Synthetic Aperture Radar (SAR) Doppler anomaly detected during the 2010 Merapi (Java, Indonesia) eruption.

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Abstract

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 more extensive- to the signal generated by targets motions; similar -but less extensive- 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 12.5 km altitude, which we propose being associated with the presence volcanic ash plume.

1. Introduction

In Synthetic Aperture Radar, variations in the Electro Magnetic Waves (EMW) travel time results in a change in the Doppler frequency that adds up to the one that is naturally generated by the relative motion between the platform and the ground targets. In Synthetic Aperture Radar, frequencies modulations control the image focusing along the two fundamental SAR directions, the azimuth (i.e. the platform motion direction) and the range (i.e. the sensor looking direction). During the synthetic aperture process (the so called image focusing) a target on the surface is seen along different paths. In standard focusing processing it is assumed both that ground targets are stationary and that between the sensor and the target the medium is the vacuum or a totally homogeneous medium. Therefore, if there is a significant path delay variation along the paths to a specific target this can result either in image defocusing or in pixel misregistration or both. As a special case, a path delay ramp across the synthetic aperture time would result in an offset in the azimuth pixels positions e.g. [1] [2]. In particular, a ramp of one phase cycle across the standard synthetic aperture would result in an offset of one pixel in azimuth. Such a relative path delay might be caused by fluctuations of
media properties in between the sensor and the surface, as already observed and discussed on L-band and C-band SAR data caused by dispersive ionospheric layers i. e. [3] [4] [5] [6]. In particular cases, further radar frequencies modulations can be induced by the own motion of specific radar targets such as vehicles e.g [2]. Moreover, a Doppler shift in ground based radar signal has been observed to be induced by volcanic ash plumes e. g. [7]. In this study, we report a Doppler anomaly in Radarsat-2 SAR data occurring during the process of image focusing on data acquired over the Merapi volcano on the 30 of October 2010. The Doppler anomaly is so intense that it gives rise to measurable sub-aperture pixel offsets within a single radar image. The Merapi volcano was in activity during the Radarsat-2 SAR image acquisition (the 2010 centennial Merapi eruption). Therefore, we test the hypothesis that the Doppler anomaly might be induced by a volcano-related phenomenon.

The Merapi volcano is one of the 145 Holocene volcanoes that populate the Indonesian archipelago. It is located in the heart of the Sunda arc in Central Java, 30 km north of the city of Yogyakarta (fig. 1). With its ~3000 m height, it is one the most dangerous volcanoes in Indonesia, characterized by the persistent growth of the summit dome, intermitted by partial or total dome collapse to generate frequent nuées ardentes (e. g. 8; 9; 10). Merapi re-awakened in late 2010, after four years of quiescence. The eruption started the 26 of October 2010 after nearly two months of enhanced levels of seismicity. Surono et al. [10] reported that after an initial phase characterized by magmatic intrusions and shallow degassing, an explosive phase took place characterized by phreatomagmatic eruptions from the 26 of October to the 1st of November that produced a sustained eruptive plume.

We have used SAR data from the Canadian Space Agency C-band Radarsat-2 sensor acquired on the 30 of October 2010 (UTC), along with the sub-aperture offset-tracking method implemented in the GAMMA codes [11] to generate 2 sub-aperture SAR data. Our aim is to map azimuth sub-aperture sub-pixel offsets potentially due to systematic errors in the
platform speed. Azimuth sub-band images correspond to consider SAR images with slightly different look directions. The resulting offset map (figure 3) substantially shows a localized pixel shift on the volcano summit and south-western flank that cannot be related to an error in the platform speed.

As former Merapi Volcano Observatory in Yogyakarta (BPPTK) reported the presence of explosions on the Merapi summit with a plume reaching several km height between 17:12 and 17:50 (UTC) on the 29 of October 2010, a possible hypothesis to explain the measured pixel offsets anomaly is to assume that there is a heterogeneous medium that locally delays the SAR signal during the data acquisition and hence causes pixel offsets. Effects are only expected for the data acquired on 30 Oct. 2010, when Merapi was erupting. Therefore, we concentrate on the Radarsat-2 data acquired the 30 of October 2010 at 22:11 (UTC) and we compare them to the data acquired by Radarsat-2 on the 06 of October 2010 (at 22:11 UTC - before the eruption started).

In the present manuscript, we firstly describe the method to measure the Doppler related azimuth shift anomaly. Secondly, we discuss the results and we propose a theoretic framework compatible to our observations. This is the first time that a space-borne SAR system is used to measure a Doppler anomaly related to volcanic activity.

3. Data and method

Radarsat-2 data are acquired in F3 mode, vertical polarization, 43.43° look angle. While common Single Look Complex (SLC) SAR images are formed using the full length of the azimuth Doppler spectrum, the sub-aperture approach uses sub-aperture images derived from different segments of the azimuth Doppler spectrum calculated from the SLC SAR data. Each of the sub-aperture images (or ‘looks”) is formed from a bandwidth equal to 0.35 times the
radar Pulse Repetition Frequency (PRF) yielding a frequency separation between the looks of 0.45 times the PRF. The idea is that as the sub-aperture images observe the same object on ground from slightly different locations along the orbit they ‘see’ through different parts of the volcanic plume. A difference in the Doppler gradients at these locations induces systematic small scale azimuth and range offsets between the two sub-aperture images resulting in relative shifts between the looks, which can be detected by cross-correlation methods. The sub-aperture images are firstly generated. Then, they are cross-correlated using 2D Fast Fourier Transform to measure the range and azimuth pixel offsets with a window size of 256 pixels every 64 SLC pixels. A biquadratic interpolator determines the offset correlation peak with sub-pixel accuracy. The processing code that we adopted here is the one implemented in the GAMMA “autofocus of SLC” code [6].

Based on [1] and the work from [4], we can propose a set of relationships between the signal path lengthening \( l \) and the sub-aperture pixel offsets:

\[
\Delta r_a (m) = V \Delta T \frac{h}{H} \frac{\partial l}{\partial x} \quad (1)
\]

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

where \( \Delta \eta \) are the sub-aperture azimuth offsets (units, m), \( \Delta r_a \) are the sub-aperture slant range offsets (units, m), \( V \) is the platform velocity (units m/s), \( \Delta T \) is the time separation between the two looks, \( FM \) is the instrument Doppler rate, and \( x \) is along track coordinate of the measured anomaly (units, m).

We propose to introduce the ratio \( h/H \) in the formula. It reflect the fact that a given time interval between sub-apertures corresponds to different along-orbit path lengths depending on the height \( h \) of the disturbing phenomenon. \( H \) is the height of closest approach (i. e. the vertical distance between the orbit and the target) and \( h \) is the height between the ground
target and the source of the Doppler anomaly. Figure 2 summarizes the geometric meaning of
the aforementioned variables.

3. Results

The sub aperture cross-correlation method applied to the SAR data acquired on the 30 of
October 2010 UTC shows a distinct azimuth and range offsets signal on the summit and South
Western flank of mount Merapi (Figure 3a, b). The sub-aperture azimuth offset is as high as
+11.6 meters (positive towards the sense of platform motion, indicating wave path
lengthening). The sub aperture cross-correlation applied to the SAR data acquired on the 06 of
October 2010 UTC does not show a consistent azimuth or range offsets signal on the summit
and south western flank of mount Merapi (Figure 3c, d). Therefore we are measuring a non-
stationary Doppler anomaly that appears in concomitance with the Merapi volcano eruption.
This evidence leads us to interpret the azimuth sub-aperture offset as the result of a localized
delay in the SAR signal caused by strong heterogeneities within the Merapi summit
atmosphere occurring on the 30 of October 2010 (UTC). This SAR signal anomaly correlates
in date and approximate location with the occurrence of the volcanic plume observed visually
and instrumentally by BPPTK on the 29 of and 31 of October 2010 UTC [10]. However, one
has to consider that with the side-looking SAR geometry the anomaly is not observed at the
exact locations of the ash but "behind it" where the radar waves propagating through the ash
are scattered from the ground. Given its relative limited areal extension, we tend to exclude
that this Doppler anomaly can be originated by atmospheric gravity waves or small scale TEC
(Total Electon Content) variations, which assessed influence on the radar signals in the higher
atmospheric levels would result in wider scale SAR azimuth offsets e.g. [3].
To test our hypothesis we make a combined use of equations 1) and 2) to provide us with some hints about the absolute signal path lengthening, which we could relate to the average height of the source of the Doppler anomaly.

4. Elements for interpretation in terms of path lengthening

In order for us to assess the consistency of the observed anomaly with a possible volcano-related atmospheric phenomenon, we propose to simplify the problem as follows. Let us approximate the measured $\Delta \eta$, $\Delta r_a$ and $l$ by Gaussian functions having the same $\sigma$ value corresponding to approximately half of the anomaly width ($\sigma = \sim 1500$ m, from figure 3a, b). 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:

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

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:

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

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

$$\Delta \eta (x) = A(1 - \frac{x^2}{\sigma^2}) e^{-\frac{x^2}{2\sigma^2}} \quad (5)$$

By deriving equation (3) we obtain:
Therefore, from (1) and maximizing each side of the equation, we obtain:

\[ \frac{B}{\sqrt{\varepsilon}} = -V \Delta T \frac{h}{H} C \frac{1}{\sigma} \]

\[ C = -\frac{\sigma B \sqrt{\varepsilon} H}{V \Delta T h} \]  \hspace{0.5cm} (6)

From (2) we obtain:

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

\[ C = \frac{\lambda FM \sigma^2}{2V^3 \Delta T} \left( \frac{H}{h} \right)^2 A \]  \hspace{0.5cm} (7)

By fixing \( \lambda = 0.056 \text{ m} \) (C-band wavelength); \( H = 759201 \text{ m} \) (altitude of Radarsat-2 platform); \( A = 1.6 \text{ m} \) (measured); \( B = 0.7 \text{ m} \) (measured); \( FM = 1773 \text{ Hz/s} \); \( \Delta T = 0.8s \) (sub aperture time interval); \( \sigma = 1500 \pm 500 \text{ m} \), we can plot \( C \) as a function of \( h \) from equation (6) and (7). We found that the sub-aperture anomalous pixel shifts can be compatible with a source located in between 6 and 12.5 km altitude yielding an absolute wave path delay between ~19 and ~25 meters (figure 4). The solution is very sensitive to \( \sigma \) so that the solution range is large because of the uncertainty on the measurements. Simplifications and approximations to derive (6) and (7) from the previous equations are additional sources of uncertainty. Nevertheless, we think
that this approach is helpful to discriminate between a upper or lower atmospheric source. The solution is also sensitive to the system $FM$ (Doppler rate) in the sense that a high $FM$ would generate less azimuth pixels shifts -given other parameters as fixed. This observation leads to foreseen strong potential differences in results obtained using different sensors. An absolute wave path delay between $\sim 19$ and $\sim 25$ meters means that a range pixel is imaged between 19 and 25 meters away on the LOS from its ‘true’ position. In a general case, one could validate the measured $C$ value by measuring the LOS pixel shift between two SAR dataset acquired on two different dates. Unfortunately, the violent dome explosions during the Merapi eruption caused the modification of the summit rim morphology and surface changes due to pyroclastic flows. Therefore, the backscattering elements before and during the eruption are not the same so that $C$ cannot be measured directly due to high degree of surface changes.

5. Discussion and 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 $\sim 6$ and 12.5 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 e.g. [12]. Therefore, we propose that the SAR signal might be perturbed by the presence 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 should 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 e. g. [7]. This paper calls to a more careful interpretation of surface displacement derived from SAR sub-pixel offsets in regions of exacerbated volcanic phenomena.

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5. References


Figure captions

Figure 1. The study area. The black rectangle represents the RADARSAT swath width. Range and azimuth directions are indicated. The dashed rectangle is the footprint of figures 3.

Figure 2: 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.

Figure 3. 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.

Figure 4. Plot of $C$ (absolute path length in slant range) 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 12.5 km altitude, yielding an absolute wave path delay between ~19 and ~25 meters. The solution is calculated for 3 different values of $\sigma$ (1 km, 1.5 km, 2 km) to give an idea of the influence of the uncertainty in the proposed solution. Fixed parameters: $l=0.056$ m; $H=759201$ m; $A=11.6$ m; $B=0.7$ m; $FM = 1773$ Hz/s; $\Delta T = 0.8$s.