AN AUTOFOCUSING ALGORITHM FOR POST-PROCESSING ISAR IMAGING BASED ON IMAGE ENTROPY MINIMIZATION

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Abstract

Fast maneuvering of aircraft targets may be one of possible reasons for Inverse Synthetic Aperture Radar (ISAR) image blurring. This is due to the range bin migration of the target's scatterers during the Radar Coherent Processing Interval (CPI). Traditional ISAR imaging techniques to compensate for this effect include "range tracking" [high resolution range profile (HRRP) alignment] and "Doppler tracking" (phase correction to the HRRP's). Furthermore, a variety of advanced signal processing techniques, which takes into account the time-varying Doppler spectra of the target's scatterers during the CPI, have been proposed in the last decades, including Time-Frequency based ISAR imaging.

In this paper we will present preliminary simulation results based on the proposed autofocusing algorithm, for which the aircraft target exhibits a high angular acceleration, which simulates fast maneuvering. The proposed ISAR imaging post-processing scheme (Section 2), is described as following: for any particular CPI consisting of N range profiles, for which ISAR image entropy exceeds a particular threshold (e.g. due to fast target maneuvering), this CPI is initially divided to two CPI's of equal length, i.e. N/2 range profiles in each, and two ISAR images are formed. It is assumed that "Range tracking" and "Doppler tracking", as described above, have already been applied. The entropy values of the above two ISAR images are calculated, and HRRP data corresponding to the worst image, i.e. that corresponding to higher image entropy, are neglected. Instead, a set of N/2 HRRP data are borrowed either from the previous or from the next CPI's HRRP data, in order to form a new improved ISAR image in the ISAR image database (i.e. a post-processing scheme). The proposed method may be further improved by subdividing the CPI in four parts of equal length and so on.

Preliminary numerical results, based on simulated radar data are presented in Section 3.1. Finally, preliminary ISAR images obtained by the authors using real radar data ('ORFEO' data from TNO, Netherlands) are presented in Section 3.2. Finally, conclusions and further related research are presented in Section 4.

Keywords: *Inverse Synthetic Aperture Radar (ISAR), Range – Doppler (RD) ISAR Imaging, Fast maneuvering of air targets, autofocusing post – processing techniques, raw radar data handling, optimum ISAR data processing, ISAR image entropy, Coherent Processing Interval (CPI).*

1. INTRODUCTION

Two – dimensional (2D) ISAR image formation is the process of reconstructing 2D images of radar targets from recorded radar-received complex data [1,2]. The *backscattered radar data*, after initial processing, such as pre-filtering, demodulation, dechirping etc. [1,2] is obtained in the form of *raw radar data* in the *baseband*. According to *traditional Range – Doppler (RD) ISAR processing*, a *matrix* containing *M×N complex (i.e. magnitude and phase) raw radar data* is obtained, for which traditional Fourier processing is applied to both rows and columns of the matrix, as it will be explained shortly at the beginning of Section 2, below [1,2]. In this way, a 2D ISAR image according to the traditional RD imaging technique is obtained. In this context, we assume in this paper that the radar transmits a *stepped – frequency (SF, [2]) waveform* consisting of M frequency steps (see Section 2, below). A sequence of M such radar pulses constitutes a radar emitted *burst*. It will be assumed in this paper that N bursts are used at the radar receiver, in order to form a matrix of dimensions M×N for the raw baseband radar complex data mentioned above. Furthermore, in the context of this paper, as it will also be explained in Section 2 below, the M complex radar data forming any particular row of the data matrix mentioned above, are considered as 'frequency – domain' data, to which an Inverse Fast Fourier Transform (IFFT) is applied, in order to obtain N *range profiles*. According to traditional RD ISAR processing, these range profiles are then 'aligned', before obtaining the final ISAR image through a Fast Fourier Transform (FFT). This alignment usually consists first of 'range *tracking'* [2,3], according to which, roughly to say, the maximum peak in the target radar echo is sought to remain at the same 'range bin' through the whole 'Coherent Processing Interval (CPI)', or so [2,3]. A possible second step [2,3] consists of the so – called *'phase tracking'* [2], where appropriate phase correction is applied to the M×N complex data of the 'range profiles', before applying the FFT for obtaining the final 2D ISAR image. After 'range tracking', and possibly 'phase tracking', are applied, then a Fast Fourier Transform (FFT) is applied to the data for each column of the radar data corresponding to the obtained target range profiles, in order to obtain the final 2D ISAR image of the target. This concludes, more or less, the process of *traditional Range – Doppler (RD) ISAR* imaging.

In the context of this paper, the term '*autofocusing'* is related to *post – processing ISAR imaging techniques*, which improve the quality of ISAR images, before further target classification or target identification techniques are applied. This term is used by several authors in different ways (see e.g. [4-11]). Many times autofocusing is applied *through image entropy minimization* [4, 9-11], method that will be adapted also in this paper. Other times it is applied through 'image contrast maximization' (see e.g. [5]), etc. In the present paper, we will mainly focus on how to improve 2D ISAR image quality through a *proposed post – processing scheme*, which neglects raw radar data of poor quality, *due to fast target manoeuvring* (simulated in the present study through high *angular target acceleration).* The criterion for applying the above proposed 'autofocusing' post – processing technique is image entropy minimization. *Ultimately*, our proposed method will lead to a *fully automatic post – processing algorithm of raw radar data handling, for improved 2D ISAR image generation, based on image entropy minimization. Even the problem of optimum number of radar data (number of used radar bursts) will be examined in a systematic way, depending on the target kinematics* (target angular acceleration etc.). Finally, the present study is based on simulated backscattered radar data using stepped – frequency (SF) emitted waveform [12]. However, ISAR imaging is performed in this study also through the use of *real raw radar data* for air civilian targets, provided by TNO, the Netherlands (the so – called 'ORFEO' data, see 'acknowledgement' at the end of this paper). Ultimately, optimum radar data handling studies will be provided by the authors for real (experimental) radar data, as well.

2. PROPOSED AUTOFOCUSING POST – processing ISAR imaging technique for a particular fast rotation of the air target simulation scenario

2.1. Raw radar data in matrix form – Simulation scenario for fast manoeuvring of the air target

As we explained in detail in the 'Introduction' Section, above, the backscattered raw radar data in the baseband (i.e. after demodulation etc.), in the frequency – domain, are in the form of a matrix with dimensions M×N, as exactly explained in Section I, above. Traditional 'Range – Doppler' procedure [1-2] for ISAR image generation is applied. Namely we assume here that M transmitted frequencies per burst are used in the transmitted SF waveform, and, furthermore, N bursts are used in order that an ISAR image is formed.

Regarding the simulation of fast maneuvering of the target, in the simulation scenario which will be considered here, this is accomplished through a fast angular acceleration of the target, as shown in Fig. 1, below. Here 2D target geometry is considered, and radar Line-of-Sight (LOS) is considered on this plane. We call this plane 'ISAR image plane' as well, for convenience. Then, in the present simulation scenario, it is assumed, without loss of generality (see e.g. [1-3]), that the axis of target rotation and angular acceleration is perpendicular to the ISAR image plane. Numerical values of these kinematic parameters of the air target will be provided in Section III, below, along with the corresponding radar parameters of the proposed simulation scenario.

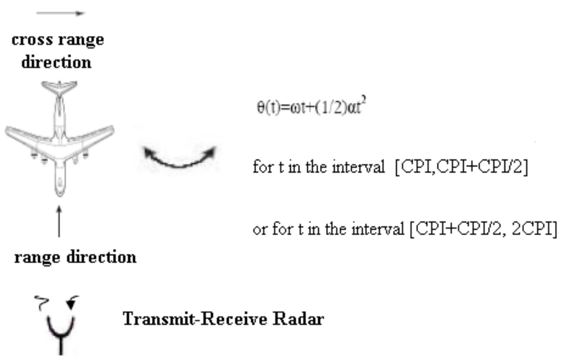

Fig. 1: Simulation of fast maneuvering of the air target in the present simulation scenario through a fast angular acceleration α , as shown in the formula for the aspect angle θ(t) above, where ω represents the angular velocity of rotation of the target, and t represents time. More details are given in the text.

2.2. Data handling for the proposed 'autofocusing' post – processing algorithm

In the proposed simulation scenario for fast angular acceleration of the air target, we will focus on the process of *deriving a set of ISAR images of 'better quality', as compared to the original set of ISAR images, through the proposed 'autofocusing' post – processing algorithm*. Better image quality means better focused ISAR image of the target, which quantitatively is accomplished through the *'image entropy' concept* [4, 9-10]. For this purpose, in the proposed simulation scenario, we will assume that 3 (three) ISAR images will be produced, corresponding to radar processing time equal to 3 (three) 'Coherent Processing Intervals' (CPI's). Here by 'Coherent Processing Interval' (CPI) we mean, as it is traditional for SAR or ISAR processing [1-3], the radar receiver required processing time in order to form an ISAR image, which, for the SF transmitted waveform considered here is equal to

$$CPI = N \times T_b \quad (1)$$

where N is the number of bursts in the CPI, as explained above, and Tb is the duration of the burst, given by the formula

$$T_b = M \times T_E \quad (2)$$

where T_E is the pulse repetition interval (or 'period' / PRI) of the radar. Then, in the simulation scenario proposed here, *fast angular acceleration of the target will be assumed to take place only during the 2nd CPI* (either during the 1st half or during the 2nd half of the 2nd CPI), *during which radar data of inferior quality will be replaced by radar data of superior quality, borrowed from radar data coming from the 1st or 3rd CPI considered here*. This procedure *will ultimately result to a better set of derived ISAR images*, as already explained above, and as will be quantitatively shown below through a *'proof-of-concept'* initial demonstration.

Namely, the proposed 'autofocusing' algorithm is as following: when a particular obtained ISAR image corresponds to a image entropy value [4, 9-10] above a particular (pre-selected) value, and this raise of image entropy value is attributed by the radar user to a temporary target fast maneuvering, then the radar user initiates the proposed algorithm, by keeping only radar data of superior quality. In the proposed simulation scenario we consider the following 2 (two) cases:

<u>(i) Case I:</u> Here we assume that the obtained ISAR image's entropy value (corresponding to the 2nd CPI) exceeds its threshold value due to targets' fast angular acceleration during the 2nd half of the 2nd CPI. Then, as shown in Table 1, below, the radar data of the lower half of the corresponding raw data matrix shown in Table 1 must be replaced by data of better quality, in a suitable way. This proposed way is the following: form the raw radar data matrix corresponding to the 2nd CPI by

(i) Neglecting the data of inferior quality (marked by the dashed line box of Table 1 / i.e. data corresponding to the *lower* half of the matrix).

(ii) Shift the data corresponding to the *upper* half of this matrix to the *bottom* part of the matrix (i.e. in the place marked by the dashed line box of Table 1).

(iii) Fill in the *upper* half of this M×N matrix with the raw radar data corresponding to the *lower half* of the data matrix of the *1st CPI*.

Using the above proposed 'autofocusing' procedure, half of the data corresponding to the 'dangerous' 2nd CPI (i.e. those corresponding to the *upper* half of the matrix) are still preserved for radar processing (i.e. not just 'thrown away'), thus ultimately providing a better set of obtained ISAR images.

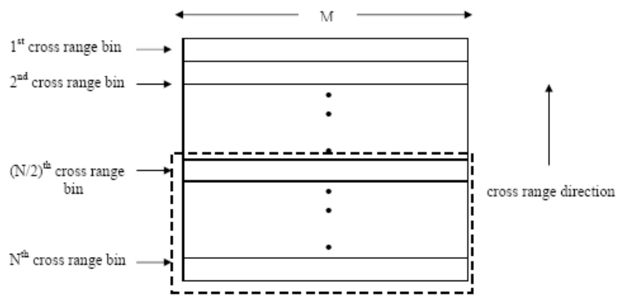

Table 1: Frequency domain raw radar data in the baseband corresponding to the 2nd CPI (out of 3 CPI's) considered in the proposed simulation scenario, which corresponds to an M×N matrix, as explained in Section IIA. From these M×N complex data, the data corresponding to the *lower* half of the matrix are considered as data of lower quality due to fast target maneuvering during the *2nd half* of the 2nd CPI, and therefore they are replaced suitably for better ISAR image formation, as explained exactly in the text.

<u>(ii) Case II :</u> Here we assume that the obtained ISAR image's entropy value (corresponding to the

2nd CPI) exceeds its threshold value due to targets' fast angular acceleration *during, in this case, the 1st half of the 2nd CPI.* For this case, we follow a procedure analogous to that of Case I, in order to obtain better ISAR image quality (not explained in detail here, for brief).

Numerical results which show 'proof-of-concept', based on the simulation scenario described above, will be provided in the next Section III.A., along with corresponding radar and target kinematics data used in the simulation. Furthermore, preliminary ISAR images based on real radar data provided by TNO, the Netherlands ('ORFEO' data, taken from civilian aircrafts, as mentioned above) will also are provided in Section III.B.

3. NUMERICAL RESULTS

3.1. Preliminary numerical results for the simulation scenario for fast maneuvring of the air target – description of radar and target kinematics parameters

The simulated target geometry is shown in Fig. 2, below, consisting of 22 point scatterers, thus simulating an aircraft target of length equal to 31 m in the range direction (vertical axis of Fig. 2 / from simulated cockpit to rear of the aircraft, in this simplified model), and 11.3 m in the cross – range direction (horizontal axis of Fig. 2 / wingspan of the airplane). The airplane is located 4.5 km away from the monostatic radar, and it rotates about an axis which is perpendicular to the ISAR image plane (which coincides with plane where the 22 point scatterers have been place, in Fig. 2). Radar and target rotation parameters are appropriately selected [14] (not shown here for brief).

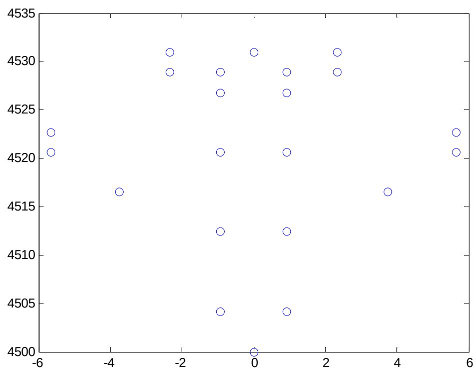

Fig. 2: Geometry of the simulated air target consisting of 22 point scatterers. See text for details.

Following our proposed autofocusing algorithm, as explained in Section II, above, ISAR images of the above simulated target are obtained for three (3) subsequent 'Coherent Processing Intervals' (CPI's). For this purpose, simulated backscattered raw radar data in the baseband are obtained through the following well – known formula [1,3]:

$$x(m,n)=\sum_{k=1}^{d} s_k \exp\left(j\frac{4\pi}{c} f_m[x_k\cos\theta_n - y_k\sin\theta_n]\right)+u(m,n) \quad (3)$$

where d is the number of scatterers (k=1 to d / here d=22), M (m=1 to M) is the number of frequency steps in the SF waveform, N (n=1 to N) is the number of bursts in the CPI [equivalently θ_n is the aspect angle of the target at the particular 'slow time' instant $t_n(\theta_n = \omega t_n + \alpha t_n^2/2)$], and u(m,n) is additive white Gaussian noise of mean zero and variance σ^2. The simulated data derived from Eq. (3), above, correspond to frequency domain raw baseband radar data, from which ISAR images are obtained according to the traditional Range – Doppler (RD) imaging procedure [1,2].

In the particular simulation experiment described here, three (3) subsequent CPI's were considered, according to our proposed autofocusing algorithm, described in Section 2, above. Fast angular acceleration of the target was considered only during the 2nd half of the 2nd CPI, for which our autofocusing algorithm, as explained in Section II, was applied. This resulted in better image focus during the 2nd CPI of fast target maneuvering, thus showing the 'proof-of-concept' for our proposed algorithm. An indicative ISAR imaging result, which corresponds to the 2nd CPI of processing, *after* application of our proposed autofocusing algorithm, is shown in Fig. 3, below (only this ISAR image, for this simulation scenario, is shown here, for brief). Corresponding ISAR image entropy values [9,10] are also calculated [14]. Finally, similar results, also showing the 'proof-of-concept' for our proposed algorithm, were obtained in the case that target's fast angular acceleration occurs in the 1st half of the 2nd CPI, according to our proposed method of Section 2 (these similar results are not shown here, for brief).

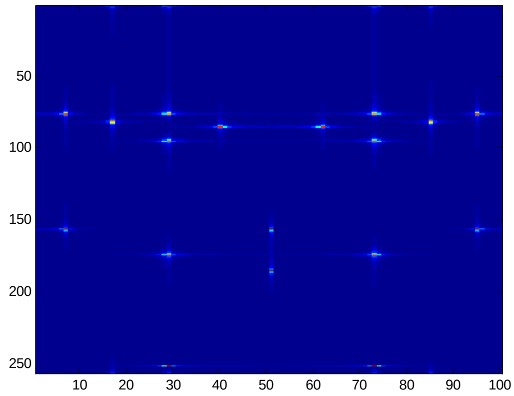

Fig. 3: ISAR image obtained for the simulated target of Fig. 2, for the data obtained during the 2nd *CPI* of the simulation experiment, for which *target fast maneuvering occurred during the 2nd half of the 2nd CPI*). Here our *proposed autofocusing algorithm was applied*, which redusced the image entropy value to E=1.44 (lower than the entropy threshold of 2.3), *thus showing the 'proof-of-concept'* of our proposed autofocusing algorithm.

3.2. Preliminary ISAR imaging results based on real radar data

In this Section we provide some preliminary ISAR imaging results based on real (experimental) radar data. Namely, these data were provided to us by TNO, the Netherlands ([13], see acknowledgement at the end of this paper), they are called by TNO 'ORFEO' data, and they are concerned with real measurement of civilian aircrafts in flight. TNO provided to us target range profiles, as well as raw baseband radar data in the frequency domain. The transmitted waveform used by TNO during this measurement campaign was 'velocity – tolerant' stepped – frequency (SF) waveform. Related information is given in [13]. Using the ISAR image formation algorithms of our research groups [at this point this is just a traditional inverse Fast Fourier Transform (IFFT) in the cross – range direction] we obtained ISAR images of many civilian aircrafts measured by TNO. A representative example of these ISAR images is shown in Fig. 4, below, concerning Embraer Brasilia EMB-120 aircraft.

In Fig. 4, above, the resolution cell in the range direction (horizontal axis) is again ΔR=c/2B=32 cm , as provided by TNO. The aircraft here consists of about 65 range bins (not shown very clearly here), which corresponds to aircraft length in the range direction (horizontal axis) of about 65 × 0.32 = 20.8 m , which compares very well with the length of this aircraft provided by its manufacturers, which is 20.0 m. Regarding the estimation of the 'wing – to – wing' dimension of this aircraft through ISAR imaging, some more precise processing and calculations in the cross – range direction have to be performed by our research group in the near future.

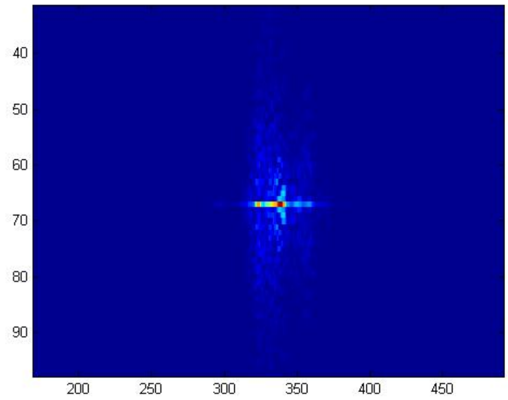

Fig. 4: ISAR image for an Embraer Brasilis EMB-120 civilian aircraft obtained using data from the 'ORFEO' measurement campaign for aircrafts in flight by TNO, the Netherlands [13], by using the ISAR imaging formation algorithm of our research group. Here, again, the horizontal axis corresponds to the 'range' direction, while the vertical axis corresponds to the 'cross – range' direction. See more details in the text.

Concluding this Section, we mention that our research group intends to work in the near future in the direction of applying the proposed autofocusing method, decribed in this paper, above, for the real 'ORFEO' data described above, as well.

4. CONCLUSION – FUTURE RELATED RESERACH

In this paper we developed, and presented preliminary numerical results, an 'autofocusing' post – processing ISAR imaging method for high maneuvering air targets. The proposed method uses the raw complex radar data in the baseband (in the frequency domain) in *a dynamically optimum way,* so that it uses the string of data coming at the radar receiver in a way such that data leading to ISAR images of poor quality are neglected, and only data leading to ISAR images of superior quality are used. The ultimate goal of this proposed 'autofocusing' post – processing procedure is that the ISAR radar user ends up with a set of ISAR images of superioir quality, based on which better image classification will be performed.

At the present stage, presented in this paper, simple point – scatterer air targets were used in the simulation. Furthermore, radar target fast maneuvering was simulated through high angular tagret acceleration, as explained in the text. Moreover, in the initial simulation scenario described above, we selected just three (3) 'Coherent – Processing – Intervals' (CPI's) in order to show an initial 'proof – of – concept' of our proposed technique. Finally, preliminary ISAR imaging results, obtained by our research group, and based on real radar data provided by TNO, the Netherlands, were shown above.

Proposed autofocusing technique will be fully automatic, for an arbitrary number of radar observation time, in terms of number of CPI's. Of course, more precise radar target modeling will be used, than the point scatterer model used above, for the proposed simulations, and our technique will be tested against real radar data, as well. Finally, our proposed autofocusing algorithm may be further refined, for example, by dividing the CPI by a factor of four (4), and not by the factor of two (2), as proposed in this paper, in order to use the received data in a possibly even more effective way, as explained above. The counter – effect to this will be, of course, larger processing time, for this proposed 'post – processing' ISAR imaging tool. Then, it is up to this algorithm designer, or to the ISAR radar user, to select the appropriate CPI subdivision factor, for optimum ISAR data processing.

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