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Inverse SAR 에서 속도를 모르는 움직이는 물체의 이미징 알고리즘

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Imaging an Unknown Velocity Target in Inverse SAR

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요 약

본 논문은 Inverse SAR 를 이용하여 속도를 모르는 움직이는 물체의 영상 이미지를 얻는 이미징 알고리즘을 제시하였고 실제 데이타를 알고리즘에 적용되었다.

실제 데이타는 stepped-frequency 변조된 레이더 신호를 송신하였고 수신된 데이타는 sampling rate 이 충분하지 않았으나 reference 신호를 mixing 시켜 unaliased 되게 만든 후 interpolation 에 의해서 해결하였다. 알고리즘을 적용시키는데 요구되는 물체의 속도는 subaperture processing 방법에 의해서 얻어졌으며 얻어진 속도에 의해서 squint-mode SAR geometry 로 변환한 후 최근에 제시된 approximation 이 없는 이미징 알고리즘을 사용하여 최종적으로 이미지를 얻게 되었다.

또한 ISAR 가 데이터를 송수신 하는 동안 물체의 속도가 변하는 경우 이것을 보상하는 방법을 제시하였다.

ABSTRACT

This paper presents Inverse SAR imaging algorithm for a unknown velocity target and a real ISAR data is processed and applied to the algorithm.

The real ISAR data is obtained by transmitting a number of pulse modulated by a *stepped-frequency* method and the received data are undersampled. We present a method applicable for the case of a undersampled data base. In this method, the original echoed signal is mixed with a reference signal to make it unaliased, followed by being interpolated. Target's velocity required for the algorithm is estimated via *subaperture processing* and after the coordinate transformation into

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squint-mode SAR with the estimated velocity, a recently proposed SAR /ISAR imaging algorithm derived without any approximation is utilized to produce the output image.

We also propose an ISAR imaging schme that is usable when a target changes its velocity during ISAR data acquisition time.

I. INTRODUCTION

Inverse synthetic aperture radar (ISAR) is and imaging technique that provides the powerful means to classify airborne targets at long range in a near real-time manner [1][3][4]. Unlike in SAR, a radar is ground-based and the motion if a target synthesize a large aperture.

One important goal in ISAR is tho develop algorithms that forms highly focused radar image of a target. However, this task is difficult due to the fact that the imaging is affected by the motion of a target, which is not precisely known. In SAR geometry, the effect od th target's motion has been considered in [6][7] and compensated to obtain a focused radar image [11]. In general, a target has both a translational motion and a rotational motion. The translational motion compensation is more essential for the image formation than the rotational motion is. Commonly, after the translational motion is first compensated, the rotational motion is compensated to obtain a more focused image. The translational motion compensation algorithm has been developed at the Naval Ocean Systems Center (NOSC) [8]. They use multiple spatial filters containing initial guess informations of a target's slant-range translational velocity and acceleration to estimate the target's translational motion. The resulting filtered spectrums are two-dimensional Fourier transformed and via computing their entropies indicating the sharpness of output image, target's velocity and acceleration are estimated. However, the above-mentioned procedure requires a significant computation time.

The imaging scheme we propose can be implemented in a real-time manner, even including the computation time required for target's motion estimation. This advantage in the computational speed is made possible by the assumption that during the short ISAR data acquisition time, the target's acceleration does not make any meaningful contribution to the echoed signal phase. The simulation results show that this assumption turns out to be plausible in practice.

In section II, we review the squint-mode SAR inversion equation that can generally be used in SAR /ISAR imaging. Section III specifies a whole imaging scheme and section IV discusses a ISAR imaging with time-varying velocity target and in section V, we present the experimental result obtained with a real ISAR data.

II. REVIEW OF IMAGING ALGORITHM

Consider a squint-mode SAR imaging system geometry in the (x,y) plane, call it a slant range domain (see Fig. 1).

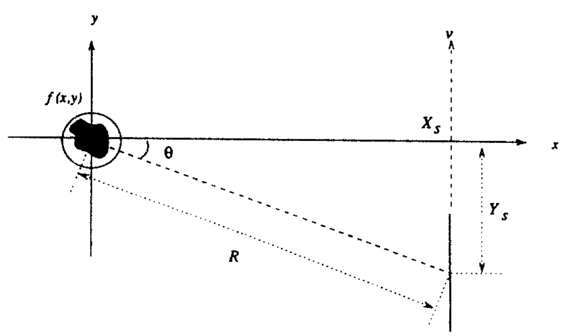

Fig. 1 Squint-mode SAR Geomrtry

The x-axis represents range and y specified the cross-range domain. A radar moves along the line $x=X_s$, with squint angle $\theta(=\arctan(Y_s/X_s))$, transmitting a pulse and receiving the corresponding echoes at discrete locations (X_s, Y_s+v) for $v \in [-Ls, Ls]$. As in Spotlight mode SAR, the transmitting antenna is always directed toward a target area that is centered around (0.,0.) in the spatial domain with its area enclosed in a disk of radius X_0, called radar's footprint. Note that X_0 is determined by the physical antenna size, range and transmitting frequency.

In this case, a total recorded echoed signal at the radar position v is first Fourier transformed with respect to time t and the resultant signal at temporal frequency ω becomes

$$s(v,\omega)=\int\int f(x,y)\exp[j2k\sqrt{(x-X_s)^2+(y-Y_s-v)^2}]dxdy \quad (1)$$

where $f(x,y)$ is the reflectivity function of the target.

Decomposing the spherical wave term in (1) into a sum of planewaves, followed by Fourier transform leads to the following inversion formula (see Appendix A):

$$F(\sqrt{4K^2-K_v^2}, K_v) = \exp[-j(\sqrt{4K^2-K_v^2}X_s+K_vY_s)] \sqrt{4K^2-K_v^2}\, S(k_v,\omega) \quad (2)$$

where k_v represents the spatial frequency domain for v and $F(k_x, k_y)$ the two-dimensional Fourier transform of $f(x,y)$ and $S(k_v, \omega)$ the Fourier transform of $s(v,\omega)$ with repect to v. (2) signifies that the echoed signals transformed in the (k_v, ω) domain correspond to the samples in the spatial Fourier transform domain of the reflectivity function, that is (k_x, k_y). The spectral support of the radar returns in this geomtry is [9]

$$2k\sin\theta-2k\frac{L_s+X_0}{R}\cos^2\theta \le k_v \le 2k\sin\theta+2k\frac{L_s+X_0}{R}\cos^2\theta \quad (3)$$

where

$$R \equiv \sqrt{X_s^2+Y_s^2}$$

The echoed signal $s(v,\omega)$ is, from (3), a bandpass signal with its center spatial frequency at $k_v=2k\sin\theta$ and bandwidth

$$4k\frac{L_s+X_0}{R}\cos^2\theta$$

Consequently, the sampling theorem forces a sample spacing in the v domain to be

$$\Delta_v \le 2\pi\frac{R}{4k(L_s-X_0)\cos^2\theta} \quad (4)$$

The range and cross-range resolutions of an output image are, by Discrete Fourier Transform theory, determined by the coverage of the echoed signals in the spatial frrquency domain (k_x, k_y). To find the resolution, first define the spatial domain $(x' \ y')$ and the spatial frequency domain (k_x', k_y') as the domains formed by rotation (x,y) and (k_x, k_y) by θ, respectively. Then, (3) implies that the spatial frequency coverage of the available data for a point scatterer can be shown to be approximately a rectangular bandpass region in the (k_x, k_y) domain with the lenght of one side $4k L_s\cos\theta/R$ in the k_v domain and $2(k_2-k_1)$ in the k_x domain. Hence, the resolutions of the reconstructed image in the squint range and cross-range domains are, respectively, as follows:

$$\Delta_x = \frac{2\pi}{2(k_2-k_1)}$$

$$\Delta_y = \frac{2\pi R}{4k_c L_s\cos\theta}$$

where k_c is the wave number at center frequency and k_1 and k_2 are minimum and maximum available wave numbers.

Ⅲ. ISAR SYSTEM MODEL

1. INVERSION

The geometry employed for the ISAR scenario is depicted in Fig. 2.

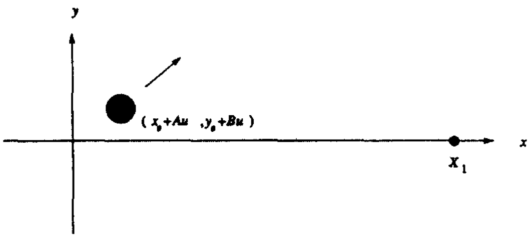

Fig. 2 ISAR Imaging Geometry

A stationary ground based radar is located at (X_1, 0.) on the (x,y) plane. A solid extended target is moving relative to the ground based radar. The radar measurements are repeatedly made at discrete times $u \in (-u_{0}, u_{0})$ while a target is in the radat footprint.

The moving target is assumed to have a constant velocity (A,B) during the radar's data acquisition. u is now a time variable but different from time variable t that is the Fourier counterpart for the temporal radian frequency ω. (In SAR community, u is usually referred to as *slow-time* while t is called *fast-time.*)

In this case, the received signal $s(u,\omega)$ is the (u,ω) domai is

$$s(u,\omega) = s_t(u,\omega) + s_c(u,\omega) \tag{5}$$

In (5), $s_t(u,\omega)$ is the moving target's echoes model as

$$s_t(u,\omega) = \int\int g(x-Au, y-Bu)\exp[j2k\sqrt{(x-X_1)^2+y^2}]dxdy \tag{1}$$

where $g(x,y)$ is the reflectivity function of the moving target and $s_c(u,\omega)$ is the static clutter signature that can be assumed to be invariant of u. By means of a coordinate transformation from y) to (x_t, y_t), as done in SAR geometry [11], $s_t(u,\omega)$ is alternatively represented as follows:

$$\tilde{s}_t(v,\omega) \equiv s_t(u,\omega)$$

$$= \int\int g_t(x_t,y_t)\exp[j2k\sqrt{(x_t-X_s)^2(y_t-Y_s-v)^2}]dx_t dy_t \tag{6}$$

where $v = u\sqrt{A^2+B^2}$, $g(x,y) \equiv g_t(x_t, y_t)$ and

$$\theta \equiv \arctan\left(-\frac{A}{B}\right) \tag{7}$$

The above angle θ in (7) is equivalent to the angle θ defined as arctan (Y_s/X_s) in Section Ⅱ if the center of mass of the moving target is at origin when $u=0$, It should be noted that $s_t(u,\omega)$ which is the function of time variable u is converted into $\tilde{s}_t(v,\omega)$ the function od spatial variable v and the resultant geometry is equivalent to the squint-mode geometry illustrated in Fig. 1.

Taking eht Fourier transform of (5) with respect to u (or v), we obtain

$$S(k_u,\omega) = \tilde{S}_t(k_v,\omega) + S(k_v,\omega)$$

$$\tilde{S}_t(k_v,\omega) = G_t(\sqrt{4k^2-k_v^2}, k_v)\frac{\exp[j(\sqrt{4k^2-k_v^2}X_s + k_v Y_s)]}{\sqrt{4k^2-k_v^2}} \tag{8}$$

$$S_c(k_u,\omega) \propto \text{sinc}(k_u, u_0) \tag{9}$$

where

$$k_v = \frac{k_u}{\sqrt{A^2+B^2}}$$

Th moving target's bandwidth in the k_v domain can be equivalently expressed as the form appeared in (3) provided that $L_s = u_0\sqrt{A^2+B^2}$ and θ is defined as in (7). Thus, with lowpass filtering of cur-off frequency π/u_0 in the *ku* domain, the static clutter component can be rejected partially or fully, depending on the target's velocity and u_0. On the other hand, if the target's velocity were known, all the parameter values necessary for invoking the inversion equation (8) would be determined. Next section discusses the velocity estimation algorithm.

2. VELOCITY ESTIMATION

According to the definition of a mean spatial Doppler shift in [11], the moving target's echoes have the following mean spatial Doppler shifts (Note that the mean spatial Doppler shift in a x domain will be denoted as K_x):

$$K_v \approx 2k\sin\theta$$

in the K_v domain and

$$K_u = K_v\sqrt{A^2+B^2} \approx 2kA$$

in the K_u domain. Since the ISAR geometry can be transformed into a squint-mode SAR geometry with a stationary target, applying the subaperture processing method introdued in [11], the estimate for (A,B) are determined by the following:

$$A = \frac{1}{N-M+1}\ \frac{\sum_i K_{ui}}{2k}$$

$$B = \left(\frac{X_i}{2k}\ \frac{\sum|K_{ui}\,u_i|}{\sum u_i^2}\right)^{\frac{1}{2}}$$

where N denotes the number of ISAR measurements during the time $u \in [-u_0, u_0]$, M is the number of measurements within a subaperture time interval, u_i is a time instant at which a measurement is made exactly halfway within an *i-th* subaperture time interval and K_{ui} is the mean Doppler shift of the *i-th* subaperture estimated from the echoed signals by the following:

$$K_{ui} = \frac{\sum_j k_{uj}\,|S_i(k_{uj},\omega)|^2}{\sum_j |S_i(k_{uj},\omega)|^2} \tag{10}$$

where $S_i(k_{uj}, \omega)$ is the spatial Fourier transform of the echoed signals pertaining to the *i-th* subaperture. K_{ui} can also be estimated by averaging the number of zero-crossing of $s_i(u,\omega)$ values that belong to *i-th* subaperture. By averaging several estimates that the subaperture processing algorithm produces for different frequency, the accuracy of the estimate will be improved.

Ⅳ. IMAGING FOR TIME-VARYING VELOCITY TARGET

1. IMAGING SCHEME

The next ISAR problem we are concerned with is to image a moving target with time-varying velocity during a data acquisition time.
This problem is similar to the SAR scenario where a radar experiences some turbulences while it travels. Many efforts have been made for compensating radar's motion [5,12].

In the discussion that follow, we assume that the signature of the static clutter is filtered out. This problem can be resolved by the following procedure. First, keep track of the target with a physical array antenna. The physical array antenna consists of a finite number of elements. The center element plays a role of both a transmitter and a receiver and the rest are for receivers (see Fig. 3).

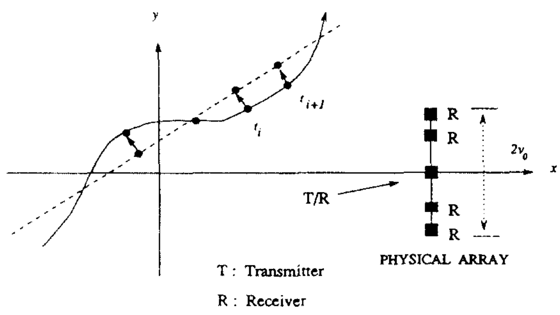

Fig. 3 Physical Array Antenna for Tracjing and Imaging

The received signals on all the elements are combined for tracking. Any tracking procedures can be adopted for this purpose[10]. Second, project the estimated trajectory of the moving target into an imaginary straight path which is the closest to that trajectory. Third, compensate the returned SAR signals as if they were returned from an imaginary target moving on the straight path. Now that the modified geometry can be interpreted as ISAR geometry with a constant velocity target, the results derived in Section Ⅲ is used. The following Fig. 4 illustrates this scheme.

2. PHASE COMPENSATION

Suppose we have an estimate for the target trajectory and have fonud the imaginary path based on that which has a slope of B/A. Let $(x_d(u), y_d(u))$ denote the estimated target location measured at time u. Then, it can be expressed as

$$x_d(u) = Au + \rho_x(u)$$
$$y_d(u) = Bu + \rho_y(u)$$

where $\rho_x(u)$ and $\rho_y(u)$ represent x-and y-directional differences between the estimated trajectory and the imaginary path measured ant time u, respectively.

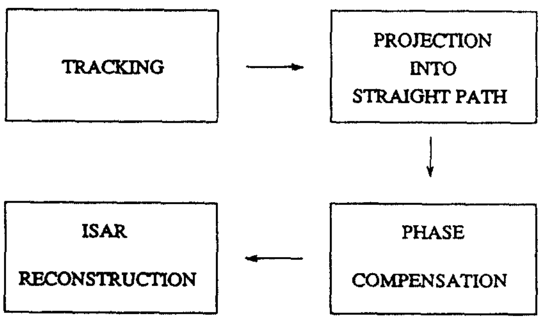

Fig. 4 Imaging Scheme for Time-Varying Velocity Target

In this geometry, if the received signal at center element on the physical array is expressed as $s(u,\omega)$, $s(u,\omega)$ can be expressed as

$$s(u,\omega) = \int\int g(x - x_d(u), y - y_d(u)) \exp[j2k\sqrt{(x - X_1)^2 + y^2}] dxdy \quad (11)$$

Transferring $x_d(u)$ and $y_d(u)$ into the phase of the exponential function and rotating (x,y) domain by $\theta = \arctan(-A/B)$, we obtain

$$s(u,\omega) \equiv s_1(v,\omega) = \int\int \exp[j2k\sqrt{(X_s + X(v) - x_1)^2 (Y_s + Y(v) + v - y_1)^2}] \cdot g(x_1, y_1)\, dx_1 dy_1 \quad (12)$$

where the spatial domain (x_1, y_1), the squint range and cross-range coordinate (X_s, Y_s) and $Y(v)$ are the x_1- and y_1- directional distances between the estimated trajectory and the imaginary path at time u, which are approximately

$$\begin{cases} X(v) \approx \rho_x \cos\theta \\ Y(v) \approx \rho_x \sin\theta \end{cases} \quad (13)$$

(13) is based upon a planewave approximation which is used in Spotlight mode SAR. Thus, this approximation will alleviate the merit of the proposed inversion equatio (2) that does not include any approximations. Hence, a spotlight mode SAR inversion equation can also be used via modifying a range distance with ρ_x (Note that ρ_y is negligible as in (12) and (13).) Following the procedure shown in Appendix A, the final inversion equation is

$$G_1(\sqrt{4k^2 - k_v^2}, k_v) = S_1(k_v, \omega) \cdot \exp[-j(\sqrt{4k^2 - k_v^2}(X_s + X(v) + k_v(Y_s + Y(v))] \quad (14)$$

Therefore, once ρ_x and θ are estimated, all the parameter values in (14) to produce the target's image will be determined.

Ⅴ. EXPERIMENT

We present results obtained by processing actual ISAR data of a DC-9 aircraft.

The radar parameters used in collecting the ISAR data is as follows: The moving aircraft illuminated by ground-based radar transmitter is located at (4768.,0.) when $u=0$. Note that the coordinate system (x,y) used in this section is two-dimensional spatial domain where the position of the radar is chosen as origin and the line connecting the radar and the aircraft at $u=0$ represents x-axis. At each slow time u, the radar transmits a stepped-frequency modulated signal and receives corresponding echoed signal [12]. Each transmitted pulse may be thougth of as a quasi-monochromatic spherical wave whcih briefly illuminates the return pulse is quadrature detected at the radar and heterodyned to yield single complex number. The echoed signal at each u is composed of 64 temporal frequencies, with frequency spacing 4 MHz and in a bandpass region identified via $f \in [9.01, 9.266]$ GHz. Overall data acquisition time is $u \in [0., 1.194]$ (sec) and the radar makes 128 slow time samplings during the period.

With the given data base in the (u,ω) domain, the subaperture processing method produces the estimate for the velocity that is found to be $(-16.4105, 148.991)$ (m/sec). Note that the actual range and velocity is not available.

In Section Ⅱ, the sample spacing in the v domaing should meet the inequality shown in (4). Using the above-mentioned parameters, the sample spacing in the u domain is 9.3 (msec) (=1.194/128) which violates the required sample spacing, resulting in undersampling. Because Eq (4) dictates that Δ_u be less than 1.67 (msec). To resolve this problem, we first mix the echoed signal with a reference signal defined as

$$\exp[-j2k\sqrt{X_s^2+(Y_s+v)^2}] \tag{15}$$

(15) is considered as a conjugate of an echoed signal from a unit-reflectivity point scatter at the origin. When mised, a resultant signal, call it *normalized* signal, comes to have significantly resuced bandwidth in the k_v (or k_u) domain. Since that signal is unaliased and the signal's bandwidth is known, which is $4kX_0/R$, we can interpolate the signal such that the sample spacing satisfies the condition (4) [3]. When the interpolated signal is mixed back with the conjugate of the reference signal in (15), one can generate a unaliased signal sequence that has the same spectral property as the original echoed signal while having sufficient sampling rate. For interpolation, this experiment takes the following procedures: First, take the Fourier transform of the normalized signal. Secondly, put a zero-padding to it in the k_u domain by 8 times as many as the original 128 samples. Finally, take the inverse Fourier transform to produce 1024 unaliased samples. In this case. With the final 1024 × 64 data base, Eq. (8) produces the output image shown in Fig. 5.

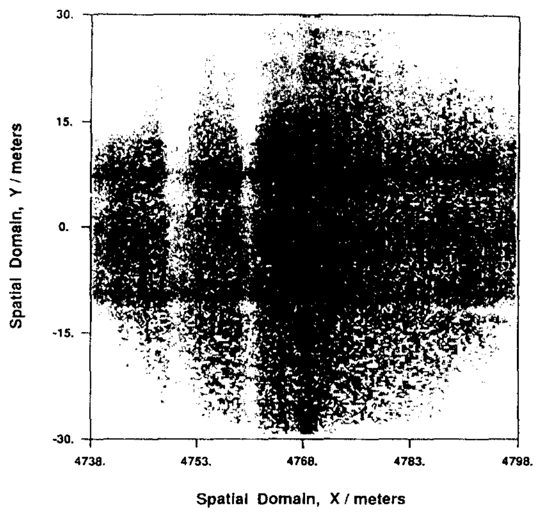

Fig. 5 Reconstructed Image

Ⅵ. CONCLUSIONS

A method to image a unknown velocity target in the ISAR geometry was presented. This method is advantageous over the already presented methods in that by the subaperture processing, the computation time is relatively short and for this reason, it can be implemented in real-time.

Due to the low sampling rate of the originally received data, which occurs quite often, the data base frequently causes ans aliasing in the output image. We showed how to resolbe this problem through the mixing and the interpolation.

In the accompanying paper that will be presented soon, we will consider the ISAR imaging under a heavy clutter. Thus, that will include the target detection and the clutter rejection.

APPENDIX

The spherical waves that appear in (1) can be decomposed in terms of plane waves as follows [2]:

$$\exp[\sqrt{(x-X_s)^2+(y-Y_s-v)^2}]$$
$$=\int \frac{\exp[-j\sqrt{4k^2-k_v^2}(x-X_s)-jk_v(y-Y_s-v)]}{\sqrt{4k^2-k_v^2}}\,dk_v \quad (A.1)$$

Putting (A. 1) into (1), one obtains

$$s(v,\omega) = \int\Big[\iint f(x,y)\exp[-j\sqrt{4k^2-k_v^2}(x-X_s)-jk_v(y-Y_s)]dxdy \cdot \frac{1}{\sqrt{4k^2-k_v^2}}\exp(jk_v v)\,dk_v$$

After some arrangements, it becomes

$$s(v,\omega) = \int \frac{F(\sqrt{4k^2-k_v^2}, k_v)\exp(jk_v v)}{\exp[-j\sqrt{4k^2-k_v^2}X_s+k_vY_s)]\sqrt{4k^2-k_v^2}}\,dk_v \quad (A.2)$$

Comparing (A. 2) with a definition of inverse Fourier transform, we have

$$F(\sqrt{4k^2-k_v^2}, k_v) = \exp[-j\sqrt{4k^2-k_v^2}X_s+k_vY_s] \sqrt{4k^2-k_v^2}\,S(k_v,\omega)$$

where $S(k_v,\omega)$ denotes the Fourier transform of $s(v,\omega)$ with respect to v.

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