FMLE SAR SPECKLE FILTER USING THE DISTANCE CONSISTENCY PROPERTY IN HOMOSKEDASTIC LOG-TRANSFORMED DOMAIN

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ABSTRACT: For Synthetic Aperture Radar (SAR) data, the log-transformed domain provides homoskedasticity and a consistent sense of distance, which are not available in the original domain.In the current paper, a Fuzzy Maximum Likelihood Estimator (FMLE) in the log-transformed domain is introduced, which makes use of the consistent sense of distance and is shown to preserves such consistency in its output. The paper also demonstrates experimentally how the ubiquitous Mean Squared Error (MSE) in the homoskedastic log-transformed domain can be used as an invaluable criteria in quantitatively evaluating SAR speckle filters. For homogeneous areas, the MSE is shown to be closely related to the standard measure of speckle suppression, namely the Equivalent Number of Looks (ENL). For heterogeneous scenes, our experimental results suggest that the lower MSE values achievable by the Fuzzy MLE filter correlates with higher values of an index which is considered as statistical evidence for better performance in subsequent tasks such as target detection or surface classification. The index is known, in computational intelligence literature, as the Area Under The ROC (Receiver Operating Characteristic) Curve (AUC).

1 INTRODUCTION

SAR is stochastic and SAR speckle filtering is the removal of stochastic "noise". The principle of many speckle filters in removing stochastic noise is to group data into homogeneous areas. In the boxcar filter, the filtering process can be described via Eqn. 1, where I_i is the intensity value of pixel i and n is the total number of pixel in the surrounding areas. The implicit assumption is that ALL pixels in the surrounding area belongs to the same homogeneous area with the estimating central point. In a filter previously proposed by the authors (Le et al., 2010), the surrounding region is partitioned into homogeneous areas and the approximation is given in Eqn. 2, where I_i is the intensity value of pixel i and k is the total number of pixels in the partitioned and homogeneous area covering the centre point.

$$f_{boxcar} = \sum_{i=1}^{n} I_i/n \qquad (1)$$

$$f_{kMLE} = \sum_{i=1}^{k} I_i/k \qquad (2)$$

By and large, while it appears logical to classify surrounding pixels as being either in the same homogeneous area with the central point or not, the concept of "homogeneous area" lacks precise definition and boundaries. This is self-evident in the need for a threshold on the variance measured to assert homogeneity in an ensemble of stochastic samples.

This paper presents a different approach, that of fuzzy logic. Fuzzy logic embraces truth values that range from 1 to 0, instead of fixing on a rigid two-member set of logical values (i.e. true and false). Thus instead of making an YES/NO decision on whether or not a data point is in the same homogeneous region with the estimating central point, a fuzzy probabilistic scale is calculated. Then the noise-removal impact of the surrounding data point will be scaled with this possibilistic probability, in contrast to the usual scheme that proceeds with "full impact" or "no impact at all".

The idea presented in this paper is structured as follows: Section 2 will describe the FMLE estimation in details. The performance of the proposed filter will be evaluated in Section 3. Finally, Section 4 concludes this paper.

2 FUZZY MLE ESTIMATION

2.1 Statistical Analysis

The foundation of the approach is the consistent sense of distance found in the log-transformed domain. It is shown in Le et al. (2010) that given two SAR intensity samples coming from the same background, their distance in the log transformed domain follows a fixed distribution.

Log transformation is defined as: ${L_I}^i = \log_2(I^i)$ where I^i is the i^{th} intensity sample in the originally measured domain, L_I^I is the value of that sample in the log-transformed domain. Log domain distance is defined as: $D = L_I^1 - L_I^2$. Assumming I^i follows a negative exponential distribution (Goodman, 1976), then distance will follow the distribution $pdf(D) = \frac{2^D}{(1+2^D)^2} \ln 2$, which is consistent. The analysis is confirmed by real-life data validations (see Le et al. (2010)) and visually demonstrated in Fig. 1a.

2.2 FMLE Estimation

Using a fuzzy logic approach, a pixel with intensity value I_i in the surrounding area of the center point I_0 has a likelihood of being in the same homogeneous area given as: $p_i = pdf(D_i)$, with $D_i = log_2(I_i) - log_2(I_0)$. We then propose a new approximation given in Eqn. 3

In implementating this estimator, we noticed there are visible black dots in the filtered image. These dots can be explained as the long-tailed nature of the intensity PDF, which manifests itself in the significant existence of very small values in the population. In the all-inclusive scheme, this will results in a single $D_0 = 0$ (at I_0) and other very large $D_{i,(i>0)}$, hence a single significant p_0 (at I_0), and other probably insignificant $p_{i,(i>0)}$. This marginalises the filtering power of surrounding pixels. An option is to exclude the centre point I_0 from its estimation (see Eqn. 4)

$$FMLE_{incl} = \frac{\sum_{i=0}^{n} p_i * I_i}{\sum_{i=0}^{n} p_i} \quad (3)$$

$$FMLE_{excl} = \frac{\sum_{i=1}^{n} p_i * I_i}{\sum_{i=1}^{n} p_i} \quad (4)$$

Both filters are applied to an simulated single-look homogeneous scene and the histogram of the filtered images are plotted in Fig. 1b and Fig. 1c. The filtering power is clearly visible. In comparing the two schemes' histogram in the same figure, it appears that the filtering power of ignoring centre point scheme is at least as powerful as that of centre point included scheme and the skewness in the histogram of the ignoring scheme is also appearing less than that of the included scheme.

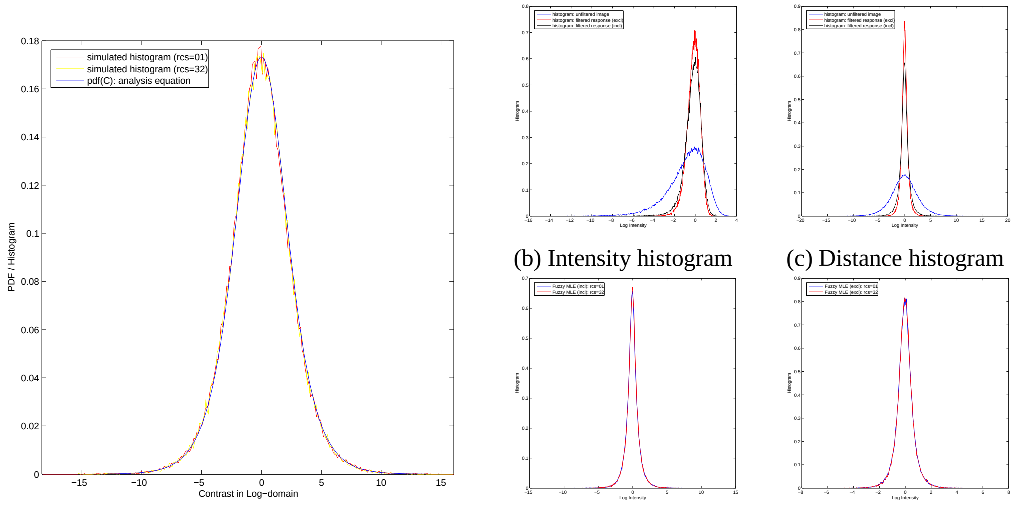
2.3 Preservation of Distance Histogram Consistency

Fig. 1d and 1e plot the distance histograms found in the outputs of applying FMLE filters on the inputs depicted in Fig. 1b. They clearly demonstrate that the filtering treatment described above preserves the consistent sense of distance. This can be explained from the consistent histogram of the fuzzy possbilistic probabilities. Unfortunately, the filtering formula given in Eqn. 3 and Eqn. 4, especially when applied to large image areas, involves large number of random variables. This renders the task of giving analytical PDF impractical. However, large scale computer simulations can provide a practical histogram, from which the PDF can estimated. Given a distance d, its corresponding probability $pdf(d)$ can be simulated by intrapolating from the saved histogram $y \equiv hist(x)$ at the value of $x \equiv d$.

2.4 Recursively Applying Fuzzy MLE Filter

The preservation of consistent distance property is the enabling factor that allows the recursive use of FMLE filters. Additional applications of the filtering process can be expected to reduce the random noise variance even further. In a sense, this scheme is similar to statistical asymptotic estimations, with the added advantage of spatial preservation.

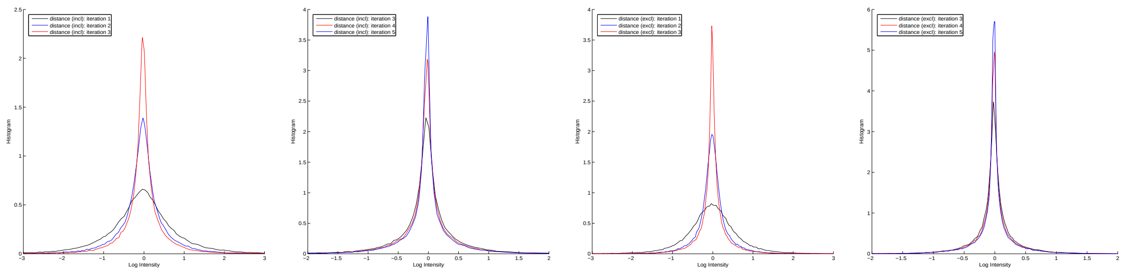
In the subsequent application of the filtering algorithm, the main different when compared with the filters in initial iteration is the way the new fuzzy probabilities being calculated. This subsequent computation of fuzzy probabilities is based on the derived distance PDF, being computed in the previous section. This process is iterated iteratively,



(a) Consistent Distance (b) Intensity histogram (c) Distance histogram (d) FMLE (incl) outputs (e) FMLE (excl) outputs

Figure 1: Consistent Distance Property and the FMLE Estimations

with the histogram obtained from the previous iteration serves as probabilistic distance PDF input of the subsequent application of the filter. This scheme allows speckle to be further depressed, as illustrated in Fig. 2



(a) FMLE (incl): 123 (b) FMLE (incl): 456 (c) FMLE (excl): 123 (d) FMLE (excl): 456

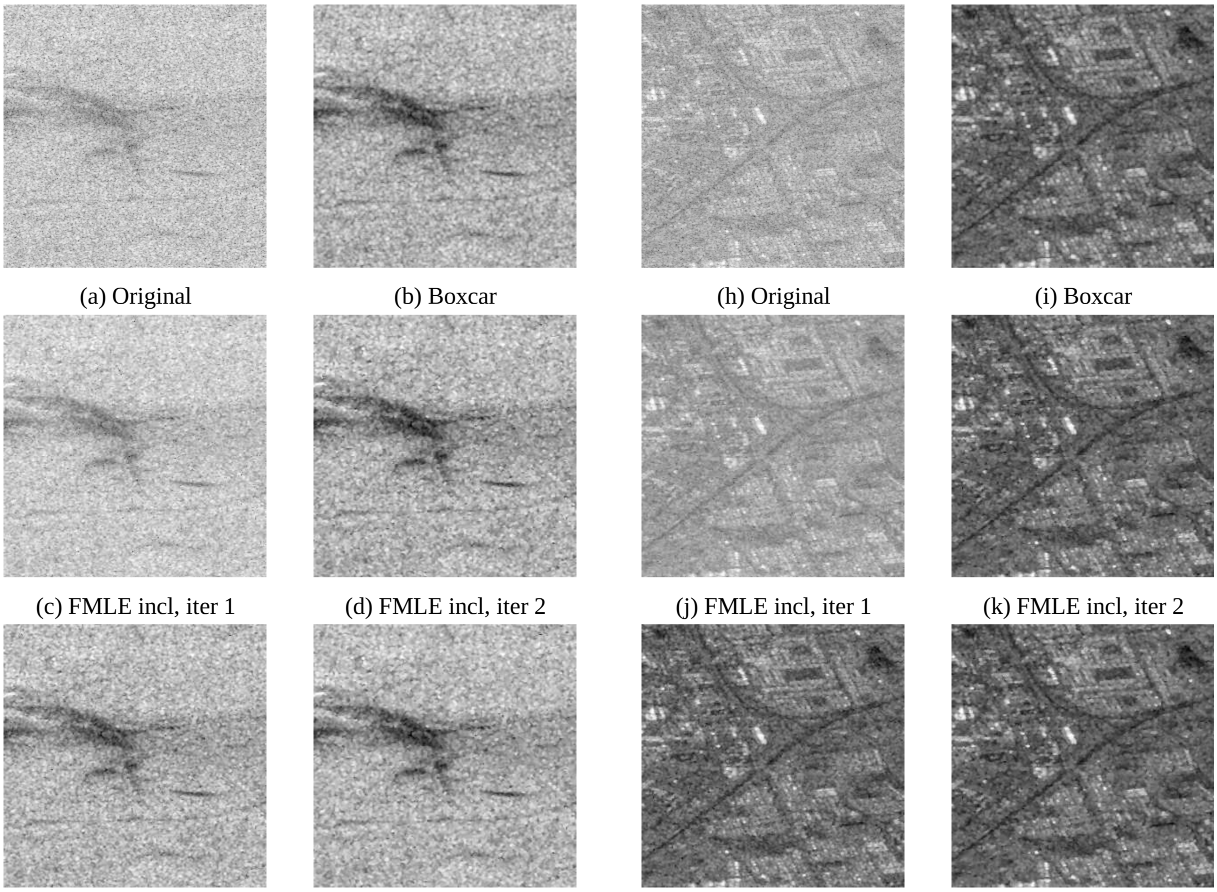
Figure 2: Iteratively Improving in Distance Histograms

3 RESULTS EVALUATION AND DISCUSSION

The performance of speckle filters are normally evaluated based on a few criteria (Nyoungui, 2002). The most widely used criteria is speckle suppression, which is often evaluated over homogeneous area. The other important criteria include radiometric preservation, something undeniably desirable in the filtered output. In practical terms, the most common usage of speckle filtered imagery include target and feature detection and classification. We highlight the use of the ROC curve and the area under it as the statistical evidence of separability between target and clutter PDFs. We then show that lower MSE achievable by FMLE filters does lead to better performance in the subsequent tasks of target detection and classification. We start with visual evaluation of the filters on real-life images.

3.1 Qualititative Evaluation on Real Images

The filters are applied to a SLC RadarSat 2 image covering the Muda Merbok area of Malaysia. Fig. 3 shows the patches of original and filtered images of both natural and urban landscape. The filtering effects are clearly visible. Apparently the second iteration outputs appears much better than the initial iteration, and offer roughly the same level of performance in comparision to that of boxcar filter.



(a) Original (b) Boxcar (h) Original (i) Boxcar

(c) FMLE incl, iter 1 (d) FMLE incl, iter 2 (j) FMLE incl, iter 1 (k) FMLE incl, iter 2

(e) FMLE excl, iter 1 (f) FMLE excl, iter 2 (l) FMLE excl, iter 1 (m) FMLE excl, iter 2

Scene of Natural Surface Scene of Urban Landscape

Figure 3: Qualitative Evaluation of FMLE filter on Real Life Images

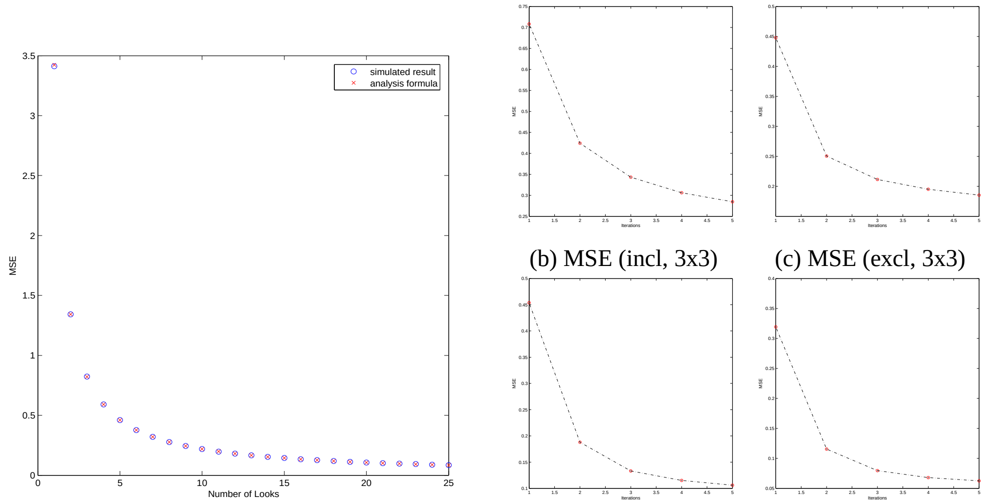
3.2 Evaluating Speckle Suppression Effects

We have found that MSE in the log-transformed domain is related to the standard Equivalent Number of Look value. Deriving from the results of Hoekman (1991) and Xie et al. (2002), the formula is given as: $MSE = \frac{1}{(ENL-0.5)ln^2(2)}$. Fig. 4a demonstrates the relationship. The use of iterative Fuzzy MLE estimations allows further suppression of speckle. This is illustrated with "tighter" distance histograms and reducing MSE, as plotted in Fig. 4

3.3 Evaluating Target Detection Performance

The normal application after applying filters on SAR images is to detect the existence of certain target within its surrounding clutters. The most common type of detector (or classifier) employs a threshold based approach in determing whether an abnormal value signifies the existence of a target. The Receiver Characteristic Curve (ROC) and the area under it (AUC) is typically used to evaluate the detectability of target features (Mazurowski and Tourassi, 2009).

It is normally claimed that applying speckle filters increases the performance of subsequent target detection tasks. The following experiment illustrates this point. In this experiment, we apply a simple 3x3 boxcar filter to two different homogeneous and SLC noise corrupted scenes that are known to be 3dB apart. And then the histograms as well as the resulting ROC curve are plotted between the pairs of target and background histogram in the two cases of unfiltered and filtered data. We noted that the ROC curve for the histograms in original domain matches perfectly with ROC for the histograms in the log-transformed domain (see Fig. 5), as expected from theory.



(a) MSE and the Equivalent Number Of Looks

(b) MSE (incl, 3x3)

(c) MSE (excl, 3x3)

(d) MSE (incl, 5x5)

(e) MSE (excl, 5x5)

Figure 4: Homogeneous Area: MSE criteria and speckle suppression power of FMLE filters

The most common types of target to be detected in image processing are point targets, line targets, and edge targets. The detectability of the targets are measured using the AUC index which is tabulated against the MSE. Fig. 6 illustrates the evaluation result in benchmarking the performance of FMLE filters for heterogenous regions. Even though the relationship is probably not linear, the correlation between MSE and Area Under the ROC curve (AUC) is apparent, Also FMLE filters apparently have better performance than boxcar filters.

4 CONCLUSION

The log-transformed domain provides a consistent sense of distance. By embracing a probabilistic approach, the proposed Fuzzy Maximum Likelihood Estimator makes use of this consistency. Experimental results suggest that the estimator's output also exhibits this consistency property, which allows recursive application of the filter discussed above. The performance of the filter is evaluated both qualitatively against real images and quantitatively via simulated experiments. The speckle suppression power is evaluated by measuring the ubiquitous MSE on simulated and perfectly homogeneous truth-grounded experiments. The results suggest that by applying the estimation recursively, this value can be reduced arbitrarily low, assuming that the number of iterations, and hence the available scene and computational power, is sufficiently large. For heterogeneous scenes, the robust Area Under the ROC Curve criteria is used as statistical evidence for better performance in the subsequent tasks of target detection and surface classification. Experiments confirm the power of FMLE filters in various heterogeneously simulated areas. They also exhibit good correlation between the MSE and the AUC index.

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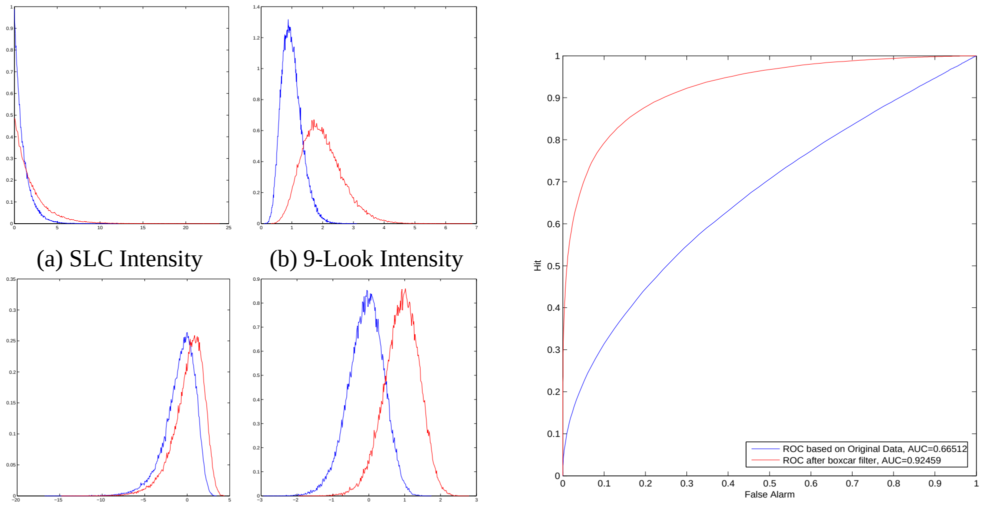
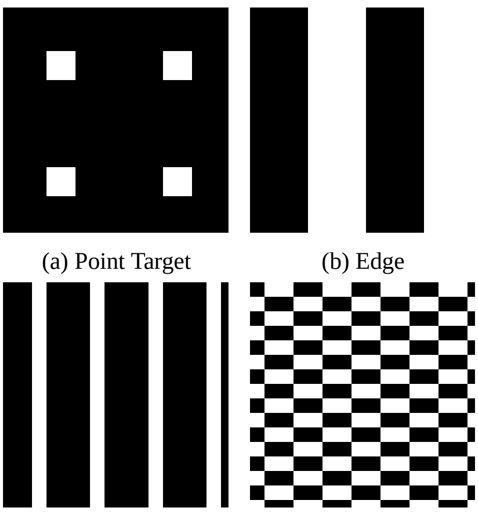


(a) SLC Intensity (b) 9-Look Intensity

(c) SLC log-intensity (d) 9-Look log-intensity

(f) Invariant ROC Curve

Figure 5: Histogram Discriminality and the ROC Curve



(a) Point Target (b) Edge

(c) Line (d) Dotted Pattern

Scene	Filter	MSE	AUC
Point Target	FMLE (incl, 3x3)	1.38	0.901
Point Target	FMLE (excl, 3x3)	1.47	0.893
Point Target	boxcar (3x3)	1.56	0.826
Point Target	boxcar (5x5)	2.67	0.502
Edge	FMLE (incl, 3x3)	0.68	0.969
Edge	FMLE (excl, 3x3)	0.73	0.964
Edge	boxcar (3x3)	1.03	0.942
Edge	boxcar (5x5)	1.51	0.934
Line	FMLE (incl, 3x3)	1.89	0.791
Line	FMLE (excl, 3x3)	2.02	0.767
Line	boxcar (3x3)	2.27	0.658
Line	boxcar (5x5)	2.88	0.375
Dotted	FMLE (incl, 3x3)	2.28	0.639
Dotted	FMLE (excl, 3x3)	2.32	0.621
Dotted	boxcar (3x3)	2.92	0.431
Dotted	boxcar (5x5)	3.35	0.382

Figure 6: Heterogeneous Patterns: MSE criteria and FMLE performance

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