Experimental Approach for Determining the Received Pattern of a Rascan Holographic Radar Antenna

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***Abstract*—Because of the nature of image formation for holographic radar, the role and relevance of antenna radiation pattern are different than for impulse radar, and thus have not been studied. We determine theoretical Rascan radiation patterns for different dielectric media, and compare simulations to experimental data from an antenna scanned across a spherical metal target at various ranges/depths. Positions at which the received signal (phase difference between object and reference beams) are the same within a single scan, and across scans at different depths provide a 3-D approximation of the effective radiation pattern that closely agrees with the simulations.**

Keywords-component; antenna; radiation pattern; GPR; holographic radar

I. INTRODUCTION

Antenna pattern is a fundamental specification when analyzing GPR characteristics. Although a radiated wave propagates spherically, the antenna pattern is the angular distribution of signal strength. The signal strength is strongest along the critical angle which may vary with antenna design, distance from the transmit point, and properties of the medium. In order to directly determine the antenna pattern the strength is measured at the same phase position. In the case of impulse radar, the strength of the pulse is measured in any direction. In the case of continuous wave (CW) radar, the strength of the wave is measured at positions of constant phase.

Holographic radar is CW. It produces a plan view from scanning along many lines. The antenna pattern has not been actually measured – only theoretically calculated. A steel ball is a convenient tool to determine the antenna pattern experimentally for holographic radar. It guarantees a strong reflection with return path exactly matching the incident path (a "perfect return path"). In this paper, the antenna pattern of holographic radar is determined by experiments using a steel ball, and is compared with a theoretical simulation.

II. THEORETICAL APPROACH

A. Holographic Radar

Holographic radar moves along parallel lines on the surface of the medium to be scanned, and produces a plan view (See Fig.1). Conventional impulse radars distinguish each reflection coming from different distances by different time-of-flight. However, holographic radar receives all the reflections arriving at the antenna position simultaneously, so depth information is not retained. Instead, the radar records an interference pattern of the transmitted and reflected waves, which is (in low loss material) an accurate plan view image of the target. This is a merit of the radar in terms of getting easily interpreted images of the target.

B. Simulation of Antenna Radiation Pattern

The antenna radiation pattern can be calculated theoretically. Fig.2 is a three-dimensional view by theoretical simulation. The symmetrical shape of the pattern looks a jellyfish. There is little directional isotropy except for weak back lobes.

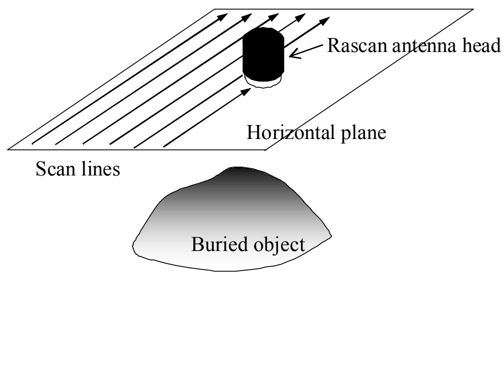

Figure 1. Scanning method of holographic radar (Rascan).

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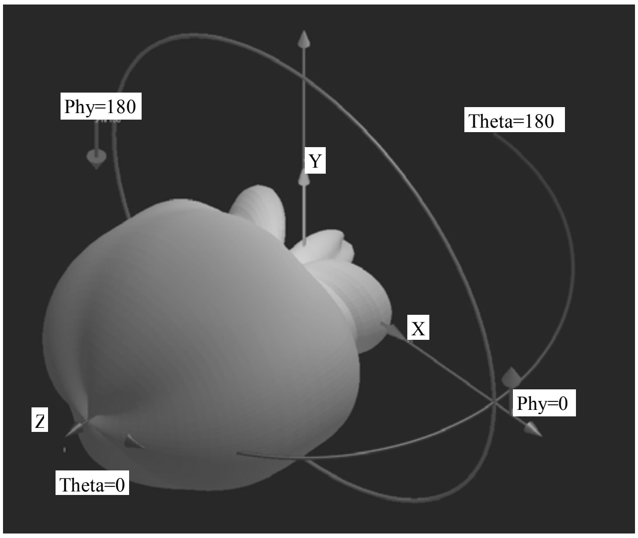


Figure 2. Three dimensional view of holographic radar antenna radiation pattern by theoretical simulation

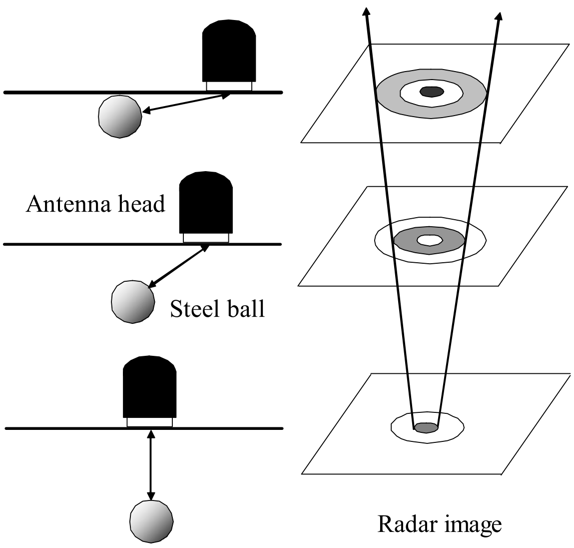


Figure 3. Relative antenna and target positions and corresponding radar images

III. EXPERIMENT

An antenna radiation pattern can be delineated by determining the strength of the electromagnetic field at the same phase position (or same two-way travel distance) within the interference pattern. The simplest method is to place receiver antennas at those positions. However, this method is not practical for two reasons. One is that positions of antennas cannot be controlled accurately. The other is that the holographic radar antenna is not designed to be used as only a receiver or only a transmitter. Thus, it is very hard to find the same phase position directly. However, instead of placing antennas, a reflector can be placed at the same position. Then, the antenna can be directly used for its designed function. However, if the reflector is a flat plate, it is very hard to keep the accurate angle that guarantees the perfect return-path reflection. A conductive sphere resolves this problem naturally and perfectly.

A. Perfect Return-Path Reflection

Polished steel is a near-perfect radar reflector. It reflects an electromagnetic wave with almost one hundred percent efficiency. A spherical steel ball reflects an incident wave and perfectly returns it to the radiated point. It is not necessary to adjust the angular position to guarantee a perfect return-path.

A holographic antenna scan (See Fig.1) produces a GPR record that looks like black and white concentric stripes (as in [1]). There is a black (or white) circle in the very center. This can be designated as known or reference phase position. For example, this is expressed as a gray circle (deepest target condition in Fig.3). In this case, the distance between the antenna head and a steel ball must be not too close and not too far. Because if the distance is very close, the wave spread is too small to determine the antenna pattern. And, if the distance is too far, the reflection is too weak to recognize. When a steel ball is moved a little closer to the scanning surface, the same targeted event expands a little outwards and forms a gray ring instead of a circle in the radar image (middle target condition in Fig.3). In this condition, to maintain the constant target distance (and phase position), the antenna head is located with a little offset from a steel ball. When a steel ball shifts further upwards to contact to the scanning board, the antenna head is located with even more offset to maintain distance/phase. And, in the image, the ring size becomes even larger. The raypath for the reference phase position may be close to horizontal

The holographic radar images for a steel ball at some depth beneath a scanning board have three kinds of information, the strength of reflection I , the distance between the antenna head and a steel ball s and the directional angle of the steel ball looking from the antenna head θ (See Fig.4).

First of all, the strength of reflected wave is the most important value when determining the antenna pattern. Each pixel in the radar image has a specific digital value. The maximum value among the pixels contained in the rings or the circle is adopted as the strength of reflection.

The distance is calculated by equation (1).

$$s = \sqrt{x^2 + y^2 + (d + r)^2} - r \qquad (1)$$

Where, s is the distance between the antenna head and a steel ball, x is the position of the antenna head on the x-axis, y is the position on the y-axis, d is the vertical distance between the scanning board and a steel ball, and r is the radius of the steel ball.

The angle is calculated by equation (2).

$$\theta = \tan^{-1} \frac{\sqrt{x^2 + y^2}}{d + r} \qquad (2)$$

Where, θ is the directional angle of a steel ball looking from the antenna head.

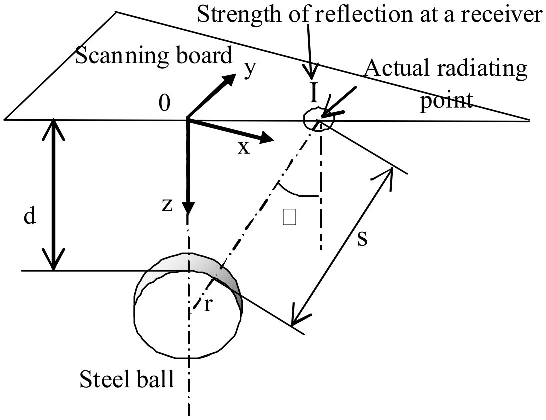


Figure 4. Parameters describing the location of an antenna head relative to a steel ball.

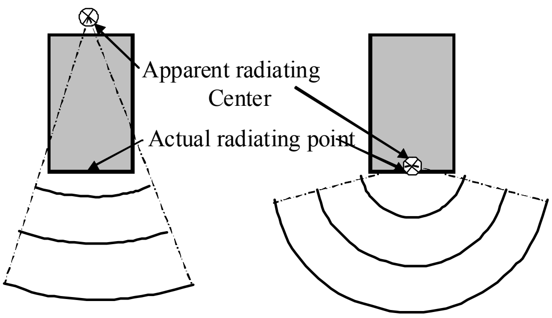


Figure 5. A schematic view of an apparent radiating center.

B. Apparent Radiating Center

An actual radiating point is the flat bottom of the antenna head. A wave front is not expected necessarily to form a perfect hemispherical shape with the radiating point as the center. The shape of the wave front determines the directional characteristics. If the shape is close to hemispherical, the wave strongly disperses. If the shape is close to flat, the dispersion is relatively mild. To express this phenomenon an apparent radiating center is defined as shown in Fig.5. The remote distance of the apparent radiating center from the actual radiating point is an important parameter for evaluating dispersion characteristics of any GPR.

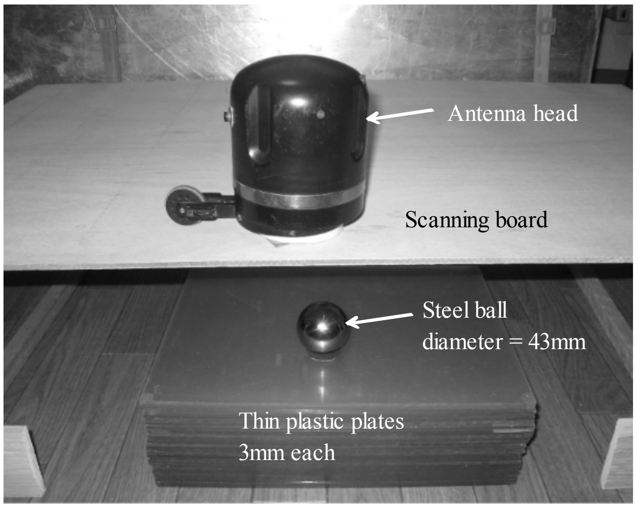


Figure 6. The experimental devices.

C. Experimental Method

To determine the antenna radiation pattern requires a three-dimensional data set. In this case, the horizontal area of the scanning board is approximately 30cm x 30cm, and the maximum depth of the steel ball is 5cm. The experimental method is extraordinarily simple. All we need is to do normal scanning works using a holographic radar antenna head over a steel ball with various depths.

The experimental device is shown in Fig.6. A steel ball with 43mm is put on thin plastic plates with thickness of 3mm each. First, a scanning board is placed over the steel ball with zero depth (the top of the ball just contacts the board), and the scan is carried out in this condition. Afterwards, removing plates one after another and scanning each time produces many images at depth increments of 3mm.

IV. RESULTS

The Rascan holographic radar produces ten images for each completed scan (5 frequencies x 2 polarizations). The radiation pattern cannot be recovered from the cross polarization images, because the phase is shifted on arrival of the reflected wave. The five parallel polarization images, in which frequencies vary from 3.6GHz to 4GHz in 0.1GHz steps, show similar characteristics. Among these, the highest frequency (4GHz) images were analyzed because the highest frequency should give the best resolution among five frequencies.

A. Holographic Images

Fig.7 is a series of 14 images recorded by Rascan holographic radar. When d=0mm, the targeted wave front defines a ring. When d increases, the ring shrinks inwards, finally becoming a black circle. The maximum signal amplitude appears at d=33mm. In further positions (i.e. d is larger than 33mm) the strength decreases. This indicates that the wave front reflects from the top surface of the steel ball when d=33mm.

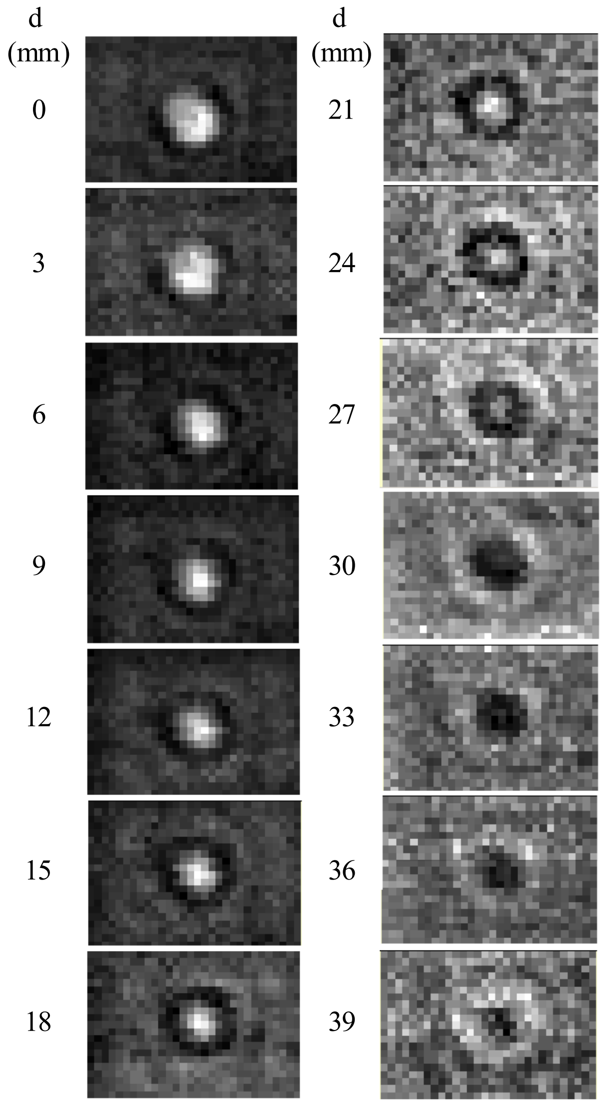


Figure 7. Holographic radar images (depth variation)

B. Apperent Radiation Center

Using the equations (1) and (2) the distances and the angles to the reflected point, which is on the surface of a steel ball, have been calculated. The shapes of the rings on the GPR images are almost perfectly circular, indicating that the distances to the ball from any point on the ring are almost equal. The distance and the angle have been calculated by the position of the ring in the image, with the result shown on Fig.8.

All the dots have been plotted as a set of values (s ,θ). The dots lie along an arc that is a part of a perfect circle, with the center of the arc corresponding to the origin. Thus, it has been proven that the actual radiating position and the apparent radiating center share the almost same position for holographic radar “Rascan”. This means that the holographic radar has a very weak directionality, with a symmetrical sensitivity like the jellyfish in Fig.2.

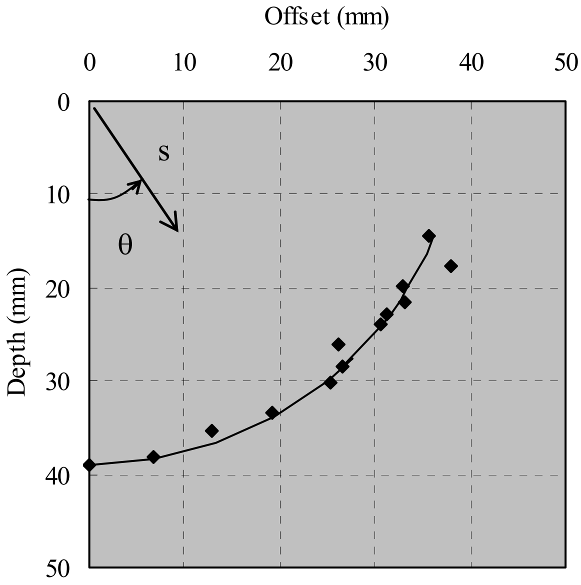


Figure 8. Apparent radiation center

C. Anistprophy of Antenna Radiation Pattern

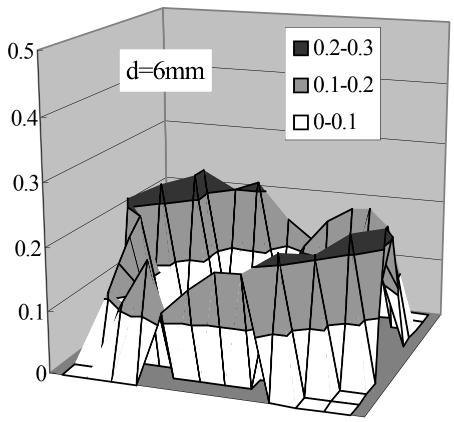
Looking through the GPR images over Fig.7, all the rings and the circles seem to have uniform signal strength. However, investigating each value shows that there exists a slight anisotropy.

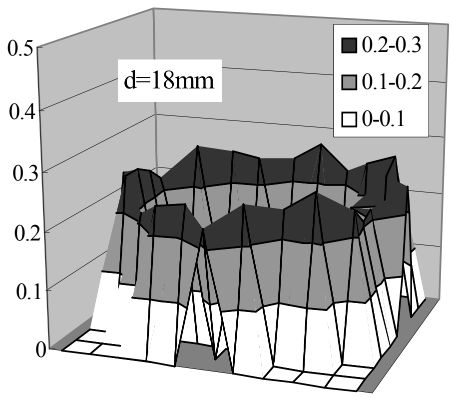
When a reflection position is located close to the top of a steel ball, the strength of reflected wave is fairly uniform. However, when a reflection position is located close to the edge of a steel ball, anisotropy appears. To illustrate this, three cases (d=6, 18 and 30mm) are shown in Fig.9. Anisotropy appears on the image from d=0mm to 12mm. It is disappearing from d=15mm to 27mm. Anisotropy completely disappears for d>30mm.

It is expected that anisotropy comes from the physical shape of the antenna poles. In case of a dipole antenna, directional anisotropy exists because the dipole arrangement originally could not be uniform to any direction. However, the anisotropy is so small in Rascan holographic radar compared with a conventional dipole antenna that the effect will not affect interpretation of images.

D. Comparison of Antenna Radiation Pattern

Measured antenna radiation pattern has been displayed on 3D chart (See Fig.10). The actual radiation point is located at the origin (0, 0, 0). The normal direction of radiation is z-axis. All the data belong to the forward radiation, because the data corresponding to back radiation cannot be experimentally obtained. The lumpy shell comes from the discrete points of data despite of some smoothing treatment. That is not essential. The theoretical radiation pattern for comparison is shown in Fig.2.





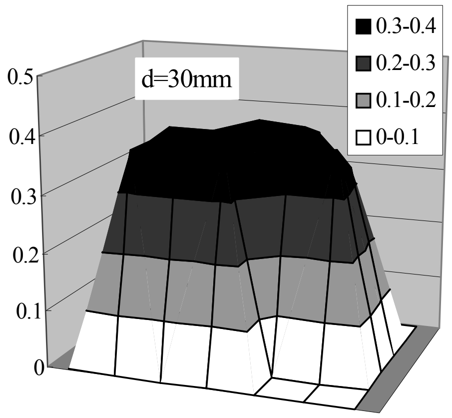


Figure 9. Anisotropy of antenna radiating pattern

Both of shapes (theoretical and measured) have quite good correspondence in overall. When the radiating direction is close to the x-y plane, the strength steeply decreases. This angle

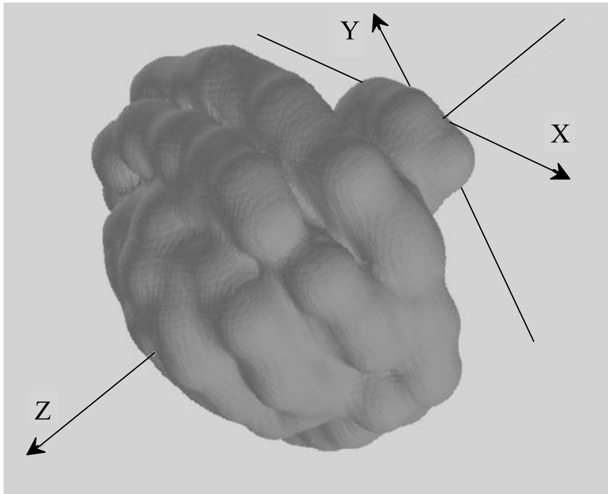


Figure 10. Three dimensional view of holographic radar antenna radiation pattern using the measured data

position is a little earlier in the measured pattern. As a result this jellyfish-shaped pattern, in contrast with the theoretical pattern, seems to be slightly shifted to forward along z-axis. The measurements were repeated several times, and this result reproduces. This difference possibly comes from a phase shift in the transition from near field to far field.

V. CONCLUSIONS

Using a spherical shaped steel ball, the radiation pattern for Rascan holographic radar has been measured. The method is very simple and it does not need any special devices; only the GPR antenna itself and a steel ball. Although the measurements agree in general with theoretical predictions, there is an unexplained phenomenon. However, this simple method could be applied for any other type of GPR to show actual conditions directly. Because the values are read from images, there might be a loss of precision relative to direct signal measurement, but this is still simple and convenient method for determining the basic shape of a radiation pattern.

In this study, the radiation pattern is predicted in parallel polarization. In future work, there will also be a possibility for cross polarization to clarify some behaviors in phase shift.

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