Sub-Pixel Offset Tracking at Volcanoes

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3 USGS science for a changing world
4 NERC GW4+ Doctoral Training Partnership
5 CEOS Committee on Earth Observation Satellites

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SUMMARY:

- Volcanoes can create large (>1 m) displacements which cannot be tracked with InSAR.
- We define a robust procedure for displacement tracking using sub-pixel offset tracking (SPOT) with SAR data.
- We use outlier detection and removal using PCA and HDBSCAN as well as averaging several window sizes to improve precision.
- We test the procedure on Merapi volcano. Where we see complex cm-m scale displacements on the steep slopes of the volcano with cm precision.

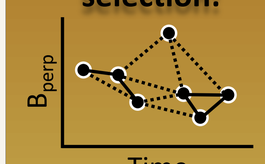
Summary of procedure

↓

Lots of SAR data

Number of Acquisitions: 10 – 100

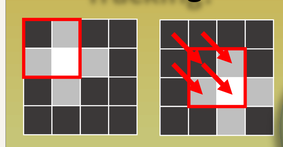
Image pair selection:



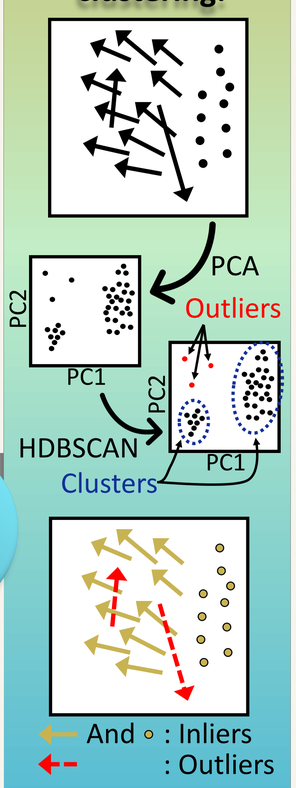
···· SPOT only

— SPOT + Hi-res InSAR

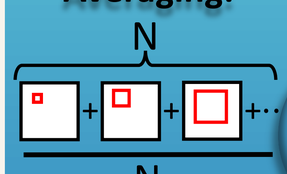
Sub-Pixel Offset Tracking:



Outlier removal using PCA and clustering:

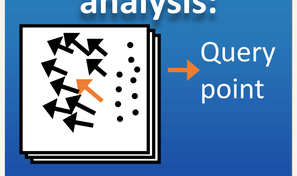


Multi-Kernel Averaging:

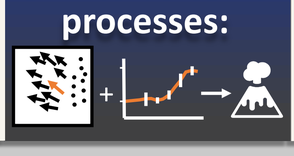


TO-DO

Time series analysis:



Link to volcanic processes:



1 InSAR vs. Sub-Pixel Offset Tracking (SPOT)

There are **two** ways to extract displacement from SAR data: **InSAR** and **Sub-Pixel Offset Tracking (SPOT)**.

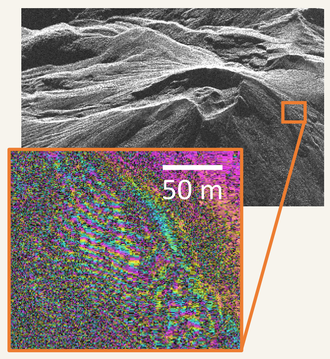


Fig 1. Example of an interferogram where the fringes get too dense to be useful.

Scan the QR-code to see an animation of the pixel offsets at Merapi volcano!

What is SPOT?

- SPOT measures the offset of matching pixel patterns between two images taken at different times.

InSAR	Sub-Pixel Offset Tracking (SPOT)
– No large baseline	– Uses SAR intensity data
– Max. displacement gradient: 1 fringe/pixel	– Minimum detection limit: 1/10 × pixel size.
– Minimum detection limit: 1 cm per interferogram, ≤1 mm for time series.	– Gives offset in slant range and azimuth direction.
	– Reduced baseline dependence.

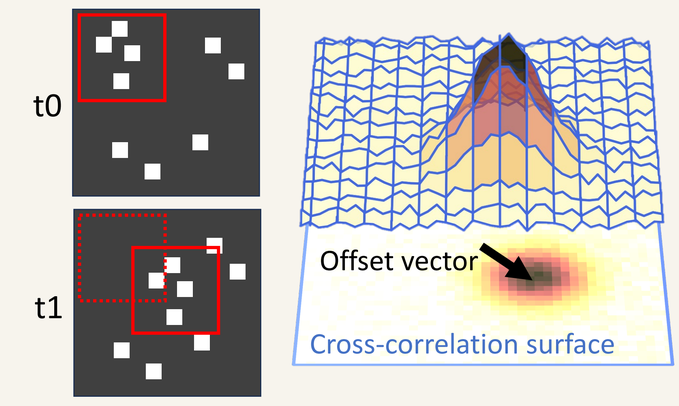
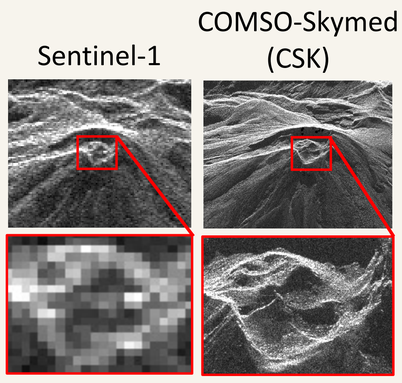


Fig 2: Sub-Pixel Offset Tracking set-up. (**Left**) shows search kernel move to find matching pattern in images taken at t0 and t1. (**Right**) shows cross-correlation surface with offset estimation at the peak.

2 SPOT and image pair selection

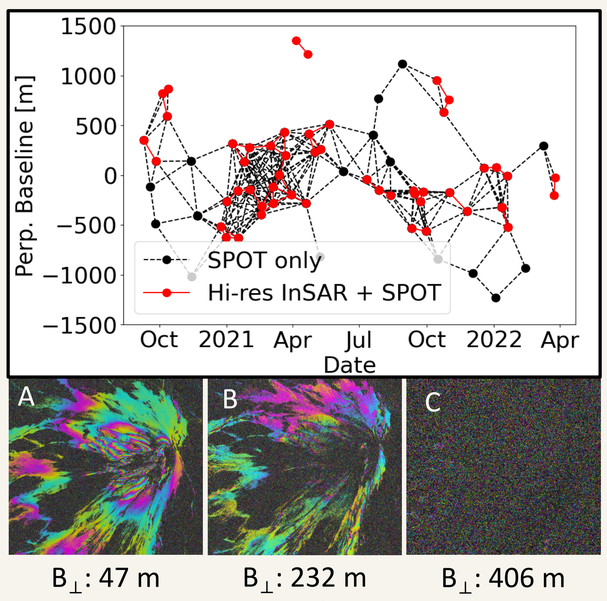
Why use SPOT?

- In extreme cases volcanoes can show large (>1m) deformation over small areas (<2 km). Often in areas with no or sparse ground monitoring.
- These large displacement (gradients) cannot be tracked with InSAR. But SPOT can track these large displacements.
- The reduced baseline dependence of SPOT also allows us to process more data to get complete temporal coverage.
- High resolution SAR is needed to increase the precision of SPOT.



	Resolution [m]	
	15	1
Perpendicular baseline ($B_\perp$)[m]	≤400	≤2700
Temporal baseline (B_t) (days)	12	1 – 32

Fig 3. Examples of SAR data resolution and information about datasets used. Red is bad for InSAR and/or SPOT, orange is feasible, green is good.



A	B	C
$B_\perp$: 47 m	$B_\perp$: 232 m	$B_\perp$: 406 m
B_t : 8 days	B_t : 7 days	B_t : 39 days
Usable	Barely usable	Not usable

Fig 4: Baseline plot for CSK descending data. A-C show examples of interferograms that become unusable with large baseline.

3 Outlier removal via clustering

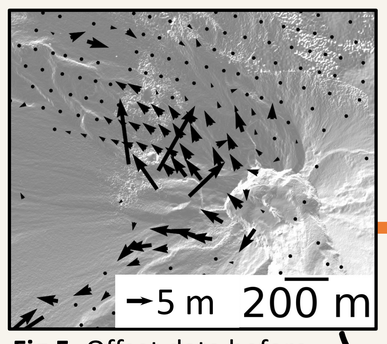


Fig 5: Offset data before outlier detection.

Outlier detection and removal:

1. Apply Principle Component Analysis (PCA) to:
   - Lat, Lon, Range offset, and Azimuth offset
2. Cluster using HDBSCAN
3. Classify and remove outliers

Apply to each image pair and window size.

PCA

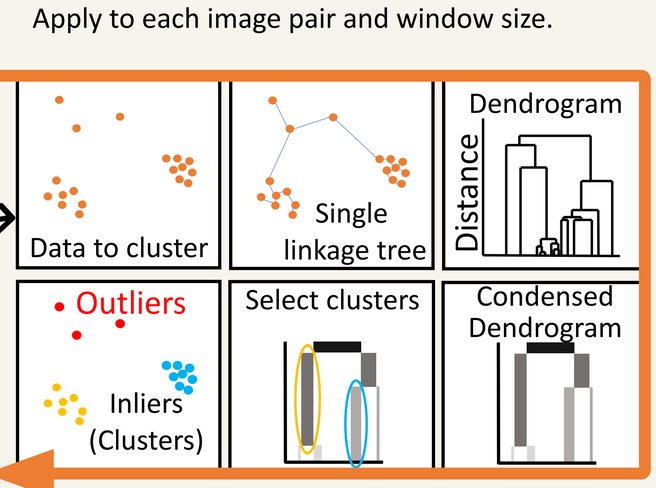


Fig 6: HDBSCAN clustering procedure.

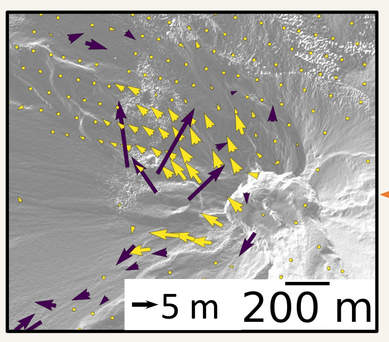


Fig 7: Offset data with outliers detected. Yellow = inlier, Purple = outlier

To do: Make testing dataset by visual inspection to test the performance of the outlier detection.

HDBSCAN \ Test data	In	Out
In	True positive	False positive
Out	False negative	True negative

4 Multi-Kernel Averaging (MKA)

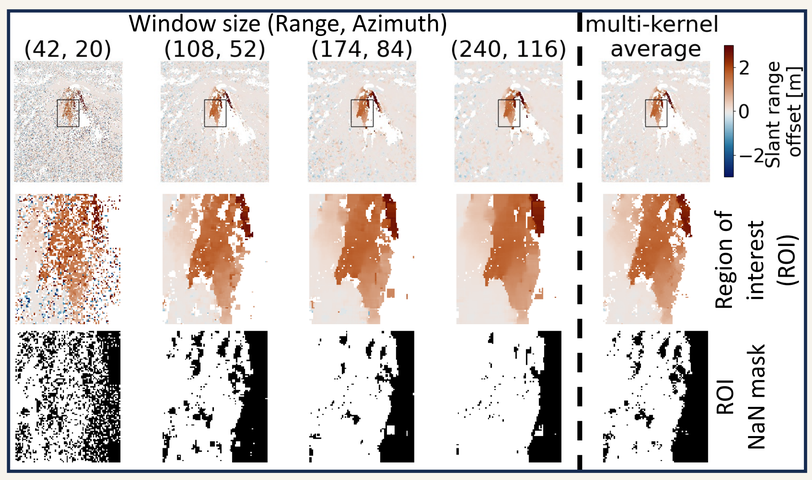


Fig 8: Example MKA result. (Top) slant range offset map with region of interest (ROI) as black rectangle. (Middle) slant range offset in ROI. (Bottom) NaN mask of ROI.

Multi-kernel averaging (MKA) uses an ensemble of offset maps from multiple different window sizes (kernels) and averages to create robust offset maps.

Procedure, per pixel:

1. Remove data outside 95% confidence interval.
2. Only use pixel if >50% of ensemble has valid data (is not NaN).
3. Take mean across the ensemble.

Benefits:

- Improves the precision by a factor of 2-3.
- Reduces noise/outliers and 'blocky' borders/gradients, and keeps small features.

Downsides:

- Computationally expensive to make ensemble.
- A-priori selection of window sizes. **(future work to mitigate)**

5 Results

	Range offset std (r=50 m) [m]		Azimuth offset Std (r=50 m) [m]		NDVI [-]
	Before	After	Before	After	
A	0.047	0.015	0.108	0.048	0.03
B	0.388	0.133	0.366	0.123	0.85
C	0.070	0.032	0.196	0.117	0.02

Fig 9 & Table 1: Comparison of offset estimation before and after HDBSCAN and MKA. B has dense vegetation, A and C don't. C has large displacements, A and B don't.

CONCLUSION:

Our outlier-removed, multi-kernel averaged offset maps can measure displacement to 1-10 cm level precision.

References

Casu, F., Manconi, A., Pepe, A., & Lanari, R. (2011). Deformation time-series generation in areas characterized by large displacement dynamics: The SAR amplitude pixel-offset SBAS technique. *IEEE Transactions on Geoscience and Remote Sensing*, *49*(7), 2752-2763.

Chae, S. H., Lee, W. J., Baek, W. K., & Jung, H. S. (2019). An improvement of the performance of SAR offset tracking approach to measure optimal surface displacements. *IEEE Access*, *7*, 131627-131637.

McInnes, L., Healy, J., & Astels, S. (2017). HDBSCAN: Hierarchical density based clustering. *J. Open Source Softw.*, *2*(11), 205.

Michel, R., Avouac, J. P., & Taboury, J. (1999). Measuring ground displacements from SAR amplitude images: Application to the Landers earthquake. *Geophysical Research Letters*, *26*(7), 875-878.