VLA ELECTRONICS MEMO #120

NATIONAL RADIO ASTRONOMY OBSERVATORY

LOSS AND COUPLING VALUES IN THE VLA TRANSMISSION SYSTEM

Read Predmore

December 19, 1973

1. Introduction

When the losses and coupling in the VLA millimeter circular waveguide was first considered in VLA Electronics Memo 104, the detailed waveguide loss and the effects of mismatch and spurious mode generation were not known. In the past year waveguide from Furukawa and Sumitomo has been delivered to NRAO and measured by Alan Parrish. In addition a number of components for the antenna coupling system have been evaluated for insertion loss, TE_{01} mismatch and spurious made generation.

These measurements and studies of TE_{01} mismatch and TE_{02} mode generation in the various components have lead to the following conclusions:

a) The beam splitter couplers are not feasible in the trunk line, since they have TE_{02} and TE_{03} mode generation as strong as -16 dB, which would cause 1 dB ripples with a 16 MHz period for two couplers 1 km apart. Presently small diameter circular (20, 16, and 11 mm) to rectangular couplers will be used at frequencies where the TE_{02} mode is cutoff, and hence least likely to be generated. Circular couplers of 60 mm size are being studied for the weaker coupling values (-25 and -30 dB) needed for the more compact VLA configurations, so that they can be left in the system, and circular to circular couplers of 20 mm diameter will be evaluated for all frequencies.

b) Circular to circular tapers (i.e., 20-60 mm) will be about 80-100 cm long with mode generation 20 log Γ_{02} less than -35 dB. This level of mode generation has been used to estimate the level of spurious mode resonance between two tapers where the TE_{02} mode is trapped. This mode effect will be moderated by loss in the 60 mm circular WG between tapers or by an attenuator placed between two closely spaced spurious mode generators. At 50 GHz, where mode generation should be strongest and WG loss lowest, the peak-to-peak spurious mode effect for tapers ℓ kilometers apart is[1]:

$$S(dB) = 42\ \Gamma_{02}^{2}\ /\ell(km),$$

$$= 0.013/\ell(km),\ \text{for } 10 \log \Gamma_{02}^{2} = -35\ dB$$

or $$S(db) = 150\ \Gamma_{02}^{2}\ /L(dB)$$

$$= 0.047/L(dB)$$

for -35dB mode generation,

where L(dB) is attenuator loss.

c) The TE_{01} ripple due to coupler and attenuator mismatches is approximately

$$R(dB) \doteq 17.4 \times \sum_{i=1}^{n} \rho_i^{\,2},$$

for n mismatches with reflection coefficents ρ_i. Eleven mismatches with a -30dB return loss gives:

$$R = 17.4 \times 11 \times (0.001) \simeq 0.2dB.$$

A -40dB return loss will lower this to 0.02dB.

A set of graphs and tables on circular waveguide, which have been useful in designing and evaluating the Waveguide Communication System (WACS), have been included in an appendix.

2. Waveguide Loss and Coupling Determination

The present IF transmission system will send four 50 MHz IF data bands in the 1-2 GHz range from each antenna to the central control building. The current power and loss budget for the transmission system is:

Upconverted power/50 MHz	- 6 dBm
Loss in antenna coupling system	- 5 dB
Loss in coupler and waveguide	-49 dB
Loss in signal distribution system	- 4 dB
Signal received/50 MHz	-64 dBm
Noise (kTB+13 dB NF)/50 MHz	-84 dBm
Final Signal to Noise =	20 dB

Using the 60 mm WG loss as measured by Alan Parrish, which gave a loss only 50% more than theory, and allowing for a 400 meter rms radius of curvature when the waveguide is directly buried, it should be possible to reduce the WG and coupler loss to -35 dB. This will give a 14 dB margin in the loss budget which may be needed:

a) to minimize mismatch effects in the antenna coupling system;

b) to dampen spurious mode effects in the signal distribution system;

c) and to allow for deterioration in the WG loss with time.

The 100 meters of directly buried WG in New Mexico will give better loss data to further refine the configuration design.

Figure 1 shows the VLA Antenna positions for the 21 km configuration along with loss curves for the predicted losses (1.1 to 2.4 dB/km). Since the waveguide loss decreases with frequency, the closest antenna stations will use the lower frequency millimeter channels with the furthermost antenna using the highest frequency where the WG loss is <25 dB. For the north and south arms where only 7 and 9 antennas will be used, channels at the lower and upper frequencies were not used. The lower channels were dropped because of their higher WG loss and their higher TE_{ON} mode generation and insertion in the diplexers used in the signal distribution system. The higher channels were eliminated because of their higher TE_{02} mode generation in the 20-60 mm tapers, and their slightly higher noise figure.

The extended array (21 km) will need the low loss properties of the circular WG to meet the 35 dB loss specification. However, the more compact configurations (B, C & D) will need additional loss between antennas to use the same couplers as Conf. A and to minimize interaction between antenna couplers due to reflections and mode conversion.

The antenna positions, coupling values and total loss are given for configuration A for the North, East and West arms in Tables I, II and III-A. Then the compact configurations for the West arm, which has the most antennas, are given in Tables III-B C and D.

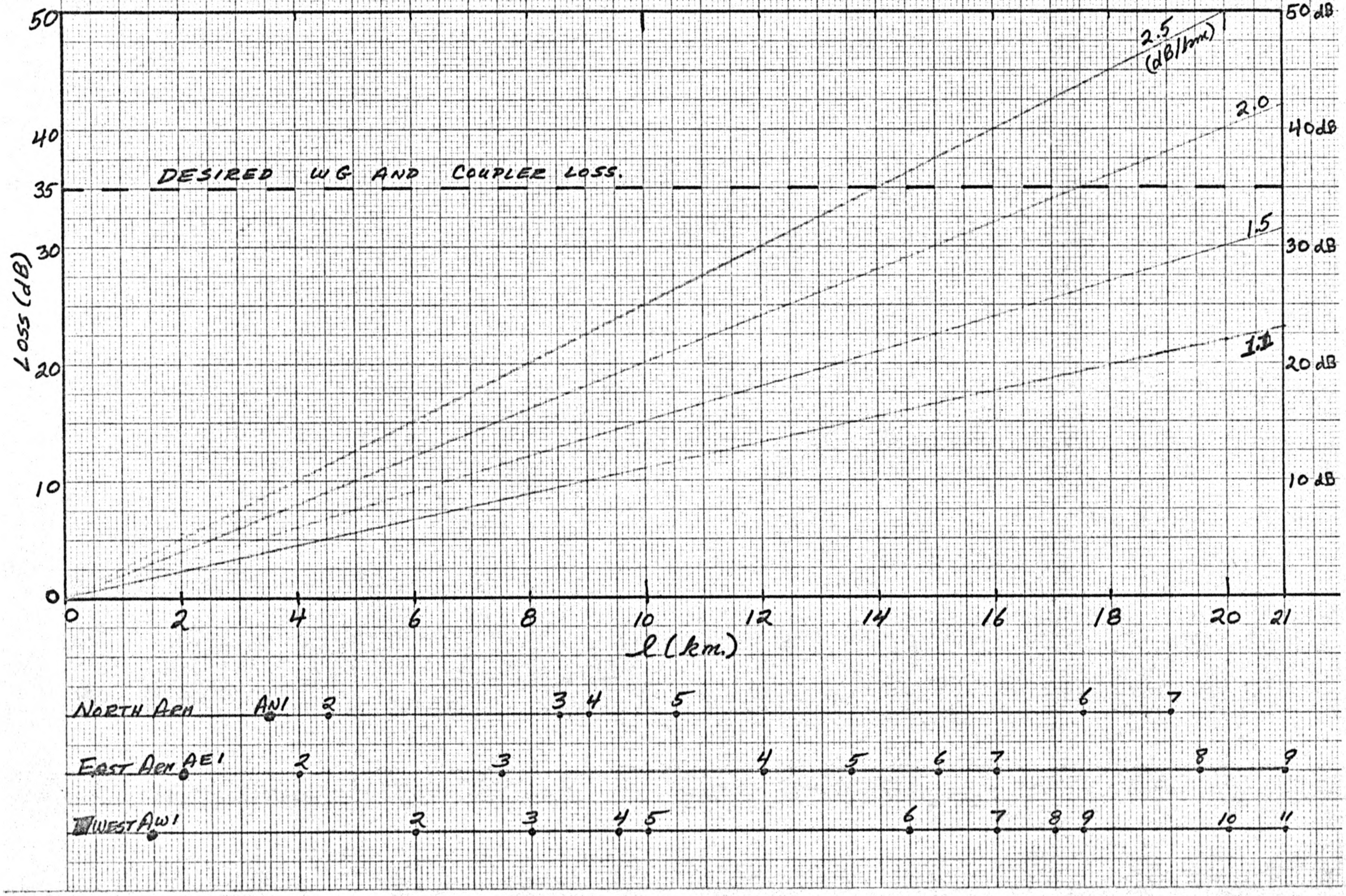
The various quantities in the tables are:

a) Channel number
b) Channel mid-band frequency
c) Channel coupler diameter chosen so TE_{02} is cut off
d) Coupling value for that channel
e) Accumulated coupler insertion and power loss
f) WG loss (dB/km) for that channel
g) Distance of antenna from the array center for the given configuration
h) Distance between antennas which is used to calculate TE_{02} ripple and beat frequency
i) Attenuation between antennas (if any)
j) Total WG loss for this channel and antenna distance
k) Total WG, attenuator and coupler loss for this antenna
l) Return loss for channels 1 to 4 from Channel 7 where the TE_{01} is cut off by the 11 mm coupler
m) TE_{02} peak-to-peak ripple
n) TE_{01} - TE_{02} beat frequency at f = 50 GHz.

References

1) A. P. King & E. A. Marcatili, BSTJ, V35-5, 1956, p. 1115 - 1128, "Transmission Loss Due to Resonance of Loosely-Coupled Modes in a Multimode System."

VLA CONFIGURATION A.



NORTH ARM CONF. A (19km).

Channel #	Signal Freq. (GHz)	Coupler Diam. (mm)	Coupling C_i (dB)	Sum of Coupler Loss (dB)	WG Loss for Channel i (dB/km)	Position Z_i (meters)	$(Z_{i+1}-Z_i)$ (meters)	Attenuator Value A_i (dB)	WG Loss (dB)	Total Loss (dB)	TE_{01} Return Loss (dB)	TE_{02} Ripple (dB)	f_{Beat} (MHz)
1	27.9	20			2.40								
2	30.3	20			2.25								
3	32.7	20	-20	1	2.00	3500	1000		7	-28	-30	0.01	174
4	35.1	16	-20	1	1.80	4500	4000		9	-30	-23	<0.01	4.1
5	37.5	16	-14	1	1.65	8500	500		14	-29		0.03	33
6	39.9	16	-14	2	1.50	9000	1500		14	-30		<0.01	11
7	42.3	11	-11	3	1.40	10500	7500		15	-29		<0.01	2.2
8	44.7	11	- 4	4	1.30	17500	1500		23	-31		<0.01	11
9	47.1	11	0	7	1.25	19000			24	-31			
10	49.5	11			1.15								
11	51.9	11			1.10								

TABLE I

EAST ARM CONF. A (21 km).

Channel #	Signal Freq. (GHz)	Coupler Diam. (mm)	Coupling C_i (dB)	Sum of Coupler Loss (dB)	WG Loss for Channel i (dB/km)	Position Z_i (meters)	$(Z_{i+1}-Z_i)$ (meters)	Attenuator Value A_i (dB)	WG Loss (dB)	Total Loss (dB)	TE_{01} Return Loss (dB)	TE_{02} Ripple (dB)	f_{Beat} (MHz)
1	27.9	20			2.40								
2	30.3	20	-25	1	2.25	2000	2000		5	-31	-60	<0.01	8.2
3	32.7	20	-20	1	2.00	4000	3500		8	-29	-47	<0.01	4.7
4	35.1	16	-15	1	1.80	7500	4500		14	-30	-39	<0.01	3.7
5	37.5	16	-11	2	1.65	12000	1500		20	-33		<0.01	11
6	39.9	16	-10	3	1.50	13500	1500		21	-34		<0.01	11
7	42.3	11	- 8	4	1.40	15000	1000		21	-33		0.01	17
8	44.7	11	- 7	5	1.30	16000	3500		21	-33		<0.011	4.7
9	47.1	11	- 3	7	1.25	19500	1500		24	-34		<0.01	11
10	49.5	11	0	10	1.15	21000			24	-34			
11	51.9	11			1.10								

TABLE II

WEST ARM CONF. A (21 km)

Channel #	Signal Freq. (GHz)	Coupler Diam. (mm)	Coupling C_i (dB)	Sum of Coupler Loss (dB)	WG Loss for Channel i (dB/km)	Position Z_i (meters)	$(Z_{i+1}-Z_i)$ (meters)	Attenuator Value A_i (dB)	WG Loss (dB)	Total Loss (dB)	TE_{01} Return Loss (dB)	TE_{02} Ripple (dB)	f [illegible] (MHz)
1	27.9	20	-30	1	2.40	1500	4500	No Attenuator	4	-35	-70dB	<0.01	3.7
2	30.3	20	-20	1	2.25	6000	2000		14	-35	-46dB	<0.01	8.2
3	32.7	20	-17	1	2.00	8000	1500		16	-34	-34	<0.01	11
4	35.1	16	-15	2	1.80	9500	500		17	-34	-25dB	0.03	33
5	37.5	16	-14	3	1.65	10000	4500		17	-34		<0.01	3.7
6	39.9	16	- 9	3	1.50	14500	1500		22	-34		< .01	11
7	42.3	11	- 8	4	1.40	16000	1000		23	-35		0.01	17
8	44.7	11	- 7	5	1.30	17000	500		22	-34		0.03	33
9	47.1	11	- 6	7	1.25	17500	2500		22	-35		<0.01	6.6
10	49.5	11	- 3	9	1.15	20000	1000		23	-35		0.01	17
11	51.9	11	0	12	1.10	21000			23	-35			

TABLE III-A

WEST ARM CONF. B (6 km)

Channel #	Signal Freq. (GHz)	Coupler Diam. (mm)	Coupling C_i (dB)	Sum of Coupler Loss (dB)	WG Loss for Channel i (dB/km)	Position Z_i (meters)	$(Z_{i+1}-Z_i)$ (meters)	Attenuator Value A_i (dB)	WG Loss (dB)	Total Loss (dB)	TE_{01} Return Loss (dB)	TE_{02} Ripple (dB)	f_{Beat} (MHz)
1	27.9	20	-30	1	2.40	415	1265	0	1	32	-36dB	0.01	13
2	30.3	20	-20	1	2.25	1680	760	1	4	25	-29	0.01	22
3	32.7	20	-17	1	2.00	2240	420	2	5	24	-24	0.01	39
4	35.1	16	-15	2	1.80	2660	140	3	5	25	-17	0.01	118
5	37.5	16	-14	3	1.65	2800	1260	0	5	28		0.01	13
6	39.9	16	- 9	3	1.50	4060	420	2	7	25		0.01	39
7	42.3	11	- 8	4	1.40	4480	280	2	7	27		0.02	59
8	44.7	11	- 7	5	1.30	4760	140	3	7	29		0.01	118
9	47.1	11	- 6	7	1.25	4900	700	1	7	26		0.01	24
10	49.5	11	- 3	9	1.15	5600	280	2	7	33		0.02	59
11	51.9	11	0	12	1.10	5880			7	35			

TABLE III-B

WEST ARM CONF. C (2 km).

Channel #	Signal Freq. (GHz)	Coupler Diam. (mm)	Coupling C_i (dB)	Sum of Coupler Loss (dB)	WG Loss for Channel i (dB/km)	Position Z_i (meters)	$(Z_{i+1}-Z_i)$ (meters)	Attenuator Value A_i (dB)	WG Loss (dB)	Total Loss (dB)	TE_{01} Return Loss (dB)	TE_{02} Ripple (dB)	f_{Beat} (MHz)
1	27.9	20	-30	1	2.40	140	435	1	1	-32	-29	0.02	38
2	30.3	20	-20	1	2.25	575	172	2	2	-24	-24	0.02	96
3	32.7	20	-17	1	2.00	747	140	2	2	-23	-19	0.02	118
4	35.1	16	-15	2	1.80	887	46	3	2	-24	-14	0.02	359
5	37.5	16	-14	3	1.65	933	420	1	2	-27		0.02	39
6	39.9	16	- 9	3	1.50	1353	147	2	2	-23		0.02	112
7	42.3	11	- 8	4	1.40	1500	87	2	2	-25		0.02	190
8	44.7	11	- 7	5	1.30	1587	46	3	2	-27		0.02	359
9	47.1	11	- 6	7	1.25	1633	234	2	2	-31		0.02	71
10	49.5	11	- 3	9	1.15	1867	93	2	2	-32		0.02	177
11	51.9	11	0	12	1.10	1960			2	-34			

WEST ARM CONF. D (0.5 km)

Channel #	Signal Freq. (GHz)	Coupler Diam. (mm)	Coupling C_i (dB)	Sum of Coupler Loss (dB)	WG Loss for Channel i (dB/km)	Position Z_i (meters)	$(Z_{i+1}-Z_i)$ (meters)	Attenuator Value A_i (dB)	WG Loss (dB)	Total Loss (dB)	TE_{01} Return Loss (dB)	TE_{02} Ripple (dB)	f_{Beat} (MHz)
1	27.9	20	-30	1	2.40	35	105	2.0	0	-31	-29	0.02	157
2	30.3	20	-20	1	2.25	140	40	2.5	1	-24	-25	0.02	413
3	32.7	20	-17	1	2.00	180	40	2.5	1	-24	-19	0.02	413
4	35.1	16	-15	2	1.80	220	40	2.5	1	-25	-14	0.02	413
5	37.5	16	-14	3	1.65	260	40	2.5	1	-28		0.02	413
6	39.9	16	- 9	3	1.50	335	75	2.0	1	-25		0.02	220
7	42.3	11	- 8	4	1.40	375	40	2.5	1	-27		0.02	414
8	44.7	11	- 7	5	1.30	415	40	2.5	1	-30		0.02	413
9	47.1	11	- 6	7	1.25	455	40	2.5	1	-33		0.02	413
10	49.5	11	- 3	9	1.15	495	40	2.5	1	-35		0.02	413
11	51.9	11	0	12	1.10	535			1	-37dB			

TABLE III-D

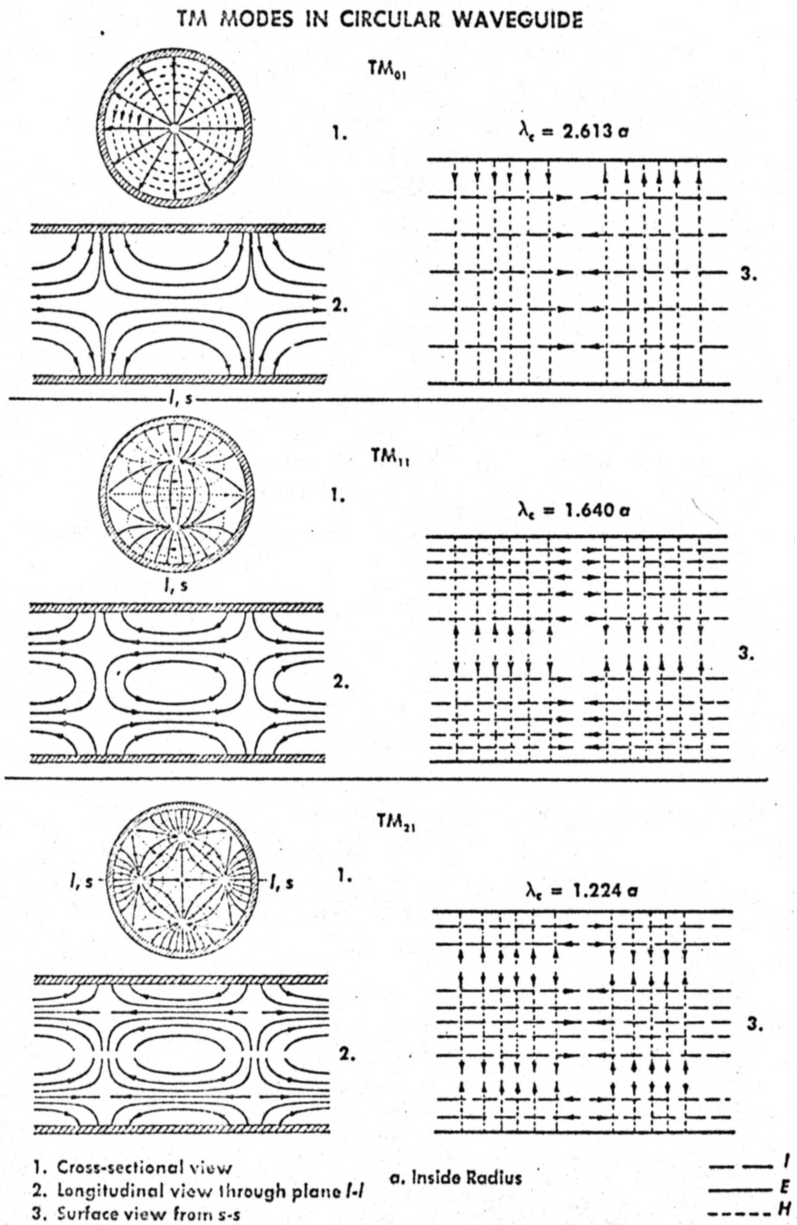
Appendix A - Characteristics of Circular Waveguide

A number of useful graphs, charts and tables concerning the TE_{01} mode in circular waveguide have been collected for general reference. This first section describes the various mode configurations while Section II shows the attenuation for various TE_{om} modes. Then interaction between various modes,and delay is discussed in Section III.

A.I

Figure I.1. in this section shows the field configuration of several TE and TM modes in circular WG. The mode cutoff frequencies and wavelengths are given in Table 1, while the relationship between waveguide diameter and cutoff frequency is emphasized in Figure I.2. Modes to the lower left of a point will propagate. For example at 25 GHz in a 16 mm waveguide the TE_{11}, TM_{01}, TE_{21}, TE_{01}, and TM_{11} modes will propagate while higher modes are cutoff. The theory of circular waveguide is discussed by R. E. Collin (Field Theory of Guided Waves, p. 195-198) and by Atwater ( ).

The transmission properties of circular waveguide systems have been thoroughly discussed in the Bell System Technical Journal. The paper by Miller (BSTJ, V33, 1954, p. 1209, "Waveguide as A Communication Medium") is a good introduction, while the 1971 IEE Conference on "Trunk Telecommunications by Guided Waves" gives a view of the world-wide interest in circular waveguide.


TM MODES IN CIRCULAR WAVEGUIDE
TM_{01}
$\lambda_c = 2.613\ a$
TM_{11}
$\lambda_c = 1.640\ a$
TM_{21}
$\lambda_c = 1.224\ a$
l, s
1.
2.
3.
1. Cross-sectional view
2. Longitudinal view through plane l-l
3. Surface view from s-s
a. Inside Radius
l
E
H

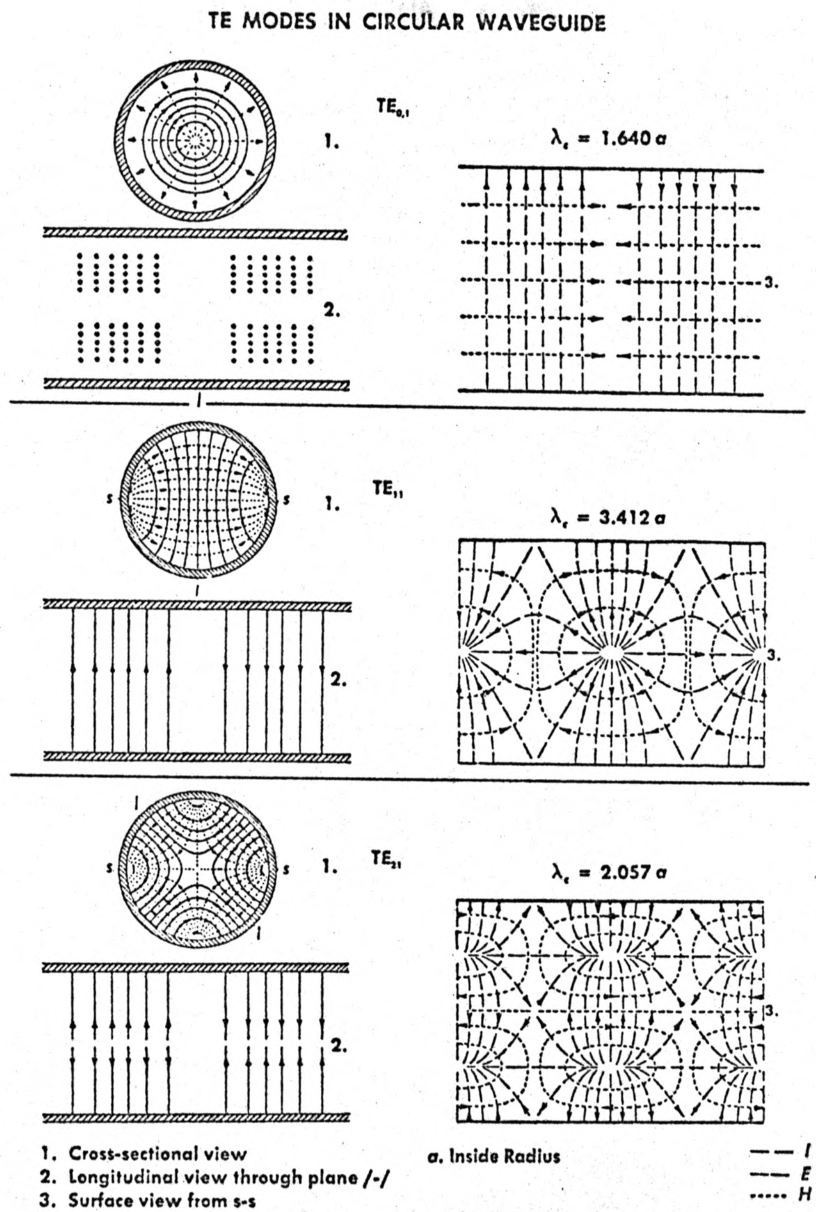

TE MODES IN CIRCULAR WAVEGUIDE
$TE_{0,1}$
$\lambda_c = 1.640\ a$
TE_{11}
$\lambda_c = 3.412\ a$
TE_{21}
$\lambda_c = 2.057\ a$
l
s
1.
2.
3.
1. Cross-sectional view
2. Longitudinal view through plane l-l
3. Surface view from s-s
a. Inside Radius
l
E
H

Figure I.1

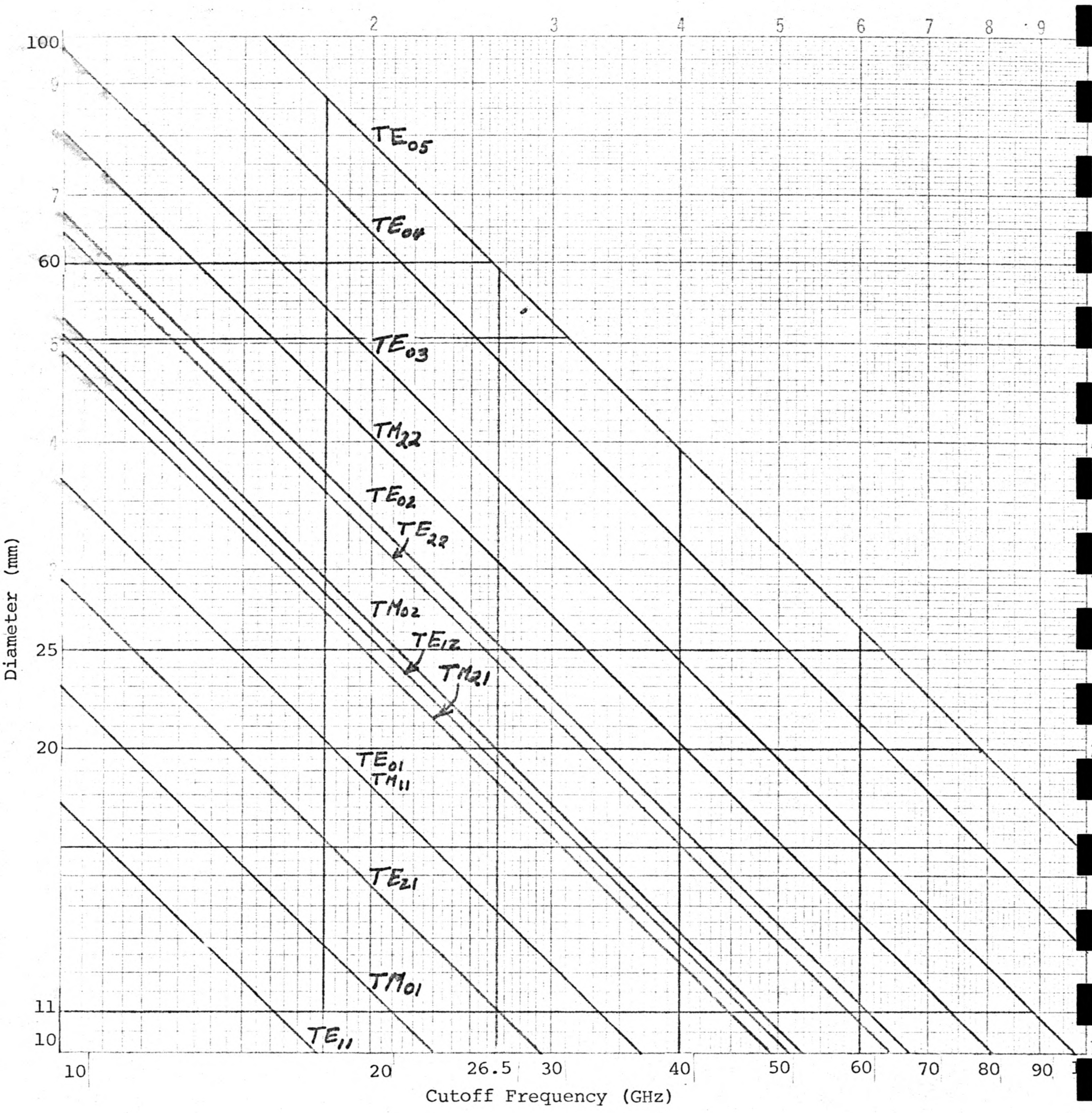


FIGURE I.2 Circular Waveguide Diameter Versus Mode Cutoff Frequencies

TABLE 1. CUTOFF FREQUENCY AND WAVELENGTH

MODE	$f_c D$ (GHz-mm)	λ_c/D	f_c (GHz) (D=60mm)
TE_{11}	175.8	1.707	2.93
TM_{01}	229.6	1.307	3.83
TE_{21}	291.7	1.029	4.86
TE_{01}, TM_{11}	365.9	.820	6.10
TM_{21}	490.4	.612	8.17
TE_{12}	509.1	.589	8.49
TM_{02}	527.1	.569	8.79
TE_{22}	640.2	.469	10.67
TE_{02}	670.2	.448	11.17
TM_{22}	804.0	.373	13.40
TE_{03}	971.4	.309	16.19
TE_{04}	1271	.289	21.2
TE_{05}	1571	.190	26.2

f_c ≡ cutoff frequency (GHz)

λ_c ≡ cutoff wavelength (mm)

D ≡ waveguide diameter (mm)

A.2 Waveguide Loss

A series of figures are presented which give the circular waveguide loss for TE_{on} modes in a perfect copper cylinder (conductivity = 5.7×10^7 mhos/meter). The loss measured in Furukawa 60 millimeter waveguide from 25 to 55 GHz is 1.5 times theoretical loss. This is due to the use of wire wound in a helix instead of a solid copper pipe; to winding imperfections, and loss in the absorbtive dielectric between the wire helix and the outer steel pipe. The experimental loss has been plotted on Figure II.1 which shows the TE_{01} loss in 60, 51, 25, 20, 16 and 11 mm diameter waveguides. The expected TE_{02} and TE_{03} loss for the same waveguides are plotted in Figure II.2 and II.3 respectively. Since the difference in loss between the TE_{01} and a TE_{on} mode is important when these modes are coupled the differential loss for TE_{01} - TE_{02} and TE_{01} - TE_{03} is plotted in dB/kilometer from 20 to 80 GHz in Figures II.4 and II.5. Some papers on mode coupling use nepers instead of dB. They are related by

$$L\ (dB) = 20 \log_{10} e \cdot L\ (nepers)$$

$$= 8.686 \cdot L\ (nepers).$$

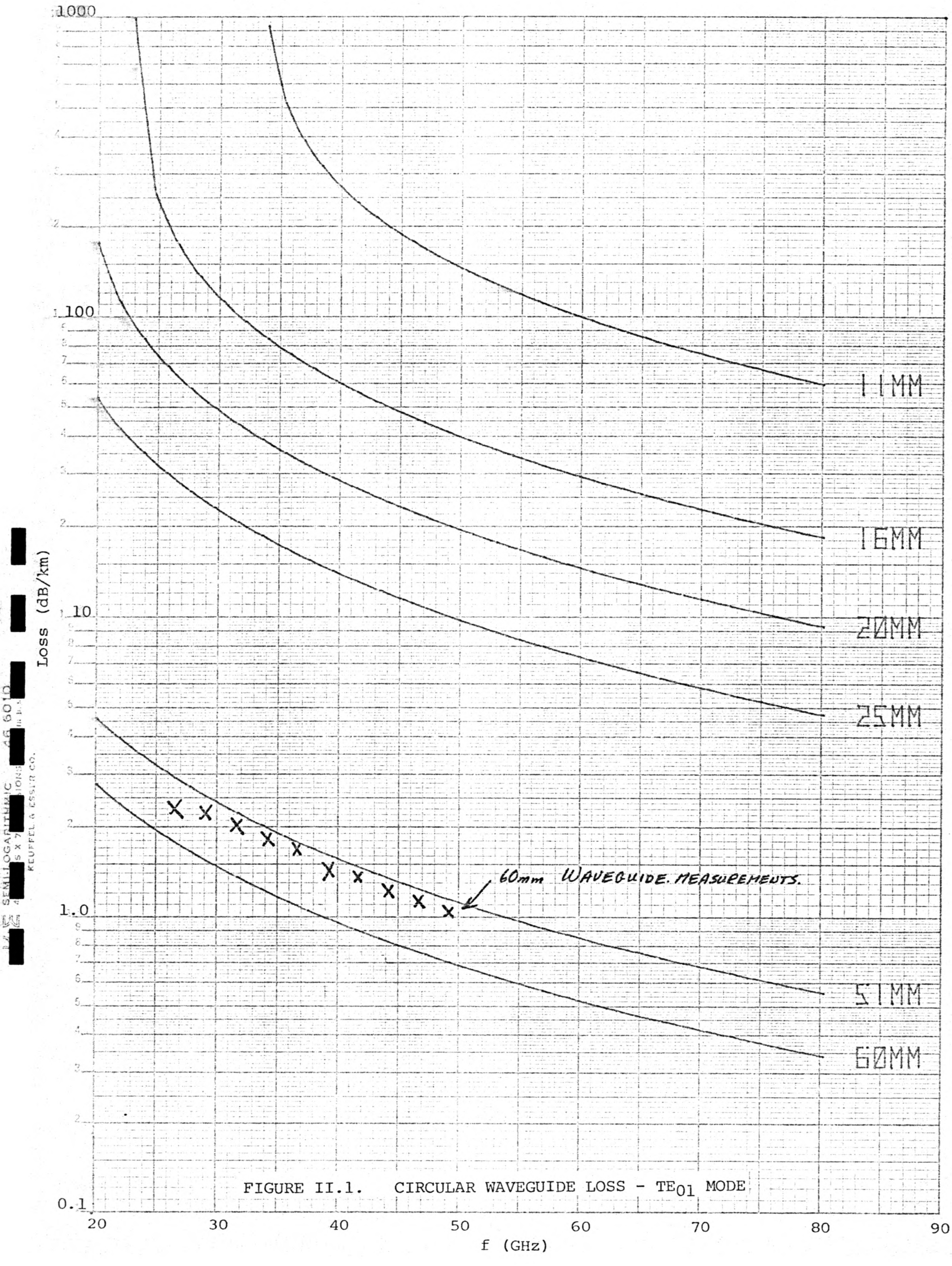


FIGURE II.1. CIRCULAR WAVEGUIDE LOSS - TE_{01} MODE

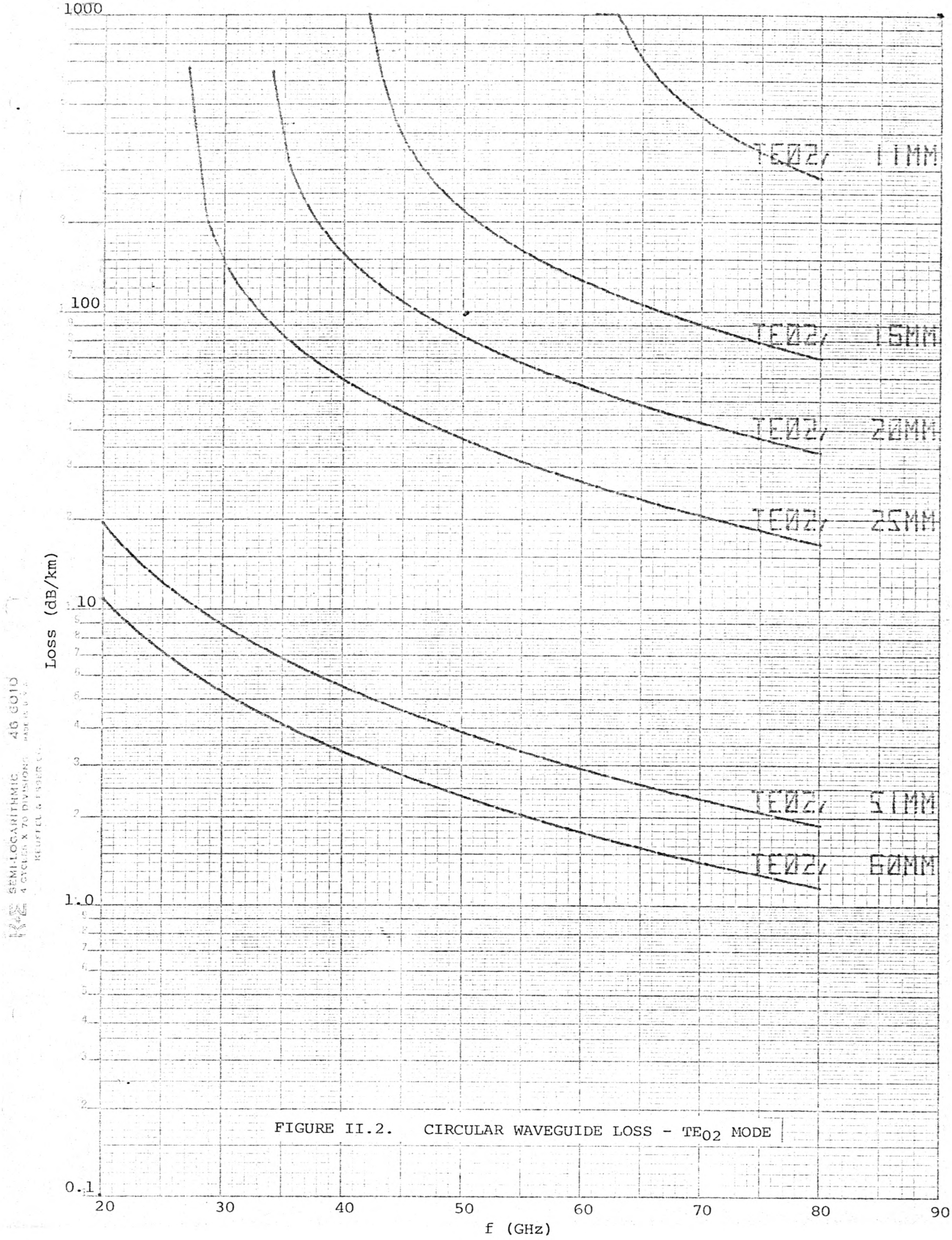


FIGURE II.2. CIRCULAR WAVEGUIDE LOSS - TE_{02} MODE

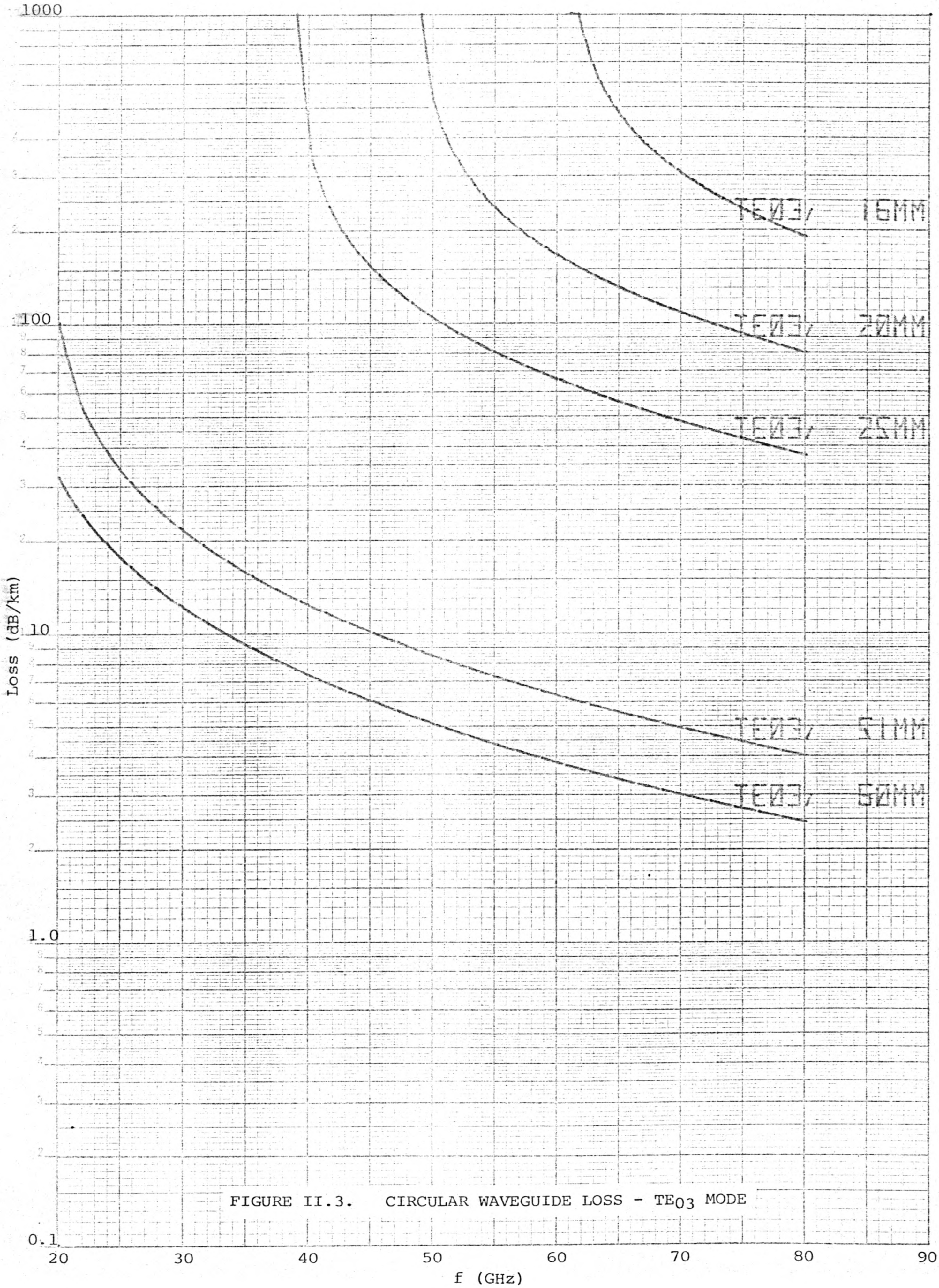


FIGURE II.3. CIRCULAR WAVEGUIDE LOSS - TE_{03} MODE

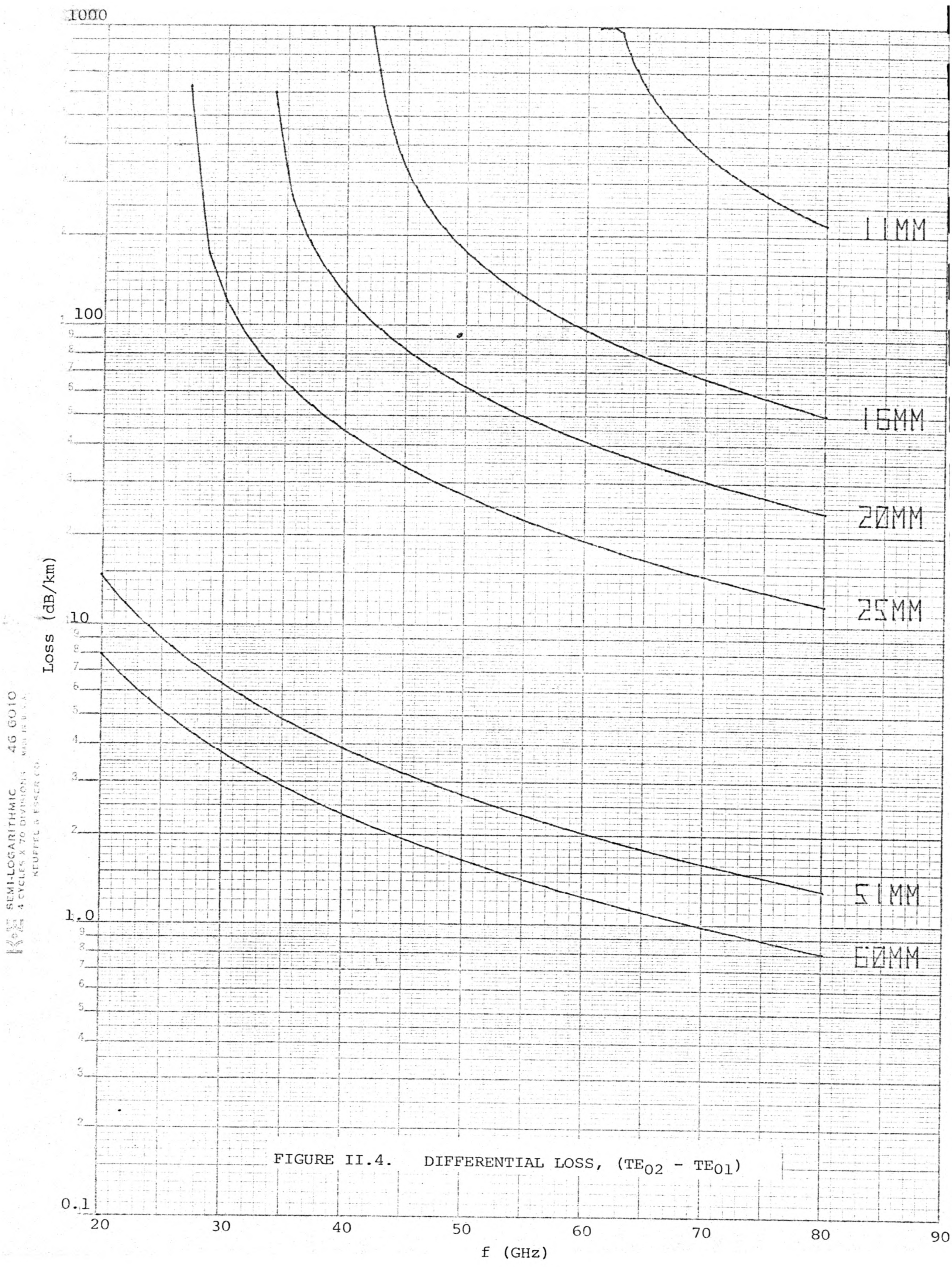


FIGURE II.4. DIFFERENTIAL LOSS, $(TE_{02} - TE_{01})$

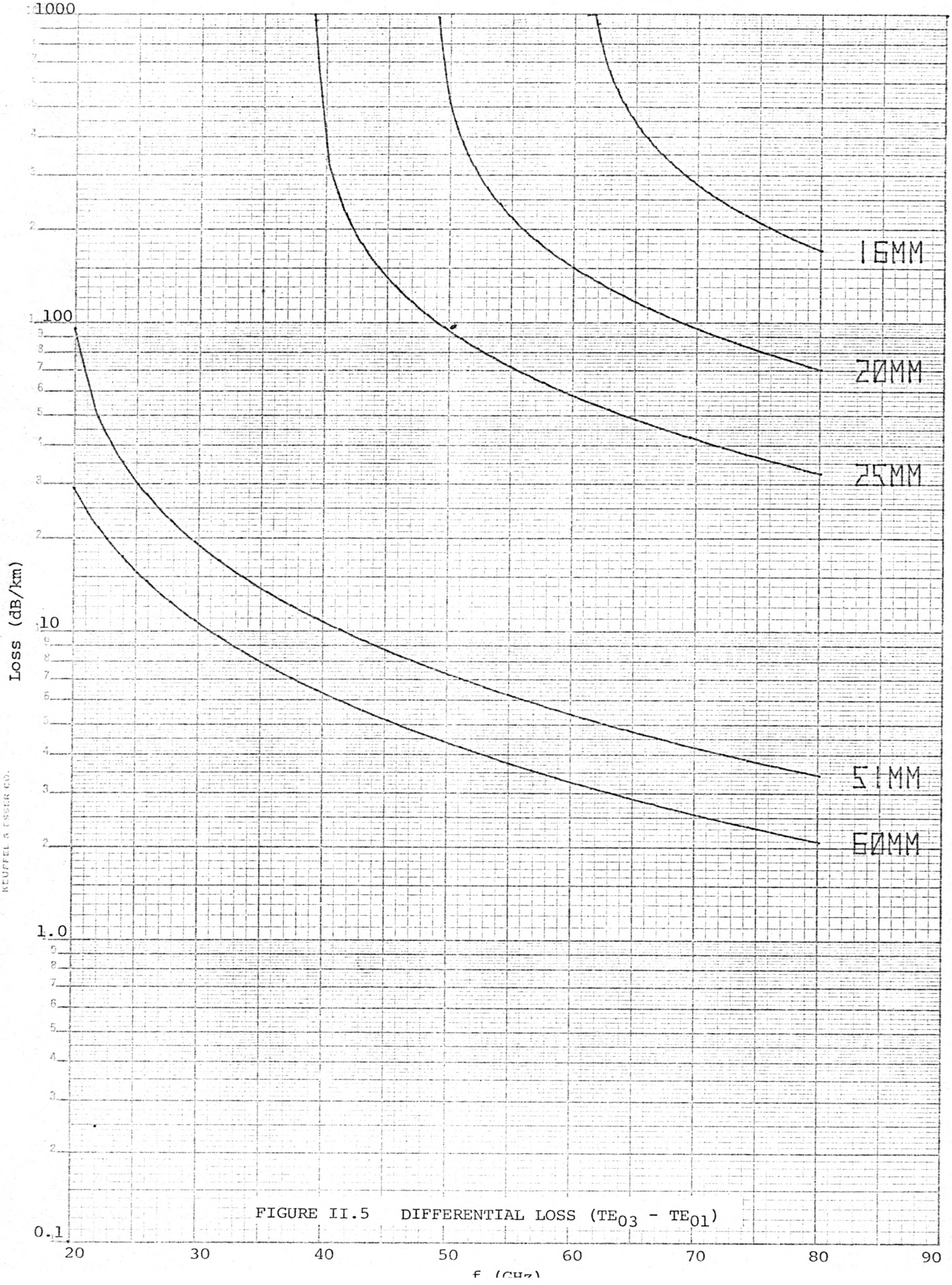


FIGURE II.5 DIFFERENTIAL LOSS (TE_{03} - TE_{01})

[redacted]

A.3 Mode Interaction and TE_{01} Dispersion

Because of the various cutoff frequencies for different modes, waves in different modes travel at different phase velocities. Figures III.1, 2 and 3 show some of the effects due to different velocities. The propagation constant for a cutoff mode is:

$$\beta_i = 2\pi/\lambda_{gi} = (2\pi\ f/c)\ .\ (1-\ (f_i/f)^2)^{\ 1/2},$$

where f is frequency,

f_i is mode cutoff frequency,

λ_{gi} is guide wavelength $\lambda_g > c/f$,

and c is the velocity of waves in free space.

The differential phase $\Delta\beta_{12}$ between two modes is just $\Delta\beta_{12} = \beta_1 - \beta_z$. This is plotted in Figure III.1 for the phase difference between the TE_{01} and the other low order modes. The beat wavelength is then shown in Figure III.2 for the same modes. The beat wavelength is the distance at a specific frequency for which $\Delta\beta.\lambda_{beat} = 2\pi$.

When two modes are coupled at two points a distance ℓ apart there will be a periodic ripple in the transmission characteristic versus frequency. The period of ripple, which is due to the destructive and constructive phase of the spurious mode, depends on the modes involved and the operating frequency. The period, f_{beat}, is defined by

$$|\Delta\beta(f+f_{beat}) - \Delta\beta(f)| = 2\pi/\ell,$$

where $$f_{beat} = (c/\ell)\ .\ \left[(1 - (f_1/f)^2)^{-1/2} - (1\ \ (f_2/f)^2)^{-1/2}\right]^{-1},$$

with f_1, f_2 the two mode cutoff frequencies.

The quantity $f_{beat} \cdot \ell$ (MHz - km or GHz - m) is graphed in Figure III.3 for coupling between the TE_{01} and twelve other circular waveguide modes.

Finally the dispersion and delay distortion due to cutoff is plotted in Figures III.4 and 5. The dispersion is plotted as group delay minus geometric delay in nanoseconds/km for circular waveguide diameters of 11 to 60 mm. Then delay distortion or differential delay due to varying dispersions across a 50 MHz band is plotted in Figure III.5 for the same range of waveguides. The 50 MHz band was chosen since this is the anticipated IF channel width for the VLA. The data in the figures is theoretical for cutoff modes in a perfect WG. In addition there will be ripples and bumps in the transmission characteristics due to waveguide imperfections, couplers, and mixer and amplifier characteristics.

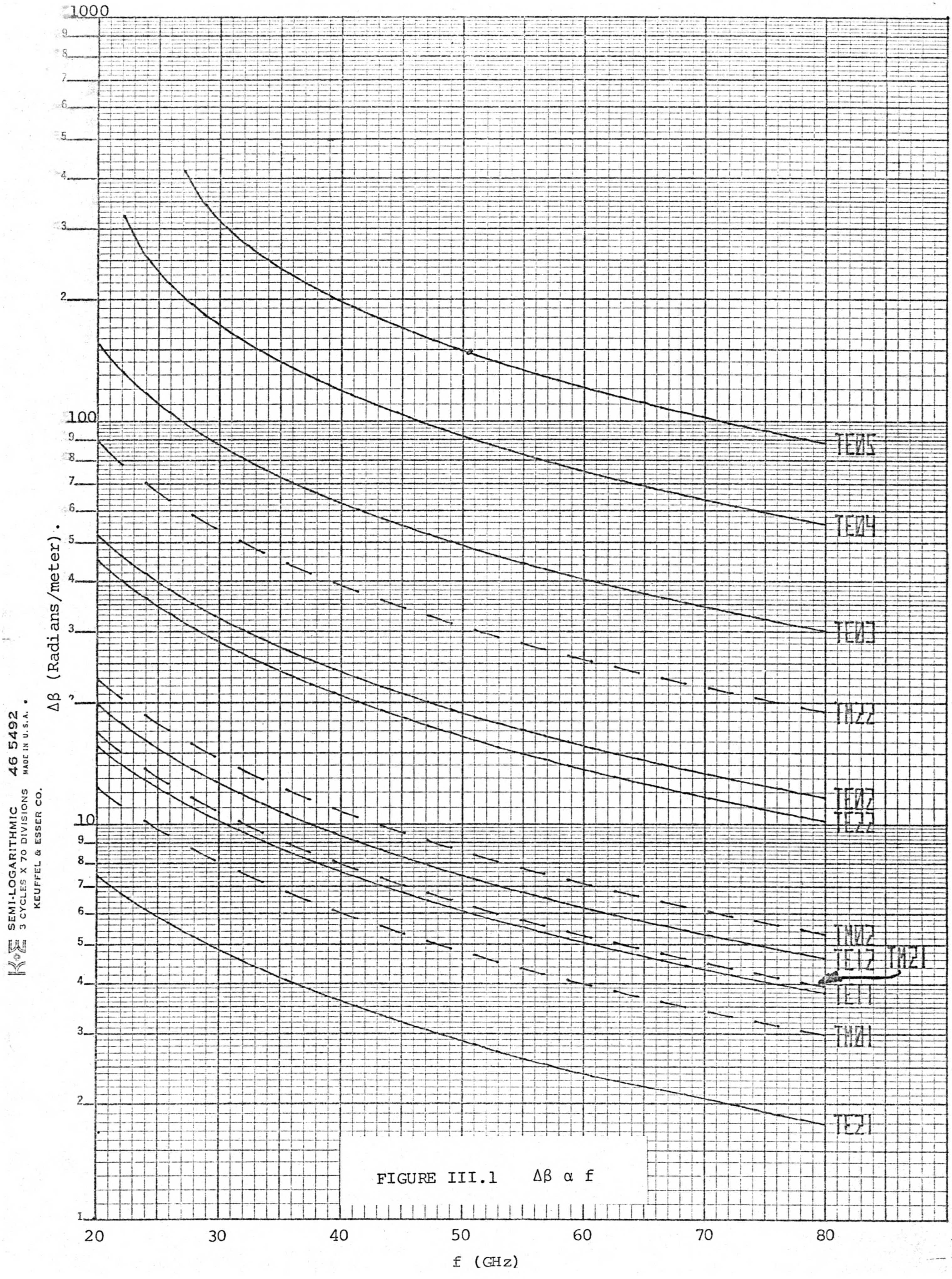


FIGURE III.1 Δβ α f

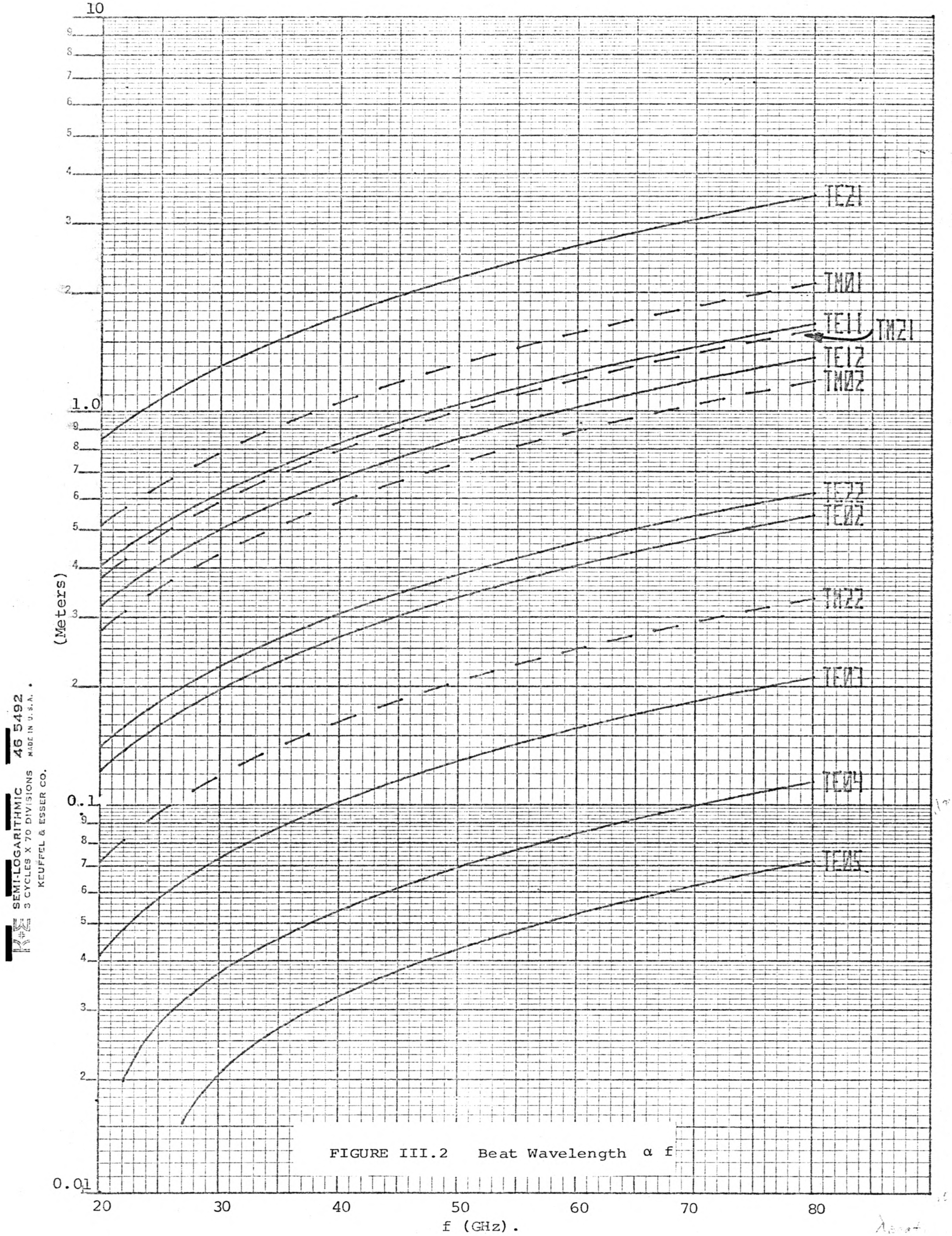


FIGURE III.2 Beat Wavelength α f

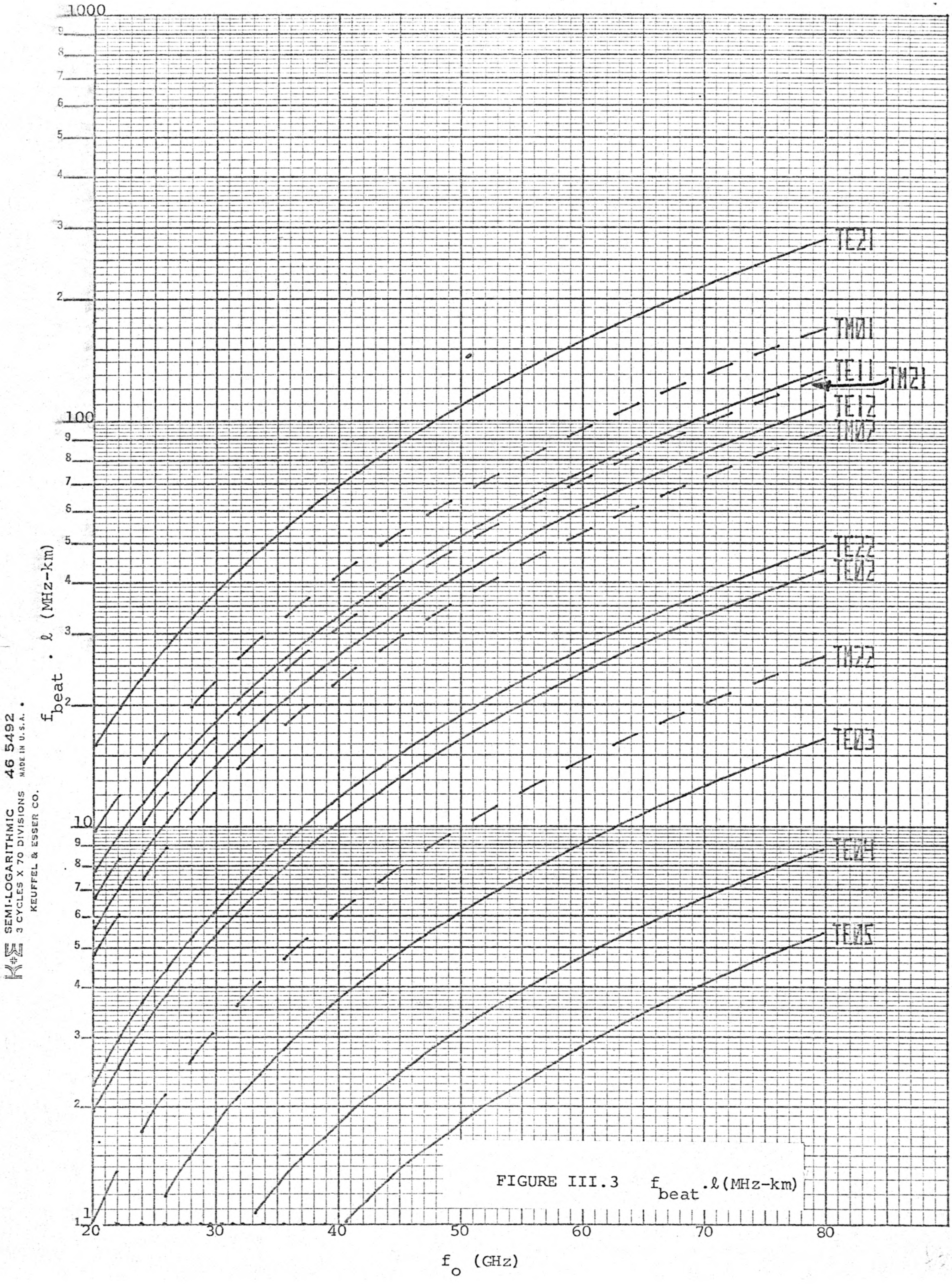


FIGURE III.3 $f_{beat} \cdot \ell$ (MHz-km)

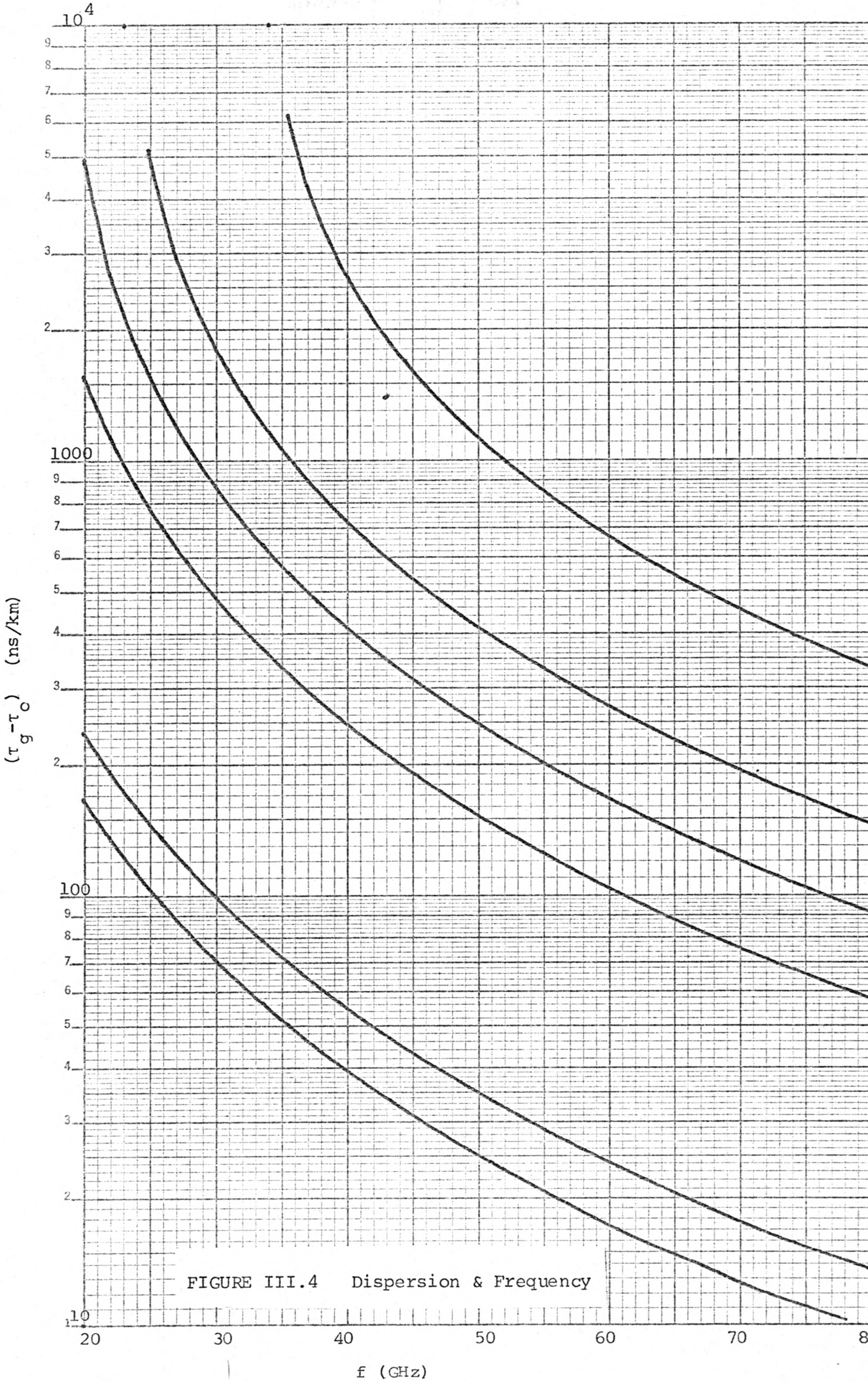


FIGURE III.4 Dispersion & Frequency

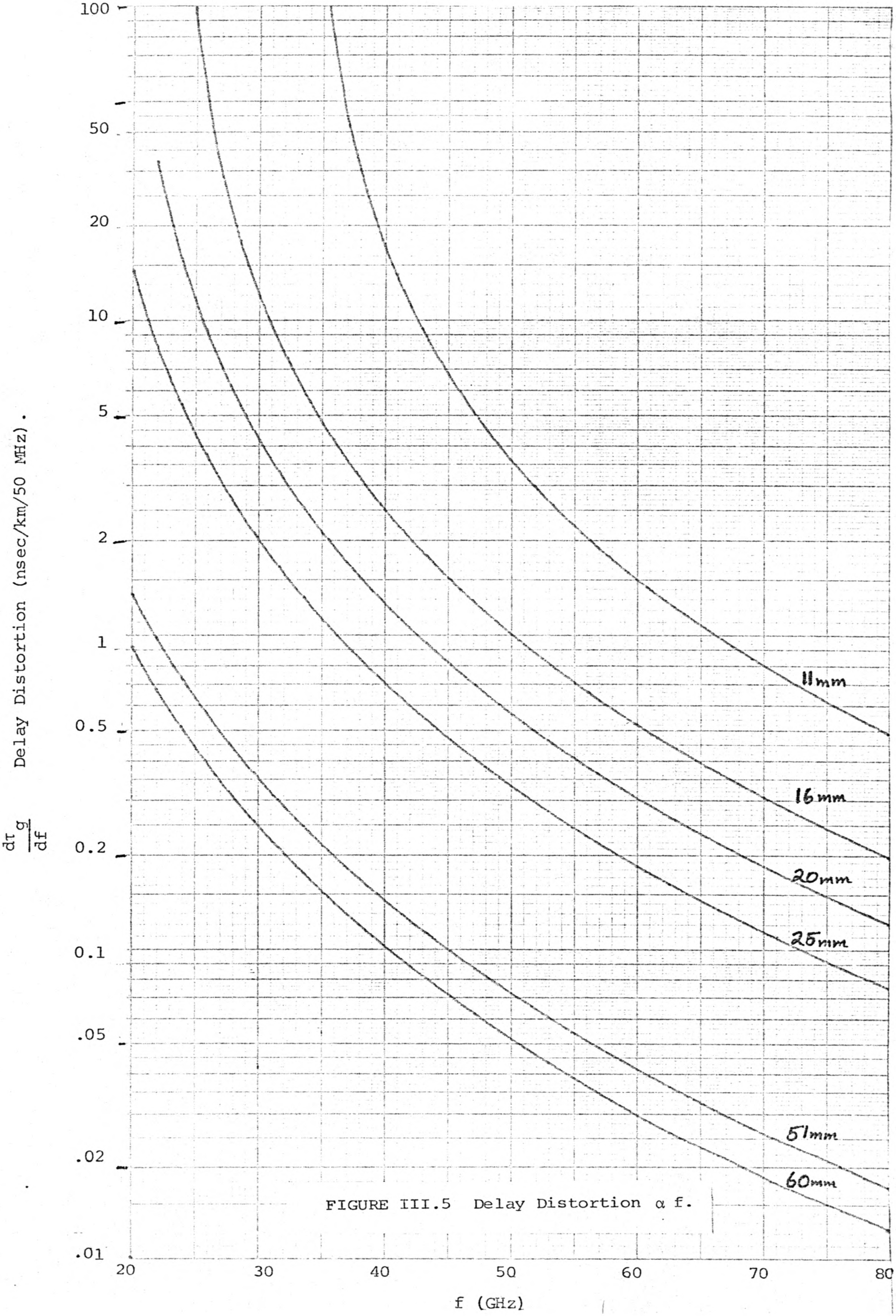


FIGURE III.5 Delay Distortion α f.

ADDENDUM TO VLA ELECTRONICS MEMO #120

NATIONAL RADIO ASTRONOMY OBSERVATORY

LOSS AND COUPLING VALUES IN THE VLA TRANSMISSION SYSTEM

Read Predmore

August 8, 1974

The revised antenna configuration of April, 1974 and the advantages of coupling directly from rectangular waveguide to 60 mm diameter circular waveguide have improved the loss budget for the waveguide transmission system.

1. Loss Budget

The figures in Table I are an estimate for the various losses in the waveguide transmission system for a best, typical and worst case. These have been derived from component specifications, and waveguide and waveguide component measurements. The three cases allow use to evaluate the effect each block in the waveguide transmission system has on the overall performance. The following section gives the revised coupler values for the Chow arrays with a factor of 3.285, which only require 24 stations for the four VLA configurations.

2. Antenna Couplers

It should be possible to decrease the total 60 mm waveguide and antenna coupler loss to less than 32 dB while leaving couplers at all antenna stations. This can be achieved because the total number of antenna stations has been decreased from 40 to 24 on each arm and since the insertion loss of a 60 mm diameter coupler should be less than 0.1 dB. Full size (60 mm) couplers can be used at the first fifteen stations where the required coupling is less than -25 dB. The anticipated specifications for this type of coupler are given in Table II.

The remaining nine stations on each arm will consist of tapers to 20 mm diameter circular waveguide and then coupling to rectangular waveguide. The TE_{01} mode in 20 mm circular waveguide has a cutoff frequency (fc = 18.3 GHz) different from the WR-28 (fc = 21.2) and WR-19 (fc = 31.6) rectangular waveguides. The differing phase velocities in the circular and rectangular waveguides can be utilized to make the couplers frequency selective. A periodic coupler or a helical coupler would be a channel dropping filter with strong coupling to one channel and low loss to other channels. This is illustrated in Figure 1 which plots coupling and coupled power insertion loss for a 3 dB coupler for channel 9. The coupler is frequency selective so that only channel 9 has a significant insertion loss.

Thus, the strong couplers required at the outer reaches of the VLA should not degrade the performance of the furthermost station as a broadband strong coupler would.

This data has been used in calculating Tables III and IV which estimate the total waveguide and coupler loss for the north, east and west arms of the VLA.

The quantities in Tables III and IV are:

(a) Station number - K;

(b) Station distance from WYE center in kilometers;

(c) Millimeter channel number for station K;

(d) Channel frequency and loss for that channel;

(e) Total waveguide loss to station K;

(f) Coupler insertion loss to station K;

(g) Required coupling from main line (60 mm) to antenna waveguide system (20 mm);

(h) Total waveguide and coupler loss.

It is anticipated that the loss from the control building to each station will by only 30 dB on the north arm and 31 dB on the east and west arms.

TABLE I

		Best Case	Typical Case	Worst Case
(1)	UP Converted Power/50 MHz	-3 dBm	-6 dBm	-9 dBm
(2)	Loss in Antenna WG System (Including Matching Pads)	-12 dB	-13 dB	-14 dB
(3)	Loss in Coupler and WG	-30 dB	-31 dB	-32 dB
(4)	Loss in Signal Distribution System	-8 dB	-9 dB	-10 dB
(5)	Matching Pads In Control Building	-3 dB	-3 dB	0 dB
(6)	Signal Received/50 MHz	-56 dBm	-62 dBm	-65 dBm
	Receiver Noise Figure	13 dB	15 dB	16 dB
	Noise Power/50 MHz (kTB + Noise Figure)	-84 dBm	-82 dBm	-81 dBm
	Final Signal to Noise	28 dB	20 dB	16 dBm

TABLE II

60 mm Coupler

Requirement	Specification	Present Results
TE_{01}° Insertion Loss	<0.1 dB	<.05 dB
TE_{01}° Return Loss	> 50 dB	> 50 dB
TE_{01}° - $TE_{10}^{\square}$ Coupling	<-25 dB	<-28 dB
Variation in Coupling Over a 1 GHz Band	< 1 dB	3 dB
Coupler Directivity	> 20 dB	> 20 dB
$TE_{10}^{\square}$ Return Loss	> 30 dB	> 20 dB
TE_{0n}° Mode Discrimination	> 20 dB	Not Known

TABLE III

EAST OR WEST ARM.

STATION #	POSITION (KM)	CHANNEL #	FREQ:LOSS GHZ:DB/KM	WG LOSS (DB)	COUPLER LOSS (DB)	ANTENNA COUPLING (DB)	TOTAL LOSS (DB)
1	-0.080*	3	32.7: 2.00	-1.9	0.0	-29.0	-30.9
2	0.045	4	35.1: 1.80	-2.1	-0.1	-29.0	-31.2
3	0.090	7	42.3: 1.40	-1.9	-0.2	-29.0	-31.1
4	0.147	6	39.9: 1.50	-2.0	-0.3	-28.0	-30.3
5	0.216	8	44.7: 1.30	-2.0	-0.4	-28.0	-30.4
6	0.295	5	37.5: 1.65	-2.4	-0.5	-28.0	-30.9
7	0.385	9	47.1: 1.25	-2.2	-0.6	-28.0	-30.8
8	0.484	2	30.3: 2.25	-3.3	-0.7	-26.0	-30.0
9	0.592	10	49.5: 1.15	-2.3	-0.8	-27.0	-30.1
10	0.710	8	44.7: 1.30	-2.6	-0.9	-27.0	-30.5
11	0.971	7	42.3: 1.40	-3.1	-1.0	-26.0	-30.1
12	1.264	9	47.1: 1.25	-3.3	-1.1	-26.0	-30.4
13	1.590	3	32.7: 2.00	-5.3	-1.2	-24.0	-30.5
14	1.946	10	49.5: 1.15	-3.9	-1.5	-25.0	-30.4
15	2.332	8	44.7: 1.30	-4.7	-1.6	-24.0	-30.3
16	3.188	4	35.1: 1.80	-7.7	-1.9	-21.0	-30.6
17	4.153	9	47.1: 1.25	-6.9	-2.2	-21.0	-30.1
18	5.223	5	37.5: 1.65	-10.5	-2.5	-17.0	-30.0
19	6.393	10	49.5: 1.15	-9.0	-3.0	-18.0	-30.0
20	7.659	6	39.9: 1.50	-13.3	-3.5	-13.0	-29.8
21	10.473	7	42.3: 1.40	-16.4	-4.0	-10.0	-30.4
22	13.644	8	44.7: 1.30	-19.5	-4.5	-6.0	-30.0
23	17.157	9	47.1: 1.25	-23.1	-5.0	-3.0	-31.1
24	21.000	10	49.5: 1.15	-25.8	-5.5	-0.1	-31.4

*Station #1 is south of the WYE center on the extension of the north arm.

NORTH ARM.

TABLE IV

STATION #	POSITION (KM)	CHANNEL #	FREQ:LOSS GHZ:DB/KM	WG LOSS (DB)	COUPLER LOSS (DB)	ANTENNA COUPLING (DB)	TOTAL LOSS (DB)
1	0.000	3	32.7: 2.00	-2.1	0.0	-27.0	-29.1
2	0.055	4	35.1: 1.80	-2.1	-0.1	-27.0	-29.2
3	0.095	7	42.3: 1.40	-1.9	-0.2	-27.0	-29.1
4	0.135	6	39.9: 1.50	-2.0	-0.3	-27.0	-29.3
5	0.195	8	44.7: 1.30	-2.0	-0.4	-27.0	-29.4
6	0.266	5	37.5: 1.65	-2.3	-0.5	-27.0	-29.8
7	0.347	9	47.1: 1.25	-2.1	-0.6	-27.0	-29.7
8	0.436	2	30.3: 2.25	-3.2	-0.7	-26.0	-29.9
9	0.534	10	49.5: 1.15	-2.2	-0.8	-27.0	-30.0
10	0.640	8	44.7: 1.30	-2.5	-0.9	-26.0	-29.4
11	0.875	7	42.3: 1.40	-3.0	-1.0	-26.0	-30.0
12	1.140	9	47.1: 1.25	-3.1	-1.1	-25.0	-29.2
13	1.434	3	32.7: 2.00	-5.0	-1.2	-24.0	-30.2
14	1.755	10	49.5: 1.15	-3.7	-1.5	-25.0	-30.2
15	2.102	8	44.7: 1.30	-4.4	-1.6	-24.0	-30.0
16	2.875	4	35.1: 1.80	-7.2	-1.9	-20.0	-29.1
17	3.745	9	47.1: 1.25	-6.4	-2.2	-21.0	-29.6
18	4.709	5	37.5: 1.65	-9.7	-2.5	-17.0	-29.2
19	5.764	10	49.5: 1.15	-8.3	-3.0	-19.0	-30.3
20	6.906	6	39.9: 1.50	-12.2	-3.5	-14.0	-29.7
21	9.443	7	42.3: 1.40	-15.0	-4.0	-11.0	-30.0
22	12.302	8	44.7: 1.30	-17.7	-4.5	-7.0	-29.2
23	15.470	9	47.1: 1.25	-21.0	-5.0	-3.0	-29.0
24	18.935	10	49.5: 1.15	-23.4	-5.5	-0.1	-29.0

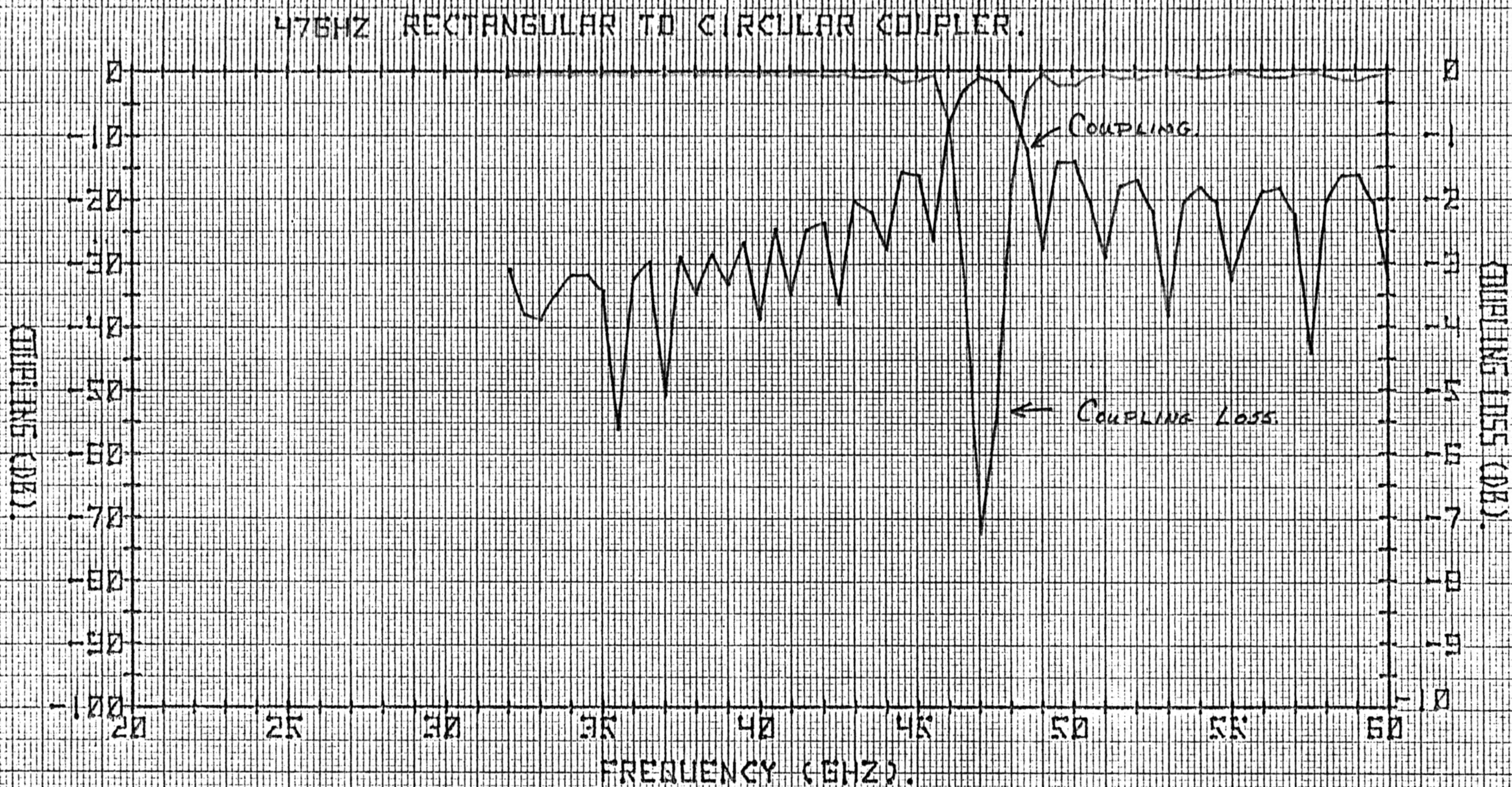


FIGURE 1

COUPLING AND COUPLING LOSS FOR 20 mm COUPLER