ORTHOGONAL COPRIME SAR

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ABSTRACT

In this paper we present a new technique able to reduce the amount of data to be stored and processed in order to obtain large swath SAR image in marine scenarios. The proposed technique is an enhancement of the recently proposed CopSAR technique and it is based on the transmission of (quasi) orthogonal waveforms, i.e. up- and down-chirps. The proposed implementation is able to achieve both data reduction and range swath extension with no appearance of ghosts, no resolution loss, and with only a limited complication of the required technology. The only costs are the reduction of the target-to-background ratio and the presence of a (non-stringent) limit on maximum ship size.

Index Terms— Synthetic Aperture Radar, Coprime Arrays

1. INTRODUCTION

The demand for high resolution and coverage of Synthetic Aperture Radar (SAR) systems for maritime applications implies, as its very first consequence, a huge increase in the amount of data to be stored and processed. Recently a new technique based on coprime sensing concepts [1]-[2] applied to SAR, i.e. Coprime SAR (CopSAR), has been presented: it is able, in the case of bright targets over a dark (not necessarily homogeneous) background to reduce the amount of data and, at the same time, to increase the range swath, with no geometric resolution loss [3]. The general approach consists in the transmission of two interlaced sequences of pulses, with two sub-Nyquist pulse repetition frequencies (PRFs) that are equal to the Nyquist PRF divided by two coprime integer numbers. Each sequence is separately processed via standard SAR processing, and the two final aliased images are combined in a very simple way to cancel out aliasing. In particular, three different CopSAR implementations were proposed, aimed at achieving data reduction and/or range swath extension. However, each implementation presents specific drawbacks. The *"basic implementation"* [3] only allows for data reduction, but it does not support an extension of range swath. *"Missing pulse implementation"* [3] is useful to reach both aims, but at the cost of the appearance of many (attenuated) ghosts on the image. Finally, *"dual frequency implementation"* [3] obtains both goals with no appearance of ghosts, but it requires the use of different frequency bands, implying not only a technology complication, but also the possible inconvenience of facing different reflectivity patterns in the two aliased images, due to the frequency-dependent behavior of the backscattering coefficient.

In this paper we present an enhancement of the CopSAR basic implementation based on the transmission of (quasi) orthogonal waveforms, i.e., up- and down-chirps: we name it *orthogonal CopSAR*. The proposed implementation is able to achieve both data reduction and range swath extension with no appearance of ghosts, no resolution loss, and with only a limited complication of the required technology. The only costs are the reduction of the target-to-background ratio (TBR) and the presence of a (non-stringent) limit on maximum ship size (as it is the case in all CopSAR implementations). First, the proposed technique is analyzed in terms of impulse response function and then it is tested on appropriate simulation case studies.

2. ORTHOGONAL COPSAR

The basic CopSAR is based on the transmission of two interlaced sequences of pulses, one at $\mathrm{PRF}_1 = \mathrm{PRF}_0/N_1$, and the other at $\mathrm{PRF}_2 = \mathrm{PRF}_0/N_2$, where PRF_0 satisfies the Nyquist condition (i.e. $\mathrm{PRF}_0 \geq 2v/L$, with v the uniform sensor velocity and L the real azimuth antenna length) and N_1 and N_2 are coprime integers [3]. The two sequences can be separately processed to obtain two SAR images, i.e., $s_1(x,r)$ and $s_2(x,r)$, where x and r are the azimuth and range coordinates, respectively. Geometric resolution of these images will not be changed with respect to the standard SAR case if the entire SAR system bandwidth is processed, but, of course, the images will be severely aliased. However, if the scene consists of bright targets on a dark background, only the true targets will be present on both aliased images at the same location, whereas aliased targets (i.e., replicas) will be at different locations on the two images. In particular, the azimuth displacement of replicas, for $s_1(x,r)$ and $s_2(x,r)$ respectively, is

$$\Delta x_{i_1} = i_1 \frac{\mathrm{PRF}_0 \lambda r_0}{N_1 2v} \quad \Delta x_{i_2} = i_2 \frac{\mathrm{PRF}_0 \lambda r_0}{N_2 2v} \quad , \tag{1}$$

where λ is the wavelength, and i_1 and i_2 are integers, so that replicas on the two images will not be at the same location unless $i_1/i_2 = N_1/N_2$. But, since N_1 and N_2 are coprime, this only happens if $i_1 = i\,N_1$ and $i_2 = i\,N_2$, so that

$$\Delta x_{i1} = \Delta x_{i2} = i\,\frac{\mathrm{PRF}_0 \lambda r_0}{2v} \quad , \tag{2}$$

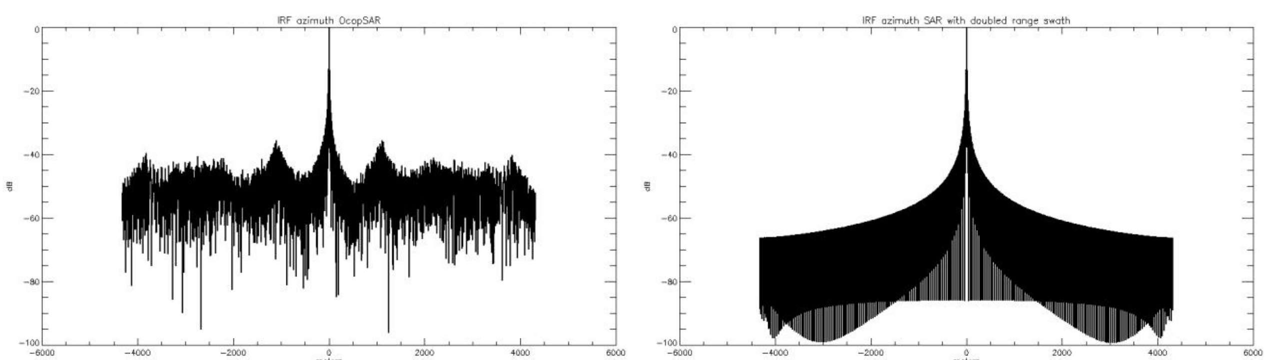
i.e., only at the positions of the replicas in the image that would be obtained in the standard acquisition mode. These replicas will be strongly attenuated by the azimuth antenna pattern and will not be considered in the following discussion [3]. Therefore, using the simple combination rule

$$s(x,r) = \begin{cases} s_1(x,r) & \text{if } \ |s_1(x,r)| < |s_2(x,r)| \\ s_2(x,r) & \text{otherwise} \end{cases}, \tag{3}$$

the obtained $s(x,r)$ image is not affected by aliasing. However, since the minimum time separation between the pulses of the two sequences is $1/\mathrm{PRF}_0$, CopSAR basic implementation does not allow us to increase the range swath with respect to standard SAR without the appearance of significant range ambiguities. Hence, CopSAR basic implementation allows only for a reduction of data amount to be stored and processed [3].

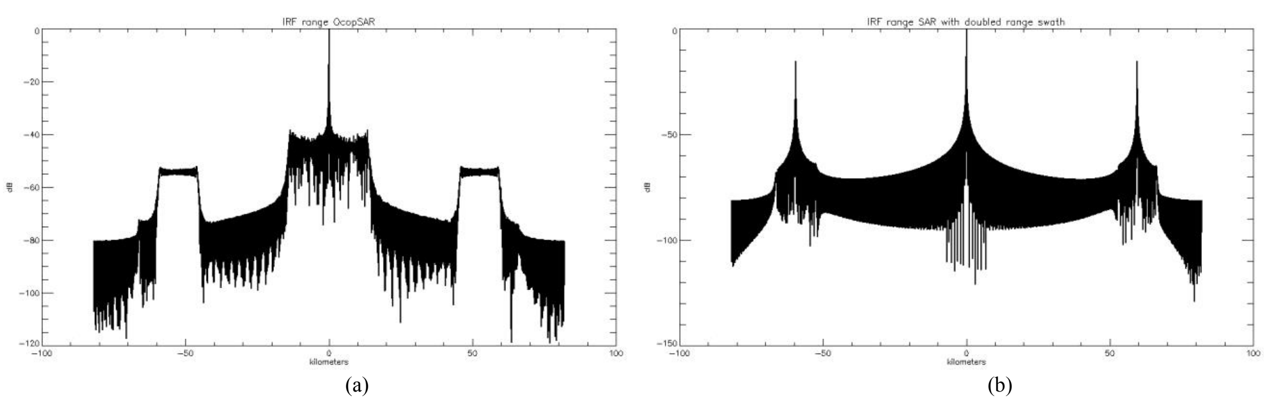
To overcome this problem and obtain an increase of the range swath, we propose a technique, which we name orthogonal CopSAR, that differs from standard CopSAR in the fact that pulses of the two interlaced subsampled sequences are mutually (quasi) orthogonal: in the first subsampled sequence up-chirp waveforms are transmitted, whereas in the second one down-chirp waveforms are used. Since up-chirp and down-chirp waveforms are quasi orthogonal [4], non-aliased images can be still obtained processing each sequence via the appropriate up- or down-chirp matched filtering during range compression. The energy of the unfocused target contribution due to the presence of the mismatched chirp will be spread over a pulse duration interval in the final focused image [4]. It is important to note that superposition at the receiver of focused and unfocused contributions is only partial, and it does not happen for all pulses: in particular, if the range swath is doubled, superposition is present only for pulses of the two subsequences transmitted at the same time or at distance $1/\mathrm{PRF}_0$, i.e., three times out of N_1N_2. The proposed technique can be implemented on single-antenna SAR sensors: in this case, "blind ranges", due to the fact that the sensor cannot receive during the transmission interval, are present in the raw signal: however, when doubling the range swath, this only happens for pulses at distance $1/\mathrm{PRF}_0$ (i.e., two out of N_1N_2). Therefore, on the final image this implies no blind range, but only the possible appearance of strongly attenuated azimuth replicas, similar to those arising in the CopSAR missing-pulse implementation, over a specific slant range interval. In the following, we consider a SAR system with two antennas (one transmitting and one receiving), for which even this inconvenience is not present.

In Fig. 1 we compare azimuth cuts of the amplitude impulse response function (IRF) of orthogonal CopSAR (a) and standard SAR (b). ERS sensor system parameters have been assumed, with the range antenna size decreased in order to



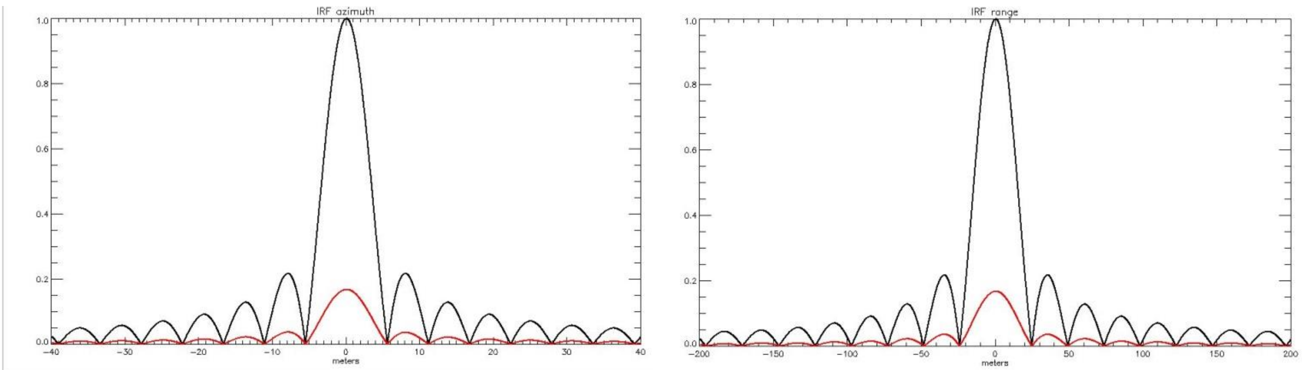
(a) (b)

Fig. 1: Normalized azimuth IRF for orthogonal CopSAR (a) and for standard SAR with doubled range swath (b).



(a) (b)

Fig. 2: Normalized range IRF for orthogonal CopSAR (a) and for standard SAR with doubled range swath (b).



(a) (b)

Fig. 3: Azimuth (a) and range (b) IRF of standard SAR (black) and orthogonal CopSAR (red), both normalized to the maximum of the standard SAR IRF.

obtain a doubled range swath. We set N_1=5 and N_2=6. It is clear that in the orthogonal CopSAR IRF only a very small residual ambiguity due to sidelobes superposition is visible just near the target. However, the level of the residual ambiguity amplitude is almost 40 dB below that of the main lobe, as it was for basic CopSAR [3]. In Fig. 2 we show the range IRF: it is evident that using orthogonal up- and down-chirp waveforms we are able to suppress the range ambiguity that appears in standard SAR when the range swath is doubled: only a very slight residual unfocused contribution due to the presence of the mismatched chirp can be appreciated. Finally, in order to verify the preservation of geometric resolution, in Fig. 3 we show an enlarged view of the region of the IRF around the main lobe. It is clear that the main lobes of the orthogonal CopSAR and SAR IRFs have the same size, so that the geometric resolution is the same. However, the overall orthogonal CopSAR IRF amplitude decreases, as theoretically expected [3].

3. EXTENDED TARGET SIMULATION

To illustrate the case of extended targets embedded in sea clutter, we simulated an ERS-1 stripmap image with a doubled range swath, in which several ships lay over a simulated ocean clutter. The ships' reflectivities were obtained from an actual SAR image. From Fig. 4 it can be noted that in the simulated SAR image several range ambiguities appear (highlighted in red), because of the interference that pulses separated by just 1/PRF_0 exert on each other when the swath is doubled in standard SAR mode. In Fig. 5 we show the image obtained applying the orthogonal CopSAR framework described Section 2: for data focusing we used the Fourier domain SAR processor used in [3], with a sequence (i.e. waveform) dependent range focusing step. Here range ambiguities are suppressed at the cost of a reduction of the TBRs for each target. We can also notice how on the CopSAR image the pattern of the long sea wave tends to be less evident than in the standard SAR image [3].
In order to prove the resolution preservation capabilities of the orthogonal CopSAR, we also simulated a Sentinel-1 stripmap image (with higher resolution than ERS-1 data), in which a very large ship (400 x 60 meters), lays over a uniform, speckled dark background. We again applied the orthogonal CopSAR framework. In Fig. 6 a comparison of a detail of the target area for standard SAR and orthogonal CopSAR is shown: we can appreciate how resolutions remain the same and only a TBR reduction of a 2.59 factor is shown.

4. CONCLUSION

In this paper we presented a new SAR data acquisition framework, which we called Orthogonal Coprime SAR. The proposed approach is an enhancement of the Coprime SAR (CopSAR) technique (in its basic implementation) recently introduced by some of the authors. Orthogonal CopSAR is based on the transmission of (quasi) orthogonal waveforms, i.e., up- and down-chirps and is able to achieve both data reduction and range swath extension with no appearance of ghosts, no resolution loss, and with only a limited complication of the required technology. The proposed technique was analyzed both in terms of impulse response function and via appropriate simulation case studies.

11. REFERENCES

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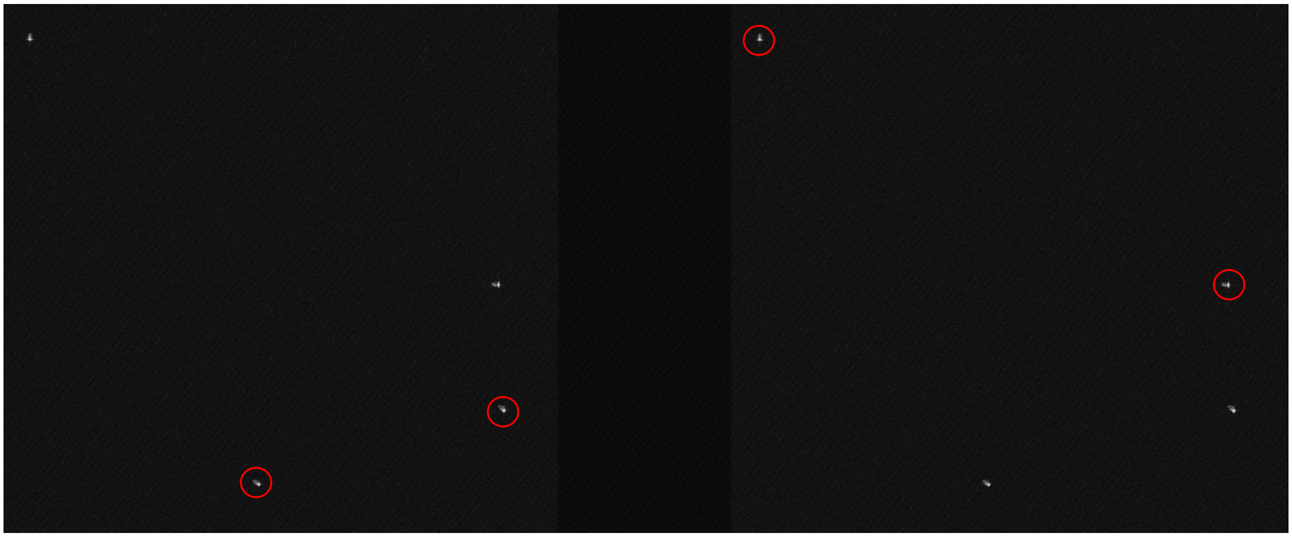


Fig. 4: Simulated image considering the interference that contiguous pulses exert on each other in standard SAR mode.

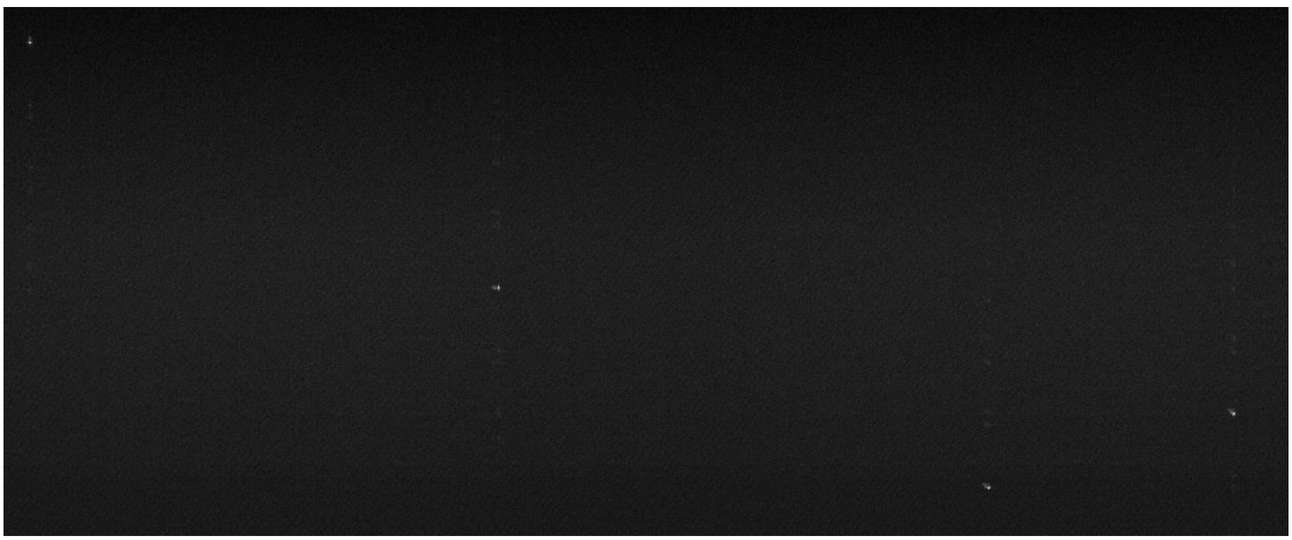
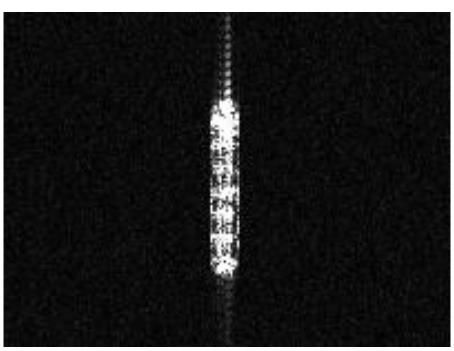
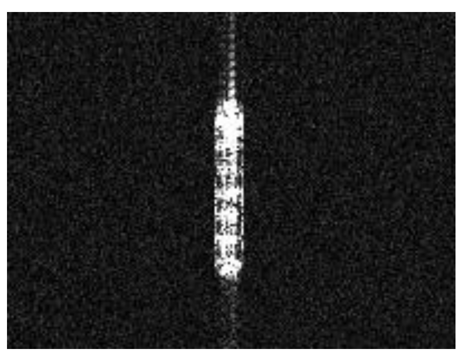


Fig. 5: Orthogonal CopSAR image relevant to the case presented in Fig. 4.



(a)



(b)

Fig. 6: Detail of Sentinel-1 images: standard SAR (a) and orthogonal CopSAR (b).