# Multi-baseline polarimetrically optimised phases and scattering mechanisms for InSAR applications

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***Abstract*— An interesting, but rarely used technique in polarimetric SAR interferometry is the enhancement of interferometric coherence by projection into an optimal polarimetric state. In particular, newly developed methods for polarimetric optimisation of multi-baseline coherences provide the possibility of simultaneous constrained coherence optimisation for more than one baseline. This technique can significantly improve the usefulness of long-term interferometric pairs and time-series, and appears, therefore, of interest to various fields of application.**

**The aim of this paper is to discuss the correct derivation of multi-baseline differential interferograms with polarimetrically optimised coherence and to outline several possible areas of application, particularly in the field of differential interferometry and permanent scatterers.**

## I. Introduction

In recent years, differential SAR interferometry has become an established technique for detecting and monitoring centimetre-scale deformations of the earth's surface, as well as glacier flows and land slides [1], [2]. Although often effective in practice, differential SAR interferometry suffers from decorrelation effects, particularly when data acquisitions over long time spans are involved [3]. In case of volumetric targets, only a mean interferometric phase centre can be tracked, which is defined by an unknown superposition of scattering contributions from the entire volume [4]. SAR polarimetry, on the other hand, is a technique which can, in certain circumstances, be used to separate multiple scattering mechanisms inside the resolution cell. This capability has successfully been used in combination with interferometric techniques to analyse the spatial distribution of scatterers in the volume [5]. In addition, polarimetric phase diversity allows the application of phase and coherence optimisation techniques, in order to minimise temporal, spatial, and system decorrelation effects (see e.g. [6]–[10])

These capabilities are of interest in differential interferometry; especially coherence optimisation can significantly improve the quality of long-term interferometric pairs [6]. The newly developed methods for polarimetric optimisation of multi-baseline coherences [11] provide the possibility of simultaneous constrained coherence optimisation for more than one baseline. However, in differential SAR interferometry, special attention has to be paid to the preservation of polarisation states in order to avoid the observation of polarimetric phase effects, which would otherwise overlay the differential motion effects. In this context, special care has to be taken to obtain polarimetric representations of the same dominant scattering mechanism along all baselines.

## II. Multi-baseline Polarimetric SAR Interferometry

A multi-baseline $n$–track geometry contains $\frac{n}{2}(n-1)$ direct baselines. Fully polarimetric, monostatic data can be represented in the Pauli basis, assuming reciprocity, by the scattering vector $\mathbf{k}_i$ in track $i \in [1, n]$:

$$\mathbf{k}_i = \frac{1}{\sqrt{2}}[S_i^{HH} + S_i^{VV},\ S_i^{HH} - S_i^{VV},\ 2S_i^{HV}]^T \tag{1}$$

The MB–POLINSAR coherency matrix $\mathbf{T}$, representing estimated covariance among the polarimetric and interferometric channels, is generated by multi–looking the outer product of the aggregated scattering vector $\mathbf{k}$:

$$\mathbf{T} = \left\langle \mathbf{k}\mathbf{k}^\dagger \right\rangle = \begin{bmatrix} \mathbf{T}_{11} & \cdots & \mathbf{\Omega}_{1n} \\ \vdots & \ddots & \vdots \\ \mathbf{\Omega}_{1n}^\dagger & \cdots & \mathbf{T}_{nn} \end{bmatrix}, \quad \text{with } \mathbf{k} = \begin{bmatrix} \mathbf{k}_1 \\ \vdots \\ \mathbf{k}_n \end{bmatrix} \tag{2}$$

where $\langle\rangle$ denotes spatial averaging, and $^\dagger$ the adjoint operator. $\mathbf{T}_{ii}$ contain the polarimetric information, while $\mathbf{\Omega}_{ij}$ $(i \neq j)$ contain baseline dependent polarimetric and interferometric information.

The coherence between two channels, in possibly different polarisations $\boldsymbol{\omega}_i \neq \boldsymbol{\omega}_j$, is defined as

$$\gamma_{ij(\boldsymbol{\omega}_i,\boldsymbol{\omega}_j)} = \frac{\boldsymbol{\omega}_i^\dagger \mathbf{\Omega}_{ij} \boldsymbol{\omega}_j}{\sqrt{\boldsymbol{\omega}_i^\dagger \mathbf{T}_{ii} \boldsymbol{\omega}_i \boldsymbol{\omega}_j^\dagger \mathbf{T}_{jj} \boldsymbol{\omega}_j}} \tag{3}$$

The PolInSAR coherence can be modelled as a composition of four major terms [12] corresponding to temporal, spatial, system and thermal decorrelation sources, respectively:

$$\gamma = \gamma_{temp}\gamma_{spatial}\gamma_{sys}\gamma_{therm} \tag{4}$$

The last two terms represent system and noise characteristics, and are unrelated to the observed scene. The first two terms represent the scene change due to the spatial and temporal separation of the baseline, and constitute important characteristics of the illuminated scene. They can be further decomposed into

$$\gamma_{temp} = \gamma_{\Delta pos}\gamma_{\Delta scat}\gamma_{\Delta atmo} \tag{5}$$
$$\gamma_{spatial} = \gamma_{range}\gamma_{DC}\gamma_{topo}\gamma_{vol} \tag{6}$$

corresponding to temporal changes due to scatterer position change, change of scattering characteristics, and atmosphere changes, as well as range, Doppler centroid, topography, and volume decorrelation.

For airborne data, after careful processing, most terms can be eliminated, except for $\gamma_{\Delta pos}$, $\gamma_{\Delta scat}$, and $\gamma_{vol}$. With a single–pass interferometry, the coherence is only a function of $\gamma_{vol}$, while for zero–baseline multi temporal data the coherence allows to estimate changes due to movement and changes of scattering behaviour. The latter is mostly related to the change of scatterers in shape, in orientation, and in the dielectric constant. $\gamma_{vol}$ can be modelled for simple vertical volumes like the Random or Oriented Volume, and the Random or Oriented Volume over Ground [13]–[15], as a function of the spatial baseline. With a larger number and sufficient variety of baselines, the parameter inversion process for these models can be improved.

If $\gamma$ represents mostly $\gamma_{\Delta pos}$ then the coherent movement function parameters can be estimated, provided a temporal series of acquisitions. On the other hand, the change in scattering characteristics is best described by the least coherent scattering mechanisms, which are apparently responsible for the decorrelation.

## III. Multi-baseline Coherence Optimisation

By considering more than one baseline, one obtains additional degrees of freedom. At first, additional acquisitions increase the number of independent observations, improving the statistical properties of the data. Secondly, depending on the spatial and temporal separation of baselines, better understanding of the change process can be recovered. E.g. the coherent change of the differential phase allows to determine the displacement of the scatterers. With more temporal data acquisitions, the determination of the displacement function can be enhanced, making it possible to estimate the time dependency and the curvature of the displacement movement.

In interferometric applications, it is important to identify the most dominant scattering mechanisms throughout all data sets, as such scattering mechanisms are associated with the smallest phase error. In [11], two coherence optimisation methods are presented for multi-baseline PolInSAR data sets.

The most general multi-baseline / multiple scattering mechanisms (MSM) method assigns a distinct scattering mechanism to each data set. This approach allows one to optimise the coherence for scattering mechanisms that might have different polarimetric signatures in different datasets. The equal scattering mechanisms (ESM) method, on the other hand, enforces equal polarimetric signatures of scatterers along all baselines ($\boldsymbol{\omega}_i$=$\boldsymbol{\omega}_j$ $\forall\, i,j$), and the application of this method is restricted to a single scattering mechanism for the dominant scatterer.

The general multi-baseline optimisation problem can thus be stated as the maximisation of a function $f_{(\boldsymbol{\omega}_1,\ldots,\boldsymbol{\omega}_n)}$ (possibly $\boldsymbol{\omega}_i$=$\boldsymbol{\omega}_j$ for ESM) incorporating coherence moduli for all baselines. In the simplest case, the optimisation function $f$ is determined by the sum over coherence moduli: $f = \sum|\gamma_{ij}|$. It can be shown, that there is no exact analytical method for the simple sum optimisation problem, for both MSM and ESM. However, the two algorithms which have been presented achieve such optimisations with a high degree of accuracy and efficiency.

These optimisation methods provide the most coherent (dominant) scattering mechanisms, which maximises the coherence in all baselines simultaneously. Adopting the coherence model that was introduced in the previous section, for adequate baseline separations the optimisation provides the scattering mechanism with the least volume decorrelation (e.g. the ground, in case of moderate extinction). In addition, it might provide the least decorrelation due to stochastic movements of the scatterers (coherent displacement of scatterers does not influence the coherence modulus, only the phase), and the smallest change in scattering behaviour.

## IV. Applications

Multi-baseline coherence optimisation delivers polarisations, in which the most stable interferometric phase information, as well as the most coherent scattering mechanisms are present. In the following, possible applications of this technique will be described.

### A. *Polarimetric Differential SAR Interferometry*

In differential interferometry (DInSAR), one is often faced with very long data acquisition intervals, and the consequently low coherence due to temporal decorrelation. Coherence optimisation is a possibility to significantly increase the phase accuracy in low coherent areas and, in this way, also the accuracy in the estimation of displacements. If no accurate DEM and/or orbit information is available, the most convenient approach to DInSAR is to use 2 interferometric pairs, one with small temporal separation for determining topography and another with larger temporal separation for determining displacement [16]. Usually, the DEM information is first subtracted from both pairs to form residual interferograms, before the residual short-term interferogram is scaled to the second baseline and subtracted in order to correct for residual error and to identify the deformation pattern.

When using coherence optimisation, it is important to ensure that the same polarisation states are used across all tracks. Neglecting to do so introduces phase components, which are related to a change in polarisation basis and not to scatterer displacement. In such a case, therefore, the usage of MB-ESM optimisation techniques is mandatory. The achieved coherence is certainly lower than when allowing individual scattering mechanisms in each track, but the corresponding optimised phase values provide pure interferometric information. Fig. 1

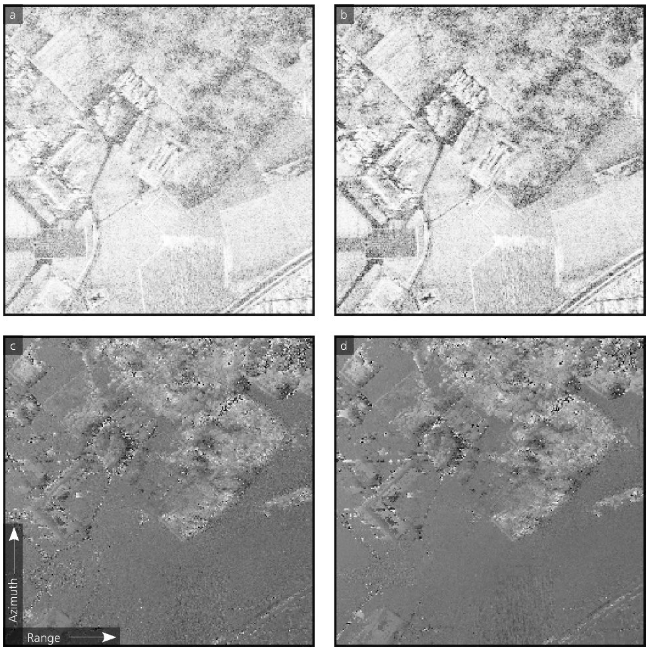


Fig. 1. Coherence optimisation over 3 baselines. (a) and (b): Optimised coherences with MB-MSM and MB-ESM, respectively. (c) and (d): corresponding optimised InSAR phases.

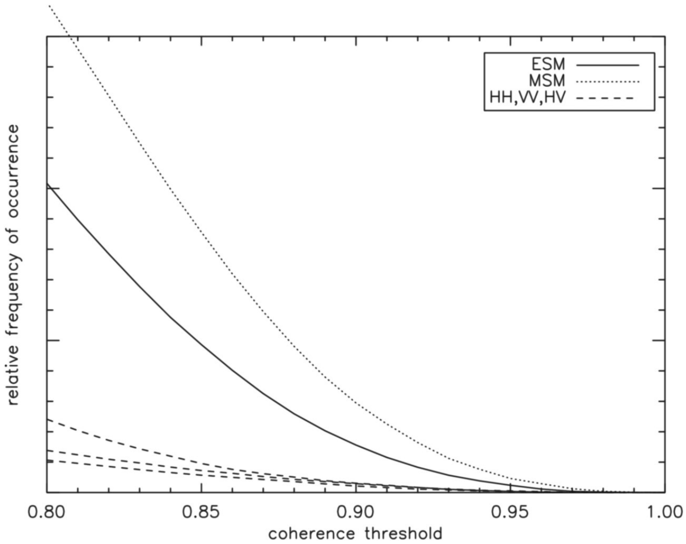


Fig. 2. Enhancement of the number of high coherent points in a forested region through ESM optimisation of a 5-track data set. Shown is the relative frequency of pixels with a coherence larger than a certain threshold in all possible interferometric pairs.

shows an example of MB-ESM optimisation compared to MB-MSM optimisation.

A remaining issue with the optimisation is that the optimal polarisation state can change from one pixel to the next. If, for example, the deformation of ground beneath a forest canopy is to be analysed, it is impossible to guarantee that the ground delivers the highest coherence in all relevant pixels. In this case, projecting all polarimetric data sets onto a polarisation state known to be characteristic for surface reflection, e.g. $\omega = [1, -1, 0]$, might be favourable. Alternatively, one may attept to identify the polarisation states with the 'lowest' and 'highest' scattering centre through maximisation of the phase diversity [17].

### *B. Optimised Permanent Scatterers*

The permanent scatterer (PS) technique is an advanced DInSAR approach, which is based on the analysis of scatterers associated with a coherent behaviour over a temporal series of SAR acquisitions [18], [19]. With the PS technique, it becomes possible to eliminate the influence of atmospheric and DEM errors, as well as to circumvent, in many cases, the temporal decorrelation of the scene. The prerequisite is a sufficiently high density of permanent scatterers, which are usually identified statistically by high coherence and constant amplitudes in all possible interferometric pairs. Unfortunately, a sufficient PS density is often not reached on natural surfaces.

Polarimetry generally enlarges the observation space; consequently it should be possible to identify at least some more PS by taking into account all 3 channels of a polarimetric data set. However, this does not consider polarisation states other than the ones directly measured by the sensor. By using MB-ESM optimisation techniques over the entire multi-temporal data set, for each pixel the optimal coherences and corresponding phase values can be derived, maximising the amount of PS candidates. This might enable the determination of stable scatterers even in highly distributed scattering media.

As a first test, coherent pixels were identified in a forested area, using a data set containing 5 spatially separated tracks with baselines up to 50 m and applying different optimisation techniques. Fig. 2 shows the percentage of pixels with a coherence larger than a certain threshold in all possible interferometric combinations. Without applying coherence optimisation, almost no coherent pixels are found due to volume decorrelation. In contrast, the MB-MSM optimisation reveals much more coherent points, but due to the disparity of involved scattering mechanisms, the remaining interferometric information is questionable. But also MB-ESM significantly increases the number of coherent points, this time under preservation of interferometric information. It appears that, for some pixels, the optimisation is able to detect polarisation states with reduced volume scattering, and, therefore, increased coherence over all possible baselines.

### *C. Change Assessment using Optimised Scattering Mechanisms*

Another possible application uses multi-baseline coherence optimisation techniques to determine the least coherent scattering mechanism over multiple baselines. Assuming partly depolarised scattering (not point targets), and the model as discussed above, these least coherent scattering mechanisms will correspond to the highest phase variance (and thus changes) in either $\gamma_{\Delta pos}$, $\gamma_{\Delta scat}$, or $\gamma_{vol}$, depending on the baseline considered. Combining the change sensitivity of coherence minima with baseline variation permits to construct an efficient change monitoring system. Adequately spatially and temporally separated datasets permit to characterise the type of change. Thereby, optimisation helps to localise the change. It should be kept in mind that lower coherences indicate higher uncertainty in the interferometric phases and scattering mechanisms. The least coherent scattering mechanisms and phases therefore represent the scattering centres with variance higher than the maximal coherent scatterers.

## V. Discussion

Coherence optimisation is a technique to enhance the interferometric coherence of fully polarimetric systems. This is achieved by the choice of a polarisation basis which has the highest possible coherence within the polarimetric observation space. For applications apart from pure coherence analysis, for instance change detection, it is important to ensure equal polarisation states at both ends of the spatial baseline. Otherwise, although mathematically optimal, interferometric and polarimetric information is mixed and reliable phase information cannot be deduced. The newly developed methods for the polarimetric optimisation of multi-baseline coherences provide the possibility of simultaneous constrained coherence optimisation for more than one baseline. These capabilities are particularly interesting in the area of differential interferometry and permanent scatterer analysis, where multiple data sets are involved.

However, under certain circumstances and in other applications, the more general MSM optimisation might be favourable. For example, the inevitable noise component in SAR data could cause physically equal polarisation states to appear slightly different. The same holds for potential Faraday-rotation effects in the ionosphere, or in case of unresolved calibration issues. Additionally, the ESM approach generally assumes $T_{ii} = T_{jj}$, which is not valid when significant changes of the reflectivity occurred between the data acquisitions. In all these cases, ESM optimisation should not be applied and MSM be used instead.

This paper mainly tries to point out the principal potential of polarimetric coherence optimisation and discusses the correct derivation of optimised phase information. Further investigations have to be conducted to quantify precisely for various applications the advantages of optimised fully-polarimetric data acquisitions compared to single-polarised data sets.

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