



TECHNICAL T r e p o r t L

USA-BRDEC-TR // 2509

Measurements in Moist and Wet Soils with the Waveguide Beyond Cutoff or Separated Aperture Dielectric Anomaly Detection Technique

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Report Date
June 1991

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91-06981



United States Army
Belvoir Research, Development and Engineering Center
Fort Belvoir, Virginia 22060-5606

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Service, Direction of Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 1991	3. REPORT TYPE AND DATES COVERED Final	
4. TITLE AND SUBTITLE Measurements in Moist and Wet Soils with the Waveguide Beyond Cutoff or Separated Aperture Dielectric Anomaly Detection Technique (U)			5. FUNDING NUMBERS	
6. AUTHOR(S) Dr. Lloyd S. Riggs (Auburn University) and Charles A. Amazeen (BRDEC).				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Belvoir Research, Development & Engineering Center ATTN: STRBE-NT Fort Belvoir, VA 22060-5606			8. PERFORMING ORGANIZATION REPORT NUMBER 2509	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES POC: Mr. Charles Amazeen, 703/664-2775				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Distribution unlimited; approved for public release.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This report present experimental results concerning the separated aperture (or waveguide beyond cutoff) buried mine detection scheme. More specifically, the experimental data presented here describes the ability of the separated aperture sensor to detect buried dielectric anomalies under moist or saturated (wet) soil conditions. This data was collected by the authors during June, July, and August 1990 at the Fort Belvoir Experimental Mine Lanes Facility, Fort Belvoir, Va. This report is part of an ongoing research project to build an engineering database to be used in a long-term research program directed toward the development of a complete understanding of the fundamental electromagnetic principles underlying the separated aperture mine detection technique and to assess the general feasibility of separated aperture mine detectors. The moist and wet soil experiments described in this report should be viewed as a continuation of earlier experimental efforts described in BRDEC Technical Report No. 2497, <i>Research With The Waveguide Beyond Cutoff or Separated Aperture Dielectric Anomaly Detection Scheme, August 1990</i> .				
14. SUBJECT TERMS			15. NUMBER OF PAGES 42	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

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Table of Contents

	Page
SECTION I INTRODUCTION.....	1
Background.....	1
Data Collection System, Sensors, and the Experimental Test Procedures Used in the Moist and Wet Soil Experiments	2
Description of the Moist and Wet Soil Experiments.....	2
SECTION II EXPERIMENTAL RESULTS	5
SECTION III CONCLUSIONS	33
SECTION IV AREAS FOR FURTHER RESEARCH.....	34



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Section I

Introduction

BACKGROUND

This report presents experimental results concerning the separated aperture (or waveguide beyond cutoff) buried mine detection scheme. More specifically, the experimental data presented here describes the ability of the separated aperture sensor to detect buried dielectric anomalies under moist or saturated (wet) soil conditions. This data was collected by the authors during June, July, and August 1990 at the Fort Belvoir Experimental Mine Lanes Facility, Fort Belvoir, Virginia. The exact experiments conducted are described in detail below.

This report is part of an ongoing research project to build an engineering database to be used in a long-term research program directed toward the development of a complete understanding of the fundamental electromagnetic principles underlying the separated aperture mine detection technique and to assess the general feasibility of separated aperture mine detectors. The moist soil experiments described in this report should be viewed as a continuation of earlier experimental efforts described in BRDEC Technical Report No. 2497, *Research With The Waveguide Beyond Cutoff or Separated Aperture Dielectric Anomaly Detection Scheme, August 1990*. Experiments described therein were conducted in very dry loamy soil and are virtually identical to the experiments in this report, with the previously mentioned exception that this report assesses sensor performance under moist soil conditions. For this reason, the reader is strongly encouraged to digest the material in Report 2497 before reading this report. Consider the following quotation taken from the Lessons Learned and Issues Raised section of Report 2497:

"A mine buried in soil with high moisture content seems to be extremely difficult to detect and, as expected, the situation is exacerbated as the mine is buried deeper. Past research efforts were conducted with two types of dipoles, a narrow band printed circuit dipole (PC dipole) used by the Cubic Corporation, and a relatively broadband brass dipole used by the NBS. It was observed that the PC dipoles give good detection performance with mines buried in homogeneous, relatively dry soil. However, the response on moist or wet soil is known to degrade. Some evidence exists supporting the notion that the broadband dipole would perform much better under these conditions. Preliminary NBS research also indicated that some frequencies penetrate moist soils much more efficiently than do others so that a "window of opportunity" may exist which can be used to enhance detection under wet conditions. These rumors and conjectures must be carefully investigated. Even if it turns out that the separated aperture approach simply does not work well in moist soil, this will still be important information regarding the generation of realistic specifications for a prototype vehicular and/or hand-held mine detector".

It is exactly the purpose of this report to address the very "rumors and conjectures" mentioned above.

DATA COLLECTION SYSTEM, SENSORS, AND THE EXPERIMENTAL TEST PROCEDURES USED IN THE MOIST AND WET SOIL EXPERIMENTS

The measurement system used to collect the moist soil data, as well as the geometry and performance characteristics of the broadband and printed-circuit sensor heads, is thoroughly discussed in Section II of Report 2497. Figure 1 (identical to Figure 11 of Report 2497) describes the specific experimental procedure used in collecting the data. Again extracting from Report 2497:

"Figure 11 is a scale drawing of the experimental configuration showing the 790 MHz broadband sensor parallel to and at a height H above the soil surface. A dielectric anomaly, usually a 12 x 12 x 3 inch nylon block, is buried at a depth D below the soil surface. For most of the experimental results presented here, the sensor head is scanned in 1.5-inch increments directly over the anomaly (receive dipole passes over the anomaly first). As shown in Figure 11, measurements are made at 27 positions for a total horizontal scan of 39 inches. At each horizontal position, the network analyzer is used to measure the transmission coefficient (S_{21}), a complex ratio of voltage at the output of the receive dipole to the voltage at the input of the transmit dipole, at 8 MHz intervals starting at 600 MHz and ending at 1,000 MHz—51 frequency samples over a 400 MHz band. Since the dipoles are resonant near 800 MHz, the transmission coefficient is measured from 200 MHz below resonance to 200 MHz above resonance. A 6-inch septum width was used for most of the data taken with the 790 MHz broadband sensor; however, the septum width can be adjusted."

DESCRIPTION OF THE MOIST AND WET SOIL EXPERIMENTS

A number of experiments were conducted in order to gain an understanding of the performance limitations of the separated aperture sensor under wet or moist soil conditions. The experimental procedure was quite simple and consisted of making horizontal scans at various sensor heights before and after wetting the soil. A hose with a nozzle adjusted to produce a fine mist was used so that the soil could be uniformly wetted. Soil moisture content was measured by weight. A sample was weighed then dried in a microwave oven and weighed again.

The first set of experiments were conducted exactly as described above using the 12 x 12 x 3 inch nylon block buried 6 inches below the loamy soil surface. The soil was wetted for 10 minutes which resulted in a 3 inch surface layer of approximately uniformly moist loam (mud) with a moisture content of 24.3%. Scans over the nylon block were made immediately before and after wetting the soil. Scans were also made approximately 24 hours, 28 hours, 3 days, and 7 days after wetting the soil and at these times the soil had dried to a moisture content of 19.8%, 20%, 16.2%, and 14.5%, respectively. Before wetting, the ambient soil moisture content was 16.8%. The broadband (NIST) sensor head was used to take all the data in this first set of experiments.

The procedure used in the second set of wet-soil experiments was identical to the first (scans made at various heights over a 12 x 12 x 3 inch nylon block buried 6 inches below the soil surface) except that the soil was wetted for 30 minutes. This 30-minute wetting resulted in a 6-inch layer of approximately uniformly moist loam with a moisture content of 22%. Scans were made just after wetting the soil and approximately 50 hours after wetting; the soil moisture content during the latter measurement (after 50 hours of drying) was 18%. In this set of experiments, scans were made with both the broadband 790 MHz and 1,000 MHz NIST sensor heads, as well as with the narrowband 790 MHz printed-circuit sensor head.

LINEAR SCALE INCHES 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39

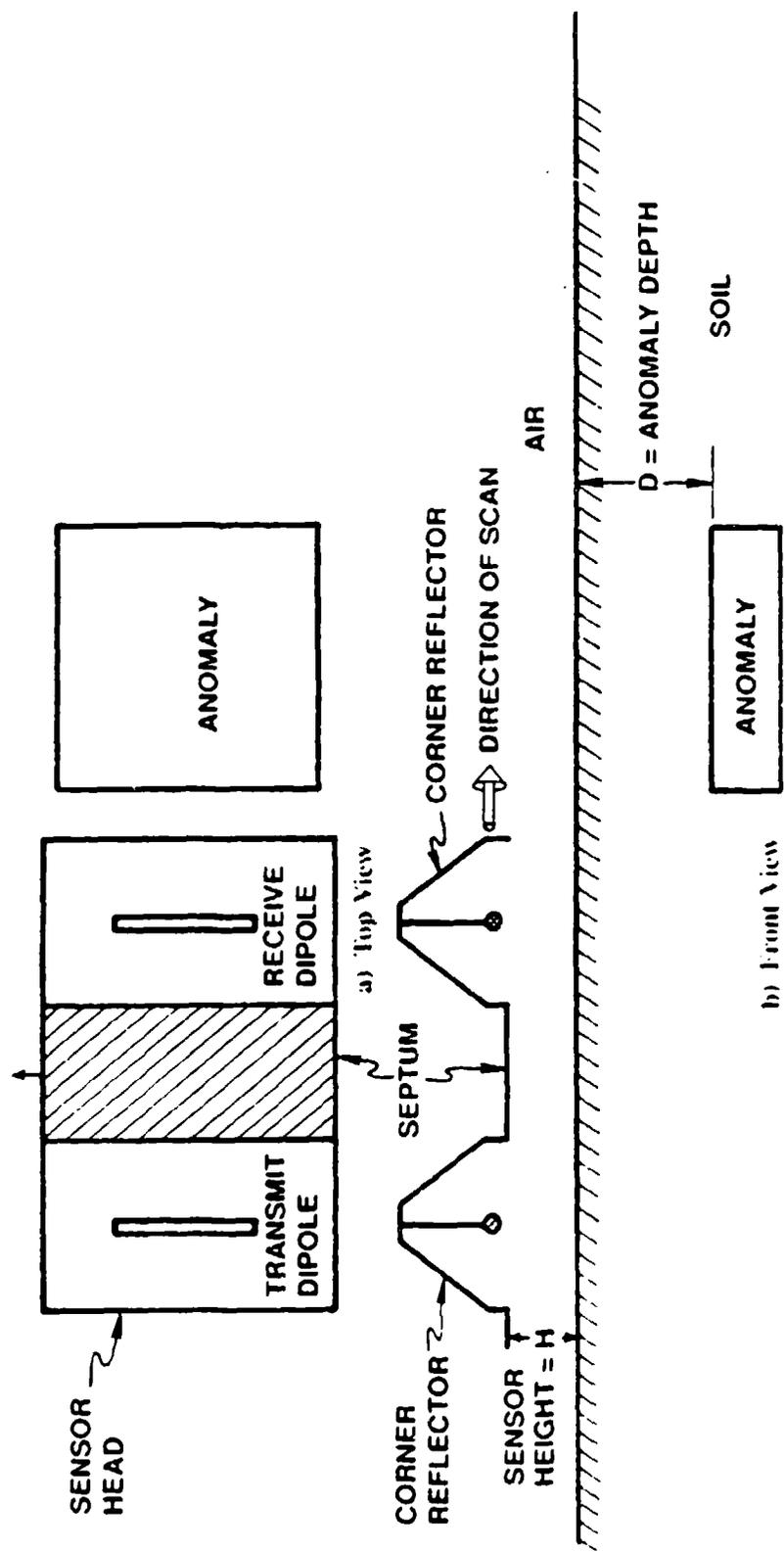


Figure 1. Scale drawing of experimental configuration showing 790 MHz sensor head parallel to and at a height H above the soil surface and dielectric anomaly (12 x 12 x 3 inch) buried at a depth D below the soil surface. The sensor head is scanned directly over the anomaly in the direction shown (received dipole passes over the anomaly first) in 1.5 inch increments for a total horizontal scan of 39 inches. The broadband and printed-circuit dipoles are resonant at 790 MHz. The broadband sensor head septum width is adjustable in 1 inch increments over a range from 1 to 6 inches; however, from most of the data shown here, the septum width is held fixed at 6 inches.

In the third and last set of experiments, the nylon target was buried 3 inches deep (recall that the target depth in the first two experiments was 6 inches) and scans were made at various sensor heights before and after wetting the soil for 30 minutes. The soil moisture content was 12.6% and 22% just before and just after wetting the soil. As was done in the second set of experiments, scans were made with both the broadband (NIST) and printed-circuit (Cubic) sensor heads.

A rather large amount of data resulted from the above three experiments and it is somewhat difficult to determine the optimum way to present the data so that all possible permutations of the variables which define the system are taken into account. Nevertheless, the figures presented in the next section, taken as a whole, do provide one with a fair understanding of how the separated-aperture sensor performs in moist and wet soils. Based on measurements taken in dry loam (moisture content around 6%), it was stated in Report 2497 that acceptable performance could be expected for anomaly depths up to 6 inches provided the sensor height does not exceed 3 inches. Results presented in the next section indicate that if the sensor is restricted to operate at or very near resonance, then the target cannot be detected in wet, loamy soil when it is buried fairly deep, say at or below 6 inches, without placing the sensor very close to the surface of the soil (within about 2 inches of the surface). On the other hand, measurements indicate that an anomaly buried 6 inches below the surface of wet loam can be readily detected at sensor heights as great as 4 inches, provided the response at frequencies significantly below the dipole resonance are used. In order to avoid mechanical damage, on all but very smooth roads, the sensor must be elevated at least a few inches above the soil surface. Therefore, the response at frequencies significantly below the dipole resonance must be used in order to detect mines buried in moist or wet soils and at the same time avoid mechanical damage to the sensor.

Section II

Experimental Results

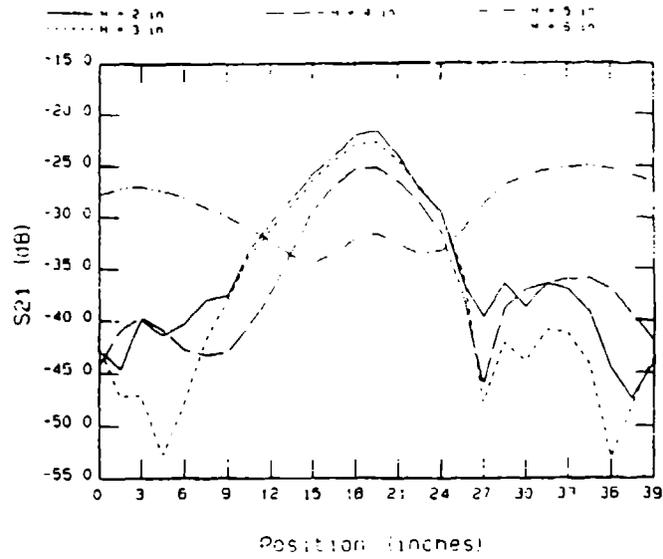
Figures 2 through 8 present data associated with experiment 1 as previously described. Figures 2, 3, and 4 give the broadband sensor response at 790 MHz as a function of position for a fixed soil moisture content with sensor height as a parameter. Figure 2a shows the sensor response before the soil was wetted and from this figure it is clear that the 6 inch deep 12 x 12 x 3 inch nylon block is easily detected even for sensor heights as great as 4 inches. Contrasted with Figure 2a, Figure 2b shows that immediately after wetting the soil, the anomaly is, for all practical purposes, virtually undetected except when the sensor is within 2 inches of the ground. Figures 3a, 3b, 4a, and 4b demonstrate how the sensor responds after the soil has dried for 24 hours, 27 hours, 72 hours, and approximately 7 days, respectively. Not surprisingly, as the soil dries, the ability of the sensor to detect the anomaly at greater sensor heights improves. For example, after drying for 24 hours (see Figure 3a), the anomaly is clearly "visible" for sensor heights of 1 and 2 inches, and it might be argued that it is visible for sensor heights up to 4 inches, although the response at 3 inches is rather disappointing. Still referring to Figure 3a, it is interesting to observe that for a sensor height of 4 inches, and when the sensor is positioned directly over the target, the transmission coefficient (S_{21}) is actually about 10 db below the background level. (Background level refers to the response level when the sensor is well away from the anomaly). It is also interesting to compare the 3 and 4 inch sensor responses of Figures 3a and 3b. In Figure 3b, the 3 inch response is "better" than the 4 inch response. In Figure 3a, the 4 inch response is better than the 3 inch response. This result is somewhat surprising and demonstrates that the response does not always degrade with increasing sensor height. Figure 4a demonstrates that even after the soil has dried for 72 hours (moisture content of 16.2%), the sensor has difficulty detecting the anomaly for sensor heights greater than 3 inches. Notice that the 4 inch sensor response of Figure 4a is "poor" being almost flat across the entire scan. Finally, Figure 4b shows that after the soil has dried for approximately 7 days (moisture content of 14.5%), the sensor has no trouble detecting the anomaly for sensor heights up to 4 inches.

It should also be mentioned that although Figures 3a and 3b are labeled with a moisture content of 19.8% and 20.0%, respectively, the soil was almost certainly drier when the data of Figure 3b was taken. Because the soil may not have been wetted uniformly and because it does not dry out uniformly, it is possible that the sample used to determine the soil moisture content was taken from an above average "wet" or "dry" spot. Also, the soil sample may not have been dried long enough to remove all the moisture. (A microwave oven was used to dry the samples.)

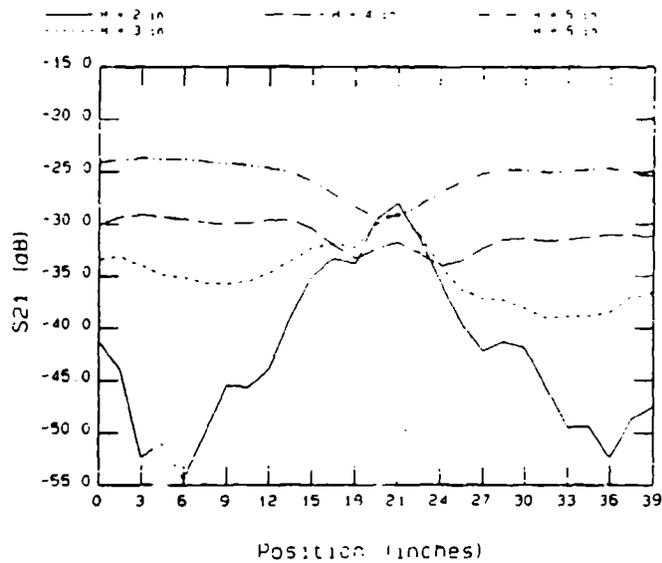
Figures 5 through 7 display the transmission coefficient (S_{21}) as a function of sensor position for fixed sensor height with soil moisture content as a parameter. Figures 5 through 7 present exactly the same information as presented in Figures 2 through 4 except that the curves are grouped according to identical sensor height rather than identical moisture content. Figure 5 demonstrates that the detector "sees" the anomaly equally well regardless of soil moisture content provided the sensor is within 2 inches of the soil surface. For a 3 inch sensor height, Figure 6a shows a rather flat response for scans taken just after wetting the soil (moisture

content of 24.3%) and 24 hours after wetting the soil (moisture content of 19.8%). The curve for a moisture content of 20% (27 hours of drying) indicates that the soil has dried enough so that the dip-peak-dip response characteristic of a dry-soil signature is beginning to emerge. It is curious that the curves for the 19.8% and 20.0% moisture content are quite different even though the scans were taken only 3 hours apart. (Recall from above that the 20.0% moisture content soil is actually dryer than the 19.8% moisture content soil.) The signature for the 16.2% moisture content (72 hours of drying) shows an even more pronounced dip-peak-dip response and finally, after 7 days of drying (curve marked 14.5%), the response is beginning to resemble the before-wetting curve (moisture content of 16.8%). Figure 6b for the 4 inch sensor height shows, as expected, that the sensor "sees" the anomaly best before the soil was wetted and after the soil has had 7 days to dry. However, the 19.8% moisture content curve (sca. taken 24 hours after wetting) shows a fairly deep depression relative to background (approximately 10 dB) when the sensor is directly over the anomaly. It's curious that for the 4 inch sensor height the anomaly seems less "visible" for the 20% and 16.2% moisture content curves than for the 19.8% curves. The data presented in Figure 7, although interesting from a scientific point of view, is probably of little practical value since it is not likely that a prototype mine detector would be operated at a sensor height much above 3 inches. Therefore, Figure 7 will not be discussed further.

Figure 8 is a plot of the transmission coefficient (S_{21}) versus frequency (not position) with the sensor positioned directly over the anomaly. The frequency response is given for the soil moisture conditions of experiment 1, as described above, and the curves in Figure 8a and Figure 8b are for sensor heights of 2 and 3 inches, respectively. The transmission coefficient (S_{21}) measured in dB, in both Figures 8a and 8b, increases linearly with frequency from 600 to 800 MHz and the response just after wetting the soil (moisture content 24.3%) is about 10 dB less than the dry-soil response (moisture content 16.8%) over this frequency range. Above the dipole resonance, from 800 to 1,000 MHz, the moisture changes the response less for the 3 inch than the 2 inch sensor height. The reason is that direct coupling from transmit to receive antenna at the 3 inch sensor height, over the 800 to 1,000 MHz frequency range, is large enough to mask any differences in response due to moisture. Over the 800 to 1,000 MHz frequency range for a 2 inch sensor height, the waveguide formed by the earth and septum is below cutoff, and the direct coupling is small, so that the difference in (S_{21}) due to moisture is more pronounced.

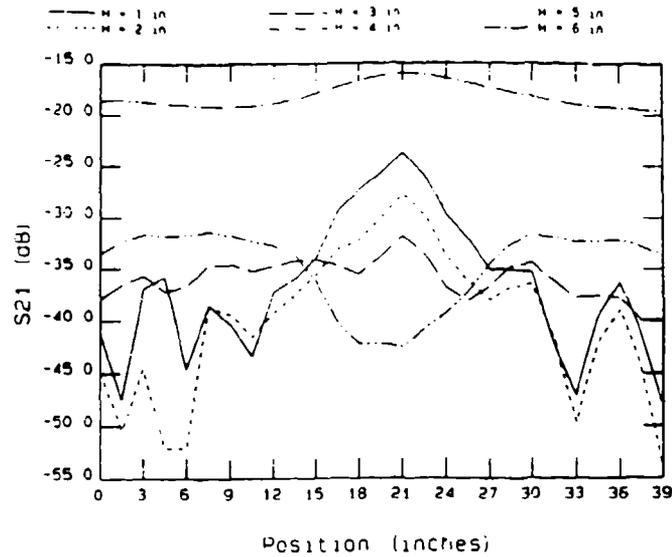


a. Moisture Content = 16.8%

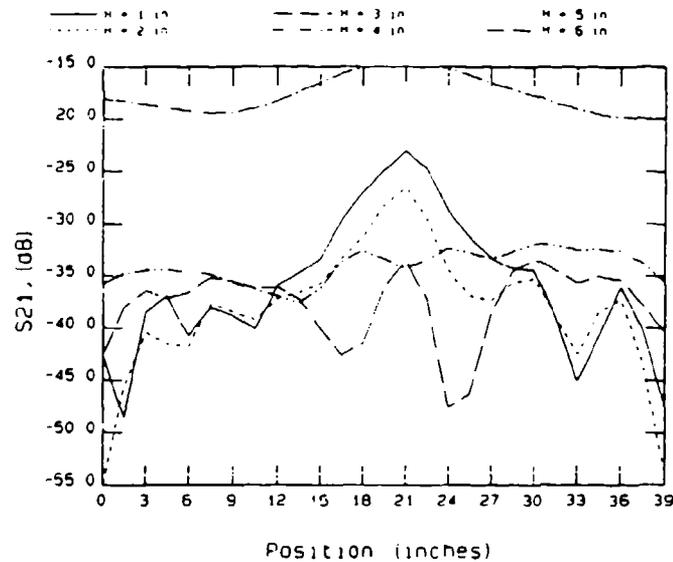


b. Moisture Content = 24.3%

Figure 2. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights (refer to legend above figures) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. In a, the soil moisture content of 16.8%. In b, the soil was wetted resulting in a 3 inch surface layer of very moist (24.3%) loam (mud).

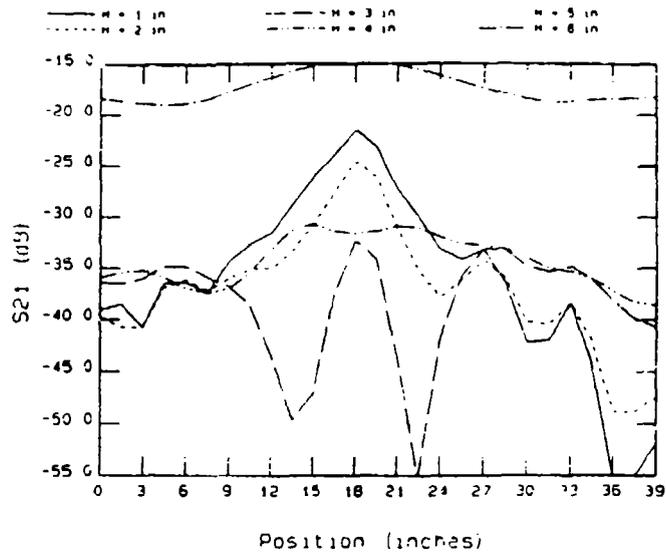


a. Moisture Content = 19.8%

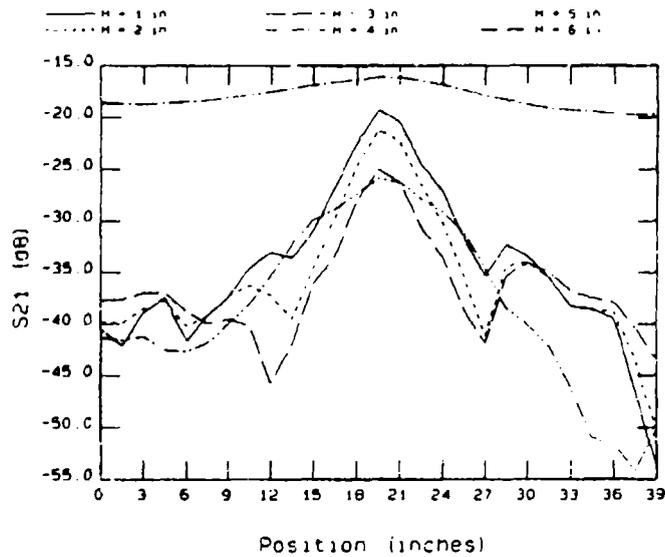


b. Moisture Content = 20.0%

Figure 3. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights (refer to legend above figures) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. In a, the soil moisture content is 19.8%—the result of approximately 24 hours of drying (compare to Figure 1). In b, the soil moisture content is approximately 20%—the result of approximately 27 hours of drying (compare to Figure 1).

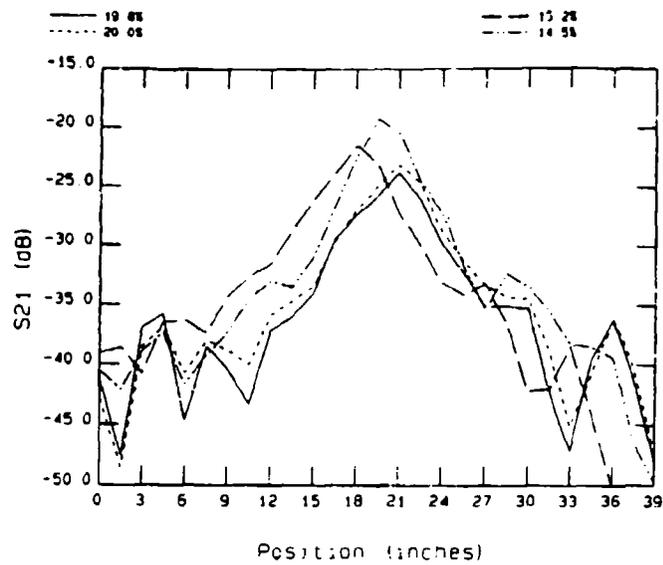


a. Moisture Content = 16.27

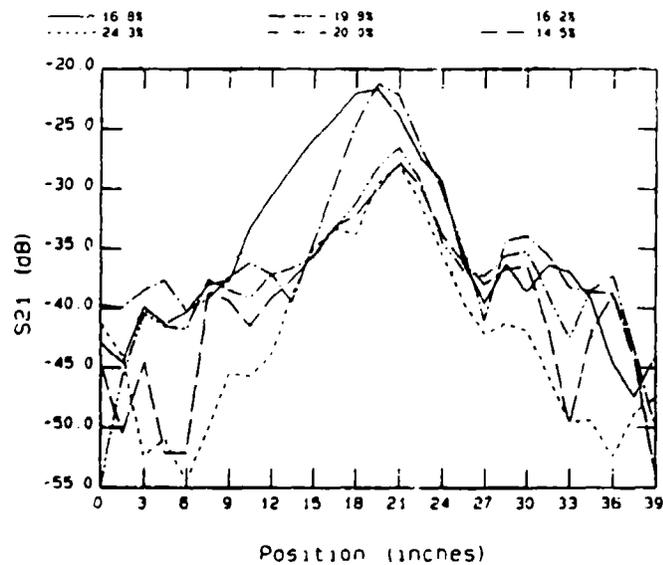


b. Moisture Content = 14.5%

Figure 4. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights (refer to legend above figures) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. In a, the soil moisture content is 16.2%—the result of approximately 72 hours of drying (compare to Figure 1). In b, the soil moisture content is approximately 14.5%—the result of approximately 7 days of drying (compare to Figure 1).

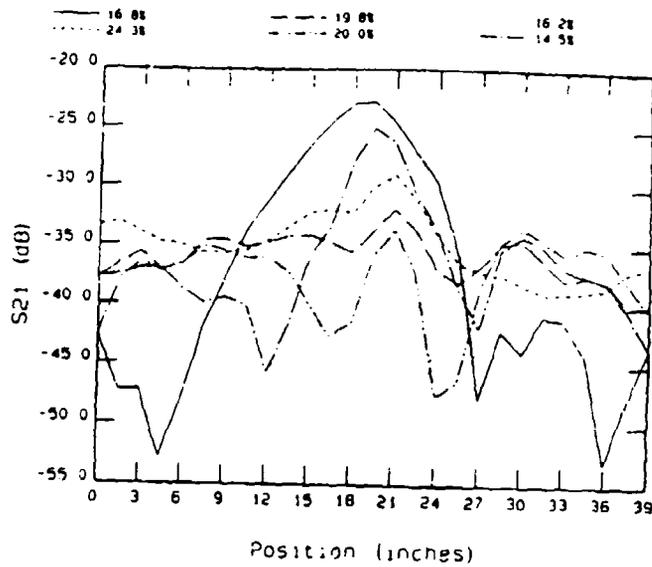


a. Sensor Height = 1 inch

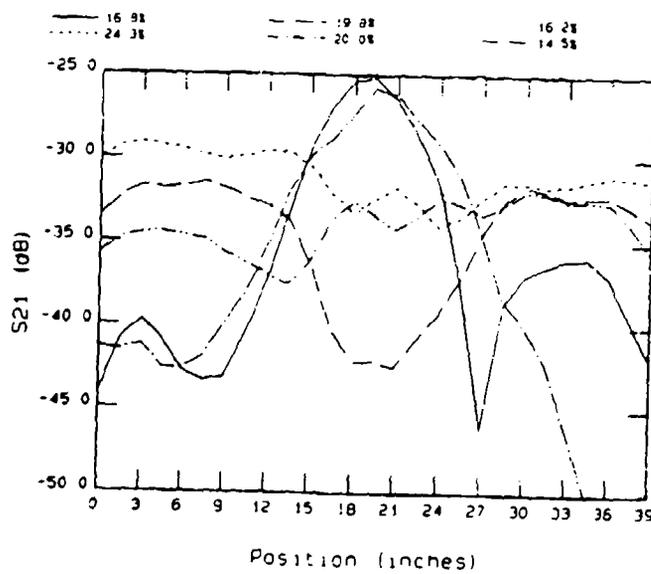


b. Sensor Height = 2 inches

Figure 5. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various soil moisture contents (refer to legend above figures) as the broadband sensor is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. The sensor height is held at 1 inch in a and 2 inches in b. See Figures 1, 2, and 3 for an explanation of the soil moisture conditions.

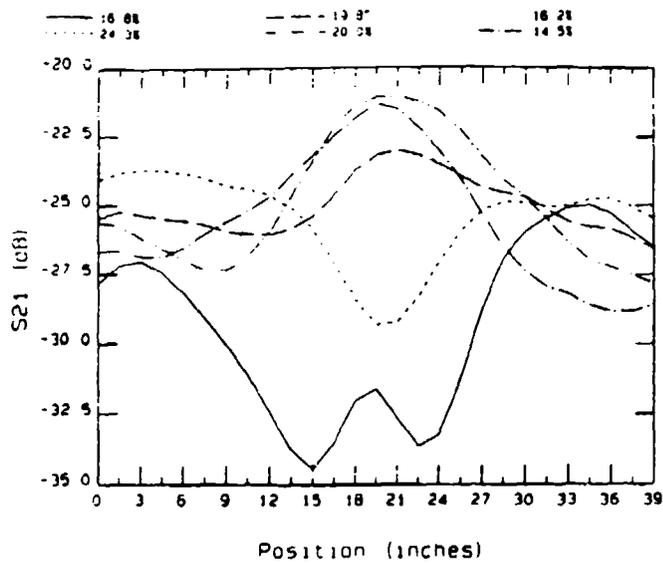


a. Sensor Height = 3 inches

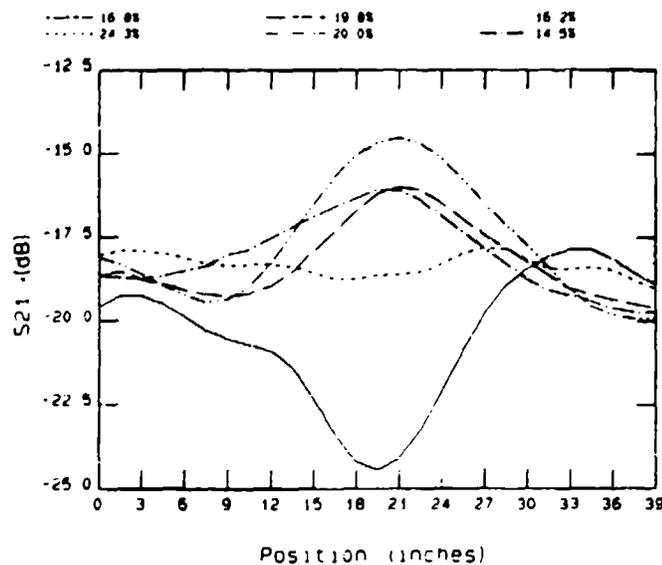


b. Sensor Height = 4 inches

Figure 6. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various soil moisture contents (refer to legend above figures) as the broadband sensor is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. The sensor height is held at 3 inches in a and 4 inches in b. See Figures 1, 2, and 3 for an explanation of the soil moisture conditions.

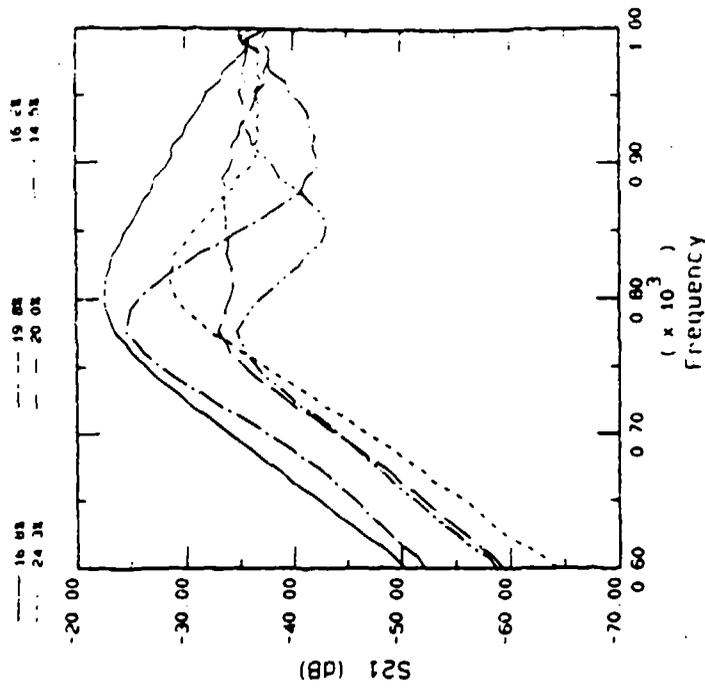


a. Sensor Height = 5 inches

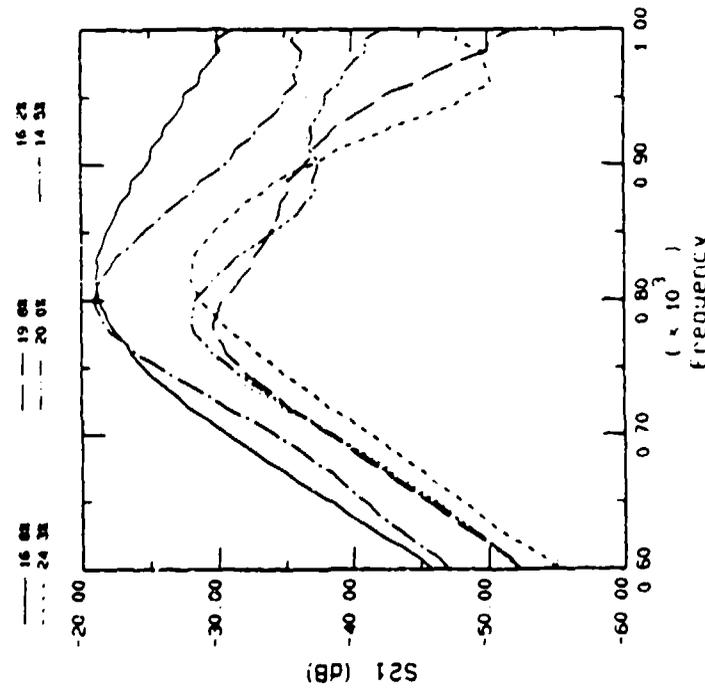


b. Sensor Height = 6 inches

Figure 7. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various soil moisture contents (refer to legend above figures) as the broadband sensor is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. The sensor height is held at 5 inches in a and 6 inches in b. See Figures 1, 2, and 3 for an explanation of the soil moisture conditions.



a. Sensor Height = 2 inches

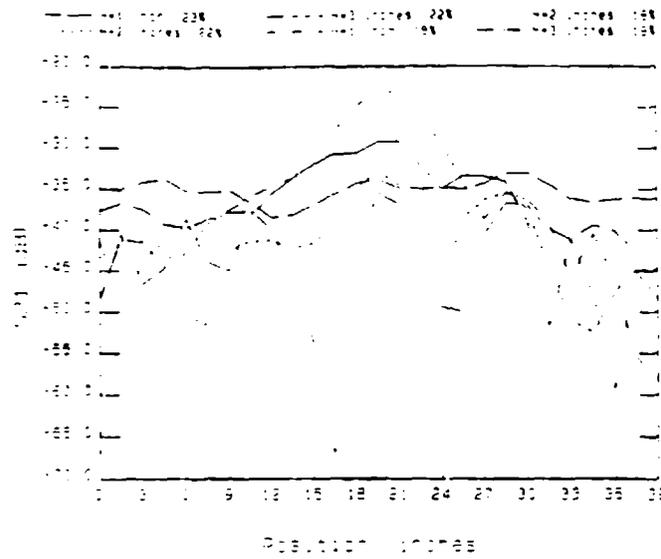


b. Sensor Height = 3 inches

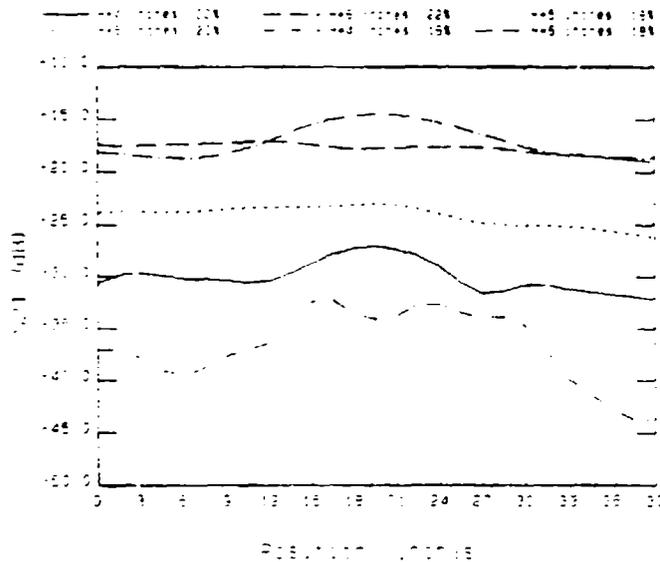
Figure 8. Measurement of transmission coefficient (S_{21}) as a function of frequency for various soil moisture contents (see legend above figures). Measurements were made using the broadband (NIST) sensor head positioned directly over a (12 x 12 x 3 inch) nylon block buried 6 inches below the loamy soil surface. The sensor head was positioned: a, 2 inches and b, 3 inches from the soil surface. The soil was wetted for 10 minutes resulting in a saturated soil layer with a moisture content of 24.3% down to a depth of approximately 3 inches. Allowing the soil to dry for approximately 24 hours; 28 hours; 3 days; and 7 days resulted in a surface moisture content of 19.8%, 20%, 16.2%, and 14.5%, respectively. Before wetting, the ambient soil moisture content was 16.8%.

Figures 9 through 14 present the results of experiment 2. Recall from above that in this experiment the soil was wetted for 30 minutes and scans were taken with the 12 x 12 x 3 inch nylon block buried 6 inches below the soil surface. The soil moisture content just after wetting was 22% and 50 hours after wetting was 18%. Figures 9 and 10 compare the sensor performance before and after wetting for various sensor heights. Figures 9 and 10 present measurements taken with the broadband (NIST) and printed-circuit (Cubic) sensor heads, respectively. Figure 9 shows that just after wetting (moisture content 22%), the anomaly is visible only when the sensor is within 2 inches of the soil surface. Notice from Figure 9a that for the 22% moisture conditions and 3 inch sensor height that the anomaly is virtually invisible—the curve for this case varies less than 5 dB across the entire scan. In contrast, Figure 10a shows that under these same conditions (3 inch sensor height, 22% moisture content), the anomaly is readily discernable when the printed-circuit sensor head is used. Figure 11 directly compares the ability of the broadband and printed-circuit sensor heads to detect the anomaly under wet soil conditions (22% moisture content). Notice, one again, that at a height of 3 inches the printed-circuit sensor performs significantly better than the broadband sensor. Figure 12 compares the performance of the printed-circuit (Cubic) and broadband (NIST) sensor heads for the 18% soil moisture content (50 hours of drying). Under drier conditions, there is much less difference in the performance of the two sensors. Figure 13 compares the frequency response of the broadband and printed-circuit sensors. The comparison is made for various sensor heights just after wetting the soil (22% soil moisture content). Figure 14a shows, as expected, that the NIST sensor has a greater broadband response than the Cubic sensor. Note, however, that the resonant frequency of the Cubic sensor changes much less with sensor height than does the NIST sensor. It was stated above with regard to Figure 11a that the Cubic sensor could "see" the anomaly much better than the NIST sensor at the 3 inch sensor height. It must be remembered, however, that this comparison was made at 790 MHz, and it is very possible that the NIST sensor performs very poorly at this particular frequency. In fact, Figure 13a shows a dip in the NIST frequency response just above 800 MHz for the 3 inch sensor height. In short, the NIST sensor might perform better than the Cubic sensor if the detection algorithm employs S_{21} values at many different frequencies over the 600 to 1,000 MHz band. On the other hand, if the detection algorithm is based on a narrow band of frequencies around the free-air resonance of the dipoles (790 MHz), it would probably be wiser to use the Cubic sensor head since its resonance frequency is a less sensitive function of sensor height. Figure 14 compares the frequency response of the NIST sensor under wet (22% moisture) and dry (16.8% moisture) conditions for various sensor heights. Around resonance (790 MHz), the moisture causes a 10 dB reduction in signal strength for the 2 inch sensor height. At the 3 inch sensor height, the moisture has caused approximately 20 dB of attenuation relative to the dry soil response near 825 MHz. The attenuation due to moisture is not as severe (less than 5 dB at resonance) for the 4 inch sensor height. At the 4 inch sensor height, the attenuation due to moisture is less pronounced because of increased direct coupling, as discussed above in reference to Figure 13.

Figure 15 compares S_{21} versus position data for various sensor heights for the 10 minute and 30 minute wetting (experiments 1 and 2 as described above). It is interesting to observe from this figure that the response for the 10 minute wetting is not significantly different from the response for the 30 minute wetting. It is also clear, once again, that at 790 MHz and under wet soil condition (either 10 minute or 30 minute wetting), the sensor needs to be within 2 inches of the soil surface to "see" the nylon block buried 6 inches below the soil surface.

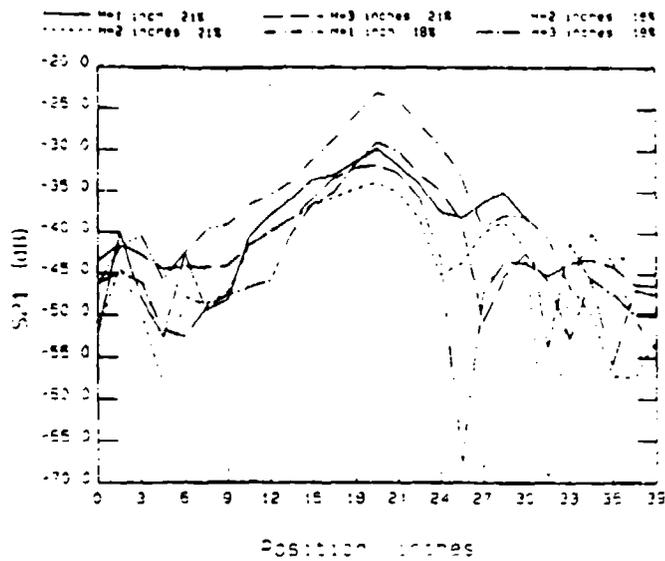


a. H = 1, 2, and 3 inches

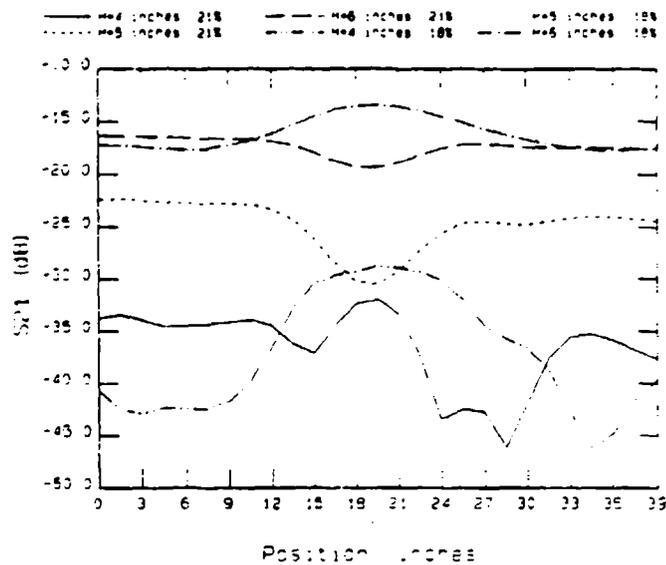


b. H = 4, 5, and 6 inches

Figure 9. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights and soil moisture conditions (refer to legend above figures) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content 22% down to a depth of approximately 6 inches. Allowing the soil to dry for approximately 50 hours resulted in a soil moisture content of approximately 18%.

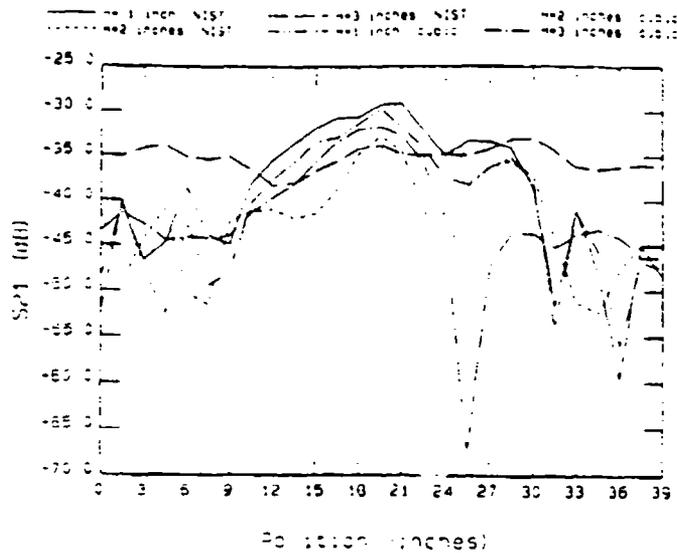


a. $H = 1, 2,$ and 3 inches

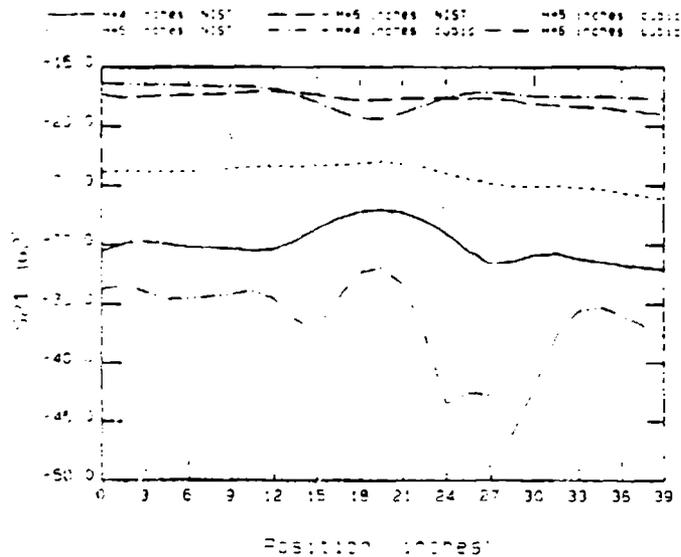


b. $H = 4, 5,$ and 6 inches

Figure 10. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights and soil moisture conditions (refer to legend above figures) as the printed-circuit sensor head is scanned over a nylon block ($12 \times 12 \times 3$ inch) buried 6 inches below the surface of loamy soil. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. Allowing the soil to dry for approximately 50 hours resulted in a soil moisture content of approximately 18%.

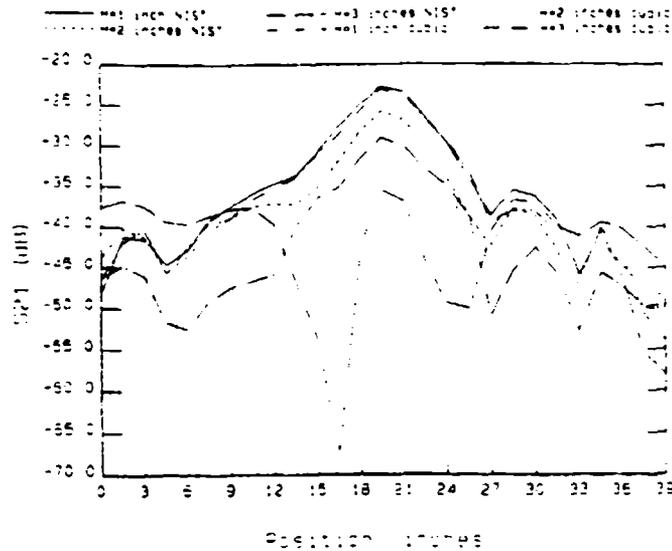


a. $H = 1, 2, \text{ and } 3$ inches

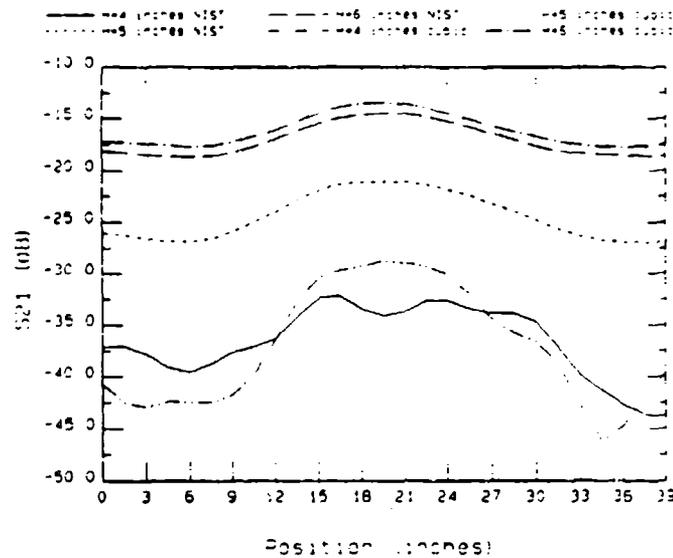


b. $H = 4, 5, \text{ and } 6$ inches

Figure 11. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights (refer to legend above figures) as the sensor head is scanned over a nylon block ($12 \times 12 \times 3$ inch) buried 6 inches below the surface of loamy soil. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. Measurements were made with both the broadband (NIST) and printed-circuit (Cubic) sensor heads (refer to legend above figures).

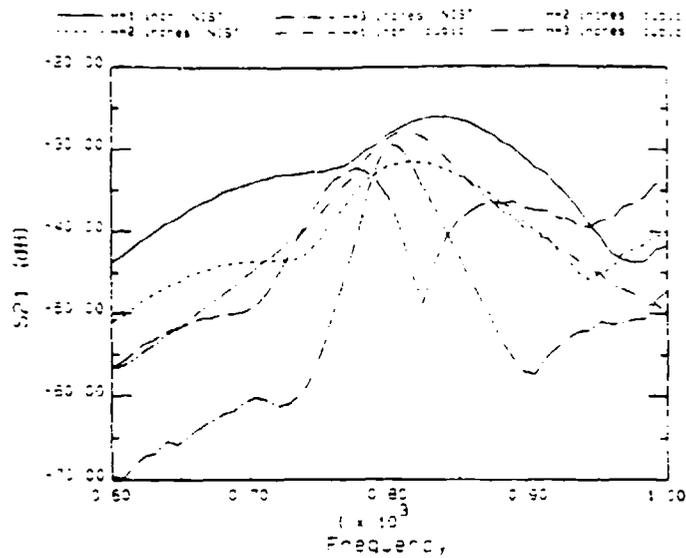


a. $H = 1, 2,$ and 3 inches

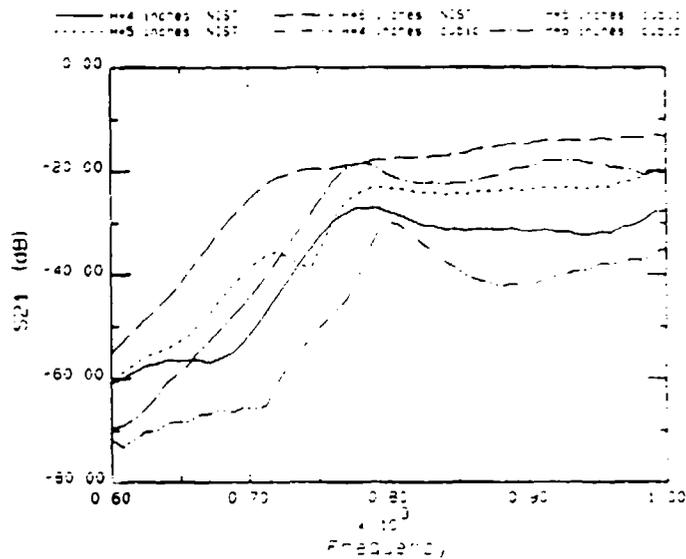


b. $H = 4, 5,$ and 6 inches

Figure 12. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights (refer to legend above figures) as the sensor head is scanned over a nylon block ($12 \times 12 \times 3$ inch) buried 6 inches below the surface of loamy soil. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. Allowing the 6 inch saturated soil layer to dry for approximately 50 hours resulted in a soil moisture content of approximately 18%. After drying, measurements were made with both the broadband (NIST) and printed-circuit (Cubic) sensor heads (refer to legend above figures).



a. H = 1, 2, and 3 inches



b. H = 4, 5, and 6 inches

Figure 13. Measurement of transmission coefficient (S_{21}) as a function of frequency using the broadband (NIST) and printed-circuit (Cubic) sensor heads for various sensor heights (see legend above figures). Measurements were made with the sensor head positioned directly over a (12 x 12 x 3 inch) nylon block buried 6 inches below the loamy soil surface. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches.

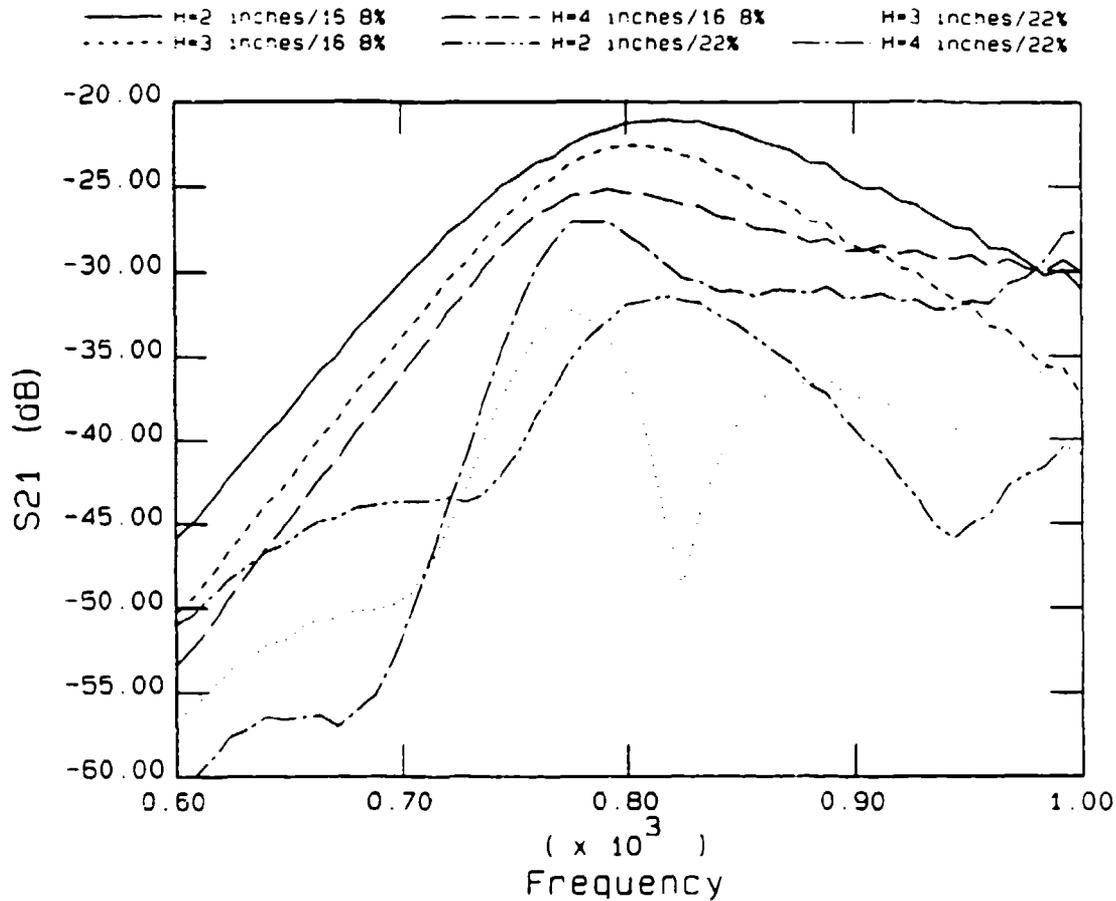


Figure 14. Measurement of transmission coefficient (S_{21}) as a function of frequency using the broadband (NIST) sensor head for various sensor heights (see legend above figure). Measurements were made with the sensor head positioned directly over a (12 x 12 x 3 inch) nylon block buried 6 inches below the loamy soil surface. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. The soil moisture content, before wetting, was 16.8%.

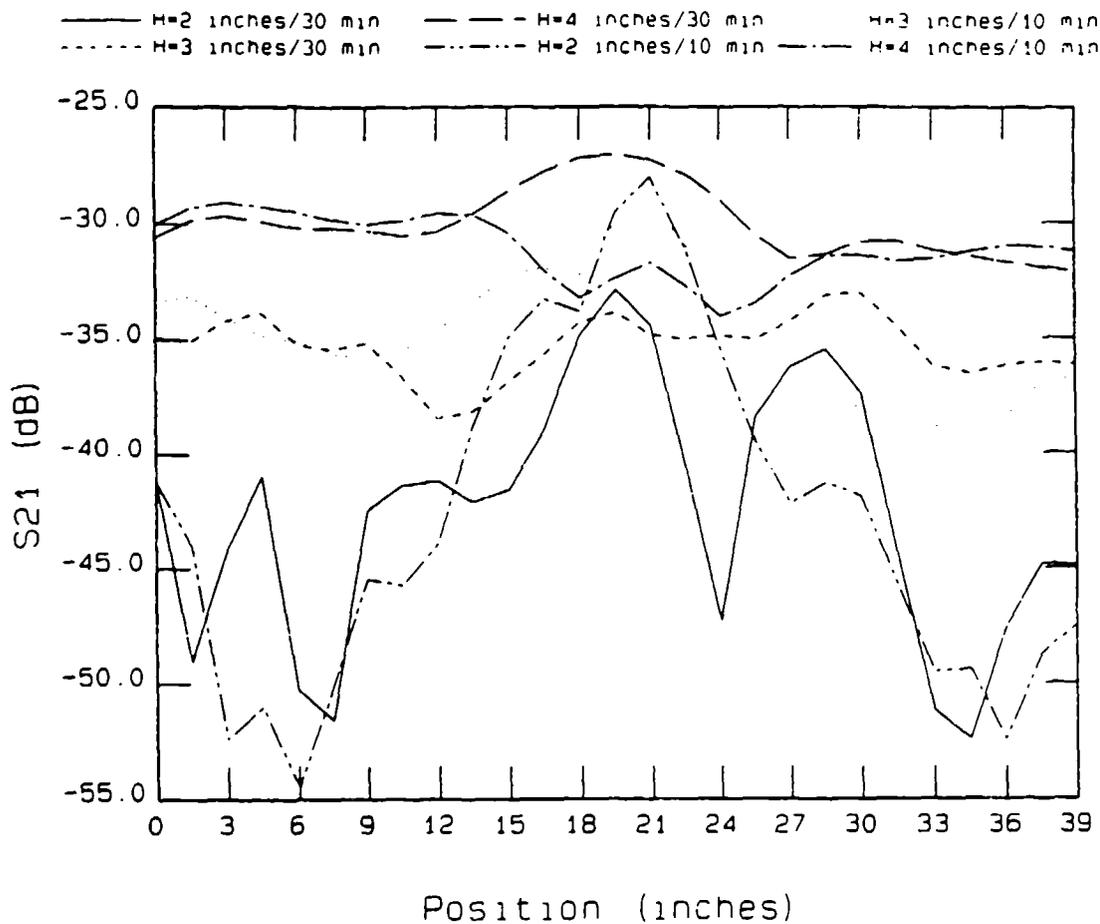


Figure 15. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights and soil moisture conditions (refer to legend above figures) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. The soil was wetted for 10 to 30 minutes resulting in a saturated soil layer with a moisture content of 24.3 to 22% down to a depth of approximately 3 to 6 inches.

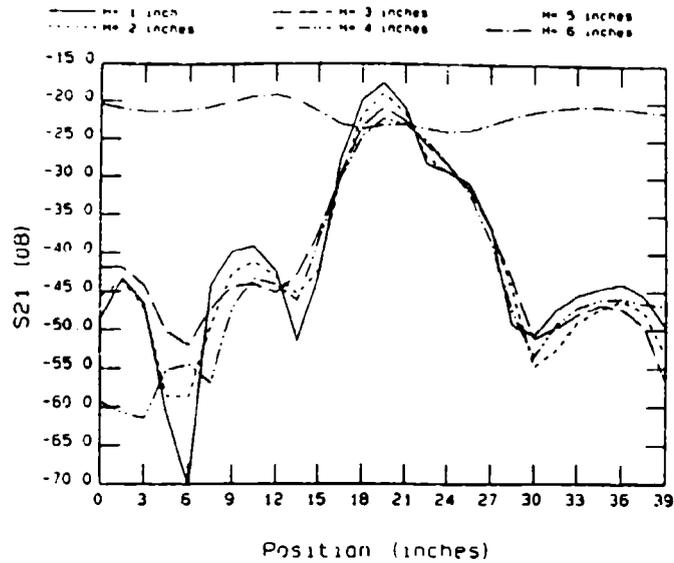
Figures 16 through 19 present results for experiment 3—12 x 12 x 3 inch anomaly buried 3 (not 6) inches deep. Recall that in this experiment the soil was wetted for 30 minutes resulting in a saturated soil layer down to a depth of approximately 6 inches. Figures 16a and 16b give the dry (12.6% moisture) and wet (22% moisture) soil response using the broadband (NIST) sensor. Referring to Figure 16b, with the anomaly buried only 3 inches deep in wet soil, the sensor can readily detect the target for sensor heights up to 4 inches. Recall that with a 6 inch deep anomaly (see Figure 2b), the anomaly was "visible" only when the sensor was within 2 inches of the soil surface. Figure 17 presents data identical to that of Figure 16 except that the printed-circuit sensor is used instead of the broadband sensor. The results given in Figure 17 are remarkably similar to those of Figure 16. Figure 18 shows that for an anomaly depth of 3 inches that there is very little difference in the dry and wet sensor response for sensor heights up to 3 inches. There is some difference between the dry and wet response at the 4 inch sensor height but the anomaly is still easily discernible at this height in the wet soil. Figure 19 gives the frequency response of the printed-circuit (Cubic) and broadband (NIST) sensors for wet and dry conditions when the sensors are positioned directly over the anomaly at a height of 3 inches. The printed-circuit sensor experiences greater attenuation above resonance (790 MHz), due to moisture, than does the broadband sensor.

Figures 20 through 22 give results using the 1 GHz broadband (NIST) sensor head. Figure 20 compares the wet and dry responses, as a function of position, for various sensor heights. At the 3 inch sensor height, the 1 GHz sensor head has trouble "seeing" the anomaly. If this curve (3 inch height, 22% moisture) is compared to the corresponding curve (3 inch height, 22% moisture) of Figure 9, it is seen that the 1 GHz broadband sensor head performs somewhat better than the 790 MHz sensor head. However, if the same comparison is made with the 790 MHz printed-circuit sensor (see Figure 10a, wet response for a sensor height of 3 inches) one observes that the printed-circuit response is superior to the one GHz response. Figure 21 provides a direct comparison of the wet-soil performance of the 1GHz and 790 MHz sensors. Figure 22 gives the frequency response of the 1 GHz sensor head for wet and dry conditions when the sensor is positioned directly over the nylon block. The most obvious and interesting feature of this figure is the null which appears around 1,050 MHz in the 18% moisture curve. A similar feature was observed in the wet 3 inch response of the broadband 790 MHz sensor (see Figure 14).

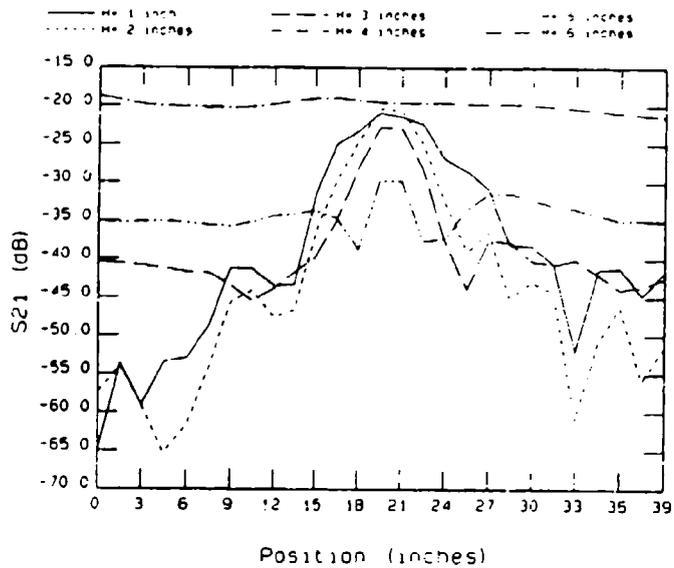
Figure 23 demonstrates the wet-soil performance of the broadband (NIST) sensor at frequencies above and below the dipole resonance frequency of 790 MHz. In fact, Figure 23d is exactly the same as Figure 2b. It was concluded earlier, in reference to Figure 2b, that the anomaly is virtually "invisible" except when the sensor is within 2 inches of the ground. This conclusion was based on the sensor's performance at the dipole resonance frequency of 790 MHz. Figure 23 shows clearly that the sensor "sees" the anomaly better at 600 MHz than at any other frequency over the 600 to 1,000 MHz range. It is quite interesting that the characteristic dip-peak-dip response is visible at 600 MHz (Figure 23a) even when the sensor is positioned 4 inches above the soil surface. (Recall that the soil is very wet.) As the scan frequency increases from 600 MHz (Figure 23a) to 952 MHz (Figure 23f), the sensor performance steadily degrades; Figure 23d shows that at 952 MHz the anomaly is "visible" only for the 1 inch sensor height. This result may, at first, seem somewhat surprising since one might expect optimum performance at 790 MHz, the antenna's resonance frequency. There are several factors which contribute to improved performance at the lower frequencies. First of all, the network analyzer used to make the measurements has excellent dynamic range (100dB) and a low noise figure so that good measurements are possible even at very low frequencies where, due to antenna mismatch, most of the signal incident on the transmit

antenna is reflected back to the source. Secondly, the attenuation of the wave launched by the transmit antenna increases as the frequency increases so that there is some advantage to operating at the lower frequencies. Lastly, because the wavelength is inversely proportional to frequency, the sensor is electrically closer to the ground (for fixed physical sensor height) at the lower operating frequency. All other parameters held fixed, performance generally improves the closer (electrically) the sensor is to the soil surface. As previously stated, the primary objective of this effort is to determine the ability of the separated aperture sensor to detect anomalies buried in wet or moist soils. The results of Figure 23 are extremely important since they demonstrate, unequivocally, that the below-resonance response of the sensor in wet soils is roughly equivalent to the resonance response of the sensor in dry soils.

Another important goal of this research effort was to determine if there are actually any significant performance differences, in wet soils, between the printed-circuit (Cubic) and broadband (NIST) sensor heads. Figure 24 compares the ability of the printed-circuit and broadband sensors to detect the nylon block buried 6 inches deep just after the soil was wetted for 30 minutes (experiment 2). The performance of the sensors are compared at 600, 648, 704, 752, 848, and 952 MHz (recall that the dipole resonance frequency is 790 MHz) while the sensor height is fixed at 3 inches. Overall, the broadband sensor performs better than the printed-circuit sensor, especially at the lower operating frequencies (compare the 600 MHz curves). This result is quite important since, as previously mentioned, the below-resonance response of the sensor is critical for successful detection of anomalies buried deep in wet soils.

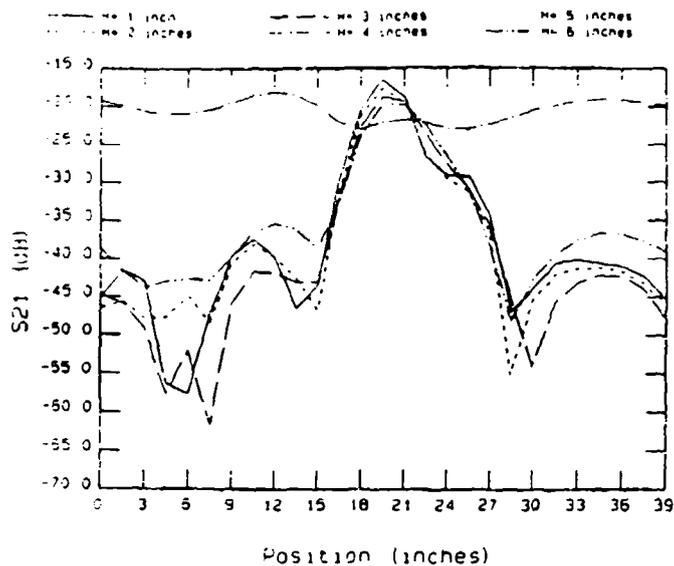


a. Moisture Content = 12.6%

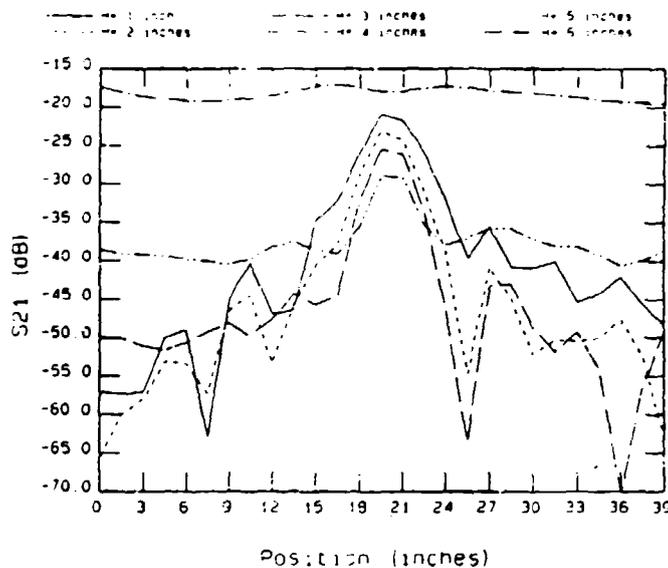


b. Moisture Content = 22%

Figure 16. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights (refer to legend above figures) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 3 inches below the surface of loamy soil. In b, the soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. In a, the ambient soil moisture content, before wetting, was 12.6%.

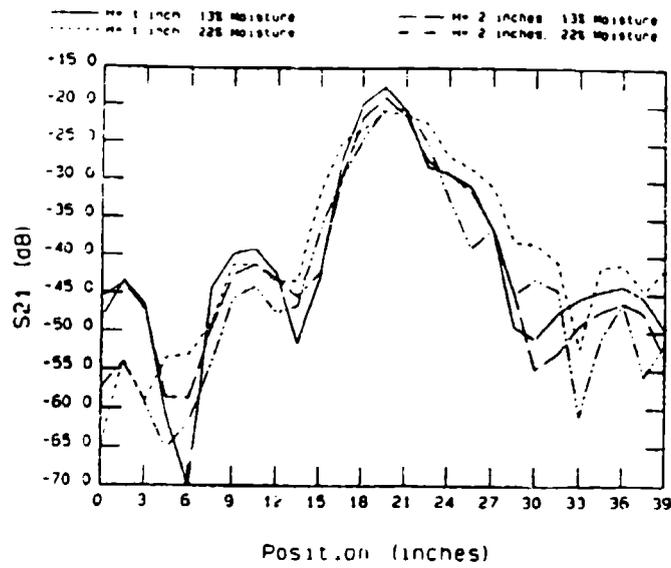


a. Moisture Content = 12.6%

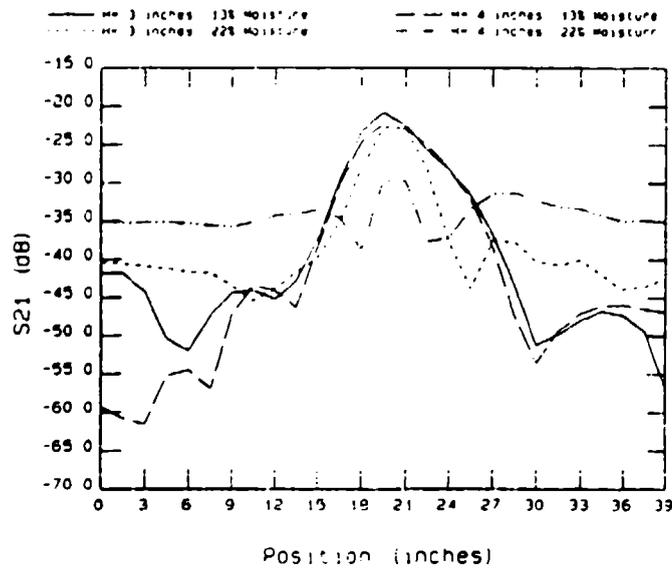


b. Moisture Content = 22%

Figure 17. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights (refer to legend above figures) as the printed-circuit sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 3 inches below the surface of loamy soil. In b, the soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. In a, the ambient soil moisture content, before wetting, was 12.6%.



a.



b.

Figure 18. Measurement of transmission coefficient (S_{21}) at 790 MHz as a function of position for various sensor heights and soil moisture content (refer to legend above figures) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 3 inches below the surface of loamy soil. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. The ambient soil moisture content, before wetting, was approximately 13%.

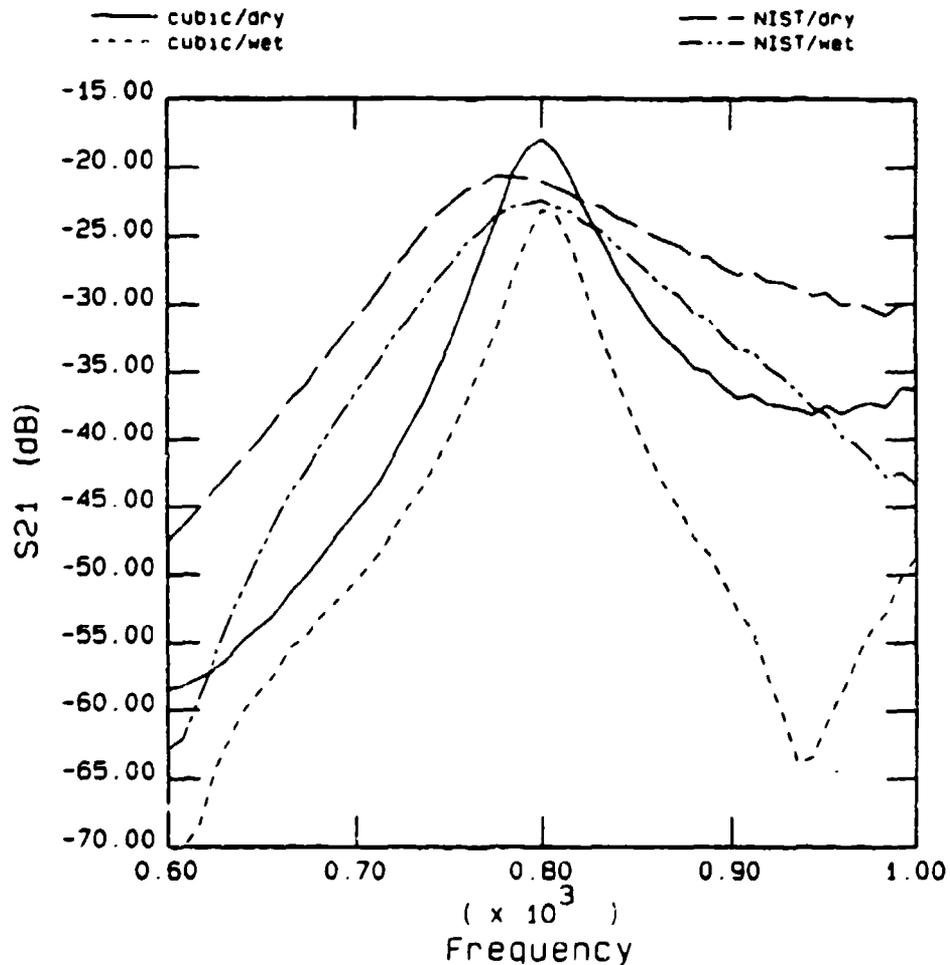
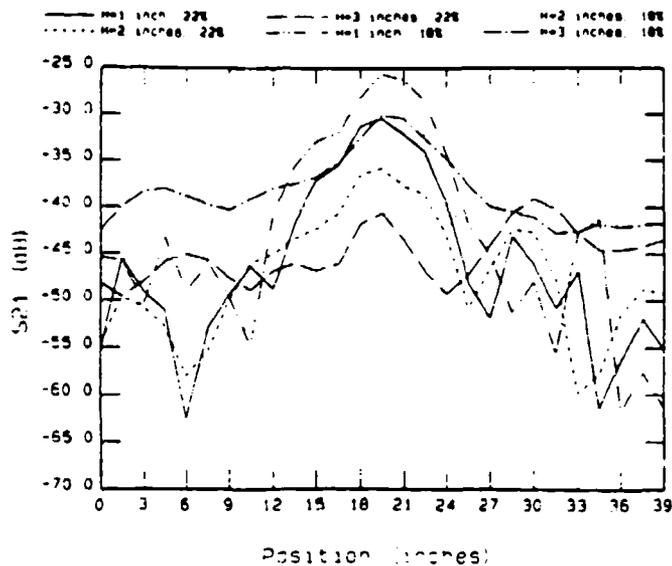
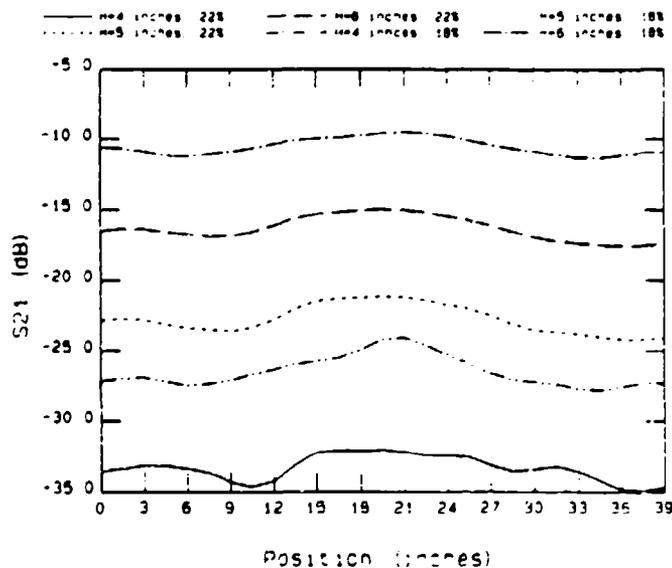


Figure 19. Measurement of transmission coefficient (S_{21}) as a function of frequency using the broadband (NIST) and printed-circuit (cubic) sensor heads (see legend above figure). Measurements were made with the sensor heads 3 inches above the soil surface and positioned directly over a (12 x 12 x 3 inch) nylon block buried 3 inches below the loamy soil surface. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% (curves labeled "wet") down to a depth of approximately 6 inches. Before wetting, the ambient soil moisture content was 12.6% (curves labeled "dry").

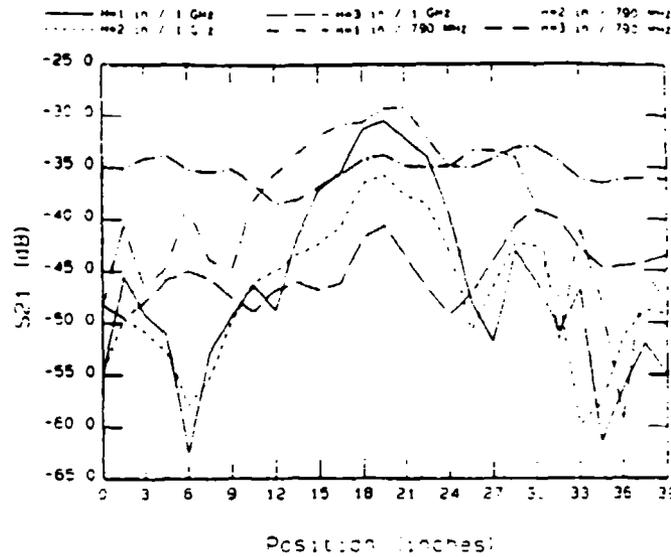


a. $H = 1, 2,$ and 3 inches

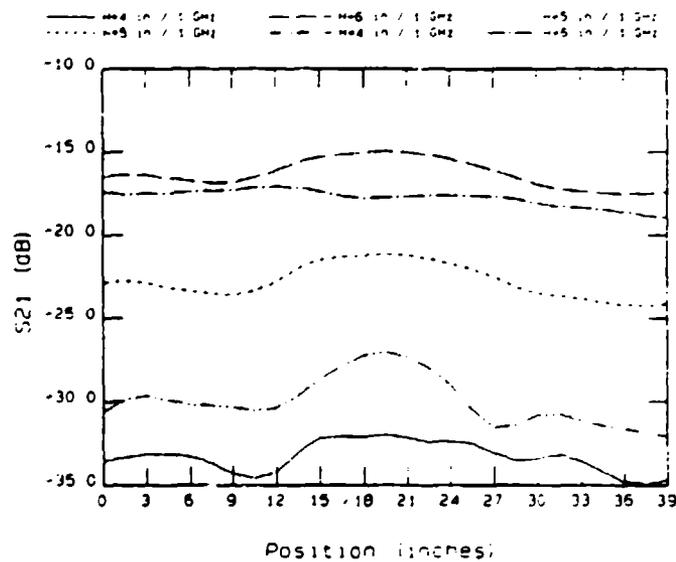


b. $H = 4, 5,$ and 6 inches

Figure 20. Measurement of transmission coefficient (S_{21}) at 1 GHz as a function of position for various sensor heights and soil moisture conditions (refer to legend above figures) as the 1 GHz broadband sensor head is scanned over a nylon block ($12 \times 12 \times 3$ inch) buried 6 inches below the surface of loamy soil. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. Allowing the soil to dry for approximately 48 hours resulted in a soil moisture content of 18%.



a. H = 1, 2, and 3 inches



b. H = 4, 5, and 6 inches

Figure 21. Measurement of transmission coefficient (S_{21}) as a function of position for various sensor heights (see legend above graphs) as the 790 MHz and 1GHz broadband sensor heads are scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. Measurements made with the 1 GHz and 790 MHz broadband sensor heads are compared.

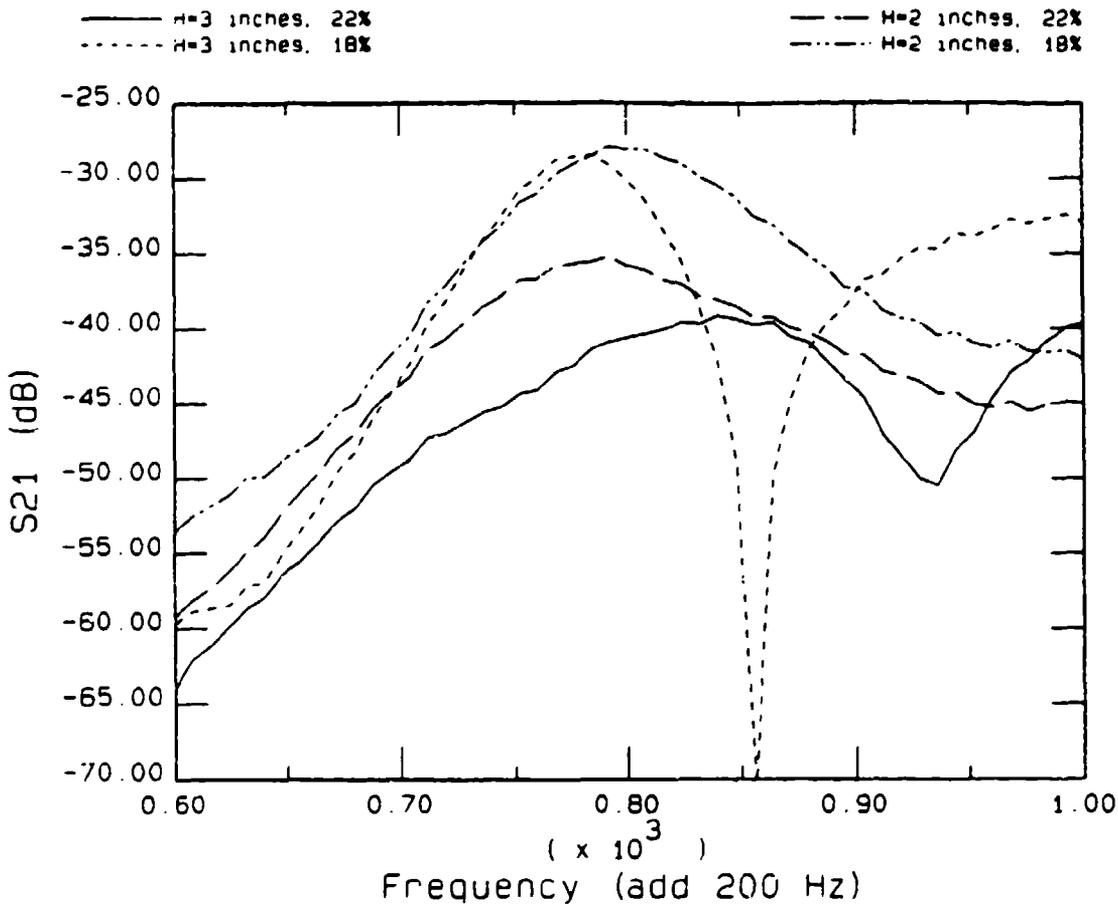


Figure 22. Measurement of transmission coefficient (S_{21}) as a function of frequency using the 1 GHz broadband (NIST) sensor head for various sensor heights and soil moisture contents (see legend above figures). Measurements were made with the sensor head positioned directly over a (12 x 12 x 3 inch) nylon block buried 6 inches below the loamy soil surface. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches. Allowing the soil to dry for approximately 48 hours resulted in a soil moisture content of 18%.

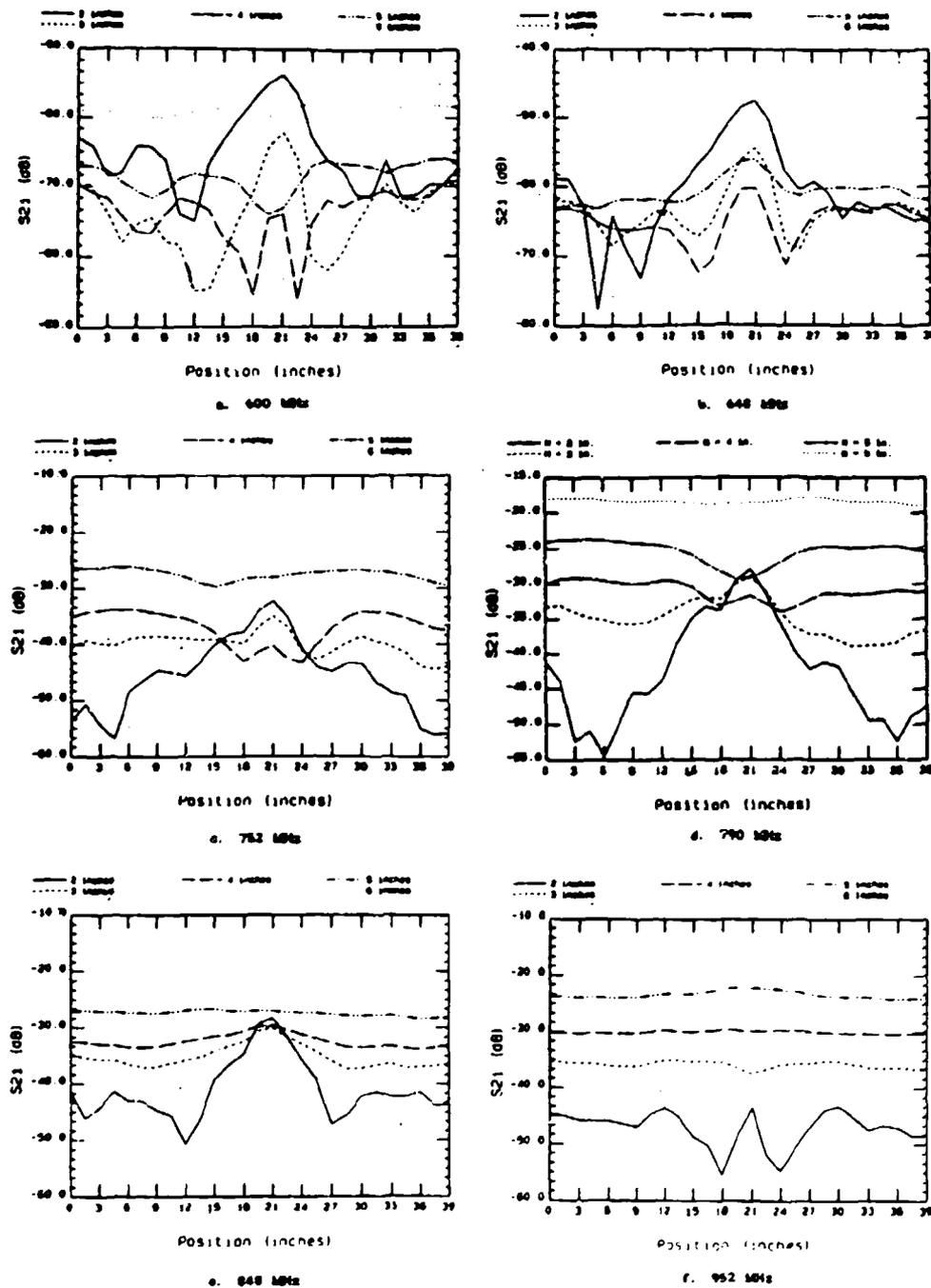


Figure 23. Measurement of transmission coefficient (S_{21}) at: a 600 MHz, b 648 MHz, c 752 MHz, d 790 MHz, e 848 MHz, and f 952 MHz as a function of position for various sensor heights (refer to legend above figures) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of very moist loamy soil. The soil was wetted for 10 minutes resulting in a 3 inch layer of very moist (moisture content = 24.3%) loam (mud).

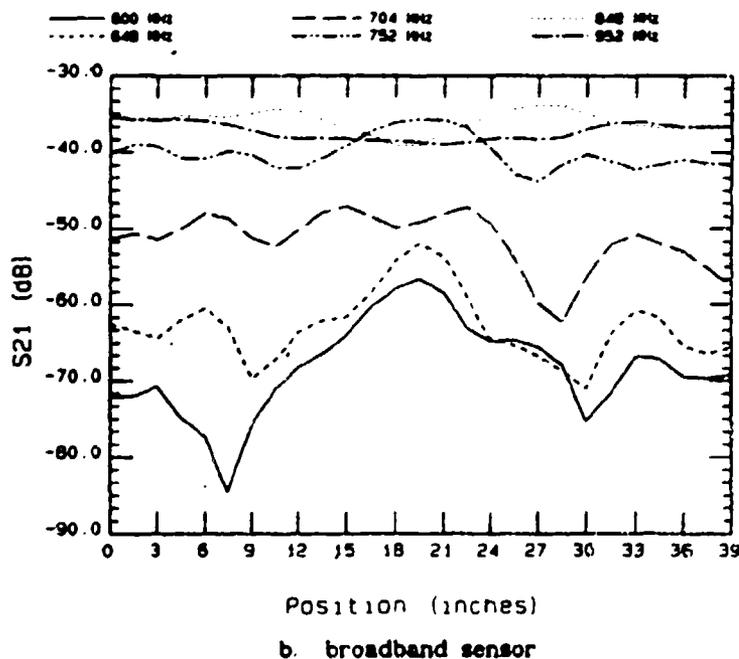
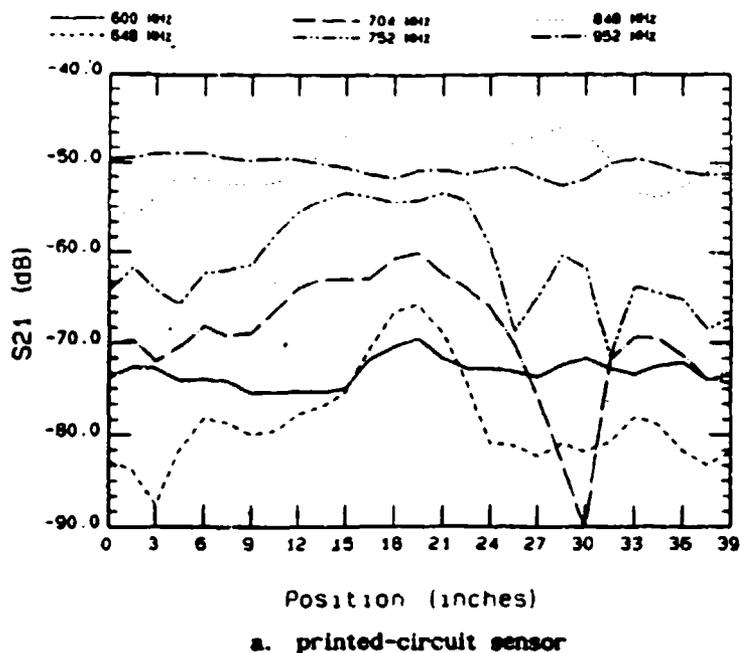


Figure 24. Measurement of transmission coefficient (S_{21}) at various frequencies (refer to legend above figures) as the a printed-circuit (Cubic) sensor head and b broadband (NIST) sensor head is scanned over a nylon block (12 x 12 x 3 inch) buried 6 inches below the surface of loamy soil. All the scans were made at a sensor height of 3 inches. The soil was wetted for 30 minutes resulting in a saturated soil layer with a moisture content of 22% down to a depth of approximately 6 inches.

Section III

Conclusions

The major thrust of this effort was to assess the ability of the separated aperture sensor to detect buried dielectric anomalies under moist or saturated soil conditions. Several important conclusions can be drawn from the experimental data presented in the previous section.

1 Under dry soil conditions, there is very little difference in performance between the narrow-band sensor (also referred to as the printed-circuit, or Cubic sensor) and the broadband (NIST) sensor. According to Report 2497, in dry soils, acceptable performance (the anomaly was "visible") can be expected for anomaly depths up to 6 inches provided the sensor (either broadband or printed-circuit) height does not exceed 3 inches.

2 It was shown (refer to Figure 13) that the resonant frequency of the broadband sensor is a more sensitive function of sensor height than is the narrow-band sensor. For this reason, the narrow-band sensor is preferred over the broadband sensor if the mine detection algorithm is based on the sensor response at resonance, or on a narrow band of frequencies near resonance.

3 When the separated aperture sensor is operated at or near its resonance frequency, it has considerable difficulty detecting dielectric anomalies buried deep in wet or saturated soils, except when the sensor is located very near the surface of the earth. In fact, immediately after wetting the soil, the anomaly is, for all practical purposes, virtually invisible except when the sensor is within 2 inches of the soil surface. (Refer to the results of experiment 1 in the previous section.)

4 The ability of both the broadband and printed-circuit sensors to detect anomalies buried deep in moist or saturated soils improves considerably at frequencies below the resonance frequency of the dipoles. It was shown in the previous section, in reference to experiment 1 (see Figure 23), that the characteristic dip-peak-dip response is visible at 600 MHz (approximately 200 MHz below the resonance frequency of the dipole) even when the sensor is positioned 4 inches above the soil surface. This result is extremely important as it implies that, for robust performance in wet soils, the detection algorithm must incorporate sensor output at frequencies well below resonance.

5 In the previous section, it was shown, in reference to Figure 24 (experiment 2), that the broadband sensor performed better than the printed-circuit sensor at frequencies well below the resonance frequency of the dipoles. Therefore, in moist and saturated soils, the broadband (NIST) sensor is preferred over the printed-circuit sensor.

Section IV

Areas for Further Research

The experimental data discussed in Report 2497, together with the material presented in this report, provide one with a fairly complete understanding of the ability of the 790 MHz sensor head to detect dielectric anomalies buried in wet or dry loam. However, it is important to realize that the conclusions reached so far are only valid for a limited set of parameters. For example, conclusions reached regarding the ability of the 790 MHz sensor head to detect the 12 x 12 x 3 inch nylon block buried in loam would not necessarily apply to the ability of the 790 MHz sensor to detect the 12 x 12 x 3 inch nylon block buried in sand. Furthermore, since the constitutive parameters of the soil and anomaly are typically nonlinear functions of frequency, one should exercise caution when attempting to scale results taken at one frequency to a higher or lower frequency. Nevertheless, the situation is not as bleak as it might at first appear. It is certainly not necessary, and probably not possible, to perform experiments with all possible combinations of the parameters of interest taken into account. Instead, the results obtained to date should be used to judiciously plan future experiments so that maximum information is obtained with minimal experimental effort.

Most of the experiments conducted to date have been directed toward understanding the capabilities and limitations of the separated aperture sensor as an anti-vehicular mine detector. Unfortunately, as discussed above, these results do not scale to higher frequencies. Therefore, some additional experimentation will be necessary to determine the optimum sensor geometry, operating bandwidth, etc., for detection of smaller antipersonnel mines. Again, the lessons learned to date can, and should, be used to limit the number of experiments necessary to evaluate the capability of the separated aperture sensor as a hand-held antipersonnel mine detector.

The wet soil experiments showed that when using the 790 MHz sensor head, the mine was far more "visible" at 600 MHz than at the resonance frequency of the dipole (790 MHz). This result is somewhat surprising, and seems to imply that in wet soils improved performance could be obtained if the resonance frequency of the dipole were lowered to 600 MHz while keeping the geometry of the sensor head fixed. Loading the dipole is one possible way of lowering its resonance frequency.

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