Earth Station Antenna Sidelobe Characteristics

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EARTH STATION
ANTENNA SIDELOBE CHARACTERISTICS

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Measured analog data showing gain as a function of angle away from the mainbeam (maximum gain) axis have been obtained for 22 types of reflector antennas designed for operation at 4 GHz for reception and 6 GHz for transmission. The antennas ranged in size from 2.8 m to 13.0 m and represented six United States manufacturers. The analog patterns have been converted to sets of digital data pairs (gain and angle) to facilitate analysis. The data then have been analyzed following techniques recommended by the CCIR for antennas for earth stations in the Fixed-Satellite Service to develop statistical characterizations of gain versus angle for the sidelobe regions. The digitization and analysis techniques are discussed and statistical results are provided, along with some background material from the perspectives of the CCIR, the FCC, and antenna manufacturers.

Key words: antenna gain patterns; antenna sidelobe gain
             characteristics; earth station antenna gain;
             orbit spacing; reference antenna patterns;
             reference radiation diagrams; statistical
             antenna gain patterns

1. INTRODUCTION

When considering possible interference in the Fixed-Satellite Service, caused to another system or experienced from another system, the earth station antenna gain at angles away from the boresight axis (assumed to be coincident with the axis of maximum gain) is an important characteristic of the earth station antenna. It always is preferable to use actual diagrams from in situ measurements. Actual data, however, often are not available. Then, it is helpful to assume some reference** radiation diagram representing a gain level exceeded only by some small

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**The reference radiation diagram should be understood to describe an envelope of the minimally acceptable radiation diagram in the principle plane of the antenna for co-polarized coupling.

percentage of the sidelobe peaks. Reducing the off-axis, or sidelobe, gain can be used as an effective discriminant against radio frequency interference. Control of these sidelobe gain characteristics, therefore, has been a matter of considerable concern from an international as well as national point of view, and recommendations have been developed for maximum allowable gain in these sidelobe regions. These concerns from an international viewpoint (reports and recommendations by the International Radio Consultative Committee, or CCIR) are summarized in Section 1.1. The concerns from a national viewpoint (reports and recommendations by the Federal Communications Commission, or FCC) are summarized in Section 1.2. The viewpoints of antenna manufacturers and users are summarized in Section 1.3.

1.1 Background from the CCIR Perspective (CCIR, Vol. IV, 1982)

Question 1/4 pertaining to "Antennas For Systems in the Fixed-Satellite Service" was developed in 1961 and modified most recently in 1974. It now is designated as Question 1-2/4. A part of that question asks "what is the state of development in the design and fabrication of antennas particularly with improved side- and back-lobe characteristics?" Subsequently, three Study Programmes were established to encourage studies on (1) "Reference Radiation Diagram of Antennae at Earth Stations in the Fixed-Satellite Service" - (1A-1/4), (2) "Radiation Characteristics of Satellite Antennae in the Fixed-Satellite Service" (1B-4), and (3) "Characteristics of Antennae at Earth Stations in the Fixed Satellite Service" (1C-1/4).

The antenna sidelobe characteristics study we have conducted responds, primarily, to Study Programme 1A-1/4, which urges that studies be carried out to determine a reference radiation pattern for coordination and interference calculations and as a design objective for new antennas with low sidelobe levels.

In response to Question 1/4 and Study Programme 1A/4, Reports 391 and 390 were adopted in 1966. There were revisions to each report in 1970, 1974, 1978, and 1982; therefore current designations are 391-4 and 390-4. Report 391-4 presents data on and recommendations for radiation diagrams of antennas for earth stations in the Fixed-Satellite Service. Report 390-4 presents more general discussion of desired characteristics for earth station antennas for the Fixed-Satellite Service.

Report 391-4 presents data used as a basis for several recommendations regarding reference radiation diagrams. These informal recommendations have been adopted formally as Recommendation 465-1 for a "Reference Earth-Station Radiation Pattern for Use in Coordination and Interference Assessment in the Frequency Range from 2 to about 10 GHz" and Recommendation 580 for "Radiation Diagrams for Use as Design Objectives for Antennas of Earth Stations Operating with Geostationary Satellites."

From Report 391-4 and Recommendation 465-1, the recommended sidelobe reference radiation diagram for antennas with diameter-to-wavelength ratio (D/λ) greater than 100 is

$$G(\phi) = \begin{cases} 32 - 25 \log \phi \text{ dBi} & \text{for} \quad 1^\circ \leq \phi < 48^\circ \\ -10 \text{ dBi} & \text{for} \quad 48^\circ \leq \phi \leq 180^\circ \ . \end{cases} \tag{1}$$

The envelope defined by (1) is shown in Figure 1.
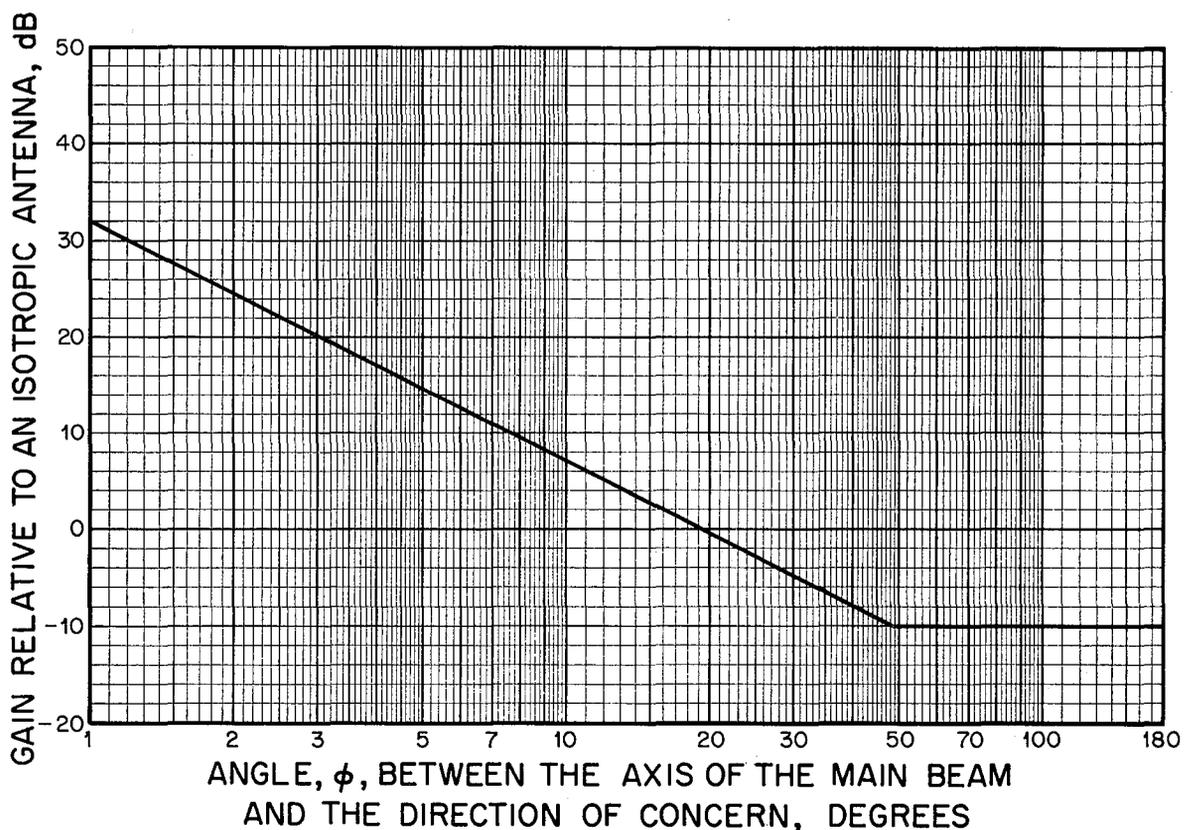
Figure 1. Reference radiation diagram from CCIR Report 391-4 and adopted in Recommendation 461-1 for earth station antennas with $D/\lambda > 100$.

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The CCIR uses the Greek letter ϕ (phi) as the symbol to represent the angle, in degrees, between the mainbeam axis and the direction of concern. The FCC, in their equations, uses the symbol θ (theta) to represent the same angle. We use ϕ (phi) in this report, except in those instances where the FCC has been quoted, to designate this angle.

A recommended sidelobe reference diagram for antennas with $D/\lambda < 100$ is not included in Recommendation 461-1. Suggested sidelobe reference radiation diagrams are included in Report 391-4 for antennas with $D/\lambda < 100$. However, the report is inconsistent in this regard. From the main text (see Section 2.3), one concludes that for $D/\lambda < 100$ the suggested reference radiation diagram is

$$G(\phi) = \begin{cases} 52-10\ \log(D/\lambda) - 25\ \log\phi\ \text{dBi} & \text{for } 100\ \lambda/D \le \phi < \phi_i \\ -10\ \text{dBi} & \text{for } \phi_i \le \phi \le 180° \end{cases} \quad (2)$$

where $\phi_i = \log^{-1}[2.48 - 0.4\ \log(D/\lambda)]$.

Annex 1 to Report 391-4, however, defines reference antenna patterns adopted at the WARC-79. For antennas with $D/\lambda < 100$, the reference antenna pattern given in Annex 1 is

$$G(\phi) = \begin{cases} 52 - 10\ \log(D/\lambda) - 25\ \log\phi\ \text{dBi} & \text{for } 100\ (\lambda/D) \le \phi < 48° \\ 10 - 10\ \log(D/\lambda) \quad\quad\quad \text{dBi} & \text{for } \quad 48° \le \phi \le 180°. \end{cases} \quad (3)$$

The envelopes corresponding to (2) and (3) above are shown in Figure 2 to illustrate the differences using typical values for D/λ (i.e., 66 and 50).

In (1), (2), and (3) above, $G(\phi)$ is the gain relative to an isotropic radiator/receptor and ϕ is the angle, in degrees, between the main beam axis and the direction of concern. These reference radiation diagram expressions define envelopes that should not be exceeded by more than 10% of the side-lobe peaks in an actual radiation diagram.

Recommendation 465-1 and Report 391-4 primarily consider sidelobe characteristics at angles greater than $1°$ from the main beam axis, hence (1) and (2) above are restricted to $\phi \ge 1°$. Annex 1 to Report 391-4 defines a complete
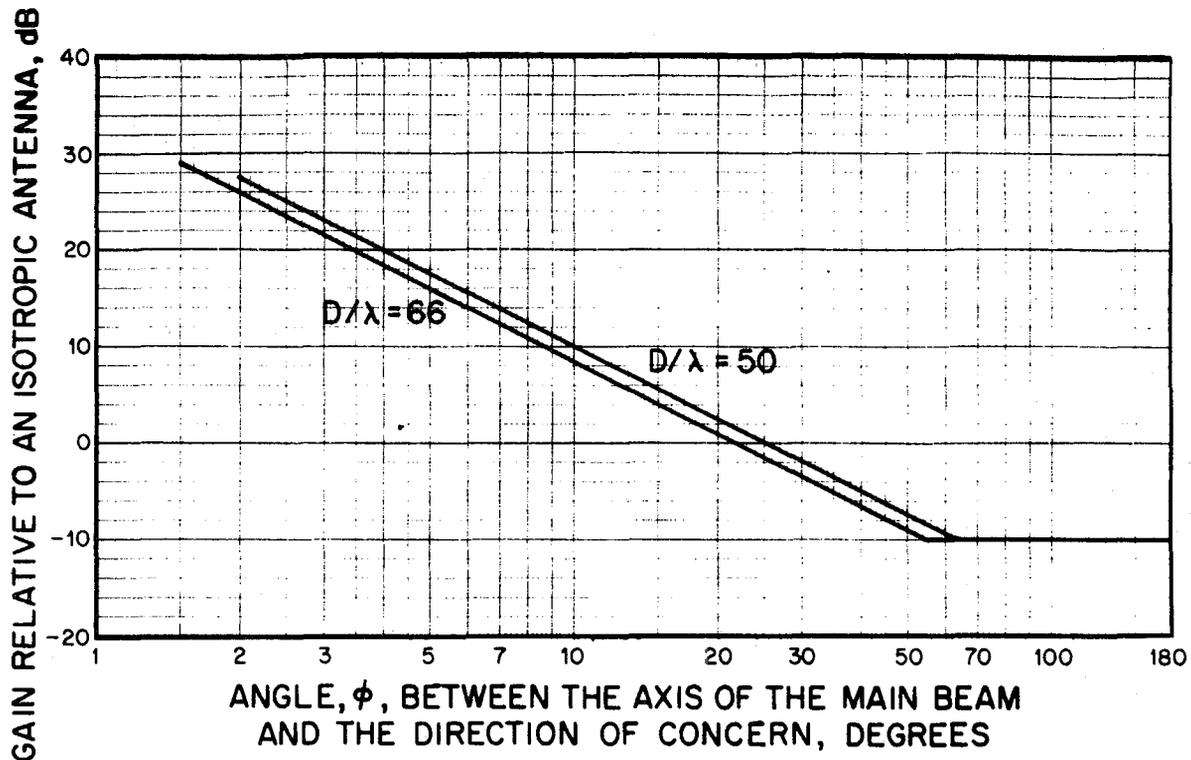
(a)
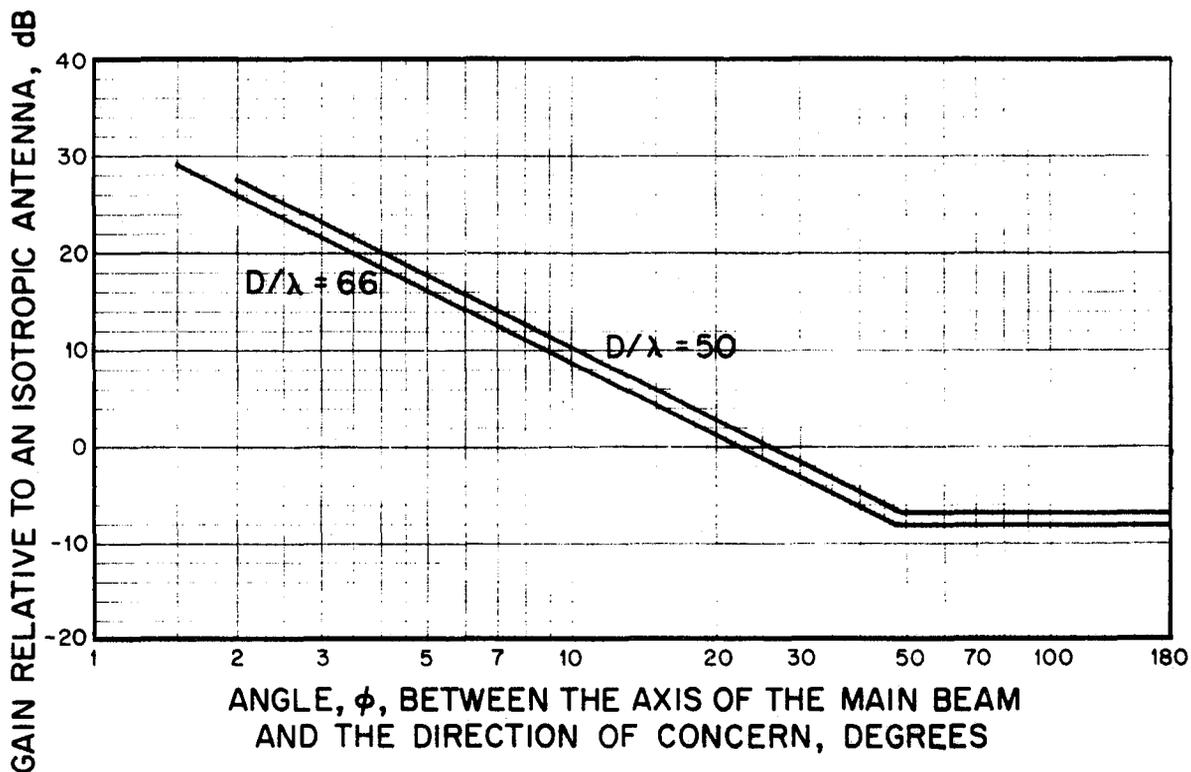
(b)

Figure 2. Reference radiation diagrams from CCIR Report 391-4 [(a) above) and as adopted by the WARC-79 [(b) above] (included as Annex 1 to CCIR Report 391-4) for earth station antennas with $D/\lambda < 100$.

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reference radiation pattern, including the main beam. Only the sidelobe region of that pattern (angles greater than 100 (λ/D)) is defined in (3) above. This limit corresponds to 1.5° for D/λ = 66 and 2.0° for D/λ = 50.

Recommendation 580 was adopted at the XVth Plenary Assembly (1982) as a design objective for antennas of earth stations installed after 1987* operating with geostationary satellites. The recommendation is that antennas with D/λ > 150 should have a radiation diagram design objective that the gain of at least 90% of the sidelobe peaks not exceed

$$G (\phi) = 29 - 25 \log \phi \text{ dBi} \qquad \text{for } 1^\circ \leq \phi \leq 20^\circ. \qquad (4)$$

It is further recommended that this requirement apply for any off-axis direction within 3° of the geostationary satellite orbit. It is to be noted that (4) recommends a 3-dB reduction in the envelope of sidelobe peak gain from that in (1) over the range $1^\circ \leq \phi \leq 20^\circ$. Figure 3 illustrates the geometry for
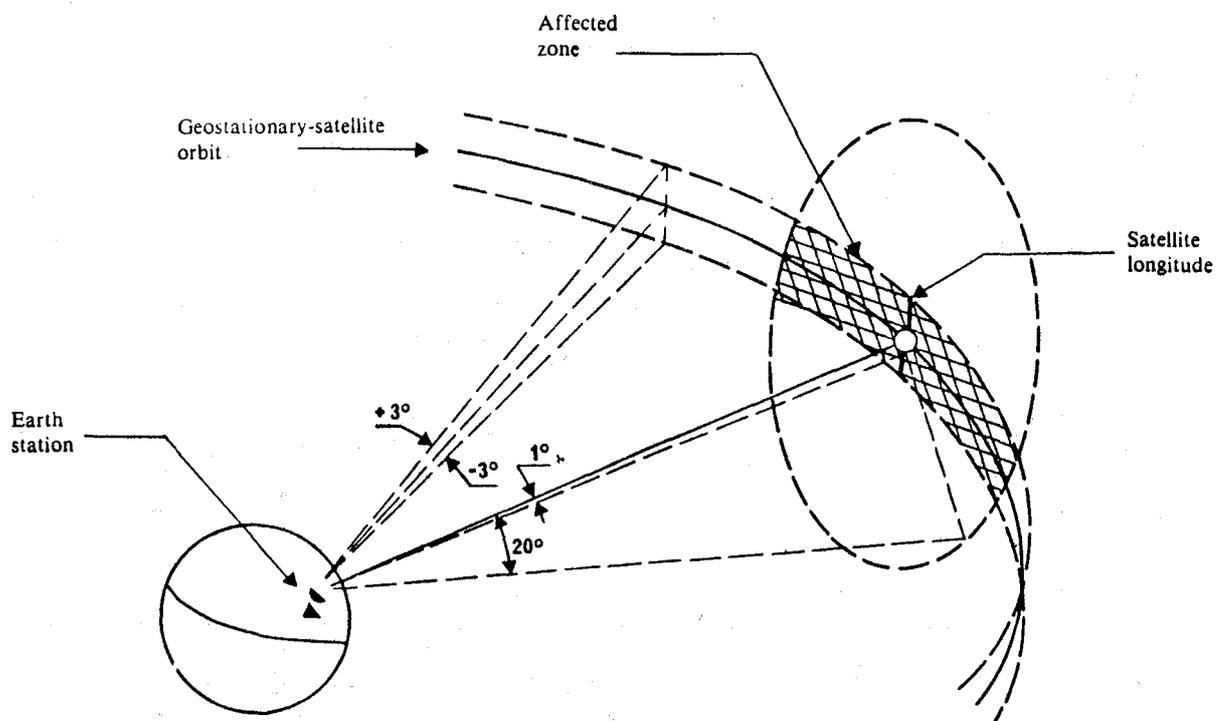
Figure 3.   Geometrical illustration of application for CCIR Recommendation 580 for reference diagram design objective for earth station antenna with D/λ > 150.

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which this recommendation has application. Further note that Recommendation 580 makes no mention of recommended sidelobe gain for angles $\phi > 20^\circ$, nor for antennas with $D/\lambda < 150$. In fact, the recommendation explicitly recognizes that information was not available to the assembly (in 1982) to allow determination of a design objective for antennas having $D/\lambda < 150$.

1.2 Background from the FCC Perspective

In its Notice of Inquiry and Proposed Rulemaking in the matter of licensing of space stations in the domestic Fixed-Satellite Service and related revisions of Part 25 of the Rules and Regulations, CC Docket No. 81-704, released November 18, 1981, the Federal Communication Commission briefly reviewed prior regulation of the domestic satellite industry and emphasized the dynamic nature of that industry. Demand for domsat services has almost outstripped supply. To a significant degree, early adoption of an open entry policy is responsible for this history. The immediate impetus for the FCC's Notice was the need to consider the desirability of reducing the current orbital spacing requirements of 4° in the C band and 3° in the Ku band (as defined in FCC Document 16495 in 1970 and updated in 1972) to a uniform 2° spacing. The Commission expressed the tentative view that the growth in domsat demand and increasing numbers of spacecraft have created serious problems of crowding in the orbital arc, requiring remedial action to prevent the foreclosure of further opportunities for growth. At the same time, the Commission sought alternative ways to increase the capacity of the domestic satellite orbit and asked for comments on the merits of various alternative approaches, including the reduced spacing concept. Finally, the Commission asked for comment on the continued appropriateness of its current processing and grant policies, in light of the current and anticipated growth on the domsat market.

The geostationary orbit in which domestic satellites are operated is critical to the communications industry. In this unique orbit, the satellite revolves once about the Earth during the same 24 hours that the Earth spins about its own axis. The geostationary satellite therefore appears to be stationary when viewed from a point on the Earth's surface. The location of the satellite is nominally defined by the longitude of the point on the Earth's equator over which the satellite appears to be positioned. Only a

portion of the geostationary orbit is visible from points within the United States, and hence usable for provision of domestic service. By international agreement, that portion of the orbital arc between approximately 20° and 180° W longitude defines Region 2, within which the continental United States lies. Within those confines, only that portion of the orbital arc between 55° and 143° W longitude is of practical use to the United States. In assigning orbital locations to domestic satellites, the FCC considers the needs of other countries in this hemisphere and recognizes that the easternmost portion of this arc (55° to 70° W) is particularly useful in accommodating those requirements of other countries in this hemisphere that cannot be satisfied by interleaving their satellites between U.S. satellites. It is the intent of the FCC to utilize, with the agreement of other administrations in Region 2, positions in this easternmost arc segment only when westerly positions are no longer available. In addition to the above constraints, the usable portion of the arc for the United States must include the satellites of our border neighbors, Canada and Mexico.

The orbital arc and its associated frequency spectrum are universally recognized as limited natural resources. Estimates of the total number of transponders (36 MHz of bandwidth) that will be required by the year 2000 vary between 1500 and 2500 for telephony, data transmission, CATV, video conference, and other services. Although the frequencies available in the domestic satellite spectrum include 12/13 GHz and 18/30 GHz, propagation conditions in the 4/6 GHz range are considered to be much more favorable than in the upper frequencies. Domestic services were first provided in these bands and are now firmly established; most satellite services are offered in these bands and ground facilities are readily available to users at reasonable costs. Thus, the vast majority of presently operating earth stations are designed to operate in these bands. In considering reductions of spacing between satellites in the geosynchronous orbit, the FCC has concluded that uniform spacing of 3° for the 4/6 GHz bands will not be sufficient to allow for the anticipated needs of the satellite industry. To the FCC it appears that a 2° orbital spacing will result in some but not excessive degradation in the quality of signals received by currently licensed antennas. The smaller diameter antennas, below 4.5 m and perhaps up to 7 m, will have to be upgraded, or more likely replaced, in order to meet standards of acceptability. The FCC believes,

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however, that given the increased diversity of programming services that can be made available by the additional satellites, the costs are not out of line.

In 1974 the Commission adopted a 4° orbital spacing criterion for the 4/6 GHz bands based on calculations made at the time by the system operators, the National Aeronautics and Space Administration and the Commission staff [Western Union Telegraph Company, 47 FCC 2d 274 (1974)]. With regard to those calculations, the FCC issued in their Rules and Regulations an antenna performance standard similar to that used in CCIR Report 391-4 and Recommendation 465-1 with the exception that the reference curve G (ϕ) = 32 - 25 logϕ would apply to all antennas in the Fixed-Satellite Service, not just to those with a D/λ > 100. However, in stating that any antenna to be employed in transmission at an earth station shall have a gain that lies below the reference curve, the FCC allowed peak sidelobe gains to be modified by averaging the peak gain of any individual sidelobe with the sidelobes adjacent to it (on each side) or the two adjacent sidelobes (on each side) provided that the level of no individual peak exceeded the gain envelope by more than 6 dB.

The FCC (1981) staff has analyzed several combinations of orbital spacings using different values of earth station sidelobe discrimination and cross-polarization isolation through computer simulation. The program calculates the single-entry interference levels between an array of signals. Each signal, in turn, is assumed to reside on the cochannel transponder of an adjacent cocoverage satellite. The carriers utilized in these calculations (FDM/FM, TV/FM, QPSK, BPSK, and SCPC/FM) span the range of services provided by five authorized 4/6 GHz systems (AT&T, RCA, WU, HUGHES, and SPC). Carrier-to-interference (C/I) calculations were made using the methodology of CCIR Report 455-2. The calculations assumed cochannel operations, geocentric (instead of topocentric) angles, and cross-polarization isolation as applicable. For FDM/FM carriers, the carrier-to-interference ratio is converted to baseband noise power (pWOp) and the FM video carriers are converted to signal-to-interference (S/I) ratios. The calculated interference is then compared to the single-entry objective for the carrier for various conditions of reduced satellite spacings and earth station antenna performance. (See FCC Notice of Inquiry, CC Docket No. 81-704, Appendix A.)

This analytic approach was developed to demonstrate, in general terms, the degree of difficulty that different orbital spacings would present and the degree of effectiveness of various technical standards. In accordance with their findings, the FCC has revised the Antenna Performance Standards (para. 25.209) to facilitate the moving of satellites from their present 4° spacing to a 2° spacing. The reference curve adopted by the FCC in their Report and Order, CC Docket No. 81-704, released August 16, 1983, is shown in Figure 4.

Between 1° and 7° the reference curve has been reduced by 3 dB to $G(\phi) = 29 - 25 \log \phi$, and the rules state that this reference curve may not be exceeded. This, in essence, reduces sidelobe peaks in this area by as much as 9 dB when compared with the old regulation where a peak may have exceeded the curve $G(\phi) = 32 - 25 \log \phi$ by as much as 6 dB. Beyond 7° the reference curve may be exceeded by 10% of the sidelobes but by no more than 3 dB. The new reference curve for any antenna employed in transmission from an earth station in the Fixed-Satellite Services then becomes:

$$G(\phi) = \begin{cases} 29 - 25 \log \phi \;\text{dBi} & 1 \leq \phi \leq 7 \\ +8 \quad \text{dBi} & 7 < \phi \leq 9.2 \\ 32 - 25 \log \phi \;\text{dBi} & 9.2 < \phi \leq 48 \\ -10 \quad \text{dBi} & 48 < \phi \leq 180 \end{cases}$$

where ϕ is the angle in degrees from the axis of the main lobe, and dBi refers to dB relative to an isotropic radiator. This then effectively reduces the allowed sidelobes for $\phi > 7$ degrees by as much as 3 dB.

In addition to the new reference curve for copolarized signals, the FCC has adopted a cross-polarization reference curve which is effectively 10 dB below the copolar reference curve for transmission in the Fixed-Satellite Service for angles between 1° and 9.2° as also shown in Figure 4.

This curve has been made part of the Rules and Regulations to compensate for the computed increases in interference levels at reduced orbital spacings. The rule for protection of receiving antennas in this service is the same as in the old rules where any antenna licensed for reception of radio transmissions from a space station shall be protected from radio interference caused by other space stations only to the degree to which harmful interference would not be
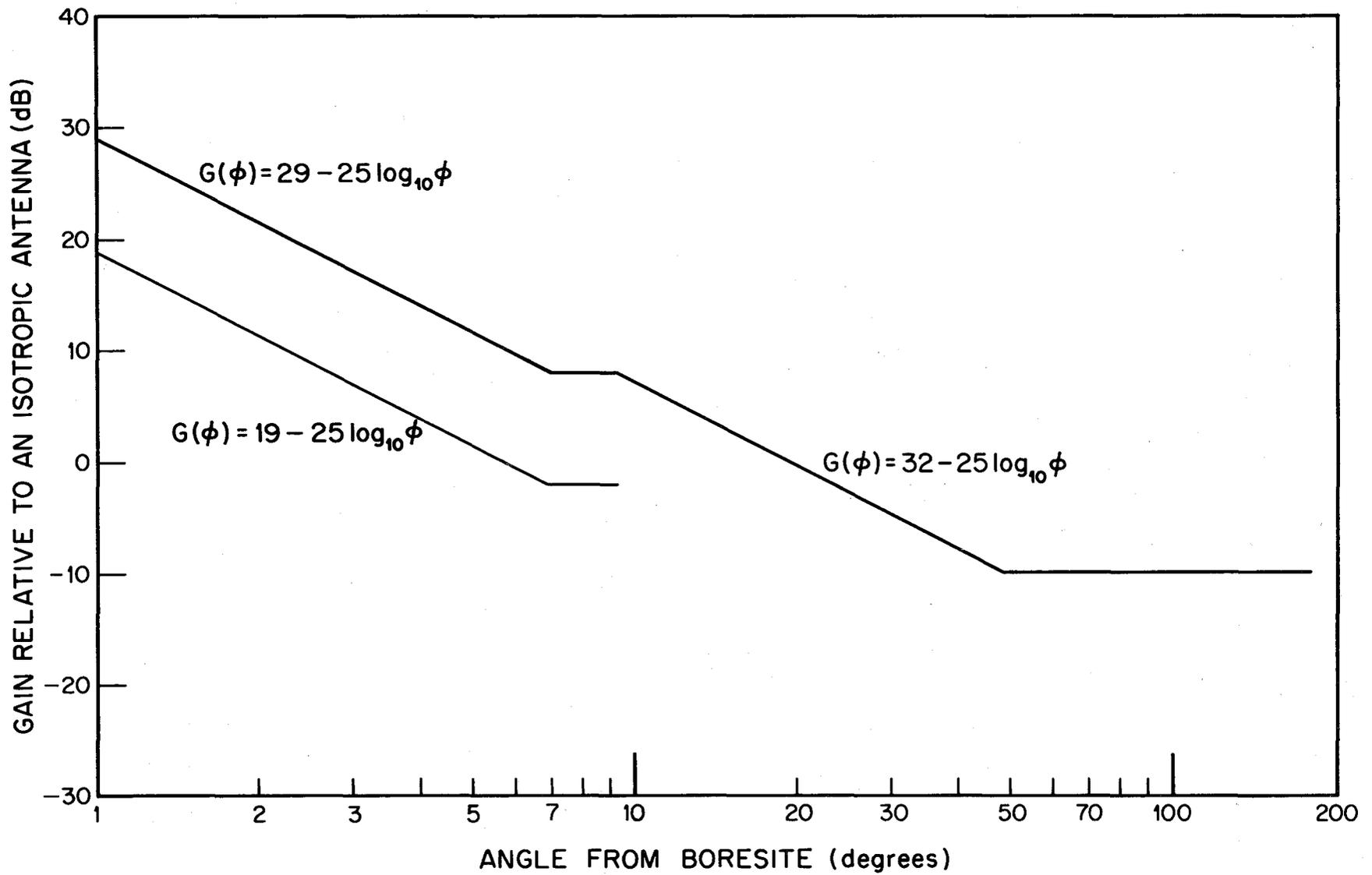
Figure 4.   FCC reference radiation diagram for copolarized and cross-polarized signals (FCC Docket No. 81-704, released August 16, 1983).

expected to be caused to an earth station employing an antenna conforming
to the standards as stated above.

The off-axis, cross-polarization isolation of any antenna to be employed
in transmission at frequencies between 5925 and 6425 MHz from an earth station
to a space station in the domestic Fixed-Satellite Service is now defined by:

$$G(\phi) = \begin{cases} 19 - 25 \log \phi & \text{dBi} & \text{for} & 1.8 \le \phi \le 7 \\ \\ 2 & \text{dBi} & \text{for} & 7 < \phi \le 9.2 \ . \end{cases}$$

With the inclusion of those satellites in the 1983 Orbit Assignment Order,
orbital separations on the average of slightly more than 2.5° over the total
orbital arc of from 67° to 143° will be effected. These separations will
remain in effect until the next orbit assignment. The FCC notes that
several manufacturers currently are marketing antennas they claim meet
or exceed the more stringent FCC antenna performance standards. (This NTIA
study does not deal with cross-polarization of antennas.) The FCC believes
it imperative that new transmit antennas comply with the revised standards
at the earliest practical date and have adopted July 1, 1984, as the appli-
cable date for enforcement of the standards of Section 25.209 for newly
installed transmit antennas. On the other hand, the FCC is delaying any
necessary modifications or replacements of existing antennas needed to
comply with the new standards until actually necessary. Since uniform 2°
orbital separations between 4/6 GHz satellites are not likely in any event
before 1987 under current launch schedules, they feel that January 1, 1987,
is an appropriate date for upgrading or replacing existing transmit antennas
and have so stated in the rules.

In the case of receive-only stations, the FCC is affording operators
the flexibility to delay or defer the costs of upgrading or replacing
antennas if they find acceptable the signal quality received under actual
conditions of reduced satellite separations. Whatever costs encountered
by satellite communication users appear to the FCC to be warranted by the
benefits afforded by the resulting capability for additional in-orbit
satellites.

1.3 Background from Manufacturers' and Users' Perspectives

Of the 35 respondents to the FCC's Notice of Inquiry (1981), the majority
generally supported the thrust of the Commission to reduce satellite spacing,
expressing belief that it was proper and would serve the public interest.
Many of the filings were extensive in scope, including detailed discussions
and data on the technical, economical, and procedural implications of spacing
reductions on the industry. By far the most prevalent comment dealt with the
timeframe for implementation of the new Rules and Regulations. Citing the
need for more time for experimentation with new types of antenna feeds and
production techniques, the users and manufacturers feel that the switchover
to the new rules concerning installation of new antennas should not be re-
quired until the 1987-1990 period. Likewise, they feel that the January 1, 1987,
date is too soon to implement the rules for all antennas. They feel that with
the move to 2° spacing as many as 5,000 4.5 m antennas and 10,000 3 m antennas
will either have to be upgraded or replaced by larger and substantially more
expensive antennas. The majority of users and manufacturers feel there are
no antennas less than 6 m in diameter that can meet, or be made to meet,
the new transmission standards or to accept the interference caused by adjacent
satellites at these spacings (some felt the minimum was 10 m.) Receive-
only antennas used in the cable TV industry are typically in the 4.5 to 7.0 m
range and users feel that all of these antennas will need to be replaced.

The two major spacecraft characteristics that affect permissible orbital
spacing are polarization and EIRP differentials between adjacent spacecraft.
This has also been a common point of debate between the FCC's analysis and
analyses of the users and manufacturers. If signals from adjacent spacecraft
are copolarized, there will be no polarization isolation between them and
the unwanted signal causes interference to the wanted signal. How much inter-
ference depends upon the characteristics of the earth station antenna and the
orbital separation between the spacecraft. However, as stated by the FCC,
if the signals of adjacent spacecraft are cross-polarized, there is polari-
zation isolation between them, and the limiting factor becomes the isolation
effectiveness of the earth station antenna. Studies supported by the users
and manufacturers point out that environmental conditions such as the de-
polarization effects of rain and snow have a pronounced effect on this aspect
of signal isolation. Users have commented that the Commission has used a
highly idealized presumption of homogeneity in their calculations. Some users

stated that relative peaks of 3 dB and more above the nominal EIRP are not abnormal. Opponents of the move to a 2° spacing state that when these situations exist, even by themselves, and are coupled with the pointing accuracies and relatively wide beamwidths of the smaller antennas, the interference will become intolerable.

A third point of contention is that of "What is an acceptable level of interference?" This is especially true for video signals. Although many schemes have been used by organizations to determine an acceptable interference criterion or standard of acceptability, none has been totally accepted by the industry. Although the FCC cites some surveys which indicate that viewers will tolerate a carrier-to-interference ratio in the region of 14-15 dB, a C/I figure of 18 dB is the minimum acceptable interference level for television reception according to most respondents to the Notice. This point of contention alone, if verified on the side of the users and manufacturers will necessitate the rejection of approximately 6000 receive-only TV antennas according to some respondents.

Various alternatives to moving to a 2° spacing have been offered by respondents to the Notice including the suggestion that the FCC use a minimum antenna spacing of not less than 2.5°. This orbital separation is an almost unanimous request for the near term (to 1990 time frame). The FCC feels that with their most recent orbital assignment, an average separation of slightly more than 2.5° will remain in effect through the 1987-1988 time frame. Other solutions to the overcrowding of the orbital arc have included using two antenna guidelines, i.e., less restrictive for antennas in locations where no appreciable interference is likely to occur. Another suggestion is to use the frequency allocations in an interspersed/reverse way where some earth stations transmit at 4 GHz and receive at 6 GHz. Finally, some suggest that the side-lobe envelope requirement begin at 2° instead of 1°. These and other proposals have been addressed in the FCC's Report and Order (CC Docket No. 81-704) released August 16, 1983.

2. SIDELOBE CHARACTERISTICS ANALYSIS
2.1 Antennas Considered

The antennas considered for this study have been produced with the intent of meeting the reference envelope required by the FCC in their Rules and Regulations which were established in 1974. Generally, these antennas have

been designed to maximize main beam gain per unit of cost without serious concern for the sidelobe gain produced by this maximization. Sidelobe characteristics were usually considered in the design of the antenna, particularly in the transmit band, but were not considered to be nearly as important as the gain in the main beam. Indeed, some of the companies contacted for pattern information had measured their antennas out to only 3 or 4 degrees beyond the main lobe using a satellite as a target transmitter. Much of the time, antennas have not been adequately measured due to a lack of range facilities and/or the cost and schedule impact of performing these measurements. On the other hand, some prototype antennas have been extensively tested but subsequent production run models have not and have been installed in the field using only mechanical references. Measurements conducted on installed antennas frequently show serious degradation from prototype performance.

There are numerous companies that design and manufacture the smaller diameter (3 m to 10 m) antennas that exhibit a wide range in the quality of performance. Performance claims are often made, particularly in the case of sidelobe levels, with data based on "averaging" (as discussed in Section 1.2) as allowed under the 1974 (FCC) regulations or by selecting favorable measurement frequencies. Some antennas are manufactured without the benefit of a full range of technologies and facilities necessary to achieve a high quality product. For example, numerous companies are able to produce high quality metal or fiberglass panels and build high quality reflector surfaces. These companies, which are based primarily on mechanical design qualifications, may not possess sufficient rf technology, measurement expertise, or range facilities, however, to produce a high quality product that has been fully evaluated. The converse can also be true where despite good rf expertise, the mechanical aspects such as reflector accuracy, surface panel alignment, gravity sag effects, and structural rigidity are poor, and a high quality product does not result. Performance tradeoffs frequently favor low cost rather than high quality, and it is especially common in the highly competitive, low cost, high volume production type of antenna. In the design of the larger and more expensive antennas such as the INTELSAT 30 m Standard A antennas, performance has generally been more predictable and in line with specified sidelobe envelopes.

It is a common feeling among the more than 35 manufacturers and users who replied to the Notice of Inquiry (CC Docket No. 81-704) that antennas with diameters of 10 m or more will have little difficulty in meeting the constraints placed upon them by the new regulations adopted by the FCC in their Report and Order. In their Notice of Inquiry and Proposed Rulemaking (CC Docket No. 81-704), the FCC states that, "antennas larger than 6 meters in diameter that are now in operation seem to actually perform better than the current rule standard, thus mitigating in practice the impact of reduced spacing...." This statement by the FCC, in light of our investigation, may not be the case when a number of antennas in that size range are studied in detail. Many of these smaller antennas have not been extensively measured and along with the large number of manufacturers and changing designs makes the task of determining the present sidelobe envelopes difficult. Data might also be obtained from well-tuned/optimized breadboard models and not be representative of production models.

For our analysis work, 18 U.S. manufacturers of satellite antennas were contacted. These manufacturers were asked to provide actual measured patterns concerning antennas in the 2- to 10-meter diameter range for both the space-to-earth (3.7 - 4.2 GHz) and earth-to-space (5.9 - 6.4 GHz) frequency ranges at C-band. We received information and measured patterns from only 12 of those companies contacted. Some manufacturers felt that their data were proprietary and would supply only smoothed patterns, such as seen in Figure 5. These were not acceptable for our analysis because of our intent to develop statistical characteristics of peak amplitudes for the sidelobes. Presumably, these smoothed patterns had been "averaged" as discussed in Section 1.2. Others stated that they had no measured data beyond 2 to 5 degrees while still others supplied ill-defined data such as erroneous angular definition. Finally, during reduction of the data, other patterns were discarded because of the inaccuracies in their presentation such as poor, blurred, or wavy copies.

Additional information and patterns were received from the Satellite Branch of the FCC. Our final analyses contain measured data from six manufacturers. While small in number, these six manufacturers supply over 75% of all antennas listed in applications to the FCC for licensing during 1982. Figure 6 is an example of the type of pattern included in our analysis.
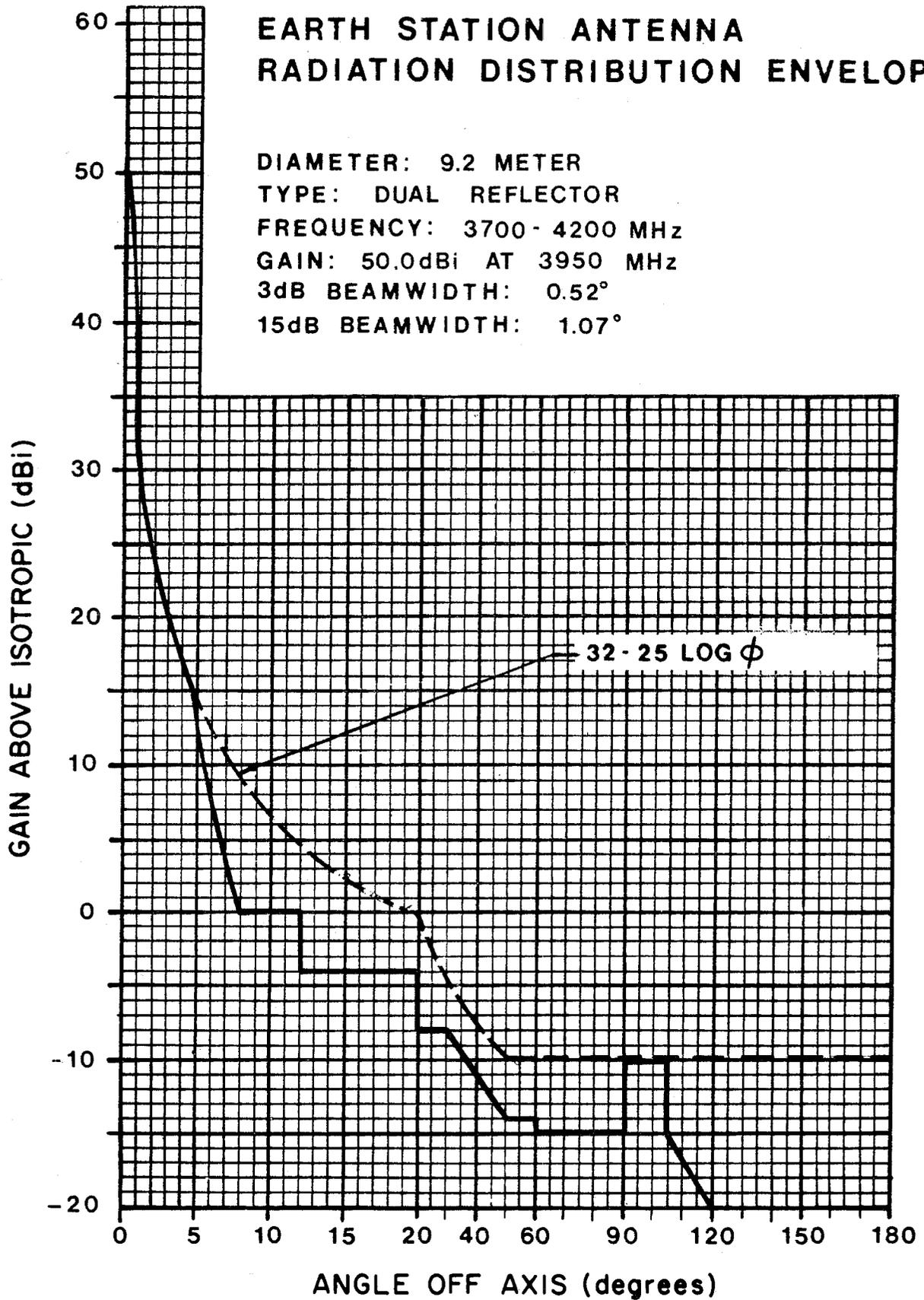
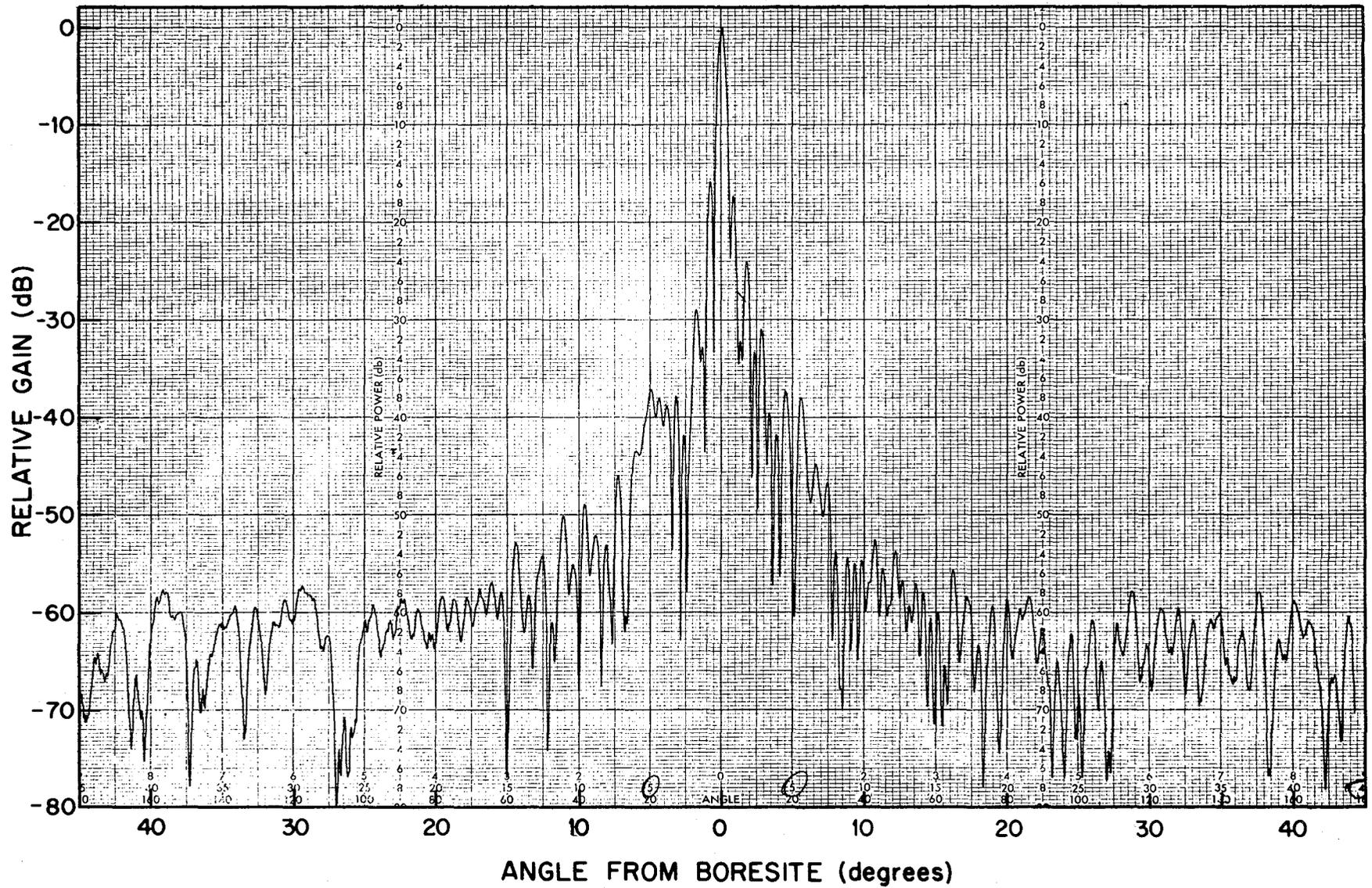Figure 5. Example of a smoothed antenna pattern.

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Figure 6.   Example of a large-scale antenna pattern.

From the usable information received, we have constructed a data base in the 3.7 to 4.2 GHz frequency range consisting of 22 separate antennas ranging from 2.8 to 13.0 meters for which 215 separate patterns have been analyzed. The derivation of this large number of separate patterns is discussed in Section 2.2. In the uplink (5.9 to 6.4 GHz) frequency range, 125 individual patterns have been analyzed. The predominance of patterns in this analysis is from antennas in the 4- to 7-meter range. The appendix contains a listing of all antennas used in this analysis.

2.2   Analysis Methodology

The patterns supplied by the manufacturers and the FCC are of several varieties and formats including those taken at several elevation cuts (0, 30, 40, and 60 degrees above the horizontal) almost entirely for desired polarization operation. For this analysis we have used only copolar pattern data taken at 0 degrees elevation. The copolar data received were also in several formats and, in most instances, manufacturers' patterns for any one particular antenna at a specific frequency are in two parts. The first part usually consists of a measurement of the pattern near the main lobe, usually between +30 degrees and -30 degrees (large-scale data) with the second part comprising the entire antenna pattern (+180 degrees to -180 degrees) or small-scale data. Examples of these are shown in Figures 6 and 7. In addition, data received on a single antenna usually included measurements at several frequencies within the band (i.e., 3.7, 4.0, and 4.2 GHz in the space-to-earth frequency range, and 5.9, 6.2 and 6.4 GHz in the earth-to-space frequency range). And finally, many antennas were measured in both the E- and H-planes. For instance, one pattern may be measured from $-180°$ to $+ 180°$ at 3.7 GHz in the H-plane. Since we have broken this pattern into two parts (negative or left side and positive or right side to be discussed later) we have two patterns for analysis. The next measurement may involve the same antennas measured from $-180°$ to $+ 180°$ at 3.7 GHz as before, but this time in the E-plane, which gives us a total of four patterns for analysis. All of these measurements were included in the analysis with the result that any one particular antenna being analyzed in a frequency range may be defined by as many as 12 separate patterns. This effect may be seen from the list of measured antennas in the appendix. The dynamic range for the gain of large-scale data is usually between 30-50 dB with the small-scale
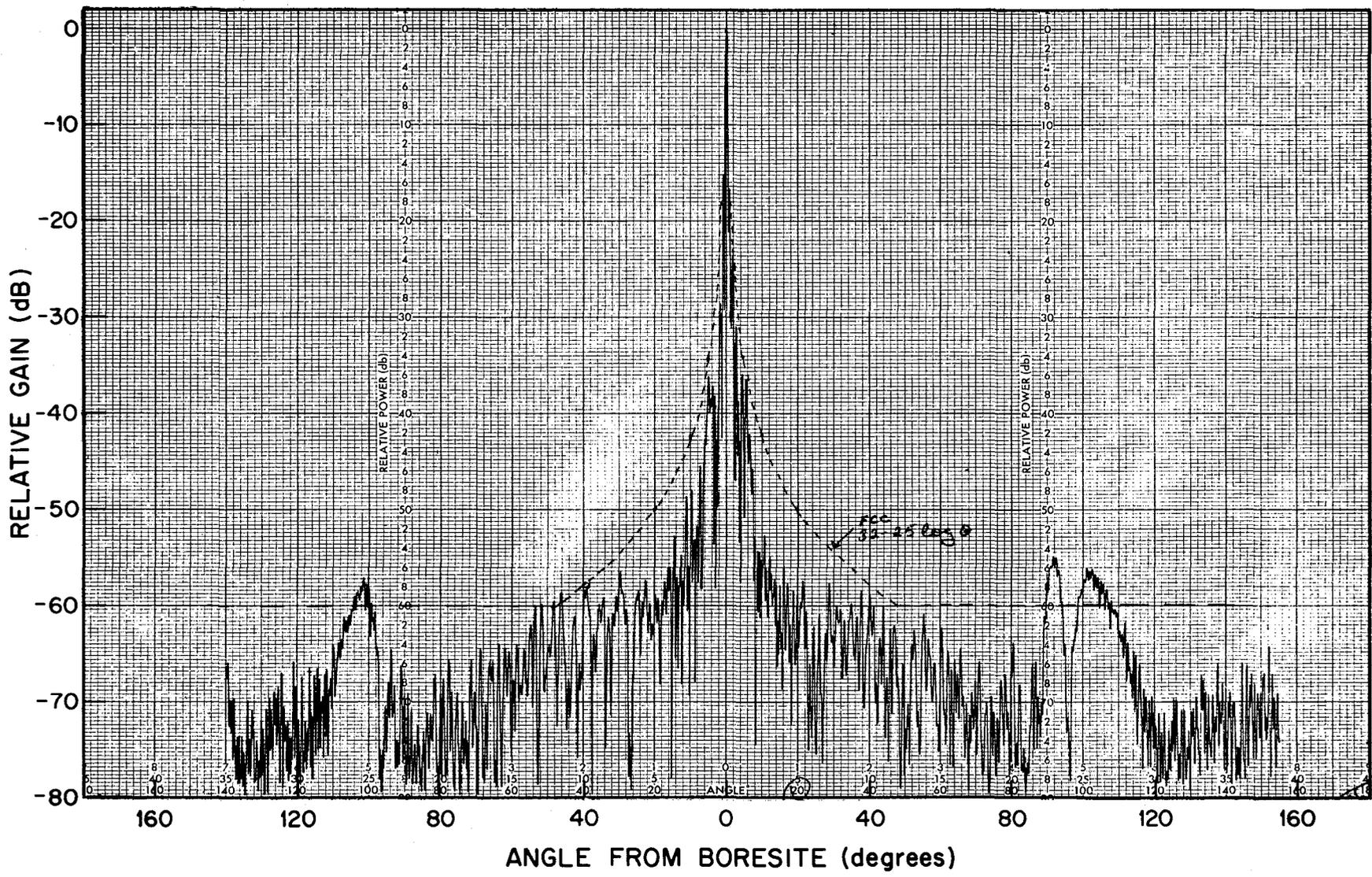
19

Figure 7. Example of a small-scale antenna pattern.

data approximately 80-120 dB. All patterns used were normalized to 0 dB by the manufacturers. All maximum gains are taken from manufacturers' published data.

Because no antenna is symmetrical on both sides of its main lobe and none of the patterns received noted in which direction (clockwise or counterwise) the antenna was rotated to produce the pattern, it was decided to break each pattern, large-scale and small-scale, into two separate parts. One part deals with the left side, $-30°$ $(-180°)$ to $0°$ or negative side of the pattern, and the other part with the right side, $0°$ to $+30°$ $(+180°)$, or positive side of the pattern. We have treated the large-scale and small-scale patterns as having been measured with the same directional rotation. In other words, the left side of a small-scale pattern for a particular antenna is the same side of that antenna as the left side of an accompanying large-scale pattern. Based on this assumption, we have combined each half of the large-scale pattern with its companion half of the small-scale pattern (left half with left half and right half with right half). This was accomplished through the computer by merging the digitized data for the two patterns as shown in Figure 8 (two positive halves or two negative halves) and discarding that portion of the small-scale data which overlays the large-scale data. By using both scales, we are able to analyze the large-scale data close to the main beam in extreme detail. Data points were digitized at 1/3 to 1/2 degree intervals on the large-scale plots, whereas the data could only be read to 1 degree on the small-scale plots. The digitized data then are converted to actual gain versus angle from boresight.

Only two characteristics of the data are used to categorize the data for analysis because of the relatively small number of antennas being analyzed and the fact that, collectively, these antennas include several variations such as size, types of antenna feeds, actual measurement frequencies, mechanical features, etc., that affect the amplitude of sidelobes. The characteristics used are operating frequency band and diameter-to-wavelength ratio (D/λ). Some data in each category come from merged large-scale and small-scale patterns that yield four patterns total per frequency, other data come only from small-scale patterns that yield two patterns total per frequency, while the remainder of the data have come from small-scale patterns for only one half of a total pattern thus yielding just one pattern per frequency.
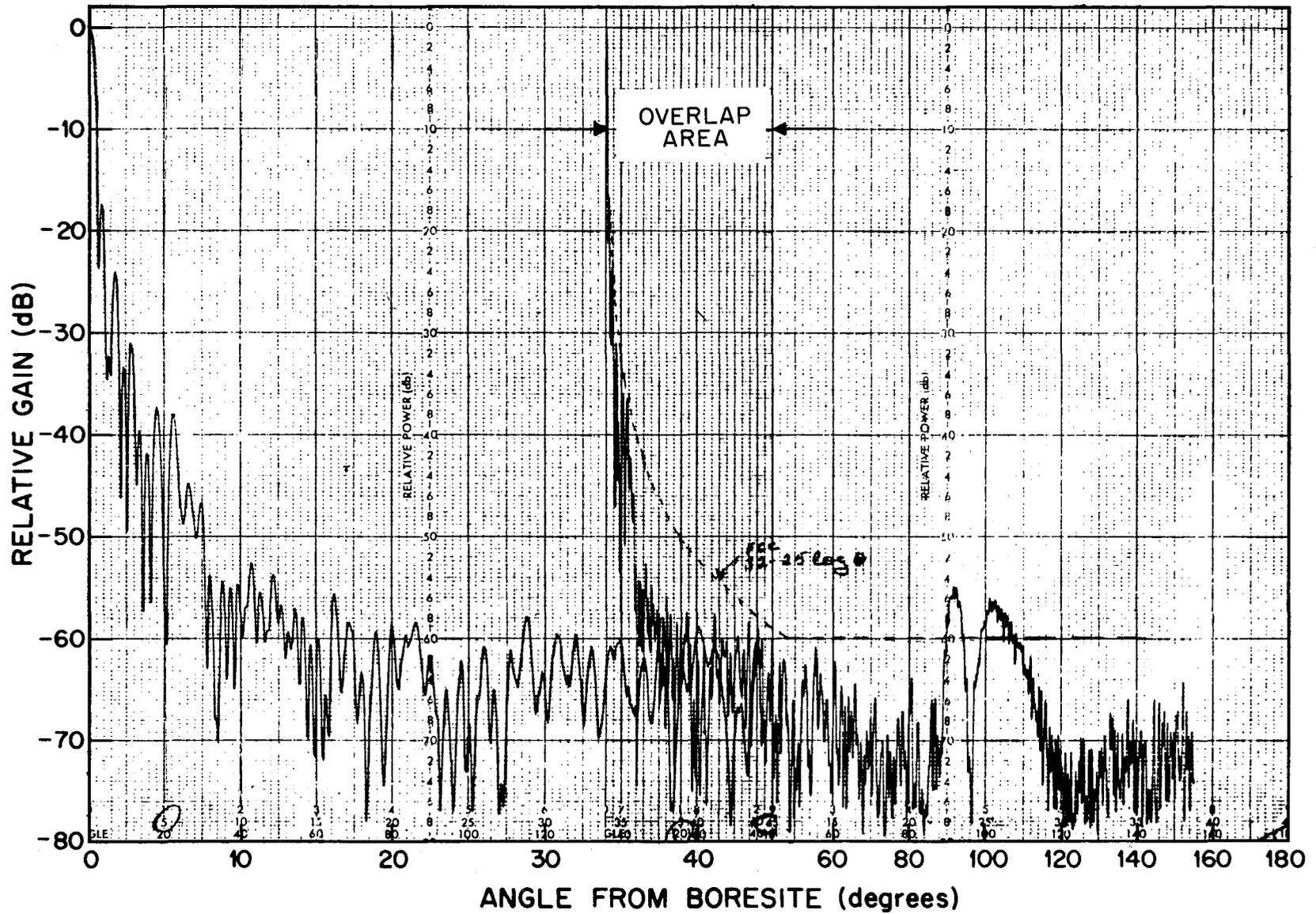
21

Figure 8. Example of the combined large- and small-scale antenna patterns showing the overlapping areas.

22

In combining the patterns as described above, we have a total of 168 patterns in the space-to-earth frequency range (4-GHz band) and 71 patterns in the earth-to-space frequency range (6-GHz band) as a data base for our analysis effort.

The data digitizing process and the logic used for selecting sidelobe peak values are illustrated in Figure 9. This example is for the right side of a large-scale pattern. Digital values (amplitude and angle with respect to boresight) are selected at $1/3^\circ$ intervals. Values which logically are local maximum values (with respect to the adjacent values) are considered to be the sidelobe peak values. The computerized logical process for selecting these peaks is as follows.

Sampling begins with the zeroth (0th) data point, and because it is the first point (presumably corresponding to main beam gain), the computer selects it as a "peak" and stores it. Point 1 is sampled and compared to 0 and is found to be negative with respect to point 0 and moves to point 2. Since point 2 is less than 1, point 1 is discarded and point 3 is compared to 2. Again, point 3 is less than (or negative with respect to point 2) the previous point and 2 is discarded. Even though the pattern trace has now gone through an actual peak, the computer is unable to recognize this fact and the peak is ignored. Moving on, point 4 is less than 3 and point 3 is discarded. The computer now compares point 4 with point 5 and notes that point 5 is greater than (positive with respect to) point 4 and that the direction of the trace has reversed itself and is now moving in a positive direction. Point 4 is now discarded and point 5 is compared to point 6. The computer program is designed to pick out point 5 as a "peak" in that the direction of the trace as defined by the gain of the individual points has switched from a positive direction before the data point to a negative direction after the point. The computer continues to compare succeeding points with previous points and stores those points where a positive-to-negative change of trace direction has been noted.

When the "peaks" of all merged antenna patterns have been stored, they are then subjected to a second computer program that deletes all data points less than 1°, and divides the data into separate increments. The angular regions chosen for analysis are [1,2), [2,4), [4,7), [7,10), [10,20), [20,40),
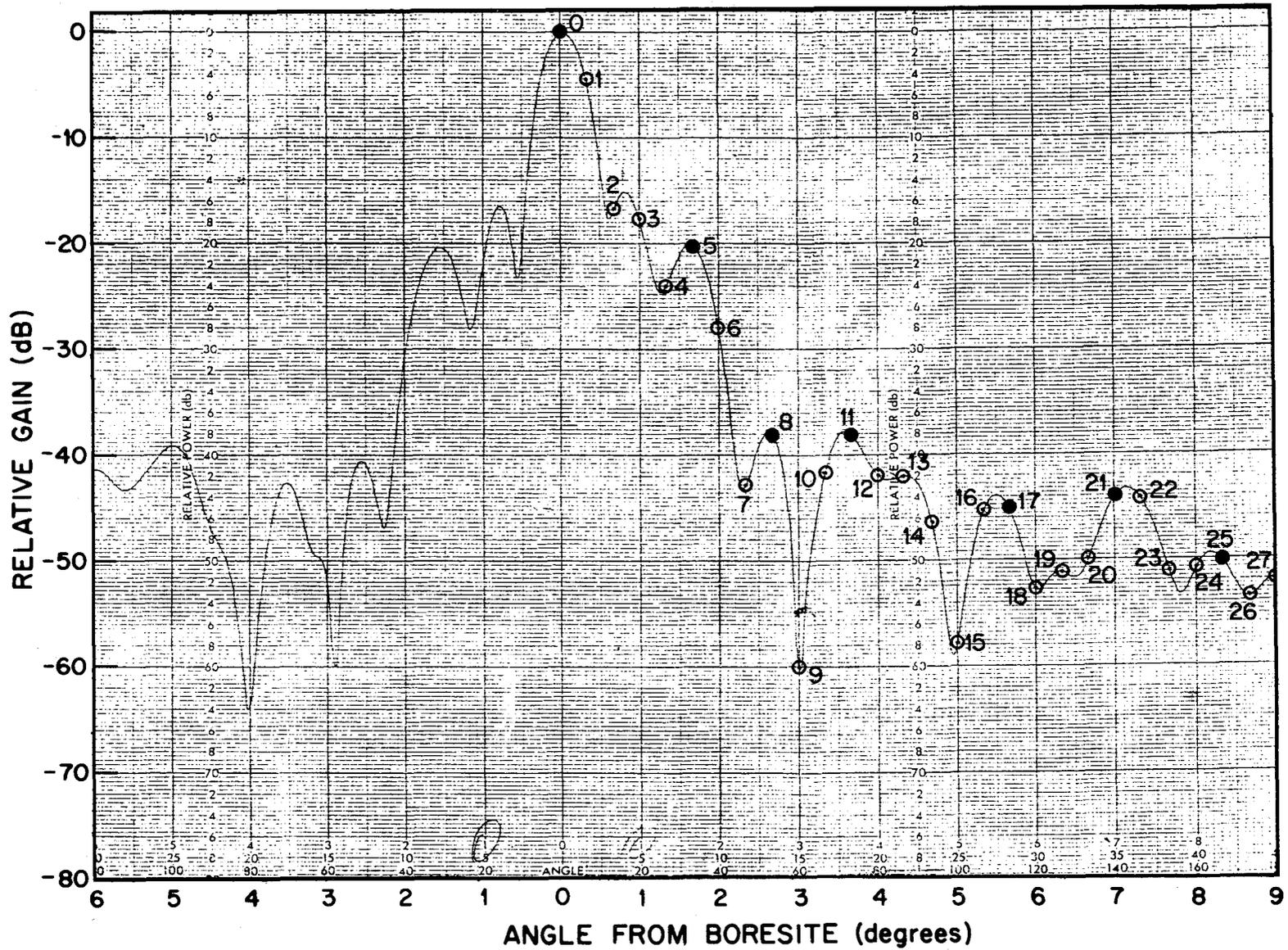
Figure 9. Large-scale antenna pattern showing the digitizing process and the logic used for selecting sidelobe peak values.

(as utilized in most CCIR reports and recommendations), and each succeeding 10° interval through 180°. Brackets indicate inclusion while parentheses indicate exclusion of points at that angle. Once the "peaks" have been separated into the proper angular regions, the computer analyzes those points within each increment for the maximum, 90%, median, 10%, and minimum values.

3. ANALYSIS RESULTS

Digitization of the analog patterns to generate corresponding files of digital data was the first effort. These files of digitized data then were divided into subsets of data according to the operating frequency band (downlink and uplink). Within each frequency band, the data were analyzed in aggregate as well as in subsets defined by diameter-to-wavelength ratio less than 100 and greater than 100. Section 3.1 presents nonstatistical results; Section 3.2 presents statistical analysis of the sidelobe peak data as determined following the process described in Section 2.2 and illustrated by Figure 9.

3.1 Nonstatistical Analysis Results

Plots, which we call "dot plots", of all the digitized data between 1° and 180° (not just the sidelobe peak values) are shown and discussed in this section. Figures 10 through 12 show these dot plots for data in the 3.700 to 4.200 GHz band. Figures 13 through 15 show data for the 5.925 to 6.425 GHz band.

Figure 10 shows the aggregated digitized data for all antennas operating in the 3.700 to 4.200 GHz band (22 antennas total). The diameter-to-wavelength ratio for these data varies from 35 to 173. Figure 11 then shows the digitized data only for antennas (12 of the 22 antennas that operate in the 3.700 to 4.200 GHz band) for which the diameter-to-wavelength ratio is less than 100. In fact, the data are for ratios ranging from 35 (D = 2.8 m) to 93 (D = 7.0 m). Figure 12 shows the digitized data only for antennas (10 of the 22 antennas that operate in the 3.700 to 4.200 GHz band) for which the diameter-to-wavelength ratio ranges from 116 (D = 8.8 m) to 173 (D = 13.0 m). From Figures 11 and 12 one observes that there are roughly equivalent amounts

Figure 10. Scatter plot showing all of the points digitized for all antennas in the 3700-4200 MHz frequency range.
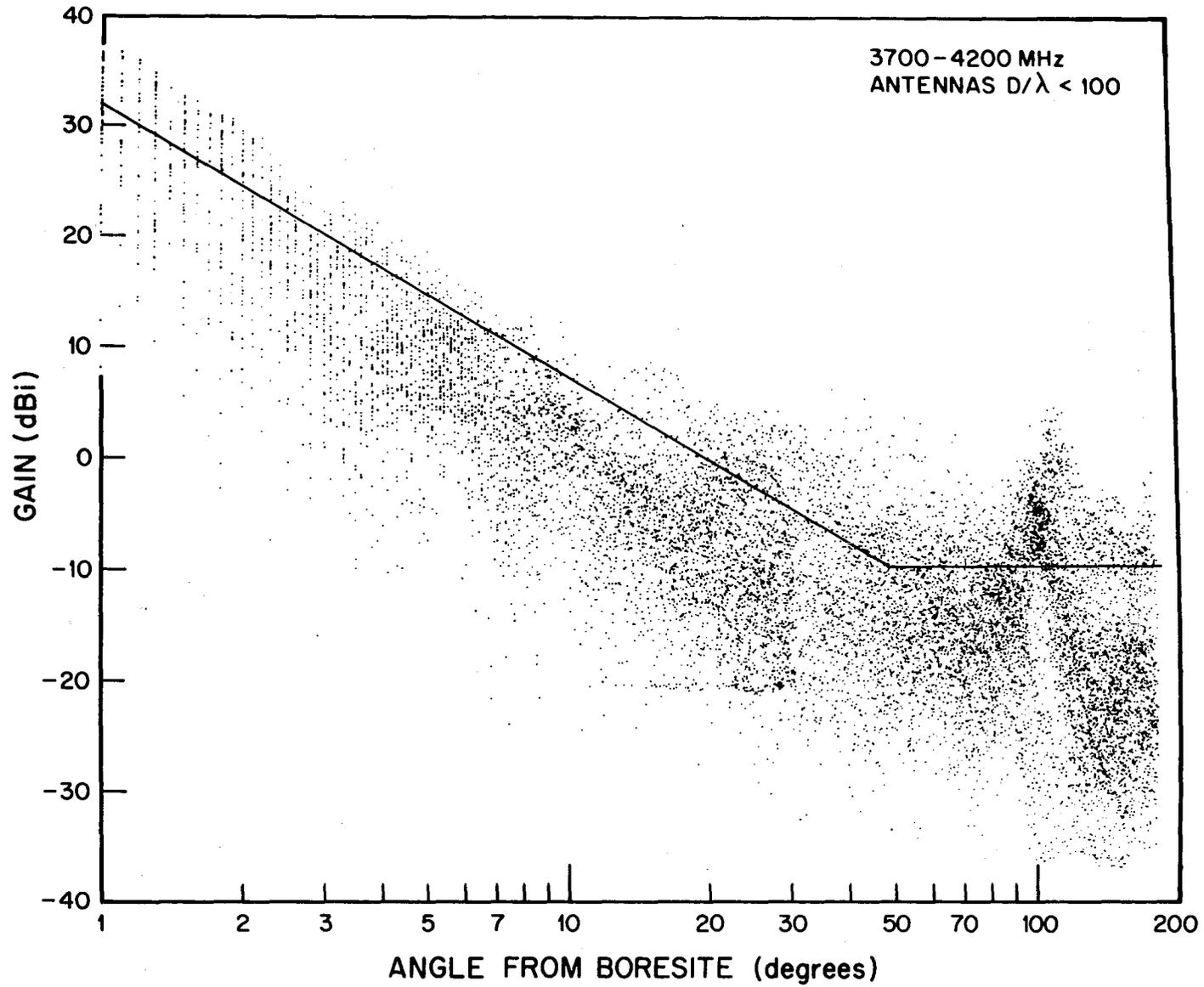
Figure 11. Scatter plot showing all of the points digitized for all antennas
with a D/λ < 100 in the 3700-4200 MHz frequency range.

Figure 12. Scatter plot showing all of the points digitized for all antennas with a D/λ > 100 in the 3700-4200 MHz frequency range.
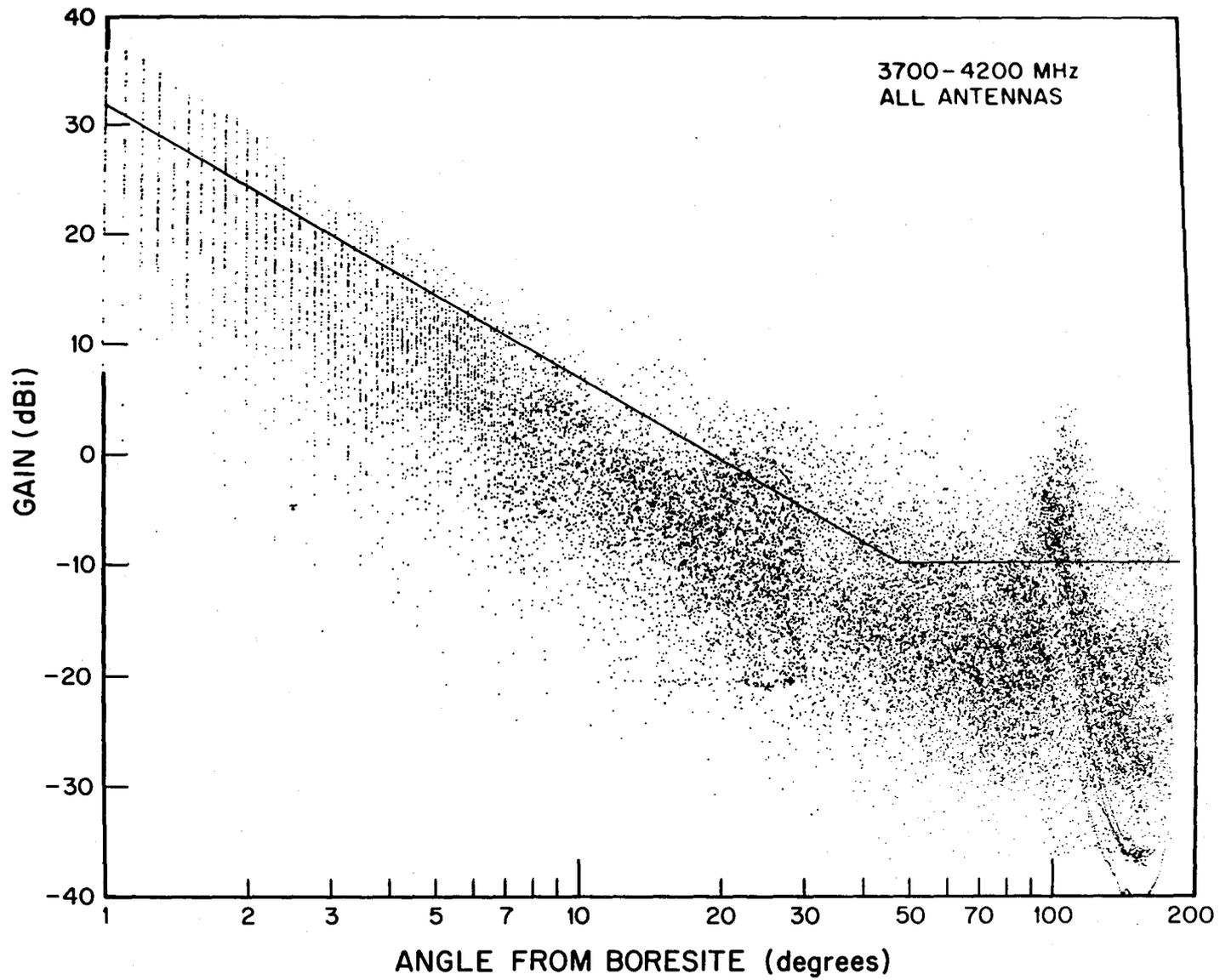
Figure 13. Scatter plot showing all of the points digitized for all antennas in the 5925-6425 MHz frequency range.

Figure 14. Scatter plot showing all of the points digitized for all antennas
with a D/λ < 100 in the 5925-6425 MHz frequency range.

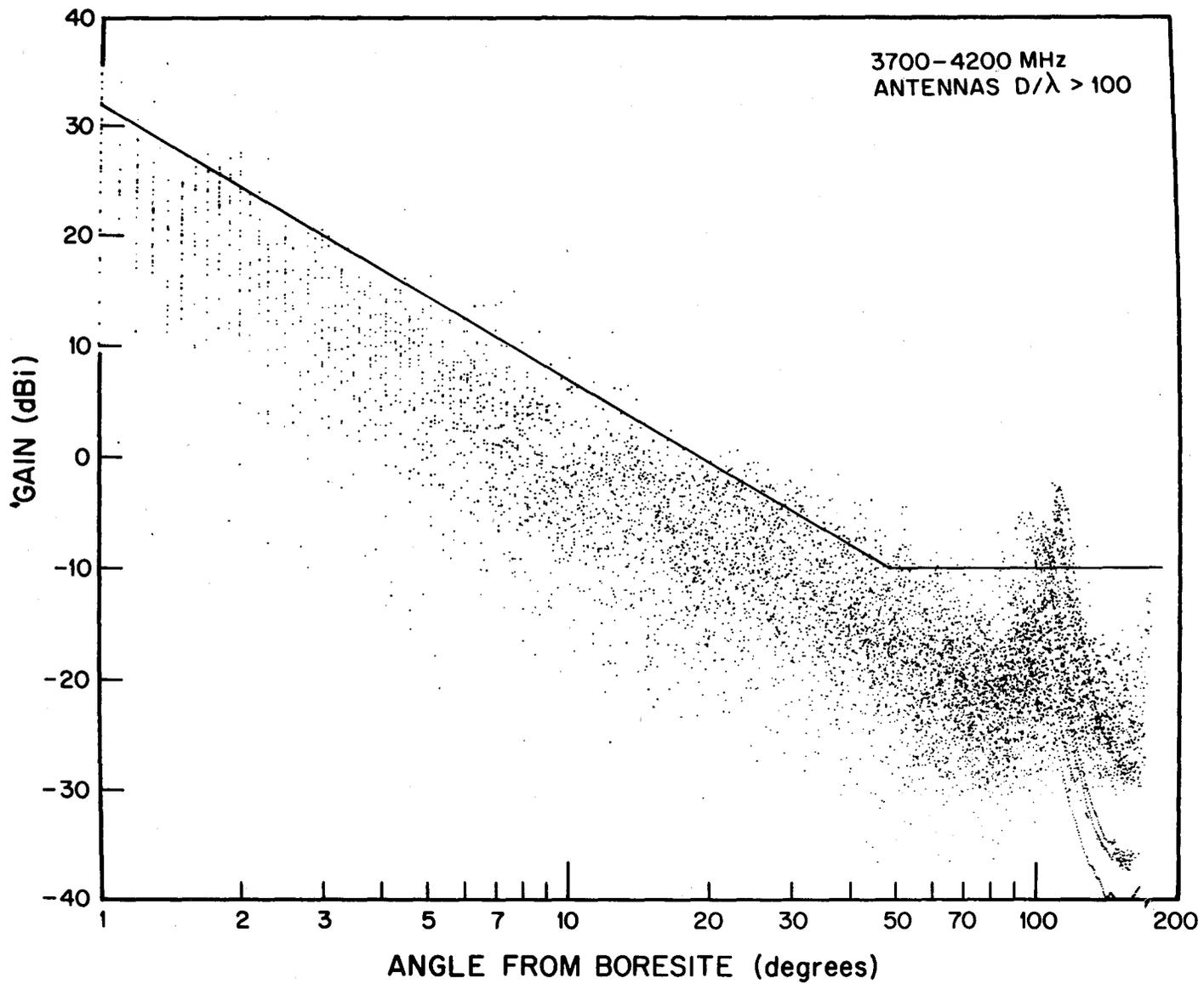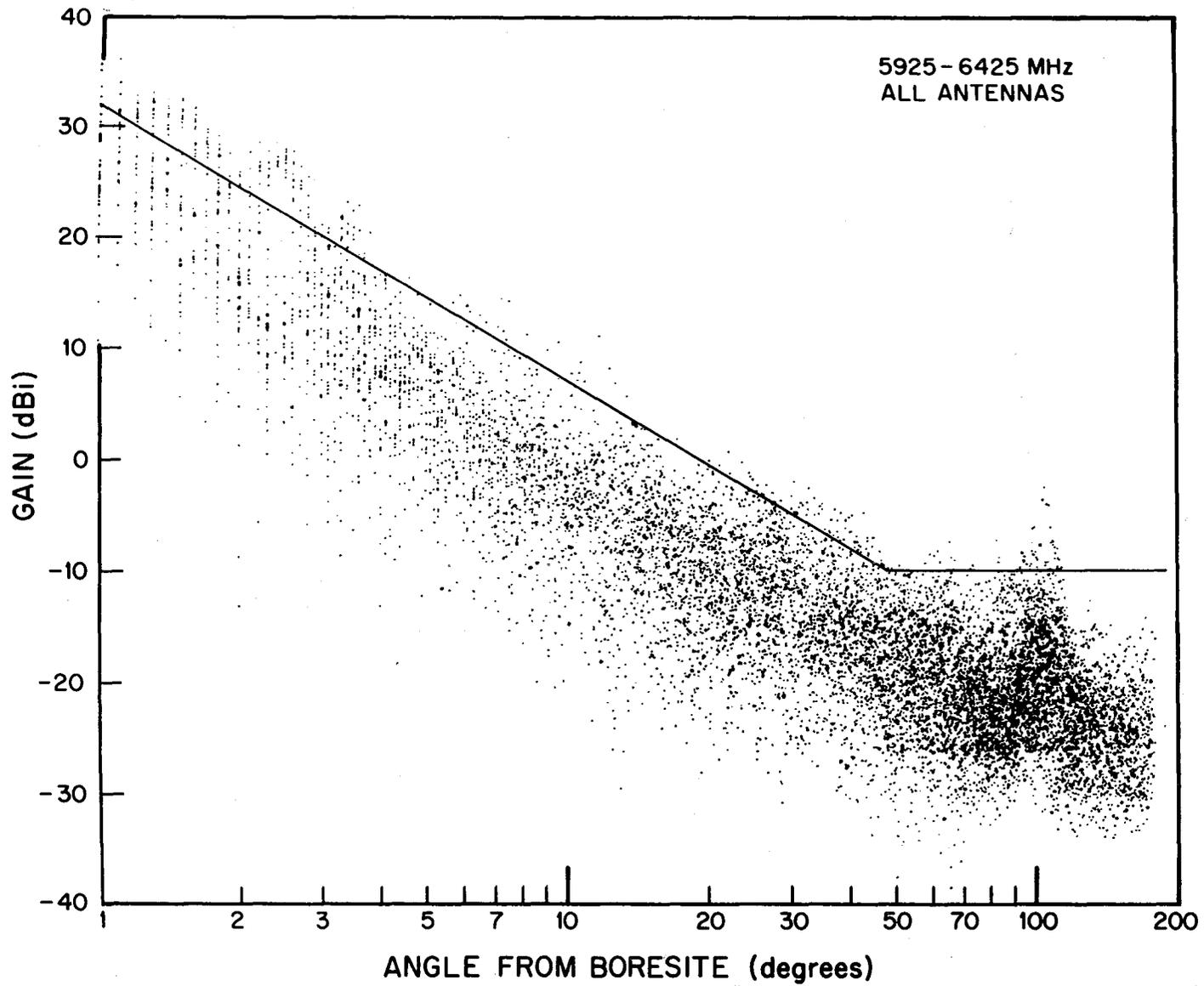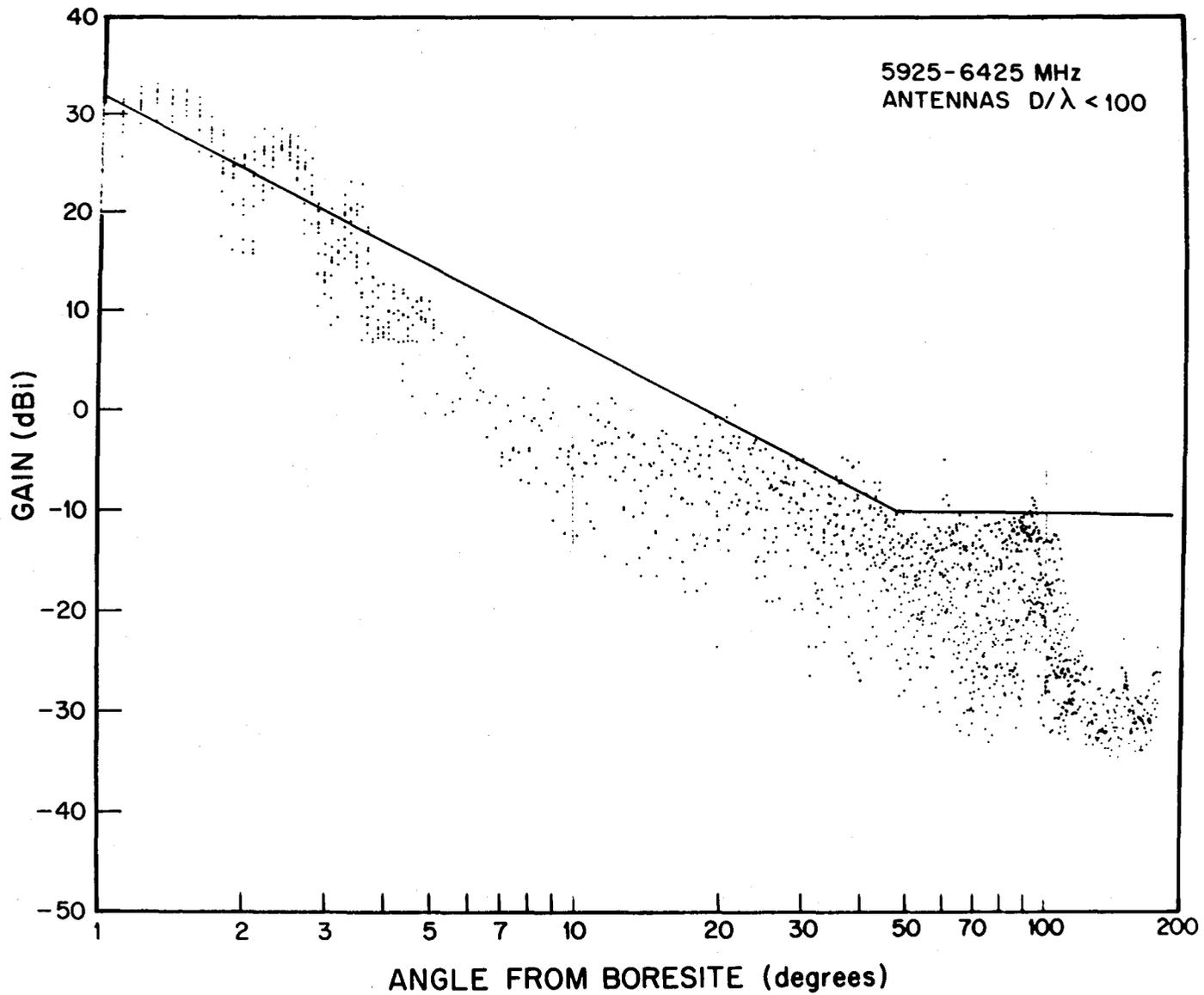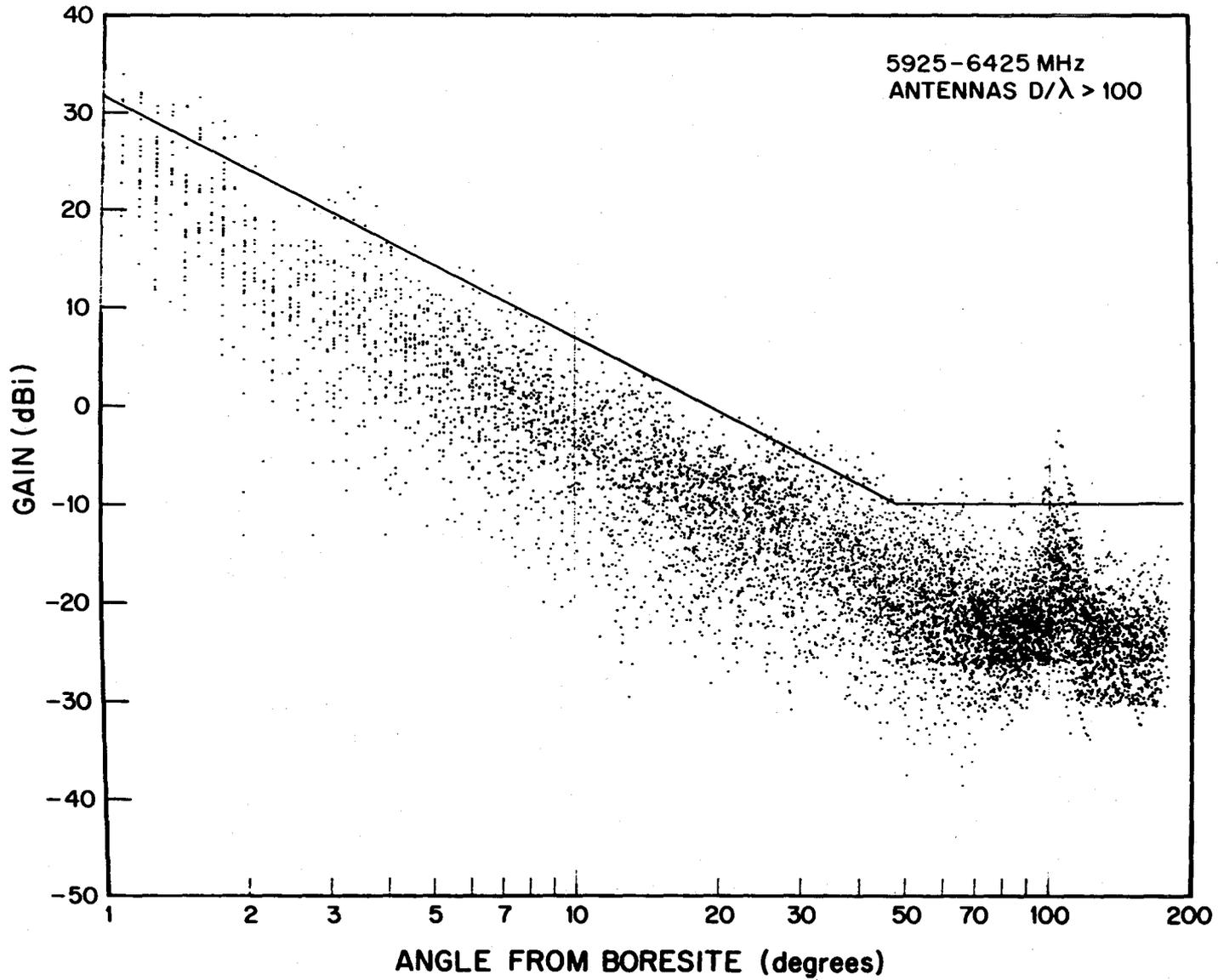Figure 15. Scatter plot showing all of the points digitized for all antennas with a D/λ > 100 in the 5925-6425 MHz frequency range.

of data for D/λ < 100 and D/λ > 100. However, the peak values that exceed
G (φ) = 32 - 25 log φ dBi primarily are data for D/λ < 100.

Figure 13 shows all digitized data for antennas operating in the 5.925
to 6.425 GHz band (15 antennas total). The diameter-to-wavelength ratios
for these data vary from 89 to 167. Figure 14 shows data from antennas
with a diameter-to-wavelength ratio of less than 100. It exhibits a notice-
able deficiency of data points in that it shows the digitized data only for a
single 4.5 m antenna. This happens to be the only set of antenna patterns
in the 6 GHz band with a diameter-to-wavelength ratio of less than 100.
These data were recorded at three frequencies, yielding data for D/λ ranging
from 89 to 96, and two polarizations for both the large-scale and small-scale
conditions (the typical set of conditions described in section 2.2) and
therefore, we see a tendency for a lobe structure in the data to about 5°.
Figure 15 shows the digitized data only for antennas (14 of the 15 that operate
in the 5.925 to 6.425 GHz band) for which the diameter-to-wavelength
ratio varies from 123 (D = 6.0 m) to 267 (D = 13.0 m).

All of the data show some high sidelobe peak amplitudes in the region
of from about 90° to 120°. These high-amplitude values, very likely, are
caused by spillover of energy directed from the transmitting antenna striking
the subreflector and the main reflecting surface coincidently.

3.2 Statistical Analysis Results

Sidelobe peak values have been sorted (with the aid of a computer), as
described in Section 2.2 and illustrated in Figure 9, from the subsets of
digitized data (described in Section 3.1). These sidelobe peak values then
have been sorted into lines defined by intervals of angle from boresight,
according to CCIR guidelines. Arithmetic differences between the sidelobe
peak values and the reference antenna performance standard

$$
G (\phi) = \begin{cases} 32 - 25 \log \phi \quad \text{dBi} & \text{for} \quad 1^{o} \leq \phi < 48^{o} \\ -10 \text{ dBi} & \text{for} \quad 48^{o} \leq \phi \leq 180^{o} \end{cases}
$$

have been calculated. Within each angular interval (line), the statistical
characteristics of these arithmetic differences have been calculated, and

these statistical characteristics have been plotted for the subsets of antenna data described earlier in Section 3.1. The statistics of these sidelobe peak values are plotted in Figures 16 through 18 for data describing the performance of antennas that operate in the 3.700 to 4.200 GHz band and in Figures 19 through 21 for data describing performance of antennas that operate in the 5.925 to 6.425 GHz band. These statistics are presented graphically with a bar plotted at the midpoint of each interval. The interpretation of this bar presentation is illustrated in each figure.

Figure 16 shows the statistics of all data for antennas operating in the 3.700 to 4.200 GHz band. Figures 17 and 18 show statistics for subsets of these data, namely for data with $D/\lambda < 100$ and data with $D/\lambda > 100$, respectively. From these figures, we note that in the interval of $1°$ to $2°$ there are 88 sidelobe peak-value samples. Forty of these samples are data for antennas for which D/λ is less than 100, and 48 of the samples are data for antennas with D/λ greater than 100. Note on Figure 16 that nearly 50% of the 88 sidelobe peak values exceed the reference standard; however, Figure 17 shows a majority of these high values are for antennas for which D/λ is less than 100. In fact, the data plotted in Figure 17 generally have considerably more than 10% of the values exceeding the reference standard, except in the intervals of $4°$ to $7°$, $7°$ to $10°$, and $10°$ to $20°$ (from $4°$ to $20°$, in short). In contrast, the data plotted in Figure 18 (antennas for which $D/\lambda > 100$) generally have fewer than 10% of the peak values exceeding the reference standard except in the region of $100°$ to $120°$.

The statistics of all data for antennas operating in the 5.925 to 6.425 GHz band are shown on Figure 19. The statistics for subsets of these data, namely, data for $D/\lambda < 100$ and data for $D/\lambda > 100$ are shown on Figures 20 and 21, respectively. For the intervals of $1°$ to $2°$ and $2°$ to $4°$, we note on Figure 19 that from samples of 84 and 103 values, respectively, considerably more than 10% of the values exceed the reference standard.

Comparing the statistics for the same intervals shown in Figures 20 and 21, it is apparent that most of the values that exceed the reference standard come from data for the one antenna for which D/λ is less than 100. Generally speaking, the data show that fewer than 10% of the sidelobe peaks exceed the reference standard when operating at these higher (earth-to-space link) frequencies, particularly for those antennas for which D/λ is greater than 100.

Figure 16.   Statistical plot of sidelobe peak values for all antennas in the
3700-4200 MHz frequency range.
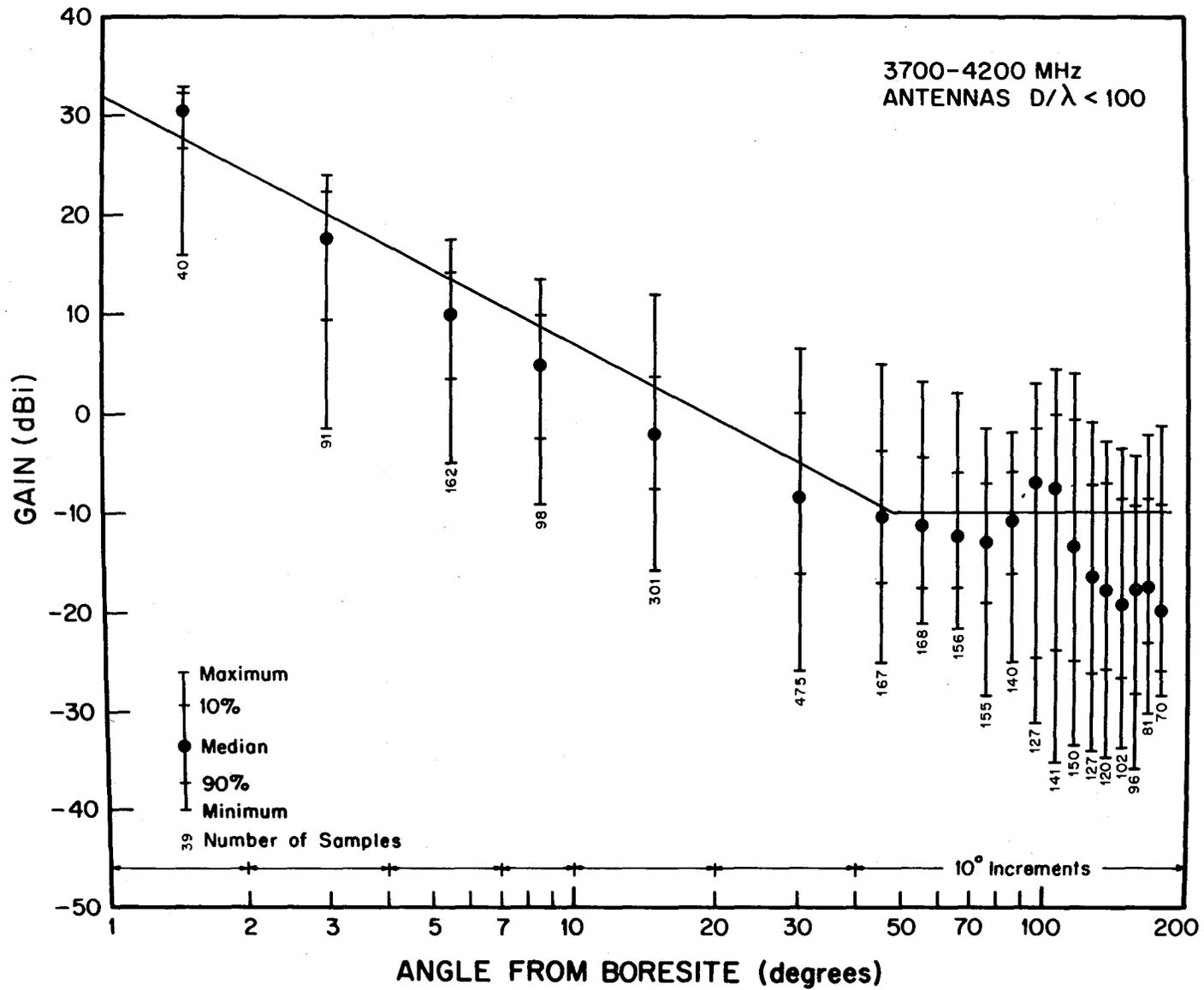
Figure 17.   Statistical plot of sidelobe peak values for all antennas with
a D/λ < 100 in the 3700-4200 MHz frequency range.

Figure 18.   Statistical plot of sidelobe peak values for all antennas with
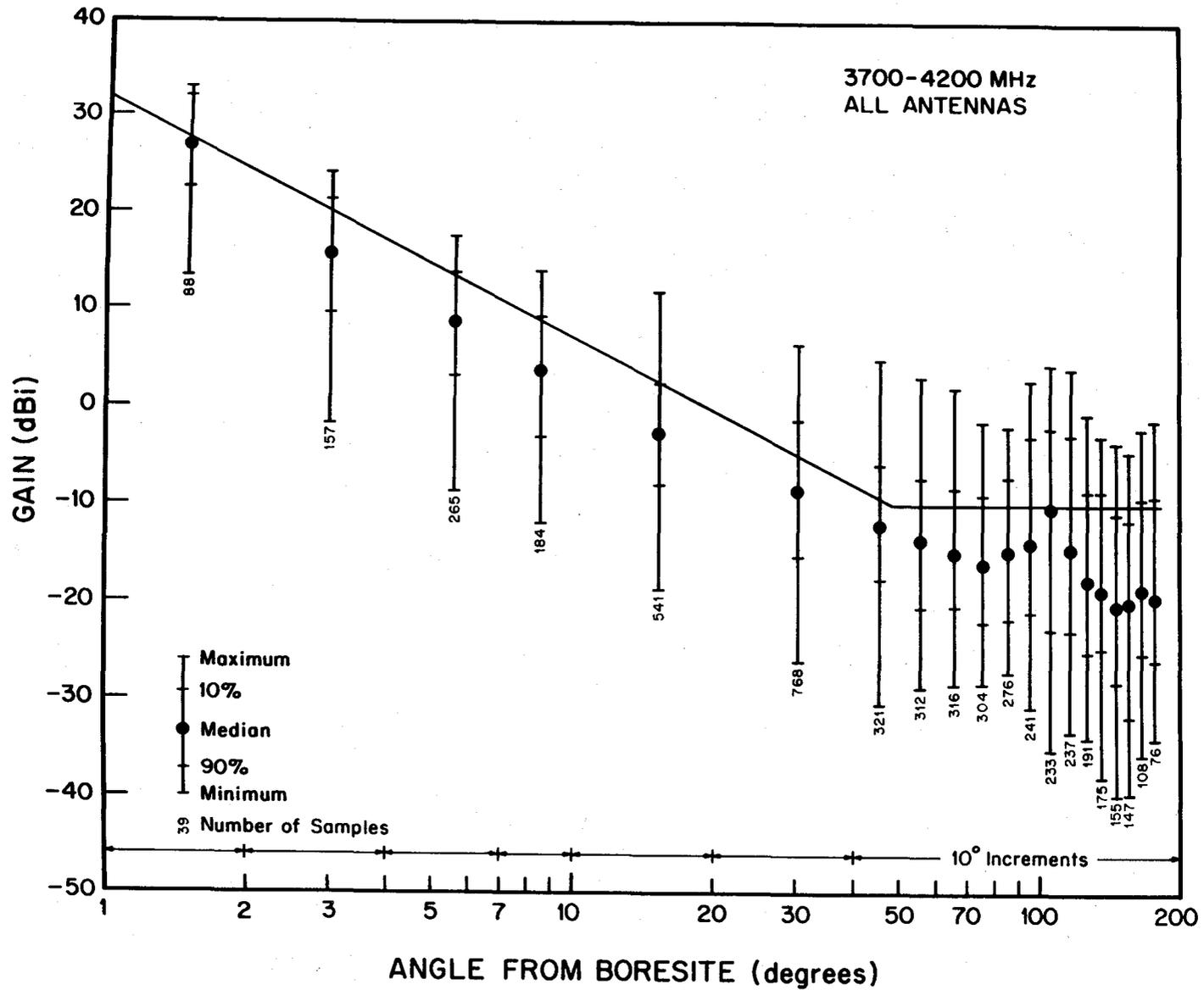a D/λ > 100 in the 3700-4200 MHz frequency range.

Figure 19.   Statistical plot of sidelobe peak values for all antennas
in the 5925-6425 MHz frequency range.

Figure 20.   Statistical plot of sidelobe peak values for all antennas
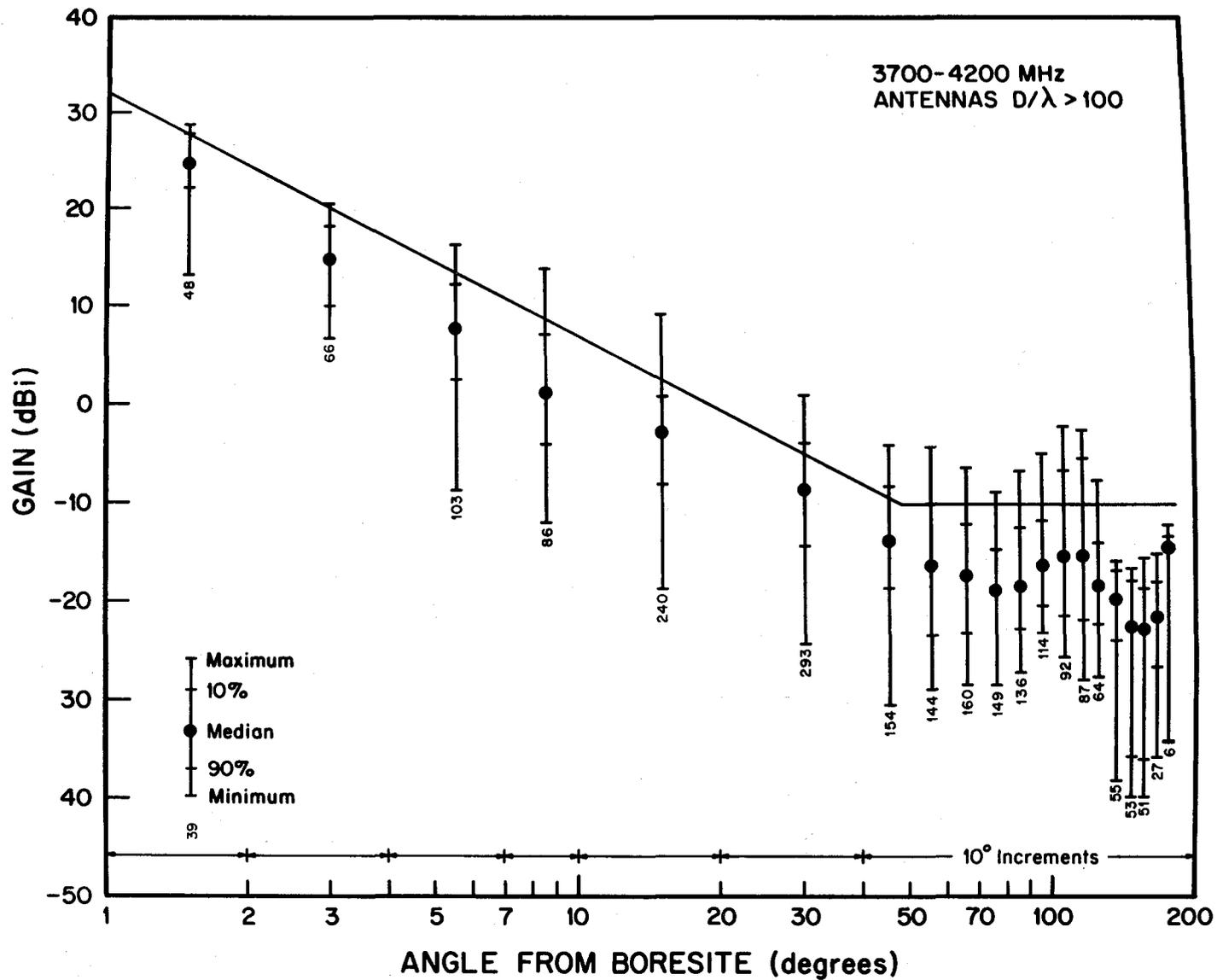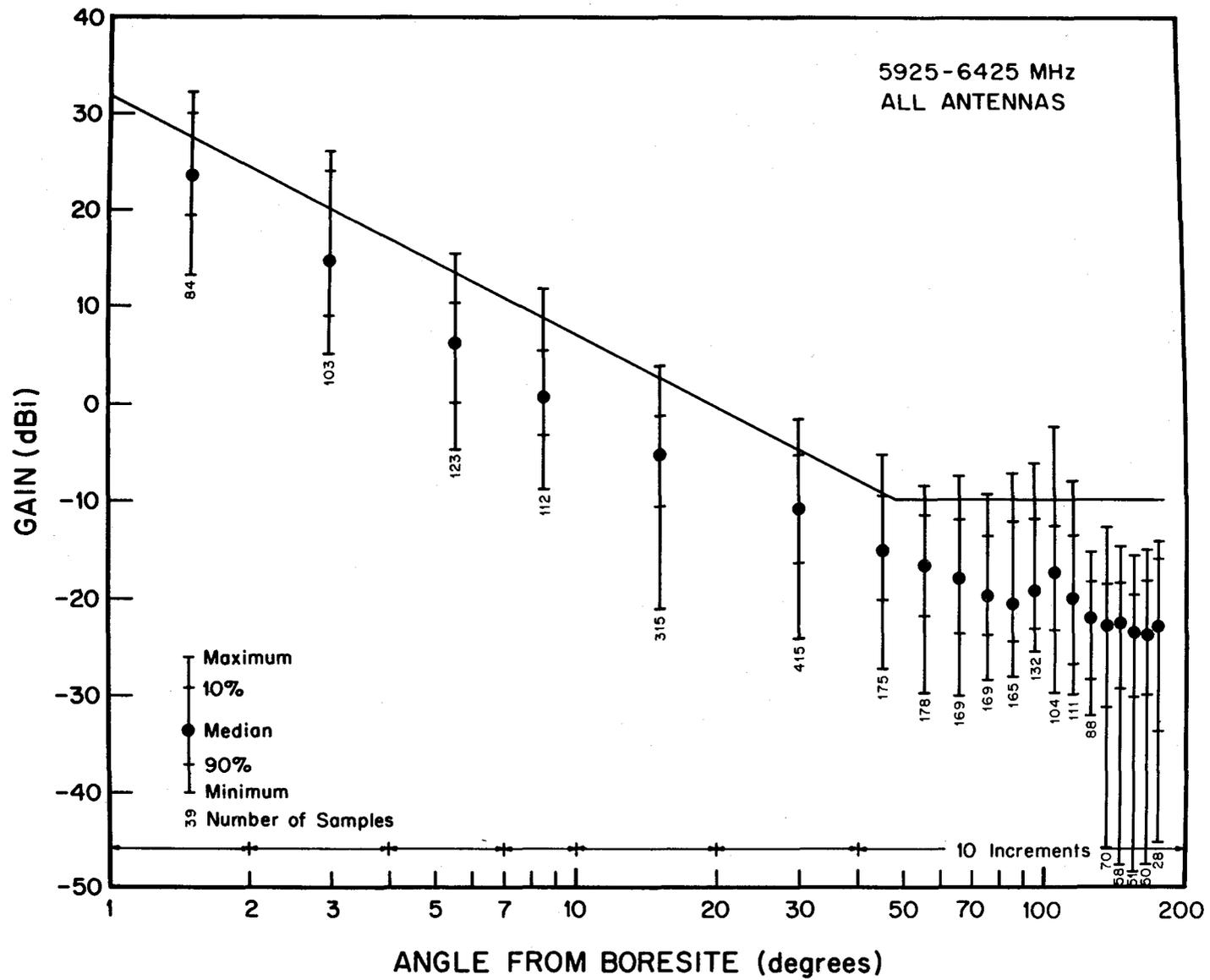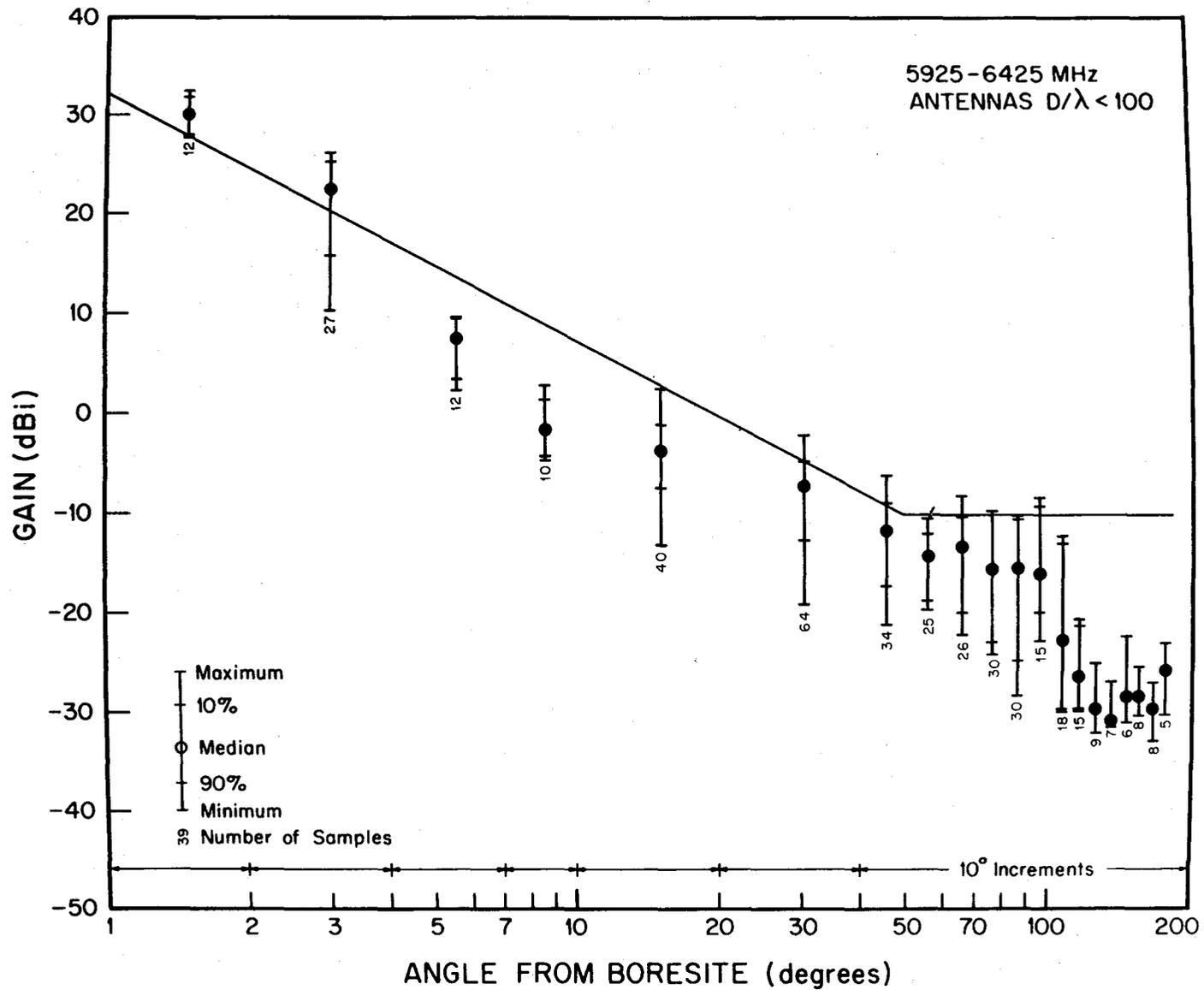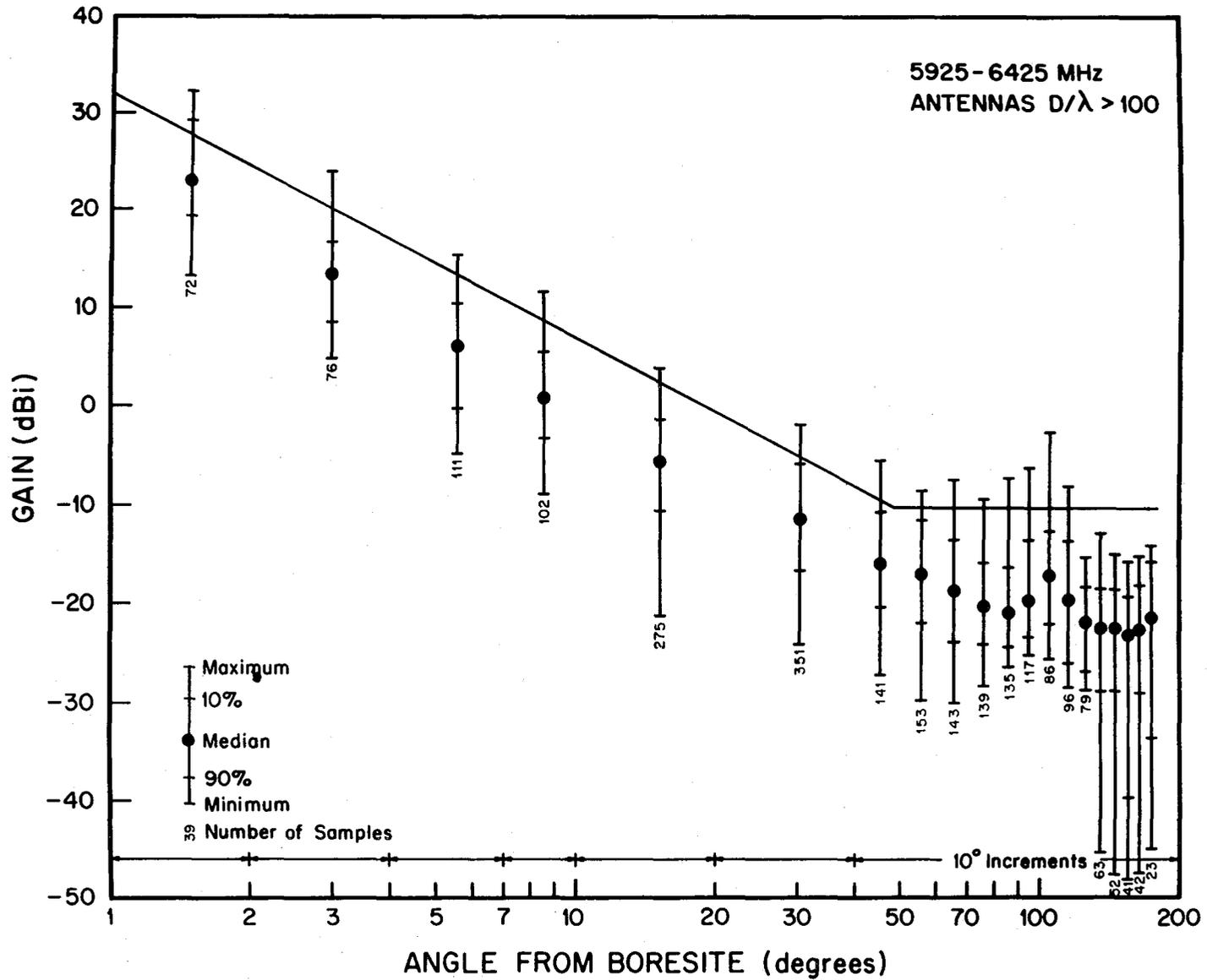with a D/λ < 100 in the 5925-6425 MHz frequency range.

Figure 21. Statistical plot of sidelobe peak values for all antennas with a D/λ > 100 in the 5925-6425 MHz frequency range.

4. CONCLUSIONS AND RECOMMENDATIONS

All antennas utilized in this analysis were designed to meet the regulations as stated in Part 25 of the FCC's Rules and Regulations on Satellite Communication published in March 1974 and updated in September of 1982. In Subpart C - Technical Standards, paragraph 25.209, Antenna Performance Standards, the following is stated:

> "a(a) Any antenna to be employed in transmission at an earth station in the Communication-Satellite Service shall conform to the following standard.
>
> Outside the main beam, the gain of the antenna shall lie below the envelope defined by:
>
> $$32 - 25 \log \theta \quad \text{dBi} \quad 1° \leq \theta \leq 48°$$
> $$-10 \quad \text{dBi} \quad 48° < \theta \leq 180°$$
>
> where θ is the angle in degrees from the axis of the main lobe, and dBi refers to dB relative to an isotropic radiator. For the purposes of this section, the peak gain of an individual sidelobe may be reduced by averaging its peak level with the peaks of the nearest sidelobes on either side, or with the peaks of two nearest sidelobes on either side, provided that the level of no individual sidelobe exceeds the gain envelope given above by more than 6 dB.
>
> (b) Any antenna employed for reception at an earth station in the Communication-Satellite Service shall be protected from interference only to the degree to which harmful interference would not be expected to be caused to an earth station employing an antenna conforming to the antenna standard of paragraph (a) of this section."

The key to many of the present antennas being able to meet the FCC's Rules and Regulations is seen in paragraph (a) above where individual antenna peaks can exceed the reference curve by as much as 6 dB, then be averaged with peaks on either side, and still conform to the reference curve. By utilizing this allowable averaging, the advertised "smoothed" curves or antenna envelopes appearing in the manufacturer's brochures of all of the antennas used in this analysis lie on or below the FCC's reference curve. Our analysis has included only data from actual measured patterns. No "smoothed" patterns have been used.

As expected, the poorest performance with respect to the 1974 (updated 1982) FCC envelope is seen in the lower frequency range (3.7-4.2 GHz) or

receiving antennas. As seen in Figure 16, in the region between 1 and 2 degrees, almost 50% of all measured data lie above the reference curve and in Figure 17, where the antenna diameters are 7 meters or less (D/λ < 100), almost 90% of the peaks lie above the envelope in this same interval. When we look at the antenna measurements between 2° and 4°, we see that the percentage of antenna peaks exceeding the reference curve decreases; however, fully 25% of the peak data still exceed the envelope. This region between 1 and 4 degrees from the antenna boresite is a sensitive area due to the new rules (Report and Order, CC Docket No. 11-704) which will allow closer spacing of satellites. This closer spacing will certainly cause more interference from adjacent satellites at these smaller diameter receiving antennas. The extent to which this increased interference will degrade the performance of the present smaller antennas is yet to be seen. However, if the comments and calculations seen in the replies of the users and manufacturers to the FCC's Notice of Inquiry (CC Docket No. 81-704) are born out, the problem could be formidable.

In the uplink or transmitting frequency range (5.925 - 6.425 GHz) the FCC envelope is exceeded by more than 15% of the peak values for antennas with a D/λ > 100 (6 m diameter or greater) as seen in Figure 19. In 1987, when the new FCC Rules and Regulations take effect for all antennas, the percentage will rise to almost 40% of the peak values for these antennas and, because of the changes in those rules, none of these antennas will be allowed to transmit. Whereas under the old rules, the antenna sidelobes (up to 6 dB above the envelope) could be "averaged" the new rules state that the peak gain of an individual sidelobe may not exceed the envelope (29-25 log ϕ) between 1° and 7°. Unless these existing transmitting antennas can be modified to meet the new standards, they will have to be replaced at considerable cost to the users.

The FCC, in their Report and Order, CC Docket No. 81-704, initially had ordered that all new equipment installed after July 1, 1984, must meet the 29-25 log ϕ gain envelope between 1 and 7 degrees. This order, in light of petitions for reconsideration from several users in the fixed-satellite service, has been deferred as of June 27, 1984, in order for the FCC to review requests for modification of the regulations. The petitioners assert that their requested revisions will enable the FCC to achieve their objectives with less cost and disruption to the users. With this delay in the implementation of new rules for antennas (FCC rules governing all new antennas),

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we recommend that further consideration be given to the problems confronting users of the smaller antennas (D/λ < 100) with regard to different reference gain envelopes such as other organizations are entertaining.

The CCIR, for example, favors a different approach for a prescribed radiation envelope. In Report 391-4, the envelope used is the same as that of the old FCC envelope (32 - 25 log φ between 1° and 48° and -10 dBi between 48° and 180°) liberalized to the extent that 10% of the peaks of the actual radiation pattern may exceed the envelope. However, the report differs greatly from the FCC regulations in that the report attributes the reference envelope only to those antennas with a D/λ greater than 100. The FCC stipulates that its rules apply to all sizes of antennas. Utilizing the data from Report 391-4, the CCIR has concluded that antennas can be constructed, using current design techniques, which can meet an even more restrictive envelope. The FCC had ruled that all antennas installed after July 1, 1984, must meet a radiation envelope defined by 29 - 25 log φ between the off-axis angles of 1 and 7 degrees. Recommendation 580 utilizes the same envelope between 1 and 20 degrees for antennas installed after 1987, 3 years after the FCC's implementation. However, the CCIR again qualifies its recommendation by allowing 10% of the actual sidelobe peaks to exceed the envelope and also by applying the envelope only to antennas with a D/λ greater than 150. Recommendation 580 does not present an envelope for antennas with a D/λ less than 150 but Report 391-4 offers a reference radiation curve for antennas with a D/λ < 100. This new envelope, as mentioned in Section 1.1, is defined by:

$$G (\phi) = 52 - 10 \log (D/\lambda) - 25 \log \phi \quad dBi.$$

This formula would apply only to the region beyond the first sidelobe peak, that is, at and beyond φ (degrees) = 100 λ/D. In addition, it would never be assumed that the reference antenna gain falls below -10 dB relative to isotropic. If this equation were used to define an envelope for antennas in our analysis, all peaks between 1 and 10 degrees for all antennas would lie either at or below the envelope. These CCIR envelopes are mentioned here only to show that other organizations such as the CCIR believe that antennas with a D/λ of approximately 100-150 should be treated differently than the larger diameter antennas.

Several manufacturers have begun to produce antennas in the $D/\lambda < 100$ range which seem to meet or exceed the new rules and regulations as set up by the FCC under Part 25, Paragraph 209. If, indeed, the FCC does not alter their rules as summarized in Section 1.2, more and more manufacturers will be producing antennas that they purport to be in agreement with the new regulations. As shown in this analysis, some manufacturers will be offering antennas which will not actually perform within the prescribed standards due to some of the factors mentioned in Section 2.1. Analyses must be performed on the new antennas and also on retrofitted antennas in order to determine which sizes are minimally acceptable for use in the marketplace. If there are no changes in the FCC regulations, users of transmitting earth-station antennas smaller than 6-7 meters will have to retrofit, if possible, existing antennas or replace them with new antennas which will meet the new U.S. regulations.

4. REFERENCES

CCIR (1978)*, Frequency sharing between networks of the fixed-satellite service, Report 455-2, Vol. XIV Plenary Assembly, Geneva.

CCIR (1982a)*, Antennas for systems in the fixed-satellite service, Question 1-2/4, Vol. IV-1, XV Plenary Assembly, Geneva.

CCIR (1982b)*, Reference radiation diagram of antennas at earth stations in the fixed-satellite service, Study Programme 1A-1/4, Vol. IV-1, XV Plenary Assembly, Geneva.

CCIR (1982c)*, Radiation characteristics of satellite antennas in the fixed-satellite service, Study Programme 1B-4, Vol. IV-1, XV Plenary Assembly, Geneva.

CCIR (1982d)*, Characteristics of antennas at earth stations in the fixed-satellite service, Study Programme 1C-1/4, Vol. IV-1, XV Plenary Assembly, Geneva.

CCIR (1982e)*, Radiation diagrams of antennas for earth stations in the fixed-satellite service for use in interference studies and for the determination of a design objective, Report 391-4, Vol. IV-1, XV Plenary Assembly, Geneva.

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*Published by the International Telecommunication Union, Geneva, Switzerland.

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CCIR (1982f)*, Reference earth-station radiation pattern for use in coordination and interference assessment in the frequency range from 2 to about 10 GHz, Recommendation 465-1, Vol, IV-1, XV Plenary Assembly, Geneva.

CCIR (1982g)*, Radiation diagrams for use as design objectives for antennas of earth stations operating with geostationary satellites, Recommendation 580, Vol. IV-1, XV Plenary Assembly, Geneva.

ITU (1982)*, International regions, Radio Regulations, Vol. 1, International Telecommunications Union, Article 8, ISBN 92-61-01221-3.

FCC (1972), Domestic communications satellite facilities, 38 FCC 2d 665, FCC 16495.

FCC (1974), Western Union Telegraph Company, Orbital spacing criteria, 47 FCC 2d 274.

FCC (1981), Licensing of space stations in the domestic fixed-satellite service and related revisions of part 25 of the rules and regulations, Notice of Inquiry and Proposed Rulemaking, CC Docket No. 81-704, FCC 30089.

FCC (1982), Rules and Regulations, Part 25, Para. 209, Satellite Communications.

FCC (1983), Licensing of space stations in the domestic fixed-satellite service and related revisions of part 25 of the rules and regulations, Report and Order, CC Docket No. 81-704, FCC 33206.

FCC (1984), Effective date of the revised rules concerning earth station antennas performance standards for newly installed antennas, 47 C.F.R., para. 25.209, CC Docket No. 81-704, FCC 5082.

*Published by the International Telecommunication Union, Geneva Switzerland.

APPENDIX: ANTENNA IDENTIFICATION

This appendix lists the antennas from which measured analog data have been derived. The patterns supplied by the manufacturers have included, in most instances, measurements of antennas at several frequencies, as shown in the tables, as well as measurements in both the electric (E) and magnetic (H) planes. Each antenna pattern supplied is defined by its manufacturer, size, measurement frequency, and measurement polarization. Information on antennas in the downlink frequency range (4 GHz) has been split into two sets of antennas. Table A-1 lists all antennas for D/λ less than 100 and Table A-2 lists those antennas for which D/λ is greater than 100. Table A-3 lists antennas in the uplink frequency range (6 GHz) for D/λ both less than and greater than 100. Manufacturer's designations in the tables are as follows:

AND - Andrew Corporation
      10500 W 153 rd Street
      Orland Park, IL   60462

AFC - Microdyne Corporation
      P.O. Box 7213
      Silver Springs Shores Ind. Park
      Ocala, FL   32672

HAR - Harris Corporation
      Satellite Communications Division
      P.O. Box 1277
      kilgore, TX   75662

St - SatCom Technologies, Inc.
      2912 Pacific Drive
      Norcross, GA   30071

SA - Scientific Atlanta, Inc.
      3845 Pleasantdale Road
      Atlanta, GA   30340

US - United Satellite Systems
      St. Hilaire, MN   56754

Table A-1. Antennas That Operate in the 3.700 to 4.200 GHz Band
(Space-to-Earth Links) for Which D/λ ≺ 100.

No.	Manuf	Model	Dia (m)	Freq (MHz)	D/λ	Gain (dBi)
1	SA	8006	2.8	3700	35	39.3
				3950	37	39.5
				4200	39	39.7
2	US	MN380	3.8	3700	47	41.7
				3950	50	42.2
				4200	53	42.7
3	AND	39139-6	4.5	3700	56	43.7
				3950	59	43.9
				4200	63	44.1
4	AND	39139-7	4.5	3700	56	43.7
				3950	59	43.9
				4200	63	44.1
5	SA	8005 PF	4.6	3700	57	43.3
				3950	61	43.5
				4200	64	43.7
6	MC	PR16.4	5.0	3700	62	43.8
				3950	66	44.0
				4200	70	44.2
7	SA	8008	5.0	3700	62	44.3
				3950	66	44.5
				4200	70	44.7
8	HAR	5243-44	6.0	3950	79	46.5
9	MC	PR-23	7.0	3950	92	47.2
10	ST	700C	7.0	3950	92	47.7
11	ST	700H	7.0	3950	92	47.4
12	SA	8010A	7.0	4000	93	47.5

Table A-2. Antennas That Operate in the 3.700 to 4.200 GHz Band (Space-to-Earth Links) for Which D/λ > 100.

No.	Manuf	Model	Dia (m)	Freq (MHz)	D/λ	Gain (dBi)
1	HAR	5251	8.8	3950	116	50.0
2	ST	920 C	9.2	4000	123	50.0
3	ST	920 CH	9.2	3950	121	50.0
4	AND	43998	10.0	3700	123	50.4
				3950	132	51.0
				4200	140	51.4
5	SA	8002A	10.0	3700	123	50.6
				3950	132	50.8
				4000	133	50.8
				4200	140	51.0
6	SA	8002A-HP	10.0	3700	123	50.3
				3950	132	50.5
				4000	133	50.5
				4200	140	50.7
7	HAR	---	10.0	3950	140	51.3
8	HAR	5260	11.0	3950	145	51.7
9	HAR	5270	13.0	4000	173	52.8
10	HAR	5270 LSL	13.0	4000	173	52.8

Table A-3. Antennas That Operate in the 5.925 to 6.425 GHz Band
(Earth-to-Space Links)

D/λ < 100

No.	Manuf	Model	Dia (m)	Freq (MHz)	D/λ	Gain (dBi)
1	AND	39139-6	4.5	5925	89	46.6
				6175	93	46.8
				6425	96	47.0

D/λ > 100

No.	Manuf	Model	Dia (m)	Freq (MHz)	D/λ	Gain (dBi)
1	HAR	5243-44	6.0	6175	123	49.0
2	SA	8010 A	7.0	6175	144	49.4
3	ST	700 C	7.0	6175	144	51.0
4	ST	700 CH	7.0	6175	144	50.0
5	HAR	5251	8.8	6175	181	53.2
6	ST	920 C	9.2	6175	189	53.2
7	ST	920 CH	9.2	6175	189	53.2
8	AND	43998	10.0	5925	197	54.0
				6175	206	54.3
				6425	214	54.5
9	SA	8002 A	10.0	6175	206	50.8
10	SA	8002 A-HP	10.0	5925	197	50.3
				6175	206	50.5
				6425	214	50.7
11	HAR	--	10.6	6175	218	54.2
12	HAR	5260	11.0	6175	226	55.0
13	HAR	5270	13.0	6000	260	55.5
14	HAR	5270LSL	13.0	6175	267	55.7

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

    Measured analog data showing gain as a function of angle away from the mainbeam (maximum gain) axis have been obtained for 22 types of reflector antennas designed for operation at 4 GHz for reception and 6 GHz for transmission. The antennas ranged in size from 2.8 m to 13.0 m and represented six United States manufacturers. The analog patterns have been converted to sets of digital data pairs (gain and angle) to facilitate analysis. The data then have been analyzed following techniques recommended by the CCIR for antennas for earth stations in the Fixed-Satellite Service to develop statistical characterizations of gain versus angle for the sidelobe regions. The digitization and analysis techniques are discussed and statistical results are provided, along with some background material from the perspectives of the CCIR, the FCC, and antenna manufacturers.

16. Key Words *(Alphabetical order, separated by semicolons)*

antenna gain patterns, antenna sidelobe gain characteristics, earth station antenna gain, orbit spacing, reference antenna patterns, reference radiation diagrams, statistical antenna gain patterns

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