Experimental Determination of the Resolution of the RASCAN-4/4000 Holographic Radar System

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***Abstract* - RASCAN-4 is the latest generation of a holographic radar system developed by the Remote Sensing Laboratory at Bauman Moscow Technical University. Direct calculation of the resolution for this system is difficult even for simple targets. However, based on the signal waveband, the image-plane resolution of this radar in low loss materials is estimated at two centimeters. The empirical testing of the resolution, sensitivity, and accuracy was performed with metal coins and other simple geometric shapes with near-unity aspect ratios (i.e. circles, squares, and triangles), as well as with elongate targets such as wires or rods. Targets were placed at varying depths and varying separations in laboratory test beds composed of dry sand or layers of urethane foam. With respect to sensitivity, it was found that simple equidimensional polygons, with width of one centimeter or larger, could be detected to the greatest depths tested (12 cm), but the images of deeper targets (greater than about 1.6 times their diameter) did not accurately reflect the actual object. Elongate targets with small diameters could also be detected to the greatest depth tested of 7.62 cm. There is no simple relationship for image fidelity. The most accurate image occurs at different frequency, depth, and polarization for different targets and transmission media. Of particular interest, the most accurate images seem to occur at a depth of about 1 to 3cm depending on the target. However, this focusing point or "sweet spot" is not always present. For the ultimate goal of determining the resolution, the empirical resolution measured in this study appears to match the nominal resolution of two centimeters for all target types at shallow depths, with some degradation of resolution with increasing target depth.**

***Keywords* – Holographic radar, resolution, sensitivity**

I. INTRODUCTION

The Remote Sensing Laboratory (RSL) at Bauman Moscow Technical University has developed an innovative type of radar system [1]. These "RASCAN" radars utilize a microwave beam to create a holographic subsurface image.

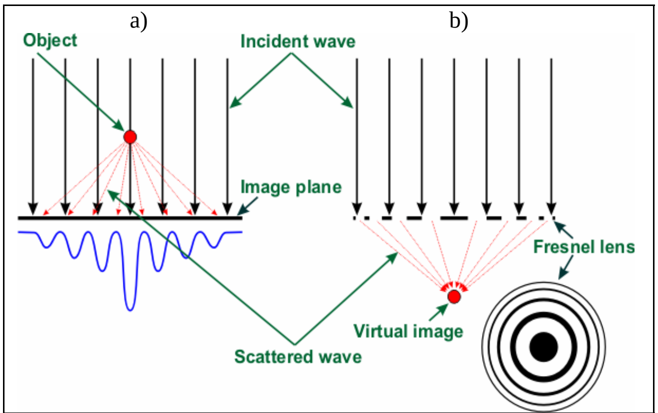
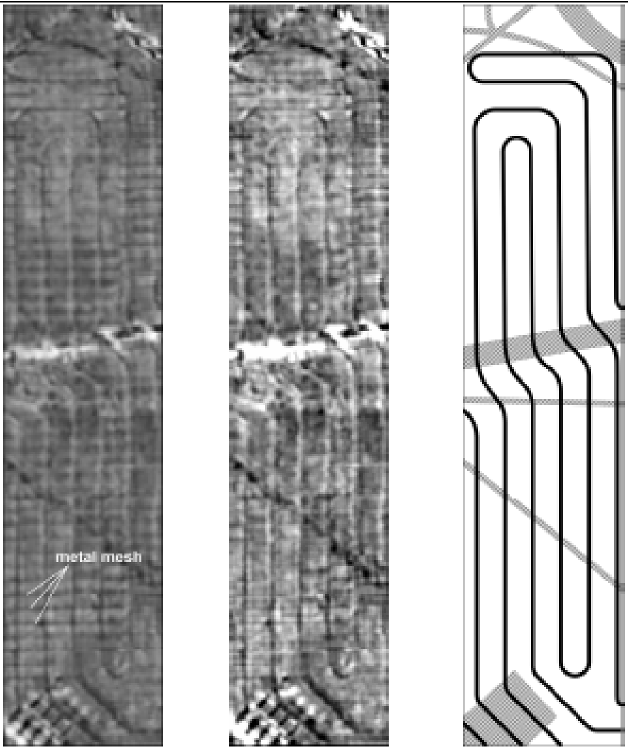


Figure 1. Drawing from [1]. a) Recording of a point source optical hologram; b) Hologram reconstruction.

As in optical holography (see Fig. 1), the transmitter emits a monochromatic illumination beam, which is reflected by targets (in this case dielectric contrasts) back to the receiver, while a reference beam is sent directly to the receiver. This creates an interference pattern at the receiver. The human brain reconstructs such interference patterns striking the eye in visible light frequencies into a 3-dimensional image of the reflective target. Or, if the interference pattern is recorded on a photographic plate, a reconstruction beam illuminating the plate creates a virtual image of the target (Fig. 1).

RASCAN uses this same holographic process, but instead of using visible light, it uses un-modulated microwaves which can penetrate the surface of dielectric materials. The interference pattern or unreconstructed image is created in a non-visible portion of the electromagnetic spectrum, so it is portrayed in gray scale colors keyed to the phase difference between the object and reference beams. Since phase differences "wrap around", and the phase difference is a complex function of dielectric properties of the media and target, as well as depth or path length, RASCAN systems simultaneously record 5 discrete frequencies at two relative polarizations (cross and parallel) of the transmitter and receiver. This ensures that any given reflector will produce a strong phase difference on at least one of the ten simultaneous images. Images are recorded by scanning closely-spaced parallel lines, with the images appearing in real time raster-by-raster. The data collection software contains a utility to combine the multiple images into a video animation that smoothly and continuously morphs between the individual images. The software also provides graphs of the phase difference magnitude along any selected row or column of pixels in an image.



a) b) c)

Figure 2. From [2]. a) Raw RASCAN image of sub-floor; b) same image after Fourier domain filtering to remove metal mesh, c) layout of pipes and communication cables based on radar results.

RASCAN has proven useful in a variety of fields where shallow, high-resolution sounding is required. Such applications include non-destructive testing of dielectric construction details, security sweeps for listening device or "bug" detection, and humanitarian demining [1], [2], [3], [4]. Fig. 2 shows one example in which the locations of undocumented hot water pipes, and power and communication cables, as well as metal mesh within a concrete floor in the Russian Senate building in Saint Petersburg, were mapped non-destructively.

Another scan was performed, testing of USA Space Shuttle heat protection tiles glued to aluminum sheeting, with two places where moisture has prevented proper bonding to the aluminum. This mimics the situation for the Space Shuttle Columbia, where it is suspected that water was trapped between the heat protection panels, and freezing followed by rapid vaporization on lift-off may have caused protective tiles to be lost.

a) 81mm mortar shell

b) holographic subsurface image of same

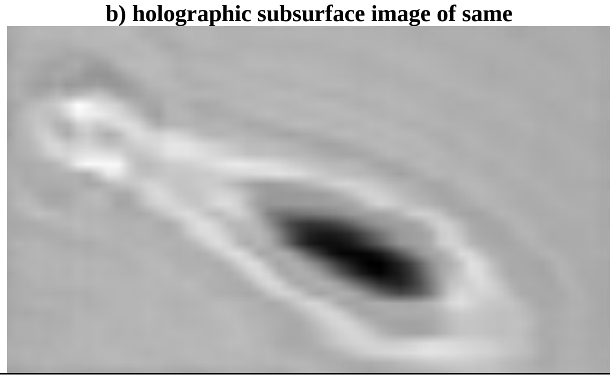


Figure 3.

Fig. 3 shows a RASCAN image of an unexploded ordnance (UXO) item buried in a dry sand test bed. This image in particular clearly illustrates that the holographic RASCAN image is a diffraction pattern.

All of these represent examples where shallow imaging with high resolution in the image plane is important. However, the question remains; what really is the resolution of a RASCAN radar system, and how can it be defined or measured? In this study, we will consider the RASCAN-4/4000, which uses five discrete frequencies in the waveband 3.6 to 4.0 GHz, at two relative polarizations of the transmitter and receiver. For this device, based on the signal waveband, and on the experience and scientific intuition of the designers, the nominal resolution in the image plane for low loss materials has been proposed to be 2cm. This resolution is "nominal" and "proposed" because direct calculation of the resolution for this system as a function of signal frequency and polarization, antenna aperture and radiation pattern, target depth (whether in the near-, mid-, or far-field), and the dielectric contrast between the transmission medium and target, is difficult – whether analytically or numerically – even for simple targets in low-loss materials. Such a calculation would not be practical, or even meaningful, in any case because the images are interference patterns only, and not true or reconstructed holograms. To calculate the resolution properly, in any formal sense, it would be necessary to reconstruct the holograms. Algorithms for reconstruction are being developed [5], but at this time, the question of practical resolution can only be addressed experimentally.

In order to test the proposed nominal resolution, a series of experiments was performed using a production model RASCAN-4/4000. Although determination of the image-plane resolution was the experimental goal, it is difficult to test resolution without also testing sensitivity and accuracy, so these performance parameters are discussed as well.

The testing was performed in laboratory beds composed of dry sand or layers of urethane foam. Two classes of targets were considered; equidimensional (circles, squares, triangles), and elongate (wires and rods). These targets were placed in test beds in a variety of configurations, and at a variety of depths to test the resolution in the near-, mid-, and far-field zones. In addition, target sizes were varied, as well as the separation distance of multiple targets (i.e. per the classical Rayleigh Criterion for resolution).

II. EQUIDIMENSIONAL TARGET TESTING

2.1 BASIC COIN TEST. A single coin at varying depths in sand

A basic test was performed with a single coin in a container of sand. Identical coins 2.5cm in diameter were buried at depths of 0, 2.54, 5.08, and 7.62cm. The resulting images from a single representative frequency and polarization are shown in Fig. 4. These interference patterns resemble those for an illuminated hole or point target (e.g. Fig. 1a).

At the surface, the coin is seen as a single target in high contrast, but with apparent diameter smaller than the actual target diameter. As depth increases, the apparent dimensions of the target expand and the contrast lessens due to growth of the ring intensities at the expense of the central peak Airy disk (see schematic in Fig. 1). However, the overall image of the coin has dimensions that are closer to the true coin diameter at this greater depth. That is, the interference pattern more accurately reproduces the actual coin at a depth of 2.54cm. This depth where the interference pattern or unreconstructed hologram most closely resembles the actual object has been dubbed the “sweet spot” (to borrow a sporting term) and had been informally observed in previous testing by the RASCAN development team, but was not systematically studied.

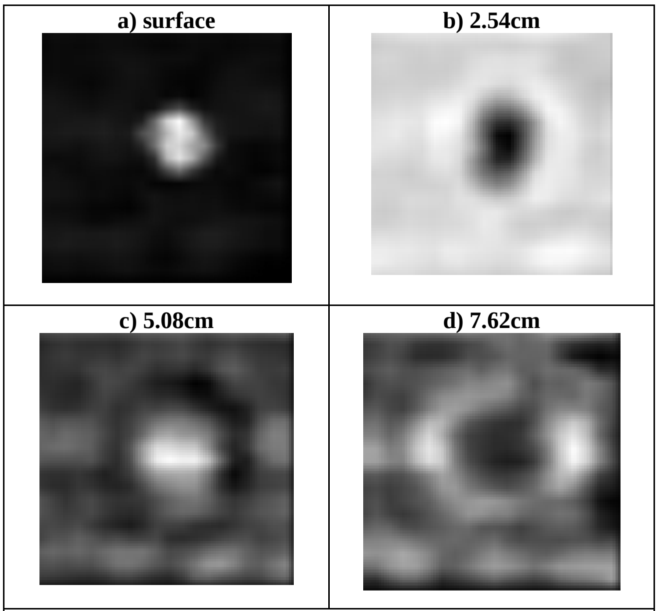


Figure 4. RASCAN images of a 2.5cm diameter coin at different depths in sand.

2.2 SWEET SPOT COINS TEST. Single coins at varying depths in urethane foam

In order to test for the presence of the “sweet spot” at finer depth divisions, a second test was performed using five 2.5cm coins between layers of urethane foam with 0.5cm thickness. The coins were placed 9cm apart, at depths ranging from 0 to 2cm, at 0.5cm increments.

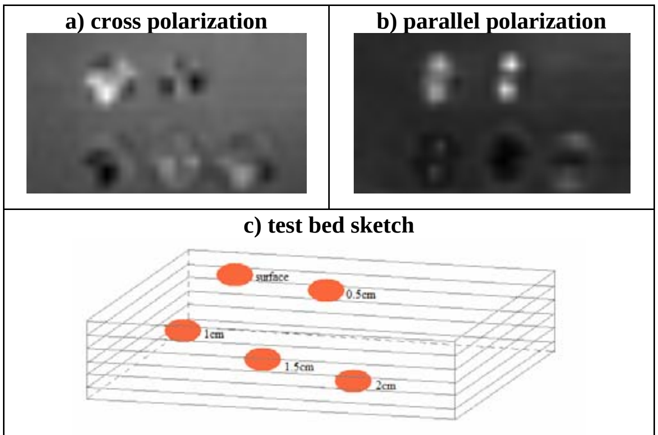


Figure 5. Representative images at a single frequency for parallel and cross-polarization for five 2.5cm coins at 0.5cm depth intervals.

When looking at the scans in Fig. 5 strictly to detect the “sweet spot”, the scans are relatively easy to interpret. The second deepest coin, at 0.5cm, typically has a higher contrast in 5 out of 10 frequency-polarization combinations, and more accurate dimensions in 8 out of 10 frequencies/polarizations than the coin at the surface.

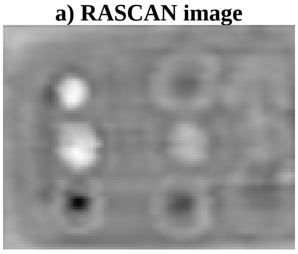
Interestingly, the third deepest coin, at 1cm, has a higher contrast than the surface or the 0.5cm deep coin in 2 out of the 10 images. This illustrates the idea that multiple frequencies/polarizations are required to confidently detect targets because the magnitude of the phase difference between the reference and object beams "wraps around", and may vary based on many parameters such as target dielectric and depth, and media dielectric and loss. These images are not sufficient to statistically prove the existence of, nor precisely define the depth of, the "sweet spot", but they clearly suggest a focusing effect at some distance from the RASCAN antenna surface.

While this test does hint at the presence of a focusing effect, which was the intended subject, it also shows a second characteristic. In most parallel polarization, the single 2.5cm coins which appear as roughly 6-pixel targets have doubled perpendicular to the raster lines to form two smaller, 3cm targets. When this test bed was first scanned, the image was discarded because the experimenter assumed an operator error. However, a second and third scan of the test bed produced the same effect. This effect was reproducible for this test bed, and could result from the plane of the coins lying at a slight angle to the plane of scanning or the face of the antenna.

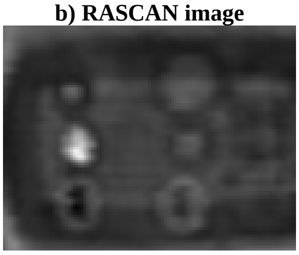
2.3 "SWEET SPOT" SPHERES TEST. Aluminum spheres at varying depths in sand.

A final test bed was designed to investigate the apparent focusing effect. Nine identical aluminum spheres of 3cm diameter were placed in a bed of sand at increasing depths from the surface to 12cm (see Fig. 6). These images do not show a simple relationship between apparent target size or dimensional accuracy and depth. The spheres at 0, 1 and 4cm all produce a bright central Airy spot with very low-amplitude concentric diffraction rings. Spheres at 2, 3, and 6cm produce distinct Airy spots with clear rings. The three deepest spheres at 8, 10 and 12cm are certainly detected, but appear only as low-amplitude rings. In this set of images, the interference pattern for the target at the surface most accurately reproduces the actual target dimensions, but the targets at 1cm and 2cm depth –particularly for the cross-polarized images – have the greatest contrast. This suggests that the "sweet spot" for imaging may depend also on the target shape (i.e. spheres in this test versus flat disks as above).

a) RASCAN image



b) RASCAN image



c) test bed sketch

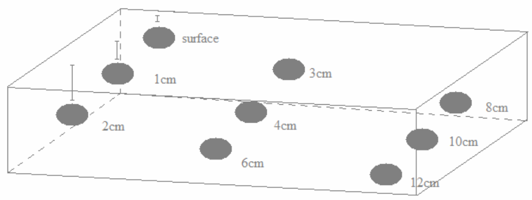
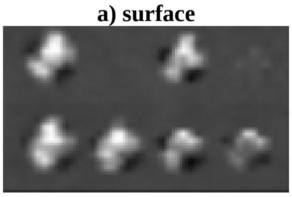


Figure 6. a-b) RASCAN images at two representative frequency-polarization combinations of aluminum spheres at depths from 0 to 12 cm in sand; c) Sketch of test bed.

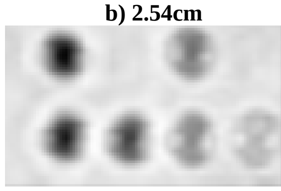
2.4 SIZE AND SHAPE TEST. Coins of differing shape and depth in urethane foam.

In order to further investigate the effects of target shape, circular coins of different diameters (2 to 3.5cm) were placed 10cm apart along a line next to square coins of similar dimension (Fig. 7).

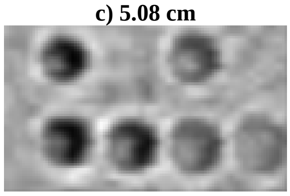
a) surface



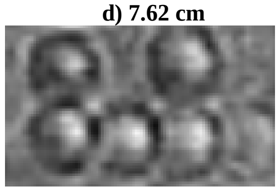
b) 2.54cm



c) 5.08 cm



d) 7.62 cm



e) test bed sketch

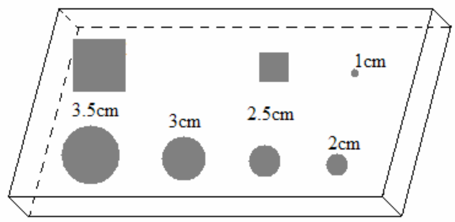


Figure 7. RASCAN images of circles and squares of different sizes at different depths in urethane foam.

The array of coins was placed on a piece of urethane foam, which was then scanned repeatedly at increasing depths (0, 2.54, 5.08, and 7.62cm) beneath other layers of foam. The array consisted of a line of decreasing-diameter circular coins, with a parallel line of square coins (if available) with side lengths equal to the diameter of the adjacent circular coin. Square coins of side length 3.5 and 2.5cm were found. Also, placed in the upper right corner of the bed, was a 1cm aluminum tack head.

The resulting series of scans (Fig. 7) again clearly shows low-amplitude Airy disks, but distinct diffraction rings for the deepest targets, and no simple relationship between image contrast and target depth. Note that the 1cm tack head is visible as a subtle bright spot at the surface, and as subtle diffraction rings at 5.08cm, but is not visible at 2.54 and 7.62cm. In addition, the distinction between square and circular coins is not discernible at any depth, with all interference patterns appearing roughly circular.

2.5 THREE SHAPES TEST. Three simple shapes of the same size at different depths.

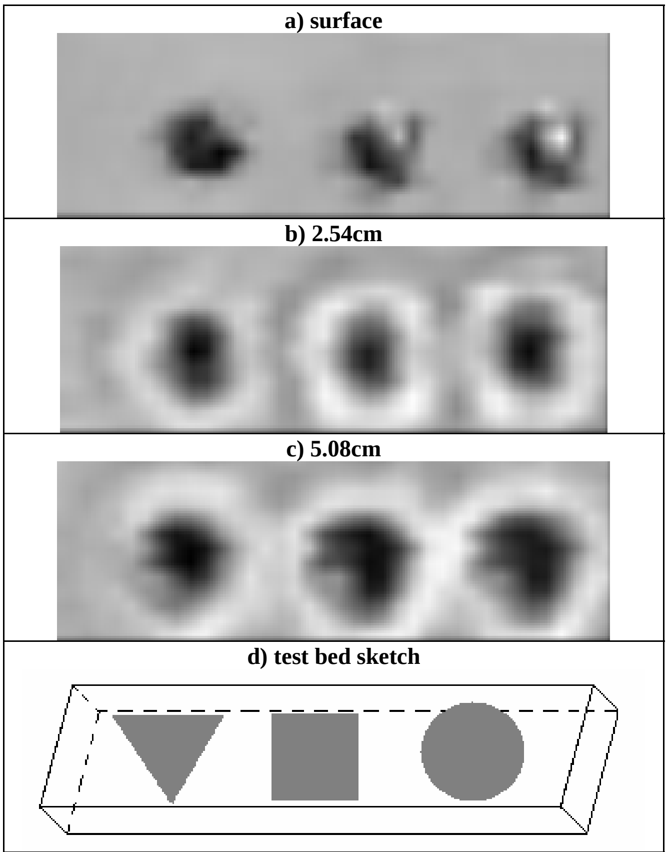


Figure 8. RASCAN images of three simple shapes at different depths in foam.

Upon observing the inability of the interference patterns for the small coins to discriminate their true shape, a test was designed using three simple metal shapes with approximately the same surface area. A triangle, square, and a circle with 3.5cm diameter were laid on urethane foam with 12cm spacing between their centers, and then scanned at sequential depths of 0, 2.54, and 5.08cm beneath additional layers of foam (Fig. 8)

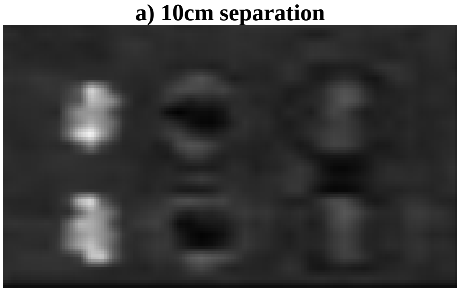
As seen in the resulting scans in Fig. 8, at the surface, all targets appear as a bright spot, with minimal diffraction rings. The images at 2.54 and 5.08cm are substantially the same, with a bright central spot, and a single distinct ring. Recalling the discussion of a “sweet spot” from above, note that the single high contrast spots in the surface scan are less than the actual target dimensions, while the diameters of the central bright spots at 2.54cm closely match the actual target dimensions, and the central bright spots at 5.08cm are larger than the true target dimensions. Although the interference pattern at 2.54cm depth depicts the targets with relatively correct dimensions, none of the images are able to distinguish the three shapes from one another. This is likely because the target size, while larger than the Rayleigh Criterion resolution, is close to the wavelength of the signal, so that hologram reconstruction will be necessary to discern the true shapes.

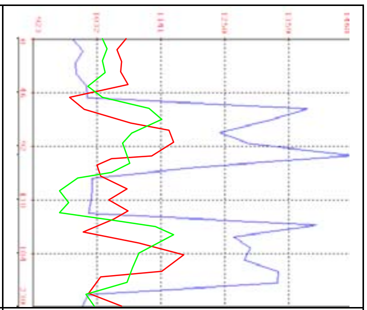
2.6 CIRCULAR TARGET RESOLUTION TEST. Coins at varying separation and depths.

The next set of scans was designed to directly test the resolution, in the Rayleigh Criterion sense, of RASCAN at different depths. Six identical 2.5cm coins were used, and placed at sequential depths of 0, 2.54, and 5.08cm. For each test, however, the distance between the coins’ centers was decreased sequentially from 10cm to 2cm in 2cm increments. The resulting images, as well as graphs of the image intensity or normalized phase difference between the reference and object beam (on the x-axis), versus pixel number or distance in mm (on the y-axis) are shown in Fig. 9. The graphs are for a vertical column of pixels through the center of each coin pair.

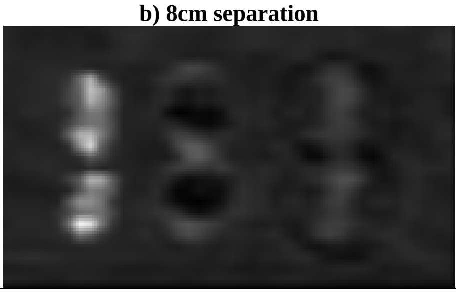
On Fig. 9, at the 10cm separation (a), targets at all depths are clearly visible and distinguishable in the images, and the intensity peaks are clearly separated. Proceeding downward in Fig. 9, it is apparent that the images of the two coins begin to merge for the deeper coins at 8cm, and for the shallowest coins at 4cm. For the RASCAN images at 2cm coin separation (Fig. 9e), it is not obvious that there are two targets from the image alone. However, from the intensity graphs, it is clear that there are distinct intensity peaks for each coin, at all depths, and for all separations – including 2cm (Fig. 9e graph).

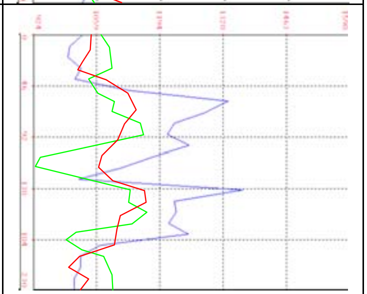
a) 10cm separation



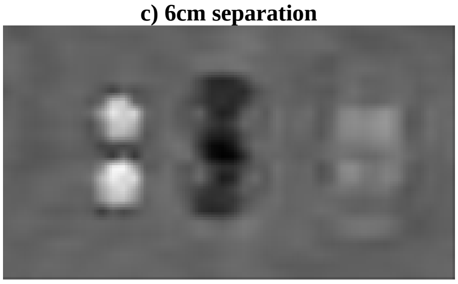


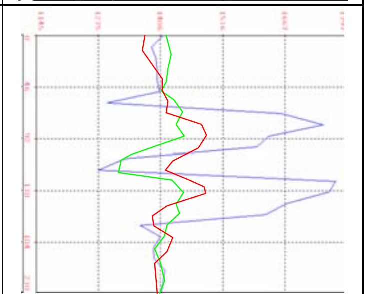
b) 8cm separation



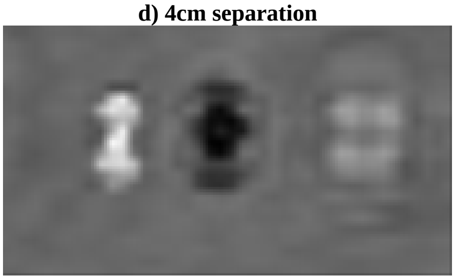


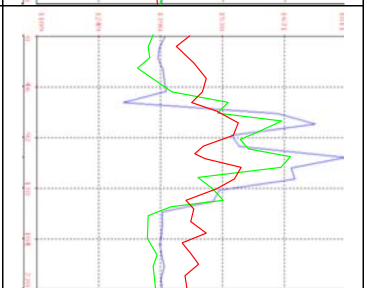
c) 6cm separation



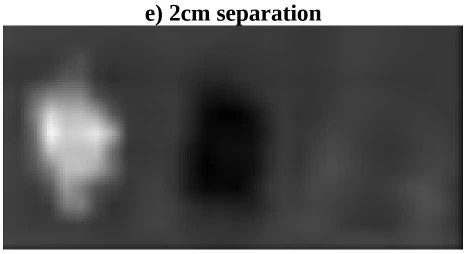


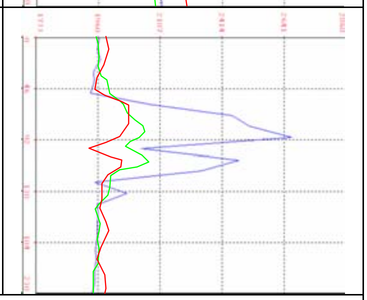
d) 4cm separation





e) 2cm separation





f) bed sketch

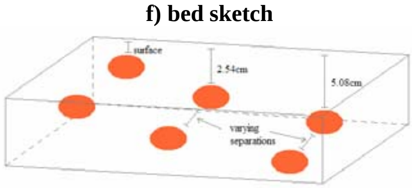


Figure 9. a-e) RASCAN images of 2cm diameter coins, at three depths, for decreasing coin separation. Pixel intensity (normalized phase difference) graphs through each of the three coin pairs shown on right: Blue=surface; Green=2.54cm; Red=5.08cm

Thus, applying the strict Rayleigh Criterion to these images, the resolution is at least 2cm at depths down to at least 5.08cm for these 2cm diameter circular targets. Note that these images illustrate also the common pattern for RASCAN images as described above for the other tests; the deeper a target, the lower the intensity of its Airy spot, and the more pronounced the diffraction rings.

2.7 TACK HEAD SEPARATION TEST. Tack heads at varying separations and depths.

The final test for equidimensional targets was designed to test the resolution of RASCAN with very small targets approximating true point targets so that target dimensions would not affect the measured resolution. A series of two rows of 1cm diameter aluminum tack heads was placed at separations ranging from 0.5cm to 6cm. The first and second pairs were 3cm apart, and the other 5 pairs were 6cm apart. This "V-shaped" arrangement of small targets (see Fig. 10) was then scanned at depths of 0, 2.54, 5.08, and 7.62cm.

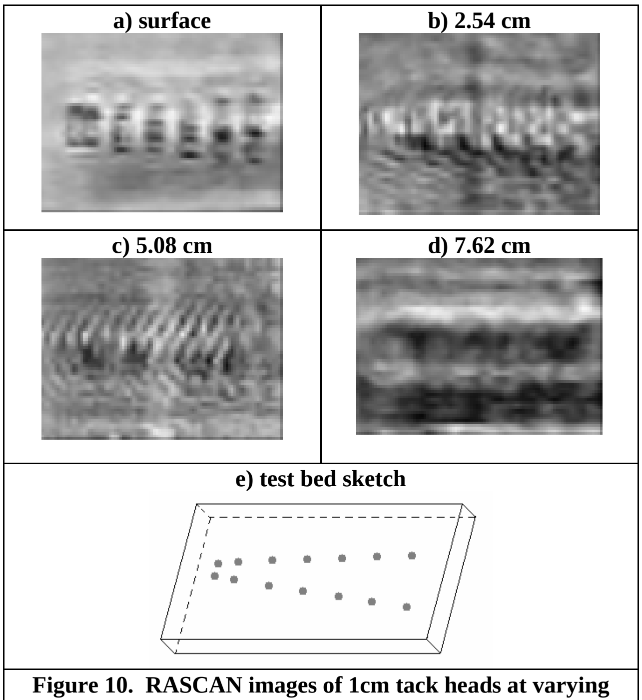


Figure 10. RASCAN images of 1cm tack heads at varying separations and depths.

The scans show an interesting trend in the interference patterns of these small targets. As seen before, 1cm targets produce interference patterns, but the patterns do not resemble the actual target. It is presumed that this is because the target is so small there is no distinctly high-amplitude Airy spot, and simply a set of diffraction rings for each tack head. These rings interfere, and produce an image that does not at all resemble the actual pattern of targets. Instead, the interference of diffraction rings from different targets produces a complex interference pattern that does not directly resemble the target pattern. Therefore, this test shows that while RASCAN is sensitive to targets at least as small as 1cm, the interference pattern from these small targets does not resemble the actual target pattern, and there is no definable resolution for targets of this type, at this small size, without hologram reconstruction.

2.8 Summary

With respect to sensitivity, the scans show that these metallic (high dielectric contrast) targets are detectable in low loss (dry sand and foam) media at even the greatest depths tested (12cm), even for very small (<2cm) diameter targets. Equidimensional targets seem to produce roughly circular interference patterns regardless of the details of their shape. The strict Rayleigh Criterion resolution seems to be at least as good as 2cm, even for images where targets appear visually to have fully merged. Finally, the interference patterns seem to best match the true dimensions of the target at some depth (dubbed the sweet spot) between 1 and 3cm.

III. ELONGATE TARGETS

After the group of equidimensional targets was scanned, a second group of elongate targets consisting of steel wires or rods was scanned. These rods were arranged either singly, or in pairs at a 7-degree angle, creating a V-shaped arrangement.

3.1 SINGLE WIRE.

In order to investigate the capabilities of RASCAN for imaging elongate targets, the first test involved scanning of a single wire with diameter 0.3mm at several depths, with example images shown in Fig. 11.

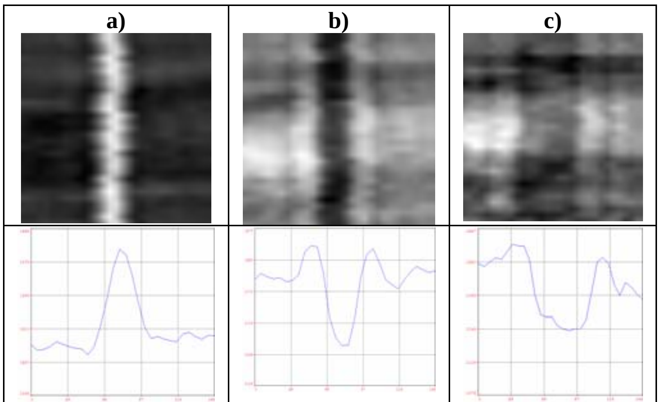


Figure 11. Single wire images and intensity graphs for depths 2.54, 5.08, and 7.62cm (a,b,c).

These interference patterns resemble those for diffraction by a slit, with a central intensity peak, and smaller side lobes that spread laterally and gain in intensity at the expense of the central peak as the depth increases. Single wire testing was performed for wires with diameters down to 0.11 mm, with all being clearly detectable. Thus it is evident that RASCAN imaging is sensitive to metal wire-like targets of almost infinitesimal diameter.

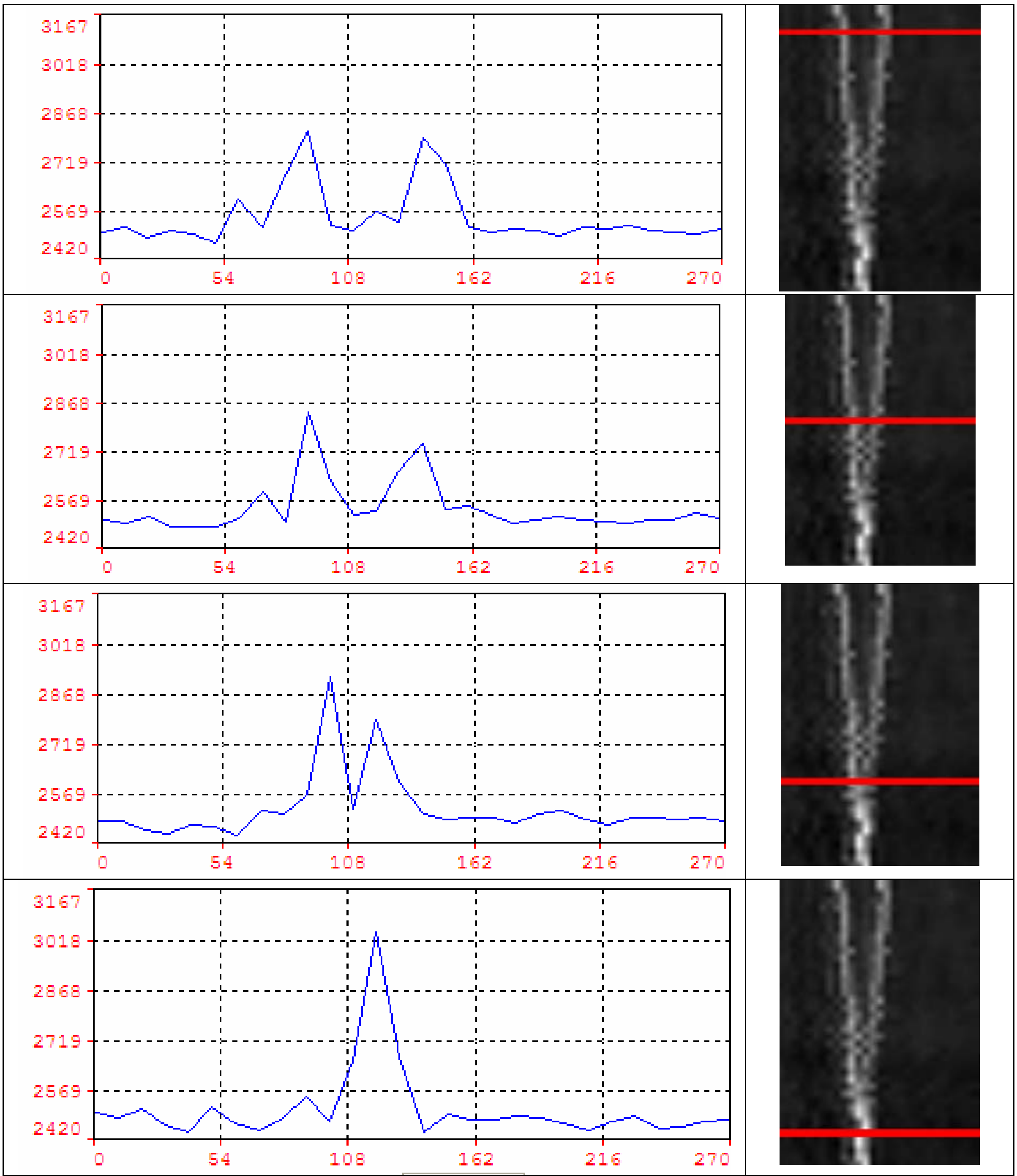
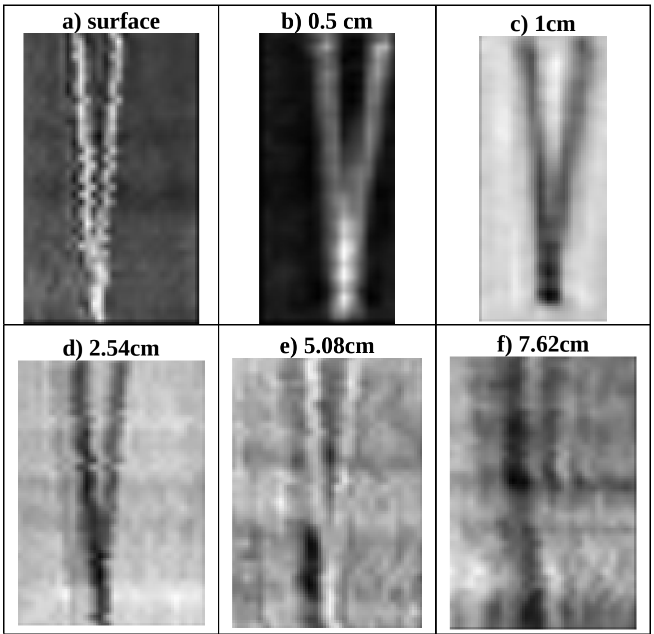


Figure 12. Intensity graphs and images showing peak-to-peak separation, and merging of peaks. The red line on the image shows the row of pixels graphed on the left.

3.1 TWO WIRES RESOLUTION TEST. Identical, very thin, intersecting wires at various depths

In order to investigate the resolution of RASCAN for imaging elongate targets, a test bed was constructed with two 0.5mm wires at a 7-degree angle in urethane foam. This configuration was chosen since, for parallel wires, discrimination of intensity peaks from adjacent wires (see Fig. 12 graphs) might be difficult. That is, it would not be possible to determine which of two wires any given intensity peak was associated with. The two intersecting wires were scanned sequentially at depths of 0.0, 0.5, 1.0, 2.54, 5.08, and 7.62cm. Images from all depths can be seen in Figure 13.

As depicted in Fig. 12, for a single test image from the surface or 0.0cm depth scan, the two wires are clearly discernible in the interference pattern image. In order to determine the resolution of the images, intensity graphs roughly perpendicular to the wires were examined to identify the minimum discernible peak separation. For example, examination of Fig. 12 a, b, and c shows distinct peaks associated with each wire that approach as the wires are closer together. Fig. 12c shows the point on the image where the peak separation is minimum, yet still distinct.



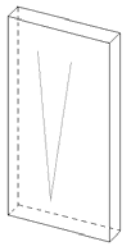


Figure 13. All images of intersecting wires from six different depths

As shown in Fig. 12d, at smaller wire separations, the intensity peaks merge. Thus, the resolution of this image is the peak-to-peak distance on the graph of Fig. 12c – which is 20mm or 2cm.

Fig. 13 shows images of the intersecting wires at each depth. At the surface, the V-shaped pattern of wires can be seen clearly. The resolution, as determined by measuring the peak-to-peak distance on an intensity graph, is 2cm, but only for cross polarization. In the parallel polarization (not shown), the resolution is 3 to 4cm. At a depth of 0.5cm, the resolution is again 2cm in the cross polarization, and 3cm in the parallel (not shown). At a depth of 1cm, in cross, the resolution varies between 2 and 3cm depending on the frequency. At depths of 1cm and greater, the interference patterns for parallel polarization do not resemble the actual wires. At a depth of 2.54cm, the cross polarization image resolution is 3cm. At 5.08cm depth, resolution is 4cm. Finally, at a depth of 7.62cm, the central peak intensity for each wire has degraded such that it becomes difficult to recognize the actual wires even on cross polarization images (see Fig. 13f), and a resolution cannot be confidently measured.

a) test bed	**b) 5.08 cm**	**c) 7.62cm**

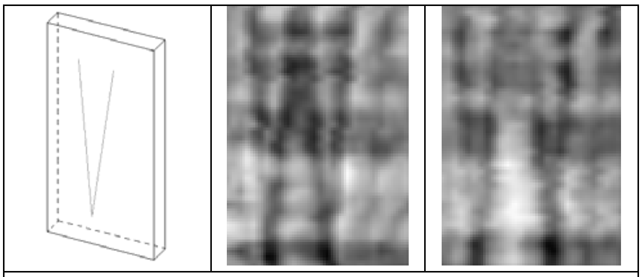


Figure 14. Interference patterns resembling four wires (b and c) rather than the actual two (a).

At the greater scanning depths, the growth of the off-center intensity peaks at the expense of the central peak, and the interference of the interference patterns from the two wires, leads to an interesting illusion in the images. Fig. 14b and 14c show images of the two wires at depths of 5.08 and 7.62cm depth. From these images alone, it might appear that there are two sets of intersecting wires, forming two V-shapes. However, the actual wire configuration is shown in Fig. 14a. Thus it is clear that a RASCAN operator must be careful to remember the interference pattern nature of images when interpreting subsurface scans.

3.2 WIRE DIAMETER TEST. Thick and thin wires at various depths

The third test of elongate targets used four V-shaped arrangements with wires or rods having different diameters. The purpose of this test was to determine whether the diameter of the wire had any effect on image quality or resolution. For this test, in one test bed, 0.25mm and 0.5mm wires were placed in urethane foam, and then scanned at different depths. In another test bed, 0.75mm and 6mm rods were buried in urethane foam. Both sets of wires/rods were scanned at depths of 0, 2.54, and 5.08cm.

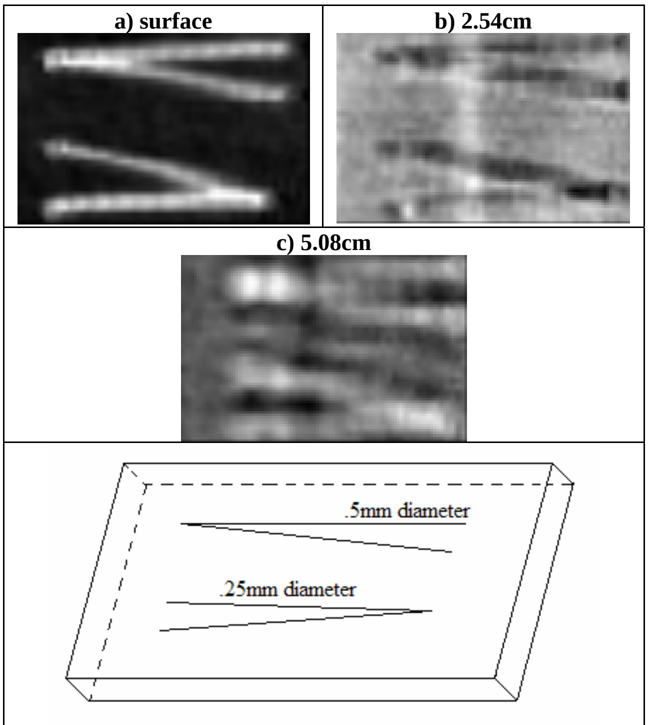


Figure 15. Images of thin wires at different depths.

Images of the thinner set of wires can be seen in Fig. 15. As with the very thin wires (Fig. 13 above), the wires of both thicknesses can be distinguished clearly on certain frequencies at a resolution of 2cm at the surface (e.g. Fig. 13a), 3cm at 2.54 cm depth, and 4cm at 5.08cm depth.

The same pattern is observed for the thicker rods. Fig. 16 shows selected images at the three scanning depths. Again, the peak-to-peak resolution was found to be 2cm for wires at the surface of the test bed, but was 3cm for wires at a depth of 2.54cm, and 4cm for wires at a depth of 5.08cm.

Note that these resolutions were measured by examining the intensity graphs. It was observed that even though on the images, the thicker wires/rods appear to merge at distances greater than the resolution stated above, examination of the intensity graphs, as in Fig. 17, shows that there are distinct peaks representing the individual wires even at locations on the image where two wires are not readily apparent. Fig. 17 shows images of the thin and thick wires at the same combination of frequency and polarization, with intensity graphs for the highlighted column of pixels shown below. For the thin wires, the peak for each individual wire rises above a background intensity level. For the thicker wires, there are distinct peaks, but they sit atop an overall peak that rises above the background level. Thus, even where the thicker wires appear to have merged on the image, the actual intensity data is able to resolve them as separate targets.

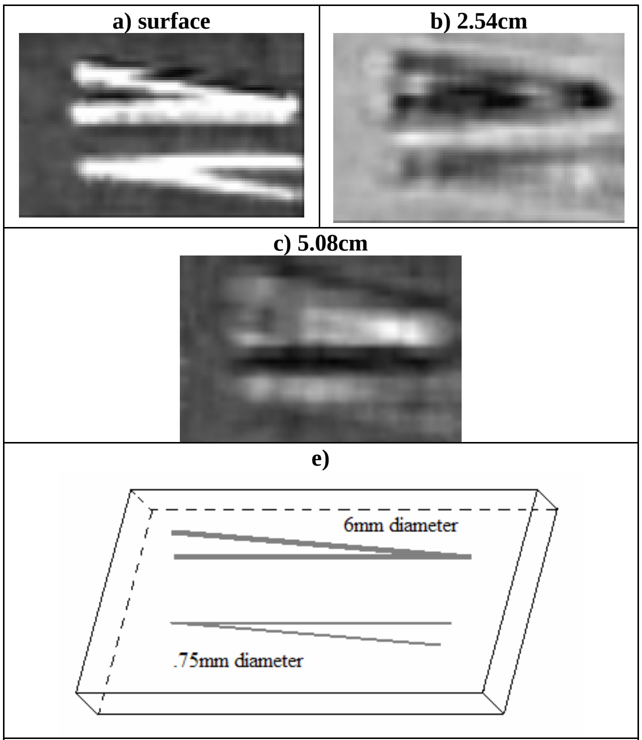


Figure 16. Images of thick wires/rods at different depths.

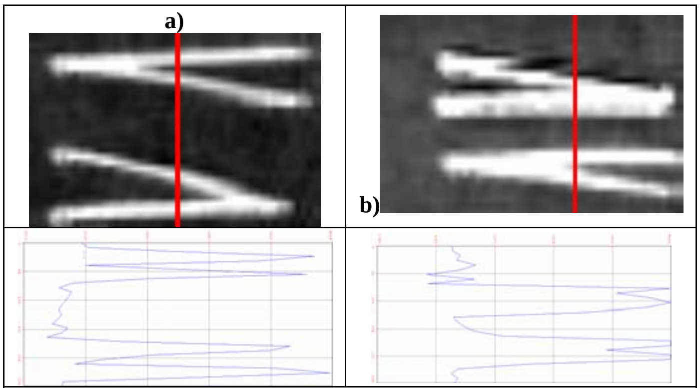


Figure 17. Images and matching intensity graphs comparing the thin (a) and thick (b) wire tests.

IV. SUMMARY

It has been demonstrated that the RASCAN-4/4000 generally does have a resolution that matches the nominal 2cm. For equidimensional targets, small coins could be seen as separate objects on graphs of the phase difference or intensity even when they appear as a single target on the actual holographic image. The complicated interference patterns created by diffractions from multiple point targets (tack heads) made testing of the resolution with point targets impractical. However, testing with wires of very small diameter relative to the signal wavelength also demonstrated the accuracy of the nominal 2cm resolution. As with all radars, and remote sensing/geophysical techniques in general, the resolution degrades with depth.

The particular frequency and polarization combination that produced the best (in the visual sense) image of any target was not predictable. However, elongate targets were consistently found to appear most distinctly on the cross polarization channel. For equidimensional targets, it has been observed that the interference patterns that comprise the holographic image seem to most accurately represent the actual target at a depth between about 1 and 3cm.

Finally, all of the scans showed clear changes in interference patterns with depth. This suggests that the holographic images contain depth information that may be retrievable; perhaps by numerical holographic reconstruction.

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