10 years of InSAR in the Kivu Rift basin: Results and Perspectives

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Outline

- Introduction:
  - Active volcanoes in the tropics: InSAR capabilities (ESA–CAT 1 / SAMAAV)
  - Major outputs

- Focus on the Kivu Rift Basin

- Sparse / systematic and multimode acquisitions

- New methodologies, new opportunities: the MSBAS method

- Studied cases

- Conclusions and perspectives
African volcanoes with no/few ground based monitoring system.

Can InSAR help (vegetation-induced decorrelation) ?

Intensive image acquisition procedure to increase chances of small baselines
Dyke intrusion in a youthful continental rift revealed by InSAR: Lake Natron (Tanzania), 2007

Area of largest estimated dyke opening coincides with largest normal stress decrease along pre-dyking normal faulting Earth Quake. Deformation was achieved by slow slip on a normal fault that promoted subsequent dyke intrusion by stress unclamping.

Calais et al., 2008
Nature
ITCZ seasonal oscillations:
Fogo and Mount Cameroon

Seasonal oscillations of the Inter-Tropical Convergence Zone => variation of precipitable water vapor in troposphere (PWV estimated by GPS and MODIS)

Monsoon: April/June and in September/October
Dry seasons: December/January and July

Heleno et al., 2010
Seasonal Tropospheric Influence on SAR Interferograms near the ITCZ – the case of Fogo Volcano and Mount Cameroon
Journal of African Earth Sciences, vol. 58; Iss. 5, 833-856, 2010

PS: No correlation between # fringes and height of ambiguity
Needs in Goma: almost no monitoring
West: Virunga Volcanic Province

- Nyamulagira: most active in African; ~2 years
  + Volcanic plume, Pele’s hair & mazuku
- Goma: 1 Mo inhabitants (+2,000% since 1977)
- Lake Kivu: CO2 + CH4

Background map: Smets et al., 2010 J. of African Earth Sciences
West: Virunga Volcanic Province

Nyamulagira: most active in African; ~2 years

Nyiragongo: 1977 & 2002. Most fluid lavas; largest lava lake + Volcanic plume, Pele’s hair & mazuku

Goma: 1 Mo inhabitants (+2,000% since 1977)

Lake Kivu: CO2 + CH4

Armed groups: field not accessible

Political context: neighbors

Background map: Smets et al., 2010 J. of African Earth Sciences
The Nyamulagira Nov. 2006 eruption (North Kivu, DR Congo)

ENVISAT ascending Swath I7: Small Temp baseline (35 days) and Bperp.

8-10 fringes with positive range change (i.e. ~ 22 to 28 cm)

1.75 fringes with negative range change (i.e. ~5 cm)

Positive range change of 7 fringes (i.e. ~20 cm)

Only visible on one small baselines pair

Wauthier et al., 2013
Cayol et al., in prep.
But also:
Nyiragongo 2002 eruption

Wauthier et al., 2012
J. Geophys. Res.
Encouraged by these results, 
Given the identified needs:

- More projects focusing on the Virunga Volcanic Province
- Enlarge the study to include ground based monitoring networks
- Link with health: volcanic hazard not limited to eruptions
- Oriented toward end-users

van Overbeke et al., 2010
Cahier du Centre Européen de Géodyn. & Seism.
Bukavu/Cyangugu 2008 EQ (South Kivu, DR Congo)

- Relocation of the event
- InSAR: Brittle rupture, no magma involved

d’Oreye et al., 2011
Geoph. J. Int.
Amount of data =>
new methodologies & new opportunities

The Multidimensional Small Baseline (MSBAS) method:

Advantage of the method:

- Combines data sets from any kind of sensor, geometry, mode, wavelength, polarisation etc...

- Very high spatio-temporal resolution

- Averages out various sources of noise (i.e. tropospheric, ionospheric, orbital, etc.) improving the signal-to-noise ratio.

- Provide vertical and horizontal time series

Principle

The Small Baseline (SBAS) method (Berardino et al. 2002; Usai, 2003).

\[ AV_{\text{los}} = \Phi_{\text{obs}} \quad \rightarrow \quad V_{\text{los}} = A^+ \Phi_{\text{obs}} \quad \rightarrow \quad d_{\text{los}}^{i+1} = d_{\text{los}}^i + V_{\text{los}}^{i+1} \Delta t^{i+1} \]

\( d \): LOS displacements

\( A \): time matrix
\( V \): Unknown velocities
\( \Phi \): Observed interferograms

When multiple data sets: for each \( k=1,2,\ldots K \) data set : \( v_{\text{los}} = \mathbf{v} \mathbf{s} = S_N V_N + S_E V_E + S_U V_U \),

where \( v_{\text{los}} \) = line-of-sight scalar velocity
\( \mathbf{v} = \) velocity vector \( \mathbf{v} (V_N, V_E, V_U) \)
\( \mathbf{s} = \) unit vector \( \mathbf{s} (S_N, S_E, S_U) \) pointing to the sat.

\[ A_{\text{los}}^k = \Phi_{\text{obs}}^k \quad \rightarrow \quad \begin{vmatrix} S_N^k A, S_E^k A, S_U^k A \end{vmatrix} \cdot \begin{bmatrix} V_N, V_E, V_U \end{bmatrix}^T = \Phi_{\text{obs}}^k \]

For all \( K \) datasets:

\[ \begin{pmatrix} A^1 \\ A^2 \\ \vdots \\ A^K \end{pmatrix} \begin{pmatrix} V_N \\ V_E \\ V_U \end{pmatrix} = \begin{pmatrix} \Phi^1 \\ \Phi^2 \\ \vdots \\ \Phi^K \end{pmatrix} \quad \text{or} \quad \hat{A} \hat{V}_{\text{los}} = \hat{\Phi}_{\text{obs}} \]

\[ \Rightarrow \text{Poster 84 for discussion} \]
Is MSBAS method valid / meaningful?

1. From a mathematical point of view:
   - The SVD solution is numerically stable – all singular values are large.
   - Rank deficiency is solved by Tikhonov regularisation (or temporal LP filtering). This is preferable to interpolation of datasets to a common grid as it propagates noises (atm., orb...) in the interpolated data.
   - (Valid if $V_N$ not >> $V_E$)

2. Does the solution have physical meaning?
   - Simulated interferograms: YES
   - Real cases of natural and anthropogenic defo. (incl. ground truth verifications) : YES
     Samsonov S. et al. GRL, 2014a, 2014b (Hawaii, Campi Flegrei)
     Samsonov S. et al. , Rem. Sens. of Env., 2014 (Vancouver)
     Samsonov S. et al., NHESS, 2014 (Saskatchewan)
     Smets B. et al., Bull. of Volc., 2014 (Conpo)
     Samsonov S. et al., Int. J. of Applied Earth Obs. and Geoinf., 2012 (French-German mines)
     Samsonov S. and N. d’Oreye, G. J. Int., 2012 (Congo)

⇒ Poster 84 for discussion
Application to the Virunga Volcanic Province, DR Congo.

Available datasets: 8 years; 3 satellites; 8 geometries => 1051 interferograms

<table>
<thead>
<tr>
<th>InSAR set</th>
<th>Time span</th>
<th>θ (°)</th>
<th>φ (°)</th>
<th>N</th>
<th>M</th>
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<td>181</td>
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</table>

N: number of SAR images
M: number of interferograms
θ: azimuth
φ: incidence (look) angle
Background = vertical mean velocity (2003-2010).

Post-eruptive long term subsidence rate changes

Figure 7. 2003-2010 east-west and vertical time series of ground deformation at points P4-P8 (rows top to bottom). Raw (first column), regularized (second column) and filtered (third column) time series are shown.
Background = vertical mean velocity (2003-2010).

Precursors

Time, year

Displacement (cm)

Fitted

-3 weeks

Signal

~3 weeks

Field

East-West detrended

Up-Down detrended

East-West

Up-Down
Are these precursors significant?
Are these precursors significant?
Are these precursors significant?
The Nyamulagira 2010 case study

Seismicity

SO$_2$

InSAR (MSBAS)

(Semts et al., Bull. Volc., 2014)
The Nyamulagira 2011-2012

Observations  Model  Residuals

Courtesy : P. Gonzalez

d’Oreye et al in prep.
TDX high resolution DEM
TDX high resolution DEM
Then enlarge the area

- Regional approach
- Multi hazards
- Triggering factors (RESIST.africamuseum.be)

- Risk assessment / societal aspects (GEORISCA.africamuseum.be)
Landslides: Stamps time series

Time Series of ENVISATAscending, Track 228.

Dark Blue = displacement of ca -5cm in LOS / 3.5 years

Landslides: Stamps >me series
Landslides: Stamps time series
Nyiragongo Lava Lake Level monitoring

Split Band InSAR $\rightarrow$ absolute phase unwrapping & WS InSAR/DInSAR

De Rauw et al, this meeting
Nyiragongo Lava Lake Level monitoring

Crater bottom rise and lava lake level fluctuation measured by shadow casted by rim and cliffs
(See poster 84 – d’Oreye et al.)
Conclusions

➢ Research in that area requires a long term perspective

➢ Sustainability of research and associated development involves:
  • Strong commitment and networking with local authorities
  • Training, maintenance of ground based systems etc.
  • Societal aspects
  • (➔ poster 83)

➢ Methodological development are promising
  • SplitBand and MSBAS are promising
  • (➔ poster 84)

➢ Main requirement in SAR data:
  • High acquisition rate
  • Appropriate geometry and baseline (Asc / Desc, incidence)
  • Wavelength (and polarization)