NEW PARAMETRIC MODEL BASED METHOD FOR NOISE REDUCTION IN THE INTERFEROMETRIC PROCESS

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Abstract

In this study, a method called K-F for reducing the filtering effects on the interferometric phase signal is proposed. The method relies on the well-known parametric model for implementing noise reduction, while maintaining a low level of information loss. Relationships between the estimated interferometric information and noise reduction have been initially defined. Optimal threshold between noise reduction and interferometric signal loss is adjusted through a parameter. The proposed method was evaluated using real interferometric data. Coherence values are always increased after the application of the proposed method.

Introduction

Synthetic aperture radar interferometry (InSAR) is a remote sensing technique [1] that exploits the phase difference between two complex signals for extracting information. It is able to generate high-resolution Digital Elevation Models(DEM) [2] with precision of the range of some meters [3], deforestation[4], desertification[5], geophysical hazard analysis [6], glacier velocity measurements [7], land use classification[8], canopy height estimation [9] and atmospheric phase screen estimation[10],[11].

The main limitations of InSAR are temporal and geometrical de-correlations, caused by variations of the ground reflectivity as a function of time, and incidence angle variations during the data acquisition [12], respectively. In addition, interferograms are also affected by the spatial variability of the water vapour content in the atmosphere [10], [11], [12].

The quality of the required InSAR products can be improved by many methods at different processing steps of the interferometric procedure [13]. One of them is the filtering of the interferometric phase [14], [15], [16]. In [17], [18] and [19], three filters have been proposed which deal with phase unwrapping and noise reduction at the same time. However, the interferometric phase is a complex unit that is presented as a given point on the unit circle, thus it is more convenient to filter the wrapped interferogram for avoiding the filtering of phase jumps that are added after the unwrapping process. Depending on the characteristics of the interferometric pair, different filters have been proposed. For example, Boxcar filter yields better result for differential interferograms, which are generated from data pairs with low perpendicular and temporal baseline, while Adaptive filter yields more appropriate results in case of relatively large temporal baseline and small perpendicular baseline [20]. The adaptive Goldstein filter is one of the most commonly used filters for satisfactorily reducing the effects of phase noise [21], [22].

Based on [23], the filtering process may cause a loss resolution, which will affect the accuracy of the extracted information. Moreover, theoretical analysis of the filtering effects done in [16] showed that areas with high coherence do not need really to be filtered. In the same paper, filtering effects on the interferometric phase signal and phase noise have been proved and indicated. It was shown that while noise reduction is maximized after filtering, the loss of interferometric phase signal is also maximized. For these reasons, the global filtering of the interferogram should be avoided and instead, authors have proposed selective filtering (SF) only for the pixels that increase their coherence value after the filter application. However this approach improves filtering results for a very low percentage of pixels.

In this paper, a filtering approach is proposed that relies on the well-known parametric model for implementing noise reduction, while maintaining a low level of loss information. For this, relationships between estimation of the interferometric information and noise reduction have been initially defined. Based on these relationships an information recognition method for the existing filters was created without suggest the use of a specific filter, and a parameter has been defined to manage filtering.

B. Relationships between noise reduction and estimated interferometric phase signal

The quality of InSAR phase is defined by the absolute coherence [24]. As it was proved in [25], the amplitude is corrupted by multiplicative noise and the phase is corrupted by additive noise. Consequently, the noisy interferometric phase can be described as:

$$y(i,j) = x(i,j + v(i,j) \quad (1)$$

where x(i,j) is the interferometric phase signal, v(i,j) is the additional noise with the standard deviation σ_v. In [16], the optimal filter response for the interferometric phase signal, (H), and for the additional noise (G) were defined as:

$$H = \frac{E\{y(i,j)x(i,j)\}}{E\{y(i,j)y^T(i,j)\}} \quad (2)$$

and

$$G = \frac{E\{y(i,j)v(i,j)\}}{E\{y(i,j)y^T(i,j)\}} \quad (3)$$

From (2) and (3), the relation between two filters can be written as:

$$H = U - G \quad (4)$$

where U=[1] allows the observed interferometric phase y(i, j) to pass the filter unaltered. Without intervene to H, minimizing Jx(H) and Jv(U- H) are equivalent, where J(·), is the Mean Square Error (MSE). Alike, minimizing Jv(G) or Jx(U - G) with respect to G is the same thing. At the optimum case, the relationship between signal and noise errors is:

$$\begin{aligned} e_x(i,j) &= x(i,j) - H^T y(i,j) \\ &= x(i,j) - [U-G]^T[x(i,j)+v(i,j)] \\ &= -v(i,j) + G^T y(i,j) = -e_v(i,j) \end{aligned} \quad (5)$$

C. Mathematical background of the proposed method

Based on eq. (4) the optimal filtering can be considered as:

$$H_{op} = U - G_{op} = U - \kappa G_0 \quad (6)$$

where G_0 is the filter response for the noise estimation, Hop and G_{op} are the optimal filter response for signal and noise respectively, and κ is a parameter that determines the performance of the used filter. Equation (6) produces the desired results of optimal filtering given that κ is known. The MSE of the interferometric phase estimation corresponding to H_{op} is:

$$\begin{aligned} J_{x(i,j)}(H_{op}) &= E\{[x(i,j) - H_{op}^T y(i,j)]^2\} \\ &= \sigma_{v(i,j)}^2 - \\ &\frac{\kappa(2-\kappa)[E\{v(i,j)v^T(i,j)\}]^T E\{v(i,j)v^T(i,j)\}}{[E\{y(i,j)y^T(i,j)\}]} \end{aligned} \quad (7)$$

It is obvious that $J_{x(i,j)}(H_{op}) \le J_{x(i,j)}(H_0), \quad \forall\kappa$ The equality is arrived for κ = 1. In order to achieve the noise reduction, κ should be chosen in such a way that the following relationship:

$$J_{x(i,j)}(H_{op}) < J_{x(i,j)}(U) \quad (8)$$

should be fulfilled. Based on (7), this inequality is valid for $0 < \kappa < 2$ .It can be easily verified that:

$$\begin{aligned} J_{v(i,j)}(G_{op}) &= E\{[v(i,j) - \kappa G_0^T y(i,j)]^2\} \\ &= J_{x(i,j)}(H_{op}) \end{aligned} \quad (9)$$

The optimal estimate $\hat{x}(i,j)$ of the filtered interferometric phase x(i, j) can be written:

$$\hat{x}(i,j) = H_{op}^T y(i,j) \quad (10)$$

Thus:

$$\begin{aligned} E\{\hat{x}_{op}^2(i,j)\} &= H_{op}^T[E\{y(i,j)y^T(i,j)\}]H_{op} \\ &= H_{op}^T[E\{x(i,j)x^T(i,j)\}]H_{op} \\ &+ H_{op}^T[E\{v(i,j)v^T(i,j)\}]H_{op} \end{aligned} \quad (11)$$

Based on (7) and (9) a loss information index of interferometric phase corresponding to the optimal filter H_{op} can be defined:

$$v_{op\_in}(G_{op}) = \frac{E\{[x(i,j) - H_{op}^T x(i,j)]^2\}}{\sigma_x^2}$$
$$= \kappa^2 G_0^T [E\{x(i,j)x^T(i,j)\}] G_0 \quad (12)$$
$$= \kappa^2 v_{op\_in}(G_0)$$

It is shown that the value of loss information index of interferometric phase depends only on κ value. The extreme cases are achieved for κ=0 and κ=1. In the first case, no loss information exist but no noise reduction at all. In the second case, maximum noise reduction is achieved with maximum loss information. Since:

$$J_{v(i,j)}(G_{op}) = G_{op}^T [E\{x(i,j)x^T(i,j)\}] G_{op}$$
$$+ H_{op}^T [E\{v(i,j)v^T(i,j)\}] H_{op}$$
$$= \sigma_x^2 G_{op}^T [E\{x(i,j)\bar{x}^T(i,j)\}] G_{op} \quad (13)$$
$$+ \sigma_v^2 H_{op}^T [E\{v(i,j)\bar{v}^T(i,j)\}] H_{op}$$
$$= J_{x(i,j)}(H_{op})$$

the loss information index of interferometric phase and noise reduction factor associated to H_{op} are defined:

$$v_{op\_in}(G_{op}) = \frac{1}{SNR}[\bar{J}_{x(i,j)}(H_{op}) - \frac{1}{x_{op\_NR}(H_{op})}] \quad (14)$$

$$x_{op\_NR}(H_{op}) = \frac{\sigma_v^2}{H_{op}^T [E\{v(i,j)v^T(i,j)\}] H_{op}}$$
$$= \frac{1}{SNR[\bar{J}_{v(i,j)}(G_{op}) - v_{op\_in}(G_{op})]} \quad (15)$$

It is clear that noise reduction factor value does not only depend on the κ value but also on the interferometric phase and noise (SNR) as well.

Given that a) $SNR_0 \geq SNR$, where SNR_0 is the SNR of the interferometric phase after filtering, b) v(·) < J(·), and c) 0 ≤v(·) ≤1, then from (14) is derived that:

$$v_{op\_in}(G_{op}) \leq \frac{1}{2SNR+1}, \quad (16)$$
$$v_{op\_in}(G_0) \leq \frac{1}{2SNR_0+1}$$

D. Estimation of the κ parameter

Equation (12) can be written as:

$$\frac{v_{op\_in}(G_{op})}{v_{op\_in}(G_0)} = \kappa^2 \quad (17)$$

which expresses the ratio of the inerferometric phase index as a function of κ. Based on equation (15), the respective ratio of the noise reduction factor is not only depending on κ value, but also on the SNR. However, using eq. (5), the ratio of the noise reduction factor can be approximated as:

$$\frac{x_{op\_NR}(H_{op})}{x_{op\_NR}(H_0)} \approx \frac{1-\bar{J}_{x(i,j)}(H_{op})}{1-\bar{J}_{x(i,j)}(H_0)} = \kappa(2-\kappa) \quad (18)$$

This approximation does not include SNR, and targets to formulate a simple κ-cost function to measure the compromise between the noise reduction and the loss of interferometric signal as:

$$f(\kappa) = \frac{x_{op\_NR}(H_{op})}{x_{op\_NR}(H_0)} - \frac{v_{op\_in}(G_{op})}{v_{op\_in}(G_0)} \quad (19)$$
$$= \kappa(2-\kappa) - \kappa^2 = 2\kappa - 2\kappa^2$$

It is obvious that the κ that maximizes f(κ), is k_0:

$$\kappa_0 = \arg\max_{\kappa} f(\kappa) = 1/2 \quad (20)$$

Optimum noise reduction and interferometric signal loss is for the value κ_0 according to the above approximation. An illustration of the ratio of the interferometric phase index (blue line), and the approximated ratio of noise reduction factor (red line) as a function of κ are showed in Fig.1a. Based in Fig.1a the value of κ can be determined according to the desired interferometric phase index and noise reduction factor values. However, according to equations (16) and (17) the interferometric phase index and noise reduction factor are also depended on SNR. Fig. 2a shows the areas of values of them for various SNR. It is observed a large variation of the noise reduction factor value according to the SNR value. Fig.1.c presents the f(κ) as it is provided by eq. (20) (red line). Based on eq. (18), it is clear that κ_0 maximizes the function f(κ) if SNR is not taken into consideration. However, in Fig. 1b it is observed that SNR can significantly contribute to the estimation of the noise reduction factor. For various SNR values a family of κ-cost functions is generated, which depends on SNR_0. In Fig. 1c, black lines present the family of κ-cost functions with SNR_0 equal to 0.7375.

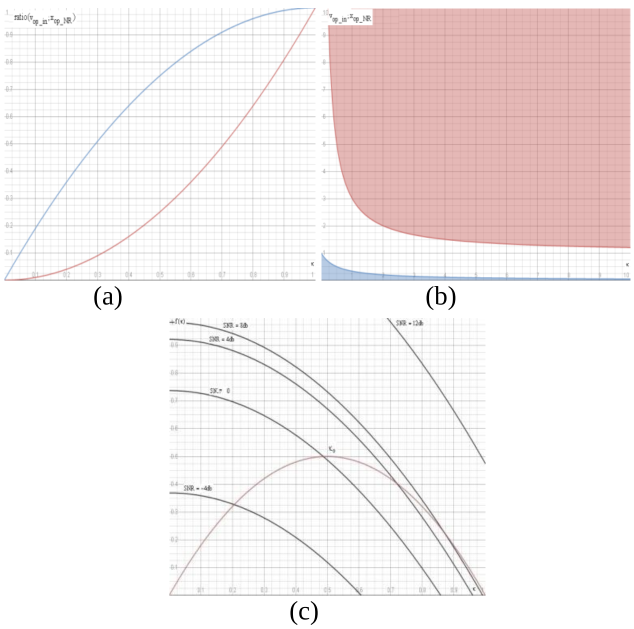

Figure 1. a) The index values depending on κ: with blue is presented interferometric phase ratio and with red the noise reduction ratio, b) The areas where the interferometric phase index $v_{op\_in}(G_{op})$ and noise reduction factor $x_{op\_NR}(H_{op})$ take their values as function of SNR, c) f(κ) function if SNR is not taken into consideration (red line) and the family of κ-cost functions for SNR_0 equal to 0.7375 (black lines).

Either using the approximated mode (eq. 20) or equation (17) the value of κ parameter can be estimated and used for increasing the performance of the filter. Equation (17) involves the estimation of SNR and SNR_0.

For this, SNR is provided by equation (21) [26], and SNR_0 is provided by equation (22) [27]:

$$SNR = 20\log 10((\max(y(i,j)) - \min(y(i,j)))/\sigma) \quad (21)$$

$$SNR_0 = \frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1} y(i,j)^2}{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1} [x(i,j) - y(i,j)]^2} \quad (22)$$

Equation (21) is used as a fast and reliable statistical method for the noise estimation. In a strictly estimation, SNR of the interferometric phase can be provided by the radar system equation, but this is out of the scope of this paper.

E. Implementation and evaluation

The performance of the proposed method, the (K-F), was evaluated using the same dataset as in [16], i.e. six Envisat ASAR images over the prefecture of Attica, Greece. The images present similar incidence angles (23^o) and the same polarization (HH). Three interferometric pairs have been created that have similar mean coherence values (Table 1). Interferometric processing has been carried out using the "Sarscape" InSAR software [28].

Table 1 Interferometric pairs

Envisat pairs	Normal Baseline (m)	Mean Coherence Value	Mean Coherence after SF	Mean Coherence after K-F
1	163,67	0,49	0,49	0,59
2	300,04	0,58	0,58	0,65
3	197,29	0,56	0,56	0,63

For the implementation of the proposed method the "Adaptive filter" was used that is available in Sarscape software. The choice was based on the characteristics of the used interferometric pairs [20],[21],[22]. For comparison purposes results have been compared with selective filtering results (SF) presented in [16]. It is observed that mean coherence is kept the same for all the pairs after the SF, whereas has significantly increased after the application of the proposed method (Table 1).
Figure 2 illustrates results of the method for the whole image and for the detail indicated by the red box. For the coherence images, white pixels present coherence values close to one, while dark pixels present values close to zero.

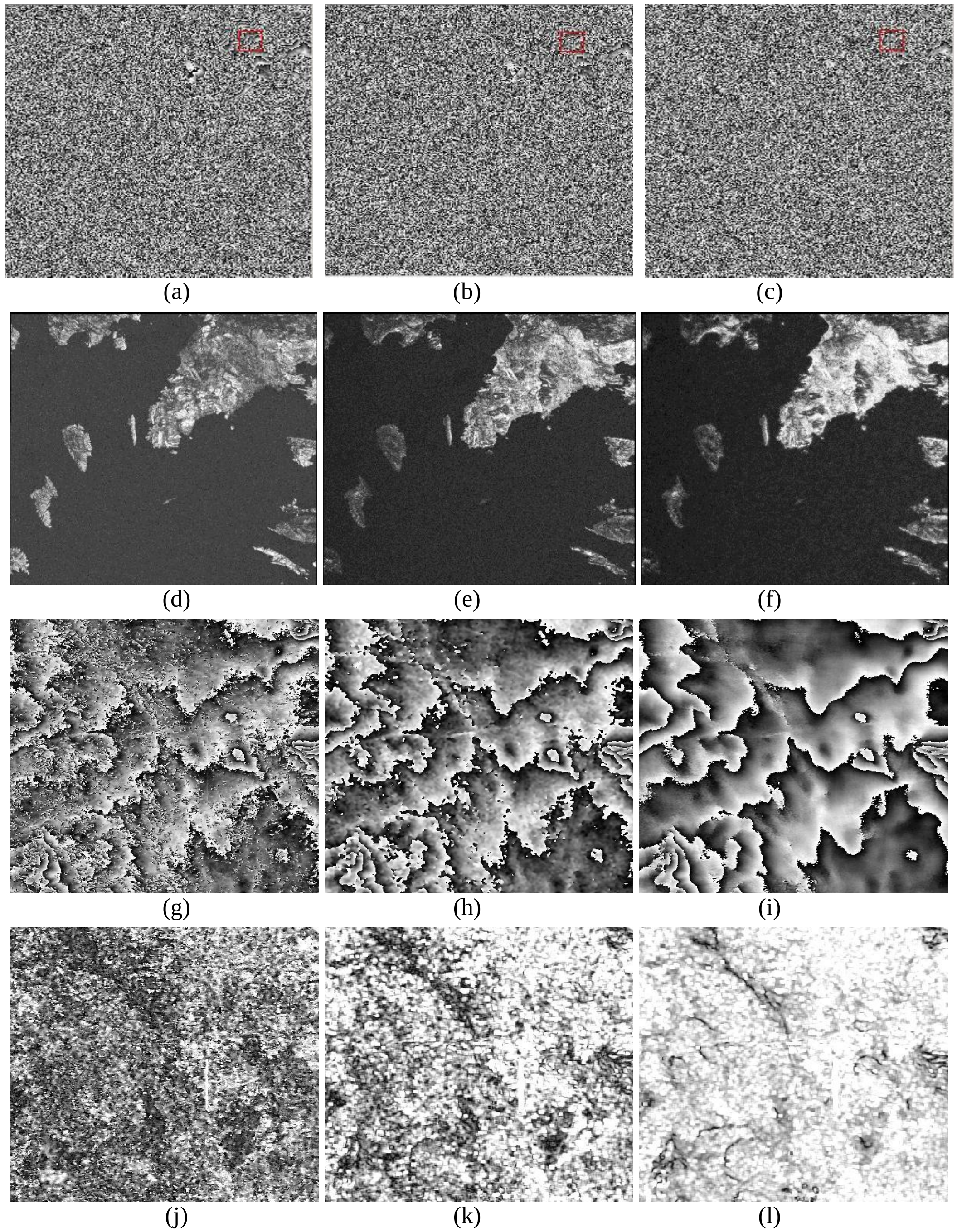

Figure 2.a) original interferometric phase (IP), b) IP after "Adaptive filter" (IP AF), c) IP after proposed method (IP K-F), d) coherence map of IP, e) coherence map of IP AF, f) coherence map of IP K-F, g) sub-image of IP (S-IP), h) sub-image of IP AF (S-IP AF), i) sub-image of IP K-F (S-IP K-F), j) coherence map of S-IP, k) coherence map of S-IP AF and l) coherence map of S-IP K-F .

It is observed that quality of the interferogram and coherence map have been significantly increased. Since coherence values are increased, the quality of InSAR products is also improved [24], [16].

For further evaluation, two sub-images have been selected for every interferometric pair, presenting low and relatively high mean coherence values, respectively. For these sub-images, the calculated mean coherence values are not increased after the application of the "Adaptive filter".

Table 2 Mean coherence value

Sub-image	Un-filtered	"Adaptive Filter"	SF method	K-F method
1/1	0,13	0,13	0,13	0,14
2/1	0,50	0,50	0,51	0,52
1/2	0,30	0,26	0,28	0,31
2/2	0,47	0,43	0,49	0,51
1/3	0,25	0,25	0,26	0,27
2/3	0,56	0,49	0,56	0,59

Coherence values are decreased or left unchanged after "Adaptive filter". They are increased after the SF method but in relation to the unfiltered data they are slightly higher. Coherence values are increased after the application of the proposed method when compared to all the previous cases (Table 2). It is also observed that K-F is more effective for sub-images with high coherence values. This is reasonable since parameter κ focuses more on minimizing the interferometric phase loss than achieving a very high level of noise attenuation. In table 3, the mean value of the κ parameter is presented for each sub-image.

Table 3 Value of κ for each sub-image

Sub-image	1/1	1/2	2/1	2/2	3/1	3/2
κ	0,6	0,2	0,54	0,45	0,57	0,16

Tables 2 and 3 show that for high coherence values κ values are low. For very high coherence values (~1), κ value tends to zero, indicating that the interferogram filtering is not really needed.

F. Conclusions

In this study effects of noise reduction on the interferometric phase have been analyzed and relationships between noise reduction and estimated interferometric phase signal have been established. Based on these relationships an information recognition method (K-F) for the existing filters was developed without suggest the use of a specific filter. The method is used as guidance for increasing the performance of the filters. K-F defines the use of a parameter in order to manage filtering. It can be automatic after the appropriate approximation described in this paper. The method was evaluated using real InSAR data. Coherence values are always increased after the application of the proposed method; however the method yields higher performance for data with relative high coherence.

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