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Spaceborne SAR based assessment of nuclear test effect: the case of North Korea

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Agenda

- Background and motivation
  - Democratic People's Republic of Korea (DPRK) conduced six nuclear tests at the Punggie-ry test site located at the foot of Mt. Mantap
  - Estimate surface displacement caused by explosions
    - Application of satellite Synthetic Aperure Radar (SAR) data
- Applied methodology
  - Sub-Pixel Offset Tracking (SPOT) technique
    - Alternative approach for estimating Earth displacement
  - COSMO-SkyMed (CSK) satellite dataset
- Representative results
  - Analisys pre/post-nuclear events
  - Estimate explotion locations
  - Tunnel network retrieval
- Conclusions

Chronology of North Korea's nuclear tests

- From 1985 to 2005 DPRK joins the Nuclear Non-Proliferation Treaty (NPT)
  - For the first time, states it has nuclear weapons
- From 2006 to 2017 DPRK conducted six declared nuclear tests

[Incorporated Research Institutions for Seismology, "Special Event: 2017 north korean nuclear test," https://ds.iris.edu/ds/nodes/dmc/specialevents/2017/09
THE DIPLOMAT, https://thediplomat.com/2017/09/north-korea-carries-out-sixth-nuclear-test-of-claimed-two-stage-thermonuclear-bomb/]

  - DPRK 1: 09/10/2006, quake 4.3 m_b, yields 1.00 kt
  - DPRK 2: 25/05/2009, quake 4.7 m_b, yields 3.41 kt
  - DPRK 3: 12/02/2013, quake 5.1 m_b, yields 11.66 kt
  - DPRK 4: 06/01/2016, quake 5.1 m_b, yields 11.66 kt
  - DPRK 5: 09/09/2016, quake 5.3 m_b, yields 21.54 kt
  - **DPRK 6: 03/09/2017, quake 6.3 mg, yields 464.16 kt**
    - **Expected a thermonuclear device**

North Korea Carries Out Sixth Nuclear Test of Claimed Two-Stage Thermonuclear Bomb

- In early 2018 a diplomatic phase began
  - North Korean leader Kim Jong-un publicly stated that he would "work toward complete denuclearization of the Korean Peninsula".

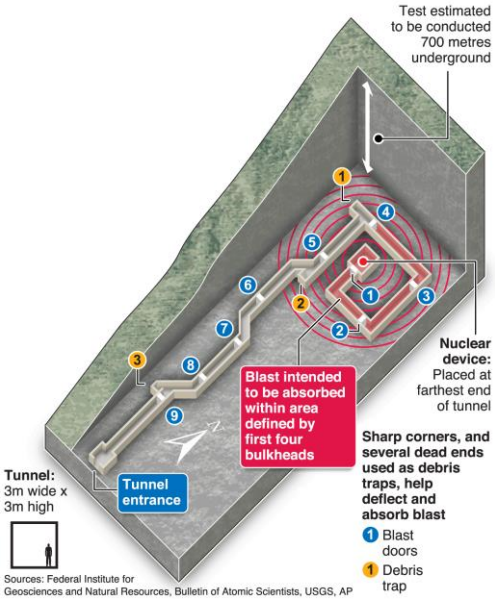
[White House, "Joint Statement of President Donald J. Trump of the United States of America and Chairman Kim Jong-un of the Democratic People's Republic of Korea at the Singapore Summit," June 12, 2018.]

Punggye-ri Nuclear Test Site

- North Korea established its only known underground nuclear test site 17 kilometers north of the village of Punggye-ri, at the foot of Mt. Mantap (2 205 m) in North Hamgyong Province
  - GPS coordinates: 41° 16’ 47.87” N 129° 5’ 10.51” E
- Site characteristics
  - Comprised of four separate tunnel systems, identified respectively as the East Portal (Tunnel No. 1), the North Portal (Tunnel No. 2), the South Portal (Tunnel No. 3) and the West Portal (Tunnel No. 4).
    - East Portal used in 2006 and evidently abandoned shortly after that single use due to contamination
  - Nuclear tests conducted in horizontal “zig-zag” tunnel terminating in a “fish hook” shape
- Dismantlement operations started on 24th of May 2018
  - A small delegation of international journalists invited to document the destruction of tunnels and buildings

[M. Greenfiel, Twitter user @ SkyGreenfield, May 5, 2018. twitter.com/skygreenfield/status/999803019804925958]

Location of the Punggye-ri facility



Schematic representation of tunnel layout



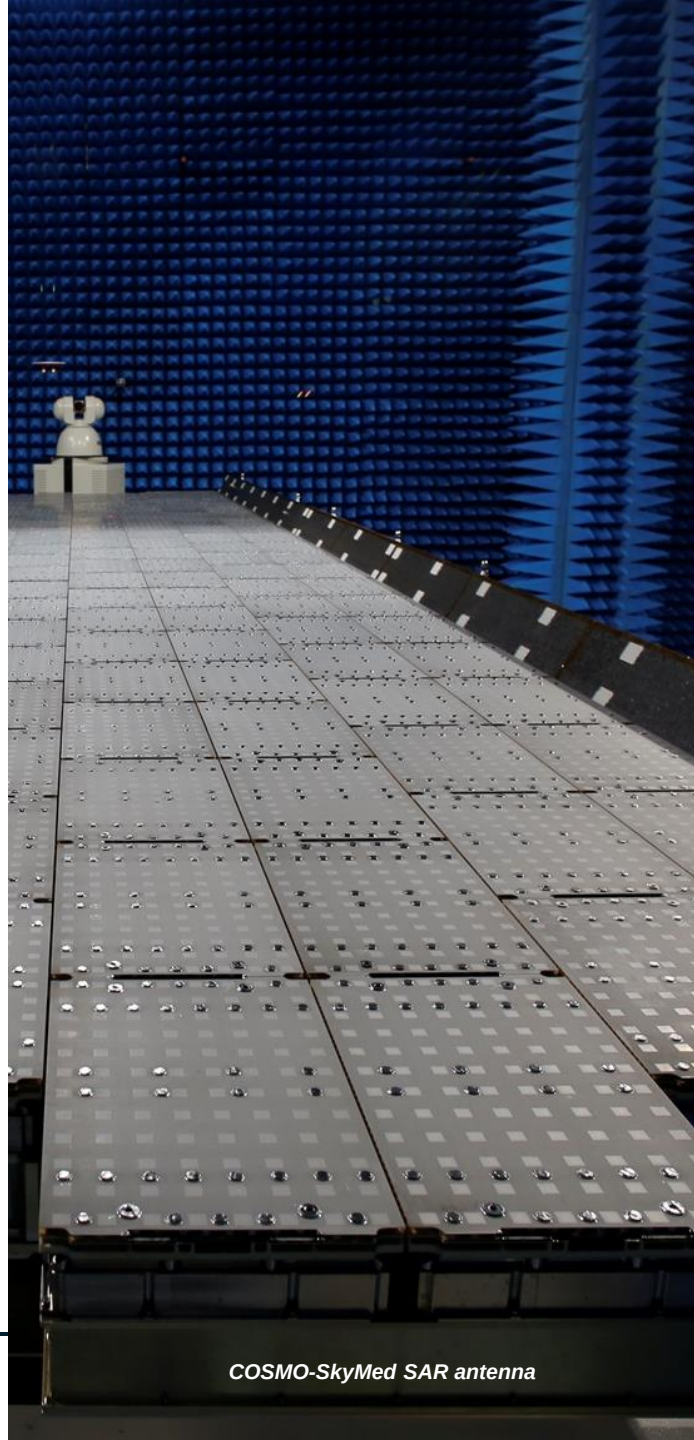





PUGGYE-RI NUCLEAR TEST SITE 24TH MAY 2018
CREDITS: M. GREENFIEL

Our goal

- Estimate surface displacement caused by nuclear tests using SAR satellite data
  - Also interesting to understand the underground tunnel network configuration
- CSK satellite constellation
  - The first Earth observation mission designed for dual purposes, both civil and military
  - Developed by the Italian Space Agency (ASI) in cooperation with the Ministry of Defense
  - Based on a constellation of satellites, equipped with synthetic aperture radars (SARs) operating in the X-band
  - On January 18th, 2021, COSMO-SkyMed Second Generation (CSG) became operational with the first of four satellites, which supplements the four first-generation satellites.
    - Today the COSMO-SkyMed constellation can boast five in-orbit and operational satellites



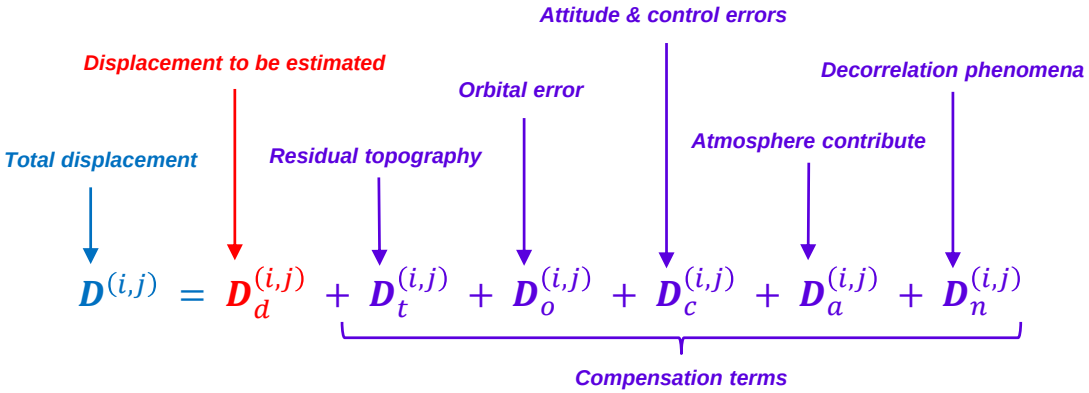
COSMO-SkyMed SAR antenna

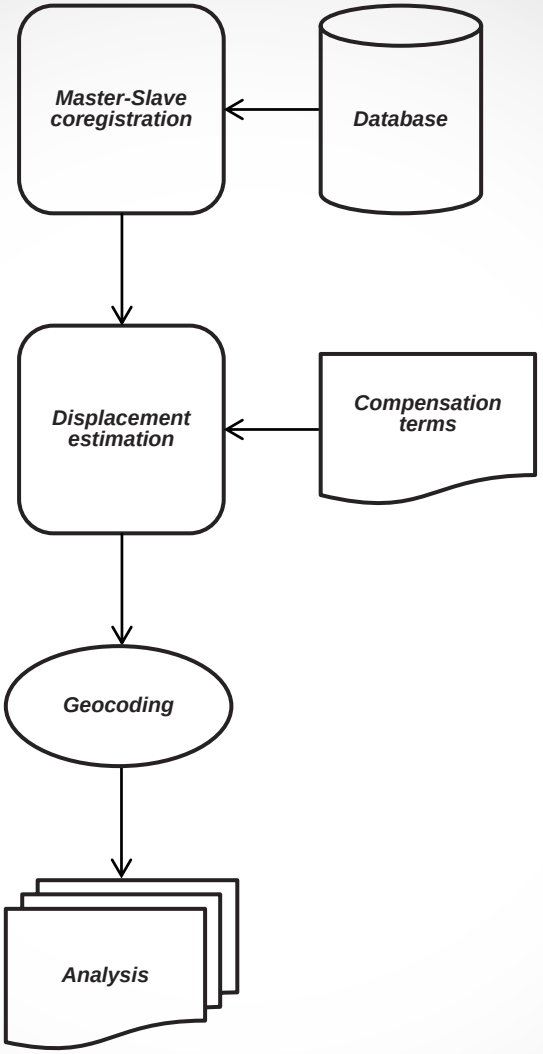
Compensation terms

Applied methodology

- The offset components of the sub-pixel normalized cross-correlation, are described by the complex parameter $\boldsymbol{D}^{(i,j)}$ (range, azimuth) which is estimated by the following equation:

[Nitti, D.O.; Hanssen, R.F.; Refice, A.; Bovenga, F.; Nutricato, R. Impact of DEM-assisted coregistration on high-resolution SAR interferometry. IEEE Trans. Geosci. Remote Sens. 2011, 49, 1127–1143.
Biondi, F.; Clemente, C.; Orlando, D. An atmospheric phase screen estimation strategy based onmulti-chromatic analysis for differential interferometric synthetic aperture radar. IEEE Trans. Geosci. Remote Sens. 2019, 1–12.]





Simplified processing workflow

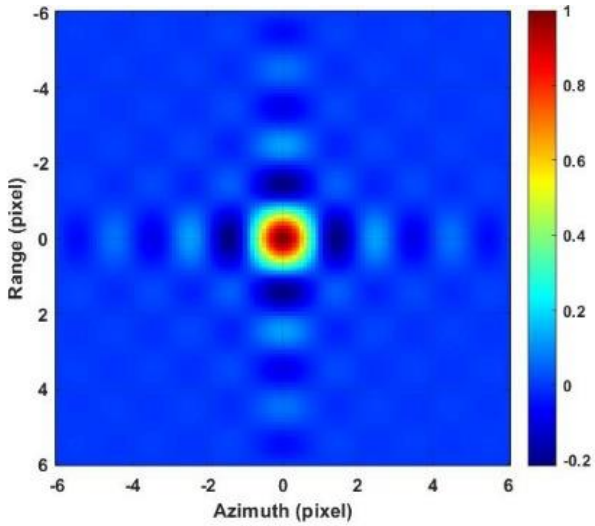
SPOT technique

- Complementary to Differential Interferometric SAR (DInSAR) and Persistent Scatters Interferometry (PSI) when radar phase information is instable

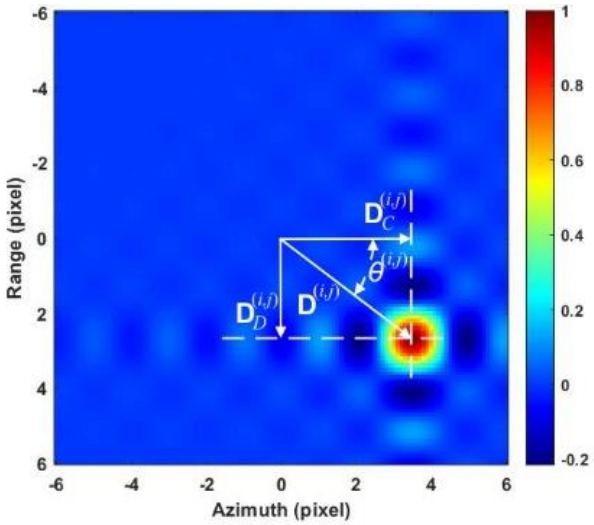
[Biondi et al., "Micro-motion estimation of maritime targets using pixel tracking in COSMO-SkyMed synthetic aperture radar data – an operative assessment," Remote Sensing, vol. 11, no. 14, pp. 1637, 2019.
Wang, Z.; Perissin, D.; Lin, H. Subway tunnels identification through Cosmo-SkyMed PSInSAR analysis in Shanghai. In Proceedings of the 2011 IEEE International Geoscience and Remote Sensing Symposium, Vancouver, BC, Canada, 24–29 July 2011.
Perissin, D.;Wang, T. Repeat-pass SAR interferometry with partially coherent targets. IEEE Trans. Geosci.Remote Sens. 2012, 50, 271–280.]

  - e.g. data acquired over vegetated area

- Main coregistration parameters
  - Initial shift: Orbital
  - Number of coherent points: 150000
  - Correpation threshold: 0.3
  - Oversampling factor: 64
  - Search pixel window: 64 x 64 pixels
  - Points skimming (minimum points): 30
  - DEM: SRTM @ 90 m
  - Doppler Centroid Estimation strategy: polynomials



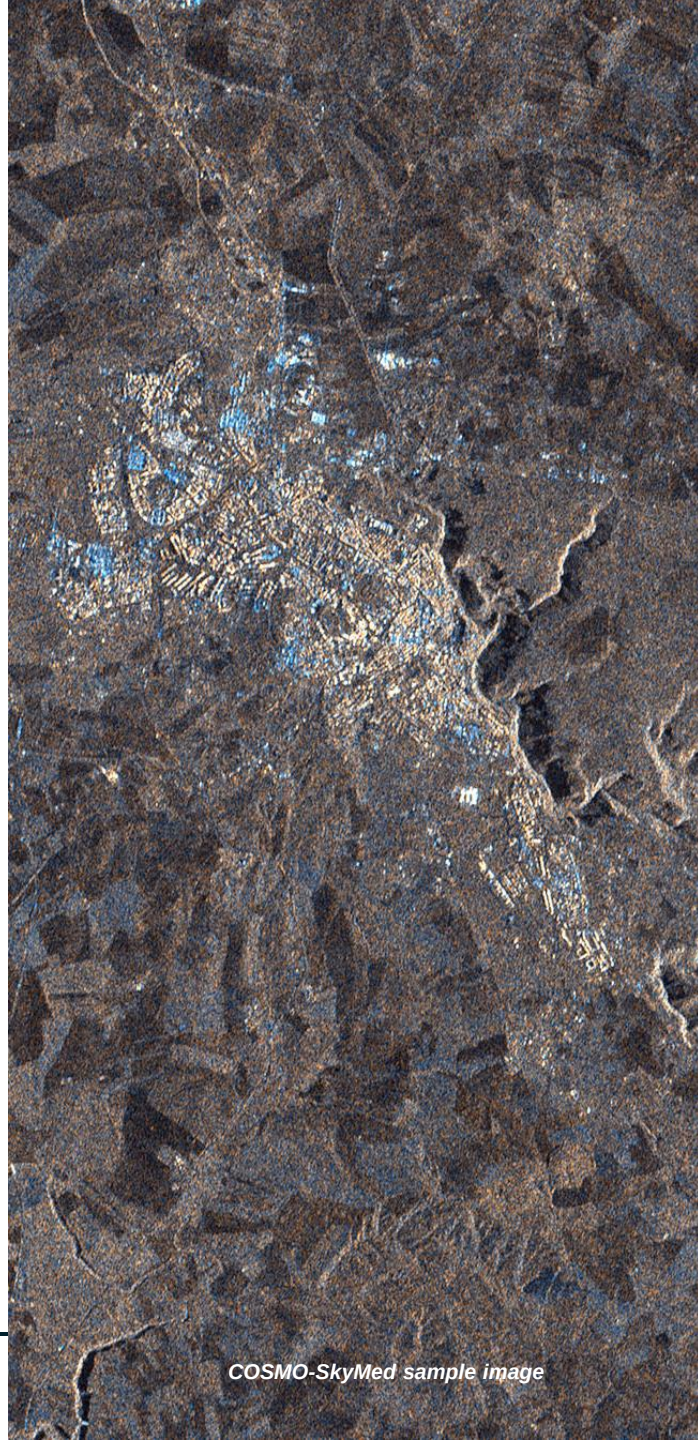
Master image



Slave image

SAR satellite dataset

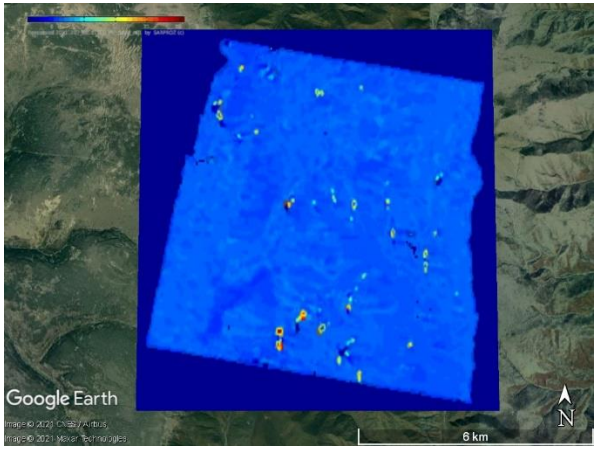
- SAR satellite dataset
  - Images acquired by CSK satellite constellation operating in X-band
  - 27 total images processed
    - 13 images pre-events
    - 14 images post-events
- Main characteristics of the SAR acquisitions
  - Spatial resolution: ~ 1 m
  - Chirp bandwidth: 250 MHz
  - Pulse Ripetition Frequency: 2.5 KHz
  - Pulse Ripetition Time: 0.23 ms
  - Antenna length: 6 m
  - Type of acquisition: Spotlight
  - Polarization: HH
  - Acquisition duration: 5 s
  - Platform velocity: 7 Km/s
  - Orbit height: ~ 600 km



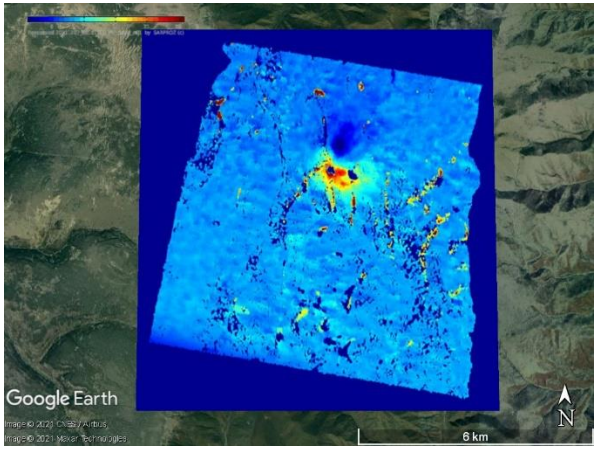
COSMO-SkyMed sample image

Eperimental results (1/3)

- Nuclear explosion occurs in a very small amount of time: not interested in the estimation of a displacement time series
  - Assuming that no other geological force caused significant movement at the Earth's surface
- Generated subsidence maps to cover the lange area around Mt. Mantap
  - No significative subsidence phenomena detected before nuclear test events
  - Very interesting subsidence phenomena observed by processing the the SAR images after the DPRK 6 event
    - North side of the mountain is in subsidence, characterized by a physical movement of the Earth's surface downwards of about -20 cm
    - South side has a positive subsidence of about +50 cm, which means a rise of the Earth's surface



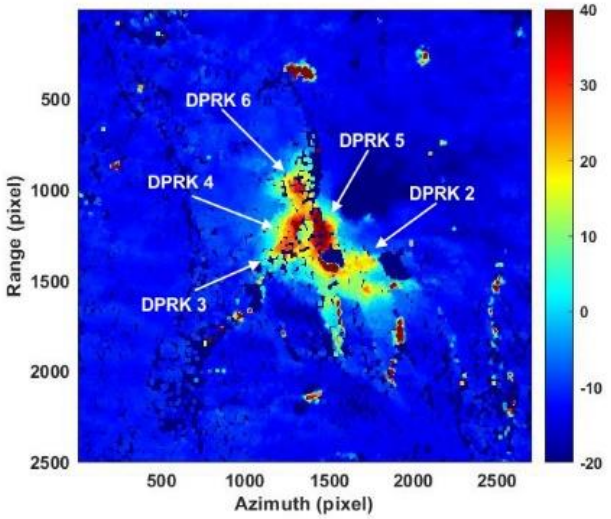
Eath displacement pre-events



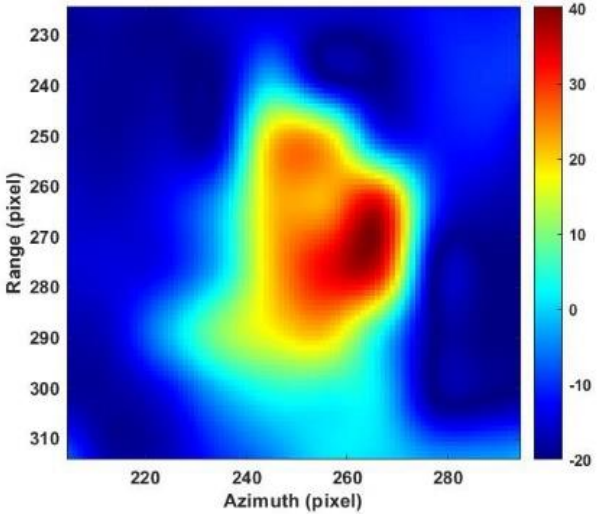
Eath displacement post-events

Experimental results (2/3)

- Analysis of the 2-D displacement-field
  - Geocoded data useful to estimate the position where the explosion occurred
  - Core of the energy pulse source with an asymmetric main lobe profile
    - not perfect uniformity, *i. e.*, “sinc-like” pattern, of the explosion or the internal material compositions of Mt. Mantap
  - Useful to understand the origin of the force field that generated the displacement, *i.e.*, the position of the nuclear weapon



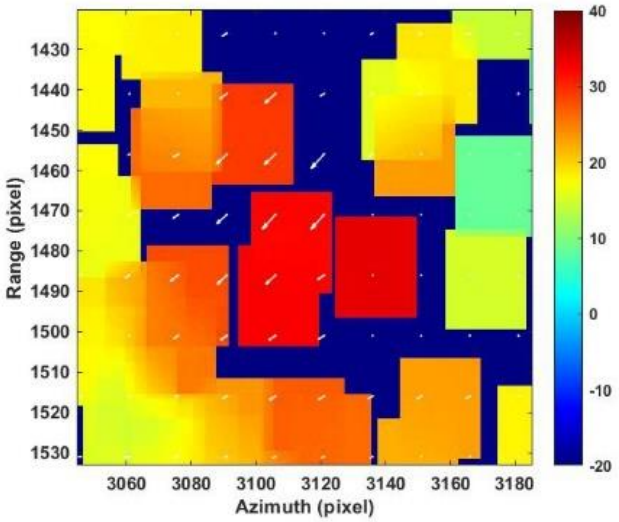
Displacement of the Mt. Matap summit with estimated locations of DPRK events



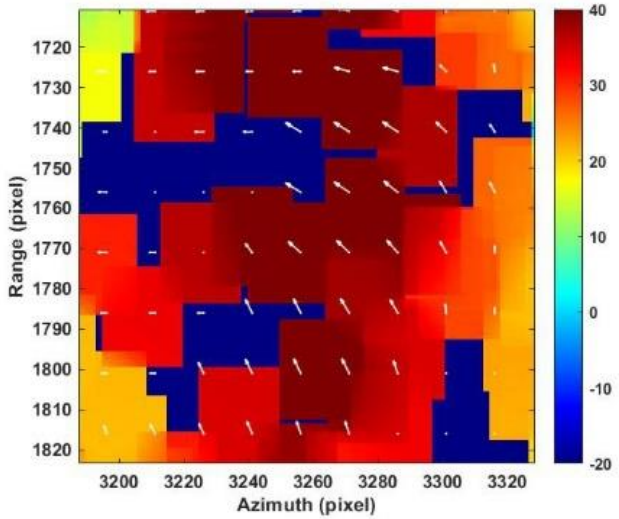
Detailed view of the DPRK 6 site

Experimental results (3/3)

- Analysis of the 2-D force-field displacement
  - Coherent representation (magnitude and phase) of the complex displacement estimated in range and azimuth directions
  - Give better information about spatial position where the origin of the energy pulse occurred
  - Useful to give interesting information about the tunnel networks



Displacement field for DPRK 5



Displacement field for DPRK 6

Conclusions

- Estimation of Earth deformation caused by the nuclear test performed at the Punggye-ri test site in North Korea
  - Six declared nuclear underground tests conduced by DPRK
- Methodology
  - Application of an alternative approach for estimating Earth displacement based on SPOT technique
    - Avoided technical defects and limitations of conventional techniques in estimating surface displacement
  - SAR data acquired by CSK satellite constellation
- Representative results
  - Overall analisys pre/post-nuclear events
  - Estimation of explosion locations
  - Retrieval underground tunnel network configuration