Distributed Scatterer Interferometry tailored to the analysis of Big InSAR Data

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Abstract

Wide-swath satellite missions with short revisit times, such as Sentinel-1 and NISAR, provide an unprecedented wealth of interferometric time series and open new opportunities for systematic monitoring of the Earth surface. The processing of the emerging Big Data with the state-of-the-art InSAR time series analysis techniques is, however, computationally challenging. A new demand has emerged for the analysis of the fast growing data volumes specifically for systematic near real-time (NRT) monitoring of the Earth surface. We have addressed this demand by the proposal of two efficient alternative estimators for NRT processing of the emerging Big Data in [1, 2]. In this contribution, a hybrid approach based on the proposed estimators is introduced and applied in efficient wide area processing of two-year archive of Sentinel-1 data over eastern part of the Trans-Mexican Volcanic Belt.

1 Introduction

The recent launch and planning of the global monitoring wide swath SAR missions provide an unprecedented wealth of data. The exploitation of the emerging Big Data entails a new demand on the computational efficiency of the state-of-the-art time series analysis techniques with distributed scatterers (DS) [3, 4, 5, 6]. On the one hand, the exploitation of all interferometric pairs increases the estimation efficiency in deformation monitoring. On the other hand, this processing scheme is computationally demanding, pitting the estimation efficiency against the computational efficiency. One attitude toward managing the challenges of Big Data is to resort to parallel computing and exploitation of a limited selection of moderately-coherent interferograms in the framework of Small BAseline Subset (SBAS) [7]. A second attitude is to migrate from the conventional state-of-the-art algorithms and invest on alternative estimators to exploit the wealth of data as far as possible (the importance of full exploitation of data is twofold: firstly it improves the signal to noise ratio in phase estimation and consequently enhances the sensitivity to mm-level deformation estimation; secondly, it is theoretically expected to decrease the estimation bias in presence of phase inconsistencies [8]). The design criterion for the alternative estimators shall be the optimization of the trade-off between the estimation and computational efficiency. A marriage of such alternative estimators with parallel computing, is an obvious further step toward a fully optimized scheme for efficient NRT mining of the Big Data.

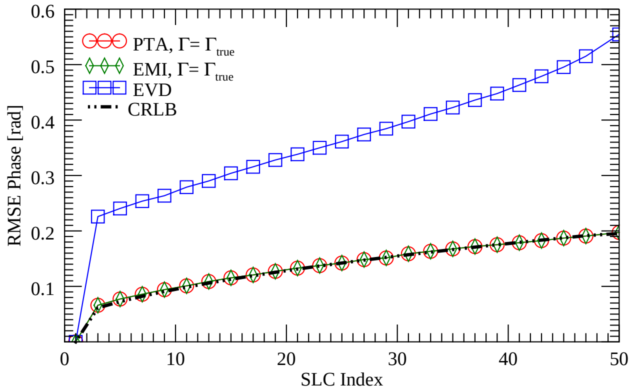
Following this design criterion, we have proposed two alternative schemes to the conventional DS interferometry. Named Sequential Estimator [1], the first proposal provides an optimum processing scheme for InSAR time series. In the reduction of the computational burden of the conventional approaches, it resorts to batch processing of the SAR time series (the data batch is hereafter referred to as mini-stack). To prevent the associated performance loss due to batch processing, the Sequential Estimator employs data compression within each mini-stack; it further forms and exploits the so-called artificial interferograms between the isolated mini-stacks. In doing so the estimator retains an estimation efficiency comparable to full-stack processing schemes [1].

The second proposed estimator aims at improving the estimation and computational efficiency for phase history retrieval. Termed Eigen-decomposition-based Maximum-likelihood-estimator of Interferometric phase (EMI) [2], the estimator reformulates the original problem of phase estimation into a Lagrangian. The solution of the resulted Lagrangian outperforms the existing state-of-the-art phase estimation approaches, both in terms of estimation and computation efficiency [2].

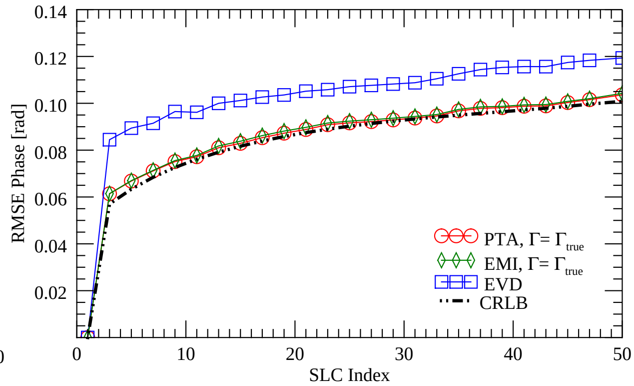
In this contribution, we propose and demonstrate the combination of the two methods, i.e. a Sequential processing scheme with EMI employed as its phase estimator. This hybrid approach improves the computational efficiency while retaining the estimation performance.

2 Hybrid Efficient Approach in Big Data Processing

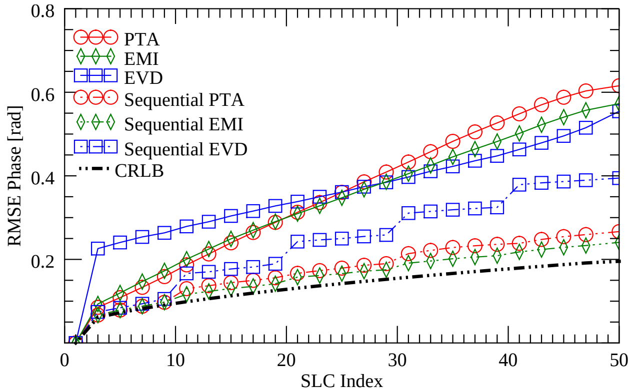
DS interferometry aims at the retrieval of systematic phase series, from all possible interferograms within a stack of coregistered SAR images. The latter phase series pertain to the topographic, deformation and atmospheric signals. The estimation of the systematic phase series is hereafter referred to as Phase-Linking (PL). Two broad conventional approaches to PL are: Phase Triangulation Algorithm [3, 4] and Eigen Value Decomposition (EVD) [5, 6]. The former follows from the Maximum Likelihood Estimation (MLE), ergo is *asymptotically* the



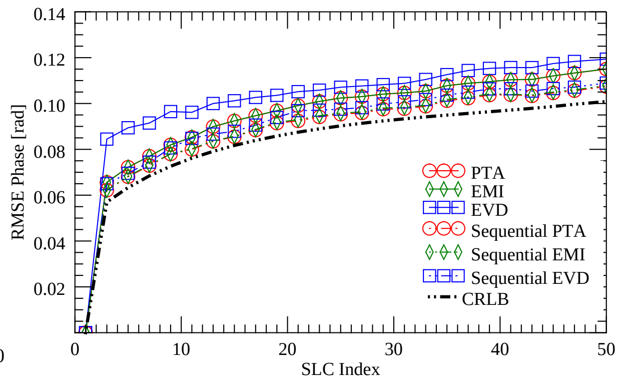
(a) exponential-decaying scenario



(b) long-term coherence scenario



(c) exponential-decaying scenario



(d) long-term coherence scenario

Figure 1: Performance assessment of different estimators compared to CRLB using simulated cases; the impact of coherence estimation error on phase estimation is studied in (a) & (b) the absence and (c) & (d) the presence of this error. In (a) (b) & (d), where coherence estimation error is absent/insignificant, EMI performs identical to PTA and EVD is shown to be suboptimum in phase estimation. Performance of the proposed hybrid method is presented as 'Sequential EMI'. Note that the hybrid method is the optimum estimator in presence of coherence estimation error, compared to the other approaches.

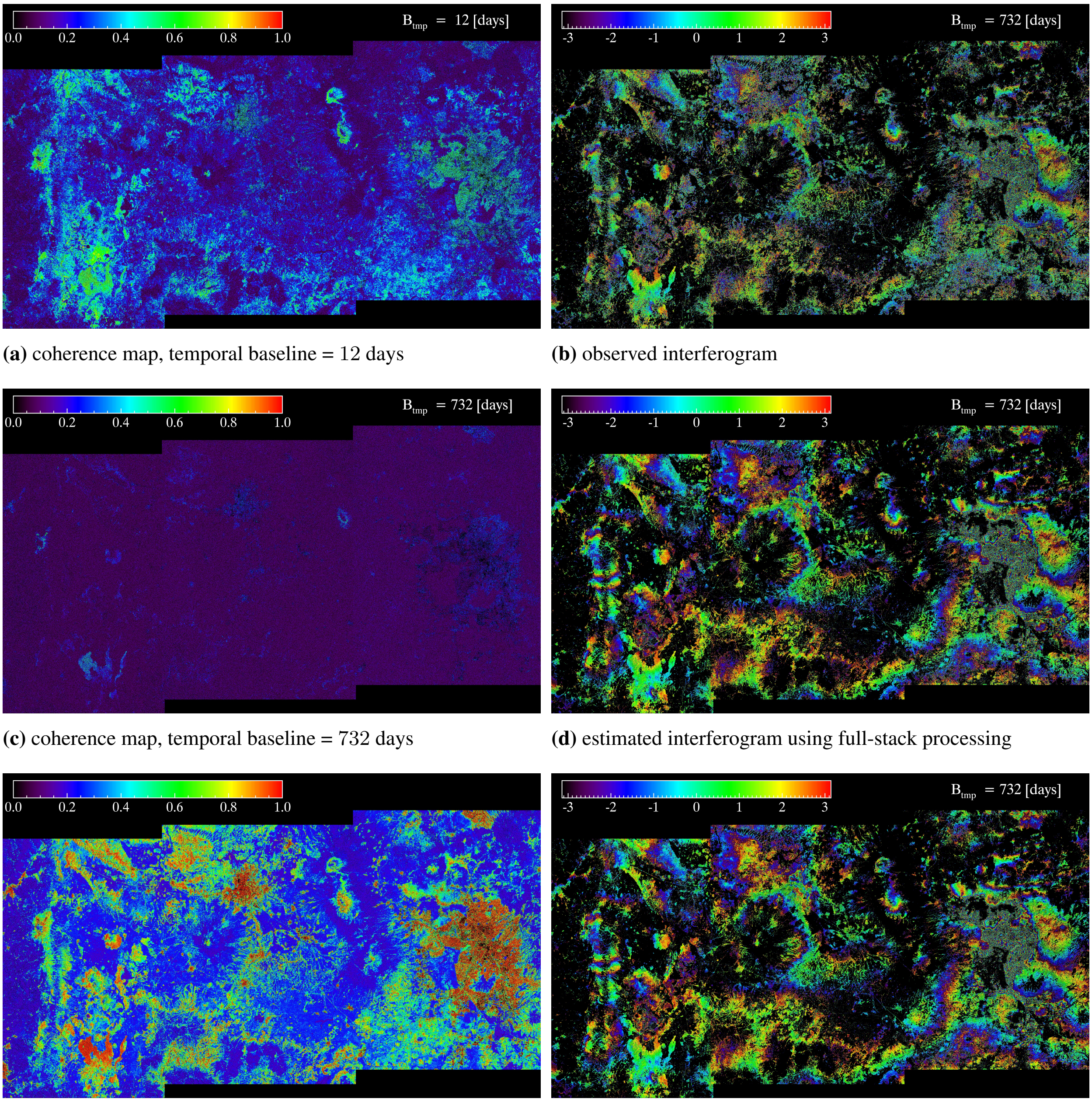
optimum estimator for PL. The latter is computationally efficient but compromises the performance in phase estimation.

Our aim is to bridge between the two mentioned PL approaches and put forward an optimum PL which enjoys both the computational efficiency of EVD and the estimation efficiency of the PTA. EMI achieves this objective[2]. It firstly proposes a new covariance model for phase estimation. Formulating an MLE with the proposed model, its efficient solution is sought through approximation of the formulated MLE and via the method of Lagrange Multipliers. Our studies in [2] indicate the comparable computational efficiency of EMI to EVD approaches and slight gain in its estimation efficiency as compared to the PTA.

The estimation and computational Efficiency of the Sequential Estimator is bound to the employed PL for the processing of each mini-stack [1]. By employing EMI as the PL of the Sequential Estimator, an efficient hybrid approach results which enjoys both estimation and computational efficiency. Using simulations, in the following the performance of EMI and the Hybrid Sequential Estimator is compared to conventional methods.

3 Validation with Simulation

For the investigations of this section, two coherence matrices are simulated following the simulation scenarios of [1]. γ_0 is set to 0.6 in both cases, while γ_∞ is respectively 0 and 0.2 for the exponential-decay and long-term coherence. Two stacks of 50 images each containing an ensemble of 300 statistically homogeneous samples are synthesized as follows: A complex circular Gaussian process is assumed; the stationarity is imposed by setting the topographic and the atmospheric induced phase components to zero; the deformation phase is simulated with a temporal linear trend with velocity of $1\ [mm/year]$; the temporal sampling, similar to Sentinel-1, is set to 6 days. As highlighted by [1], performance of PTA is affected by the well-known error in coherence estimation. In order to investigate this effect, PL is studied in two cases: In the first case, the coherence matrix $\hat{\Gamma}$ is set to the simulated coherence; representing a scenario where the coherence error is negligible. In the second case, $\hat{\Gamma}$ is set to the estimated coherence. This case is closer to reality as coherence is unknown and its estimation is inevitable. The RMSE of phase estimation is reported in Fig. 1.a and b for the former and Fig. 1.c and d for the latter case. The



(a) coherence map, temporal baseline = 12 days

(b) observed interferogram

(c) coherence map, temporal baseline = 732 days

(d) estimated interferogram using full-stack processing

(e) a posteriori coherence map, after the sequential processing

(f) estimated interferogram using sequential processing

Figure 2: Inspection of the performance of the proposed hybrid approach in phase estimation; left column: coherence map of the observed data compared to the a posteriori coherence of the estimated phases after the hybrid sequential processing. right column: observed and estimated interferograms with the longest temporal baseline of 732 days. Comparing (b) to (d) and (f) the improved SNR as a result of phase linking is apparent. Comparing (d) to (f) the agreement of the conventional and Sequential approaches is observable. In all provided interferograms and coherence maps, spatial adaptive multi-looking is considered alike. Densely vegetated areas are masked in visualization of the interferograms.

theoretical lower bound for PL is provided by Cramér-Rao Lower Bound (CRLB) [9].

As depicted in Fig. 1.a and b, in the absence of coherence estimation error, EMI and PTA perform identically and close to the CRLB, while EVD provides a suboptimum estimation deviant from the CRLB. However, the coherence estimation error degrades the performance of PL, as evident from Fig. 1.c and d. In the latter figures, two solutions are considered for the phase estimation, namely the conventional PL processing based on the full data stack, as well as the proposed Sequential Estimator employing different estimator as its PL. As evident, using EMI as its PL algorithm, the Sequential Estimator is able to slightly improve the performance and approach the CRLB. The hybrid approach is therefore seen to slightly outperform the state-of-the-art techniques in DS interferometry, while improving the computational efficiency for Big Data processing.

4 Efficient Wide Area Processing: Trans-Mexican Volcanic Belt

The performance of the proposed hybrid approach is demonstrated in processing a time series of Sentinel-1 over part of the Trans-Mexican Volcanic Belt. The data compromises of 59 SAR images spanning two years of acquisition from October 2014 to October 2016. The Sequential Estimator with EMI as its PL is considered for the efficient processing. For comparison purposes, full-stack processing with EMI is performed as well. A snapshot of the results is provided here.

4.1 Performance in Phase Estimation

The observed and estimated interferograms accompanied by their coherence maps are summarized in Fig. 2 for visual inspection. Comparing the smallest and longest temporal baseline coherence maps in subfigures (a) and (c) indicates the severe temporal decorrelation; the a posteriori coherence depicts the improved coherence as the result of the efficient phase estimation. The observed and estimated interferograms with the longest temporal baseline of 732 days are provided in the right column. Spatial adaptive multi-looking is considered for all interferograms. Comparison of subfigure (f) and (d) shows the agreement between the full-stack and the sequential approach. From the comparison of the latter interferograms with the observed interferogram in (b), the improved SNR is visually evident.

4.2 Quantitative Performance Assessment

The computational efficiency of the hybrid approach has been studied and discussed before [2, 1]. Here the focus is on quantitative assessment of the estimation efficiency for the chosen test site. The discrepancy between the estimated phases of the hybrid Sequential approach and the full-stack processing is evaluated for each processed resolution cell in the time series. The phase discrepancies consist of $r_{rg} \times r_{az}$ values in the spatial and $n-1$ values in the temporal direction. To have a statistical analysis on the performance, the $r_{rg} \times r_{az} \times (n-1)$ values are accumulated. The spatio-temporally accumulated phase discrepancies are clustered according to their respective a posteriori coherence. The normalized histogram of each cluster is presented, with its first and second order moment describing the bias and variance of the estimator, respectively (Fig. 3). The agreement of the efficient and full-stack approaches increases with the a posteriori coherence, as the quality of phase-retrieval. Note that the low coherence levels pertain to fast decorrelating regions. From simulation analysis, the Sequential Estimator is expected to outperform full-stacking techniques (cf. Fig. 1.c) in such cases. Therefore, comparison with full-stacking techniques is inconclusive for coherence of low coherence levels.

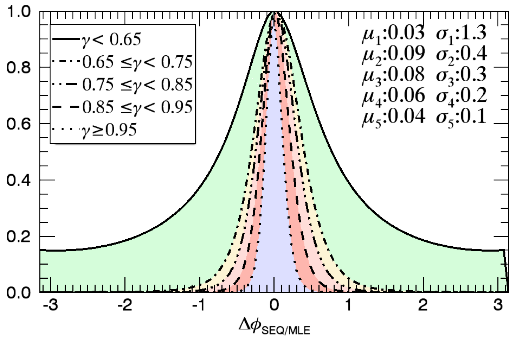


Figure 3: Quantitative performance assessment of the estimation bias and variance of the Sequential Estimator compared to full-stack processing at different a posteriori coherence levels. The bias (μ_i) and standard deviation (σ_i) of the estimator is reported relative to the a posteriori coherence.

5 Conclusions

In efficient processing of the emerging Big Data from the current and future SAR missions, we have proposed two phase estimation schemes [1, 2]. The two estimators are combined to further improve the estimation and computational efficiency of time series analysis in the realm of distributed scaterrer interferometry. The performed simulation analysis and wide area processing with 2-year archive of Sentinel-1 data demonstrate the estimation accuracy and precision of the proposed hybrid algorithm. In fast decorrelating DS regions, simulations indicate the improved performance of hybrid approach over the conventional full-stack processing. Performance assessments with real data is currently ongoing and will be reported in future communications.

References

[1] H. Ansari, F. De Zan, and R. Bamler, "Sequential Estimator: Toward Efficient InSAR Time Series Analysis," *IEEE Transactions on Geoscience and Remote Sensing*, pp. 1–16, 2017.

[2] ——, "Efficient Phase Estimation for Interferogram Stacks," *submitted to IEEE Transactions on Geoscience and Remote Sensing*.

[3] A. Monti Guarnieri and S. Tebaldini, "On the Exploitation of Target Statistics for SAR Interferometry Applications," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 46, no. 11, pp. 3436–3443, Nov. 2008.

[4] A. Ferretti, A. Fumagalli, F. Novali, C. Prati, F. Rocca, and A. Rucci, "A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 49, no. 9, pp. 3460–3470, Sep. 2011.

[5] G. Fornaro, S. Verde, D. Reale, and A. Pauciullo, "CAESAR: An Approach Based on Covariance Matrix Decomposition to Improve Multibaseline & Multitemporal Interferometric SAR Processing," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 53, no. 4, pp. 2050–2065, Apr. 2015.

[6] N. Cao, H. Lee, and H. C. Jung, "A Phase-Decomposition-Based PSInSAR Processing Method," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 54, no. 2, pp. 1074–1090, Feb. 2016.

[7] F. Casu, S. Elefante, P. Imperatore, I. Zinno, M. Manunta, C. De Luca, and R. Lanari, "SBAS-DInSAR Parallel Processing for Deformation Time-Series Computation," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 7, no. 8, pp. 3285–3296, Aug. 2014.

[8] F. De Zan, M. Zonno, and P. Lopez-Dekker, “Phase Inconsistencies and Multiple Scattering in SAR Interferometry,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 53, no. 12, pp. 6608–6616, Dec. 2015.

[9] A. Guarnieri and S. Tebaldini, “Hybrid Cramer-Rao Bounds for Crustal Displacement Field Estimators in SAR Interferometry,” *IEEE Signal Processing Letters*, vol. 14, no. 12, pp. 1012–1015, Dec. 2007.