SPACE-TIME CODE APPLICATION ON THE BLOCK CODING OF A SIAR MIMO RADAR

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ABSTRACT

The idea in space-time code is to code the information both spatially and temporally and transmit the coded sequence over several antenna elements using the same bandwidth. This type of coding has the ability to increase throughput. In this article, we will apply this space-time code on the block coding of Multiple In Multiple Out (MIMO) radar on a SIAR (Synthetic Impulse Aperture Radar) system. The aim is to evaluate the performance of the SIAR system, from the variations of the simulation parameters including in the SIAR radar equation, the visualization of the connecting signals.

Keyword: *radar, MIMO, SIAR, space-time code*

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1. INTRODUCTION

SIAR (Synthetic Impulse Aperture Radar) is a new type of radar system based on the use of multiple transmit and receive antennas. This includes the idea of Multiple In and Multiple Out (MIMO) radar.
These transmit antennas transmit orthogonal signals with multiple carrier frequencies and the receiving antenna array decomposes the signal components radiated according to the frequency codes.
It is capable of forming multiple beams at the same time, particularly suitable for detection and tracking in a multi-target environment.
In addition, it has the ability to measure four-dimensional (4D) parameters of targets: range, velocity, azimuth, and elevation.
This article will evaluate these 4D parameters at the coding block level.

2. RADAR EQUATION OF SIAR AND ITS CHARACTERISTICS

A radar relies on scattered echo energy to detect targets. The radar equation describes quantitatively the relationships among radar detection range, radar parameters, and target characteristics. The major roles of the radar equation are:

- to estimate the radar detection range according to the parameters of its subsystems;
- to estimate the transmitting power based on the radar detection range;
- to provide an important guidance to choose the subsystem parameters in the radar system design.

2.1 SIAR Radar Equation

The number of transmit antennas is N_t and the gain of a single transmit antenna is G_t. The number of receive antennas and the gain of a single receive antenna are N_r and G_r respectively. The transmit pulse width is T_e. The total bandwidth of the transmitted signal $B = N_t\Delta f$, and we set $T_e\Delta f = 1$.

The product of the time-width and bandwidth equals $T_eB = N_t$. The range of target is R and the radar cross-section (RCS) of the target is σ.

Multiple-carrier frequency signals are transmitted at the same time and are orthogonal to each other in SIAR.

Therefore, the powers of transmitted signals are not added in space. Then the received echo power of the target by every transmitted signal component separated by each receive antenna is [1]

$$P'_{r,SIAR} = \frac{P_tG_eG_r\sigma\lambda^2}{(4\pi)^3R^4} \quad (01)$$

The impulse synthesis for SIAR is to compensate the phases of the separated signals and then sum all the compensated signals. Therefore, for the target, the power resulting from impulse synthesis increases ${N_t}^2$ times. Similarly, N_r received signals are performed by DBF, and the power will then increase ${N_r}^2$ times.

If the number of pulses for coherent integration in SIAR is N_2, the power of N_2 coherent integrations will increase ${N_2}^2$ times. Therefore, the total gain of the target echo after receive DBF, transmit aperture synthesis, and coherent integration equals [1]

$$A_{SIAR} = (N_tN_rN_2)^2 \quad (02)$$

Then the echo power of the target for SIAR equals [1]

$$P_{r,SIAR} = N_tP'_{r,SIAR}A_{SIAR} = \frac{N_tP_tG_eG_r\sigma\lambda^2}{(4\pi)^3R^4}(N_tN_rN_2)^2 \quad (03)$$

For the conventional surveillance radar, the dwell-time at a beam direction is limited to beam scanning. For example, if the beamwidth is 2° the beam scanning speed is 6rpm, and the pulse repetition frequency (PRF) is 300Hz. The SIAR does not require beam scanning. The number of pulses N_2 for coherent integration is only limited to system coherence and the target speed. It is only required for the target not to move beyond a spatial resolution cell. So, the number of pulses for coherent integration in SIAR can be up to several hundreds.

If movement compensation across range cells is performed, more pulses for coherent integration will be available. In general, the rotation speed of a surveillance radar is 6 rpm, and then the data rate is 10 seconds. As the SIAR adopts 1 second for coherent integration in all beam directions, then its data rate is 1 second. It is clear that the data rate of SIAR is higher than that of a conventional surveillance radar.

2.2 Energy Utilization Ratio of SIAR

The noise power of a receiver is ${N_0}' = KT_0BF_n$, where F_n denotes the noise figure of the receiver, K is the Boltzmann constant, and T_0 represents the standard noise temperature. The noises received by each antenna in different pulse repetition periods are the independent and identically distributed random noises. In SIAR, the noise power after impulse synthesis, receive DBF, and coherent integration will be increased $(N_tN_rN_2)$ times.

Then the output of signal-to-noise ratio equals [1][2]

$$\left({}^{S}/_{N}\right)_{SIAR} = \frac{P_{r,SIAR}}{{N_0}'N_tN_rN_2} = \frac{N_tP_tG_tG_r\sigma\lambda^2}{(4\pi)^3KT_0BF_nR^4}N_tN_rN_2 = K_{SNR,1}{N_t}^2N_rN_2 \quad (04)$$

where

$$K_{SNR,1} = \frac{N_t P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 K T_0 B F_n R^4} \tag{05}$$

denotes the signal-to-noise ratio of a single transmitted component separated by a single receive antenna. Equation (04) is the radar equation of SIAR.

If radar works in the single-target tracking mode, then the energy utilization ratio of a SIAR radar is only $1/N_t$ as much as that of PAR. The energy utilization ratio of an SIAR will be improved when there are multitargets in different beam directions. If there are targets at all beam directions, then the transmitted energy will not be wasted.

2.3 Performance of SIAR

Assume that the antenna gain of are recognition receiver is G_j and the range between there recognition receiver and radar is R_j.

For a single transmit channel of SIAR, the power received by the reconnaissance receiver is [1][2]

$$P'_{r,SIAR} = \frac{P_t G_e G_j \lambda^2}{(4\pi)^3 {R_j}^2} \tag{06}$$

The carrier frequencies of Ne transmitted signals in SIAR are different, but their differences are small (the total bandwidth of transmitted signals of the experimental system is only 0.5MHz), and the bandwidth is far less than the bandwidth of the reconnaissance receiver. The total power received by the reconnaissance receiver is the product of power density and bandwidth.
Thus, the power received by the reconnaissance receiver of the SIAR equals

$$P_{r,SIAR} = N_t {P'}_{r,SIAR} = \frac{N_t P_t G_e G_j \lambda^2}{(4\pi)^3 {R_j}^2} \tag{07}$$

The reconnaissance receiver disables the ability to scout out the position and the operating frequency of each transmit antenna of SIAR, so that it cannot obtain the transmit gain.

3. 4D AMBIGUITY FUNCTION OF SIAR

3.1 Ambiguity function of conventional radar

The ambiguity function is to describe quantitatively the resolution capability of ranges and velocities of a radar system under a multitarget scenario.
In conventional radar, beam scanning, pulse compression, and beamforming are separate from each other; hence only a 2D (range and Doppler) ambiguity function should be considered.
Generally, the ambiguity function is derived from resolving two different targets, taking the mean square error (MSE) as the optimal resolution criterion.

Generally, the transmitting signal is narrowband and can be expressed as a complex signal [3]:

$$S_t(t) = u(t) e^{j 2\pi f_0 t} \tag{08}$$

where $u(t)$ is the complex envelop of the transmitting signal and f_0 is the carrier frequency.
Then the ambiguity function of the time delay τ and Doppler ξ is [3]

$$\chi(\tau,\xi)=\int_{-\infty}^{+\infty}u(t)u^*(t+\tau)e^{j2\pi\xi t}dt \quad (09)$$

3.2 4D Ambiguity function

However, the range and angle of the SIAR are coupling and the matched filtering is performed in 3D parameters of range, azimuth, and elevation [3]. Therefore, the ambiguity function with 4D (range, azimuth, elevation, and Doppler) should be analyzed in SIAR. The 4D ambiguity function of the SIAR will be derived first and then its resolution capability will be analyzed. In addition, the computing formula of its beam width will be given. The illustrative diagram of a space resolution cell is shown in Fig 1, in which $\Delta r,\ \Delta\theta,$ and $\Delta\varphi$ denote the resolution cells of range, azimuth, and elevation respectively.

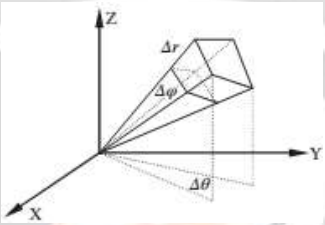

Fig -1: Resolution cell in space

In the narrowband case, we can obtain the receive pattern of the SIAR by conventional DBF (Digital Beamforming), that is,

$$F_r(\theta,\varphi)=\sum_{i=1}^{N_r}\exp\big(j2\pi f_0(\tau_{rl}-\tau_{rl}')\big) \quad (10)$$

where $\tau_{rl}'=d_r\cos\varphi\cos(\theta-\theta_{rl})/c$.
According to the matched filtering theory, the 4D ambiguity function of the SIAR can be expressed as

$$A(\tau,\theta,\varphi,\xi)=\int_{-\infty}^{+\infty}x(t+\tau)h^*(t,\theta,\varphi)\exp(j2\pi\xi t)\,dt \quad (11)$$

4. SYNOPTIC SCHEME OF SPACE-TIME CODE

The space-time coding scheme for multiple-antenna systems can be described by the diagram in Figure 2. For each block of transmissions, the transmitter selects a T x M matrix in the codebook according to the bit string $[b_1,b_2,\dots,b_{2^{RT}}]$ and feeds columns of the matrix to its transmit antennas. The receiver decodes the R bits based on its received signals which are attenuated by fading and corrupted by noise. The space-time block code design problem is to design the set, $C=\{S_1,S_2,\dots,S_{2^{RT}}\}$, of 2^{RT} transmission matrices in order to obtain low error rate.

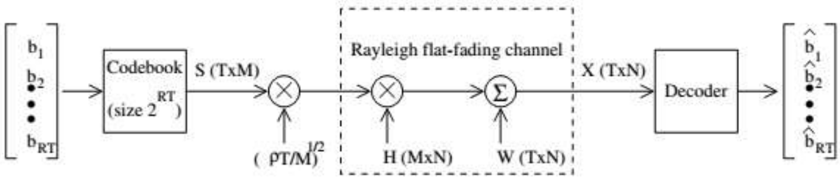

Fig -2: Space-time block coding scheme

5. SYNOPTIC SCHEME OF SIAR SYSTEM

The composition of the SIAR experimental system is shown in Fig 3 [5], including antenna subsystems, transmitting subsystem, receiving subsystem, frequency synthesis subsystem.

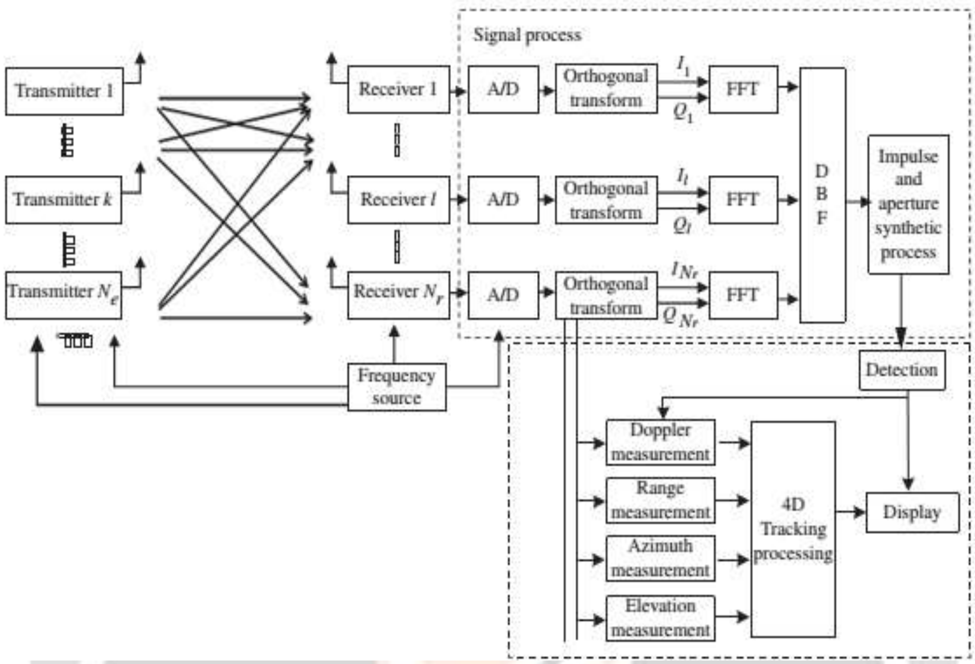

Fig -3: Synoptic scheme of SIAR system

The frequency source generates N_t RF excitation signals to N_t transmitters and provides coherent local oscillators for each receiving channel. According to the course location and Doppler information of the target provided in the search process, the target's range, azimuth, elevation, and Doppler frequency can be measured and tracked.

5.2 Antenna subsystem

The antenna array of the SIAR experimental system is given in Fig 4, which consists of $N_t$transmit antenna elements and N_r receive antenna elements distributed uniformly on two circles. The diameters of the two circles are 90 and 45 m respectively. Each transmit antenna has an independent transmitter.

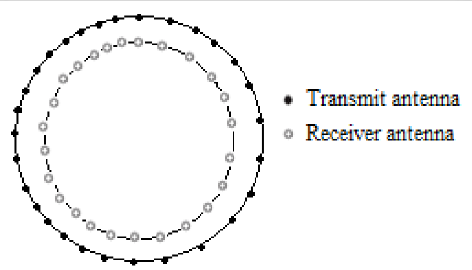

Fig -4: Antenna subsystem SIAR

5.3 Transmitting subsystem

Because the transmit antennas of the SIAR transmit different signals, distributed transmission is needed. The experimental SIAR system includes 25 full solid-state transmitters. The composition of each transmitter is shown in Fig 5 [5], including two 5 W front-stage power amplifiers, two 100 W power amplifiers, two 600 W final-stage power amplifiers, and one combiner. The excitatory signal of 10 mW of pulse poweris amplified up to 1000 W and sent to the transmit antenna via the antenna feeder.

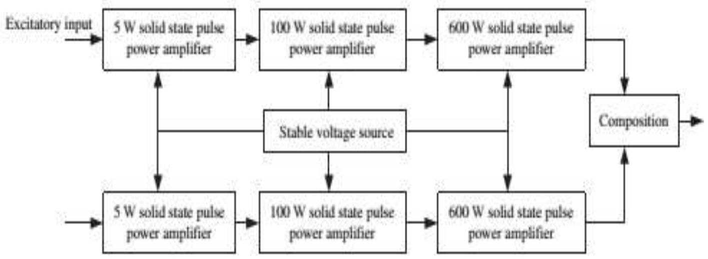

Fig -5: Block diagram of a transmitter

5.4 Receiving subsystem

Due to the limit of the operating frequency of the final-stage power amplifier in the transmitter, the operating center frequency of the experimental system is selected to be 99.2 MHz. The center frequency falls in the range of the FM (frequency modulation) broadcasting frequency.

The major challenge for the receiver is how to suppress the interferences from FM broadcasting. In practice, it is required that the suppression is up to 80 dB. On the other hand, there are strict requirements for amplitude balance and phase linearity over the whole operating frequency.

The receiving subsystem of the SIAR is composed of 25 one-time mixing superheterodyne receivers. The mixer uses the local oscillator (LO) frequency of 96 MHz, and then the 99.2 MHz radio frequency signals are down-converted to 3.2 MHz intermediate frequency signals.

The block diagram of one receiver is shown in Fig 6 [5]. Intermediate frequency signals are obtained after the received signals pass through the T/R (transmit/receive) switch (positive-intrinsic-negative, or PIN), band-pass filter (BPF), low-noise amplifier, filter, mixer, and lowpass amplifier. During operation of transmission, the receiver is protected by switching off the T/R switch via the PIN.

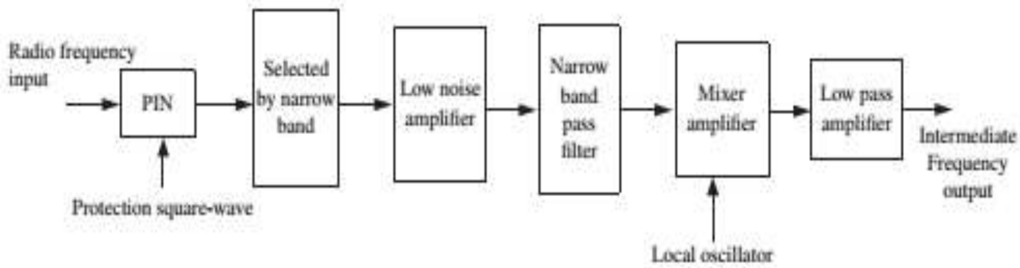

Fig -6: Block diagram of a receiver

5.5 Frequency synthesis subsystem

The frequency source of the experimental SIAR system is required to produce 25 coherent excitatory signals. Their carrier frequencies equal $f_k = f_0 + (k - 13)\Delta f$, k = 1–25, $\Delta f = 0.02$MHz (frequency spacing), and $f_0 = 99.2$MHz. It is also required to produce 25 LO signals for the receivers.

Coherent direct digital synthesizers (DDSs) are employed to produce 25 orthogonal excitatory signals, whose composition is shown in Fig 7. Using a 96 MHz constant temperature crystal oscillator, the 480 MHz clock reference signal is produced through a frequency quintupler. The 480 MHz clock reference signal provides a clock reference for 25 DDSs via power amplification and power division.

Under the synchronization clock, the 25 DDSs produce 25 radio frequency excitatory signals according to the frequency control word. In addition, the 96 MHz constant temperature crystal oscillator provides an LO signal for 25 receivers via power amplification and power division, and produces various clock control signals for the radar according to requirements.

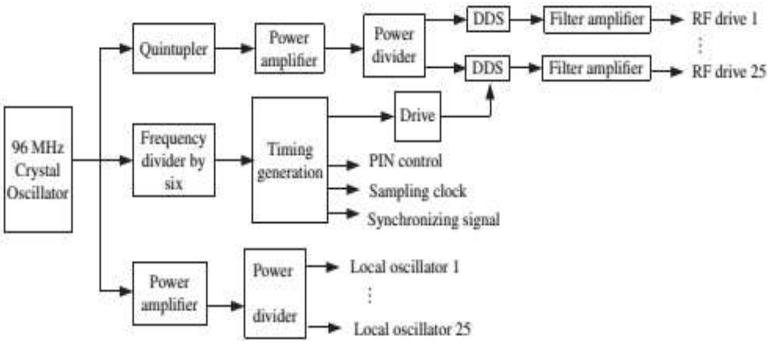

Fig -7: Block diagram of the frequency synthesis subsystem

6. SIMULATIONS

6.1 Characteristics of SIAR system

For the characteristics of a RIAS system, we will see the signal-to-noise ratio SNR as a function of range, the RCS effective surface as a function of the wavelength and as a function of range, the ambiguity functions.

The simulation parameters follow the following values: the numbers of transmit and receive antennas are 25 of each, the transmitted power $P_t = 3MW$, operating at a frequency of 110 MHz, the transmission antenna gain at 45 dB, the receive gain at 30dB. For a pulse number 250, there is a pulse duration 0.2µs, an effective area RCS (Radar Cross Section) 0.1 m^2, a radar loss at 6dB and a noise at 3dB. A maximum range of 250Km with a spacing of 0.25m was established.

6.2 Results and discussions

- **SNR as a function of range**

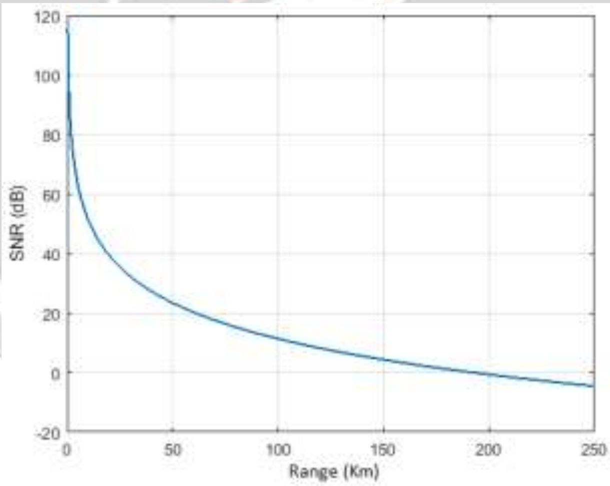

Chart -1: SNR as a function of range

From the curve it can be seen that at a distance near the radar, the SNR rate is high, so the signals are not yet sensitive to different kinds of noise.
But by moving away from the radar, this rate will decrease which means that the noise affecting the radar signals increases and will also increase the probability of false alarm.
However, at a given range or distance, the SIAR radar is more noise-resistant than conventional radar, making its signal quality better than that of the latter.

❖ **RCS as a function of wavelength**

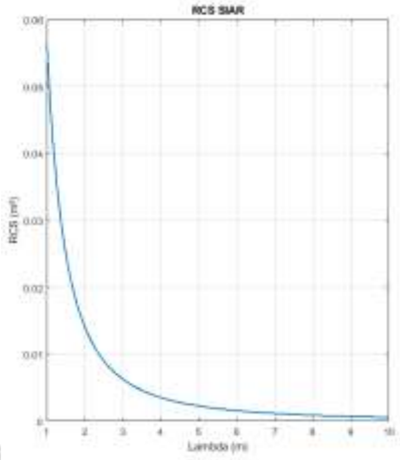

Chart -2: RCS as a function of wavelength

This result shows that RCS values decrease as a function of wavelength, that is, the longer the wavelength increases, the lower the RCS. This means that to increase the ability of the target to radiate electromagnetic energy to the radar, it is necessary to reduce the wavelength (high frequency).

And we note that even if at a longer wavelength, the SIAR radar can still detect a target with very low RCS. As a result, the SIAR radar is able to detect hidden or stealthy targets. Therefore, it demonstrates its higher performance than a conventional radar.

❖ **RCS as a function of range**

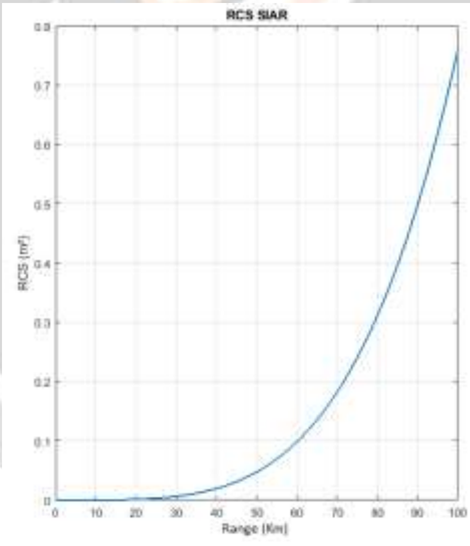

Chart -3: RCS as a function of range

The RCS curve increases from one litter to another. It can therefore be said that for a larger range, the target's ability to radiate electromagnetic energy to the radar should also be greater in order to ensure the detection of the target therein. The SIAR radar shows that even at great distances, the detection of a target is always possible with a small RCS.

❖ **Ambiguity function**

The major performances of the experimental SIAR system are described here after in combination with practical experiments, including detection performance and the resolutions of range, azimuth, and elevation.

The processing result of real target echoes is used to evaluate the resolution performance of the radar. The target is viewed as a point target and the −3 dB width of the main lobe of the impulse response is used to represent the resolution.

For the SIAR experimental system, we have the ambiguity functions of range, azimuth and elevation.

- *Range ambiguity function*

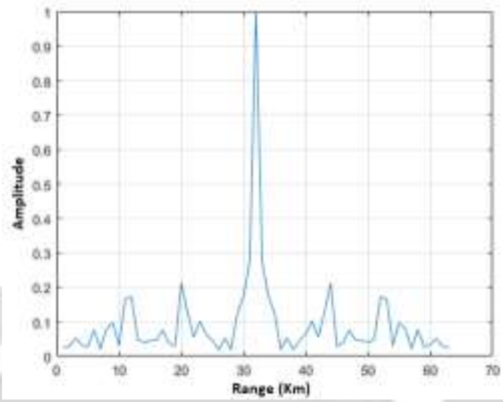

Chart -4: Range ambiguity function

The range resolution is approximate to the −3 dB pulse width after impulse synthesis (pulse compression). In the experimental system, the pulse width after impulse synthesis is 2μs, corresponding to a range resolution of 300 m.

Note that the signal gives a very narrow main lobe with secondary lobes but at low levels. According to this diagram of the range ambiguity function, the radar can give good detection accuracy at a given distance.

- *Azimut ambiguity function*

The azimuth resolution is approximately equal to the −3 dB width of the main lobe after synthesis in the azimuth domain. The result of impulse synthesis processing in the azimuth domain is shown in chart 5. The −3 dB width of main lobe in the azimuth is 1,2°.

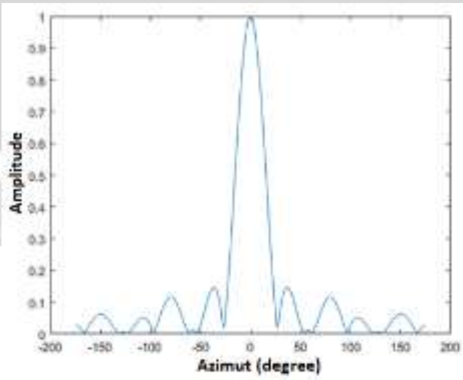

Chart -5 : Azimut ambiguity function

For a given azimuth beamwidth, the figure shows the SIAR radiation diagrams with a given SIAR grating aperture (45 m and 90 m). The level of the side lobes varies according to the opening of the network; it is higher for a small opening. The side lobe levels can be reduced when the peaks of the emission pattern offered by the transmission network correspond to the troughs of the reception pattern offered by the reception network. The azimuth resolution is improved due to the opening of the transmission network, which is once larger than the opening of the reception network.

- *Elevation ambiguity function*

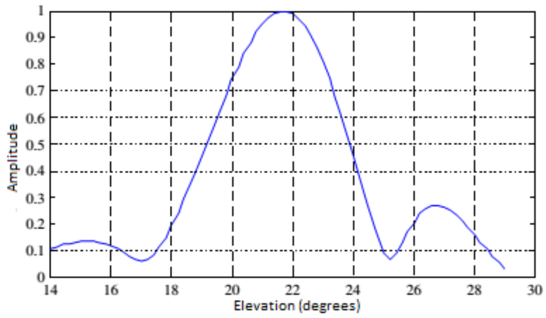

Chart -6: Elevation ambiguity function

The elevation resolution is approximate to the −3 dB width of the elevation main lobe in the pattern after synthesis. However, in the experimental SIAR system, the elevation beam width is relevant to the steering angle in elevation. The array antenna is placed horizontally and the equivalent aperture is small in low elevation, so the elevation resolution in low elevation is very bad.

Chart 6 gives the result of impulse synthesis in the elevation pattern (here assume that the target's azimuth is known beforehand); the elevation is steered to 21.5° and the −3 dB beam width is 3.5°. To improve the elevation measurement accuracy in low elevation, the antenna array is often placed vertically, or the antenna is collocated in a site with a certain altitude difference in a random manner so as to enlarge the aperture of the antenna array in the vertical dimension and then improve the resolution capability in the elevation dimension.

7. CONCLUSIONS

In short, Synthetic Impulse and Aperture Radar (SIAR) uses multiple antennas to transmit orthogonal signals with multicarrier frequencies. These signals have unique characteristics in wavelength selection, antenna types, Doppler processing, and beamforming. Special signal processing is required at reception to achieve better detection.

The ambiguity function was proposed for the study of radar resolution. In other words, when there are range and velocity differences between the "interference target" and the target, the ambiguity function can describe quantitatively the effect of the "interference target" on the target

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