# Frost Filtering Algorithm of SAR Images with Adaptive Windowing and Adaptive Tuning Factor

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**Abstract.** A Frost filtering algorithm of synthetic aperture radar (SAR) images with adaptive windowing and adaptive tuning factor is proposed to resolve the problem that the traditional Frost filtering algorithm cannot balance speckle suppression and edge preservation effectively. The tuning factor and the window influence the performance of the Frost filter significantly. When the tuning factor and the window are too big or too small, the Frost filter cannot lead to effective balance between speckle suppression and edge preservation. Through the adaptive changing of the windowing and tuning factor, the proposed algorithm can not only suppress speckle effectively, but also keep the marginal information of image better. The proposed algorithm is applied to SAR images, and it is compared with the Lee filter, the Gamma MAP filter, the traditional Frost filter, and the modified frost filter only using adaptive tuning factor. Despeckling experiments demonstrate that the proposed algorithm can suppress speckle in homogeneous regions more sufficiently, while it can preserve edge information more effectively. Therefore, the proposed algorithm achieves a better balance between speckle suppression and edge preservation.

## Introduction

Owing to coherent imaging system, speckle appears in synthetic aperture radar (SAR) images. The speckle degrades the quality of SAR images, and it affects the subsequent edge detection, image segmentation, and target recognition. Therefore, it is indispensable to reduce speckle effectively in SAR image processing [1,2]. Concerning this issue, many techniques have been proposed to suppress speckle. There are two major categories of techniques for speckle reduction in SAR images. The first technique is multi-look processing, and the second technique is image domain filtering. The multi-look processing improves SAR images by averaging several uncorrelated images of one terrain, but it results in a loss of spatial resolution. The image domain filtering tries to suppress speckle after the image is formed, including the local statistics filters such as Lee filter [3,4], Kuan filter [5,6], Frost filter [7-9], and Gamma MAP filter [10]. The Lee filter and Kuan filter are in the form of a linear weighted filtering. The Frost filter, on the contrary, is not just the simple linear weighted form. It is assumed that the impulse response of the system is constant under the conditions of limited bandwidth, and the actual image is estimated by the convolution of the observed image and the corresponding impulse. Finally, the filter equations can be derived by the minimum mean square error criterion [7,9]. For the traditional Frost filter, the window and the tuning factor are both fixed. When the tuning factor and the window are too big or too small, the Frost filter cannot yield an effective balance between speckle suppression and edge preservation. A modified Frost filter was proposed in [11], where the tuning factor is adaptively adjusted based on regional characteristics of SAR images. Compared to the traditional Frost filter, the modified Frost filter with adaptive tuning factor can achieve better performance. However, the size of window is still fixed, not reflecting the differences of various terrains such as homogeneous and heterogeneous regions. In this paper, we propose a Frost filter with adaptive windowing and adaptive tuning factor. The window size and the tuning factor are adaptively adjusted in terms of regional characteristics. In homogeneous regions, a large window is used to sufficiently suppress speckle. In heterogeneous regions, a small window is adopted to well preserve edges and fine details. In order to demonstrate the performance of the proposed Frost filter, despeckling experiments on various SAR images are provided, which shows that the proposed double-adaptive Frost filter can suppress speckle as much as possible while preserve edge and fine details effectively.

## Modified Frost filter based on adaptive tuning factor

The Frost filter was proposed in [7]. Similar to the Lee filter and the Kuan filter, the Frost filter is also based on the minimum mean square error criterion. However, the Frost filter does not owns the simple linear weighted form by the means of the real image and the observed image. It is assumed that the impulse response of the system is constant under the conditions of limited bandwidth, and the actual image is estimated by the convolution of the observed image and the corresponding impulse. Finally, the filter equations can be derived by the minmium mean square error criterion. The Frost filter can be expressed as [9]

$$\hat{I}(i,j)=\frac{\sum_{s}\sum_{h}P_{sh}m_{sh}}{\sum_{s}\sum_{h}m_{sh}},\quad m_{sh}=e^{-KC_I^2 d_{sh}}, \tag{1}$$

where $(i,j)$ is the location of current pixel, $\hat{I}(i,j)$ denotes the output of the filter, $P_{sh}$ denotes the values of pixels among the window centered at $(i,j)$, $K$ ($K>0$) is the tuning factor, $C_I$ is the coefficient of variation that is defined by the ratio of the sample standard deviation to the sample mean, and $d_{sh}$ is the distance between any pixel in the current window to the current pixel. Obviously, the value of the tuning factor $K$ is important for the performance of the Frost filter. When the value of $K$ is small, the Frost filter can suppress speckle well, but it cannot preserve edges and fine details effectively. As the value of $K$ increases, the ability of speckle suppression of the Frost filter is getting worse, but the edge preserving has gradualy improved.

Since the tuning factor in the Frost filter is important but not easy to predefined, a modified Frost filter based on adaptive tuning factor was proposed in [11]. This method computes the tuning factor adaptively by using the regional characterisics and the values of region pixels simultaneously. The centered pixel in current window is comtaminated by speckle, and, in some degree, the degree of such comtamination depends on whether the centered pixel is the most representative in current window. The $t$ statisitcs were used to measure the representative of the centered pixel, because the sample mean and sample variance for $t$ statistics can be estimated by the mean and variance of all pixels in current window [11]. In another word, the $t$ statistics were adopted to measure the degree of speckle contamination for the centered pixel, and then the adaptive tuning factor was constructed as follows:

$$K(s,h)=T(t_0)\cdot Q(s,h), \tag{2}$$

$$T(t_0)=\frac{\left|I(t_0)-u(t_0)\right|}{\delta(t_0)}, \tag{3}$$

$$Q(s,h)=\frac{\left|I(s,h)-I(t_0)\right|}{\frac{1}{(2N+1)^2-1}\sum_{m=i-N}^{i+N}\sum_{n=j-N}^{j+N}\left|I(m,n)-I(t_0)\right|}. \tag{4}$$

Here, $K(s,h)$ is the adaptive tuning factor that is composed of the $t$ statistic value $T(t_0)$ and the gray characteristics of neighborhood pixels $Q(s,h)$, $I(t_0)$ is the centered pixel value, $u(t_0)$ and $\delta(t_0)$ are the mean and the standard deviation of the pixels in current window centered at $t_0$, respectively. The square window is used, and the size of window is denoted as $N$ . Obviously, the above tuning factor is adaptively adjusted based on regional characteristics, leading to better performance of the Frost filter in comparison with the fixed tuning factor used in the traditional Frost filter. In this paper, we further improve the modified Frost filter with the adaptive tuning factor by using the adaptive windowing. The size of window is not fixed but adjusted adaptively according to regional characteristics. The proposed double-adaptive Frost filter is demonstated to own better trade-off between speckle suppression and edge preservation.

**Frost filter with adaptive windowing and adaptive tuning factor**

The adaptive windowing method was proposed to overcome the limitation of the traditional filters using the fixed-sized window [1,12,13]. For the adaptive windowing, the size of window is not fixed but adaptively adjusted based on regional characteristics. In order to save computational load, only the boundary pixels of the current window are used to determine the size of the next window. Denoting $(i, j)$ as the location of the current pixel, the coefficient of variation and the threshold are defined in current window as follows:

$$C_{ij} = \frac{\sigma_{ij}}{m_{ij}}, \tag{5}$$

$$T_{ij} = \eta\left(1 + \sqrt{\frac{1+2\sigma_F^2}{8\left(W_{ij}-1\right)}}\right)\cdot\sigma_F . \tag{6}$$

Here, $\sigma_{ij}$ and $m_{ij}$ are the sample standard deviation and the sample mean respectively, which are defined on the boundary pixels of the current window. $T_{ij}$ is a threshlod that determines the smoothness of the processed images. $\sigma_F^2$ and $W_{ij}$ are the variance of speckle and the window size, respectively. $\eta$ is a system parameter whose value is recommended as 1 [12]. Finally, the size of window centered at $(i, j)$ is adaptively adjusted as follows:

$$W_{ij} = \begin{cases} \min\left[W_{ij}+2, W_{\max}\right], & if\ C_{ij} \le T_{ij} \\ \max\left[W_{ij}-2, W_{\min}\right], & if\ C_{ij} > T_{ij} \end{cases}. \tag{7}$$

Here, $W_{\max}$ and $W_{\min}$ denote the maximum and the minimum window size, respectively. In order to improve the running efficiency, the adaptive windowing starts with the smallest window. For current window, the coefficient of variation $C_{ij}$ and the threshold $T_{ij}$ are calculated respectively by using (5) and (6). If $C_{ij}$ is not larger than $T_{ij}$, the size of window gradually increases until an appropriate size of sliding window is obtained. This means that the size of window depends on the regional characterisitcs. For homogeneous regions, a large window is usually obtained to suppress speckle well. For heterogeneous regions, a small window is obtained to effectively preserve edges. Finally, for the window that the adaptive windowing method yields, its heterogeneity is detected by comparing the variation coefficient of this window with the speckle variation coefficient. If the variation coefficient of the window is smaller than the speckle variation coefficient, the window belongs to a homogenous region, and the box filter is directly used to suppress speckle sufficiently. Obviously, due to the adaptive choice of window size, speckle suppression and edge preservation are well balanced. In a word, the proposed double-adaptive Frost filter includes three parts. Firstly, an appropriate window size is achieved by using the adaptive windowing method. Secondly, the heterogeneity of this window is detected and the box filter is used for the homogeneous region.

Finally, the modified Frost filter with adaptive tuning factor is used. The flow chart of the proposed double-adaptive Frost filter is shown in Fig. 1.

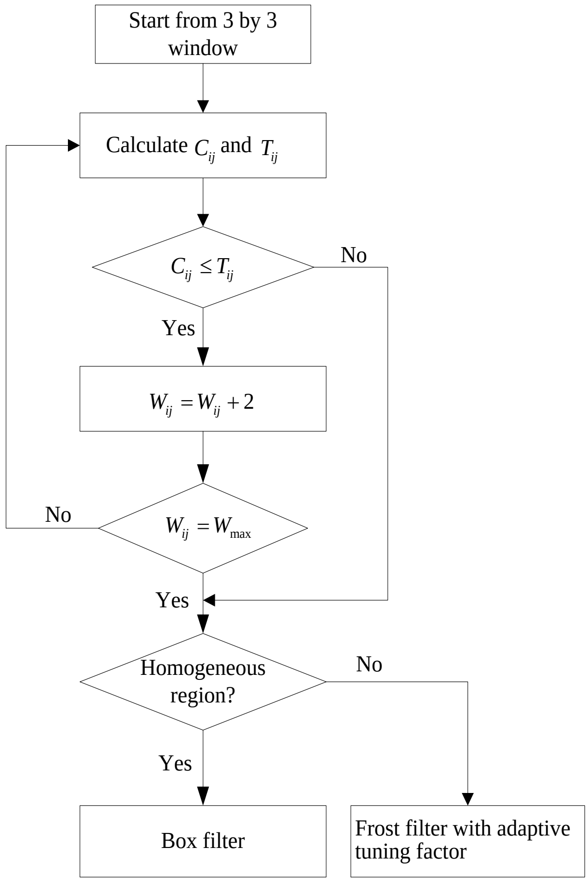



Fig. 1. Flow chart of the proposed double-adaptive Frost filter

## Despeckling experiments

The proposed double-adaptive Frost filter was tested on SAR image in Fig. 2. Some quantitative measures shown in Table 1 are provided to evaluate the performance of various filters. ENL denotes the equivalent number of looks [14], which is defined by the ratio of mean square to variance in a homogeneous region. ENL shows the ability of speckle suppression. The bigger the ENL is, the stronger ability of speckle suppression the filter owns. DCV is defined by the difference of coefficient of variations between the filtered image and the true image in an edge region [15]. This measure reflects the ability of edge preservation. The smaller the DCV is, the better ability of edge preservation the filter has. Obviously, due to the use of the structure information in sliding window, the Frost filter leads to better trade-off between speckle suppression and edge preservation in comparison with the Lee filter and the Gamma MAP filter. Compred to the traditional Frost filter, the Frost filter with adaptive tuning factor can suppress speckle better and preserve edges more effectively. So the Frost filter with adaptive tuning factor is an efficient modification of the traditional Frost filter that uses the fixed tuning factor. The proposed double-adaptive Frost filter simultaneously makes the window size and the tunning factor adaptively adjusted in terms of regional characteristics, so it sufficiently suppresses speckle in homogeneous regions and effectively preserve edges and fine details, leading to the biggest ENL and the smallest DCV. Similar results are concluded from another SAR image experiment shown in Fig. 3. In a word, due to the combined use of adaptive windowing and adaptive tuning factor, the proposed double-adaptive Frost filter can lead to the best balance between speckle suppression and edge preservation.

(a) SAR image

(b) Lee filter

(c) Gamma MAP filter

(d) Frost filter

(e) Frost filter with adaptive tuning factor

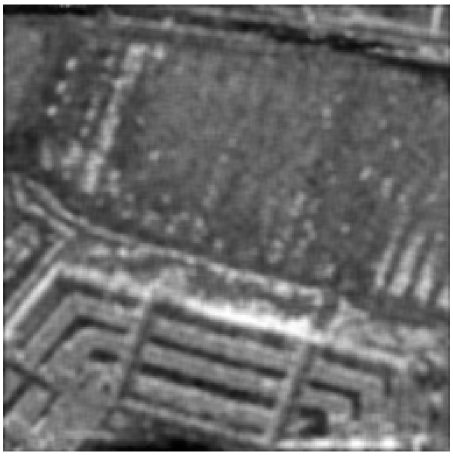
(f) the proposed double-adaptive Frost filter

Fig. 2. Despeckling results of SAR image (3 by 3 minimum window and 11 by 11 maximum window were used for the proposed double-adaptive Frost filter, and the fixed 5 by 5 window was used for other filters)

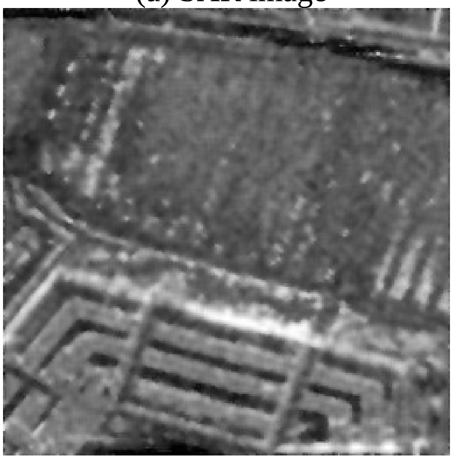
Table 1. Quantitative measures evaluating the performance of various filters in Fig. 2.

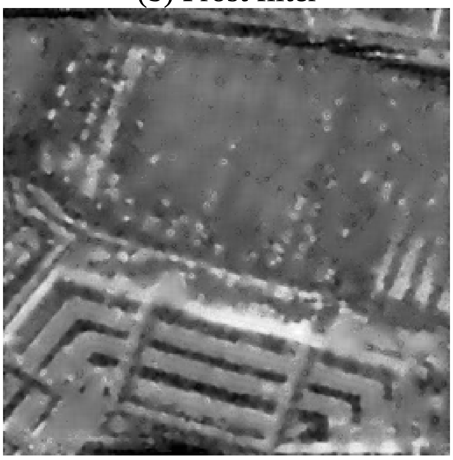
| | ENL | DCV |
|---|---|---|
| Lee filter | 64.7782 | 0.0360 |
| Gamma MAP filter | 69.2958 | 0.0378 |
| Frost filter | 69.7871 | 0.0311 |
| Frost filter with adaptive tuning factor | 70.4677 | 0.0279 |
| The proposed double-adaptive Frost filter | 113.0439 | 0.0198 |

(a) SAR image



(b) Frost filter





(c) Frost filter with adaptive tuning factor (d) the proposed double-adaptive Frost filter

Fig. 3. Despeckling results of another SAR image (3 by 3 minimum window and 11 by 11 maximum window were used for the proposed double-adaptive Frost filter, and 5 by 5 window was used for other filters)

## Summary

In order to improve the traditional Frost filter and the modified Frost filter with adaptive tuning factor, the double-adaptive Frost filter is proposed in this paper. The tuning factor and the size of window are both adaptively adjusted according to regional characteristics. In homogeneous regions, a large window is obtained to smooth speckle well. In heterogeneous regions, a small window is gained to preserve edges and fine details effectively. For an appropriate window that the adaptive windowing yields, its heterogeneity is detected and the box filter is directly used to sufficiently suppress speckle for homogeneous regions. The proposed double-adaptive Frost filter is tested on various SAR images, and it is compared with other filters such as the Lee filter, the Gamma MAP filter, the traditional Frost filter, and the modified Frost filter only using adaptive tuning factor. Despeckling experiments demonstrate that, due to the use of adaptive windowing and the adaptive tuning factor, the proposed double-adaptive Frost filter can sufficiently suppress speckle in homogeneous regions and well preserve edges and fine details, leading to the best performance for SAR image interpretation.

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