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SYSTEM REQUIREMENTS FOR
A
DIRECT R.F. TO R.F. RE-ENTRANT TRAVELING WAVE TUBE
COMMUNICATIONS SATELLITE TRANSPONDER

Louis J. Ippolito
- Goddard Space Flight Center -

Abstract

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Conventional techniques for obtaining frequency conversion and amplification in an active repeater communications satellite down-convert the received radio frequency signal to an intermediate frequency for amplification and then up-convert to a new radio frequency for further amplification and re-transmission. This paper describes the requirements for a re-entrant traveling wave tube frequency converter system which accomplishes all amplification and frequency translation at microwave frequencies, eliminating the bandwidth and signal handling limitations of conventional systems employing an intermediate frequency.

Transponder requirements for a wideband synchronous orbit communications satellite link are presented and the effects of multiple carriers on the system response are investigated. System and component design criteria are developed for the link and experimental re-entrant systems are described. *Author*

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I. INTRODUCTION

The primary function of an active communications satellite involves the reception, amplification and re-transmission of information-bearing radio frequency signals between two or more ground terminals. The signal received at the satellite must be translated to a different carrier frequency before satellite re-transmission to prevent interaction between the input and output signals. The satellite equipment for performing these functions is termed a transponder or a repeater.

Conventional techniques for obtaining frequency conversion and amplification require the received signal at the satellite to be reduced to an intermediate frequency for amplification and then translated to a new radio carrier frequency for further amplification and retransmission. Figure 1-1 shows a typical frequency translation satellite transponder system.

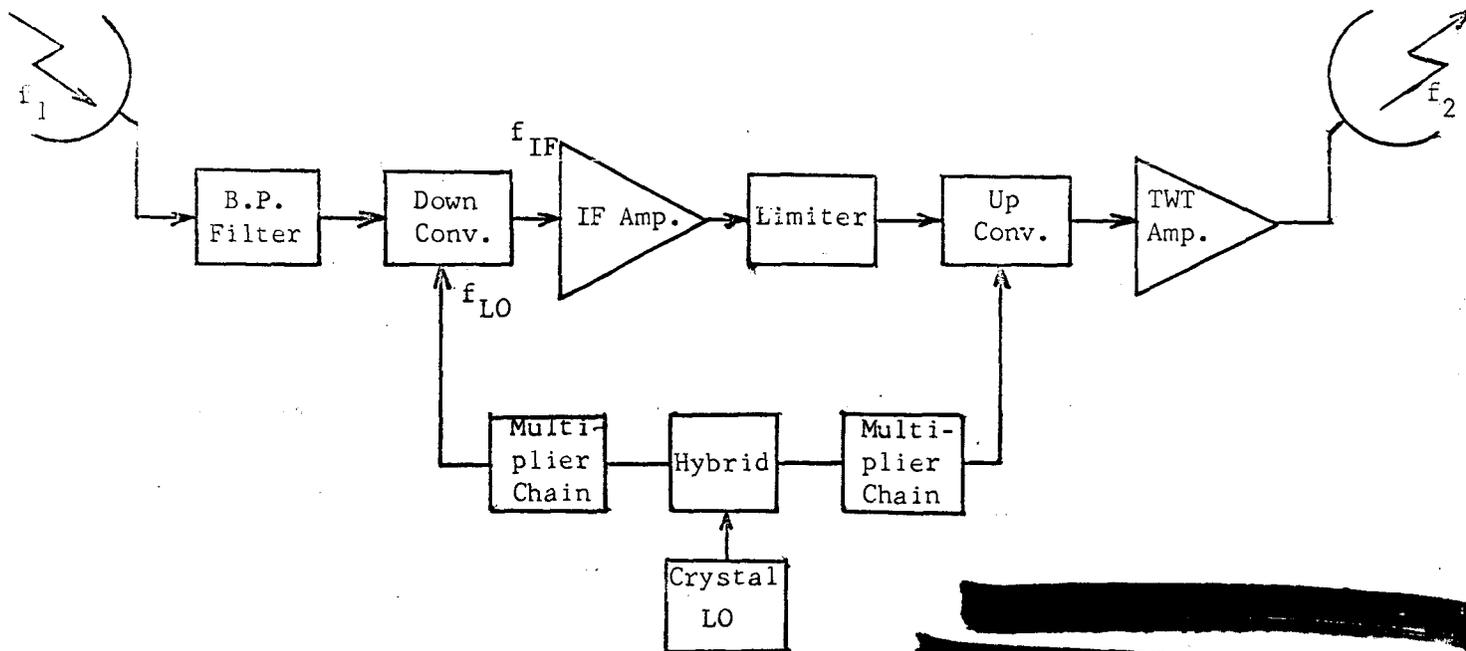


Figure 1-1

Frequency Translation Satellite Transponder

The received signal at f_1 is down converted to f_{IF} and most of the amplification occurs at this frequency. After limiting, the signal is up converted to f_2 and is amplified in the traveling wave tube to obtain the necessary transmission power.

A modulation conversion transponder utilizes similar frequency translation techniques but in addition employs a modulation conversion scheme to convert the uplink modulation to a different form for downlink transmission. The modulation conversion is accomplished in the IF portion of the transponder.

In current communication satellite transponders, an IF below 100 Mc is utilized, and usable bandwidth is 25 Mc or less. Ground station transmitting and receiving capabilities require the satellite to receive signals near the -80 dbm level and re-transmit at +33 dbm or greater, depending in part upon the satellite orbit.

Future communication satellite requirements, such as the use of multiple access ground stations and wideband video transmission networks indicate that bandwidths of 200 Mc or greater with higher transmitted output powers than those currently available will be necessary.

On present systems the presence of the IF sets a limitation on the maximum usable bandwidth and size-weight-power restrictions on the satellite limit the power available for transmission in the output stage. These limitations can be removed by the employment of direct microwave to microwave conversion where all amplification is accomplished at microwave frequencies.

One such type of direct RF to RF system utilizes a traveling wave tube (TWT) in the serrodyne mode to obtain frequency translation and a re-entrant loop to obtain high amplification.^(1,2) A second direct RF to RF technique, the type to be discussed in this paper, utilizes a traveling wave tube for amplification and a non-linear impedance device as the frequency converter. The TWT is operated in a re-entrant, or reflex, mode to obtain gain at both the uplink and downlink frequencies.

Figure 1-2 shows the block diagram of a re-entrant TWT direct RF to RF transponder.

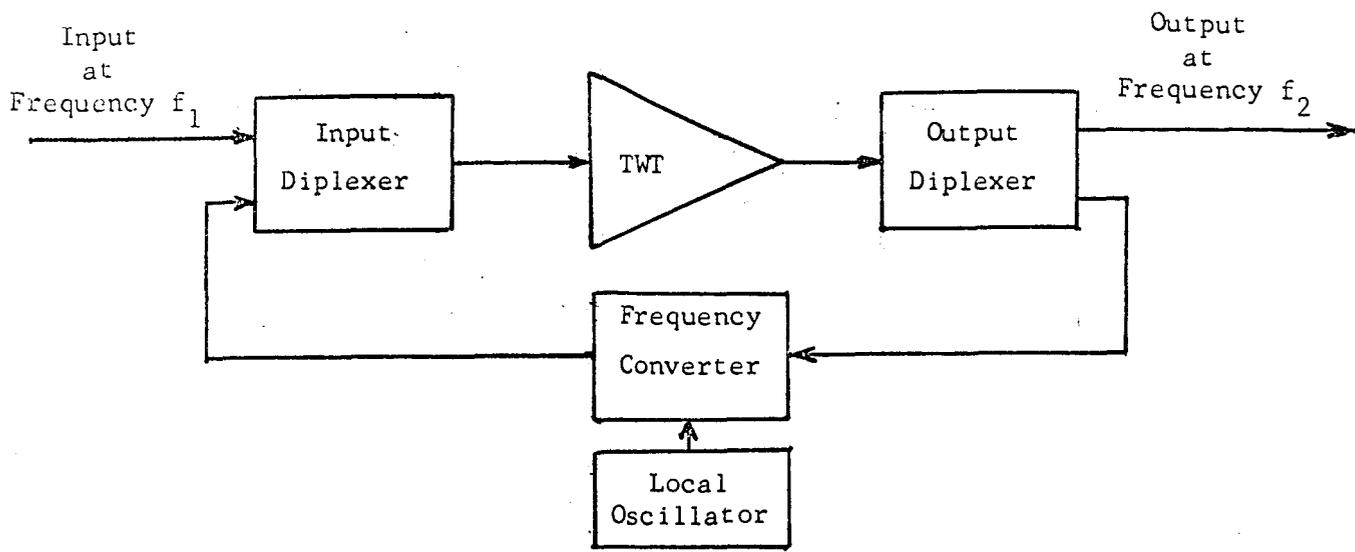


Figure 1-2

Re-entrant TWT Direct RF to RF Amplifier

The input signal at a carrier frequency f_1 passes through the first diplexer and is amplified by the TWT. It is then directed by the second diplexer to the frequency converter where it is converted to carrier frequency f_2 . This signal again passes through the first diplexer and it re-enters the TWT where it is again amplified.

Repeater systems employing a form of RF to RF conversion have been in use since 1956 in microwave relaying systems for long-distance TV transmission,⁽³⁾ and a reflex repeater system employing a 100 Mc frequency shift was proposed in 1962 for a synchronous altitude communications link.⁽⁴⁾ In all previous systems, however, the frequency shift and usable bandwidth are not sufficient for employment in a wideband transponder with a multiple access capability. Present frequency band allocations for communications satellites require that the received, or uplink, frequency fall near the 6000 Mc region and the re-transmitted, or downlink, frequency be in the 4000 Mc area.

Realization of this frequency translation and the necessary gain and bandwidth in a usable satellite transponder require that system components be specifically tailored and integrated, using state-of-the-art techniques, for use in a re-entrant loop.

The absence of an IF chain in the direct RF to RF converter removes the bandwidth restrictions inherent in the conventional system. Overall transponder bandwidths of 500 Mc can be attained, if desired, by proper component selection and design. Traveling wave tubes are available which can accommodate signals across an octave bandwidth.

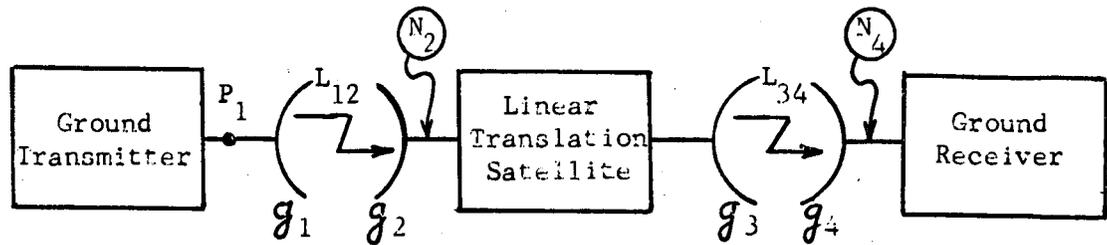
Wide system bandwidths would allow multiple carriers to be placed across the band at given intervals, and the channel bandwidth and channel capacity could be varied to suit the needs of the desired communications link. The transmission parameters of the transponder, therefore, would be designed to allow adequate bandwidth and noise characteristics for multi-station access, with sufficient dynamic range and transmitted power to cover widely diverse communications links.

In addition, the wideband transparent satellite will allow the use of completely different modulation techniques through the same satellite, permitting the user to select a modulation scheme best suited for his particular requirements.

The choice of a gain limited (constant satellite transmitted power) or a linear (constant satellite gain) communications transponder will depend on the desired link requirements and characteristics. A multiple carrier system, for example, may require a completely linear translation system to avoid intermodulation effects. Optimum conditions for both cases will be developed in later sections.

II. SATELLITE LINK REQUIREMENTS

The effects of system noise contributions can be observed by an investigation of the overall carrier to noise ratio at the ground receiver of the link. Figure 2-1 shows the location of the various power level parameters in the link and describes the nomenclature used for noise analysis.



P_1 = Transmitted Carrier Power

$$g_i = \text{Antenna Gain} = N_i \frac{4\pi A_i}{\tau_i^2}$$

where N_i = antenna efficiency

A_i = effective antenna aperture (ft)²

τ_i = free space wavelength

$$L_{12} = \text{Uplink Free Space Attenuation} = \left(\frac{\tau_1}{4\pi d_{12}} \right)^2$$

$$L_{34} = \text{Downlink Free Space Attenuation} = \left(\frac{\tau_2}{4\pi d_{34}} \right)^2$$

where d_{12} and d_{34} = Free Space Transmission Range

N_2 = Uplink Thermal Noise Power

N_4 = Downlink Thermal Noise Power

Figure 2-1

Satellite Link System Parameters

Thermal noise introduced in the system is referred to two points in the link. The uplink noise power, N_2 , referred to the satellite input terminals, is the sum of the thermal noise introduced by the uplink free space link and by that internally generated in the satellite. The downlink noise power, N_4 , referred to the ground receiver input terminals, is the sum of the thermal noise introduced by the downlink free space link and by that internally generated in the ground receiver.

The carrier to noise ratio at the input terminals to the spacecraft, using the nomenclature of Figure 2-1*, is

* Unless otherwise noted, all power levels are expressed in milliwatts (mw), and all gain or loss factors are expressed as dimensionless quantities.

$$\left(\frac{C}{N}\right)_S = \frac{g_1 g_2 L_{12} P_i}{N_2} \quad (2-1)$$

where $N_2 = kT_s B_s$

k = Boltzman's constant, $(1.38 \times 10^{-14} \text{ mw/Mc/}^\circ\text{K})$

T_s = Effective noise temperature of the spacecraft input terminals, ($^\circ\text{K}$)

B_s = Satellite noise bandwidth (Mc)

For a linear repeater satellite with no internal power limiting the total power present at the output terminals of the satellite is

$$g_1 g_2 g_s L_{12} P_i + g_s N_2$$

where:

g_s = satellite electronic power gain

The carrier to total noise ratio at the ground receiver terminals is

therefore,

$$\left(\frac{C}{N}\right)_T = \frac{g_1 g_2 g_s g_3 g_4 L_{12} L_{34} P_i}{g_3 g_4 g_s L_{34} N_2 + N_4} \quad (2-2)$$

where $N_4 = kT_g B_g$

T_g = Effective noise temperature of the ground receiver input terminals, ($^\circ\text{K}$)

B_g = Ground receiver noise bandwidth, (Mc)

The link losses and antenna gains can be broken up into uplink and downlink contributions.

$$L_T \equiv L_U L_D$$

where $L_U = g_1 g_2 L_{12}$ and $L_D = g_3 g_4 L_{34}$

Therefore, Equation 2-2 becomes

$$\left(\frac{C}{N}\right)_T = \frac{L_T g_s P_i}{L_D g_s N_2 + N_4} \quad (2-3)$$

For $B_s = B_g = B$, Equation 2-3, in terms of effective noise temperature, is

$$\left(\frac{C}{N}\right)_T = \frac{g_s L_T P_i}{k (g_s h_0 T_s + T_g) B} \quad (2-4)$$

From this result an effective system noise temperature can be defined as

$$T_e = g_s h_0 T_s + T_g \quad (2-5)$$

Figure 2-2 shows T_e for various satellite and ground noise temperatures as a function of $G_s L_D$.

Rearranging terms, and expressing in db, equation 2-4 can be written

$$\left[\left(\frac{C}{N}\right)_T - P_i - L_T \right] = g_s - N_e \quad (2-6)$$

Let

$$\left(\frac{C}{N}\right)_T - P_i - L_T = K \quad (2-7)$$

Then

$$g_s - N_e = K \quad (2-8)$$

Figure 2-3 shows Equations (2-7) and (2-8) with the common coordinate K plotted vertically. This plot can be utilized in determining any one of the parameters $\left(\frac{C}{N}\right)_T$, g_s , P_i , N_e , or L_T for a given satellite link. As an example of the use of this graph, consider the link with the parameters shown below.

$$G_s \text{ (db)} = 110 \text{ dbm}$$

$$P_i = 5 \text{ Kw}$$

$$L_U \text{ (db)} = -137 \text{ db}$$

$$L_D \text{ (db)} = -137 \text{ db}$$

$$L_T \text{ (db)} = -274 \text{ db}$$

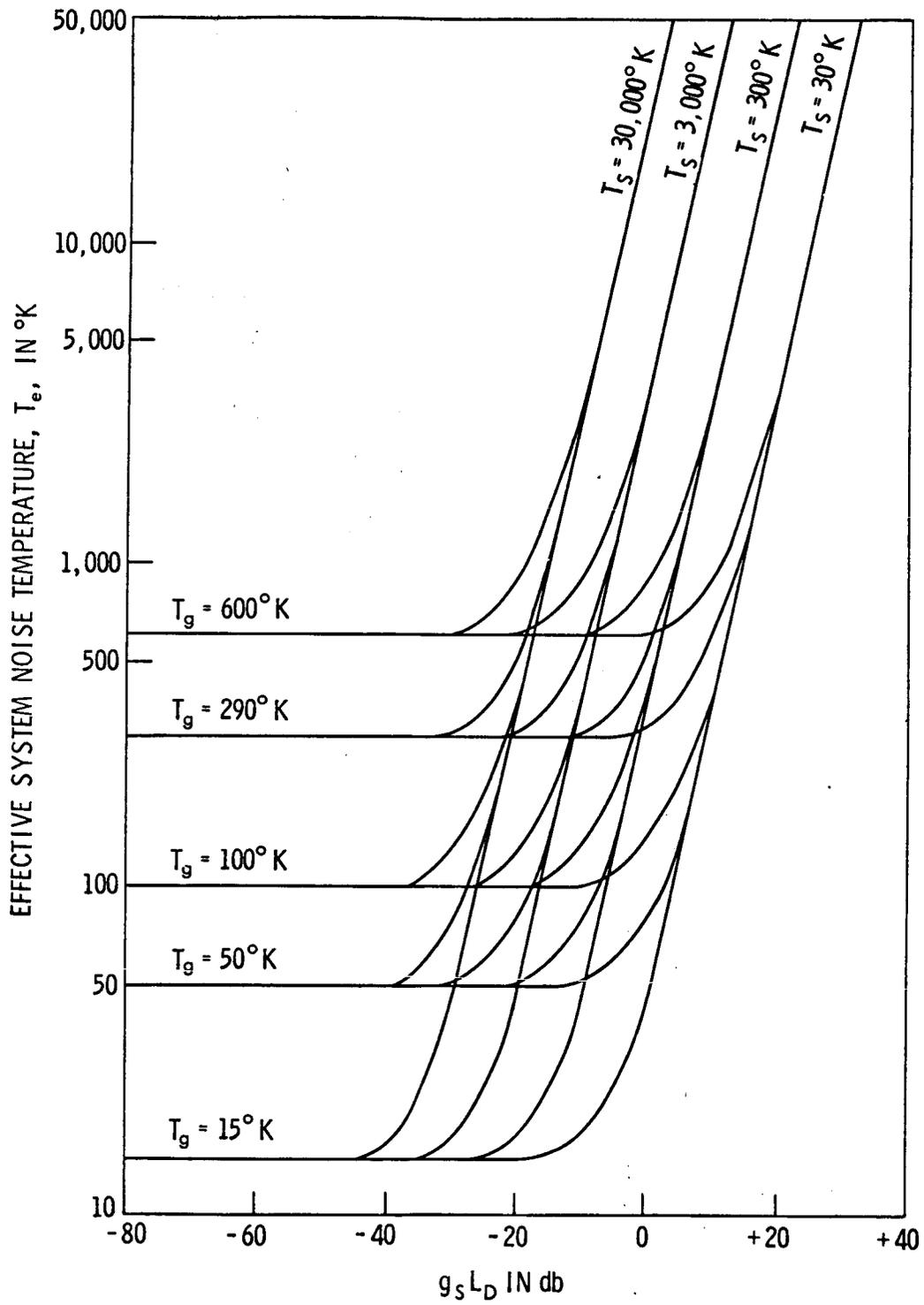


Figure 2-2—Effective System Noise Temperature as a Function of Satellite Power Gain

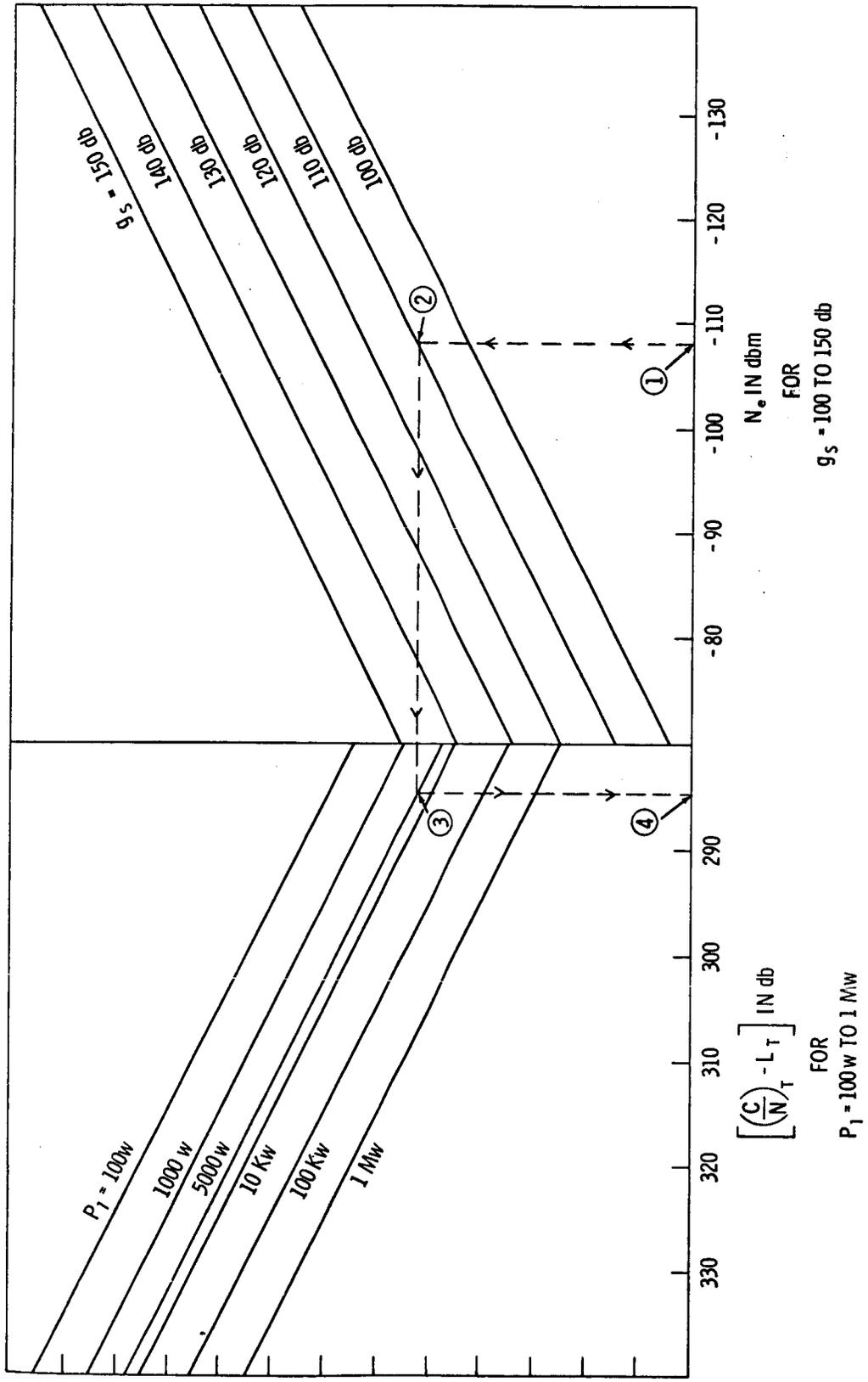


Figure 2-3-Carrier to Noise Ratio vs. System Parameters N_e , G_s , P_T and L_T

$$T_e = 100^\circ\text{K} \quad \text{and} \quad B = 10 \text{ Mc}$$

$$\therefore N_e = -108 \text{ dbm}$$

It is desired to find the total carrier to noise ratio on the ground, $\left(\frac{C}{N}\right)_T$. First the point $N_e = -108 \text{ dbm}$ (point ①) on Figure 2-4) is located. Then this line is followed to the intersection with $G_s = 110 \text{ db}$ line (point ②). Then proceed over to the $P_1 = 5 \text{ Kw}$ line (point ③). Finally the intersection of this line with the right abscissa (point ④) gives

$$\left[\left(\frac{C}{N}\right)_T - L_T\right] = 285 \text{ db}$$

Therefore

$$\left(\frac{C}{N}\right)_T = 285 - 274 = 11 \text{ db}$$

III. TRANSPONDER REQUIREMENTS

A range of satellite requirements will now be determined for the direct RF to RF transponder utilizing the parameters and the results of Section II.

Considering first the completely linear repeater system, the required satellite electronic gain will be determined by the minimum allowable satellite transmitted power for adequate reception at the ground receiver.

If the satellite gain is increased, holding all other parameters the same, a maximum attainable total carrier to noise ratio will be reached above which no amount of added gain will produce an improvement.

From Equation (2-4)

$$\left(\frac{C}{N}\right)_T = \frac{g_s L_T P_i}{k g_s L_o T_s B + k T_g B}$$

The uplink contribution to the total signal to noise ratio is,

$$\left(\frac{C}{N}\right)_U = \left(\frac{C}{N}\right)_T \Big|_{T_g=0} = \frac{g_s L_T P_i}{k g_s T_s L_o B} = \frac{L_o P_i}{k T_s B} \quad (3-1)$$

Similarly, the downlink contribution to the total signal to noise ratio is,

$$\left(\frac{C}{N}\right)_D = \left(\frac{C}{N}\right)_T \Big|_{T_s=0} = \frac{g_s L_T P_i}{k T_g B} \quad (3-2)$$

The total carrier to noise ratio can be expressed as

$$\left(\frac{C}{N}\right)_T = \frac{\left(\frac{C}{N}\right)_U \left(\frac{C}{N}\right)_D}{\left(\frac{C}{N}\right)_U + \left(\frac{C}{N}\right)_D} \quad (3-3)$$

or

$$\left(\frac{N}{C}\right)_T = \left(\frac{N}{C}\right)_U + \left(\frac{N}{C}\right)_D$$

The relative effect of the uplink noise referred to the ground receiver ($k g_s L_D T_s B$) and of the downlink noise ($k T_g B$) on the total carrier to noise ratio will depend on the magnitude of g_s , assuming all other parameters remain the same.

Figure 3-1 shows the variation of total carrier to noise ratio with satellite gain for satellite noise temperatures of 300°K and 3000°K, and noise bandwidths of 1 Mc and 50 Mc. The "knee" of each curve occurs where both noise contributions are equal or where

$$g_s L_D T_s = T_g \quad (3-4)$$

Below this point the downlink noise predominates; above this point the uplink noise, which includes the internally generated noise of the satellite, is the major contributor.

The choice of satellite gain for a given communications link solely on the basis of maximum attainable carrier to noise ratio indicates that a value above the "knee" of the carrier to noise-gain curve for the link should be chosen. In this area, however, the satellite noise temperature is a major contributor to the

carrier to noise ratio and any rise in satellite noise, caused, for example, by component degradation or aging, will produce a strong drop in the total carrier to noise ratio. In the link shown in Figure 3-1, a rise of T_s from 300°K to 3000°K (corresponding to an increase in satellite noise figure of about 7.5 db) will degrade the total carrier to noise ratio by 10 db.

All present day communication satellites operate well below the knee of the gain curve. Operation in this range minimizes the effect of uplink noise, making the resulting carrier to noise ratio almost completely dependent on the ground receiver noise temperature, where low cooled temperatures can be maintained.

Satellite links employing point to point communication with small ground stations, however, will require a better balance between uplink and downlink noise contributions for a usable system. With the uplink limited in available transmitted power, and the downlink limited in sensitivity, the satellite transponder will require a lower front end noise temperature and a higher electronic gain to produce a usable link. Hence, for the small ground station link, operation at or near the "knee" of the gain curve will result in the most efficient use of all components in the link.

In general, for a communications transponder, whether a large ground station or a limited ground station link, the operating gain for minimum degradation of the carrier to noise ratio by satellite noise effects should, therefore, be

$$g_s \leq \frac{T_g}{L_o T_s} \quad (3-5)$$

Once the particular satellite link of interest and its desired communications characteristics are specified, the optimum point of operation on the gain curve can be predicted.

The effect of internally generated satellite noise on the carrier to noise

ratio is directly related to the satellite gain, as evidenced above. Figure 3-2 indicates the total carrier to noise ratio as a function of satellite receiver noise temperature for satellite gains of 110, 123 and 130 db.

Operation at $g_s = 110$ db, corresponding to operation below the "knee" on Figure 3-1, results in minimum degradation of carrier to noise ratio with noise temperature. At 130 db however, the carrier to noise ratio is reduced by nearly 17 db as the noise temperature increases from 300°K to 3000°K.

Let

$$g_s' = \frac{T_g}{L_o T_s} \quad (3-6)$$

which corresponds to the maximum allowable gain, from Equation (3-5).

Then the resulting carrier to noise ratio is

$$\begin{aligned} \left(\frac{C}{N}\right)_T &= \frac{g_s' L_T P_i}{k g_s' L_o T_s B + k T_g B} \\ &= \frac{T_g/T_s L_o P_i}{2 k T_g B} \\ &= \frac{L_o P_i}{2 k T_s B} \end{aligned} \quad (3-7)$$

This corresponds to the uplink contribution (Equation 3-1), degraded by 3 db.

$$T_s = \frac{L_o P_i}{2 k B \left(\frac{C}{N}\right)_T} = \frac{L_o P_i}{k B \left(\frac{C}{N}\right)_u} \quad (3-8)$$

Figure 3-3 shows the required satellite noise temperature as a function of the total carrier to noise ratio for channel bandwidths of 1, 5, 10, and 25 Mc. This graph indicates that to maintain a 20 db carrier to noise ratio a T_s of 30,000°K at 1 Mc and 3000°K at 25 Mc is required in the satellite.

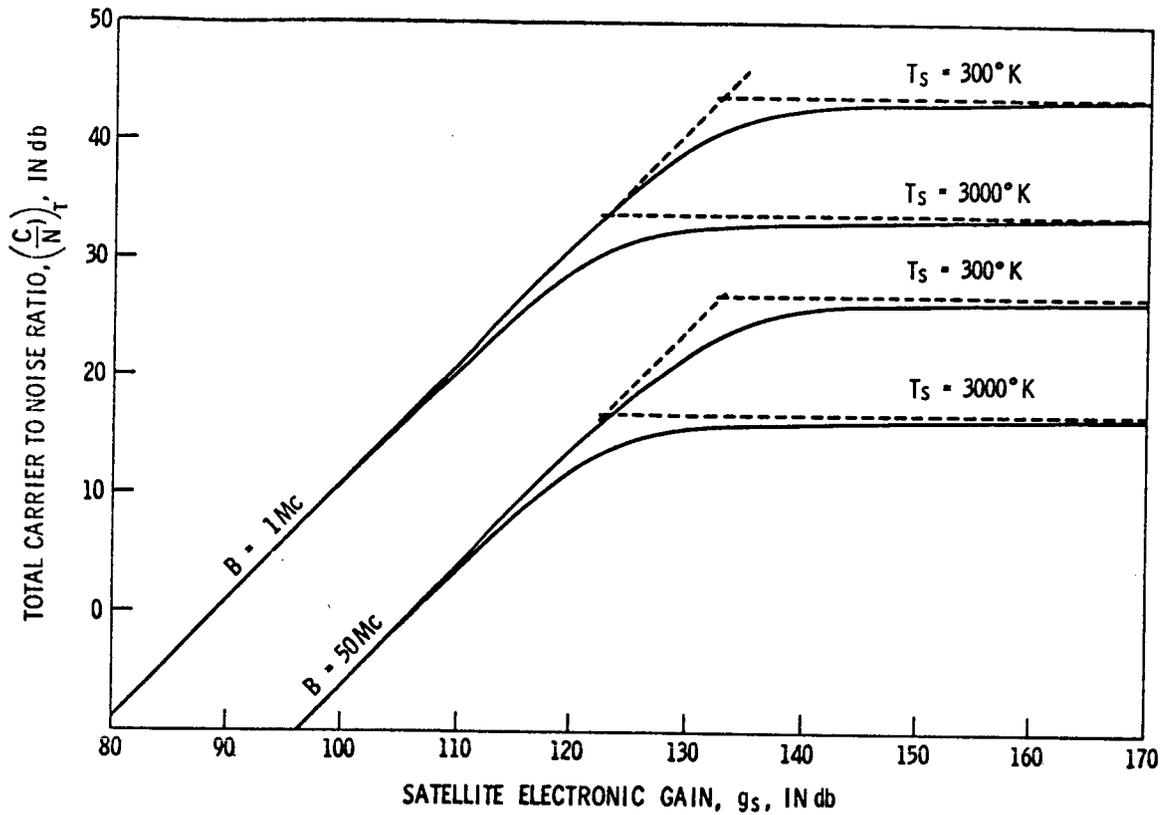


Figure 3-1—Total Carrier to Noise Ratio as a Function of Satellite Gain

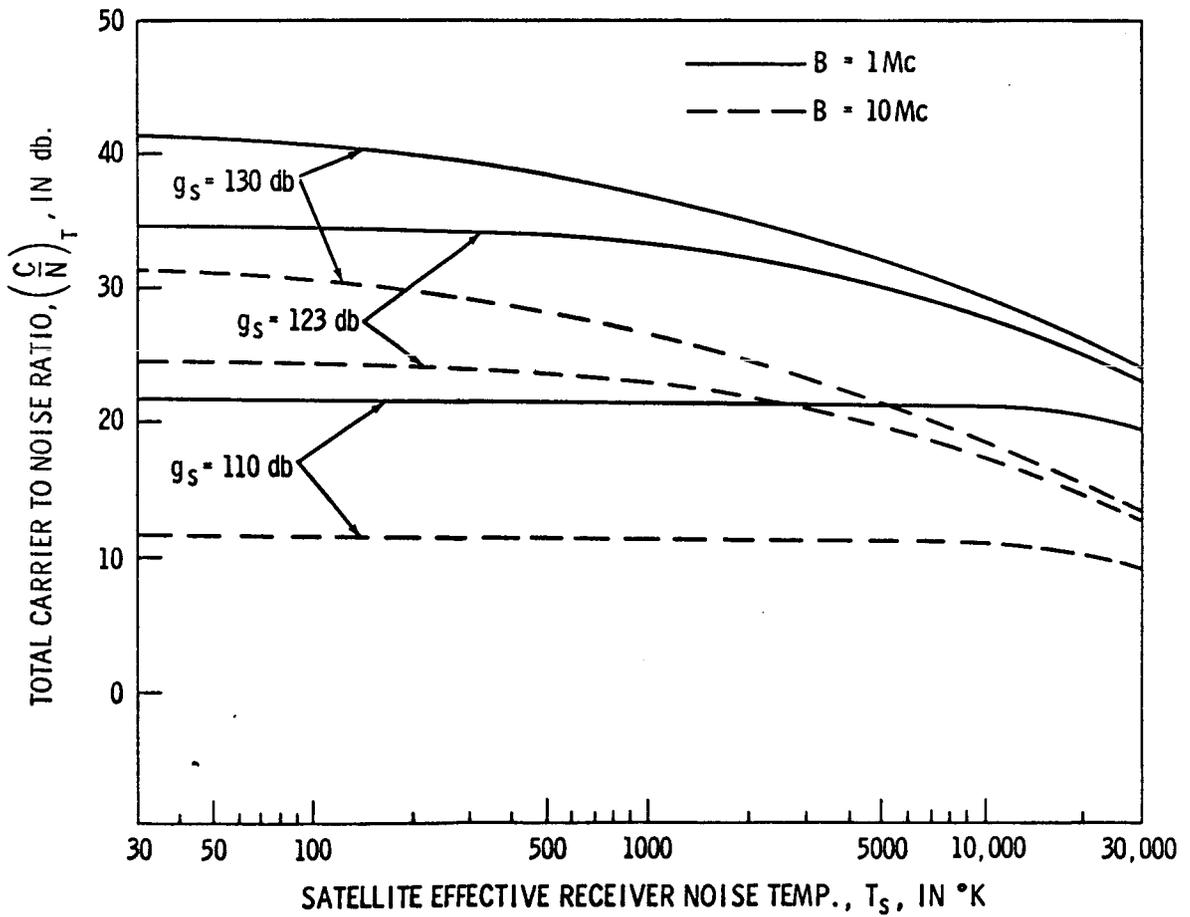


Figure 3-2—Total Carrier to Noise Ratio as a Function of Effective Satellite Noise Temperature

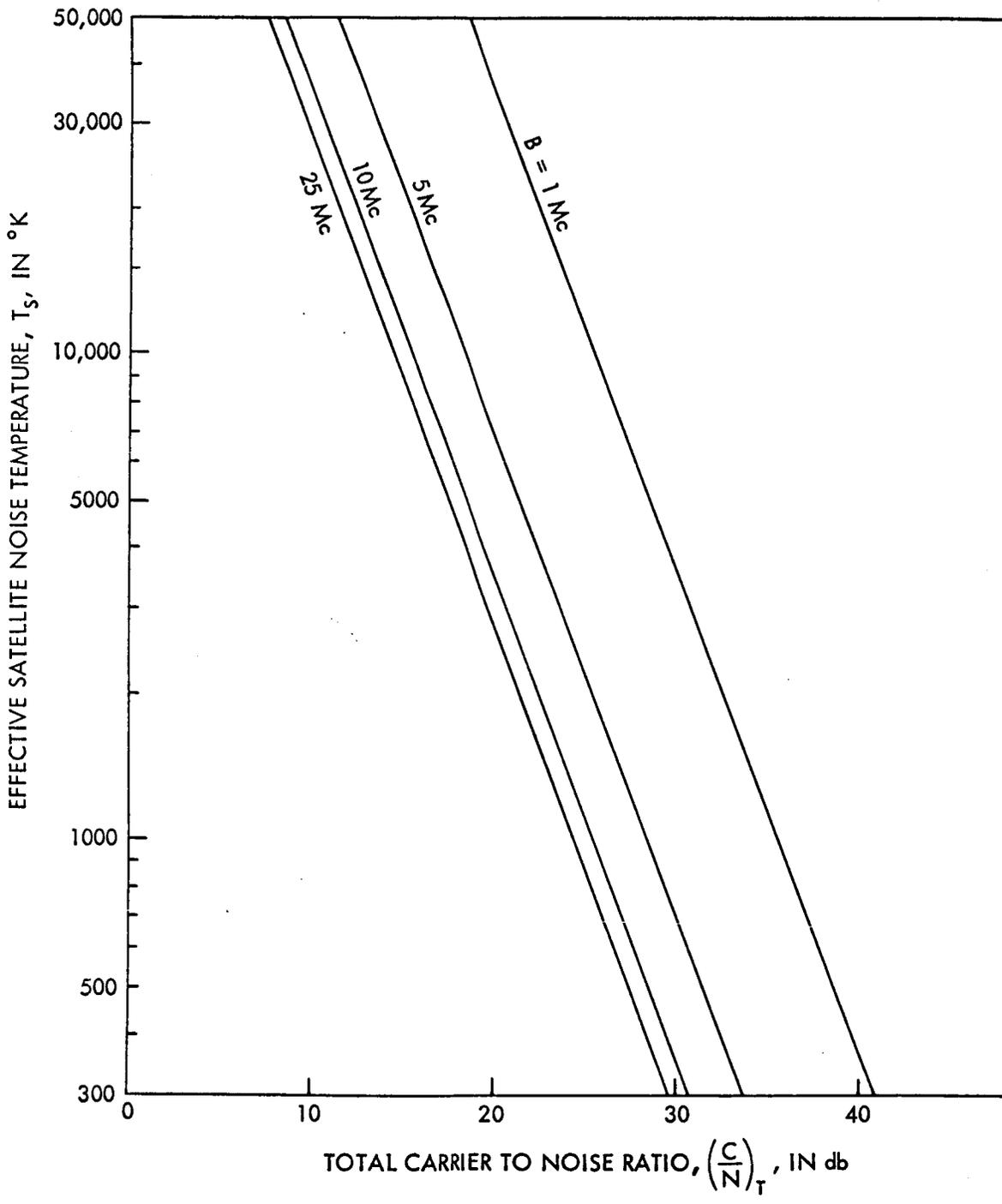


Figure 3-3-Satellite Noise Temperature for $G_s L_D T_s = T_g$

These two temperatures correspond to satellite front end noise figures of about 12 db and 10 db, respectively. It can be seen that for operation at or near a 20 db carrier to noise ratio, a satellite noise figure of 10 db is a reasonable value for the link described.

Once the required total predetection carrier to noise ratio has been determined for a given link, the necessary noise figure can be determined from

$$T_s \leq \frac{L_u P_i}{2 k B \left(\frac{C}{N}\right)'_T} \quad (3-9)$$

where $\left(\frac{C}{N}\right)'_T$ = the minimum allowable ground receiver predetection carrier to noise ratio for satisfactory link operation.

Turning now to the gain limited transponder, the satellite transmitted power is a constant, hence,

$$g_s L_u P_i \equiv P_s \quad (3-10)$$

Therefore, Equation (2-4) becomes

$$\begin{aligned} \left(\frac{C}{N}\right)_T &= \frac{\left(\frac{P_s}{L_u P_i}\right) L_T P_i}{k \left(\frac{P_i}{L_u P_i}\right) L_D T_s B + k T_g B} \\ &= \frac{L_D P_s}{k \left(\frac{P_s L_D}{P_i L_u}\right) T_s B + k T_g B} \end{aligned} \quad (3-11)$$

In this case, the parameters of interest for the transponder are P_s and T_s .

$$\therefore T_e = \frac{P_s L_D}{P_i L_u} T_s + T_g \quad (3-12)$$

The results of the analysis of the linear transponder can be utilized for the gain limited transponder by replacing the gain term g_s with the term $\frac{P_s}{L_U P_1}$, where P_s is a constant. For example, to determine the requirements for operation with a $\left(\frac{C}{N}\right)_T = 20$ db on the $B = 1$ Mc and $T_s = 3000^\circ\text{K}$ curve of Figure 3-1,

$$\frac{P_s}{L_U P_1} = 110 \text{ db}$$

Therefore, for $L_U = -137$ db and $P_1 = 67$ dbm the required P_s will be 40 dbm or 10 watts.

For the direct RF to RF transponder, the realization of the gain limitation is made more difficult since no IF limiters can be used. Therefore, RF limiting utilizing ferrite devices may be necessary if adequate limiting cannot be realized in the output power stages.

For multiple carrier systems where gain limiting is desired one TWT operating saturated will be required for each one (or two) carriers. If limiting prior to the re-entrant loop could be accomplished, multiple output tubes may not be required.

Using presently available components, the necessary gain and input sensitivity for a communications link cannot be realized in the re-entrant loop alone. Therefore, in addition to the re-entrant amplifier an output power stage and a low-noise pre-amplifier front end are required. Figure 3-4 shows the power level and gain distribution of one possible configuration for the sample link.

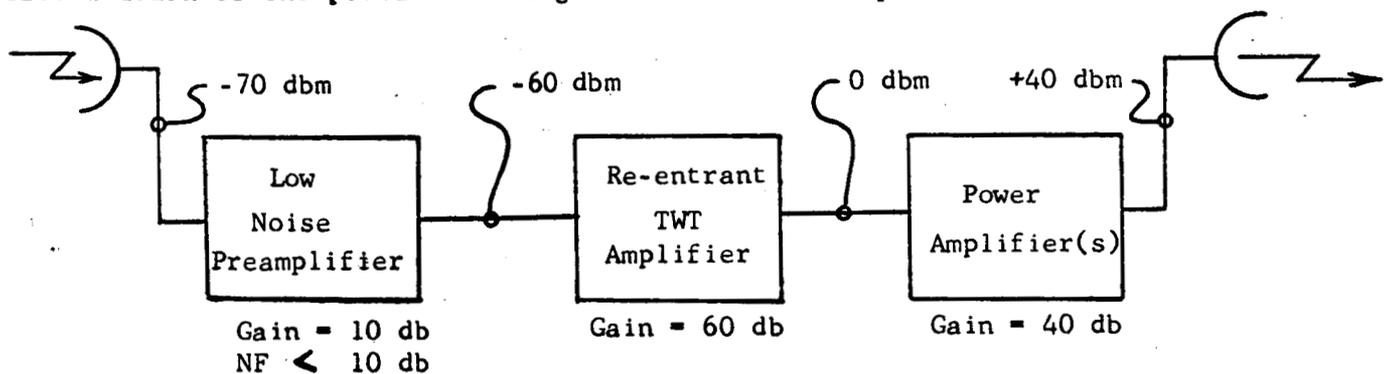


Figure 3-4

Power Level Distribution for Direct RF to RF Transponder

As mentioned previously, a gain limited multiple carrier system would require multiple output power TWTs to obtain the necessary limiting on each carrier. For the linear system, however, two possibilities exist. All of the carriers could be passed through a single power TWT operating well below saturation in its linear (constant gain) region. Or, each carrier could be directed to a separate TWT for linear amplification. In the first system, the TWT must be able to accommodate the total power requirements of all of the carriers, and must have sufficient dynamic range to handle the two extreme conditions of one carrier alone or all carriers simultaneously. The second system requires that each TWT have a power capability to accommodate one carrier and a dynamic range necessary to accommodate that carrier.

In summary, the power and noise characteristics that can be attained in the required amplifying devices will determine the number of system stages needed. That combination of available r.f. components which can realize the necessary gain and sensitivity requirements in the minimum size and weight will determine the optimum RF to RF re-entrant transponder configuration.

IV. CRYSTAL MIXER RE-ENTRANT AMPLIFIER

Figure 4-1 shows a block diagram of the re-entrant TWT amplifier utilizing a crystal mixer for frequency conversion.

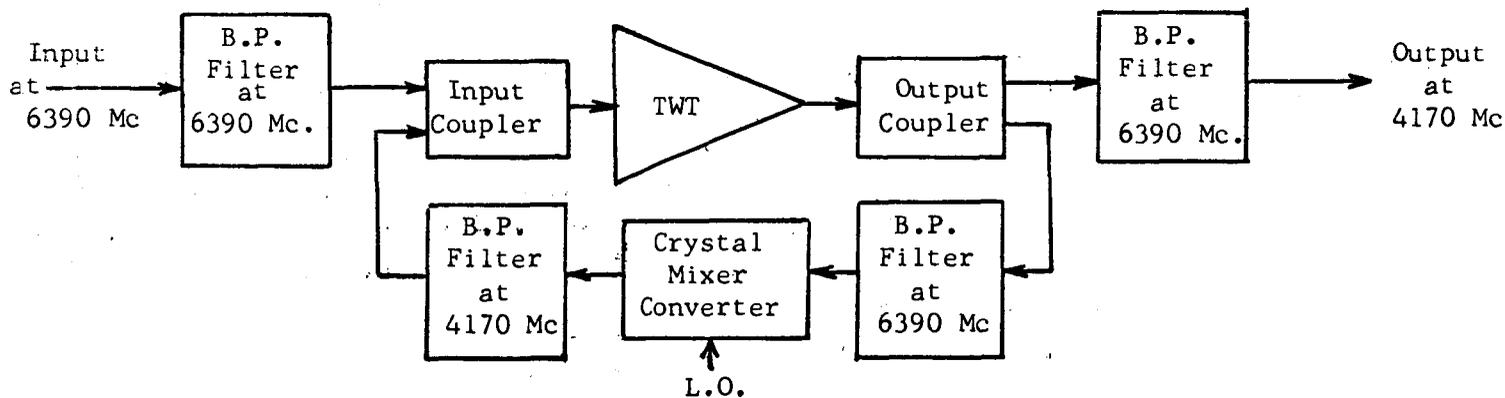
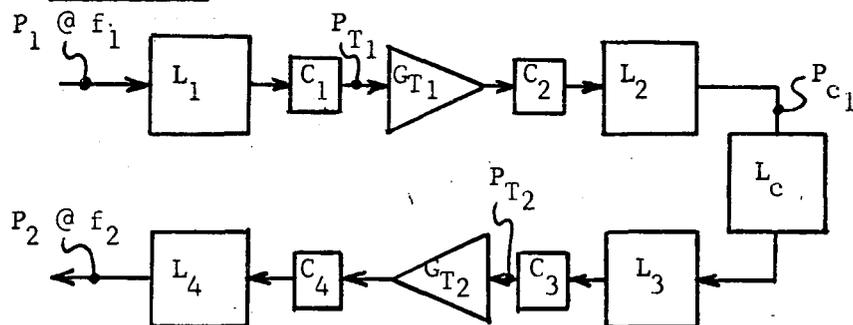


Figure 4-1

Crystal Mixer Re-entrant TWT Amplifier

The input signal at 6390 Mc passes through the input coupler and enters the TWT. After amplification, the output coupler directs the signal through the re-entrant loop where it is converted to 4170 Mc at the crystal mixer converter. This signal then re-enters the TWT through the input coupler and is directed by the output coupler through the output filter at 4170 Mc.

The power levels through the loop will be determined by the realizable gain and power output of the TWT. The power level distribution for an input carrier level of P_1 dbm can be determined by considering the loop as a system of two cascaded TWT amplifiers with the filters and the converter interposed between them, as shown in Figure 4-2.



- L_i = Midband Filter Insertion Loss
- C_i = Coupler Loss
- L_c = Crystal Mixer Conversion Loss
- G_{T1} = TWT Gain at Frequency f_1
- G_{T2} = TWT Gain at Frequency f_2

Figure 4-2

Cascaded Re-entrant Amplifier Representation

The power level at the output port, P_2 , will be

$$P_2 = \frac{G_{T1} G_{T2}}{L_1 L_2 L_3 L_4 C_1 C_2 C_3 C_4 L_c} P_1 \quad (4-1)$$

Assuming that

$$L_1 = L_2 = L_3 = L_4 \equiv L$$

$$C_1 = C_2 = C_3 = C_4 \equiv C$$

Then

$$P_2 = \frac{G_{T_1} G_{T_2}}{16G LC L_c} \quad (4-2)$$

The overall gain in db is

$$G_s \text{ (db)} = G_{T_1} + G_{T_2} - 4L - 4C - L_c \quad (4-3)$$

Also,

$$P_c \text{ (db)} = P_1 + G_{T_1} - 2L - 2C \quad (4-4)$$

Figure 4-3 indicates the total system gain G_s , the power output P_2 , and the mixer input level P_c , for the TWT gain of 20 to 50 db per pass. For this curve, the TWT gain is assumed to be the same for both the input and the output signal frequencies. A conversion loss of 10 db is typical for broadband mixing utilizing a local oscillator of 2220 Mc or 10560 Mc.

Figure 4-4 shows the resulting power distribution for the re-entrant amplifier for a single carrier input level of -60 dbm and a TWT gain of 40 db.

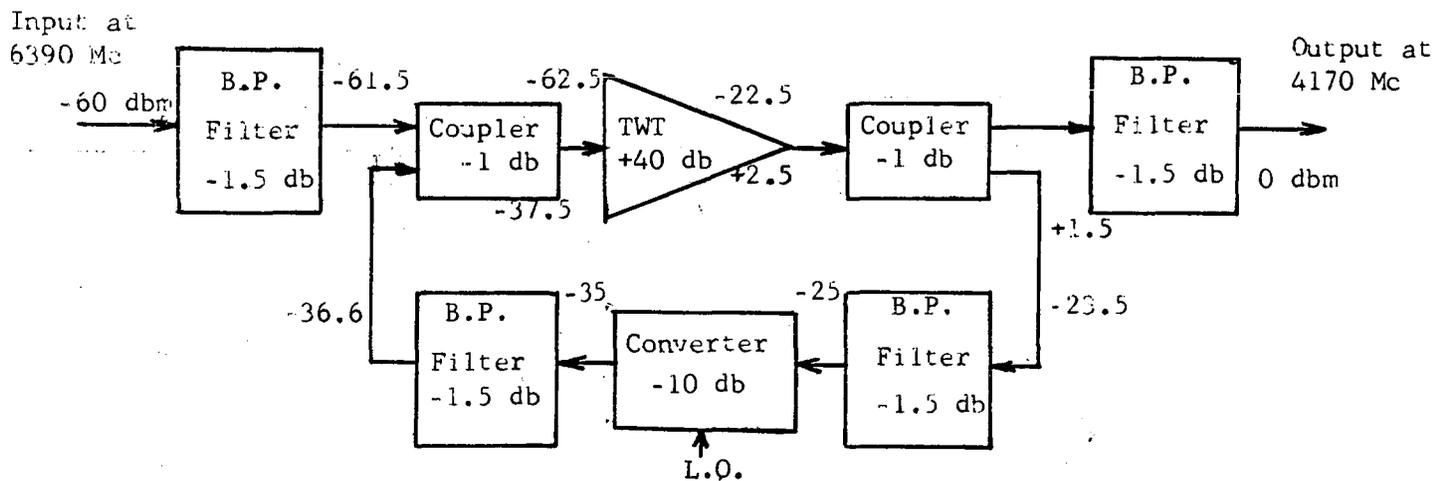


Figure 4-4

Single Carrier Power Level Distribution for the Re-entrant Amplifier

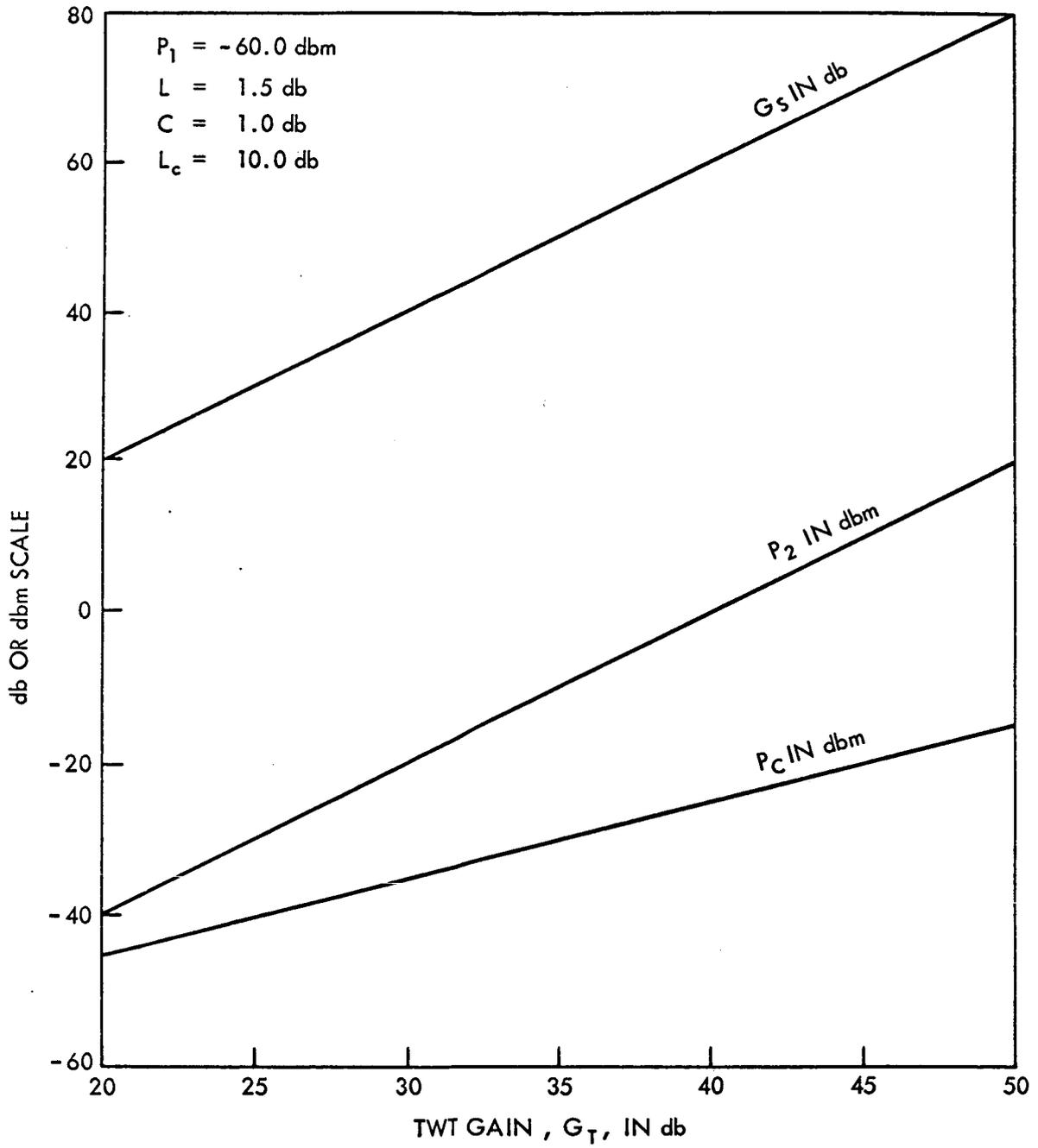


Figure 4-3—Power Level Characteristics of Re-entrant Amplifier vs. TWT Gain

For multiple carrier operation of the loop, the power handling capability of the TWT and the converter will be of primary interest in determining the allowable input signal level and number of carriers.

The overall noise figure N_a , of the re-entrant amplifier loop can be expressed in terms of the TWT noise figure as

$$N_a = L + \frac{C-1}{\frac{1}{L}} + \frac{N_{T1}^{-1}}{\frac{1}{L} \frac{1}{C}} + \frac{N_{T2}^{-1}}{\frac{1}{3L} \frac{1}{3C} \frac{1}{L_c} G_{T1}} \quad (4-5)$$

where

- L = insertion loss of input filter
- C = insertion loss of input coupler
- L_c = conversion loss of frequency converter
- N_{T1} = noise figure of TWT at frequency f_1
- N_{T2} = noise figure of TWT at frequency f_2
- G_{T1} = power gain of TWT at frequency f_1

For N_{T2} (db) less than 30 db, the third term becomes negligible and

$$N_a = L + LC - L + LCN_{T1} - LC$$

$$N_a = LCN_{T1} \quad (4-6)$$

Expressed in db,

$$N_a \text{ (db)} = N_{T1} \text{ (db)} + L + C \quad (3-8)$$

For a transponder utilizing a pre-amplifier with a relatively low noise figure, the overall noise figure of the transponder can be significantly reduced by the re-entrant loop TWT.

The re-entrant TWT noise figure required to maintain a 10 db total transponder noise figure is shown in Figure 4-5 as a function of pre-amplifier noise

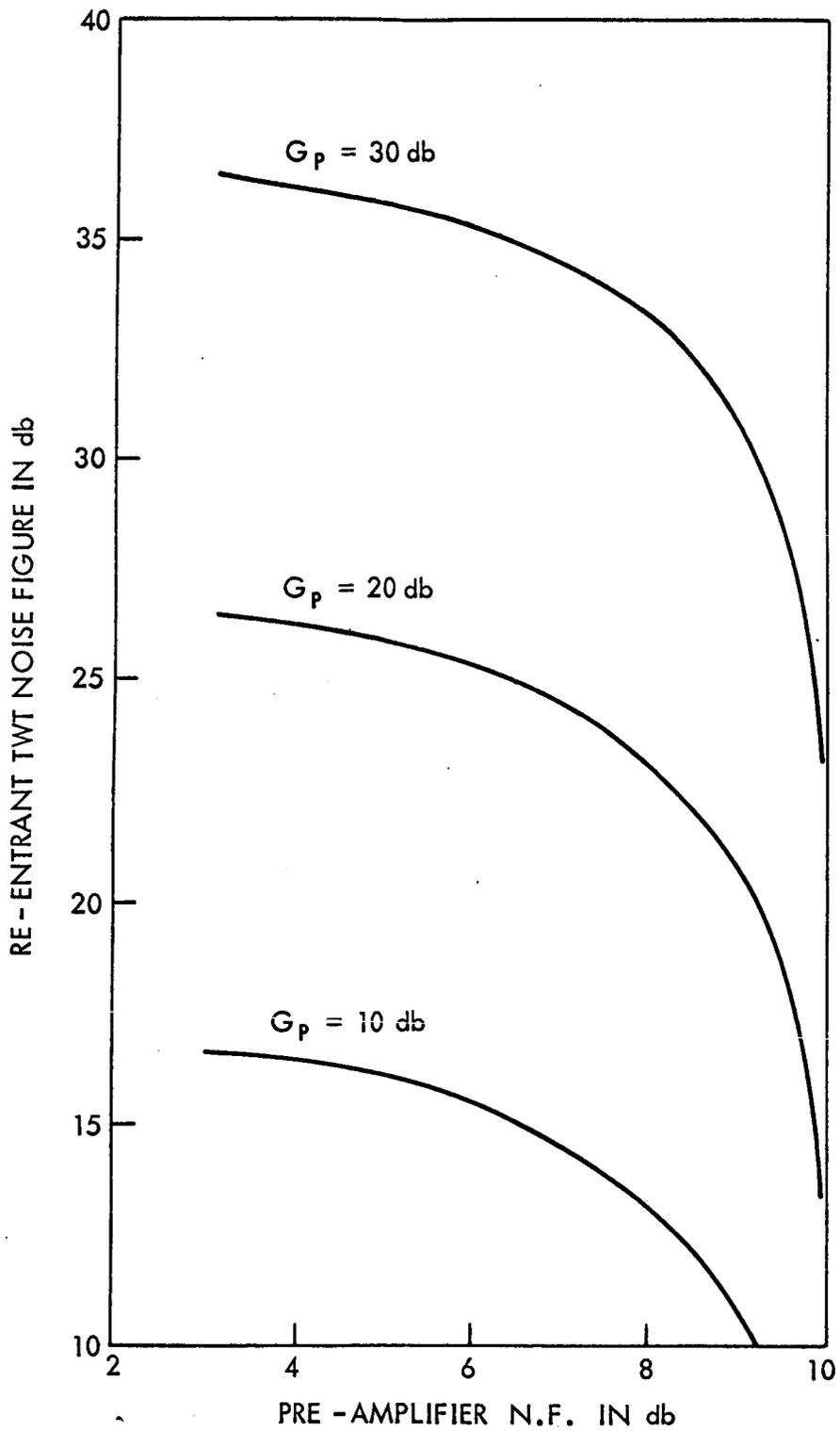


Figure 4-5—Pre-Amplifier and Re-entrant TWT Noise Requirements to Maintain a 10 db Total System Front End Noise Figure

figure, for pre-amplifier gains, G_p , of 10, 20 and 30 db. As can be seen from the curves, the pre-amplifier gain sets strong requirements on the loop TWT. Medium power TWTs typically have noise figures from 25 to 30 db and higher, hence a preamplifier gain of 20 db or more is necessary to maintain the 10 db total noise figure.

Typical tunnel diode amplifiers have exhibited 5 db noise figures with 17 db of small signal gain at 6390 Mc, indicating that a re-entrant TWT noise figure of 22.8 db or better would be required.

The TWT in the system of Figure 4-4 must have sufficient dynamic range to accept both the 6390 Mc signal (-62.5 dbm) and the 4170 Mc signal (-37.5 dbm). A multiple carrier system must in addition have adequate dynamic range to operate over all possible carrier loads and level fluctuations.

The power handling capability of the crystal converter also is a factor for multiple carrier systems where the generation of intermodulation products must be considered along with the dynamic range.

Table 4-1 summarizes the power requirements for the loop TWT and the frequency converter for 1, 2, 6, 10, 20, and 50 carriers. The received carrier power at the satellite is assumed to be -70 ± 2 dbm per carrier, and the system parameters are as shown in Figures 3-4 and 4-4. It is further assumed that negligible carrier suppression occurs in the TWT and that all system components exhibit a flat response across the transponder bandwidth. The dynamic range of the TWT includes the signals at both the uplink and downlink frequencies.

The loop TWT saturated output power required for satisfactory multiple-carrier loop operation cannot be determined without a consideration of the intermodulation characteristics of the tube. The allowable level of intermodulation noise and the carrier spacing scheme must be specified for determination of the optimum input carrier level for efficient operation. A carrier power backoff will

Table 4-1
 Power Requirements of Re-Entrant Loop TWT and Frequency
 Converter for Multiple Carrier Conditions

| Number of Carriers | Total Combined Carrier Power into Loop TWT | | Dynamic Range of Carrier Power into Loop TWT | Maximum Combined Output Power of Loop TWT | Total Combined Carrier Power into Frequency Converter | Dynamic Range of Carrier Power into Frequency Converter |
|--|--|-----------------------|--|---|---|---|
| | at Uplink Frequency | at Downlink Frequency | | | | |
| Each at -70 ± 2 dbm Received Carrier Power | dbm | dbm | db | dbm (mw) | dbm | db |
| 1 | -62.5 ± 2 | -37.5 ± 2 | 29 | +4.5 (2.82) | -25 ± 2 | 4 |
| 2 | -59.5 ± 2 | -34.5 ± 2 | 32 | +7.5 (5.63) | -22 ± 2 | 7 |
| 3 | -57.7 ± 2 | -32.7 ± 2 | 33.8 | +9.3 (8.50) | -20.2 ± 2 | 8.8 |
| 6 | -54.7 ± 2 | -29.7 ± 2 | 36.8 | +12.3 (17.0) | -17.2 ± 2 | 11.8 |
| 10 | -52.5 ± 2 | -27.5 ± 2 | 39 | +14.5 (28.2) | -15 ± 2 | 14 |
| 20 | -49.5 ± 2 | -24.5 ± 2 | 42 | +17.5 (56.3) | -12 ± 2 | 17 |
| 50 | -45.5 ± 2 | -20.5 ± 2 | 46 | +21.5 (141) | -8 ± 2 | 21 |

be required as the number of carriers is increased in order to keep the intermodulation products below a predetermined level. Third order intermodulation products predominate in straight-through operation, while the even order products become a factor when the re-entrant loop is introduced.

Very little experimental data on multiple carrier TWT performance above two carriers exists, and none is available for a TWT in a re-entrant loop. Detailed measurements of commercially available traveling wave tubes operating between the saturation and linear gain regions have been made for two and three equal level carriers.⁽⁵⁾ The results for three carriers indicate that the carrier input levels must be at least 15 db below the input level for normalized saturation output* to keep third order output products 20 db below the carriers. Two watt saturated output power tubes were used, and the three carriers were spaced at 105 Mc and 70 Mc intervals.

Application of these data to the re-entrant loop condition can be made under the assumption that the 2220 Mc spacing between the uplink and downlink frequency bands will allow operation with third order products 20 db below the carriers. Then, from Table 4-1, the maximum combined output power of the TWT for 3 carriers is +9.3 dbm. Allowing a 15 db margin, therefore, requires that the normalized saturation output power be +24.3 dbm. Assuming a gain suppression a saturation of about 6 db, the required saturated output power is 30.3 dbm, or about 1 watt. Thus, for three -60 dbm carriers impressed at the input of the system of Figure 4-4, a one watt tube would be required to obtain satisfactory output at 0 dbm per carrier.

The results of Table 4-1 and the above discussion are intended only as a preliminary indication of some of the requirements necessary for multiple carrier operation of the re-entrant transponder. A more complete analysis of the loop

* The input level for 'normalized' saturation output is defined here as the input level at saturation minus a factor equal to the gain compression at saturation.

TWT requirements must await more definitive data on the multiple carrier inter-modulation problem, especially the effects of re-entrant operation through a single traveling wave tube.

V. EXPERIMENTAL RE-ENTRANT SYSTEMS

An experimental re-entrant amplifier employing a 1 watt minimum broadband traveling wave tube was set up to demonstrate the feasibility of re-entrant frequency conversion. The input frequency band was centered at 6390 Mc and the output frequency band at 4170 Mc. The waveguide filters were designed for a 60 Mc passband and frequency conversion was accomplished with a 1N23 series microwave diode.

Figure 5-1 shows the complete re-entrant amplifier system described above. Power measurements for loop gain and bandwidth were made for input levels above, at, and below the input power to saturate the loop. Figure 5-2 shows the output response for the above conditions. It can be seen that the system is input power level sensitive and can be optimized for any input by tuning of the converter and filter cavities. A slight shrinkage of bandwidth occurred because the filter pairs were not tuned to the same exact center frequency. Curve 3 of Figure 5-2 has the smoothest response, with a 2.75 db peak to peak ripple across a 42 Mc bandwidth. At this input, which was 1 db below the input to cause loop saturation, the TWT gain at the input frequency was 40 db and the output frequency was subjected to a 2 db suppression, resulting in a net gain of 30 db.

The measurements were made with the loop tuned for optimum linear response across the band, hence overall loop gain was not maximized. Loop gains of 40 db were obtained by tuning for optimum gain across a narrower bandwidth.

The feasibility of wideband direct conversion for communications satellites was further demonstrated by TRW Space Technology Laboratories with the NASA sponsored development of a laboratory model direct RF to RF transponder consisting

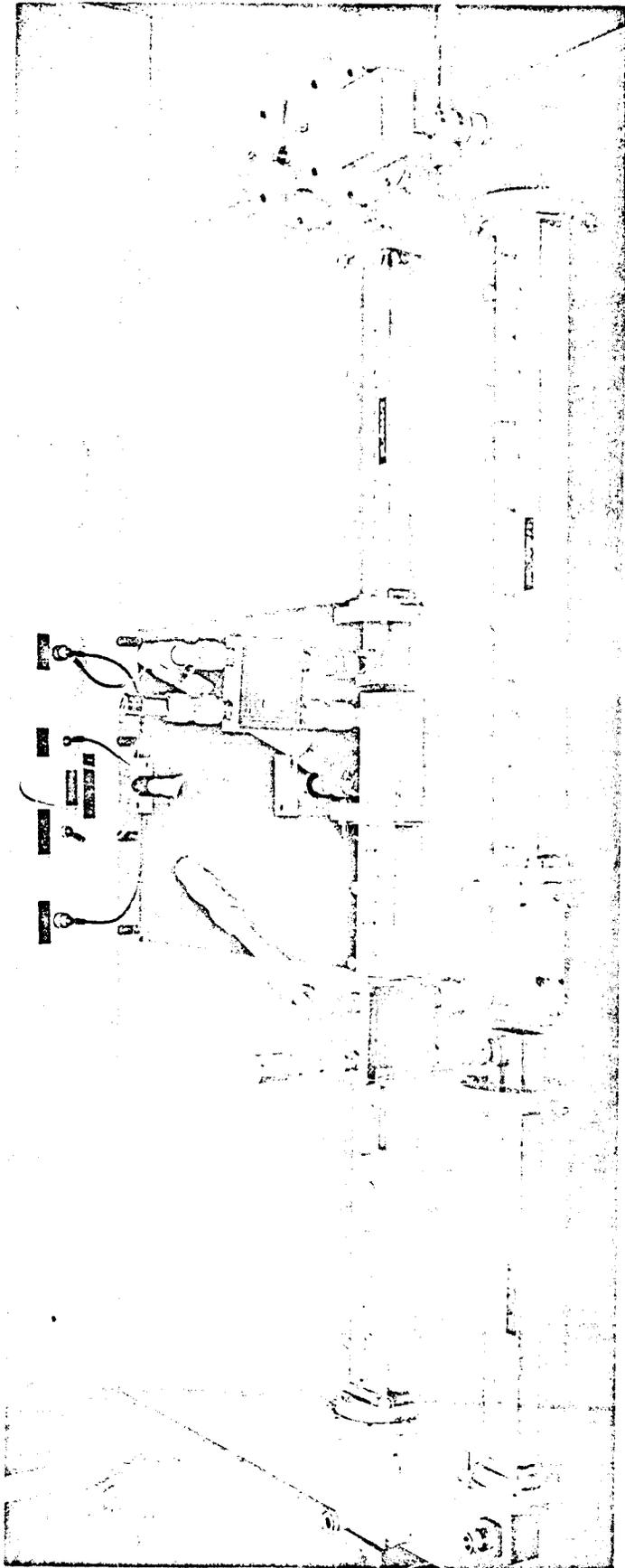


Figure 5-1

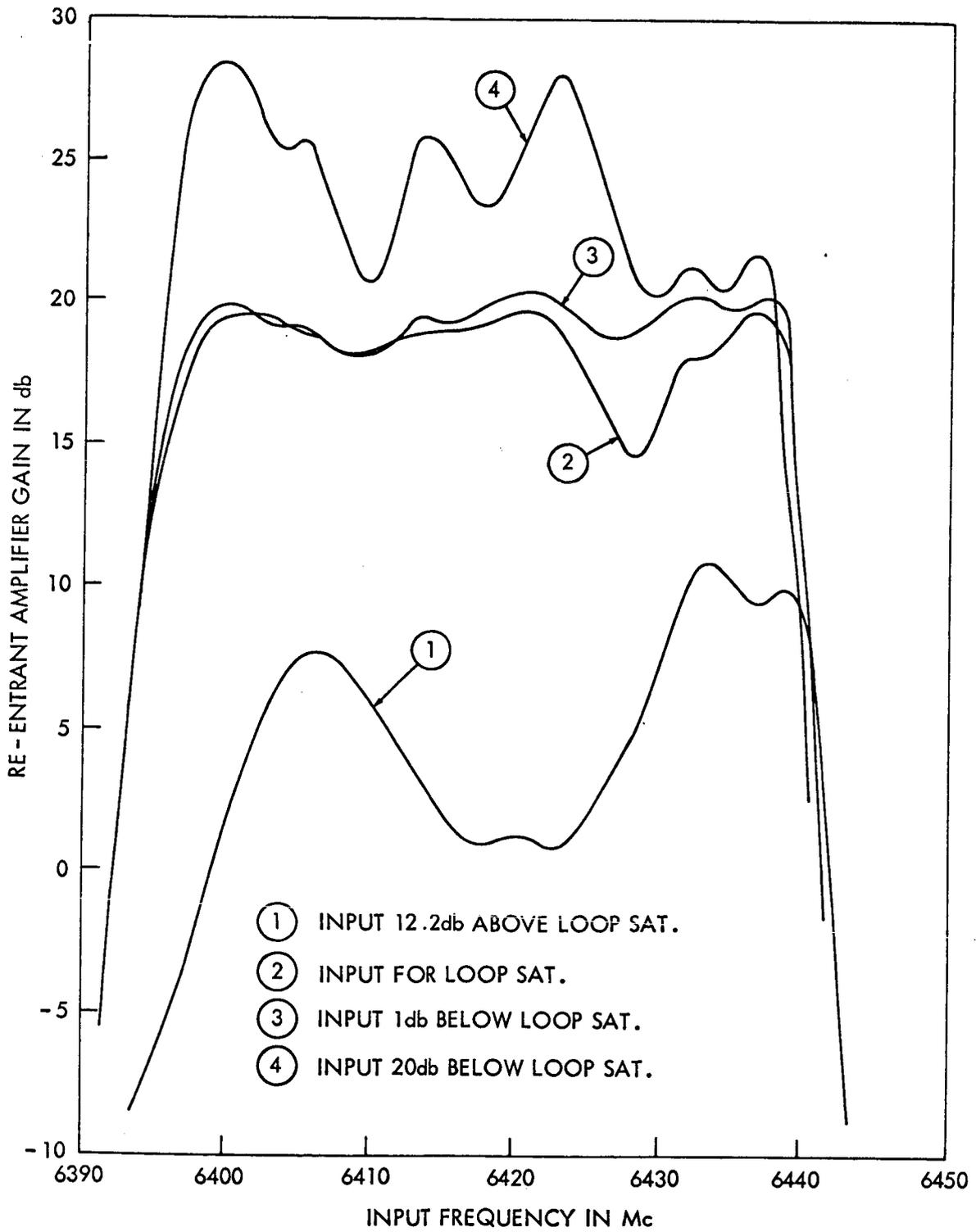


Figure S-2 - Re-entrant Amplifier Response as a Function of Input Level

of a tunnel diode front end, a re-entrant TWT amplifier, and a TWT power output stage.

Overall transponder gains of 95 to 105 db across a 500 Mc bandwidth were obtained for an input level of -70 dbm, with a 9.5 db input noise figure. The re-entrant amplifier gain was 66 ± 2 db at -60 dbm input across a 300 Mc bandwidth, and the frequency converter exhibited a conversion loss of less than 10 db across the 500 Mc transponder bandwidth.

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