# InSAR Data Coherence Estimation Using 2D Fast Fourier Transform

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**Abstract.** Interferometric coherence is an important indicator of reliability for interferograms obtained by interferometric synthetic aperture radar (Interferometric SAR, InSAR). Areas with low coherence values are unsuitable for interferometric data processing. Also, the coherence may be used as a classification indicator for various coverage types. Coherence magnitude can be calculated as an absolute value of the correlation coefficient between two complex SAR images with averaging in a local window. The problem of coherence estimation is in its dependence on the phase slope caused by relief topography (topographic phase). A coherence estimation algorithm is proposed that is based on the 2-FFT peak height assessment without calculation of the correlation coefficient. It is shown that such estimate has significantly less dependence on the topographic phase slope and provides satisfactory results in InSAR data quality assessment.

**Keywords:** Synthetic aperture radar images, InSAR systems, coherence estimation

## 1 Introduction

Interferometric data processing (InSAR) for extraction of information about the Earth terrain and its changes becomes one of the general guidelines in development of contemporary space-based radar systems together with the implementation modes of ultra-high spatial resolution (1–3 meters) and full-polarimetric processing [1–3]. The InSAR processing for building the digital elevation models (DEM) includes the following steps: synthesis of the pair of complex synthetic aperture radar (SAR) images and their coregistration; forming the interferogram by the element-wise complex multiplication of these SAR images; compensation of the phase slope caused by side-looking imaging geometry; multilooking (noncoherent summation); phase noise supression; phase unwrapping (the elimination of phase ambiguities); and conversion of the absolute phase interferogram in elevation grid data and its projection.

Interferometric coherence is an important indicator of suitability of the data scene obtained by a radar remote sensing system for the further processing and solving the final problem, *i.e.* the DEM generation or terrain changes mapping. The coherence factor is calculated as an absolute value $\gamma_0$ of the correlation coefficient between samples of two complex SAR images (single-look data complex, SLC) taken in the local windows

$$\hat{\gamma_0} = \frac{|\sum \dot{z}_1(m,n) \cdot \bar{z}_2(m,n)|}{\sqrt{\sum |\dot{z}_1(m,n)|^2 \cdot \sum |\bar{z}_2(m,n)|^2}}, \tag{1}$$

where $z_{1(2)}(m,n)$ are the SLC samples ($\bar{z}_{1(2)}(m,n)$ are the complex-conjugate samples) [1–4, 6], $\hat{\gamma_0}$ takes values in interval [0,1], and near-zero values correspond to areas of high or full decorrelation, which are not suitable for interferometric data processing. An intrinsic radar signal decorrelation is caused by the radar looking angle difference (geometric decorrelation) and by the Earth surface variability (temporal decorrelation). Strong decorrelation occurs due to loss of echo-signal (typical for water surfaces), volume scattering (forest vegetation), signal layover, and shadowing, etc. Commonly, the areas with coherence lower than 0.2–0.3 are unsuitable for conversion into DEM.

So, the coherence value may be used as an interferometric phase quality indicator, which gives an opportunity to reject the areas, where the phase is unstable and is not related to the Earth topography. Also, rejection of the decorrelated areas before phase unwrapping simplifies this processing step because some unwrapping algorithms become slower and unstable while processing such areas.

The other way of the interferometric coherence utilization implies its usage as a parameter in adaptive phase noise filters. A commonly used Goldstein-Baran adaptive frequency filter adapts a frequency response in dependence on local coherence [5]

$$F(k,l) = |S(k,l)|^{1-\hat{\gamma}} \cdot S(k,l), \tag{2}$$

where $S(k,l)$ and $F(k,l)$ are the spectra of raw and filtered interferograms relatively, taken in a local window; $\hat{\gamma}$ is the local coherence estimate. So, the lower coherence leads to extension of filter's bandwidth and vice versa. For this reason, the coherence map is usually calculated before the phase noise supression stage in the InSAR processing chain.

However, this approach entails some problems because, in fact, a random variable is estimated here, but not a random process. So, any phase slopes caused by both natural topography variability and by point-of-view geometry (remote sensing radar systems have a side-looking configuration) lead to the degradation of estimate (1). Its value depends on the slope and tends towards the value $\gamma_0 \approx 0.2...0.3$, *i.e.* a bias of the estimate for independent Gaussian values of the correlation coefficient [3], which in practice takes the value about 0.1–0.3 (Fig 1).

Thus, coherence loses its properties as measure of the interferogram quality because its value becomes independent on the relation between topographic and fluctuating components of the phase.

The problem of coherence estimate degradation was described by [3, 4, 7], and some approaches for its correction were proposed. The basic approach involves a

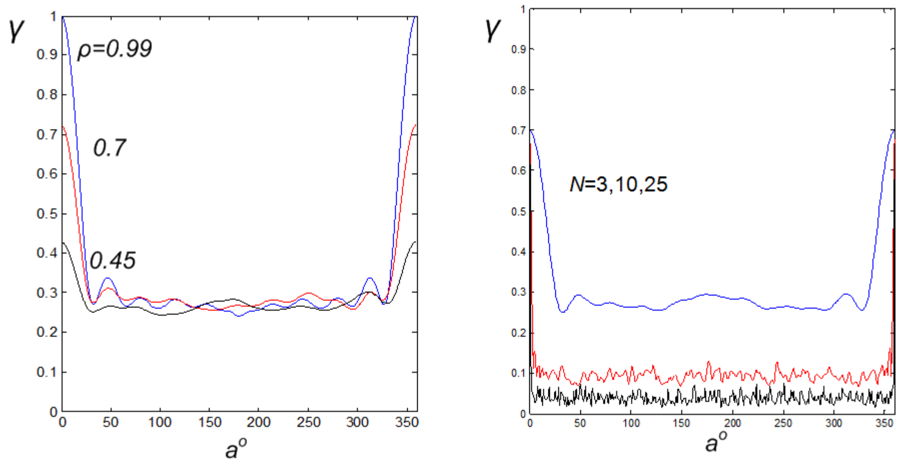


**Fig. 1.** Dependencies of $\hat{\gamma}_0$ coherence estimate on the phase slope angle for different simulated correlation coefficients (a) and local window (sample) sizes (b).

reference digital elevation map (with lower spatial sampling frequency, as a rule) for phase compensation prior to the coherence estimation. But such reference DEM with a sufficient sampling factor is often unavailable for a specific territory (especially for the Northern ones). Another aprroach implies elimination of the phase components from estimate [3] andcalculation of an estimate based on images magnitude. But as it is shown [8], such estimates have a large bias and they can not be used for detection of low-coherent areas. So, a reasonable approach may lie in an adaptive phase slope estimation and its compensation, as it offered in [3, 9], but some additional measures should be considered to improve the efficiency of such approach.

## 2 A 2-FFT interferometric coherence estimate

To eliminate the effect of coherence estimates degradation, we construct the estimate in a way, which makes it immunable to phase slope value. Since a constant phase slope can be considered as the interferogram spatial frequency modulation, it is reasonable to use a 2D fast Fourier transform (2-FFT) to determination of modulation frequencies, which can be found as

$$[\omega_x, \omega_y] = \operatorname{argmax}\{\mathfrak{F}^2[\dot{z}_1 \cdot \bar{z}_2]\}, \tag{3}$$

where $\omega_x$ and $\omega_y$ are the spatial frequencies in both spatial dimensions, which are estimated in an interferogram sample of $M \times N$ size. A common idea for 2-FFT coherence estimation is that further spatial frequency demodulation is performed according to the rule:

$$z_{2c} = z_2 \cdot \exp[-j(\frac{\omega_x}{M} + \frac{\omega_y}{N})], \tag{4}$$

that eliminates influence of the phase slope on the estimate value. After substitution of (4) into (1), instead of $z_2$ the correlation coefficient would give a correct estimate for coherence magnitude [3, 9].

Here, the main problem is that such way has a low computational efficiency: the advantages of the FFT application are negated by the need of a correlation coefficient computation, and, so, a computational time for this estimate exceeds the same one for the usual estimate. From the other side, the images' magnitude information gives minor contribution to the estimate value, as it is shown in [8]. Moreover, radar brilliant points significantly degrade the estimate in their neibourhood. So, it is reasonable to normalize images magnitudes taking

$$|z_1| = 1, |z_2| = 1 \tag{5}$$

and calculate a peak value of the discrete spectrum for a normalized interferogram (in the local window) as follows

$$M = \max\{\mathfrak{F}^2[z_1 \cdot z_2]\}. \tag{6}$$

In this case, taking into account the Parseval's identity, for a scene sample $M \times N$ with a constant phase slope, one can get that the following:

1) for fully coherent scenes a 2-FFT spectrum has a single peak $P$ of an $M \times N$ height in a position matching to a spatial frequency value;

2) fully incoherent scenes may be considered as a discrete white noise with the spectrum fluctuating near 1.

Dependence of the spectrum peak value $P$ and scene decorrelation $\gamma$ may be retrieved by simulation of Gaussian homogenous scenes with different correlations (Fig. 2).

As can be seen from Fig. 2, the dependence between a normalized spectrum peak value $P/(M \times N)$ and a simulated correlation is slightly biased. So, a possible way for coherence estimation is to recalculate a peak value (or peak to mean value ratio) into a coherence magnitude in the following way:

$$\hat{\gamma}_2 = \frac{P}{M \times N}. \tag{7}$$

Estimate $\hat{\gamma}_2$ is less dependent of the phase slope value than a standard one $\hat{\gamma}_0$, which affects only peak location within a spectrum. Figure 3 demonstrates the estimate behaviour by the simulation of homogenous scenes with different simulated correlation coefficients.

As can be seen, that for high correlations, the estimate tends to fall down near the slopes of $\pi$ radians to the level about 0.71 of $\hat{\gamma}_2$, which is related to sampling effects.

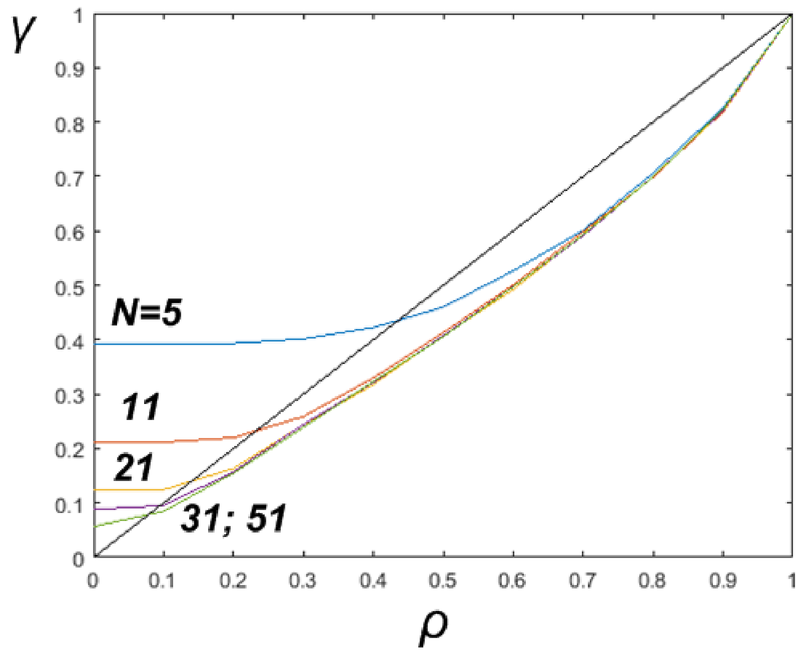


**Fig. 2.** Depedencies of a normalized spectrum peak value of the 2-FFT spectrum on the simulated correlation coefficients of different local window (sample) sizes.

## 3 Experimental results

An experimental assesment of the proposed method of interferometric coherence estimation was carried out within application of a reference DEM. Since the coherence value indicates, first of all, the fluctuations level of the absolute phase around the topographic phase, and the latter is closely related with the reference DEM heights [2], it is obviously to use a statistics of phase deviations to assess the quality of the coherence estimates. Such assesment was performed in the following way:

1) the reference DEM was reprojected into a flight vehicle coordinate system (range-azimuth), and then the heights were recalculated to reference absolute phase values using an InSAR height ambiguity factor; the reminder shift was fixed through the cross-correlation between the reprojected DEM and the scene absolute phase obtained after phase unwrapping stage;

2) coherence estimates $\hat{\gamma}_0$ and $\hat{\gamma}_2$ were calculated with the window size $19\times19$;

3) coherence values interval [0,1] were splitted into subintervals with a fixed step 0.05;

4) for each subinterval $i$ the standard deviation of the absolute phases and reference absolute phases $\sigma_{\psi i}$ were counted in corresponding image points.

The obtained dependence of $\sigma_\psi$ on $\hat{\gamma}$ acts as a quality indicator for the interferometric coherence estimate. The better estimates should give a less-fluctuating

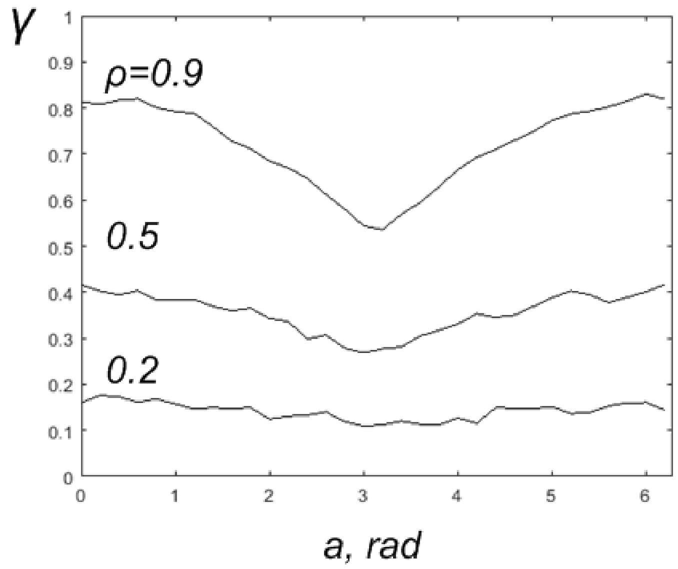


**Fig. 3.** Dependencies of $\hat{\gamma}_2$ coherence estimate on the phase slope angle for different simulated correlation coefficients.

decreasing dependence at least for low- and medium-valued coherences (except extreme-low values) with a possible wider range for both coherence and standard deviation values. This means that a better estimate is more sensitive to the level of phase noise fluctuations.

The reference DEM covered a territory 8 × 5 km, which contained average hills and river valleys and had the vertical height accuracy about 1.7 m, which is, at least, triple times better than the expected ALOS PALSAR DEM accuracy (about 7–8 m [10]. An interferogram has a size of 2000 × 750 elements. The obtained dependecies $\sigma_{psi}(\hat{\gamma})$ are shown in Fig. 4. The range of values for $\hat{\gamma}_0$ was about 0.25–0.75, and 0.2–0.6 for $\hat{\gamma}_2$. Extremely high values ($\hat{\gamma}_0 > 0.7$ and $\hat{\gamma}_2 > 0.55$) were excluded because they were, as a rule, corresponded to terrain elements that are not joined with the Earth relief (buildings, facilities, roads, engineer communications, etc).

As it is seen from Fig. 4, $\hat{\gamma}_2$ estimate has more wide band for the standard deviation than $\hat{\gamma}_0$ and it has a linear decreasing section for 0.2-0.45 coherence values, so it better reflects the quality of the InSAR data; $\hat{\gamma}_0$ has an abnormal behaviour, the standard deviation increases within the coherence value. Both estimates have an abnormal behaviour for extremely low and extremely high coherences.

## 4 Conclusions

A coherence estimation algorithm is proposed based on 2-FFT normalized peak height assessment. It is shown that such estimate has a significantly less depen-

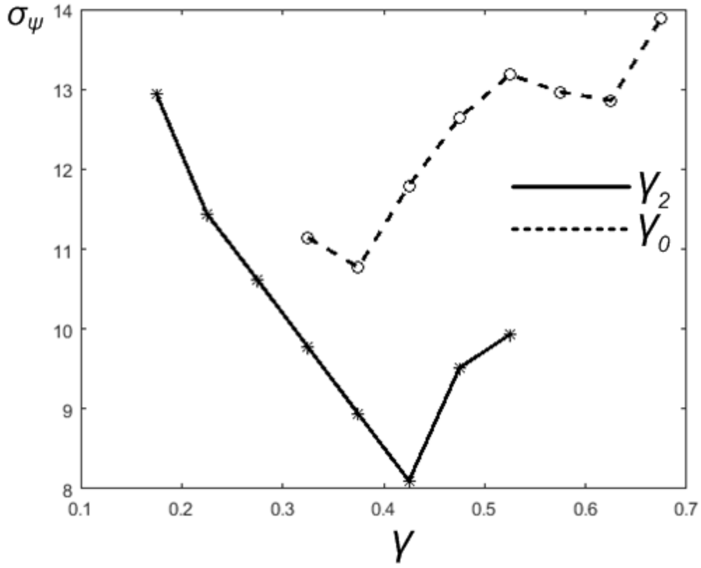


**Fig. 4.** Dependency of the absolute phase standard deviation on the coherence estimates.

dence on the topographic phase slope. A method of coherence estimates quality assesment is proposed, based on calculation of InSAR absolute phase deviation from a reference DEM. It is also shown, that proposed coherence estimate has a quazi-linear decreasing section on the $\sigma_\psi(\hat{\gamma})$ dependency that correctly characterizes it as a quality measure for InSAR data.

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