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PolTimeSAR: why we need full polarimetry to detect changes in a SAR time series

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ABSTRACT

This paper investigates the role of polarimetry in detecting change within SAR time series. First, in the context of visualization, a qualitative analysis shows that different time signals can have decorrelated behaviors from one polarization to another. Based on this observation, we propose an extension of the so-called REACTIV change visualization algorithm that merges the different polarimetric channels. Then, the quantitative performance is evaluated to recognize the gain of polarimetry in the context of detecting long events such as construction sites. The paper compares several fusion schemes that show significant detection improvement for dual polarization Sentinel-1 data. A final step is to investigate the role of polarimetry in the detection of short duration events. The availability of complete polarimetric data is proving to be crucial over continental areas to detect all point events in a time series.

Keywords time-series · change detection · permanent scatterer · coefficient of variation

1 Introduction

Recently, the increasing availability of remote sensing data makes the exploitation of time series easier. As a result, SAR change detection, which traditionally involves two images taken at two different dates, can be generalized to the stability or change analysis for a whole series of images over a given time range. However, there is still little work about the detection of a change in SAR time-series. Among these works, some authors focus on the change detection matrix, analyzing the changes between all possible pairs Lê et al. [2014], Lê [2015], Bruzzone et al. [2017]. Others analyze the contribution of interferometric coherence Schulz et al. [2010], Damini et al. [2013]. In Quin et al. [2014], Colin Koeniguer and Nicolas [2020], the authors focus on temporal statistics. Anyhow, there are even fewer works that address the role that polarimetry can play for change detection in time-series.

Yet, polarimetry may be helpful for various reasons:

- to improve detection performance
- to improve the posterior characterization of the change.

Among the works that are interested in changes in polarimetric time series, the approach described in Nielsen et al. [2017, 2016], Nicolas [2018] proposes homogeneity tests of speckle statistical populations, in the full or partial polarimetric case. The authors provide the statistical framework for testing the set of polarimetric coherence matrices. However, these works do not question the differences in performance obtained with or without polarization.

Another line of work in Marino [2019] concerns agricultural applications. This approach uses the notion of change detection matrix, already studied in Lê et al. [2014]: the change detection considers all possible date pairs. The method is equivalent to perform $N(N - 1)/2$ bi-date change detection tests where N is the number of images. For these tests, the strategy in Marino [2019] is to determine the polarimetric mechanisms that maximize the difference modulus or the ratio of polarimetric coherence matrices projected on this polarimetric mechanism. Thus, this mechanism maximizes the signal difference or contrast between two dates. The results reveal that polarimetric mechanisms exhibiting change evolve over time.

Without considering the detection performance, few studies have analyzed the behavior of polarimetry on the observed statistical signals. However, the sharp analysis of time statistics is crucial in the development of detection algorithms and has supported many recent developments Nicolas [2018, 2006]. Notably, the following questions arise:

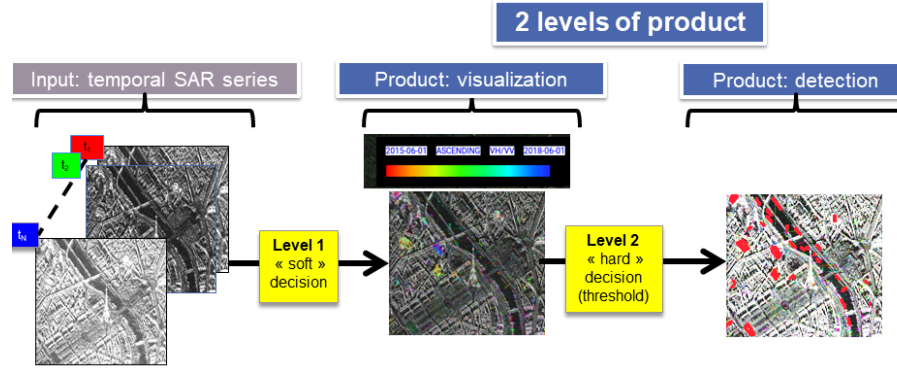


Figure 1: The REACTIV algorithm for change detection analysis concerns two kinds of products: Visualization and Detection

- Are in-homogeneity temporal patterns similar in all polarimetric channels?
- In chaotic patterns such as agricultural plots, are the polarimetric information correlated?

At Onera, we recently proposed an approach that tests the homogeneity of a temporal amplitude profile, using the statistical properties of the coefficient of variation Colin Koeniguer and Nicolas [2020]. We have developed two different product levels, illustrated in figure 1. A first product concerns the visualization: it corresponds to an emphasis on the changes by the color where the coefficient of variation encodes saturation Colin Koeniguer et al. [2018]. A second product concerns automatic detection Colin Koeniguer et al. [2019]. The coefficient of variation can serve as a criterion for detecting all kinds of changes. Two specific approaches exist: the first one is dedicated to long events of the step type; the other one is dedicated to the detection of short-time events. This article aims at analyzing the benefit of polarimetry, first for the visualization of generic change, second for the specific detection of long and short events.

In section 2, we propose a scheme to generalize the REACTIV visualization algorithm in the case of polarimetric data. We show how the result may differ from single-polarimetric visualizations. In section 3, the change detection algorithm is analyzed from a polarimetric point of view. This analysis is performed mainly on construction test sites by using dual polarimetric Sentinel-1 data. Finally, in section 4, we analyze the behavior of polarimetry in the case of short-events, both on full polarimetric UAVSAR data, and on dual-polarization Sentinel-1 data. Section 5 concludes the crucial role of polarization in change detection.

2 Visualization

The REACTIV color composition uses the HSV representation space to highlight changes. The method uses the coefficient of variation to encode the saturation channel. This strategy means that for values corresponding to theoretical stable speckle, the saturation is set to zero, and the resulting pixel is grayscale encoded. As soon as a in homogeneity occurs, then the value of the coefficient of variation increases, and the saturation increases proportionally, causing the color to appear even more brightly when the value is high. Also, the colored areas of the final visualization primarily depend on this parameter.

Comparing the values of the coefficient of variation obtained in each polarimetric channel thus makes it possible to see the influence of the polarimetric channel in the final rendering. This visualization can be done on a huge scale using the GEE platform, by using Sentinel-1 data in dual-polarization VH and VV Colin Koeniguer et al. [2018]. In practice, the results are different, especially in agricultural areas. The figure 2 shows the coefficients of variation in polarization VV and VH in a colored composition. The coefficient of variation VH codes the cyan color, and that of the polarization VV codes the red color. This visualization clearly shows that some agricultural parcels exhibit a much more significant variation in one polarization than in another, without clearly seeing a preferred polarimetric channel.

This same analysis has been performed on UAVSAR polarimetric data. In urban areas, few contrasts between the coefficient of variation computed in the different polarimetric channels appear. In agricultural regions again, there are contrasts between polarimetric channels. In fig. 3, two different areas are shown. Most of the time, the HV polarimetric channel exhibits a higher coefficient of variation. Locally, the coefficient of variation may be higher in co-polarizations, especially on bare surfaces such as water and bare grounds. Along with this observation, a qualitative analysis of the time series shows that the polarimetric colors vary from one acquisition to another. Then, temporal signals are often

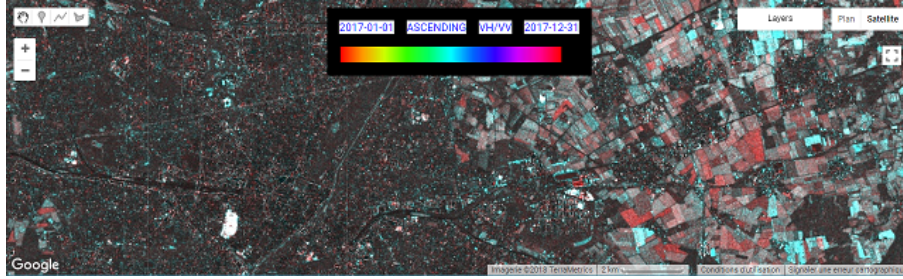


Figure 2: Composition of the different coefficient of variations obtained in VV and VH polarization - GEE platform -



Figure 3: Composition of the different coefficient of variations obtained in HH, VV and VH polarization - UAVSAR -

totally decorrelated between polarimetric channels. Consequently, results of REACTIV color composition on each polarimetric channel can differ substantially.

This observation motivated the proposition of a colored composition merging the polarimetric channels, according to the diagram represented on the figure 4. To be sure to be sensitive to any change, we consider for the saturation, the maximum of the coefficients of variation for the different polarizations of the lexicographic base. The intensity value remains the maximum intensity obtained, all polarimetric channels combined. Finally, the hue is associated with the date of maximum signal, in the polarimetric channel whose coefficient of variation is maximum. Note that it is not necessarily the date of the overall maximum.

This new schema has been re-tested using the Google Earth Engine platform. In fig. 5, the colored compositions obtained for each channel are compared with the colored composition obtained on the proposed fusion scheme. Locally, the colors are on average more vivid, and we can witness color changes, as illustrated by the zoom on the figure 6.

On the UAVSAR images, the resulting composition gives also interesting results, as can be seen in figure 7. On areas surrounded in yellow, it is not only the saturation that can differ but also the hues. This observation proves that the dates of the maximum signal are not equivalent from one polarization to another.

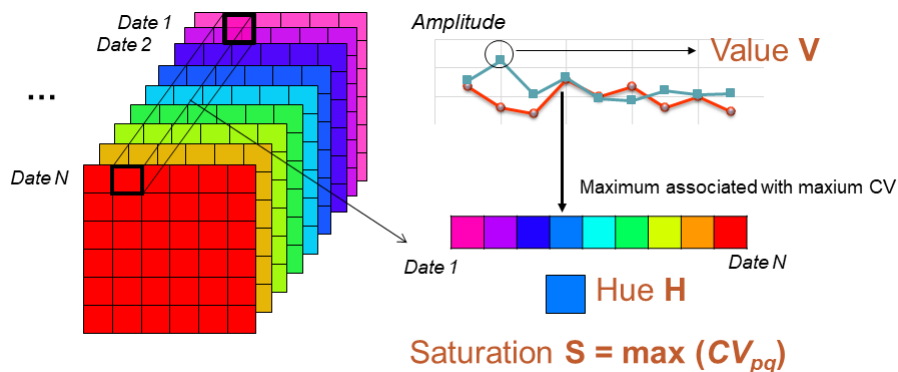


Figure 4: REACTIV new scheme extended to the polarimetric case.

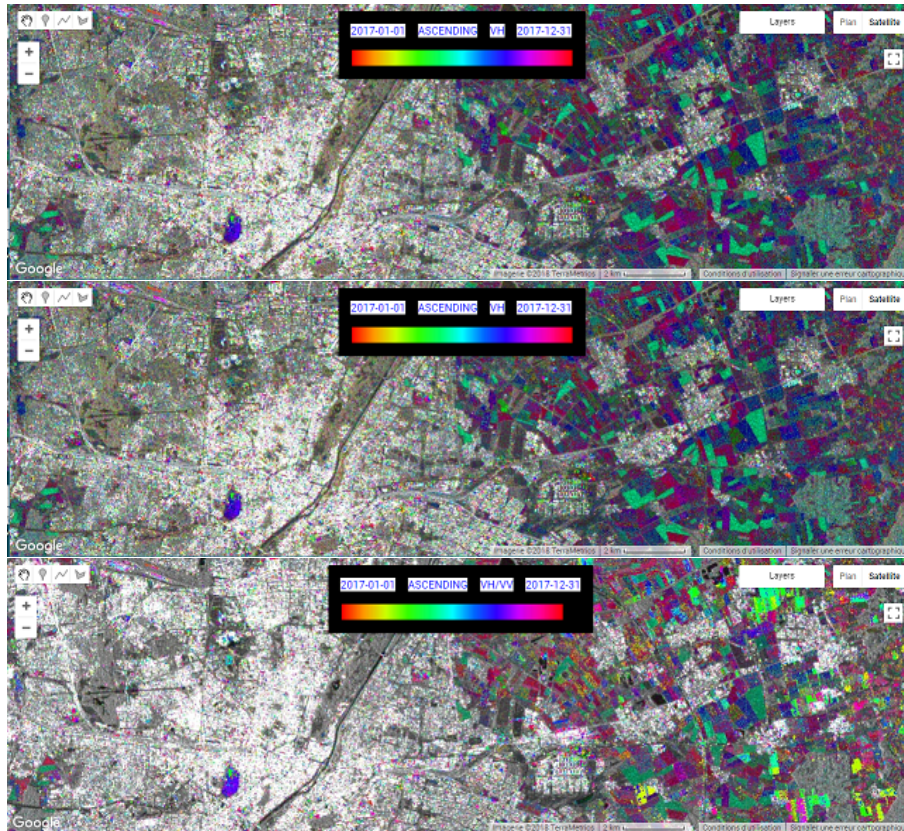


Figure 5: REACTIV products on Sentinel 1 - GEE platform - For separated polarimetric channels, and for the new fusion product

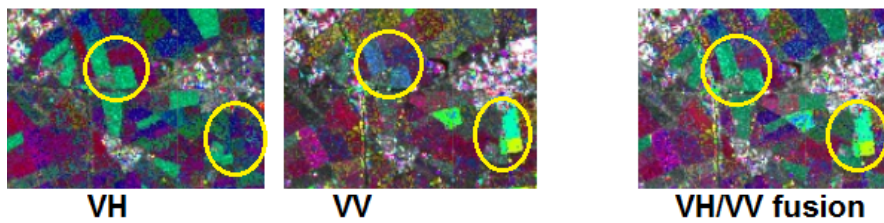


Figure 6: REACTIV products on Sentinel 1 - GEE platform - For separated polarimetric channels, and for the new fusion product - Zoom

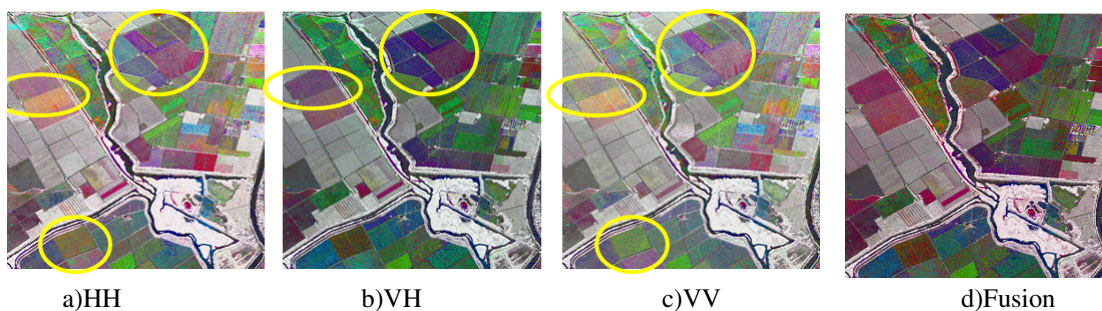


Figure 7: REACTIV products on UAVSAR - For separated polarimetric channels and for fusion scheme.

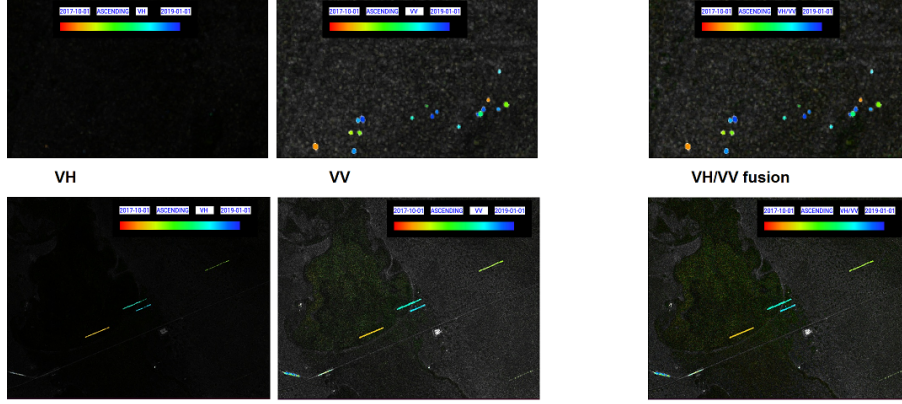


Figure 8: REACTIV products on Sentinel-1 - GEE platform - For separated polarimetric channels VH and VV, and for the new fusion product - Petra Diamond Mine

Finally, the importance of polarimetry is also visible in areas that contain vehicles. On Earth, on Sentinel-1 data visualized thanks to the platform, it appears that the VV polarization highlights some objects much better than the VH polarization. We can see it by example for the trains, or the trucks visible around the Petra Mine, a diamond mine located in South Africa, in fig.8. The presence of vehicles is presumably due to the exploitation of the Mine. On the different representations, the trains are much less visible in the VH polarization, and the trucks are only seen in VV polarization. For these two types of targets, the merged composition is very close to the composition made in VV polarization.

In summary, the merged color composition makes it possible to highlight all the areas subject to changes, often perceptible in only one of the available polarizations. On natural areas, however, the color defined by the maximum chaotic signal differs from one polarimetric channel to another. This choice of colored composition is less suitable for this type of environment. Since this type of change can not be defined by a single date, a polarimetric time analysis should be dedicated to this type of medium.

3 Detection of long events

This section considers long type events, for example, those related to the construction of a building. We resume the work proposed in Colin Koeniguer and Nicolas [2020] with the proposal of two different detection criteria. The first criterion is simply the coefficient of variation that participates in the REACTIV color composition. The second one uses the coefficient of variation ratios calculated for the sub-profiles before and after a fixed date, it is defined by:

$$C_1(x(t)) = 1 - \frac{1}{N - 2M + 1} \sum_{p=M}^{N-M} \frac{\gamma(x(t)_{t \in \{1 \dots p\}})}{\gamma(x(t)_{t \in \{p+1, \dots N\}})}, \frac{\gamma(x(t)_{t \in \{p+1, \dots N\}})}{\gamma(x(t)_{t \in \{1 \dots p\}})} \quad (1)$$

where p is the variable corresponding to a given break date of the sequence, γ_p and γ_{p+1} are the coefficients of variation computed on the two sub-parts of the temporal profile before and after the date p , M is the minimum number of images required to compute the coefficient of variation (we choose $M = 5$), and N is the number of images in the series.

Detection is equivalent to threshold the criterion. The criterion can be computed for each polarimetric channel independently. Each threshold makes it possible to define a probability of detection and a false alarm. In practice, it is legitimate to ask the question of how to improve the detection performance using polarimetric information.

Several tests were carried out on a Sentinel-1 stack of images acquired around Palaiseau, south of Paris. We conduct this analysis in the same scenario as the one discussed in Colin Koeniguer and Nicolas [2020] because it allows for quantitative performance assessments on a large number of changes. This area contains many construction sites due to the growth of the University Paris-Saclay. The considered area is about 15 km x 12 km. Acquisition dates lie between June 2015 and June 2017. Indeed, the intensive development of a set of annotated data has been carried out in this area by using topographic datasets available at different dates: a topographic database produced by IGN (French National Geographic Agency), and an OSM database, corresponding respectively at dates before and after the observed time

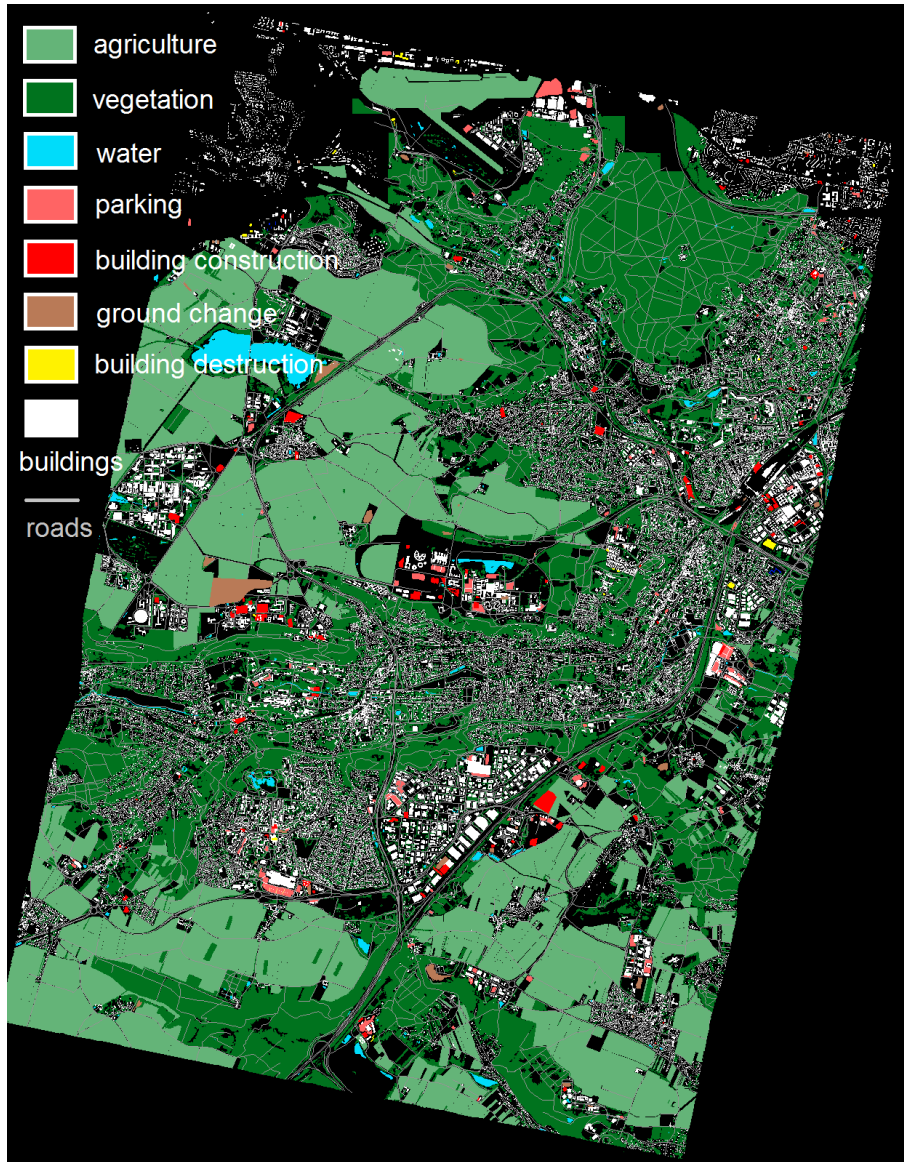


Figure 9: Ground Truth over the test area, Palaiseau, France. Generic change class includes parking areas, changes on ground areas, and building construction/destruction

range. Figure 9 illustrates the resulting ground truth. Among changes studied in the performance evaluation process, parking areas, building construction or destruction, and ground changes are assigned to a generic change class.

Among the changes, we have a particular interest in construction site events. In practice, the construction of a building results in the implementation of building sites, visible on the temporal signal as long term steps. We evaluate the contribution of polarimetry to both the coefficient of variation method and the Omnibus method Nielsen et al. [2017], Conradsen et al. [2016], which is the state-of-the-art reference method.

In the Omnibus method, the threshold criterion is the result of a hypothesis test of homogeneity of all observed coherence matrices, supposed to follow a Wishart law. The criterion is then expressed using the ratio between geometric mean and arithmetic mean temporal determinants of these matrices.

In all cases, we reduced ourselves to a hypothesis test carried out with an Equivalent Number of Looks (ENL) equal to 1. Using ROC curves, we then compared the effectiveness of the following criteria:

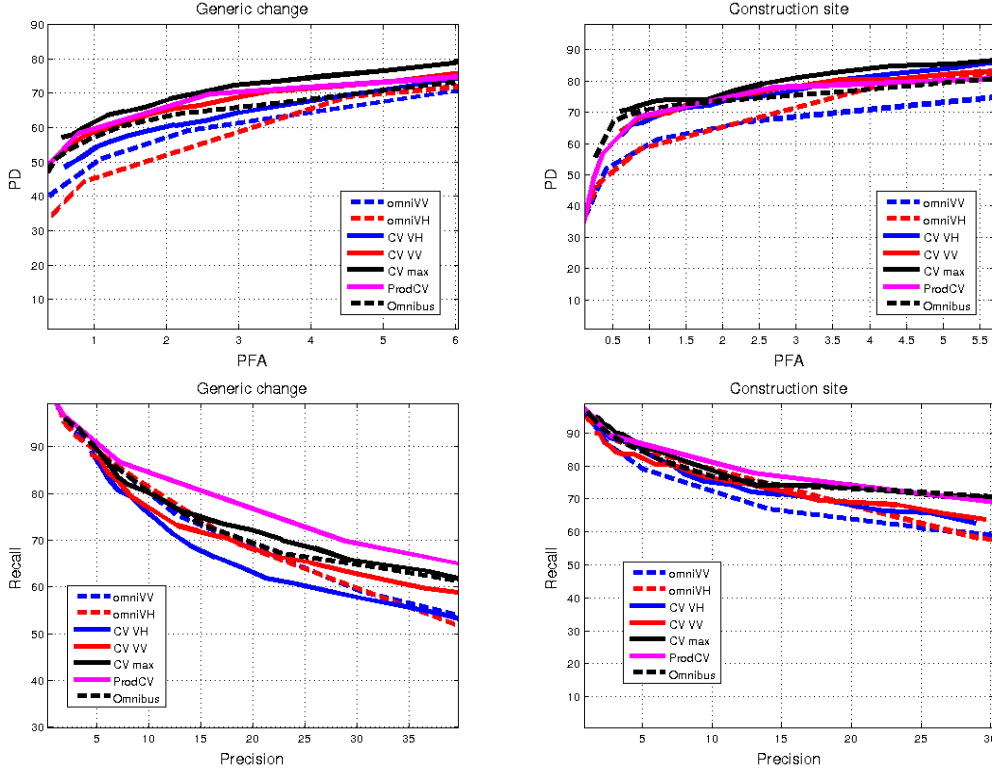


Figure 10: Coefficient of Variation Versus Omnibus method: PD/PFA and Precision Recall curves, for construction of generic changes

- The coefficient of variation for each polarization, the maximum of these two coefficients, and the product of coefficients of variation obtained in VH and VV polarizations.
- The omnibus criterion for each polarization individually, and that obtained for the polarimetric case.
- the specific criterion C_1 proposed for step-signal detection, first for each polarimetric channel, and then the maximum of the individual criteria.

Considering the maximum of two criteria is based on the observation that very often when we can observe a rupture qualitatively in the temporal profile, we observe it only for a single polarization. This polarization is presumably the polarimetric signature of the target that is detected. Also, it is natural to choose in the polarimetric channel for the change is most noticeable. The figure 10 presents the false alarm detection/probability curves and the recall precision curves for the coefficient of variation and the Omnibus criterion, in two cases: the one where we consider all the categories of change, and the one where we consider only the construction sites, that are the best-detected changes. Overall, the performance of detection in VV channel is better than for the VH polarization. Whatever the type of detector chosen, coefficient of variation or omnibus, merging the two polarization channels improves performance. The curves show that the methods based on the coefficient of variation are better than the Omnibus criterion. Choosing the maximum of the coefficients of variation leads to better probabilities of detection for a fixed false alarm rate. However, the product of the coefficients of variation gives slightly better accuracy for a fixed detection rate. The two methods of fusion, therefore, appear complementary.

In figure 11, we now compare the coefficient of variation performance, with the one of the criterion C_1 . One again, use of polarimetry brings significant gain. C_1 performance is always better than the one of the coefficient of variation itself. The best fusion method is the one that considers the maximum among polarimetric channels for C_1 , whether for probability of detection or for accuracy.

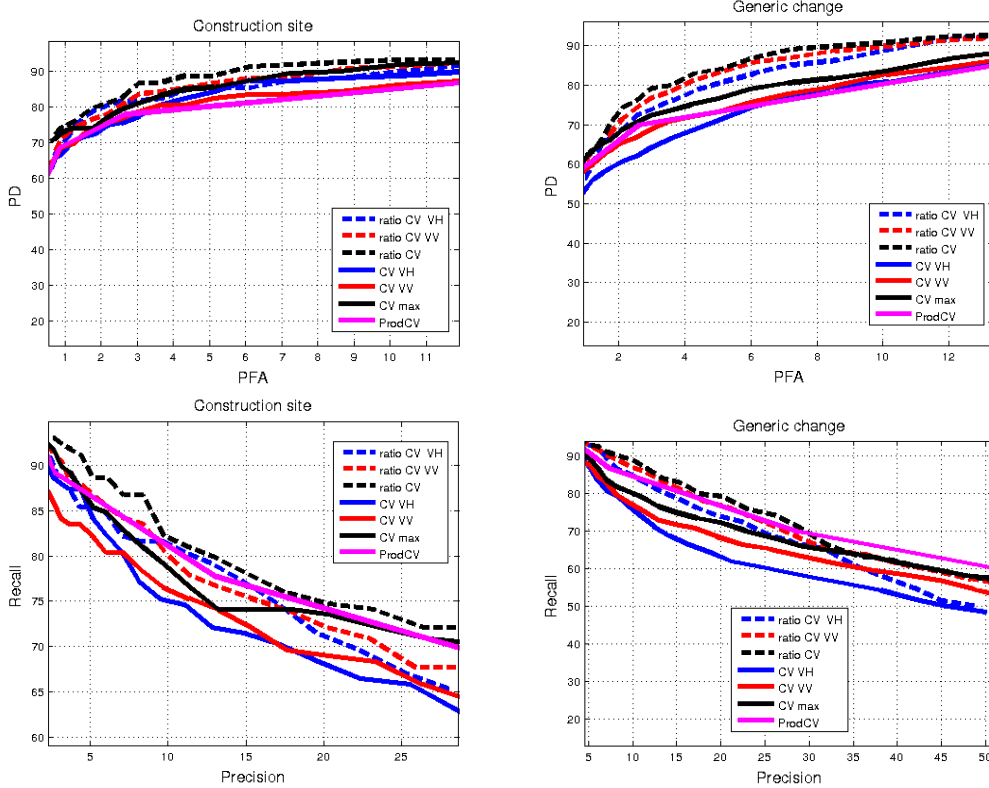


Figure 11: Coefficient of Variation Generic Versus Specific method: PD/PFA and Precision/Recall curves, for construction changes

4 Detection of short events

In Colin Koeniguer and Nicolas [2020], we proposed a change detector dedicated to very short event, ie appearing during a limited time in the observation range. The detection criterion is written as:

$$C_2(x(t)) = \frac{\gamma(x(t)_{t \in \{1 \dots N\} \setminus \{t_{\max}\}})}{\gamma(x(t)_{t \in \{1 \dots N\} \setminus \{t_{\min}\}})} \quad (2)$$

where t_{\max} and t_{\min} are the dates for which the signal $x(t)$ is respectively maximum and minimum.

As for the long event change detection, we define this criterion for each polarimetric channel, and we question the role of polarimetry. To analyze the influence of polarimetry, we fix different thresholds corresponding to a given rate of changes, and we compare for each threshold the number of targets thus detected in each polarimetric channel. We have performed this test on the Sentinel-1 time-series over Saclay, by merely comparing the target rates that are found by the VH polarization, the VV polarization, and by the two polarizations.

Figure 12 illustrates that there is clear predominance of detection in the VV polarization. Both polarizations detect few targets at once. In the area under consideration, we have 91% of targets identified only by the VV polarization, 8% by the VH polarization, and only 1% of targets are selected by the two polarimetric channels.

Several similar tests can be carried out in several places around the world thanks to the GEE platform. The trends found qualitatively remain the same. The number of points detected in the VV polarization is still higher than the number of spots detected in VH polarization on continental areas. There are a small number of locations identified by both polarizations, but it is the lowest number.

On the sea, the trends are opposite: the VH polarization obtains the highest number of detection. This result is consistent with Touzi et al. [2004]: among the conventional single-channel polarizations (HH, VV, or HV), HV provides the best ship-sea contrast at incidence angles smaller than 50° . Exceptions occur when the ship orientation coincides with the

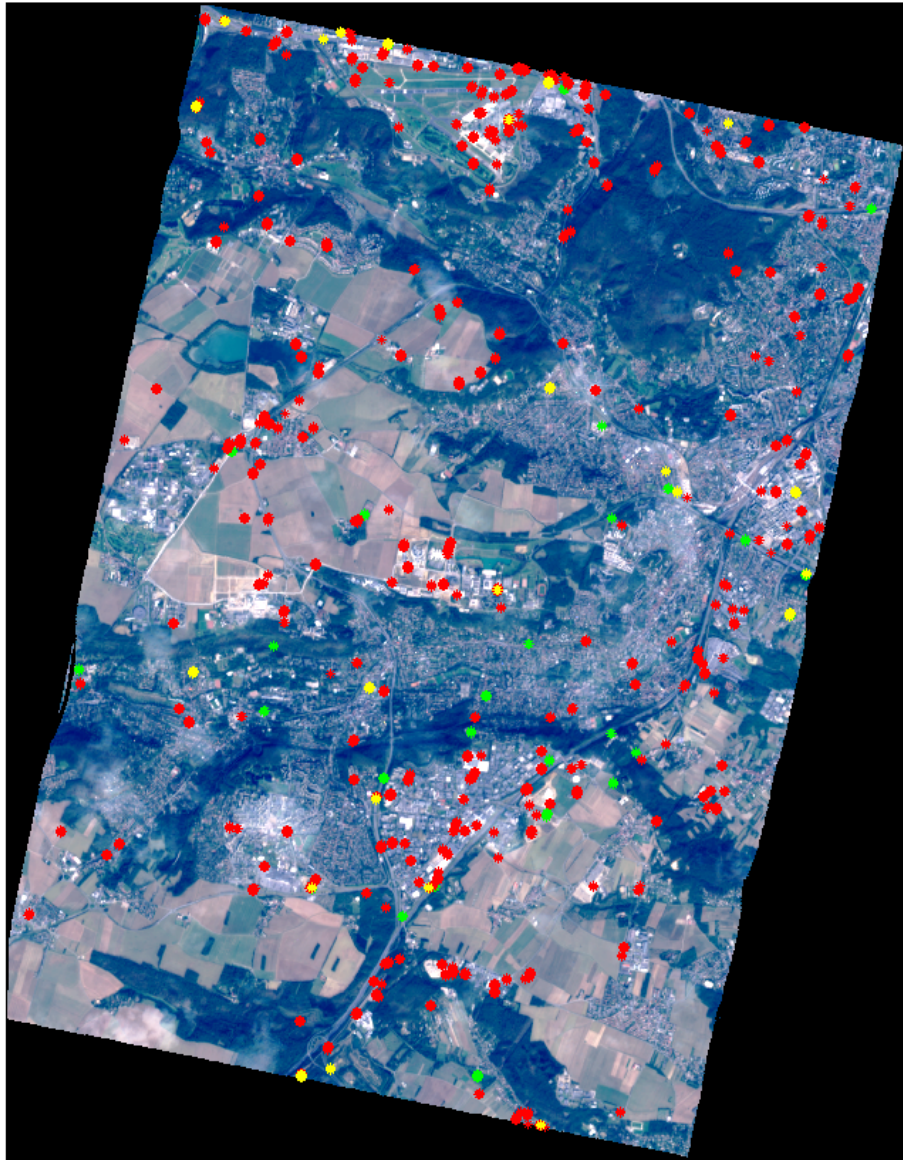


Figure 12: Point-Event detected over Saclay, superimposed on an optical Sentinel 2 image - Red: only by VV polarization (91%). Green: only by VH polarization (8%). Yellow: by both polarizations (1%). Palaiseau surroundings (France)

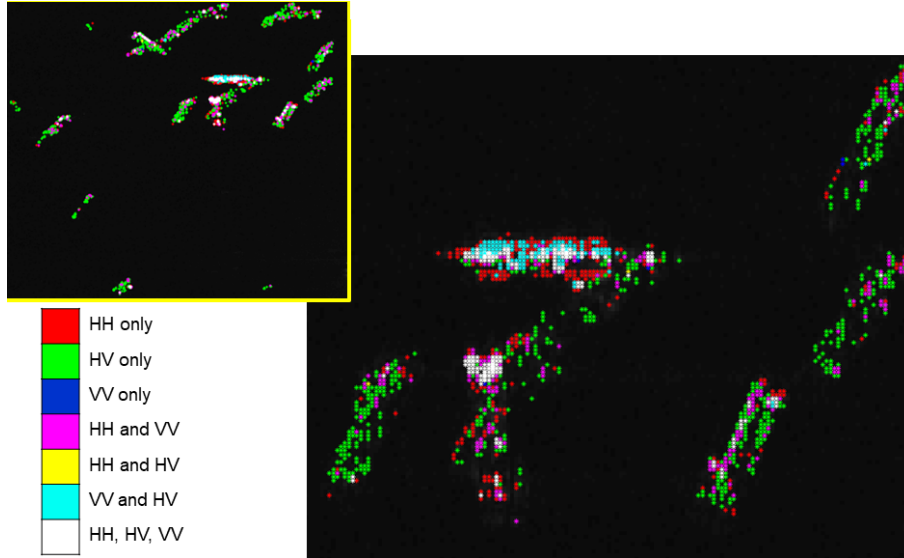


Figure 13: Point-Event detected over boats in UAVSAR stack

acquisition trajectory axis: in this case, the phenomenon of double-rebound is amplified and becomes predominant.

We have reinforced these observations using the analysis of different scenes in UAVSAR polarimetric images. On a sea area, most of the pixels belonging to these boats are well found by our detector, for meager false alarm rates. In this scenario, it is possible to make a manual ground truth by outlining the boats and considering that the pixels belonging to the delimited shapes are pixels to be detected. This way of defining a ground truth has two main drawbacks. First, the ground truth relies on the data itself, and not on independent information. Secondly, most radar detections are isolated bright points sparse on the covered surface and not connected pixels. Therefore, the ROC curves would have no relevant meaning. For this reason, we consider the percentage of points detected by type of polarization. The figure 13 shows qualitative results. We see that the VH polarization is critical in the detection, except for the boat oriented parallel to the trajectory of the sensor. In this case, the double bounce effect prevails.

The figure 14 presents a tabulation of the polarimetric channels most favorable to the detector. The first crucial observation, illustrated by the pink boxes, is that all polarizations are necessary if we want to cover at least half of the detection in continental surfaces. This result is right in the different areas encountered: dense urban as in San Francisco, or industrial areas. This outcome is significant: detecting short events in a time series requires a full polarimetric acquisition. There is no pair of two polarizations which allow exceeding the score of 24 %. The most favorable polarimetric pair seems to be the VV/VH couple, the least efficient pair of polarization being the HH/HV couple. On ocean surfaces, the situation is slightly different. As noted qualitatively, the HV channel is the most favorable and accounts for just under half of the detections.

5 Conclusion

This article has investigated the role of polarimetry in SAR time-series. The REACTIV visualization method, which highlights the changes through the use of saturated colors, has been generalized to the polarimetric case. The effects of the fusion are particularly noticeable in crops. These areas undergo chaotic changes, and polarimetric signals are not correlated along time.

As part of the detection of construction-type changes, the fusion of several criteria calculated in the different polarimetric channels brings a gain in performance. This gain has been demonstrated on a double polarization Sentinel-1 stack of images. We have compared several approaches. The first two involve the coefficient of variation. The third considers the ratio of arithmetic and geometric means, derived from a homogeneity test of a Gaussian temporal statistical population. Concerning the methods based on the coefficients of variation, the proposed fusion scheme retains either the maximum

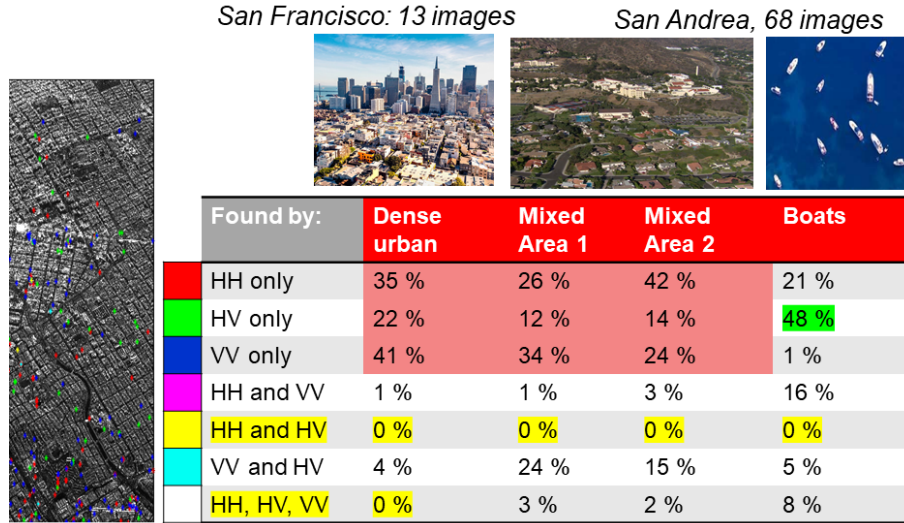


Figure 14: Point-Event detected over different scenes in UAVSAR stacks

or the product of the criteria. In summary, the most efficient fusion method found so far is to retain the maximum among the specific criteria based on the ratios of coefficients of variation, calculated individually for each polarization.

In the context of the detection of short events, our approach is to threshold the specific criterion developed to detect such changes. Depending on the polarization used, we then quantify for a given threshold, the number of targets found relative to a specific event. We compare this number for all possible polarimetric combinations: single polarimetric, dual polarimetric or full polarimetric mode. This approach has been performed on the same Sentinel 1 time-series as in the case of long-events.

For this scene, we show that the majority of the detection plots are carried out for the VV polarization, and about 10% is carried out for the VH polarization. Both polarizations detect very few targets at once: the polarimetric information is therefore complementary.

For high-resolution data in urban or peri-urban areas, the detection plots are mainly distributed between each of the polarimetric channels. Therefore, the acquisition of the three polarimetric channels is essential if we want to detect this type of events in the time series. The most efficient dual-pol mode is the VV/VH mode, but it alone makes miss a full third of targets.

For marine data, the situation is very different. The VH polarization alone covers half of the detection spots. The VV polarization provides minimal detection gain. The polarization HH is useful in the very particular case where the detection concerns a boat that is perfectly aligned with the axis of the trajectory of the antenna. The main idea is that a full polarimetric acquisition is essential if we want to be able to detect short-events in a time series.

Subsequently, we will continue to examine carefully more ambitious polarimetric fusion strategies in the future.

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Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

abbreviations

The following abbreviations are used in this manuscript:

CDM	Change Detection Matrix
CV	Coefficient of Variation
DInSAR	Differential Interferometry SAR
ENL	Equivalent Number of Looks
GRD	Ground Radar Detected
HSV	Hue Saturation Value
IGN	Institut Géographique National (French National Geographic Agency)
MIMOSA	Method for generalized Means Ordered Series Analysis
ONERA	Office National D'Etudes et de Recherches Aérospatiales (The French Aerospace Lab)
OSM	Open Street Map
PD	Probability of Detection
PFA	Probability of False Alarm
REACTIV	Rapid and EASY Change detection on Time-series using coefficient of Variation
RGB	Red Green Blue
ROC	Receiver Operating Characteristic
SAR	Synthetic Aperture Radar
SLC	Single Look Complex

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