INVERSE SYNTHETIC APERTURE RADAR IMAGING FOR POINT SCATTERERS USING APES ALGORITHM

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ABSTRACT

In this study, An adaptive FIR filtering approach , which is referred to as the amplitude and phase estimation of a sinusoid (APES) is presented. We also describe how to apply the FIR filtering approaches to inverse synthetic aperture radar imaging. We show numerical examples that APES can yield more accurate spectral estimates with much lower sidelobes and narrower spectral peaks than inverse fast Fourier transform (FFT) method. We also applied one dimension APES which performs APES algorithm to rows and columns separately for imaging.

I. INTRODUCTION

The classical approaches to spectral estimation include the discrete Fourier transform (DFT), and its variants which are typically based on smoothing the spectral estimate or windowing the data [1], [2]. Another matched-filter bank (MAFI) spectral estimation method is CAPON [3]. The APES is known to have better statistical performance than the Capon. It has been found to outperform the Capon estimator in applications such as continuous-spectrum estimation, radar image feature extraction, synthetic aperture radar imagery, etc. It has been suggested that the performance superiority is in part because the Capon is biased downward, whereas the APES is unbiased [6] APES can be interpreted as adaptive finite impulse response (FIR) filtering based approaches to spectral estimation.

In this paper, we present an adaptive finite impulse response (FIR) filtering approach, which is referred to as the amplitude and phase estimation of a sinusoid (APES) algorithm, for inverse synthetic aperture radar (ISAR) imaging for point scatterers, which have different amplitude and coordinate.

The matched filter bank estimators have received considerable attention in a variety of applications including target range signature estimation and synthetic aperture radar (SAR) imaging. It is well known that APES can yield more accurate spectral estimates with much lower sidelobes and narrower spectral peaks than the fast Fourier transform (FFT) method, which is also a special case of the FIR filtering approaches [4].

We compare the results obtained by one dimension APES (1D-APES, two dimension APES (2D-APES) methods and fast Fourier transform (FFT). We show by means of situational examples the APES methods can provide more accurate spectral estimates, narrower spectral peaks and lower sidelobe levels than the fast Fourier transforms method (FFT).

II. PROBLEM FORMULATION

Direct Problem: Calculation of Scattered Signal for Given Reflectivity Distribution.

Let's assume N scatterer located the positions (x_1,y_1), (x_2,y_2), …..(x_N,y_N) respectively. This area is illuminated by radar to obtain reflectivity image of the observed area. Under the far field conditions, incident field is assumed to be plane wave.

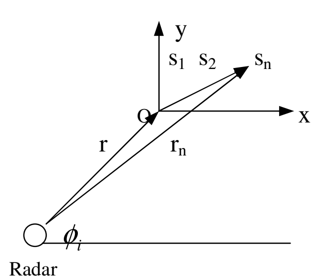

Figure 1. Geometry of imaging scenario.

The position vector of n. scatterer, according to Oxy coordinate system in fig.1, is given by

$$\vec{s}_n = x_n \vec{u}_x + y_n \vec{u}_y \quad (1)$$

r>> $\max_n |s_n|$ is satisfied, thus distance from radar to n. scatterer is expressed as,

$$r_n = r + \vec{s}_n . \vec{u}_r \quad (2)$$

Where $\vec{u}_r$ is unit vector from radar to O point and also defines propagation direction.

Let the radar illuminates the scatterer by direction that makes ϕ_i angle with Ox axis depicted in fig.1. Received signal is given as,

$$s(k_x, k_y) = \frac{e^{-j2kr}}{r^2} \sum_{n=1}^{N} a_n e^{-j2(k_x x_n + k_y y_n)} \quad (3)$$

Where k is defined as,

$$k = \sqrt{k_x^2 + k_y^2} = 2\pi f / c \quad (4)$$

Where f is operation frequency, c is speed of light and

$$k_x = k \cos(\phi_i) \quad (5)$$

$$k_y = k \sin(\phi_i) \quad (6)$$

e^{-j2kr}/r^2 term contains attenuation and constant phase rotation which does not change with k_x and k_y, so this term can be omitted.

For continuous target, obtained signal is given by

$$s(k_x, k_y) = \iint_{\substack{observed \\ area}} \sigma(x, y) e^{-j2(k_x x + k_y y)} dxdy \quad (7)$$

In practice, radar sends pulses whose pulse duration is τ with modulation frequency f_0, so it has bandwidth approximately $B = 1/\tau$. Observing the target with different observation directions and frequency value, one obtains Fourier transform of reflectivity of target in discrete points.

Inverse Problem: Calculation of Reflectivity Image of Observed Object for Given Scattered Signal

As expressed in direct problem, scattered signal is Fourier transformation of reflectivity distribution, so classical approach for obtaining $\sigma(x, y)$ is inverse Fourier transformation of $s(k_x, k_y)$. However, operational limitation such as limited bandwidth of radar and observation directions, one obtains Fourier transform of $\sigma(x, y)$ not for all k_x, k_y but discrete limited values. Using computers, inverse Fourier transform can be performed using fast Fourier transform algorithm (IFFT). Because of these, Classical IFFT cause low resolution and high sidelobe level. Some windowing functions is used for suppressing sidelobe level, but these methods cause resolution decreasing.

In APES method, spectrum estimation of reflectivity is improved and high resolution can be obtained.

We begin with a dataset $Y(m,n)$ of size [M x N]. In this case, we are interested in using a two-dimensional set of either filter or prediction coefficients of size [p x q]. In order to perform the inversion of $\hat{R}$, it is necessary that pq < MN/2, otherwise the rank of $\hat{R}$ which is ≤ (N – q)(M - p) will be less than the dimension of $\hat{R}$, which is pq [1].

The forward covariance matrix will be determined as

$$\hat{R}_F = \frac{1}{(N-q)(M-p)} \sum_{n=q+1}^{N} \sum_{m=p+1}^{M} vec[y(m,n)] vec[y(m,n)]^H \quad (8)$$

where the sub-matrix of data $\underline{y}$ is defined as

$$y = \begin{bmatrix} Y(m,n) & \cdots & Y(m,n-q) \\ \vdots & & \vdots \\ Y(m-p,n) & \cdots & Y(m-p,n-q) \end{bmatrix} \quad (9)$$

where $\hat{R}$ is defined as,

The vec[.] operation consists of stacking the columns of data on top of each other. The operator $(.)^H$ is the complex conjugate transpose of the matrix. Next, we find the backward covariance matrix with the operation

$$\hat{R}_B = J \hat{R}_F J \quad (10)$$

where J is the exchange matrix (the identity matrix flipped left-to-right) of the same size as $\hat{R}_F$. This operation is equivalent to flipping $\hat{R}_F$ up-down and then left-right. The combined forward-backward covariance matrix is then found simply as

$$\hat{R}=\frac{\hat{R}_B+\hat{R}_F}{2} \tag{11}$$

we are given a dataset $\underline{Y}(m,n)$ of size [M x N], and wish to use an estimator with a filter coefficient matrix of size [p x q]. We then define the quantity

$$\hat{Q}(w_x,w_y)=\hat{R}-\frac{[\underline{g}(w_x,w_y)\underline{g}^H(w_x,w_y)+\underline{\tilde{g}}(w_x,w_y)\underline{\tilde{g}}^H(w_x,w_y)]}{(M-p+1)(N-q+1)} \tag{12}$$

where $\hat{R}$ is defined as in (11), and the vectors $[\underline{g},\underline{\tilde{g}}]$ are defined as

$$\underline{g}(w_x,w_y)=\sum_{n=0}^{N-q}\sum_{m=0}^{M-p}\underline{y}e^{-j(mw_x+nw_y)},\quad \underline{\tilde{g}}(w_x,w_y)=\sum_{n=0}^{N-q}\sum_{m=0}^{M-p}\underline{\tilde{y}}e^{-j(mw_x+nw_y)} \tag{13}$$

with $\underline{y}$ as in (9) and $\underline{\tilde{y}}$ is simply

$$\underline{\tilde{y}}=\begin{bmatrix} Y^*(M-m-1,N-n-1) & \cdots & Y^*(M-m-1,M-n+q-1) \\ \vdots & & \vdots \\ Y^*(M-m+p-1,N-n-1) & \cdots & Y^*(M-m+p-1,N-n+q-1) \end{bmatrix} \tag{14}$$

We then take the inverse of $\hat{Q}$ (which can be shown to exist since the inverse of $\hat{R}$ exists, being Hermitian and positive definite). Next, we need to define the vectors

$$\underline{a}_{p,q}(w_x,w_y)=\underline{a}_p(w_x)\otimes\underline{a}_q(w_y) \tag{15}$$

Where

$$\underline{a}_p(w_x)=[1\quad e^{jw_x}\quad\cdots\quad e^{jw_x(p-1)}],\qquad \underline{a}_q(w_y)=[1\quad e^{jw_y}\quad\cdots\quad e^{jw_y(q-1)}] \tag{16}$$

The $\otimes$ operator is the Kronecker product of the vectors. Finally, the expression for the APES spectral estimator is given by

$$\hat{\phi}_{APES}(w_x,w_y)=\frac{\underline{a}_{p,q}^H(w_x,w_y)\hat{Q}^{-1}(w_x,w_y)\underline{g}(w_x,w_y)}{L_xL_y\underline{a}_{p,q}^H(w_x,w_y)\hat{Q}^{-1}(w_x,w_y)\underline{a}_{p,q}(w_x,w_y)} \tag{17}$$

This quantity must be computed for each two-dimensional frequency pair (w_x,w_y). Thus, if implemented directly, the APES estimator would not be very efficient.

III. EXPERIMENTAL RESULTS

As an example, we compared the ISAR images of discrete point scatterers obtained by IFFT, 1-D APES and 2-D APES. 1-D APES performs APES algorithm to rows and column separately. Positions and amplitudes of the scatterers is given as fallows,

xs(1)=-12; ys(1)=12; as(1)=3;
xs(2)=-9; ys(2)=-6; as(2)=2;
xs(3)=-9; ys(3)=6; as(3)=1;
xs(4)=-6; ys(4)=9; as(4)=2;
xs(5)=3; ys(5)=-9; as(5)=1;
xs(6)=3; ys(6)=-3; as(6)=1;
xs(7)=6; ys(7)=-6; as(7)=1;
xs(8)=6; ys(8)=9; as(8)=2;
xs(9)=9; ys(9)=-3; as(9)=1;

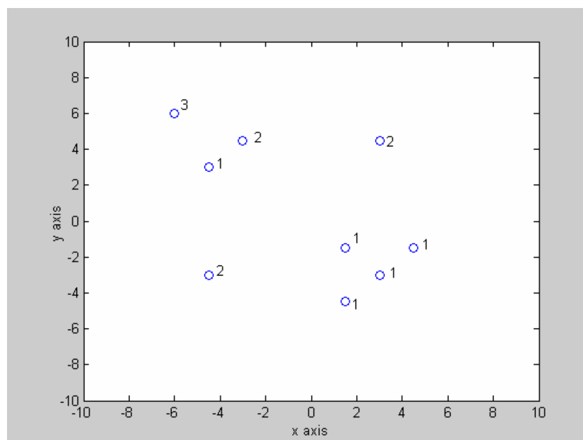

Fig.2-) Positions and amplitudes of the scatterers

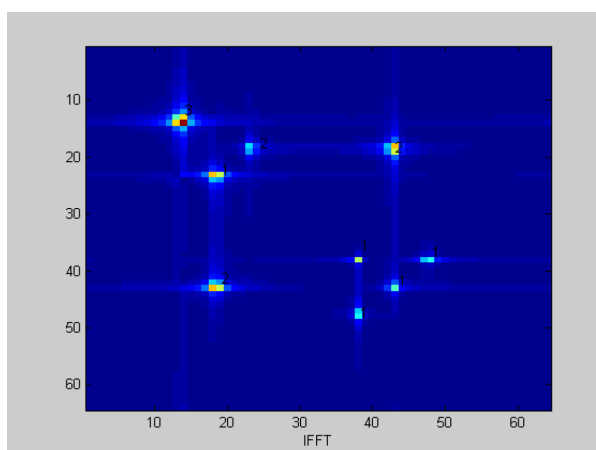

Fig.3-) ISAR image of scatterers using IFFT algorithm

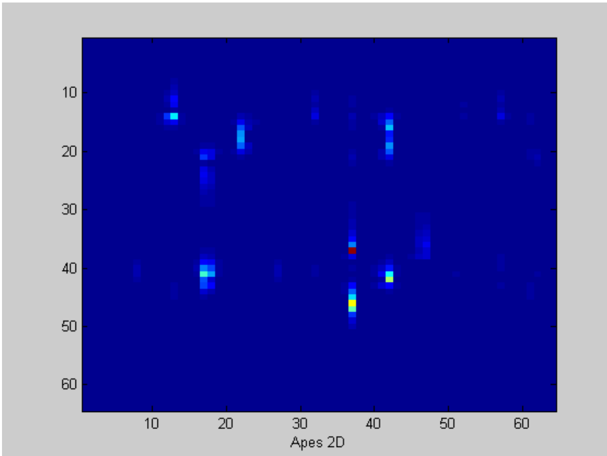

Fig.4-) SAR image of scatterers using 1-D APES algorithm

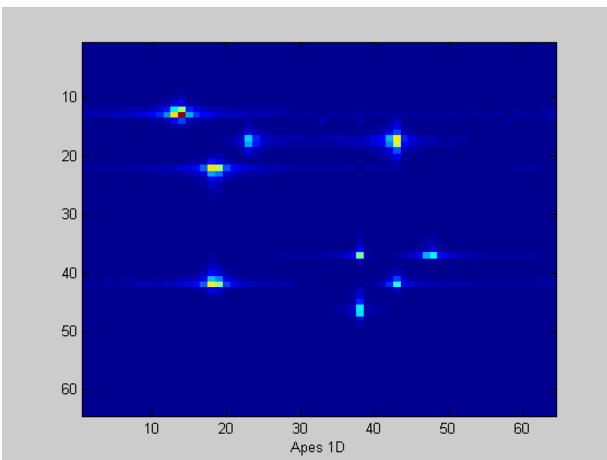

Fig.5-) SAR image of scatterers using 2-D APES algorithm

IV. CONCLUSION

We have presented an adaptive FIR filtering approach which is the APES spectral estimation method. We have compared the APES method with IFFT and also we compared the 1-D APES with the 2-D APES method. We have shown by means of experimental examples that the APES method can yield better resolution with much lower sidelobes and narrower spectral peaks than IFFT, which is also a special case of the FIR filtering approaches (see fig3 and fig.5). And also we have shown that 2-D APES gives more accurate spectral estimates and better result than the 1-D APES method.

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