



**Corso di Dottorato di Ricerca in
INGEGNERIA DELL'INFORMAZIONE**

Tesi di Dottorato di Ricerca

**ADVANCES AND EXPERIMENTS OF
TOMOGRAPHIC SAR IMAGING
FOR THE ANALYSIS OF COMPLEX
SCENARIOS**

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La scienza è figliola dell'esperienza che mai non falla.

Leonardo Da Vinci, 1452-1519

La filosofia è scritta in questo grandissimo libro che continuamente ci sta aperto innanzi a gli occhi (io dico l'universo), ma non si può intendere se prima non s'impara a intender la lingua, e conoscer i caratteri, ne' quali è scritto. Egli è scritto in lingua matematica, e i caratteri son triangoli, cerchi, ed altre figure geometriche, senza i quali mezzi è impossibile a intenderne umanamente parola; senza questi è un aggirarsi vanamente per un oscuro laberinto.

Galileo Galilei, 1564-1642

*Pulchra sunt quae videmus,
quae scimus pulchriora,
longe pulcherrima quae ignoramus.*

Niels Stensen, 1638-1686

Sommario

È previsto che il numero di immagini radar ad apertura sintetica (SAR) disponibili per una stessa scena aumenti esponenzialmente in futuro, grazie soprattutto agli sviluppi tecnologici nel settore. Per sfruttare completamente l'informazione contenuta in dati acquisiti in diversità (di angolo di vista, cioè con basi multiple, di tempo e di polarizzazione) allo scopo di produrre misure nuove e/o più accurate, attualmente sono in corso di sviluppo tecniche di processing che costituiscono un'evoluzione dell'ormai matura interferometria SAR a dati di sola fase. In particolare, combinando coerentemente (modulo e fase) i dati SAR, è possibile ottenere un imaging e un'estrazione di informazioni migliori della scena osservata. Tra queste tecniche, un avanzamento promettente è costituito dalla Tomografia SAR, una modalità interferometrica a basi multiple che permette l'imaging 3-D nello spazio range-azimuth-quota, separando pertanto scatteratori multipli a quote diverse (cosiddetti in layover) all'interno della stessa cella SAR in scenari complessi. Recentemente, all'Università di Pisa è nata una nuova modalità interferometrica detta Tomografia Differenziale dalla fusione sinergica tra Tomografia SAR e l'interferometria differenziale convenzionale. In questo modo, diventa possibile anche la stima delle velocità di deformazione relative tra scatteratori multipli in layover.

In questa tesi vengono presentati progressi teorici e risultati sperimentali per l'analisi di scenari complessi. In particolare, il problema dell'imaging tomografico è stato affrontato esplorando differenti opzioni algoritmiche capaci di migliorare il contrasto dell'immagine 3-D lungo l'asse di quota e, possibilmente, anche di aumentare la risoluzione. Inoltre, per automatizzare la stima delle quote o delle coppie quota/velocità di deformazione, è stato sviluppato un algoritmo di rivelazione, che può essere utilizzato anche come uno step preliminare per la validazione estensiva dell'informazione tomografica estratta. Considerando scatteratori volumetrici (come, ad esempio, la chioma degli alberi in uno scenario forestale), tecniche di combinazione coerente dei dati basate su analisi tomografiche sono state proposte ed investigate, con particolare riguardo all'estrazione della quota del terreno sotto la chioma forestale e alla derivazione non basata su modelli di un set di dati coerenti a basi multiple contenente solo lo strato in quota d'interesse. Infine, il contesto tomografico-differenziale è stato sfruttato per l'analisi tomografica robusta di scatteratori volumetrici affetti da decorrelazione temporale. Per ciascun settore applicativo investigato esperimenti estensivi sono stati condotti con dati SAR a basi multiple su scenari urbani e forestali.

Abstract

It is expected that the number of synthetic aperture radar (SAR) images available for a same scene will increase exponentially in the future, thanks to the technical developments in this area. In order to fully exploit the information lying in data acquired in looking angle (multi-baseline, MB), time, and polarization diversity, developments are underway of processing techniques which constitute an evolution of the mature phase-only SAR interferometry for producing new and/or more accurate measures. In particular, by combining coherently (i.e. amplitude and phase) the SAR data, new opportunities are arising for an improved imaging and information extraction of the observed scene. Among these techniques, a very promising advance is constituted by SAR tomography, a MB interferometric mode allowing a full 3-D imaging in the range-azimuth-height space, thus separating multiple scatterers in layover at different heights in the same SAR cell in complex scenarios. Recently, a new interferometric mode called Differential SAR Tomography has been conceived at the University of Pisa from the synergic fusion of SAR Tomography and the conventional Differential Interferometry, allowing the estimation of also the possible relative deformations between multiple layover scatterers.

In this thesis, theoretical advances and experimental results are presented in the analysis of complex scenarios. In particular, the tomographic imaging problem is addressed by exploring different algorithmic options able to enhance the image contrast and possibly also increase the scatterer resolution in height. Moreover, in order to automate the estimation of the height or height/deformation velocity, a scatterer detection algorithm has been developed, which constitutes also a preliminary step for the extensive validation of the information extracted. With regards to volumetric scatterers (e.g. the scatterer in forest scenarios), tomography-based coherent data combination techniques have been proposed and investigated, in particular for the extraction of the sub-canopy digital terrain model and for deriving in a non-model based fashion a coherent MB dataset with only the signal from the scattering layer of interest. Finally, the differential tomographic framework has been exploited for the robust tomographic analysis of temporal decorrelating volumetric scatterers. For each investigated topic, extensive experiments have been carried out with MB urban and forest SAR data.

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Contents

| | |
|--|------------|
| Sommario | III |
| Abstract | V |
| Acknowledgements | VII |
| List of Figures | XI |
| List of Tables | XIX |
| List of Symbols and Operators | XXI |
| List of Acronyms and Abbreviations | XXV |
| 1 Introduction | 1 |
| 1.1 Synthetic aperture radar imaging | 1 |
| 1.2 SAR interferometry | 2 |
| 1.3 Multidimensional imaging: SAR Tomography and Differential SAR Tomography | 4 |
| 1.4 Contributions and outline of the thesis | 7 |
| 2 3-D SAR Tomography: Concept and Imaging Techniques | 11 |
| 2.1 The SAR Tomography concept | 11 |
| 2.2 Characterization of the achievable precision limits | 14 |
| 2.3 High contrast adaptive imaging | 18 |
| 2.3.1 Theoretical background of adaptive imaging | 19 |
| 2.3.2 Experiments with real urban data | 20 |
| 2.3.3 Experiments with real forest data | 30 |
| 2.4 Knowledge-based imaging | 42 |
| 2.4.1 Derivation of the interpolation matrix | 44 |
| 2.4.2 Simulated and real data experiments | 46 |
| 2.5 SAR Tomography with low bandwidth data | 51 |
| 2.6 Conclusions | 60 |
| | IX |

| | | |
|----------|--|------------|
| 3 | Scatterer Identification with Tomo-SAR in Urban Scenarios | 65 |
| 3.1 | Scatterer detection | 65 |
| 3.2 | Experiments with real spaceborne data | 74 |
| 3.3 | Conclusions | 79 |
| 4 | SAR Tomography-Based Techniques for the Analysis of Volumetric Scatterers | 83 |
| 4.1 | Estimation of the sub-canopy DEM in forest scenarios | 83 |
| 4.2 | Separation and estimation of the reflectivity of the scattering layers | 93 |
| 4.3 | Conclusions | 104 |
| 5 | Differential Tomographic Imaging for Non-Stationary Scenarios | 113 |
| 5.1 | The differential SAR tomography concept | 113 |
| 5.2 | Characterization of the achievable precision limits with the Diff-Tomo processing | 115 |
| 5.2.1 | A study case: CRLB for DEM estimation with MB-multitemporal data | 116 |
| 5.3 | Scatterer identification with the adaptive differential tomographic imaging . . | 122 |
| 5.4 | Differential tomography for the analysis of temporal decorrelating volumetric scatterers | 140 |
| 5.4.1 | MUSIC profiling of temporal decorrelating volumes | 140 |
| 5.4.2 | A generalization of the MUSIC algorithm | 143 |
| 5.4.3 | Experiments with real data | 145 |
| 5.5 | Conclusions | 152 |
| 6 | Conclusions and Perspectives | 155 |
| | References | 157 |
| | List of Publications | 165 |

List of Figures

| | | |
|------|---|----|
| 1.1 | - Examples of urban and forest layover geometries. | 5 |
| 2.1 | - Reference MB acquisition geometry; for the sake of simplicity, in this sketch acquisitions are aligned along z | 12 |
| 2.2 | - Performance prediction: example of Tomo-SAR CRLB and HCRBs on scatterer height estimation for two scatterers in layover. | 18 |
| 2.3 | - Simulated tomographic responses to a stable scatterer with $SNR = 25$ dB. | 20 |
| 2.4 | - Rome dataset, Cinecittà area. Red dashed lines in the radar image indicate the azimuth lines at constant range in which vertical tomographic experiments have been carried out. | 23 |
| 2.5 | - Example of the typical buildings present in the test suburban area. | 24 |
| 2.6 | - From top to bottom: BF and ABF tomographic slices extracted in correspondence of the four dashed azimuth lines of Fig. 2.4, saturated amplitudes. | 25 |
| 2.7 | - From top to bottom: BF and ABF tomographic slices extracted in correspondence of the four dashed azimuth lines of Fig. 2.4, normalized amplitudes w.r.t. the multibaseline averaged data power. | 26 |
| 2.8 | - From top to bottom: BF and ABF tomographic slices extracted in correspondence of the four dashed azimuth lines of Fig. 2.4, normalized amplitudes w.r.t. the multibaseline averaged data power. | 27 |
| 2.9 | - Examples of BF and ABF profiles reported in normalized amplitudes. | 28 |
| 2.10 | - BF range-azimuth sections extracted at four different vertical heights, amplitudes. | 29 |
| 2.11 | - ABF range-azimuth sections extracted at four different vertical heights, amplitudes. | 30 |
| 2.12 | - Realizations of tomographic profiles; canopy centroid height 13 m; HH-like case. | 34 |
| 2.13 | - Realizations of tomographic profiles; canopy centroid height 23 m; HH-like case. | 36 |
| 2.14 | - BioSAR-I dataset, Google Earth and radar image, Remningstorp forest site (Sweden). | 37 |
| 2.15 | - Az. 1050 m: nominal height PSF. | 38 |

| | |
|---|----|
| 2.16 - Az. 1050 m: BF tomographic slice without phase recalibration, HH polarization. | 38 |
| 2.17 - Az. 1050 m: normalized BF profiles extracted in correspondence of the corner reflector (rg. 455 m) before and after phase recalibration, HH polarization. | 39 |
| 2.18 - Az. 1050 m: BF tomo images, HH polarization. | 39 |
| 2.19 - Az. 1050 m: ABF tomo images, HH polarization. | 40 |
| 2.20 - Az. 1050 m: BF and ABF profiles extracted in correspondence of the corner reflector after the sparse grid phase recalibration, HH polarization. | 40 |
| 2.21 - Az. 1050 m: BF and ABF profiles extracted in correspondence of a forested cell after the sparse grid phase recalibration, HH polarization. | 40 |
| 2.22 - Az. 1050 m: BF and ABF tomo images, sparse grid recalibration, HV polarization. | 41 |
| 2.23 - Az. 1050 m: BF and ABF profiles extracted in correspondence of the same forested cell of Fig. 2.21 after the sparse grid phase recalibration, HV polarization. | 41 |
| 2.24 - Az. 2380 m: BF and ABF tomo images, sparse grid recalibration, HH polarization. | 42 |
| 2.25 - Az. 2380 m: BF and ABF tomo images, sparse grid recalibration, HV polarization. | 42 |
| 2.26 - Az. 2380 m: BF and ABF profiles extracted in correspondence of a forested cell after the sparse grid phase recalibration, HV polarization. | 42 |
| 2.27 - PSF before and after interpolation. $K = 5$, spatial lags [0, 1.7, 3.2, 4.1, 7], $K_V = 8$ | 47 |
| 2.28 - Tomo profiles before and after interpolation. $K = 13$, spatial lags [0, 2, 2.96, 4, 5.024, 5.92, 8.04, 9.04, 10.12, 12, 16.52, 18.08, 24], $K_V = 25$ | 48 |
| 2.29 - Tomographic profile of two compact speckled scatterers in thermal noise before and after interpolation, with the same tomographic array of Fig. 2.28. The SOI measures 12 height r.u. The result of the more classical IBF has been reported for comparison. | 48 |
| 2.30 - PSF before and after (robust) interpolation, with and without calibration errors. $K = 43$, spatial lags in Tab. 2.1, $K_V = 15$ | 50 |
| 2.31 - PSF before and after (robust) interpolation, with calibration errors, and in presence of non exact knowledge of the calibration error standard deviation. $K = 43$, spatial lags in Tab. 2.1, $K_V = 15$, $\sigma_e = 0.04$ | 50 |
| 2.32 - Tomographic profile of two compact speckled scatterers in thermal noise before and after interpolation, with miscalibration errors, and with monostatic and bistatic acquisitions. $K = 43$, spatial lags in Tab. 2.1, $K_V = 15$, $\sigma_3 = 0.04$ | 51 |
| 2.33 - Profiles of compact scatterers before and after interpolation corresponding to two SAR cells of the dataset over the city of Rome (last slice of Fig. 2.6). Single look processing. $K = 43$, spatial lags in Tab. 2.1, $K_V = 15$ | 52 |
| 2.34 - Single look BioSAR-I image at the emulated satellite resolution (saturated amplitudes). | 52 |
| 2.35 - Az. 1050 m: ABF tomo images with full and satellite data (saturated amplitudes). | 53 |

| | |
|--|----|
| 2.36 - Az. 2380 m: ABF tomo images with full and satellite data (saturated amplitudes). | 54 |
| 2.37 - Perspective effects for a volumetric layer with a high (Case 1) and low (Case 2) range resolution, range-elevation plane. | 54 |
| 2.38 - Perspective effects on a flat terrain patch due to finiteness of the radar bandwidth. | 55 |
| 2.39 - Geometric interpretation of the spectral shift. | 56 |
| 2.40 - Mapping of the SAR system bandwidth to ground range frequencies. The common band used for interferometry is shaded in yellow. | 56 |
| 2.41 - Azimuth-averaged ground reflectivity spectrum in near range for the baseline 0 m and 80 m of the BioSAR-I dataset. For the sake of convenience, the spectral domain has been converted in MHz. Given this frequency conversion, we stress again that the change of the looking angle between the two images has not caused a shift of the radar bandwidth. Instead, it causes a shift of the ground reflectivity spectra. | 57 |
| 2.42 - Az. 1050 m: ABF tomo images after CB pre-filtering of satellite emulated data (saturated amplitudes). | 58 |
| 2.43 - Az. 2380 m: ABF tomo images after CB pre-filtering of satellite emulated data (saturated amplitudes). | 58 |
| 2.44 - Limit condition for the selection of a common bandwidth W_C | 59 |
| 2.45 - Orthogonal-to-critical baseline ratio as a function of the range for the 80 m horizontal baseline of the BioSAR-I dataset. | 60 |
| 2.46 - Az. 1050 m: ABF tomo images with $W = 14.7$ MHz before and after CB pre-filtering (normalized amplitudes). | 61 |
| 2.47 - Az. 2380 m: ABF tomo images with $W = 14.7$ MHz before and after CB pre-filtering (normalized amplitudes). | 62 |
| | |
| 3.1 - Map of the eigenbased estimates of the number of multiple scatterers over the urban area around the San Paolo stadium of the city of Naples (9 looks). Data have been acquired by the ERS-1 and ERS-2 satellites in the period 1997-1998. | 67 |
| 3.2 - Mean values of the estimated $SNRs$ of 5 hypothetical scatterers in presence of miscalibrations, with $N_S = 2$ as a function of the SNR as a function of the SNR of one scatterer. Blue continuous line: true scatterers; red dashed lines: other scatterers (overfitting). | 68 |
| 3.3 - Mean value of the fitting error ϵ_F (in %) as a function of the number of estimated components with $N_S = 2$, for the non-uniform baseline distribution, and for different values of SNR | 70 |
| 3.4 - Block scheme of the proposed hybrid ABF-model fitting in the complex data domain algorithm for model order selection. | 71 |
| 3.5 - Detection performance of the ABF-LS hybrid detection method for a single non-compact scatterer corrupted by residual miscalibrations ($\sigma_e = 0.04$). Refer to text for other details. | 72 |
| 3.6 - Detection performance of the ABF-LS hybrid detection method for two non-compact scatterer with equal SNR corrupted by residual miscalibrations ($\sigma_e = 0.04$). Refer to text for other details. | 73 |

| | | |
|------|---|-----|
| 3.7 | - Scatterers identified (red dots superimposed on the single look radar image) with the robust ABF-LS over the Cinecittà area of the city of Rome, 5 azimuth looks processing. | 75 |
| 3.8 | - Concept of double scatterers separation through the geocoding of their coordinates. | 75 |
| 3.9 | - Geocoded single scatterers locations (red dots) superimposed to a technical map, 5 az. looks processing. | 76 |
| 3.10 | - Geocoded double scatterers locations (blue and red dot pairs) superimposed to a technical map, 5 az. looks processing, detailed area of Fig. 3.9. Red dots: dominant scatterers; blue dots: secondary scatterers. | 77 |
| 3.11 | - ABF tomografic slices corresponding to the top and bottom slices of Fig. 2.6, processed by averaging 3 azimuth looks, and reported in saturated amplitudes. | 77 |
| 3.12 | - Scatterers identified (red dots superimposed on the single look radar image) with the robust ABF-LS over the Cinecittà area of the city of Rome, 3 azimuth looks processing. | 78 |
| 3.13 | - Histograms of the height differences of the identified double scatterers. . . . | 79 |
| 3.14 | - Scatterplots and two dimensional histograms of the estimated heights of the common scatterers with 3 and 5 looks processing. | 80 |
| 3.15 | - Histograms of the estimated SNRs. | 81 |
| 4.1 | - DTM estimated with full resolution HH data. | 84 |
| 4.2 | - Comparison between SAR and LIDAR DTMs after offset compensation. . . . | 85 |
| 4.3 | - DTM error histogram (full resolution data). | 85 |
| 4.4 | - DTM estimated with full resolution HV data. | 86 |
| 4.5 | - DTM estimated with HV data by means of the double peak method. | 87 |
| 4.6 | - Scatterplots between height estimates obtained with different polarizations and methods. The red line has been plotted as reference, and it indicates the perfect correlation between estimates. | 88 |
| 4.7 | - DTM estimated with a plain single-baseline InSAR processing (baseline 30 m). | 89 |
| 4.8 | - Histograms of the height error between the DTMs estimated by means of ABF and InSAR. | 90 |
| 4.9 | - DTM estimated with M-RELAX. | 92 |
| 4.10 | - DTM estimated with COMET. | 92 |
| 4.11 | - Values of the Rao test decision statistics (a) and model order detection mask (b). White pixels correspond to the bald areas. | 94 |
| 4.12 | - DTM estimated with M-RELAX after the model order selection process. . . . | 94 |
| 4.13 | - DTM estimated with COMET after the model order selection process. . . . | 94 |
| 4.14 | - Overall proposed processing chain for layer cancellation. | 95 |
| 4.15 | - Schematic view of a filtering process with a vector filter. | 96 |
| 4.16 | - Schematic view of a filtering process with a matrix filter. | 96 |
| 4.17 | - Filter response as a function of the height expressed in resolution units, near range case, centroid separation 25 m, ground (pass band, green) and canopy (stop band, red) sector widths 20 m. | 99 |
| 4.18 | - Az. 1050 m: ABF tomographic slice before and after cancellation, HH data, centroid separation 25 m, ground and canopy sector widths 20 m. . . . | 100 |

| | | |
|------|--|-----|
| 4.19 | - Az. 1050 m: ABF tomographic slice before and after cancellation, HH data, centroid separation 25 m, ground and canopy sector widths 20 m. . . . | 100 |
| 4.20 | - Az. 2380 m: ABF tomographic slice before and after cancellation, HH data, centroid separation 25 m, ground and canopy sector widths 20 m. . . . | 101 |
| 4.21 | - Az. 2380 m: ABF tomographic slice before and after cancellation, HH data, centroid separation 25 m, ground and canopy sector widths 20 m. . . . | 101 |
| 4.22 | - Filter response as a function of the height expressed in resolution units, near range case, centroid separation 15 m, ground sector (pass band, green) width 4 m, canopy sector (stop band, red) width 20 m. | 102 |
| 4.23 | - Az. 1050 m: ABF tomographic slice before and after cancellation, HH data, centroid separation 15 m, ground sector width 4 m, canopy sector width 20 m. | 102 |
| 4.24 | - Az. 1050 m: ABF tomographic slice before and after cancellation, HH data, centroid separation 15 m, ground sector width 4 m, canopy sector width 20 m. | 103 |
| 4.25 | - Az. 2380 m: ABF tomographic slice before and after cancellation, HH data, centroid separation 15 m, ground sector width 4 m, canopy sector width 20 m. | 103 |
| 4.26 | - Az. 2380 m: ABF tomographic slice before and after cancellation, HH data, centroid separation 15 m, ground sector width 4 m, canopy sector width 20 m. | 104 |
| 4.27 | - Original, ground and canopy reflectivities obtained with full resolution HH data. | 105 |
| 4.28 | - Original, ground and canopy reflectivities obtained with full resolution HV data. | 106 |
| 4.29 | - Layer reflectivity statistics of full resolution HH data. | 106 |
| 4.30 | - Layer reflectivity statistics of full resolution HV data. | 107 |
| | | |
| 5.1 | - Formation of the global array from two arrays belonging to two different passes. | 116 |
| 5.2 | - CRLB as a function of SNR with $\Delta c = 0$ and complete correlation/decorrelation between passes. | 120 |
| 5.3 | - CRLB as a function of SNR with $\Delta c = 90$, for different geometric decorrelations and different decorrelation between passes, and φ_t known. Two-passes case. | 121 |
| 5.4 | - CRLB as a function of SNR with $\Delta c = 90$ m, $\chi = 1$ and $b = 0.05$, with φ_t known/unknown. Two-passes case. | 121 |
| 5.5 | - CRLB for an alternating bistatic acquisition, as a function of SNR for different decorrelation between passes, with $b = 0.05$, and φ_t known. Two-passes case. | 121 |
| 5.6 | - CRLB for a bistatic acquisition, with $b = 0.05$, and φ_t known. Ten-passes case. | 122 |
| 5.7 | - Baseline-time sampling pattern and PSF of the 30-track dataset over Naples. 125 | |
| 5.8 | - Baseline-time sampling pattern and PSF of the 63-track dataset over Naples. 127 | |

| | | |
|------|--|-----|
| 5.9 | - Simulated Tomo and Diff-Tomo ABF profiles of a single scatterer with a residual of deformation velocity of 3 mm/yr. | 128 |
| 5.10 | - Estimated Diff-Tomo spectra (in dB) of two simulated point-like targets at a height difference below the Rayleigh resolution limit and with a relative motion. | 128 |
| 5.11 | - Range-azimuth images of the Naples dataset. | 129 |
| 5.12 | - Picture captured with Google Streetview of the typical buildings present in the analyzed area of Naples. | 130 |
| 5.13 | - Diff-Tomo spectra of a single point-like scatterer in the “Mergellina” area. . | 130 |
| 5.14 | - Diff-Tomo spectra of a double scatterer on a flank of the San Paolo stadium. | 130 |
| 5.15 | - Photo of a flank of the San Paolo stadium. The metallic structure giving rise to the layover phenomenon of Fig. 5.14 is well visible. | 131 |
| 5.16 | - Color coded estimated velocities of the single and double scatterers, and locations of the triple scatterers, superimposed on the radar image. | 132 |
| 5.17 | - Color coded estimated velocities of the single and double scatterers on the selected test area. The color coding is the same of Fig. 5.16. | 133 |
| 5.18 | - Deformation velocity differences of the detected single scatterers on the test area with respect to available independent D-InSAR measurements, superimposed to the radar image. The color coding is the same of Fig. 5.16. . . | 134 |
| 5.19 | - Normalized histograms of the deformation velocity differences shown in Fig. 5.18. | 134 |
| 5.20 | - Histogram of the height differences of the identified double scatterers with the 30-track dataset. | 135 |
| 5.21 | - Example of Diff-Tomo spectra (in dB) of a double scatterer with sub-Rayleigh height difference on a flank of the San Paolo stadium detected with the 30-track dataset. | 135 |
| 5.22 | - Histogram of the estimated SNR difference (in dB) between double scatterers. | 136 |
| 5.23 | - Color coded estimated velocities of the single and double scatterers, and locations of the triple scatterers, superimposed on the radar image, 3 azimuth looks processing. Color coding is the same of Fig. 5.16. | 137 |
| 5.24 | - Scatterplots and two-dimensional histograms of the estimated velocities of the common scatterers with 3 and 5 looks processing. | 138 |
| 5.25 | - Scatterplots and two-dimensional histograms of the estimated heights of the common scatterers with 3 and 5 looks processing. | 138 |
| 5.26 | - Map and normalized histogram of the deformation velocity differences w.r.t. available independent D-InSAR measurements of the detected single scatterers with the Rome dataset. The color coding of the velocity map is the same of Fig. 5.16. | 139 |
| 5.27 | - Baseline-time acquisition pattern used for the simulations (circle: monostatic, cross: multistatic). | 141 |
| 5.28 | - Long-term temporal decorrelation. | 141 |
| 5.29 | - Tomo-SAR MUSIC pseudo-spectra in absence of temporal decorrelation. . | 141 |
| 5.30 | - Tomo-SAR MUSIC pseudo-spectra in presence of temporal decorrelation. . | 142 |
| 5.31 | - Spatial-temporal spectral support. | 143 |
| 5.32 | - Diff-Tomo MUSIC pseudo-spectrum, multistatic acquisition. | 143 |
| 5.33 | - Diff-Tomo DSPE pseudo-spectrum, multistatic acquisition. | 145 |
| 5.34 | - Tomo-SAR DSPE pseudo-spectra in presence of temporal decorrelation. . . | 146 |

| | |
|--|-----|
| 5.35 - Baseline-time acquisition pattern and corresponding Diff-Tomo PSF of the BioSAR-I dataset. | 146 |
| 5.36 - Estimated temporal coherence at different time intervals. | 147 |
| 5.37 - Diff-Tomo pseudo-spectra and Tomo-SAR extracted profiles (az. 1050 m, rg. 547.5 m). | 148 |
| 5.38 - Az. 1050 m: Tomo-SAR profiles extracted from the Diff-Tomo spectra at $\omega_t = 0$ | 149 |
| 5.39 - Az. 2380 m: Tomo-SAR profiles extracted from the Diff-Tomo spectra at $\omega_t = 0$ | 150 |
| 5.40 - Height difference between top of the canopy and ground heights measured from LIDAR data. | 151 |
| 5.41 - Height difference map between the canopy and the ground scattering centroid estimated with M-RELAX from the HV MB data. | 152 |
| 5.42 - Histogram of the estimation error RADAR–LIDAR. | 152 |



List of Tables

| | | |
|-----|--|-----|
| 2.1 | - Orthogonal baselines and acquisition times of the ERS-1/2 dataset over the Cinecittà area of the city of Rome. | 21 |
| 2.2 | - System parameters used for the statistical analysis. | 31 |
| 2.3 | - Parameters characterizing the acquisition; b is the orthogonal-to-critical baseline ratio. | 31 |
| 2.4 | - Estimation performance of the layer centroid heights obtained with BF and ABF; canopy centroid height 13 m; HH-like case. | 33 |
| 2.5 | - Estimation performance of the layer centroid heights obtained with BF and ABF; canopy centroid height 13 m; HV-like case. | 35 |
| 2.6 | - CRLB expressed in m on the estimation of the layer centroids, reported in meters; canopy centroid height 13 m. | 35 |
| 2.7 | - Estimation performance of the layer centroid heights obtained with BF and ABF; canopy centroid height 23 m; HH-like case. | 35 |
| 2.8 | - CRLB expressed in m on the estimation of the layer centroids, reported in meters; canopy centroid height 23 m. | 36 |
| 4.1 | - ABF dominant peak method: standard deviations of the estimated DTMs w.r.t. the LIDAR DTM for different datasets and for different polarizations. | 87 |
| 5.1 | - Typical parameters of the TanDEM-X system used for the CRLB analysis. | 119 |
| 5.2 | - Orthogonal baselines and acquisition times of the ERS-1/2 30-track dataset over the suburban area surrounding the San Paolo Stadium in the city of Naples. | 125 |
| 5.3 | - Orthogonal baselines and acquisition times of the ERS-1/2 63-track dataset over the suburban area surrounding the San Paolo Stadium in the city of Naples. | 126 |

List of Symbols and Operators

With \hat{a} we indicate an estimate of the unknown deterministic parameter a . Vectors are denoted with lower-case boldface letters (e.g. \mathbf{a}), while matrices are upper-case (e.g. \mathbf{A}). The k -th element of a vector is indicated with $[\mathbf{a}]_k$, while the (l, m) -th element of a matrix with $[\mathbf{A}]_{l,m}$.

| | |
|-------------|--|
| x | Azimuth coordinate |
| y | Ground range coordinate |
| z | Vertical height coordinate |
| r | Slant range coordinate |
| s | Elevation (normal-to-slant range) coordinate |
| v | Deformation velocity on the line-of-sight direction |
| Δx | Azimuth resolution |
| Δz | Vertical height (Rayleigh) resolution |
| Δr | Slant range resolution |
| Δs | Elevation (Rayleigh) resolution |
| Δv | Velocity (Fourier) resolution |
| θ | Elevation (look) angle, measured between the line-of-sight and the z -axis |
| W | Radar chirp bandwidth |
| λ | Radar wavelength |
| H | Radar platform altitude |
| $g(x, r)$ | Complex amplitude SAR image after focusing at given range and azimuth coordinates |
| $g_k(x, r)$ | k -th complex amplitude SAR image of a stack after focusing at given range and azimuth coordinates |
| $y_k(x, r)$ | k -th complex amplitude SAR image of a stack after deramping and calibration |

| | |
|-------------------------------|--|
| K | Total number of SAR images in a stack |
| $\mathbf{y}(n)$ | Data vector at the n -th look in a multilook SAR cell, containing the complex amplitudes y_k for the homologous pixel in the image stack |
| N | Total number of looks in a multilook cell |
| $R_k(r, s)$ | Distance between target and sensor at the k -th SAR image of a stack |
| $f(x, r)$ | Range-azimuth point-spread function |
| $\gamma(x, r, z)$ | 3-D radar reflectivity function |
| $\bar{\gamma}(s, v)$ | Radar reflectivity function in the elevation-deformation velocity plane |
| $\mathbf{P}_\gamma(\omega_s)$ | Intensity distribution along elevation |
| φ | Interferometric phase |
| b_\perp | Component of the baseline between two images in the direction orthogonal to the line-of-sight |
| $b_{\perp k}$ | Component of the baseline between the k -th image of a stack and the master image in the direction orthogonal to the line of sight |
| $b_{\parallel k}$ | Component of the baseline between the k -th image of a stack and the master image in the direction parallel to the line of sight |
| B_C | Critical baseline |
| b | Orthogonal-to-critical baseline ratio |
| ϕ | Baseline tilt angle, measured between the baseline and the y -axis |
| ω_s | Spatial frequency (directly proportional to the elevation coordinate) |
| $\mathbf{a}(\omega_s)$ | Spatial steering vector calculated for the frequency ω_s |
| N_S | Number of scatterers in layover in the same SAR cell |
| P_i | Backscattered power of the i -th scatterer in layover |
| SNR | Signal-to-noise ratio |
| SNR_i | Signal-to-noise ratio of the i -th scatterer |
| $\omega_{s,i}$ | Spatial frequency of the i -th scatterer in layover |
| \mathbf{R}_y | Covariance matrix of vector $\mathbf{y}(n)$ |
| \mathbf{R}_i | Covariance matrix of the i -th speckle vector |
| $E\{\cdot\}$ | Statistical expectation operator |
| $\text{tr}\{\cdot\}$ | Matrix trace operator |
| $\mathbf{b}_i(n)$ | Realization of the speckle vector of the i -th scatterer in layover at the n -th look |
| $\mathbf{v}(n)$ | Additive thermal noise vector, at the n -th look |
| σ_v^2 | Power of the thermal noise |
| \mathbf{A}_i | Diagonal steering matrix of the i -th scatterer in layover |
| FIM | Fisher information matrix |
| $\text{diag}\{\cdot\}$ | Diagonal operator |
| \odot | Shur-Hadamard product |
| \otimes | Kronecker product |

| | |
|--|--|
| $\text{vec}\{\cdot\}$ | vectorization operator |
| $(\cdot)^H$ | Hermitian operator |
| $(\cdot)^T$ | Transpose operator |
| $(\cdot)^*$ | Complex conjugate operator |
| $\tilde{\mathbf{e}}$ | Vector containing the phase errors due to calibration residuals |
| \mathbf{e} | Vector containing the calibration residuals expressed in λ -units |
| \mathbf{R}_e | Covariance matrix of vector \mathbf{e} |
| σ_e^2 | Power of the calibration residuals |
| \mathbf{FIM}_H | Hybrid FIM |
| $\mathbf{h}(\omega_s)$ | Filter coefficient vector of ABF |
| δ | Loading factor for ABF |
| Δf | Amount of spectral shift in range (m^{-1}) |
| W_C | Bandwidth (MHz) used for common band pre-filtering |
| $\mathbf{y}_I(n)$ | Data vector after interpolation |
| K_V | Number of SAR images in the interpolated data stack |
| \mathbf{H}_I | Interpolation matrix |
| $\Lambda(\mathbf{y}; \xi)$ | Likelihood function of the data vector as a function of the parameter vector ξ |
| λ_k | k -th eigenvalue of the data covariance matrix |
| $m_A(\cdot)$ | Arithmetic mean operator |
| $m_G(\cdot)$ | Geometric mean operator |
| $\alpha(n)$ | Vector containing the complex amplitudes of each scatterer in layover at the n -th look |
| $\alpha_i(n)$ | Vector containing the complex amplitudes of the i -th scatterer in layover at the n -th look |
| $\varepsilon_F(m)$ | Least-squares fitting error after the estimation of m scatterers |
| P_{CE} | Probability of model order correct estimation |
| P_{OE} | Probability of model order overestimation |
| P_{ME} | Probability of missed model order estimation |
| Δ_z | Extension in vertical height of a scattering layer |
| $\mathbf{y}_F(n)$ | Data vector after filtering |
| \mathbf{H}_F | Matrix filter |
| $d(s, t_k)$ | Deformation (m) in the line-of-sight direction at time t_k |
| ω_t | Temporal frequency (directly proportional to the velocity) |
| $\omega_{t,i}$ | Temporal frequency of the i -th scatterer in layover |
| $\mathbf{a}(\omega_{s,i}, \omega_{t,i})$ | Spatial-temporal steering vector of the i -th scatterer in layover |
| ϕ_t | Collective phase shift from one pass to the other of the radar platform |
| \mathbf{R}_t | Element-wise multiplicative contribution to the total data covariance matrix due to temporal changes |



List of Acronyms and Abbreviations

| | |
|-----------|---|
| ABF | Adaptive Beam Forming |
| 2-D ABF | 2-D (space-time) Adaptive Beam Forming |
| AIC | Akaike Information Criterion |
| ATI-SAR | Along-track SAR interferometry |
| BF | BeamForming (Fourier-based) |
| 2-D BF | 2-D (space-time) BeamForming |
| CB | Common Band |
| COMET | COvariance MAtching Estimation Techniques |
| CRLB | Cramér-Rao Lower Bound |
| DEM | Digital Elevation Model |
| Diff-Tomo | Differential SAR Tomography |
| D-InSAR | Differential InSAR |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) |
| DTM | Digital Terrain Model |
| DOA | Direction Of Arrival |
| DSPE | Distributed Signal Parameter Estimator |
| EDC | Efficient Detection Criteria |
| ERS-1/2 | European Remote Sensing satellite 1/2 |
| ESA | European Space Agency |
| EXIP | EXtended Invariance Principle |
| FIM | Fisher Information Matrix |
| HCRB | Hybrid Cramér-Rao Bound |
| IBF | Interpolated Beam Forming |
| InSAR | SAR interferometry |
| ITC | Information Theoretic Criteria |
| LIDAR | LIght Detection And Ranging |

| | |
|-------------|---|
| LS | Least-Squares |
| 2-D LS | 2-D (space-time) Least Squares |
| MB | MultiBaseline |
| ML | Maximum Likelihood |
| M-RELAX | Multilook RELAXation algorithm |
| 2-D M-RELAX | 2-D (space-time) Multilook RELAXation algorithm |
| MDL | Minimum Description Length |
| MUSIC | MUltiple SIgnal Classification |
| 2-D MUSIC | 2-D (space-time) MUltiple SIgnal Classification |
| NLA | Non-uniform Linear Array |
| Pol-InSAR | Polarimetric InSAR |
| PSF | Point-Spread Function |
| PSI | Persistent Scatterer Interferometry |
| PSL | Peak Sidelobe Level |
| RELAX | RELAXation algorithm |
| SAR | Synthetic Aperture Radar |
| SOI | Sector Of Interest |
| std | standard deviation |
| SVD | Singular Value Decomposition |
| Tomo-SAR | SAR Tomography |
| VHF | Very High frequency |
| XTI-SAR | Across-track SAR Interferometry |
| w.r.t. | with respect to |