RADC-TR-69-69
Final Technical Report
July 1969

A THEORETICAL EVALUATION OF THE FPS-6 RADAR ANTENNA IN TROPOSCATTER COMMUNICATIONS SYSTEMS

Page Communications Engineers

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Page Communications Engineers

FOREWORD

This techhical report was prepared by Page Communications Engineers, Inc. under Contract AF30(602)-4197, Project 9191. The contractor's secondary report number is PCE-R-4132-00-30501A. The Rome Air Development Center project engineer is Mr. Italo A. Fantera, Communications Applications Branch.

This report has been reviewed by the Information Office and there are no restrictions on its distribution.

PUBLICATION REVIEW

This report has been reviewed and is approved.

Approved: Italo A Fantera
ITALO A. FANTERA
Project Engineer

Approved: Richard M. Cosel
RICHARD M. COSEL
Colonel, USAF
Chief, Communications Division

FOR THE COMMANDER: Fred I Diamond
for **IRVING J. GABELMAN**
Chief, Advanced Studies Group

ABSTRACT

This report theoretically analyzes the effect of using a fan-shaped antenna reflector, having an aspect ratio of 3.5 to 1, for troposcatter communications. The analysis is performed relative to the performance which would be achieved when using a circular cross-sectioned parabolic reflector having the same free-space antenna gain. Parameters which are considered in the analysis include the orientation of the fan-shaped reflector, aperture-to-medium coupling loss, differential path delay, and scatter models based on Waterman and Friis-Crawford-Hogg.

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The purpose of this report is to compare the theoretical performance of AN/FPS-6 radar antennas with conventional circular cross-sectioned parabolic antennas of the same gain on troposcatter communications circuits.

The comparative analysis is in terms of received signal power and in terms of differential multipath delay. The analysis includes the two cases where the fan-shaped radar antenna is oriented in its two orthogonal positions, i.e. narrow dimension in the vertical plane, broad dimension in the horizontal plane, and vice-versa. The analysis also includes the effects of path geometry and operating frequency to show the effects of narrow beam performance versus broad beam performance.

Inasmuch as the scope of this effort was not intended to include comparative performance based on a comprehensive, finely-gained analysis of the troposcatter mechanism, it nevertheless is considered accurate and adequate in describing the conflicting performance requirements of minimum differential multipath delay and maximum realized antenna gain.

ITALO A. FANTERA
Project Engineer

A THEORETICAL EVALUATION OF THE FPS-6 RADAR ANTENNA IN TROPOSCATTER COMMUNICATIONS SYSTEMS

1. GENERAL

The purpose of this report is to compare the theoretical performance of FPS-6 antennas with conventional parabolic antennas of the same gain on troposcatter communications circuits.

The FPS-6 antenna is part of a height-finding radar. In the usual application, its vertical beamwidth is much less than its horizontal. On troposcatter paths, the "common volume" seen by such antennas would be different than that seen by conventional parabolic dishes having equal horizontal and vertical beamwidths. The result is a difference in path loss and multipath delay effects. This report is restricted to the case where two FPS-6 antennas on the radio path are oriented with the narrow beams first in the vertical plane and then in the horizontal plane. Their path losses are compared to the parabolic dish case using theoretical models of Waterman;[1] and Friis, Crawford, and Hogg.[2] Estimates are made of multipath delay using the method of Beach and Trecker.[3]

2. ANTENNA CHARACTERISTICS

The FPS-6 antenna is a truncated semi-parabolic reflector with associated waveguide feed elements and rotating joints. The normal operating frequency of the radar system is in the 2700 to 2900 MHz band. In this range the antenna's gain is approximately 40 dB over isotropic. The beam pattern differs in the horizontal and vertical planes due to the reflector shape and has a beamwidth of 3.2 degrees in azimuth and 0.85 degrees in elevation when mounted as shown in Figure 1. The height of the antenna is 30 feet and the width is 8.5 feet. A pressurized waveguide system is used for the feedhorn which is tapered to provide maximum antenna efficiency.

The parabolic dish used for comparison has a diameter of 16 feet with a gain of 40 dB and a beamwidth of 1.65 degrees at 2800 MHz.

It is assumed, in the theoretical analysis of this report, that surface tolerances are such that the antennas will operate efficiently up through the frequency of 8 GHz, so that antenna gains will be proportional to the square of frequency and beamwidths will be inversely proportional to frequency. The FPS-6, presumably designed for the 2700-2900 MHz band, will most likely not meet this requirement.

3. TROPOSCATTER SIGNAL LEVEL COMPARISONS

Various models have been used to describe troposcatter propagation. The two employed in this report are scattering and reflections from randomly oriented surfaces. So far as comparisons of antenna systems are concerned, both models appear to yield similar results. An effective earth's radius equal to 4/3 true radius and smooth earth profiles are assumed for both models.

3.1 Scattering Theory

Assuming a scattering mechanism, A. T. Waterman[1] formulated general expressions for troposcatter path loss as a function of arbitrary antenna patterns. He considers a beamwidth to be "broad" in a particular orientation when the scattered signal contribution in the region of the edges of the common antenna volume defined by that beamwidth is negligible. When the beamwidth becomes "narrow," signals scattered near the corresponding edges of the volume are an important contribution to the total signal so that an "aperture-to-medium coupling loss" is suffered when this beamwidth is decreased, due to the loss of an important portion of the scatter volume.

Waterman has developed expressions for received power which depend upon the relation between the beamwidths in the horizontal and vertical planes and the scatter angle. Assuming identical transmit and receive antennas, they are:

For broad horizontal and vertical beamwidths:

$$P_r = \frac{P_t G^2 \lambda^2 b\, 2^m}{4\pi^2} \left(5^{1/m} - 1\right)^2 \left(5^{2/m} - 1\right)^{1/2} \frac{a^{m-2}}{d^{m-1}} \qquad (1)$$

For narrow horizontal and broad vertical beamwidths:

$$P_r = \frac{P_t G^2 \lambda^2 b\, 2^m}{4\pi^2} (5^{1/m} - 1)^2 \; \phi \; \frac{a^{m-1}}{d^m} \tag{2}$$

For broad horizontal and narrow vertical beamwidths:

$$P_r = \frac{P_t G^2 \lambda^2 b\, 2^m}{4\pi^2} \; \frac{1}{2} \; (5^{2/m} - 1)^{1/2} \; \psi^2 \; \frac{a^m}{d^m} \tag{3}$$

For narrow horizontal and vertical beamwidths:

$$P_r = \frac{P_t G^2 \lambda^2 b\, 2^m}{4\pi^2} \; \frac{1}{2} \; \psi^2 \phi \; \frac{a^{m+1}}{d^{m+2}} \tag{4}$$

where P_r = Received power.

P_t = Transmitted power.

G = Antenna gain.

λ = Wavelength.

b = A constant relating scattering cross section to scattering angle.

m - Scattering angle exponent taken equal to 4 (various researchers[1,4] have determined m to have a value between 4 and 6).

ψ = Vertical beamwidth.

ϕ = Horizontal beamwidth.

a = Effective earth radius = 5280 statute miles.

d = Great circle radio path length.

Figures 2 and 3 show comparisons between FPS-6 signal level performance and that of a 16-foot dish for the two orientations of the FPS-6 as a function of radio frequency.

On any particular troposcatter path, the antenna pattern can be considered broad in both the horizontal and vertical planes for a sufficiently low radio frequency. In this situation, equation (1) shows that signal level is independent of the antenna pattern, so that any two antenna configurations with the same total gains and transmit power would produce the same received signal. In Figure 2, for example, this occurs up to a frequency of 0.5 GHz for the 400 mile path and up to 1.9 GHz for the 100 mile path.

As frequency is increased, either the horizontal or vertical beamwidths begin to cause aperture-to-medium coupling loss, so that equations (2) and (3) become appropriate. In comparing two antenna systems, this is the region where frequency dependent differences begin to occur, since in some region one antenna system may still be considered broad in both planes while the other becomes narrow and therefore dependent upon its beamwidths.

At still higher frequencies, both systems become narrow in both planes so that equation (4) applies. For two antennas with the same gains and different patterns, the product $\phi\psi$ is considered constant. Thus in this frequency range, the ratio of two signal levels is found to be equal to the ratio of the vertical beamwidths, and again independent of frequency. Figure 2 shows that comparing the FPS-6 with the narrow beam in the horizontal plane to the 16 foot parabolic dish, this occurs above 2.95 GHz, where the FPS-6 shows almost a 3 dB superiority over the dish. Similarly, Figure 3 shows the FPS-6 to be almost 3 dB inferior to the dish above 1.8 GHz when the FPS-6 is oriented with the narrow beamwidth in the vertical plane.

In Figures 2 and 3, discontinuities in the slopes of the curves indicate points where different models applied. Choice of the models was based on the criterion that the received signal level be a continuous function of frequency.

This leads to the condition that a vertical beamwidth be considered narrow if $\psi < d/a \sqrt{2}$ and broad if $\psi > d/a \sqrt{2}$, and that a horizontal beamwidth be considered narrow if $\phi < (5^{2/m} - 1)^{1/2}$ d/a and broad if $\phi > (5^{2/m} - 1)^{1/2}$ d/a.

3.2 Reflection Theory

Friis, Crawford, and Hogg[2] assume a propagation mechanism consisting of randomly oriented reflecting surfaces in the atmosphere. They then deduce that the scattered signal in any small volume of space is proportional to the reciprocal of the sixth power of the distance ρ between the volume and straight line joining the two end points of the radio path. For a particular antenna pattern, the important step in evaluating path loss is the evaluation of the integral

$$\int_V \rho^{-6} \, dV \quad , \tag{5}$$

where V is the volume common to both the antenna patterns. Friis et al evaluate this integral for various ratios of horizontal to vertical beamwidth ratios - "aspect ratios," using a particular simplification of the common volume geometry which greatly facilitates computation of the above integral. For comparison of received signal levels over the same path using different pairs of identical and identically oriented antennas, their model results in the relationship:

$$\frac{P_{ra}}{P_{rb}} = \frac{A_b \psi_b^3 (2 + \psi_b/\theta) \, f(\psi_a/\theta)}{A_a \psi_a^3 (2 + \psi_a/\theta) \, f(\psi_b/\theta)} \tag{6}$$

where P_{ra} = Received power for antenna system a.

P_{rb} = Received power for antenna system b.

$\psi_{a,b}$ = Vertical beamwidth, system a, b.

θ = Path length / (2 x effective earth radius)

$$f(x) = 1 + \frac{1}{(1+x)^4} - \frac{1}{8} \left(\frac{2+x}{1+x} \right)^4$$

Gain of antenna system a = Gain of system b.

$A_{a,b}$ = Aspect ratio of antenna a, b.

= 1 for parabolic dish

= 3.77 and 0.265 for FPS-6.

The results of this relationship are plotted in Figures 2 and 3 and are indicated by "FC&H Model."

Unfortunately, the simplification used by Friis, Crawford, and Hogg to obtain this result appears to be valid only for situations where the horizontal beamwidth is reasonably less than θ, i.e., conditions of narrow beamwidth and long path length. This is a consequence of the peculiar "pie shaped" antenna patterns assumed in order to integrate equation (5). An attempt was made to integrate equation (5) for a more appropriate antenna pattern model; however, computational difficulties arose which have not yet been satisfactorily resolved. As a result, most of the Friis, Crawford and Hogg results are shown by dashed lines indicating their inadequacy.

It is reasonable to assume, as with the Waterman model, that for low frequencies, the difference between the FPS-6 and the parabolic-dish signal levels would approach zero.

4. MULTIPATH CONSIDERATIONS

In addition to comparing the relative amounts of power received, a comparison of multipath effects should be made before coming to any conclusions about the performance of the fan shaped antenna. In this discussion, only the multipath effects due to the geometry of the longest and shortest vertical paths will be considered. Using the approach of Beach and Trecker,[3] a comparison of multipath between the fan shaped beam and the circular beam may be made.

The multipath delay, $t_{\mu s}$, is computed to be:

$$t_{\mu s} = 2.68 \ d \left[\frac{d}{2a}\right]^2 \left[\left(\frac{d/2a + \psi}{d/2a}\right)^2 - 1\right] \text{microseconds} \qquad (7)$$

where the path length, d, is in statute miles, and it is assumed the antennas are oriented so that the bottom of the beams graze the horizon. Delay is shown in Figures 4, 5, and 6 for various combinations of antennas and path lengths. It is important to note that longer delay times are usually accompanied by a substantial attenuation of the delayed signal with respect to the main signal, so that its effect upon system performance is less then would be expected by delay time considerations only. However, these figures show that the FPS-6 with its wide beamwidth in the vertical plane has the greatest delay time, the parabolic dish is intermediate, and the FPS-6 in its normal height-finding orientation with narrow vertical beamwidth suffers the least delay.

5. CONCLUSIONS

5.1 General

For comparison of signal levels using the various antenna patterns, it appears that with high gain antennas and long radio paths, the fan shaped pattern is superior when the narrow beamwidth is oriented in the horizontal plane. This is shown in Figure 2, where for example, the 400 mile path shows the FPS-6 to be almost 3 dB better than the dish at frequencies above 2.95 GHz. However, the models used in this study only indicate a superiority of 1-3 dB. This can easily be off-set by the degradation in system performance due to multipath delay, a problem which becomes increasingly important with increasing path length. Figure 6 shows that the narrow horizontal beamwidth case has typically twice the multipath delay of the parabolic dish case. For high speed data transmission, this halves the maximum keying rate due to the intersymbol interference limitations, and for FM-FDM systems, an increase in path IM noise on the order of 12 dB could be expected. Using similar reasoning, it may be anticipated that for longer radio paths where either maximum keying speed in high speed data transmission or path IM in FM-FDM is the governing design parameter, the fan shaped antenna with narrow vertical beamwidth may be the superior antenna.

However, on long radio paths, typical parabolic antenna diameters are on the order of 60 to 85 feet. Fan shaped antenna of the same gains would be 32 x 112 feet to 45 x 160 feet. It would appear that the excessive cost of constructing such fan shaped antennas with the long dimension in the vertical plane should override any modest improvement in performance over the equivalent-gain parabolic dish.

5.2 The FPS-6 Antenna

Since the FPS-6 antenna has a gain equivalent to a 16 foot parabola, it is reasonable to assume that it would not be used on a troposcatter circuit longer than approximately 100 miles. With an assumed top operating frequency of 3 GHz, reference to Figures 2 and 3 show that only the Waterman model appears appropriate to describe its performance. For the usual orientation of the FPS-6, with the narrow beamwidth in the vertical plane, signal level performance may be expected to be identical with that of the parabolic dish below 3 GHz. For the condition that the narrow beam is in the horizontal plane, FPS-6 performance is identical to that of the parabolic dish up to 2 GHz, but then there is a slow degradation in FPS-6 performance from 2 to 3 GHz, where its aperature-to-medium coupling loss comes into play.

5.3 Reflection Theory Limitations

The reflection theory of Friis, Crawford, and Hogg is considered by the National Bureau of Standards[5] to be an appropriate explanation of over-the-horizon radio propagation. Efforts are being made at Page to extend the results of this theory to short radio paths and wide antenna beamwidths by a more appropriate integration of equation (5).

6. REFERENCES

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3. C.D. Beach and J.M. Trecker, "A Method for Predicting Interchannel Modulation due to Multipath Propagation in FM and PM Troposphere Radio Systems," BSTJ, Vol. 42, Jan. 1963.

4. H. Staras, "Antenna to Medium Coupling Loss," IRE Trans. AP, pp. 228-231, April 1959.

5. NBS Technical Note 101, revised May 1966.

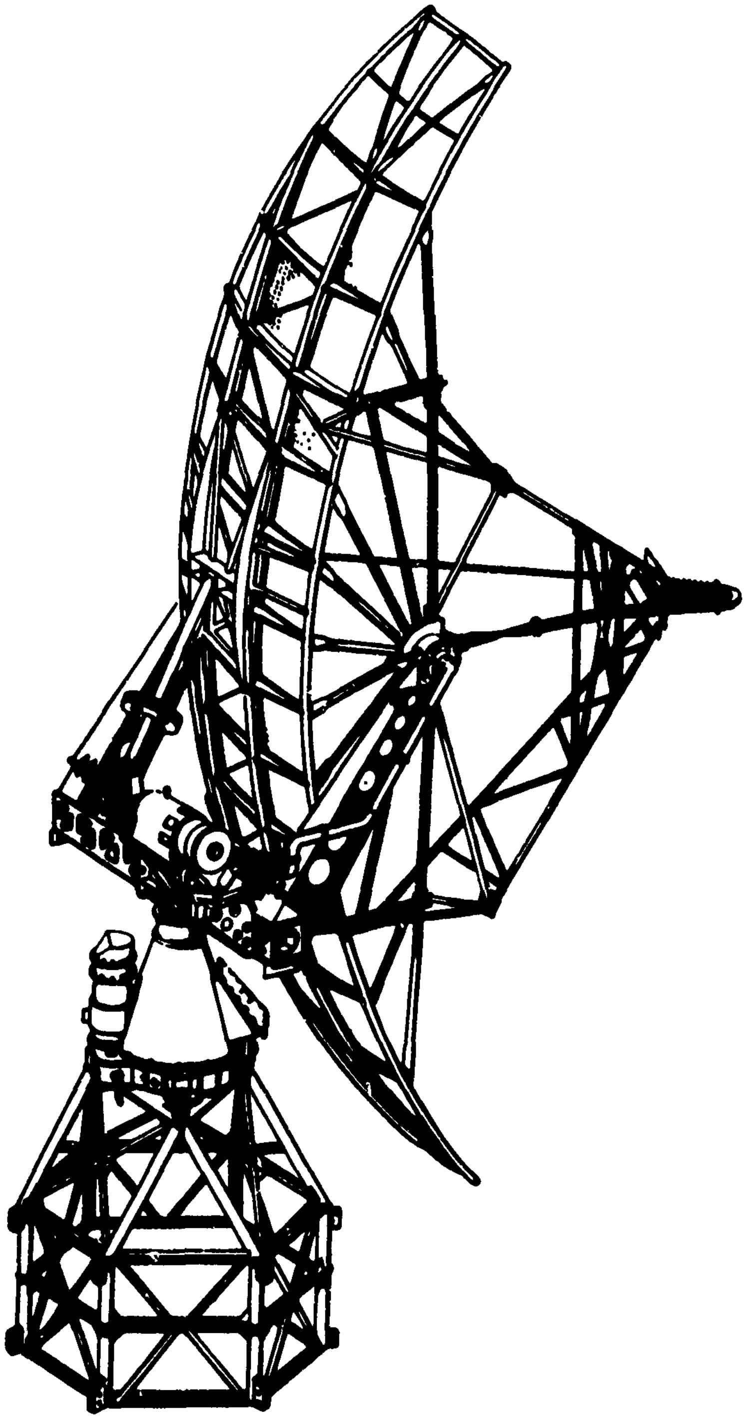

Figure 1. Antenna Group OA-339/FPS-6, for AN/FPS-6

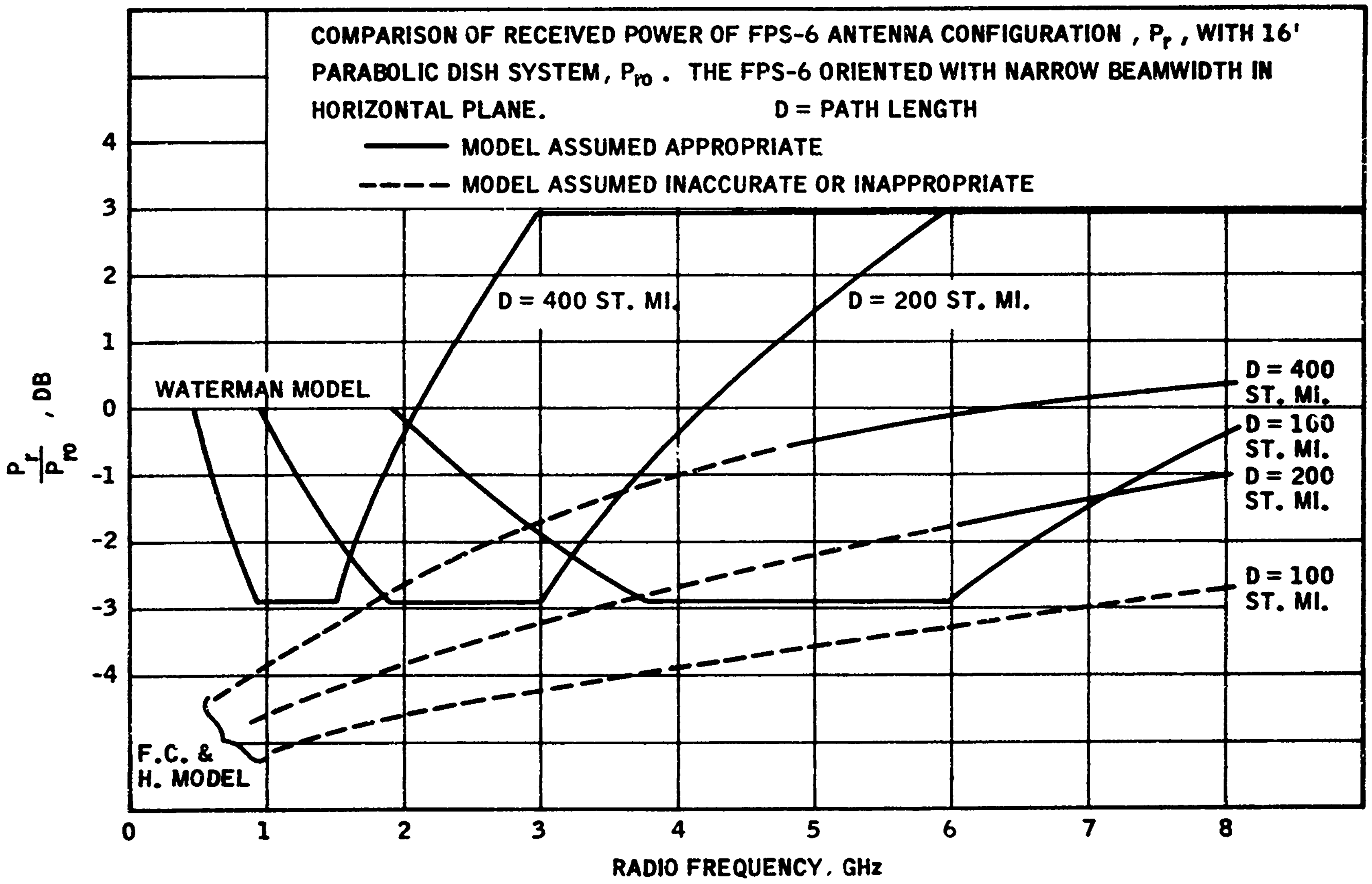
COMPARISON OF RECEIVED POWER OF FPS-6 ANTENNA CONFIGURATION, P_r, WITH 16' PARABOLIC DISH SYSTEM, P_{ro}. THE FPS-6 ORIENTED WITH NARROW BEAMWIDTH IN HORIZONTAL PLANE.
D = PATH LENGTH
MODEL ASSUMED APPROPRIATE
MODEL ASSUMED INACCURATE OR INAPPROPRIATE
D = 400 ST. MI.
D = 200 ST. MI.
WATERMAN MODEL
D = 400 ST. MI.
D = 100 ST. MI.
D = 200 ST. MI.
D = 100 ST. MI.
F.C. & H. MODEL
$\frac{P_r}{P_{ro}}$, DB
4
3
2
1
0
-1
-2
-3
-4
0
1
2
3
4
5
6
7
8
RADIO FREQUENCY, GHz

Figure 2

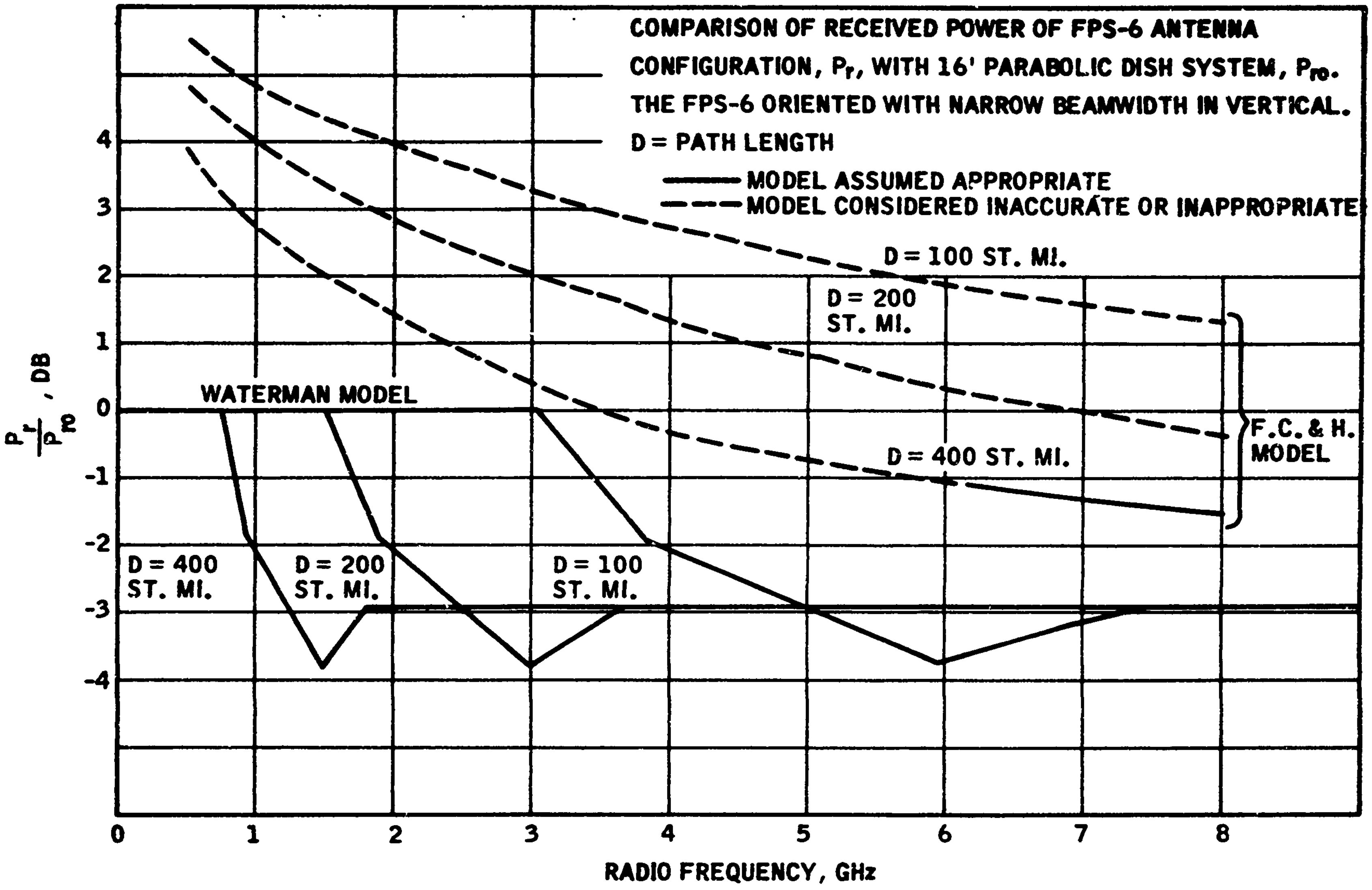
COMPARISON OF RECEIVED POWER OF FPS-6 ANTENNA CONFIGURATION, P_r, WITH 16' PARABOLIC DISH SYSTEM, P_{ro}. THE FPS-6 ORIENTED WITH NARROW BEAMWIDTH IN VERTICAL.
D = PATH LENGTH
MODEL ASSUMED APPROPRIATE
MODEL CONSIDERED INACCURATE OR INAPPROPRIATE
D = 100 ST. MI.
D = 200 ST. MI.
D = 400 ST. MI.
F.C. & H. MODEL
WATERMAN MODEL
D = 400 ST. MI.
D = 200 ST. MI.
D = 100 ST. MI.
$\frac{P_r}{P_{ro}}$, DB
4
3
2
1
0
-1
-2
-3
-4
0
1
2
3
4
5
6
7
8
RADIO FREQUENCY, GHz

Figure 3

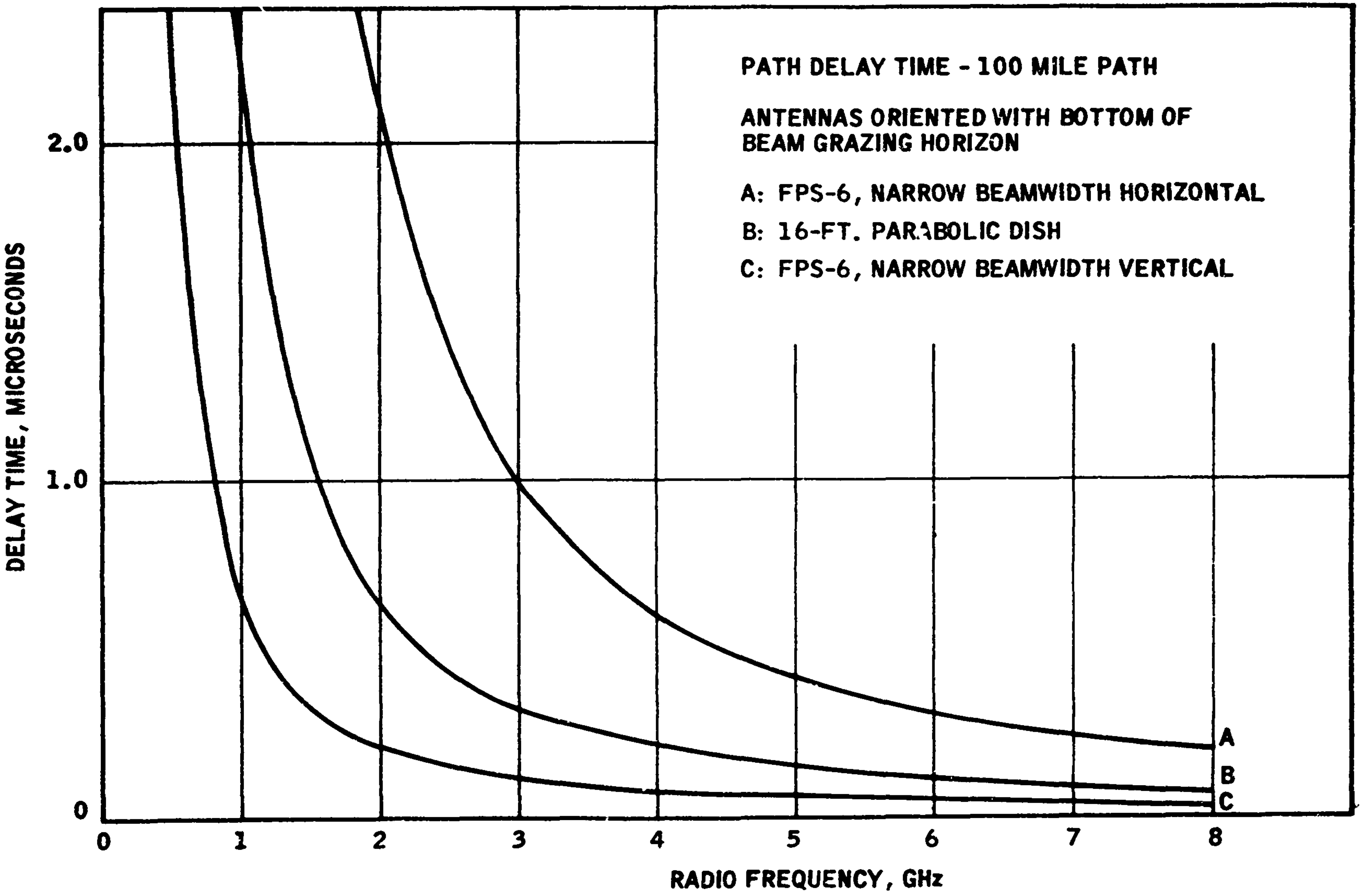
PATH DELAY TIME - 100 MILE PATH
ANTENNAS ORIENTED WITH BOTTOM OF BEAM GRAZING HORIZON
A: FPS-6, NARROW BEAMWIDTH HORIZONTAL
B: 16-FT. PARABOLIC DISH
C: FPS-6, NARROW BEAMWIDTH VERTICAL
DELAY TIME, MICROSECONDS
2.0
1.0
0
0
1
2
3
4
5
6
7
8
RADIO FREQUENCY, GHz
A
B
C

Figure 4

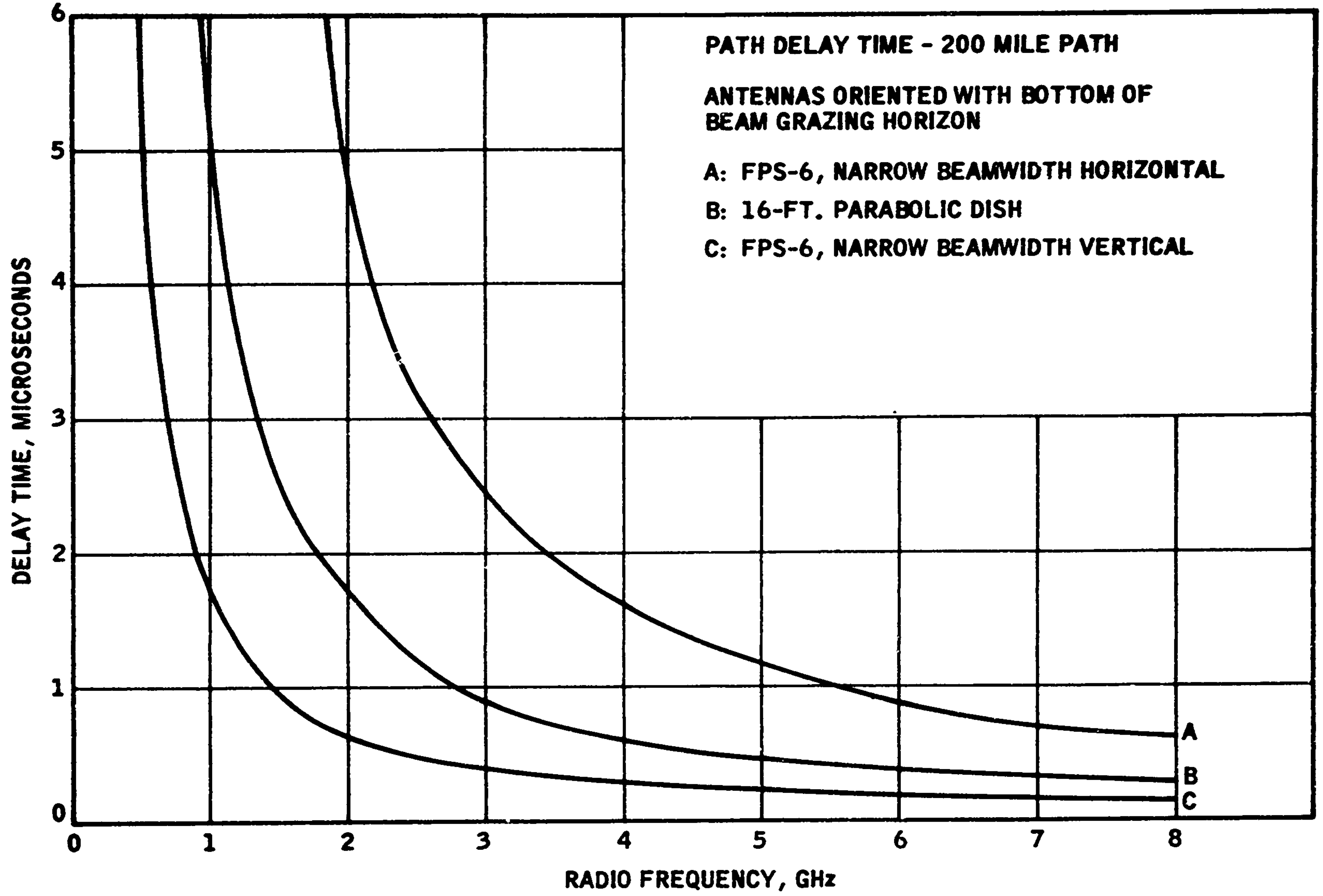
PATH DELAY TIME - 200 MILE PATH
ANTENNAS ORIENTED WITH BOTTOM OF BEAM GRAZING HORIZON
A: FPS-6, NARROW BEAMWIDTH HORIZONTAL
B: 16-FT. PARABOLIC DISH
C: FPS-6, NARROW BEAMWIDTH VERTICAL
DELAY TIME, MICROSECONDS
0
1
2
3
4
5
6
RADIO FREQUENCY, GHz
0
1
2
3
4
5
6
7
8
A
B
C

Figure 5

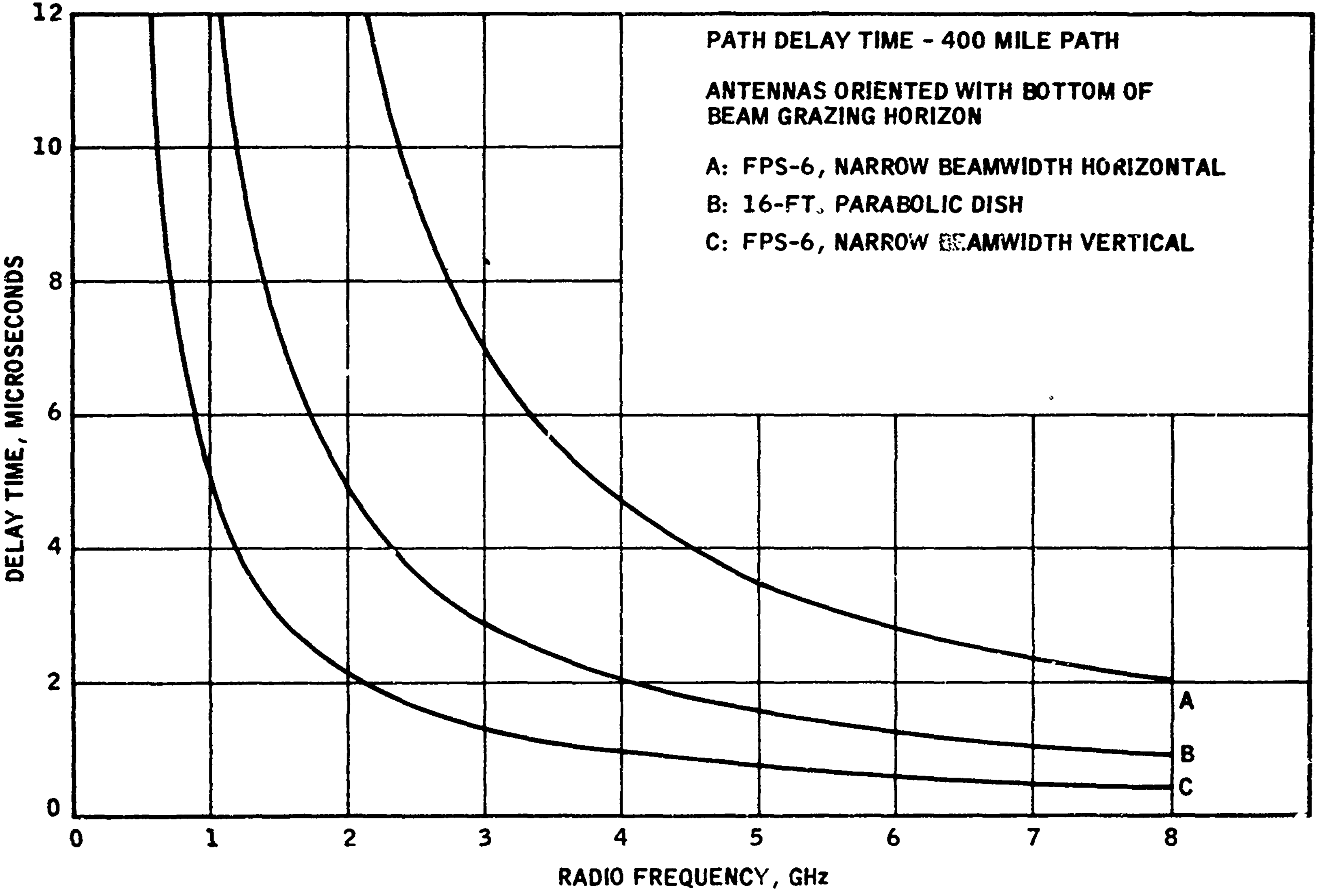
PATH DELAY TIME - 400 MILE PATH
ANTENNAS ORIENTED WITH BOTTOM OF BEAM GRAZING HORIZON
A: FPS-6, NARROW BEAMWIDTH HORIZONTAL
B: 16-FT. PARABOLIC DISH
C: FPS-6, NARROW BEAMWIDTH VERTICAL
DELAY TIME, MICROSECONDS
0
2
4
6
8
10
12
RADIO FREQUENCY, GHz
0
1
2
3
4
5
6
7
8
A
B
C

Figure 6

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Security Classification

DOCUMENT ITROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Page Communications Engineers 3300 Whitehaven Street NW Washington DC 20007	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

A THEORETICAL EVALUATION OF THE FPS-6 RADAR ANTENNA IN TROPOSCATTER COMMUNICATIONS SYSTEMS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report

5. AUTHOR(S) *(First name, middle initial, last name)*

6. REPORT DATE July 1969	7a. TOTAL NO. OF PAGES 15	7b. NO. OF REFS

8a. CONTRACT OR GRANT NO AF30(602)-4197 b. PROJECT NO. 9191 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) PCE-R-4132-00-30501A 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* RADC TR-69-69

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES RADC Project Engineer: Italo A. Fantera (EMCAW)	12. SPONSORING MILITARY ACTIVITY Rome Air Development Center (EMCAW) Griffiss Air Force Base, New York 13440

13. ABSTRACT

This report theoretically analyzes the effect of using a fan-shaped antenna reflector, having an aspect ratio of 3.5 to 1, for troposcatter communications. The analysis is performed relative to the performance which would be achieved when using a circular cross-sectioned parabolic reflector having the same free-space antenna gain. Parameters which are considered in the analysis include the orientation of the fan-shaped reflector, aperture-to-medium coupling loss, differential path delay, and scatter models based on Waterman and Friis-Crawford-Hogg.

DD FORM 1 NOV 65 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Communications Troposphere Radar Antennas						

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Security Classification

AFLC—Griffiss AFB NY 20 Aug 69-76