Filtering strong noisy synthetic aperture radar (SAR) interferogram with integrated Contoured Median and Goldstein two-step filter

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Abstract: At present, most of the traditional filters such as Goldstein, Lee, Median, Mean, and Periodic filter, can not meet the demand of noise suppression for interferograms contaminated by phase noise. Repeat filtering, however, will result in serious loss of fringe pattern. In this paper, a two-step filter is presented. The filter inherits the good edge preservation characteristics of the Contoured window filter and the strong smoothing capability of the Goldstein filter. In addition, it introduces the pseudo-coherence of interferogram to improve the adaptiveness of the Goldstein filter. Experimental results with both simulated and real data show that the proposed filter performs quite well both in noise reduction and in detail preservation. Moreover, it can partially recover continuous interferometric fringes from area without signals, and is applicable for interferograms with very dense and heavily curved fringes.

Key words: InSAR, strong noisy, Contoured median Filter, Goldstein Filter, noise reduction, fringe preservation

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1 INTRODUCTION

As an advanced technique for spatial information acquisition, Interferometric synthetic aperture radar (InSAR) has been widely applied to vast area topographic mapping and high precision surface deformation monitoring. However, the accuracy and reliability of the topographic and deformation measurements are highly dependent on the quality of interferograms (Li, et al., 2004; Yin, et al., 2009). Due to the factors such as temporal and geometrical decorrelation, thermal noise, Doppler centroid decorrelation, and atmospheric water vapor, the phases in SAR interferogram are always very noisy (Zebker & Villasenor, 1992; Li, et al., 2004; Yin, et al., 2009). The noise will introduce error into InSAR-derived DEM and/or deformation products, and furthermore, cause phase residues and hinder the process of phase unwrapping. For this reason, interferogram filtering is a necessary step before application.

Currently the filtering algorithms can be divided into two types, the frequency domain and the spatial domain filter. For the frequency domain filter, the representative methods are Goldstein filter and its modified ones (Goldstein & Werner, 1998; Baran, et al., 2003; Li, et al., 2008). The Goldstein filter is widely used because of its strong smoothing capability and fast operation. Nowadays many international commercial or share softwares for SAR data processing, such as Gamma and Doris, use this algorithm. For the spatial domain filter, the representative method is Lee filter (Lee, et al., 1998), which utilizes information from fringe orientation. Lee filter can generally achieve satisfying results, however, it requires local phase unwrapping which degrades its efficiency. As a result, its application is limited. The Contoured window filter proposed by Yu, et al. (2007) can suppress most of noises and preserve the fringes pattern when an accurate and large contoured window are used.

In practical application, the interferometric phase information is regarded as unreliable when the corresponding coherence falls in a range of 0.25—0.30, and needs to be masked before unwrapping. For the coherence between 0.30 and 0.45, the phase is useful while affected by strong noise (so-called interferogram with strong noise). Previous research indicates that for interferogram with strong noise, significant phase noise can remain after applying the Goldstein filter (Wu, et al., 2006; Meng, et al., 2006). Other algorithms, such as Lee, Contoured window, median, mean, periodic filter (Eichel & Ghiglia, 1993), also fail to meet the demand of noise reduction and fringes edge preservation. At the moment, software for SAR data processing usually suggests repeat filtering of interferogram with strong noise. However, repeat filtering that aims at noise reduction
will cause serious damages to the fringe pattern. The Median adaptive two-step filter proposed by Liao, et al. (2003) can realize noise reduction and fringe edge preservation well, but is not suitable for interferograms with dense and heavily curved fringes. In this paper, the integrated Contoured median and Goldstein two-step filter (referred as new filter below) is proposed for filtering noisy interferogram. The new filter performs much better on noise reduction and fringe edge preservation. Moreover, it is suitable for interferograms with dense and heavily curved fringes.

2 INTEGRATED CONTOURED MEDIAN and GOLDSTEIN TWO-STEP FILTER

2.1 Principle of the integrated Contoured median and Goldstein two-step filter

The distribution of interferometric fringes is direction-dependent. In the tangential direction of fringes, the fringe frequencies are low and mainly concentrated near zero, while the noise frequencies are usually much higher. Therefore, the high-frequency noise can be easily filtered off by a low pass filter with the fringe signal is unchanged (Yu & Fu, 2007). Contoured window filter firstly extracts fringe orientations from interferogram, then determines the contoured window by tracing local fringe orientation, and finally carries out low-pass filter in the contoured window. A large amount of experiments demonstrate that this algorithm can suppress most of the noises in electronics speckle interferograms and SAR interferograms. However, for the SAR interferogram with strong noise, the determination of fringe orientation is seriously affected by noise. In this case, the accuracy of fringe orientation map is low and we can only acquire small approximate contoured window. This kind of window can preserve fringe edge well but has limited capability for noise reduction. Therefore, further smoothing is necessary for an interferogram after applying the Contoured window filtering.

Goldstein filter suppresses noises in SAR interferograms by smoothing the intensity of Fourier transformed samples $Z(u, v)$ of the overlapped small interferogram patches (Goldstein and Werner, 1998). This algorithm is sensitive to the phase noise and gradients, and works well on maintaining image features (Cai, et al., 2009). The filtering algorithm is defined as follows:

$$Z'(u, v) = S\{Z(u, v)\}^\alpha \cdot Z(u, v)$$  \hspace{1cm} (1)

where $S\{ \}$ is a smoothing operator; $Z(u, v)$ is smoothed Fourier samples; $\alpha$ is the filter parameter, ranges between zero and one. The filtering strength grows as $\alpha$ increases. When $\alpha$ is zero, no filtering is imposed. In contrast, the strongest filtering is applied when $\alpha$ is one.

The Contoured window filter can remove a considerable part of noises in a SAR interferogram, so a post slight smoothing is sufficient to suppress the remained noise. However, due to the uneven distribution of noises, taking $\alpha$ as a single constant will lead to over-filtering in patches with weak noises and under-filtering in patches with strong ones. Hence an adaptive smoothing is needed. The coherence of two registered single-look complex (SLC) images varies inversely with the intensity of noise while the multilook number is invariable, the higher the coherence, the lower the noise level (Franceschetti, et al., 1999). Thus the coherence is a measure of noise. Baran, et al. (2003) assign the Goldstein filter parameter $\alpha$ to $1-\frac{\alpha}{\bar{\gamma}}$, where $\bar{\gamma}$ is the mean coherence value over the effective patch. The modification relates the strength of filtering to the coherence and therefore makes the filter more realistic and flexible for operational applications (Li, et al., 2008). However, the coherence is calculated from two registered SLC images that can not be acquired by the Contoured window filter.

The definition of the pseudo-coherence was first proposed by Ghiglia and Pritt (1998) when assessing the result of phase unwrapping. Its formula is shown as follows:

$$pc = \frac{\sqrt{(\sum \cos\phi(i, j))^2 + (\sum \sin\phi(i, j))^2}}{N}$$  \hspace{1cm} (2)

where $N$ is the number of pixels within the moving window, and $\phi(i, j)$ is the interferometric phase. Pseudo-coherence is calculated from interferogram itself, and most importantly, its value can vary inversely with the intensity of noise and is limited to one. Due to little difference between the coherence and the pseudo-coherence, we use the pseudo-coherence to represent the noise intensity of the interferogram filtered by the Contoured window filter. Like Baran’s way, we modify the Goldstein filter parameter $\alpha$ to $1-\frac{pc}{\bar{pc}}$, where $\bar{pc}$ is the mean pseudo-coherence value over the effective path:

$$Z'(u, v) = S\{Z(u, v)\}^\alpha \cdot Z(u, v)$$  \hspace{1cm} (3)

Fig. 1(a) shows the coherence map of patch A, and Fig. 1(b) shows the corresponding pseudo-coherence map. Fig. 1(c) displays the differences between the interferograms filtered by Baran’s filter and our modified Goldstein filter, with a mean of 0.079 radians. It is clear that the difference is small. In this perspective, the scheme of employing pseudo-coherence in place of coherence is feasible.

![Fig. 1](image-url)
2.2 Procedure of the integrated Contoured median and Goldstein two-step filter

The integrated Contoured median and Goldstein two-step filter can be implemented with the following procedures:

1. Computation of fringe orientation map. The technique of square difference accumulation as proposed by Yang, et al. (2007) will be adopted to calculate the fringe orientation in this paper. Fig. 2 shows a simulated interferogram and the corresponding fringe orientation map calculated.

2. Determination of contoured windows. Tracing along the fringe orientation, we acquire the equal-phase lines. The contoured windows can be acquired by widening the equal-phase lines in both sides (Yu & Fu, 2007), which is shown in Fig. 3(a). The size of the window is 7 pixels in radial direction and 3 pixels in normal direction indicates that tracing three points along the fringe orientation and its opposite direction separately, and then widening 1 pixel in both sides.

3. Performing Median filtering in the contoured window.

4. Computation of the pseudo-coherence map of the interferogram filtered with the Contoured median filter, and conducting our modified Goldstein filtering.

![Image](a) Simulated interferometric phase map; (b) Fringe orientation map (unit: rad)

![Image](a) Tracing process; (b) Contoured window (Yu & Fu, 2007)

3 EXPERIMENTS AND DISCUSSION

3.1 Validation with the simulated data

Firstly, the universal multifractal technique (Peckond, et al., 1993) is adopted to simulate the DEM. Secondly, based on the simulated DEM, ERS1/2 imaging parameters and given perpendicular baselines (chosen randomly between 50 and 200 m), we simulate phase map and wrap it (Li, et al., 2008), which is referred as “true” phase for convenience. Thirdly, the coherence map is simulated by synthesizing the factors of thermal decorrelation (based on ERS-1/2 sensor parameters), geometrical decorrelation (Lee, et al., 1999), and temporal decorrelation (Baran, et al., 2003). The thermal decorrelation is calculated based on the system SNR of ERS-1/2, i.e., 11.7 db, and the geometrical decorrelation is calculated with imaging geometrical parameter. The slope map is derived from the simulated DEM, and the temporal decorrelation is simulated with the fractal technique. At last, we simulate the phase noise based on the relationship among phase noise, multilook number and coherence (Franceschettiig, et al., 1999):

\[
\sigma_L^2(\gamma;L) = \int (\phi - \phi_L)^2 PDF(\phi; \gamma; L; \phi_L) d\phi
\]

where \(\sigma_L^2\) is phase variance; \(\gamma\) is interferometric coherence; \(L\) is multilook number; \(\phi\) is interferometric phase and \(\phi_L\) is the expectation of \(\phi\); \(PDF\) is the probability density function of interferometric phase and can be calculated by

\[
PDF(\phi; \gamma; L; \phi_L) = \frac{(1 - \gamma^2)^{\beta/2}}{2\pi \Gamma(2L-1)} \left[ \frac{(2L-1)\beta}{(1 - \beta^2)^{1/2}} \right]^{\pi/2} \arcsin \beta \left[ \Gamma(L) \right]^{(2L-1)/2} \frac{1}{(1 - \beta^2)^2} \right]^{(1/2)}
\]

where \(\beta = \sqrt{\gamma \cos(\phi - \phi_L)}\), \(\Gamma\) is the Gamma function.

Based on the above formula, this paper simulates the phase noise map for \(L=1\), and then calculate the simulated noisy interferometric phases by adding the simulated phase noise to the “true” phases. Fig. 4(a) shows the simulated noisy interferometric phase map.

In this section, to validate the performance of the new method, we filter the simulated noisy interferogram with the Lee, Goldstein, twice Goldstein, Median adaptive two-step and new filter, respectively. The results are shown in Fig. 5.

Fig. 5 shows that there are still noises remain in the interferogram filtered by the Goldstein filter, while that filtered by twice Goldstein filter is much lower. However, the distribution of residual noise is uneven (Fig. 5(d)). Several parts are over-filtered, such as the rectangles in the upper right and lower right corners, and several parts are under-filtered, such as the rectangles in the middle-lower left and middle-upper right corners. The results of Lee filter and Median adaptive two-step filter are similar to each other, with evident more noises and also more details than that of the twice Goldstein filtering. The new filter however can both filter off the noises like twice Goldstein filtering and preserve the fringe details like Lee filter and Median adaptive two-step. We can hardly find any noises in the result of the new filter.

For a quantitative evaluation of these filters, we adopt the following assessment criteria (Yin, et al., 2009):

1. Phase Residue Number (PRN). Residue represents phase inconsistency or jump, and less residues means less noises. The number of residues has crucial impact on phase unwrapping and therefore makes itself a key criteria for assessing the quality of an interferogram (Liao & Lin, 2003).

2. Phase Standard Deviation (PSD). PSD represents the degree of phase smoothness, and smaller PSD means smoother phase and fewer noises. The formula for calculation of PSD is defined as (Goldstein & Werne, 1998):

\[
PSD = \sqrt{\frac{\sum (\phi(i,j) - \overline{\phi}(i,j))^2}{N-1}}
\]
where $\widehat{\phi}(i, j)$ is the linear phase ramp in moving window.

(3) Mean Square Error (MSE). MSE represents the closeness between the filtered and the “true” phase, and smaller MSE means better fidelity. The formula for calculation of MSE is as follows:

$$EPI = \frac{\sum |\phi_i(i, j) - \phi_j(i, j + 1)| + |\phi_i(i, j + 1) - \phi_j(i, j)|}{N + 1}$$

Table 1 lists the evaluation results of the filtered interferograms. It shows that, for the new filter, the improvement ratio in terms of PSD, EPI, PRN and MSE reached 92.15%, 99.13%, 99.91% and 77.13%, respectively. Comparing with Goldstein, Lee, Median adaptive two-step filter, the PSD and PRN of the new filter are the smallest, which means that the new filter’s capability of noise reduction is the highest. The EPI of the new filter is the closest to one and the MSE of the new filter is the smallest, both of which demonstrate that the new filter’s capability of phase preservation is also the best. For a further comparison, we extract the cross sections of line 360 as marked on Fig. 5(f) from each interferogram and the results are shown in Fig. 4. Visible noises and glitches are found in the results of Goldstein and Lee filter, but fewer noise and glitches in the results of Median adaptive two-step filter. The phases filtered by the new filter are almost the same as “true” ones, which testifies the superiority of the new filter again.

3.2 Validation with real data

In this section, two descending images (Frame: 2583, Track: 222) acquired by ERS-2 on 6 September and 11 October 2000 over volcano Enta in Italy are used. The perpendicular baseline is 305 m. The image pair is interferometrically processed with 5 looks in azimuth direction and 1 look in range direction, and the final resolution is 25 m×25 m. Fig. 6 shows the generated interferogram.

Two patches, marked as A (300×300 pixels) and B (300×300 pixels) in Fig. 6(a), are chosen for further analysis. Mean coherences of patch A and B are 0.333 and 0.237, respectively, and the fringes within them are very dense. The Lee, Goldstein, Twice Goldstein, Median adaptive two-step and the new filter are applied to reduce the noise in the interferogram patches, respectively. The results are shown in Fig. 7(b-f) and Fig. 8(b-f). Table 2 lists the statistics of the evaluation. Because the “true” phases, i.e., the noise-free phases, are unknown, only two criteria (PRN and PSD) are applicable here.

The results illustrate that, in some parts containing dense fringes, like the left part of patch A, the Lee and Median adaptive two-step filter do not work well in fringes continuity preservation. Although the Goldstein filter does not have such kind of problem, visible and uneven noises are easily found in their results. The fringes in the interferogram filtered with the new filter are, however, smooth and continuous, and full of details. Moreover, in some
places where almost no signals can be found, like the upper right corner in patch A, some continuous fringes are recovered after filtering with the new filter. From Table 2, we can see the two criteria for the new filter are the best. After applying the new filter, patch A has improved by 73.8% and 98.2% respectively, in terms of The PSD and RPN, while that for patch B are 85.5% and 98.2%, respectively. This demonstrates the strong capability of noise reduction of the new filter. For the real interferograms, we may conclude that the new filter is much more powerful than Lee filter and Median-adaptive two-step filter.

![Fig. 5 Simulated Interferogram and their filtered version with five filters](image)
(a) Simulated interferogram; (b) Results of Lee filter; (c) Results of Goldstein filter; (d) Results of twice Goldstein filtering; (e) Results of Median adaptive two-step filter; (f) Results of new filter

![Fig. 6 Two patches marked as A and B are selected for further analysis](image)
(a) Interferogram over Enta; (b) Coherence map
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Fig. 7 Real interferogram and their filtered version with 5 filters (patch A)
(a) Original interferogram; (b) Results of Lee filter; (c) Results of Goldstein filter; (d) Results of twice Goldstein filtering; (e) Results of Median adaptive two-step filter; (f) Results of new filter

Fig. 8 Real interferogram and their filtered version with 5 filters (patch B)
(a) Original interferogram; (b) Results of Lee filter; (c) Results of Goldstein filter; (d) Results of twice Goldstein filtering; (e) Results of Median adaptive two-step filter; (f) Results of new filter

Table 2 Evaluation results of different filters (real interferogram)

<table>
<thead>
<tr>
<th>patch</th>
<th>filter</th>
<th>Magnitude</th>
<th>PSD</th>
<th>Improvement</th>
<th>Magnitude</th>
<th>RPN</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Original phase</td>
<td>0.8549</td>
<td>14370</td>
<td>—</td>
<td>14370</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Lee filter</td>
<td>0.4136</td>
<td>2670</td>
<td>51.6%</td>
<td>2670</td>
<td>81.4%</td>
<td>—</td>
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<tr>
<td></td>
<td>Goldstein filter</td>
<td>0.6058</td>
<td>8310</td>
<td>29.1%</td>
<td>8310</td>
<td>42.2%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Twice Goldstein filtering</td>
<td>0.3674</td>
<td>4271</td>
<td>57.0%</td>
<td>4271</td>
<td>70.3%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Median-adaptive two-step filter</td>
<td>0.3106</td>
<td>1403</td>
<td>63.7%</td>
<td>1403</td>
<td>90.2%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>New filter</td>
<td>0.2243</td>
<td>1275</td>
<td>73.8%</td>
<td>1275</td>
<td>91.1%</td>
<td>—</td>
</tr>
</tbody>
</table>

to be continued
Repeat filtering however will over-filter some parts in an interferogram. The complex spatial adaptive filter proposed by Liao, et al. (2003) proceeds an interferogram iteratively based on the phase gradient. As strong noises will disturb the extraction of phase gradient, a Median filtering is applied in advance to suppress the noises preliminarily in their method. However, the ordinary Median filter is not fit to interferogram with dense fringes. That is why the fringe continuity is poor in the interferogram filtered with Median adaptive two-steps filter.

Goldstein filter shows strong smoothing capability and fine fringe continuity preservation characteristics for interferogram with dense fringes, while Contoured window filter has good edge preservation characteristics but limited noise reduction capability. Considering of this, we propose the integrated Contoured median and Goldstein two-step filter, in which the pseudo-coherence is used as the adaptive parameter for Goldstein filter. The first step of the new filter is to extract fringe orientations through the technique of square difference accumulation and to determine the contoured window by tracing local fringe orientation. Then, it carries out low-pass filter in the contoured window. Due to the strong edge preservation capability of Median filter, this step can keep the fringes well while at the same time remove noises partly, and even capture some signals in area with low coherence. The second step of the new filter is to smooth the pre-filtered interferogram with the pseudo-coherence modified Goldstein filter. It can quickly and adaptively remove the remaining noises. Due to the full use of the good edge preservation characteristics of Contoured window filter and the strong smoothing capability of Goldstein filter. The introduction of pseudo-coherence as adaptive parameter, the new method can greatly and evenly suppress the noises while at the same time maintain the fringe details well.

However, for the areas with very strong decorrelation, despite of the advantages of the new filter, the noise will still dominant in phase map. But by masking these areas, the Branch-cut phase unwrapping can be carried out successfully. Moreover, the pseudo-coherence is different from coherence. In some areas where phases vary significantly due to cliff or large deformation, the pseudo-coherence is very low but the noise level not necessarily very low (Zhao, 2009), which could be a limitation of the new method. The future research will focus on how to acquire more accurate fringe orientation and contoured window.

### 4 CONCLUSIONS

At present, most of the traditional filter such as Goldstein, Lee, median, mean, and periodic filter, can not meet the demand of noise suppression for interferograms contaminated by serious noise. A modification to the Goldstein radar interferogram filter. *IEEE Transaction on Geoscience and Remote Sensing*, 41(9): 2114–2118


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强噪声SAR干涉图的等值线中值–Goldstein二级滤波

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摘 要: 结合等值线滤波条纹边缘保持能力强和Goldstein滤波平滑效果好的特点, 并且引入伪相干值对Goldstein滤波因子进行改进, 提出InSAR干涉图的等值线中值–Goldstein二级滤波方法。模拟数据和真实数据的实验结果证明, 强噪声干涉图经过新方法滤波后相干水平大大降低而分布均匀, 条纹细节信息保持良好, 在原本看不到信号的区域也可以恢复部分条纹, 并适用于条纹密集和曲率变化大的干涉图。

关键词: InSAR, 干涉图, 等值线中值滤波, Goldstein滤波, 去噪, 条纹保持

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1 引 言

合成孔径雷达干涉测量技术InSAR(Synthetic Aperture Radar Interferometry)作为一种先进的空间信息获取手段, 被广泛地应用于大面积的地形测绘和高精度的形变监测中。然而干涉数据的时间与空间去相相关、大气误差以及系统本身的热噪声等引起的去相关噪声严重影响了干涉图的质量(Zebker和Villasenor, 1992; Li等, 2004; 尹宏杰等, 2009), 阻碍了相位解缠的进行, 因此必须对干涉图进行去噪。

目前干涉图去噪的方法可以分为频率域和空间域两类。频率域有代表性的是Goldstein滤波(Goldstein和Werner, 1998)及其改进的方法(Baran等, 2003; Li等, 2008)。Goldstein滤波目前应用最广, 其平滑效果好, 运行速度快, 许多国际商业或免费SAR数据处理软件(如Gamma和Doris等)都采用该方法。空间域有代表性的是Lee滤波(Lee等, 1998), 该方法利用了条纹方向的信息, 能取得较好的结果, 但要引入局部相位解缠, 比较耗时, 所以实用性不强。于起峰等人(2007)提出的等值线滤波在等值线窗口足够大而准确的情况下, 理论上能很好地去噪并且不破坏条纹。

在实际应用中, 相干值低于0.25—0.30的干涉图区域, 干涉相位一般被认为不可靠, 在解缠时须把它们掩膜掉。对于相干值在0.30—0.45间的干涉图区域, 其相位可以利用, 但噪声一般很强, 可称为强噪声干涉图, 研究表明在应用Goldstein方法对其进行滤波后还会残留相当一部分噪声(Wu等, 2006; Meng等, 2007); 其他方法, 如Lee滤波、等值线滤波、中值滤波、均值滤波和圆周期滤波(Eichel和...
干涉条纹边的要求。通常SAR数据处理软件建议对强噪声干涉图重复滤波。为了达到去噪效果而简单地重复滤波势必会过度平滑部分区域，使干涉图失真。廖明生等(2003b)提出的中值滤波–Goldstein二级去噪方案，能较好地去除强噪声和保持边缘，但不适用于条纹密集和曲率变化大的干涉图。本文针对强噪声干涉图提出了等值线中值–Goldstein二级滤波方法，可以更好地去噪和保持条纹，并能应用于条纹密集和曲率变化大的干涉图。

2 等值线中值–Goldstein二级滤波

等值线中值–Goldstein二级滤波原理

干涉条纹图的分布具有明显的方向性。对于InSAR干涉条纹图，在条纹的切线方向，干涉图本身有用信息和随机噪声对应的频谱是分开的，使用普通的低通滤波就能把噪声滤掉而且不损害条纹的有用信息(于起峰和伏思华，2007)。等值线滤波先根据图像分布差异求取条纹方向，再严格按条纹方向跟踪得到等值线窗口，最后在等值线窗口内做低通滤波。大量实验证明该滤波方法对散斑干涉图和InSAR干涉图的噪声有很强的抑制能力。但是目前对于强噪声干涉图，条纹方向的获取会受噪声的影响，等值线窗口获取方法也有待改进，通过精度有限的条纹方向图只能跟踪得到较小的近似等值线窗口。这种近似等值线滤波窗口虽然能较好地保持条纹信息，但去噪能力有限。因此有必要对等值线滤波结果做恰当的平滑处理。

Goldstein滤波主要通过对图像频谱作平滑处理而达到去噪目的，该方法对相位噪声和相位梯度很敏感，能较好地保护影像特征信息(蔡国林等，2009)。滤波算法如式(1):

$$Z'(u, v) = S \frac{1}{\alpha} Z(u, v)$$  (1)

式中，$Z(u, v)$是对图像进行傅里叶变换得到的频谱值；$S$是平滑系数；$Z'(u, v)$是平滑处理后的频谱值；$\alpha$是一个常数，在0到1之间取值，滤波的强度随$\alpha$增大而增大，$\alpha$为0时不滤波。

等值线滤波结果噪声强度较低，对其频谱作上述平滑处理可以去除大部分噪声。但设置单一的常数$\alpha$会导致干涉图弱噪声区域过度滤波，而强噪声区域欠滤波。因此，应该依据局部的相位噪声强度作自适应滤波。当干涉图视数一定时，其相干性越高，相位方差越小，反之越大(Franceschetti等，1999)。因此相干性可以直接表征相位噪声强度(Baran等，2003)。对Baran在2003年提出用1–$\gamma$取代式(1)中的$\alpha$，$\gamma$为有效窗口内相干性平均值。这种改进后的算法能实现自适应滤波结果，获得比Goldstein滤波更好的结果。但相干性是针对复数干涉对统计得到的，我们无法获取等值线滤波结果的相干性。

伪相干图(Pseudo-coherence)首先是Ghiglia和Pritt(1998)在评定相位解缠结果时提出来的，计算方法如下：

$$pc = \frac{1}{N} \sqrt{\sum_{i,j} \cos^{2} \phi(i, j) + \sum_{i,j} \sin^{2} \phi(i, j)}$$  (2)

式中，$N$是计算窗口内像素个数，$\phi(i, j)$是干涉图相位值。伪相干图由于干涉图本身统计得到，随着相位噪声强度减小而增加，最大不超过1。通常情况下，复数干涉图的相干值和对应干涉图的伪相干值差别很小。因此本文用伪相干性来表征等值线滤波结果的噪声强度。参考Baran的方法，我们用1–$pc$代替式(1)的$\alpha$，$\bar{pc}$为有效窗口内伪相干性平均值，得改进的Goldstein滤波算法:

![图1 相干图与伪相干图对比](a) Etna火山区截取的子干涉图的相干图；(b) Etna火山区截取的子干涉图的伪相干图；(c) 用伪相干值和相干值分别作Goldstein滤波自适应因子得到的结果差分图(单位：rad)
\[ Z'(u,v) = S \left\{ \frac{Z(u,v)}{\sqrt{D(u,v)}} \right\} \times Z(u,v) \]  

（3）

图1(a)显示了从意大利Etna火山区截取的干涉图(图5中的子干涉区域A)的相干值，图1(b)为期对应的伪相干值。分别用Baran改进的和本文改进的算法对该干涉图滤波，两种算法结果的均方误差仅为0.079 rad。将二者结果作差并列于图1(c)，可以看出差别甚微，说明用伪相干值和相干值分别作为Goldstein滤波算法中的自适应因子所得到结果很接近，用本文改进的Goldstein滤波算法可以实现对等值线滤波结果的作自适应平滑是可行的。

2.2 等值线中值–Goldstein二级滤波实现步骤

等值线中值–Goldstein二级滤波步骤可以概括如下：

(1) 求取条纹方向图。本文采用的是平方差累积法(杨夏等, 2007)，图2是一幅模拟的干涉条纹图及其条纹方向图。

(2) 求取等值线窗口。利用对应条纹方向图，以当前点为中心用方向跟踪法(于起峰和伏思华, 2007)得到等值线窗口，跟踪过程如图3(a)所示。本文采用7×3的等值线窗口，即向前后各跟踪3个点后再向两边各扩展1个点后得到的窗口。

(3) 在等值线窗口内做中值滤波。

(4) 求取等值线中值滤波结果的伪相干图，作本文改进后的Goldstein滤波。

3 实验结果与分析

3.1 模拟数据实验

本文先采用多分形技术(Pecknold等, 1993)模拟出DEM，再由模拟的DEM基于ERS1/2的成像几何参数和给定垂直基线长度(在50 m到200 m之间随机抽取)模拟出缠绕的相位(Li等, 2008)。图5显示了Etna火山区域的干涉图及部分干涉图的伪相干值。将它们做差并列于图5(c)，可以看出差别甚微，说明用伪相干值和相干值分别作Goldstein滤波算法中的自适应因子所得到结果很接近，用本文改进的Goldstein滤波算法可以实现对等值线滤波结果的作自适应平滑是可行的。

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(4) 求取等值线中值滤波结果的伪相干图，作本文改进后的Goldstein滤波。

![图2 模拟条纹图及条纹方向图](image)

(a)模拟干涉相位条纹图；(b)条纹方向图

![图3 等值线窗口过程示意图](image)

(a)等值线跟踪过程；(b)等值线窗口示意图
为了定量评价滤波效果，本文采用以下几种评价指标：

(1) 相位奇异点数(廖明生和林珲，2003a)。反映相位的跳变程度，值越小表示噪声越少。干涉图滤波效果直接影响到相位解缠的进行，而相位解缠的准确性和相位奇异点数息息相关，所以相位奇异点数是衡量滤波效果的重要指标。

(2) 相位标准偏差(Goldstein和Werner，1998)。反映相位平滑程度，值越小表示相位越平滑，噪声越少。计算公式如下：

\[ \text{PSD} = \sqrt{\frac{\sum (\phi(i,j) - \bar{\phi}(i,j))^2}{N-1}} \]  

(3) 均方误差。反映滤波后的相位和“真实”相位接近程度，计算公式如下：

\[ \text{RMS} = \sqrt{\frac{\sum (\phi(i,j) - \phi_0(i,j))^2}{N-1}} \]  

式中，\( \phi(i,j) \)和\( \phi_0(i,j) \)分别表示滤波后的和“真实”的相位值。在相位跳变点采取加减2π的方法来消除因相位跳变产生的计算误差，在下面边缘保持指数的计算中采取同样的做法。

(4) 边缘保持指数(韩春明等，2003)。反映滤波后的相位和“真实”相位的边缘和梯度信息的相似度，其值越接近于1表示滤波方法条纹边缘和梯度信息保持能力越强。计算公式如下：

\[ \text{EPI} = \frac{\sum [(\phi(i,j) - \phi(i+1,j) + \phi(i,j) - \phi(i,j+1)]}{\sum [(\phi_0(i,j) - \phi_0(i+1,j) + \phi(i,j) - \phi_0(i,j+1))]} \]  

统计图5中各干涉图的评价指标值，并列于表1。从表中可以看出，新滤波方法的相位标准偏差、边缘保持指数、奇异点数和均方误差的改善率分别达到了92.15%、99.03%、99.91%和77.13%。跟Goldstein滤波、Lee滤波、中值滤波-自适应二级去噪方案结果相比，新滤波的方法标准偏差和奇异点数均最小，说明该滤波方法的去噪能力最强；另外新滤波的边缘保持指数最接近于1，均方误差也最小，说明新滤波结果最接近于原始干涉图，该滤波方法的条纹保持能力最强。为了更直观的对比各种滤波方法的条纹保持能力，抽取图5各干涉图的其中一行(图5(g)直线标注位置)作剖面图(图4)。

<table>
<thead>
<tr>
<th>滤波方法</th>
<th>相位标准偏差</th>
<th>边缘保持指数</th>
<th>奇异点数</th>
<th>均方误差</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>占比</td>
<td>改善率</td>
<td>大小</td>
<td>改善率</td>
</tr>
<tr>
<td>不含噪声的干涉图</td>
<td>0.0534</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>加噪后的干涉图</td>
<td>1.0386</td>
<td>—</td>
<td>11.4049</td>
<td>—</td>
</tr>
<tr>
<td>Lee滤波</td>
<td>0.3325</td>
<td>67.99%</td>
<td>3.4271</td>
<td>76.67%</td>
</tr>
<tr>
<td>一次Goldstein滤波</td>
<td>0.7254</td>
<td>30.14%</td>
<td>8.8623</td>
<td>24.44%</td>
</tr>
<tr>
<td>两次Goldstein滤波</td>
<td>0.2515</td>
<td>75.79%</td>
<td>2.9653</td>
<td>81.11%</td>
</tr>
<tr>
<td>中值滤波-自适应二级去噪方案</td>
<td>0.1601</td>
<td>84.59%</td>
<td>1.7321</td>
<td>92.96%</td>
</tr>
<tr>
<td>新滤波</td>
<td>0.0815</td>
<td>92.15%</td>
<td>1.1010</td>
<td>99.03%</td>
</tr>
</tbody>
</table>
通过剖面图发现Lee滤波和Goldstein滤波结果有较多噪声和毛刺，中值滤波–自适应二级去噪方案滤波噪声稀少，基本没有毛刺而且边缘保持较好。而新滤波结果相位剖面几乎和“真实”相位一样，进一步说明了新滤波性能优越。

3.2 真实数据实验

真实数据实验采用意大利Enta火山地区的干涉对。选取欧空局ERS-2卫星于2000年9月6日和10月11日获取的该地区两幅降轨图像(Frame:2583, Track:222)用来生成干涉图，干涉对垂直基线为305 m，方位向经过5个像素的多视处理，分辨率大约是25 m × 25 m。图6(a)是原始的干涉图。

选图6a中所标的两块区域A(330 × 330像元)和B(300 × 300像元)进行分析。A区和B区的噪声均较强，平均相干值分别只有0.333和0.237，而且条纹密集。用Lee滤波、一次Goldstein滤波、两次Goldstein滤波、中值滤波–自适应二级去噪方案和新滤波分别
对干涉图A和B进行滤波。图7(b)一(f)和图8(b)一(f)是A和B区滤波后的结果，表2则列出了统计结果。由于无法获取没受噪声污染的干涉相位，这里只给出了残差点数和相位标准偏差两个评价指标的结果。

结果图显示Lee滤波和中值滤波-自适应二级去噪方案对于条纹较密区域，例如A区干涉图左边部分，不能保持条纹连续性。Goldstein滤波虽然没有破坏条纹连续性，但滤波后还遗留相当一部分噪声而且分布极不均匀。新滤波结果图不仅条纹平滑连续，而且细节丰富，甚至在一些基本看不到信号的区域，例如A区的左上角，滤波后可以恢复部分连续的条纹。从表2可以看出新滤波结果的两项指标均为最优，A区相位偏差降低率和奇异点减少率分别为73.8%和91.1%，而B区则分别达85.5%和98.2%，说明其去噪效果最好。对于真实的强噪声InSAR干涉图，综合干涉相位图和定量指标来看，相比Lee滤波、Goldstein滤波和中值滤波-自适应二级去噪方案，新滤波能更好地去噪和保持条纹信息，具有明显的优越性。
4 结 论

对于强噪声干涉图，经典方法滤波往往无法满足去噪要求，重复滤波又会导致部分区域过度平滑。廖明生等人提出的复数空间自适应滤波主要是利用相位梯度信息进行平滑迭代，而强噪声对梯度信息提取影响很大，通过预先进行小窗口中值滤波可以达到减弱噪声的目的，但简单的低通滤波在条纹密集时容易破坏条纹特征，所以中值滤波-自适应二级去噪方案在本文真实数据实验中不能很好保持条纹连续性，这不利于相位解缠的进行。

本文结合等值线中值滤波条纹边缘保持能力强但去噪能力有限和Gooldstein滤波平滑能力强且在条纹密集和曲线变化大时能保持条纹连续性的特点，提出了等值线中值-Goldstein二级滤波方法。第一级滤波用平方差累积法求取条纹方向图并严格求取等值线窗口，再在等值线窗口内做中值滤波。由于中值滤波有很强的边缘保持能力，这一级滤波在去除部分噪声的同时能很好地保持和增强干涉图的条纹信息，在相位凌乱的低相干区域甚至能检获部分条纹特征；而第二级滤波依据伪相干图能快速、自适应地去除第一级滤波后余下的大部分噪声并使相位平滑。由于充分利用了等值线滤波条纹边缘保持能力强和Goldstein滤波平滑效果好的特点，并且引入了伪相干值对Goldstein滤波因子进行了改进，新滤波方案能大大降低噪声水平，且滤波后噪声分布均匀，条纹细节保持良好。

研究发现，如果相位图某些区域本身是失相干或者相干性很低，应用新滤波后仍然是随机噪声为主导成分，通过掩膜这些区域然后应用经典的枝切法可以得到很好的解缠效果。另外需要注意的是，伪相干值不同于相干值，它是基于干涉图本身进行局部统计得到的。在相位变化大的区域，如地形陡峭或形变梯度大的区域，尽管噪声很小，其伪相干值也可能低(赵超英，2009)，这是本方法的弊端所在。如何更精确地获取强噪声干涉图的条纹方向图和等值线窗口是下阶段要研究的问题。

志 谢 感谢欧空局提供的ERS-2图像(AO-4458, 4914)。

| 表2 真实干涉图的滤波结果评价 |
|--------------------------|-----------------|-----------------|
| 区域 | 滤波方法 | 相位标偏差 | 奇异点 |
|     |     |  | 大小 | 改善率 | 大小 | 改善率 |
| A | 未经滤波 | 0.8549 | — | 14370 | — |
|    | Lee滤波 | 0.4136 | 51.6% | 2670 | 81.4% |
|    | 一次Goldstein滤波 | 0.6058 | 29.1% | 8310 | 42.2% |
|    | 两次Goldstein滤波 | 0.3674 | 57.0% | 4271 | 70.3% |
|    | 中值滤波-自适应滤波二级方案 | 0.3106 | 63.7% | 1403 | 90.2% |
|    | 新滤波 | 0.2243 | 73.8% | 1275 | 91.1% |
| B | 未经滤波 | 0.9149 | — | 9321 | — |
|    | Lee滤波 | 0.3793 | 58.5% | 949 | 89.8% |
|    | 一次Goldstein滤波 | 0.6602 | 27.8% | 3912 | 58.0% |
|    | 两次Goldstein滤波 | 0.3113 | 66.0% | 933 | 90.0% |
|    | 中值滤波-自适应滤波二级方案 | 0.2809 | 69.3% | 511 | 94.5% |
|    | 新滤波 | 0.1328 | 85.5% | 164 | 98.2% |

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