A Survey on ISAR Autofocusing Techniques

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Abstract – In many years of research several ISAR autofocusing techniques have been proposed. Today, we can divide them into two main categories: parametric and non-parametric techniques. The Prominent Point Processing and the Phase Gradient Algorithm are two classical examples of non-parametric techniques, whereas the more recent Image Contrast and Entropy based techniques represent a new generation of parametric techniques. In this paper the advantages and disadvantages of each technique will be highlighted and a performance analysis will be carried out by means of ISAR image reconstruction of real data.

I. Introduction

Inverse Synthetic Aperture Radar (ISAR) is a well established technique used to provide an electromagnetic image of the target. The basic idea is to obtain high resolution in two dimensions, given by the range and Doppler coordinates. To achieve such a result, high bandwidth pulses are transmitted and target echoes, received at different aspect angles, are coherently processed to form the image. One of the critical steps of the ISAR technique is "image focusing" or "motion compensation" [1]. Only radial motion compensation is considered here because it is the dominant factor. Rotational motion can be another defocusing factor, but it is only evident with very high resolution and/or targets with large rotational rates [1]. This operation is accomplished by multiplying the received signal by a time varying phase term $e^{j\vartheta(t)} = e^{-j\frac{4\pi f}{c}R_0(t)}$ where $R_0(t)$ is the range time history of a "focusing" point O belonging to the target. When no external data are available, the motion compensation must be performed only by using the radar received signal. In such a case, the image focusing is called ISAR image autofocusing.

In many years of research in the field of ISAR autofocusing several techniques have been developed, each of them showing pros and cons. Autofocusing algorithms can be classified as parametric and non-parametric. Parametric methods need a parametric model of the radar received signal, whereas non-parametric techniques do not need it.

In this paper we focus on four representative ISAR autofocusing techniques, namely the Prominent Point Processing (PPP) and the Phase Gradient Algorithm (PGA), as non-parametric techniques, and the Image Contrast Based Technique (ICBT) and Entropy Based Technique (EBT), as parametric techniques. A performance analysis will be carried out by means of real data.

II. Non-Parametric ISAR Autofocusing Techniques

As mentioned in the introduction, non-parametric autofocusing techniques do not assume any model. Therefore we will refer to the phase history $\vartheta(t)$ as a generic function. Classic techniques such as the PPP and PGA belong to this class. A brief review of the PPP and PGA will be given in sub-section II.1 and II.2 respectively.

II.1 Review of PPP

The PPP is a two-stage technique: the first is to set up a rough alignment profile to profile, before applying a form of phase compensation in the second step. The principle ideas for this technique were obtained by delving into two other areas of research, namely time delay estimation [2] and adaptive beamforming [3]. Following is a brief overview of the algorithm and a more complete description is given in [4].

The main steps of the algorithm are as follows.

<u>Step 1</u>: Measure and store complex envelopes of echo samples and generate range profiles.

$$A_{ik} \quad e^{j\phi_{ik}} \tag{1}$$

where i is the range cell index and k is the profile number.

<u>Step 2</u>: Search in range for a good phase synchronizing source and call it the reference range R_0

$$A_{0k} \quad e^{j\phi_{0k}} \quad A_{0k} \cong A, \text{ for all k} \tag{2}$$

R_0 is found by measuring the normalized echo variance in each range cell, and is that range for which the value is a minimum. This approach relies on the assumption that a dominant scatterer with large radar cross-section exists.

<u>Step 3</u>: Phase conjugate at R_0

$$A_{0k} \quad e^{j\phi_{00}} \tag{3}$$

Correction is accomplished by phase rotating the complex envelopes of the signals from R_0 received by the different profiles. The proper phase shift for the k^{th} profile is the negative of the phase difference

$$\Delta\phi_{0k} = \phi_{0k} - \phi_{00} \tag{4}$$

The complex signal envelope of the k^{th} profile becomes

$$A_{0k} \quad e^{j\phi_{0k}} \cdot e^{-j(\phi_{0k}-\phi_{00})} \cong A_{0k}\, e^{j\phi_{00}} \tag{5}$$

<u>Step 4</u>: Phase rotate at all range profiles by $\phi_{0k} - \phi_{00}$

$$A_{ik} \quad e^{j(\phi_{ik}-\phi_{0k}+\phi_{00})} \tag{6}$$

This algorithm is known as the minimum variance algorithm (MVA) or the dominant scatterer algorithm (DSA) due to the reasoning it uses to choose the reference range cell. A more robust version of the procedure, which combines the echoes from several reference range cells, has been implemented for the comparison in this paper. Called the multiple scatterer algorithm (MSA) [5], this modified algorithm essentially averages the phase differences (after unwrapping) to provide the phase correction. Typically three reference range cells (scatterers) are sufficient to produce focussed images.

II.2 Review of PGA

The PGA algorithm is a non-parametric autofocusing technique in which the residual phase term after range alignment is obtained by estimating its derivative (gradient) and integrating the result [6]. Let us denote as $P_r(i,k)$ the aligned complex range profiles, where *i* is the range cell index and *k* is the profile number. The data matrix $P_r(i,k)$ can be written as:

$$P_r(i,k) = A(i,k)\, e^{j\phi(i,k)} e^{j\phi_\varepsilon(k)} \tag{7}$$

where $P_c(i,k) = A(i,k)\, e^{j\phi(i,k)}$ is the aligned complex range profiles after phase adjustment, $A(i,k)$ is the not-aligned range profile matrix and $\phi_\varepsilon(k)$ is the residual phase term (to be compensated), independent of the range bin. A raw range-Doppler image is obtained by taking the 1D-FFT of $P_r(i,k)$ w.r.t. *k*. The result is:

$$I_r(i,n) = I_c(i,n) \otimes h(n) \tag{8}$$

where $I_c(i,n)$ the phase compensated image in range *i* and cross-range *k* domain and $h(n)$ is the cross-range impulse response of the ISAR system before residual phase removal. In eq.(8) the symbol $\otimes$ denotes convolution. The $I_r(i,n)$ is generally a blurred image because of the impulse response spreading. The goal of the PGA is to estimate $\phi_\varepsilon(k)$, through its derivative, by processing the raw image $I_r(i,n)$. The main steps are:

Step 1: for each range bin *I*, select the stronger scatterer and center it in the origin of the cross-range axis by means of a circular shift.

Step 2: window the circular shifted image in order to preserve the width of the dominant blur for each range bin and reject data that cannot contribute to the residual phase estimation. Let $I_{rcw}(i,n)$ be the image after steps 1) and 2).

Step 3: Estimate the gradient of the residual phase $\phi_\varepsilon(k)$ as

$$\hat{\dot{\phi}}_\varepsilon(k) = \frac{\sum_i \mathrm{Im}\left(P_{rcw}^*(i,k)\, P_{rcw}(i,k)\right)}{\sum_i \left|P_{rcw}(i,k)\right|^2} \tag{9}$$

where $P_{rcw}(i,k)$ is the 1D-IFFT of $I_{rcw}(i,n)$ wrt to *n*.

Step 4 : Estimate the residual phase $\hat{\phi}_\varepsilon(k)$ by integrating $\hat{\dot{\phi}}_\varepsilon(k)$ and multiply $P_r(i,k)$ by the phase term $e^{-j\hat{\phi}_\varepsilon(k)}$, repeat steps 1) to 4) until the rms error of the residual phase difference between two consecutive iterations is less than few tens of radian.

At the end of the iterative process, $h(n)$ tends to a Kronecker's delta and the $I_r(i,n)$ becomes equal to $I_c(i,n)$.

III. Parametric ISAR Autofocusing Techniques

Parametric autofocusing techniques make use of a parametric model to provide target motion compensation. A brief review of the ICBT and EBT will be given in sub-section III.1 and III.2, respectively.

III.1 Review of ICBT

In this section we briefly recall the autofocusing technique based on the image contrast maximisation, proposed in [7,8,9]. For spatial resolution of the order of one metre, the distance $R_0(t)$ of the focusing point can be approximated by its Taylor series expansion around the central time instant *t*=0 and stopped at the second order term:

$$R_0(t) \cong \alpha + \beta\ t + \gamma\ \ t^2 \tag{10}$$

where $\alpha = R_0(0)$, $\beta = \dot{R}_0(0)$ and $\gamma = \ddot{R}_0(0)/2$. The zero order coefficient α can be ignored because it only produces a range shift in the ISAR image. Therefore, the focusing parameters to be estimated are β and γ.

Let $I\left(x_1, x_2; \tilde{\beta}, \tilde{\gamma}\right)$ be the intensity of the discrete image obtained by compensating the signal with the phase term $e^{j\frac{4\pi f}{c}\left(\tilde{\beta} t + \tilde{\gamma}\ t^2\right)}$ and let the image contrast $IC\left(\tilde{\beta}, \tilde{\gamma}\right)$ be defined as follows:

$$IC(\beta,\gamma) = \frac{\sqrt{A\left\{\left[I^2(x_1,x_2,\beta,\gamma) - A\left\{I^2(x_1,x_2,\beta,\gamma)\right\}\right]^2\right\}}}{A\left\{I^2(x_1,x_2,\beta,\gamma)\right\}} \tag{11}$$

where operator $A(\cdot)$ represents the spatial mean on the image coordinates (x_1, x_2). The image contrast function $IC(\beta,\gamma)$ is the ratio between the standard deviation and the mean of the squared image intensity $I^2(x_1, x_2; \beta, \gamma)$ and gives a measure of the image focus. Mathematically, the estimates of the focusing parameters are obtained by maximising the image contrast:

$$\left(\hat{\beta}, \hat{\gamma}\right) = \arg\left(\max_{\beta,\gamma}\left[IC(\beta,\gamma)\right]\right) \tag{12}$$

Eq. 12 represents a typical optimisation problem. The global maximum can be found by using the Nelder-Mead (Simplex) Method. The *IC* shows a strongly multimodal behaviour far from the global maximum, hence a suitable initialisation technique must be provided in order to obtain an initial guess sufficiently close to global maximum. The initialisation technique provides an initial guess of both β and γ. The guess β_{in} is estimated by means of the Radon transform and γ_{in} by means of a linear search based on the *IC* with a choice of $\beta = \beta_{in}$.

The main steps of the algorithm are summarised below:

1) Estimate β_{in} by means of the radon transform;

2) Estimate γ_{in} by means of the linear search;

3) Solve the optimisation problem of eq. 12 with the initial guess $\left(\hat{\beta}_{in}, \hat{\gamma}_{in}\right)$;

4) Use the solution of eq. 12 for the image focusing.

III.2 Review of EBT

The EBT algorithm was proposed in [10-11]. The image entropy is used both for range bin alignment and residual phase adjustment. In this section we describe the EBT algorithm directly applied to the image $I\left(x_1, x_2; \tilde{\beta}, \tilde{\gamma}\right)$. The estimation procedure of the focusing parameters (β, γ) is the same of the ICBT. The difference between the two algorithms rely on the image focus parameter, which, in this case, is the image entropy:

$$IE(\beta,\gamma) = -\sum_{x_1}\sum_{x_2} \ln\left(\bar{I}(x_1,x_2,\beta,\gamma)\right)\cdot \bar{I}(x_1,x_2,\beta,\gamma) \qquad (13)$$

where $\bar{I}(x_1,x_2,\beta,\gamma) = I^2(x_1,x_2,\beta,\gamma) \big/ A\left(I^2(x_1,x_2,\beta,\gamma)\right)$.

The estimates of the focusing parameters are obtained by minimizing the image entropy:

$$\left(\hat{\beta},\hat{\gamma}\right) = \arg\left(\min_{\beta,\gamma}\left[IE(\beta,\gamma)\right]\right) \qquad (14)$$

IV. Performance analysis and comparison

The performance analysis will be carried out by means of: 1) Visual inspection; 2) Image intensity peak value; 3) Image Contrast; 4) Image Entropy and 5) Computational Load.

IV.1 Data Set

The data set used for comparing the autofocusing algorithm performance was collected using a low power instrumented radar system developed by the Defence Science and Technology Organisation (DSTO). The radar is capable of transmitting simple frequency stepped waveforms in the band 8.0 – 18.0 GHz. During the measurement the radar was housed in a mobile van near the Adelaide airport (Australia). Tables I gives the relevant radar parameters used to collect the dataset. Data were taken using horizontally polarised transmit and receive antennas mounted on a pedestal that was pointed manually to track the targets. Aircraft image data was gathered soon after take-off from Adelaide airport at ranges between 1.5 and 3.0 km.

IV. 2 Results

In this section we show an example of a 737 ISAR image reconstructed by using the PPP, PGA, ICBT and EBT algorithms. These images are reported in Fig.1,2,3,4. The comparison analysis among the three algorithms has been carried out by considering: 1) image "visual quality"; 2) peak value of the image intensity (Table II); 3) image contrast (Table III); 4) computation efficiency.

We note that: 1) A large Doppler spreading occurs in the PPP image; 2) ICBT and EBT images are very similar and show a better spatial resolution than the PPP and PGA. This is confirmed by looking at the airplane nose and wing. In fact, in the ICBT and EBT images, the single scatterers are resolved well. 3) According to the image peak and contrast values, the ICBT and the EBT algorithms show the best performance; 4) The computational load for the ICBT and EBT is roughly ten times longer then the PGA and PPP. It is worth noting that an efficient code implementation could drastically drop the computational time and enable fast radar imaging.

TABLE I
RADAR PARAMETERS

N° of sweeps	512
N° of transmitted frequencies	128
Lowest frequency	9.26 GHz
Frequency step	1.5 MHz
Range resolution	0.78 m
Radar height (h_s)	Ground level
Target type	Boeing 737
PRF/Sweep Rate	20 kHz / 156.25 Hz

TABLE II
IMAGE PEAK

NON PARAMETRIC ALGORITHMS		PARAMETRIC ALGORITHMS	
PPP	PGA	ICBT	EBT
37.03 dB	39.51 dB	41.05 dB	42.39 dB

TABLE III
IMAGE CONTRAST

NON PARAMETRIC ALGORITHMS		PARAMETRIC ALGORITHMS	
PPP	PGA	ICBT	EBT
1.01	1.24	1.29	1.26

V. Conclusions

In this paper, we have provided a quick survey on the main ISAR autofocusing techniques presented in the literature. In detail, PPP and PGA have been considered as representative of non parametric techniques, whereas ICBT and EBT as parametric techniques. PPP and PGA are two-step techniques, consisting of range alignment and residual phase adjustment. ICBT and EBT use an iterative method to optimize the image focus. The results show that ICBT and EBT have better quality images in terms of visual inspection as well as in terms of image contrast and image peak value. Their main drawback is a larger computational time than PPP and PGA. Nevertheless, a suitable DSP implementation could drastically improve the computational time and allow fast ISAR imaging.

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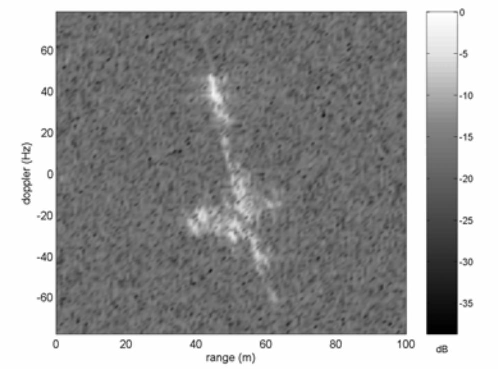

Fig.2 – PGA ISAR image of a Boeing 737

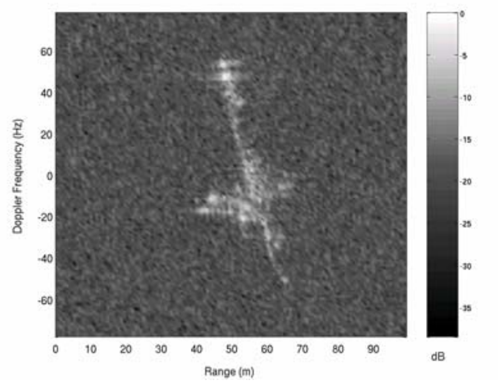

Fig.3 – ICBT ISAR image of a Boeing 737

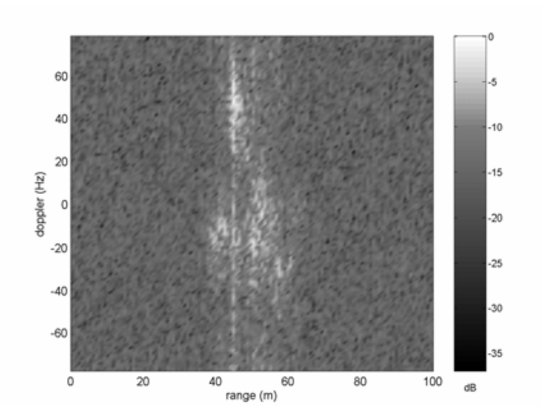

Fig.1 – PPP ISAR image of a Boeing 737

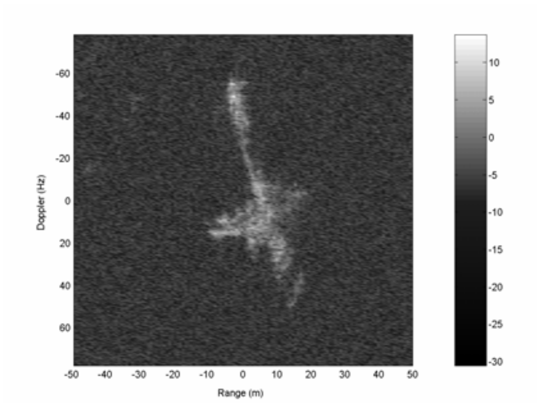

Fig.4 – EBT ISAR image of a Boeing 737