UNIVERSITÀ DI PISA
Scuola di Dottorato in Ingegneria "Leonardo da Vinci"

Corso di Dottorato di Ricerca in
INGEGNERIA DELL'INFORMAZIONE

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

Matteo Pardini

Anno 2010

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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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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 omologous 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
$\overline{\gamma}(s,v)$	Radar reflectivity function in the elevtion-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
$E\{.\}$	Statistical expectation operator
$\mathrm{tr}\{.\}$	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
$\mathrm{diag}\{.\}$	Diagonal operator
$\odot$	Shur-Hadamard product
$\otimes$	Kronecker product

$\mathrm{vec}\{.\}$	vectorization operator
$(.)^H$	Hermitian operator
$(.)^T$	Transpose operator
$(.)^*$	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
$m_A(.)$	Arithmetic mean operator
$m_G(.)$	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