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Sentinel-1 InSAR: first results from seismic and volcanic applications

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GAMMA REMOTE SENSING

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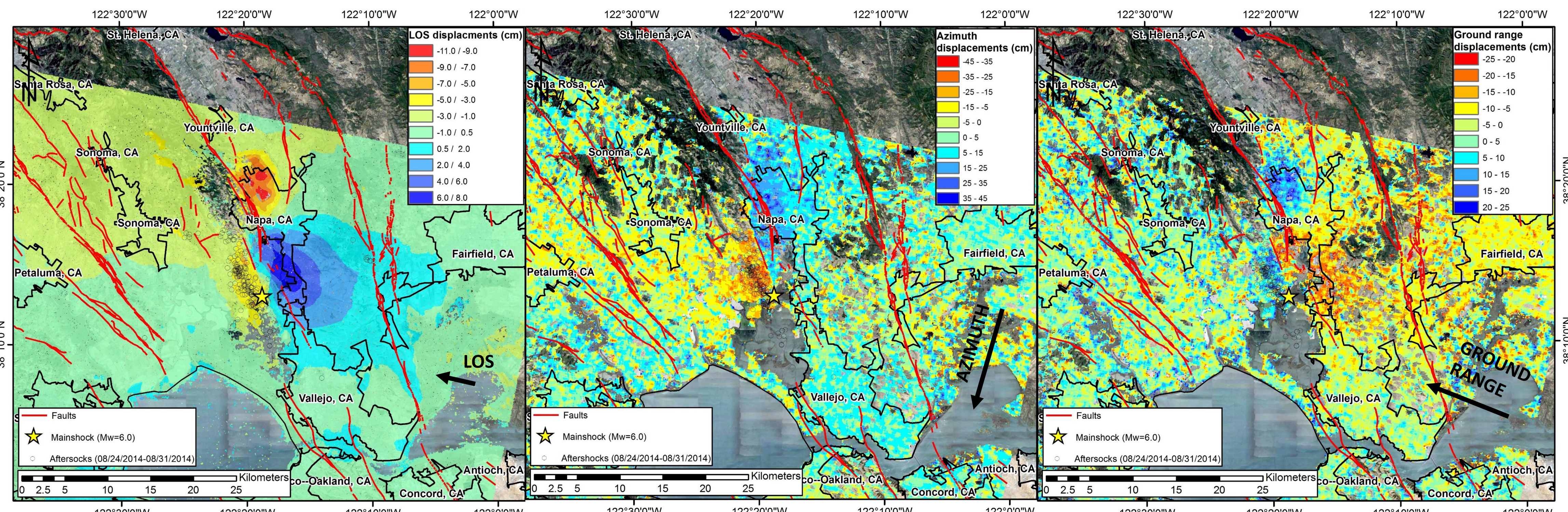
ABSTRACT After the launch of Sentinel-1 mission on April 3, 2014, the first monitored natural events were the Mw 6.0 Napa (California, USA) earthquake and the Fogo (Cape Verde) Volcano eruption. The available data were in Stripmap (ERS-Envisat like) and TOPSAR Interferometric Wideswath (IW) mode, respectively. In particular, the new TOPSAR mode is suitable to monitor large areas thanks to the wide coverage and the medium-high (about 12 m per pixel) spatial resolution.

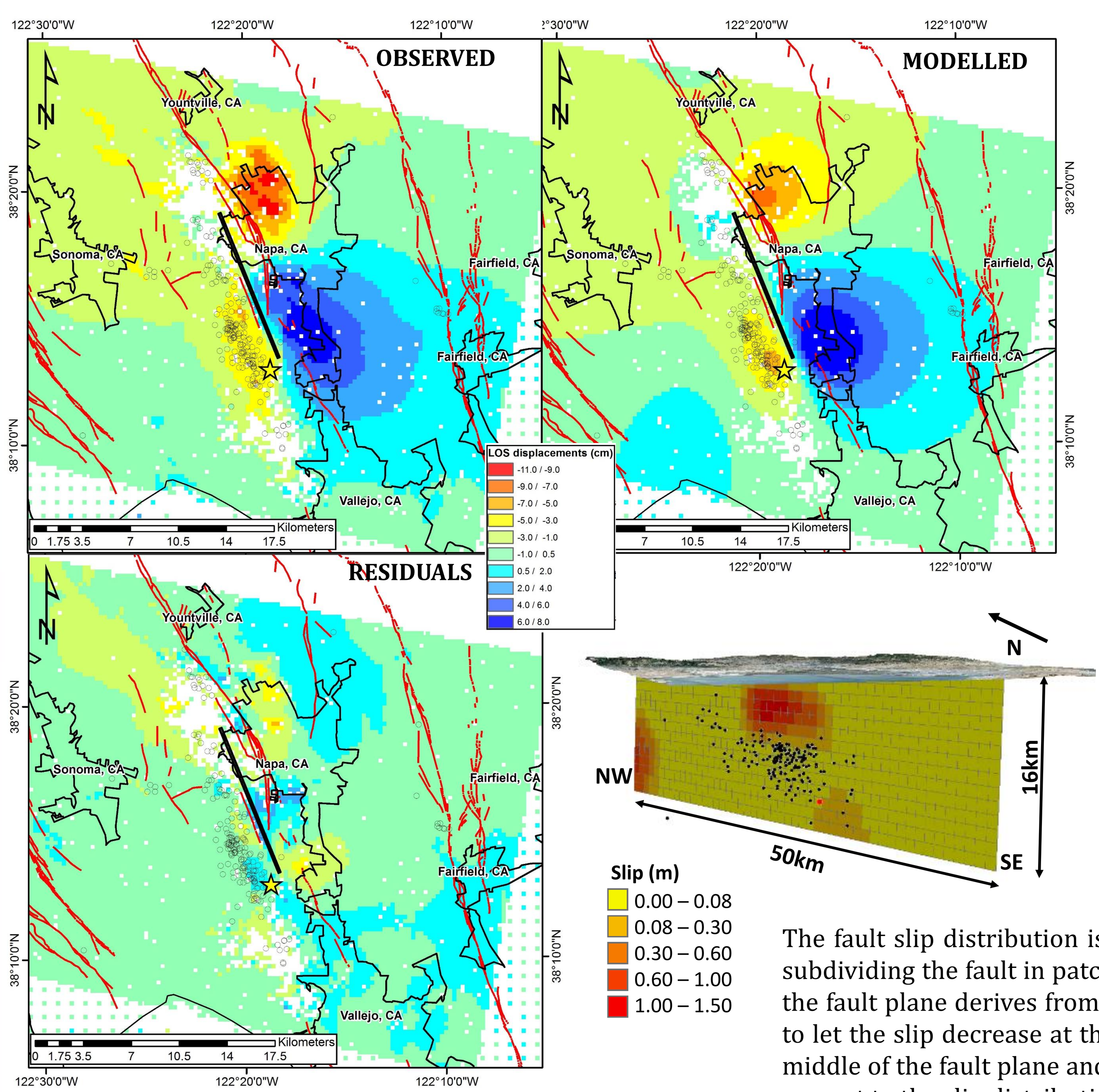
We have estimated the coseismic surface deformation field of Napa earthquake, a Mw 6.0 event occurred on August 24, 2014, by applying differential SAR interferometry (DinSAR) on two images taken before and after the mainshock. In addition, the offset tracking technique was applied in order to retrieve 3-D surface movements. We used the detected DinSAR coseismic displacement field to infer the seismic source features through an analytical inversion analysis assuming a homogeneous elastic half-space. The source geometry (position and orientation of the fault plane) has been obtained with a nonlinear optimization scheme, assuming uniform slip on the fault plane; than we obtained the best-fitting slip distribution on the fault plane by means of a linear inversion.

Last November 23, 2014, an eruption started on Fogo Volcano (Cape Verde), almost 20 years from the previous one. A pair of Sentinel-1 images in TOPSAR mode and along ascending path, dated November 3 and November 27, 2014 were used to investigate deformations occurring on the caldera and volcano edifice during the first sineruptive phase. Source inversions were carried out in order to simulate the effect of the feeding dyke on the surface displacements. Moreover, an estimate of the lava field extension was performed.

NAPA EARTHQUAKE

The earthquake-induced deformations of the Napa earthquake were mapped with satellite and airborne interferometric synthetic aperture radar. The Napa earthquake is the first monitored natural event with the Sentinel-1 satellite mission, launched on April 3, 2014. The deformations along the descending orbit (satellite moving south, looking west) are obtained differentiating two SAR images dated August 7, 2014 and August 31, 2014. We used GAMMA software package to calculate the Line-of-Sight (LOS) displacements and also the azimuth and ground range displacements (figures below). The observed displacements are compatible with a right-lateral strike slip movement. The CMT solution provides a plane with strike=157° , dip=83° and a slip of 174 cm.





Finite-fault inversion

A preliminary inversion of the DinSAR data has been performed with a two-step approach: a non linear inversion to constrain the fault geometries with uniform slip, followed by a linear inversion to retrieve the slip distribution on the fault plane. The observed data are modelled with a finite dislocation fault in an elastic and homogeneous half-space. The nonlinear inversion algorithm is based on the Levenberg-Marquardt least-squares approach, which is modified with multiple random restarts to guarantee the catching of the global minimum in the optimization process. The LOS displacement map is subsampled over a regular grid with density increasing in the area affected by the maximum displacement (300m x 300m) and less dense far from the coseismic area (1km x 1km). Points falling within areas with a low level of coherence are masked out. The inversion is carried out with all the 9 fault parameters free, assuming a rigidity modulus of 30 GPa. The best-fit solution is shown in Table below, together with the RMS of the residuals after the nonlinear inversion. This solution has a seismic moment equal to 1.85e18 Nm, corresponding to a moment magnitude of 6.1, in agreement with the CMT solution. The strike and dip angles are 157.8° and 87.2°, respectively, defining a fault plane with a good fit with the aftershock distribution.

Lenght	Width	Top depth	Strike	Dip	Rake	Slip	RMS
m	m	m	deg	deg	deg	m	m
11365	3198	1929	157.8	87.2	182.8	1.7	0.007

The fault slip distribution is estimated through a Singular Value Decomposition linear inversion, subdividing the fault in patches of 1km x 1km (figures on the left). The position and orientation of the fault plane derives from the nonlinear modelling, while the length and the width are widened to let the slip decrease at the fault edges. An area with slip values of 30–150 cm is present in the middle of the fault plane and extends southward from 2 km to 8 km. The hypocenter position with respect to the slip distribution shows that the rupture propagated toward NW.

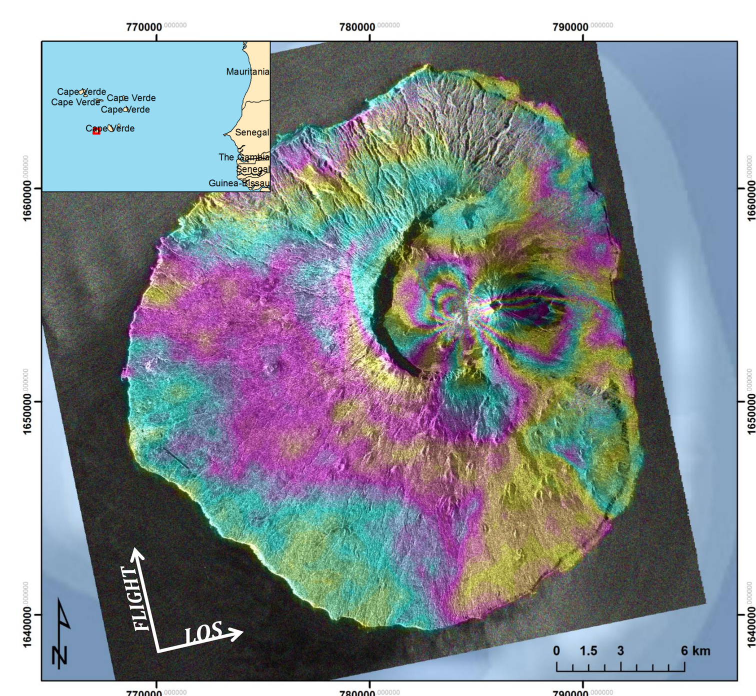
Future work

DinSAR LOS, azimuth and ground range displacements will be jointly inverted in order to better constrain the fault geometry and the slip distribution. Furthermore, DinSAR data will be combined together with GPS data in order to retrieve the full 3D displacement field.

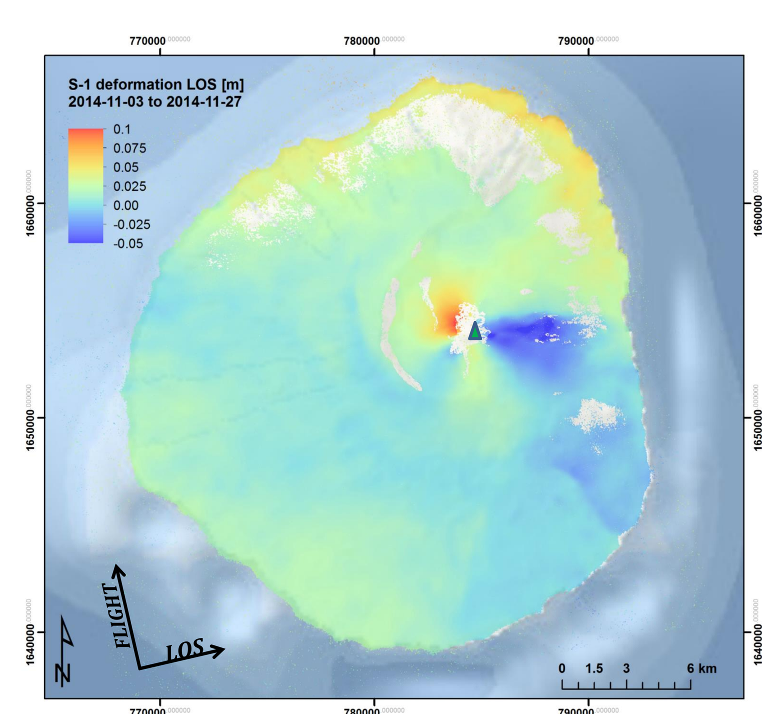
FOGO ERUPTION

SAR interferometry

Standard differential SAR interferometry has been used to estimate the sineruptive deformation. The pre-eruptive Sentinel-1 image is dated November 3, 2014, and the post-event acquisition is dated November 24, 2014. The images are in TOPSAR mode, on ascending path, with a incidence angle of about 33.9 degrees. The spatial baseline is 16.7 m, therefore no significant topographic residual are expected, also if a TanDEM-X elevation model has been used to remove the topographic phase component.



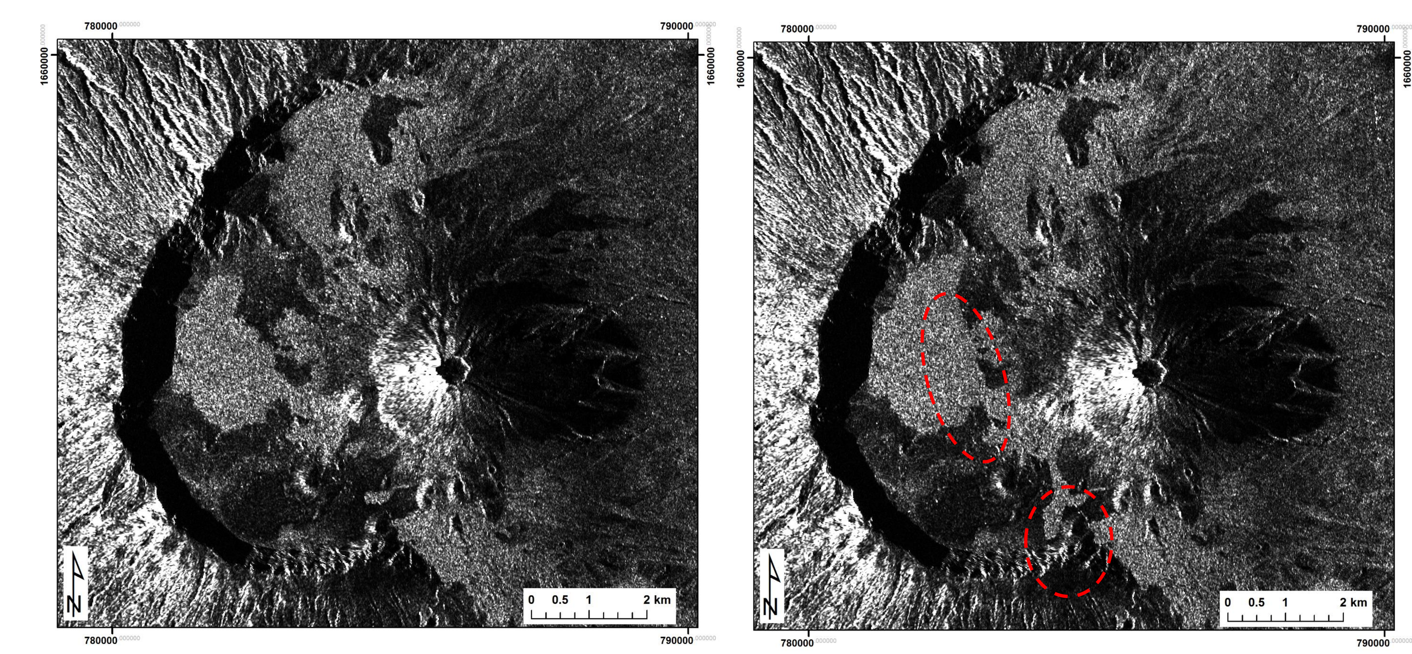
Sentinel-1 interferogram generated by exploiting an ascending image pair. The interferogram has been computed by applying a multi-look factor of 4x1 pixels in range d and azimuth, respectively, aiming at achieving the best spatial resolution, i.e. about 15m. Goldstein & Werner phase noise filtering has also been applied to improve the SNR.

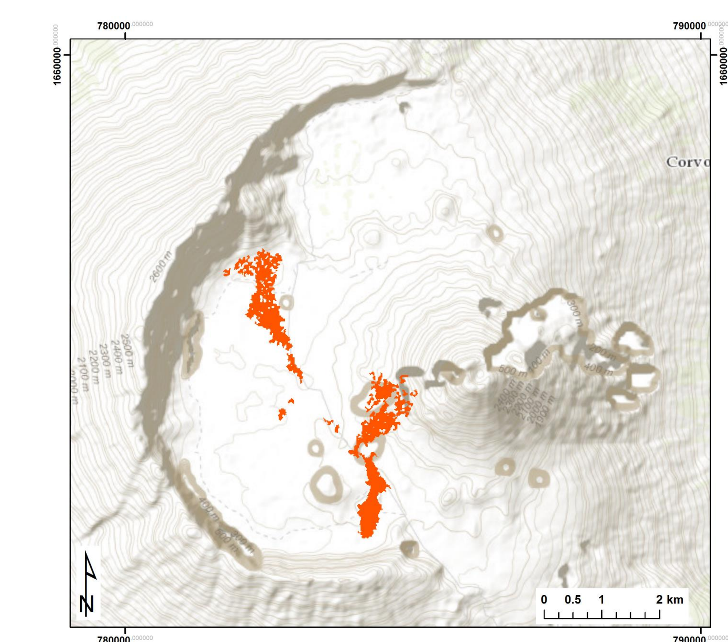


The deformation map along the LOS has been successfully retrieved by means of minimum most flow unwrapping. The resulting map shows two main patterns located WNW and E with respect to the volcano peak (Pico do Fogo, green triangle in the map). The western unwrapped pattern reaches a maximum LOS deformation of about 11 cm towards the satellite, and the eastern side shows a displacement with a maximum close to -6 cm.

SAR change detection

The Sentinel-1 images have also bee exploited to estimate the lava field coverage during the first phases of the eruption. A change detection map has been done considering the backscattering coefficients of the two SAR images, and computing a Normalised Change Index: NCI = $(bs_{pre} - bs_{post})/(bs_{pre} + bs_{post})$. Before NCI computation, the two images have been de-speckled by applying a Frost noise filter.

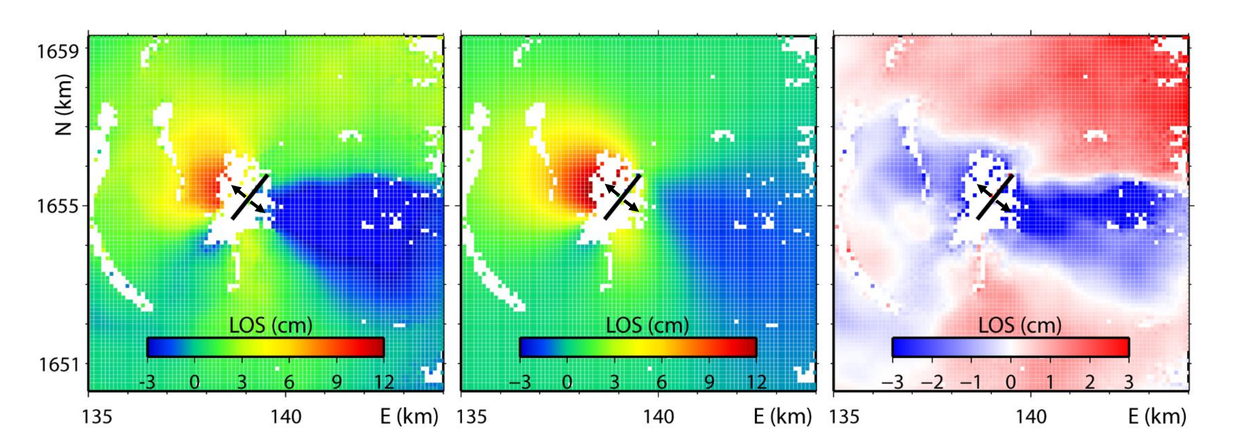




The figures above, show the pre-eruption backscattering image and the post-eruption backscattering image, left and right panel, respectively, zoomed on the caldera area. The red-dashed lines highlight the presence of new lava deposited by 27th of November 2014, i.e. only after four days of eruption. To better figure out this new lava filed, the NCI map has been segmented considering a threshold on the NCI values. The figure on the right report the detected lava filed (orange area), superimposed on a reference map. The rough estimation of the areal coverage, at this stage of the eruption, is more than 1.6 km².

Source Modelling

The ascending data is subsampled with a step of 100 m and inverted by the Neighbourhood Algorithm (Sambridge, 1999). Several attempts are computed in order to model the data, finding that pressurized sources such as a sphere or a spheroid are not suitable since they are unable to reproduce the wide negative LOS area in the eastern sector of the volcano. Instead, an opening dike (see figure below) reproduces the high LOS values reaching 9-12 cm and part of the negative values. The dike, whose trace is represented with the black line, is not perfectly vertical since it slightly dips of 82° towards SE, and opens less of 80 cm, for a total volume change of 2.8 10^6 m³.



TLC_East (km)	TLC_North (km)	Depth (km)	Length (m)	Width (m)	Strike (°)	Dip (°)	Opening (cm)
138.65±0.25	1654.65±0.25	0.1	1450±200	2500	38±5	82.3±2	78±7