Single-look light-burden superresolution differential SAR tomography

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Research and application is spreading of techniques of coherent combination of complex-valued synthetic aperture radar (SAR) data to extract rich information even on complex observed scenes, fully exploiting existing SAR data archives, and new satellites. Among such techniques, SAR tomography stems from multibaseline interferometry to achieve full-3D imaging through elevation beamforming (spatial spectral estimation). The Tomo concept has been integrated with the mature differential interferometry, producing the new differential tomography (Diff-Tomo) processing mode, that allows 'opening' the SAR cells in complex non-stationary scenes, resolving multiple heights and slow deformation velocities of layover scatterers. Consequently, the operational capability limit of differential interferometry to the single scatterer case is overcome. Diff-Tomo processing is cast in a 2D baseline-time spectral analysis framework, with sparse sampling. The use of adaptive 2D spectral estimation has demonstrated to allow joint baseline-time processing with reduced sidelobes and enhanced height–velocity resolution at low computational burden. However, this method requires coherent multilooking processing, thus does not produce full range-azimuth resolution products, as it would be desirable for urban applications. A new single-look adaptive Diff-Tomo processor is presented and tested with satellite data, allowing full range-azimuth resolution together with height–velocity sidelobe reduction and superresolution capabilities and the low computational burden.

Introduction: Differential synthetic aperture radar (SAR) interferometry (D-InSAR) and 3D SAR tomography (TomoSAR) are two advanced operation modes of SAR interferometry [1, 2]. The first above-mentioned is an operational interferometric technique, it is based on multiple pass satellite SAR acquisition, typically spaceborne, to accurately measure surface displacements (very small scatterer velocities) through coherent time series analysis or time rate of change estimation of the interferometric phase (temporal harmonic extraction). TomoSAR is a recently born interferometric technique [2–4], and can be set in the more general framework of coherent SAR data combination; it exploits multibaseline (MB) acquisition to perform full-3D imaging for analysis of volumetric scatterers [1, 2] or multiple point-like layover scatterers [2–4]. It is an elevation beamforming technique, i.e. vertical imaging by spectral analysis in the spatial (baseline) domain, and it constitutes a powerful evolution of standard phase-only interferometry [1, 5] for topographic mapping. It is rapidly developing and expanding including extensive experimenting with real satellite data, and is raising increasing interest for operational and planned satellite SAR missions.

More recently, an innovative interferometric (or rather coherent SAR data combination) technique synergically integrating the D-InSAR [5] and MB TomoSAR [2] concepts, termed differential SAR tomography (Diff-Tomo) or 4D (3D + time) imaging, has been proposed in [6]. Some of its potentials, deriving from the new capability of joint height–velocity resolution of multiple scattering components mapped in a same SAR pixel, have been demonstrated with real urban layover data [3]. Particular benefits from recovering differential operation in otherwise D-InSAR-missed urban layover areas or building structure details resulted, especially for modern high-resolution spaceborne SAR sensors with meter-order horizontal resolution, producing very rich yet 'garbled' information. The emerged Diff-Tomo processing (Univ. of Pisa patent) is set in a 2D baseline-time spectral analysis framework, fully exploiting the MB-multipass data. It allows separating and identifying the spatial–temporal harmonics produced by each layover scattering component characterised by its height and velocity. This technique can be set in the general field of computational imaging, and as such the kind of processing plays a fundamental role. In particular, being the baseline-time domain sampling very sparse, classical 2D (irregular) Fourier spectral analysis would produce unacceptable 2D sidelobes in the estimated height–velocity scattering power distribution [6]. Noteworthy, the use of adaptive 2D spectral analysis has been shown to enable joint baseline-time processing with sensibly reduced sidelobes and also useful height–velocity superresolution, through data-dependent 2D frequency null setting [6].

However, the good, widely known, and light burden superresolution adaptive Diff-Tomo processing is based on the use of baseline-time correlation estimates, thus requiring coherent multilooking processing for their derivation; this does not result in a differential tomographic product at the full range-azimuth data resolution. While this framework can be well suited for possible applications of Diff-Tomo for natural scenarios, multilooking can be less acceptable for applications where full range-azimuth resolution products are more desirable, typically in deformation motion estimation, e.g. from subsidence or structural tensions, of multiple layover scatterers in urban and critical infrastructure scenarios. Recently, adopting the compressive sensing method [4] has been proposed for urban tomographic processing, yet this is at the cost of a very heavy computational burden.

New single-look superresolution Diff-Tomo processing: In this Letter, a new adaptive differential tomographic processor is presented with single-look operation (single snapshot in the array processing jargon), targeting to allow full resolution in the range-azimuth plane together with the good height–velocity sidelobe reduction, and superresolution capabilities of the original multilook adaptive processing, extending the concepts in [7, 8] from 3D to 4D imaging. The goal is to make Diff-Tomo joint fast, with superresolution, and operative on a pixel by pixel basis, typically for urban applications.

Let assume to process calibrated (co-registered, atmospheric compensated, and deramped [1–3]) baseline-time data from multiple passes, with a complex SAR image acquired at each pass by a typical monostatic SAR system. Bistatic acquisition repeated in time is also recently possible from spaceborne platforms, thanks to the new tandem satellite system TanDEM-X; the described method is easily extended to this case. For each given range-azimuth resolution cell, the complex amplitudes of the corresponding observed pixels in the SAR images can be arranged in a baseline-time data vector $\boldsymbol{y}$.

In this Letter, a two-step algorithm is developed to obtain the baseline-time correlation information for the input of the adaptive processing from the single-look baseline-time data $\boldsymbol{y}$. At first, a knowledge-based non-stationary interpolator [7] is employed to reconstruct data uniformly sampled along both the baseline and the time domain, exploiting a barely light a-priori information about the multiple moving scatterers scenario. This a-priori information consists of the extent of a height sector and a deformation velocity sector in which the multiple scatterers can be contained [the so-called sector of interest (SOI) [7], here in both the height and velocity dimension]. This light a priori information is easily derivable, e.g. from general knowledge of the kind of observed scenario (such as suburb or city centre, slow or quick subsidence), or from ancillary Earth Observation or in situ data. The fully baseline-time sampled interpolated data (see Fig. 1) can be obtained as

$$\boldsymbol{y}_I = \boldsymbol{H}_\mathrm{I}\boldsymbol{y} \tag{1}$$

where $\boldsymbol{H}_\mathrm{I}$ is an interpolation matrix, derived analogously to [7] in closed form, and the interpolated data are represented in the vector stacked [6] format $\boldsymbol{y}_\mathrm{I}$.

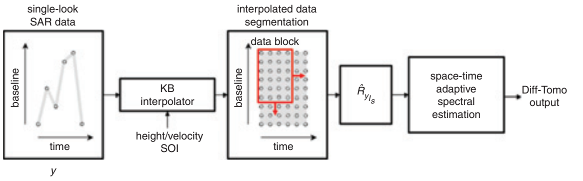

Fig. 1 *Single-look adaptive Diff-Tomo processing scheme*

Once the interpolation stage is performed, adaptive 2D spectral estimation for uniform data in a deterministic framework can be exploited. The concept is to replace the statistical coherent multilook average for the estimation of the baseline-time correlation matrix with coherent averaging in the (uniform) baseline-time domain, exploiting a segmentation step of the baseline-time interpolated data into multiple overlapped data blocks (Fig. 1), each used as a virtual look. Once the baseline-time correlation matrix $\hat{\boldsymbol{R}}_{\boldsymbol{y}_{I_s}}$ is available, the height-deformation velocity power distribution can be estimated by applying the adaptive processing, here in the hybrid spatial–temporal 2D version as follows:

$$\hat{P}(h, v) = \frac{1}{\boldsymbol{a}^\mathrm{H}(h, v)\hat{\boldsymbol{R}}_{\boldsymbol{y}_{I_s}}^{-1}\boldsymbol{a}(h, v)} \tag{2}$$

where h is the height and v is the deformation velocity. Also, $\boldsymbol{a}(h, v)$ is the so called steering vector, coding the general spatial–temporal harmonic [6], pertinent to a block of the segmented uniform data (in vector stacked format), in particular evaluated for the SAR radar wavelength, the slant range distance of the given cell, and the baseline-time sampling values of the block. In Fig. 1 the complete scheme of the new single-look processing chain is reported.

Simulated and real data processing tests: To first analyse the potentials of the new single-look Diff-Tomo processor described here, simulated data results have been obtained for a realistic satellite MB multipass acquisition pattern, that of the real C-band ERS-1/2 data used in the sequel, with total baseline of 1460 m, which corresponds to a Rayleigh height resolution limit [2] of 6.5 m, and a time span of 5 years, that results in a Fourier velocity resolution of 5.5 mm/year [6]. By setting various deformation velocity values and SNRs of multiple layover scatterers, and different a-priori information (SOI) parameters, stability of the new processing method has been checked, also for typical phase miscalibration levels [2, 8]. Here, a sample representative result is reported in Fig. 2 (right), showing a height–velocity single-look adaptive Diff-Tomo distribution for two layover scatterers (ideal point-like) with height separation below the Rayleigh resolution (sub-Rayleigh 'double scatterer'). Total SNR is 23 dB, one scatterer is located at 0 m height and is subjected to a uniform motion with velocity of −3 mm/year, the other one is 3 dB stronger than the former, is located at 5 m height, and has a deformation velocity of −2 mm/year. While Diff-Tomo with classical 2D Fourier processing [3, 6], reported in Fig. 2 (left) as a performance reference, cannot resolve the two scattering components, and is also affected by very high sidelobes, it is apparent how the two scatterers are neatly separated and their location in the height–velocity domain is well estimated by the new method. Together with the super-resolution (produced both in the height and deformation velocity dimensions), the sidelobes are strongly reduced, the peak sidelobe level (PSL) now amounting to −10 dB.

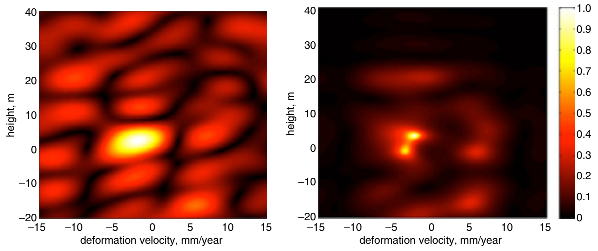

Fig. 2 *Diff-Tomo output (normalised amplitude) for sub-Rayleigh double scatterer, simulated data, left: single-look Fourier, right: single-look adaptive (same colour bar for both)*

To get a flavour of the achievable accuracy of the new single-look adaptive Diff-Tomo method, a Monte Carlo analysis has been also carried out for the case study above. The RMSEs of scatterer height and deformation velocity estimates resulted equal to 0.5 m and 0.8 mm/year, respectively, [similar to those achievable for the simpler single scatterer case by the best classical D-InSAR algorithms [5]].

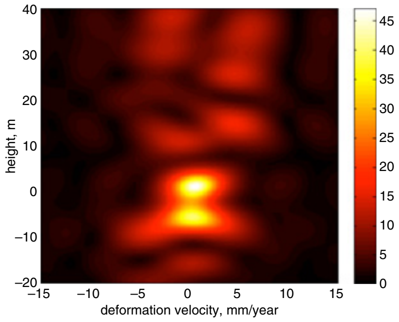

Fig. 3 *Single-look adaptive Diff-Tomo output (amplitude) for sub-Rayleigh double scatterer, real ERS-1/2 satellite data*

To prove the effectiveness of the proposed method, a first test has been also carried out with real data. The employed dataset (ack. CNR-IREA) consists of 40 ERS-1/2 SAR images acquired over a district in Rome, Italy: the Rayleigh/Fourier resolutions are 6.5 m and 5.5 mm/year, respectively, as in the simulations. Fig. 3 shows the single-look adaptive Diff-Tomo distribution for a pixel of the dataset characterised by a real sub-Rayleigh double scatterer, in the presence of real-world effects (including scatterers non-idealities). It can be noted the good achieved height/velocity super-resolution (again, plain Fourier Diff-Tomo could not resolve the two scatterers), and also the good sidelobes level (PSL of −9 dB). Comparison of the analogous velocity estimates obtained over the district area with available conventional velocity field (coarse scale) measurements derived by D-InSAR yielded small differences of about 1 mm/year standard deviation, indicating consistency of the new processing algorithm.

Conclusions: The proposed Diff-Tomo processing method can offer both low height–velocity sidelobes and good height–velocity superresolution starting from single-look non-uniform baseline-time data; the well tested adaptive superresolution processing has been successfully extended to handle the single-look data, so optimising it for urban/infrastructure applications, preserving its low computational burden. Processing time evaluations have shown that the new Diff-Tomo algorithm (with non-optimised coding) is more than 50 times faster than compressive sensing Diff-Tomo.

High-resolution spaceborne SAR sensors such as COSMO-SkyMed, TerraSAR-X, Sentinel-1, Radarsat-2, and also advanced tandem systems such as TanDEM-X, could benefit of the proposed method to possibly allow even single building monitoring.

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One or more of the Figures in this Letter are available in colour online.

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