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A Change Detector Based on an Optimization with Polarimetric SAR imagery

Armando Marino, *Member, IEEE*, Irena Hajnsek, *Member, IEEE*

Abstract

The possibility to detect changes in land cover with remote sensing is particularly valuable considering the current availability of long time series of data. SAR can play an important role in this context, since it can acquire complete time series without limitations of cloud cover. Additionally, polarimetry has the potential to improve significantly the detection capability allowing the discrimination between different polarimetric targets. This paper is focused on developing two new methodologies for testing the stability of observed targets (i.e. Equi-Scattering Mechanisms hypothesis) and change detection. Both the algorithms adopt a Lagrange optimization, which can be performed with two eigen-problems. Interestingly, the two optimizations share the same eigenvectors. Three statistical tests are proposed to set the threshold for the change detector. Two of them are mostly aimed at point targets and one is more suited for distributed targets.

All the algorithms and procedures developed in this paper are tested on two different quad-polarimetric dataset acquired by the E-SAR DLR system in L-band (SARTOM 2006 and AGRISAR 2006 campaigns). The dataset are accompanied by ground surveys. The detectors are able to identify targets and areas with validated changes or showing clear differences in the images. The theoretical pdf exploited to model the optimum ratio fits adequately the data and therefore has been used for the statistical tests. Regarding the output of the tests, two of them provided good results, while one needs more care and adjustments.

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Keywords

Synthetic Aperture Radar, Polarimetry, Change Detection, Equi-Scattering Mechanisms.

I. INTRODUCTION

Change detection is a valuable topic in SAR remote sensing and polarimetry can improve the results of single polarimetric algorithms [1], [2], [3], [4], [5], [6]. The polarization of the transmitted and received waves can be exploited to extract more information about the observed targets, since different targets are expected to have different polarimetric behaviors. Besides the physical rationale, polarimetry allows to acquire four images that will naturally bring more information compared to a single image (unless the three images are perfectly correlated, which is generally not the case). From a mere signal processing point of view, this information is supposed to improve the detection output.

The aim of this paper is to develop an algorithm aimed at change detection and evaluate the error made after the Equi-Scattering Mechanism (ESM) hypothesis [7], [8], [9]. A very brief introduction to polarimetry will be provided here with the mere purpose to show the tools exploited in the following.

A single target is defined as a deterministic target which does not change its polarimetric behavior in time/space. Therefore, it can be represented by a single scattering matrix $[S]$ or equivalently a single scattering vector [7], [10]:

$$\underline{k}_L = [HH, HV, VH, VV]^T, \quad (1)$$

where H and V stands for linear horizontal and vertical and the repeated letter is for transmitter-receiver. The previous is obtained employing the Lexicographic basis set. In the case of a reciprocal medium and monostatic sensor, $HV = VH$ and \underline{k}_L is three-dimensional complex

20 (i.e. $\underline{k}_L \in \mathbb{C}^3$) [7]. Another largely used basis set to convert $[S]$ into a scattering vector is the
 21 Pauli basis. In the reciprocal case, this is $\underline{k}_P = 1/\sqrt{2} [HH + VV, HH - VV, 2 * HV]^T$.
 22 A Scattering Mechanisms (SM) $\underline{\omega}$ is an ideal target and is defined as a normalized scattering
 23 vector: $\underline{\omega} = \frac{\underline{k}}{|\underline{k}|}$.

24 The targets observed by a SAR system are often distributed over an area larger than the res-
 25 olution cell and composed by different objects. For this reason, each pixel of such distributed
 26 targets has a specific polarimetric behavior. Such targets take names of *partial targets* and
 27 they can be characterized via their second order statistics [7], [10]. In this context, a target
 28 covariance matrix can be estimated as $[C] = \langle \underline{k} \underline{k}^{*T} \rangle$, where $\langle \cdot \rangle$ is the finite averaging op-
 29 erator. In case that the Single Look Complex (SLC) pixel can be modeled by a Complex
 30 Gaussian, the second order statistics are necessary and sufficient to completely characterize
 31 a partial target. In case of the Pauli basis, the covariance matrix is indicated by $[T]$ and takes
 32 the name of *Coherency* matrix.

33 If two different acquisitions \underline{k}_1 and \underline{k}_2 are available two SM $\underline{\omega}_1$ and $\underline{\omega}_2$ can be considered
 34 and a polarimetric and interferometric coherence can be estimated [8], [9]:

$$\gamma = \frac{\underline{\omega}_1^{*T} [\Omega_{12}] \underline{\omega}_2}{\sqrt{(\underline{\omega}_1^{*T} [T_{11}] \underline{\omega}_1) (\underline{\omega}_2^{*T} [T_{22}] \underline{\omega}_2)}}, \quad (2)$$

35 where $[T_{11}] = \langle \underline{k}_1 \underline{k}_1^{*T} \rangle$, $[T_{22}] = \langle \underline{k}_2 \underline{k}_2^{*T} \rangle$ and $[\Omega_{12}] = \langle \underline{k}_1 \underline{k}_2^{*T} \rangle$.

36 In the following the hypothesis of Equi-Scattering Mechanisms (ESM) is tested [7], [11].
 37 The latter assumes that the partial target under analysis does not change during the two
 38 acquisitions. It is generally followed by two positions:

- 39 1. γ is estimated on two identical $\underline{\omega}$: i.e. $\underline{\omega}_1 = \underline{\omega}_2$. This avoids decorrelation effects due to
 40 the change of selected target.
- 41 2. The second order statistics of the partial targets in the first and second acquisitions are the

42 same: i.e. $E [\underline{k}_1 \underline{k}_1^{*T}] = E [\underline{k}_2 \underline{k}_2^{*T}]$.

43 The second hypothesis is operatively applied considering finite averaging, leading to $[T_{11}] =$
 44 $[T_{22}]$. Furthermore, it is defined the matrix $[T] = ([T_{11}] + [T_{22}])/2$ and the corresponding
 45 interferometric coherence can be written as:

$$\gamma_{ESM} = \frac{\underline{\omega}^{*T} [\Omega_{12}] \underline{\omega}}{\underline{\omega}^{*T} [T] \underline{\omega}}. \quad (3)$$

46 From a mathematical point of view the expression of γ_{ESM} is easier to tackle than γ . This
 47 led to the proliferation of algorithms working on γ_{ESM} more than γ [7], [12], [13].

48 II. OPTIMIZATIONS

49 A. Error factor for Equi-Scattering Mechanisms (ESM)

50 The ESM hypothesis assumes that the partial target does not change polarimetrically be-
 51 tween the two acquisitions. This of course is not always the case and some test has to be
 52 devised able to tell when the hypothesis is fulfilled or when it will introduce errors in the
 53 estimations. A test for ESM based on *Geometrical Perturbation* filters [14], [15] was al-
 54 ready developed by the authors [16]. The main characteristic of such test is the capability to
 55 separate polarimetric information from the overall power of the partial target (i.e. Trace of
 56 the covariance matrix). It is valuable for testing the feasibility of a ESM hypothesis because
 57 the Pol-InSAR coherence γ is independent of changes in the Trace of the matrices.

58 In this paper, a different approach is followed which will lead to a complementary results
 59 to the one obtained in [16]. After $\underline{\omega} = \underline{\omega}_1 = \underline{\omega}_2$ is considered, the Pol-InSAR coherence can
 60 always be written as:

$$\gamma = \frac{\underline{\omega}^{*T} [\Omega_{12}] \underline{\omega}}{\underline{\omega}^{*T} [T] \underline{\omega}} \frac{\underline{\omega}^{*T} [T] \underline{\omega}}{\sqrt{(\underline{\omega}^{*T} [T_{11}] \underline{\omega}) (\underline{\omega}^{*T} [T_{22}] \underline{\omega})}} = \gamma_{ESM} \gamma_e. \quad (4)$$

61 To make the formulation more compact, the quadratic forms in the denominator can be identified as $P_1 = \underline{\omega}^{*T}[T_{11}]\underline{\omega}$ and $P_2 = \underline{\omega}^{*T}[T_{22}]\underline{\omega}$. Few properties of the factor γ_e are:

- 63 1. It is real positive (i.e. $\gamma_e \in \mathbb{R}^+$) since all its composing elements belong to \mathbb{R}^+ .
 64 2. It is defined in the interval $\gamma_e \in [1, \infty[$:

$$\gamma_e = \frac{(P_1 + P_2)/2}{\sqrt{P_1 * P_2}} = \frac{AM}{GM} \geq 1, \quad (5)$$

65 where AM stands for Arithmetic Mean and GM for Geometrical Mean and it is always $AM \geq$
 66 $GM \quad \forall P_1, P_2 \in \mathbb{R}^+$.

- 67 3. $\gamma \geq \gamma_{ESM} \quad \forall [T_{11}], [T_{22}], [\Omega_{12}]$. This comes from the previous property.

68 The main idea of the proposed methodology is to retrieve the stationary points of γ_e in
 69 order to understand which are the SM that suffer more (less) from the ESM assumption. This
 70 also returns the maximum error made after the ESM hypothesis is adopted. The optimization
 71 can be easily accomplished with a Lagrange methodology, where the numerator is optimized
 72 while the denominator is constrained to be constant [17]. Please note, this is a methodology
 73 largely exploited in the SAR polarimetric community [7], [10].

74 To be more general, the derivation will be made considering $\underline{\omega}_1 \neq \underline{\omega}_2$. The Lagrangian is:

$$L = \underline{\omega}_1^{*T}[T]\underline{\omega}_2 - \lambda_1 (\underline{\omega}_1^{*T}[T_{11}]\underline{\omega}_1 - C_1) - \lambda_2 (\underline{\omega}_2^{*T}[T_{22}]\underline{\omega}_2 - C_2). \quad (6)$$

$$\begin{aligned} \frac{\partial L}{\partial \underline{\omega}_1^{*T}} &= [T]\underline{\omega}_2 - \lambda_1 [T_{11}]\underline{\omega}_1 = 0 \\ \frac{\partial L}{\partial \underline{\omega}_2^{*T}} &= [T]^* \underline{\omega}_1 - \lambda_2 [T_{22}]\underline{\omega}_2 = 0 \end{aligned} \quad (7)$$

After few calculations the system of equations can be found, which corresponds to two di-

agonalizations:

$$[T_{11}]^{-1}[T][T_{22}]^{-1}[T]\underline{\omega}_1 = \lambda_1\lambda_2^{*T}\underline{\omega}_1, \quad (8)$$

$$[T_{22}]^{-1}[T][T_{11}]^{-1}[T]\underline{\omega}_2 = \lambda_2\lambda_1^{*T}\underline{\omega}_2.$$

75 After some algebraic manipulations, it is possible to derive the identity:

$$[T_{11}]^{-1}[T][T_{22}]^{-1}[T] = [T_{22}]^{-1}[T][T_{11}]^{-1}[T] = \frac{1}{4} [[T_{22}]^{-1}[T_{11}] + 2[I] + [T_{11}]^{-1}[T_{22}]] = [A]. \quad (9)$$

76 Therefore, only one diagonalization has to be performed:

$$\underset{\omega \in \mathbb{C}^3}{Opt} \gamma_e \rightarrow [A]\underline{\omega} = \lambda_e \underline{\omega}. \quad (10)$$

77 After the diagonalization it will be possible to express $[A]$ with eigenvectors and eigenval-
 78 ues: $[A] = [U_e]^{*T}[\Sigma_e][U_e]$, where $[\Sigma_e] = \text{diag}(\lambda_{1e}, \lambda_{2e}, \lambda_{3e})$ with $\lambda_{1e}, \lambda_{2e}, \lambda_{3e} \in \mathbb{R}^+$ and
 79 the columns of $[U_e]$ are the eigenvectors. The eigenvalues correspond to the maximum or
 80 minimum errors committed in the estimation of the PolInSAR coherence after the ESM as-
 81 sumption and the eigenvectors represent the scattering mechanisms suffering such errors.

82 Since the matrix $[A]$ is generally not Hermitian the eigenvectors are not expected to be or-
 83 thogonal (i.e. the maximum and minima of γ_e are generally not constrained to be orthogonal
 84 each other). In the next section, a proof will be provided that the eigenvalues of $[A]$ exist and
 85 are always real positive for all T_{11} and T_{22} Hermitian semi-positive definite matrices.

86 *B. Change detection with power ratio*

87 The previous algorithm is not directly focused on change detection. The aim of this section
 88 is to understand if a similar methodology can be exploited to optimize another polarimetric
 89 observable (i.e. operator) that has more relevance for change detection. The ratio of the

90 power in the two acquisitions varying the SM is selected:

$$\underset{\underline{\omega} \in \mathbb{C}^3}{Opt} \rho_{12}, \quad \rho_{12} = \frac{\underline{\omega}^{*T} [T_{11}] \underline{\omega}}{\underline{\omega}^{*T} [T_{22}] \underline{\omega}}. \quad (11)$$

Mathematically, this is the ratio of two quadratic forms that are real positive, since the matrices $[T_{11}]$ and $[T_{22}]$ are Hermitian semi-positive definite. The optimization can be again accomplished with a Lagrangian methodology which ends in a diagonalization:

$$L = \underline{\omega}^{*T} [T_{11}] \underline{\omega} - \lambda (\underline{\omega}^{*T} [T_{22}] \underline{\omega} - C), \quad (12)$$

$$\frac{\partial L}{\partial \underline{\omega}^{*T}} = [T_{11}] \underline{\omega} - \lambda [T_{22}] \underline{\omega} = 0$$

$$[T_{22}]^{-1} [T_{11}] \underline{\omega} = \lambda \underline{\omega}.$$

91 To conclude, $[T_{22}]^{-1} [T_{11}] = [U_r]^{*T} [\Sigma_r] [U_r]$, where $[\Sigma_r] = \text{diag}(\lambda_{1r}, \lambda_{2r}, \lambda_{3r})$ with $\lambda_{1r}, \lambda_{2r}, \lambda_{3r} \in$
 92 \mathbb{R}^+ and the columns of $[U_r]$ are the eigenvectors. The maximum eigenvalue λ_{1r} represents
 93 the maximum ratio ρ_{12} . In order to understand if this is the $\underline{\omega}$ suffering the maximum change
 94 in the two acquisitions, another optimization should be performed. This is the ratio:

$$\rho_{21} = \frac{\underline{\omega}^{*T} [T_{22}] \underline{\omega}}{\underline{\omega}^{*T} [T_{11}] \underline{\omega}}, \quad (13)$$

95 which ends up with the diagonalization of the matrix: $[T_{11}]^{-1} [T_{22}]$. This is because the power
 96 could increase or decrease in the two acquisitions (i.e. the target could appear either in the
 97 first or second acquisitions). Therefore, the scattering mechanism that suffers the maximum
 98 change $\underline{\omega}_{max}$ is:

$$\underline{\omega}_{max} = \underset{\substack{\underline{\omega} \in \mathbb{C}^3 \\ \underline{\omega} \in \mathbb{C}^3}}{Argmax} \left[\underset{\substack{\underline{\omega} \in \mathbb{C}^3 \\ \underline{\omega} \in \mathbb{C}^3}}{Opt} \rho_{12}, \underset{\substack{\underline{\omega} \in \mathbb{C}^3 \\ \underline{\omega} \in \mathbb{C}^3}}{Opt} \rho_{21} \right]. \quad (14)$$

99 It is interesting to note that $([T_{11}]^{-1} [T_{22}])^{-1} = [T_{22}]^{-1} [T_{11}]$, therefore they will have the same
 100 eigenvectors, but inverted eigenvalues (the power of a matrix does not change the eigenvec-
 101 tors) [18]. Summarizing, diagonalizing $[T_{22}]^{-1} [T_{11}]$, all the information about the eigenvec-

102 tors and eigenvalues of its inverse will be available, and only one of the two problems has to
 103 be solved. This means that:

$$\underline{\omega}_{max} = \underset{\omega \in \mathbb{C}^3}{\text{Argmax}} \left[\underset{\omega \in \mathbb{C}^3}{\text{max}}(\rho_{12}), 1 / \underset{\omega \in \mathbb{C}^3}{\text{min}}(\rho_{12}) \right]. \quad (15)$$

104 With the goal of improving the visualization of the results, the eigenvalues can be inverted
 105 when they are smaller than one and their sign changed (i.e. making it negative). In other
 106 words:

$$\begin{cases} \hat{\rho}_{max} = \rho_{max} & \text{if } \rho_{max} \geq 1, \\ \hat{\rho}_{max} = -\frac{1}{\rho_{max}} & \text{if } \rho_{max} < 1. \end{cases} \quad (16)$$

107 As a final remark, the optimization of the power ratio is a relatively old problem and a sim-
 108 ilar result was found by Novak et al. [19] and called Polarimetric Match Filter (PMF). In
 109 the PMF, the ratio is calculated between the power of the target and the surrounding clutter
 110 (generally estimated locally with guard windows). The optimization maximizes the contrast
 111 between target and clutter selecting the best SM to be used for the following detection (gen-
 112 erally accomplished with a Constant False Alarm Rate methodology). Therefore, the PMF
 113 is applied over one quad-pol acquisition and exploited for target detection, while the change
 114 detector proposed here, exploits two quad-pol acquisitions.

115 *C. Relationship between the two algorithms and discussion*

116 In the previous sections two different optimizations were proposed, both based on diago-
 117 nalizations of two defined matrices. It is interesting to understand if there is some relation-
 118 ship between the two set of solutions. In other words, are the $\underline{\omega}$ that change more also the
 119 one that suffer more after a ESM hypothesis (ii)? In Appendix, a proof is provided that the
 120 eigenvectors of γ_e are the same as the eigenvectors of ρ_{12} . Therefore, $[U_e] = [U_r][P]$, $\forall [P]$

121 permutation matrix (i.e. the order of the columns of the eigenvectors matrix can be rear-
122 ranged).

123 The proposed algorithms are sensitive to changes in the backscattering between the two
124 images. This means that radiometric calibration errors between the two polarimetric acqui-
125 sitions (i.e. the scattering matrix of the second acquisitions has a different gain than the one
126 of the first acquisition) will be revealed by the detector. Therefore, this feature may have
127 the potential to be exploited for performing some corrections in case of eventual calibra-
128 tion problems. It should also be noticed that if very small changes (ratio close to 1) of the
129 backscattering over large areas is investigate, then special care should be taken in calibrating
130 with high accuracy the data. Future work will be carried out on trying to exploit the proposed
131 optimization to devise some procedure to improve the calibration.

132 Few words should be spent regarding the results of the ESM test. As mentioned previously,
133 the authors already developed a ESM test based on Geometrical Perturbation filters [16]. The
134 latter is particularly suited as a pre-processing test of the Pol-InSAR coherence γ , since this
135 is independent of the total power of the partial target (i.e. Trace of the covariance matrix).
136 However, after the ESM hypothesis is performed and we are interested in understanding the
137 amount of error made, the analysis should be done on the ESM coherence γ_{ESM} more than
138 the original Pol-InSAR coherence γ . γ_{ESM} is dependent on the overall amplitude of the
139 partial target. In other words, if $k_1 = ck_2$ with $c \in \mathbb{R}$ the final value of γ_{ESM} would be
140 different varying the factor c (i.e. $\lim_{c \rightarrow \infty} \gamma_{ESM} = 0$, while $\lim_{c \rightarrow \infty} \gamma = \gamma$).

141 To conclude, if the interest is to test whether the ESM hypothesis can be made or not
142 (i.e. to produce a mask where the ESM assumption is fulfilled and where not) the algorithm
143 based on Geometrical Perturbation should be employed [16]. On the other hand, if the ESM
144 hypothesis cannot be avoided, because there is no other ways to solve the problem, than the

145 algorithm proposed here (based on the Lagrange optimization) should be exploited, since it
 146 provides a direct measure of the error made.

147 III. STATISTICAL TEST

148 The aim of this section is to devise statistical tests aimed at setting the threshold of the
 149 proposed detectors. The first step is to know (or estimate) the *probability density function*
 150 (pdf) of the observable under analysis [20]. In this paper two optimizations were proposed:
 151 of γ_e and ρ_{12} . Unfortunately, the analytical expression of the pdf for γ_e is unknown and
 152 its evaluation is not trivial. On the other hand, the power ratio has a well-known distribu-
 153 tion [10]. For this reasons, this paper is concentrated in developing statistical tests on the
 154 optimization of ρ_{12} . Finding the analytical version of the pdf of γ_e or fitting some known
 155 distribution will be subject of future analysis.

156 A. pdf of Power Ratio

157 An expression for the pdf of the powers (or intensities) ratio was already derived by Lee et
 158 al. [10]. This is based on the assumption that the initial complex pixel (SLC) can be modeled
 159 by a complex Gaussian process (i.e. texture effects are neglected) [21]. The expression for
 160 the Intensity Ratio (IR) pdf is:

$$f_R^{(n)}(r) = \frac{\tau^n \Gamma(2n) (1 - |\rho|^2)^n (\tau + r) r^{n-1}}{\Gamma(n) \Gamma(n) [(\tau + r)^2 - 4\tau |\rho|^2 r^2]^{(2n-1)/2}}, \quad (17)$$

161 where n is the number of independent looks and Γ is the Gamma function. It has to be noted
 162 that such pdf is based on the knowledge of the true values of τ and ρ , which are defined by
 163 the underlying statistical distribution. If S_1 and S_2 are the two images composing the ratio,

164 the value of ρ can be estimated as:

$$\rho = \frac{\sum_{k=1}^n S_1 S_2^*}{\sqrt{\sum_{k=1}^n |S_1|^2 \sum_{k=1}^n |S_2|^2}} \quad (18)$$

165 and τ is estimated with:

$$\tau = \frac{\sum_{k=1}^n |S_1|^2}{\sum_{k=1}^n |S_2|^2}, \quad (19)$$

166 which are also the Maximum Likelihood Estimators (MLE) in case of Gaussian pixel. Clearly,
 167 exploiting the MLE estimates instead than the true values (which are unknown) may intro-
 168 duce some estimation error.

169 Figure 1 presents some plots varying different pdf parameters. In all the cases, the mean
 170 value of the ratio is $\tau = 5$. In the first two tests, the number of independent averaged pixels is
 171 varied keeping constant the correlation between the two images. As expected, increasing the
 172 number of looks the variance reduces while the mean does not change. In particular, if only
 173 one look is available the distribution resembles a negative exponential (as the distribution of
 174 a single look intensity). In the second test, the correlation between the two images is varied
 175 while the number of looks is kept constant. Interestingly, it appears that the more the images
 176 are correlated, the more the variance of the distribution reduces (even with one single look).
 177 In particular, given $\rho = 1$, the distribution is a Delta of Dirac centered on the mean value.
 178 In other words, if the two images are perfectly correlated each other, the detection becomes
 179 a deterministic problem and the speckle on the single images does not affect anymore the
 180 estimation of the ratio (i.e. the speckle cancels out in the ratio). This has large consequences
 181 when developing an anomaly detector as showed in the following.

182 A final remark is that the IR pdf was derived for the ratio of quadratic forms of the same
 183 matrix where $\underline{\omega}_1$ and $\underline{\omega}_2$ are kept constant. Having two different coherency matrices at the
 184 numerator and denominator is not problematic, since it can just be justified with a change of

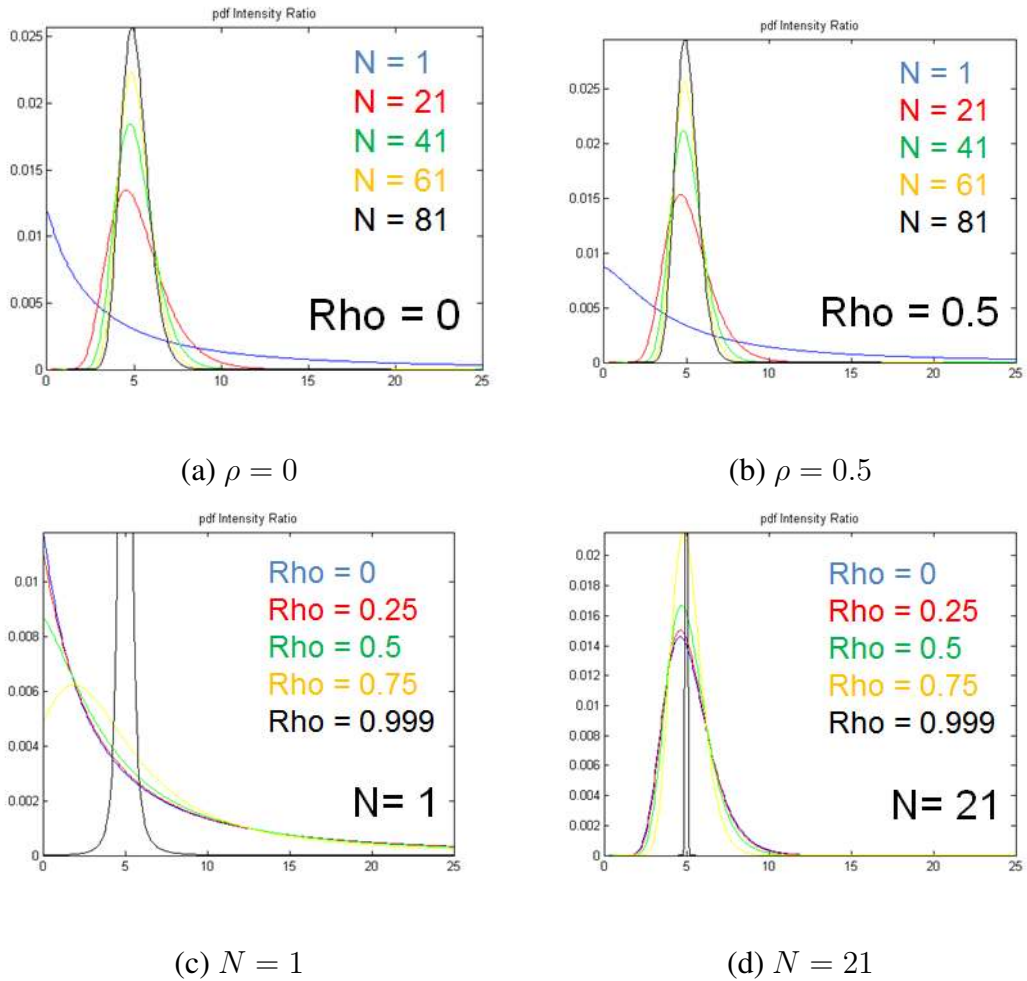


Fig. 1. pdf of Intensity/Power Ratio: (a) varying N and keeping $\rho = 0$; (b) varying N and keeping $\rho = 0.5$; (c) varying ρ and keeping $N = 1$; (d) varying ρ and keeping $N = 21$. The average value is $\tau = 5$ for all the plots.

185 the scattering mechanism and does not modify their statistics. In the case of the proposed de-
 186 tector, the ω is the result of an optimization and therefore can theoretically modify the target
 187 observed and therefore the distribution. Nevertheless, the IR pdf is a good approximation for
 188 homogeneous areas, since the partial targets in the two images are the same and therefore the
 189 $\underline{\omega}_{max}$ will not change (unless for some speckle effects that are reduced performing adequate
 190 averaging). On the other hand, if the scene presents some heterogeneity the IR is not satis-
 191 factory anymore. In actual fact, if the area is heterogeneous the IR pdf will not work even in
 192 the case of the classic polarimetric ratio, since it assumes homogeneous Gaussian scattering.
 193 In the validation section the fit will be analyzed in order to assess the feasibility of the IR pdf
 194 for the optimized ratio. Besides, in the future more work will be focused on trying to include
 195 some texture parameter in the pdf of the intensity ratio.

196 *B. Anomalies detector*

197 This test evaluates the pixels that show up as anomalies over the background. It is par-
 198 ticularly indicated for point targets since changes on extended areas (i.e. distributed targets)
 199 will be rejected. In order to perform the test optimally, the pdf of target and clutter should
 200 be known, which requires a priori information that generally are not available for point tar-
 201 gets. In this paper, only the pdf of the clutter is considered and a Constant False Alarm Ratio
 202 (CFAR) methodology is employed [20], which tries to keep constant the probability that one
 203 background pixel may be higher than the threshold (i.e. Probability of False Alarm P_f).

204 If ρ^M is the maximum between ρ_{12} or $\frac{1}{\rho_{21}}$ the test hypothesis are:

$$\left\{ \begin{array}{l} H_0 = \rho^M < T_s, \\ H_1 = \rho^M \geq T_s, \end{array} \right. \quad (20)$$

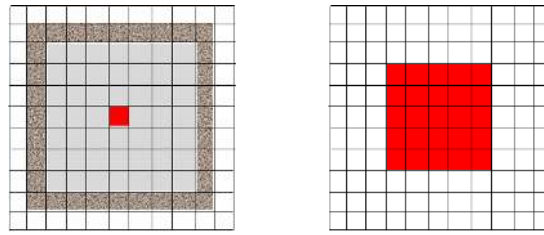
205 and P_f can be calculated as:

$$P_f = 1 - \int_0^{T_s} f_R^{(n)}(r) dr. \quad (21)$$

206 The analytical solution of the integral is unknown and in our tests the integrations will be per-
207 formed numerically. This makes the algorithm slower, but assures a solution with a desired
208 level of accuracy.

209 The statistics of the background can be extracted locally following an ordinary method-
210 ology based on *guard* windows. The single pixel under analysis is surrounded by an area
211 rejected by the analysis. Around the guard area, a ring of pixels is used to estimate the statis-
212 tics of the clutter background. The windows dimensions depend on the sensor parameters
213 (e.g. resolution) and the dimension of targets of interest. A graphical representation is pro-
214 vided in Figure 2.a, where the central red pixel is under test and the surrounding gray pixels
215 are rejected by the analysis. Only the ring of brown pixels is used to extract the statistics of
216 the background. More details on this will be provided in the validation section.

217 Few words should be spent regarding the estimation of the pdf parameters. The correlation
218 ρ and ratio τ can be estimated in a straightforward way with a sample mean. The parameter
219 more complicated to estimate is the Equivalent Number of Look, n which can be derived in
220 a ordinary fashion considering the squared mean over the variance. The problem with such
221 estimator is that it does not take into account eventual texture or generally some heterogene-
222 ity, that may bias strongly the resulting n . The strategy followed in this paper is to evaluate
223 n locally over all the dataset (exploiting moving windows) and then select the value to use
224 in a supervised way. More sophisticate ways can be devised that consider adaptive windows
225 or segmentations. They are not treated in this paper since the main aim is to present the
226 algorithms without altering too much the detection masks with supplemental pre- or post-



(a) Anomaly detector (b) Distributed Changes detector

Fig. 2. Examples of windows exploited by two statistical tests: (a) Guard moving windows for Anomaly Detector; (b) Simple box-car window for Distributed Changes detector.

227 processing. The latter may cover the real performances making not clear if the results are
 228 due to the proposed algorithms or to the pre- and post-processing.

229 C. Distributed Changes detector

230 In case that the detector is focused on distributed targets another statistical test is necessary,
 231 since the interest is focused on changes of the background itself (ring and central pixels
 232 belong to the same distribution). The test is based on selecting a *physical* threshold (T_p) and
 233 detecting the distributions of pixels that are above T_p with a sorter confidence (a probability
 234 of Detection P_d). T_p can be derived from models (physical or empirical) of target changes
 235 (e.g. due to different moisture content or different phenological stages of agricultural plants).
 236 Figure 2.b represent an example of window used in this test. Now, the only pixels employed
 237 in the analysis are the ones in the red region.

238 After setting T_p the P_d is calculated as:

$$P_d = 1 - \int_0^{T_p} f_R^{(n)}(r) dr. \quad (22)$$

239 Equivalently, the Probability of Missing Detection $P_m = 1 - P_d$ can be exploited. One
 240 detection is called when the probability that the distribution under analysis is above the
 241 threshold has a sorter value $P_d \geq \hat{P}_d$ (for instance 99.9%). From an intuitive point of view,

242 evaluating P_m means to test the left tail of the distribution, while evaluating P_f means to test
243 the right tail.

244 *D. Two stages test*

245 In this last section the two previous statistical tests are combined to deal with point targets
246 in changing clutter. As it will be showed in the validation section the anomaly detector
247 suffers from a large false alarm rate. On the other hand, the Distributed Changes detector
248 cannot be used for point targets in clutter because some distributed targets exhibiting changes
249 may generate false alarms (this is when the focus is exclusively on point targets). For this
250 reason, an initial anomaly detector is performed returning an initial threshold T_i . In order
251 to avoid false alarms when the background is very stable an initial values for T_i is set. T_i
252 is then used by a second Distributed Changes detector that evaluate the confidence that the
253 distribution of pixels under analysis is above such threshold. This second stage will reduce
254 more the false alarms since a collection of pixels is evaluated and not just one pixel.

255 In other words, the final algorithm is composed by two stages, the first estimate an initial
256 threshold based on a probability of False Alarm estimated with a ring around a guard window
257 and the second is based on a probability of detection estimated on an internal window (around
258 the central pixel). Figure 3 shows a flow chart for the 2 Stages test.

259 IV. VALIDATION WITH REAL DATA

260 *A. Data Presentation*

261 The algorithm is tested on two different quad-pol E-SAR data in L-band, both acquired in
262 2006. The first dataset is from the SARTOM campaign [22], and was specially focused on
263 target detection with tomography and polarimetry. The resolution is 1.5 m in slant range and

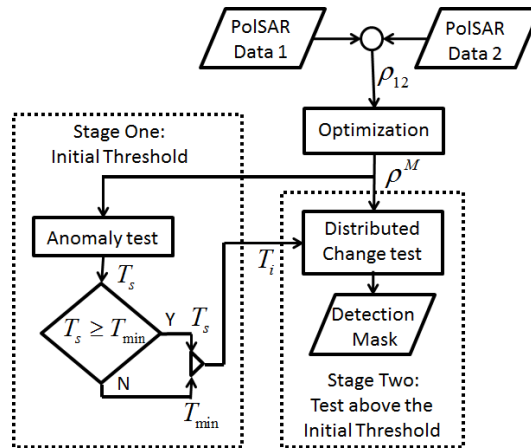
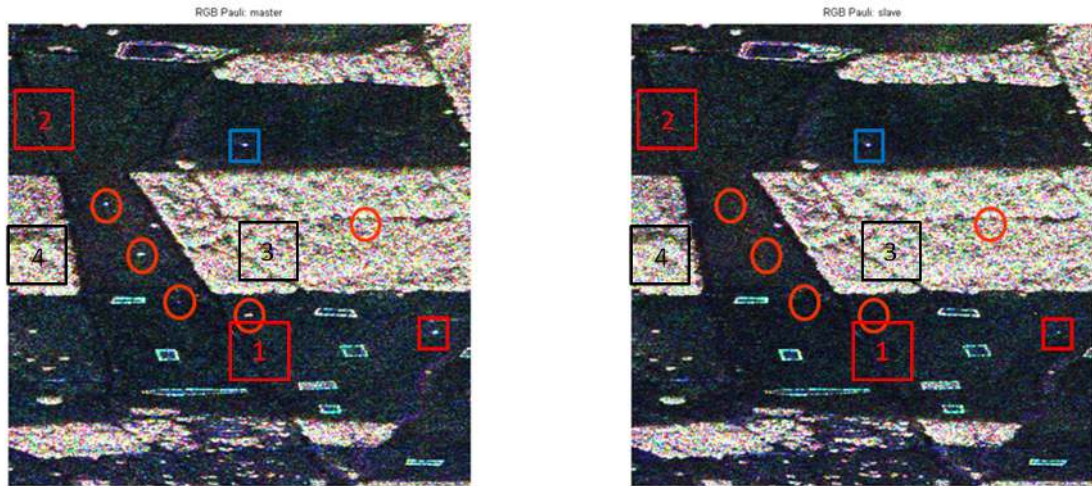


Fig. 3. Flow chart of the 2 Stages Detector. An initial threshold is evaluated during the first stage and then used by the second stage to set a test for a distributed target.

264 0.9 m in azimuth (the pixel sampling is 1.5 m and 0.44 m respectively). For this reason, in the
 265 test area, several targets were located in open field and under vegetation. Additionally, some
 266 of the targets were moved during the acquisitions. Figure 4 shows the RGB Pauli images of
 267 the test area for two separated acquisitions. The spatial baseline is zero (in average) and the
 268 temporal one is four days. Several targets among two trihedral corner reflectors (CR) in open
 269 field, one CR in the forest and two jeeps in open field were removed during the four days
 270 (they are indicated with red circles in the images). Details on the squares will be provided in
 271 the following.

272 The second dataset was acquired in the framework of the AGRISAR campaign [23].
 273 Again, the resolution is 1.5 m in slant range and 0.9 m in azimuth (the pixel sampling is
 274 1.5 m and 0.44 m respectively). The dataset is specially tailored for polarimetric observation
 275 of agricultural fields, therefore long time series of data are available. The two acquisitions
 276 exploited in this work were acquired the 5th of July and the 2nd of August (2006). RGB Pauli
 277 images are showed in Figure 5. Again, they have zero spatial baseline (in average) and the
 278 temporal one is about one month. Several fields appear to change significantly in the images.



(a) Pauli RGB (master)

(b) Pauli RGB (4 days after)

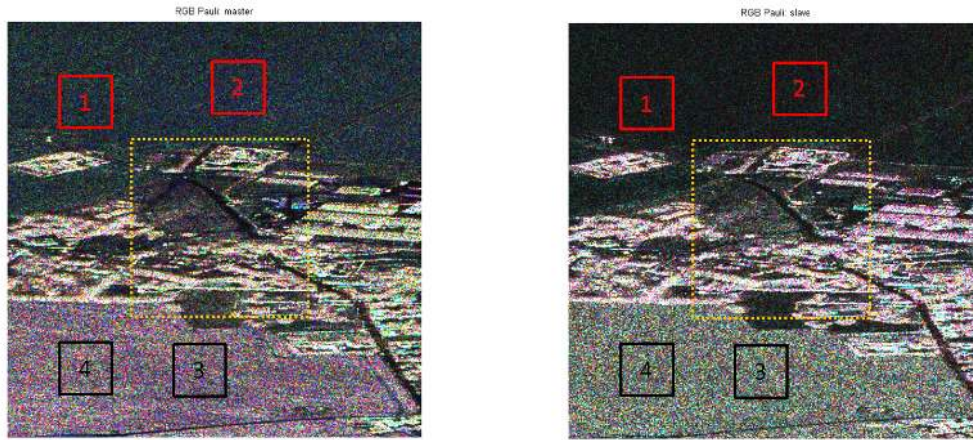
Fig. 4. RGB Pauli images of the SARTOM test site with 4 days of temporal baseline: (a) Master acquisition (b) Slave acquisition (4 days after). Red circles: targets removed; Red rectangle (without number): unknown target with visible change; Blue rectangle: target replaced after 4 days; Red rectangles (with number): bare ground with short grass; Black rectangles: coniferous forest approximately 20m high. Image size 1300x440 m (DLR E-SAR L-band SARTOM2006 Campaign).

279 Moreover, the area covers some build up areas (the settlement of Göslow, close to Görmin,
 280 Germany). The area was selected because it shows two different fields, one harvested (with-
 281 out large changes) and another vegetated. The red and black squares indicate areas where a
 282 more detailed analysis will be carried out in the following.

283 Finally, Figure 6 presents two aerial photographs (taken from Google Earth) to compare
 284 with the SAR images. Please note, the distortion of the radar images is due to the non squared
 285 pixel.

286 B. Optimization of error factor

287 The first algorithm under analysis is the optimization of the error factor γ_e . The average
 288 used for the estimation of the power components exploited a 11x11 boxcar filter. The eigen-



(a) Pauli RGB (master)

(b) Pauli RGB (1 month after)

Fig. 5. RGB Pauli images of the AGRISAR test site: (a) Master acquisition; (b) Slave acquisition (1 month after). Red rectangles: winter wheat; Black rectangles: unknown crop; Orange rectangle: area used for further analysis. Image size 1300×440 m (DLR E-SAR L-band AGRISAR2006 Campaign).



(a) SARTOM



(b) AGRISAR 2006

Fig. 6. Google Earth aerial photographs of the two test sites: (a) SARTOM (b) AGRISAR 2006. Please note, the SAR images suffer a distortion due to the non squared pixel. Also, in the AGRISAR picture the North is pointing down.

289 values of the optimization over the SARTOM dataset are presented in Figure 7 (please note
290 the scaling is different for the three images). The minimum of γ_e is particularly close to one
291 (i.e. absence of error) except for few point targets. As a comparison the ratio for the second
292 component of the Pauli decomposition is presented. $HH - VV$ was selected because it is
293 sensitive to dihedral scattering which is generally strong for man-made targets. Forest and
294 bare ground do not show significant changes after four days, nevertheless, it can be observed
295 a slightly different temporal behavior where the ground changes more than the forest. During
296 the two acquisitions the weather conditions were different with rain in the second acquisition.
297 It could be speculated that the different moisture introduced more polarimetric difference on
298 the ground compared to the forested areas. Please note, the movement of the scatterers and
299 consequent interferometric temporal decorrelation do not translate generally in polarimetric
300 changes. The maximum eigenvalue shows that seven point targets present a change larger
301 compared with other areas. Five of these points are the known removed targets. In the next
302 section, more details will be provided about the other two targets. A further remark should
303 be made regarding the middle optimal point of γ_e . This is a stationary point (zero derivative),
304 but it is not possible to predict if it corresponds to a maximum/minimum or a saddle point
305 (the second derivatives should be evaluated). For this reason, it has to be considered with
306 care.

307 The output of optimizing γ_e for the AGRISAR dataset is presented in Figure 8, with again
308 the $HH - VV$ for comparison. At difference than the previous dataset, the distributed targets
309 present large changes. This implies that the ESM hypothesis over such targets would lead
310 to severe errors. Interestingly, the minimum eigenvalue can be relatively small also in areas
311 where the partial target is changing significantly. This is a clear indicator that the change
312 is mainly focused on a particular direction (i.e. single target) in the polarimetric space and

313 there are areas in the space where the change is not large. This leads to the idea that the
314 eigenvectors may be used to try to understand the typology of change undertaken by the
315 partial target. These are only speculations and more studies should be carried out to evaluate
316 this possibility.

317 Finally, in order to check that the mathematical optimization is performed properly, ten
318 points (five in the SARTOM and five in the AGRISAR dataset) were used to extract the
319 coherency matrices $[T_{11}]$ and $[T_{22}]$. Then, a Monte Carlo simulation was used to generate one
320 million random scattering mechanisms uniformly distributed on a unitary complex sphere
321 on \mathbb{C}^3 and the quantity γ_e was evaluated using the coherency matrices. In all ten cases,
322 the optimization was able to provide a maximum value of γ_e higher than the brute force
323 algorithm even though in some cases these were very close each other.

324 *C. Optimization of Power Ratio*

325 The results of the optimization of ρ_{12} for the SARTOM dataset are presented in Figure 9.
326 Again the coherency matrices were filtered with an 11x11 boxcar. As explained in previous
327 sections, a large change may provide either a very large or very small ρ_{12} depending if the
328 target is present in the first or second acquisition. The methodology followed here is to invert
329 the eigenvalue when this is smaller than one and change its sign (i.e. making it negative). The
330 resulting variable was defined as $\hat{\rho}_{12}$. To ease the visual interpretation, a rainbow colortable
331 can be used, where red is for changes where the first acquisition is higher and blue where
332 the second acquisition is higher. Such visualization is showed in Figure 10 for the maximum
333 and minimum eigenvalues. A complementary way to show the optimization results could be
334 to produce an image with the highest values of eigenvalues and inverted eigenvalues for each
335 pixel (i.e. to have one single image with the maximum change possible). This representation

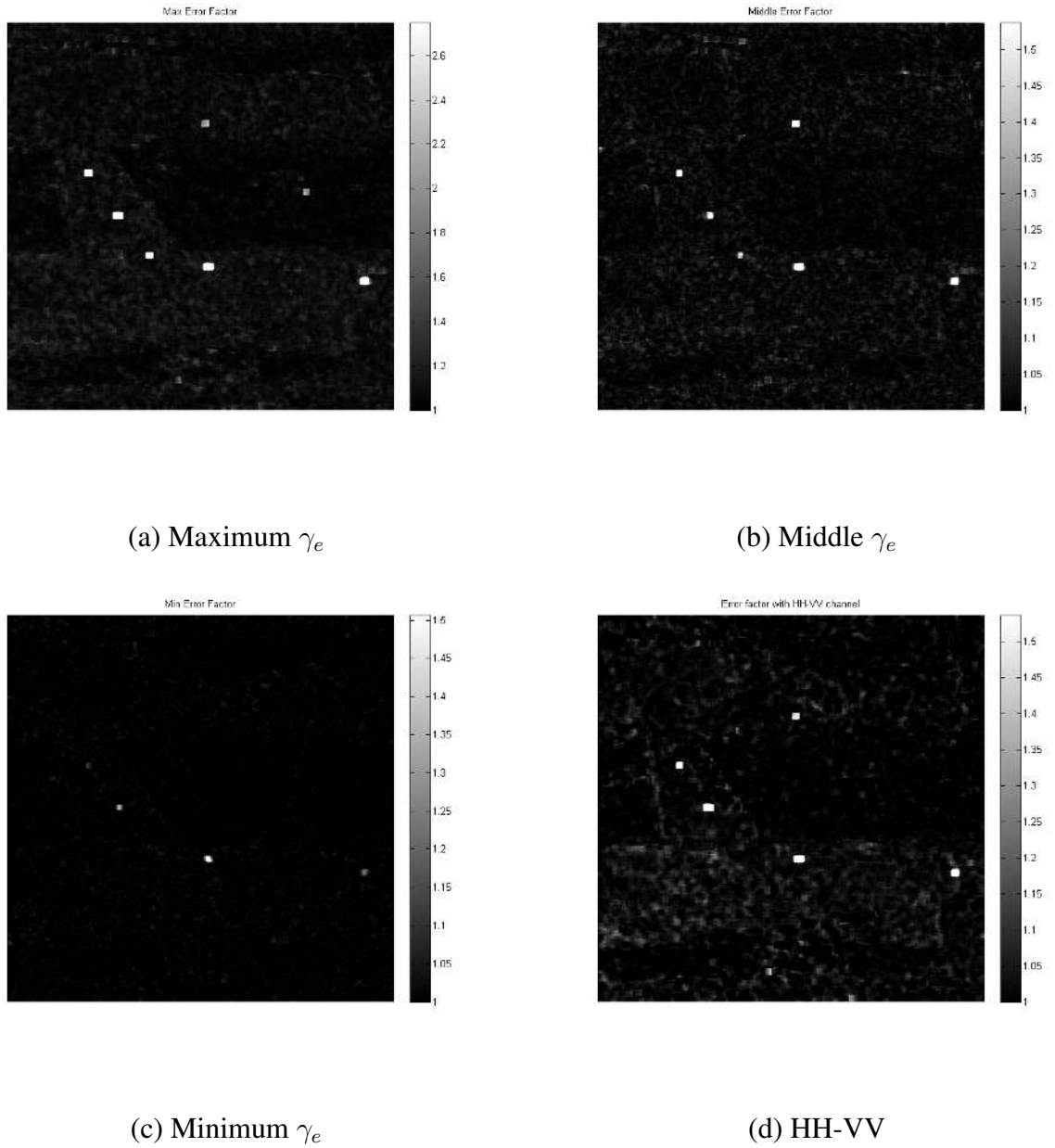


Fig. 7. Optimization of the error factor γ_e (SARTOM). (a) Maximum γ_e ; (b) Middle γ_e ; (c) Minimum γ_e ; (d) Error factor for $HH - VV$. Averaging: 11x11 boxcar.

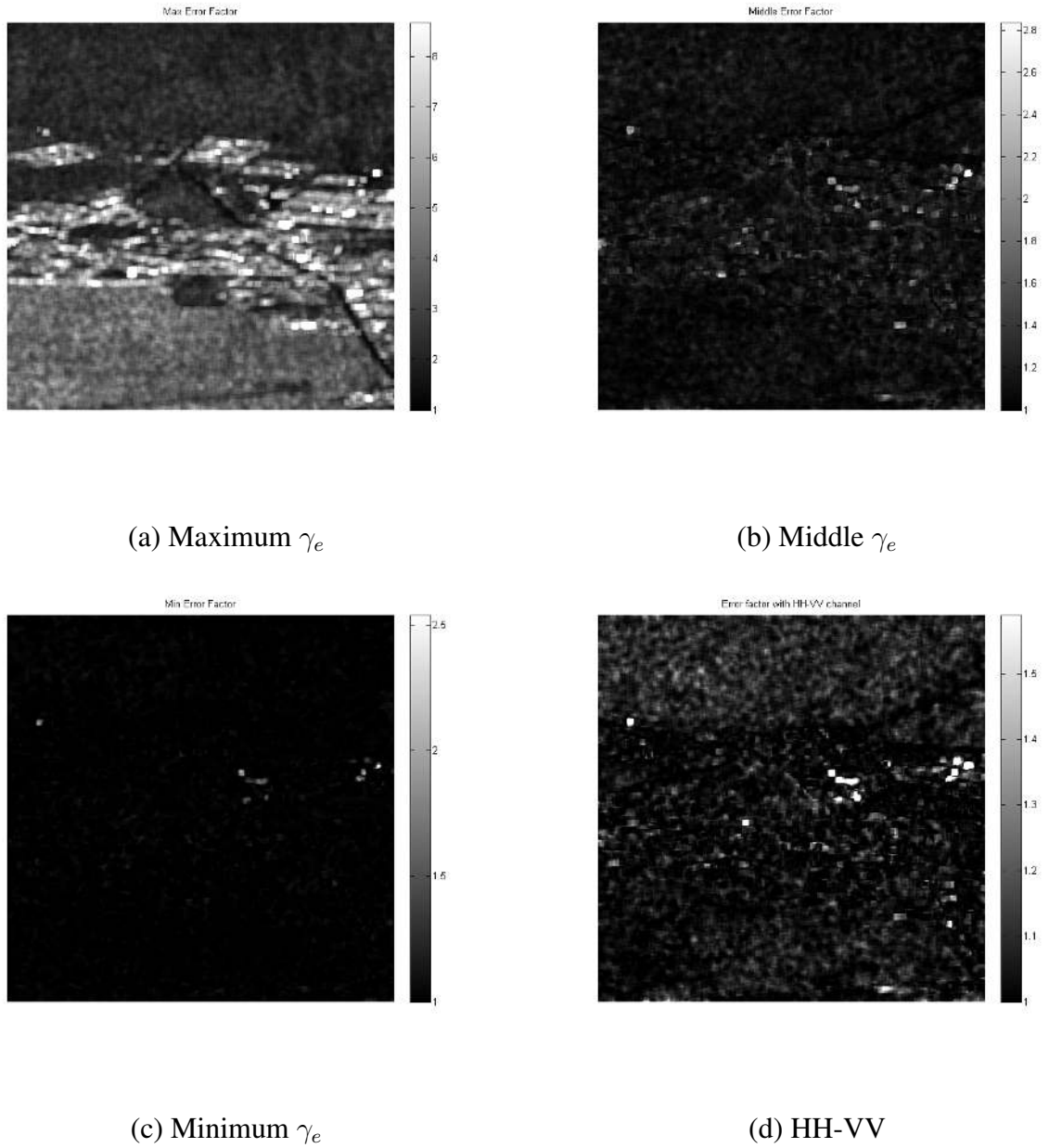


Fig. 8. Optimization of the error factor γ_e (AGRISAR). (a) Maximum γ_e ; (b) Middle γ_e ; (c) Minimum γ_e ; (d) Error factor for $HH - VV$. Averaging: 11x11 boxcar.

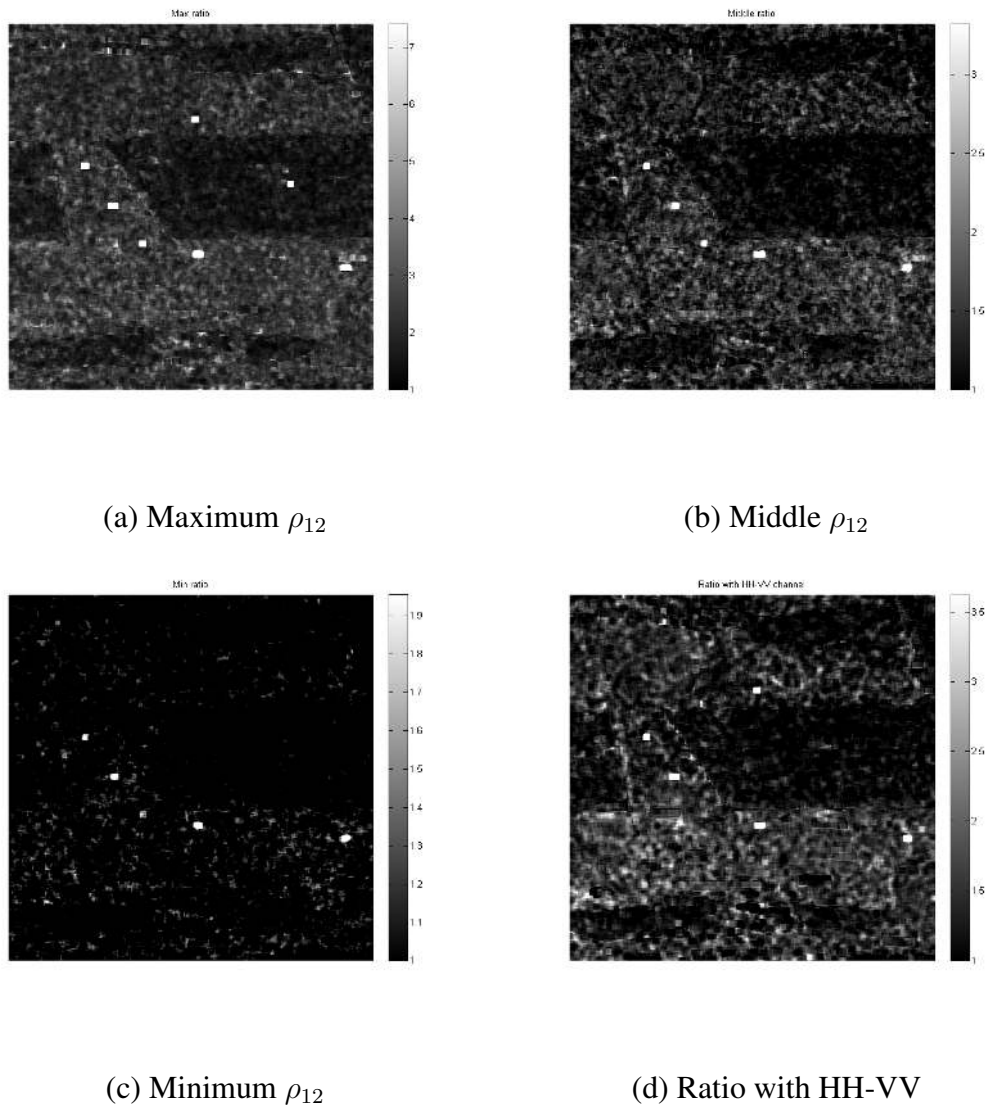


Fig. 9. Power ratio optimization (SARTOM): (a) Maximum of ρ_{12} (b) Middle of ρ_{12} ; (c) Minimum of ρ_{12} ; (d) Ratio evaluated with $HH - VV$. Averaging: 11x11 boxcar.

336 is avoided here because it will mix the results of the different eigenvalues masking the real
 337 output of the algorithm.

338 All the targets with validated changes can be easily detected with the maximum eigen-
 339 value, including the corner reflector under canopy cover. Interesting, using only the $HH -$
 340 VV the latter cannot be detected anymore. Two further point targets have a relatively large
 341 ratio. The one in the red rectangle seems to almost disappear in the second acquisition as a

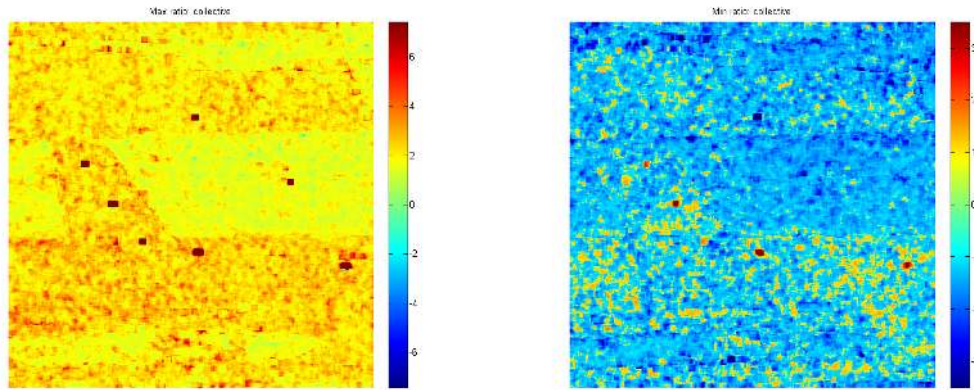
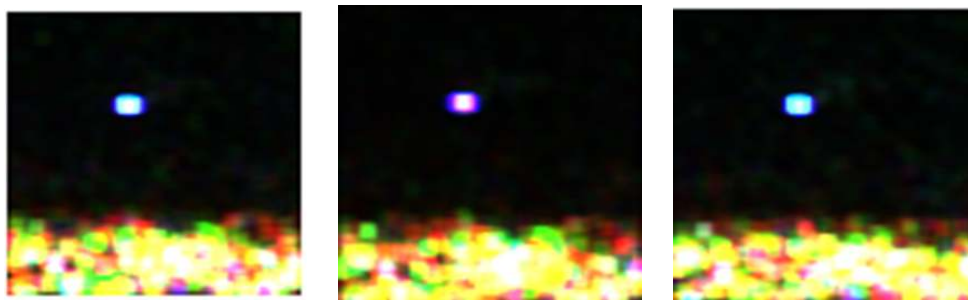
(a) Maximum $\hat{\rho}_{12}$ (b) Minimum $\hat{\rho}_{12}$

Fig. 10. Power ratio optimization after modifying the ratio (SARTOM): (a) Maximum of $\hat{\rho}$ (b) Minimum of $\hat{\rho}$.

The red is for changes where the target is present in the first acquisition and blue for targets present in the second acquisition. Averaging: 11x11 boxcar.



(a) Master

(b) Slave (4 days after)

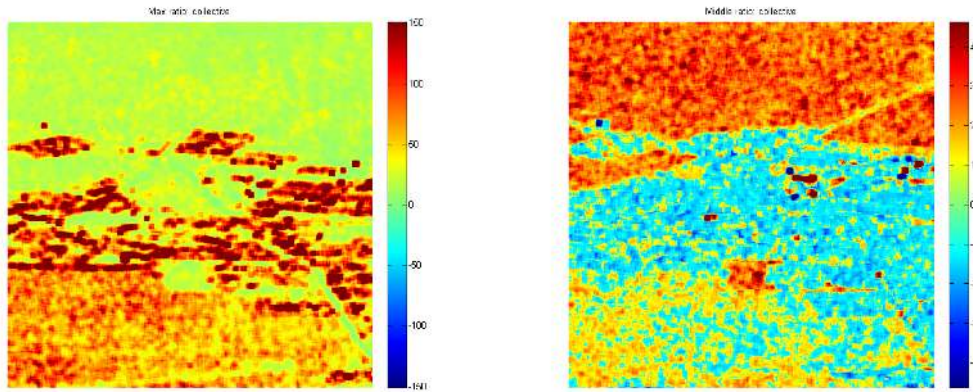
(c) Slave (after 40min)

Fig. 11. Pauli RGB images of a corner reflector (SARTOM): (a) Master acquisition; (b) Slave acquisition, 4 days after the Master (the one exploited in the previous analysis); (c) Slave acquisition, 40min after the Master (it is not used in the rest of the manuscript). The corner reflector was removed and relocated on the fourth day (it was not used for calibration purposes).

342 portion of it was removed. Unfortunately, a ground survey for this target is not available to
343 confirm this speculation. The point in the blue rectangle is a trihedral corner reflector posi-
344 tioned on the ground without pedestal. This was removed at the end of the first acquisition
345 and then replaced on the ground four days after. It was not used for calibration purposes, but
346 it only functioned as a target to detect. In order to have some insight on this corner reflector
347 another acquisition is considered, taken 40min after the Master (during this 40 minutes the
348 corner reflector was not touched). A zoom of the Pauli RGB images is provided in Figure 11
349 and reveals that the color around the corner reflector appears different in the two acquisitions.
350 The reason for such difference in backscattering and polarimetric behavior is unknown to the
351 authors, nevertheless, the visible change can be detected by the algorithm.

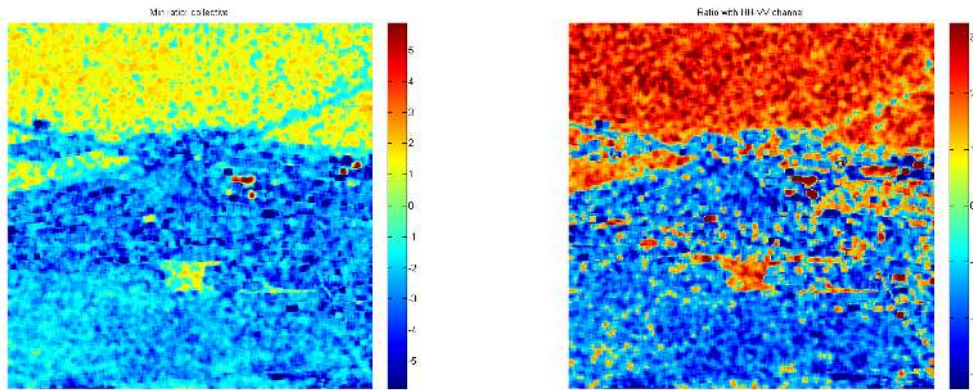
352 Figure 12 shows the results of the ρ_{12} optimization on the AGRISAR dataset. Here only
353 the rainbow masks are presented for sake of brevity. As already observed, the field at the bot-
354 tom of the image is suffering the largest changes as well as the buildup areas. Interestingly,
355 the minimum eigenvalue shows that there are some targets present in the second acquisition
356 but not in the first one. Using the $HH - VV$ error is not possible to evaluate that the bottom
357 field is suffering larger changes than the up one (even though these are clearly evident also
358 in the RGB image).

359 It is interesting to notice that the optimization is able to pick up more changes in the farm
360 building than the ratio of $HH - VV$. To check that these changes are really present in the data, a
361 brief polarimetric analysis is performed on a smaller area (for an easier visualization) which
362 is zoomed on some farm buildings. Figure 13 presents the entropy and mean alpha angle
363 as derived by the Cloude-Pottier decomposition (i.e. eigenvector problem of the Coherency
364 matrix) [7]. The red rectangles in the α images help identifying some areas where α (which
365 is linked to the scattering mechanism) changes. Some of these areas appear in the maximum



(a) Maximum $\hat{\rho}_{12}$

(b) Middle $\hat{\rho}_{12}$



(c) Minimum $\hat{\rho}_{12}$

(d) Ratio for HH-VV

Fig. 12. Power ratio optimization (AGRISAR): (a) Maximum of $\hat{\rho}$ (b) Middle of $\hat{\rho}$; (c) Minimum of $\hat{\rho}$; (d) Ratio for $HH - VV$. The red is for changes where the target is present in the first scene and blue for targets present in the second scene. Averaging: 11x11 boxcar.

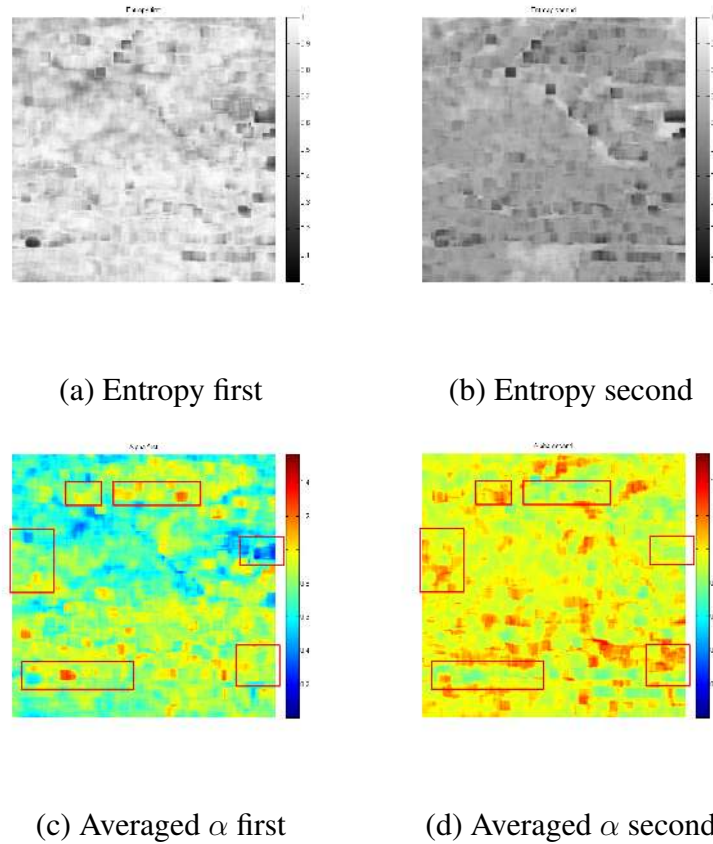


Fig. 13. Cloude-Pottier decomposition of the Coherency matrices: (a) Entropy of first acquisition; (b) Entropy of second acquisition; (c) Averaged α of first acquisition; (d) Averaged α of second acquisition. The red rectangles identify some of the changes in the entropy that can be identified with the maximum eigenvalue of the optimization, but not with the single channel ratio. Averaging: 11x11 boxcar.

366 eigenvalue of the power ratio, but they can not be identified in the ratio of $HH - VV$.

367 As for the γ_e , a Monte Carlo simulation was employed to perform a brute force maximiza-
 368 tion of ρ_{12} and again the Lagrange methodology provides the highest value.

369 V. STATISTICAL TESTS

370 In this section, a test of fit for the theoretical pdf and an analysis of the statistical tests
 371 are provided. Again, the SARTOM and AGRISAR dataset will be employed to highlight the
 372 different behavior of the tests for point and distributed targets.

373 *A. Test of IR pdf*

374 A test of fit for the intensity ratio pdf for two polarimetric channels (e.g. co-polarizations
375 ratio) was already performed in [10], here the focus is on the output of the optimization
376 of ρ_{12} . Theoretically, the pdf should still fit the data as long as the area under analysis is
377 homogeneous (which is also one fundamental hypothesis for the derivation of the IR pdf).
378 To test these, the two E-SAR dataset are exploited.

379 Firstly, four areas in the SARTOM dataset were selected (both red and black rectangles
380 in Figure 4), two of them are bare ground (with short grass) and other two are forested
381 areas (coniferous approximately 20m high). Each of the areas is a tile of 80x80 pixels. The
382 histograms of the maximum ratio and the theoretical pdf are presented in Figure 14. In
383 comparing histograms and theoretical pdf, care was given in exploiting identical horizontal
384 axis and normalizing both over their integral. In order to have a more exhaustive analysis the
385 Cumulative Distribution Function CDF is presented in Figure 15.

386 A simple visual interpretation of the curves seems to suggest that the fit may be adequate
387 even though it is not perfect. The CDF allow a deeper look at the tails of the distributions
388 which are of large interest for detection purposes. Specifically, it seems that Ground1 and
389 Forest4 show the largest difference in the CDF. This is visible in the pdf with a higher peak
390 of the histogram resulting in a sharper increase of the CDF. Such difference may also be
391 related to imprecision in estimating the pdf parameters (as explained previously).

392 In general, the visual interpretation may have some limitations, therefore in this paper
393 some Goodness-of-Fit (GoF) tests were exploited in order to have a more quantitative anal-
394 ysis [24]. In this context a very large variety of GoF tests could be exploited and a thor-
395 ough comparison goes outside the purpose of this paper. Here, only two very well-known

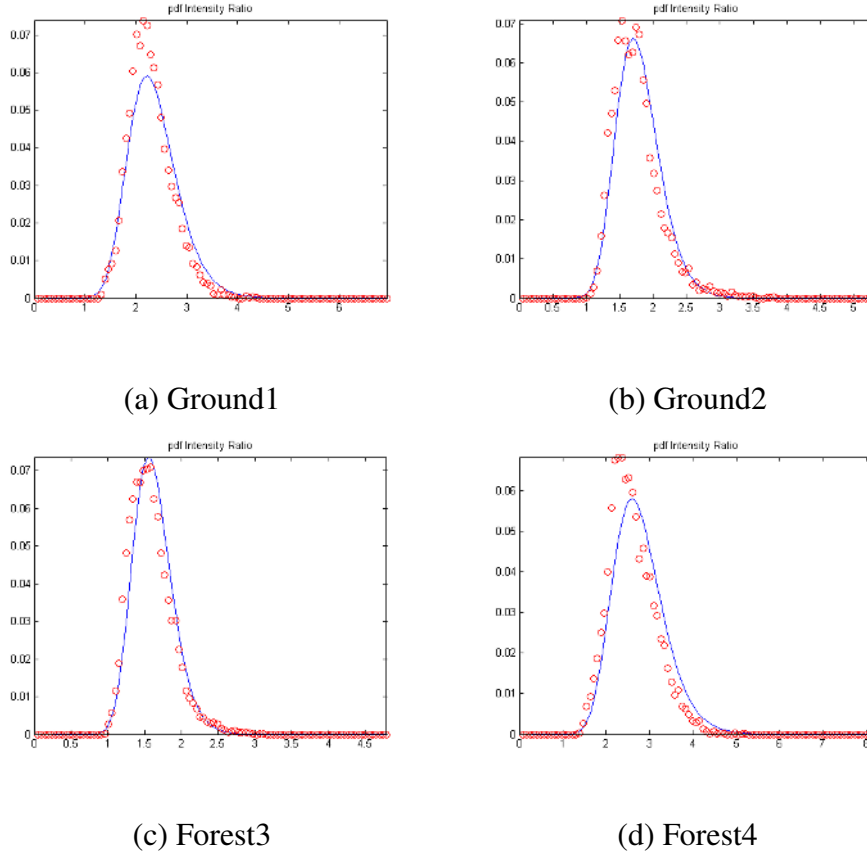


Fig. 14. pdf of optimized ρ_{12} for the SARTOM data. Red circles: histogram points (data); Blue line: fitted pdf.

396 tests are considered (one focused on the pdf and the other on the CDF). The first test is the
 397 Kolmogorov-Smirnov (KS) two samples test:

$$D_{ks} = \max_x \|F_1(x) - F_2(x)\|, \tag{23}$$

398 where F_1 and F_2 are the CDF of the two random variables under analysis. Knowing the
 399 distributions it is possible to set a threshold on D_{ks} with a sorter confidence value: $P(D_{ks} >$
 400 $D_n) = \alpha$. This means that the CDF of the data will be contained in the theoretical CDF with
 401 a probability of $1 - \alpha$. Here, such final probability is set to 95%

402 The second test is the Pearson's Chi-Squared (χ^2) test. The test statistics is:

$$X^2 = \sum_i \frac{(f_o(i) - f_e(i))^2}{f_e(i)}, \tag{24}$$

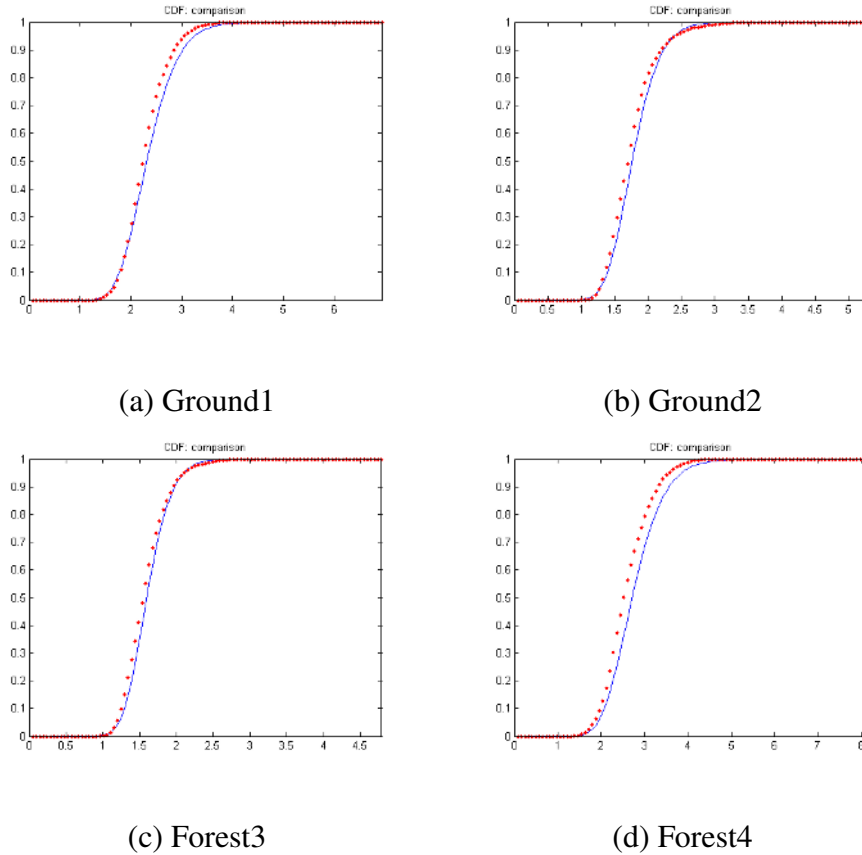


Fig. 15. CDF of optimized ρ_{12} for the SARTOM data. Red circles: histogram points (data); Blue line: fitted CDF.

403 where f_o is the observed pdf (the histogram) and f_e is the expected (theoretical) pdf. Such test
 404 statistics X^2 should be a χ^2 distribution with a defined degree of freedom. The distribution
 405 of X^2 is tested and the hypothesis that observed and theoretical distributions are the same is
 406 rejected if X^2 is not χ^2 . A confidence value can again be set using a parameter α in order
 407 to associate a probability to the fit. In this paper, the value of α was set to 0.05, as for the
 408 previous case.

409 All the areas passed both the tests showing that the fit should have a confidence of at least
 410 95%. The observed suitability of the IR pdf encouraged the exploitation of such distribution
 411 for the automatic detectors. Clearly, the use of local estimators (as showed in the follow-
 412 ing tests) would not be able to estimate properly the pdf parameters in case the area is not

413 homogeneous. In the latter situation, some pre-segmentation scheme may improve the per-
 414 formance. Another factor that is important to take into account is the number of samples used
 415 to compare the theoretical and observed distributions. In this paper, 80x80 pixels were used
 416 to estimate the fitting parameters, but then of this 100 random samples were exploited by the
 417 GoF test (since this is approximately the number of pixels used by the adaptive detector). A
 418 value N can be calculated as:

$$N = \frac{N_1 N_2}{N_1 + N_2}, \quad (25)$$

419 where N_1 is the number of samples from the theoretical pdf and N_2 from the data. In our
 420 case, $N_1 = N_2$, therefore $N = N_1/2 = 50$. As a rule of thumb, in order to have an adequate
 421 test the value of N should be greater or equal than four (i.e. eight samples each).

422 The pdf of the intensity ratio was derived under the assumption of complex Gaussian
 423 pixels, however, SAR intensity images in some cases present texture (i.e. a fluctuation of
 424 the radar cross-section). Therefore, it is important to understand if the pdf for the ratio can
 425 still be used when some moderate texture is present in the data. A widely used model for
 426 texture on intensity images is the K-distribution [21]. The description of such distribution is
 427 outside the purpose of this paper, here it is only mentioned that one of the pdf parameters
 428 is called *order parameter* ν and is a good indicator for the presence of radar cross-section
 429 fluctuations (i.e. texture). In particular, for $\nu \rightarrow \infty$ the cross section is constant and the
 430 K-distribution reduces to a Gamma distribution (where the Gaussian hypothesis is fulfilled),
 431 while for $\nu \rightarrow 0$ the texture effects are very evident. The estimation of ν is not very easy
 432 since the Maximum Likelihood Estimator does not have a closed form. For this reason, some
 433 different estimators (which require numerical solution), has to be employed. In this paper,
 434 the "Normalized Logarithm of Intensities" is used since it showed good results as long as the

435 Number of independent Looks is large enough [21], [25]. The estimator can be written as:

$$\ln \langle I \rangle - \langle \ln I \rangle = \ln \nu - \Psi^0(\nu) + \ln L - \Psi^0(L), \quad (26)$$

436 where I is the averaged intensity, Ψ^0 is the digamma function and L is the Equivalent Num-
437 ber of Looks. The value of ν was derived solving the expression in numeric. The area of
438 analysis contained 80x80 pixels and the intensity pixels were averaged with a 11x11 boxcar
439 filter.

440 The resulting values of ν for the areas are reported in the following: $\nu\{Ground1\} = 1.3$;
441 $\nu\{Ground2\} = 0.92$; $\nu\{Forest3\} = 0.5$; $\nu\{Forest4\} = 0.9$. The estimated values of
442 ν show the presence of some texture that may be also seen in the intensity images (e.g.
443 clearings in forests and paths on bare ground). From these results, it may be inferred that
444 the IR pdf does not appear particularly sensitive to texture, since the histograms still fit the
445 theoretical pdf. A possible explanation is that if the radar cross section fluctuations are
446 equal in the two acquisitions (i.e. the change behavior is preserved by the different texture
447 components) then the texture will cancel out in the ratio.

448 The second experiment considers the AGRISAR data. The changes here are much higher
449 and it is interesting to understand if the IR statistical model is still valid when the mean ratio
450 is largely higher than one. The large rectangles in Figure 5, shows the areas used for esti-
451 mating the distributions. Two areas are on a harvested field (i.e. bare ground) presenting a
452 relatively low backscattering and low changes (presumably due to growing of short grass).
453 The second two areas are in a vegetated field presenting large backscattering which is chang-
454 ing due to different phenological stages (i.e. the periodic plant and animal life cycle events).
455 The pdf and CDF of the areas with fitted theoretical distributions are showed respectively in
456 Figure 16 and 17.

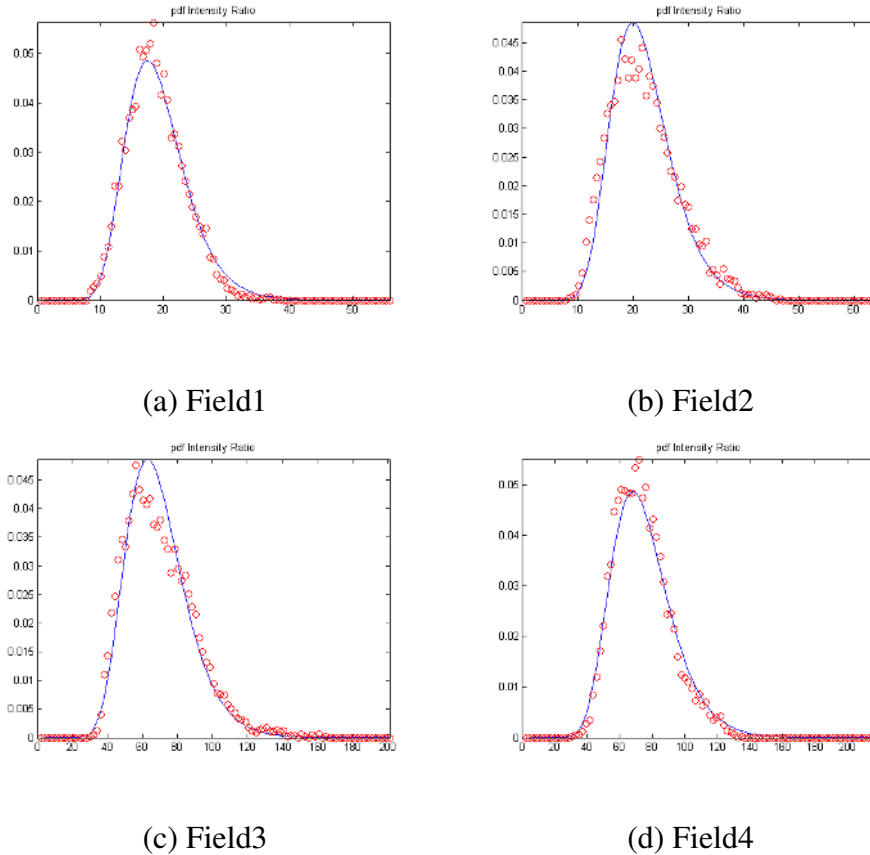


Fig. 16. pdf of optimized ρ_{12} for the AGRISAR data. Red circles: histogram points (data); Blue line: fitted pdf.

457 Again the fit appears adequate even though Field1 and Field3 show some differences on
 458 the maximum value of the peak (as exhibited previously). Again the KS and the χ^2 tests are
 459 performed in order to check that the fit has some statistical significance. All the areas passed
 460 the KS and the χ^2 tests with $N = 50$. The estimation of the order parameter ν was repeated
 461 for this second dataset as well. The resulting values of ν for the fields are reported in the
 462 following: $\nu\{Field1\} = 1.96$; $\nu\{Field2\} = 1.24$; $\nu\{Field3\} = 2.48$; $\nu\{Forest4\} = 2.66$.
 463 In this dataset the texture effects are less strong and this is also visually evident from the
 464 intensity images, where the fields appears more homogeneous.

465 As a final summary, the KS and χ^2 test showed that it should be possible to use the IR
 466 distribution as a general model, however, some problem may be encountered in case of areas

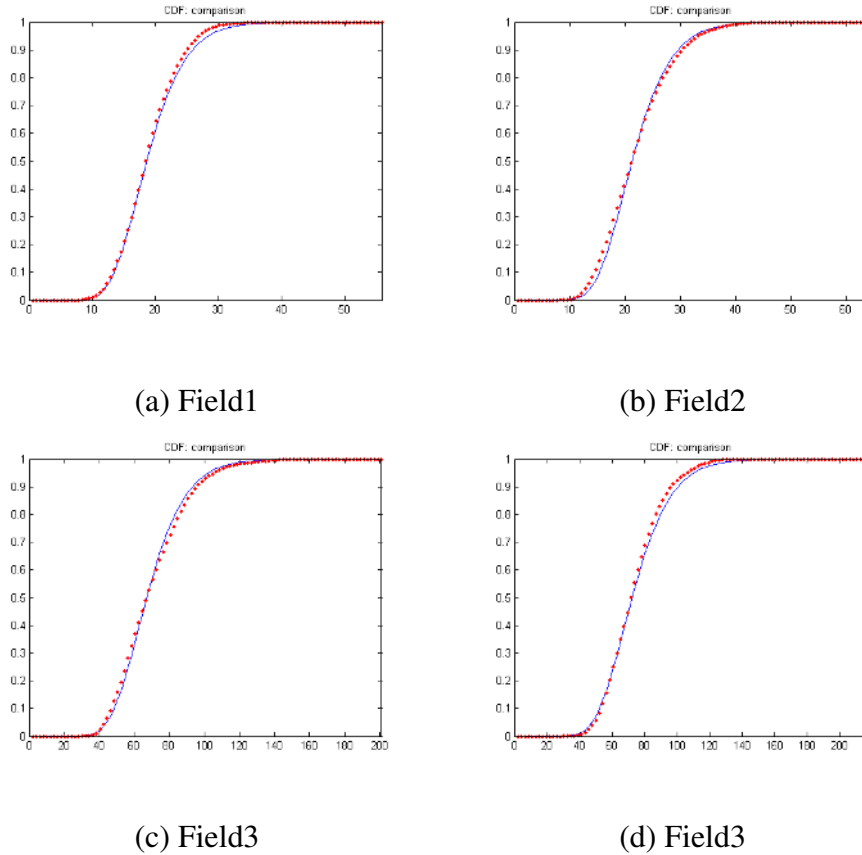


Fig. 17. CDF of optimized ρ_{12} for the AGRISAR data. Red circles: histogram points (data); Blue line: fitted CDF.

467 that show large texture effects especially if the different targets do not present an homo-
 468 geneous behavior in time (i.e. they change in different way). Possible future work in this
 469 direction could consider a pre-segmentation step.

470 *B. Anomaly detector*

471 This test is especially suited for point targets. In this experiment, the guard window is a
 472 squared 21x21 pixels, while the clutter window is a ring one pixel broad around the guard
 473 window (i.e. 88 pixels in total). Two probabilities of False Alarms are exploited: $P_f = 10^{-6}$
 474 and $P_f = 10^{-8}$.

475 The resulting detection masks over the SARTOM dataset are presented in Figure 18, where



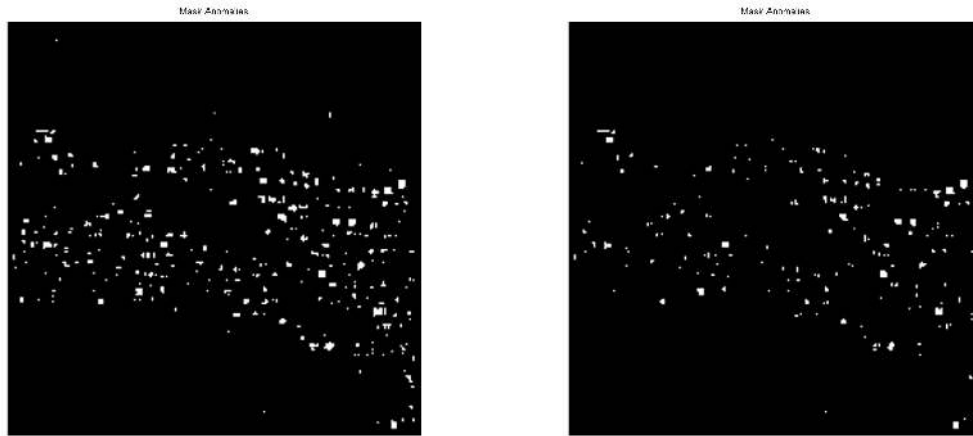
$$(a) P_f = 10^{-6}$$

$$(b) P_f = 10^{-8}$$

Fig. 18. Anomaly detection for $\max(\rho_{12})$ (SARTOM). (a) $P_f = 10^{-6}$; (b) $P_f = 10^{-8}$.

476 many false alarms are evident. Even though, modifying the P_f or estimating more accurately
 477 the pdf parameters the number of false alarms should reduce, the authors believe that their
 478 occurrence has a more profound reason and is intrinsic of the anomaly test. When the back-
 479 ground is particularly stable in the two images (i.e. its correlation ρ is proximal to one) the
 480 standard deviation of the ratio is very small (proximal to zero) and the threshold will be set
 481 near the mean value (which is proximal to one). In these circumstances, the likeliness that
 482 a small change in the central pixel is above the threshold is rather high. From a statistical
 483 point of view, those detected points are not false alarms, however, they do not correspond to
 484 genuine real-targets and they should be rejected. As for most detectors, the final mask may
 485 always be improved and cleaned adding some post-processing algorithms (e.g. a morpho-
 486 logical opening filter), but this will not solve the methodological issues. To conclude, the
 487 authors suggest care in evaluating the mask of the anomaly detector and different tests are
 488 proposed in the following.

489 For the sake of completeness, the same anomaly test is performed on the AGRISAR data
 490 and showed in Figure 19, again with probabilities $P_f = 10^{-6}$ and $P_f = 10^{-8}$. The detections

(a) $P_f = 10^{-6}$ (b) $P_f = 10^{-8}$ Fig. 19. Anomaly detection for $\max(\rho_{12})$ (AGRISAR). (a) $P_f = 10^{-6}$; (b) $P_f = 10^{-8}$.

491 are mainly located in the buildup areas and should correspond to point targets (e.g. vehicles
 492 that were moved or just parked with a different orientation with respect to the flight path).

493 C. Distributed Changes detection

494 The test is mainly focused on distributed targets and selects areas that are above a defined
 495 threshold with a P_d higher than a sorter value (the P_m can be equivalently used). In this
 496 particular experiment, the area considered to estimate the pdf contains 11x11 pixels. The
 497 probability of missing detection is chosen as $P_m = 0.001$.

498 The results for the SARTOM dataset are showed in Figure 21, with thresholds equal to
 499 $T_p = 2$, $T_p = 5$, $T_p = 10$ and $T_p = 20$.

500 The false alarms are reduced strongly except when the value of T_p is particularly low. With
 501 a threshold $T_p = 5$ it is possible to detect all the targets that changed in the scene (including
 502 the corner reflector that was only slightly moved). With the threshold equal to 10 or 20 only
 503 large changes are detected.

504 The AGRISAR dataset is probably more adequate for this kind of detection, since this

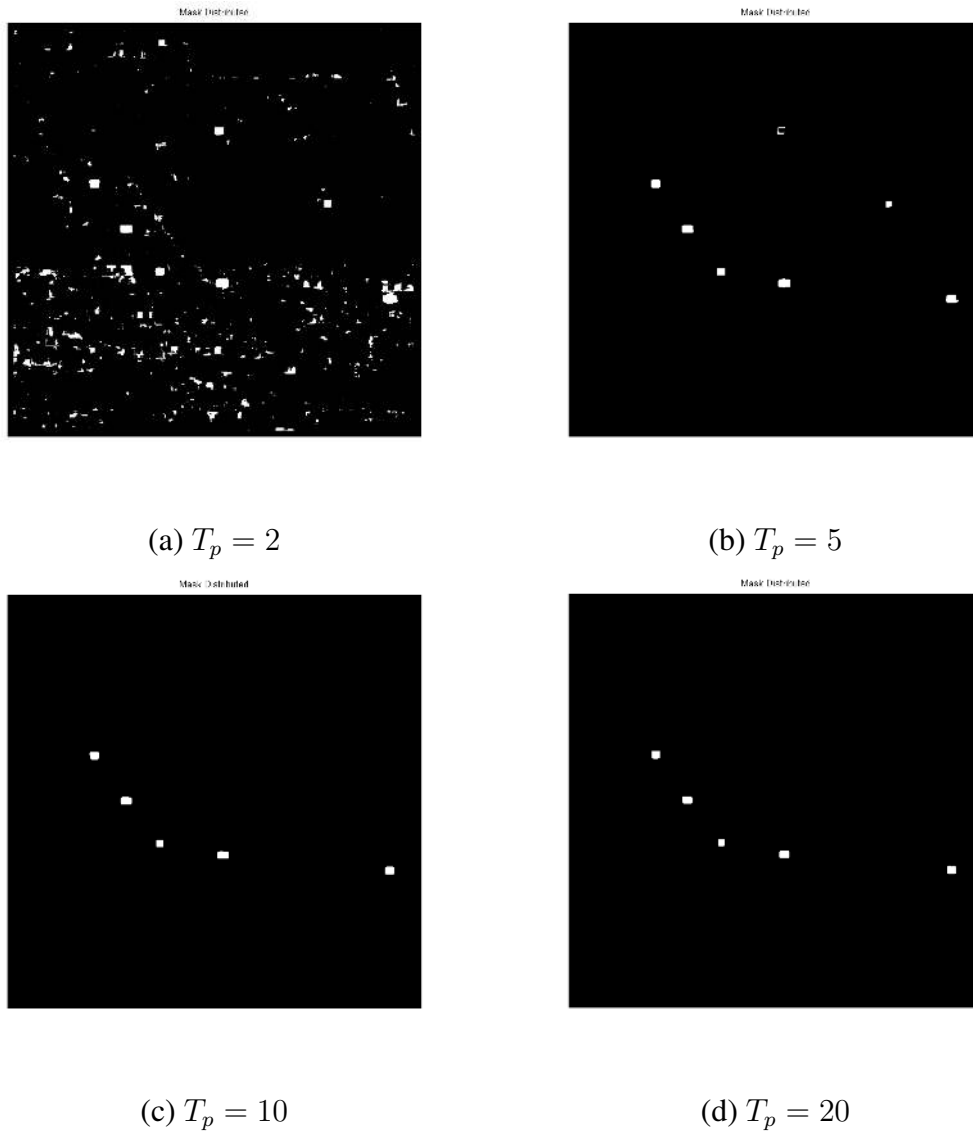


Fig. 20. Distributed Changes detection over SARTOM data for $\max(\rho_{12})$. $P_m < 10^{-3}$. (a) $T_p = 2$; (b) $T_p = 5$; (c) $T_p = 10$; (d) $T_p = 20$.

505 test site presents an abundance of dynamic distributed targets. Considerable larger changes
506 are expected on agricultural fields, different values of the physical threshold are selected:
507 $T_p = 10$, $T_p = 20$, $T_p = 50$ and $T_p = 100$. Interestingly, it can be observed that the two
508 main fields (up and bottom of the image) can be separated based on the amount of changes.
509 In particular, the uppermost field does not change more than $T_p = 20$. Moreover, the bottom
510 field would not be detected with $T_p = 50$ or $T_p = 100$. The buildup area again presents the
511 highest changes among the observed land covers.

512 *D. Two stage test*

513 The final test tries to combine the previous two in order to produce an automatic algorithm
514 for detection of point targets in dynamic clutter. The P_f of the first stage anomaly detector is
515 10^{-6} , the second test is performed with $P_m = 0.001$ and the minimum value for the anomaly
516 threshold is $T_i = 5$, since this was showed a robust value in the previous tests.

517 The resulting detection mask for the SARTOM and AGRISAR dataset are presented in
518 Figure 22. All the targets that experienced a change in the SARTOM dataset are detected,
519 included the corner reflector inside the forest and the one that was moved. In the AGRISAR
520 data the detector is able to pick up the differences in the built up area neglecting the fields.
521 Unfortunately, a validation for the vehicles location in the AGRISAR settlements is not avail-
522 able.

523 As a final remark, it has to be said that in order to compare more appropriately different
524 algorithms (also including other typologies of detectors) more data accompanied by ground
525 measurements should be acquired. With such dataset, valuable tools to compare different
526 detectors such as Receiver Operating Characteristics (ROC) curves can be estimated. Un-
527 fortunately, ROC curves could not be assessed exploiting the current datasets for two main

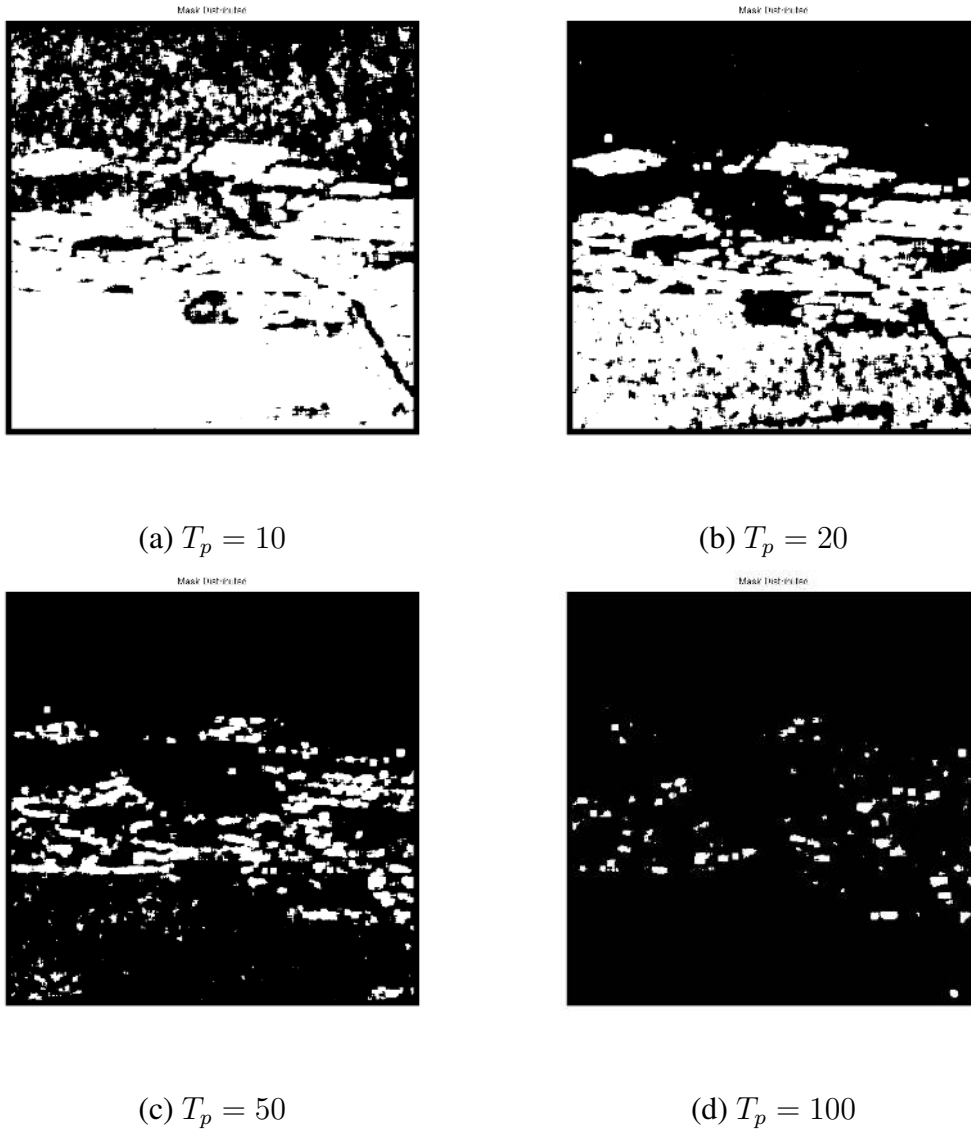


Fig. 21. Distributed Changes detection over AGRISAR data for $\max(\rho_{12})$. $P_m < 10^{-3}$. (a) $T_p = 10$; (b) $T_p = 20$; (c) $T_p = 50$; (d) $T_p = 100$.

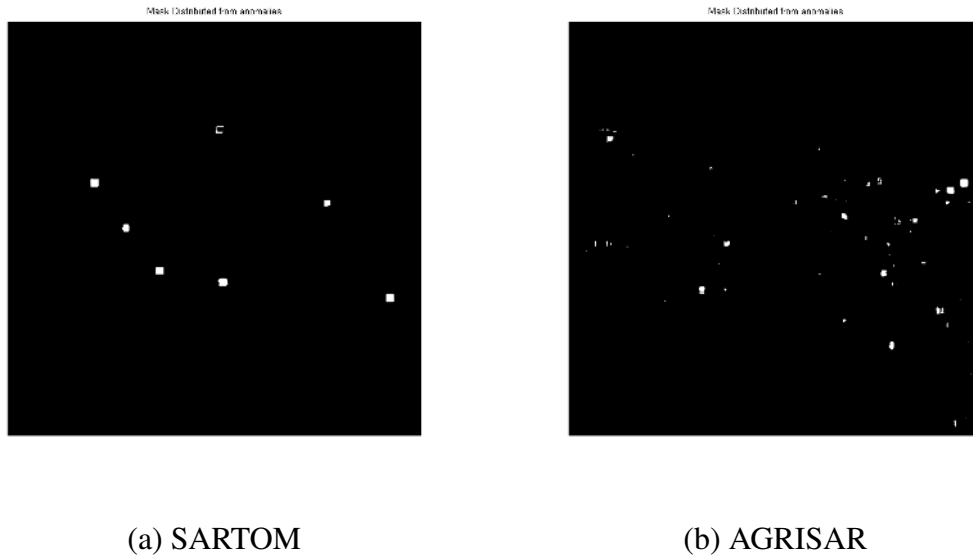


Fig. 22. Combined detector for (a) SARTOM and (b) AGRISAR dataset. $P_f = 10^{-6}$, $P_m = 0.001$, minimum $T_i = 5$.

528 reasons. Firstly, only five targets in the entire scene have validated changes and this cannot
 529 provide an accurate estimation of the probability of detection. Secondly, ancillary informa-
 530 tion regarding the rest of the scene is not available, hence it is not trivial to find an extensive
 531 unchanged area to estimate the false alarm rate (i.e. many detections that could be classified
 532 as false alarms may actually be genuine changes). For this reason, a more extensive analysis
 533 and validation exploiting ROC curves is left as future work.

534

CONCLUSIONS

535 In this work, two analytical optimizations exploiting a Lagrange methodology are pro-
 536 posed. The first is aimed at an error factor γ_e for the Pol-InSAR coherence when an Equi-
 537 Scattering Mechanism hypothesis is performed, while the second is focused on an intensity
 538 ratio ρ_{12} varying the scattering mechanism. Both the optimizations can be accomplished
 539 with eigen-problems. Interestingly, it was demonstrated that the eigenvectors resulting from
 540 the two diagonalizations are the same. The detectors are finalized with thresholds on the

541 respective eigenvalues.

542 In the second part of the paper, three statistical tests are devised for the power ratio ρ_{12} .
543 The tests are based on the pdf of the Intensity Ratio (IR) proposed by Lee *et al.* [10],
544 which assumes that the SLC complex pixel can be modeled as complex Gaussian random
545 variable. The first test is an anomaly detector evaluating differences between the background
546 clutter and a central pixel under analysis. This algorithm is adaptive, using guard windows to
547 extract the clutter statistics and it is more appropriate for detecting changes to point targets.
548 The second test analyzes an area of interest detecting the pixel distributions that are above
549 a physical threshold with a sorter confidence. The threshold can be set a-priori knowing
550 the typology of target to be observed. This test is more appropriate for distributed targets.
551 Finally, one last test combines the first two in a two stage algorithm, in order to devise a
552 detector for point targets embedded in dynamic clutter.

553 The algorithms were tested on two different quad-polarimetric L-band E-SAR DLR dataset.
554 The first was acquired during the SARTOM 2006 campaign and it is largely dedicated to
555 point target detection, while the second is from the AGRISAR 2006 campaign and is fo-
556 cused on agricultural observation (i.e. changes suffered by distributed targets). Both dataset
557 are accompanied by ancillary ground data. Some of the vehicles/targets in the SARTOM
558 dataset were removed in between the two acquisitions and the AGRISAR agricultural fields
559 were experiencing known changes. The optimization results were adherent to the ground
560 information and visual interpretation. The theoretical pdf was tested over several areas in the
561 two dataset showing adequate visual fitting. Moreover, all the areas passed the Kolmogorov-
562 Smirnov and the χ^2 test with 95% confidence except one field in the AGRISAR dataset that
563 did not pass the χ^2 test. The distribution for such field appeared to be multi-modal with areas
564 inside the field that were experiencing very little change. In this context, a pre-segmentation

565 stage may improve the fit.

566 The statistical tests for the power ratio were examined on the two dataset. It was observed
 567 that the anomaly detector suffers from large false alarm rate. This is because the test detects
 568 very small anomalies when the background is particularly stable (for this reason the authors
 569 suggest caution when using it). The second test is more beneficial for detecting changes of
 570 distributed targets (as the fields in the AGRISAR dataset). Additionally, it was possible to
 571 discriminate between different land covers based on the magnitude of their change. Finally,
 572 the two stage test showed good results either on the SARTOM or the AGRISAR dataset. In
 573 the latter, it was possible to isolate the point targets and reject the large agricultural fields.
 574 As a final recommendation, the choice of the statistical test depends on the focus of the
 575 detection. If distributed targets are of interest (e.g. changing in backscattering due to soil
 576 moisture) the Distributed Changes detector should be used, on the other hand if the focus is
 577 on point targets (e.g. vehicles) than the 2-Stage detector should be exploited.

578 APPENDIX

579 *E. γ_e and ρ_{12} have the same eigenvectors*

A well-known theorem that will be exploited in the following is the sequent: giving two diagonalizable matrices $[Q]$ and $[Q]^p$, they have the same eigenvectors and eigenvalues $\lambda_{[Q]} = \lambda_{[Q]^p}^p$ [18]. Consequently, $[T_{22}]^{-1}[T_{11}]$ and $[T_{11}]^{-1}[T_{22}]$ has the same eigenvectors and inverse eigenvalues. The two matrices to test are $[A_1] = \frac{1}{4} ([T_{22}]^{-1}[T_{11}] + 2[I] + [T_{11}]^{-1}[T_{22}]) = [U_1][\Sigma_1][U_1]^*T$ and $[A_2] = [T_{22}]^{-1}[T_{11}] = [U_2][\Sigma_2][U_2]^*T$, where $[U_1]$ and $[U_2]$ are two unitary matrices where the columns are the eigenvectors. It is possible to write, $[\Sigma_1] = [U_1]^*T[A_1][U_1]$ and $[\Sigma_2] = [U_2]^*T[A_2][U_2]$. Substituting the matrices $[A_1]$ and $[A_2]$ it can be

derived:

$$\begin{aligned}
[\Sigma_1] &= \frac{1}{4} \left([U_1]^* T [T_{22}]^{-1} [T_{11}] [U_1] \right. \\
&\quad \left. + 2[U_1]^* T [I] [U_1] + [U_1]^* T [T_{11}]^{-1} [T_{22}] [U_1] \right) \\
&= \frac{1}{4} \left([U_1]^* T [T_{22}]^{-1} [T_{11}] [U_1] + 2[I] \right. \\
&\quad \left. + [U_1]^* T [T_{11}]^{-1} [T_{22}] [U_1] \right) \\
[\Sigma_2] &= [U_2]^* T [T_{22}]^{-1} [T_{11}] [U_2]. \tag{27}
\end{aligned}$$

580 By definition $[U_2]$ diagonalize $[T_{22}]^{-1}[T_{11}]$, therefore, it will also diagonalize $[T_{11}]^{-1}[T_{22}]$.

581 Since $[I]$ is already diagonal, if $[U_1]$ is set equal to $[U_2]$, $[\Sigma_1]$ will be the sum of diagonal

582 matrices and therefore still diagonal. Because the diagonalization is a unique operation, $[U_2]$

583 or a permutation of $[U_2]$ (i.e. rearrangement of columns) must be the only possible unitary

584 matrix $[U_1]$ that diagonalize $[\Sigma_1]$. For this reason, $[U_1] = [U_2][P]$, with $[P]$ any permutation

585 matrix. To summarize, the eigenvectors are the same even though their ranking (linked to

586 the value of the eigenvalues) may be different.

587 *F. The eigenvalues for γ_e and ρ_{12} are real positive*

The eigenvalues resulting the optimization of γ_e and ρ_{12} are generally different, however they both keep the property of being real positive. In order to demonstrate this, the product of matrices $[T_{11}]^{-1}[T_{22}]$ can be considered. They are both Hermitian semi-positive definite matrices (the inverse of a Hermitian matrix is still Hermitian). For convenience, it is written $[T_{11}]^{-1} = [B]$ and $[T_{22}] = [C]$, with $[B]$ and $[C]$ any Hermitian semi-positive definite matrices. We want to demonstrate that $[B][C]$ has real positive eigenvalues. Please note, this does not mean that $[B][C]$ is semi-positive definite (i.e. $\underline{\omega}^* T [B][C] \underline{\omega} \notin \mathbb{R}^+$) unless $[B]$ and $[C]$ are commuting matrices (i.e. $[A][B] = [B][A]$). If the diagonalization of each matrix is

performed it is possible to write:

$$[B] = [U_B][\Sigma_B][U_B]^*{}^T, \quad (28)$$

$$[C] = [U_C][\Sigma_C][U_C]^*{}^T.$$

588 where $[U_B]$, $[U_C]$ are unitary matrices and $[\Sigma_B]$, $[\Sigma_C]$ are diagonal matrices. The product
589 $[B][C]$ can be written as:

$$[B][C] = [U_B][\Sigma_B][U_B]^*{}^T[U_C][\Sigma_C][U_C]^*{}^T. \quad (29)$$

590 It can be demonstrated that similarity transformations do not change the eigenvalues of a
591 matrix (which are basis invariant). The selected similarity is $[U_B][\Sigma_B]^{-\frac{1}{2}}[U_B]^*{}^T$. Therefore,
592 after the similarity is applied we have:

$$[U_B][\Sigma_B]^{\frac{1}{2}}[U_B]^*{}^T[U_C][\Sigma_C][U_C]^*{}^T[U_B]^*{}^T[\Sigma_B]^{\frac{1}{2}}[U_B]. \quad (30)$$

593 Considering, $[U_B][\Sigma_B]^{\frac{1}{2}}[U_B]^*{}^T = [B]^{\frac{1}{2}} = [D]$ is Hermitian, it can be written: $[D][C][D]^*{}^T$.
594 The latter is Hermitian since, $[D][C][D]^*{}^T = ([D][C][D]^*{}^T)^*{}^T$ and therefore it is diagonaliz-
595 able and have real positive eigenvalues. Considering $[D][C][D]^*{}^T$ has the same eigenvalues
596 of $[B][C]$, then the latter is diagonalizable and has real positive eigenvalues.

597 Once proved that $[T_{11}]^{-1}[T_{22}]$ has real positive eigenvalues, it is straightforward to extend
598 this to the matrix $\frac{1}{4} [[T_{22}]^{-1}[T_{11}] + 2[I] + [T_{11}]^{-1}[T_{22}]]$, since it can be decomposed in the
599 sum of three components each one with real positive eigenvalues and equal eigenvectors.

600

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