FADING SIGNAL: AN OVERLOOKED ERROR SOURCE FOR DISTRIBUTED SCATTERER INTERFEROMETRY

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ABSTRACT

We reveal the presence of a peculiar physical signal which compromises the accuracy of Earth surface deformation estimates for distributed scatterers [1]. The observed signal is short-lived and decays with the temporal baseline; however, it is distinct from the stochastic noise attributed to temporal decorrelation. To indicate its nature, this physical effect is referred to as *fading signal*. Designing a simple approach in the evaluation of distributed scatterers, we reveal a prominent bias in the deformation velocity maps. The bias is the result of propagation of small phase error through the time series. We further discuss the role of the phase estimation algorithms in significant reduction of the bias and put forward the idea of a unified analysis-ready InSAR product for achieving high-precision deformation monitoring.

***Index Terms*—** Big Data, Fading Signal, SAR Interferometry, Distributed Scatterers, Error Analysis, Time Series Analysis

1. INTRODUCTION

Through extensive analysis of Sentinel-1 data, we observe a systematic, yet temporally inconsistent, error source for Distributed Scatterers (DS) [1]. If present, the it can severely compromises the reliability of Interferometric Synthetic Aperture Radar (InSAR)-derived deformation velocity maps. The observed error is attributed to the systematic variation in the scattering properties of the sub resolution scatterers [2]. Here we summarize our demonstrations of:

- the presence of the error source in interferograms;
- the propagated error to the deformation velocity maps;
- the effect of processing algorithms on mitigating the error.

In these demonstrations, we distinguish between two types of observations in InSAR: single-look versus the multilook interferometric phases. The former is for instance related to the Persistent Scatterers (PS), where the single complex valued pixels are exploited within the time series. The latter multilooked observations are the result of spatial averaging (i.e. multilooking). Spatial averaging is the cornerstone of many advanced InSAR time series analysis techniques, with [3] and [4] setting the two overarching trends in this regard. Although effective in improving the Signal to Noise Ratio (SNR) of the natural land covers, known as DS, multilooking changes the statistical properties of the interferograms and introduces peculiar physical signal. Consequently, a phase bias is observed between the single-look and multilooked observations. As the phase bias vanishes with temporal baseline, it is hereafter referred to as fading signal. Revealing the presence and the impact of this fading signal on Earth surface deformation retrieval is the focus of this paper.

2. METHODOLOGY IN REVEALING THE FADING SIGNAL

2.1. Evaluation of Phase Bias and Prediction of Deformation Velocity Bias

We firstly introduce a measure to quantify the interferometric phase bias which pertains to the fading signal. Using error propagation we introduce a second measure to calculate the expected deformation velocity bias from the phase biases.

In the introduction of our first measure, we assume to know the interferometric phase $\Delta\tilde{\phi}$ which is free of the systematic and stochastic inconsistencies. Knowing this phase, the error of the multilooked interferograms can be evaluated for each DS at each interferogram, i.e.:

$$\epsilon_{\Delta\phi_{ik}}(x,y) = \Delta\phi_{ik}(x,y) - \Delta\tilde{\phi}_{ik}(x,y). \quad (1)$$

Here $\Delta\phi$ shows the multilooked phases over DS regions, subscripts i, k refer to the master and slave acquisition index and x, y are the spatial coordinates of the DS. The phase $\Delta\tilde{\phi}$ can be substituted by high SNR PS phases.

In principle one can estimate the phase bias from the phase errors by allowing an averaging operator on a chosen ensemble; the averaging is necessary to reduce the stochastic noise. In our bias estimation, we choose a temporal averaging within the time series. The averaging is performed on the calculated phase error of each DS within the interferograms with identical time lag l separation from their respective master scene. A normalization with respect to the temporal baseline of the interferograms is further considered. Following the temporal averaging and baseline normalization, the intended measure reads as:

$$\delta^l{}_{(x,y)} = \frac{1}{n-l} \sum_{i=1}^{n-l} \frac{\epsilon_{\Delta\phi_{i,i+l}(x,y)}}{\Delta t_{i,i+l}}. \quad (2)$$

We further quantify the expected bias in the deformation velocity given the biases of interferograms by introducing a second measure. Following the mean propagation law for linear models [5], the deformation velocity bias reads as:

$$\epsilon_{d_v}(x,y) = \frac{1}{bw} \frac{\lambda}{4\pi} \sum_{k=1}^{bw} \delta^k{}_{(x,y)}, \quad (3)$$

where λ is the radar wavelength and bw stands for the number of consecutive interferograms per scene which are exploited in the deformation estimation (see Fig. 1).

ϵ_{d_v} provides a mean to verify the empirical velocity biases of section 2.2 with the predicted deformation velocity bias from the phase errors in multilooked interferograms.

2.2. Evaluation of Deformation Bias

Here, we design an experiment to reveal the propagation of the phase bias of multilooked interferograms to the deformation estimates. As the benchmark of the experiment, we perform Persistent Scatterer Interferometry (PSI) to allow the deformation estimation based on pure single-look observations. Should inconsistent systematic effects exist within the multilooked interferograms, the deformation estimates vary depending on which interferograms are employed for their retrieval. We perform multiple processing rounds to corroborate this proposition.

In the first processing round, we exploit all possible interferograms within the time series to estimate the phase history; here phase estimation is performed by the Eigendecomposition-based Maximum-likelihood-estimator of Interferometric phase (EMI) [6]. In the following processing rounds, we test the ingestion of different subsets of the interferograms for deformation estimation; for this purpose we designed Enhanced Short temporal BAseline Subset approach (E-StBAS) phase estimator [1] as a variation of the well-known Small BAseline Subset approach (SBAS) technique of [3]. Fig. 1 provides a schematic comparison of the two approaches in phase estimation. Note that we deliberately exploit the short temporal baseline interferograms which are expected to be more severely biased in the presence of the fading signal.

Retrieving the consistent phase series for DS using either EMI or E-StBAS, the deformation signal is estimated following a 3D phase unwrapping and decomposition of signal to deformation and atmospheric components.

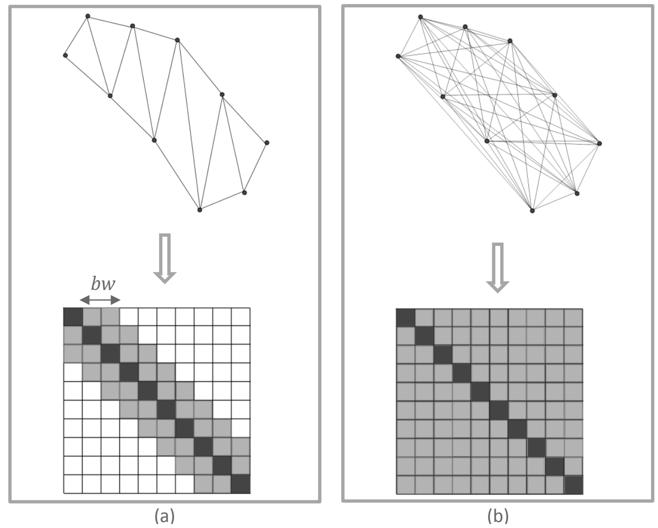

Fig. 1: Different levels of data exploitation for deformation analysis. Top sketch mimics Synthetic Aperture Radar (SAR) images with dots and the exploited interferograms with arcs; the sketch below shows the corresponding Complex Coherence Matrix (CCM) where diagonal elements refer to the images and the filled off-diagonals represent the employed interferograms. Images are assumed to be temporally sorted. (a) E-StBAS as the partial exploitation of the data with short temporal baseline interferograms of up to band bw, and (b) EMI as the the full exploitation of the interferograms.

PS-derived deformation signal are used as the benchmark for validation. Being single-look observations, the PS are exempt of phase inconsistencies. Therefore, the associated deformation shall be free of systematic biases. The performance evaluation is conducted as following: a spatial grid of size 1 km^2 is chosen for down-sampling both displacement time series and displacement velocity maps. Atmospheric and ground motion signals are assumed to be stationary within this spatial window. For all PS and DS within the defined reference grid cells, an average of the deformation signal substitutes the sparse estimates. The empirical velocity bias then follows from:

$$\epsilon_d(x,y) = \langle d_{\text{DS}}(x,y) \rangle - \langle d_{\text{PS}}(x,y) \rangle, \quad (4)$$

where $\langle . \rangle$ is the mentioned averaging operator, x, y are the spatial coordinates of the down-sampled grid and ϵ_d is the evaluated bias. d represents the deformation velocity.

3. FADING SIGNAL OVER DIFFERENT CLIMATES AND LAND COVERS

We chose a vegetated and humid area over Sicily, Italy as compared to an arid region in Tibetan Plateau (see [1] for details on the test site, various land covers and the data set). Over Sicily, E-StBAS schemes with bw 5 and 10 are adapted and compared with EMI and the reference PS benchmark.

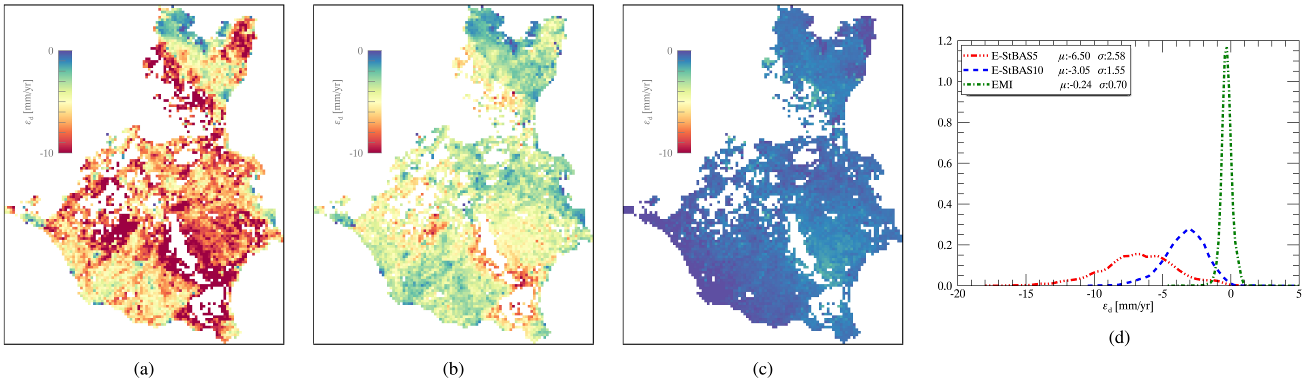

Fig. 2: Empirical deformation velocity bias from (4) over Sicily region, evaluated for (a) E-StBAS5, (b) E-StBAS10, (c) EMI. (d) Empirical probability density function (PDF) of the biases for the latter schemes.

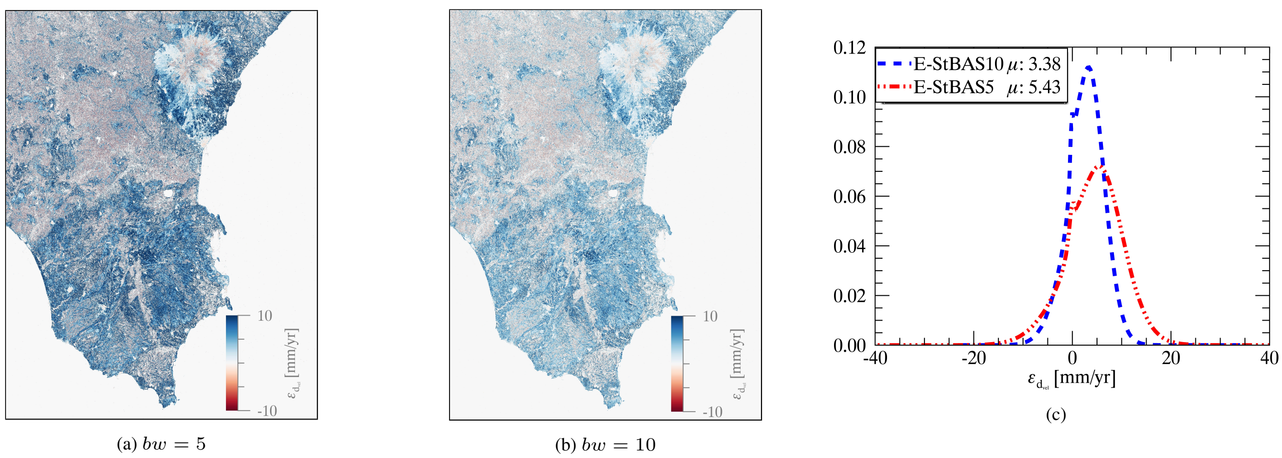

Fig. 3: Predicated deformation velocity bias from (3) over Sicily region, evaluated for (a) E-StBAS5 scheme, (b) E-StBAS10 scheme (c) the empirical PDF of spatially accumulated error measures. The deformation velocity bias is predicted as 3.38 and 5.43 mm/yr for E-StBAS10 and E-StBAS5, respectively (cf. Fig. 2). The sign change is conventional. Note that the equivalent threshold on temporal baseline for the two schemes reads as 30 and 78 days.

Fig 2 summarizes this comparison. The shorter the temporal baseline of the exploited interferograms, the more pronounced is the bias in the deformation velocity estimates. The full exploitation of all possible interferometric pairs in the time series via EMI, the mentioned bias is effectively reduced. Furthermore, the interferometric phase bias is evaluated according to (2) followed by the prediction of the velocity bias by (3). The results are provided in 3. The comparison between the prediction and empirical evaluation of the velocity bias corroborates the fact that fading signal is the source of the deformation estimation bias.

To provide a comparison over an arid climate with sparser vegetation, the velocity bias prediction is conducted for the Tibetan test site (see Fig. 4). The bias is seen to be less severe over this region, a change in the sign of the prevailing bias is observed compared to Sicily. A more curious observation is the correlation between the sign of the bias and the type of land cover, which is more clear to discern on this test site. The sign difference indicates different physical phenomena behind the induction of the fading signal [1]. For the in-depth analysis of the results, the reader is referred to [1]. For further explanation on the source of the bias and its physical interpretation see [1] and [7].

4. CONCLUSION AND RECOMMENDATIONS

In this paper we primarily focused on the observation of a peculiar systematic signal in InSAR. We conclude that:

- multilooked interferograms reveal a short-lived, systematic phase component which is absent in single-look phase observations;
- phase bias is larger for shorter temporal baseline, albeit more coherent, interferograms;
- the sign, magnitude and temporal behavior of the fading signal varies at different regions and land covers. This variability renders the calibration of the fading signal intricate;
- the propagation of even small phase biases in long time series compromises the accuracy of displacement ve-

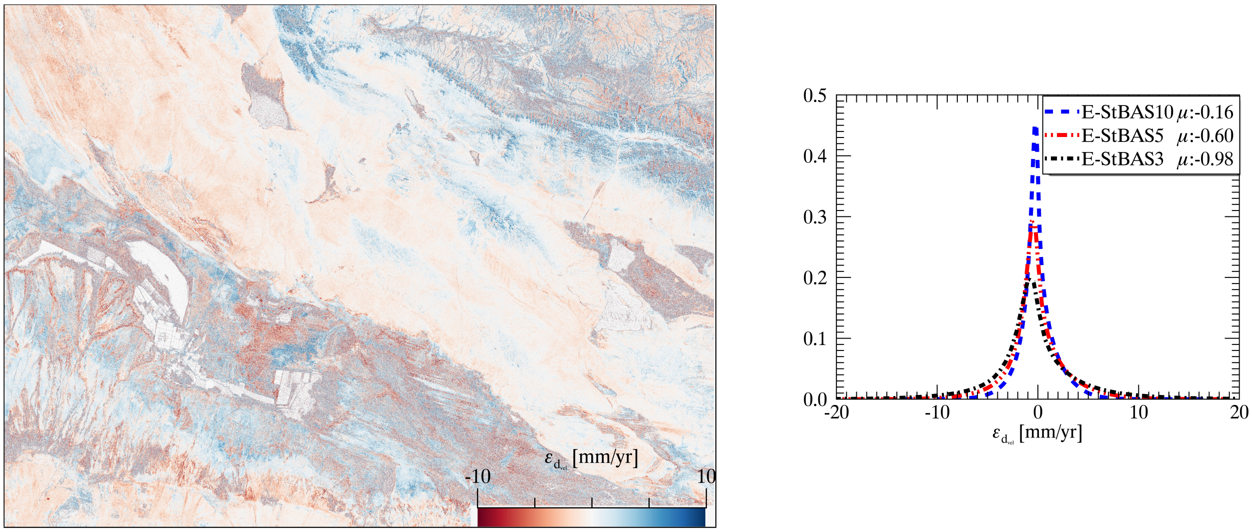

Fig. 4: Predicated deformation velocity bias from (3) over Tibet region (left) spatial error for E-StBAS5. (right) The empirical PDF of the predicted error in deformation velocity. The deformation velocity bias is predicted as -0.16, -0.60 and -0.98 mm/yr for E-StBAS10, E-StBAS5 and E-StBAS3, respectively. The corresponding threshold on temporal baseline reads as 54, 90 and 177 days, respectively.

locity maps from an achievable sub-millimetric to centimetric per year level.

The presence of phase biases have consequences for the accuracy of InSAR in deformation analysis. The problem is highly exacerbated for Big Data processing. Common practice in processing large time series is to mostly exploit the short temporal baseline interferograms; similar to the designed E-StBAS scheme. The reason is that short baseline interferograms are less affected by temporal decorrelation and believed to be more reliable for deformation estimation. However, the analysis of this paper proves that these interferograms are the most affected by the fading signal and most prone to propagate systematic errors through the time series.

Our recommendation for ensuring the accuracy in deformation monitoring is to introduce a new intermediate product level for InSAR, e.g. the reconstructed consistent wrapped phase series using EMI (as proposed in [8]). The envisioned product would:

- contain the consistent physical signal components such as, but not limited to, atmospheric variations and surface displacements;
- significantly reduce the interferometric phase bias and stochastic noise, thereby enhance the reliability of InSAR for deformation retrieval;
- reduce the amount of interferometric data from the $n(n-1)/2$ pairwise interferograms within the data stack to a time series of $n-1$ higher quality and, optionally, down-sampled interferograms;
- provide a unified product for accurate deformation monitoring to the user community.

5. REFERENCES

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