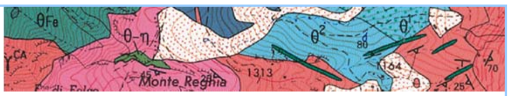

# Synthetic Aperture Radar Doppler Anomaly Detected During the 2010 Merapi Eruption.

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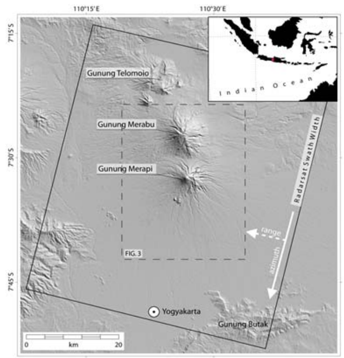
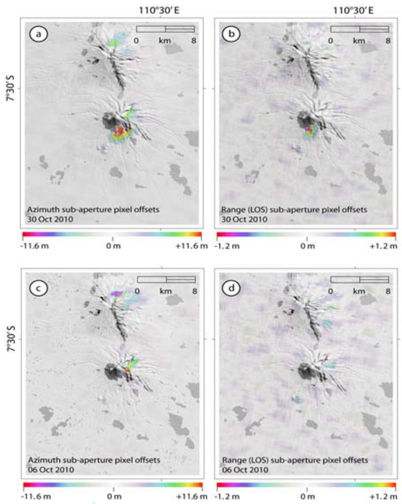
In this study we report the presence of a localized Doppler anomaly occurring during the focusing of a Radarsat-2 dataset acquired on the Merapi volcano (Indonesia) during the devastating 2010 eruption. The Doppler anomaly is manifested as a ~3km wide bull-eye shape azimuth pixels shifts between two sub-aperture images. The Doppler anomaly is centered on the summit-south flank of the Merapi volcano. The pixel shifts reaches up to 11.6 meters. Since the Merapi volcano was undergoing a large eruption during the data acquisition, it is possible that there is a volcano-related phenomenon that has delayed the radar signal so much to create measurable pixel offsets within a single SAR dataset, similar -but having more extensive area- to the signal generated by targets motions; similar -but having less extensive area- to the signal generated by ionospheric perturbations. It is known that the SAR signal is delayed as it passes through heterogeneous layers of the atmosphere, but this delay typically affects the SAR signal to a fraction of the phase cycle or few centimeters depending on the radar wavelength employed by the system. We investigate the source of this anomalous metric signal; we review the theoretical basis of SAR image focusing and we try to provide a consistent physical framework to our observations. Our results are compatible with the SAR signal being perturbed during the actual process of image focusing by the presence of a contrasting medium located approximately between 6 and 12 km altitude, which we propose being associated with the presence volcanic plume.



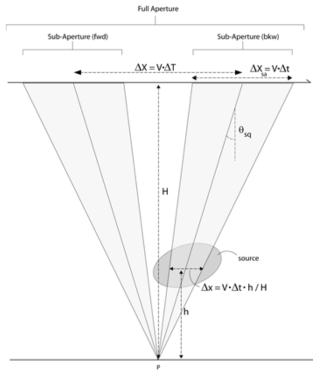

The study area. The black rectangle represent the RADARSAT swath width.
Range and azimuth directions are indicated. The dashed rectangle is the footprint of following figures

Observations:




Pixel offsets measured by sub-aperture cross correlation calculated on the SAR data acquired on the 30 of October 2010 during the Merapi volcano eruption; a) azimuth direction, b) range direction. Apparent pixel offsets measured by sub-aperture cross correlation calculated on the SAR data acquired on the 06 of October 2010, before the Merapi volcano eruption; c) azimuth direction, d) range direction

*Let's suppose the source of the anomaly is an atmospheric feature:*




Geometry of the sub-aperture acquisition. $\Delta T$ is the time separation between looks, $\Delta t$ is the sub-aperture integration time, $V$ is the along track velocity of the platform, $\theta_{sq}$ the squint angle of the sub aperture look. $H$ is the distance between ground surface and the sensor. $h$ is the Line of Sight distance between the ground target and the disturbing atmospheric phenomenon.

Based on Cumming and Wrong (2005) and the work from Meyer *et al.* (2009) and the previously described geometry, we can propose a set of relationships between the signal path lengthening *l* and the sub-aperture pixel offsets:

$$\Delta r_a\,(m) = V\,\Delta T\,\frac{h}{H}\frac{\partial l}{\partial x} \qquad (1)$$

$$\Delta\eta\,(m) = \frac{2V^3\Delta T}{\lambda\,FM}\left(\frac{h}{H}\right)^2\frac{\partial^2 l}{\partial x^2} \qquad (2)$$

Strong dependance on *h/H*, i.e. for low *h* the signal should be only affected by extrem atmospheric phenomena.

Elements for interpretation in terms of path lengthening:

Let call "A" and "B" the measured maximal sub-aperture offsets (azimuth and range respectively). Let "C" be the maximal absolute signal lengthening to be estimated:

$$l(x) = Ce^{-\frac{x^2}{2\sigma^2}} \qquad (3)$$

In order to be consistent with equations (1) and (2), we propose the following approximations for $\Delta\eta$, $\Delta r_a$ based on the areal size of the measured anomaly and the maximum values A and B measured on our offsets results:

$$\Delta r_a(x) = B\frac{x}{\sigma}\,e^{\frac{1}{2}-\frac{x^2}{2\sigma^2}} \qquad (4)$$

(this guaranties that the maximum value of $\Delta r_a$ is B)

$$\Delta\eta\,(x) = A\left(1-\frac{x^2}{\sigma^2}\right)e^{-\frac{x^2}{2\sigma^2}} \qquad (5)$$

By deriving equation (3) we obtain:

$$\frac{\partial l}{\partial x} = -C\frac{x}{\sigma^2}\,e^{-\frac{x^2}{2\sigma^2}}$$

$$\frac{\partial^2 l}{\partial x^2} = \frac{C}{\sigma^2}\left(\frac{x^2}{\sigma^2}-1\right)e^{-\frac{x^2}{2\sigma^2}}$$

Therefore, from (1) and maximizing each side of the equation, we obtain:

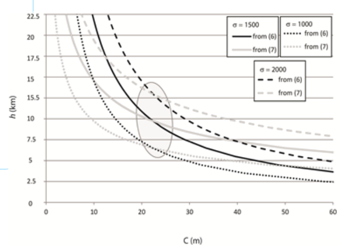
$$\frac{B}{\sqrt{e}} = -V\,\Delta T\,\frac{h}{H}\,C\frac{1}{\sigma}$$

$$C = -\frac{\sigma\,B\sqrt{e}}{V\,\Delta T}\frac{H}{h} \qquad (6)$$

From (2) we obtain:

$$A = \frac{2V^3\,\Delta T}{\lambda\,FM}\left(\frac{h}{H}\right)^2\frac{C}{\sigma^2}$$

$$C = \frac{\lambda\,FM\,\sigma^2}{2V^3\,\Delta T}\left(\frac{H}{h}\right)^2 A \qquad (7)$$




Plot of *C* (absolute path length) as a function of *h* (relative height of the source) from equations (6) and (7) we propose that the Doppler anomalous values can be compatible with a source located in between 6 and 14 km altitude,yielding an absolute wave path delay between ~19 and ~25 meters. The solution is calculated for 3 different values of s (1 km, 1.5 km, 2 km) to give an idea of the influence of the incertitude to the proposed solution. Fixed parameters: *λ=0.056 m; H=759201 m; A=11.3 m; B=0.7 m; FM = 1773 Hz/s; ΔT = 0.8s.*

## *Conclusions:*

Sub-aperture pixel offsets technique allowed us to highlight an anomaly on the Doppler parameters estimation of a Radarsat-2 SLC data acquired on the 30 of October 2010 (UTC) over Merapi volcano. Sub-aperture pixel offsets reaches 11.6 meters in the azimuth direction (positive towards the platform sense of motion). At that time, Merapi volcano was undergoing an eruptive explosive phase. Sub-aperture pixel offsets technique applied to the RADARSAT-2 dataset acquired before the eruption started (06 October 2010) does not reveal any areal extensive Doppler anomaly. Therefore, we are inclined to think that there is a volcano-related phenomenon that has consistently delayed the SAR signal during the actual process of image acquisition. Our measurements are compatible with the presence of a heterogeneous medium located on top south western flank of the Merapi volcano between ~6 and 14 km altitude that influenced the SAR signal so much to cause measurable sub-pixel offsets during image focusing. Both volcanic ash cloud particles and plumes can delay radar waves as already observed with Global Positioning System. Therefore, , we propose that the SAR signal might be perturbed by the presence of dense volcanic plume on the 30 of October 2010 (UTC), which has been observed on the ground and instrumentally.. In this study we do not take into account the influence of particles/target owns motions on the SAR Doppler measurements but in the future we shall investigate SAR Doppler anomalies induced by rapid mass movements (such as surges and pyroclastic flows) occurring during the synthetic aperture as well as the influence of Doppler anomalies generated by plume particles motions as already observed by ground based radars. This paper calls to a more careful interpretation of surface displacement derived from SAR sub-pixel offsets in regions of exacerbated volcanic phenomena.
risk management. The approach proposed in this study could allow assessing the usability of a number of tide gauges suspected to be affected by local ground motions, and, finally, help for estimating sea level evolution over the past century.

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**Used softwares**: GAMMA (GAMMA-RS), Envi (Exelvis)

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