System Parameters Design and Imaging Simulation of an Experimental Vehicle SAR

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***Abstract*—Synthetic aperture radar (SAR), which is capable of producing high-quality microwave images in all day, all night and under all weather conditions, has great potential in both commercial and military applications. So SAR imaging is rapidly becoming a key technology in the community of modern remote sensing. However, due to long development period and high cost of the whole SAR system, It's very essential to develop a generalized SAR test bed with characteristics of multi-frequency, wide-band, low-cost, which is flexible and reconfigurable. For this reason, a Vehicle SAR system is developed which is introduced in this paper. First, the relationship among system parameters is analyzed and system parameters are designed according to the specific imaging region. In addition, the imaging geometry is established and signal model is derived. Finally, back projection (BP) algorithm simulation result of point targets demonstrates the validity of parameters.**

***Index Terms*—SAR; Vehicle SAR system parameters; back projection algorithm.**

I. INTRODUCTION

Synthetic aperture radars, with its remote sensing imaging capability under any weather and in any time, has been widely applied in commercial and military fields[1]. For instance, modern airborne and spaceborne SARs are capable of producing high-quality microwave images. However, with the development of science and technology, breakthrough in key technology of advanced SAR is getting more and more difficult. Due to long period of development and high cost for the whole SAR system, a generalized SAR test bed with multi-frequency, wide-band, good-flexibility, strong-configurability and low-cost[2] is very necessary for microwave imaging study. A Vehicle SAR system is introduced in this paper, which can provide support for SAR imaging study. It consists of advanced electronic measuring instruments and customized equipment.

When Vehicle moves on a fixed velocity along a straight line, Vehicle SAR system tries to transmit controlled ideal waveform by means of arbitrary waveform generator and vector microwave signal generator. Baseband signal is up-converted to radio-frequency (RF) signal by microwave signal generator. In practice, due to the amplitude and phase imbalance in the microwave signal generator (orthogonal modulator) analog I/Q channels, RF signal is severely distorted. In order to transmit ideal RF signal, pre-distortion correction of baseband signal needs to be done in advance. While ideal RF signal is radiated by transmitting antenna, echo signal is received by receiving antenna. The role of microwave signal generator is to down-convert high-frequency echo signal to intermediate-frequency(IF) signal, then IF signal is sampled by high-speed analog to digital converter (ADC) customized according to the requirement. The sampled discrete sequence is used for echo signal simulation[3].

In Vehicle SAR system, above all, only when system parameters are set properly can radar system be designed successfully. There exists close relationship among parameters. System's figure of merits include working platform(vehicle), frequency(X, Ku) and operation mode(resolution, radar range, imaging wide swath etc.), system sensitivity and so on. In terms of specific imaging region and system sensitivity, which is characterized by equivalent backscattering coefficient, signal pulse width, bandwidth, frequency, antenna view angle should be defined. After that, antenna size, pulse repetition frequency (PRF) and transmission power are optimally set further. Finally, back projection algorithm simulation experiments for echo signal of ideal point targets demonstrate the validity of parameters.

Back projection imaging algorithm is widely used in imaging because of high image quality and being compensated easily[4]. It is a time domain algorithm, whose principle is the inverse projection of radar echo data to each pixel of imaging area, whereby pixel values can be obtained by means of calculating the two-way radar echo delay time of the range between radar antenna and every imaging pixel. Back projection algorithm is applicable to any platform trajectory. The rectilinear case is the simplest to be discussed.

II. VEHICLE SAR SYSTEM PARAMETERS DESIGN

Vehicle SAR system tries to transmit high-frequency, wide-band linear frequency modulation(LFM) signals[5]. To guarantee radar's slant range resolution D_r, the LFM signal bandwidth B_r can be expressed as

$$B_r = c/\left(2\rho_r \sin\phi\right) \tag{1}$$

where c is the speed of light, ρ_r is ground range resolution, $D_r = \rho_r \sin\phi$, and ϕ is radar beam incidence angle, $\phi \in (30^\circ, 60^\circ)$. Baseband signal pre-distortion correction need to be done in advance to eliminate the microwave signal generator(orthogonal modulator) analog I/Q channels imbalance in amplitude and phase, which is described as follows.

The maximum LFM signal pulse width τ is determined by minimum system detection range, which is given by

$$\tau \le 2R_{\min}/c \tag{2}$$

In terms of specific imaging scene, for instance, Vehicle SAR range $R \le 1Km$ and radar platform height $H = 400$ m, the maximum τ is:

$$\tau \le 2\times 750/3\times 10^8 = 5\mu s \tag{3}$$

The Doppler bandwidth a is expressed as:

$$B_d = 2V/D_a \tag{4}$$

where V is vehicle speed, approximately 20m/s, and D_a represents antenna azimuth direction size, about 10 cm.

The relationship between Doppler bandwidth and PRF is as follows:

$$PRF \ge B_d \tag{5}$$

The maximum of PRF is determined by real-time sampling device of data collector. Meanwhile, In order to improve average power of transmitted signal, PRF should be as large as possible. Here it is set as 5000 Hz.

In terms of system sensitivity which is characterized by Noise equivalent Sigma Zero($NE\sigma^0$), to meet imaging application requirements of Vehicle SAR system, namely $NE\sigma^0 \le -25dB$, all parameters in relation to $NE\sigma^0$ need to be designed. The equation of $NE\sigma^0$ is

$$NE\sigma^0 = \frac{(4\pi)^3 KT_0F_nR^3L\times 2V}{P_{av}G^2\lambda^3D_r}\sin\phi \tag{6}$$

where K is Boltzmann constant， T_0 is absolute temperature, F_n is system noise coefficient, L is system overall loss, and P_{av} is average power, G is antenna gain, λ is radar wavelength.

System overall parameters are shown in Table 1:

Table 1

Parameter	value	Paramet	value
f_c (GHz)	10	T_0 (K)	273+20
B (GHz)	0.4	V (m/s)	20
PRF (Hz)	5000	F_n (dB)	5
τ (us)	4.06	L (dB)	6.5
P_{peak} (dB)	30	φ (°)	$30^\circ \sim 60^\circ$
G (dB)	20	H (m)	400

$NE\sigma^0$ satisfies imaging application requirements when antenna view angle ranges from 30° to 60° ($NE\sigma^0 \le -30dB$), as is shown in Fig 1.

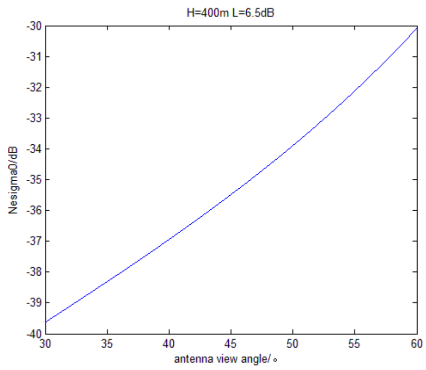

Fig 1 Relations between antenna view angle and Nesigma0

III. BASEBAND SIGNAL CORRECTION AND ECHO MODEL

What is mentioned above refers to transmitted signal high frequency and wide bandwidth. However, Due to microwave signal generator(orthogonal modulator) analog I/Q channels imbalance in amplitude and phase, it will cause severe distortion of RF signal. In order to eliminate the error, baseband signal pre-distortion correction should be done in advance until signal figure of merits satisfy performance requirements, for example, smoothness within band is ± 2 dB .

Correction procedures are as follows:

1) Output RF signal to spectrum analyzer;

2) Amplitude correction: envelope of waveform is extracted in frequency domain;

3) Phase correction: when LFM signal $B_r\tau \gg 1$, amplitude and phase error of time domain is proportional to that of frequency domain, thus frequency domain amplitude and phase error can be used for time-domain correction. Once system error function $e(t)$ is extracted, its reciprocal compensates signal amplitude and phase error. According to stationary phase principle, ideal linear modulation frequency signal $S_{LFM}(t)$ is the product of pre-distortion signal $s(t)$ and $e(t)$, the expression is defined as

$$s(t) = S_{LFM}(t)/e(t) \tag{7}$$

4) The waveform of RF signal, which has been up-converted is observed with high-performance oscilloscope. In Addition, the data of RF signal is stored in oscilloscope. The waveform data is copied and extracted, the result of waveform is shown in Fig 2.

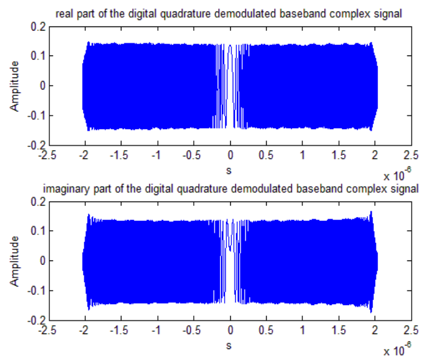

Fig 2 Approximately ideal LFM signal

Here, signal is defined as X band, pulse width τ is $4.06us$, and signal bandwidth B_r is $1GHz$.

Fig 2 shows RF signal is approximately ideal LFM signal. When correction is completed, Vehicle SAR system can transmit approximately ideal LFM signal.

The three-dimensional image coordinate of SAR system is illustrated in Fig 3. Suppose vehicle moves on a fixed velocity along a straight line in single plane. The radar works in side-looking, stripmap-mode[6]. Ideal point targets positioned at $t(x_n, y_n), n=1,2,...$ with reflectivity σ_n are distributed on imaging region which centers at $(X_c, 0)$. Radar located at position $(0,u_i), i=...-1,0,1...$ transmits LFM pulse $\mathrm{Re}\{p(t)\}$ to imaging region. The expression of $p(t)$ is defined as[7]

$$p(t)=e^{j(2\pi f_c t+\pi k_r t^2)}, |t| \le \tau/2 \tag{8}$$

where f_c is the carrier frequency, k_r is frequency modulation rate, τ is pulse width, $B_r = k_r \tau$

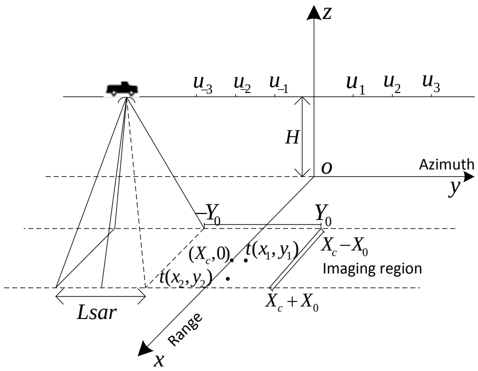

Fig 3 Imaging geometry

The echo signal at the receiver is:

$$s(t,u)=\sum_n \sigma_n p(t-t_n) \tag{9}$$

where $t_n = 2\sqrt{x_n^2+(y_n-u)^2}/c$, $\sigma_n=1$, t_n represents the two-way delay time from radar to targets. For notational simplicity, range attenuation and antenna weighing are ignored.

The baseband signal after demodulation is:

$$s(t,u)=\sum_n \sigma_n e^{-j4\pi\sqrt{x_n^2+(y_n-u)^2}/\lambda} e^{j\pi k_r (t-2\sqrt{x_n^2+(y_n-u)^2}/c)^2} \tag{10}$$

In practice, the continuous signal was sampled into a discrete series.

$$t = i/F_r \ (i=0,1,...,N_r) \tag{11}$$

$$u = j \cdot V/PRF \ (j=-N_a/2,...-1,0,1...,N_a/2) \tag{12}$$

where F_r is range sampling rate, N_r is range sampling points, and N_a represents azimuth sampling points.

IV. BACK PROJECTION FORMULA AND SIMULATION EXPRIEMENT

Once parameters is designed, to verify parameters' validity, echo signal is simulated. Before simulation, back projection imaging algorithm is presented.

Back projection algorithm is based on time-domain processing. The first step in back projection is to apply range matched filter to the time-domain data $s(t,u)$. The filtering operation can be expressed as:

$$s_M(t,u) = s(t,u) \otimes p^*(-t) \tag{13}$$

where $\otimes$ stands for time domain convolution, $p^*(\cdot)$ denotes conjugate complex of $p(\cdot)$.

The value of an image pixel (x_i, y_j) located at position of imaging region is given by integration over the synthetic aperture dimension

$$f(x_i, y_j) = \int s_M(t_{ij}(u), u) du \tag{14}$$

In practice, the data are discretely sampled, so we must replace the integral with a sum[8]:

$$f(x_i, y_j) = \sum_u s_M(t_{ij}(u), u) \tag{15}$$

where x_i is range coordinate, and y_j is azimuth coordinate, $t_{ij}(u) = 2\sqrt{x_i^2+(y_j-u)^2}/c$ is the two-way delay time from radar to image pixel (x_i, y_j) .

Obviously, the trajectory of $(t_{ij}(u), u)$ is hyperbolic. In practice, the value of $t_{ij}(u)$ and imaging grid points do not coincidence, in order to realize precise focusing in azimuth, an interpolation can be performed. One way is to improve range resampling rates so as to make azimuth focusing performance better. It's presented in the following paragraph.

Back projection algorithm flow chart is presented as Fig 4:

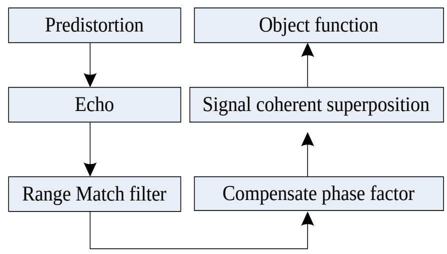

Fig 4 Algorithm flow chart

Three point targets are given:

1) the center of image scene $(750, 0)$;

2) different range position, identical azimuth position with above **1)** $(750+20*DX, 0)$ *;*

3) identical range position,different azimuth position wirh **above 1)** $(750, 0+20*DY)$ *;*

where DX denotes range resolution, and DY denotes azimuth resolution. The imaging result is illustrated in Fig 5:

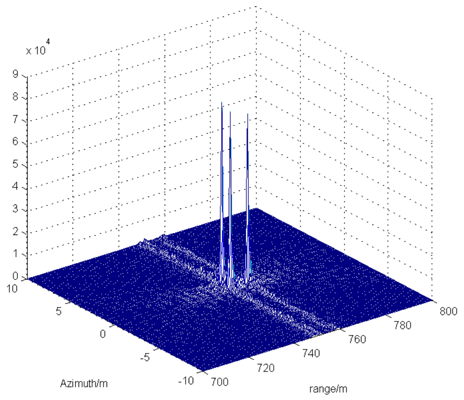

Fig 5 Imaging results without interpolation

In Fig 5, There are obvious point targets in imaging region, which can explain back projection algorithm is applicable to wide beam Vehicle SAR system. However, There exists strong azimuth sidelobe. The main reason is that sampling points are difficult to coincide with theoretical accumulation curve. An interpolation need to be performed. Here the method of improving range resampling rate is introduced to make the performance of azimuth focusing better.The result is shown as Figure 6

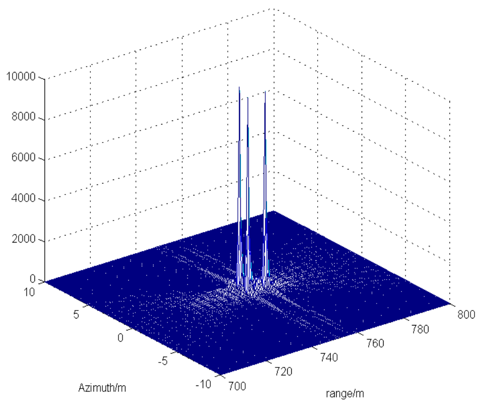

Fig 6 Imaging results with eight times interpolation

As is presented in Fig 6, azimuth sidelobe are reduced greatly. The azimuth focusing performance of image is improved when range resampling rate is set eight times larger than before. In theory, the finer interpolation is adopted, the better performance of image will be obtained. Due to compuation load and PC's performance, the times of interpolation should be chosen properly.

The simulation result of point targets is shown as Fig 7 with eight times interpolation. Figure 7 shows three resovled point targets with correct positions as predifined.

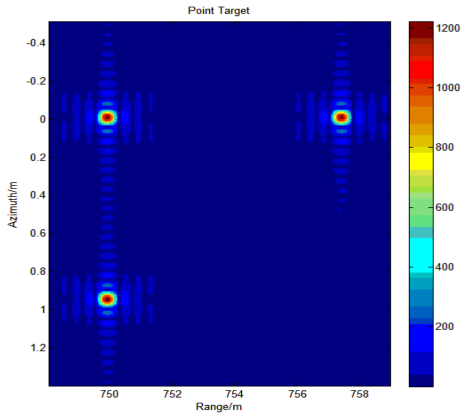

Fig 7 Point targets

V. Conclusion

The paper designs Vehicle SAR system's parameters. In practice, due to orthogonal modulator analog I/Q channels imbalance in amplitude and phase, RF signal is of severe distortion. Baseband signal pre-distortion correction must be done in advance. When signal figure of merits satisfy performance requirements. Transmitting ideal LFM signal through the simulation, then back projection algorithm is used to simulate point targets imaging based on echo signal model to demonstrate parameters' validity. The result shows that the design of parameters is suitable.

VI. Acknowledgment

This work was supported by the National Basic Research Program of China (2010CB731903).

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