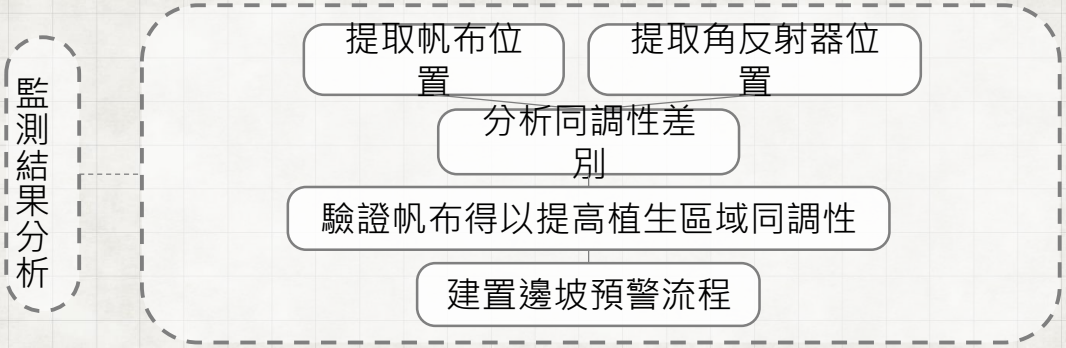
# 3 研究區域與方法

## 3.3研究流程與區域



# 3 研究區域與方法

## 3.3研究流程與區域



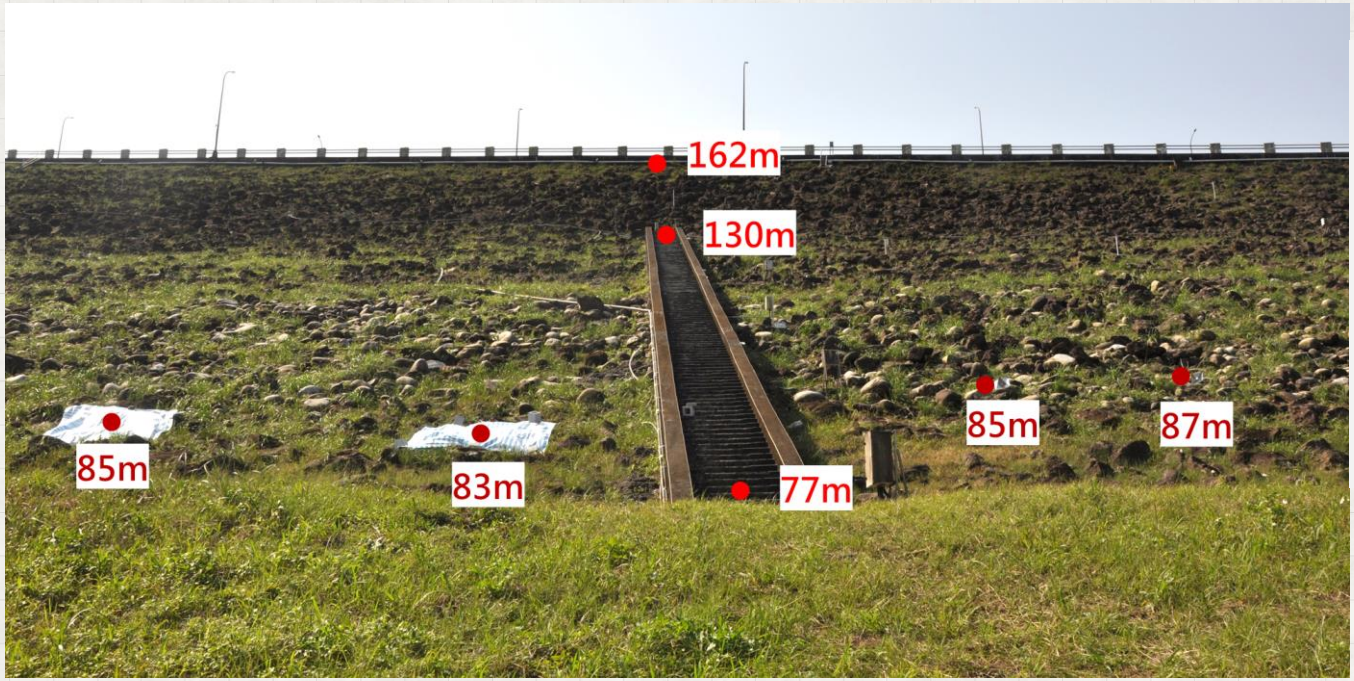
# 4 結果與討論

## 4.1 case1.基隆新山水庫



# 4 結果與討論

## 4.1 case1.基隆新山水庫




- 現場帆布、角反射器位置與距離

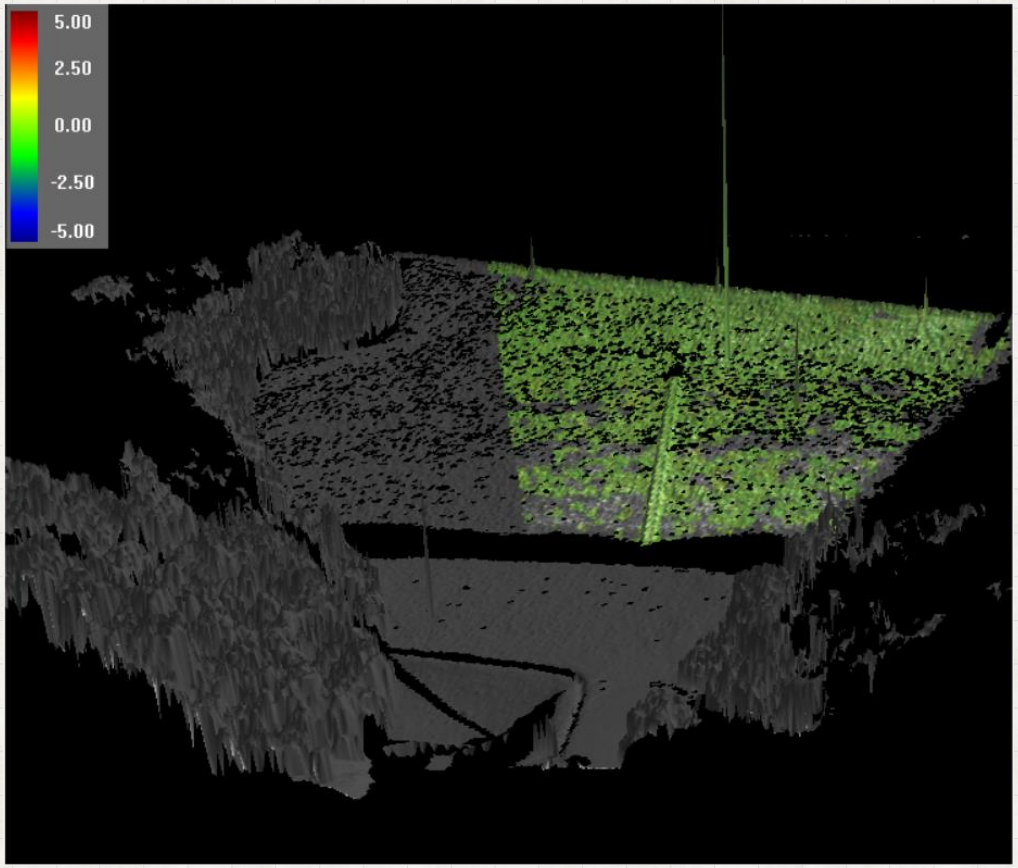
- 掃描距離:70m-200m
- 花費總時間:1.5hr
- 仰角:10度
- 多角度:90,105,120
- 邊坡坡度:20度
- 草的高度:約50cm

| | |
|---|---|
| 距離向解析度 | 0.375m |
| 方位向解析度 | 0.456m |

at 85m.

# 4.1 case1.基隆新山水庫

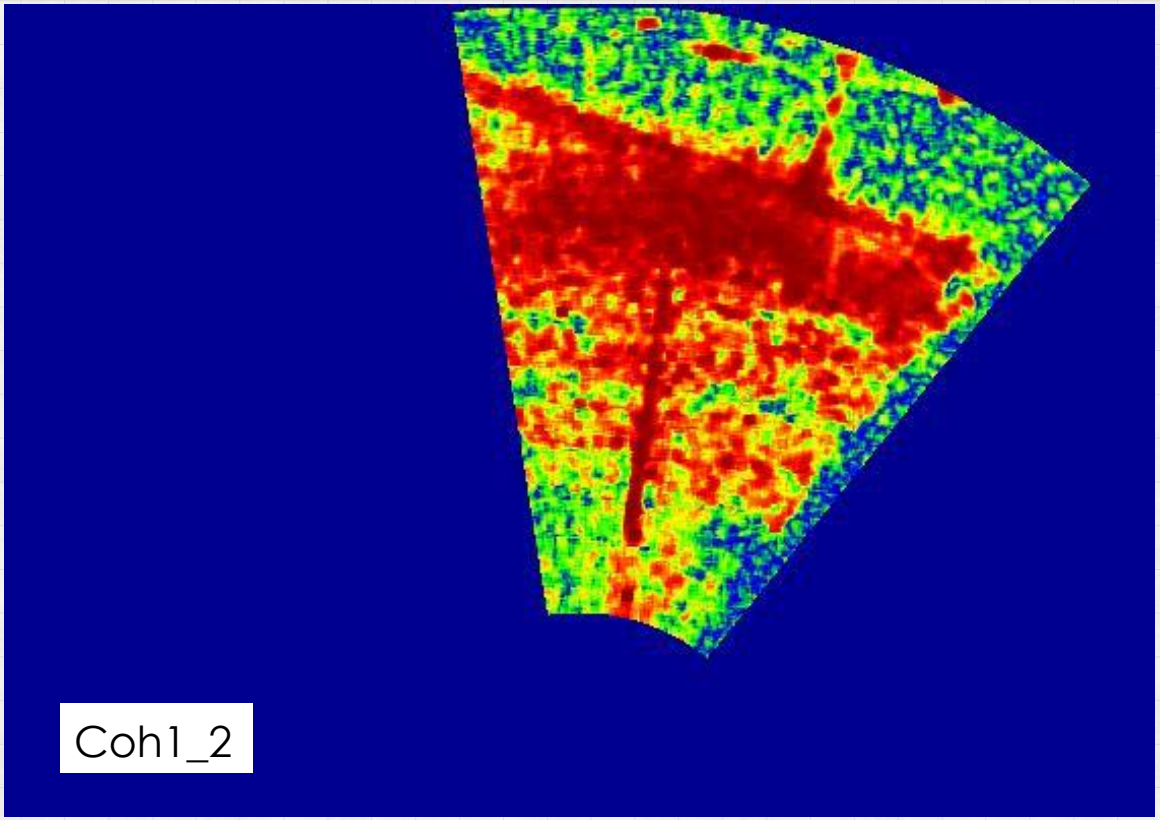
3D地形套疊



# 4 結果與討論

## 4.1 case1.基隆新山水庫

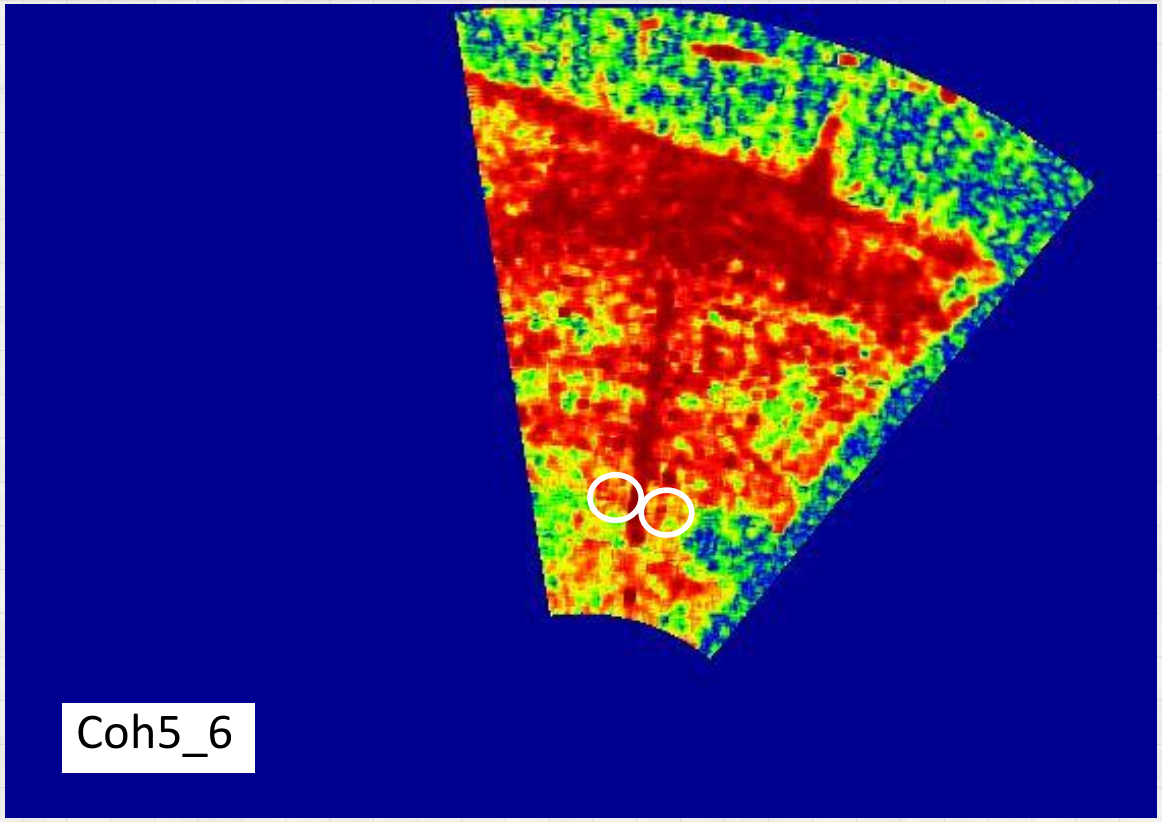
| 編號 | 場景敘述 | coherence |
|---|---|---|
| 1 | 12:23 原始場景 | - |
| 2 | 12:29 原始場景 | Coh1_2 |
| 3 | 12:36 原始場景 | Coh2_3 |
| 4 | 12:58 布1+布2+角1+角2 | Coh3_4 |
| 5 | 13:04 布1+布2+角1+角2 | Coh4_5 |
| 6 | 13:11 布1+布2+角1+角2 | Coh5_6 |



# 4 結果與討論

## 4.1 case1.基隆新山水庫

| 編號 | 場景敘述 | coherence |
|---|---|---|
| 1 | 12:23 原始場景 | - |
| 2 | 12:29 原始場景 | Coh1_2 |
| 3 | 12:36 原始場景 | Coh2_3 |
| 4 | 12:58 布1+布2+角1+角2 | Coh3_4 |
| 5 | 13:04 布1+布2+角1+角2 | Coh4_5 |
| 6 | 13:11 布1+布2+角1+角2 | Coh5_6 |



# 4 結果與討論

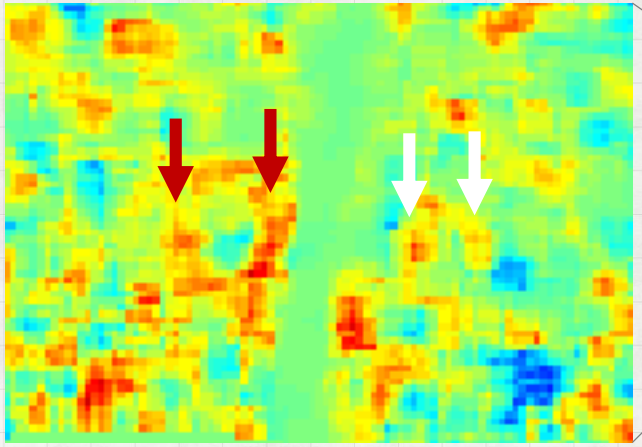
## 4.1 case1.基隆新山水庫

| 編號 | 場景敘述 | coherence |
|---|---|---|
| 1 | 12:23 原始場景 | - |
| 2 | 12:29 原始場景 | Coh1_2 |
| 3 | 12:36 原始場景 | Coh2_3 |
| 4 | 12:58 布1+布2+角1+角2 | Coh3_4 |
| 5 | 13:04 布1+布2+角1+角2 | Coh4_5 |
| 6 | 13:11 布1+布2+角1+角2 | Coh5_6 |

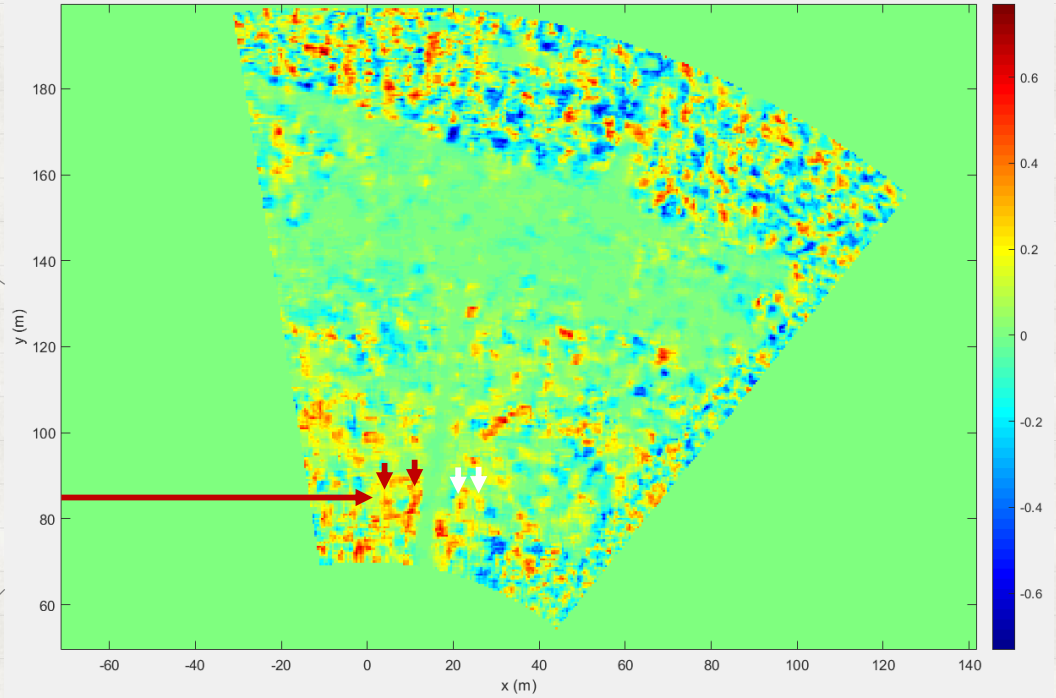
相減

相減後數值大的區域表示coherence有明顯變高的跡象。

紅箭頭為帆布放置區域，白箭頭為角反射器放置位置。



放大圖




• coh5_6減coh1_2圖

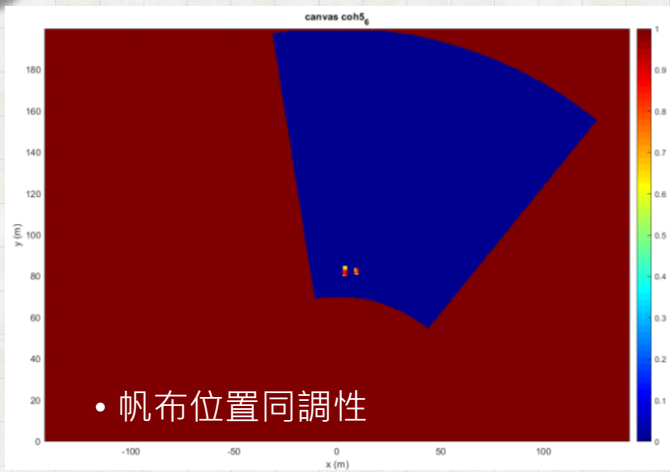
# 4 結果與討論

## 4.1 case1.基隆新山水庫

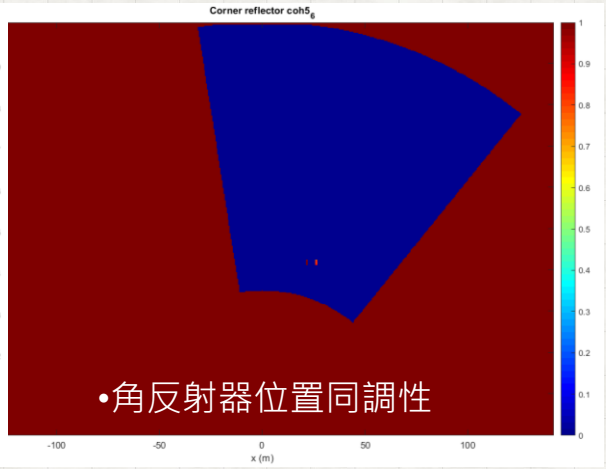
## 帆布與角反射器同調性提升數值

| | 帆布1 | 帆布2 |
|---|---|---|
| Coh1_2平均 | 0.4460 | 0.4036 |
| Coh5_6平均 | 0.7633 | 0.7871 |
| **提升平均數值** | 0.3173 | 0.3835 |

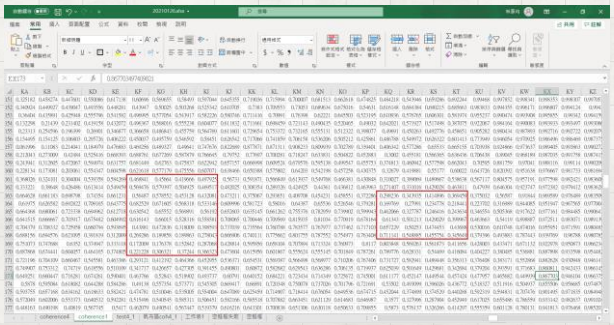
| | 角1 | 角2 |
|---|---|---|
| Coh1_2平均 | 0.6252 | 0.5948 |
| Coh5_6平均 | 0.9869 | 0.8160 |
| **提升平均數值** | 0.3617 | 0.2212 |



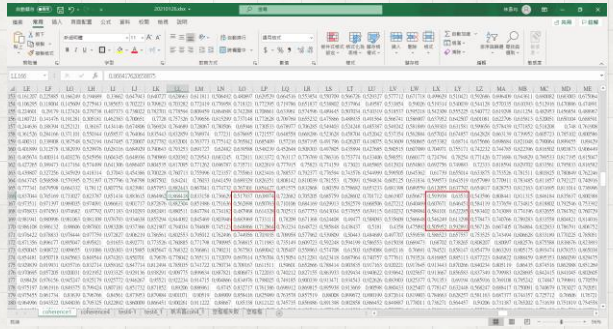

• 帆布位置同調性




•角反射器位置同調性



• 帆布位置同調性數值



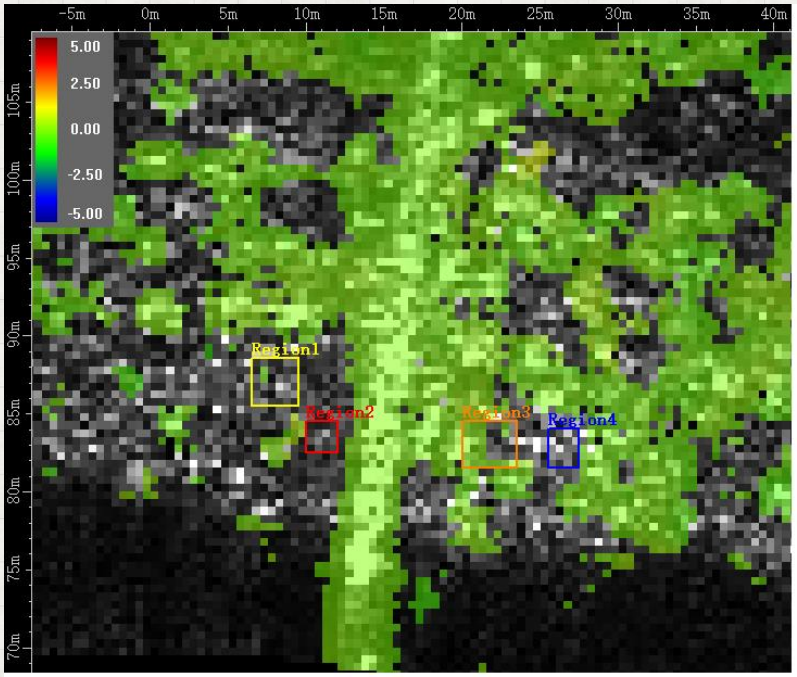
•角反射器位置同調性數值

# 4 結果與討論

## 4.1 case1.基隆新山水庫

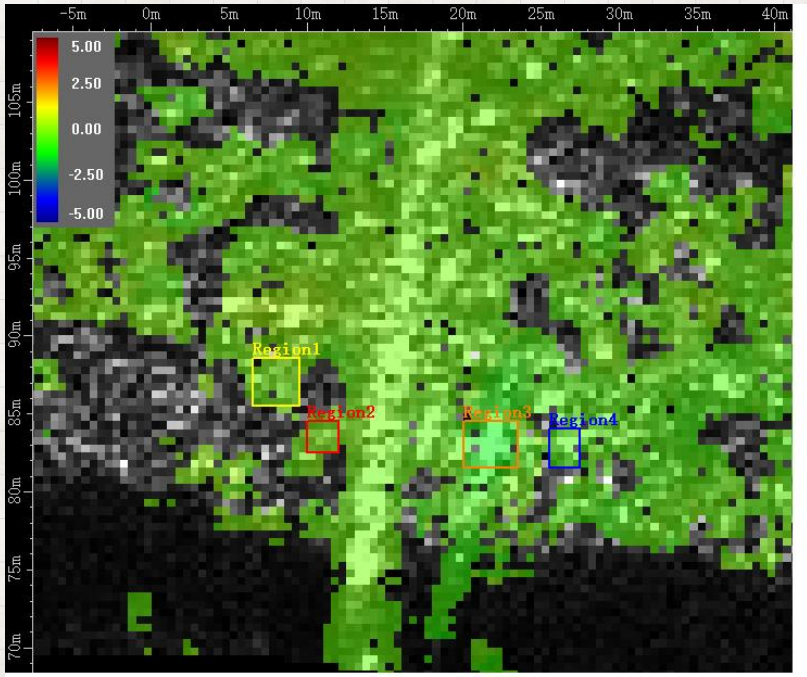
## 同調性提高幫助後續變形計算

Region1~4分別為帆布1、2，角1、2




**原始場景**

Region1~4位置同調性皆不佳，無法顯示變形量。

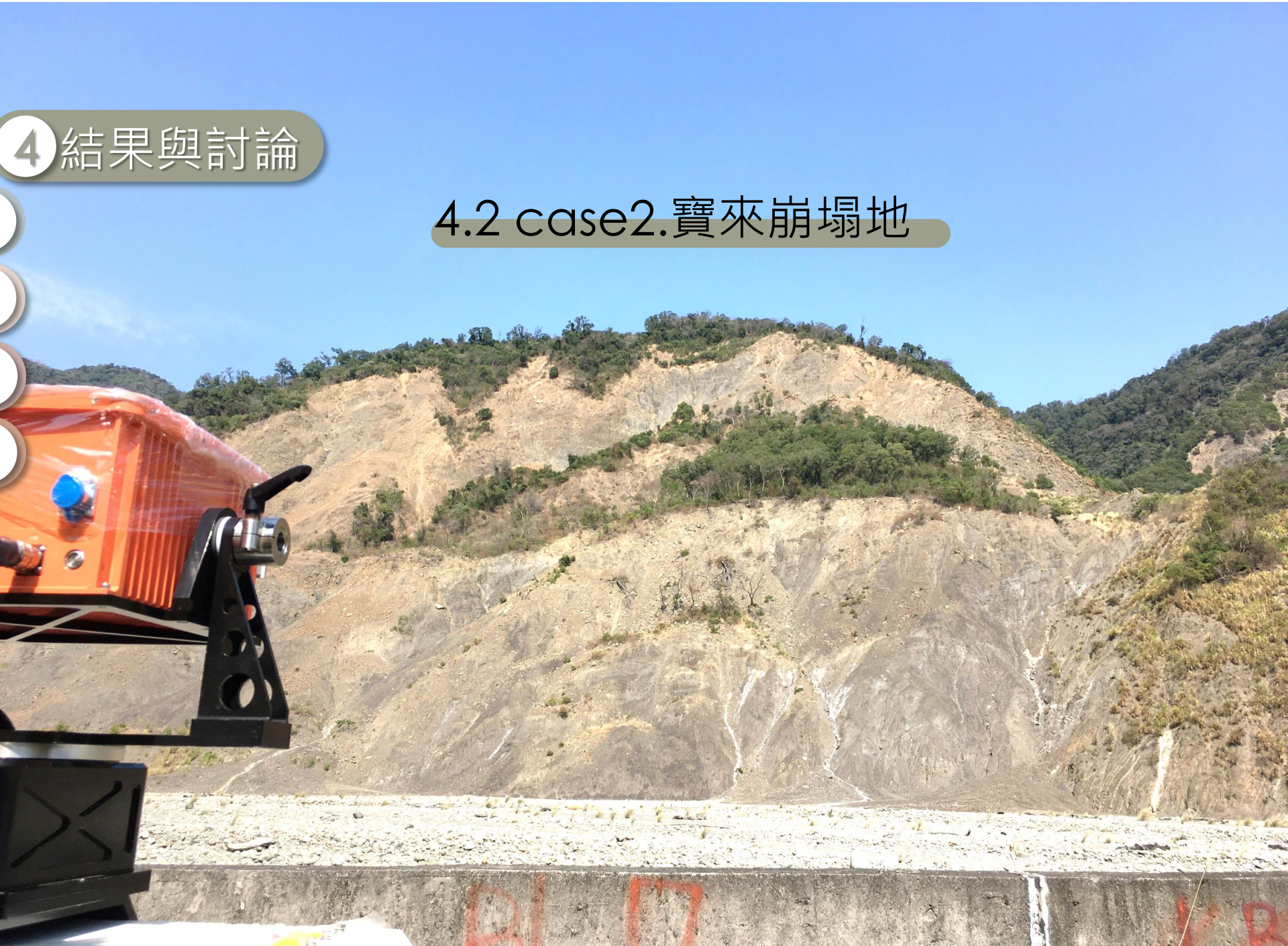



**放置帆布、角反射器**

Region1-4位置同調性提高，可顯示變形量。

# 4 結果與討論

## 4.2 case2.寶來崩塌地



# 4 結果與討論

## 4.2 case2.寶來崩塌地





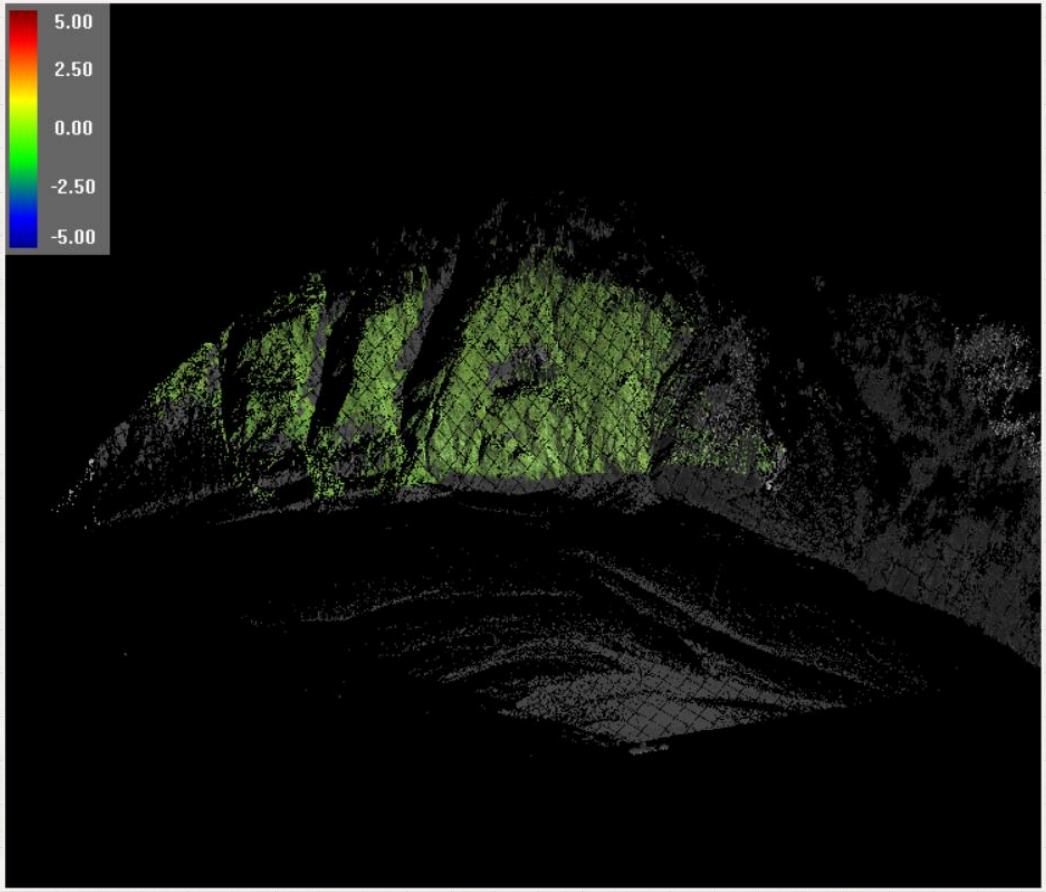

| | |
|---|---|
| 距離向解析度 | 0.375m |
| 方位向解析度 | 1.447m |

at 270m

- 掃描距離:250m-500m
- 花費總時間:3hr
- 仰角:0度
- 多角度:60,75,90,105,120
- 邊坡坡度:約60度

# 4.2 case2.寶來崩塌地

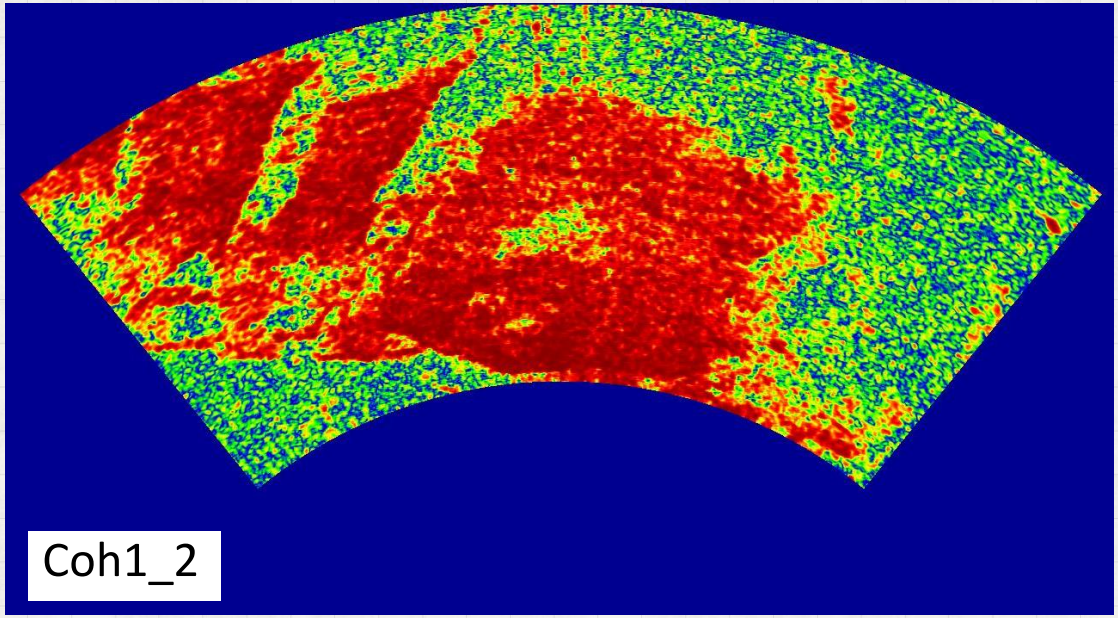
3D地形套疊



# 4 結果與討論

## 4.2 case2.寶來崩塌地

| 編號 | 場景敘述 | Bin時間紀錄 | coherence |
|---|---|---|---|
| 1 | 原始場景 | 11:07 | - |
| 2 | 原始場景 | 11:18 | Coh1_2 |
| 3 | 原始場景 | 11:29 | Coh2_3 |
| 4 | 原始場景 | 11:42 | Coh3_4 |
| 5 | 原始場景 | 11:53 | Coh4_5 |
| 6 | 原始場景 | 12:04 | Coh5_6 |
| 7 | 原始場景 | 12:16 | Coh6_7 |
| 8 | 原始場景 | 12:50 | Coh7_8 |
| 9 | 布1(270m)+布2(267m) | 13:46 | Coh8_9 |
| 10 | 布1(270m)+布2(267m) | 13:57 | Coh9_10 |
| 11 | 布1(270m)+布2(267m) | 14:08 | Coh10_11 |
| 12 | 布1(270m)+布2(267m) | 14:19 | Coh11_12 |



# 4 結果與討論

## 4.2 case2.寶來崩塌地

| 編號 | 場景敘述 | Bin時間紀錄 | coherence |
|---|---|---|---|
| 1 | 原始場景 | 11:07 | - |
| 2 | 原始場景 | 11:18 | Coh1_2 |
| 3 | 原始場景 | 11:29 | Coh2_3 |
| 4 | 原始場景 | 11:42 | Coh3_4 |
| 5 | 原始場景 | 11:53 | Coh4_5 |
| 6 | 原始場景 | 12:04 | Coh5_6 |
| 7 | 原始場景 | 12:16 | Coh6_7 |
| 8 | 原始場景 | 12:50 | Coh7_8 |
| 9 | 布1(270m)+布2(267m) | 13:46 | Coh8_9 |
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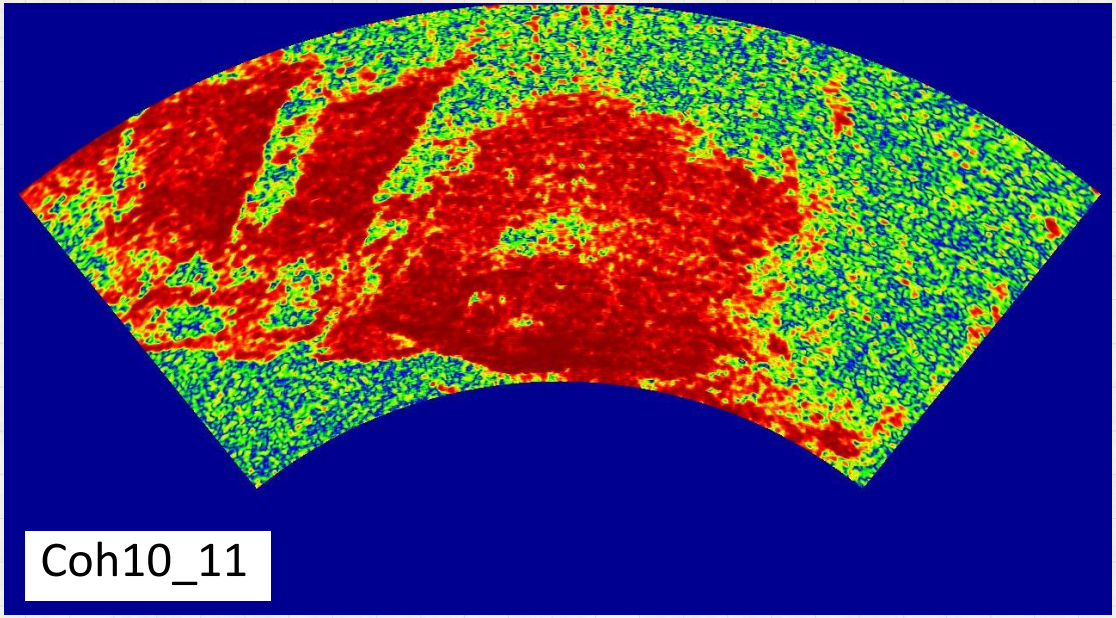
| 11 | 布1(270m)+布2(267m) | 14:08 | Coh10_11 |
| 12 | 布1(270m)+布2(267m) | 14:19 | Coh11_12 |

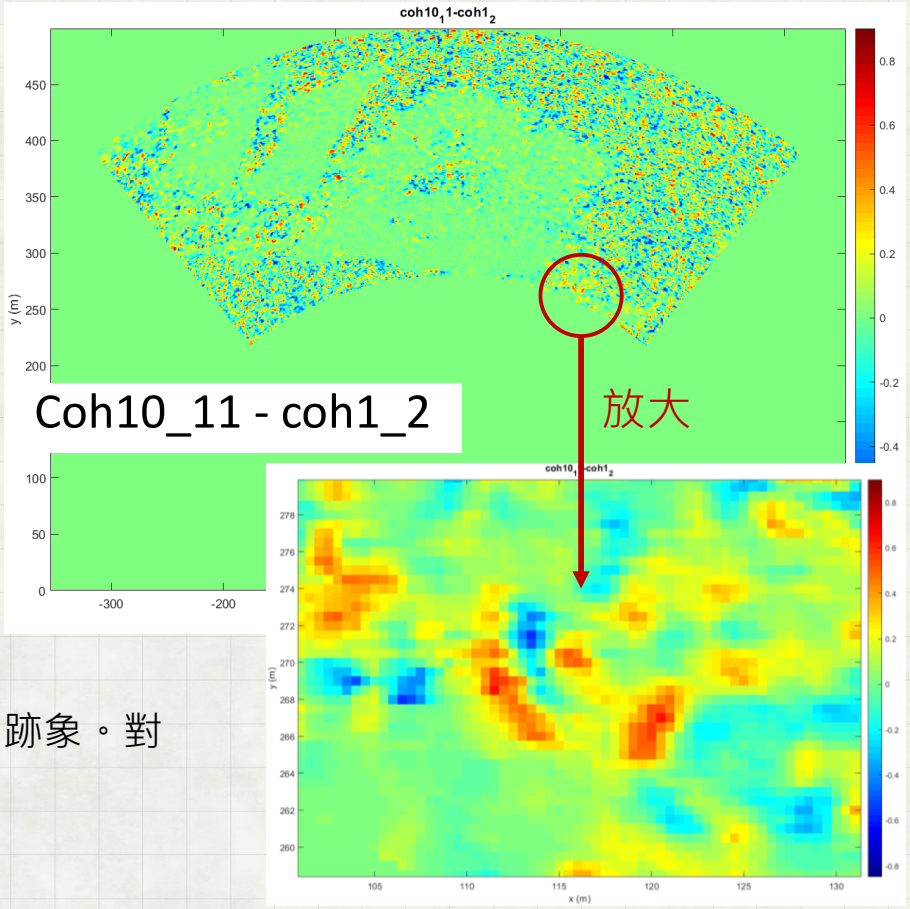


# 4 結果與討論

## 4.2 case2.寶來崩塌地

| 編號 | 場景敘述 | Bin時間紀錄 | coherence |
|---|---|---|---|
| 1 | 原始場景 | 11:07 | - |
| 2 | 原始場景 | 11:18 | Coh1_2 |
| 3 | 原始場景 | 11:29 | Coh2_3 |
| 4 | 原始場景 | 11:42 | Coh3_4 |
| 5 | 原始場景 | 11:53 | Coh4_5 |
| 6 | 原始場景 | 12:04 | Coh5_6 |
| 7 | 原始場景 | 12:16 | Coh6_7 |
| 8 | 原始場景 | 12:50 | Coh7_8 |
| 9 | 布1(270m)+布2(267m) | 13:46 | Coh8_9 |
| 10 | 布1(270m)+布2(267m) | 13:57 | Coh9_10 |
| 11 | 布1(270m)+布2(267m) | 14:08 | Coh10_11 |
| 12 | 布1(270m)+布2(267m) | 14:19 | Coh11_12 |

相減




相減後數值大的區域表示coherence有明顯變高的跡象。對應距離方向，判斷為帆布及角反射器的擺放位置。

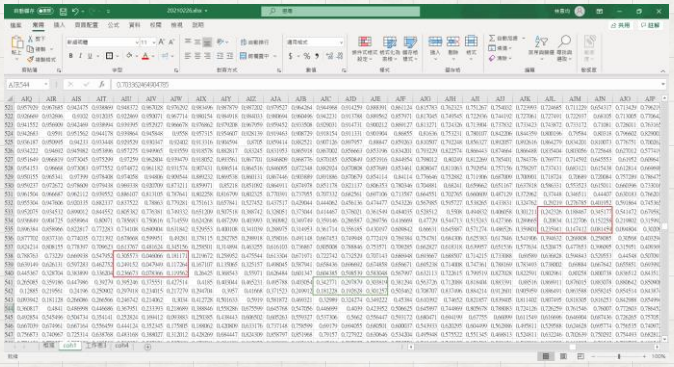
# 4 結果與討論

## 4.2 case2.寶來崩塌地

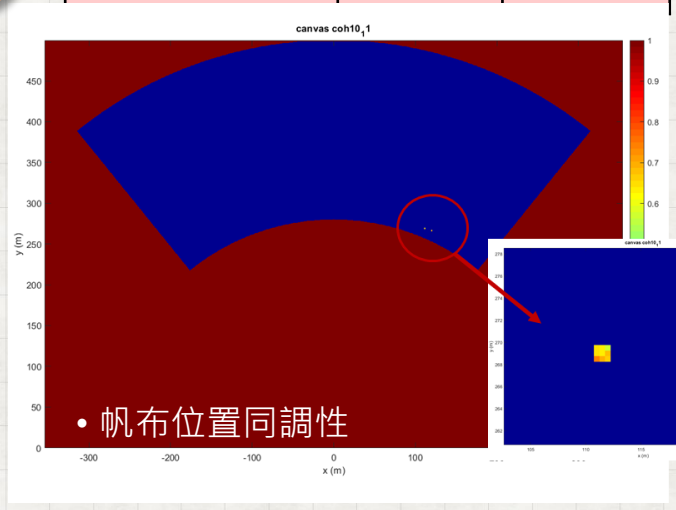
## 帆布與角反射器同調性提升數值

| | 帆布1 | 帆布2 |
|---|---|---|
| Coh1_2平均 | 0.1535 | 0.1916 |
| Coh10_11平均 | 0.6573 | 0.6972 |
| **提升平均數值** | 0.5038 | 0.5056 |

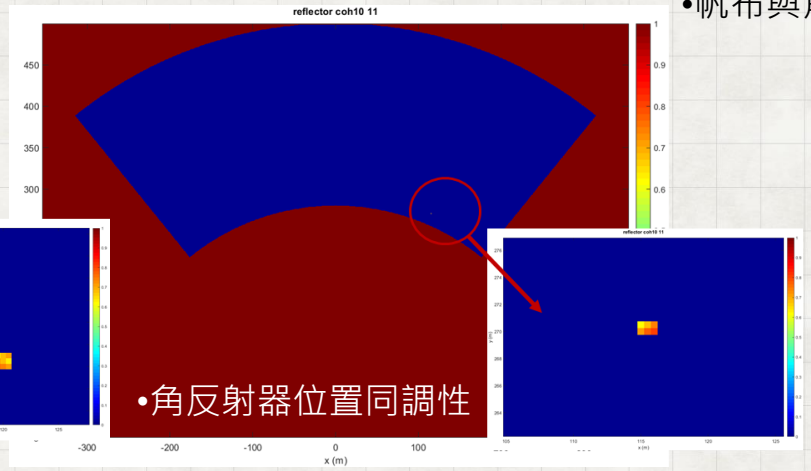
| | 角反射器 |
|---|---|
| Coh1_2平均 | 0.2699 |
| Coh10_11平均 | 0.7195 |
| **提升平均數值** | 0.4496 |



•帆布與角反射器位置同調性數值




• 帆布位置同調性



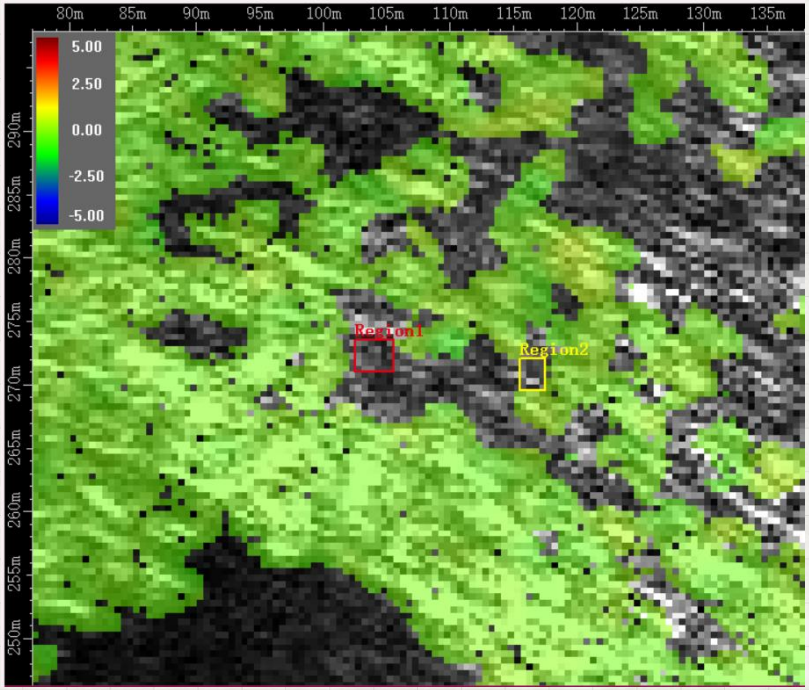

•角反射器位置同調性

# 4 結果與討論

## 4.2 case2.寶來崩塌地

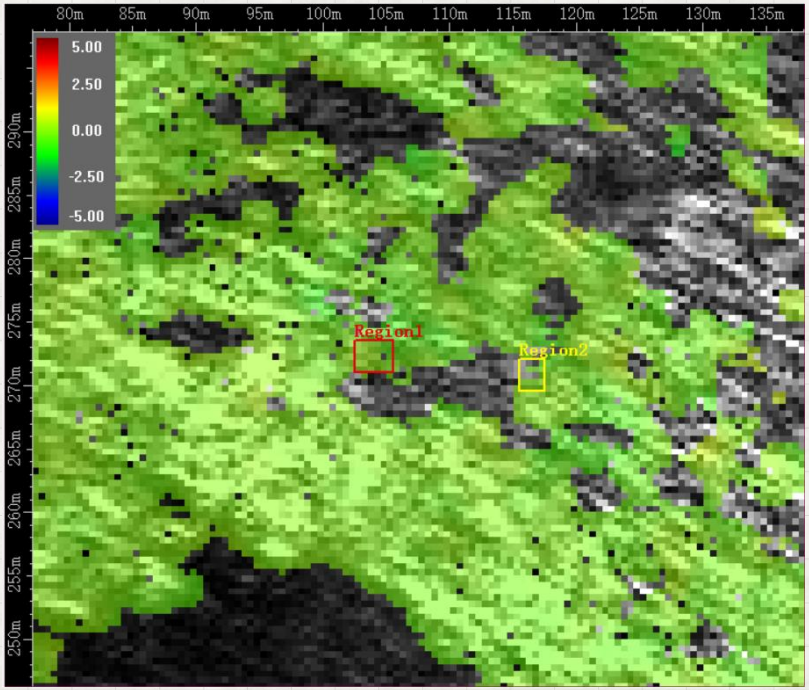
同調性提高幫助後續變形計算

Region1~2分別為帆布1、2




**原始場景**

Region1、2位置同調性皆不佳，無法顯示變形量。




**放置帆布**

Region1、2位置同調性提高，可顯示變形量。

# 4 結果與討論

## 4.3 建置邊坡預警流程

**前期**

- 佈設傳統監測儀器，ex傾斜管、GPS。
- D-GBSAR長期監測掃描(次/月)。
- 佈設角反射器，增加測量密度。

1、目標區變形明顯大幅提升
2、目標區第一次災害發生後

**後期**

- C-GBSAR即時掃描(次/小時)。
- 植生區域佈設**帆布**，降低粗糙度、減少散射。
- 裸露區佈設**帆布**，防止雨水入滲，減少二次災害機會。

# 5 結論與建議

- 在植生上鋪設帆布能有效提升coherence，可使後續計算變形量有較高可信度。
- 帆布與角反射器佈置使同調性提高的能力比較：

角反射器因金屬材質關係，同調性相對較高，可提升較多。

- 建置邊坡預警流程，以達節省人力、物力成本。且望更有效發覺災害發生。


Thank
you
for
your
attention !



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## Discontinuous GBSAR deformation monitoring

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**Fig. 4.** Displacement maps of Barberà de la Conca between the first campaign (14/11/2011) and the campaigns of 19/12/2011 (a), 08/05/2012 (b) and 20/03/2013 (c). The blue polygons on the top indicate the stable areas.

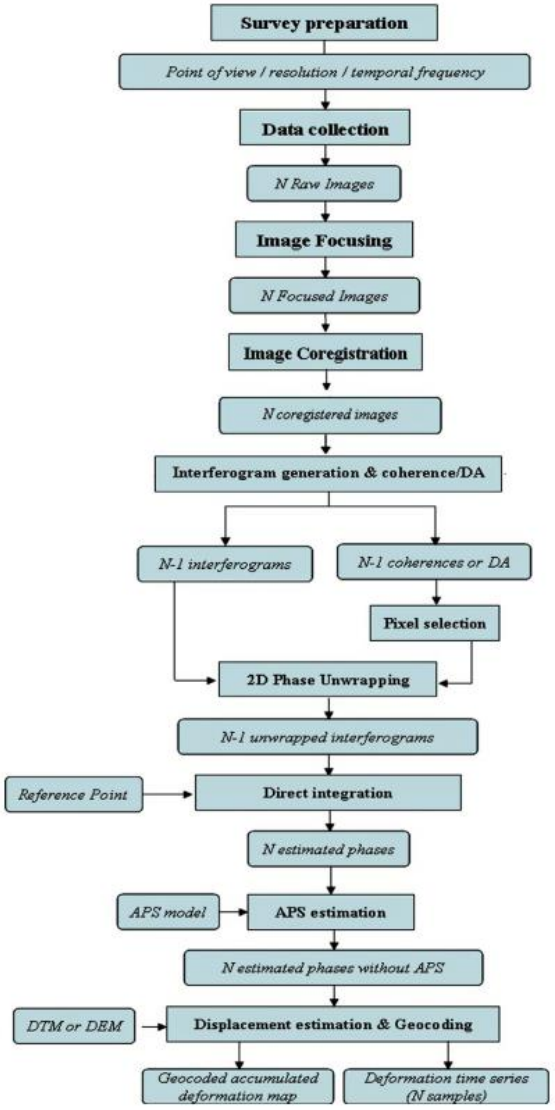


**Fig. 1.** Flow chart of D-GBSAR data processing and analysis procedure used in this work.