Remote Sensing Radar Interferometry and Precise Localization of the North Korean Nuclear Explosions

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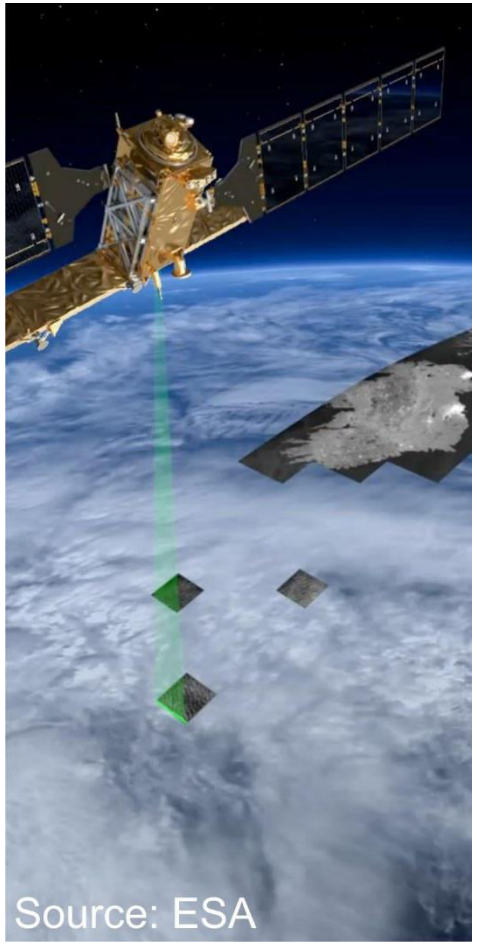
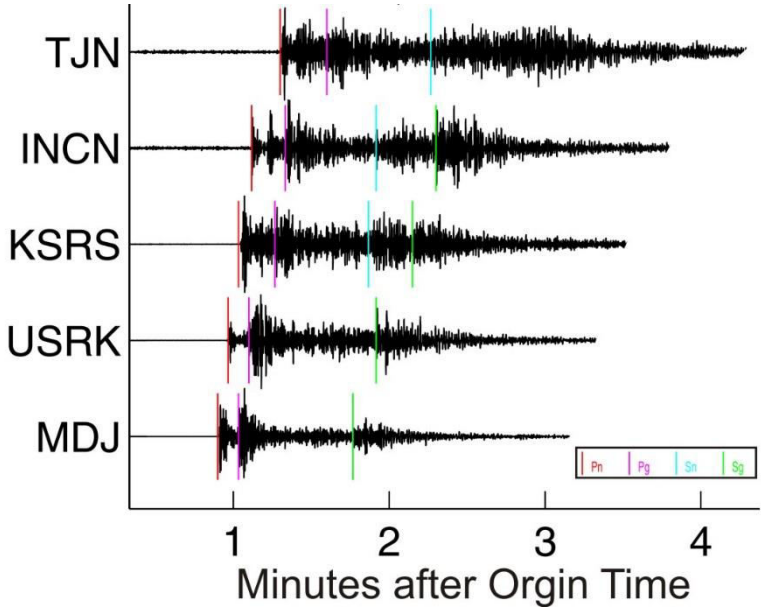
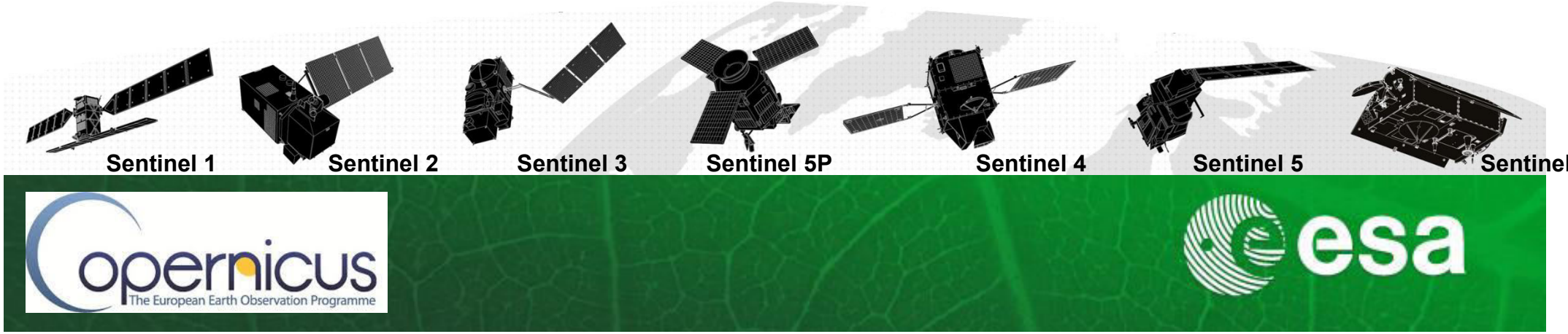
Outline



- Radar Interferometry with satellite-borne radar data for change detection along with nuclear explosions
- Correlation of seismic signals and relative localization of the nuclear explosions
- Achievement of precise source locations by combination of seismic and remote sensing technologies



Remote Sensing: Radar Mapping of the Earth

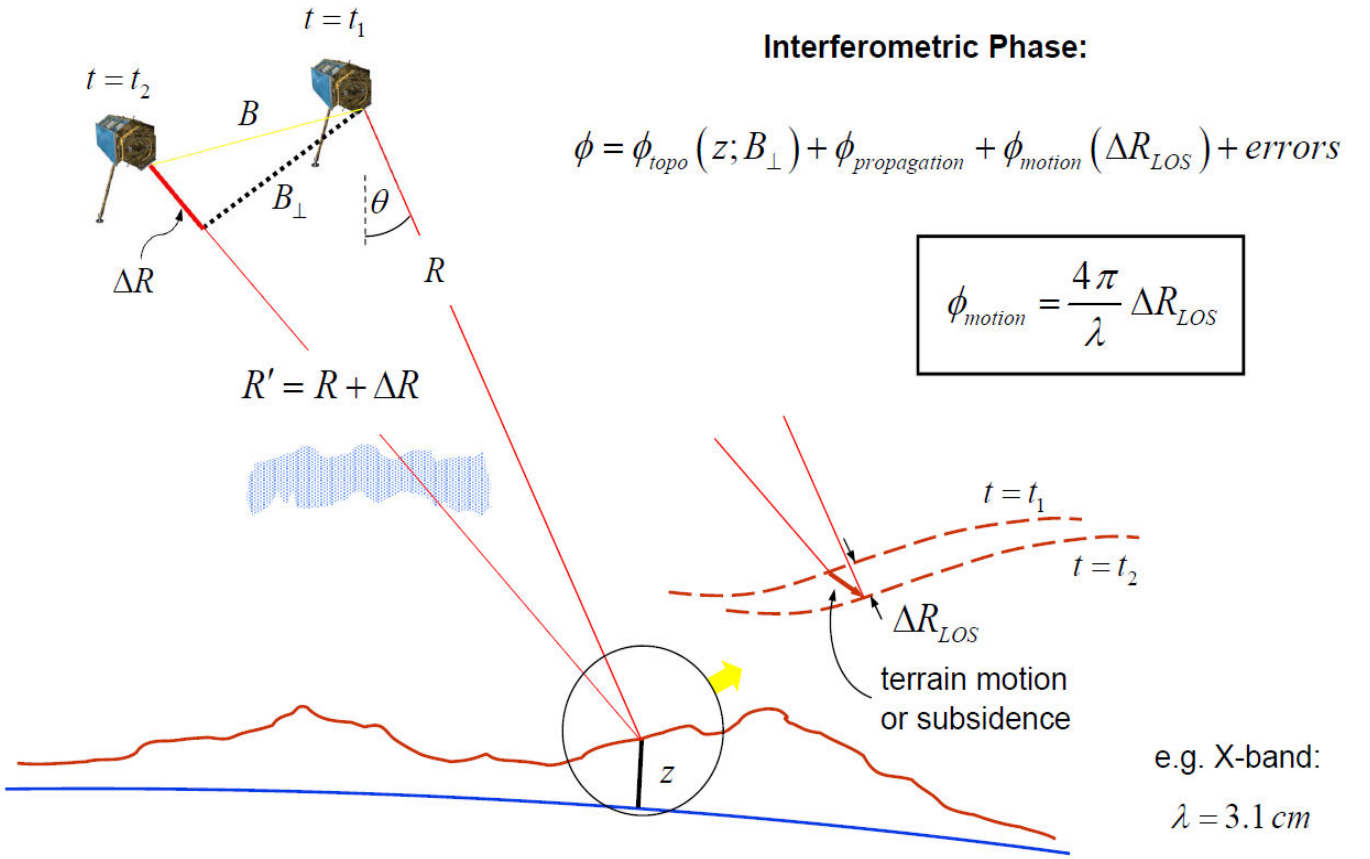


Sentinel 1: Land and ocean monitoring

- Two polar-orbiting satellites with weather-independent day and night performing C-band synthetic aperture radar imaging (SAR)
  Wavelength: 5.6 cm, Frequency 5.405 GHz
- Weight: 2.3 t, Dimensions: 2.8 x 2.5 x 4.0 m, 12 m-long radar antenna
  Orbit height: 693 km, Revisit time: 6 days (at the equator)
- Operating in four acquisition modes: Interferometry is best with the interferometric wide swath mode (IW) with 250 km swath
  Spatial resolution: 5 to 20 m
- Free and open data access policy – Online available within 24 hours

DInSAR: Method and Processing

Repeat-Pass and Differential InSAR Geometry



Interferometric Phase:

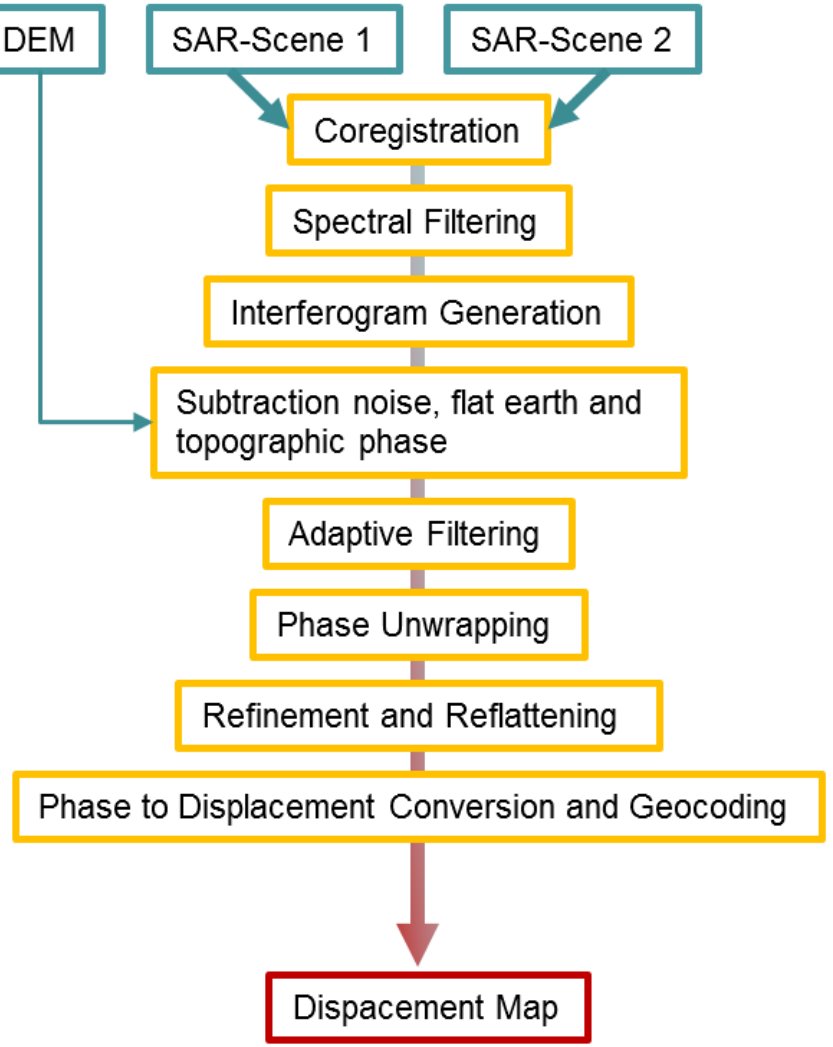
$$\phi = \phi_{topo}\left(z; B_\perp\right) + \phi_{propagation} + \phi_{motion}\left(\Delta R_{LOS}\right) + errors$$

$$\phi_{motion} = \frac{4\pi}{\lambda}\Delta R_{LOS}$$

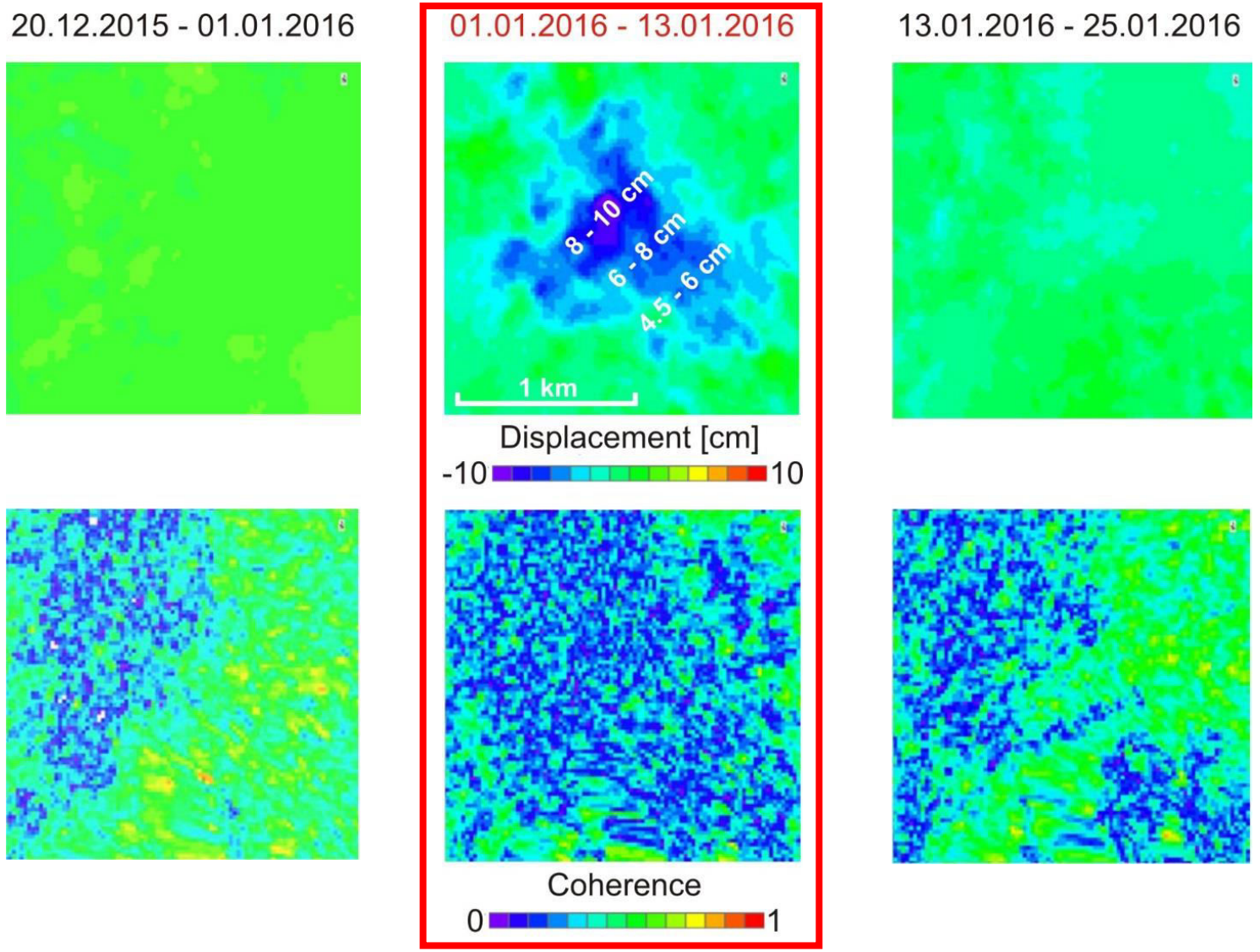
e.g. X-band:

$\lambda = 3.1\,cm$

R. Bamler: SAR Interferometry — Repeat-Pass and Differential InSAR



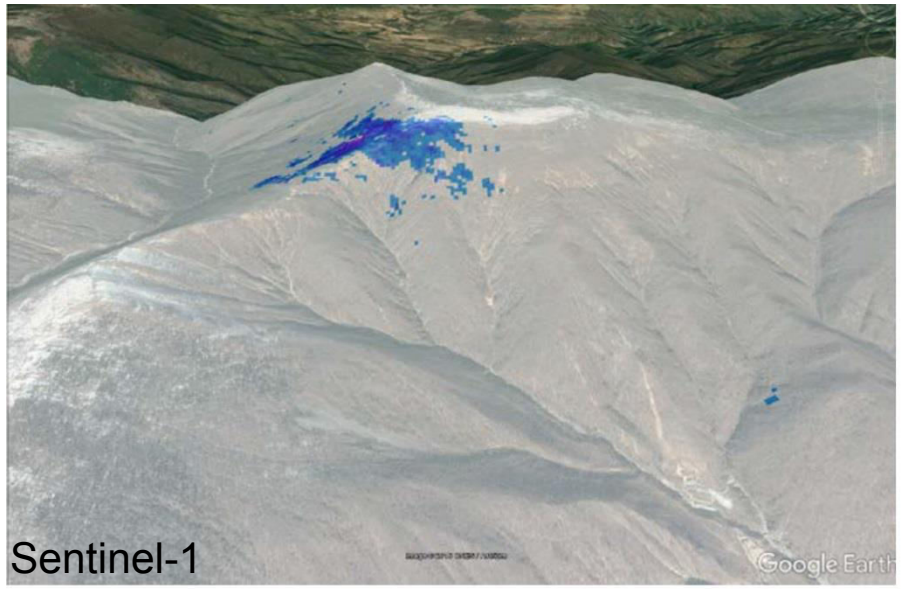
DInSAR: Results and Validation of the 2016-01-06 Nuclear Test



- Area of subsidence is detected 3 km Northwest from the west tunnel entrance at the North Korean Nuclear Test Site.
- Close spatial and temporal coincidence of the displacement area to the nuclear test site suggest a correlation with the underground test.

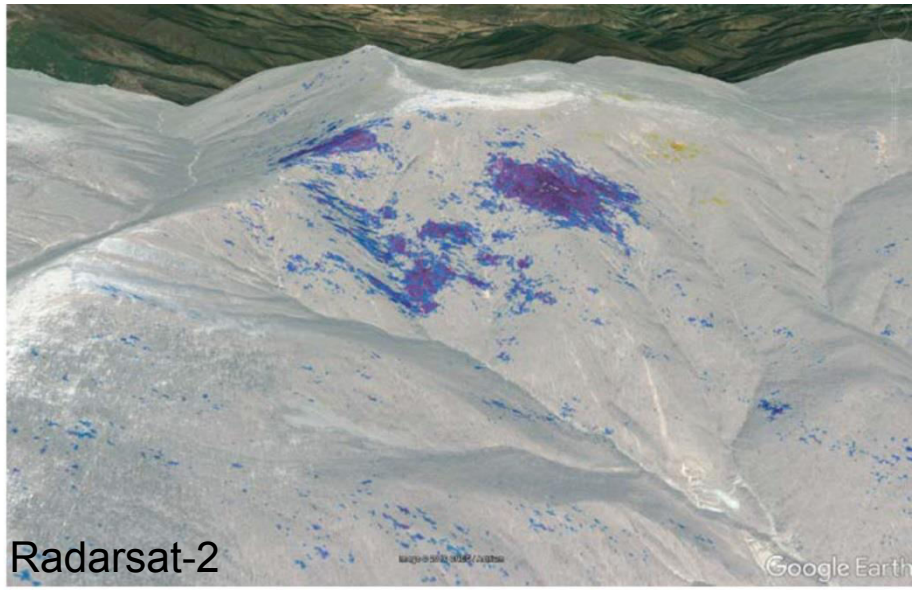
Surface Displacement after the Nuclear Explosions in 2016

Displacement Map for 2016-01-06 nuclear test

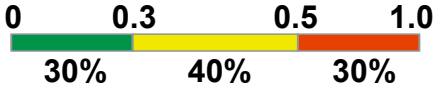


- Resolution: 20 m
- Mean Coherence: 0.5
- Acquisition time: 12 days
- Detected displacements: 84 – 90 %

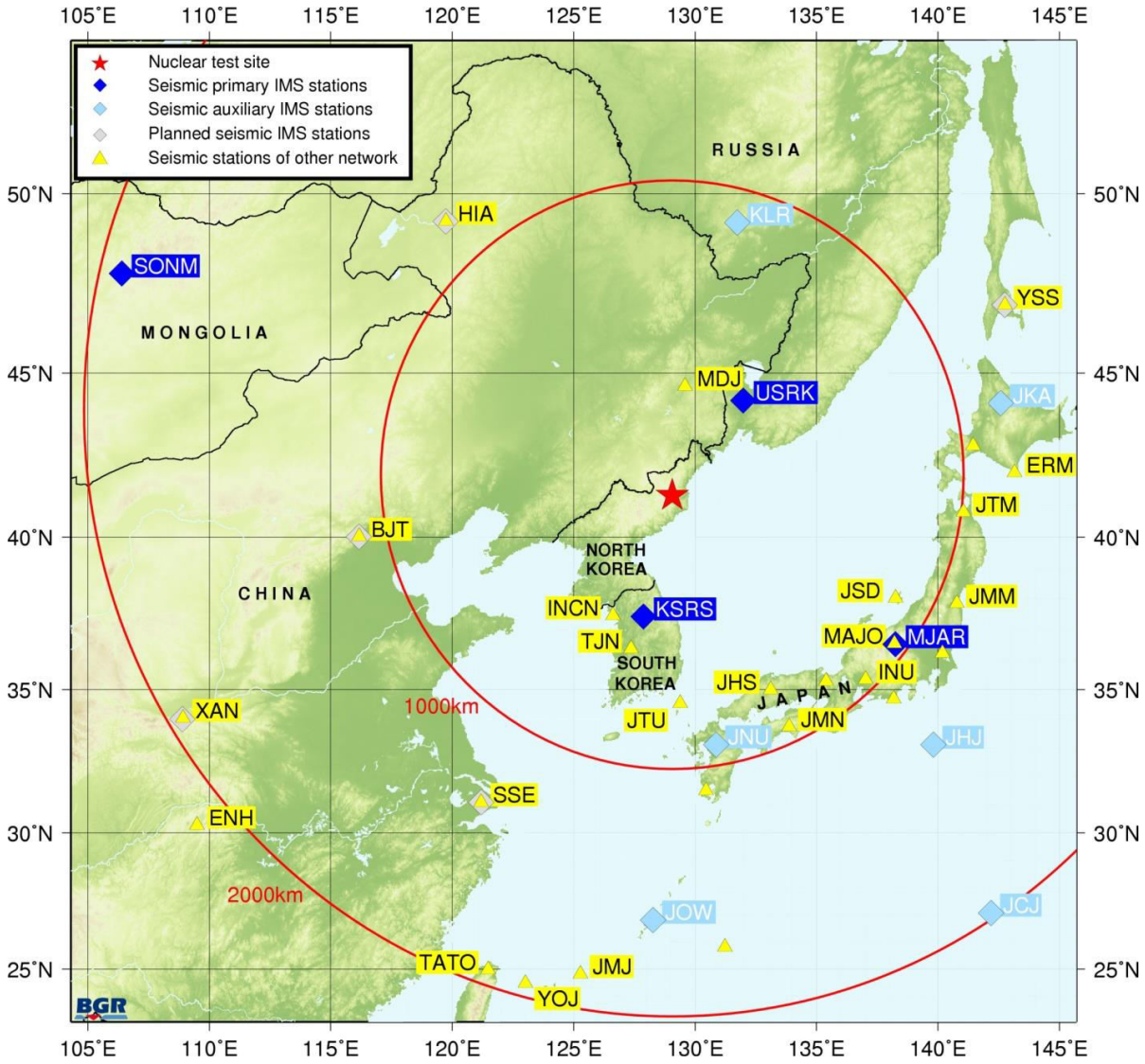
Displacement Map for 2016-09-09 nuclear test



- Resolution: 5 m
- Mean Coherence: 0.4
- Acquisition time: 24 days
- Detected displacements: 93 %



Seismic Localization

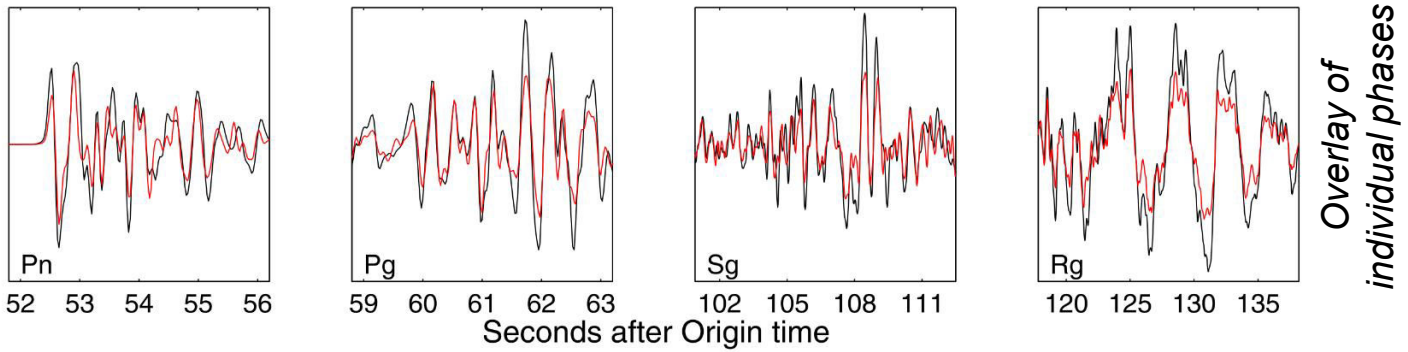


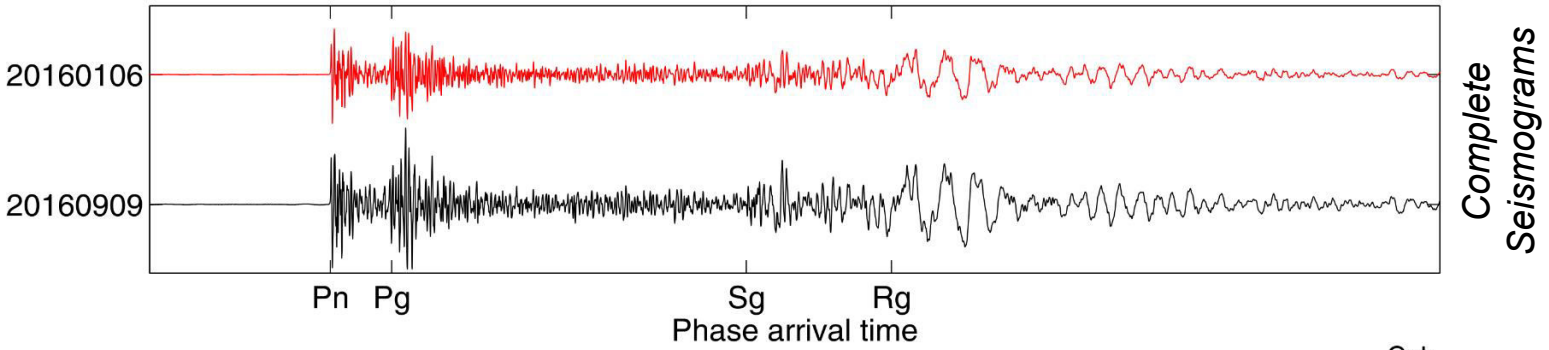
Seismic IMS stations used for localization of 2016-09-09 nuclear test

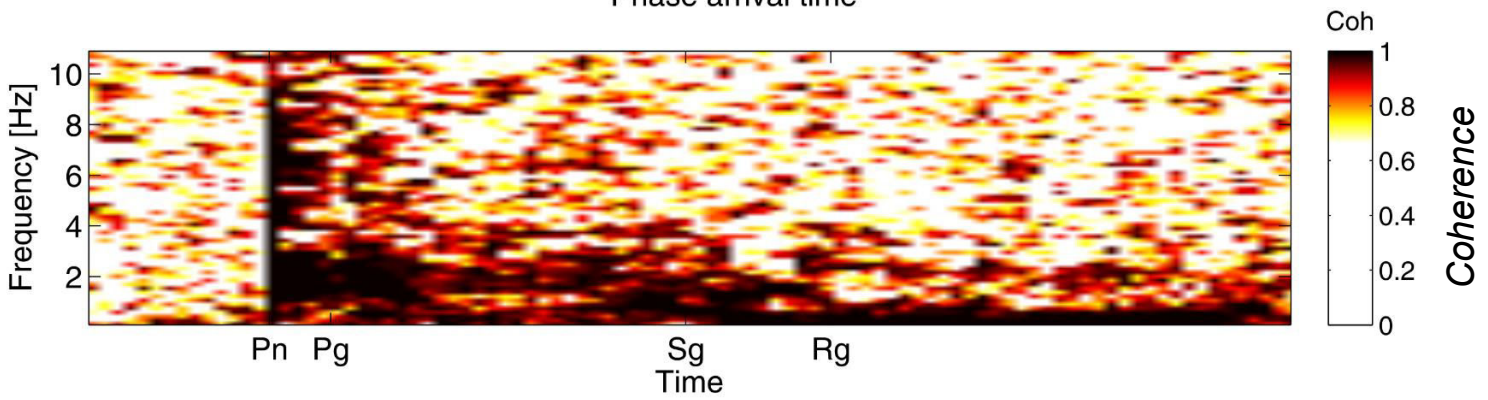
Location uncertainty

- Teleseismic localization with up to 97 IMS stations
  - Error ellipse ↓ 2006: 880 km²
  - Error ellipse ↓ 2016: 150 km²
- Regional localization with up to 18 IMS- and IRIS stations
  - Error ellipse ↓ 2006: 93 km²
  - Error ellipse ↓ 2016: 47 km²
- Relative localization
  - Error ellipse ↓ 2006: 0.4 km²
  - Error ellipse ↓ 2016: 0.2 km²

Comparison of the Seismograms



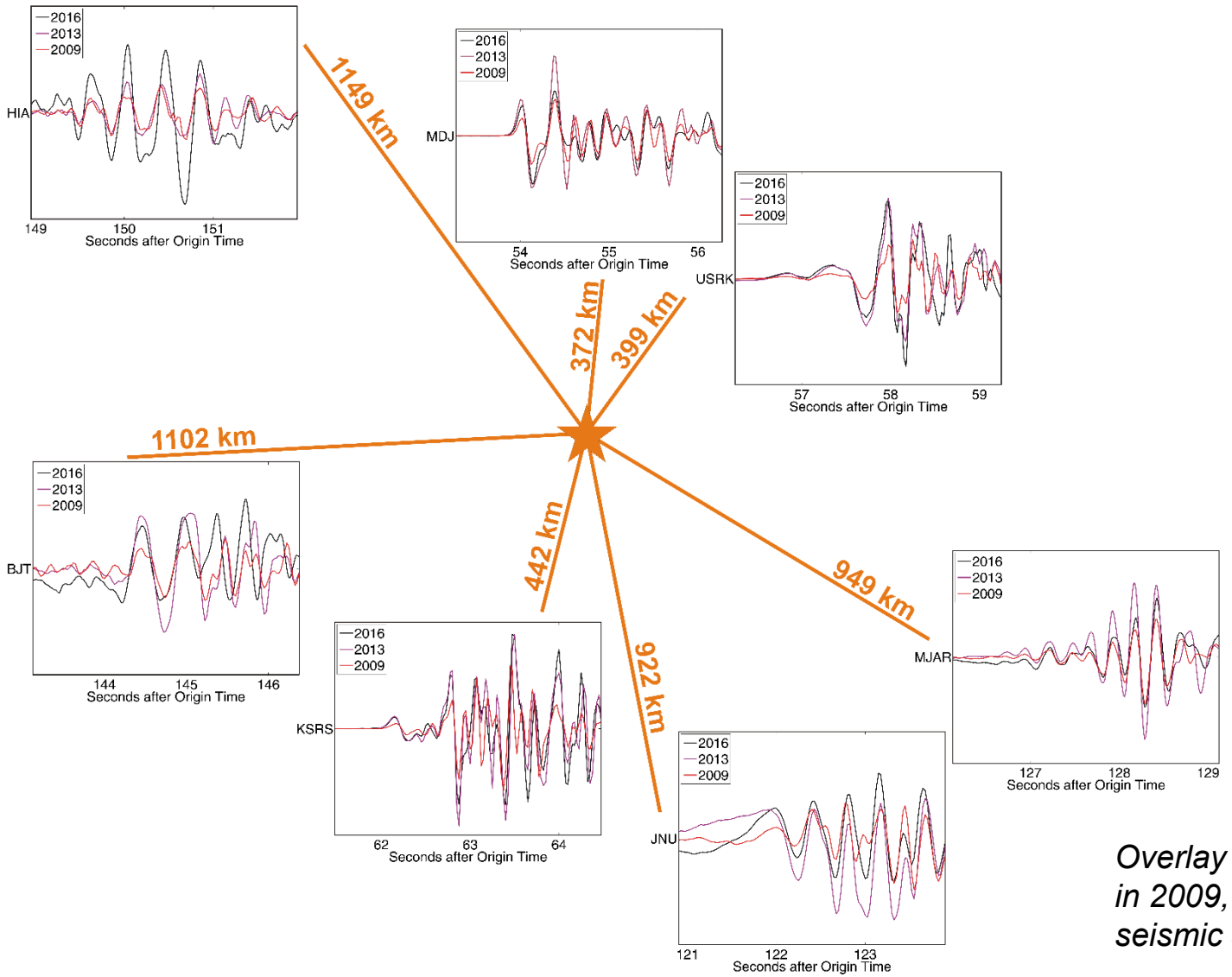




- The correlation of the seismograms for the nuclear explosions on 2016-01-06 (red lines) and 2016-09-09 (black lines) recorded at station **MDJ** confirms the high similarity.
- The amplitude differences reflect the stronger nuclear explosion on 2016-09-09 (Magnitude 5.3) than the one on 2016-01-06 (Magnitude 5.0).

*Position of the station Mudanjiang (**MDJ**) 372 km from the nuclear test site*

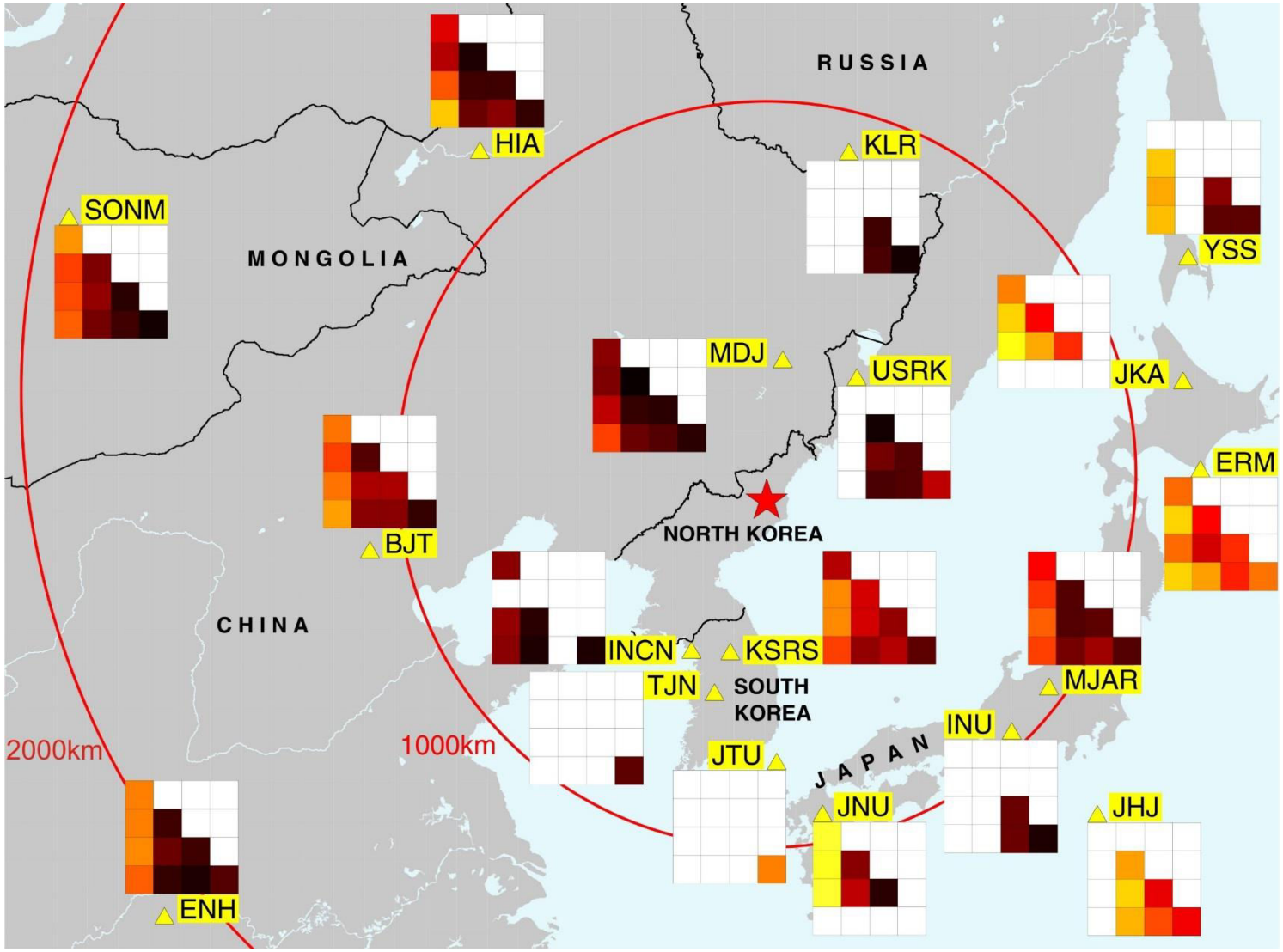
Comparison of the P waves



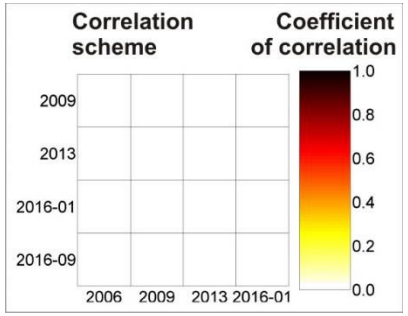
- The coherent frequency, the signal duration and the amplitude distribution in the wave train suggest a strong similarity between the source mechanism of the events.
- Small travel time differences of the signals substantiate the closely spaced location of the events.

Overlay of the P-waves of the nuclear tests in 2009, 2013, and January 2016 for selected seismic stations in regional distances

Correlation of the P waves

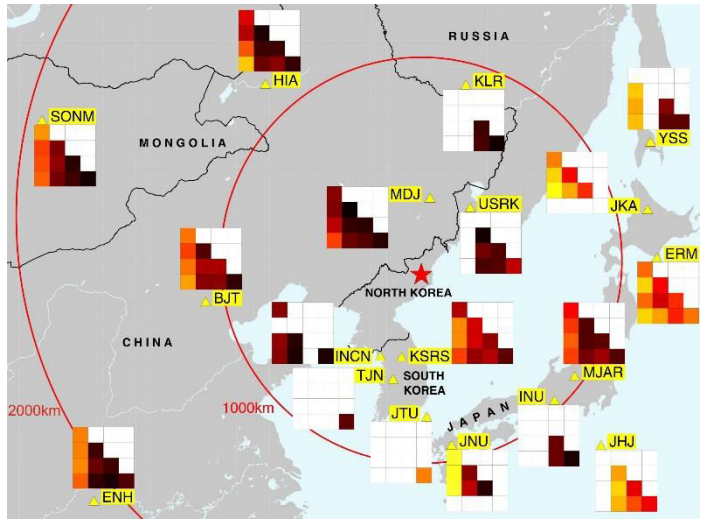


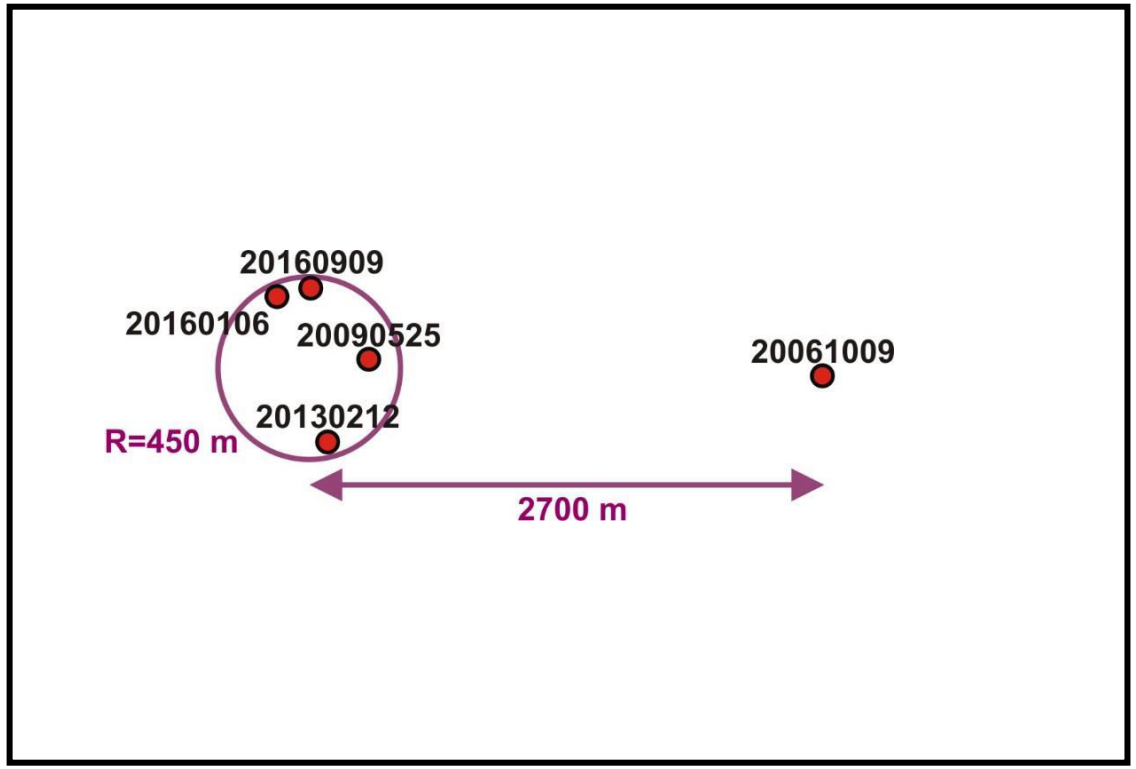
- Short and impulsive Pn wave trains provide reliable correlation of the five seismic events.
- Higher correlation coefficients between the signals of the four events 2009-2016 Lower correlation coefficients in comparison with the 2006 event.
- Correlation for stations north and west to the nuclear test site (red star) is higher than for the eastern stations



Results of the correlation of Pn signals for each pair of nuclear tests individually estimated for each station

Relative Localization





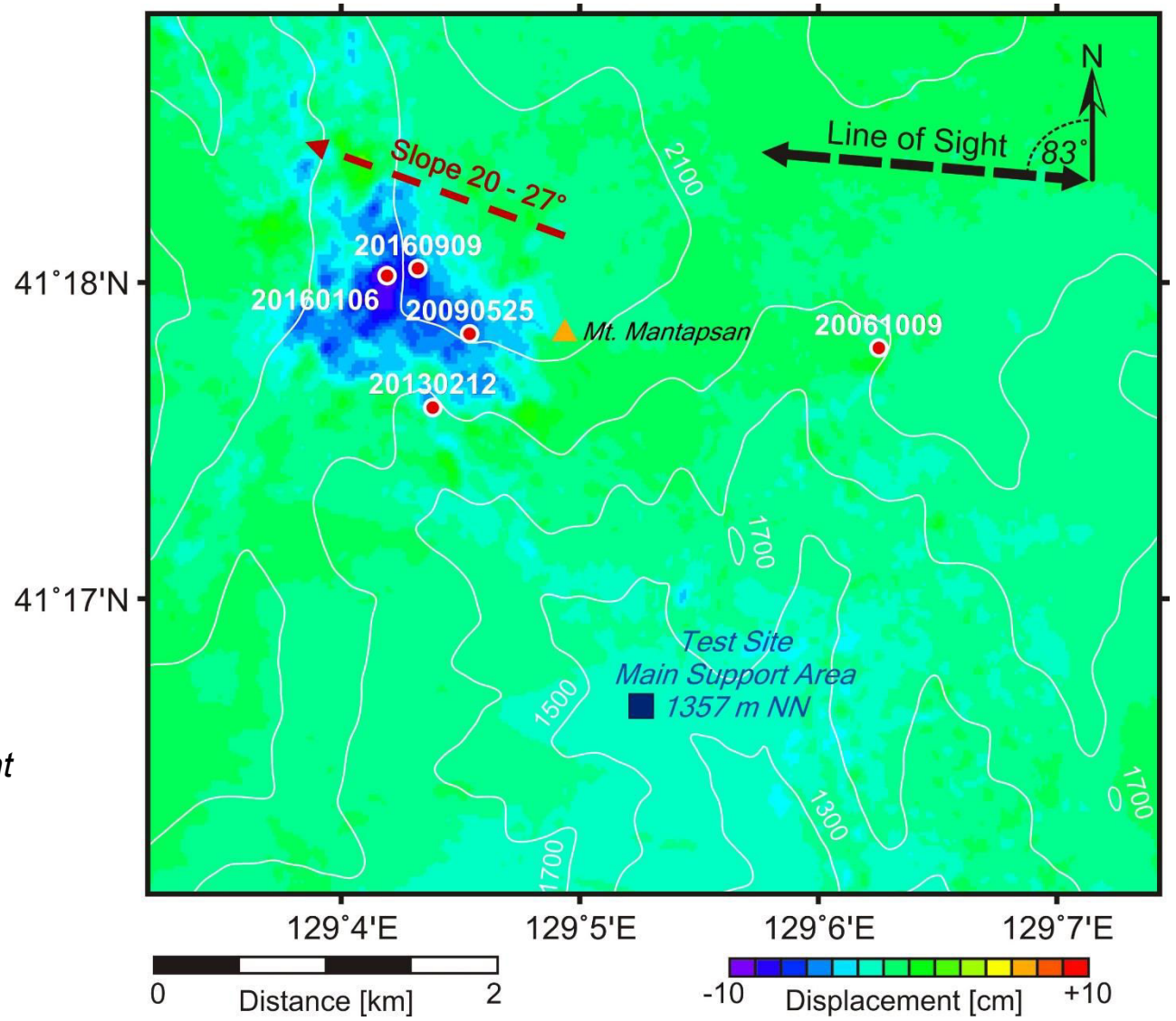
- Estimation of travel time differences for all pairs of events at the correlation maximum
- Travel time differences are lower than 0.5s.
- 103 travel time differences for the Pn wave are selected, having a correlation coefficient larger than 0.4
- Relative localization is applied with the Double Difference Algorithm (HypoDD, Waldhauser 2000).

		20061009	20090525	20130212	20160106	20160909
Number of stations		12	13	15	18	16
Accuracy of localization	E-W	450m	250m	225m	232m	239m
	N-S	315m	216m	215m	197m	210m

Combination of Relative Localization and Radar Interferometry

Determination of the absolute location for the North Korean nuclear explosions 2006 – 2016

- Adjustment of the precise relative location distribution to the results of the radar interferometry
- Selection of 2016-01-06 event for reference
- Fixing of the event position to the center of the area with the maximum surface displacement



Topographic map with the area of subsidence after the 2016-01-06 event resulting from radar interferometry. The estimated locations of the five nuclear tests are marked in red.

Conclusions

- DInSAR analysis identifies a delimited area of subsidence at the North Korean nuclear test site after both nuclear explosions in January and September 2016.
- Coherent seismic signals allow the estimation of travel time differences and to perform the relative localization with high accuracy.
- Results of radar interferometry are consistent with the seismic observations and contribute to the improvement of the localization.
- Satellite-borne radar missions open up avenues to complement the IMS by implementing of remote sensing tools as national technical means
- Acquisition strategies of satellite missions need to be adapted for systematic monitoring of potential test sites. Therefore operational processing and evaluation of radar data should be targeted for change detection.