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Sidelobe Gain Characteristics for Ku-Band Earth-Station Antennas

J. M. Harman
R. D. Jennings

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

Alfred C. Sikes, Assistant Secretary
for Communications and Information

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PREFACE

Certain commercial equipment and software products are identified in this report to adequately describe the design and conduct of the research. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

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SIDELOBE GAIN CHARACTERISTICS FOR Ku-BAND EARTH STATION ANTENNAS

J. M. HARMAN and R. D. JENNINGS*

Measured analog data showing gain as a function of angle away from the mainbeam (maximum gain) axis have been obtained for 14 models of reflector antennas designed for operation at 11/12 GHz for reception and at 14 GHz for transmission. The antennas ranged in size from 3.5 to 11.0 m and represented equipment from four U. S. 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 International Radio Consultative Committee (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 to show compliance with Federal Communications Commission (FCC) and CCIR recommendations. Background material from the perspectives of the CCIR, the FCC, and antenna manufacturers is also provided.

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 percentage of the sidelobe peaks. Reducing the off-axis, or sidelobe, gain can be used as an effective discriminant against

*The authors are with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U. S. Department of Commerce, Boulder, Colorado 80303.

**The reference radiation diagram should be understood to describe an envelope of the minimally acceptable radiation peak gains in the principle plane of the antenna for copolarized coupling.

radio-frequency interference. Control of these sidelobe gain amplitudes, 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, 1982a-h)

CCIR Question 1/4, pertaining to antennas for systems in the Fixed-Satellite Service, was developed in 1961 and modified most recently in 1974. It is now designated as Question 1-2/4 (CCIR, 1982a). A part of that question asks "what is the state of development in the design and fabrication of antennas particularly with improved sidelobe and backlobe characteristics?" Three Study Programmes have been established, in support to this question, to encourage studies on (1) "Reference Radiation Diagram of Antennas at Earth Stations in the Fixed-Satellite Service"-(1A-1/4) (CCIR, 1982b), (2) "Radiation Characteristics of Satellite Antennas in the Fixed-Satellite Service" (1B/4) (CCIR, 1982c), and (3) "Characteristics of Antennas at Earth Stations in the Fixed-Satellite Service" (1C-1/4) (CCIR, 1982d).

The study of antenna sidelobe characteristics reported herein 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-1/4, Reports 390 and 391 were adopted in 1966. There have been revisions to each report in 1970, 1974, 1978, and 1982. Therefore, current designations are 390-4 (CCIR, 1982e) and 391-4 (CCIR, 1982f). 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 a general discussion of desired characteristics for earth station antennas for the Fixed-Satellite Service.

Report 391-4 presents data that are used as a basis for several recommendations regarding reference radiation diagrams. These 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" (when the antenna diameter/wavelength is greater than 100) (CCIR, 1982g) and Recommendation 580 for "Radiation Diagrams for Use as Design Objectives for Antennas of Earth Stations Operating with Geostationary Satellites" (when D/λ exceeds 150) (CCIR, 1982h).

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

$$G = \begin{cases} 32 - 25 \log \phi & \text{dB} \quad \text{for} \quad 1^\circ \leqq \phi < 48^\circ \\ -10 & \text{dB} \quad \text{for} \quad 48^\circ \leqq \phi \leqq 180^\circ \end{cases} \qquad (1a)$$

and is shown in Figure 1. In this and succeeding expressions, G is the gain relative to an isotropic radiator/receptor and ϕ is the angle, in degrees,

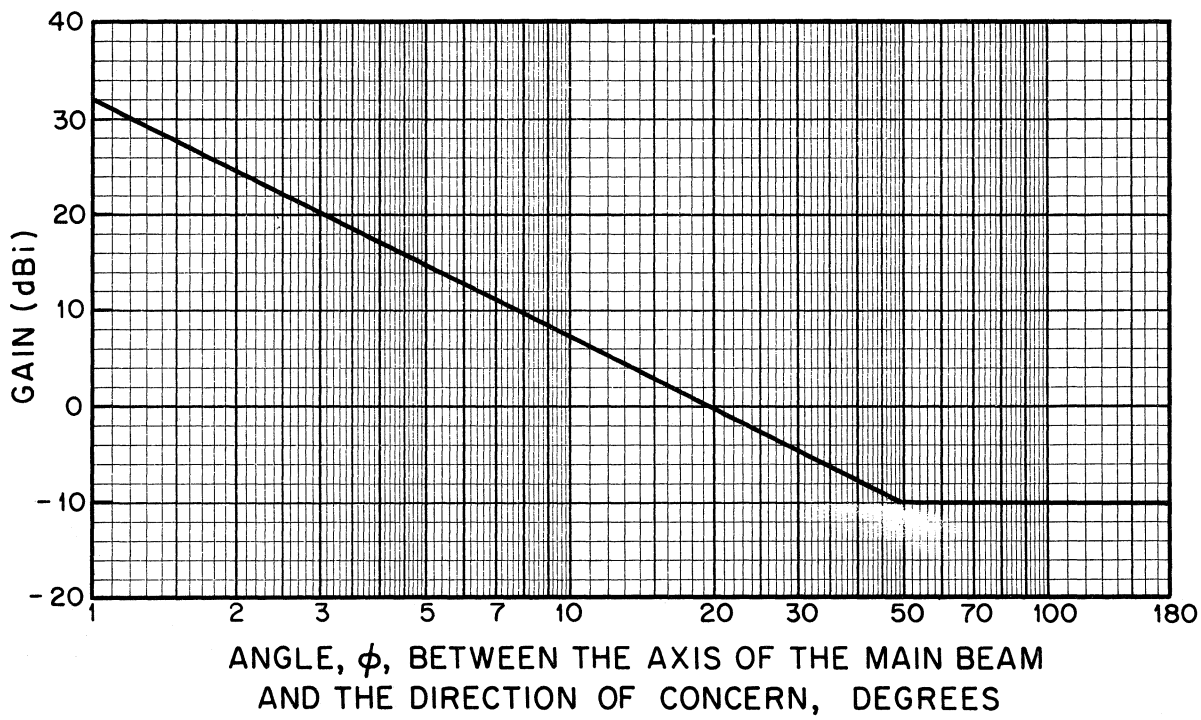

Figure 1. Reference radiation diagram from CCIR Report 391-4 and adopted in Recommendation 461-1 for earth-station antennas with D/λ > 100.

between the mainbeam axis and the direction of concern. This reference radiation diagram expression defines an envelope that should not be exceeded by more than 10 percent of the sidelobe peaks in an actual radiation diagram.

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 its 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.

Report 391-4 and Recommendation 465-1 primarily consider sidelobe characteristics at angles greater than 1° from the mainbeam axis and deal with antennas having a D/λ exceeding 100, hence, (1) above is restricted to $\phi \geqq 1°$ and is to be used only with antennas having a $D/\lambda > 100$. Annex I to Report 391-4, however, defines a reference antenna pattern (adopted at the WARC-79) for antennas with $D/\lambda < 100$. This reference antenna pattern is:

$$G = \begin{cases} 52 - 10 \log (D/\lambda) - 25 \log \phi \text{ dB} & \text{for} \quad (100\ \lambda/D)° \leqq \phi < 48° \\ 10 - 10 \log (D/\lambda) \text{ dB} & \text{for} \quad 48° \leqq \phi \leqq 180°. \end{cases} \qquad (1b)$$

This reference pattern also has been proposed as MOD I to Recommendation 465-1.

Recommendation 580 was adopted at the XVth Plenary Assembly as a design objective for antennas of earth stations installed after 1987 (a provisional date to be reviewed by the XVIth Plenary Assembly) operating with geostationary satellites. The recommendation is that antennas with $D/\lambda > 150$ should have a radiation diagram design objective that the gain of at least 90% of the sidelobe peaks not exceed

$$G = 29 - 25 \log \phi \text{ dBi} \qquad \text{for } 1° \leqq \phi \leqq 20°. \qquad (2)$$

It is further recommended that this requirement apply for any off-axis direction within 3° of the geostationary satellite orbit in consideration of antenna orientation. Figure 2 illustrates the geometry for which this recommendation has application. It is to be noted that (2) recommends a 3 dB reduction in the envelope of sidelobe peak gain from that in (1a) over the range $1° \leqq \phi \leqq 20°$. Further note that Recommendation 580 makes no mention of recommended sidelobe gain for angles $\phi > 20°$.

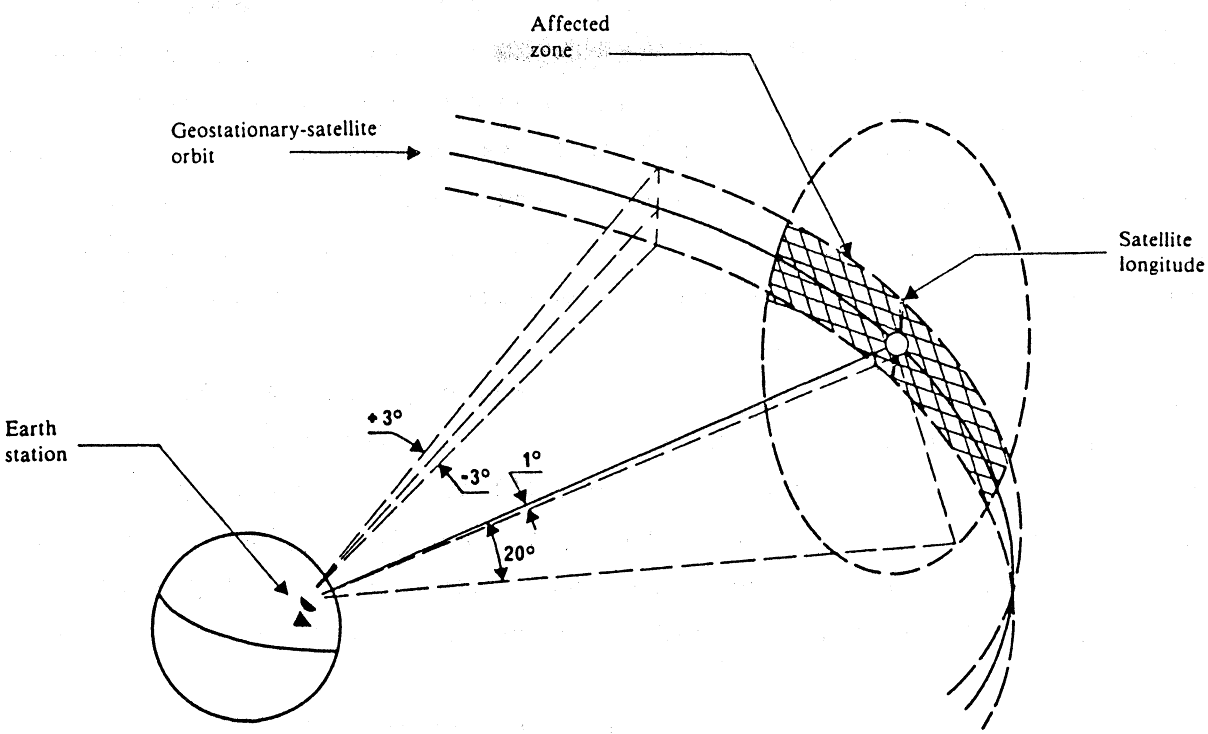

Figure 2. Geometrical illustration of application for CCIR Recommendation 580 for reference diagram design objective for earth station antenna with $D/\lambda > 150$.

1.2 Background from the FCC Perspective

In 1981, the Federal Communications Commission briefly reviewed prior regulation of the domestic satellite (domsat) industry and emphasized the dynamic nature of that industry in its Notice of Inquiry and Proposed Rulemaking (FCC, 1981). Demand for domsat services has almost outstripped the collective ability to supply the required services. 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 3° in the 14/11 GHz (Ku) band and 4° in the 6/4 GHz (C) band (as defined in FCC document 16495 in 1970 and updated in 1972) (FCC, 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 is positioned. Only a portion of the geostationary orbit is visible from points within the United States, and hence usable for providing domestic service. By international agreement, that portion of the orbital arc between approximately 20° and 180° west longitude serves ITU Radio Region 2 (ITU, 1982), within which the continental United States lies. Within those confines, only that portion of the orbital arc between 50° and 143° west longitude is of practical use to the continental 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 (50° to 62° 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 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 the frequency spectrum available to support radio communications 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 (FCC, 1983). The frequencies available in the domestic satellite spectrum include 6/4 GHz, 14/11 GHz, and 30/18 GHz. Because propagation conditions in the 6/4 GHz band are more favorable than in the upper bands, it is the band most widely used.

Domestic services were first provided in this band and are now firmly established; most satellite services are offered in this band 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 this band. However, as the resources available within this band become more fully utilized, increasing use of the 14/11 GHz band will be made.

In considering reductions of spacing between satellites in the geostationary orbit, the FCC has concluded that uniform spacing of 3° 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 3 m and perhaps up to 6 m, will have to be upgraded (redesigned, increase size by adding panel extensions, etc.) or, likely, replaced in order to meet standards of acceptability. The FCC believes, however, that given the increased diversity of services that can be made available by the additional satellites, the costs are not out of line.

In 1977 the Commission adopted a 3° orbital spacing criterion (FCC, 1977) based on a conservative analysis of the Satellite Business Systems operating system. With regard to that analysis, 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 stating that the reference curve seen in (1) above would apply to all antennas in the Fixed-Satellite Service. 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.

In 1981 the FCC staff analyzed, through computer simulation, several combinations of orbital spacings using different values of earth station sidelobe discrimination and cross-polarization isolation (FCC, 1981). 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. 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. The FCC feels that their analysis demonstrates the general feasibility of 2° orbital separations at 14/11 GHz.

In accordance with their findings, the FCC has revised the antenna performance standards of the Rules and Regulations to facilitate the moving of satellites from their present 3° spacing to a 2° spacing. The reference curve adopted by the FCC in its Report and Order, CC Docket No. 81-704 (FCC, 1983), is shown in Figure 3. The calculated carrier-to-interference ratios provide high levels of isolation for moderate size antennas conforming to the new antenna sidelobe standard. While some of the smallest antennas contemplated may not conform to the new standard, the isolation requirements are also lower in practice for these services because of the overall lower transmission link performance expected by the user. Moreover, additional margins are available for intersatellite interference at 14/11 GHz because of the absence of terrestrial interference, the potential presence of some cross-polarization isolation, and the potential advantages that can be obtained with frequency offsets through coordination with adjacent satellite operators.

Between 1° and 7° the reference curve has been reduced by 3 dB to $G(\phi) = 29 - 25 \log \phi$ dB, 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 $G(\phi) = 32 - 25 \log \phi$ dB by as much as 6 dB. Beyond 7° the reference curve may be exceeded by 10 percent 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:

$$G(\phi) = \begin{cases} 29 - 25 \log \phi \text{ dBi} & \text{for } 1.0° \leqq \phi \leqq 7.0° \\ +8 \text{ dBi} & \text{for } 7.0° < \phi \leqq 9.2° \\ 32 - 25 \log \phi \text{ dBi} & \text{for } 9.2° < \phi \leqq 48.0° \\ -10 \text{ dBi} & \text{for } 48.0° < \phi \leqq 180.0° \end{cases} \qquad (3)$$

where ϕ is the angle in degrees from the axis of the main lobe, and G, in decibels, is the gain relative to an isotropic radiator.

In addition to the new reference curve for copolarized signals, the FCC has adopted a cross-polarization reference curve that 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 3.

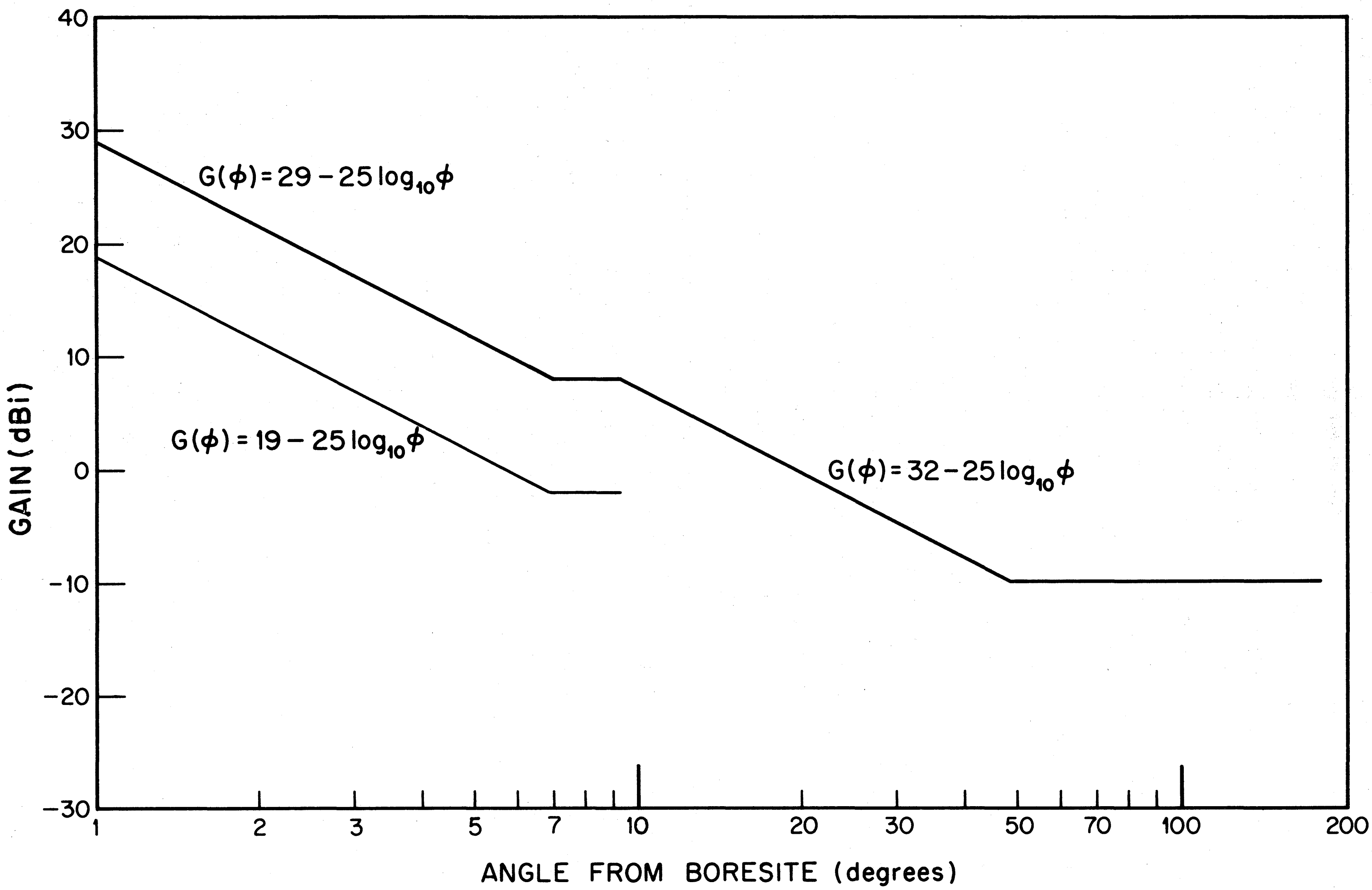

Figure 3. FCC reference radiation diagram for copolarized and cross-polarized signals (FCC Docket No. 81-704, released August 16, 1983).

This curve has been made part of the Rules and Regulations to compensate for the computed increases in interference levels at reduced orbit spacings. The rule for protection of receiving antennas in this service is the same as in the 1977 Rules and Regulations. That document specifies that 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 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 14.0 and 14.5 GHz from an earth station to a space station in the domestic Fixed-Satellite Service is now defined by:

$$G(\phi) = \begin{cases} 19 - 25 \log \phi \ \text{dBi} & \text{for} \quad 1.8^\circ \leq \phi \leq 7.0^\circ \\ 2 \ \text{dBi} & \text{for} \quad 7.0^\circ < \phi \leq 9.2^\circ . \end{cases} \quad (4)$$

The 1983 Orbit Assignment Order positioned satellites between 62° and 146° at approximately 2.5° intervals. The most recent orbit assignment (FCC, 1985) positions all U.S. satellites at 2° intervals as seen in Table 1. The FCC notes that several manufacturers currently are marketing antennas with cross-polarization performance they claim meets or exceeds the more stringent FCC antenna performance standards. (This study does not examine cross-polarization performance of antennas.) The FCC believes it is imperative that the new transmit antennas comply with revised standards at the earliest practical date and adopted July 1, 1984, as the applicable 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 14/11 GHz satellites are not likely for several years, the FCC feels that January 1, 1987, is an appropriate date for upgrading or replacing existing transmit antennas and has so stated in the rules. As noted earlier, the CCIR proposes to allow another year for the incorporation of their design objective for existing antennas.

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. The FCC feels that any additional costs

Table 1. FCC Orbital Assignments (July 25, 1985)

POSITION	NOMENCLATURE	FREQUENCY
146.0	AURORA-2	4/6
144.0	WESTAR VII	4/6
142.0	AURORA-1	4/6
140.0	GALAXY IV	4/6
138.0	SATCOM I-R	4/6
136.0	SPACENET 4 and	4/6 & 12/14
	GSTAR 3	12/14
134.0	unassigned and	4/6 (vert. pol.)
	COMSAT GENERAL B	12/14
132.0	GALAXY I and	4/6
	WESTAR B	12/14
130.0	SATCOM III-R and	4/6
	GALAXY B	12/14
128.0	ASC-1	4/6 & 12/14
126.0	TELSTAR and	4/6
	MARTIN MARIETTA B	12/14
124.0	WESTAR V and	4/6
	FEDERAL EXPRESS B	12/14
122.0	unassigned and	4/6 (vert. pol.)
	SBS 5	12/14
120.0	SPACENET 1	4/6 & 12/14
117.5	CANADA	12/14
116.5	MEXICO	4/6 & 12/14
113.5	MEXICO	4/6 & 12/14
112.5	CANADA	12/14
111.5	CANADA	4/6
110.0	CANADA	12/14
108.0	CANADA	4/6
107.5	CANADA	12/14
105.0	GSTAR 2	12/14
103.0	GSTAR 1	12/14
101.0	FORD 1	4/6 & 12/14

Table 1 (continued)

POSITION	NOMENCLATURE	FREQUENCY
99.0	WESTAR IV and	4/6
	SBS 1	12/14
97.0	TELSTAR and	4/6
	SBS 2	12/14
95.0	GALAXY III and	4/6
	SBS 3	12/14
93.0	FORD 2	4/6 & 12/14
91.0	WESTAR III and	4/6
	SBS 4	12/14
89.0	unassigned and	4/6 (vert. pol.)
	unassigned	12/14
87.0	SPACENET 3	4/6 & 12/14
85.0	TELSTAR and	4/6
	RCA A	12/14
83.0	ASC 2	4/6 & 12/14
81.0	SATCOM IV and	4/6
	RCA B	12/14
79.0	WESTAR II and	4/6
	MARTIN MARIETTA A	12/14
77.0	FEDERAL EXPRESS A	12/14
76.0	COMSTAR D4	4/6
75.0	COMSAT GENERAL A	12/14
74.0	GALAXY II	4/6
73.0	WESTAR A	12/14
72.0	SATCOM II-R	4/6
71.0	GALAXY A	12/14
69.0	SPACENET 2	4/6 & 12/14
67.0	SATCOM VI and	4/6
	RCA C	12/14
64.0	ASC 4	4/6 & 12/14
62.0	SATCOM VII and	4/6
	SBS 6	12/14

encountered by satellite communication users (to retrofit or replace antennas that do not meet the new standards) are warranted because of the benefits afforded by the resulting capacity 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), there were only 3 manufacturers who addressed the move to 2° spacing in the 14/11 GHz frequency range. They generally supported the Commission's thrust to reduce satellite spacing, expressing the belief that it was proper and would serve the public interest. Comments from these respondents dealt mainly with the time frame 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 felt that the switchover to the new rules concerning installation of new antennas should not be required until the 1987-1990 period. Stating that there is, at present and in the near future, no immediate spectrum scarcity in the 14/11 GHz band, a reduction in satellite spacing, given the present state of the art, will limit the fundamental ability of the band to utilize small earth stations. They also stated that since there is no critical need to adopt reduced spacing for the 14/11 GHz band, consideration should be given to other policies such as establishment of minimal acceptable criteria for spacecraft design, e.g., dual polarization and other advanced techniques. If, in future years, less separation between satellites becomes necessary, they believe that a spacing somewhat less than 3°, perhaps 2.5°, should be considered. The 2.5° spacing would allow an increase, in the orbital arc of 50° to 143°, from the present 28 orbital slots to 33 positions and allow a 2.4 dB reduction of signal degradation over the 2° spacing concept. Users and manufacturers contend that moving Ku-band satellites to a 2.5° spacing could satisfy the need for satellites in this frequency range for at least two decades.

Users and manufacturers conclude that the domsat market will continue to expand both in quantitative terms and in the scope of services to be provided, although the particular advantages of satellite distribution as compared to other media should focus domsat uses primarily on wide distribution of thin route traffic. The Ku band could continue to expand for some time with 3° spacing, and no present reduction in spacing is, therefore, required to assure the opportunities for growth. However, some reduced spacing may be desirable in the future to assure long-term Ku-band development.

2. SIDELOBE CHARACTERISTICS ANALYSIS

2.1 Antennas Considered

The antennas considered in this study have been designed for earth-station use at 14 GHz for transmission and 11/12 GHz for reception with intent to meet the reference envelope noted in (1) above. This envelope was required by the FCC in their Rules and Regulations, which were established in 1974. Generally, these antennas have been designed to maximize mainbeam gain, sometimes without adequate concern for the sidelobe peaks produced by this maximization. Sidelobe characteristics were considered in the design of the antenna, particularly in the transmit band, but in all probability were not considered to be as important as the gain in the main beam. Indeed, some of the companies contacted for pattern information had measured their antennas to only one or two degrees beyond the axis of the main beam 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. Many antennas have been installed in the field using only mechanical references. Measurements conducted on existing antenna installations frequently show serious degradation from prototype performance.

There are numerous companies that design and manufacture the smaller diameter (3 to 6 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, many 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 radio-frequency (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 often favor low cost rather than high quality. This compromise is especially common in the highly competitive, low cost, high volume production type of antenna. In the design of larger and more expensive antennas, such as INTELSAT Standard A and B antennas, performance has generally been more predictable and in line with specified sidelobe envelopes.

For our analysis work, 22 U.S. manufacturers of satellite antennas were contacted. These manufacturers were asked to provide actual measured patterns concerning antennas in the 2- to 10-m diameter range for both the space-to-Earth (receive) and Earth-to-space (transmit) functions at Ku-band frequencies. Of these 22 manufacturers only 4 were able to supply the requested patterns (these 4 companies are also the only ones with measured antenna pattern data on file with the FCC). The remainder either had patterns only to a few degrees off boresight or had no patterns at all. Several of the remaining 18 manufacturers stated that they had representative "smoothed" patterns, as seen in Figure 4, but this type of pattern was not acceptable for our analysis. The antennas from which performance measurements have been taken and used in this analysis ranged in diameter from 3.5 to 11.0 m, however, most data were for antennas with diameters of 4 to 7 m. The data represent 14 different antennas and four antenna manufacturers. Figure 5 is an example of the type of pattern included in this analysis.

2.2 Analysis Methodology

The patterns supplied by the manufacturers and the FCC include several variations and formats including those taken at several elevation cuts (i.e., 0°, 30°, and 45° above the horizontal) and several frequencies (for both receive and transmit). For this analysis we have used only copolar pattern data taken at 0° elevation. The copolar data received, in most instances, were manufacturers' patterns for a particular antenna at a specific frequency and 0° elevation. The information usually was presented in two parts. The first portion consisted of a pattern measurement near the main lobe, usually between -9° and +9° (large-scale data) and a second pattern included the antenna

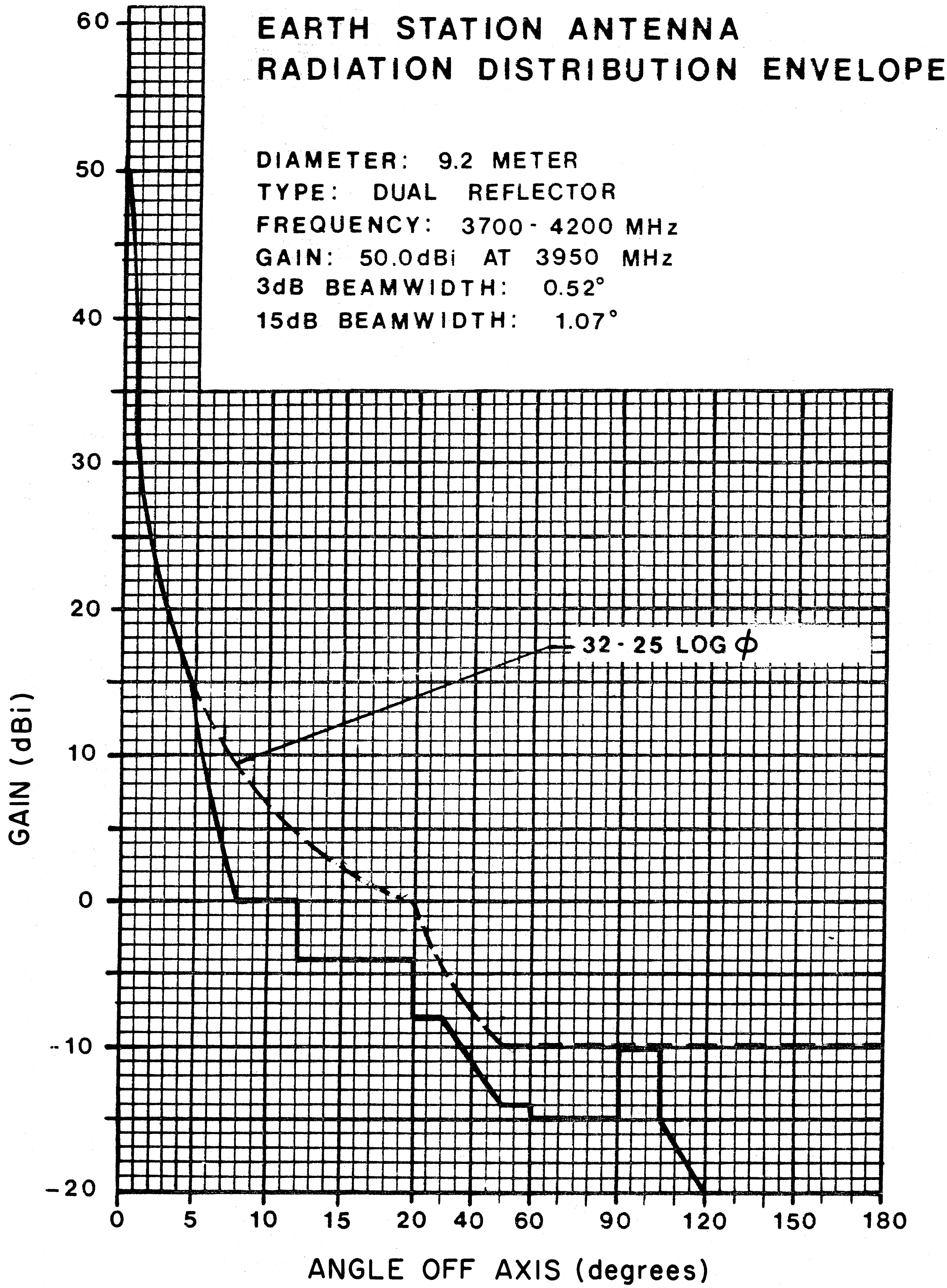

Figure 4. Example of a smoothed antenna pattern.

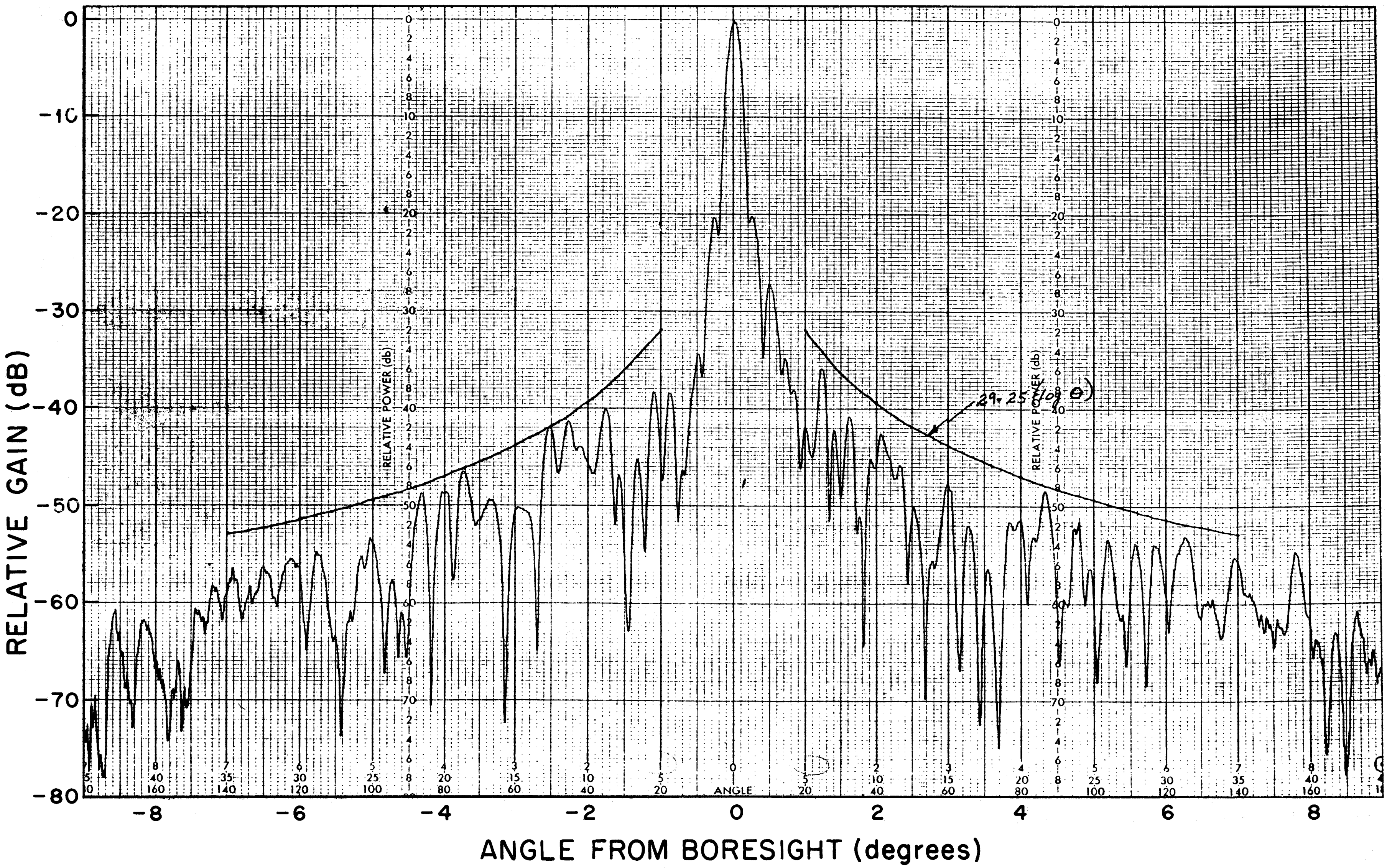

Figure 5. Example of a measured antenna gain pattern used in this analysis.

pattern from about -100° to +100° (small-scale data). Examples of these two scales are shown in Figures 6 and 7. In addition, data received on a single antenna usually included measured patterns at several frequencies within a particular band (i.e., 11 and 12 GHz in the space-to-Earth frequency range, and 14.0 and 14.5 GHz in the Earth-to-space frequency range). Finally, many antennas were measured in both the E- and H-plane. The results are that any one particular antenna being analyzed in a frequency range may be defined by as many as eight separate patterns. For instance, one pattern may be measured from -9° to +9° at 11 GHz in the H-plane. Since we have broken these patterns into two parts (negative or left side and positive or right side, as discussed below), we have two patterns for analysis. A second measurement may involve the same antenna measured from -9°to +9° at 11 GHz, as before, but this time in the E-plane, which, when combined with the H-plane data, gives us a total of four patterns for analysis. All available measurements (E- and H-plane data, receive and transmit bands, and left and right halves, and all frequencies) have been included in this analysis. 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 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 counterclockwise) 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, -9° (or -100°) to 0° or negative side of the pattern, and the other part with the right side, 0° to +9° (or +100°), 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. We have combined each half of the large-scale pattern with its companion half of the small-scale pattern (left half with the left half and right half with the right half) in order to better define the peak data near the main beam. This was accomplished through the use of a 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 that overlays the

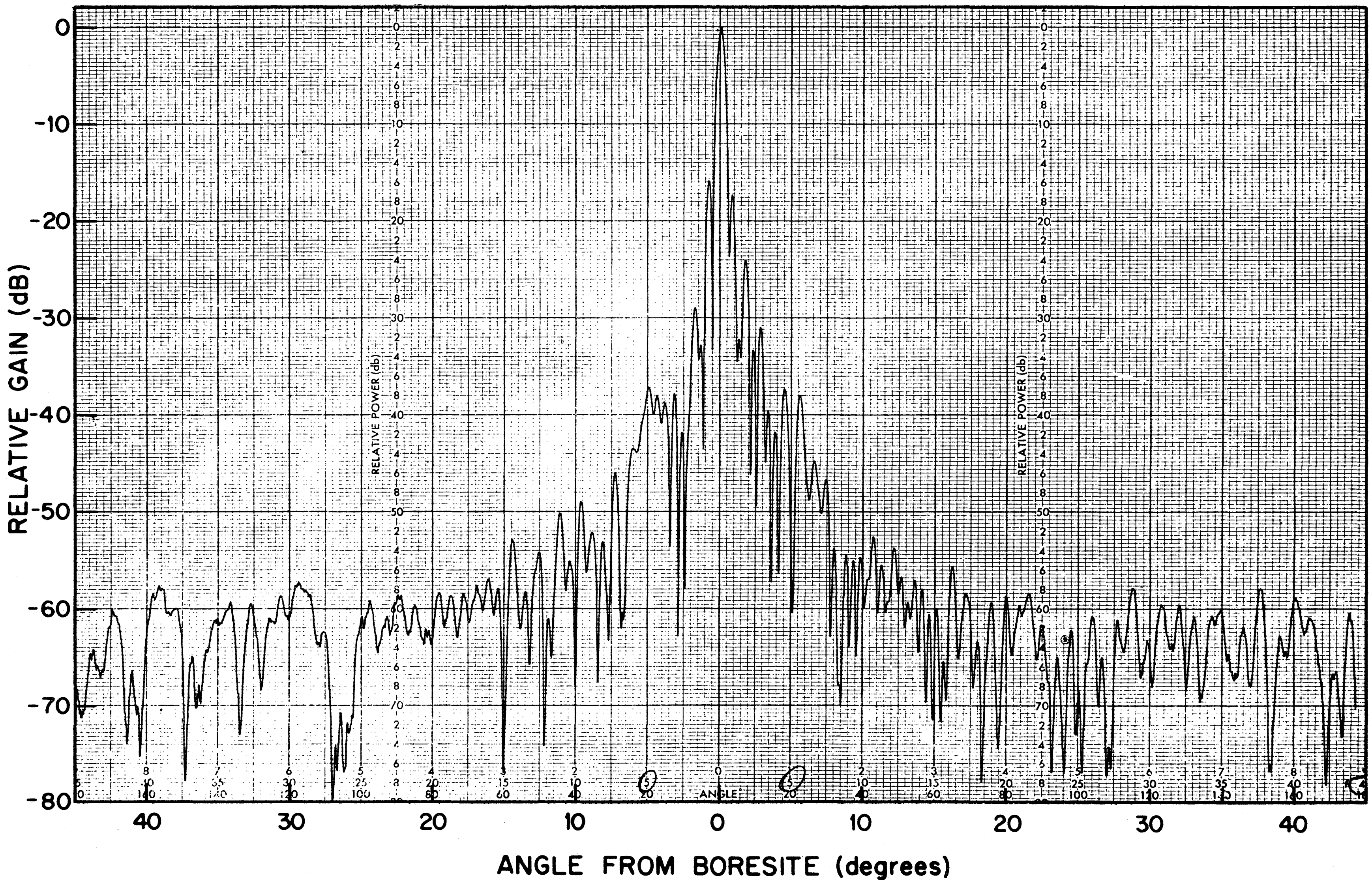

Figure 6. Example of a large-scale antenna pattern.

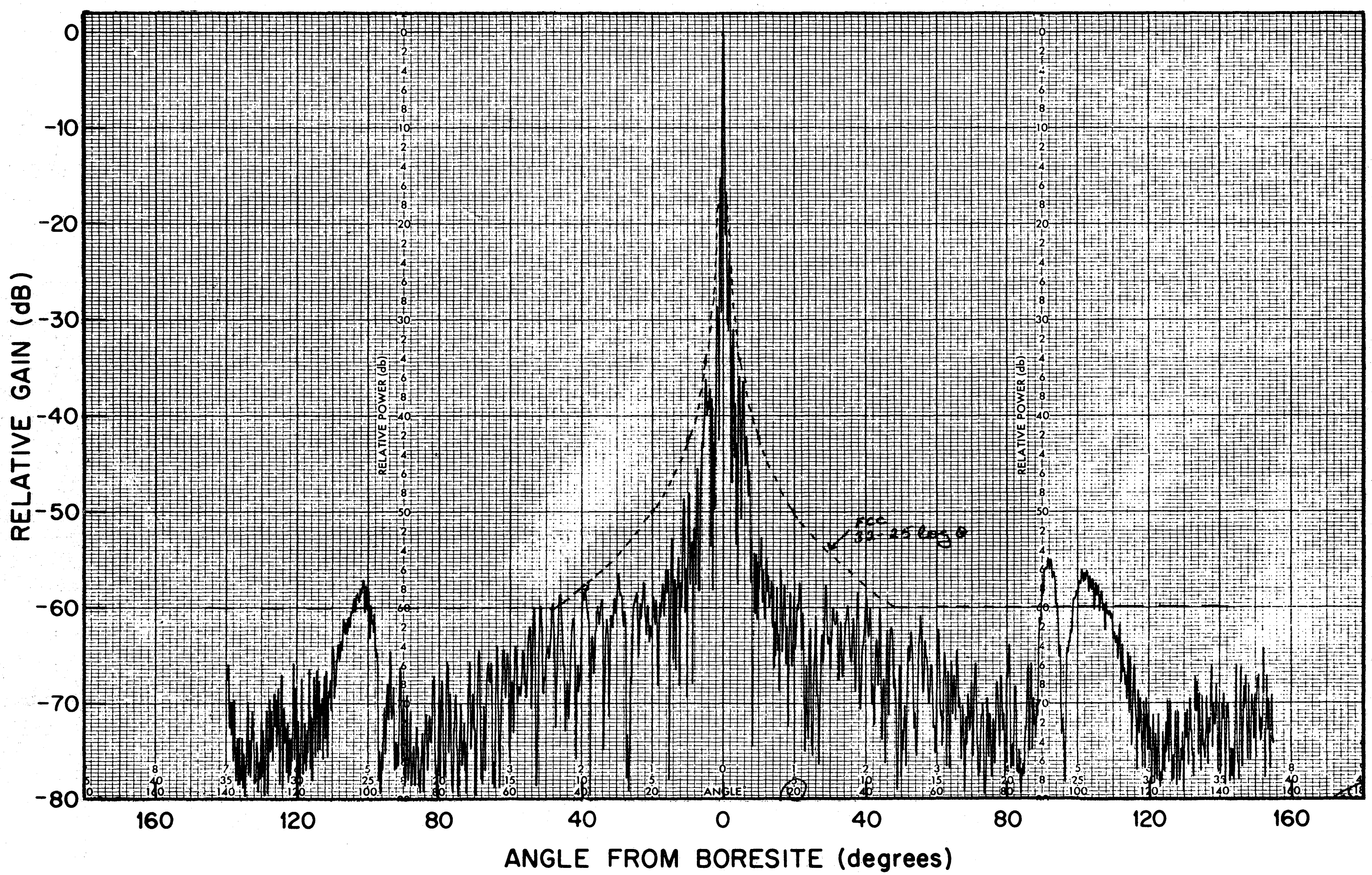

Figure 7. Example of a small-scale antenna pattern.

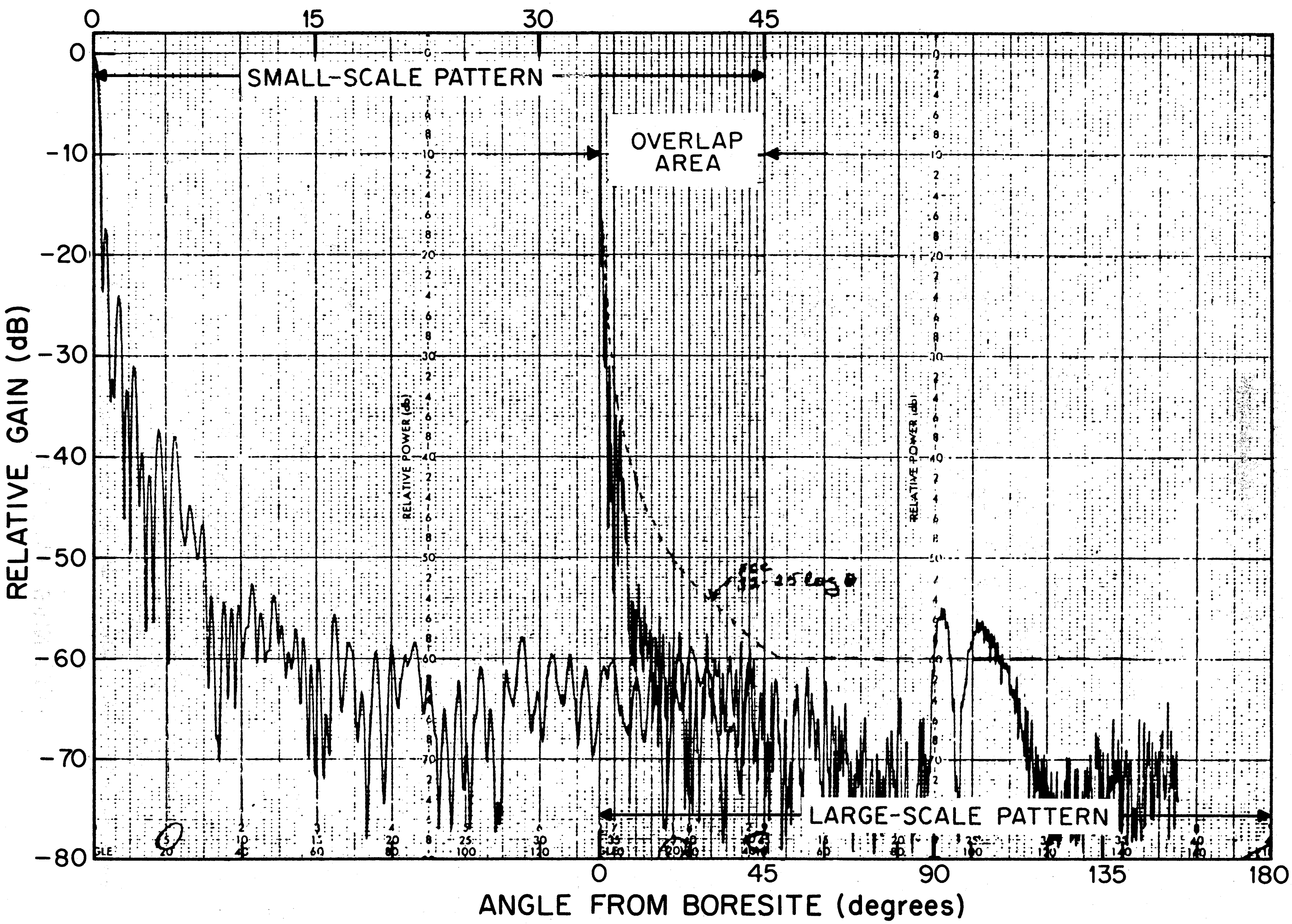

Figure 8. Example of the combined large- and small-scale antenna patterns showing the overlapping areas.

large-scale data. Digital samples were taken at 1/3- to 1/2-deg intervals on the large-scale plots, whereas the data could be read only to 1 deg on the small-scale plots. The digitized data then were converted from relative values to actual gain versus angle from boresight.

Only one characteristic of the data was 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 the sidelobes. The only characteristic used is the operating frequency band. Some data in each category come from merged large-scale and small-scale patterns that yield two 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. In combining the patterns as described above, we have a total of 50 patterns in the space-to-Earth frequency range (11/12 GHz band) and 46 patterns in the Earth-to-space frequency range (14 GHz band) as the 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 deg intervals. Values that 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 the mainbeam 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 on to point 2. Since point 2 is less than point 1, point 1 is discarded and point 3 is compared to point 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 actual peak is ignored. Moving on, point 4 is less than 3 and point 3 is discarded. The computer now compares point 5 with point 4 and notes that point 5 is greater than (positive with respect to) point 4 and that the direction of

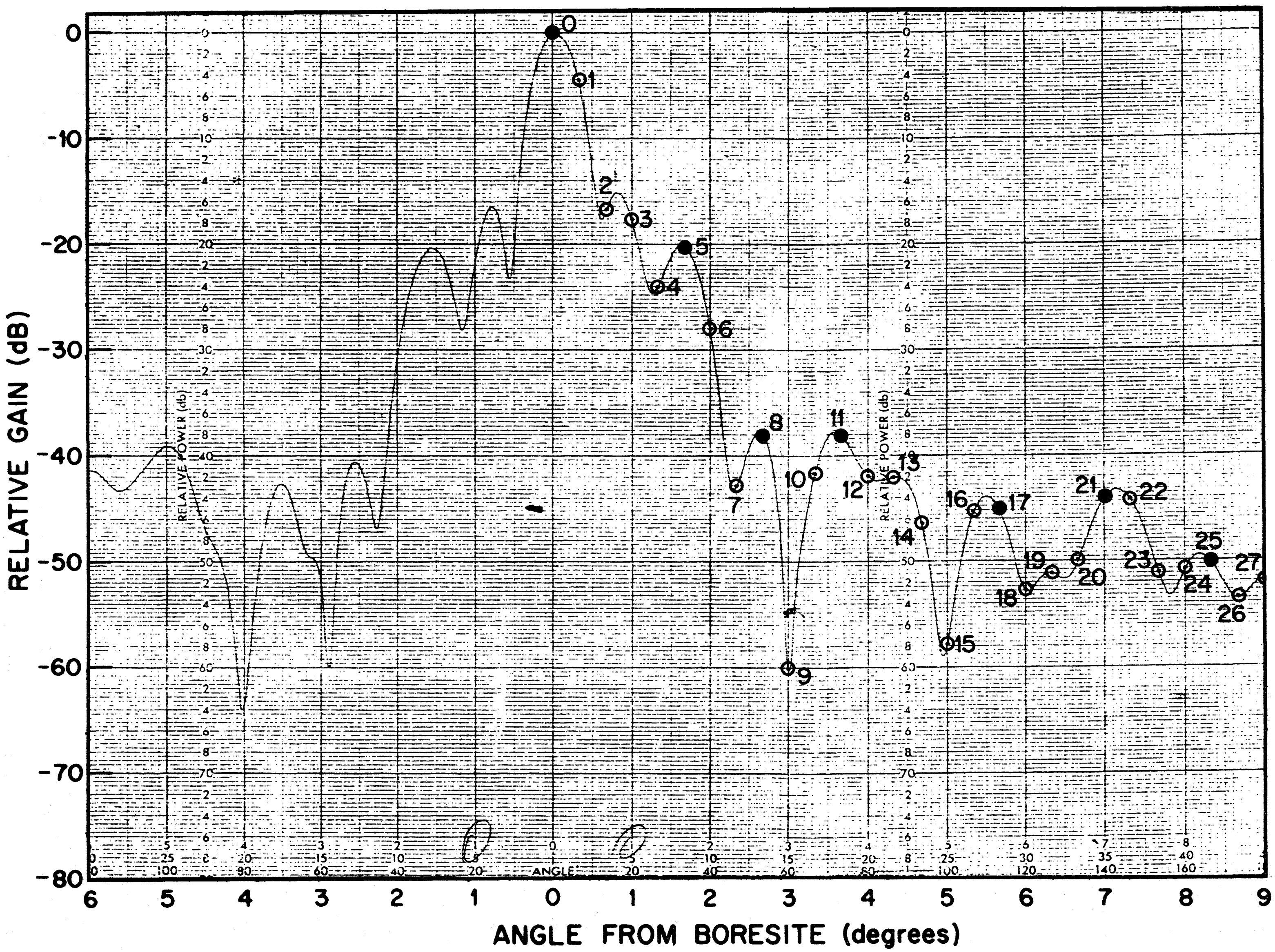

Figure 9. Large-scale antenna pattern showing the digitizing process and the logic used for selecting sidelobe peak values.

the trace has reversed itself and is now moving in a positive direction. Point 4 is now discarded and point 6 is compared to point 5. The computer program is designed to pick out point 5 as a "peak" because 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 where a positive-to-negative change of trace is noted.

When the "peaks" of all 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), [40,70) and [70,100). These angular regions are the same as those in most CCIR documents. Brackets indicate inclusion while parentheses indicate exclusion of data points at that angle. Once the peak gain values have been separated into the proper angular regions, the computer analyzes those data within each increment for the maximum, 90%, median, 10%, and minimum values. The statistical plots seen in Figures 10 and 11 were derived in the following manner according to the process outlined in CCIR Report 391-4:

- the difference between each sidelobe peak and the level of reference radiation diagram at the angle where the peak exists is calculated by computer. Then a statistical evaluation is applied as shown in Figures 10 and 11. The sidelobe peak on the border of an angular region is included in the angular region of the smaller angle.

- The statistical data in specific angular regions is drawn at the midpoint of the respective angular region.

3. ANALYSIS RESULTS

Digitization of the analog patterns to generate corresponding digital data was the first effort. These digitized data then were divided into subsets of data according to the operating frequency band (downlink and uplink). 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. All antennas considered in this

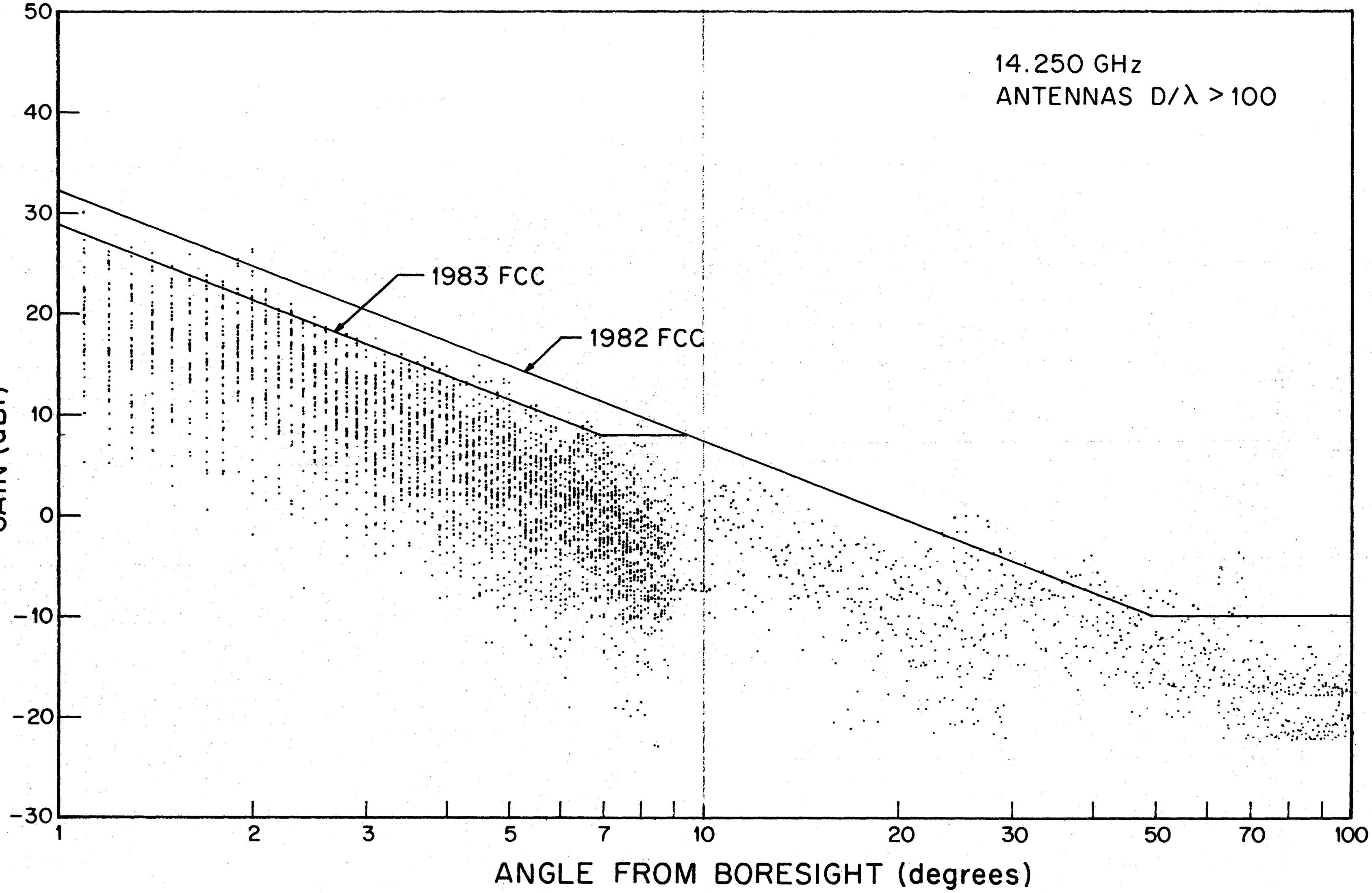

Figure 11. Scatter plot showing all of the points digitized for all antennas with a $D/\lambda > 100$ in the 14.250 GHz frequency range.

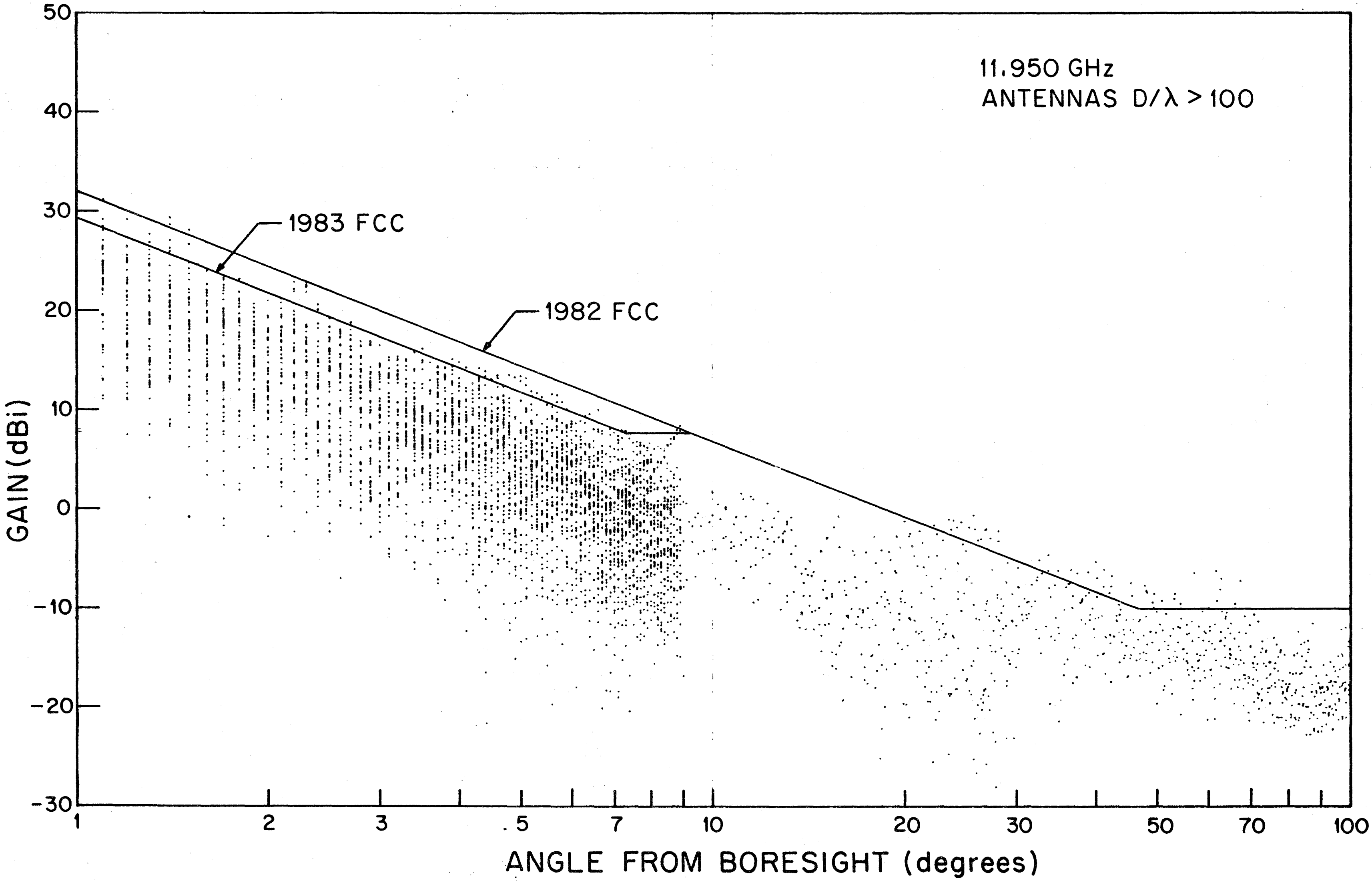

Figure 10. Scatter plot showing all of the points digitized for all antennas with a $D/\lambda > 100$ in the 11.950 GHz frequency range.

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

"(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:

$$G(\theta) = \begin{cases} 32 - 25 \log \theta \text{ dBi} & 1^\circ \leqq \theta \leqq 48^\circ \\ -10 \text{ dBi} & 48^\circ < \theta \leqq 180^\circ \end{cases}$$

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 the 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 sidelobe peaks can exceed the reference curve by as much as 6 dB, then be averaged with the peaks on either side, and thereby conform to the reference curve. By using this allowable averaging, the advertised "smoothed" curves or antenna envelopes appearing in manufacturers' 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 and all statistical values are in reference to the above envelope.

As adopted in April 1983 and released in CC Docket No. 81-704 (released August 16, 1983), the FCC has revised paragraph 25.209 as follows:

"(a) The gain of any antenna to be employed in transmission from an earth station in the fixed-satellite service shall lie below the envelope defined below:

(i) In the plane of the geostationary satellite orbit as it appears at the particular earth station location:

$29 - 25 \log_{10} \theta$ dBi	$1° \leqq \theta \leqq 7°$
+8 dBi	$7° < \theta \leqq 9.2°$
$32 - 25 \log_{10} \theta$ dBi	$9.2° < \theta \leqq 48°$
-10 dBi	$48° < \theta \leqq 180°$

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 not exceed the envelope defined above for θ between 1° and 7°. For θ greater than 7°, the envelope may be exceeded by 10% of the sidelobes, but no individual sidelobe may exceed the envelope by more than 3 dB."

In Figures 10 through 13, the 1982 FCC requirement in (1) above is drawn to demonstrate how well the antennas under investigation perform according to the requirement for which they were constructed. The new (1983) FCC envelope in (3) above also has been added to show how well the antennas used in this analysis conform to that requirement.

3.1 Nonstatistical Analysis Results

Plots, which we call "dot plots," of all the digitized data points (not just the sidelobe peak values) between 1° and 100° are shown so that the reader can see all the points that were used in the statistical analysis. Figures 10 and 11 show these dot plots for data in the receive frequency range (11/12 GHz) and the transmit frequency range (14 GHz), respectively.

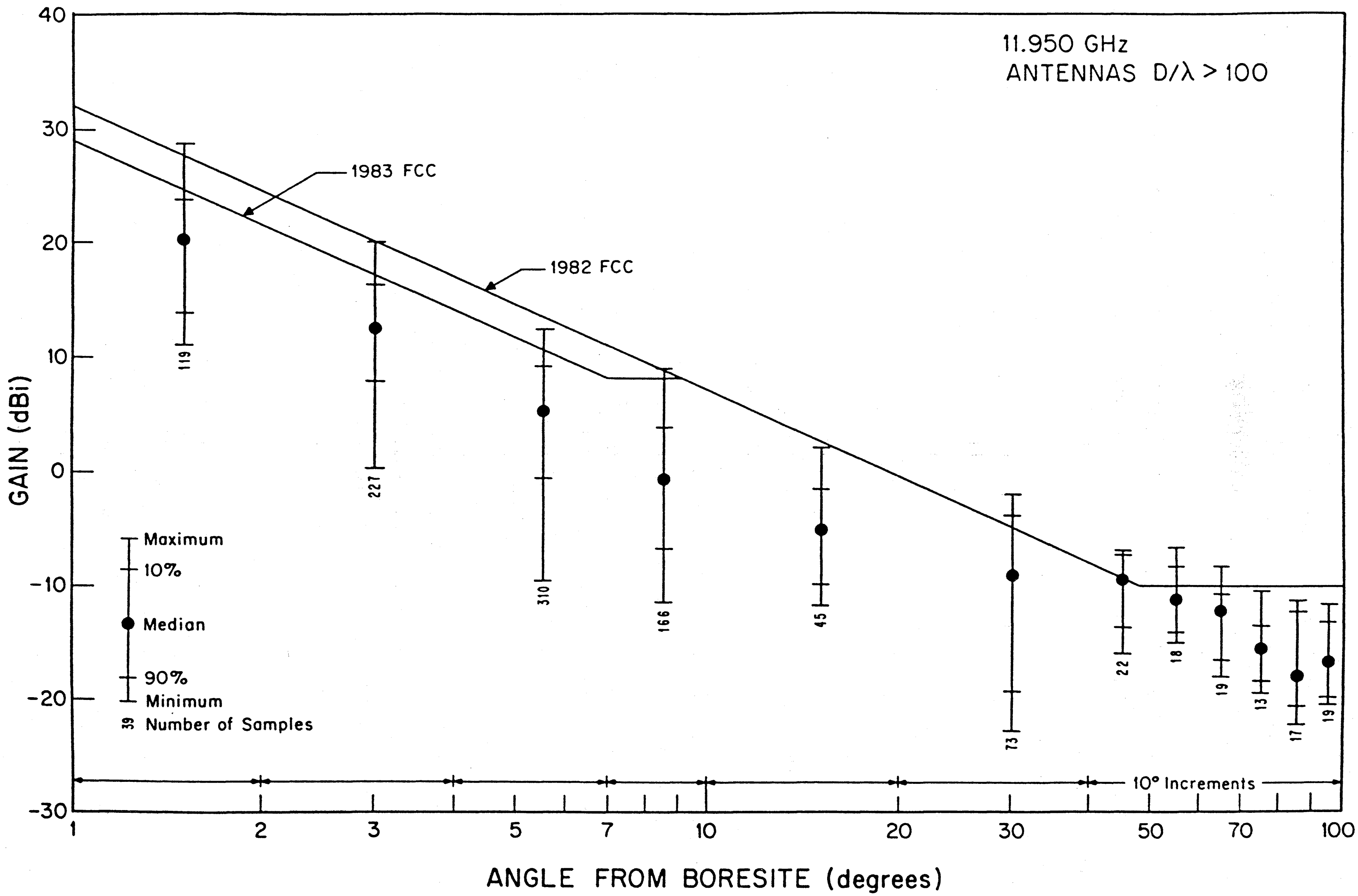

Figure 12. Statistical plot of sidelobe peak values for all antennas in the 11.950-12.120 GHz frequency range.

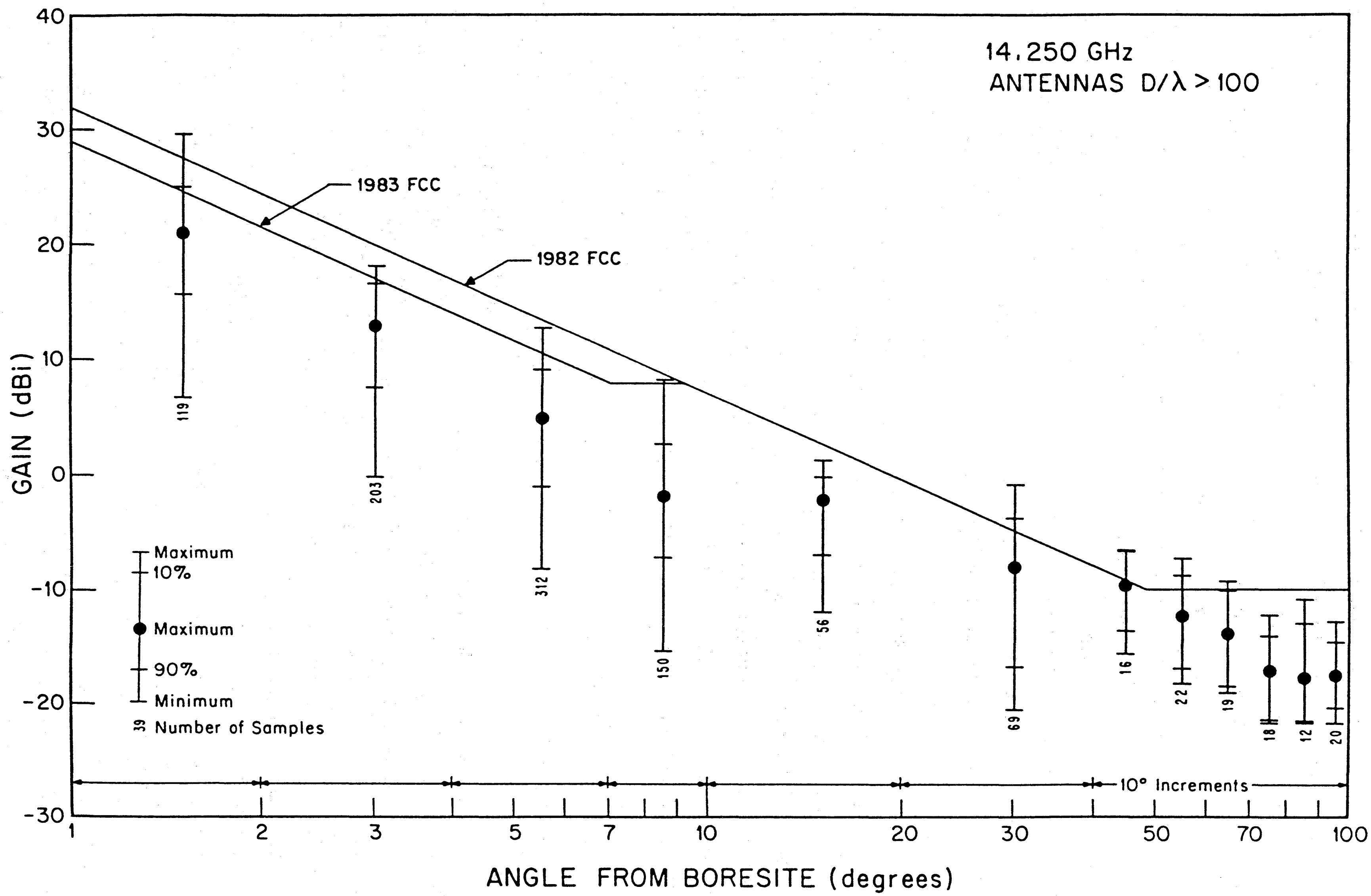

Figure 13. Statistical plot of sidelobe peak values for all antennas in the 14.250 GHz frequency range.

In these plots we can see that relatively few of the points exceed the 1982 FCC reference curve between 1° and 20° and, in all probability, do meet the FCC standard within that increment, but that beyond 20° the number of points exceeding the curve increase dramatically at both the transmit (14 GHz) and the receive frequencies (11/12 GHz). Within the increment of 20° to 70° it is likely that several of these antennas do not meet the 1982 FCC criteria in (1) above even though the manufacturers claim compliance. This is especially true in the transmit frequency band where some peaks exceed the curve by as much as 7 or 8 dB. With respect to the 1983 FCC regulations, where no peak may exceed the curve between 1° and 7°, it is obvious that some of the antennas measured will require extensive modification in order to meet the new criteria.

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 incremental areas defined by intervals of angle from boresight according to CCIR guidelines. Arithmetic differences between the sidelobe peak values and the reference antenna performance standard

$$G = \begin{cases} 32 - 25 \log \phi \text{ dBi} & \text{for } 1° \leqq \phi < 48° \\ -10 \text{ dBi} & \text{for } 48° \leqq \phi \leqq 180° \end{cases}$$

have been calculated. Within each angular interval, the statistical characteristics of these arithmetic differences have been calculated. 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 Figure 12 for the receive frequencies (11/12 GHz) and in Figure 13 for the transmit frequencies (14 GHz).

For the lower frequencies (Earth-receive) seen in Figure 12, it is apparent that the antennas would meet the 1982 FCC requirements (for which these antennas were constructed) especially where the FCC allowed 10 percent of the peaks to exceed the curve by as much as 6 dB and allowed the peaks to be averaged with adjacent peaks. However, when compared with the new (1983) FCC Rules and Regulations, one can see that extensive improvement is required before these antennas can meet the new standards. This is true, especially for the 14 GHz (transmit) band, seen in Figure 13, in the area between 1° and 4° where almost 10 percent of the peaks exceed the new criteria. This, of course, is the most critical area, as it is where adjacent satellites will be positioned.

4. CONCLUSIONS

This analysis has examined sidelobe gain data from 14 reflector antennas, designed for operation at 11/12 GHz for reception and 14 GHz for transmission, and ranging in size from 3.5 to 11.0 m. These 14 antennas represented four U.S. manufacturers. Four of the antennas were designed as receive-only antennas with reflector diameters ranging from 2.8 to 7.0 m. The remaining 10 antennas have been designed for transmit/receive applications presumably with expectation that sidelobe levels would be in accordance with the reference performance standard, namely, that not more than 10 percent of the peaks would exceed the envelope

$$G = \begin{cases} 32 - 25 \log \phi \quad \text{dB} & \text{for } 1° \leqq \phi \leqq 48° \\ -10 \quad \text{dB} & \text{for } 48° \leqq \phi \leqq 180°. \end{cases}$$

The poorest performance with respect to the 1974 FCC envelope is seen in the 14 GHz, or transmitting frequency range. As seen in Figure 13, approximately 5 percent of the sidelobe peaks lie above the 1982 envelope and approximately 12 percent lie above the 1983 FCC envelope in the area between 1° and 2°. Again in the area between 2° and 4°, although all peaks lie below the 1982 envelope, almost 10 percent of the peaks lie above the new (1983) envelope. The situation is similar for the receive frequency antennas albeit to a lesser degree. The region between 1° and 4° from the antenna boresight is a sensitive area due to the new rules (Report and Order, CC Docket No. 81-704), which will allow closer satellite spacings. This closer spacing will certainly cause more interference both to and from adjacent satellites with the 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. Many of the antennas used in this analysis will have no chance to meet the new requirements and will either require extensive modification or complete replacement when the FCC requirements go into effect in January of 1987.

Several manufacturers have begun to produce antennas that are expected to meet or exceed the most recent Rules and Regulations as set up by the FCC under Part 25, Paragraph 209. As more and more manufacturers begin to produce these "new" antennas, analysis should be performed (similar to this analysis) to determine if the market is "seeing" antennas that conform to the 1983 FCC standard.

From the analysis results, one concludes that:

(1) Sidelobe performance of the antennas used in this analysis generally meet the performance standard outlined in the 1974 FCC requirements and in CCIR Recommendation 465-1.

(2) Sidelobe performance of these same antennas (at the same operating frequencies) generally would not meet the performance objective outlined in the new (1983) FCC performance standard and in CCIR Recommendation 580 for operation at earth-station receiving frequencies. However, operation at transmitting frequencies generally would be in accordance with Recommendation 580 except at angles between 1° and 4° away from the axis of the main beam.

(3) For sidelobe performance to conform with FCC 1983 requirements, CCIR Recommendation 580 and Draft Recommendation 465-1 (MOD I) will require redesign of new antennas and retrofitting of existing antennas.

(4) As measured sidelobe gain data are available for newly designed and/or retrofitted antennas, additional analyses should be performed to determine the extent to which actual performance conforms with FCC rules and CCIR Recommendation 580 and Draft Recommendation 465-1 (MOD I).

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* Published by the International Telecommunication Union, Geneva, Switzerland

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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 (11/12 GHz) and uplink frequency range (14 GHz) have been split into two sets of antennas. Table A-1 lists all of the antennas in the downlink frequency range and Table A-2 lists all of the antennas in the uplink frequency range. Manufacturers' designations in the tables are as follows:

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

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

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

RSI - Radiation Systems Inc.
1501 Moran Road
Sterling, VA 22170

Table A-1. Antennas That Operate in the 11.700 to 12.100 GHz Band (Space-to-Earth Links)

No	Manuf	Model	Dia (m)	Freq (GHz)	d/λ	Gain (dBi)
1	HAR	5342	3.5	11.95	139	50.5
2	HAR	5346	6.1	11.95	243	55.4
3	HAR	5349	8.1	11.95	322	57.8
4	HAR	5351	9.0	11.95	358	58.5
5	HAR	5363	11.0	11.95	438	60.9
6	AFC	PR12	3.6	11.95	143	50.6
7	AFC	PR16.4	5.0	11.90	199	51.9
8	STC	550KS	5.5	11.95	219	55.0
9	STC	550KS	5.5	12.12	221	55.2
10	STC	700KS	7.0	11.95	279	56.9
11	STC	920KS	9.2	11.95	366	59.2
12	STC	1100KS	11.0	11.95	438	60.9
13	STC	700K	7.0	11.95	279	57.0
14	RSI	700TCK	7.0	11.95	279	54.8
15	RSI	450TCK	4.5	11.95	179	51.3

Table A-2. Antennas That Operate in the 14.0 to 14.5 GHz Band (Earth-to-Space Links)

No	Manuf	Model	Dia (m)	Freq (GHz)	d/λ	Gain (dBi)
1	HAR	5342	3.5	14.25	167	51.9
2	HAR	5346	6.1	14.25	290	56.5
3	HAR	5349	8.1	14.25	385	59.1
4	HAR	5351	9.0	14.25	428	59.8
5	HAR	5363	11.0	14.25	523	61.7
6	AFC	PR12	3.6	14.25	171	52.1
7	AFC	PR16.4	5.0	14.25	238	53.3
8	STC	550KS	5.5	14.25	262	56.2
9	STC	700KS	7.0	14.25	333	57.9
10	STC	920KS	9.2	14.25	438	62.0
11	STC	1100KS	11.0	14.25	523	62.0
12	STC	700K	7.0	14.25	333	58.0
13	RSI	700TCK	7.0	14.50	333	54.8
14	RSI	450TCK	4.5	14.25	214	51.3

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J. M. Harman and R. D. Jennings

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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 14 models of reflector antennas designed for operation at 11/12 GHz for reception and at 14 GHz for transmission. The antennas ranged in size from 3.5 to 11.0 m and represented equipment from four U. S. 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 International Radio Consultative Committee (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 to show compliance with Federal Communications Commission (FCC) and CCIR recommendations. Background material from the perspectives of the CCIR, the FCC, and antenna manufacturers is also provided.

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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