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Apply Super-SVA to SAR Imaging with Both Aperture Gaps and Bandwidth Gaps

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***Abstract*—**Synthetic aperture radar (SAR) imaging usually requires echo data collected continuously pulse by pulse with certain bandwidth. However in real situation, data collection or part of signal spectrum can be interrupted due to various reasons, i.e. there will be gaps in spatial spectrum. In this case we need to find ways to fill out the resulted gaps and get image with defined resolution. In this paper we introduce our work on how to apply iterative spatially variant apodization (Super-SVA) technique to extrapolate the spatial spectrum in both azimuthal and range directions so as to fill out the gaps and get correct radar image.

***Keywords*—**SAR imaging, Sparse aperture, Stepped frequency chirp signal, high resolution, Super-SVA

I. Introduction

IN SAR system, stepped frequency chirp signal (SFCS) is often used for achieving high range resolution. SFCS is a combination of chirp signal and stepped frequency continuous waveform, and has advantages of the both signals. It has gained more and more attention in recent years [1]-[5]. In practice if the frequency step is larger than the bandwidth of subchirp, then it can be very helpful for using less number of subchirps to obtain larger bandwidth and reducing the influence of target motion on the quality of synthesized signal. However the bandwidth gaps will bring high grating lobes in range profile. In this paper we show iterative spatially variant apodization (Super-SVA) can be used to extrapolate the bandwidth of each subchirp so as to fulfill the bandwidth gaps between subchirps and efficiently eliminate grating lobes.

Sparse aperture can also be gapped-data problem aroused when certain received data are missing due to system error or some data must be discarded because of being corrupted by interfering sources [6]. Bi/multi-static scenarios with separated receivers at different azimuth angle locations can also lead to sparse aperture [7]. These aperture gaps will produce artifacts in imaging and reduce the achievable resolution. In [8] and [9], the authors showed that by applying super-SVA processing on each sub-aperture data, a full aperture spectrum can be recovered, and a high resolution image can be further obtained.

In this paper we focus on the problem with two kinds of gaps, i.e. frequency gap in SFCS and aperture gap in azimuthal direction, exist at the same time. In this case, data spectrum will lose continuity in both range and azimuth directions. In the following, we will show that super-SVA technique still works, i.e. it can be used to extrapolate data along both directions simultaneously so to get full spectrum without gaps. The gap-filled data then can be processed to get image without major artifacts.

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II. The Principle of super-SVA

Super-SVA is a robust super resolution technique without requiring a-priori knowledge of scene content. It can be used to extrapolate the signal bandwidth in a simple, straightforward, iterative manner by repeatedly using SVA [10]-[11]. SVA is an image domain algorithm which effectively eliminates sidelobes of SAR image while not broadening mainlobe. This property of SVA is achieved through the selection of a particular frequency domain amplitude weighting function for each pixel in SAR image [12].

A. SVA

SVA is a nonlinear operator based on cosine-on-pedestal frequency domain weighting functions. The cosine-on-pedestal weighting functions are given by

$$W(n) = 1 + 2\alpha\cos(2\pi n / N), 0 \le \alpha \le 0.5 \quad (1)$$

By taking the length-N discrete Fourier transform of the function we can get the Nyquist-sampled impulse response (IPR):

$$w(m) = \alpha\delta_{m,-1} + \delta_{m,0} + \alpha\delta_{m,1} \quad (2)$$

Where $\delta_{m,n}$ is the Kronecker delta function:

$$\delta_{m,n} = \begin{cases} 1, m = n \\ 0, m \ne n \end{cases} \quad (3)$$

The IPR contains only three nonzero points, so that the weighting is achieved by convolution in the image domain by the three-point kernel give in (2).

Let g(m) be the samples of either the real (I) or imaginary (Q) component of image, so the SVA-filtered image samples will be

$$g'(m) = \alpha(m)g(m-1) + g(m) + \alpha(m)g(m+1) \quad (4)$$

The task is to find $\alpha(m)$ which minimizes $|g'(m)|^2$ subject to the constraints 0≤ $\alpha(m)$ ≤0.5. When $\alpha(m)$ is unconstrained, the optimal value is

$$\alpha_u(m) = \frac{-g(m)}{g(m-1)+g(m+1)} \quad (5)$$

And $g'(m) = 0$. When $\alpha(m)$ lies in the interval [0, 0.5], the output image would be

$$g'(m) = \begin{cases} g(m), & \alpha_u(m) < 0 \\ 0\,, & 0 \le \alpha_u(m) \le 0.5 \\ g(m) + 0.5\times[g(m-1)+g(m+1)], & \alpha_u(m) > 0.5 \end{cases} \quad (6)$$

B. Super-SVA

Super-SVA is one kind of super resolution method based on SVA. It can be used to broaden spectrum by iteratively using SVA and frequency-domain inverse amplitude weighting operation. Fig.1 shows the flow chart of the algorithm [8].

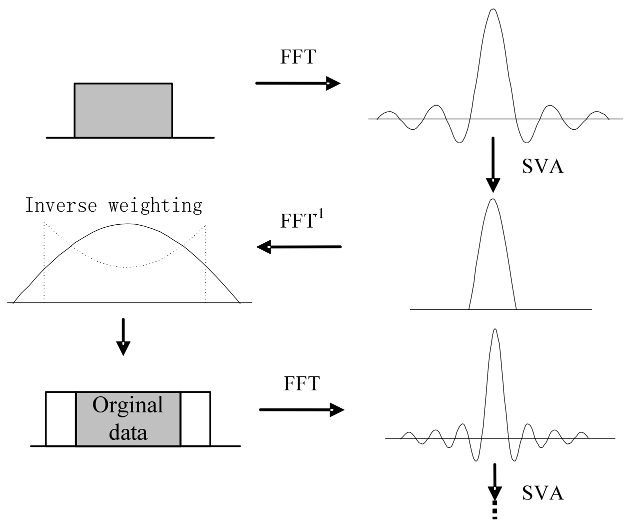

Fig. 1 The flow chart of super-SVA

In the above flow chart, after firstly performing FFT on original data, SVA is then applied to the resultant image to remove sidelobs. Then inverse FFT is performed. Since SVA is a nonlinear operation, the image is no longer band-limited at this point. The next step in the deconvolution process is to apply an inverse amplitude weight to the frequency domain data. The inverse weight is the inverse Fourier transform of a sinc function mainlobe. The weighted signal must be truncated to keep the total extrapolation less than 60% of the original signal, thus avoiding singularities in the inverse function. After weighting and truncating, the original signal is used to replace the center portion of the extrapolated signal. The above extrapolation procedure can be repeated several times to get much higher resolution as desired.

III. Gaps Filling By Using Super-SVA

Consider a stationary target region composed of a set of point target with reflectivity σ_n located at the coordinates $(x_n, y_n)(n=1,2\ldots)$. The radar platform located at (0, u) and moves with constant velocity along a straight path. Suppose the transmitted wide-band pulse signal is $p(t)$, and the radar measured echo signal is

$$s(t,u) = \sum_n \sigma_n p\left(t - \frac{2\sqrt{x_n^2 + (y_n - u)^2}}{c}\right) \quad (7)$$

By taking 2D Fourier transform over t and u, we can obtain 2-D spectrum as

$$S(\omega, k_u) = P(\omega)\sum_n \sigma_n \exp(-jk_x x_n - jk_u y_n) \quad (8)$$

with $k_x = \sqrt{4k^2 - k_u^2}$ and $k = 2\pi/\lambda$ is the wave number, $P(\omega)$ is the signal spectrum. k_x, k_u is refer to as the spatial frequency.

When SAR data with both aperture and bandwidth gaps exist, i.e. k_x and k_u are not continuous. The 2-D spectrum will be divided into several blocks by gaps, although each block of spectrum can still be used to get a low resolution image individually. After applying Super-SVA to each block of spectrum, continuous spectrum can be obtained. Fig. 2 shows the flow chart of processing.

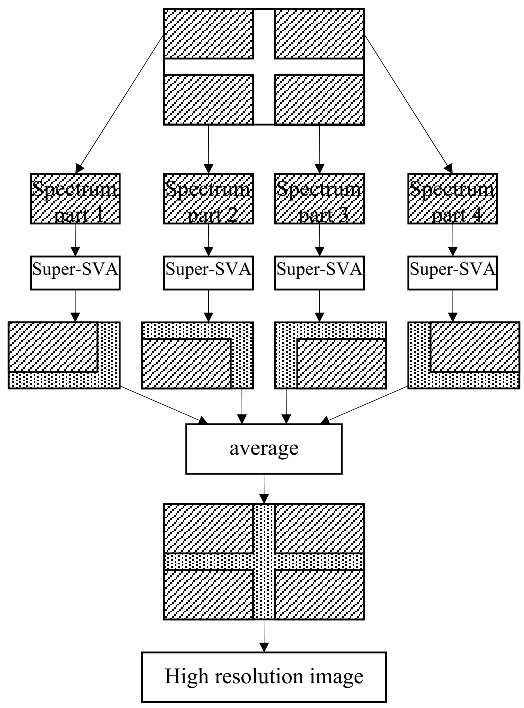

Fig. 2 Super-SVA gap filling procedure

IV. Simulations

In this section, some simulation results are presented to show the performance of the algorithm. The transmitted signal is stepped frequency chirp and the frequency step (Δf) is larger than the bandwidth of subchirp (B_m), as shown in Fig. 3.

Let B_m=40MHz，Δf=64MHz，the number of subchirp is 3. So the synthetic bandwidth is 168MHz with two gaps of 24MHz. Furthermore we simulated a sparse aperture system to image two point targets close to each other, with 30% aperture data missing in azimuthal direction. The gap is located at the center of the aperture. Fig.4 illustrates the sparse spectrum with both two kinds of gaps exist. Image gotten based on the sparse spectrum has high sidelobes and noticeable artifacts, as shown in Fig. 5. If just use one block of the small continuous spectrum, we will get a low resolution image as shown in Fig. 6. After applying Super-SVA to extrapolating each part of continuous spectrum individually in both azimuthal and range directions, we get the whole spectrum without gaps. Fig. 7 shows the whole spectrum with all gaps filled as well as broadened. Fig. 8 shows the recovered image with much high resolution realized and with no artifacts shown, the two point targets are clearly separated.

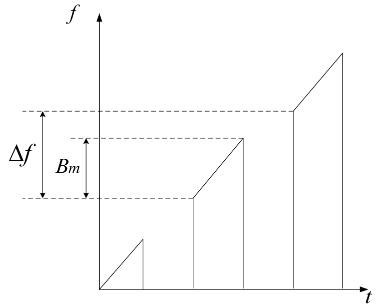

Fig. 3 frequency curves of transmit signal as function of t

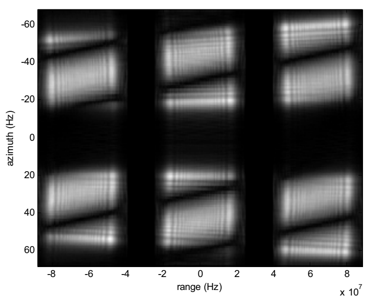

Fig. 4 spectrum with aperture gaps and band gaps

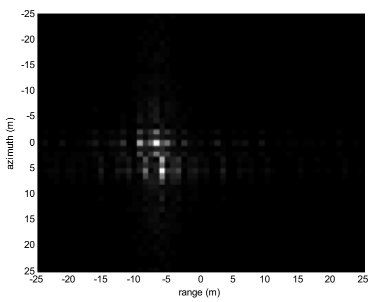

Fig. 5 Image from sparse spectrum

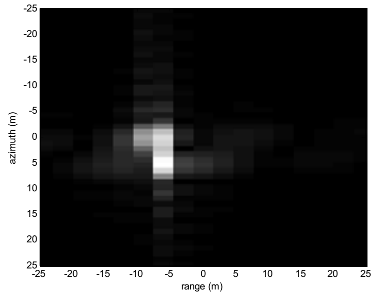

Fig. 6 Image from a block of spectrum

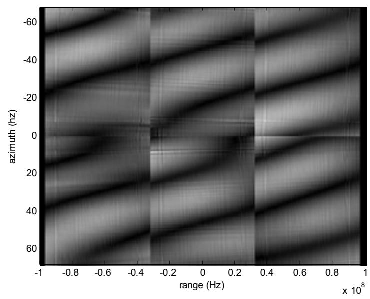

Fig. 7 The extrapolated spectrum

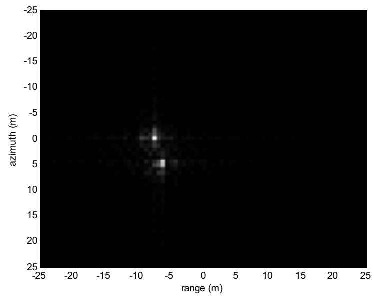

Fig. 8 Final image gotten from the whole spectrum with gaps filled

V. Conclusion

Due to various reasons, SAR data spatial spectrum may exist gaps in both range and azimuthal directions. The sparse spectrum can be “filled” by applying Super-SVA to each block of spectrum. We show that by using Super-SVA the spectrum can be extrapolated simultaneously along both directions and finally get full data spectrum without any gaps exist. Simulation results verified the efficiency of the algorithm. Compared with the image from original sparse spectrum, the image from extrapolated spectrum has high resolution, low grating lobes and no artifacts. In the near future, we will test the method developed in this paper by processing real radar data.

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