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EVALUATION OF COMMERCIAL TRAVELING WAVE TUBES FOR APPLICATION IN DIRECT RF TO RF TRANSPONDERS

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I. Clay Prillaman
Communications Satellite Research Branch

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ABSTRACT

A traveling wave tube (TWT) finds application in communication satellite transponders where it is used to simultaneously amplify many signals over a broad spectral range. In this respect a study program was undertaken to investigate the feasibility of developing a wideband, direct RF to RF conversion transponder that utilized mixing techniques in a re-entrant TWT amplifier loop to effect a 6 to 4 Gc frequency shift. This study was performed under a Communications Supporting Research Task entitled, "Direct RF to RF Converters for Communication Satellites." In support to this endeavor, several commercially available TWTs were procured and evaluated so as to determine and thoroughly understand tube performance under wideband multi-signal usage. The tubes were designed for "C" band operation and were of the one or two watt output power variety. This report summarizes the evaluations that were made. General tests embracing gain, noise figure, power output, and VSWR were conducted on four different tubes. Additional tests including carrier suppression, intermodulation effects and impedance were conducted on a representative tube. Analyses and data are presented with respect to as many as three carriers. Discussions include relationships of points of intermodulation product interference with respect to carrier power input, and carrier gain suppression dependency on interferring signal frequency. No further studies are being performed with respect to this endeavor.

CONTENTS

EVALUATION OF COMMERCIAL TRAVELING WAVE TUBES

FOR

APPLICATION IN DIRECT RF TO RF TRANSPONDERS

1.0 INTRODUCTION

Traveling wave tubes (TWT), because of their inherent broadband characteristics, are widely used in microwave communications. They have also been successfully employed as the final power stage in the communications transponders of the Relay and Syncom satellites. These satellite transponders receive the communicated microwave signal (usually 6 Gc), down-convert and amplify it at an intermediate frequency (usually 100 Mc) and, finally, up-convert it to a different microwave frequency (usually 4 Gc) for power amplification and retransmission to earth. These transponders are restricted in bandwidth (25 Mc) by virtue of the low frequency intermediate amplification and, therefore, the number of communication channels which can be handled through a satellite are limited. Multi-access, synchronous altitude satellite, as could be used in a world-wide communications network, should have a bandwidth capability of several times that which was demonstrated by the Relay and Syncom satellites. For this reason a program was undertaken to study the feasibility of directly converting from one microwave frequency (6 Gc) to another (4 Gc) without using the low, intermediate frequency amplification.[1,2,3,4,5] This direct Rf to Rf conversion is achievable by using a TWT in the re-entrant mode to effect both conversion and amplification at microwave frequencies. The broadband microwave amplification characteristics of the TWT make it ideally suited for this purpose.

In support of the direct Rf to Rf study program, where a TWT would be used in a re-entrant mode, it was desirable to evaluate several tubes to fully determine and understand exact characteristics and behavior under conditions necessitating many signals being simultaneously amplified over a broad spectral range. Tubes of the "medium power output" variety (1 or 2 watts saturated power output) and with 30 db to 60 db gain were selected and commercially procured from various manufacturers.

General tests of a basic nature, embracing qualities deemed essential for use in a re-entrant mode, were performed on four tubes. These tests include power output, gain, VSWR and noise figure. More detailed tests, including carrier suppression, intermodulation effects and impedance were performed on a representative tube.

This paper gives results of and comments pertaining to these tests.

2.0 TWT COMPARISON

2.1 General

Commercially available TWTs are usually categorized according to certain characteristics; e.g., low noise; low, medium or high power output; 20 db gain, etc; etc.

It has been found that any attempt to repeat manufacturer's test data, furnished with a tube, as part of an evaluation program is only partially successful. This is due to several factors. Specifics of test conditions are not stated (such as termination into complex conjugate impedance or with a perfect 50 ohm load) nor are tolerances usually given for operating voltages. Further, TWTs, by nature, are rather eccentric.

Saturated power output and small signal gain—both as functions of frequency—are usually furnished by the manufacturer. Some manufacturers also furnish gain data at the minimum guaranteed power output. These are usually several db lower than the gain at actual saturation for most of the operating frequency range. Rarely is gain given at saturation.

If utilization of maximum power output is important in TWT applications (as for use in satellites, for example), it would seem equally important to know if sufficient signal were available to achieve saturation. Thus it would be necessary to know at what input level a TWT saturates. Perhaps such information could be obtained from the manufacturer on request. The reason for supplying the gain at some given output less than saturation is, however, not without merit. The nature of TWTs is such as to make difficult the determination in the laboratory of the actual point of saturation. This reason is given by one manufacturer and could well apply to others. (A method for normalization of this point is given in section 2.2). It is felt that a gain at saturation could be given within reasonable tolerances, however.

VSWR and noise figure, if furnished at all, are usually given in very non-specific terms which apply to the whole frequency range (e.g. "VSWR = less than 2.0"). This "Madison Avenue" approach to the less impressive characteristics is not unique with TWT manufacturers but it is, nonetheless, regrettable.

Although tube life tests were not made as part of this evaluation, certainly this is an important consideration for actual satellite applications. The procedure used in turning on a TWT is important to tube life as well as to proper service. Turn-on procedure is not always supplied with the TWT, and sometimes when it is supplied it is incomplete or confusing. The requirement of proper filament warm-up is obvious, to the initiated, but less obvious is the sequence and manner of turning on the high voltages. This frequently spells the difference between getting "on the air" and throwing an overload relay (assuming the helix power supply has overload provisions.)

Another factor affecting tube life but poorly specified–if at all–is the cooling required by the collector. A good rule of thumb would be to find out, before a tube is operated, specifically how much cooling is required and in what manner it should be achieved. Additional criticisms will be offered in the following sections.

The four tubes represented in the test program are designated A, B, C, and D.

The operating range specified by the manufacturer was 4 Gc to 8 Gc for Tubes A, B and C, and 5 to 7 Gc for tube D. Due to the limitations of the signal generators available in the laboratory, a slightly abbreviated 4-7.6 Gc test range was employed.

2.2 Tube Data

Power Output and Gain

It is frequently desirable to achieve maximum power output from electronic devices. This occurs in the TWT at saturation. Any increase of input power beyond saturation will yield a power output which is less than the original saturated level.

The saturated power output and gain at saturation for the four tubes tested are shown in Figures 2-1 and 2-2, respectively (a 50 ohm load, with VSWR less than 1.05, was used for terminating the TWT under test).

The small signal (region of operation where the output power is a linear function of the input power) gain of the TWT is typically 6-10 db greater than the gain at saturation. Small signal gain characteristics are displayed as a function of frequency in Figure 2-3.

It may be noted that the gain curves of Figures 2-1 and 2-2 show a tendency to peak toward the center of the operating spectrum showing a design center (the

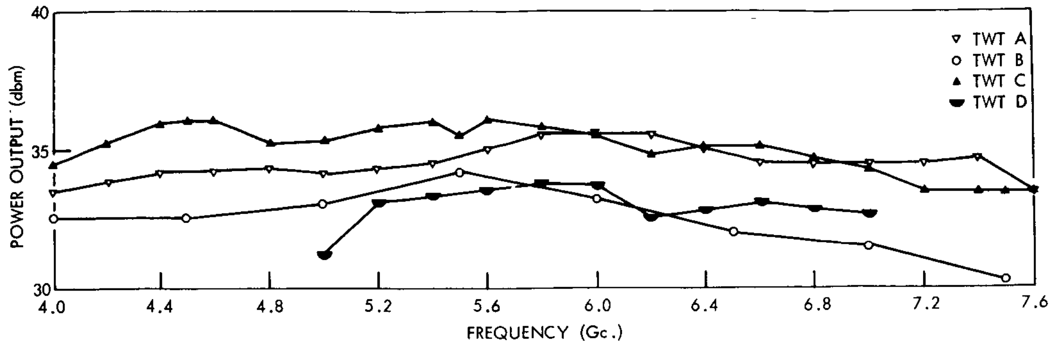

Figure 2-1—Saturated Power Output vs. Frequency

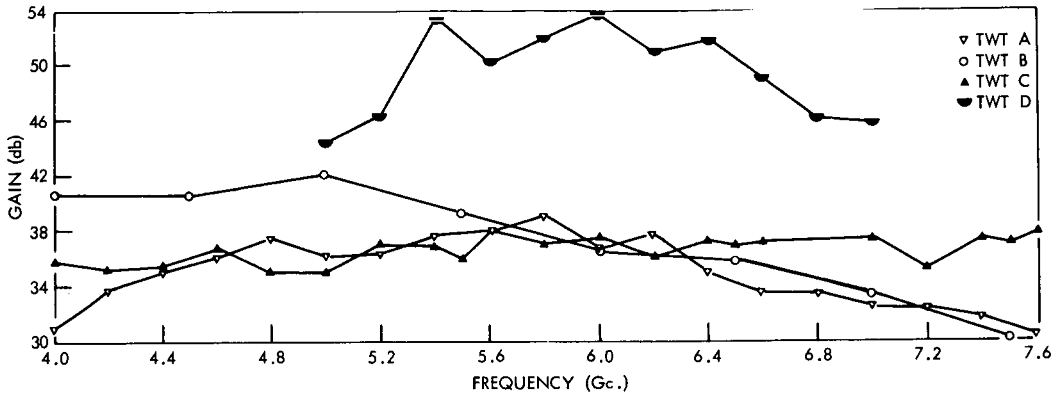

Figure 2-2—Gain at Saturation vs. Frequency

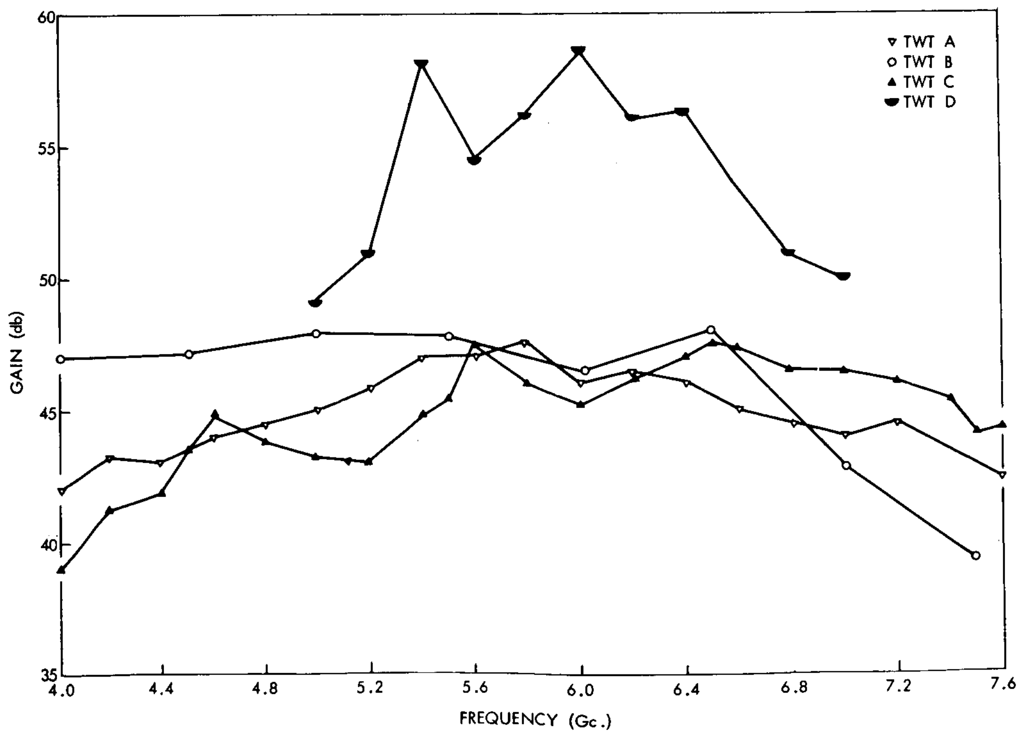

Figure 2-3—Small Signal Gain vs. Frequency

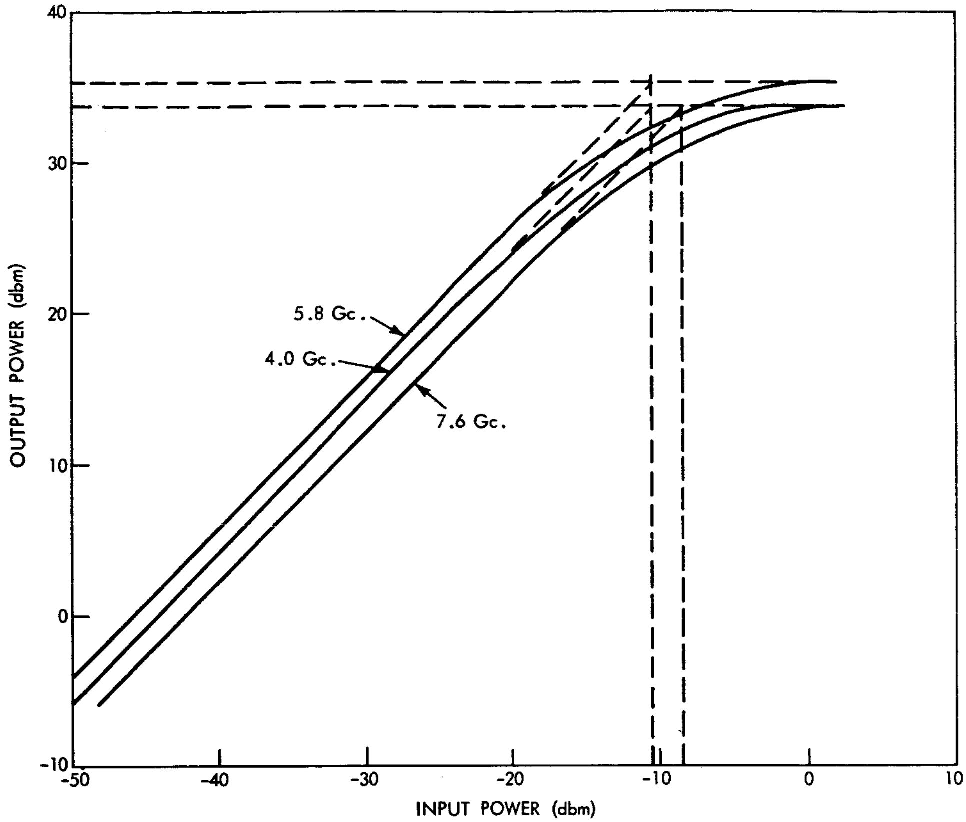

Figure 2-4—Power Output vs. Power Input for TWT A

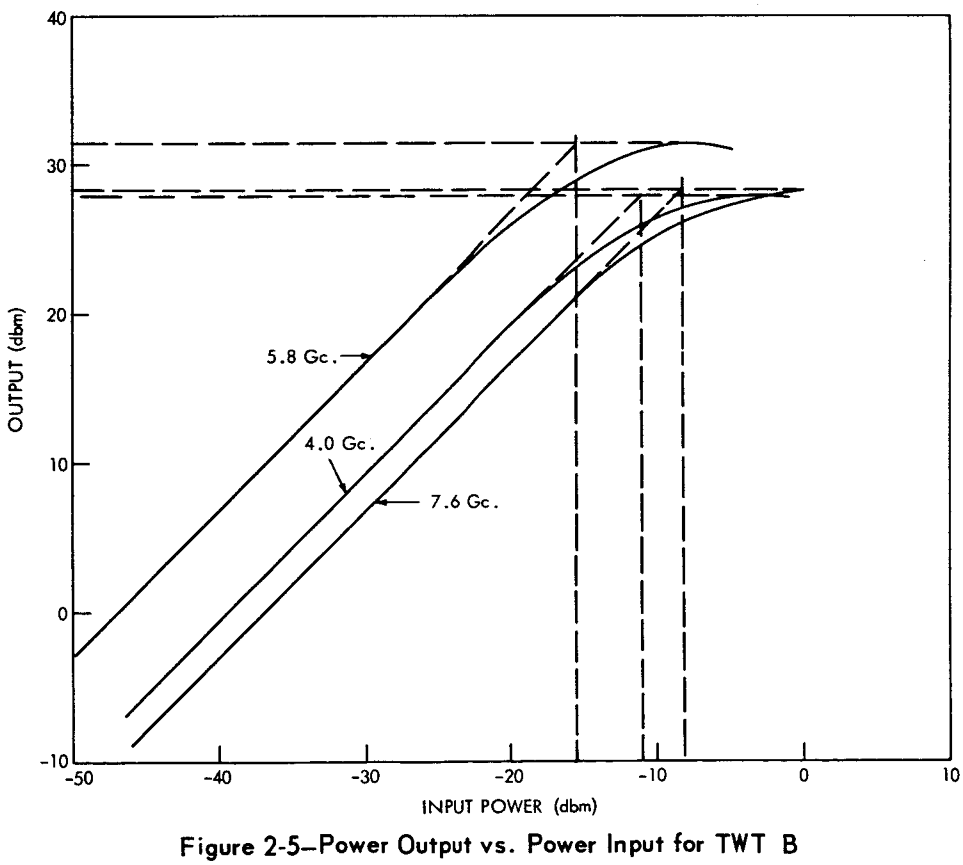

Figure 2-5—Power Output vs. Power Input for TWT B

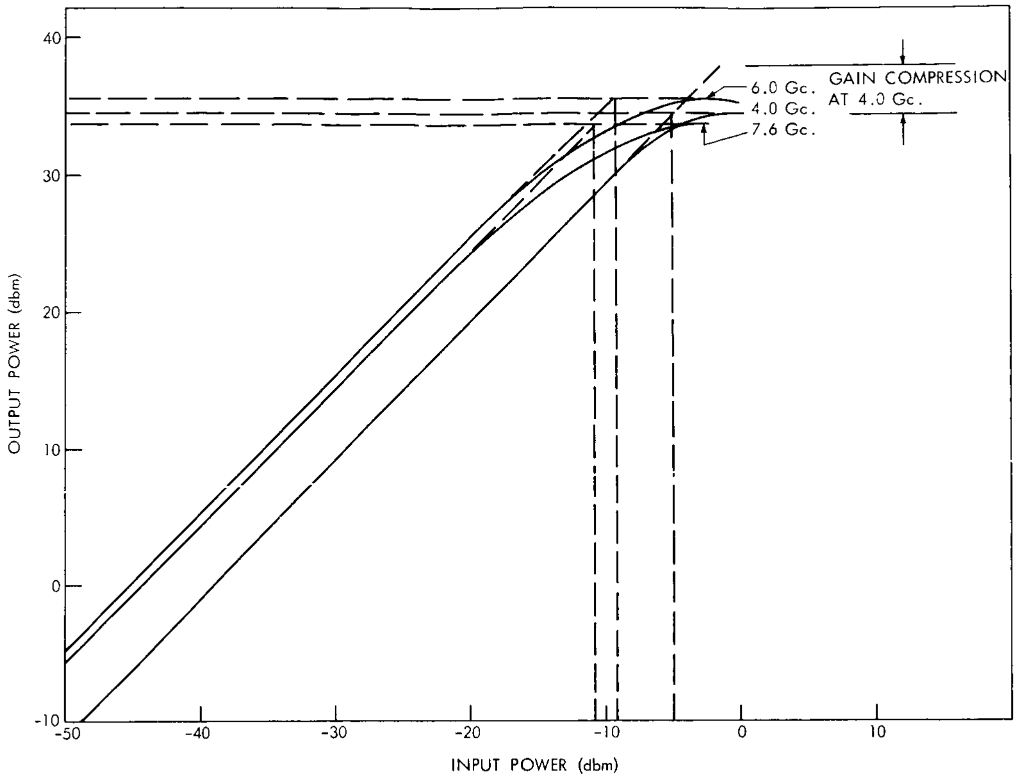

Figure 2-6–Power Output vs. Power Input for TWT C

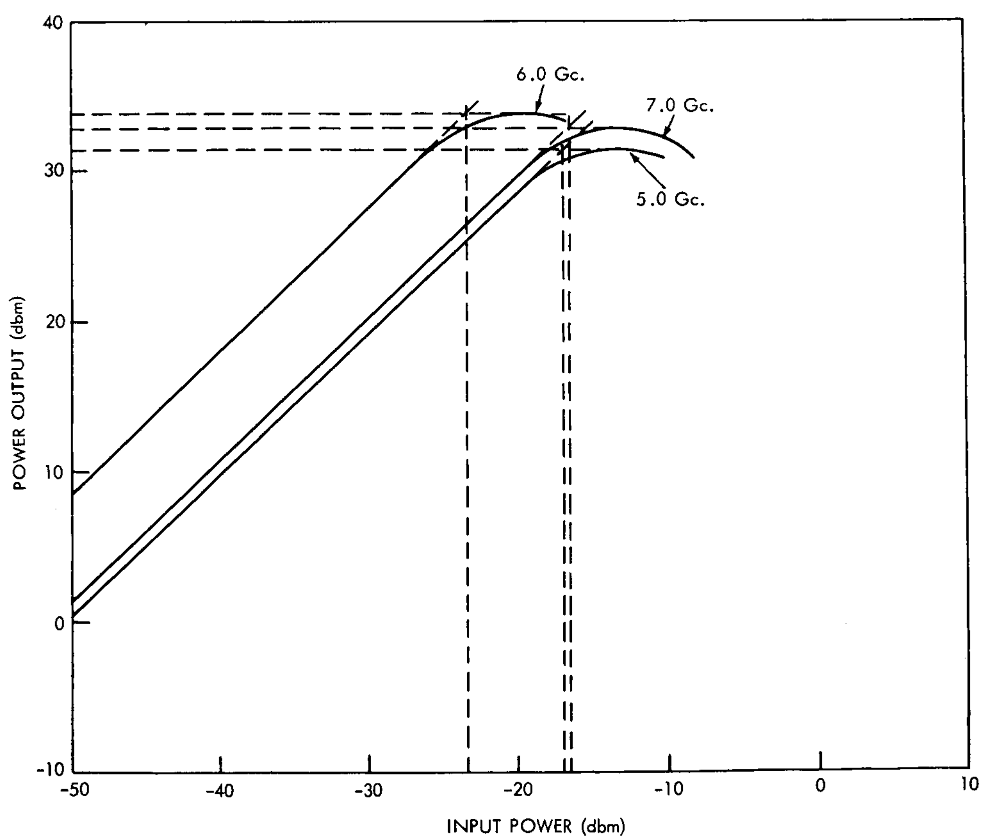

Figure 2-7–Power Output vs. Power Input for TWT D

curves for tube B being an exception). This tendency is characteristic of TWTs. The peaking is rather pronounced on tube D, exhibiting the most variation of gain with frequency of any tube tested. Tube D is not considered typical although it did meet manufacturer's specifications.

The manner in which gain (or P_0) falls off as the TWT input is increased toward saturation is of interest. The slopes of the power output curves vary from frequency to frequency, and from tube to tube. Further, the actual point of saturation is difficult to determine. It is desirable to establish a common reference point. A graphical method of normalizing the input power to such a reference is sometimes employed. This reference point is less than the actual input power required to saturate the tube, at a particular frequency, by an amount equal to the gain compression at that frequency. Unless otherwise specified, 0.0 db will refer to this reference point throughout the rest of this paper, (0.0 db = $P_{in.}/P_{in.\,Normalized}$, expressed in db). The power output curves in Figures 2-4 through 2-7 illustrate the graphical determination of the 0.0 db input reference.

The gain compression at 4.0 Gc is shown at the upper right in Figure 2-6. In this instance the compression is 3.5 db; establishing the normalized input power to saturate at a -5.0 dbm level. (This level will be used in Part 3.0 of this paper).

Tube B exhibited a tendency for the power output and gain to increase several db as the tube warmed up. Usually one hour or more was required before these characteristics approached stability. For this reason the data presented for this tube in Figure 2-5 do not agree with some of the frequencies presented in Figures 2-1 through 2-3. It should be noted that the lower output and gain exhibited after the specified 3 minute warm-up did meet the manufacturer's minimum specification, however.

Table 2-1 compares the small signal gain and saturated power output measured in the laboratory with the same data furnished with the tubes. Perhaps the main advantage of such a table is to show the futility of the effort, in the first place.

VSWR

VSWR is useful to determine the range of power losses, due to mismatch, at the input and output terminals of the TWTs.

It was mentioned earlier that VSWR data are not supplied with the tubes. Presumably the manufacturers do take the data but would rather forget it. A representative of one manufacturer indicated the data was taken for all tubes,

Table 2-1
Measured Data of Four TWTs
(Deviation from Manufacturer Furnished Data)

Frequency (Gc)	TWT A		TWT B		TWT C		TWT D	
	Sat. P_0 (db)	S.S. Gain (db)	Sat. P_0 (db)	S.S. Gain (db)	Sat. P_0 (db)	S.S. Gain (db)	Sat. P_0 (db)	S.S. Gain (db)
4.0	+0.3	-1.0	+4.6	+4.0	+3.7	+2.5	-	-
4.2	-0.7	-0.8	-	-	-	-	-	-
4.4	-0.8	-2.4	-	-	-	-	-	-
4.5	-	-	+3.1	+2.2	+3.0	+2.5	-	-
4.6	-0.8	-0.5	-	-	-	-	-	-
4.8	-0.7	-0.5	-	-	-	-	-	-
5.0	-0.9	0.0	+1.7	+1.5	+2.6	-0.3	+1.9	+5.1
5.2	-1.2	-0.7	-	-	-	-	+2.8	+5.3
5.4	-0.5	+0.5	-	-	-	-	+1.9	+5.5
5.5	-	-	+2.5	+0.3	+1.5	+0.3	-	-
5.6	-1.5	-1.0	-	-	-	-	+0.6	+3.4
5.8	-1.5	+0.6	-	-	-	-	+0.3	+2.0
6.0	-1.0	-1.0	+2.1	-0.6	+1.8	+1.3	-0.8	+3.4
6.2	-1.1	+0.3	-	-	-	-	-1.8	+2.4
6.4	-1.5	+1.5	-	-	-	-	-0.6	+7.5
6.5	-	-	+1.2	+3.2	+1.5	+4.0	-	-
6.6	-1.5	+1.5	-	-	-	-	-0.7	+6.3
6.8	-1.0	+1.5	-	-	-	-	-0.6	+6.5
7.0	-1.5	+1.6	+2.2	+0.8	+1.5	+5.0	-1.7	+6.2
7.2	-1.5	+3.0	-	-	-	-	-	-
7.4	-0.8	+2.0	-	-	-	-	-	-
7.5	-	-	+1.3	-0.8	+1.4	+5.6	-	-

and could be obtained at the customer's request. The data taken by this manufacturer is with the tube not operating, however. Such data may be much better or much worse than that taken under the more realistic operating conditions.

The VSWRs measured at the input terminals of three tubes are shown in Figure 2-8. Output terminal VSWRs for two tubes are shown in Figure 2-9. The output terminal of tube D and both terminals of the tube B were located in such a manner as to preclude measurements without the use of an interconnecting component in the test set-up. Use of any such device would only serve to establish minimum and maximum VSWR and such data would not be directly comparable with the data presented for the other tubes.

Noise Figure

The amount of noise generated in a TWT will establish the lower limits of the input level which may be used. None of the four tubes were of the "low noise" type. This is tantamount to saying a high noise figure is to be expected. Noise figures of 25.0 to 30.0 db are typical of this type tube.

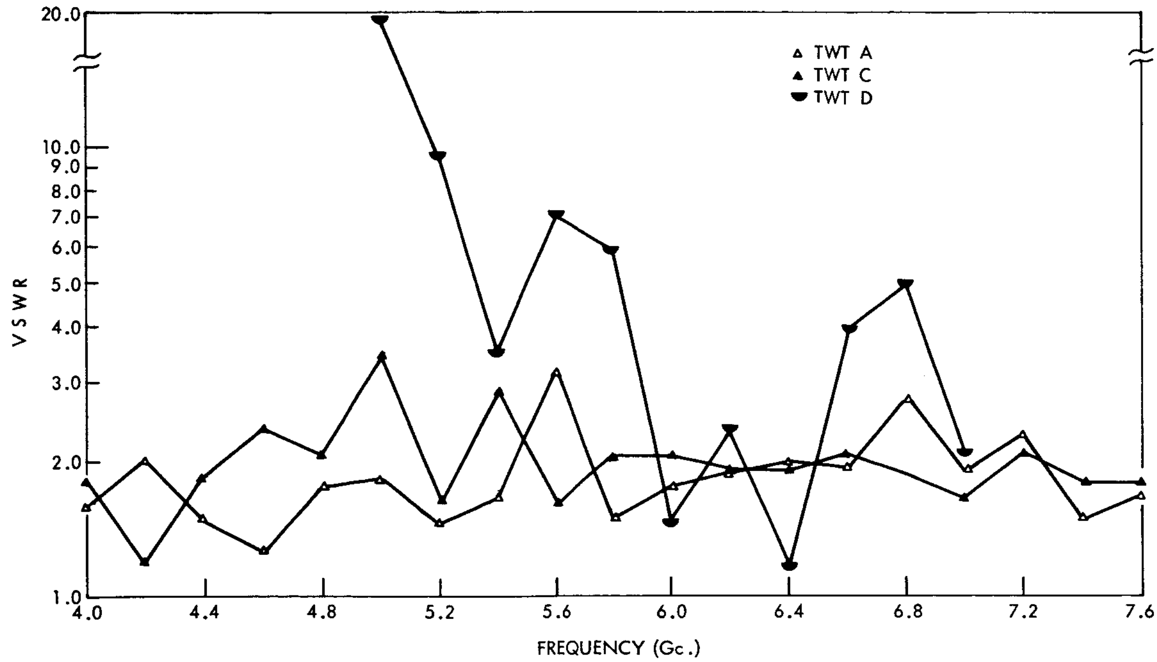

Figure 2-8- Input Terminal VSWR vs. Frequency

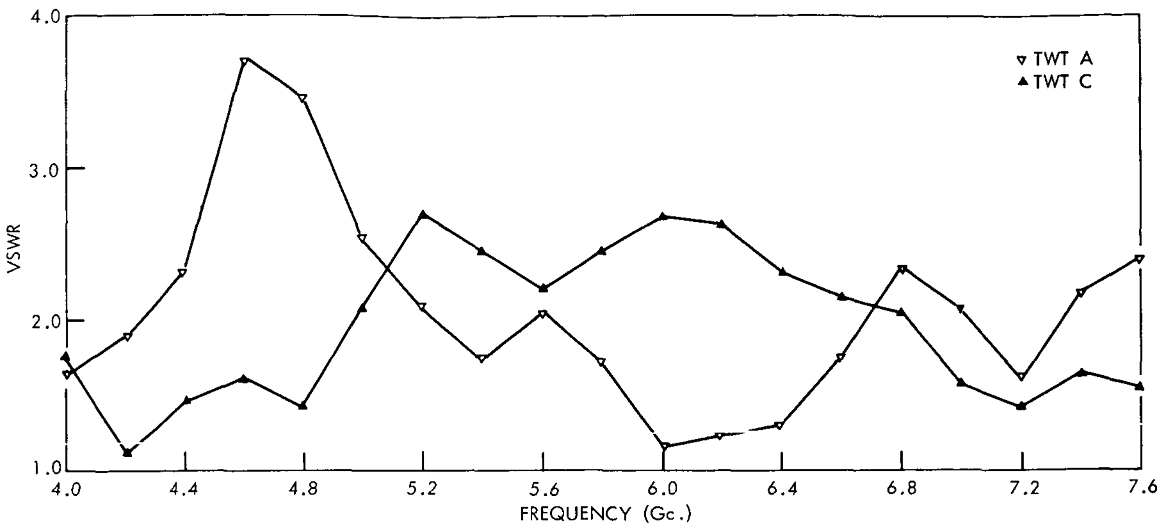

Figure 2-9–Output Terminal VSWR vs. Frequency

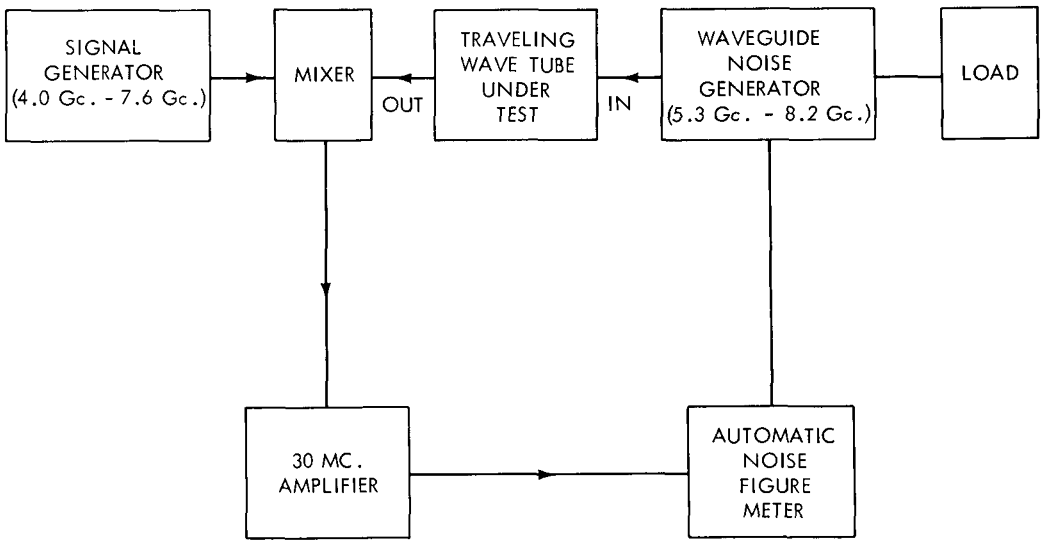

Figure 2-10–Block Diagram of Test Set-Up for Noise Figure Measurements

Table 2-2 shows the noise figure of the tubes measured over a range of 5.4 Gc to 7.6 Gc. (This abbreviated test range was dictated by available noise generators.) The test set-up used for the measurement is shown in the block diagram of Figure 2-10. It would have been desirable to limit the noise bandwidth but no filter was available. Readings of greater than 30.0 db were not ascertainable with the Noise Figure Meter employed.

Table 2-2
Noise Figure (db) of Four Traveling Wave Tubes

Frequency (Gc)	TWT A	TWT B	TWT C	TWT D
5.4	26.5	28.0	>30.0	30.0
5.6	25.0	28.0	29.0	30.0
5.8	> 30.0	29.5	26.0	29.5
6.0	> 30.0	30.0	28.0	>30.0
6.2	25.0	29.5	29.0	30.0
6.4	25.0	29.0	26.5	28.5
6.6	28.0	29.5	30.0	29.5
6.8	25.0	29.5	28.5	28.5
7.0	23.0	30.0	28.5	29.0
7.2	28.5	29.5	28.5	-
7.4	25.0	30.0	29.5	-
7.6	26.5	30.0	29.5	-

A theoretical dynamic range (range of operation from where the signal is just equal to the noise–to the point of saturation) may be established. This range should be considered only typical, of this type TWT. Assume a typical gain of 40 db, with a saturated power output of 33 dbm, and a typical noise figure of 30 db. Further, assume that the bandwidth of operation will be limited to 100 Mc, by a bandpass filter.

-114 dbm/Mc of bandwidth = thermal noise

30 db = N.F.

20 db = 100 Mc referred to 1 Mc

- 64 dbm = equivalent noise generator at the input

40 db = gain of tube

- 24 dbm = output noise level

Thus, such a tube saturating at a level of -5 dbm would have a dynamic range of 59 db.

3.0 EVALUATION OF REPRESENTATIVE TUBE

3.1 General

Selection of one single tube for a more detailed evaluation than that presented in Part 2.0, could be based on two philosophies. Either the tube judged to be of best overall quality or a typical tube could be selected. A study of the graphs in Part 2.0 does not indicate any clear choice between Tube A and Tube C. This fact seems to indicate that both tubes are typical. Tube C was ultimately chosen for further evaluation.

Carrier Suppression and Intermodulation Distortion are the two main additional tests presented in detail for this tube. For satellite application, it is desirable to know how a TWT will behave with multiple signals applied to the input. Results of measurements with more than two signals are not available. Three signals were used with this tube.

It was necessary to choose three frequencies near the low end of the tubes' spectrum because of the availability of signal generators employed in the tests.

The three frequencies that were selected are 4.000 Gc, 4.070 Gc, and 4.175 Gc. Fortunately these frequencies were in the general region that has been assigned for communication satellite transmission back to earth. These frequencies are separated by 70 Mc and 105 Mc, respectively. This separation was chosen to be compatible with the separation used in the TRW Space Technology Laboratories (STL) studies that were conducted in support of the direct Rf to Rf conversion program.[3] The STL frequency separation was used by them in a computer study of the intermodulation products for a 6 carrier system. It should be additionally noted that these three frequencies generate four intermodulation products which fall below the 4.0 Gc lower spectrum limit. However, this is of no consequence since it was found that the gain and power output at the four product frequencies were not degraded.

3.2 Power Output and Gain

The saturated power output and gain for TWT C are shown as functions of frequency in Figure 3-1. These same curves were shown in Figures 2-1 through 2-3, along with the other tubes, but are presented here for easy comparison and study. The gain at 30 dbm output was taken for a comparison with the data furnished by the manufacturer. That comparison was not deemed to be of sufficient worth to be included here. The plot is presented here to show how the gain falls off near saturation at discrete frequencies throughout the operating range.

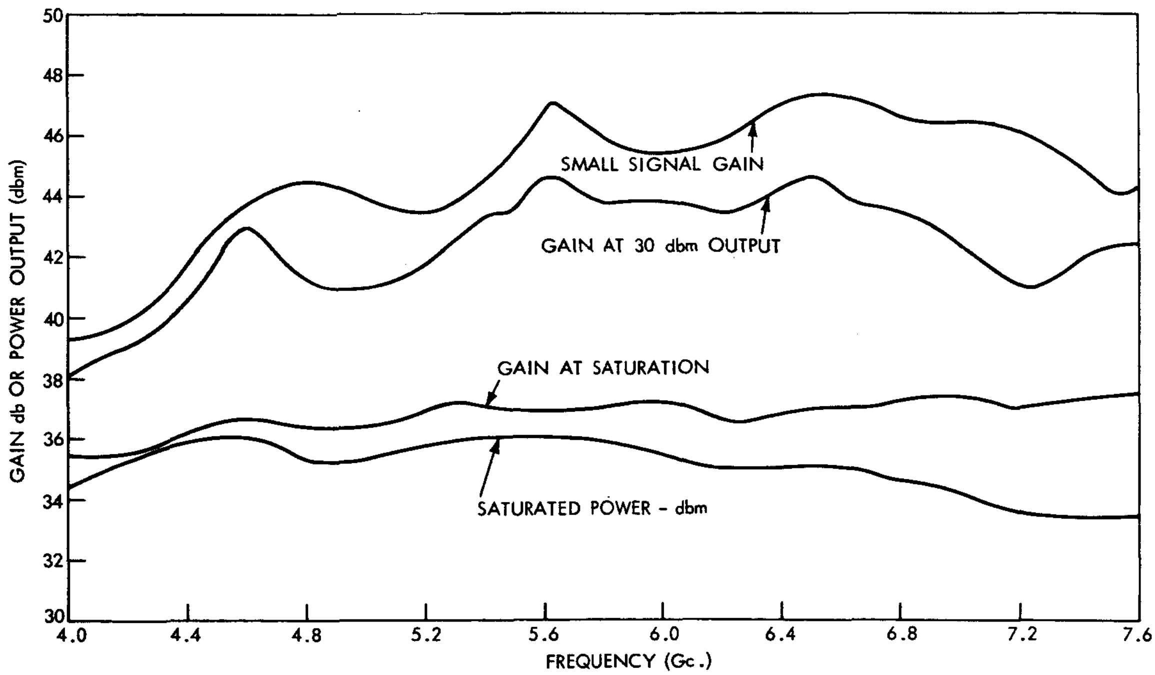

Figure 3-1-Gain and Power Output of TWT C

The saturation power curve seems reasonably constant with frequency, varying ±1.25 db from a mean output of 34.75 dbm. Such a power output variation would, no doubt, be acceptable in a satellite application. Based on this characteristic only, the tube would lend itself to operation anywhere within this frequency range. The gain at saturation shows a slightly flatter frequency response, varying only ±1 db from a mean of 36.5 db.

The power curve for 4.0 Gc is repeated in Figure 3-2 showing the determination of the normalized saturation power input in detail. (The curves for 6.0 Gc and 7.6 Gc, shown in Figure 2-6, will not be repeated here.) This point, -5.0 dbm, is the 0.0 db reference point which is used extensively in sections 3.3 and 3.4. This same reference point is used for F_2 (4.070 Gc) and F_3 (4.175 Gc) since the 0.0 db points for these frequencies were extremely close to that found for F_1 (within 0.2 db).

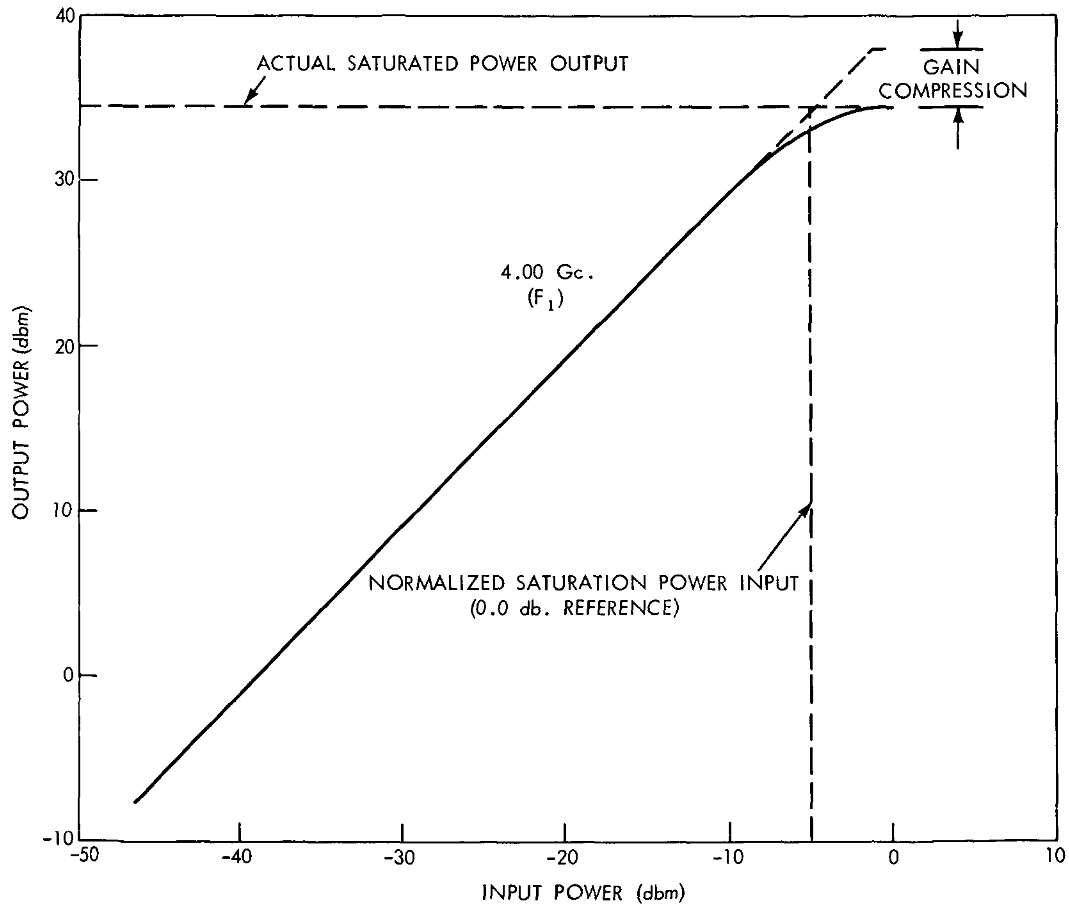

Figure 3-2-Normalization of Saturation for TWT C

3.3 Carrier Suppression

When two or more signals are present at the input of a TWT, the output of any signal will depend upon the magnitude of the other signal input(s), as well as its own input level. It is probably generally known that any one carrier output level will be suppressed by another carrier, if the interfering carrier is of sufficient magnitude.

Certainly, in most satellite applications of the TWT the ability to amplify more than one signal (multiple access) without any deleterious effect on any other signal, would be highly desirable. Carrier Suppression characteristics of the representative tube, TWT C, are therefore presented here in some detail.

It is indicated by Space Technology Laboratories (STL) of Thompson Ramo Woolridge that "the suppression characteristics of a traveling wave tube are produced by the differential efficiency of beam interaction with strong, and weak signals applied simultaneously to the helical slow wave structure of the tube. Thus the gain to the small signal is reduced when applied in the presence of a strong signal of different frequence." [3]

There is no need to confine any discussion to what happens to a "small" signal in presence of a "large" signal since none of the signals may necessarily be small. Hence, in this paper, the problem of what happens to any signal(s) in the presence of another signal(s), will be discussed and appropriate data presented.

For this study, three unmodulated signals (F_1, F_2 and F_3) were fed into tube C, and the output at a single frequency was measured on a spectrum analyzer see Figure 3-12 for a block diagram of the test set-up). The two interfering signals were switched off, each in turn, and the output again observed on the analyzer. The level of each applied signal was then varied in turn while the output of the test frequency was observed. This procedure was then repeated for each of the other two frequencies. (The power meters shown in Figure 3-12 were used for monitoring and calibration.) The lower power input levels were chosen as that input level which presented essentially negligible interference. The upper level was dictated by the available equipment.

Carrier suppression for tube C is plotted in Figures 3-3 through 3-8, inclusive. On each graph the normalized power output of F_3 is shown for a convenient reference.

Figure 3-3 shows the output of F_3 when only F_1 was present as an interfering signal. The power input at F_3 was held constant, at each of the three levels, while the input at F_1 was varied from -15.0 db to +3.5 db. With the input level to F_3 at -15.0 db, no suppression of F_3 is evident until the power input level at F_1 is greater than -12.5 db. As the input level of the interfering carrier, F_1, is increased to 0.0 db, F_3 is suppressed 5.0 db. However, the same 12.5 db increase of F_1 only causes a 3.5 db suppression of F_3—when the input level at F_3 is 0.0 db. The power output at F_3 falls off approximately 3.5 db for a corresponding 3.5 db increase in signal level of the interfering signal, F_1, at each input level of F_3 below 0.0 db.

Figures 3-4 through 3-7 show the suppression F_3, by two interfering carriers. One interfering signal F_2 is held at a constant input level, for each of four levels, respectively, while the input level at the second interfering signal is varied.

These graphs show essentially the same suppression of F_3 output, whether the interfering signal was F_1 or F_2; provided the input levels to F_1 or F_2 were the same for either case. This is true of every input level to F_3. As an example: when the input level at F_2 and F_3 was -15.0 db each (Figure 3-4) and the input at F_1 was 0.0 db, the output level of F_3 was 16.0 dbm. In Figure 3-6, the same 16 dbm output level for F_3 is evident, where the roles of F_1 and F_2 are reversed. (F_2 = 0.0 db and F_1 = 15.0 db).

The additional effect of introducing the second interfering signal is interesting: In Figure 3-4, when the input at F_3 is -15.0 db and F_2 is also present a -15.0 db level, F_3 is suppressed 0.5 db for a -12.5 db input at F_1. (This is compared to 0.0 db suppression with F_2 not present.) For input levels at F_1 larger than -12.5 db, the additional suppression in the presence of F_2 is likewise .5 db. When two signals of equal inputs of -5.0 db, each, interfere with F_3 at a -15.0 db input level, the additional suppression caused by the second signal is 1.5 db (Figure 3-5).

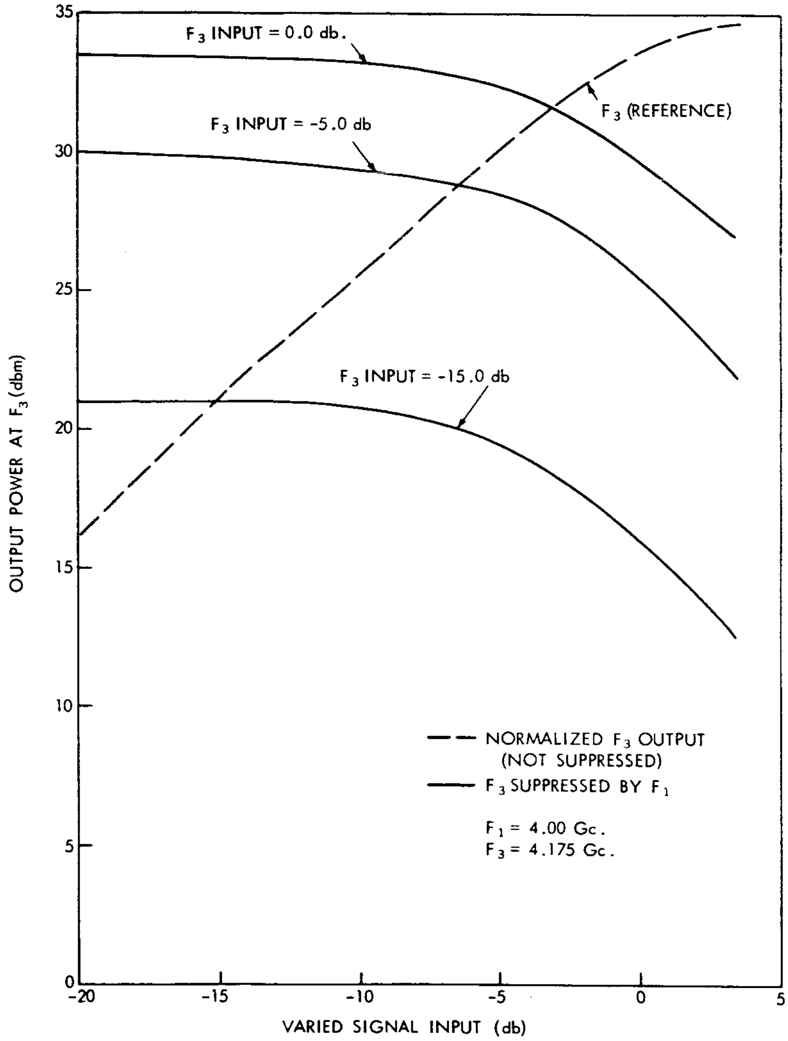

Figure 3-3–Carrier Suppression; TWT C

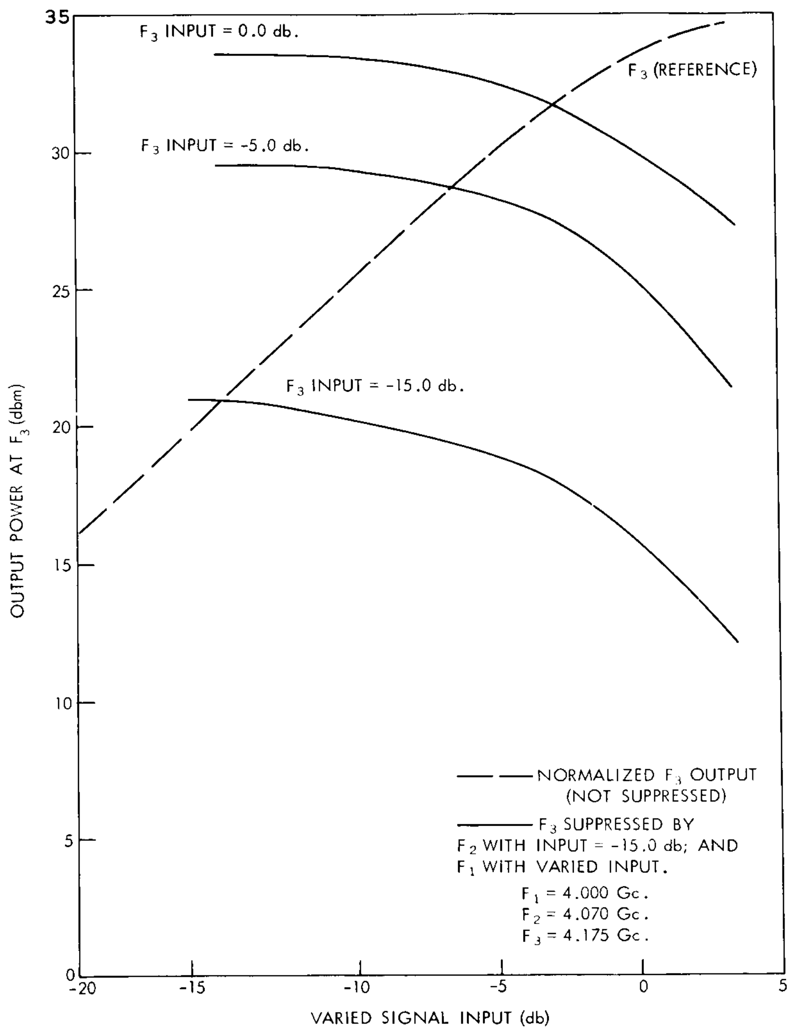

Figure 3-4-Carrier Suppression; TWT C

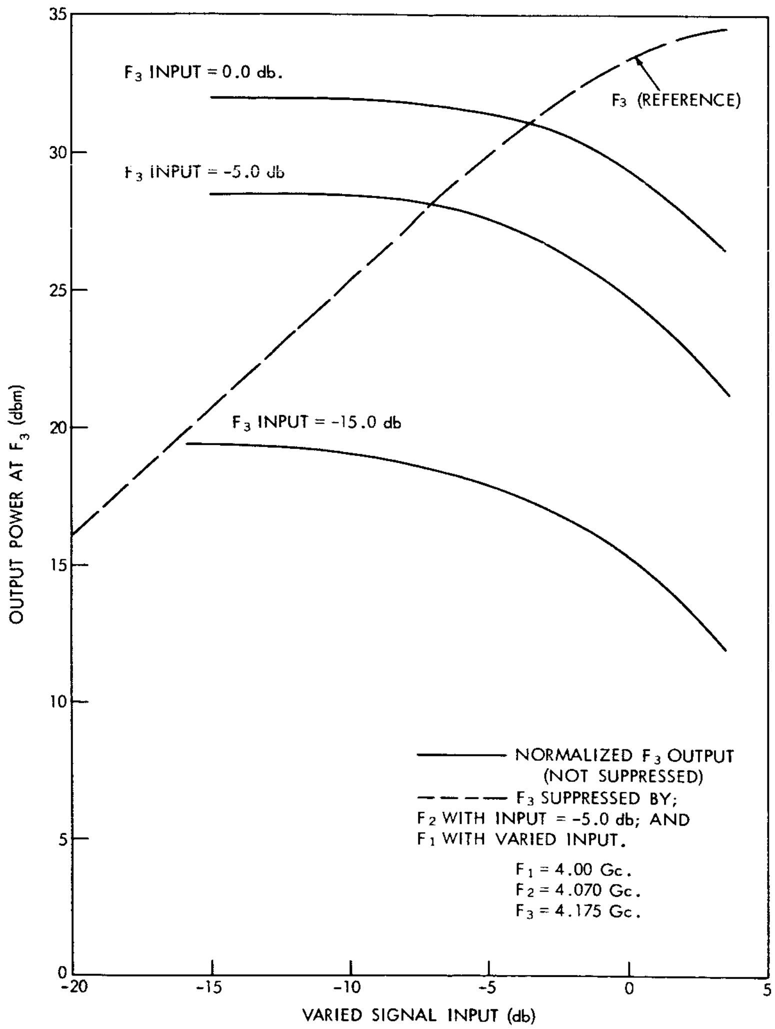

Figure 3-5–Carrier Suppression; TWT C

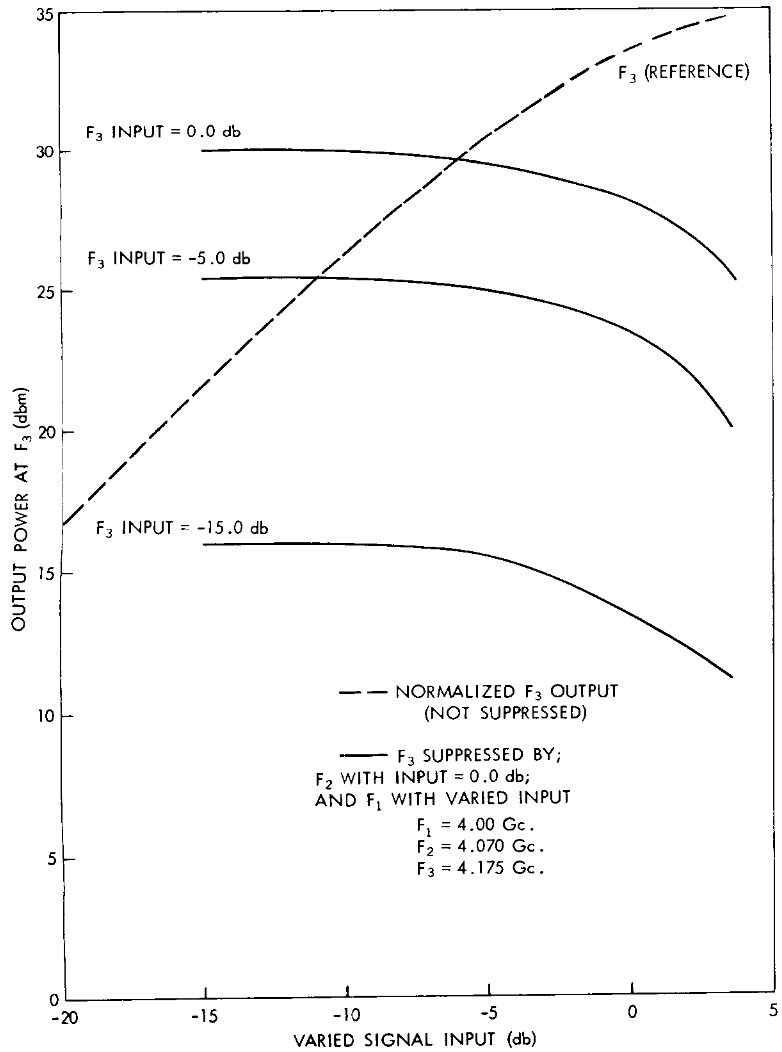

Figure 3-6–Carrier Suppression; TWT C

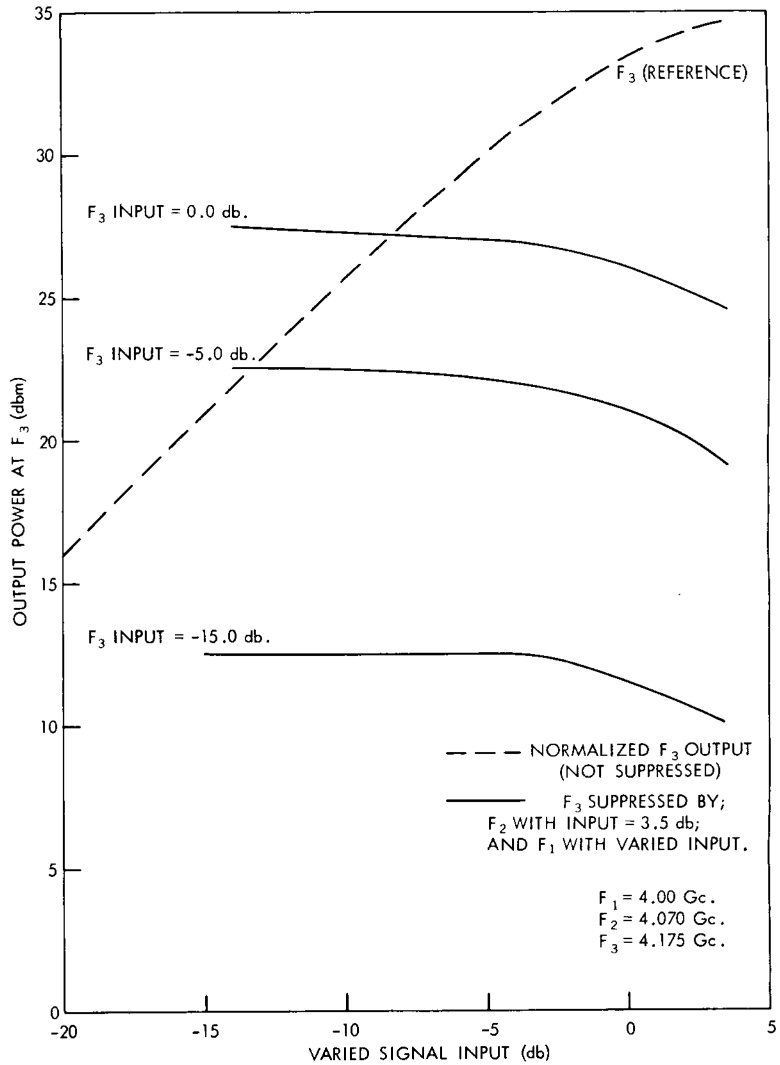

Figure 3-7–Carrier Suppression; TWT C

In this case 1.5 db suppression is caused by each interfering signal, F_1 and F_2. The greatest suppression of F_3 (Figure 3-7) observed is when the input at F_3 is -15.0 db and two interfering signals at a level of +3.5 db each are applied. The F_3 output drops from 21.0 dbm to 10.0 dbm, or a 11.0 db suppression. The output of F_3, with the same input, is suppressed 8.5 db when only one interfering carrier F_1 is present at the +3.5 db level. Thus, at these levels the second interfering signal only causes an additional 2.5 db suppression of the carrier.

Figure 3-8 compares the output of F_3–not suppressed, suppressed by F_1 only, and suppressed by F_1 and F_2 –all signals, when present, have the same level input. As already noted above, the maximum suppression was not achieved at these power levels but the graph shows a quick comparison for applications where all signal levels are the same (application of equal signals, multiple access to a TWT in a synchronous altitude satellite).

Within the realm of carrier suppression, particularly with respect to frequency dependency, it seems to be generally accepted throughout the TWT trade that the gain of a carrier is degraded more by an interfering signal of lower frequency than by one of higher frequency of the same input level. [6,3] The limited test results presented here have not corroborated this to any significant degree. Figure 3-9 affords a display wherein the roles of F_1 and F_3 are interchanged. The dashed-line curves are the unsuppressed outputs of F_1 and F_3, shown for reference, from which it can be seen that the gain at F_1 is 1 db more than at F_3 for all levels of input power lower than -5.0 db; while the gain is the same for both frequencies at input levels of 0.0 db and above.

The solid-line curves show the suppressed outputs of F_1 and F_3 when first F_1 is held at constant power levels and F_3 is the varied interfering signal, and then, F_3 is held at the same constant levels while varying F_1. From these it can be seen that with the input held constant at -15.0 db F_3 is suppressed 1.5 db by the lower frequency F_1 when F_1 is increased from -15.0 db to a -5.0 db level. F_1 output is suppressed by an equal amount for the same change in F_3 when the roles are reversed, which according to the concept should be suppressed a lesser amount. Continuing this same case, the F_3 output is suppressed an additional 3.5 db when the interfering F_1 input is further increased to 0.0 db and, when the roles are reversed, F_1 is suppressed only an additional 3.0 db for an interfering F_3 increase to 0.0 db; this does support the concept. Thus, for this particular case of test, at the -15.0 db constant input level for the chosen carrier (F_3), the output of the carrier was suppressed a total of 5.0 db when a lower interfering frequency (F_1) was varied from a -15.0 db to a 0.0 db input level compared to a total 4.5 db suppression when the lower frequency served as the carrier and was interferred with by the higher frequency. In general, this case corroborates the concept. On the other hand, for a test case where the input carrier was held

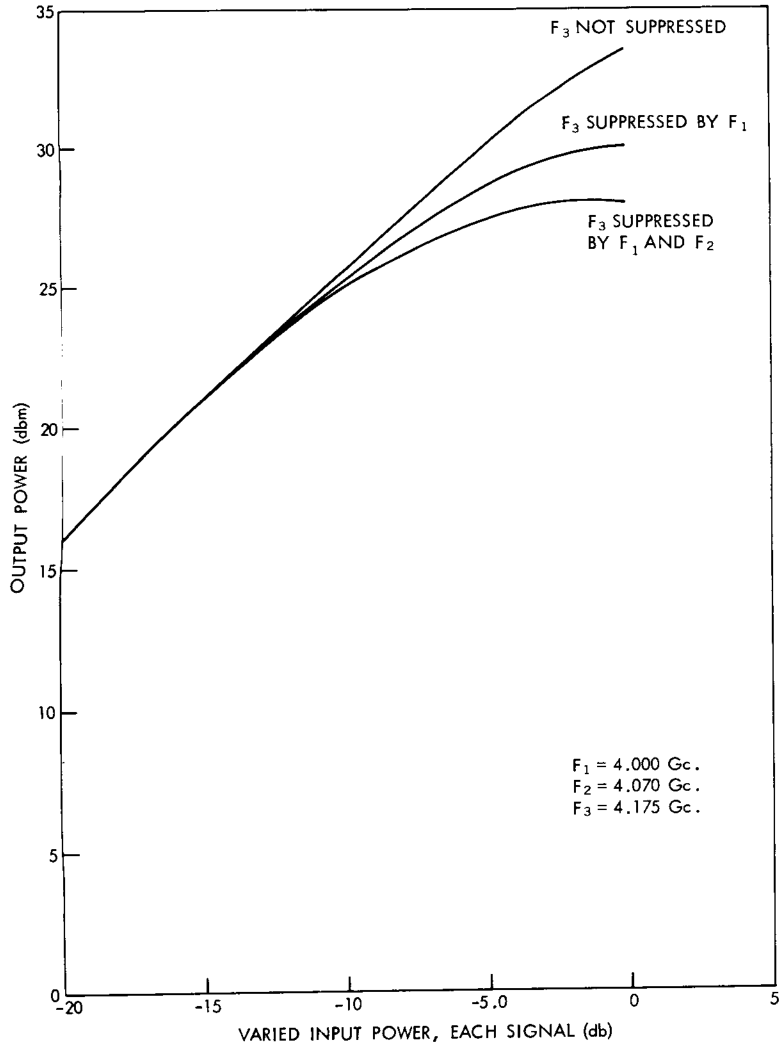

Figure 3-8-Carrier Suppression; TWT C

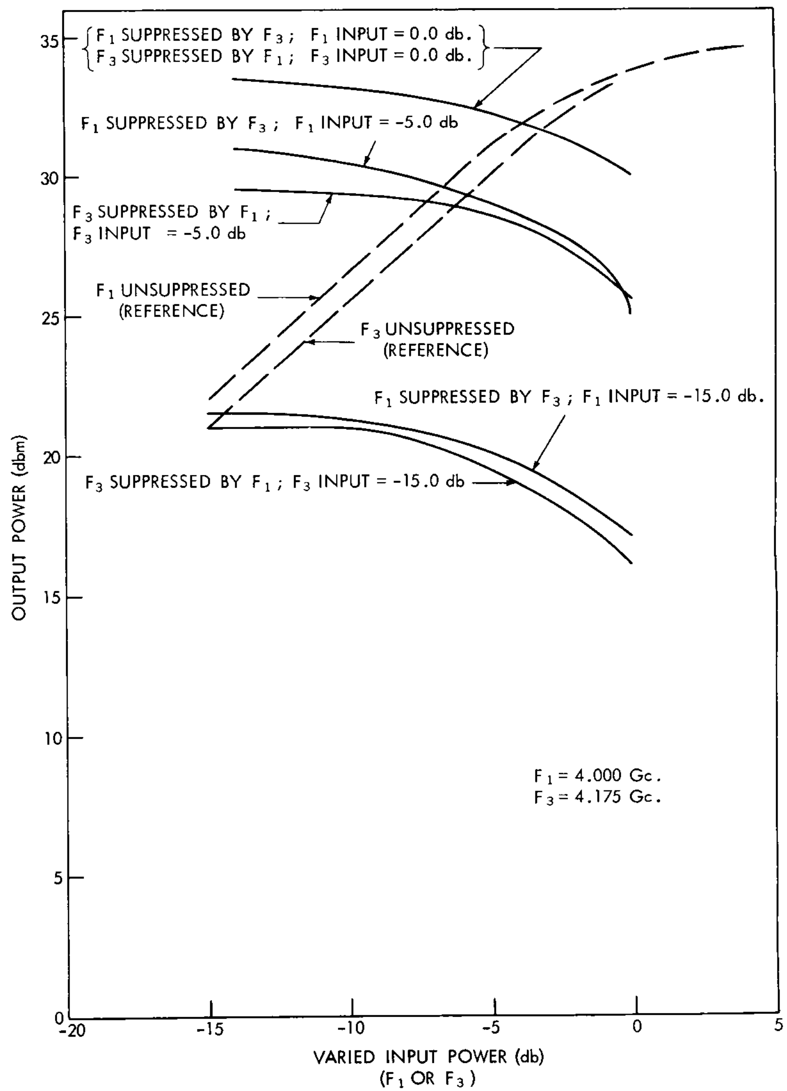

Figure 3-9-Carrier Suppression; TWT C

constant at a -5.0 db level, it was found that when the lower frequency F_1 served as the carrier it was suppressed more by the higher interfering frequency F_3 than when their roles were reversed. This is contrary to the accepted interference concept. Finally, in a third case where the input carrier was held constant at a 0.0 db level, there were no noticeable differences in the amounts of suppression for interchanging the roles of the higher F_3 and lower F_1 frequencies as the carrier and interfering signals, respectively. Consequently, based on the tests that were made, one is only able to conclude that the gain of a carrier may or may not be degraded more by an interfering signal of lower frequency. Such differences as have been discussed here seem to be within an allowable margin of error, in any event.

Carrier suppression frequency dependency has been noted by STL in their study that was performed for Goddard with respect to a communications satellite transponder. Several curves showing the gain suppression of two different traveling wave tubes are presented in the concluding report[3] of this effort. These two referenced tubes were tested for usability as intermediate transponder amplifiers. A reproduction of these gain characteristics is presented in Figures 3-10 and 3-11.

In Figure 3-10 the 6.0 Gc signal, with input at -31 dbm, (which is about 10 db lower input than normalized saturation) is suppressed 7 db by the lower frequency 4.0 Gc signal at an input level of 0.0 db. The 4.0 Gc signal, with input also at -31 dbm (also 10 db below normalized saturation), is suppressed about 0.8 db by the higher frequency 6.0 Gc at an input level of 0.0 db. This shows a definite tendency to support the frequency dependency concept. On the other hand, the characteristics of the other tube shown in Figure 3-11 are somewhat different. Here the 6.0 Gc signal with -30 dbm input (14 db below normalized saturation) is only suppressed about 1.5 db by the lower frequency, 4.0 Gc signal, with input at 0.0 db. The 4.0 Gc signal, with input level at -31 dbm (11 db below normalized saturation) is suppressed about 1.0 db by the higher frequency, 6.0 Gc signal, with an input level of 0.0 db. This also tends to support the concept, but to a questionable degree by virtue of the small difference in suppression. Also in Figure 3-11, there is negligible difference between either the suppression of a 4.6 Gc carrier or a 6.0 Gc carrier—when suppressed by a 4.0 Gc interfering signal—when the input levels to the suppressed carriers are -50 dbm, each. This does not add to the support of the concept.

In view of the fact that the STL data and the data on TWT C are random in nature, one can only conclude that the suppression of a carrier seems to be more a function of the individual TWT (eccentricities) than of the frequency separation, or of whether the suppressing signal is higher or lower in frequency. Further substantiation is supported by limited test data that were also taken on a TWT of

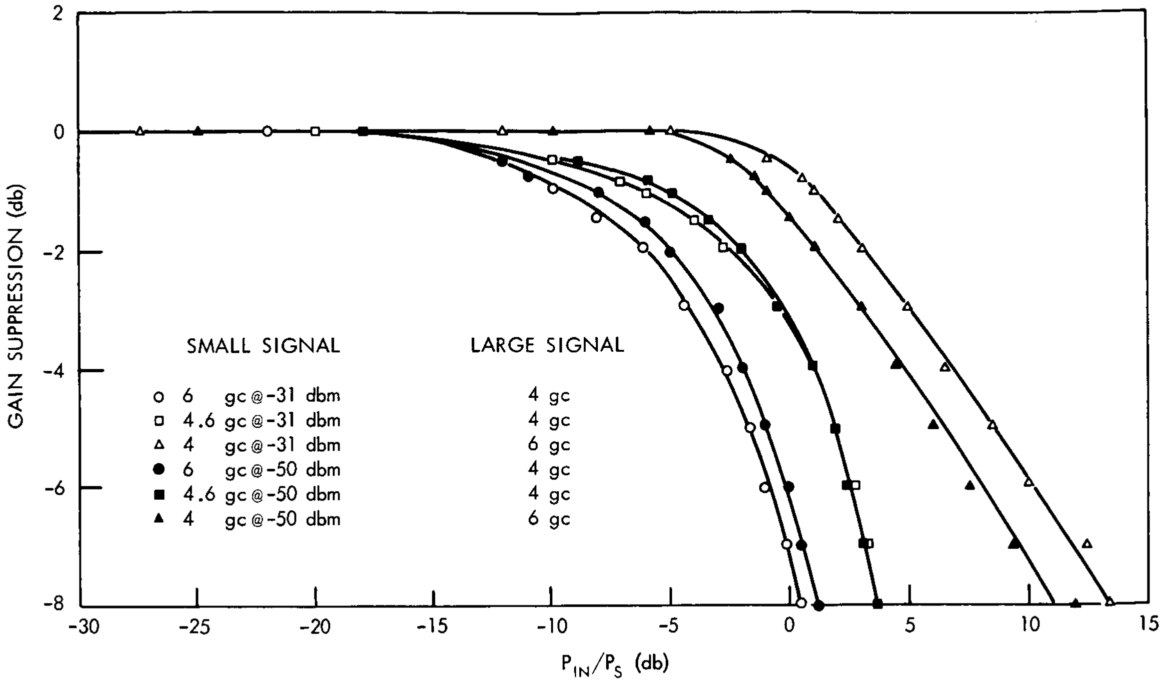

Figure 3-10–Gain Suppression Characteristics TWT - MEC M-5184, S/N 100

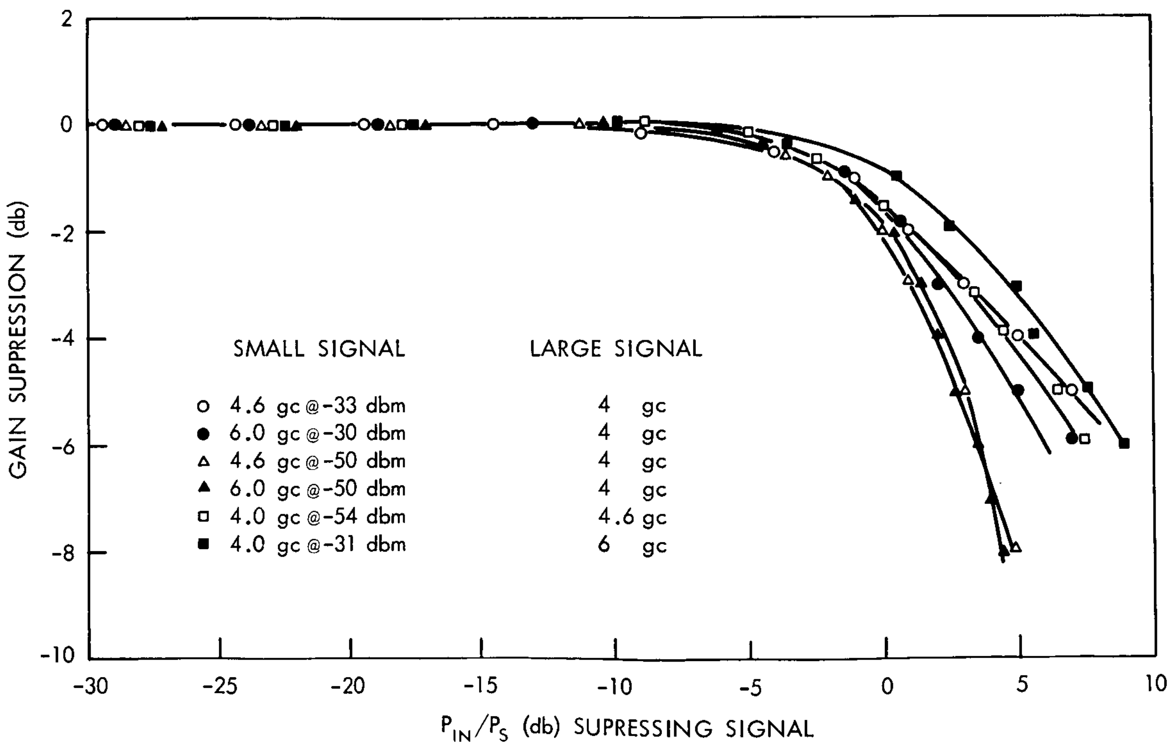

Figure 3-11–Gain Suppression Characteristics TWT - GE ZM-3110

the same type that has been successfully used as the final power amplifier in a synchronous altitude satellite. The tests that were performed on this particular type of TWT indicated differences of less than 1 db in suppression whether the suppressing signal was of higher or lower frequency. The frequency separation was 100 Mc in these tests.

In conclusion, as discussed above and as shown in Figure 3-24, the application of a second or third signal to the input of the TWT will not cause any substantial suppression of the output of either (or any) of the carriers if the input to either (or any) of the carriers does not exceed -15.0 db.

3.4 Intermodulation Distortion

Intermodulation is defined by IRE (52 IRE 17.S1) as the modulation of the components of a complex wave by each other in a non-linear system.

Intermodulation distortion, as used in this paper, will refer to any frequency components (henceforth called products) generated in the traveling wave tube, which are a result of two or more frequencies applied at the input; and which are caused by one or more frequencies; or harmonics thereof, intermodulating with one or more frequencies, or harmonics thereof. (This definition is given to preclude the inclusion of harmonics and subharmonics of the individual frequencies and/or other ambiguities that frequently arise among persons engaged in electronics.)

These new frequency products are commonly referred to as 2nd, 3rd . . . n^{th} order products depending upon the order of the non-linearities which produce them. Even order products will generally be of such frequency separation as to fall outside the operating range of the device. Some of the odd order products will likewise be negligible for the same reason.[7]

With respect to applying three frequencies—A, B and C—to the input of the non-linear TWT C, only two types of 3rd order products are of any consequence. One type, 2A-B, is a result of the second harmonic of A intermodulating with the fundamental B. The second type, A + B - C, is a result of the three fundamentals intermodulating with each other.

Under this test program three frequencies were fed into the TWT and the resulting third order intermodulation products were observed on a spectrum analyzer. Then each of the three carriers were turned off, in turn, and the resulting products for two carrier inputs were likewise observed on the analyzer. The equipment set-up for these measurements is shown in Figure 3-12.

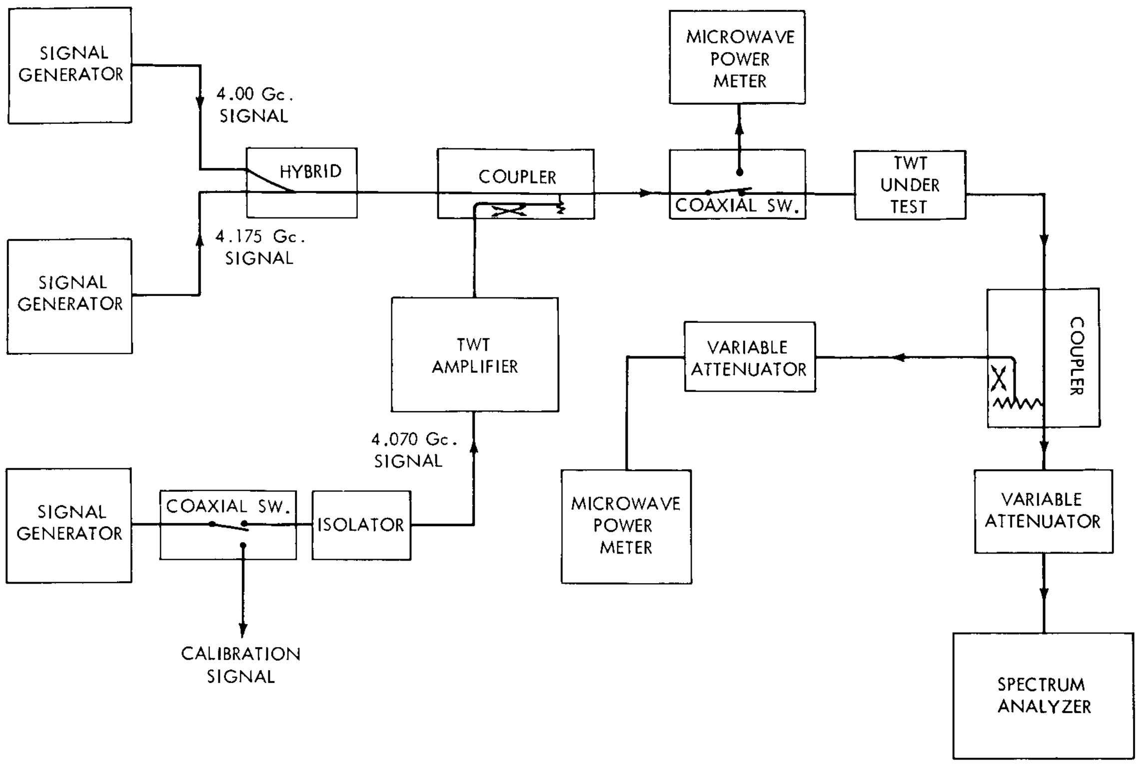

Figure 3-12-Test Set-Up for Measurement of Carrier Suppression and Intermodulation Distortion

The assumed frequency assignments that were discussed in Section 3.1 are listed below:

F_1 = 4.000 Gc

F_2 = 4.070 Gc

F_3 = 4.175 Gc

Resulting are six frequencies where 2A-B type intermodulation products are present: 3.825 Gc, 3.930 Gc, 3.965 Gc, 4.140 Gc, 4.280 Gc and 4.350 Gc. Also resulting, are three frequencies where A + B - C type products are present: 3.895 Gc, 4.105 Gc, and 4.245 Gc.

It should be noted that at three of the above frequencies higher order products are also known to be present (a 4A-3B type 7th order product is present at 4.280 Gc; a 3A-3B + C type 7th order product is present at 3.965 Gc; and a 5A-4B type 9th order product is present at 4.350 Gc), but their separate effects are not measurable. No 5th order products fall at any of the discrete test frequencies.

No attempt was made to compute if any additional seventh or other higher order products were present at the test frequencies since their separate effects would also not be measurable and of even less significance. Indeed the effects at the frequencies cited above are not apparent in the data that is to be presented.

In the conduct of the actual intermodulation tests the gain and saturated power output of the tube was carefully measured at each of the frequencies and was essentially the same as was measured for the carriers. Also no tunable bandpass filter was available for use in these tests; to preclude the development of other products in the spectrum analyzer, hence, great care was used in locating and identifying the IM products. Similarly, variations in the gain of the spectrum analyzer with frequency and insertion losses of cables and components were considered when calibrating at each test frequency.

The power outputs of each third order product, for a variety of input power levels to each of three carriers, is shown in Figures 3-13 through 3-21. The simultaneous power outputs of the three carriers are also shown. Figure 3-22 shows the effects on the 2A - B type products, of interchanging the roles of the two frequencies intermodulating which generate the products. Figure 3-23 shows the effect, on three of the products, of adding a third signal to the input. A comparison of the spectra obtained for two carrier and three carrier inputs, at each of two input levels, is shown in Figures 3-24 through 3-27.

In Figures 3-13 through 3-16, a single carrier (F_1) is held constant (at -15 db, -5 db, 0 db and +3.5 db respectively) while two carriers (F_2 and F_3) are varied together from -15 db to 0.0 db, each. In Figures 3-17 and 3-18 two carriers (F_2 and F_3) are held constant (at -15 db and 0.0 db) while the third carrier F_1 is varied over the -15 db to 0.0 db range. Figure 3-19 shows the roles of F_1 and F_3 interchanged from those presented in Figure 3-13; i.e., F_3 is constant and F_1 is varied with F_2. Figure 3-20 shows the roles of F_1 and F_3 interchanged from that presented in Figure 3-15.

A study of Figures 3-13 through 3-20 is interesting and provides information that is useful to establish frequency assignments and power input levels.

If the power output of any one product is arbitrarily limited to 20 db below the output of any of the carriers, input power levels can be picked from the graphs. In Figure 3-13, the first interfering product, $2F_2 - F_3$ (3,965 Mc), becomes 20 db below F_1 when the inputs of F_2 and F_3 reach a level of -11.5 db each. The same power inputs may be used for F_1 and F_2, Figure 3-19, where the roles of F_1 and F_3 are interchanged. Here the interfering product is $2F_2 - F_1$ (4,140 Mc), which is 20 db below the level of F_3. There are no levels shown in Figures 3-14 through 3-16 where the 20 db limitation may be met. In Figure 3-17

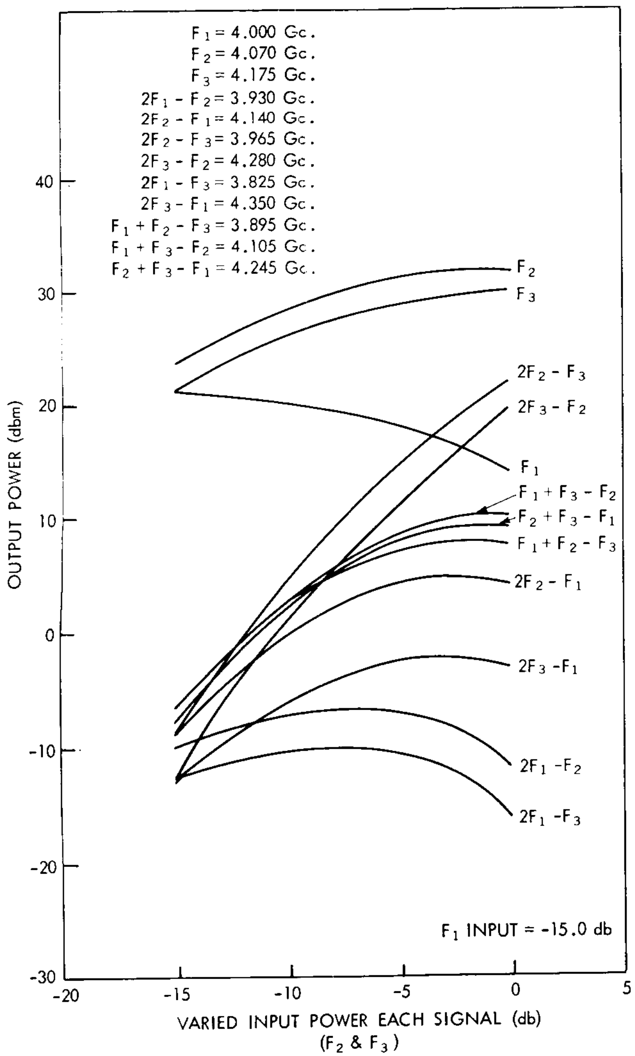

Figure 3-13-Intermodulation; TWT C

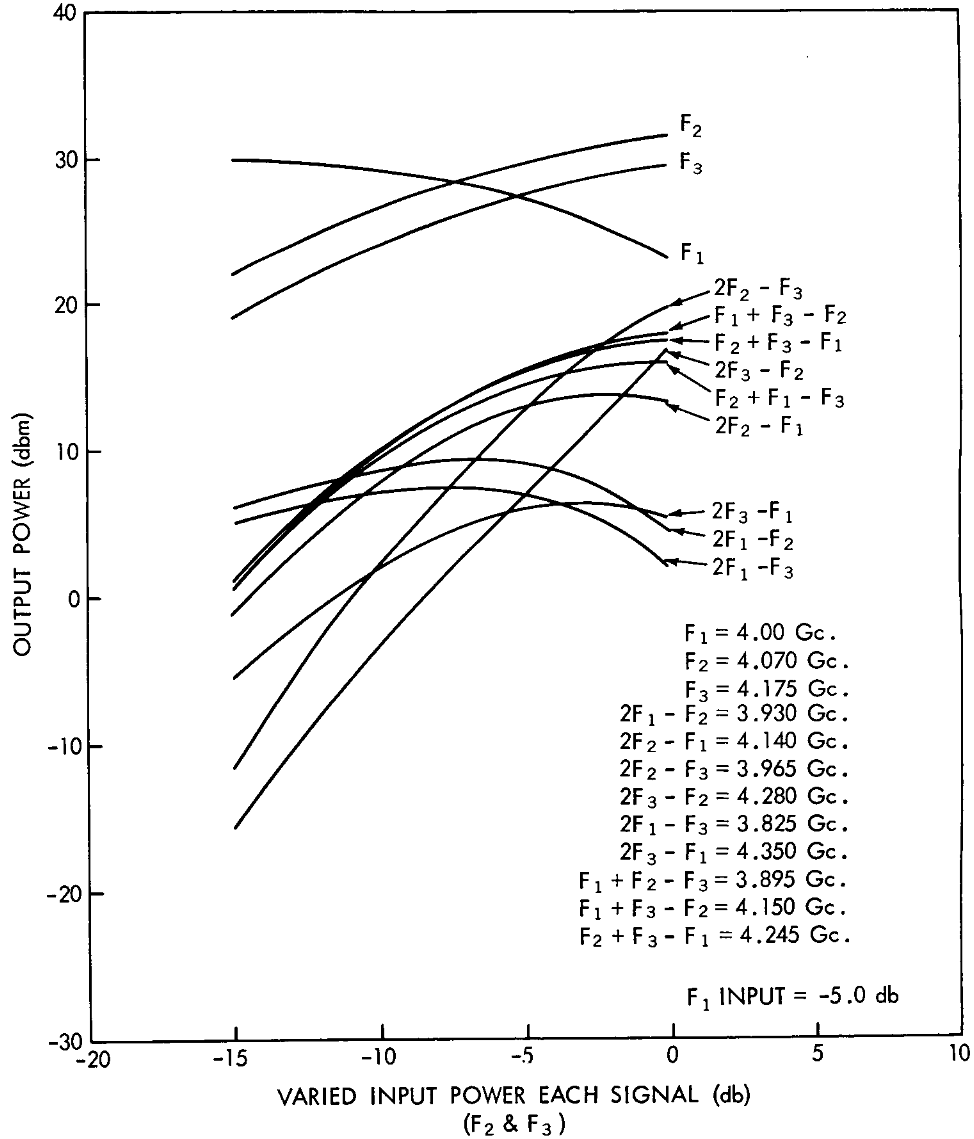

Figure 3-14-Intermodulation; TWT C

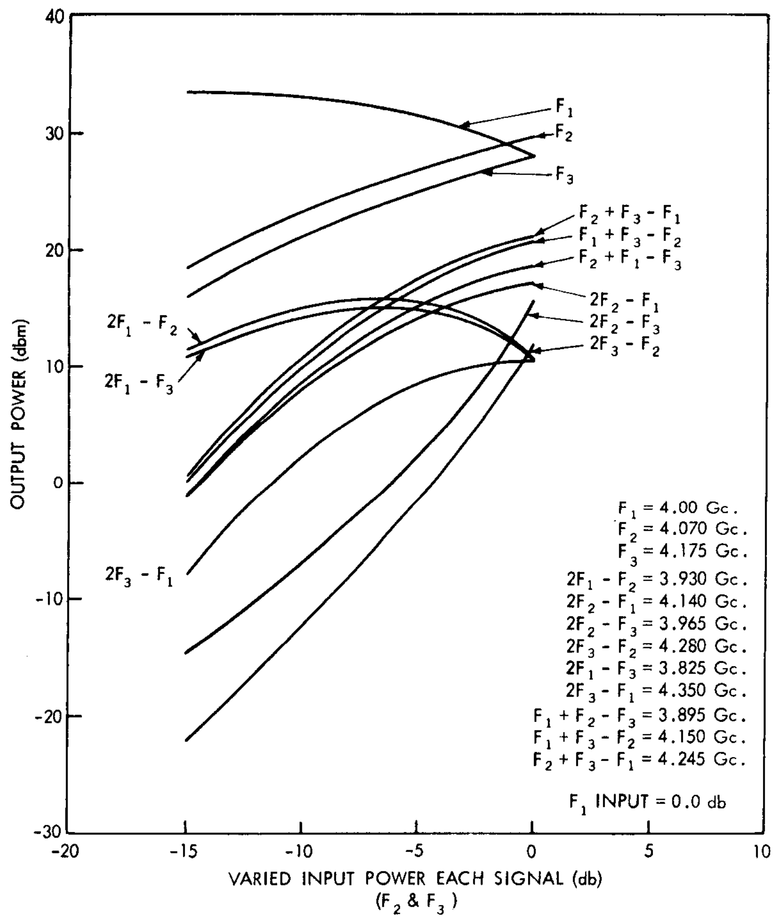

Figure 3-15-Intermodulation; TWT C

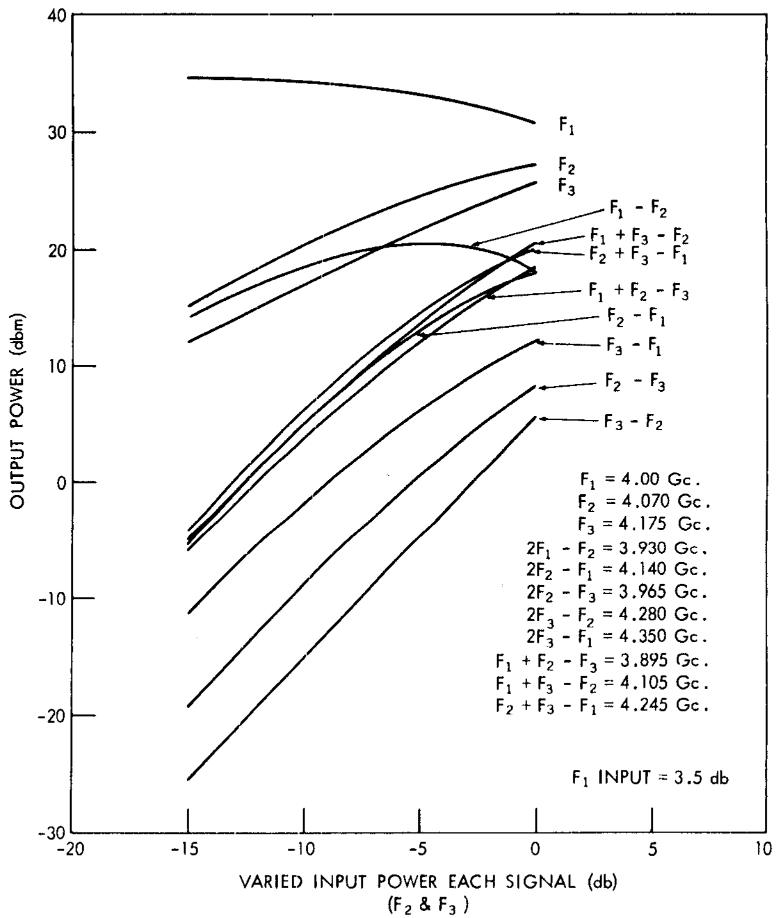

Figure 3-16-Intermodulation; TWT C

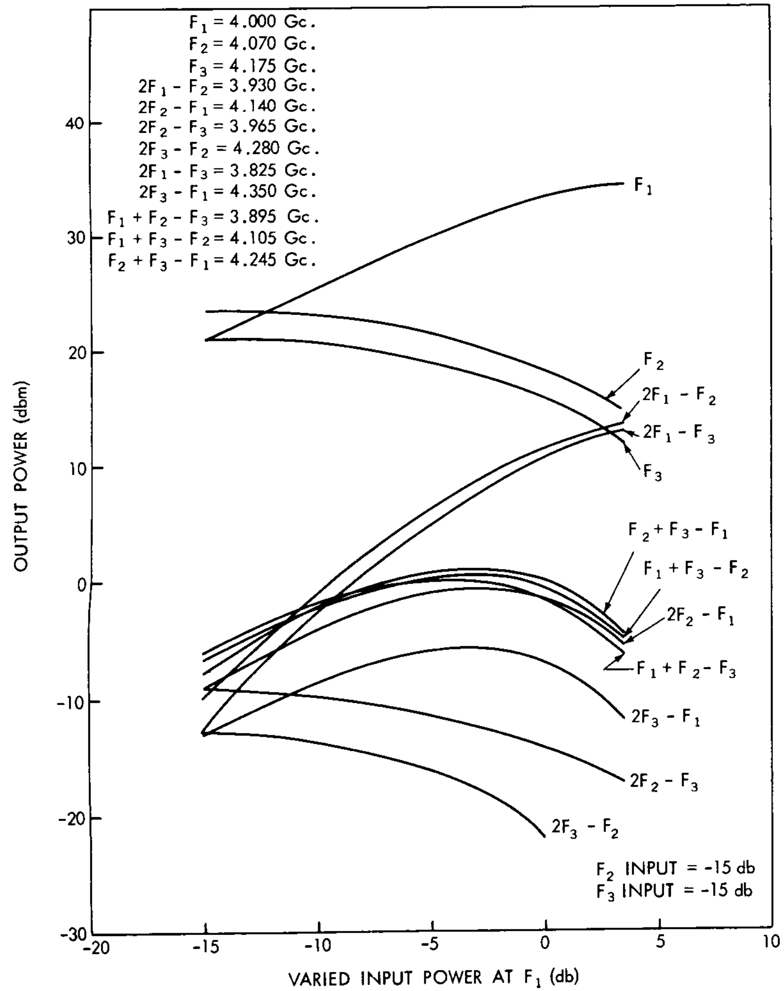

Figure 3-17-Intermodulation; TWT C

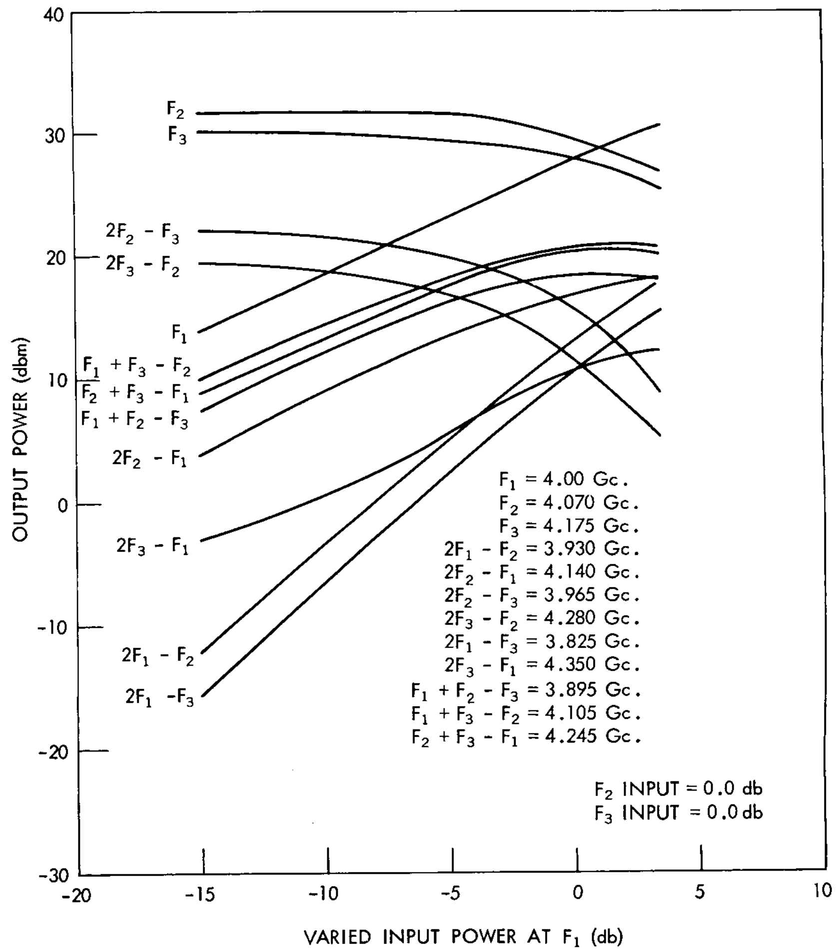

Figure 3-18-Intermodulation; TWT C

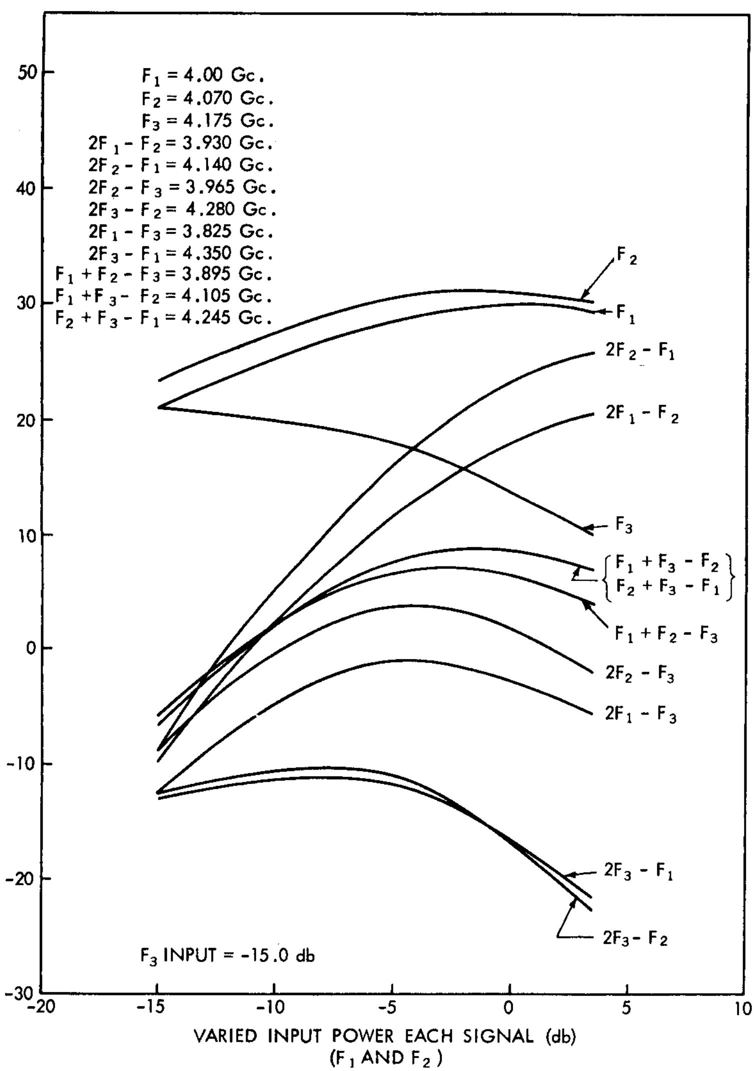

Figure 3-19–Intermodulation; TWT C

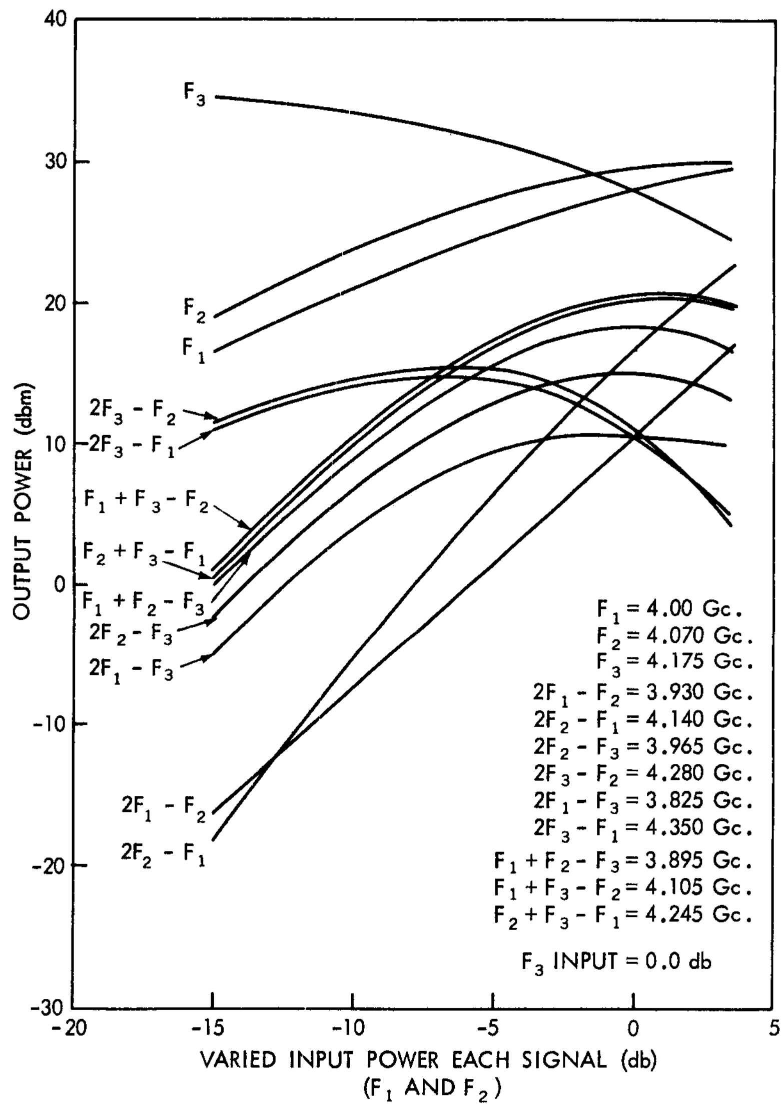

Figure 3-20–Intermodulation; TWT C

where F_2 and F_3 are each held at -15 db, operation of F_1 at a -9 db level is possible ($2F_1 - F_2$, 3,930 Mc, interferes with F_3).

If, in further analyzing the graphs, it is additionally stipulated that any product more than 35 Mc from a carrier shall be neglected, then carrier levels may be increased before certain interfering product levels become restrictive. For example, in Figure 3-17 it may be seen that F_1 can now be increased an additional 4 db to the -5 db level, where $2F_2 - F_1$ will interfere with F_3; the 3,825 Mc, 3,930 Mc, 3,895 Mc, 4,105 Mc and 4,245 Mc product frequencies being neglected.

Theory dictates that the power output of a $2F_2 - F_1$ product should vary proportionally to $(P_2)^2 P_1$, and a $2F_2 - F_3$ product should vary proportionally to $(P_2)^2 P_3$, etc.[8] Accordingly, referring again to the situation where the roles of F_1 and F_3 are interchanged, the total power input for either of the two cases is the same. In this respect, referring to Figure 3-13 where the $2F_2 - F_3$ product is 20 db down from F_1; the power input at F_1 is -15.0 db corresponding to a power ratio of .03162, and the power input at F_2 and F_3 is -11.5 db each, corresponding to a power ratio for F_2 and F_3 of .07079. Thus, the total power input ratio is .03162 + .07079 + 07079 = .17320; whence, converting back to db, the total power input is approximately -7.6 db below the reference. Similarly from Figure 3-19, when the role is reversed, the $2F_2 - F_1$ product is likewise 20 db down from F_3 for the same total power input of -7.6 db, because F_3 is now at -15 db and F_1 and F_2 are now at -11.5 db each. Under these conditions, for equal power inputs, these two products will be the first to interfere whether or not the 35 Mc restriction is applied (F_1 or F_3 are at a -15 db input level, respectively). In Figure 3-17, where the $2F_2 - F_1$ product is 20 db down from F_3; F_1 is at -5 db, which is 4 db higher than where the $2F_1 - F_2$ product is 20 db down from F_3. The total power input to the tube is -4.2 db in the former case and -7.2 db in the latter case. The $2F_1 - F_2$ product increases much more rapidly because F_1 constitutes the squared term.

From the above illustration, it may be seen that the points of interference are determined much more by the power level of a particular frequency than by any relationship of the total power input. Thus in a multi-access system interfering products may be controlled somewhat if the power levels can be predicted and programmed.

With respect to this suggestion of "predicted programming," unfortunately, all is not gravy. Under the arbitrary limit assignment of 20 db product interference within a 35 Mc range of separation from the carriers, analyzing Figure 3-17, the $2F_2 - F_3$ product is at an output level of -9 dbm, when the input level at F_1 is -15 db. This product may be expected to remain constant at the -9.0 dbm output level for reduced input power levels at F_1 since F_2 and F_3 are held constant and will not be further suppressed. However, the power output at F_1 may be expected to be essentially a linear function of the power input below -15.0 db input, and can be extrapolated in Figure 3-17 to be 11.0 dbm at -25 db input level. This is only 20 db above the $2F_2 - F_3$ product at the -25 db F_1 input level. If the F_1 input level is further reduced, the $2F_2 - F_3$ product interference is less than the allowable 20 db margin and becomes of concern, its separation from F_1 being 35 Mc. Similarly, the $2F_3 - F_2$ product will become less than the 20 db interference margin for reduced F_1 input levels below -29 db, but is of no concern because it is separated from F_1 by 280 Mc. The task of "predicted programming" is, therefore, not an easy one. The amount of reduction of a carrier with respect to others and the operating restrictions necessitate considerable thought and control. The complexity of the suggested programming can further be shown through additional analysis of Figures 3-13 through 3-21 in connection with the power series equation. For example, it can be shown that an identical situation to the above would exist for the $2F_2 - F_1$ product, if F_1 and F_2 were held constant at -15 db input and the input at F_3 reduced to -25 db. Also it can be shown that for another case where F_1 and F_3 are held at the same -15 db level, the equivalent products that are generated are separated more than 35 Mc from F_2 and are of no concern. However, if in the last case the arbitrary separation is removed, each product will be about 20 db below the F_2 output when the input to F_2 is -30 db and would, therefore, be of concern. It should be pointed out that the complexity of programming the carrier levels will also depend upon the gains for the carrier frequencies from one TWT to another.

Figure 3-21 is a plot of the output level of each of the three carriers and of the products; when all three inputs are varied together. From this graph it may be readily seen that each of the three A + B - C type products are larger in amplitude than are any of the 2A - B type. No reason for this could be found since the A + B - C type products should vary as $P_A P_B P_C$.

As mentioned previously, the 2A - B type products resulting from two carriers intermodulating, were found to be relatively consistent in amplitude when the roles of the two carriers are interchanged. Good comparisons were obtained with and without the presence of a third carrier, and regardless of the input levels. The effects of adding the third carrier are a reduction in the amplitude of each existing 2A - B type product, while four additional 2A-B type products and three new A + B - C type products are generated.

The results of interchanging two carriers and the effect on the products generated by the addition of a third carrier are shown in Figure 3-22. The input to F_1 was held constant at 0.0 db and the input to F_3 was varied. The resultant carrier amplitudes and the amplitude of the $2F_3 - F_1$ product are shown on the graph. This process was repeated with F_2 also applied to the input at a level of 0.0 db.

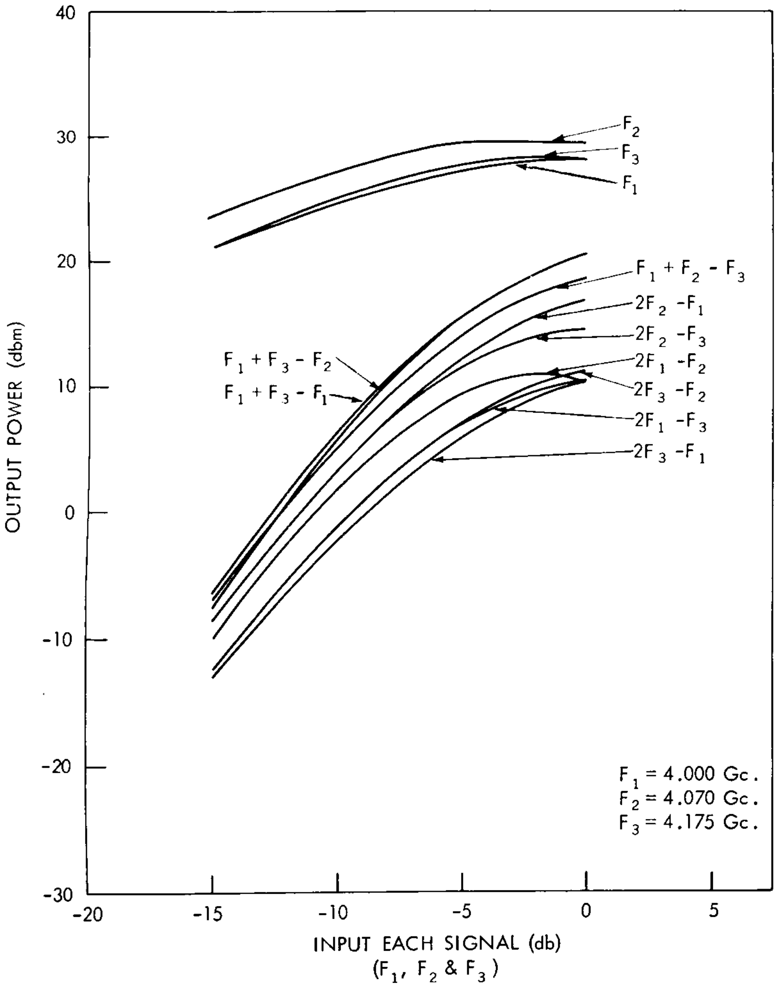

Figure 3-21-Intermodulation; TWT C

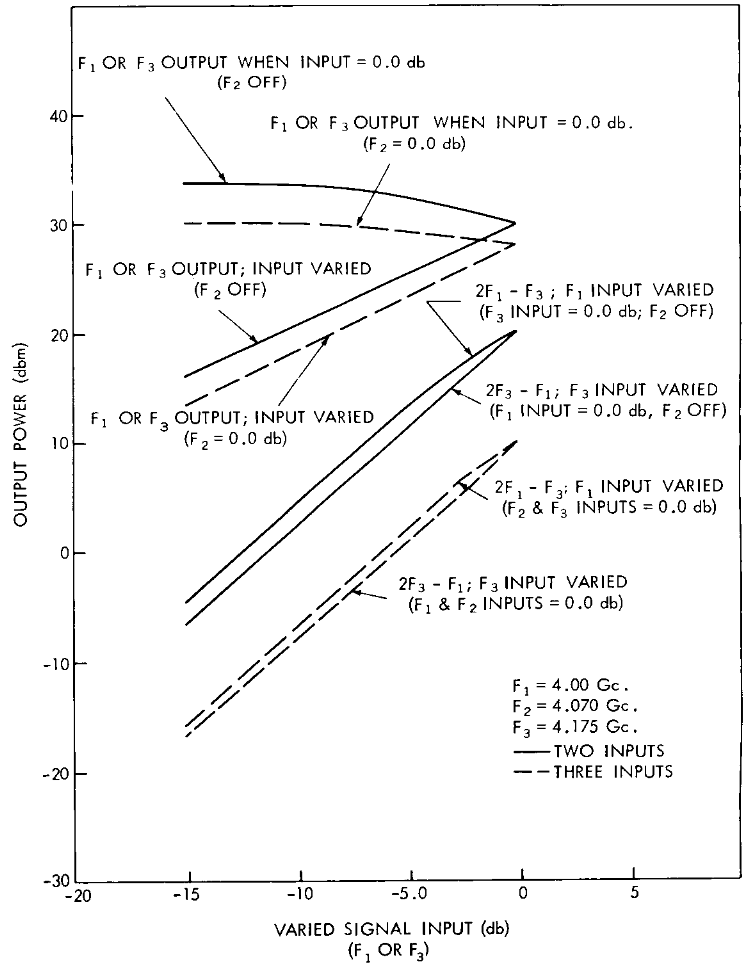

Figure 3-22-Intermodulation; TWT C

The roles of F_1 and F_3 were then interchanged in and without the presence of F_2, and the resultant amplitudes of F_1, F_3 and the corresponding product ($2F_1 - F_3$) are likewise plotted on this graph. (Note: The squared term in the product is the varied input signal in each case.) This interchanging of the carrier roles results in less than 2 db difference in the amplitudes of the corresponding products, for all input levels. Greater accuracies should probably not be expected.

The reduction of power output of three representative 2A - B type products obtained when a third signal is applied to the input is shown in Figure 3-23. In this case all input levels were varied together. The power output of the products as evidenced at -15.0 db input levels, is essentially the same whether two or three signals are present.

The two carrier spectrum is compared with the three carrier spectrum in Figures 3-24 and 3-25. The suppression of the $2F_1 - F_3$ (3,825 Mc) and the $2F_3 - F_1$ (4,350 Mc) products by the third carrier at the input is very apparent in the display of Figure 3-25. In both graphs, it may be readily seen that A + B - C products are larger in amplitude than are the 2A - B type products.

Modulation was not used in these tests, but in general the same analogy of the test results should be applicable. Proper spacing of the carriers—with regard to the intelligence bandwidth to be used—could be chosen to prevent cross modulation.

When two carriers are applied to the input, the resulting 2A - B and 2B - A products are symmetrically spaced about the two carriers (as illustrated in the two carrier spectrums shown in Figures 3-24 and 3-25). The frequency separation of the two products is three times the separation of the carriers. If equal bandwidths of intelligence modulates the carriers, there will be a bandwidth of intermodulation products, correspondingly spaced about each of the original products, which will have a bandwidth three times greater than the original bandwidth of each carrier. This phenomenon applies to each third order product generated by any number of carriers.

In the three carrier spectrum, as illustrated in Figure 3-25, the minimum spacing between each carrier and the nearest third order product is 35 Mc. Serious cross modulation of the carriers may result when the modulation is such that the intelligence bandwidth is 1/2 this separation, assuming symmetry; i.e., if X = allowable bandwidth which just causes cross modulation, $3/2\ X + X/2 = 35$ Mc, and X = 17.5 Mc. In this case, some third order products are also separated by 35 Mc, but this gap is closed at a different rate. Thus $3/2\ X + 3/2\ X = 35$ Mc, and X = 11.66 Mc—which is the allowable bandwidth before these new products intermodulate with each other.

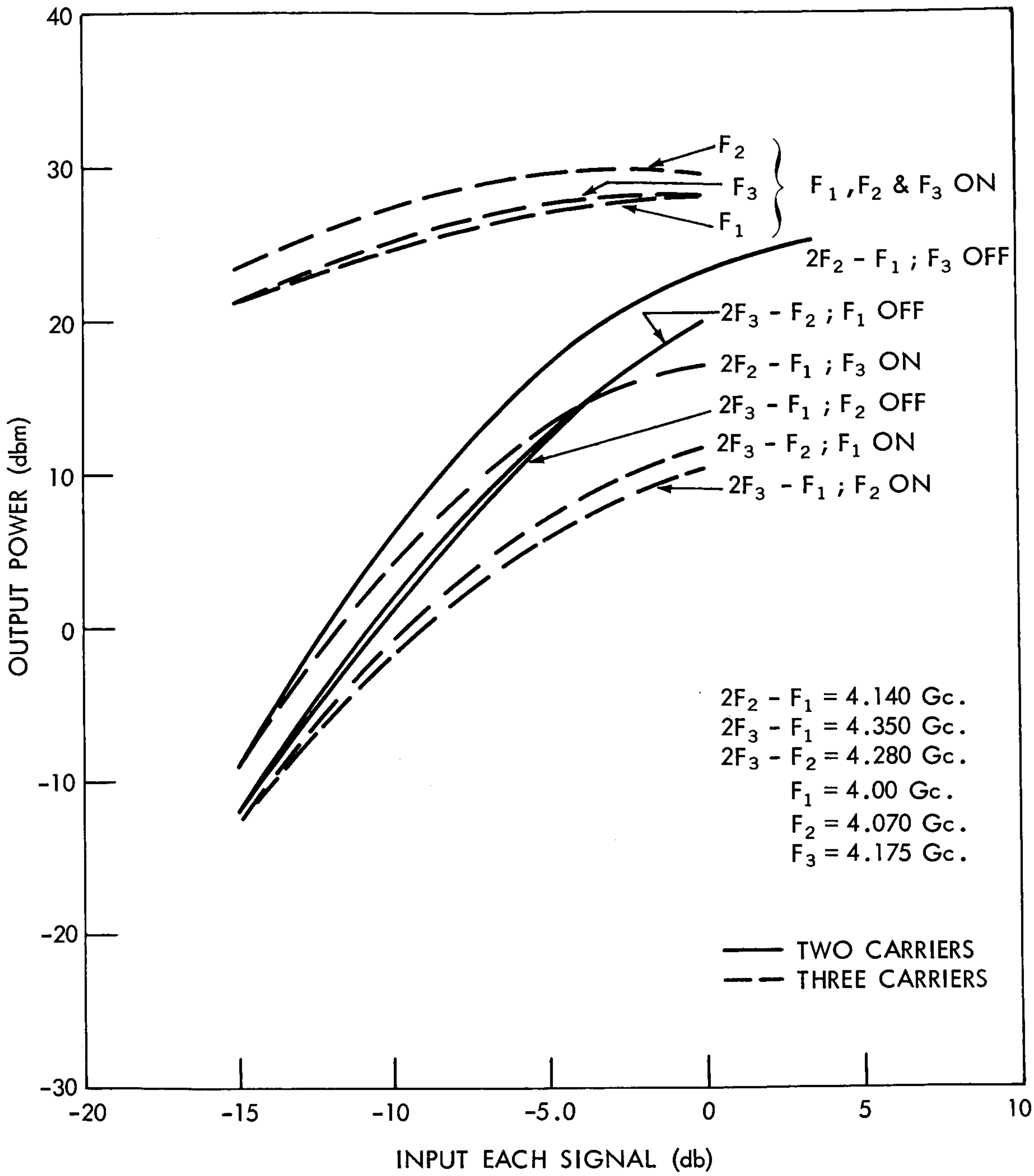

Figure 3-23-Intermodulation; TWT C

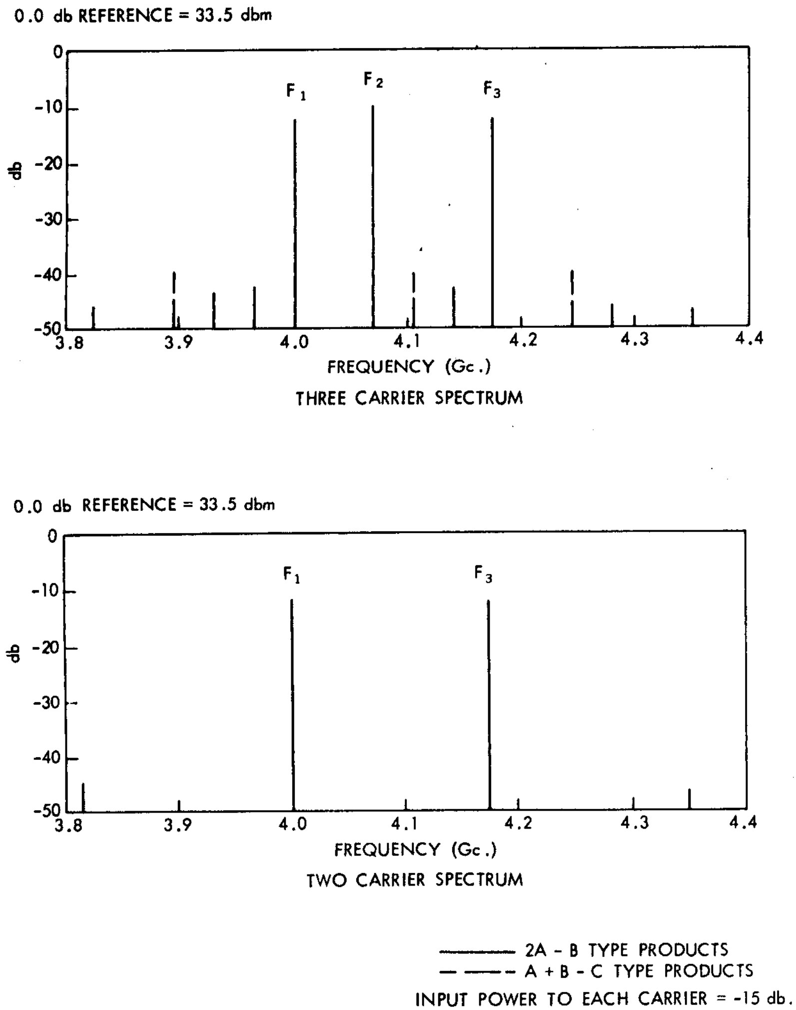

Figure 3-24-Intermodulation Spectra; TWT C

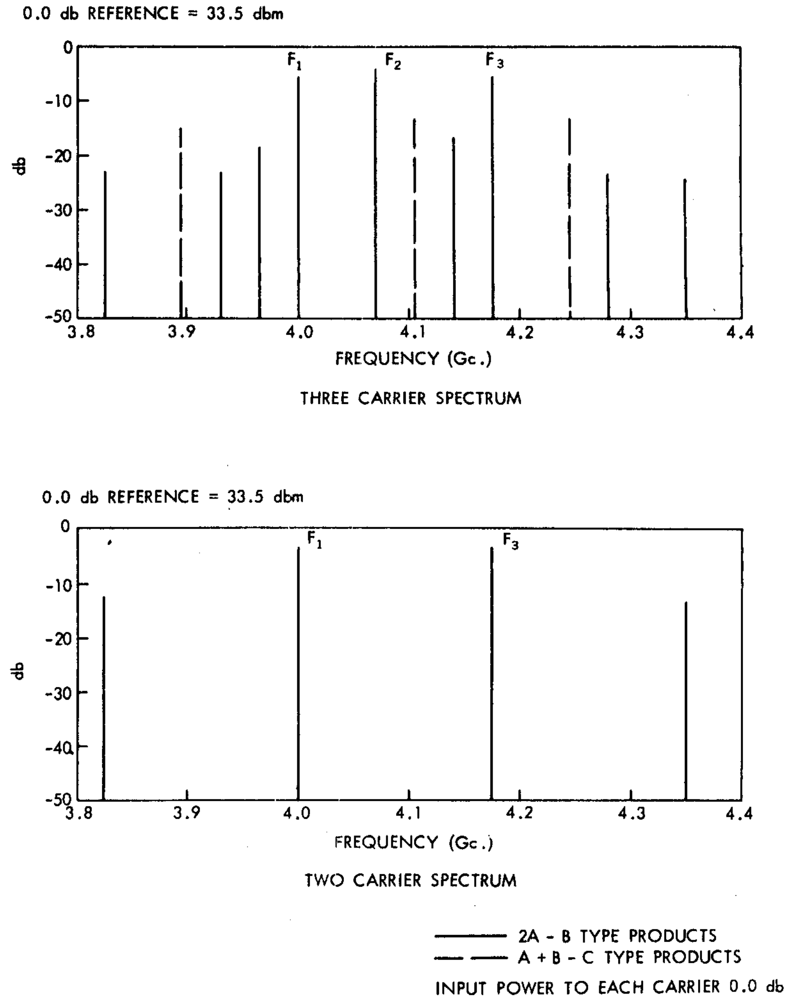

Figure 3-25-Intermodulation Spectra; TWT C

Data have already been presented in this section which verify that neither total power output nor the distorted power output is particularly a function of total input power. Rather they are more a function of the power input level at a particular frequency, and the number of input frequencies. However, the total power outputs as a function of total power input may be of interest. Figure 3-26 shows the distribution of power output as a function of total power input, for each individual input signal, two signals and three signals. Note that, in general, the total power output for multiple signal input is less than the power output obtained for a single signal of the same power input. (Curve "C" with total input power less than -3.5 db being an exception).

Figure 3-27 shows the total distortion power output, for two and three carrier inputs. For a ready comparison, the total power output of the carriers is also shown; for the same total power input levels.

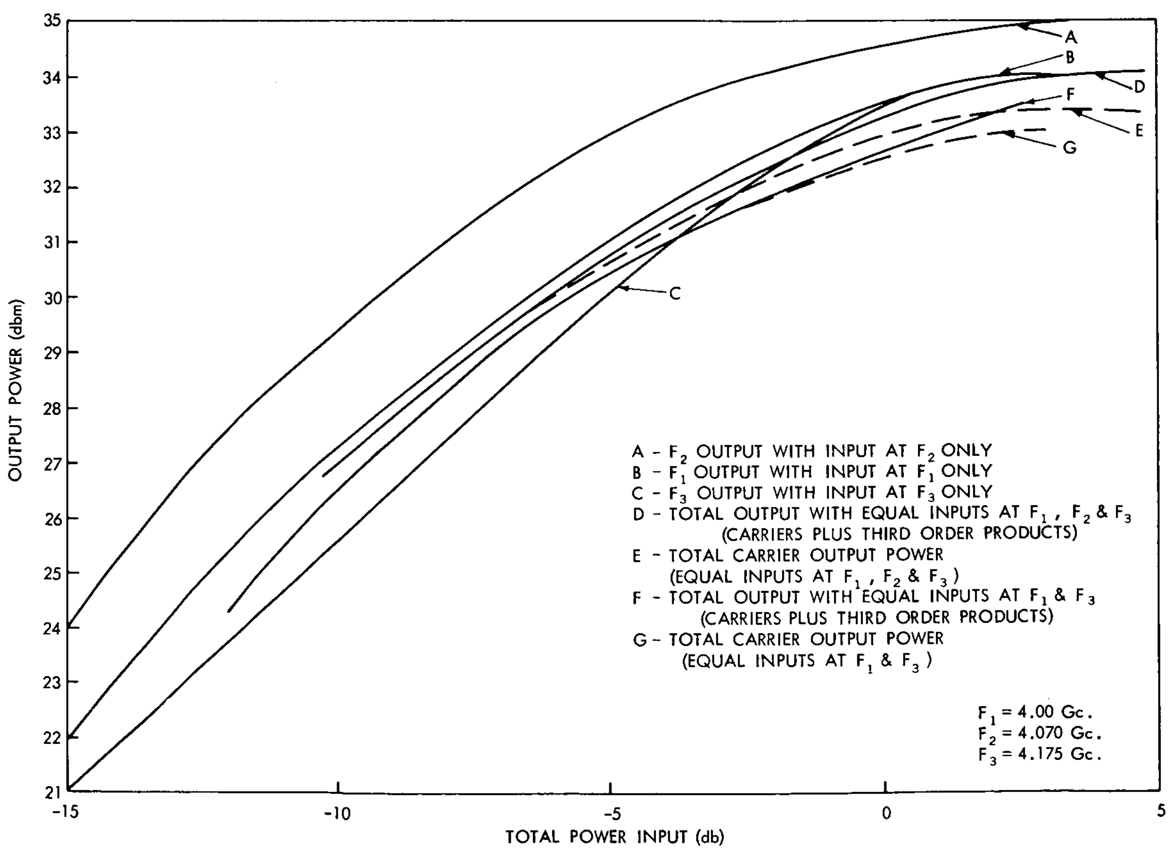

Figure 3-26–Power Output Curves; TWT C

The data in Figures 3-26 and 3-27 were computed from the data used in preparing the other graphs in this section.

It has been shown that this tube may be operated with three signals applied to the input if the input power to each signal is -15.0 db, or less. At about -16 db input each, all products should be 30 db or more below the level of any carrier.

If a fourth signal is added at a frequency of 4.245 Gc, the results are somewhat worse. Specifically, there will be an A + B - C type product thus generated, which will fall at each input frequency; i.e., $F_2 + F_3 - F_4 = F_1$, $F_1 + F_4 - F_3 = F_2$, $F_1 + F_4 - F_2 = F_3$, and $F_2 + F_3 - F_1 = F_4$. No 2A-B type products fall at a carrier frequency until five or more carriers are applied, with the same alternate spacing as before. Additional computations have not been made.

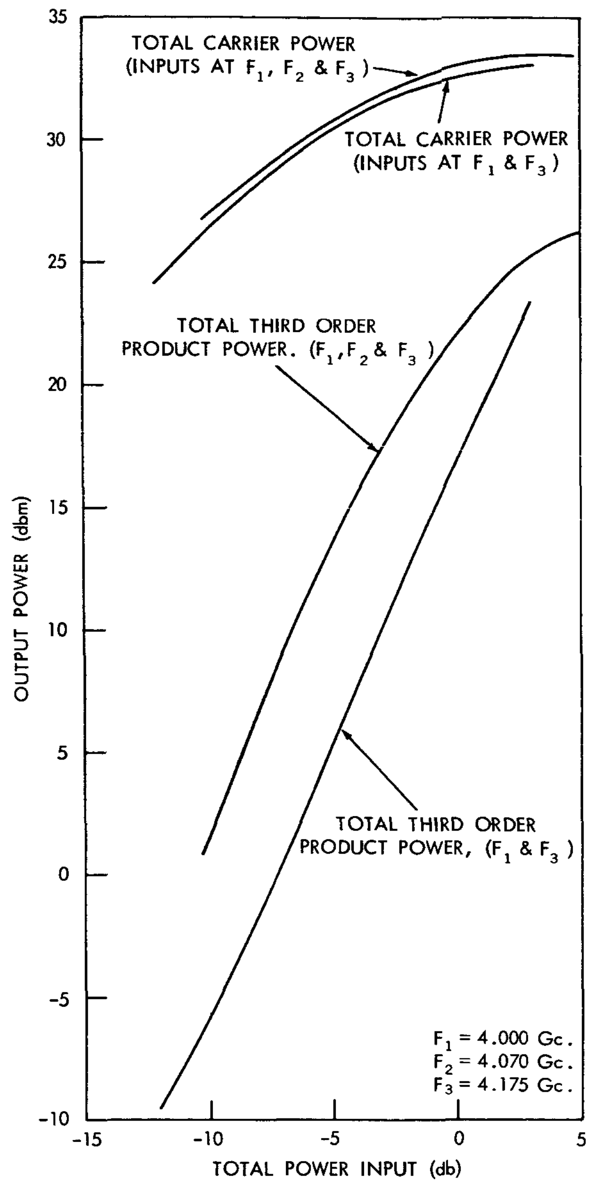

Figure 3-27–Distortion Power Curves; TWT C

3.5 VSWR and Impedance

Maximum transfer of power to and from the TWT will certainly be desirable in satellite applications. This will, of course, be achieved when the terminating impedance is the complex conjugate of the TWT impedance. The VSWR's alone are useful in obtaining the limits of any departures from the maximum transfer.

The VSWR as a function of frequency for the input terminal to the TWT is shown in Figure 3-28. The same information for the output terminal is shown in Figure 3-29. The VSWR with only the filaments on is of interest from the standpoint of switching transients, and is also presented.

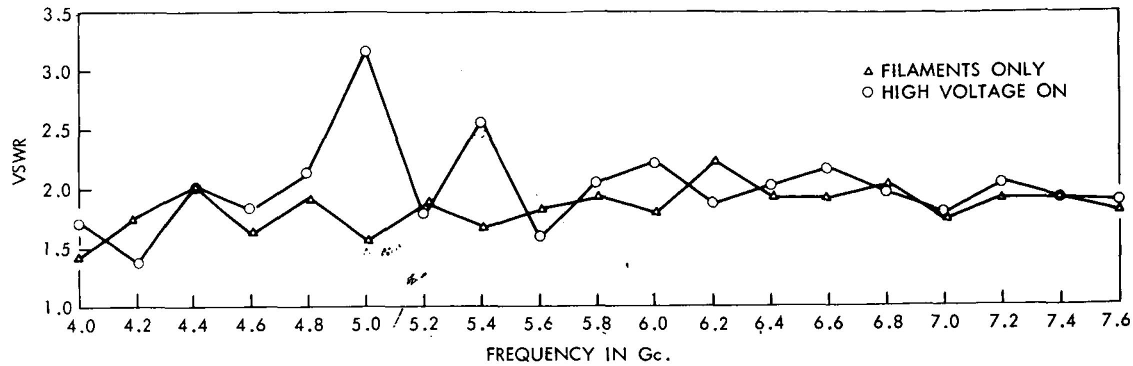

Figure 3-28–Input Terminal VSWR vs. Frequency TWT C

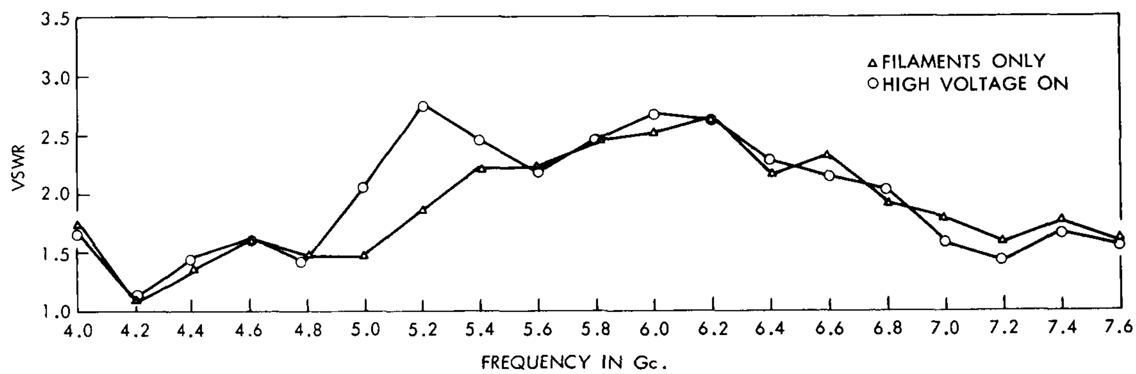

Figure 3-29–Output Terminal VSWR vs. Frequency TWT C

The range of the mismatch losses (departures from maximum power transfer to a load) may be calculated assuming a VSWR for the interfacing terminations.[9] Expressed in db, the maximum loss is

$$10 \log \left(\frac{\sigma_1 \sigma_2 - 1}{\sigma_1 \sigma_2 + 1} \right)^2$$

while the minimum loss is, expressed in db by

$$10 \log \left(\frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2} \right)^2$$

where σ_1 is the VSWR of the source and σ_2 is the VSWR of the load.

Assume that the input and output will each work into a VSWR of 1.05 (which is a very optimistic assumption). The "worst case" input terminal VSWR is found to be 3.15 at a frequency of 5,000 Mc. (Figure 3-28). The range of mismatch is calculated to be 1.25 db to 1.47 db. The corresponding output terminal mismatch loss at this frequency ranges from .49 db to .64 db. The maximum possible total loss for the TWT at this frequency would be 2.11 db.

The worst case output terminal VSWR is 2.75 at 5,200 Mc (Figure 3-29). The range of mismatch loss at this frequency is determined to be from .970 db to 1.17 db. The input loss at this same frequency ranges from .299 db to .413 db. The maximum possible total loss for the TWT becomes 1.583 db for this frequency.

An interface VSWR would most likely be greater than 1.05, should this tube be used in a system. Therefore, it seems reasonable to assume that any untuned, broadband system incorporating this tube–or a similar tube–could reasonably be expected to have a 3.0 db total mismatch loss. A 100% increase in the dc to rf efficiency would be required to overcome this loss alone, in such a system.

The VSWR results are converted to impedance on the Smith Charts shown in Figures 3-30 and 3-31. Constant VSWR circles for a VSWR of 2.0 and of 3.0 are circumscribed on each plot, for convenience. The distribution of the points with respect to frequency seems to be rather random, on each graph. The division of inductively reactive and capacitively reactive points is about equal on both charts.

3.6 Noise Figure

The broadband noise figure of the TWT was measured over the frequency band of 4,000 to 7,600 Mc. The set-up shown in Figure 2-10 was used for these measurements (Note: No band pass filter was available for limiting the noise bandwidth). The test results are presented in Table 3-1.

TITLE DATE

IMPEDANCE COORDINATES—50-OHM CHARACTERISTIC IMPEDANCE

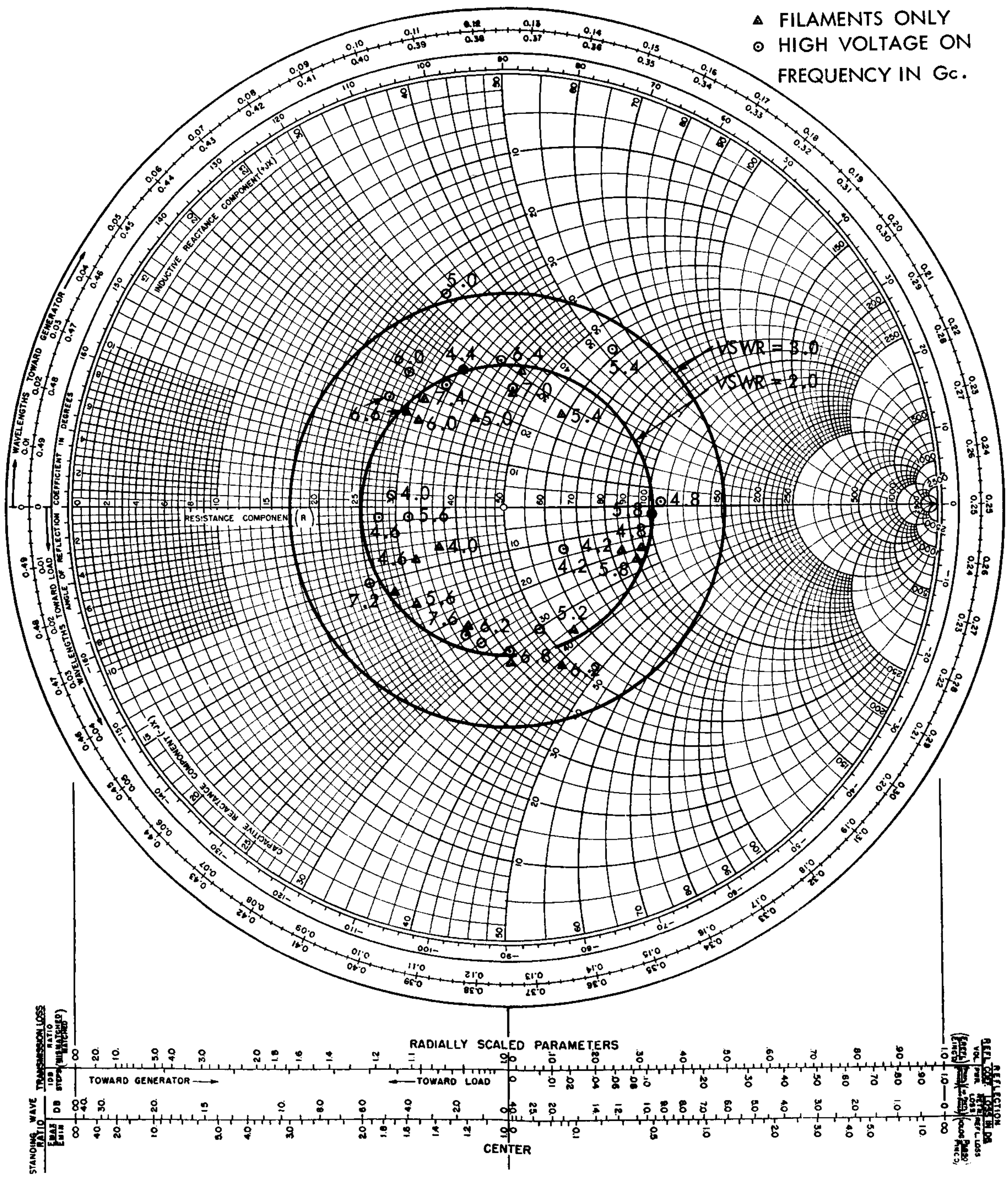

Figure 3-30–Input Terminal Impedance – TWT C

TITLE DATE

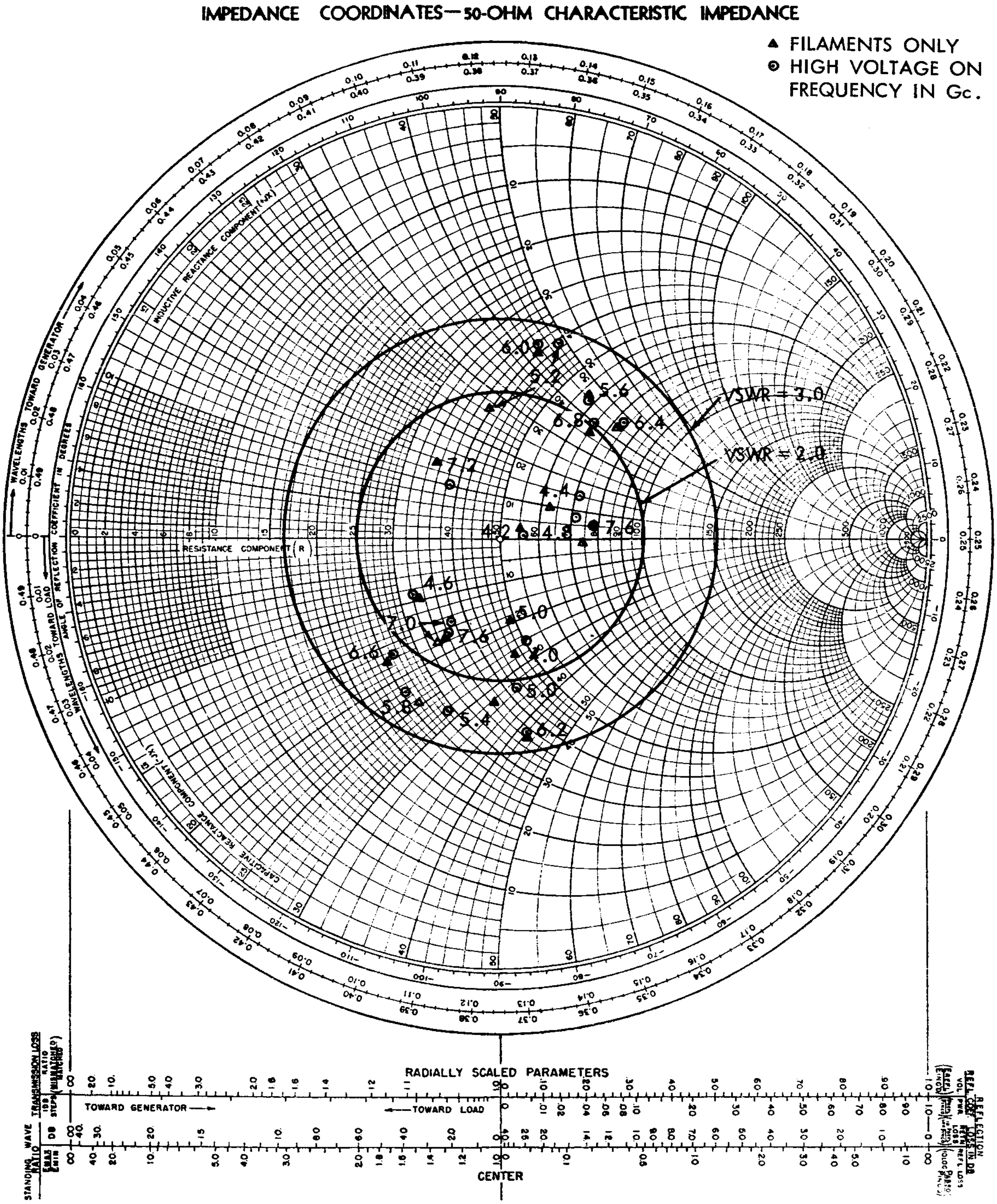

Figure 3-31–Output Terminal Impedance – TWT C

Table 3-1

Frequency	Noise Figure
4.0 Gc	> 30.0 db
4.2 Gc	> 30.0 db
4.4 Gc	> 30.0 db
4.6 Gc	30.0 db
4.8 Gc	27.0 db
5.0 Gc	> 30.0 db
5.2 Gc	26.0 db
5.4 Gc	> 30.0 db
5.6 Gc	29.0 db
5.8 Gc	26.0 db
6.0 Gc	> 30.0 db
6.2 Gc	29.0 db
6.4 Gc	26.5 db
6.6 Gc	30.0 db
6.8 Gc	28.5 db
7.0 Gc	28.5 db
7.2 Gc	28.5 db
7.4 Gc	29.5 db
7.6 Gc	29.5 db

The data presented here give only a relative idea of actual NF due to the inherent inaccuracies involved. The published manufacturer's specification for the tube type states merely that the NF shall be less than 35.0; while the test data supplied with the tube state that the NF is less than 35.0. No mention is made of what techniques were employed in ascertaining the fact. The data shown here do not show that it is necessarily less than 35.0 neither do they show it to be more than 35.0. This tube is not represented, categorically, as a "low noise" tube, however. Further, a 25 to 35 db noise figure is probably typical of most medium power tubes of whatever manufacturer.

It has already been shown in Section 2.2 that this tube, with an assumed operating bandwidth of 100 Mc, could be expected to have a dynamic range of 59.0 db.

4.0 Conclusions

Traveling wave tubes have been used for a number of years as broadband microwave power amplifiers. Perhaps the chief reason for such wide acceptance is that nothing better has been available. However, with only a little magnanimity, it must be acknowledged that they have filled a variety of needs quite successfully.

The analyses and discussions that have herein been presented were performed on a basis of providing the "Direct RF to RF Converter" design studies with a better understanding of TWT characteristics under wideband multi-signal usage. The endeavor certainly accomplished this since at its on-start one would receive a variety of answers to any given question depending upon the personal preference of the individual responding. Hopefully, this documentation of the endeavor will serve in the future to familiarize similar R&D activities with TWT characteristics and usage. In general, the results of this evaluation program indicate that commercial tubes of the type tested could be employed in wideband multiple access transponders, within certain limitations. However, it must be realized that should a specific spacecraft program require utilization of traveling wave tubes in a transponder, in all probability the TWT flight hardware would be that of a specified development–if for no other reason than to prove qualification and reliability. In this event any inherent tube deficiencies and limitations that were noted during a development with respect to the intended application could probably be overcome.

Based on the commercial type TWT evaluations the chief limitations of concern for wideband, multi-signal usage are noise and intermodulation effects. Therefore, signal levels at the satellite could not be allowed to vary more than several db. (possibly 10-20 db, or more.)

An inherent high noise figure for a tube would not be detrimental, if a low noise preamplifier is used ahead of the TWT. The intermodulation effects may be kept within tolerable limits by keeping carrier input levels at predetermined values below saturation.* (See Section 3.4) These levels will make carrier suppression negligible, as well. More than three input signals may be possible under the above considerations and with well planned frequency assignments.

A procedure for determining tube requirements is readily suggested by the above considerations. First, power output and gain requirements should be determined on the basis of power needed when the input level is reduced to well below saturation and well above noise. Secondly, the tube should have the lowest possible VSWR and highest efficiency.

As this is written, tube techniques are being advanced which should give more acceptable characteristics than previously. Tubes are now being built that are higher in power output with substantial reduction in size, weight, and input requirements. Also, these newer tubes have miniature input and output connectors, which should improve VSWR, somewhat. There is no indication that these advanced tubes will have any less distortion. The more efficient tube designs may be considered for use in a multiple tube transponder, such as suggested by STL[3] for minimizing distortion–when several carriers are to be used.

The reliability of traveling wave tubes and space environmental effects were not considered during the evaluations that were made.

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*Note: Watkins Johnson[10] has found that major changes in design have no apparent effect on the amplitude of the intermodulation products. One exception, of several tubes tested, indicated the distortion was worse in a tapered helix type tube.

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