Adaptive Digital Beam-Forming Algorithm for High-Resolution, Wide-Swath Synthetic Aperture Radar

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Abstract

Intensive research is currently ongoing in the field of Smart Multi-Aperture Radar Techniques (SMART) for high-resolution wide-swath Synthetic Aperture Radar (SAR) imaging. This work investigates the possibility of applying direction of arrival estimation methods to spaceborne SMART SAR systems, that employ receive beam steering. A novel algorithm based on the actual spatial distribution of the received signal power is analyzed by Monte Carlo simulation versus the main system parameters. Its performance is compared with that of the conventional Scan-On-Receive approach. The Cramér Rao Lower Bound is also reported as a benchmark on the achieved performance.

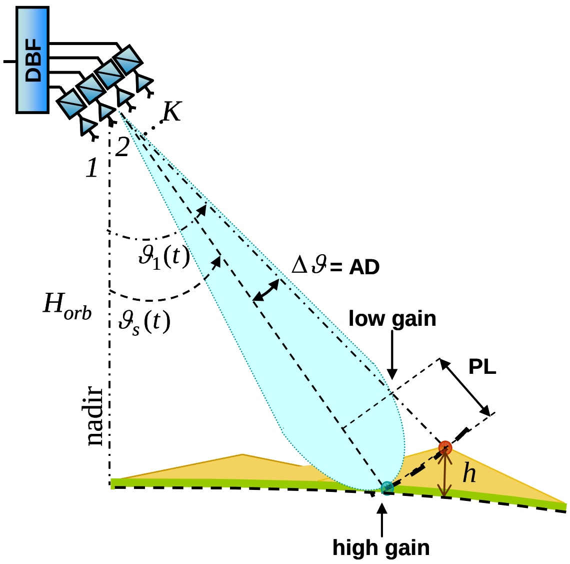

Fig. 1. SCORE in the presence of elevation, *h*.

PARAMETER	UNIT	VALUE
Geometry		
Orbit Height	km	520
Antenna Tilt Angle (β)	deg	32.25
Swath Limits (off-nadir ang., ground range)	deg km	[29.6, 34.9] [300, 370]
Radar Parameters		
PRF	Hz	1775
RF Center Frequency	GHz	9.65
Pulse Bandwidth	MHz	250
TX Antenna		
Height	m	0.50
Length	m	2.45
RX Antenna		
Height (H_a)	m	1.5
Nr. of sub-apert. in el. (K)		15 (x 0.10 m)
Length	m	9.8
Nr. of sub-apert. in az.		7

Tab. 1. Reference system parameters.

Introduction

Spaceborne SAR for remote sensing applications is experiencing a golden age. Nevertheless the current generation of spaceborne SAR does not allow for high resolution imaging and, simultaneously, wide coverage [1]. The importance to overcome this basic limitation has motivated an intensive research on the so called SMART systems, i.e. new SAR systems employing multiple transmit/receive channels and Digital Beam-Forming (DBF) techniques [1-3].

Among SMART SAR, the system proposed by Suess et al. [3], denoted as HRWS combines the flexibility offered by a multi-channel architecture with a limited download data volume. The HRWS SAR system is based on an algorithm for steering the elevation beam pattern, called Scan-On-Receive (SCORE): a wide swath is illuminated by using a small transmit antenna; whereas on reception a large multi-channel antenna and DBF are employed to obtain a sharp and high gain pattern, which follows the pulse echo as it travels along the ground swath. The steering direction of the receive pattern corresponds to the expected direction of arrival (DOA) of the echo, which is assumed *a priori* known. In particular, according to [3], it is computed under the hypothesis of a stringent spherical Earth model, i.e. no topographic height is taken into account. Under this assumption, the DOA of the received echo is univocally related to each slant-range position, i.e. to each instant of the recorded time-window. Nevertheless, in the presence of topographic height, there is a displacement between the actual DOA and SCORE steering (maximum gain) direction (see Fig. 1).

In [6] it was shown that losses of several dB could occur when no information about topographic height is conveyed in the steering mechanism. This observation suggested the option to compute adaptively the steering direction of the receive beam, by processing the signals available from the vertical sub-apertures of the multi-channel receive antenna. In [7] a novel algorithm for receive beam steering, the Adaptive Digital Beam-Forming (ADBF), based on the estimation of the actual DOA of the received echo was proposed. The ADBF performance was analyzed by Monte Carlo (MC) simulation versus the imaged scene parameters, proving the capability of ADBF to overcome SCORE limitations [6, 7]. In this paper, the analysis is further developed by focusing on the dependence of the ADBF performance on the SAR systems parameters. In particular, the ADBF performance is computed versus those parameters, such as dimension of the antenna and number of sub-apertures, whose value is bound by physical and economical constraints and strongly affects the complexity of ADBF itself.

Adaptive Digital Beam-Forming

According to the adaptive approach, as for the conventional SCORE, a sharp receiving beam is synthesized by processing the signal received by the multiple sub-apertures through the DBF technique. Nevertheless, in the adaptive case, the steering direction is no more assumed *a priori* known, but corresponds to the estimated DOA of the echo at each instant of the recorded time-window.

The problem of estimating the DOA of the echo is addressed by analyzing the signals obtained from the vertical sub-apertures, after performing onboard range compression and coregistration. These two “pre-processing” steps allow to trace back the wideband signal impinging on the receive antenna to the narrowband model [4]. Then, the DOA of the echo is estimated by using fast estimation methods conceived for narrowband signals: Beamforming and Capon are considered [4].

In order to easily explain the approach, consider the chirp echo received from a point-like target located at slant range distance R^{tx} and R_1^{rx} from the transmit and first receive sub-aperture, respectively. After demodulation, range compression and coregistration to the first channel, the complex samples, recorded by the K receive channels and corresponding to the two-way time-delay $(R^{tx}+R_1^{rx})/c_0$, can be written as [6, 7]:

$$\mathbf{y} = \alpha \cdot \mathbf{a}(\vartheta_1) + \mathbf{v}, \tag{1}$$

where, α is a complex amplitude, which accounts for the backscattering, propagation and processing mechanism; $\mathbf{y}$, $\mathbf{a}$, and $\mathbf{v}$ are K-dimensional complex vectors, whose $k-th$ element is associated to the $k-th$ sub-aperture. In particular, $\mathbf{v}$ represents the thermal noise contribute; $\mathbf{a}$ denotes the spatial steering vector and collects the information related to the DOA, ϑ_1, corresponding to the point-like target location (see Fig. 1). For the HRWS receiver, whose sub-apertures are displaced according a Uniform Linear Array geometry, the $k-th$ element of $\mathbf{a}$ is given by [6]:

$$\left[\mathbf{a}(\vartheta_1)\right]_k = \exp\left\{-j2\pi \frac{d}{\lambda}\sin(\beta-\vartheta_1)(k-1)\right\}, \tag{2}$$

where $k=1$, …, K; d denotes the array inter-element spacing; λ the carrier wavelength; β the tilt angle of the receive antenna measured with respect to nadir.

The signal in eq. (1) complies with the array model of narrowband signals [4]. In fact, the recorded samples at each channel differ only by a phase term, independent of the bandwidth of the echo and equivalent to the propagation delay over the array of a planar waveform with wavelength λ and DOA ϑ_1. Multiple, equivalent, independent observations, or "snapshots", of the data in (1) can be obtained by subsequent azimuth acquisitions. Note that, for typical system parameters, a number of snapshots below 70 allows neglecting the variations of the DOA and range cell migration associated with the slightly different acquisition geometry.

The availability of multiple, $N \geq K$, snapshots allows for proper estimation of the data covariance matrix. Then the actual DOA, ϑ_1, can be estimated by computing Beamforming or Capon functionals, and selecting the DOA, $\hat{\vartheta}_1$, corresponding to their maximum [4].

It is worth noting that steering the receive beam in the estimated DOA corresponds to directing it towards the instantaneous centre of the chirp signal. In order to properly deal with long chirp signals, a further frequency dependent beam spreading has to be considered, as it is done for the conventional SCORE algorithm [3]. In this paper we neglect this frequency dispersion and assume that both adaptive and conventional approaches allow to retrieve the energy of the echo without losses, if the receive beam has been locked to the centre of the chirp.

Data Model

The signal in eq. (1) should be generalized to account for extended targets and eventual (due to range ambiguity or layover) multiple simultaneously received echoes. In this work, we assume homogeneous backscattering all over the illuminated swath, and constant topographic height along the isorange surface delimited by the range cell size and by the mainlobe aperture of azimuth pattern. Then, eq. (1) can be rewritten as [5, 6]:

$$\mathbf{y}(n) = \sum_{i=1}^{N_s} \sqrt{\tau_i}\, \mathbf{a}(\vartheta_i) \otimes \mathbf{x}_i(n) + \mathbf{v}(n), \quad n = 1, \cdots, N \tag{3}$$

where, $\otimes$ denotes the Hadamard (element by element) product; N the number of snapshots; N_s the number of simultaneously received, extended, homogeneous backscattering sources, ($i = 1$ is the useful echo); $\mathbf{v}$ the thermal noise contribute, modeled as a complex Gaussian spatially white process, with zero mean and power σ_v^2; $\mathbf{a}$ the spatial steering vector; ϑ_i the source DOA, modeled as an unknown constant; τ_i the radar reflectivity, or texture, modeled as a real, positive, unknown deterministic parameter; $\mathbf{x}_i$ the speckle, modeled as complex correlated Gaussian random vector with a zero mean, unit variance and covariance matrix $\mathbf{C}_i$; with $\mathbf{x}_i(n_p)$ independent of $\mathbf{x}_i(n_q)$ when $n_p \neq n_q$, for $i = 1, \cdots, N_s$. The speckle is assumed strongly correlated at the array sensors (triangular shaped covariance sequence, height normalized to the critical one in the order of 10^{-4} [6]).

Numerical Results

The HRWS SAR system described in Tab. 1 is considered. Moreover, a reference acquisition scenario is assumed. It is characterized by the following parameters: N_s = 2 backscattering sources, i.e. the useful signal (*i*=1) and the closest range ambiguity (*i*=2), with a DOA of 30.15° and 39.60° off-nadir angle, respectively, and a topographic height of 3000 m; the signal-to-noise ratio at the output of the array, $ASNR_i = K\ \tau_i / \sigma_v^2$, associated with the useful source and the ambiguity is 9 dB and 3 dB, respectively; the number of snapshots, N, is 50. Starting from this reference scenario, the performance of SCORE and ADBF are evaluated versus each single parameter of interest, by keeping constant the value of the other parameters. The results corresponding to the reference scenario are indicated by an asterisk in each figure.

SCORE and ADBF performance are evaluated by: Angular Displacement (AD), i.e. the difference between the actual DOA and the steering direction, $AD = \Delta\vartheta = \vartheta_1 - \vartheta_s$; Pattern Loss (PL), i.e. the value of the receive pattern, steered towards ϑ_s, which weights a signal coming from the actual DOA, ϑ_1, normalized to the maximum of the pattern (see Fig. 1):

$$PL = C_{\vartheta_s}^{R}(\vartheta_1) \Big/ C_{\vartheta_s}^{R}(\vartheta_s) \,, \tag{4}$$

where $C_{\vartheta_s}^{R}(\vartheta)$ is the value of the elevation receive beam pattern, steered towards ϑ_s and computed at the elevation angle ϑ. Note that SCORE steering direction is a deterministic quantity [3]; whereas ADBF steering direction is a random variable, i.e. the estimated DOA, $\hat{\vartheta}_1$. The ADBF performance is evaluated by MC simulation (10^4 trials): the AD as the root mean square error of $\hat{\vartheta}_1$; the PL as an average of the two losses computed on the patterns steered in $(\vartheta_1 + \mu_{\hat{\vartheta}_1}) \pm \sigma_{\hat{\vartheta}_1}$, where $\mu_{\hat{\vartheta}_1}$ is the bias and $\sigma_{\hat{\vartheta}_1}$ the standard deviation of $\hat{\vartheta}_1$. The Cramér Rao Lower Bound (CRLB) performance is also reported as a benchmark [6]: the AD is the square root of the CRLB on $\hat{\vartheta}_1$, $\sqrt{CRLB\{\hat{\vartheta}_1\}}$; the PL is computed on the two patterns steered in $\vartheta_1 \pm \sqrt{CRLB\{\hat{\vartheta}_1\}}$.

Fig. 2 reports the AD versus the number of sub-apertures, when the receive antenna height is kept constant. The ADBF performance proves to be satisfactory also for a low number of elements. Nevertheless, it is worth noting that, when K decreases, the inter-element spacing, d, grows and the DOA unambiguous range (UR), $[\beta - \arcsin(\lambda/2d), \beta + \arcsin(\lambda/2d)]$, reduces. In particular, for $K = 8$ and $K = 4$, the ambiguity and the signal collapse on the same DOA. This makes the computation of the CRLB bad conditioned; moreover if the two signals would not be superimposed but just closer, a degraded ADBF performance would be expected. In general, the SAR system should be designed such that the UR covers the swath extension and possibly the location of the first ambiguity.

In Fig. 3 the AD is computed versus the antenna height, by keeping the inter-element spacing, i.e. the UR, constant and by modifying K. ADBF strongly outperforms SCORE also for $K = 4$. The results obtained versus the antenna height with a constant $K = 15$ (not reported for lack of space) shows an invariance of the ADBF performance with respect to Fig. 3, confirming that $K = 15$ provides a redundant information.

It is worth stressing that Fig. 3 is obtained with a constant ASNR. Nevertheless, in general, if a subset of the sub-apertures is employed (this is the case of $K < 15$), the ASNR reduces and consequently the estimation performance degrades. Fig. 4 shows the performance computed, as in Fig. 3 by keeping d constant and modifying K, but changing the ASNR: here the SNR at each element of the array, $SNR = ASNR / K$, is constant. Fig. 4.a shows that DOA estimation performance is satisfactory also when a low number of elements is used: with $K = 4$ the AD of the ADBF is around $0.22°$. The corresponding receive pattern can be synthesized by using the whole receive antenna ($H_a = 1{,}5\ m$, $K = 15$), so that the antenna gain does not change: the PL is almost negligible (Fig. 4.b).

Conclusions

The ADBF algorithm, based on a data-adaptive receive pattern steering mechanism, has been recently proposed to overcome the limitations of conventional SCORE in the presence of topographic height [6, 7]. Here the ADBF has been further analyzed by MC simulation versus those instrument parameters, whose value strongly affects the complexity and cost of the SMART SAR system and of the ADBF itself. The results show that satisfactory performance could be reached by using a small sub-set of the available sub-apertures, only *4* elements prove to be enough, with advantageous reduced complexity of the ADBF.

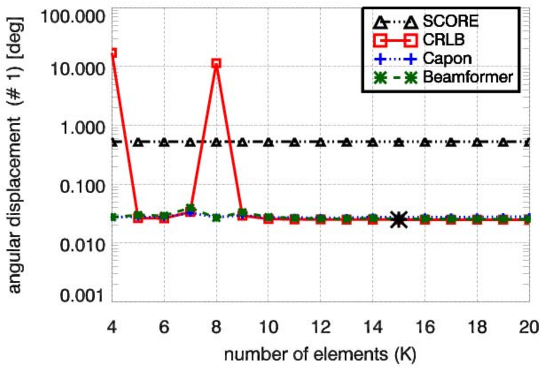

Fig. 2. AD vs. the number of sub-apertures used for DOA estimate (H_a = $1.5\ m$).

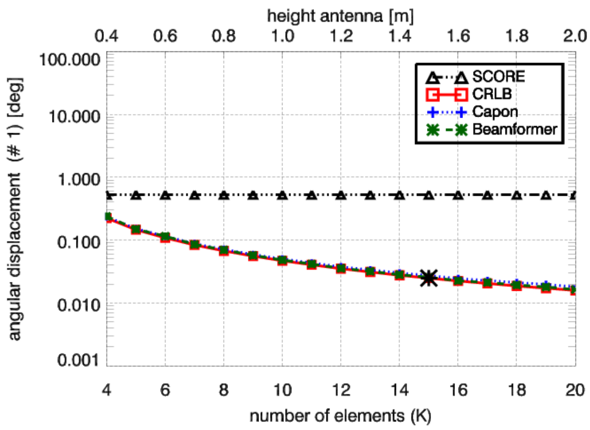

Fig. 4.a. AD vs. the number of sub-apertures and corresponding antenna height used for DOA estimate ($d = 0.1\ m$, SNR_1=$-2.76\ dB$, SNR_2=$-8.76\ dB$, $ASNR_i$=$K\cdot SNR_i$ varies).

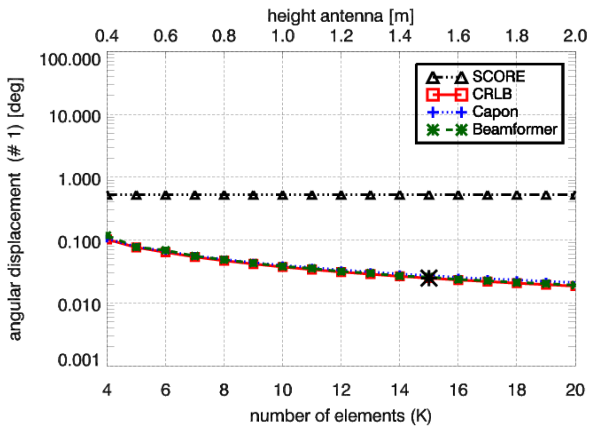

Fig 3. AD vs. the number of sub-apertures and corresponding antenna height used for DOA estimate ($d = 0.1\ m$, $ASNR_1 = 9\ dB$, $ASNR_2 = 3\ dB$).

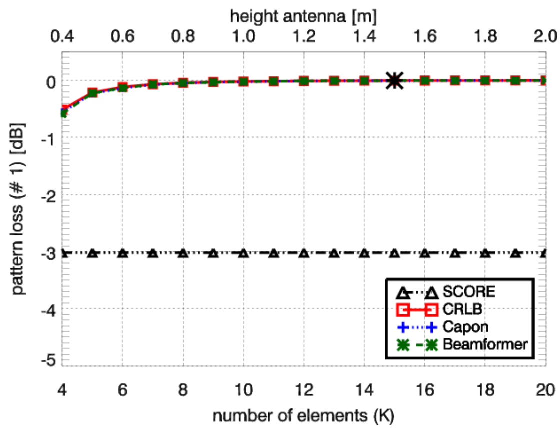

Fig. 4.b. PL vs. number of sub-apertures and corresponding antenna height used for DOA estimate ($d = 0.1\ m$, SNR_1= $-2.76\ dB$, SNR_2= $-8.76\ dB$, $ASNR_i$=$K\cdot SNR_i$ varies). The receive pattern is synthesized by using the whole receive antenna (H_a=$1{,}5\ m$, K =15).

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