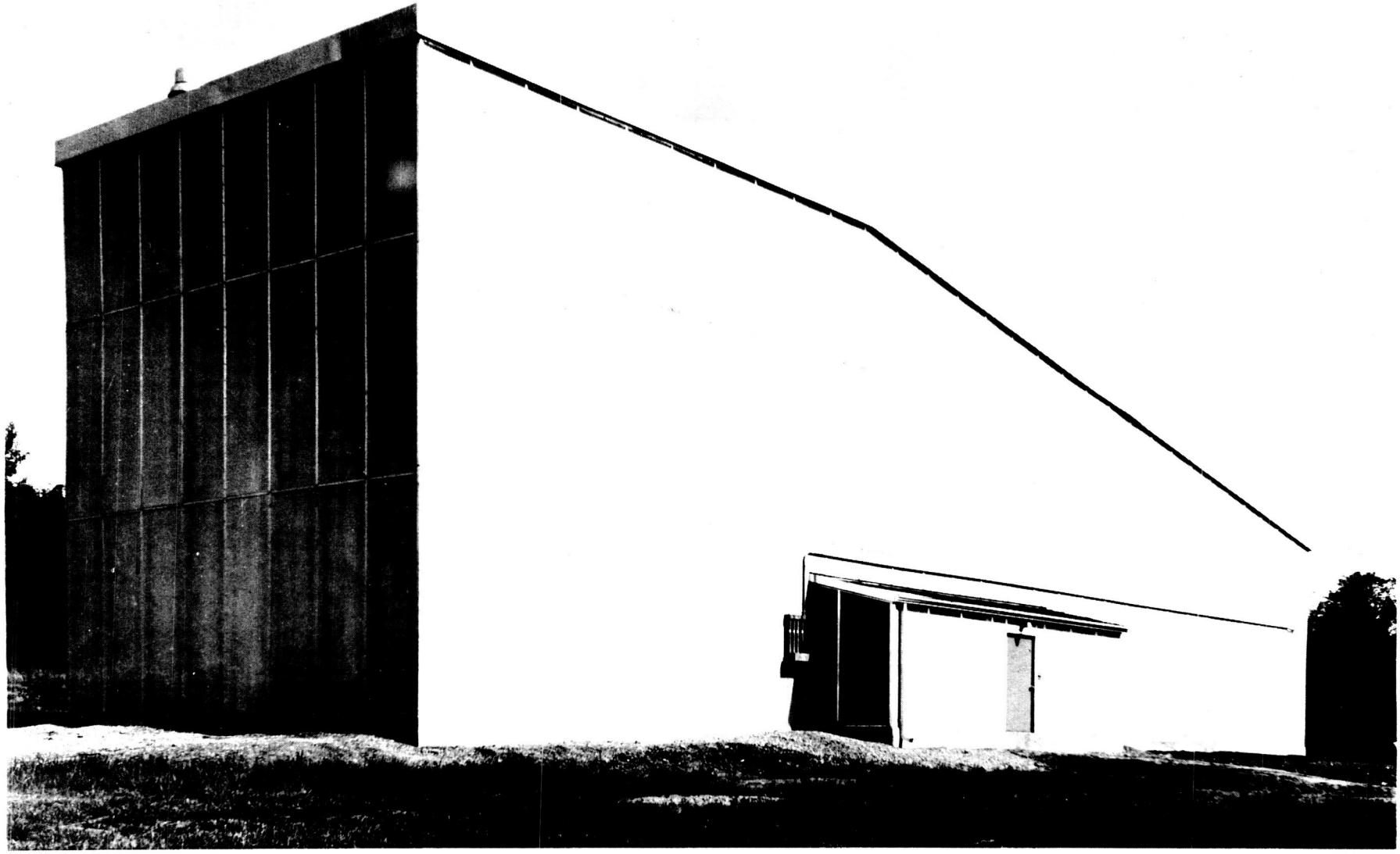
"Measurement of the B. F. Goodrich Tapered Chamber at the Marshall Space Flight Center"

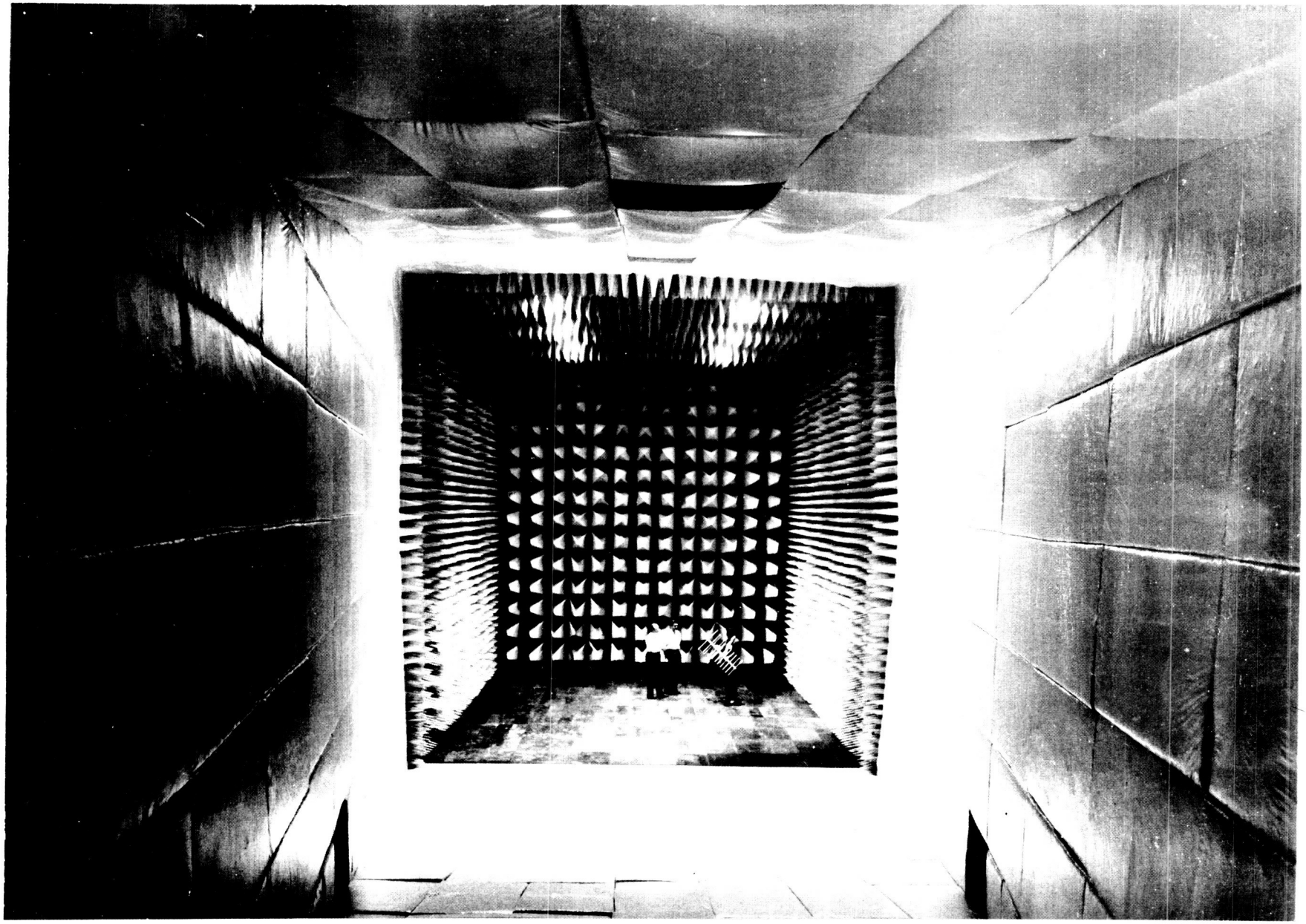
A Report to the
Marshall Space Flight Center
B. F. Goodrich Report MR-27

The B. F. Goodrich Company
Sponge Products Division
Microwave Department
Shelton, Connecticut

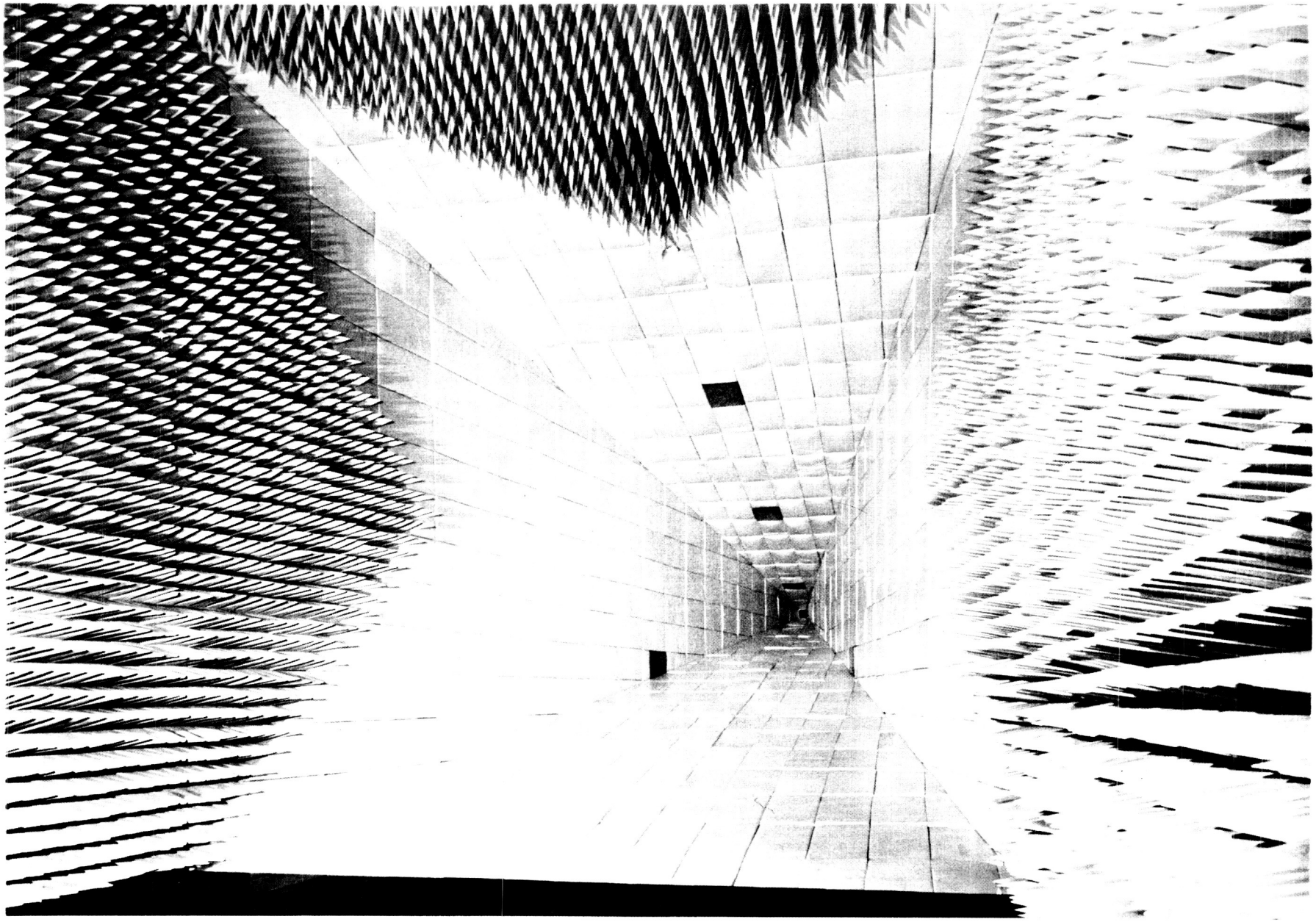
June 30, 1965



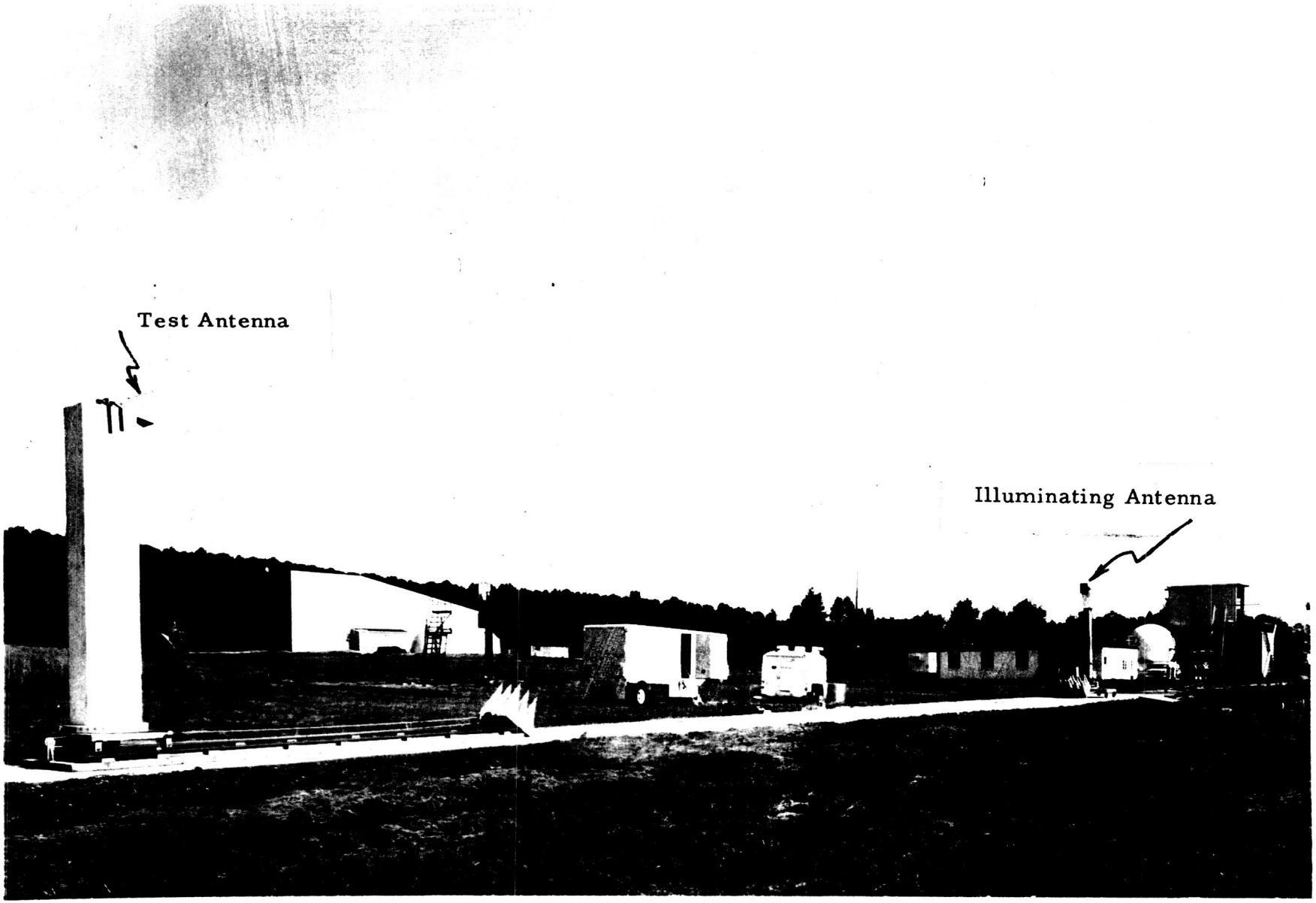
Building provided by B. F. Goodrich to contain chamber. Note how roof follows slope of taper. Use of rectangular floor plan allows large laboratory/control room to be located within building on one side of taper with utility room on other side. Equipment and storage room occupies space beneath taper.



Internal view looking from small end of tapered region toward spacious 30 x 30 x 40 ft test region. Huge 70 inch thick pyramidal absorber (VHP-70) covers back wall. 26 inch thick material covers side walls, floor and ceiling of test region. Quiet zone is especially wide and reflection-free as consequence of chosen design.



View of illuminating end of chamber showing horn shaped geometry. Chamber is driven by source antenna located near taper apex. Source antenna may be any convenient type and size (including dipole or open waveguide). Series of doors along side of taper provide access for source antennas.



Outdoor range showing new chamber in background. In foreground is "reflectionless" traverse mechanism in process of measuring reflection properties of outdoor range under conditions identical to those used within chamber. Severe reflections were encountered from ground and from trees at edge of range. Chamber was measured to be orders of magnitude better.

SUMMARY

A contract was awarded to the B.F. Goodrich Company by the National Aeronautics and Space Administration for supply of a 120 foot long state-of-the-art anechoic facility to be built on a NASA provided outdoor slab at the Marshall Space Flight Center, Huntsville, Alabama. It was specified that the anechoic chamber "improve the accuracy and quality of radiation patterns to a degree that has not been obtained here-to-fore" over the frequency range of .25 to 100 GHz. and that it be shielded to 80 db. It was further specified that the building be capable of disassembly/reassembly and include air conditioning.

The building provided by the B.F. Goodrich Company was constructed of structural steel frame work to which laminated asbestos cement-fiber panels were mounted. Shielding was achieved using soldered copper foil.

The new B.F. Goodrich "tapered chamber[1] design was used in conjunction with B.F. Goodrich pyramid shaped[2] VHP type absorbing material in view of the requirement for a chamber of exceptional performance. This novel design employs a chamber in the shape of a huge pyramidal horn instead of the conventional rectangular shape. It has been established that the "tapered" design when properly carried out offers significant advantage over the conventional chamber both with respect to width of quiet zone and level of reflectivity. Such improvement is achieved because the diverging geometry of this new design effectively prevents occurrence of the usual specular reflections from side walls, floor, and ceiling.

Liberal use was made in the chamber of the B.F. Goodrich VHP (Very High Performance) type absorber. A 70 inch thick version (VHP-70) was used on the entire back wall and a 26 inch version along the test region.

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[1] U.S. and Foreign Patents Applied For

[2] U.S. Patent 2,464,006

The anechoic performance of the completed facility was measured by the B.F. Goodrich Company at 7 frequencies between 65 MHz and 10 GHz. using the "Free Space VSWR" measurement technique. Comparison of this data with that from other chambers confirmed achievement of performance at the state-of-the-art. These measurements indicated that this chamber may be relied upon to provide antenna and reflectivity patterns that will have error of 1 db or less at the 40 db down level from S-Band up, and less than 1 db error at the 20 db down level to as low as 220 MHz.

Additional measurements were made to allow for an interesting comparison of reflection levels on the adjacent outdoor antenna range with those of the new chamber. Identical measurement conditions were used with the same antennas, same antenna heights, and same path length. Reflections were found to be a number of orders of magnitude poorer on the outdoor range. Reflection sources (listed in order of severity) were identified as the ground, the trees beyond the range, and a nearby equipment van.

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SECTION I - PERFORMANCE REQUIREMENTS

Specifications pertaining to NASA contract NAS8-13125 for an anechoic chamber required electrical performance as follows:

A. Anechoic Performance

1. A -40 db quiet zone over the frequency range of .25 to 100 GHz. when illuminated with a 15 db gain source antenna at 100 ft. path distance. Quiet zone dimensions to be 12 ft. diameter and 25 ft. length.

2. A -50 db quiet zone over the frequency range of 1.0 to 100 GHz. when illuminated with a 25 db gain source antenna at 100 ft. path distance. Quiet zone dimensions to be 10 ft. diameter and 20 ft. length.

3. A -60 db quiet zone over the frequency range of 2.0 to 30 GHz. when illuminated with a 25 db gain source antenna at 100 ft. path distance. Quiet zone dimensions to be 10 ft. diameter and 20 ft. length.

The specified value for quiet zone reflectivity represents the minimum acceptable performance. This performance is specifically defined as follows: "The level of reflected energy arriving at any point within the quiet zone from any and all directions will be at least the specified number of db below the level of direct energy."

B. Shielding Performance

A -80 db insertion loss to plan waves over the frequency range of .25 to 10 GHz.

SECTION 2 - DESIGN OF THE CHAMBER

A. Anechoic Considerations

In view of the specified NASA requirement for a state-of-the art facility, the B. F. Goodrich Company proposed on the basis of a chamber using the new "tapered" design. Instead of the conventional rectangular shape, this design utilizes a chamber in the shape of a huge pyramidal horn that varies from a small cross section at the illumination end to a large cubical shaped test region containing the quiet zone. Detailed study of a number of recently installed chambers of this type has provided extensive evidence showing that this novel design provides significant improvement over prior art.

1. Background on the "Tapered" Design

This new chamber concept evolved out of in-house B. F. Goodrich supported R & D on the problems of rectangular chambers at low frequencies. Our work along these lines had been instigated after increasing use of the newer measurement techniques based on a moving probe had revealed that even the best chambers of the day exhibited severe periodic amplitude variations and severe phase deviations across the quiet zone at lower frequencies. The measurement techniques commonly employed at that time (based on a comparison of antenna patterns) had not been well suited to revealing this problem. The problem was considered severe since these periodic variations were commonly in the range of 1 to 7 db in amplitude at VHF-UHF frequencies. Phase was likely to vary by much more than the $\lambda/8$ commonly allowed at far field distance. Chambers showing such deviations from the uniform conditions of "free space" could not be expected to provide antenna and backscatter patterns that were typical of those desired for "free space".

Our initial effort established that these periodic amplitude variations were attributable to relatively high levels of reflected energy that arrived in the test region after direct reflection from the side walls, floor, and ceiling. Through angle of arrival measurements it was established that these reflections were predominantly of a specular rather than non specular nature, i.e., the angle of reflection equalled the angle of incidence. It was further established that these reflections were more severe at lower frequencies primarily for the following reasons:

1. As frequency is decreased it becomes increasingly difficult to achieve adequate absorption out at the wide angles of incidence (commonly 60 to 70 degrees from normal) at which energy illuminates the side walls, floor, and ceiling in a typical rectangular chamber and

2. As frequency is decreased it becomes increasingly difficult to use source antennas with sufficient directivity to minimize direct illumination of these surfaces.

The B. F. Goodrich R & D program approached this problem from three different directions:

a. Through attempts to design broad band absorbing materials having optimum or improved performance at wide angles of incidence.

b. Through attempts to find ways in which to "baffle" these surfaces for reduced reflection over wide frequency ranges.

c. Through attempts to find new basic chamber designs.

Suffice it to say that solution to the problem was not be be found from extensive and intensive work in the areas of baffles and special materials. From the work on basic designs came a number of interesting new ideas, the most applicable of which was the concept of "tapered" chamber.

2. Characteristics of a Chamber to the Tapered Design

At the present time tapered chambers are better known in terms of their measured properties than their basic theoretical phenomona. In excess of 2,000 man hours of measurement and experimentation on

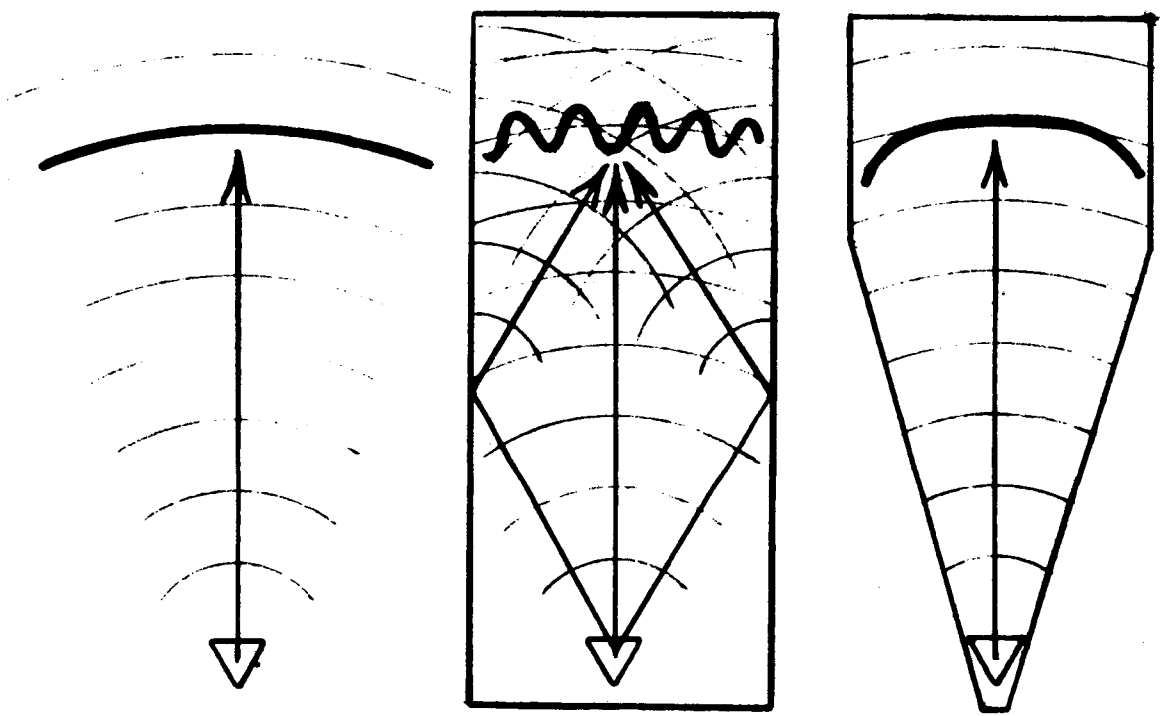
both scale model and actual chambers has provided the B. F. Goodrich Company with a clear view of the requirements for optimum performance and avoidance of problems. It is now well documented that tapered chambers are characterized as follows:

A.) A well designed tapered chamber exhibits an especially wide test region of uniform amplitude and phase. The amplitude distribution may be so broad as to be down only a few db near the walls of the chamber. Phase is generally within 10 degrees of that expected for "free space" over a width greater than half the chamber. Periodic amplitude variations such as characterize the quiet zone of a conventional chamber are completely absent.

The diagram of Figure 2.1 shows a comparison of the fields found across the test region for three pertinent cases. It is evident in the diagram for the rectangular chamber that this geometry allows specular reflection to take place directly from the side walls, floor, and ceiling into the test region. The direct illumination field in the test region is thus contaminated by the presence of four undesired signals arriving from each of these four surfaces. The observed periodicity is attributable to the fact that probe motion causes these vectors to rotate with respect to each other.

On the other hand, the diagram for the tapered chamber has been drawn to show no reflection from the adjacent sloping walls. This appears to well represent the actual condition since probing the test region of a well designed tapered chamber generally reveals a complete absence of cyclic variations. The amplitude distribution in the central region of the chamber is found to closely follow the smooth uniform field expected for free space. The reason for this phenomona appears related to the fact that this diverging geometry causes energy near the absorbing walls to propagate in a direction parallel to the walls rather than at an angle to them such as would allow specular reflections to take place. Propagation in the vicinity of the absorbing walls of the taper thus appears similar to ground wave propagation over lossy earth as experienced at low frequencies. The observed decrease in field amplitude near the walls of a tapered chamber is explained on the basis of absorption attributable to a component of the Poynting vector into the dissipative wall covering material.

B.) A second characterizing feature is that a well designed tapered chamber exhibits a test region that has a significantly lower



a) Free Space

b) Rectangular Chamber

c) Tapered Chamber

Figure 2.1 - Comparison of field amplitude across test region for three cases of interest.

Figure 2.1

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level of reflected energy than a chamber to the conventional design. This improvement is directly and simply attributable to the fact that a tapered chamber effectively avoids the previously described specular reflections from side walls, floor, and ceiling.

Elimination of this source of reflection allows antenna and cross section patterns to be measured with improved accuracy. The improvement is greatest for forward aspect angles where reflections from the walls of a conventional chamber are generally most severe. It is fortunate that the tapered design offers greatest improvement for forward aspect angles since this angle range is most important for a number of common measurements such as gain, beamwidth, boresight, depth of first null, height of first side lobe, etc.

C.) A third feature characterizing the tapered design is that the two previously considered advantages (wide field uniformity and low reflection level) are available even with source antennas of very low directivity. It turns out that the level of reflected energy in a tapered chamber is essentially independent of directivity of the antenna used to drive the taper.

The above is in sharp conflict with the conventional design where the level of undesired energy arriving in the test region after reflection from the side walls, floor, and ceiling is a direct function of level of energy illuminating these surfaces. With a rectangular chamber conditions are encountered where one may have a choice of either a wide test region or a low reflection level depending upon the chosen source directivity. A broad beamed antenna can provide a wide test region but at the expense of high level wall illumination which can lead to significant pattern error. A source antenna of narrow beamwidth may effectively reduce wall reflected energy but at the expense of pattern error from too severe an amplitude distribution across an antenna under measurement. At low frequencies it becomes difficult to practice to acquire sufficient source directivity to restrict illumination of these wall surfaces.

Since in a tapered chamber the level of reflected energy in the test region is essentially independent of source directivity, a unique opportunity is here presented to use broad illumination to acquire the advantage of wide field uniformity without the usual disadvantage of poorer reflection level.

With respect to practical illumination of a tapered chamber, it is of interest to note that chamber performance is also essentially independent of the type of source antenna. What appears to be important is that the taper be driven by an area source that provides illumination over an area bounded by the four absorbing walls at any convenient point at the small end of the taper. In practice this is readily achieved by mounting almost any antenna type in the taper at a point where the physical size of the antenna approximates the cross section area of the taper at that point. As long as this condition is met, the test region of a tapered chamber shows essentially no difference when driven by any one of a number of common antenna types such as a dipole, a dipole with reflector, an open end waveguide, a waveguide to coax adapter, a corner reflector, a horn, a log periodic (within factor of 3 of low frequency limit), a parabola, or a yagi. Tapered chambers have been used in practice with each of these types. The choice of source antenna thus resolves into a matter of preference and convenience. It is well to bear in mind, however, that performance typical of a tapered chamber is not achieved if an antenna is located at a point where the taper cross section area is appreciably larger than the driving antenna. Under this condition, as in the conventional chamber, specular reflection can take place directly from the taper walls into the test region. It appears that in practice there should be a gap of less than a wavelength between the driving antenna and the absorbing walls.

It is hoped that the tapered concept will soon be as well known in terms of basic theoretical phenomona as it is in terms of the measured properties described above.

3. Status of the Tapered Design

It has now been over a year since the first tapered chamber was installed by the B. F. Goodrich Company. The interim has provided opportunity for this concept to be thoroughly investigated experimentally and well judged. This experience provides the following observation on a comparison of the tapered with the conventional design:

"The tapered design provides advantage over the rectangular design when a chamber is to be used at or below frequencies where it becomes difficult to adequately handle reflections from side walls, floor, and ceiling through the combination of source antenna directivity and absorber quality."

It currently appears that this transition frequency is roughly in the range of 1000 MHz for chambers with typical ratios of length to width. At higher frequencies source antenna directivity and absorbent materials with low reflection coefficient at wide incidence angles can usually reduce reflections from these surfaces to the point where an appropriate test region is offered for high accuracy measurements. At frequencies below 1000 MHz, source directivity and absorber performance are generally unable to adequately reduce reflections from these surfaces and it is here that the tapered design offers clear advantage. It is to be noted that the above conclusions apply equally well whether the patterns in question are antenna patterns or radar cross section patterns since both are affected in the same manner by reflections from these surfaces.

The rapidity with which this new idea has been accepted may be judged by the fact that the B. F. Goodrich Company has now provided tapered chambers of this proprietary design to the following organizations: McDonnell Aircraft (two), Wheeler Laboratory, Naval Research Laboratory, Bunker-Ramo Corporation, Langley Research Center, Space Technology Labs., Marshall Space Flight Center, Manned Spacecraft Center, University of Michigan Radiation Laboratory, Bell Telephone Laboratories, Gilfillan Corporation, Sylvania EDL, Dalmo-Victor Corporation, American Electronics Lab., ITT Kellogg, and General Electric. It is significant that a number of these are quite large in size with the five largest having overall lengths of 156 feet, 120 feet, 110 feet, 94 feet, and 90 feet.

4. Details of the Design of this Chamber

The 120 foot length available for this chamber was divided into an 80 foot length for the taper and 40 foot length for the test region. While the relative length of these two regions is largely a matter of preference, the break was here made at these dimensions to provide a spacious 30 x 40 x 30 foot test region at the large end of the chamber. The taper was made to decrease linearly in dimensions from the test region to a point where the cross section within the four walls reached zero. By tapering down to a point, opportunity is presented to appropriately mount source antennas of all sizes including those that might be very small. Access to within the small end of the taper for mounting these antennas is provided by a series of five doors of varying size. Antennas as large as 9 foot in width may be brought into the taper region through the largest of the doors provided.

Further design from the performance aspect is concerned mainly with the determination of appropriate absorbent materials and the extent of the surface to be covered by various absorber types.

In this regard the NASA specifications state as follows: "The chamber shall be constructed using premium absorber in the area of the model tower. This absorber shall be the best available absorber that has been developed to date." In view of this the B. F. Goodrich Company specified use of a 70 inch thick version of the VHP (Very High Performance) absorber, i.e., VHP-70 on the entire back wall. This region behind the antenna or object under test is the most sensitive for either antenna or backscatter pattern measurement and hence is most demanding of absorber quality.

This absorber is customarily measured at a minimum of three frequencies to establish effective qulity control and compliance with published commercial specifications which appear in the following table:

Table 2.1 - Minimum Normal Incidence Reflection Coefficient

	Absorber Type	
Frequency	VHP-70	VHP-26
120 MHz.	30 db	
200 MHz.	35 db	
300 MHz.	40 db	30 db
500 MHz.	45 db	35 db
L Band	50 db	40 db
S Band	50 db	50 db

In order to insure that the reflection level in the test region would not exceed the specified db value, it was necessary to cover the back wall of the chamber with an absorber having a normal incidence reflection coefficient at least equal to this number of db. This will seem reasonable if the reflection coefficient is thought of in terms of its actual meaning, i.e., the ratio of reflected to incident voltage. Thus covering the back wall with a material of this reflection coefficient will insure that the region in front of this wall will have at least this large a db ratio of wall reflected to direct energy.

This presented a small conflict in the design of this chamber since the specifications here call for a 40 db quiet zone to as low as 250 MHz. and the VHP-70 absorber normally provides 40 db down to 300 MHz. This was handled by making a special version of the VHP-70 where the composition was optimized at 250 MHz. This proved effective and each piece used in the chamber was established as having a reflection coefficient in excess of 40 db at the lower frequency in addition to meeting the commercial specifications.

A thinner version of this same material, i.e., VHP-26, was used on the side walls and ceiling of the test region. Experience had shown that this choice was appropriate in view of the specified performance limits for the chamber. The commercial specifications on this material are also shown in Table 2.1. A wedge shaped transition region was used to avoid reflection from the interface with the different absorber at mouth of the taper.

The entire 30 x 40 foot floor region was covered with B. F. Goodrich PD-22 absorber which is a 22 inch thick rigid structural absorber designed for weight loading to 1,000 pounds per square foot. It has a semi-resilient vinyl foam layer on the outer surface to combine durability and ease of cleaning with low reflection properties.

The entire surface of the tapered region is covered with a special absorber, THV-14, (Tapered Horn, Vinyl covered, 14 inches thick) having characteristics well suited to the special electrical requirements for this region.

All vent duct openings were covered with the CV-26 absorber (Chamber Vent type, 26 inches thick). This is a special version of the VHP material that is made with a very open porous foam to impose negligible pressure drop on the system.

B. Shielding Considerations

The shielding requirement of 80 db isolation from .25 to 10 GHz. with absorber installed was sufficiently lenient as to allow consideration of solutions somewhat less expensive than those required to provide 100 db isolation. As a consequence, the B. F. Goodrich Company put the shielding out for bid to a number of shielding contractors without restriction on the type of shielding construction.

A subcontract for the shielding was subsequently awarded the Amerind Corporation of Royersford, Pennsylvania who proposed on the basis of a soldered foil system. This company used the following procedure: 1 oz. copper foil was adhered directly to the plywood inner surface of the structure. Copper staples were used to provide additional holding security. An rf tight assembly was achieved by soft soldering all seams between adjacent foil pieces and over all staple heads. Protection was given to vent openings with typical honeycomb filter material. All incoming electrical lines were appropriately filtered. A standard shielded door was employed.

A subcontract was awarded to Grobowski and Associates, Washington, D.C., for measurement of the shielding effectiveness prior to installation of the absorbent material. Measurements made at 10 gc. using procedures of MIL-STD-285 confirmed achievement of isolation in excess of that specified for the chamber. It seems likely that after installation of the dissipative absorbent material the chamber will provide above 100 db isolation over the specified range.

C. Construction Considerations

A subcontract was awarded to the A & E firm of Westcott and Mapes, New Haven, Connecticut for design of the entire building which was to rest on a NASA provided outdoor slab.

Subcontract for construction of the entire facility was awarded to Brice Building Company Incorporated, Birmingham, Alabama.

A free standing, self supporting, weather proof building was provided to house the anechoic chamber. The building is unique in that the entire structure is capable of being disassembled and reerected at another location (as specified). Bolts and other fastening devices were employed for attachment of all structural components.

The exterior structure consists of structural steel framing, steel roof decking, cemestos curtain wall panels, and built-up roofing. The interior chamber walls and ceiling were framed with wood studs and joists, and covered with 1/2" plywood to provide a smooth lining for the absorbent material installation. Heating, air conditioning, and insulation were supplied to keep temperatures between 70 and 80 degrees F with outdoor ambient temperatures from 0 to 105 degrees F.

Electrical power to serve present needs and further equipment demands was provided.

An outline drawing of the facility is shown in Figure 2.2.

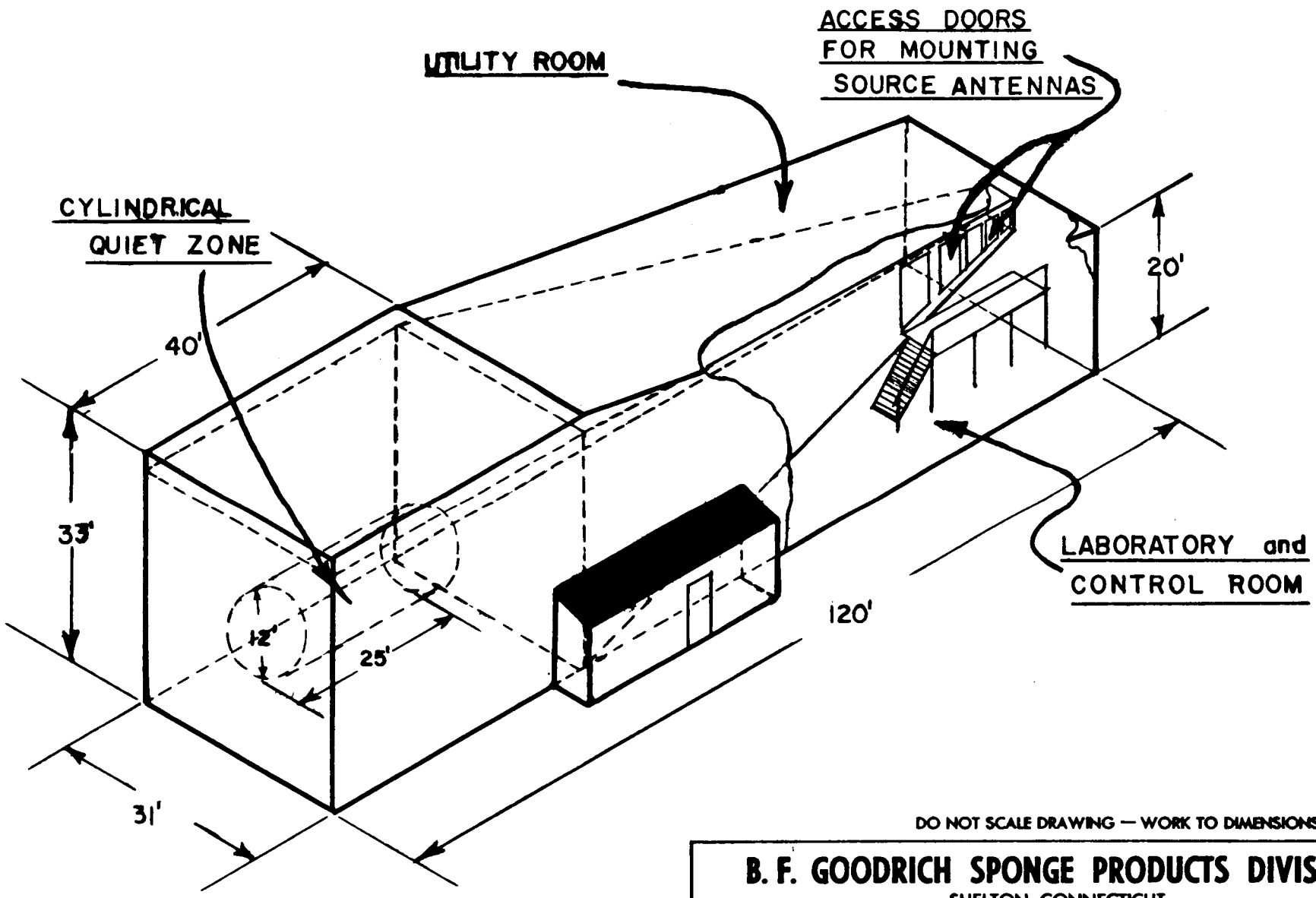

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FIGURE 2.2

Figure 2.2

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SECTION 3- DESCRIPTION OF MEASUREMENTS

For background in the subject of measurement of both chambers and absorbers, reference is made to the University of Michigan Report 5391-1-F entitled "A Study of VHP Absorbers and Anechoic Rooms" by R. E. Hiatt, E. F. Knott, and T.B.A. Senior. This excellent treatment of the subject was brought into being for the National Aeronautics and Space Administration. It is frequently referenced as a standard for measurement procedures in the absence of MIL. Specs. for this field.

A. The B.F. Goodrich "Free Space VSWR" Technique of Chamber Measurement

1. Generalities

As the name implies, this new method may be thought of as the free space analogy to the familiar measurement of the real part of the reflection coefficient of a load on a transmission line from the measurement of VSWR in a slotted section. For chamber measurement, the transmission line is represented by free space, the probe is represented by a test antenna and the load is represented by the portion of the chamber that is illuminated by the test antenna. It is apparent that movement of a probe in a perfect chamber would reveal only a monotonic variation of amplitude. In an imperfect chamber, however, periodic variations of amplitude are encountered as a result of the standing waves set up by finite reflections from the chamber surfaces. The magnitude of reflected energy appearing at the test antenna is a function of the magnitude of the encountered VSWR.

In slotted line work probe motion is possible only along the direction of propagation whereas in free space probe motion may be in any direction. This additional factor can be used to advantage in two ways: 1.) by moving the probe in particular directions the contribution of certain regions may be kept in essentially constant phase relationship thus allowing the contribution from other regions to be studied and independently measured, and 2.) by measuring the distance required for movement to complete one cycle of the periodic variation (and comparing this to the free space wavelength), the angle of movement with respect to the standing wave pattern may be determined. The ability of this method to thus reveal the angle of arrival as well as magnitude of reflected energy is quite useful in determining the importance of various regions within the chamber.

While in principle this basic technique appears well suited to use with omni directional probe antennas, certain disadvantages are encountered in practice. These are 1.) lack of adequate sensitivity. It becomes difficult to accurately measure VSWRs of less than a few tenths of a db which limits accurate measurement of chamber reflections with this type of probe to about -40 db., 2.) error from the probe cable. Reflections from the cable feeding an omni directional antenna are likely to be greater than those from a well designed chamber and 3.) an omni directional antenna receives reflections similtaneously from all parts of the chamber. The recorded amplitude distribution becomes complex in the presence of numerous vectors and cannot be analyzed by simple techniques.

These disadvantages are avoided by using a directional probe antenna and recording data with the antenna orientated in an adequate number of discrete directions. The "Free Space VSWR" method of measurement specifically involves probing the test region with the test antenna oriented at every 10 degree step in aspect angle. This method thus provides a separate value for the level of reflected energy arriving in the test region from 20 different directions. A plot of such data provides a useful description of the chamber in terms of reflection vs antenna aspect angle. This method thus also provides a measurement of field amplitude across and along the test region to help express the characteristics of the chamber in terms that are important in actual use.

Data Collection - the procedures of the "Free Space VSWR" method of measurement are described and discussed in the following:

The chamber is set up as if to run a pattern using a typical antenna for illumination and a moderate gain antenna as the test antenna (usually a standard gain horn or low frequency yagi) at full path distance. The test antenna is mounted on low reflection, traverse mechanism which allows movement over a distance close to the full width of the chamber. The amplitude of signal received by the test antenna is recorded during movement on a rectangular recorder.

To measure reflections from the side wall, the test antenna is moved across the chamber and a recording made of the encountered amplitude variations. Ten recordings are made as this operation is repeated with the test antenna set at every 10° step of aspect angle from 0° (on-axis) through 90° (toward the side wall). The recording at 0° shows how closely the chamber approximates the amplitude distribution of free space and hence indicates how good an environment has been created for acquiring patterns typical of free space.

The periodic variations reveal how far the level of reflected energy is below the pattern level. The test antenna is moved across the chamber in measuring the side wall reflected energy for two reasons: 1.) the back wall reflected energy is kept at essentially constant phase during movement in this direction and 2.) movement in this direction requires the shortest distance of travel to complete one cycle of the periodic variation. With the typical geometry of the rectangular chamber, the tranverse travel distance for a single cycle is in the order of two and a half times the free space distance as is brought out by the relationship $\lambda_{\text{chamber}} = \lambda_{\frac{\text{free space}}{\sin \phi}}$ where ϕ is the aspect angle at which the test antenna is directed toward the specular reflection point on the side wall. (ϕ in a typical rectangular chamber is in the range of 20 to 25 degrees.) Movement in a direction which provides the shortest distance between maximums and minimums becomes increasingly important at low VHF frequencies where even a single cycle in the transverse direction may require movement over a sizeable fraction of the chamber width. It will be appreciated that quantitative values for the level of side wall reflected energy cannot be attained at frequencies so low that it is not possible to move from an in phase to an out of phase condition.

To measure reflections from the back wall, the test antenna is moved in a direction along the chamber, i.e., parallel to the direction of propagation. Another ten recordings of amplitude variations are made with one for every 10° step of test antenna aspect angle from 90° (toward side wall) through 180°, the travel distance to complete one cycle with movement is the familiar half wave as found in slotted line measurements. A direction of travel along the chamber is chosen for back wall measurements since, under this condition, the phase difference between side wall energy and direct energy varies very slowly and, hence, is unlikely to obscure periodic variations attributable to the back wall.

Data Analysis - the 20 recordings acquired in the above manner form the complete data for a single frequency. Each is analyzed to provide a separate value for the amount of reflected energy encountered at each step in angle. Individual recordings are analyzed in the following manner:

A typical recording will show a periodic amplitude variation attributable to chamber imperfections that is superimposed on the basic variation attributable to changing path distance and/or scanning of the two antenna patterns. The periodic component is enveloped by drawing a line connecting the maximums and another connecting the minimums. The spacing between these two lines is the free space VSWR in db. This VSWR comes about as the result of vector addition of a vector representing the pattern energy with another representing the reflected energy. The relative levels of both vectors are a function of and may be quantitatively determined from the magnitude of the observed VSWR. This determination is speeded in practice by a curve such as that included here as Figure 3.0.

While the stronger of the two is generally the pattern level and the weaker of the two is the reflected energy, it is occasionally necessary to resolve ambiguity between the two. In practice this is usually accomplished by identifying the value which respresents the pattern level by comparing the two values determined from the VSWR curve with a known pattern for the test antenna. The quantity of primary interest (i.e., the level of reflected energy at a particular angle in db below the level of direct energy) is equal to the number of db that the pattern level is below the direct level at that angle plus the number of db that the level of reflected energy is in turn below that pattern level. This quantity is the ratio of reflected energy arriving at the test region from the direction in question to the direct energy arriving from the direction of the source antenna.

The "Free Space VSWR" method thus describes a chamber in terms of a plot of reflected energy vs. aspect angle for each frequency. It is our belief that such curves should be aquired ~~method~~ at a minimum of one high, one middle, and one low frequency since different problems manifest themselves in different parts of the spectrum.

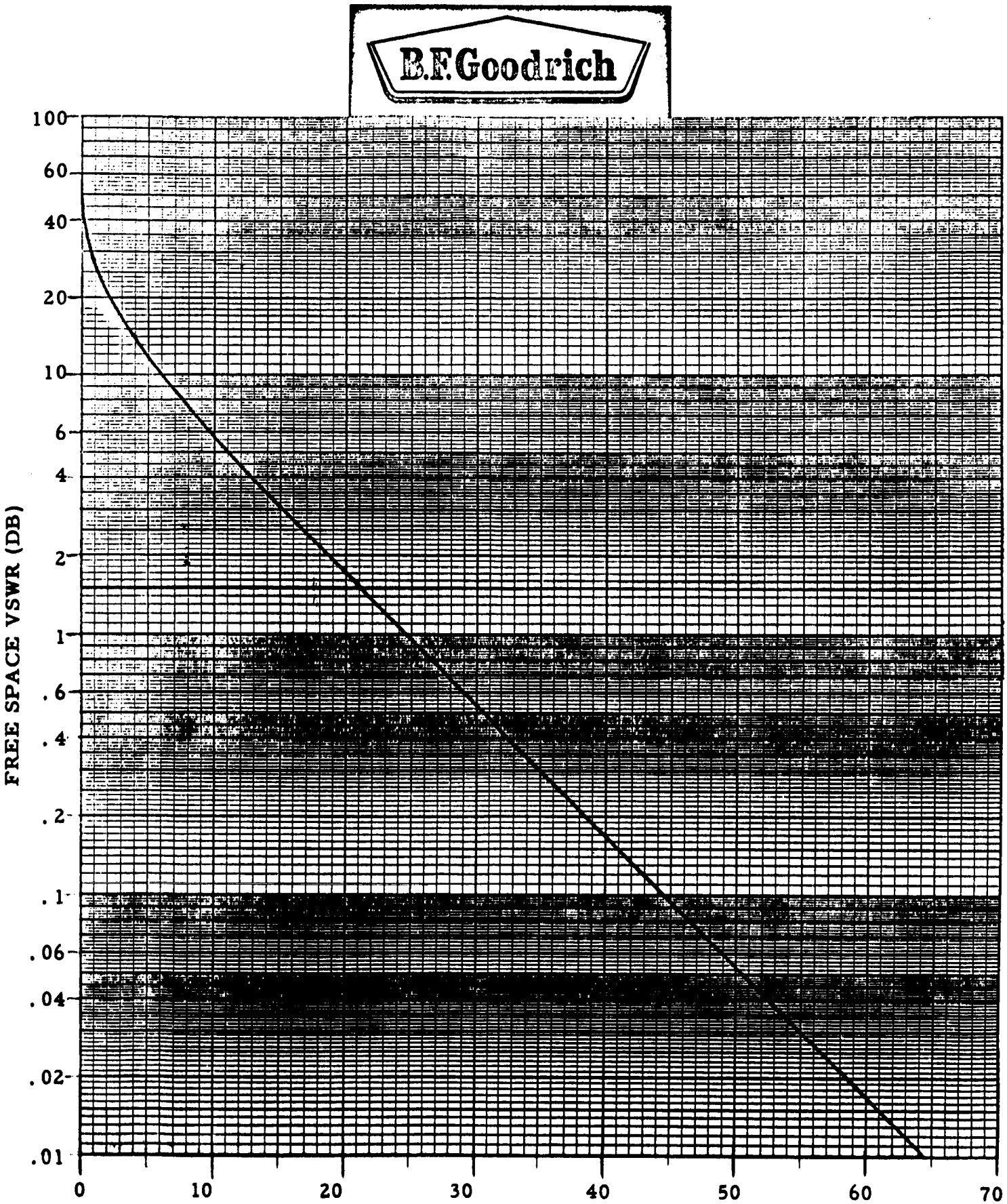


FIGURE 3.0 - LEVEL OF REFLECTED ENERGY BELOW LEVEL OF PATTERN (DB)

EXAMPLE: From the above curve it is determined that a VSWR of .2 db indicates the presence of a small vector at a level of 38 1/2 db below the level of the main signal.

These curves present chamber characteristics in a manner which is well suited to revealing whether the specified minimum performance has been achieved at every angle. Curves of this type are especially useful for diagnostic work in identifying and studying source of reflection within a chamber. They are of further value since with this data an engineer can predict the maximum error that the chamber can cause to his antenna patterns at particular frequencies and aspect angles. The attached Figure 3.1 is especially useful for this purpose.

2. Details of this Chamber Measurement

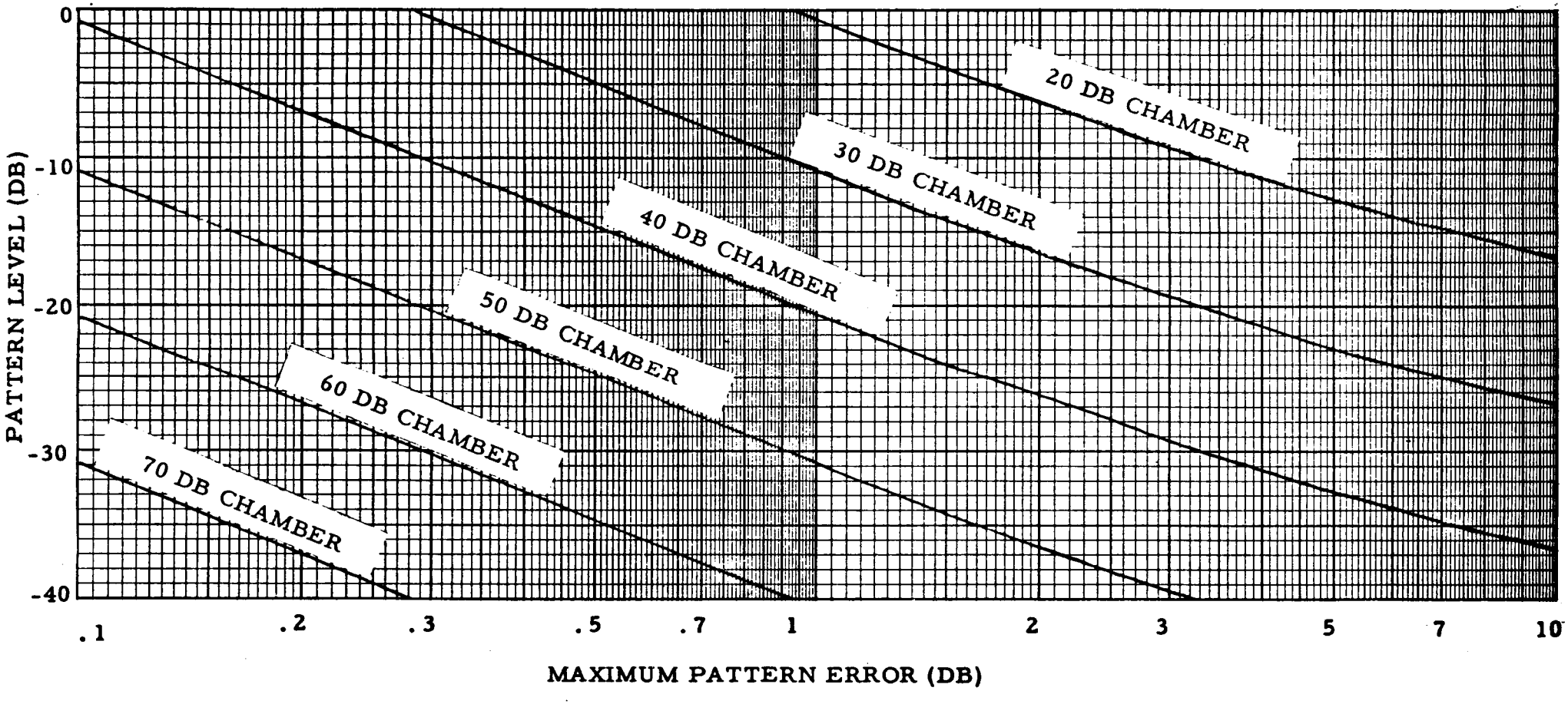
The "Free Space VSWR" method was used as described above to measure performance of the NASA MSFC tapered chamber. Antennas used for these measurements are listed in the following table:

Table 3.1 Antennas Used in the NASA MSFC

Chamber Measurements

Frequency	Test Antenna Type	Source Antenna Type
65 MHz.	Yagi	Yagi
120 MHz.	Yagi	Yagi
220 MHz.	Yagi	Yagi
440 MHz.	Yagi	Yagi
1250 MHz.	Standard Gain Horn	Standard Gain Horn
3.0 GHz.	Standard Gain Horn	Standard Gain Horn
10.0 GHz.	Horn (6" x 6" aperture)	Parabola (18 inch)

At each frequency the source antenna was located within the taper at a point where there was only a small gap to the absorbent material on the taper surface. The test antenna was moved transversely and longitudinally by a "reflectionless" traverse mechanism which consisted of a foam support column mounted on a cart that was also made of foam. The column was adjustable in azimuth and calibrated in 10° increments. The cart ran on a set of tubular plastic rails with motion directed from outside the chamber by a remotely controlled motor drive system. Recordings were made with the recorder chart controlled by a geared selsyn system between the cart drive motor and the recorder. Logarithmic pen response was used for all measurements.



PATTERN ERROR AT VARIOUS PATTERN LEVELS VS. CHAMBER PERFORMANCE

Example: The above curves indicate that a 40 db chamber may contribute as much as .1 db error at the peak of a pattern, .3 db error at a pattern level 10 db down from the peak, 1 db error at 20 db down on a pattern, 3 db error at 30 db down, and close to infinite error at the 40 db level on a pattern.

Figure 3.1

Identical procedures and equipment were used to measure both the chamber and adjacent outdoor range.

Figures 3.2 and 3.3 have been added to demonstrate how the basic recordings of probe amplitude are used in practice to determine a value for the level of reflected energy at a particular aspect angle.

B. B. F. Goodrich Quality Control Measurements on Absorbent Materials

The problem of how to make good measurements on materials at low frequency has been a difficult one. Development of good low frequency absorbers was actually held back for many years by the difficulties of making good quality control measurements with adequate accuracy.

At one time it was thought that measurements could be made in free space that were sufficiently accurate down to UHF-VHF frequencies. The above referenced University of Michigan report however brought out that accuracy from this type of measurement was limited by errors attributable to edge reflection and size effects when the units of material were less than 5 to 10 wavelengths on a side in size. It was considered impractical to make general production measurements at these frequencies on pieces of this size. This report concluded that the only practical way to make accurate low frequency measurements was within an enclosed waveguide system which flared to a size sufficient to simulate "free space" to an adequate degree. This means of measurement would avoid both edge and size effects since the sample under test would appear semi-infinite in size as a result of the conducting wall images. Such a measurement system was originally designed and developed by the Naval Research Laboratory.*

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* Emerson, W.H., Sands, A.G., and McDowell, M.V., "Development of Broadband Absorbing Materials for Frequencies as Low as 500 Mc.", May 1954, Naval Research Laboratory Report MR300.

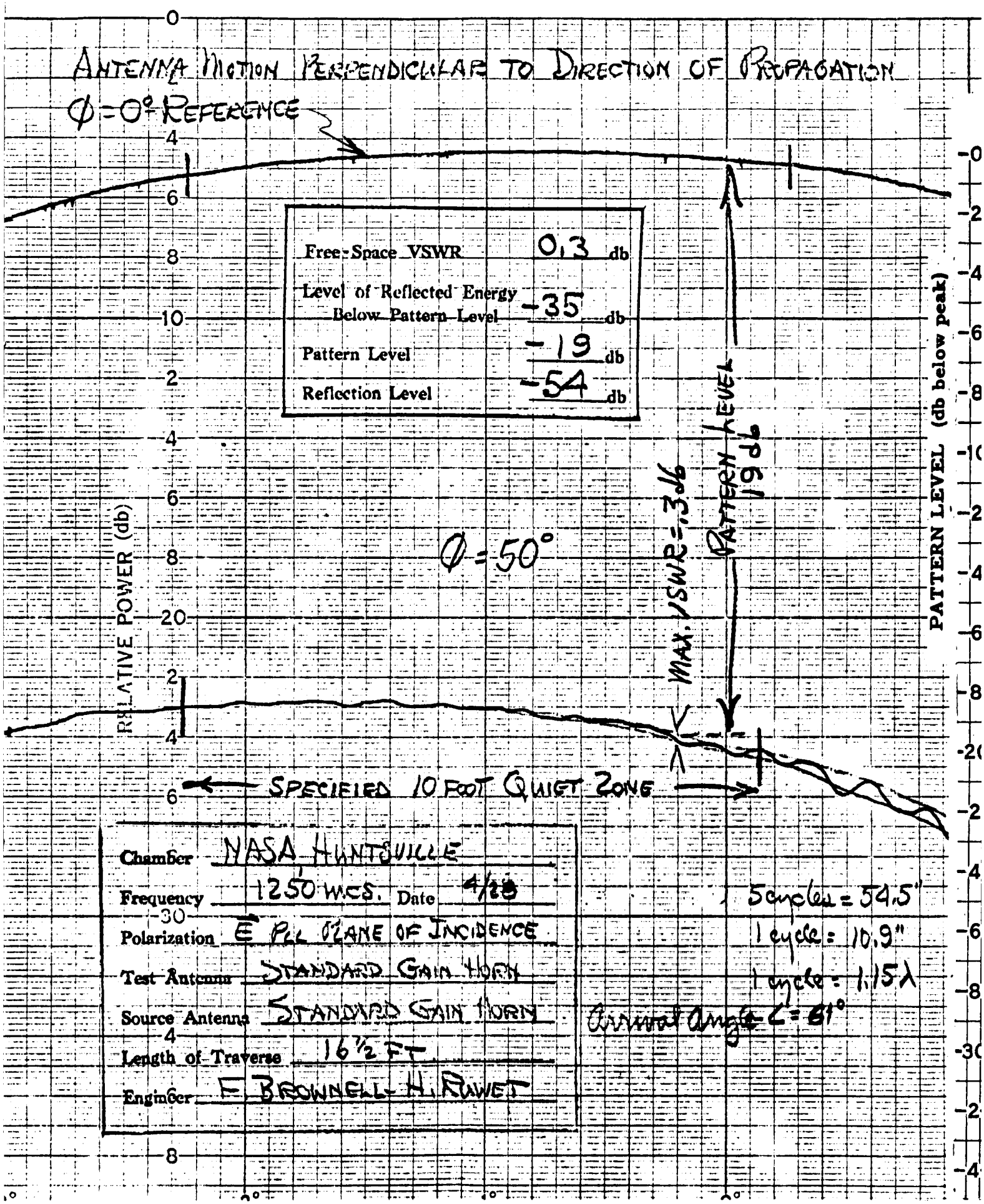


Figure 3.2 - Example of determining "Reflection Level" value from basic recording of amplitude across test region of chamber.

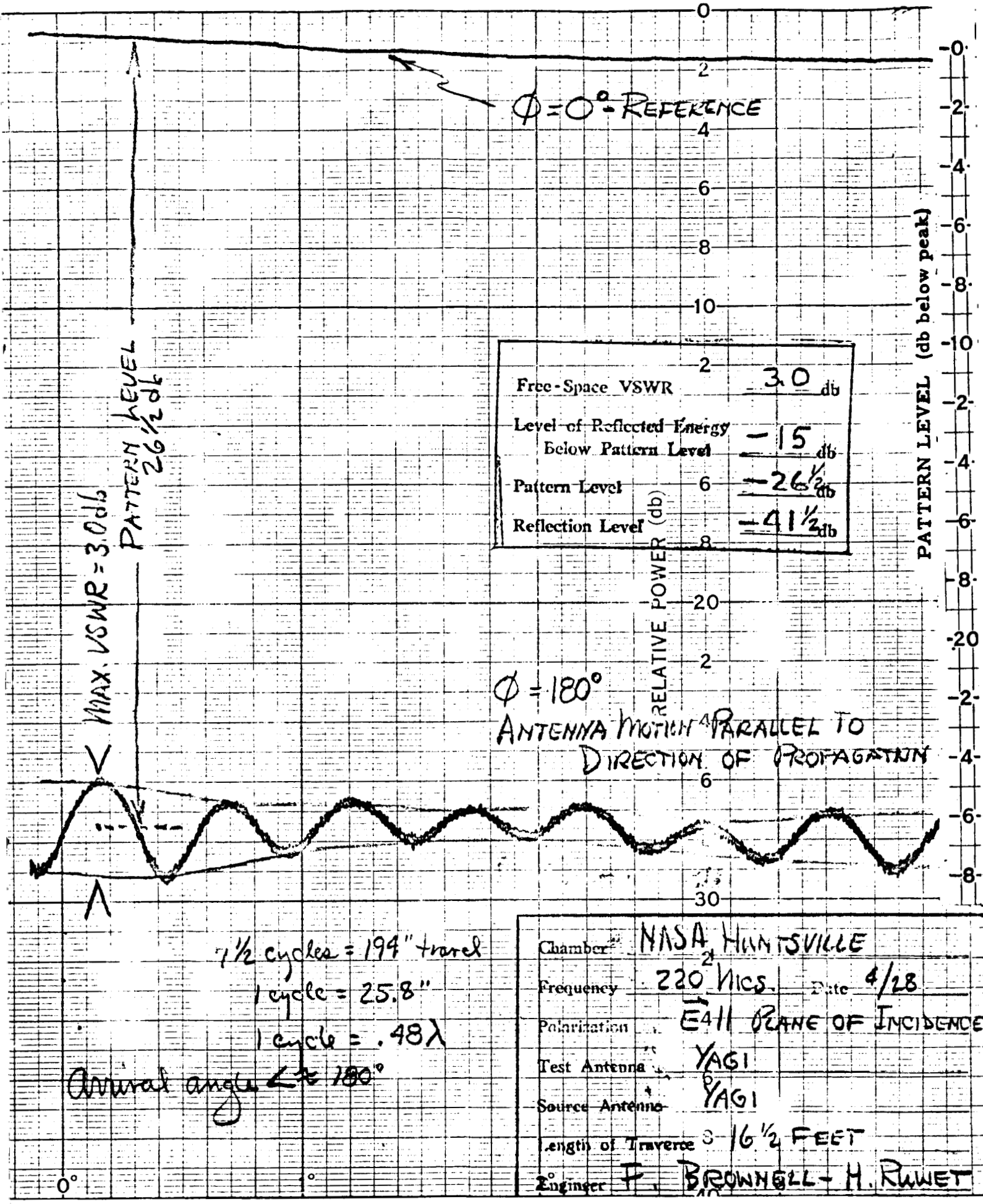
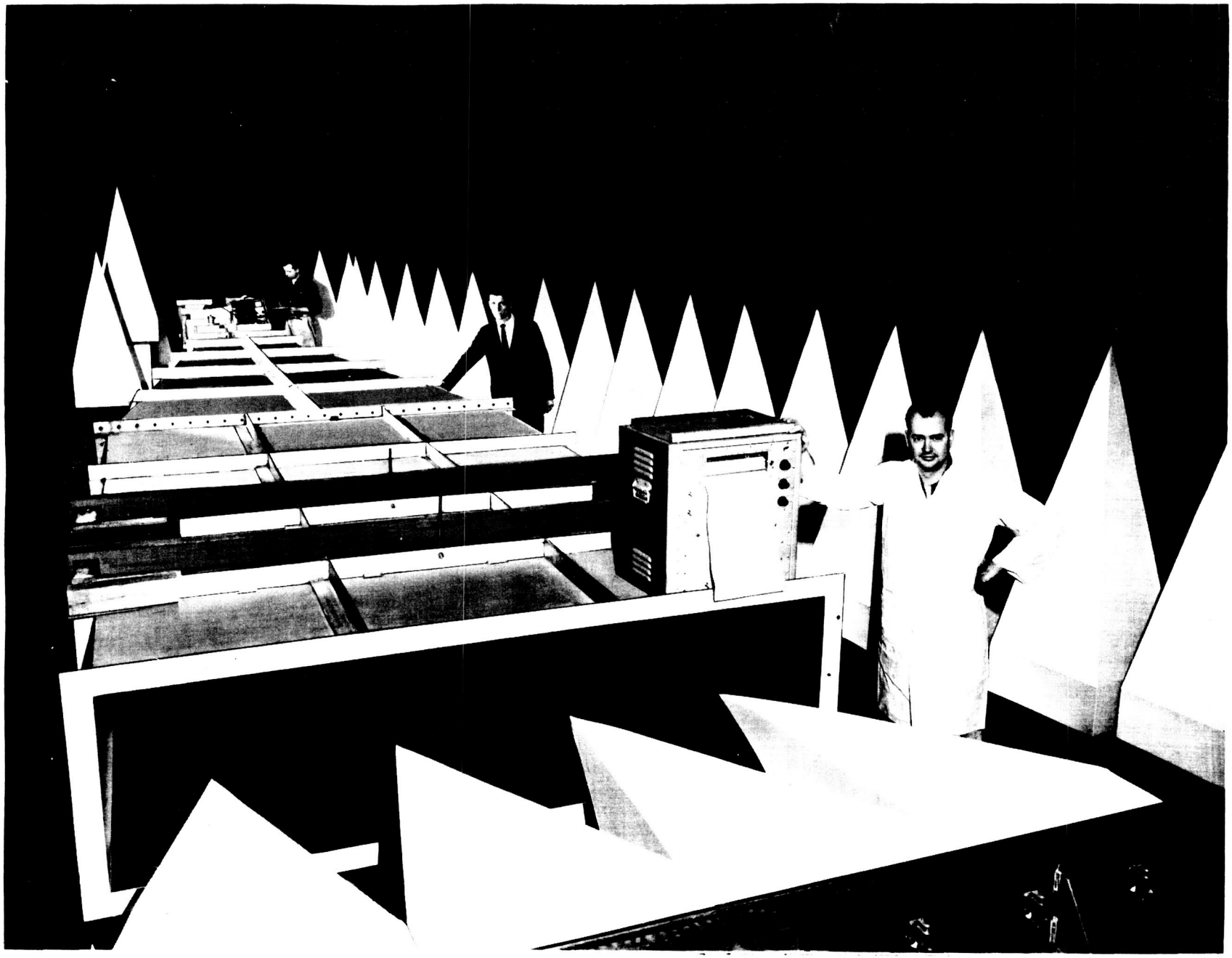


Figure 3.3 - Example of determining "Reflection Level" value from basic recording of amplitude along direction of propagation.



50 FOOT LONG TEST FACILITY USED FOR QUALITY CONTROL MEASUREMENTS, 100 - 400 MCS.

The B. F. Goodrich Company now has equipment of this type in three different sizes to measure the normal incidence reflection coefficient of production materials over the frequency range of 100 MHz. through 1800 MHz. Each of these equipments gradually tapers from a waveguide slotted section to a large region of rectangular cross section in which the material under test mounts in front of a short. It will be appreciated that energy both reflected and scattered from the absorbing material appears back at the probe as VSWR from which the reflection coefficient is determined. Special techniques are used to avoid measurement inaccuracy attributable to discontinuities from the flanges, the taper, and mechanical imperfections. It is interesting to note in passing that the flared system used to cover the low frequency end is a rather impressive piece of equipment since it uses a horn that is over 50 ft. in size.

Each piece of VHP material installed in this chamber was measured at three frequencies on these equipments to establish compliance with the B. F. Goodrich commercial specifications.

SECTION 4 - PERFORMANCE CHARACTERISTICS OF THE COMPLETED FACILITY

A. Chamber Performance

Measurement of the chamber with the "Free Space VSWR" technique as described in Section 3 provides the curves of Figure 4.1 through 4.6. These are plots of the level of reflected energy (in db below the level of direct energy) vs. aspect angle of the test antenna. They also represent plots of the level of reflected energy entering the test region for various angles of arrival.

It is to be appreciated that the plotted points are conservative since they are based in every case on the largest single amplitude cycle of the VSWR encountered during the entire run across and along the quiet zone. No averaging of data has been used. As a result, good faith can be placed in knowing that the chamber in practical use will, under essentially all conditions, be better than indicated by these curves. Taking the worst reflection found at any point in the entire quiet zone at any aspect angle provides the following minimum values for performance for this chamber:

Table 4.1. Minimum Measured Performance

Frequency	Level of Reflected Energy
10,000 MHz.	-65 db
3,000 MHz.	-57 db
1,250 MHz.	-49 db
440 MHz.	-40 db
220 MHz.	-41 db
120 MHz.	-25 db
65 MHz.	-19 db

Plot of Residual Chamber Reflections vs Angle

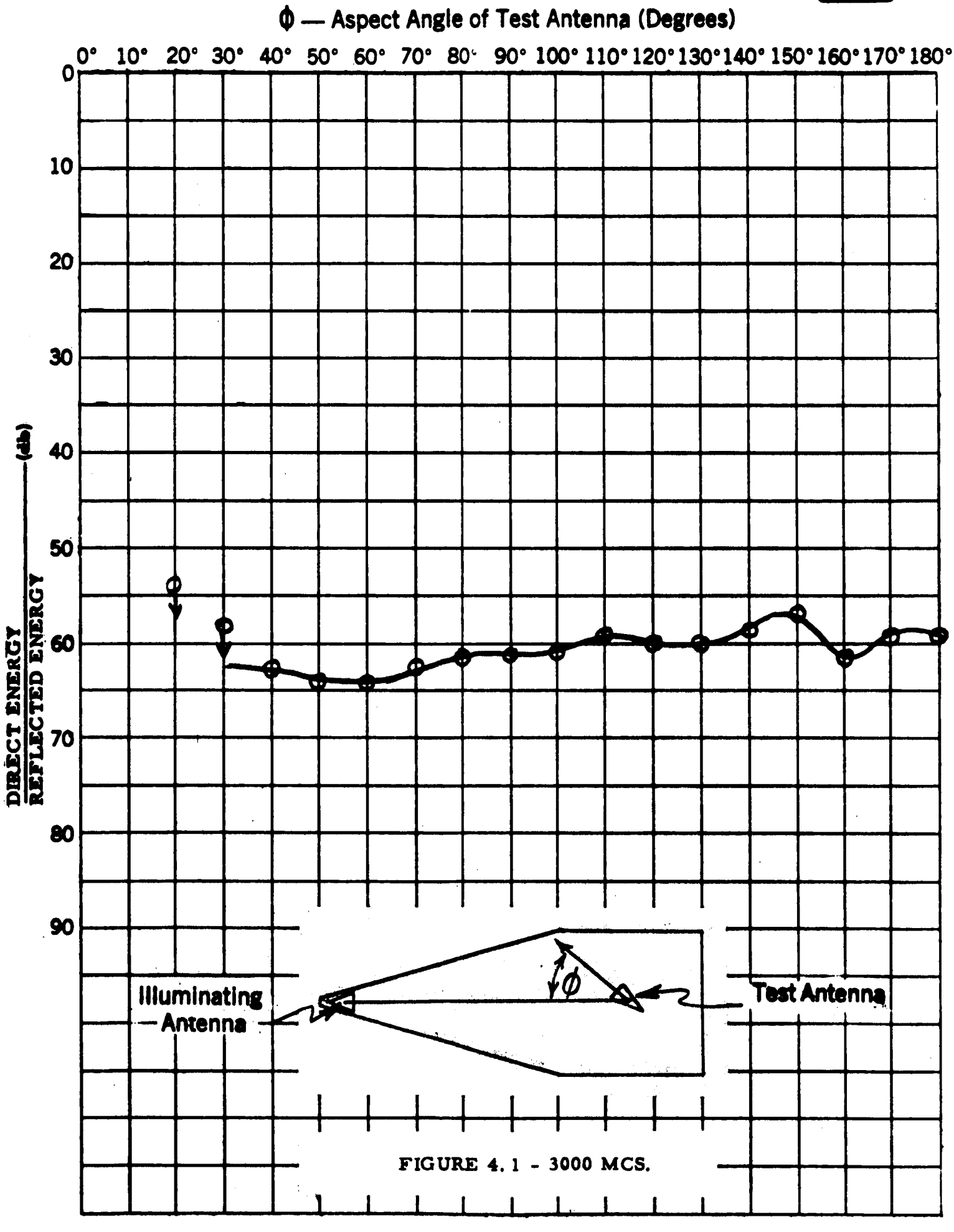


FIGURE 4.1 - 3000 MCS.

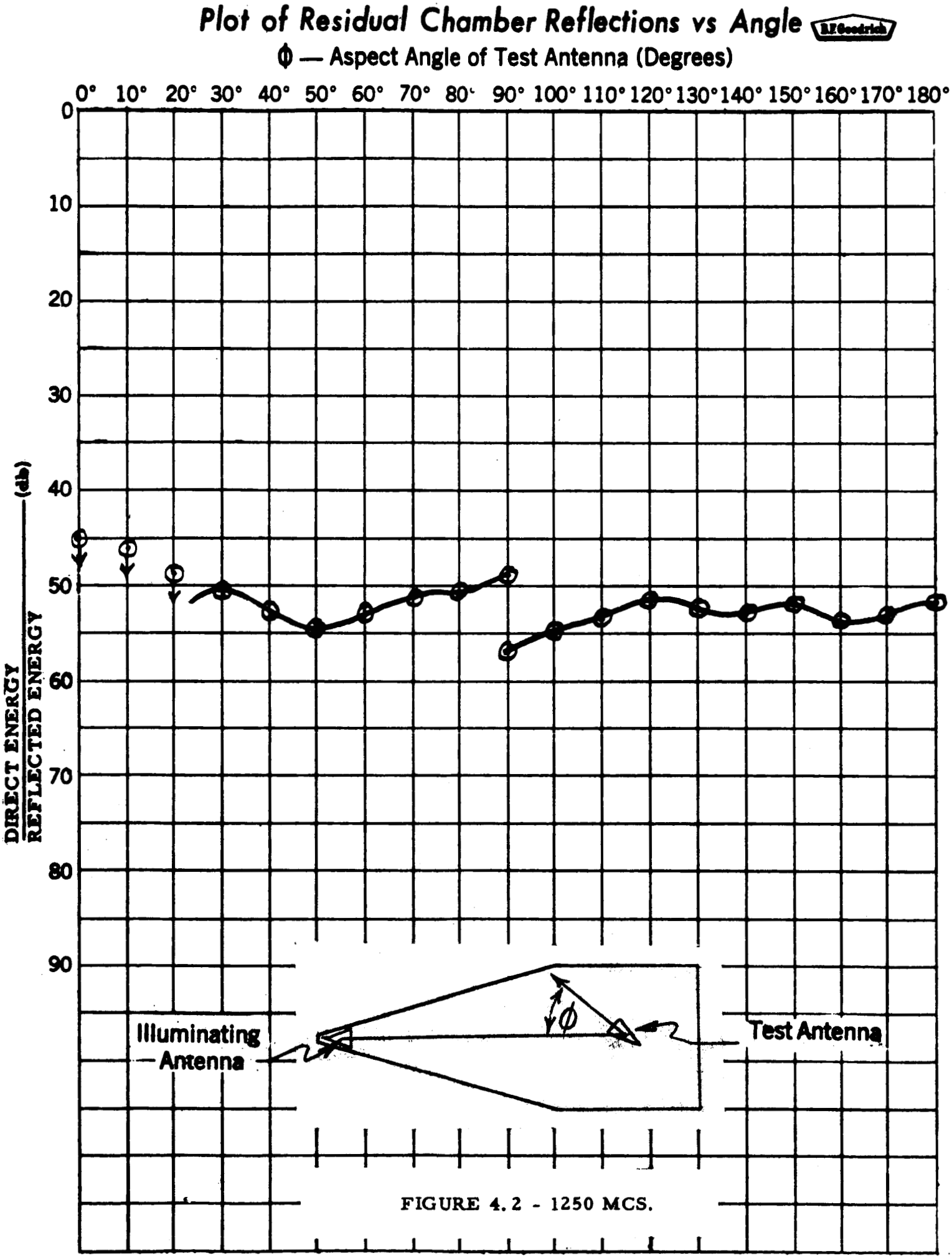


FIGURE 4.2 - 1250 MCS.

Plot of Residual Chamber Reflections vs Angle

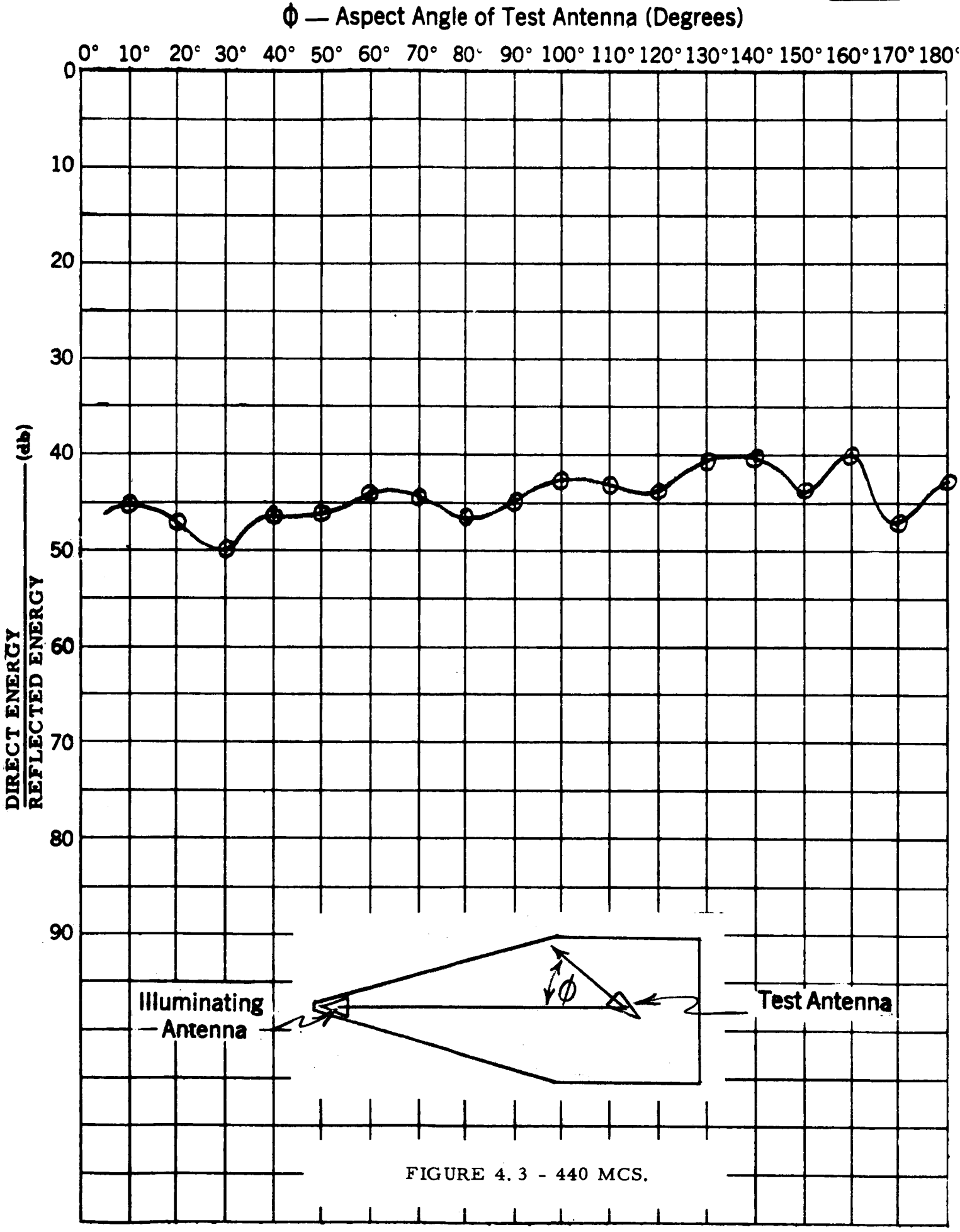


FIGURE 4.3 - 440 MCS.

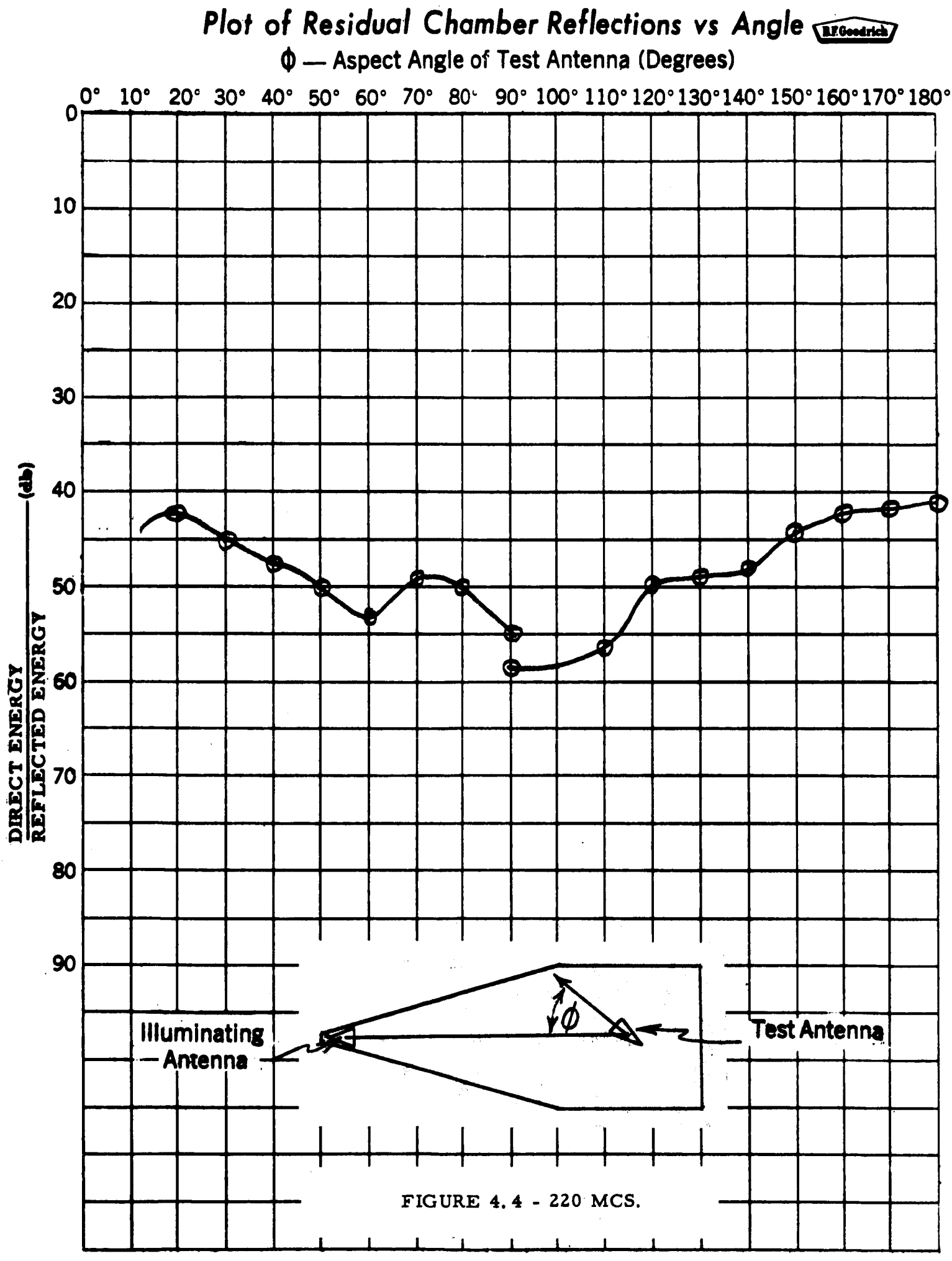


FIGURE 4.4 - 220 MCS.

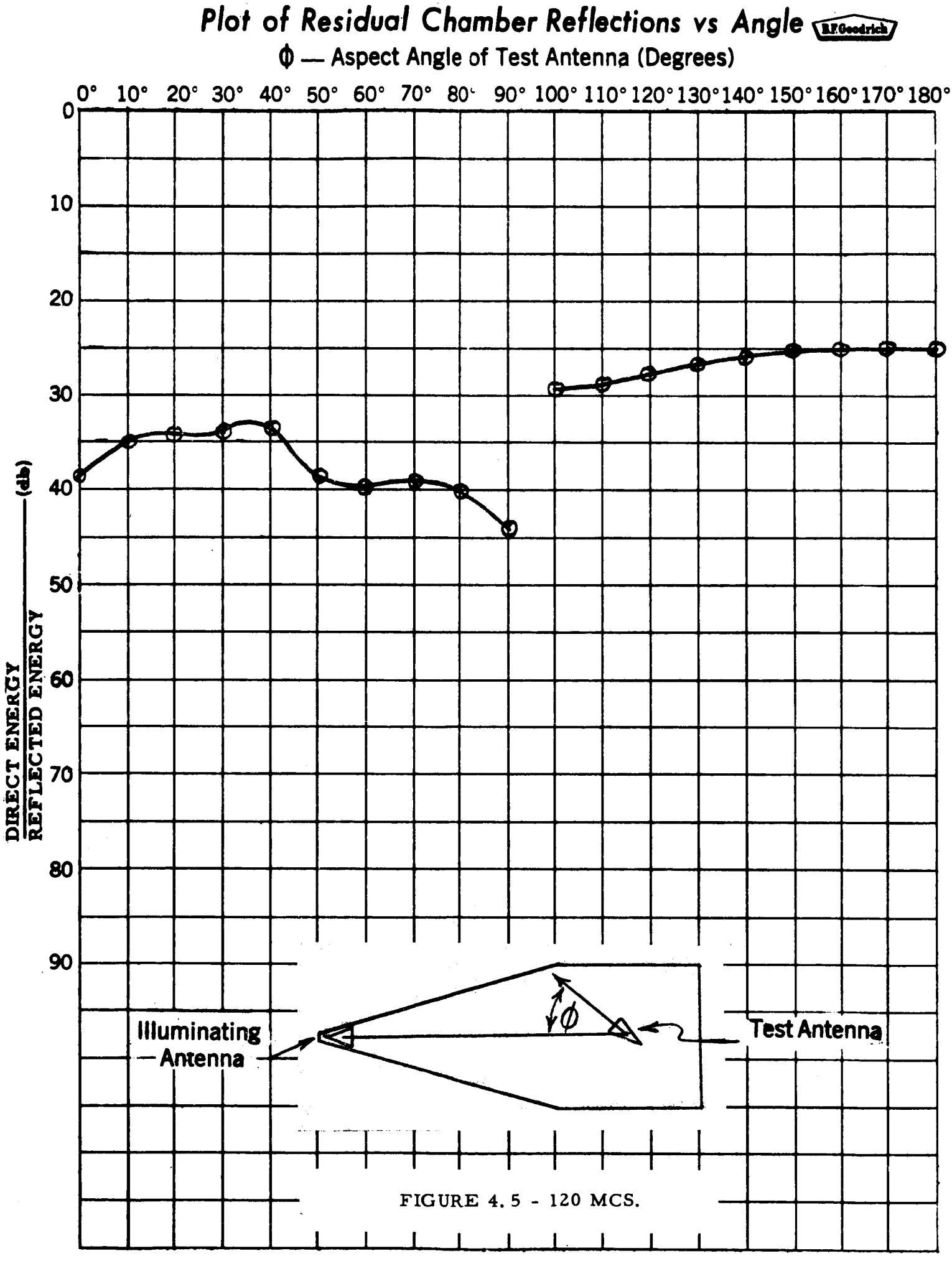


FIGURE 4.5 - 120 MCS.

Plot of Residual Chamber Reflections vs Angle

B.F.Goodrich

ϕ — Aspect Angle of Test Antenna (Degrees)

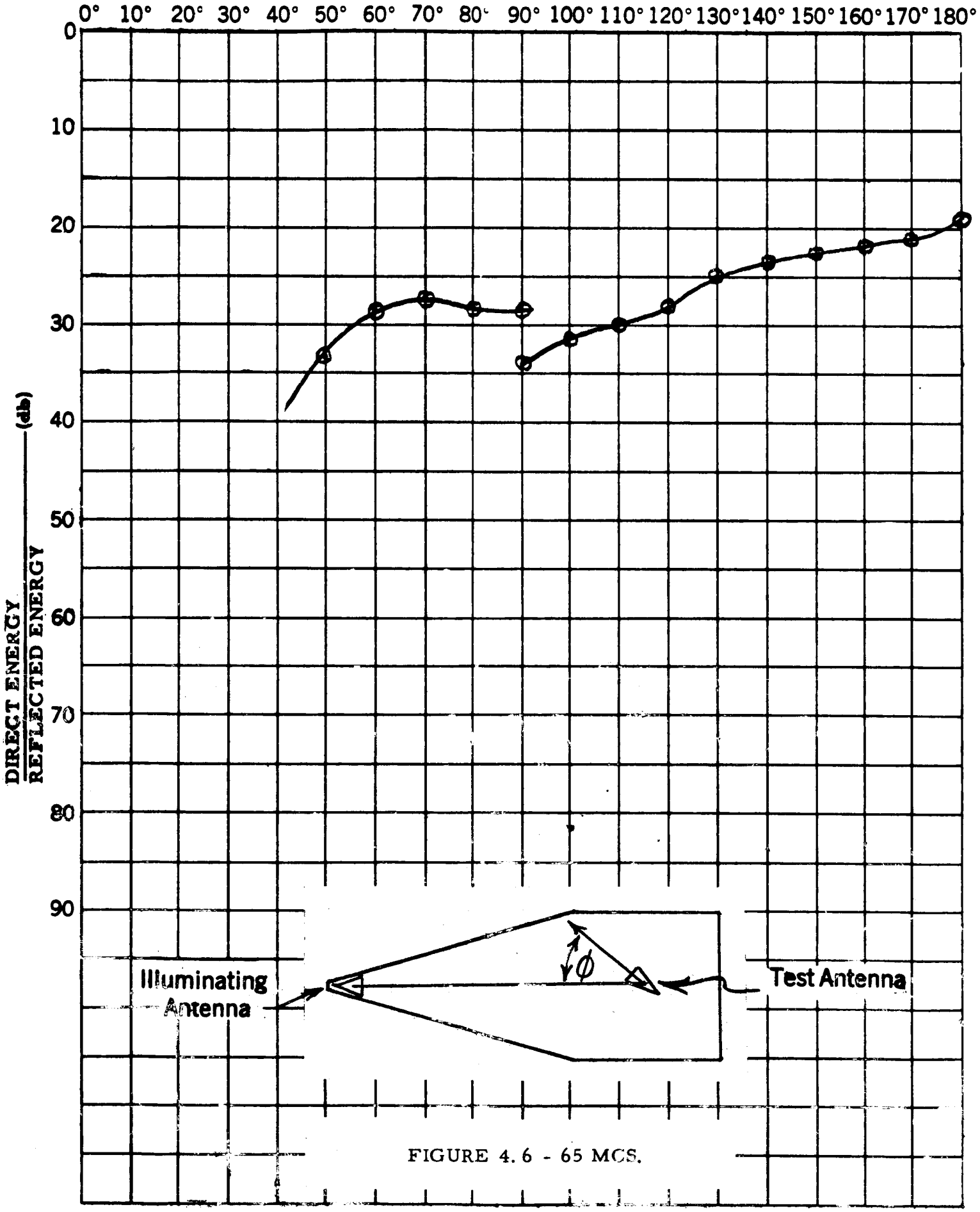


FIGURE 4.6 - 65 MCS.

Reference to the original amplitude recordings shows that clear data is available for this determination except at X Band. Difficulty in obtaining discrete values was here encountered since the periodic variations attributable to chamber imperfections were too small to be observed or were smaller than the variations due to noise. Study of the curve shows that if reflections were as poor as -65 db they would have been able to be seen.

Another characteristic of the chamber is brought out in Figure 4.7 which shows the recorded amplitude distribution across the chamber at each measurement frequency when the chamber is driven as a typical tapered chamber (labeled "Tapered Operation"). The smooth reflection-free field that characterizes a well designed tapered chamber will be noted. While phase was not measured in this chamber it is known that phase is also uniform across a wide central region of a tapered chamber. The actual amplitude distribution associated with the chamber is actually wider than indicated by these recordings, since part of the observed amplitude change is attributable to the scanning of the patterns of the antennas at both ends of the chamber by the motion across the chamber. The 16 ft. traverse provides a 4 1/2 degree scan on the respective patterns of both antennas to provide a total scan of 9 degrees.

It will also be noted that at a number of frequencies curves entitled "Simulated Rectangular Operation" are superimposed on the tapered distribution. These curves were acquired with the test antenna moved sufficiently far out from the apex of the taper to allow specular reflections (similar to those of a conventional chamber) to take place. The deleterious effect of such variations across the aperture of an antenna under measurement can be appreciated.

It may be noted that the measurements made at 220 MHz., 120 MHz., and 65 MHz. were outside the specified frequency range for the chamber and were not required by the contract. This additional work represents an interest on the part of B. F. Goodrich to take advantage of the opportunity presented by this chamber to learn more about chamber phenomona at lower frequencies. The results of these measurements and basic data recordings are also made available to NASA with the thought that this information will be useful should need arise to use the facility in that part of the frequency spectrum.

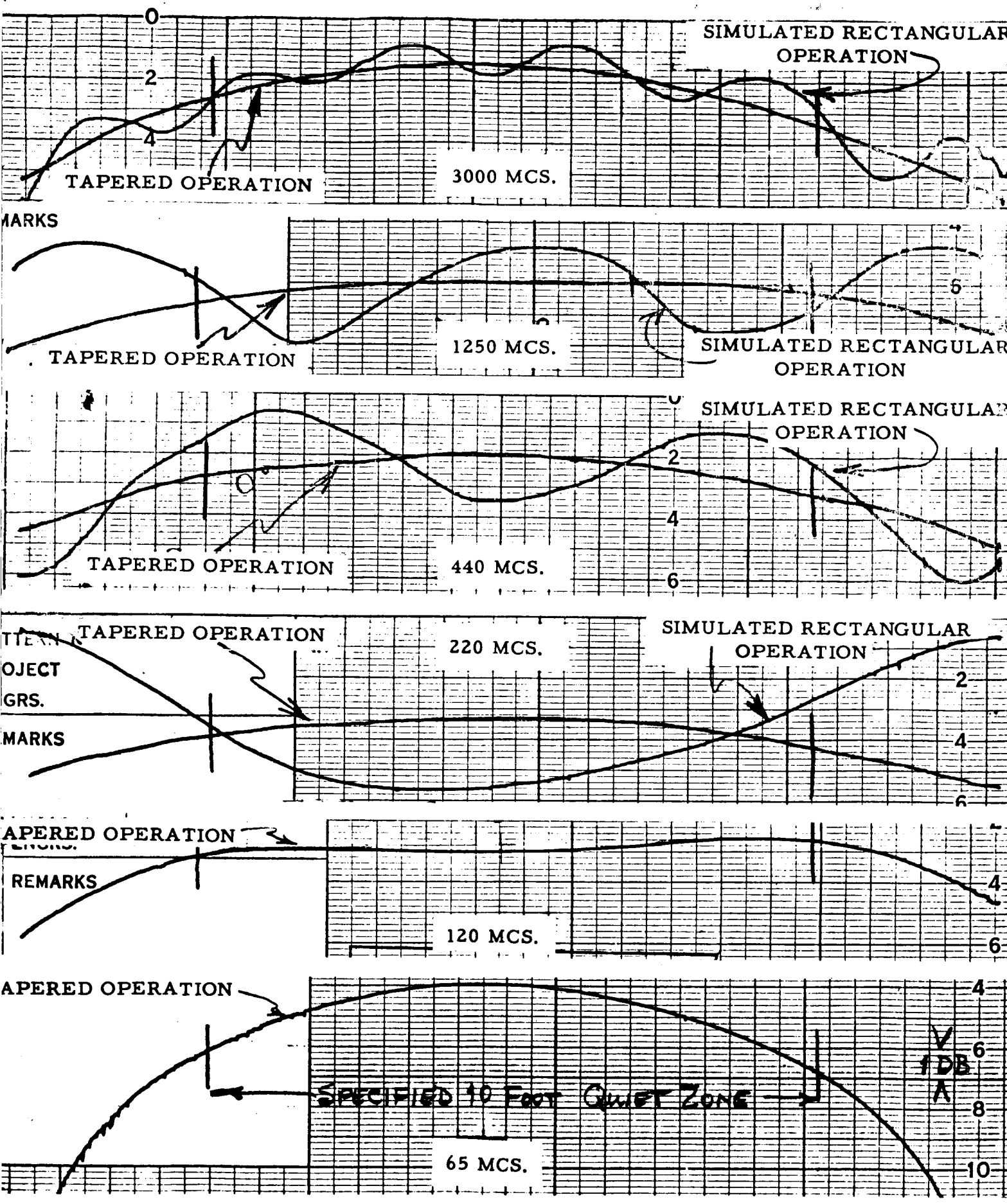


Figure 4.7 Recordings of field amplitude across test region at various frequencies. Note smooth amplitude distribution attributable to driving chamber from near apex of taper. "Simulated rectangular operation" achieved by driving chamber sufficiently far out from apex to allow typical specular reflections to take place from the side walls, floor, and ceiling.

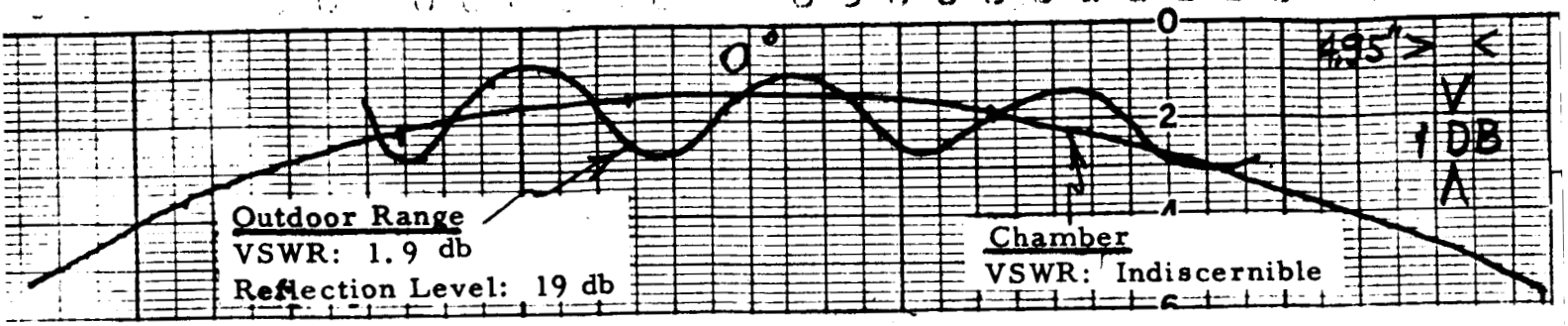
B. Outdoor Range Performance

A most interesting secondary experiment was performed by measuring the adjacent outdoor range in the same manner as the chamber. It was expected that this experiment would provide the first known opportunity for a comparison of accurate reflectivity data from an outdoor range with that from an indoor range that had been measured under identical well controlled conditions.

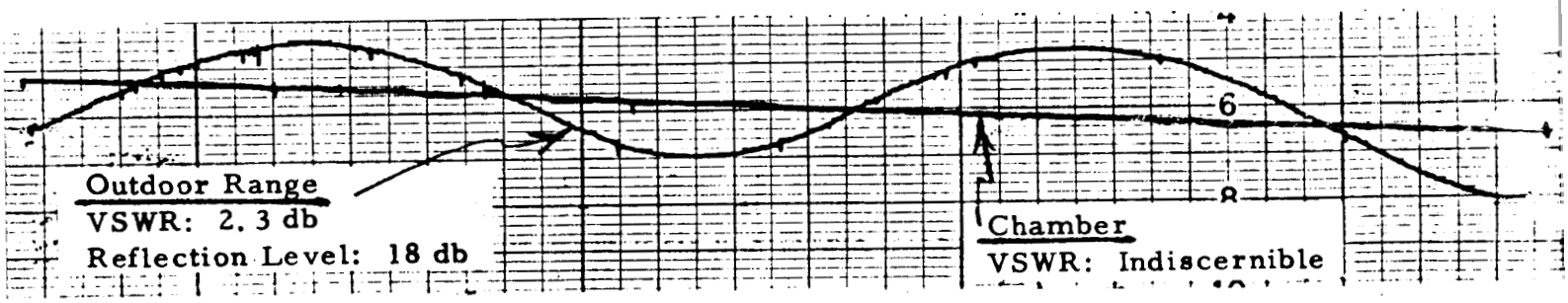
The outdoor range in this case was along a flat concrete pad (of about 10 foot width) that was elevated by approximately a foot above the surrounding flat ground. The outdoor measurements were made with all significant aspects the same as the indoor measurements. i.e., the frequency was also at 3,000 MHz., the same standard gain horns were used as both source and test antennas, the same height above ground (13 feet) was used on the outdoor range as height above floor in the chamber, the path length outdoors was also made 100 foot, the same antenna traverse mechanism was used, and the antenna travel distance was also made to be 16 feet.

Figure 4.8 provides a number of comparisons of basic amplitude recordings made on the indoor and outdoor ranges. Figure 4.9 provides a comparison of the level of reflected energy at all aspect angles for both ranges.

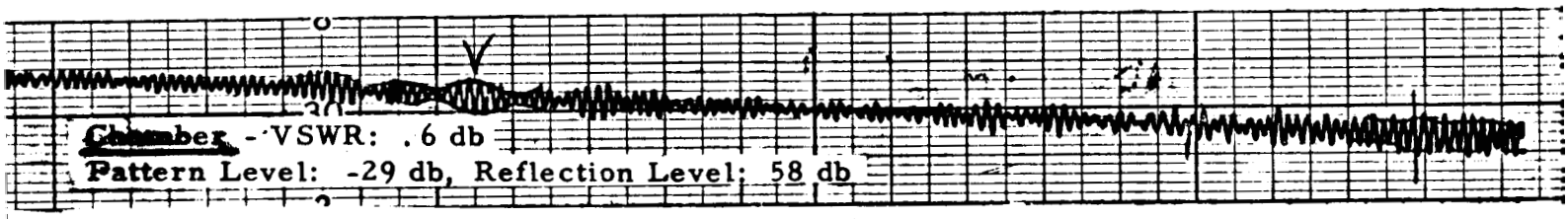
Considering first the comparison of amplitude recordings, Figure 4.8, a. shows both a wide smooth amplitude distribution that resulted from a traverse across the test region within the chamber, and a distribution with large periodic component that came from a vertical traverse on the outdoor range. The vector causing the cyclic variation in the later curve undoubtedly results from specular reflection at the ground surface midway between the two antennas. Figure 4.8, b. shows a similar comparison for both ranges but with antenna traverse made along the direction of propagation. A periodic variation of similar amplitude is again recorded for the outdoor range. As would be expected it is necessary to move much further in this direction to complete one cycle since movement along the direction of propagation causes both the direct and reflected vectors to change phase in a similar manner.



a. Antenna motion perpendicular to direction of propagation. ϕ = 0 degrees (Test antenna toward source antenna).



b. Antenna motion parallel to direction of propagation. ϕ = 0 degrees.



c. Curve above - Chamber, ϕ = 180° (Test antenna toward chamber back wall), antenna motion parallel to direction of propagation.

d. Curve below - Outdoor range, ϕ = 180° (Test antenna toward trees at back of range), antenna motion parallel to direction of propagation.

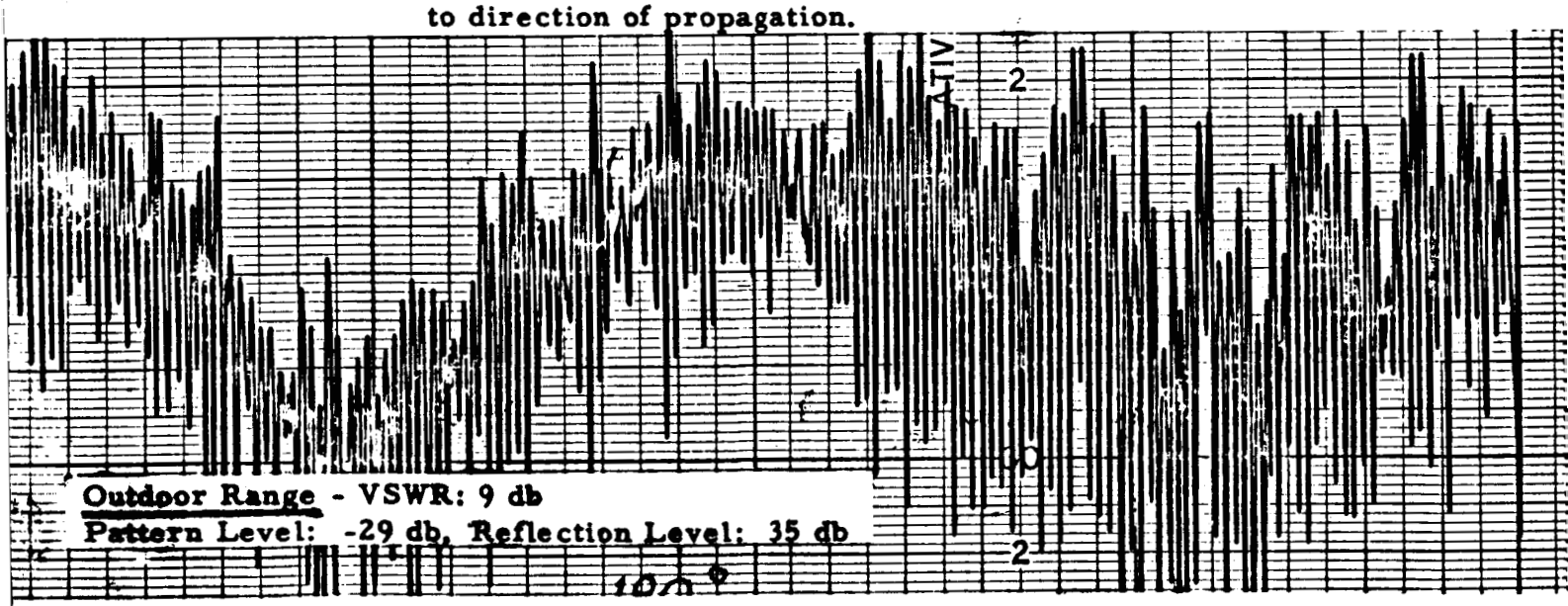


Figure 4.8 - Comparison of amplitude recordings made on the adjacent outdoor range with those made within the chamber. Large improvement offered by chamber is evident.

Measurement conditions identical for both, i.e. frequency - 3000 Mcs, antennas - standard gain horns, height above ground = height above floor = 13 feet, path length - 100 feet, antenna travel - 16 feet.

No sign of periodicity is noted on the recordings made within the chamber. The 2 db periodicity variation observed on the outdoor range recordings represent a significant deviation from the uniform amplitude required for measurements to be typical of free space conditions. This value of free space VSWR indicates that the level of reflected energy is here only 18 or 19 db below the level of direct energy. It is to be appreciated that in practical use of this range both the reflection level and the period of cyclic variation will be dependent upon the geometry of measurement and the discrimination provided by both the test and source antennas in the direction of the reflection point. Had either antenna been broader in pattern (such as might be encountered in measurement of a smaller antenna) a more severe level of reflected energy would have been encountered and consequently, even more severe variations of amplitude would be expected over a typical test region.

Figures 4.8 c and d reveal another interesting characteristic of the outdoor range. Both these recordings were made by providing movement along the propagation axis with the test antenna oriented toward the back of each range ($\phi = 180°$). In a reflectionless environment this would provide a smooth curve showing only a small monotonic change of amplitude with change of distance. The curve would be identical in shape to one made with $\phi = 0°$ (like that shown in Figure 4.8, b) but at a level 29 db below it since the pattern of the standard gain horn used is known to be down 29 db at this angle. The curve of Figure 4.8, c made in this manner in the chamber is similar to that expected in a perfect environment except for similtaneous reception of a small vector representing reflection from the back wall. Since this vector causes a "free space VSWR" of .6 db, it may be determined that this small reflection vector is another 29 db below the level of the larger vector representing the pattern level and therefore is approximately 58 db below the level of direct energy.

The curve 4.8, d made on the outdoor range deviates by a large amount from that expected for a perfect environment. Two separate sources of reflected energy appear to be present. One is manifested by a very long period which presents only about

two cycles for the 16 foot of travel. This is the same period noted in Figure 4.8, c. that was attributed to ground reflection. We thus see evidence to indicate that ground reflected energy is here at such a high level as to represent a significant factor in determining the signal recorded by the antenna even when this antenna is oriented away from the direction of arrival of the reflected energy.

Severe periodic variations with a much shorter period are also very much in evidence on this recording. The period is here noted to be similar to that found on the comparable recordings made within the chamber. A clue to the source of this reflection is given by the fact that appreciable periodic amplitude variation was also noted when the test antenna was not in motion. It was deduced that this reflected energy was coming from trees at the back of the outdoor range that were swaying in the wind. The test antenna was oriented directly toward these trees from a distance of about 200 feet for the aspect angle of this recording. It is interesting to note that the reflected energy encountered looking in this direction on the outdoor range was down only about 35 db from the direct energy in contrast to a level of 58 db measured in this direction within the chamber.

It is of interest to consider what Figure 4.8, c and d indicate for pattern accuracy when this particular antenna is oriented in the rear direction ($\phi = 180°$) on the two ranges. It may be directly seen on the recordings that there is an uncertainty in the pattern level (-29 db down) of only plus or minus .3 db within the chamber, and a much greater uncertainty in the order of plus or minus 5 db on the outdoor range.

Figure 4.9 provides a comparison of the level of reflected energy encountered at various aspect angles on both the indoor and outdoor range under identical measurement conditions. Significant differences are apparent. The value for reflected energy of only 8 db shown at the upper left was made with the test antenna declined by 15°. This measurement was made to provide basis for an estimate of how much reflected energy would be encountered by a low gain test antenna with insufficient directivity to provide discrimination against this source of error.

The following summary statements appear appropriate for the conditions compared on the two ranges:

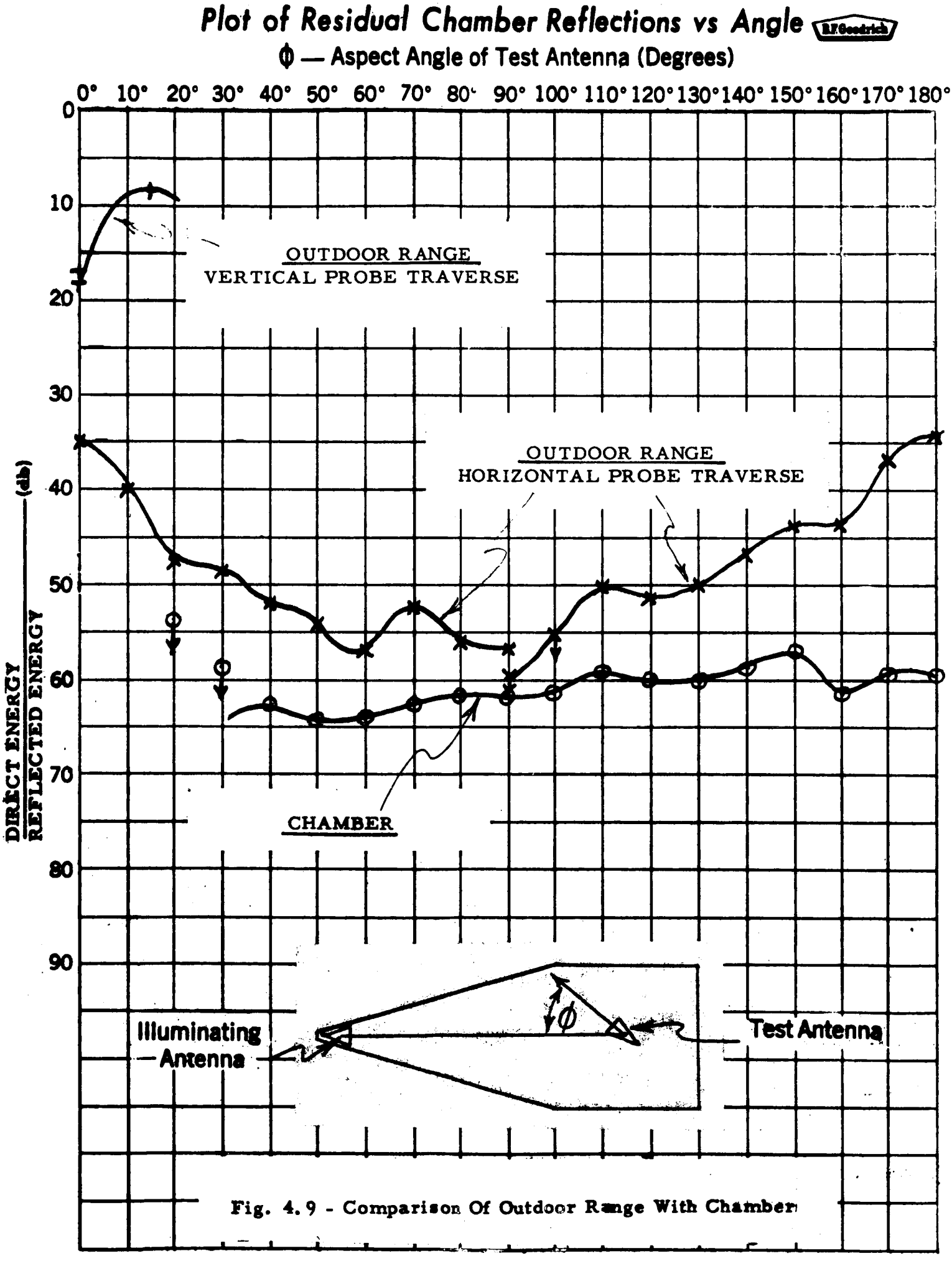


Fig. 4.9 - Comparison Of Outdoor Range With Chamber

1.) The chamber may be expected to provide much better measurement accuracy than the outdoor range.

2.) The outdoor range exhibits such high levels of reflected energy as to be of questionable value for antenna measurement.

SECTION 5 - CONCLUSIONS

A comparison of the data from this chamber with that from the many others (including those of other vendors) measured by this company allows the conclusion to be drawn that this chamber offers performance as high as any other known to this company and better than all but a few that are comparable. (Reference Section 6)

Possession of the data of Figure 4.1-4.6 allows quantitative conclusions to be drawn regarding the accuracy of patterns to be measured in this chamber. An estimate of expected pattern accuracy can be acquired by using the minimum chamber performance values that appear in Table 4.1 to determine a maximum pattern error. Figure 5.1 represents the result of such a determination. This curve will prove useful in determining the degree to which patterns made within this chamber can be relied upon. It is to be recalled that the data of Table 4.1 is based on the highest reflection found at the worst point in the quiet zone for the least favorable aspect angle. As a result the pattern errors indicated by the curves in Figure 5.1 may be considered as conservative maximums that may only be infrequently encountered in practice. It is believed that the dip in the curves near 220 MHz. is attributable to the fact that the VHP-70 absorber was purposely optimized at this frequency.

A summary of the measured data indicates that the chamber may be relied upon to provide 1 db or better accuracy to the 40 down level on patterns at S-Band and above, and this same accuracy to the 20 db down level on patterns to a frequency as low as 200 MHz. The chamber will be useful for certain purposes down to at least 60 MHz.

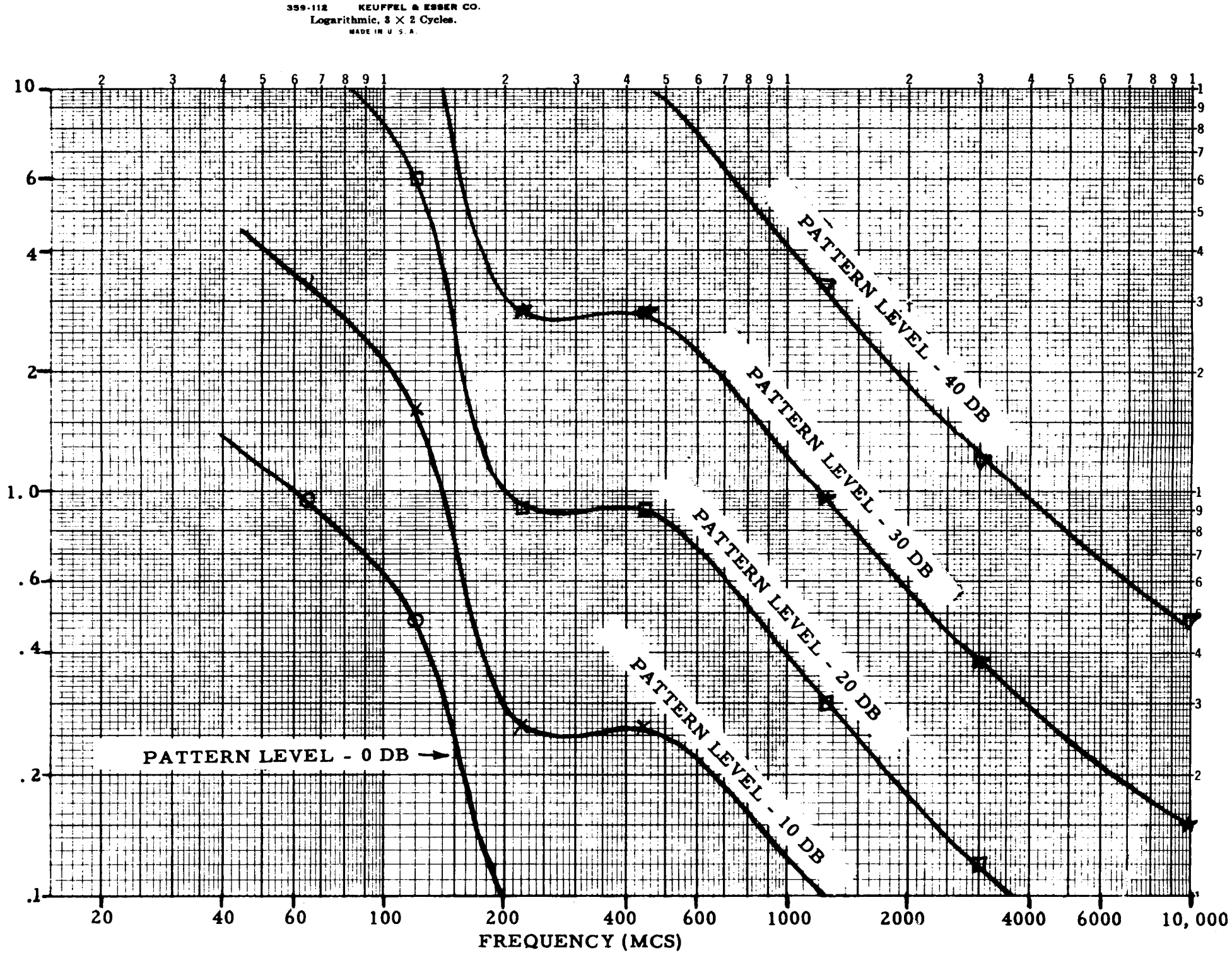


Figure 5.1 - Maximum pattern error attributable to chamber vs. frequency and pattern level

Figure 5.1

SECTION 6 - BIBLIOGRAPHY

B.F. Goodrich Report

MR-07 "Evaluation of the Martin Chamber"

MR-08 "Evaluation of the Sperry Chamber"

MR-09 "Evaluation of the AIL Chamber"

MR-10 "Comparison of a Conventional Rectangular Chamber with one of Novel Design"

MR-11 "Evaluation of the NASA Goddard Vertical Anechoic Facility"

MR-12 "Measurement of the Emerson and Cuming NASA Chamber by the B.F. Goodrich Co."

MR-13 "Design of an Indoor State-of-the-Art Bistatic Range"

MR-14 "State-of-the-Art Anechoic Backscatter Ranges"

MR-15 "A Treatise on Microwave Anechoic Chambers"

MR-16 "Measurement of the Horn Shaped Bunker-Ramo Chamber"

MR-17 "Measurement of the Naval Research Lab Tapered Chamber"

MR-18 "Measurement of the B.F. Goodrich Fort Monmouth Chamber"

MR-19 "Measurement of the Emerson and Cuming Chamber at Fort Monmouth by the B.F. Goodrich Co."

MR-20 "Measurement of the Reflectivity Chamber at Sylvania, Buffalo"

MR-21 "Measurement of the Jet Propulsion Laboratory Chamber"

MR-22 "Reflectivity Measurements of the ITT-Gilfillan Anechoic Chamber"

MR-23 "Measurement of the B.F. Goodrich Chamber at Sylvania EDL, Mountain View, California"

MR-24 "Measurement of the B.F. Goodrich Chamber at the Raytheon Company, Bedford, Mass."

MR-25 "Measurement of the B.F. Goodrich Tapered Chamber at the Dalmo-Victor Co., Belmont, California"

MR-26 "Measurement of the Emerson and Cuming Chamber at [redacted] by the B.F. Goodrich Co."

MR-27 "Measurement of the B.F. Goodrich Tapered Chamber at the Marshall Space Flight Center."

MR-28 "Measurement of the B.F. Goodrich Chamber at the MIT Lincoln Laboratory."

MR-29 "Measurement of the B.F. Goodrich Tapered Chamber at ITT-Kellogg, Chicago, Illinois."

MR-30 "Measurement of the two B.F. Goodrich Chambers at the Langley Research Center."

MR-31 "Measurement of the B.F. Goodrich Chamber at the Manned Spacecraft Center."

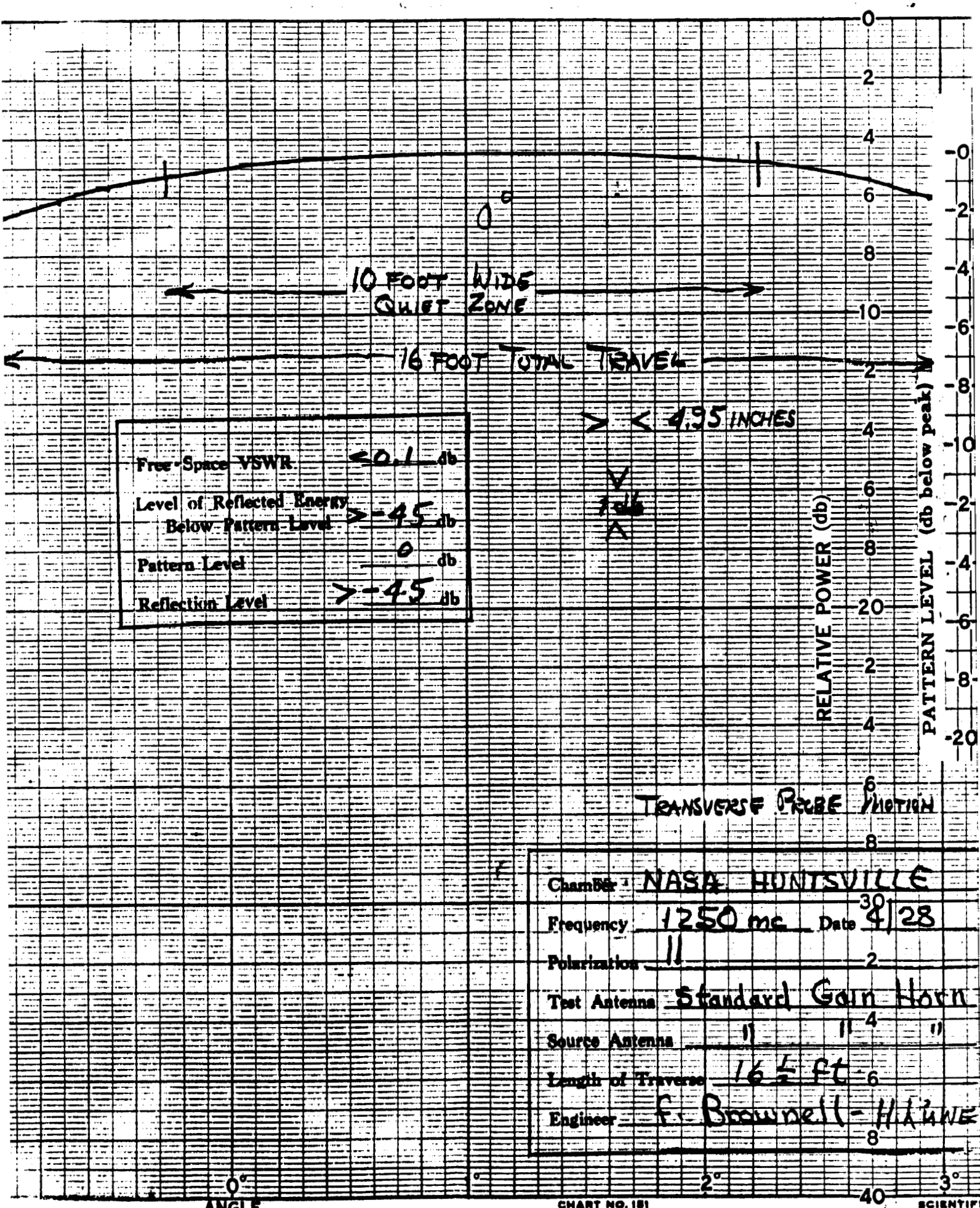
MR-32 "Measurement of the B.F. Goodrich Chamber at Martin-Orlando."

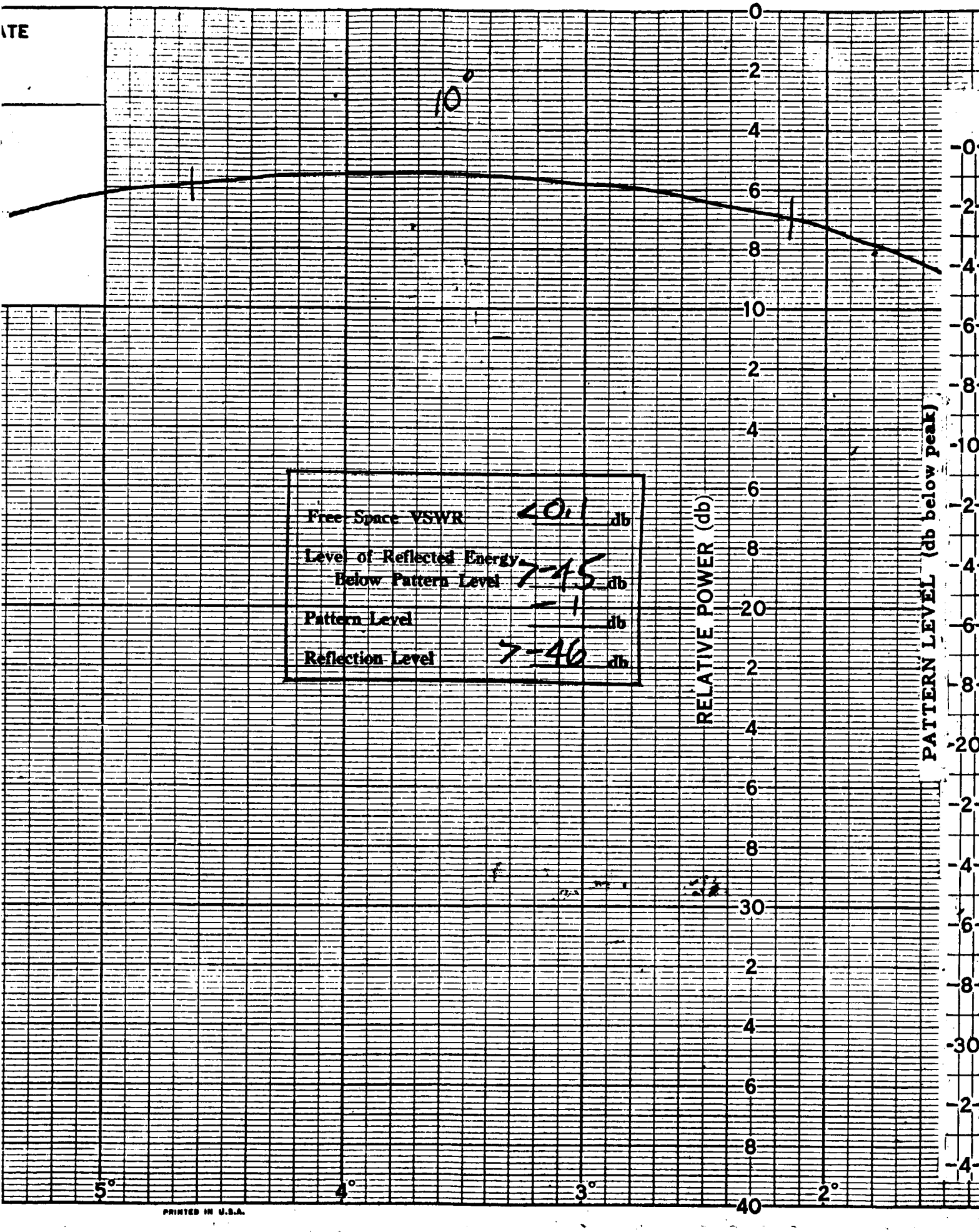
BASIC DATA

NASA has been provided with copies of all of the basic data recordings made by the B.F. Goodrich Company during measurement of the chamber and the outdoor range.

Copies of each of the 20 original recordings for one of the frequencies have been here attached to provide opportunity for others who might be interested to follow just how the basic data is used to develop plots of reflection level vs. aspect angle. The frequency in this case is 1.25 GHz. The plot of the actual reflection values that were determined from this particular data appears in Figure 4.2.

It will be noted that the highest VSWR encountered both across and along the quiet zone is used to determine reflection values for each angle. As a result the chamber is described in terms of its minimum performance.


0°
10 FOOT WIDE QUIET ZONE
16 FOOT TOTAL TRAVEL
> < 4.95 INCHES
Free-Space VSWR <0.1 db
Level of Reflected Energy Below Pattern Level >-45 db
Pattern Level 0 db
Reflection Level >-45 db
1 db
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
TRANSVERSE PROBE MOTION
Chamber NASA HUNTSVILLE
Frequency 1250 mc Date 4/28
Polarization ||
Test Antenna Standard Gain Horn
Source Antenna " " "
Length of Traverse 16 ½ ft
Engineer F. Brownell - H. Lune
ANGLE
CHART NO. 151
SCIENTIFI



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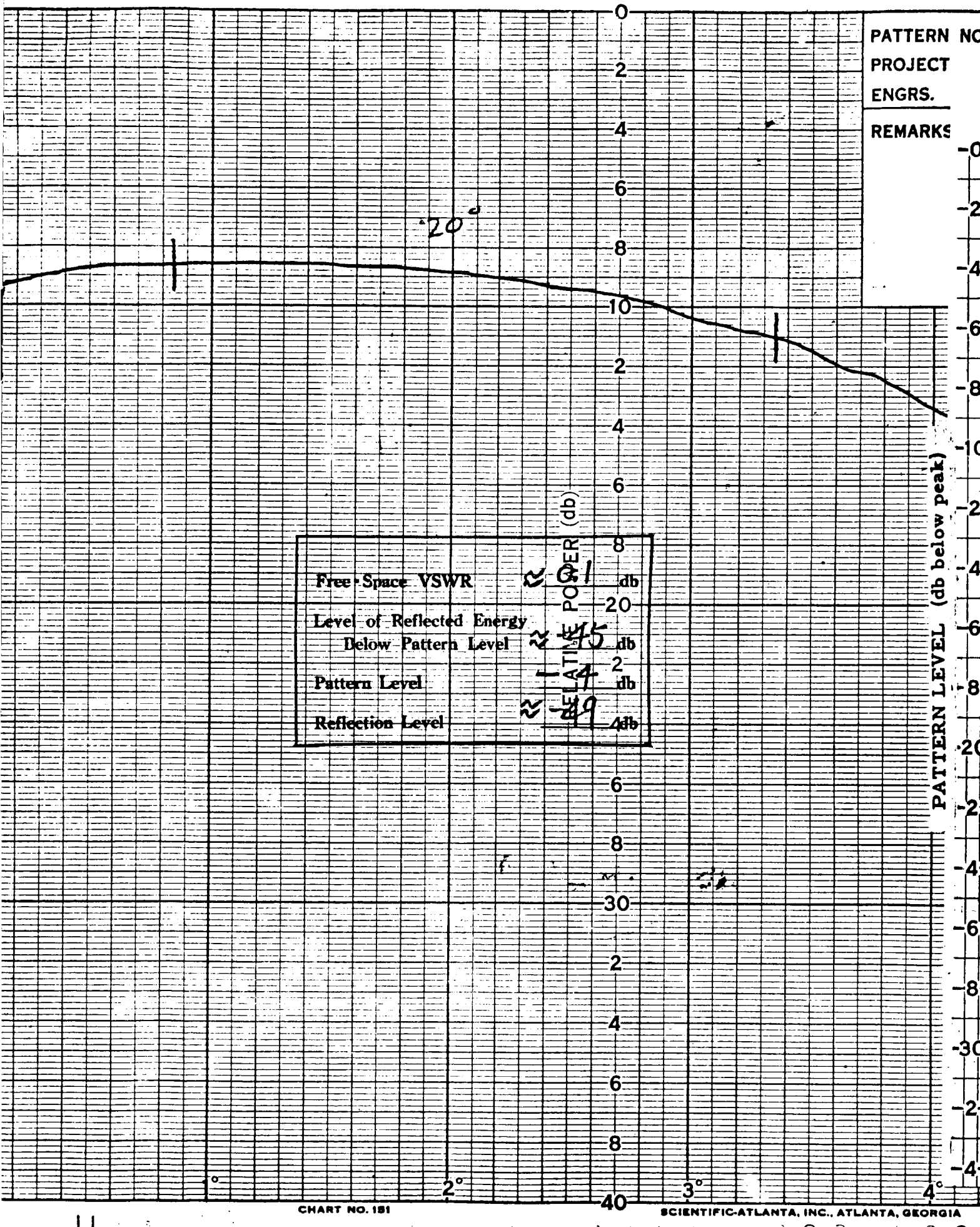
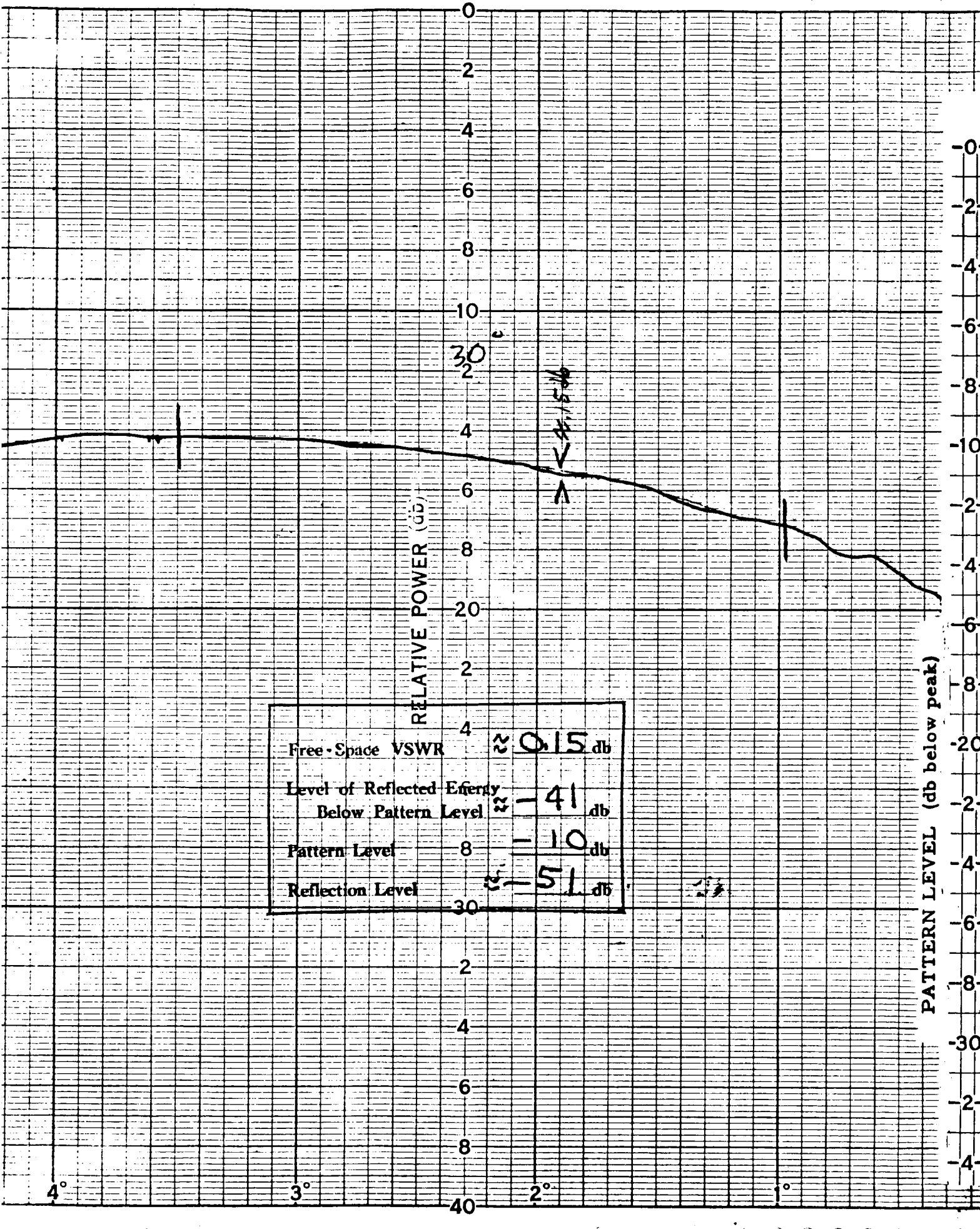
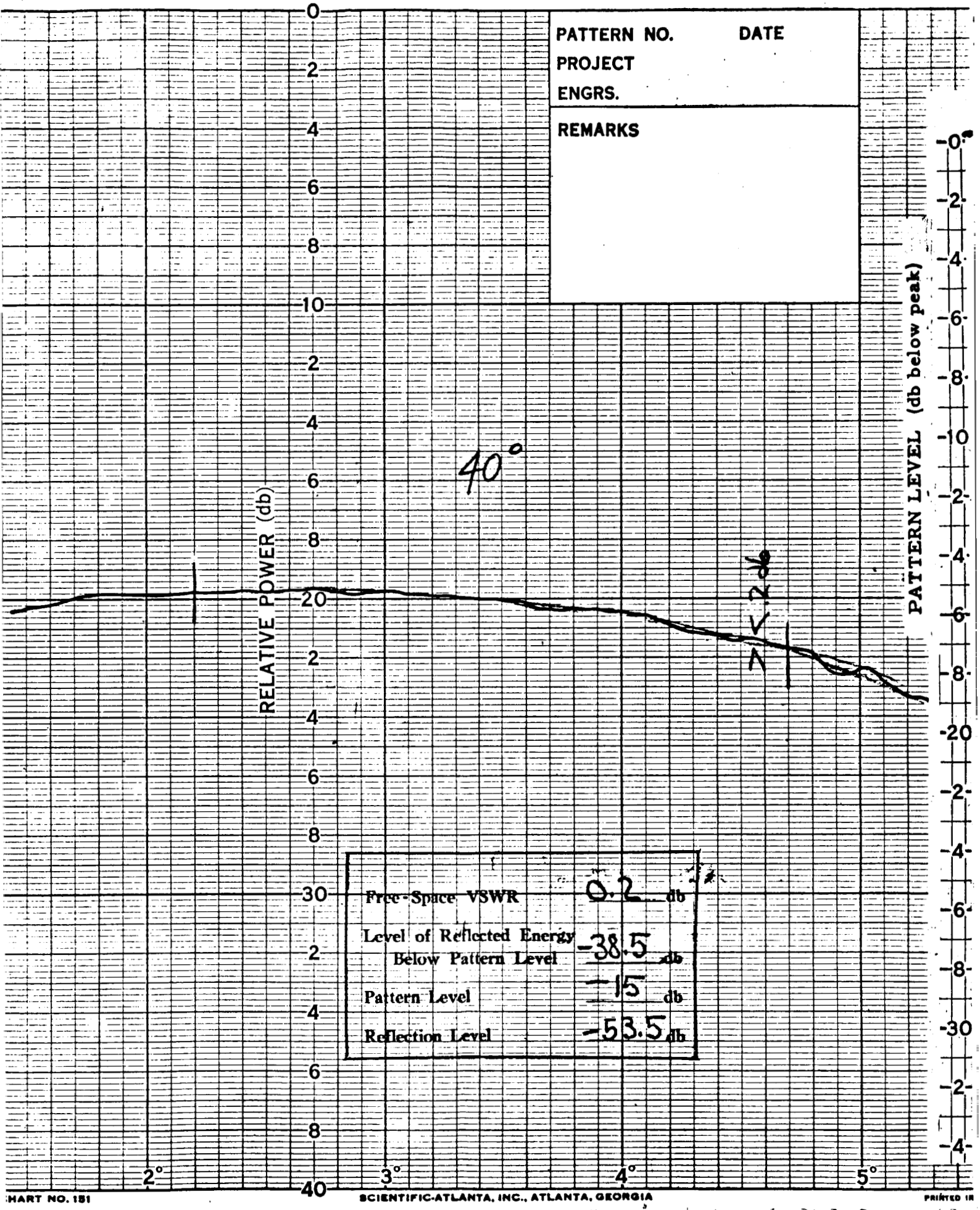
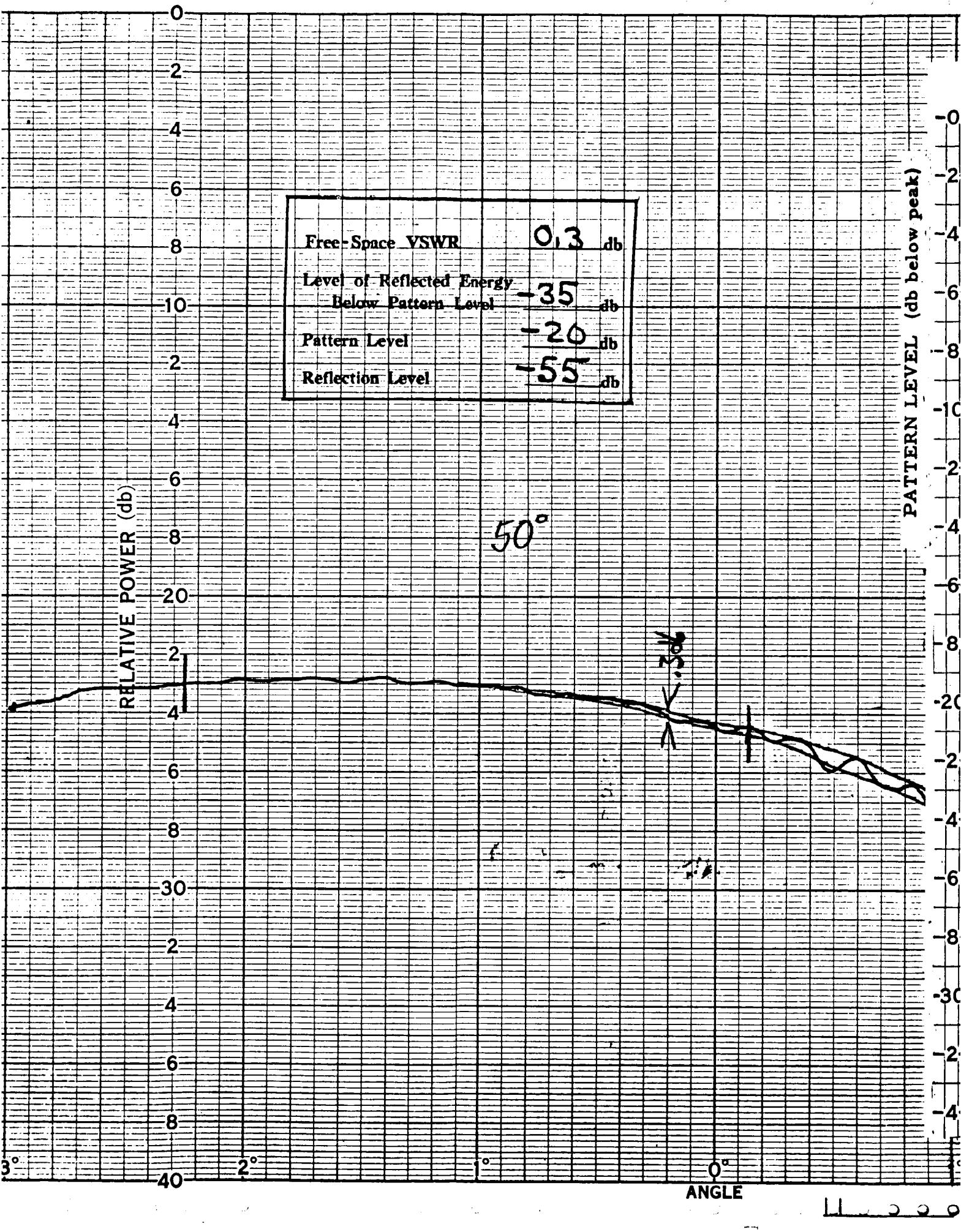

PATTERN NO
PROJECT
ENGRS.
REMARKS
20°
Free-Space VSWR ≈ 1 db
Level of Reflected Energy Below Pattern Level ≈ -15 db
Pattern Level -14 db
Reflection Level ≈ -29 db
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
1°
2°
3°
4°
CHART NO. 151
SCIENTIFIC-ATLANTA, INC., ATLANTA, GEORGIA


RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
4°
3°
2°
1°
30°
Free-Space VSWR ≈ 0.15 db
Level of Reflected Energy Below Pattern Level ≈ -41 db
Pattern Level -10 db
Reflection Level ≈ -51 db


PATTERN NO.
DATE
PROJECT
ENGRS.
REMARKS
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
40°
2°
3°
4°
5°
Free-Space VSWR 0.2 db
Level of Reflected Energy Below Pattern Level -38.5 db
Pattern Level -15 db
Reflection Level -53.5 db


Free-Space VSWR 0.3 db
Level of Reflected Energy Below Pattern Level -35 db
Pattern Level -20 db
Reflection Level -55 db
50°
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
ANGLE
3°
2°
1°
0°

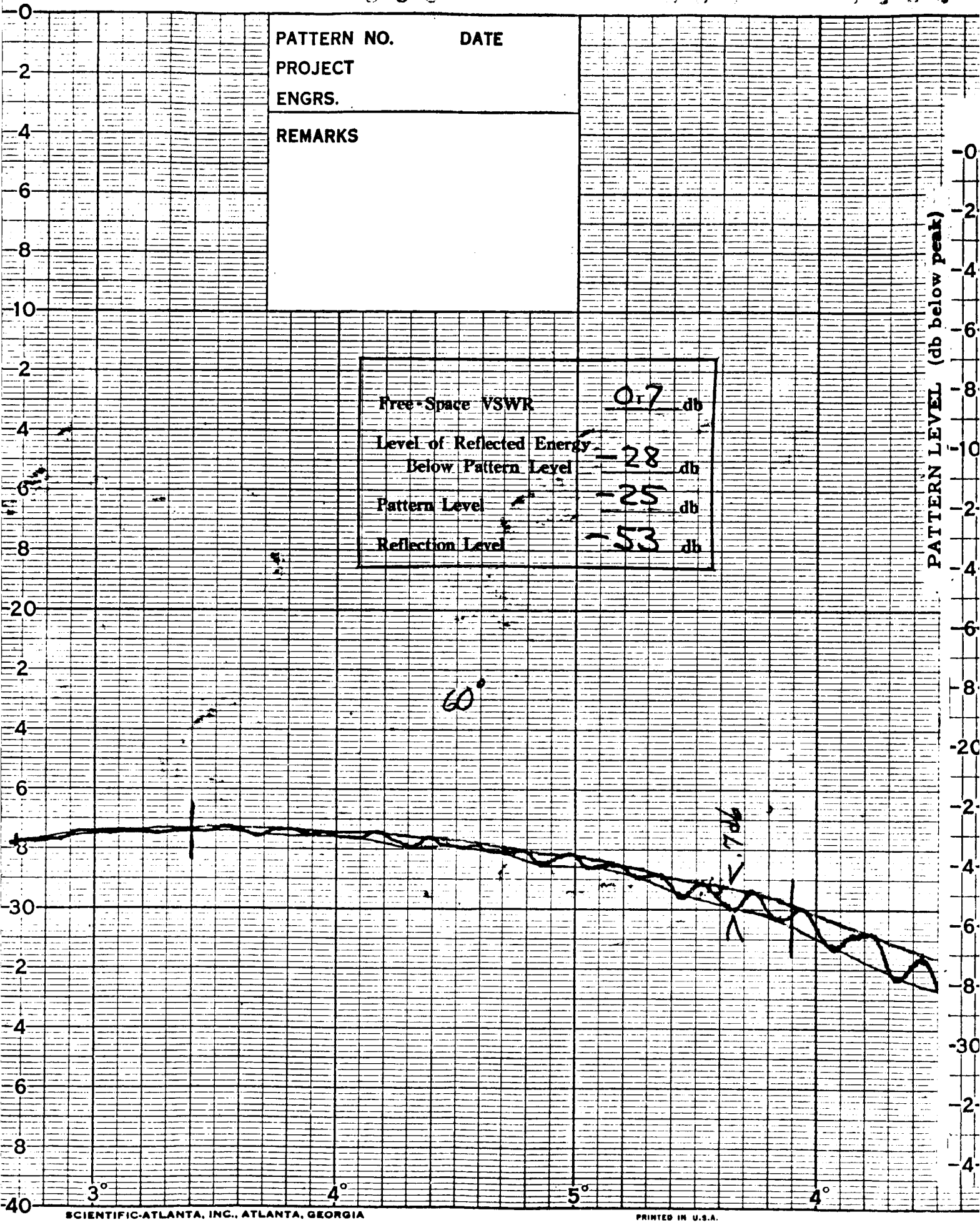
PATTERN NO. DATE

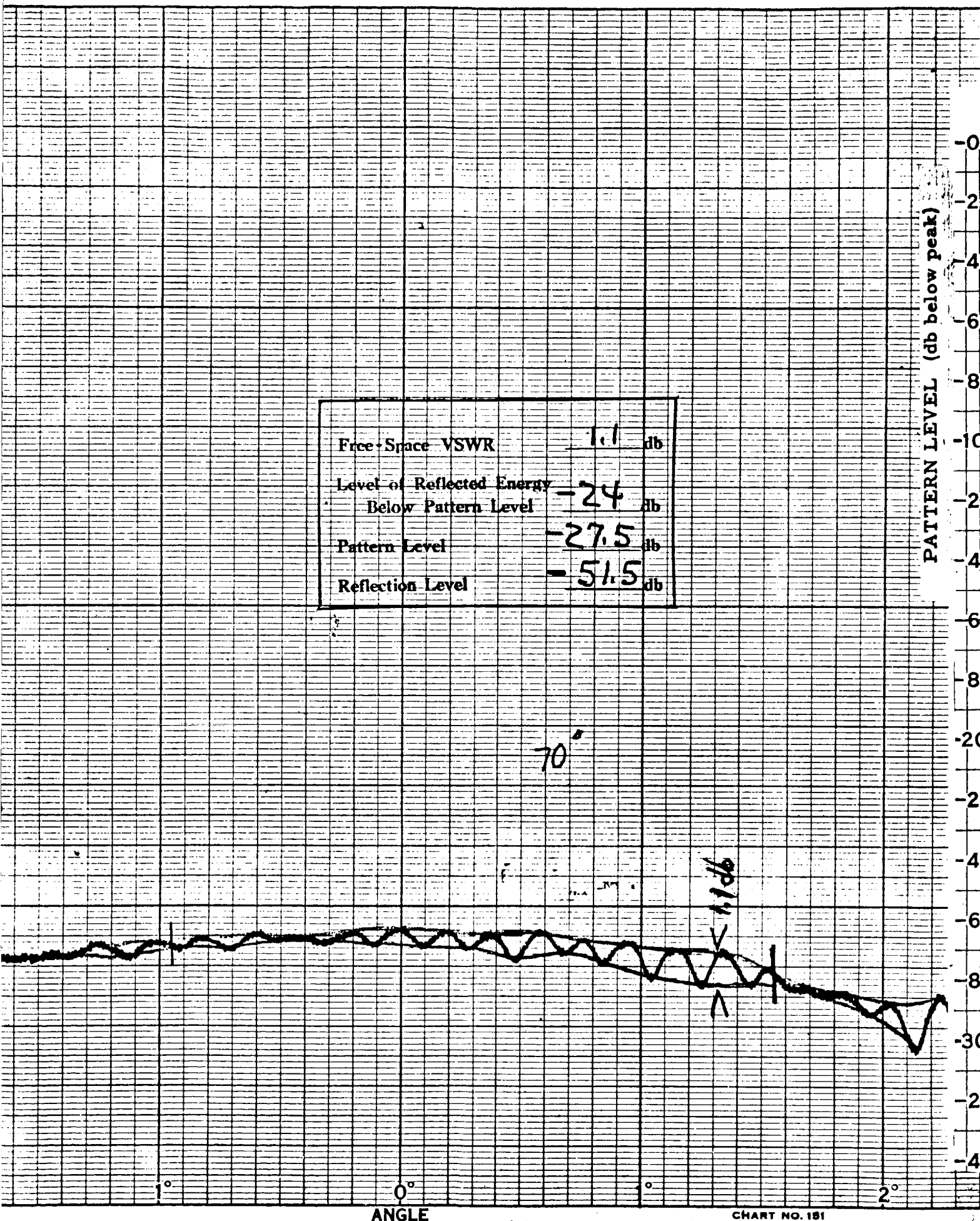
PROJECT

ENGRS.

REMARKS

Free-Space VSWR	0.7	db
Level of Reflected Energy Below Pattern Level	-28	db
Pattern Level	-25	db
Reflection Level	-53	db




Free-Space VSWR 1.1 db
Level of Reflected Energy Below Pattern Level -24 db
Pattern Level -27.5 db
Reflection Level -51.5 db
70°
1.1 db
PATTERN LEVEL (db below peak)
-0
-2
-4
-6
-8
-10
-2
-4
-6
-8
-20
-2
-4
-6
-8
-30
-2
-4
1°
0°
1°
2°
ANGLE
CHART NO. 151

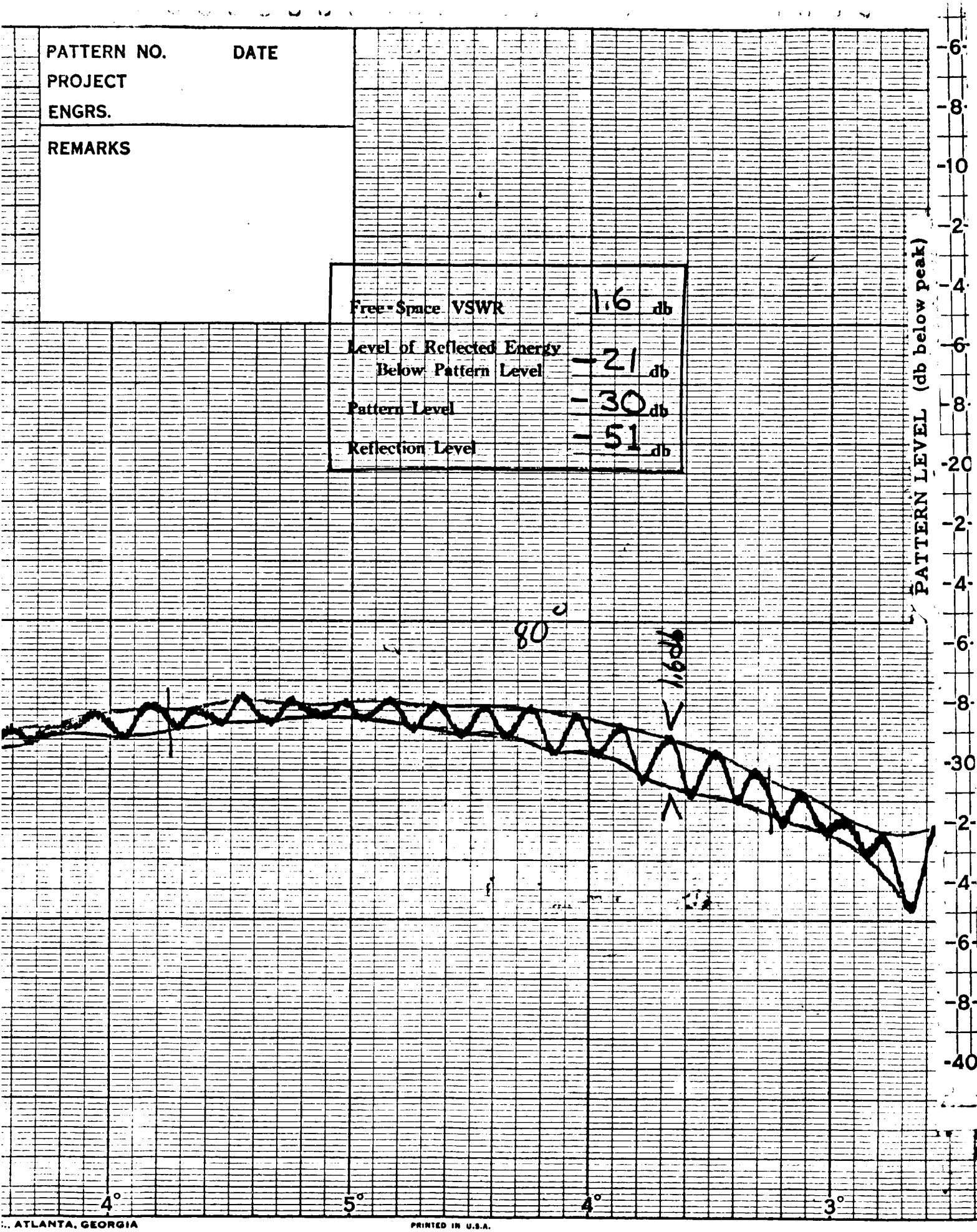
PATTERN NO. DATE

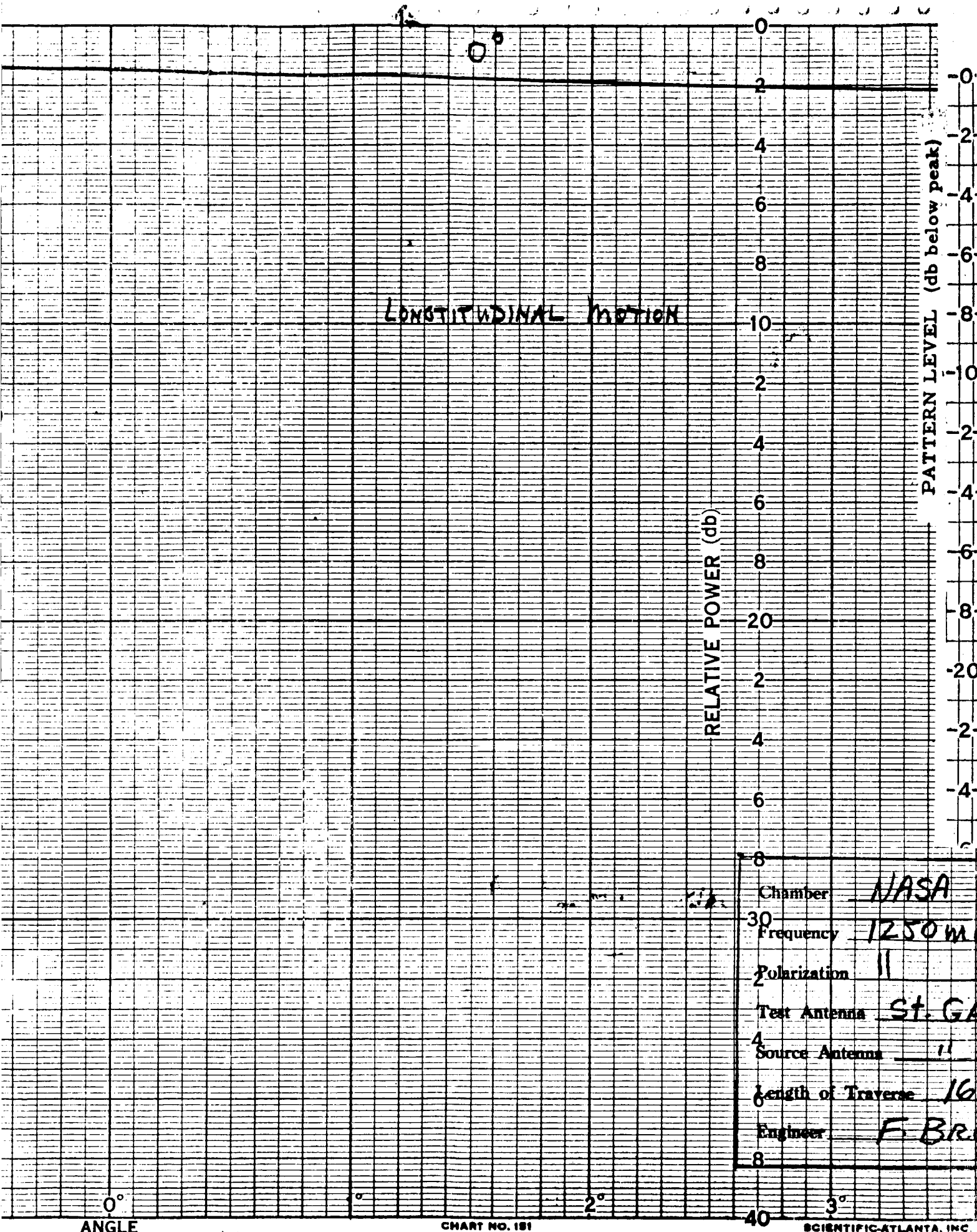
PROJECT

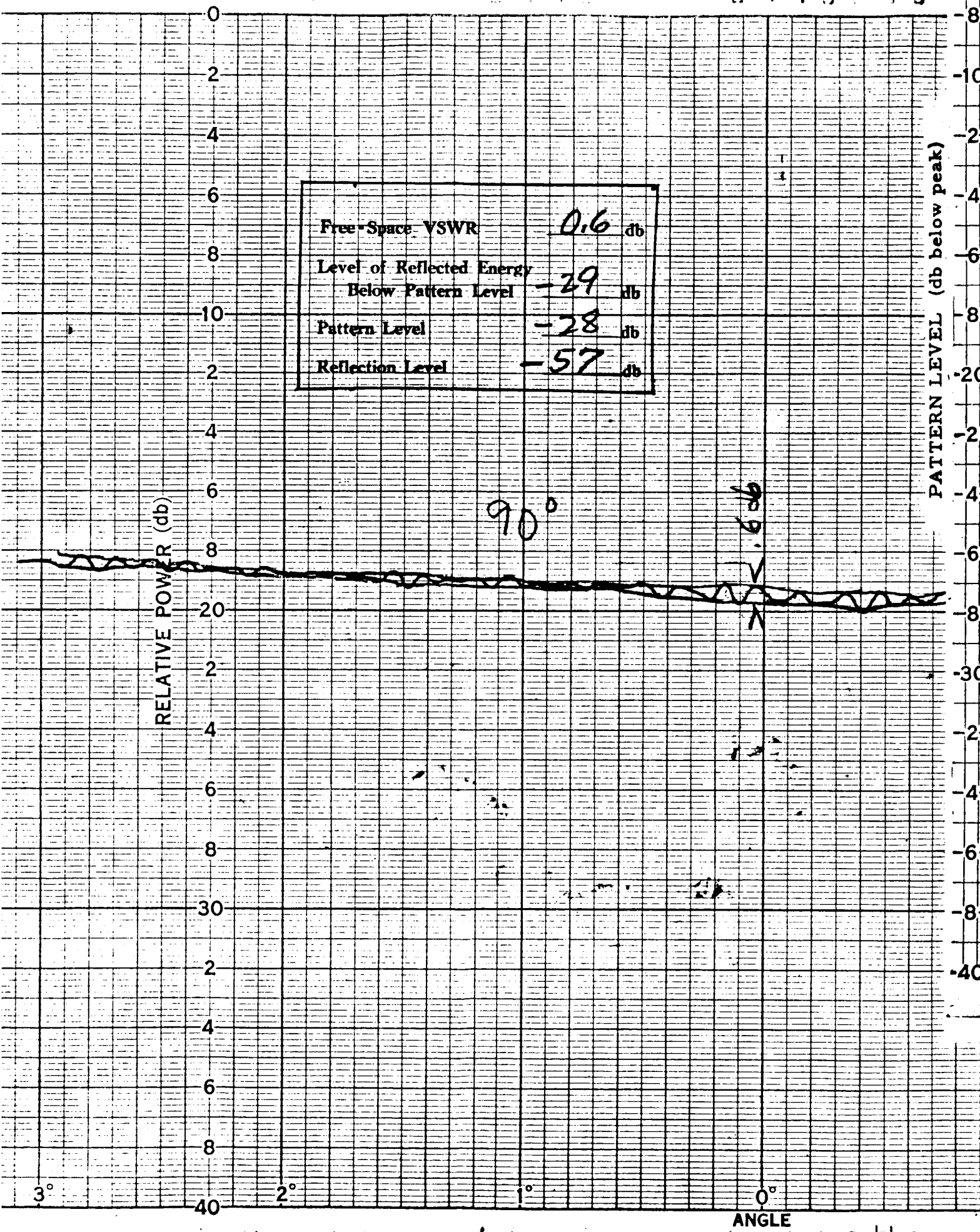
ENGRS.

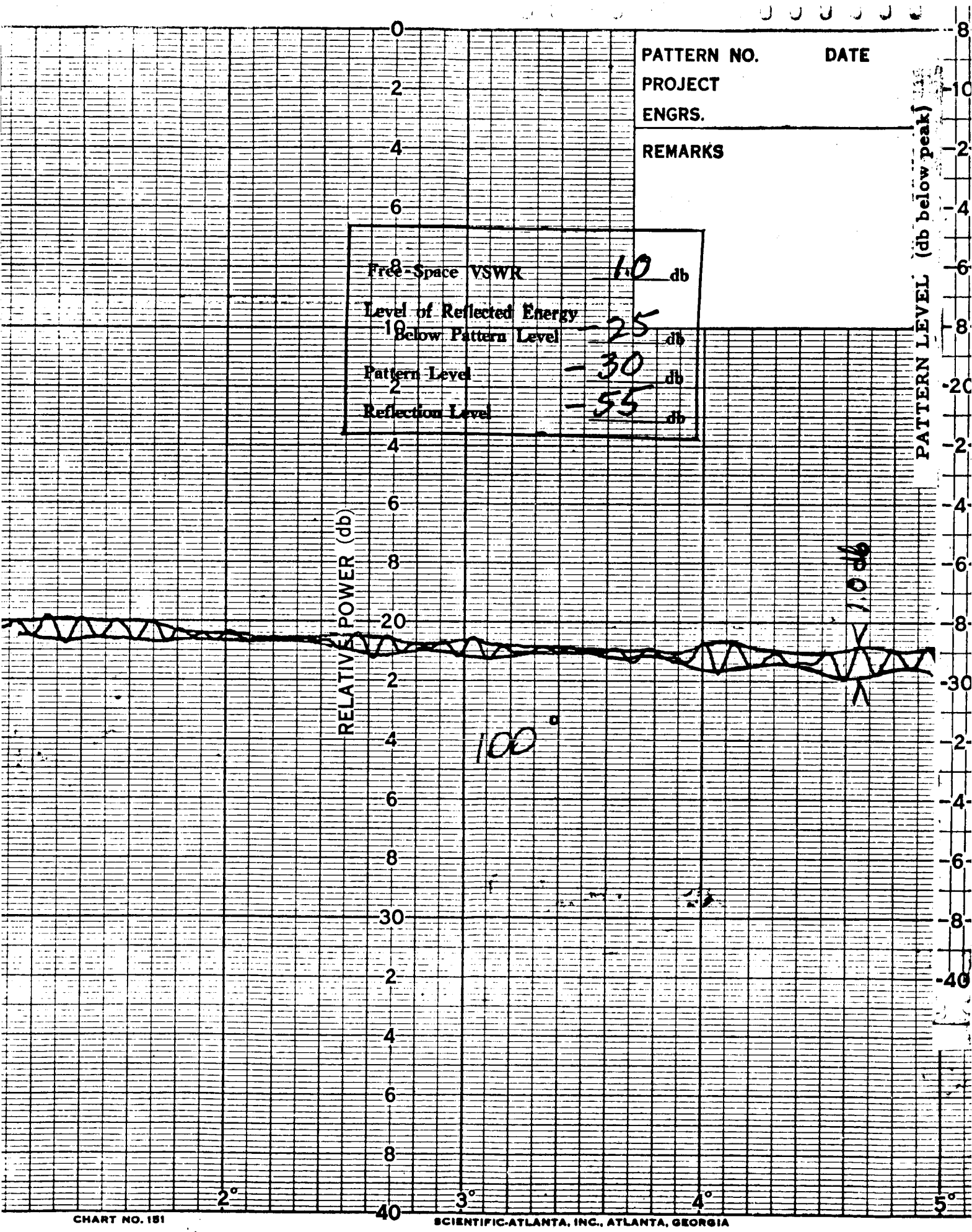
REMARKS

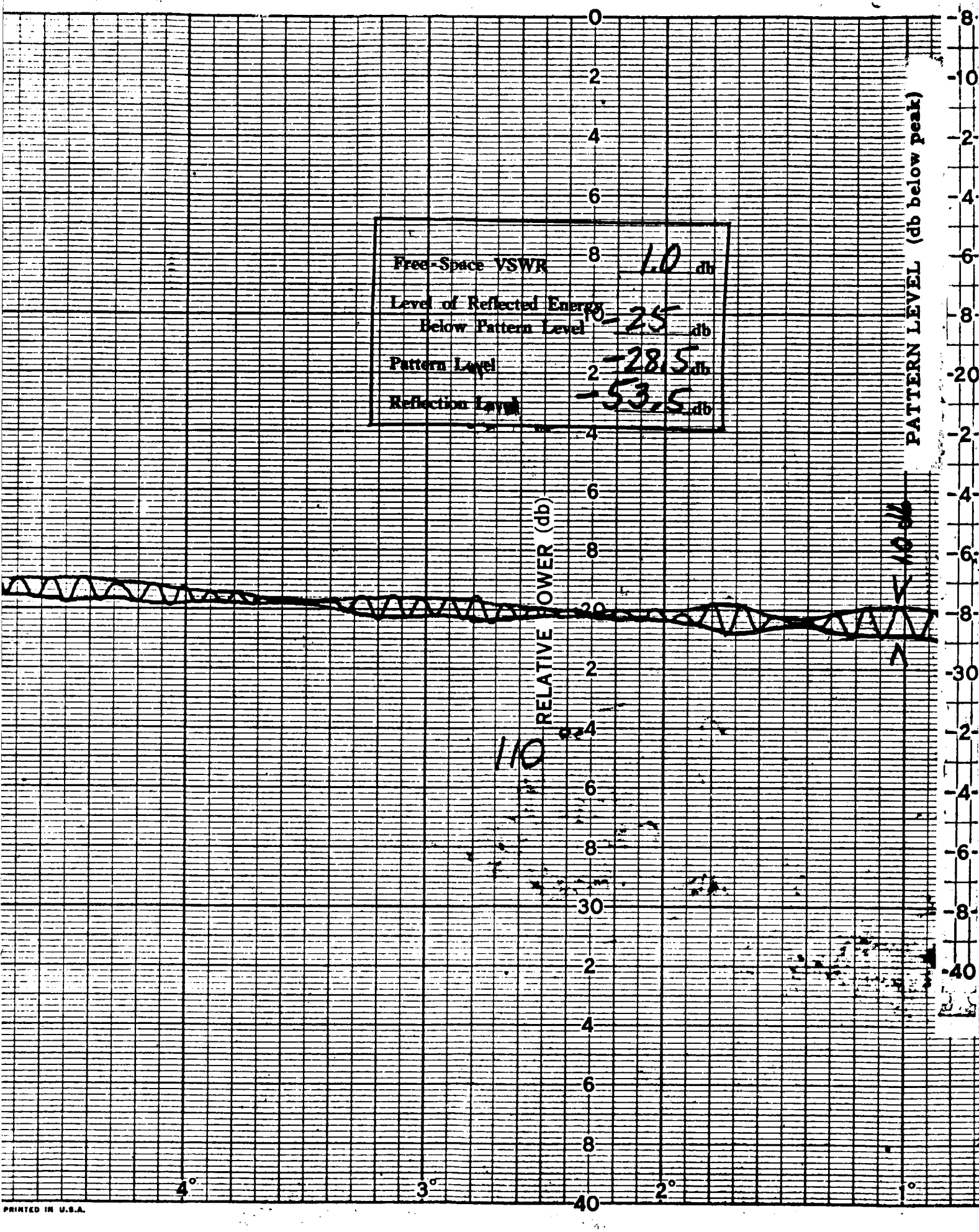
Free-Space VSWR	1.6 db
Level of Reflected Energy Below Pattern Level	-21 db
Pattern Level	-30 db
Reflection Level	-51 db




0°
LONGITUDINAL MOTION
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
0
2
4
6
8
10
2
4
6
8
20
2
4
6
8
30
2
4
6
8
40
-0
-2
-4
-6
-8
-10
-2
-4
-6
-8
-20
-2
-4
0°
1°
2°
3°
ANGLE
Chamber NASA
Frequency 1250 M
Polarization ||
Test Antenna St. GA
Source Antenna "
Length of Traverse 16
Engineer F. BR
CHART NO. 151
SCIENTIFIC-ATLANTA, INC.


Free-Space VSWR 0.6 db
Level of Reflected Energy Below Pattern Level -29 db
Pattern Level -28 db
Reflection Level -57 db
90°
0.6 db
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
ANGLE
3°
2°
1°
0°


PATTERN NO.
DATE
PROJECT
ENGRS.
REMARKS
Free-Space VSWR 10 db
Level of Reflected Energy Below Pattern Level -25 db
Pattern Level -30 db
Reflection Level -55 db
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
100°
10 db
2°
3°
4°
5°
CHART NO. 151
SCIENTIFIC-ATLANTA, INC., ATLANTA, GEORGIA



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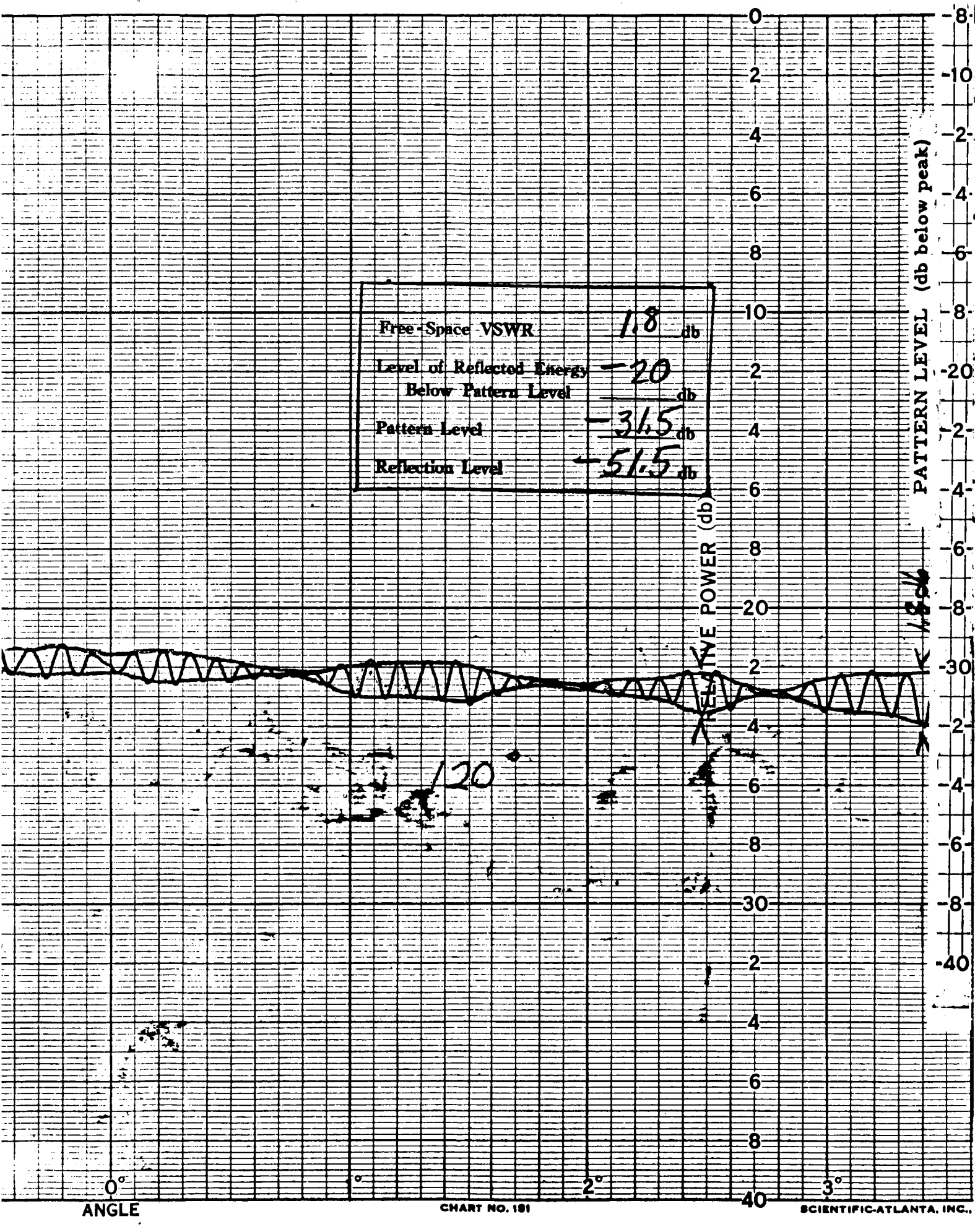
Free-Space VSWR 1.8 db
Level of Reflected Energy Below Pattern Level -20 db
Pattern Level -31.5 db
Reflection Level -51.5 db
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
120°
0°
1°
2°
3°
ANGLE
CHART NO. 181
SCIENTIFIC-ATLANTA, INC.

ERN NO. DATE

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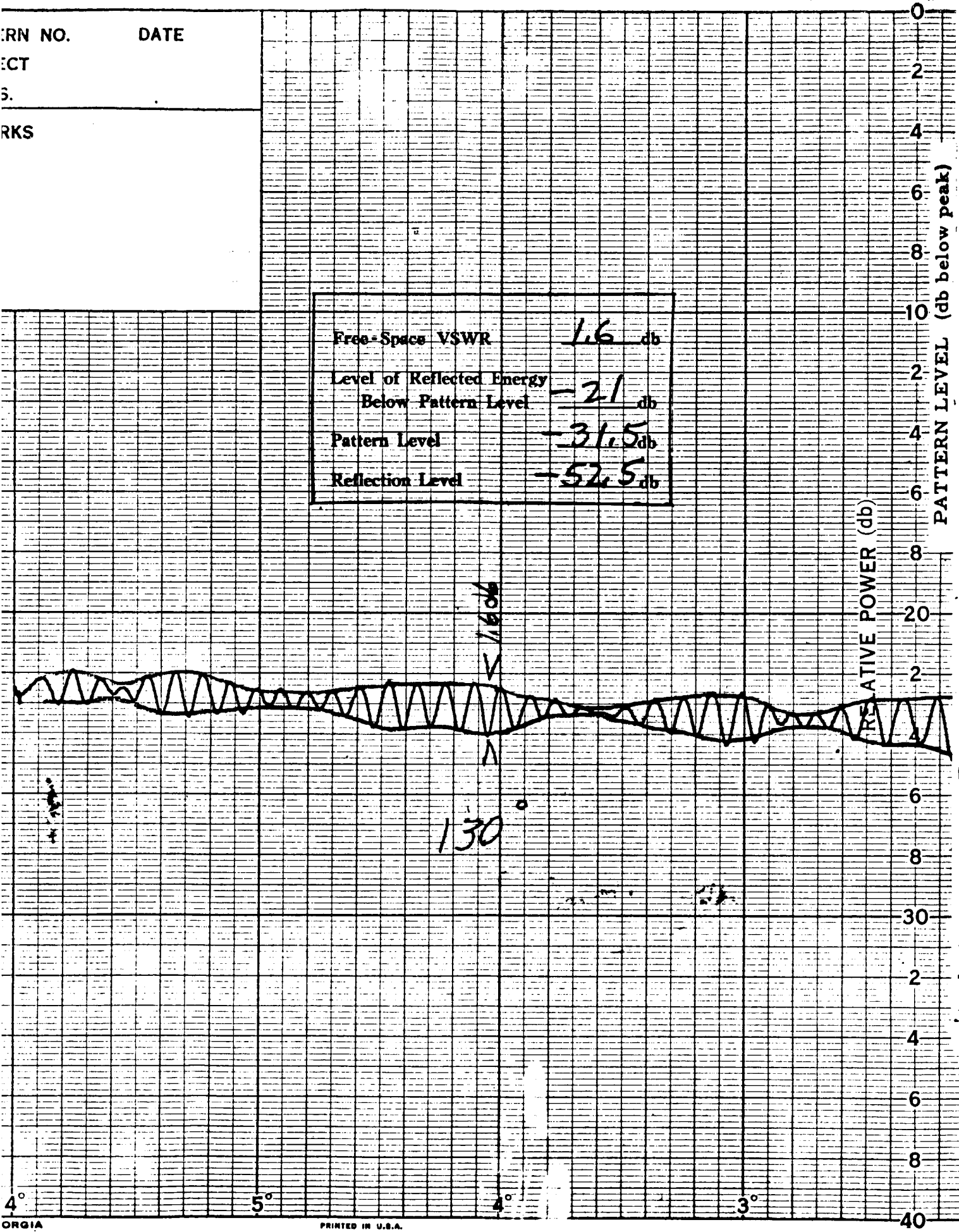
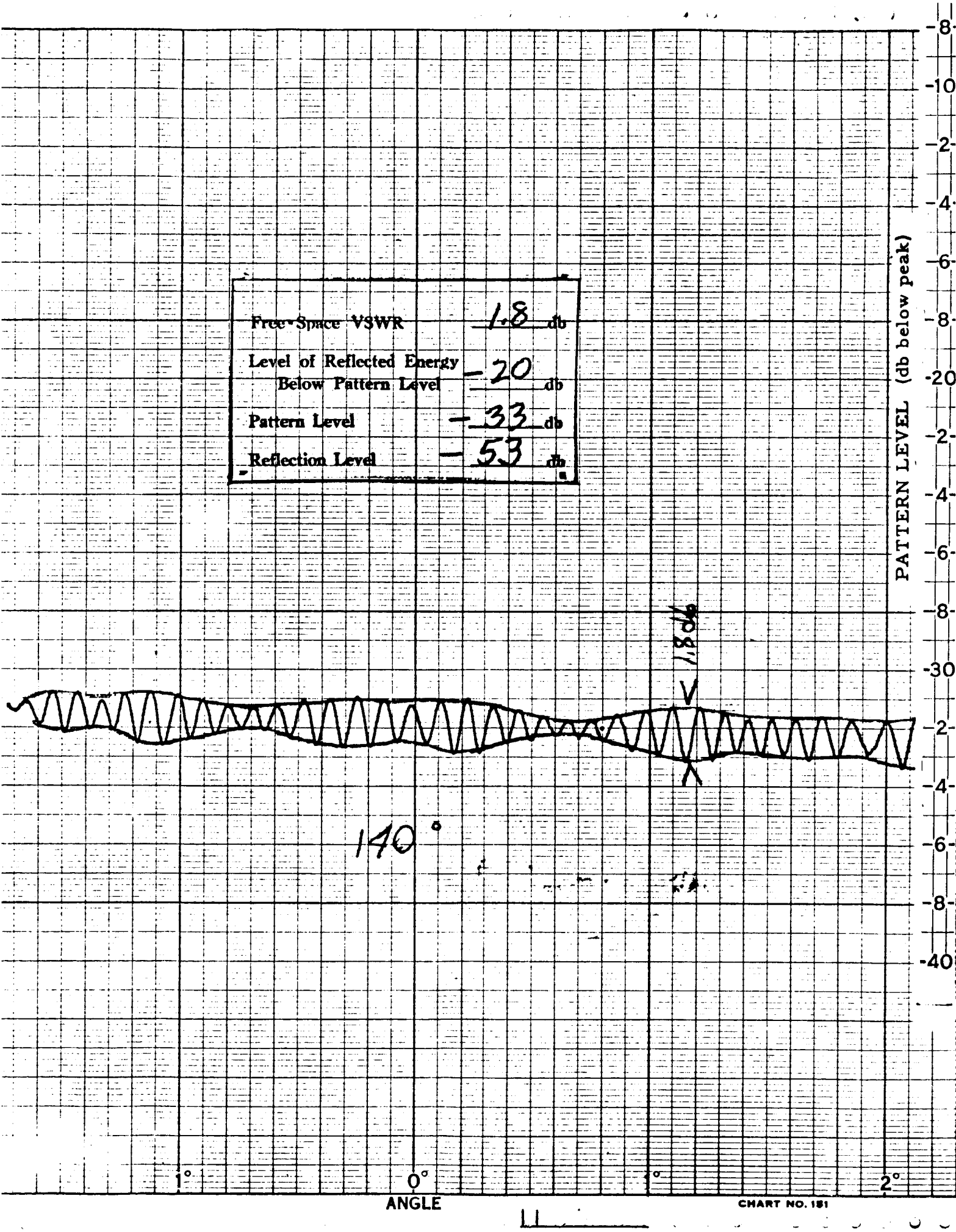
Free-Space VSWR	1.6 db
Level of Reflected Energy Below Pattern Level	-21 db
Pattern Level	-31.5 db
Reflection Level	-52.5 db




Free-Space VSWR 1.8 db
Level of Reflected Energy Below Pattern Level -20 db
Pattern Level -33 db
Reflection Level -53 db
1.8 db
140°
PATTERN LEVEL (db below peak)
-8
-10
-2
-4
-6
-8
-20
-2
-4
-6
-8
-30
-2
-4
-6
-8
-40
1°
0°
1°
2°
ANGLE
CHART NO. 151

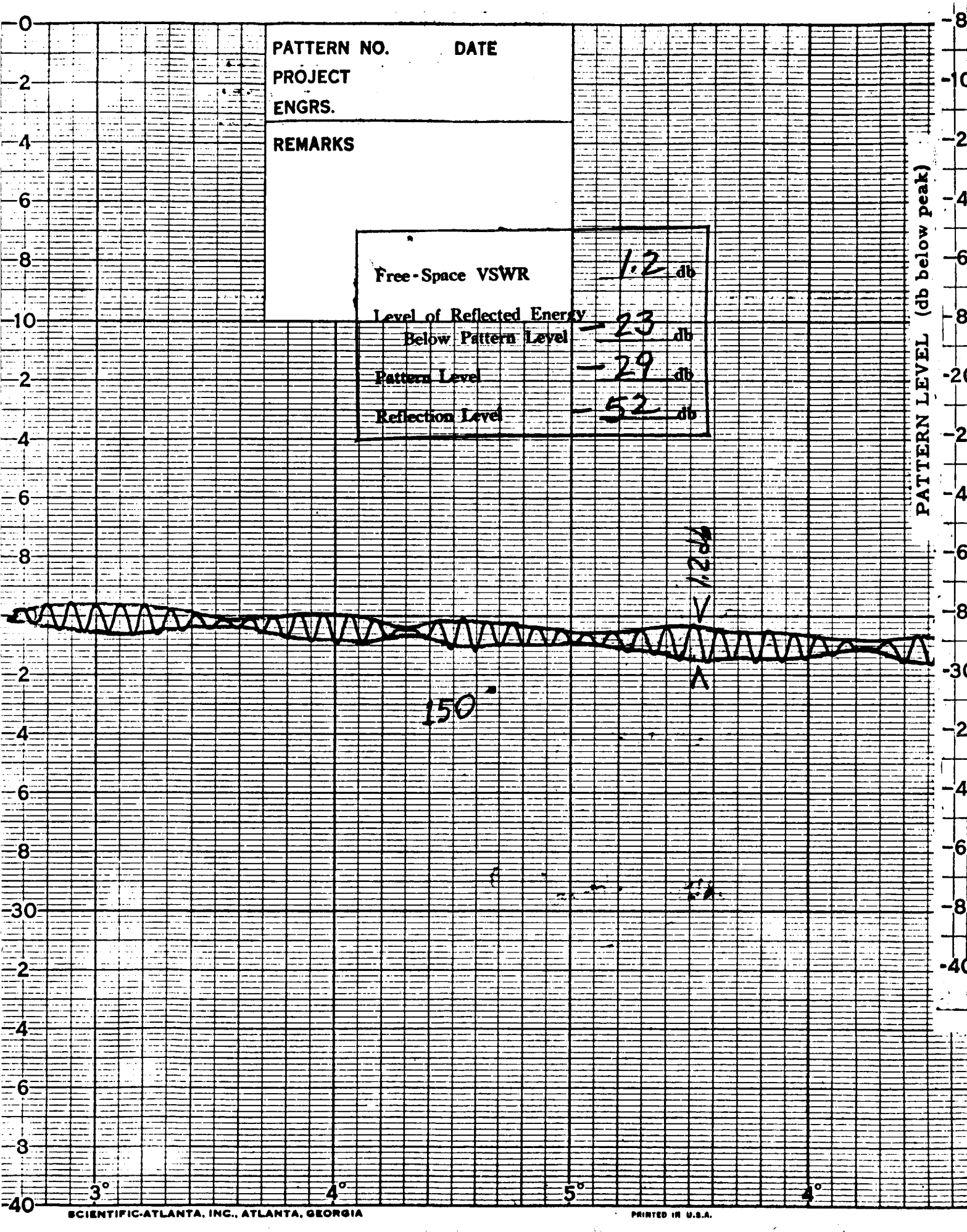
PATTERN NO. DATE

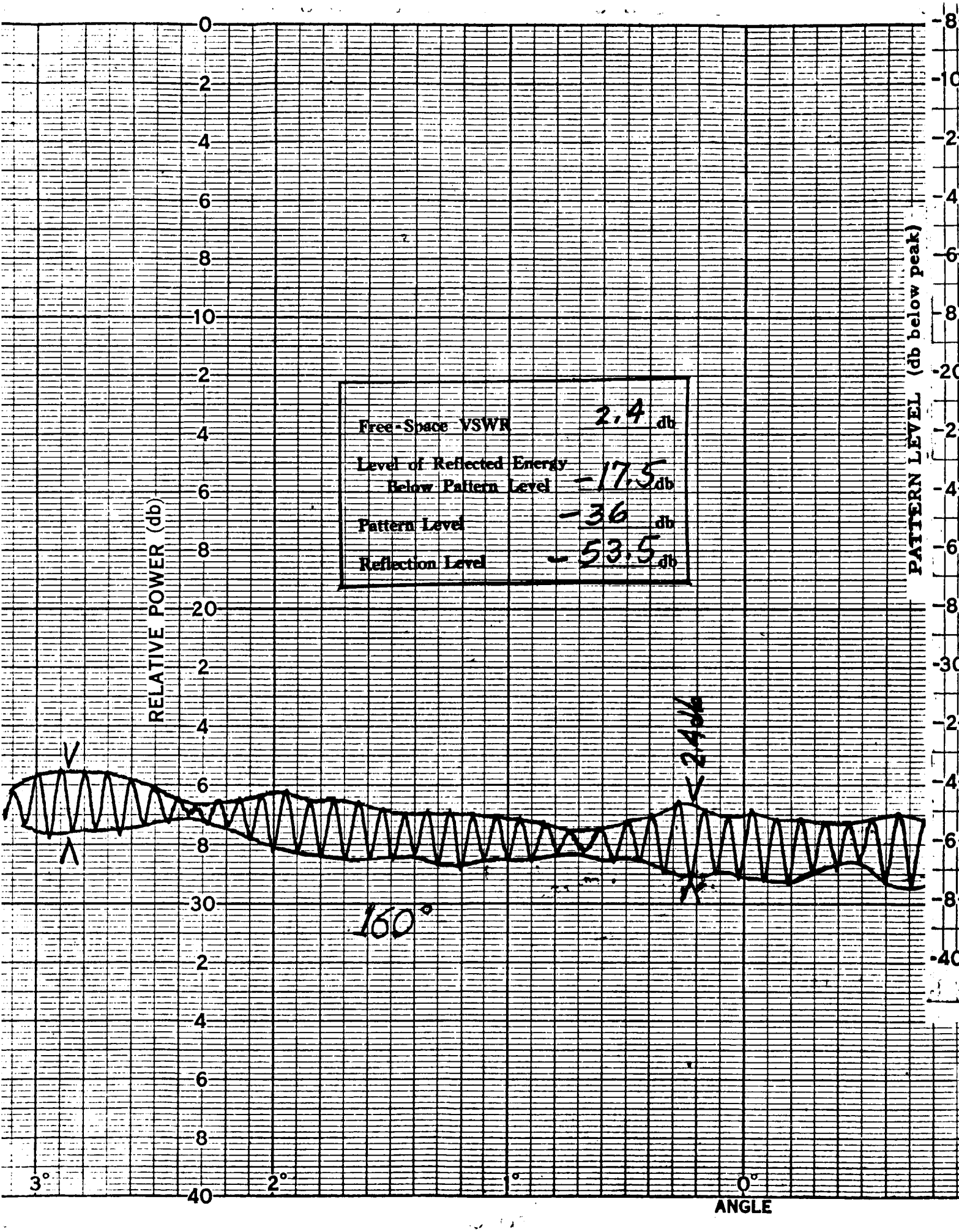
PROJECT

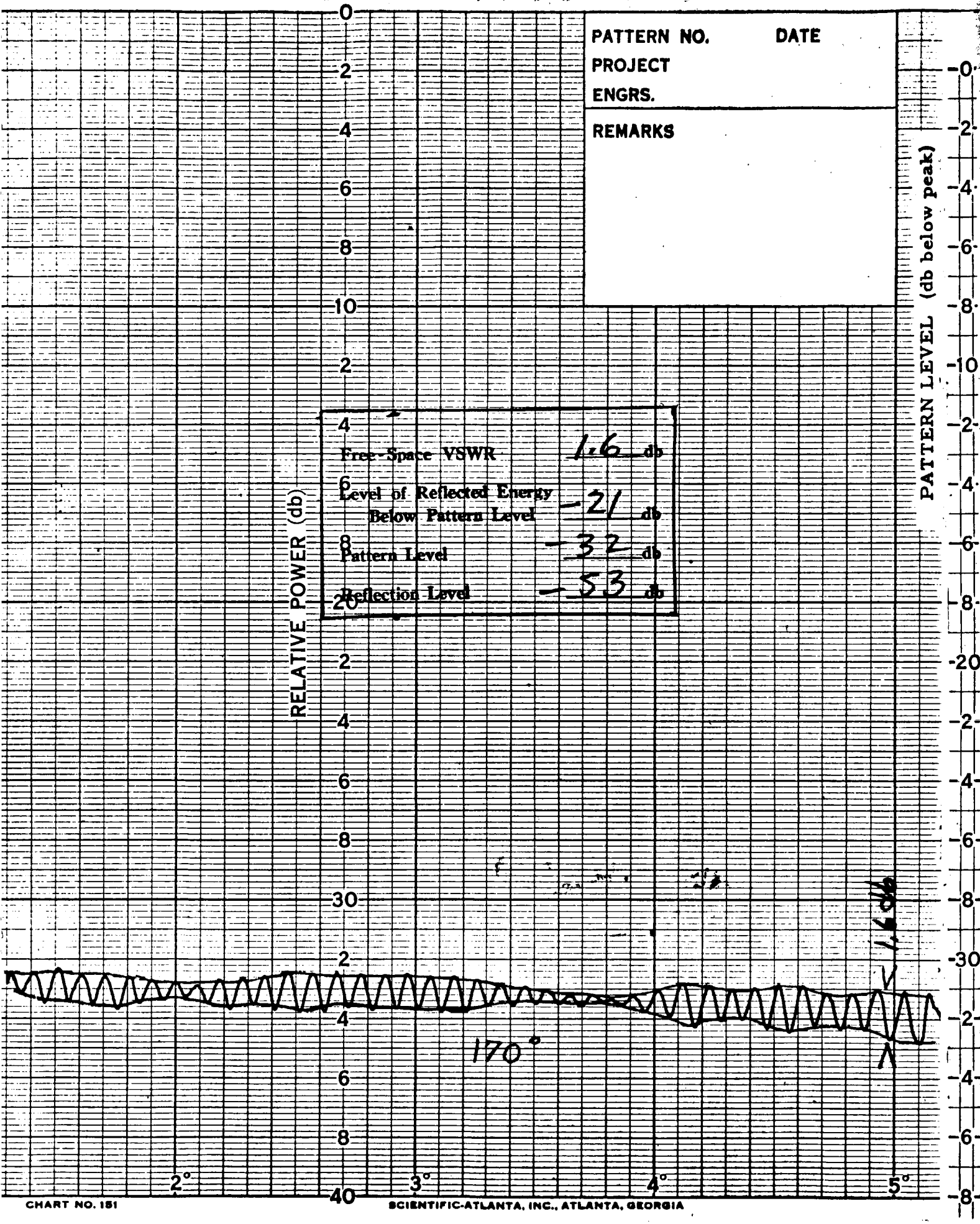
ENGRS.

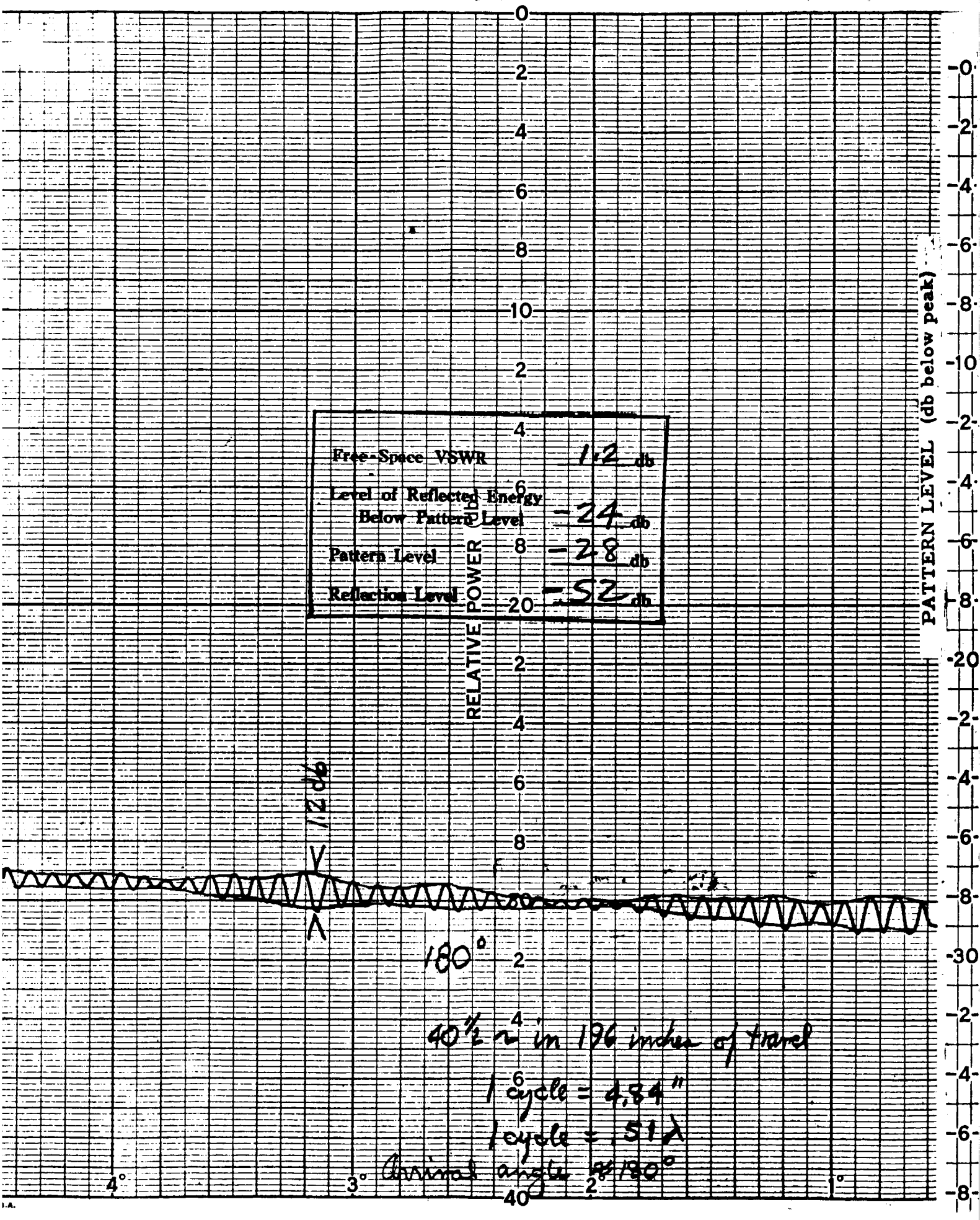
REMARKS

Free-Space VSWR	1.2 db
Level of Reflected Energy Below Pattern Level	-23 db
Pattern Level	-29 db
Reflection Level	-52 db




RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
ANGLE
3°
2°
1°
0°
Free-Space VSWR 2.4 db
Level of Reflected Energy Below Pattern Level -17.5 db
Pattern Level -36 db
Reflection Level -53.5 db
2.4 db
160°


PATTERN NO.
DATE
PROJECT
ENGRS.
REMARKS
Free-Space VSWR 1.6 db
Level of Reflected Energy Below Pattern Level -21 db
Pattern Level -32 db
Reflection Level -53 db
RELATIVE POWER (db)
PATTERN LEVEL (db below peak)
1.6 db
170°
2°
3°
4°
5°
CHART NO. 151
SCIENTIFIC-ATLANTA, INC., ATLANTA, GEORGIA


Free-Space VSWR 1.2 db
Level of Reflected Energy Below Pattern Level -24 db
Pattern Level -28 db
Reflection Level -52 db
RELATIVE POWER db
PATTERN LEVEL (db below peak)
.72 db
180°
40½ ~ in 196 inches of travel
1 cycle = 4.84"
1 cycle = .51λ
Arrival angle ≈ 180°