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Radar Imaging by Using GTD Near-field Model and Antenna Array-factor

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1. Introduction

As one of the image processing method of radar sensor, it is most typical method which employs synthetic aperture radar (SAR) processing. In this paper we investigate radar image of scattering models by using an extended idea of array-factor (AF) in antenna theory. Applying phase difference between each element of the array becomes so-called phased array beam-forming and weighting to each element becomes adaptive beam processing [1], [2]. Also, regarding AF as near sources, it has been directly applied to far-field transforming algorithm [3]. Since AF is considered as a sum of delayed phase signals from each antenna element, we can construct image of the signal from the sum which depends on degree of phase matching between the receiving signal and its coordinate. This procedure is a kind of aperture synthesis, also known as delay and sum (DAS), especially in the field of ultrasound medical imaging and acoustics [4].

In this paper, we present radar image constructing method using the AF theoretical and measured near-field of simple model such as 2-dimensional conducting strip and corner reflector. SAR algorithm is generally adequate in far- and even if near-region. Therefore, antenna aperture length is not necessary to be so long for target in near region, simple and practical AF method alternatively becomes valid. This situation indicates surface penetrating radar such as mine-finding or wall-through sensor. Fortunately near-field modelling is not so difficult by using Geometrical Theory of Diffraction (GTD) or Uniform Asymptotic Theory of Diffraction (UAT) if target shape is simple. We show 2-dimensional model, for simplicity, using GTD/UAT and construct its image using AF and DAS algorithm for short range radar. As expected, examining theoretical and experimental results are so interesting. When span distance between radar and target is in near and Fresnel region AF-DAS image is more explicit than SAR and in far region both images are almost similar. In addition, by employing GTD/UAT near-field model, obtained image becomes to be clearer compared with far-field model.

2. Radar Imaging by AF Focusing

For electromagnetic field formed by multiple element sources, these elements are assumed to have same isotropic radiation pattern as point source. And then far-field created by these sources is expressed as superposition of each source considering phase difference of the source depended on the source coordinate. We call this superposition formula array-factor (AF) and it is mathematically same expression to Fourier series. Since real element antenna has directivity, total array antenna pattern is evaluated by multiplied the pattern to AF as weighting. This AF neglects mutual coupling among elements, so actual array pattern may be somewhat different from this model.

Now, regarding isolated point sources are located in arbitrary coordinates of free space, we can obtain AF as follows,

$$f(\theta,\phi) = \sum_n a_n \exp\{jk(x_n u + y_n v + z_n \cos\theta)\}, \quad u = \sin\theta\cos\phi,\ v = \sin\theta\sin\phi \qquad (1)$$

where (θ, ϕ) are observation angle variables in spherical coordinate system, and (x_n, y_n, z_n) are n-th element coordinates. As above, treating antenna system to be discrete, since we can independently operate each phase, amplitude and coordinates of each element, this array system has wide applications according on system aim. In this paper we discuss and show the simple and practical imaging process using this AF for near region target.

Radar imaging method indicated in this paper uses the early mentioned AF and DAS concept which expresses correlation between phase of measured echo and theoretical signal. All transmitting and receiving element are always not necessary to be active, they are independent each

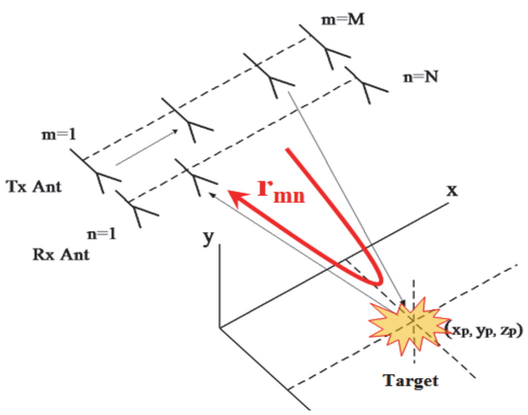


Figure 1: Radar Delay-Path and AF-Sum

other. It is also available to scan one element antenna by mechanical if target assumes to be fixed within processing rate time.

Equation (1) is derived as plane wave which radiates to observation or incidents from source in far region. For near region, therefore, focusing compensation is necessary. As shown Figure 1, coordinates of transmit and receive antenna are $(x_m^t, y_m^t, z_m^t) = \boldsymbol{r}_m^t$, $(x_n^r, y_n^r, z_n^r) = \boldsymbol{r}_n^r$, respectively, and coordinates of target, which becomes image data, is described as $(x_p, y_p, z_p) = r_p$. Here $\boldsymbol{r}$ is position vector. The signal radiated from transmitting antenna returns to receiving antenna from the target. This optical wave path is expressed as

$$r_{mn}(x_p, y_p, z_p) = |\boldsymbol{r}_p - \boldsymbol{r}_m^t| + |\boldsymbol{r}_n^r - \boldsymbol{r}_p| \qquad (2)$$
$$= |(x - x_m^t)^2 + (y - y_m^t)^2 + (z - z_m^t)^2|^{1/2} + |(x - x_n^r)^2 + (y - y_n^r)^2 + (z - z_n^r)^2|^{1/2},$$

where we replace target coordinate $\boldsymbol{r}_p$ to imaging area variable $\boldsymbol{r}$. Assuming k is wave-number and $P_r(f)$ is receiving power at radar receiver with frequency f, phase path is described by kr_{mn}, and correlation between the power and wave path of the radar and the target is given by

$$Q'(\boldsymbol{r}) = \frac{1}{MN} \sum_{m=1}^{M} \sum_{n=1}^{N} P_r(f) \exp\{jkr_{mn}(x, y, z)\} \qquad (3)$$

where M and N are number of transmitting and receiving antenna element, respectively. Radar receiving power as a_n is proportional to gain of array antenna with AF.

Above equation is a case of very narrow band radar. It is necessary to take frequency band-width into account. As well known, band-width of step-frequency CW radar determines the range resolution. Now f_ℓ is a step frequency at ℓ-th ($1 \leq \ell \leq L$), Equation (2) can be modified to

$$Q(\boldsymbol{r}) = \frac{1}{LMN} \sum_{\ell=1}^{L} \sum_{m=1}^{M} \sum_{n=1}^{N} P_r(f_\ell) \exp\{jkr_{mn}(x, y, z)\}. \qquad (4)$$

This estimating function $Q(\boldsymbol{r})$ directly makes radar image of illuminated region including target. In this way, the procedure of focusing delayed path can be understood as phase matching degree of receiving power to illuminated target in near region. In other ward, it is indicated that Eq. (4) $Q(\boldsymbol{r})$ has a peak in spatial spectrum at a minimum value of r_{mn} as well as peak direction in AF. In addition there occurs “ambiguity” in $Q(\boldsymbol{r})$ according to parameters. It is a same phenomenon such as “grating-lobe” in AF which is also so-called “aliasing” in Fourier transformation theory.

For more accurate simulation, it is necessary to consider beam directivity of element antenna and material characteristics of observation area around target. The latter is important for mine detection system because of delay change by media permittivity. For actual number of L, M, N, the mine detection radar was reported, in which the separation between the radar and observation area is 6-7 meters, frequency band-width is 20 %, and array aperture length is approximately 2 meters in order to find metallic objects on ground [5].

3. GTD/UAT Formulation for 2-Dimensional Target in Near-field

The GTD or UTD (Uniform Theory of Diffraction) is well established high-frequency predicting method proposed by J. B. Keller in ‘50 for electrically large objects, which extends GO (Geometrical Optics) to diffraction ray concept using Fermat’s principle [6]. The original GTD is formulated from exact solution of half-plane diffraction, so, required coefficients are simply expressed by elementary functions and become to be infinite at shadow boundary (SB). The UTD is improved theory which avoids this GTD defect by using the Fresnel’s integral instead of the elementary function. In this paper we employ UAT method, which is mainly established by S. W. Lee in ’70 and has obtained expressions of diffraction from edge condition without comparing to canonical solution. All GTD/UTD/UAT employ the concept of ray, therefore, main applications are limited to uncomplicated shaping object or 2- dimensional problem.

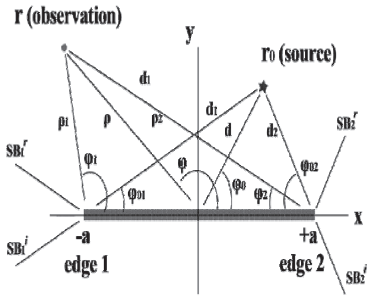


Figure 2: Geometry of Strip

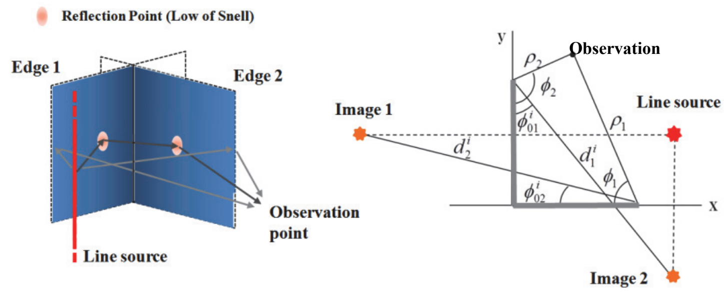


Figure 3: Two-face Reflector and its Images

In this section, we treat near-field scattering of conducting strip and 2-face corner reflector when a local source radiates. If incident wave is plane wave, their scattered far-field is easily obtained as sinc-function by method of Physical Optics (PO) [7], [8]. As above mentioned, however, it is simple and easy for this problem to use ray technique [8], [9], such as UAT, since we concentrate near-field of these array and target.

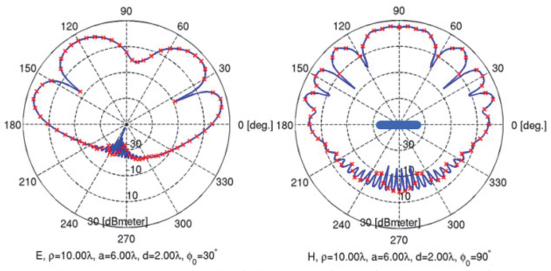


Figure 4: Near-field of Strip, (left); E-pol., $\phi_0 = 30°$, (right); H-pol., $\phi_0 = 90°$

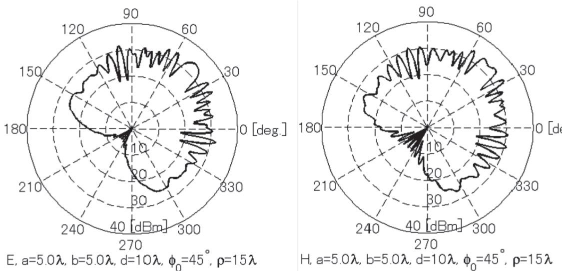


Figure 5: Near-field of 2-face Reflector at incident $\phi_0 = 45°$, (left); E-pol., (right); H-pol.

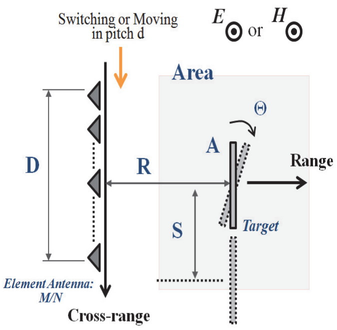
The conducting strip is considered as combined conducting 2 half-plane. Then, 2 edges exist in 2-dimensinal problem. Total field consists of 4 waves, namely a reflected wave from strip, 2 diffracted waves from each 2 edges and incident wave from a line source as shown in Figure 2. The strip is placed in x-y plane. Angle variables from the origin, edges, and distances are denoted as the figure. The 2-face corner reflector consists of a two strip and there are 5 waves to observation point, that is 2 double or single reflected waves from strip, 2 diffracted waves from each 2 edges and incident wave from a line source as shown in Figure 3.

At first, scattered field by a half-plane is described as $u_{hp}^t(\boldsymbol{r}) = u^G(\boldsymbol{r}) + u^d(\boldsymbol{r})$ where u^G is modified geometrical term, $u^G(\boldsymbol{r}) = \left[F(\xi^i) - \frac{\exp\{-j(\frac{\pi}{4}+\xi^{i2})\}}{2\sqrt{\pi}\xi^i}\right] + \tau\left[F(\xi^r) - \frac{\exp\{-j(\frac{\pi}{4}+\xi^{r2})\}}{2\sqrt{\pi}\xi^r}\right]$, next scattered field of strip by a line source, which consists of two half-plane, is given as $u_{sp}^t(\boldsymbol{r}) = u_{hp}^t(\rho_1, \phi_1) + u_{hp}^t(\rho_2, \phi_2) - u_{ext}(\boldsymbol{r}), u_{ext} = U\left(\cos\frac{\phi}{2}\right)\{u^i(\xi^i) + u^d(\xi^r)\}$ where $F(x)$ is Fresnel's integral defined by $F(x) = \sqrt{\frac{j}{x}}\int_x^\infty \exp(-jt^2)\,dt$ and $U(x)$ is Heaviside's Step function $U(x) = 1\ (x > 0);\ = 0(x < 0)$. In above equations, ξ^i and ξ^r are detour parameters of incident and reflected wave, respectively, given as $\xi^{i,r} = -\sqrt{\frac{4kd\rho}{d+\rho_{1,-1}+\rho}}\cos\frac{\varphi^{i,r}}{2}$. In Eq. (4), u^d is diffraction field associated with Keller's diffraction coefficients expressed by elementary function and τ is determined by polarization, namely $\tau = -1$ for E-wave and $\tau = +1$ for H-wave. These formulas are available even if observation point is on SB. For 2-face reflector, existence of a double or single reflected wave is depended on whether or not reflection point within or out reflecting SB [8]. Figure 4 is near-field RCS of a 6λ-length strip at observation $\rho = 10\lambda$ when a cylindrical wave incidents from $\mathrm{d} = 2\lambda$, while Figure 5 is RCS of a $5\lambda \times 5\lambda$ corner reflector at $\rho = 15\lambda$ and $\mathrm{d} = 10\lambda$. These results are examined by exact solutions (× in Fig. 4) and almost agree with them.

4. Radar Image Simulation and Measurement

Figure 6 shows measurement system and typical parameters to evaluate the formulation. The center frequency is C-band and relative band-width is 34 %. Figure 7 is UAT E-polarized near-field calculation of conducting plate (strip) compared with PO far-field model. The plate separates

$R = 1\text{m}$ (1.4λ) from the antenna. It is found that near-field UAT modelling is more accurate. Comparison of calculation and measurement is shown in Figure 8 and both figures indicate the edge diffracted wave. The real targets are also shown with white colour in these figures. Figure 9 and 10 show calculated results of a plate by AF and SAR at observation point $R = 0.3$ (0.4λ) and $R = 5$ m (6.8λ), respectively. The case of $R = 0.3$ is near- and 5 m is far-field region. SAR image in near region is not so good result. SAR is basically mono-static mode [10], meanwhile, AF radar is bi-static mode and transmitting or receiving element is different position.



■ Typical Target: Conducting strip / 2-face reflector

Size	A	30cm (×60cm)
Offset distance	S	0-0.5 m
Tilt angle	Θ	0-45 deg

■ Typical Measurement Parameters

Observation Mapping Area	Area	Az:2m×Range:1m
Distance	R	5 m
Number of Tx and Rx Ant	M/N	M=N=21
Length of array aperture	D	1.8 m
(Scanning) Ant pitch	d	10 cm
Center frequency	f_0	4.1 GHz
Frequency band-width	B	1.4 GHz
Step of frequency	⊿f	20 MHz
Polarization		E/H
Pixel size of image		1cm × 1cm

Figure 6: Measurement geometry and parameters

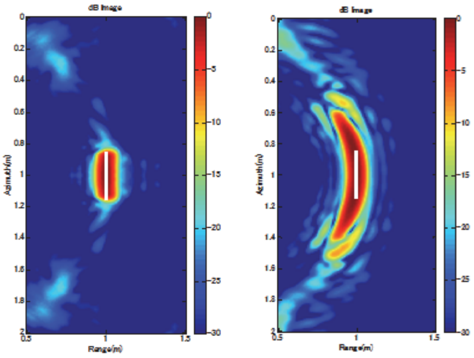


Figure 7: Strip, (l) UAT near-, (r) PO far-field

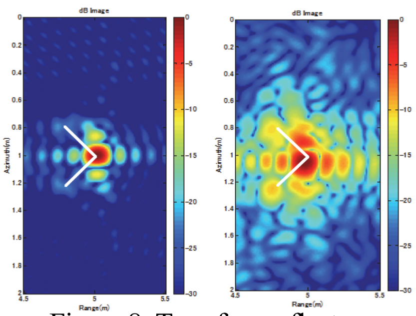


Figure 8: Two-face reflector (l) Calculation, (r) measurement

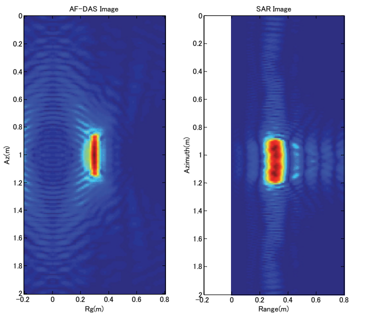


Figure 9: Calculation $R = 0.3$m, (left) AF, (right) SAR

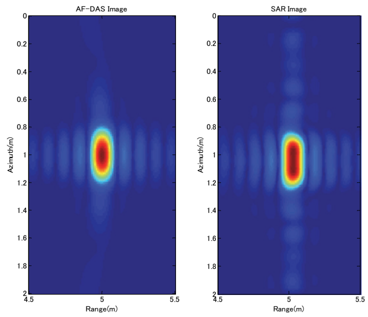


Figure 10: Calculation $R = 5$m, (left) AF, (right) SAR

5. Conclusion

We show that simple but practical imaging method using AF and near-field scattering model by high-frequency method, UAT, and compare with measurement data. From these resultants it is proposed that near-field model is necessary for more accurate modelling, and imaging by focused AF is enough for near region target. In future, we plan to combine this imaging procedure to reflection and refraction of multiple dielectric flat sheets [7], [8] in order to study modelling such as surface penetrating radar, after this, to simulate image recognition analysis using cross-polarimetric decomposition technique from 3-dimensinal modelling and imaging [10].

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