A comparison of SAR image speckle filters

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ABSTRACT

High quality images of Earth produced by synthetic aperture radar (SAR) systems have become increasingly available, however, SAR images are difficult to interpret. Speckle reduction remains one of the major issues in SAR imaging process, although speckle has been extensively studied for decades. Many reconstruction filters have been proposed and they can be classified into two categories: multilook and/or minimum mean-square error (MMSE) despeckling using the speckle model; and maximum *a posteriori* (MAP) or maximum likihood (ML) despeckling using the product model. The most well known Lee, Kuan, and Frost filters belong to first category. These filters are based on conventional techniques that were originally derived for stationary signals, such as MMSE. In the second category, filters are based on the product model, such as the MAP Gaussian filter and the Gamma filter, and require knowledge of the *a priori* probability density function. These filters force speckle to have nonstationary Gaussian or gamma distributed intensity mean. The speckle filtering is mainly Bayesian model fitting that optimizes the MAP criteria. Scene reconstruction is performed using an inversion of the ascending chain. An objective measure is required to compare the technical merits of these filters, and Shi *et al.* presented a comparison 15 years ago. In this paper, a brief introduction of speckle, product, and filter models is summarized. A review of some most widely used SAR image speckle filters is given. And stationary speckle filters, like Lee, Kuan, and Frost filters, and nonstationary speckle filters like Gamma MAP filter are studied. Despeckling results on stationary and nonstationary SAR image of these speckle filters are presented.

Keywords: SAR image, speckle filters

1. INTRODUCTION

In the last two decades, high quality images of Earth produced by synthetic aperture radar (SAR) systems have become increasingly available. However, SAR images are difficult to interpret. This is mainly due to two specificities of the SAR system. First, SAR is coherent imagery and therefore subject to the speckle phenomenon. Secondly, microwave propagation leads images which are distance sampled to strong geometrical distortions. We only focus on the speckle reduction in this paper.

Although speckle has been extensively studied for decades, speckle reduction remains one of the major issue in SAR imaging process. Many reconstruction filters have been proposed and they can be classified into two categories: multilook and/or minimum mean-square error (MMSE) despeckling using the speckle model; and maximum *a posteriori* (MAP) or maximum likihood (ML) despeckling using the product model. The famous Lee,[1] Kuan,[2] and Frost[3] filters in the first category provide MMSE reconstructions based on measured local statistics. In the second category, different scene distributions are used: Gaussian,[4] Gamma,[5] and model-based.[6] Touzi gives an excellent review of many SAR filters.[7]

In this paper, a brief introduction of speckle, product, and filter models is summarized in section 2. A review of some most widely used SAR image speckle filters is given in section 3. Despeckling results for these SAR image speckle filters are presented in section 4. And finally section 5 is the conclusion.

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2. SPECKLE, PRODUCT, AND FILTER MODELS

2.1 Multiplicative Speckle Model

SAR is modeled as a 2-dimension (2-D) linear sysmtem of range and azimuth. And speckle is modeled as a white zero-mean complex Gaussian process n. The most commonly used speckle noise model is the multiplicative model. The observed signal intensity at the 2-D spatial position t is the product of the scene signal intensity and the speckle noise intensity. That is $I(t) = S(t)\,u(t)$, where $I(t)$ is the observed signal intensity of the pixel located at t, $S(t)$ is the scene reflectivity, and $u(t)$ is the intensity of speckle noise. The speckle noise intensity is modeled as a unit mean gamma distribution.[8]

2.2 Product Model

A significant breakthrough in the understanding of radar image properties was the appreciation that many types of clutter derive from two unrelated processes can be encapsulated in a product model.[9] For a given scene distribution $P(S(t))$, the product model asserts that the probablity density function (PDF) of the observed intensity is given by $P(I(t)) = \int_0^\infty P(I(t) \mid S(t))\, P(S(t))\, dS(t)$.

2.3 Filter Models

For speckle reduction filters, it is important to know whether the speckle noise process is stationary or not, white or correlated noise. Two categories of speckle filters can be identified.

2.3.1 Stationary Multiplicative Speckle Model Filters

These filters assume that the speckle random process is stationary over the whole image. The most well known Lee,[1] Kuan,[2] and Frost[3] filters belong to this category. These filters are based on conventional techniques that were originally derived for stationary signals, such as MMSE.

2.3.2 Nonstationary Multiplicative Speckle Model Filters

Filters in this category assume that speckle is not locally stationary within the moving processing window. These filters are based on the product model previously descriped, such as the MAP Gaussian filter[4] and the Gamma filter,[510] and require knowledge of the *a priori* PDF. These filters force speckle to have nonstationary Gaussian or gamma distributed intensity mean. The speckle filtering is mainly Bayesian model fitting that optimizes the MAP criteria. Scene reconstruction is performed using an inversion of the ascending chain.

Both of these categories assume that the multiplicative speckle noise model is satisfied at each pixel. There is also various approximation of the multiplicative speckle noise model, which is not considered in this project.

3. REVIEW OF THE SPECKLE FILTERS

3.1 The Lee Filter[1]

In Lee filter, the multiplicative speckle model is first approximated by a linear model, and then the MMSE criterion is applied. The speckle reduction filter can be formulated as $\hat{S}(t) = I(t)\,W(t) + \bar{I}(t)\,(1 - W(t))$, where $W(t) = 1 - C_u^2/C_I^2(t)$, is the weighting function, and $C_u = \sigma_u/\bar{u}$, $C_I(t) = \sigma_I(t)/\bar{I}(t)$ are the variation coefficients of the speckle $u(t)$ and the image $I(t)$, respectively.

3.2 The Kuan Filter[2]

In the approach of the Kuan filter,[2] the multiplicative speckle model is first transformed into a single-dependent additive noise model, and then the MMSE criterion is applied. The speckle filter has the same form as the Lee filter but with a different weighting function $W(t) = \left(1 - C_u^2/C_I^2(t)\right) / \left(1 + C_u^2\right)$. The Kuan filter makes no approximation to the original model. From this point of view, it can be considered to be superior to the Lee filter.

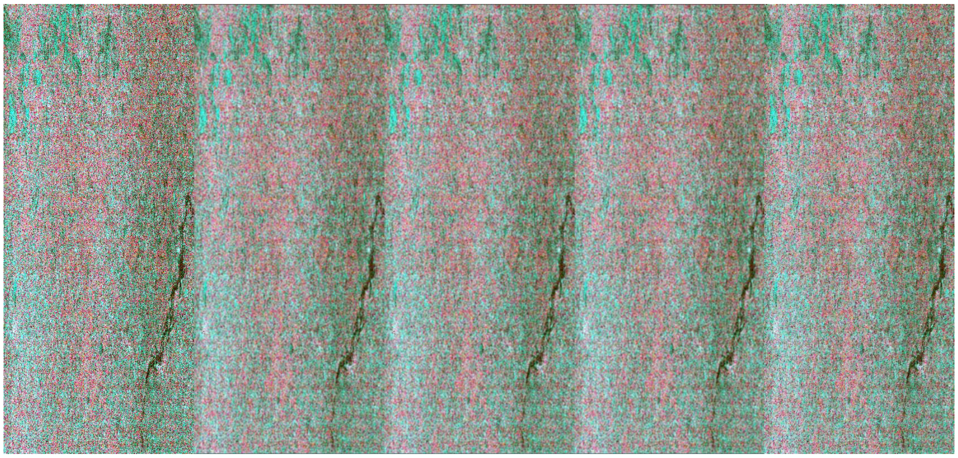

Figure 1. A sample Envisat image (from left to right): (a) original image; (b) Lee filtered image; (c) Kuan filtered image; (d) Frost filtered image; (e) Gamma MAP filtered image

3.3 The Frost Filter[3]

The Frost filter is different from the Lee and Kuan filters with respect that the scene reflectivity is estimated by convolving the observed image with the impulse response of the SAR system. The impulse response of the SAR sysmtem is obtained by minimizing the mean square error between the observed image and the scene reflectivity model which is assumed to be an autoregressive process. The filter after some simplifications can be written as $m\left(t\right)=e^{-KC_I^2\left(t_0\right)\left|r\right|}$, where K is a constant controlling the damping rate of the impulse response function, and t_0 denotes the pixel to be filtered. When the variation coefficient $C_I\left(t_0\right)$ is small, the filter behaves like an low pass filter smoothing out the speckles. When $C_I\left(t_0\right)$ is large, it has a tendency to preserve the original observed image.

3.4 The Gamma MAP Filter[5]

Kuan *et al.* first proposed the MAP approach for speckle filtering.[4] This approach requires the *a priori* knowledge of the PDF of the scene. In the Kuan MAP filter, the scene reflectivity is assumed to be Gaussian distributed. However, this is not quite realistic since it implicitly assumes a negative reflectivity. Lopes *et al.*[5] modified the Kuan MAP filter by assuming a gamma distributed scene and setting up two thresholds. The Gamma MAP filter is given by $\hat{S}\left(t_0\right)=\left(\left(\alpha-L-1\right)\bar{I}\left(t_0\right)+\sqrt{\bar{I}^2\left(t_0\right)\left(\alpha-L-1\right)^2+4\alpha LI\left(t_0\right)\bar{I}\left(t_0\right)}\right)/2\alpha$, for $C_u\leq C_I\left(t_0\right)\leq C_{max}$, where L is the number of looks, $C_{max}\left(t_0\right)=\sqrt{2}C_u$, and $\alpha=\left(1+C_u^2\right)/\left(C_I^2\left(t_0\right)-C_u^2\right)$. For $C_I\left(t_0\right)<C_u$, $\hat{S}\left(t_0\right)=\bar{I}\left(t_0\right)$; for $C_I\left(t_0\right)>C_{max}$, $\hat{S}\left(t_0\right)=I\left(t_0\right)$.

4. RESULTS

The Lee, Kuan, Frost and Gamma MAP filters are evaluated using a sample Envisat ASAR image[11] and a simulated ALOS PALSAR image.[12] Since the test images are all single look intensity image, we have $C_u=1/\sqrt{L}=1$. For the Gamma MAP filter, $C_{max}=\sqrt{2}C_u$.

4.1 Stationary Region

A sample Envisat ASAR image is used to evaluate the despeckling performance of different filters in a stationary region. As shown in Fig. 1, from left to right, we have the original SAR image, Lee filtered image, Kuan filtered image, Frost filtered image, and Gamma MAP filtered image.

From Fig. 1, it is shown that these filters have a very similar performance in a locally stationary region, even though the filters equations exhibit different formulations.

4.2 Nonstationary Region

A simulated ALOS PALSAR image is used to evaluate the despeckling performance of different filters in a nonstationary region. As shown in Fig. 2, from left to right, we have the original SAR image, Lee filtered image, Kuan filtered image, Frost filtered image, and Gamma MAP filtered image.

Scene signals may be nonstationary even withini a small region, due to edges, curvilinear features, or point targets. As shown in Fig. 2, despeckling filter using product model performs better in nonstationary region.

The above study on speckle filtering suggests the following despeckling procedure:

1) stationary-nonstationary region detection;

2) maximizing locally stationary region;

3) despeckling of locally stationary areas;

4) despeckling of locally nonstationary areas.

5. CONCLUSION

In this paper, we studied the multiplicative speckle model and product model of SAR image. Stationary speckle filters, like Lee, Kuan, and Frost filters, and nonstationary speckle filters like Gamma MAP filter are studied. Despeckling results on stationary and nonstationary SAR image of these speckle filters are presented.

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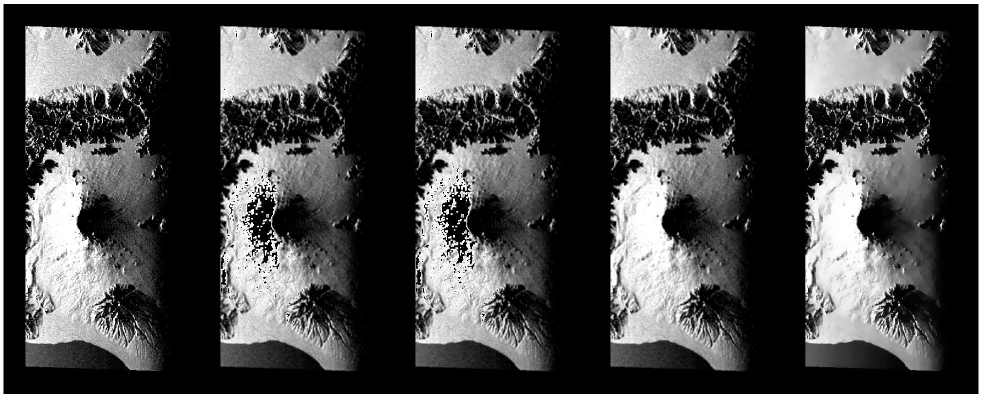

Figure 2. A simulated ALOS image (from left to right): (a) original image; (b) Lee filtered image; (c) Kuan filtered image; (d) Frost filtered image; (e) Gamma MAP filtered image