Feasibility Study of Along-track SAR Interferometry with the COSMO-Skymed Satellite System

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Abstract—**Currently, particular interest is growing on spaceborne along-track synthetic aperture radar interferometry (ATI-SAR). In this work, we investigate the possibility of applying the ATI-SAR technique to the Italian COSMO-SkyMed satellite system with the latest hardware concept of split antenna mode. A preliminary study on the possible achievable accuracy on current velocity and coherence time estimation, as a function of environmental and radar parameters, is developed, based on Cramér-Rao lower bound analysis and physical signal models. Possible multibaseline ATI configurations are included in the study. First results are presented about the choice of the optimal split configuration.**

Keywords- synthetic aperture radar interferometry, ocean currents, coherence time, multibaseline, multichannel

I. INTRODUCTION

COSMO-SkyMed is a constellation of small satellites developed by Alenia Spazio for Earth observation, see Fig.1 [1]. The launch of the first satellite is scheduled for 2005, and the constellation should be fully sent into orbit for 2007. The system is designed for monitoring the Mediterranean area. In particular, applications will include land environmental disaster controlling and damage assessment; monitoring of coastlines, seas and internal waters; agricultural monitoring; and topographic mapping, using Synthetic Aperture Radar (SAR) images with a resolution in the order of one meter and reduced revisit times over the observed sites. Currently, particular interest is growing on spaceborne Along-Track SAR Interferometry (ATI-SAR) and a few studies have been carried out on this topic (Interferometric Pendulum, SRTM, TerraSAR-X, etc.), see e.g. [2]. The application of an ATI-SAR mode to COSMO-SkyMed would provide the system of additional sensing capabilities about the sea surface, like surface current patterns, velocity variations, coherence time, turbulence phenomena [2, 3]. This information is important for monitoring the coast wash and for a prompt answer to environmental threats, like oil spills. In this framework, a feasibility study is being carried out under contract of the Italian Space Agency (ASI) on possible integration of ATI functionalities in COSMO-SkyMed. The implementation of ATI-SAR requires the availability of at least two separate SAR phase centres, in order to acquire SAR images of the same sea scene, separated by a time-lag. This can be obtain by splitting along the horizontal direction the single SAR antenna [2]. COSMO-SkyMed is provided by a X-band phased array antenna, composed of five separated electrical panels, for a total length of 5,6 m [1]. The modular nature of the antenna makes the system fit for ATI-SAR, while the short length of the antenna and hence of the achievable baseline is a critical factor. The COSMO-SkyMed maximum achievable acquisition time-lag is on the order of 0,5 ms, while the ATI time-lag should ideally be around 10 times longer [2], in order to optimally measure the current velocity and sea coherence. In fact, the coherence time is not shorter than 10 ms, in X-band. As a consequence, the images are not affected by coherence loss, but the short acquisition time-lag results in a low interferometric sensitivity and makes the system vulnerable to thermal noise. Fortunately, the high spatial resolution of COSMO-SkyMed (the nominal value is 3mx3m in StripMap mode), allows to reduce noise, by filtering over many pixels (looks), keeping an acceptable final resolution. Nevertheless, in particular acquisition conditions, the backscattered power can fall below the instrument noise level (NESZ), making the system performance challenging. This acquisition conditions are set by environmental parameters, like the wind velocity and direction, and by geometric radar features like the incidence angle. Final performance also depends on the baseline length, the phase centre number, the number of looks. As a consequence, in order to make the most of ATI-SAR performance, it is essential a preliminary study of the possible achievable accuracy on current velocity and coherence time estimation, as a function of these environmental and radar quantities. This first work analyzes COSMO-SkyMed split mode ATI performance for varying wind velocity and a few possible split antenna configurations. The models employed for scattering and coherence time prediction are physical-based. The impact of the antenna splitting in terms of possible signal-to-noise ratio loss is accounted for through the proper SAR radar equation. Estimation performance prediction is based on Cramér-Rao Lower Bound (CRLB) analysis from information theory, also including possible multibaseline configurations [4].

II. SPLIT ANTENNA MODE

COSMO-SkyMed is provided by an active phased array antenna, composed of five horizontal electrical panels of eight vertical tiles each (length 5.6 m, height 1.4 m). The modular nature of the antenna allows obtaining a multiple channel system, by splitting the antenna horizontal aperture in sub-arrays. The number and distance of the synthesized phase centers depend on the split antenna mode: the transmission can be standard (STTX) or alternate (ALTX), by using a variable

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number of panels; the reception can be on two or more phase centers, composed by a variable number of panels [5].

III. Statistical Data Model

Consider a multibaseline ATI-SAR satellite system with K two-way phase centres aligned to form a uniform linear array (ULA). The baseline length B is defined as the distance between the first and the last phase centre in the array. Assume that N independent looks are available. In the typical range of satellite incidence angles, the Bragg scattering mechanism dominates, and, in the upwind and downwind conditions considered herein, the pixel complex amplitudes collected from the array of K sensors for the nth look can be modelled as [4, 6]

$$\mathbf{y}(n) = \sqrt{\sigma^2}\,\mathbf{A}\mathbf{x}(n) + \mathbf{v}(n), \quad n=1,2,\ldots, N, \tag{1}$$

where $\mathbf{y}(n)$, $\mathbf{v}(n)$, and $\mathbf{x}(n)$ are K-dimensional complex vectors, and $\mathbf{A}$ is a $K \times K$ matrix. In details, $\mathbf{v}(n)$ models the white thermal noise with power σ_v^2; σ^2 is the received backscattering power of the Bragg source, which depends on the size of the resolution cell, the radar wavelength and polarization, the local incidence angle, the local wind intensity and direction [7,8], and the SAR radar equation; vector $\mathbf{x}(n)$ represents a multiplicative speckle distortion affecting the backscattering Bragg source. For up- and down-wind, it is modelled as a complex-valued correlated Gaussian process, with zero mean, unit power, and Gaussian shaped autocorrelation [3,6]

$$[\mathbf{C}]_{i,l} = \exp\left\{-\left(\frac{(l-i)\,\tau}{(K-1)\,\tau_c}\right)^2\right\}, \tag{2}$$

where τ and τ_c are the acquisition time lag, and the sea coherence time, respectively;

$$\mathbf{A} = diag\{\,1 \;\cdots\; \exp[\,ji\varphi/(K-1)] \;\cdots\; \exp[\,j\varphi]\} \tag{3}$$

is the steering matrix, where φ is an unknown deterministic parameter representing the interferometric phase, i.e., the phase difference between the two furthest phase centres in the array [4,6]. If the wind velocity, u, and direction are given, the knowledge of the interferometric phase is related to the current surface velocity v_s as

$$v_s = \frac{\lambda v}{4\pi B \sin\vartheta_i}\;\varphi + C, \tag{4}$$

where λ is the radar wavelength, v the platform speed, ϑ_i the incidence angle, and C a constant accounting for net Bragg wave velocity and possible tilt modulation effects. As a result of the above assumptions, the data vector $\mathbf{y}(n)$ is Gaussian distributed, with zero mean and covariance matrix

$$\mathbf{R} = E\{\mathbf{y}(n)\mathbf{y}^H(n)\} = \sigma^2\mathbf{A}\mathbf{C}\mathbf{A}^H + \sigma_v^2\mathbf{I}. \tag{5}$$

The interest here is to evaluate the achievable estimation performance of the surface velocity, v_s, and coherence time, τ_c, when σ^2, $\mathbf{C}$ and possibly σ_v^2 are unknown nuisance parameters. In the particular case of K=2, τ_c is not identifiable if thermal noise level is unknown [3,4]. In this case, σ_v^2 is assumed known by online periodic calibrations.

IV. CRLB Analysis

In this section, we derive an evaluation of the COSMO-SkyMed achievable ATI performance, as a function of the radar and environmental parameters. Information theory states that any unbiased estimator has variance greater than or equal to the CRLB value [9]. In our problem, the CRLB can be assumed as the effective estimation variance, since asymptotically efficient estimators are used in ATI [3,4] and operation with a large number of looks is expected [2]. If $\boldsymbol{\chi}$ is the P-dimensional vector of unknown parameters, the CRLB on the parameter $\chi_i = [\boldsymbol{\chi}]_i$, for i=1, …, P, is obtained as the ith diagonal element of the inverse of the Fisher Information Matrix (FIM),

$$CRLB(\chi_i) = [\mathbf{J}_{FIM}^{-1}]_{i,i}, \tag{6}$$

where $\mathbf{J}_{FIM}$ is the FIM. The FIM for a complex Gaussian random vector, with zero mean and covariance matrix $\mathbf{R}$, is a real, symmetric matrix constructed as [9]

$$[\mathbf{J}_{FIM}]_{i,j} = N\,\mathrm{tr}\left\{\mathbf{R}^{-1}\frac{\partial\mathbf{R}}{\partial\chi_i}\mathbf{R}^{-1}\frac{\partial\mathbf{R}}{\partial\chi_j}\right\}, \tag{7}$$

where N denotes the number of looks, and $\mathrm{tr}\{\cdot\}$ the trace operator. Let the vector of unknown parameter for the model described in Section III be

$$\boldsymbol{\chi} = [\varphi \quad \sigma^2 \quad \tau_c \quad \sigma_v^2]^T. \tag{8}$$

Then, the partial derivatives of $\mathbf{R}$, to be plugged in equation (7), are

$$\frac{\partial\mathbf{R}}{\partial\sigma^2} = \mathbf{A}\mathbf{C}\mathbf{A}^H, \quad \frac{\partial\mathbf{R}}{\partial\varphi} = j\sigma^2\mathbf{A}\mathbf{C}\mathbf{A}^H \odot \mathbf{L}_c, \tag{9}$$

$$\frac{\partial\mathbf{R}}{\partial\tau_c} = \sigma^2\mathbf{A}\mathbf{C}\mathbf{A}^H \odot \mathbf{L}_t, \quad \frac{\partial\mathbf{R}}{\partial\sigma_v^2} = \mathbf{I}, \tag{10}$$

where $\odot$ is the Hadamard (elementwise) product, $\mathbf{L}_c$ and $\mathbf{L}_t$ are two $K \times K$ Toeplitz matrices with elements

$$[\mathbf{L}_c]_{r,c} = \frac{r-c}{K-1}, \quad [\mathbf{L}_t]_{r,c} = 2\frac{(c-r)^2}{(K-1)^2}\frac{\tau^2}{\tau_c^3}, \quad 1 \le r, c \le K. \tag{11}$$

From equations (4), (6-7), and (9-11), the CRLB on the surface velocity, v_s, and on the sea coherence time, τ_c, can be numerically derived. In the particular case of $K=2$, the root CRLB on the surface velocity, v_s, assumes the well known form [3]

$$\mathrm{CRLB}^{1/2}(v_s) = \frac{\lambda v}{4\pi\, B\sin\vartheta_i}\frac{1}{\sqrt{2N}}\frac{\sqrt{1-(\rho_s\rho_t)^2}}{\rho_s\rho_t}, \tag{12}$$

where

$$\rho_s(\tau, \tau_C) = \exp\{-(\tau/\tau_c)^2\}, \tag{13}$$

$$\rho_t(\mathrm{SNR}) = 1/(1+\mathrm{SNR}^{-1}), \tag{14}$$

are the sea coherence and the thermal noise correlation coefficient respectively, and SNR is the signal-to-noise ratio. Expressing the bound as a function of SNR allows to highlight the relationship between the achievable estimation performance and the environmental parameters. In fact, SNR can be expressed as

$$\mathrm{SNR} = \sigma^0/\mathrm{NESZ}, \tag{15}$$

where σ^0 and NESZ denote the backscatter coefficient and the noise equivalent sigma zero, respectively. The NESZ is determined by the radar system characteristics (see Tab. I and II for the assumed COSMO-SkyMed parameters).

V. PHYSICAL SIGNAL MODELS

Signal parameters to feed the statistical model are derived from physical models. The backscatter coefficient, σ^0, collects the SNR dependence on the environmental parameters. In particular, in the mid range of incidence angles ($20° \le \vartheta_i \le 60°$), typical of satellite systems, the sea radar backscatter coefficient is reasonably well described by the Moore and Fung model [8]

$$\sigma^0(\phi, \vartheta_i, u) = \left[A + B\cos\phi + C\cos 2\phi\right] e^{-(\vartheta_i - \bar{\vartheta})/\vartheta_0} \left(\frac{u}{\bar{u}}\right)^{\gamma}, \qquad (16)$$

where ϕ and ϑ_i denote the azimuth and incidence angle, respectively ($\phi = 0°$ upwind, $\phi = 180°$ downwind), u is the wind velocity, $\vartheta_0 \approx 5°$ is the incidence angle attenuation coefficient, $\gamma \approx 2$ is the wind velocity growth coefficient, A, B, C are proper constants depending on the reference value of the incidence angle, $\bar{\vartheta}$, and wind velocity, $\bar{u}$. Fig. 2 shows the sea radar backscatter coefficient as a function of the wind velocity, for two different incidence angles. Only values for $u > 2 \div 4$ m/s are significant. Further, the CRLB dependence on the environmental parameters, and in particular on the wind velocity, is related to the presence of term $\mathbf{C}$, i.e., τ_c, in (9) and (10), as [10]

$$\tau_c = 3\frac{\lambda}{u} erf^{-1/2}\left(2{,}7\frac{x}{u^2}\right), \qquad (17)$$

where x is the spatial resolution. The curve of the coherence time as a function of the wind velocity, u, is reported in Fig. 3, for the assumed ground range resolution of COSMO-SkyMed, $x = 2.7\,m$. Note that the limited coherence time causes SAR defocus, yet this effect does not change the SNR.

VI. NUMERICAL RESULTS

In this section we report preliminary results of the potential performance of COSMO-SkyMed split mode for current velocity and coherence time estimation, obtained by using the ATI-SAR model described in Section III-IV-V. The antenna split configuration considered herein is obtained by transmitting with the whole aperture, and receiving on $K = 2, 3$ uniformly spaced phase centers, each formed by the $n_R = 1,\ 2,\ 3$ external antenna panels (in the latter case the subarrays are partially overlapped). This configuration is denoted as STTX+SPAN*Kl* (standard transmission and split antenna mode reception), where K indicates the number of synthesized phase centers, and l is a letter indicating n_R (see Tab. II for details). Note that n_R enters SNR through the radar equation (NESZ). COSMO-SkyMed parameter values assumed to derive the reported results are listed in Tab. I. Also, N=1000 looks are assumed, which is a typical value for spaceborne ATI [2], downwind aspect, and PRF=3632 Hz which is a preliminary value selected accounting for azimuth and range ambiguities [5]. The estimation performance is measured by the root CRLB derived in Section IV. Fig. 4 shows the root-CRLB for the configurations described in Tab. II. All the configurations give quite close results. In particular, STTX+SPAN*2c* and STTX+SPAN*3d*, which differ only for the number of phase centers, have almost the same performance, indicating that the use of more phase centers does not yield higher estimation accuracy. In fact, due to the short acquisition time lag, the data are strongly correlated, and the availability of more samples does not bring richer information. The best performance is reached by STTX+SPAN*2b*. This configuration is characterized by a higher reception gain (proportional to n_R) than STTX+SPAN*2a*, and longer baseline, i.e., higher sensitivity w.r.t. the STTX+SPAN*2c*, STTX+SPAN*3d*. Fig. 5 shows the root-CRLB on the coherence time, normalized to its actual value. All the curves except the last one, denoted by u.t. (unknown thermal noise level), are obtained by assuming the noise mean power known (CRLB analysis as in Section III but for dropping the noise parameter in the FIM). The best configuration is still STTX+SPAN*2b*, whereas STTX+SPAN*2c* and STTX+SPAN*3d* show weaker performance. Also in this case the availability of more phase centers does not means higher accuracy. Nevertheless, it is worth noting that when $K > 2$, the estimation can be obtained without the knowledge of σ_v^2, with some loss with respect to the case of $K = 2$ and σ_v^2 known. However, achievable accuracy is not enough for N=1000, conversely from what happens for velocity estimation.

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TABLE I. COSMO-SKYMED PARAMETERS

Platform velocity	7548 m/s
Slant range distance	732 Km
Antenna aperture (length, height)	5.6 m, 1.4 m
Carrier frequency	9.58 GHz
Incidence angle	$25^\circ \le \vartheta_i \le 50^\circ$
TX peak power	5 KW
Noise figure	7 dB
Noise temperature	290 K
Bandwidth	99.3 MHz

TABLE II. SPLIT MODE CONFIGURATION PARAMETERS

Split mode configuration	n_R	K	B [m]
STTX+SPAN2a	1	2	2.24
STTX+SPAN2b	2	2	1.68
STTX+SPAN2c	3	2	1.12
STTX+SPAN3d	3	3	1.12

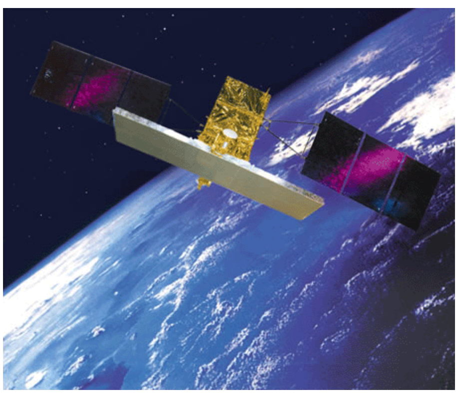

Figure 1. Artist impression of COSMO-SkyMed satellite (http://www.aiad.it)

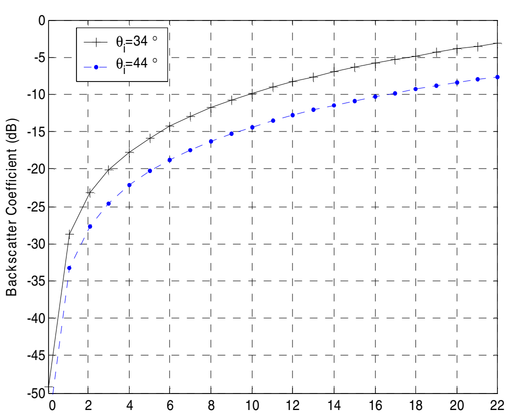

Figure 2. Backscatter coefficient vs. wind velocity

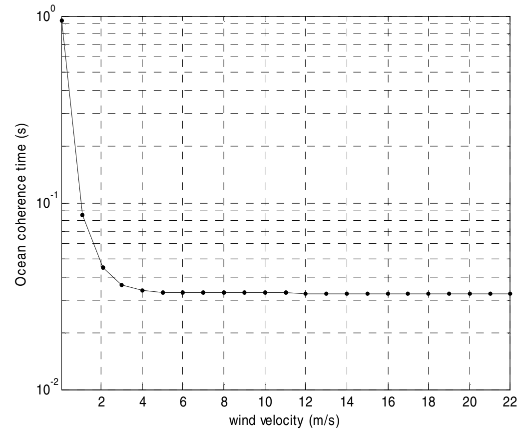

Figure 3. Ocean coherence time vs. wind velocity, $\vartheta_i = 34^\circ$

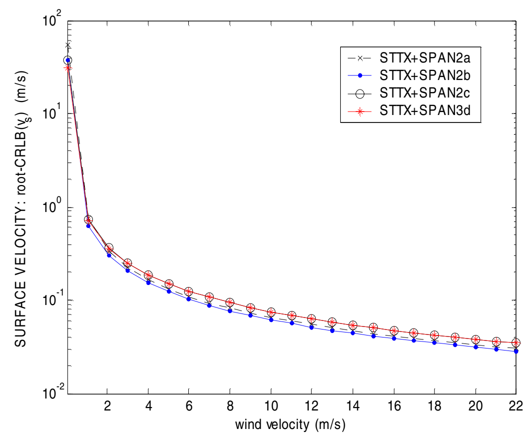

Figure 4. Root CRLB on surface current velocity vs. wind velocity, $\vartheta_i = 34^\circ$, PRF=3632 Hz

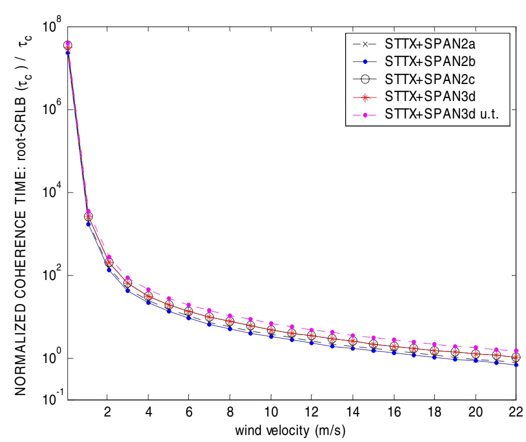

Figure 5. Normalized root CRLB on coherence time vs. wind velocity, $\vartheta_i = 34^\circ$, PRF=3632 Hz