

Wall-through Radar Modeling by Applying Array-factor and GTD Near-field

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Abstract—We propose modeling method for the wall through radar by using near-field GTD as a near-region target model and delayed path-length for multi-layered dielectric sheets. Radar image can be constructed by AF (array-factor), which is a kind of synthetic aperture imaging. For near-region target, we apply focusing procedure of optical ray to the AF summation and the wall through pass. Refraction coefficient of N-layered dielectric sheets is exactly derived as boundary wave problem and applied to the wall through radar imaging. Theoretical near-field AF images are compared with far-field model, traditional SAR (synthetic aperture radar) image, and measured data.

I. INTRODUCTION

As one of the image processing method of radar sensor, it is most typical method which employs synthetic aperture radar (SAR) processing. We investigate radar image of scattering models by using an extended idea of array-factor (AF) in antenna theory. Since AF is considered as a sum of delayed signals from each antenna element, we can construct image of the signal from the sum which depends on phase matching between the receiving signal and its coordinate.

In this paper, we show radar image theoretical and measured near-field of simple model such as 2-D conducting strip and corner reflector. SAR algorithm will be 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 to be a valid method. This situation indicates surface penetrating radar such as mine-finding or wall-through sensor.

We take three kind of modeling points into account. First the beam pattern of transmitting and receiving antennas is considered instead of point sources which are normally adapted to the AF. It is important, especially in near-field, to consider actual pattern of the antennas because transmitting-field to the target and/or receiving-field from the one are depend on array scanning angle. Second,

modeling of the wall is treated as reflection and refraction of dielectric multiple N-layered flat sheets which is exactly solved as electromagnetic boundary problem. Additionally we get not only exact refraction coefficients but also actual path-length among these sheets which can compensate phase length between antennas and target so that the constructed image is to be clearer. Then, third, near-field target modeling is described by using Geometrical Theory of Diffraction (GTD) and/or Uniform Asymptotic Theory of Diffraction (UAT) if target shape is simple. Imaging accuracy is all improved by the aforementioned modeling effects compared with measurement data.

Below, imaging method using AF and near-field scattering formulation by GTD/UAT are discussed, and simulation results with measurement are indicated.

II. 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). 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. Regarding isolated point sources are located in arbitrary coordinates in free-space, we can obtain AF as

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

where (x_n, y_n, z_n) are coordinates of n -th array element, (θ, ϕ) are zenithic polar and azimuthal angles, respectively, of observation angle in spherical coordinates system and $u = \sin \theta \cos \phi$, $v = \sin \theta \sin \phi$.

Radar imaging method indicated in this paper uses the early mentioned AF and delay path concept which expresses correlation between phase of measured echo and theoretical signal [1]. All transmitting and receiving element are always not necessary to be active, they are independent each other.

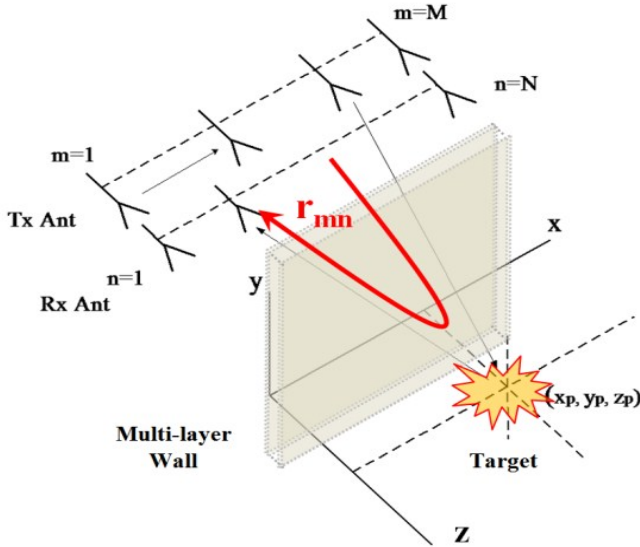


Fig. 1. Radar delay-path and multi-layered wall

The AF equation is derived as a plane wave which radiates to observation or incidents from source in far region. For near region, therefore, focusing compensation is necessary. As shown Fig.1, coordinates of transmit and receive antenna are $(x_m^t, y_m^t, z_m^t) = \mathbf{r}_m^t$, $(x_n^r, y_n^r, z_n^r) = \mathbf{r}_n^r$, respectively, and coordinates of target, which becomes image data, is described as $(x_p, y_p, z_p) = \mathbf{r}_p$. Here \mathbf{r} is position vector. The signal radiated from transmitting antenna returns to receiving antenna from the target. This optical wave path is expressed as $r_{mn}(x_p, y_p, z_p) = |\mathbf{r}_p - \mathbf{r}_m^t| + |\mathbf{r}_n^r - \mathbf{r}_p|$, here we replace target coordinate \mathbf{r}_p to imaging area variable \mathbf{r} . Assuming k is wave-number and $P_r(f)$ is actual receiving power at radar receiver with frequency f , phase path is described by kr_{mn} , and correlation between the power and

wave path between the radar and the target is given by

$$Q'(\mathbf{r}) = \frac{1}{MN} \sum_{m=1}^M \sum_{n=1}^N P_r(f) \exp\{jkr_{mn}(x, y, z)\} \quad (2)$$

where M and N are number of transmitting and receiving antenna element, respectively. Radar receiving power, a_n , is proportional to gain of array antenna. Eq. (2) 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 or CW radar determines the range resolution. Now f_ℓ is a step frequency at ℓ -th ($1 \leq \ell \leq L$), Eq. (2) can be modified to

$$Q(\mathbf{r}) = \frac{1}{LMN} \sum_{\ell=1}^L \sum_{m=1}^M \sum_{n=1}^N P_r(f_\ell) \exp\{jkr_{mn}(x, y, z)\}. \quad (3)$$

For more accurate simulation, it is necessary to consider beam directivity of Tx/Rx antenna. Assuming this directivity (antenna pattern with gain) as $G_{\ell mn}^{t,r}(f_\ell, r_{mn})$, which depends on frequency and direction to observation point (angle or near-region distance r_{mn}), Eq. (3) is modified to

$$Q_s(\mathbf{r}) = G_{\ell mn}^t(f_\ell, r_{mn}) \cdot G_{\ell mn}^r(f_\ell, r_{mn}) \cdot Q(\mathbf{r}). \quad (4)$$

It should be noted this Equation is not used raw measurement data because receiving power originally includes beam directivity. The directivity as weighting operates for transmitting and receiving near-field and $P_r(f_\ell)$ in Eq. (3) should be exchanged to normalized radar cross-section of the target, $\sigma(\ell)$. This estimating function $Q_s(\mathbf{r})$ directly makes radar image of illuminated region including target, namely $Q_s(\mathbf{r})$ equals to image illumination strength, pixels. 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 Eqs. (3) or (4) has a peak in spatial spectrum at a minimum value of r_{mn} .

III. 2-D NEAR-FIELD GTD FORMULATION

The GTD is well established high-frequency method for electrically large objects [2]-[5], which extends GO (Geometrical Optics) to diffraction ray concept using Fermat's principle. In this paper we

employ UAT method, which has obtained expressions of diffraction from edge condition without comparing to canonical solution. All GTD/UAT employ the concept of ray, therefore, main applications are limited to uncomplicated shaping object or 2- D problem.

The conducting strip is considered to be combined conducting 2 half-plane. Then, 2 edges exist in 2-D 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 [5], [6]. 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 the strip, 2 diffracted waves from each 2 edges and incident wave from a line source as shown in Fig. 2. For 2-face reflector, existence of a double or single reflected wave is depended on whether or not reflection point within or out reflecting shadow boundary. Fig. 3 is RCS of a $5\lambda \times 5\lambda$ corner reflector at $\rho = 15\lambda$ and $d = 10\lambda$. These results are examined by exact solutions and almost agree with them. We can similarly calculate 3-dimensional corner reflector by combing half-plane.

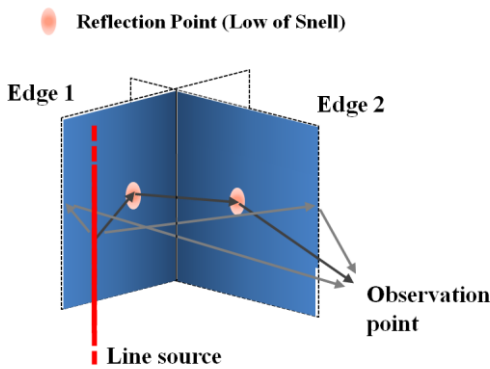


Fig. 2. Two-face reflector and its images for GTD/UAT

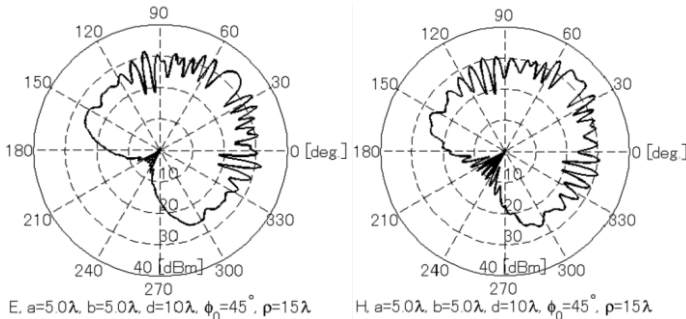


Fig. 3. Near-field patterns of two-face reflector at incident $\phi_0 = 45^\circ$, (upper): E-pol., (lower): H-pol.

IV. SIMULATION AND MEASUREMENT

In measurement, the operating frequency is C-band and band-width is 34 %. Fig. 4 is UAT E-polarized near-field of conducting strip compared with conventional PO far-field model [7] as $\sigma(\ell)$. The plate separates $R = 1\text{ m}$ (1.4λ) from the antenna. It is found that near-field UAT is more accurate than PO. Comparison of calculation and measurement is shown in Fig. 5 which is the case of 2-face corner reflector. Both figures indicate the edge diffracted wave. The real targets are also shown with white colour in these figures.

On the other hand, for traditional synthetic aperture radar (SAR) image using measured data, these SAR image in near region indicates not so good result (not indicated) . SAR is basically mono-static, meanwhile, AF radar in measurement is bi-static mode.

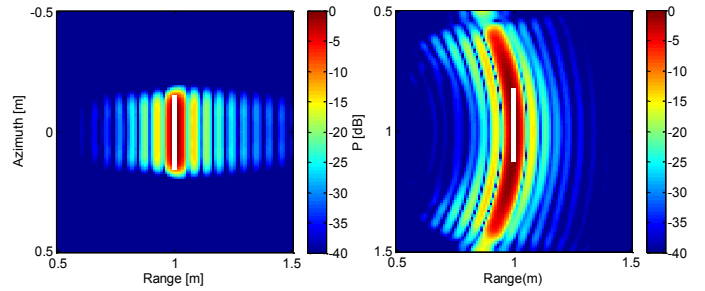


Fig. 4. Conducting strip reflector theoretical images: (Left) theoretical by GTD/UAT, (Right) conventional PO

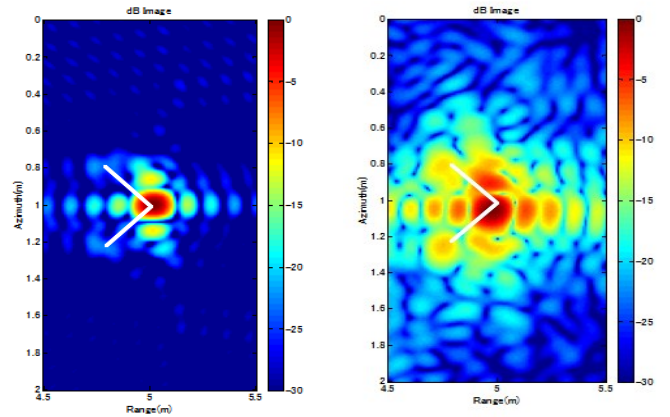


Fig. 5. Two-face reflector images: (Left) theoretical by GTD/UAT, (Right) measurement image.

Next, we show the effect by antenna beam pattern. Resultants of simulation and measurement in Fig. 6 show the effect of antenna beam consideration for a

2-D conducting strip whose width 6.8λ . Right figure is result of the measurement. It is shown from the figure that image can be improved by consideration antenna beam.

V. CONCLUSION

We show that simple but practical imaging method using AF and near-field scattering. From these resultants with measurement, it can be proposed that near-field model is necessary for more accurate modeling and imaging by focused AF is enough for near region target. Our plan for the study is indicated in Fig. 7. Considering refraction of multiple dielectric flat sheets, this image modeling can be applied to various type radars such as surface penetrating radar in order to recognize target. In near future we will simulate and analysis the polarimetric de-composition from 3-D model and image [8].

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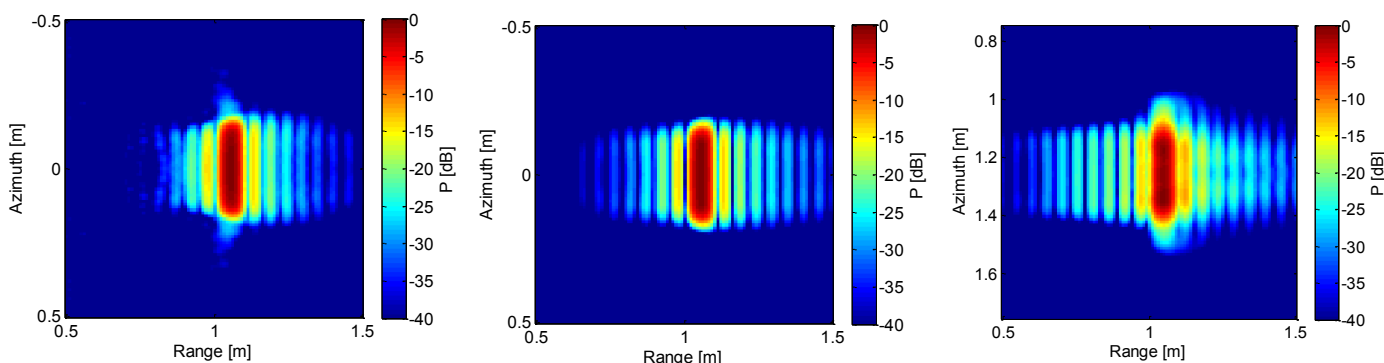


Fig. 6. Comparison of images with/out antenna beam effect and measurement: (Left) without consideration antenna beam, (Middle) with consideration, (Right) Result using measurement data

Radar Image Processing:

- Array-factor with Beam Weighting,
- Focusing Compensation,
- 3-D scanning and imaging

Wall modeling:

- N-layered Dielectric Sheets,
- Exact Refraction Coefficient,
- Delayed Path Compensation

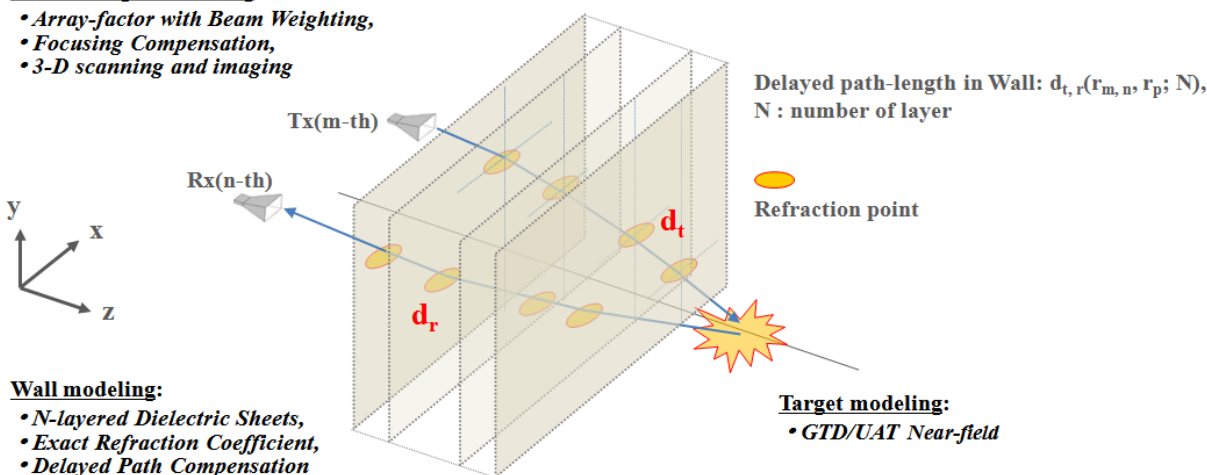


Fig. 7. Near-field imaging procedure model including refraction and delayed path in multi-layer wall