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ABSTRACT

The rapid growth of communication traffic (voice, data, and video) requires the development of additional frequency bands before the 1990's. The frequencies currently in use for satellite communications at 6/4 GHz are crowded and demands for 14/12 GHz systems are increasing. Projections are that these bands will be filled to capacity by the late 1980's. The next higher frequency band allocated for satellite communications is at 30/20 GHz. For interrelated reasons of efficiency, power level, and system reliability criteria, a candidate for the downlink amplifier in a 30/20 GHz communications' satellite is a dual mode traveling wave tube (TWT) equipped with a highly efficient depressed collector. This paper gives a summary of the analyses which determine the TWT design requirements. The overall efficiency of such a tube is then inferred from a parametric study and from experimental data on multistaged depressed collectors. The expected TWT efficiency at 4 dB below output saturation is 34 percent in the high mode and 22 percent in the low mode.

I. INTRODUCTION, GENERAL REQUIREMENTS, AND ASSUMPTIONS

Lewis Research Center is evaluating the technological requirements of a digital communications' satellite operating in the uplink/downlink bands at 30/20 GHz. For the purposes of this study we anticipate that a broadband traveling wave tube (TWT) will be the downlink amplifier in the system.

The use of a large bandwidth (17.7 to 20.2 GHz) requires that the slow wave structure of the tube be a helix or some derivative of a helix such as a ring and bar construction.

To overcome the loss in signal power due to rain the TWT will be designed for dual mode operation. It is assumed that with 10 dB of rain attenuation and with two well-spaced ground terminals per downlink beam (two station diversity) the system reliability can be maintained at 99.9 percent.

The envisioned system would assign several channels to each TWT. The tube must be operated backed-off from saturation in order to provide the instantaneous power demands for multichannel use. Normally, for most amplifiers this would result in an excessive loss of efficiency. However, TWT's can be equipped with multistaged depressed collectors (MDC) which can recover much of the loss. This characteristic of an MDC is due to the fact that the energy spread of the spent beam increases as saturation is approached. Below saturation the beam is less turbulent, has less of an energy spread, and is collected more efficiently.

For linear performance, all amplifiers, solid state or TWT, must operate below saturation.

This study was conducted to arrive at the design requirements of a TWT suitable for the downlink segment of a 30/20 GHz digital communications' satellite, and specifically to determine the power rating of the tube and to predict its efficiency at its operating point.

Figure 1 shows a partial list of assumptions that were used in the study. Each of the nine channels was assigned a bandwidth of 274 MHz. Consistent with quadriphase shift keying (QPSK) modulation, the bit rate is 274 Mb/sec per channel. A bit error rate (BER) of 10^{-6}, a 10 dB rain margin, and two ground receiver diversity is assumed to yield a system reliability of 99.9 percent.

II. THE EFFECT OF INTERFERENCE BETWEEN CHANNELS

QPSK modulation produces a frequency spectrum having a sin W/W form in which the main lobe of this spectral distribution carries over 90 percent of the signal energy. To pass the main lobe alone through a band pass filter (BPF) the BT product must be equal to 2; where B is the 3 dB bandwidth of the filter and T is the symbol transit time. The filter bandwidth must, of course, be 274 MHz wide in order to multiplex the nine channels into the total available bandwidth of 2.5 GHz.

Loss of the QPSK frequency side lobes causes distortion in the detected signal and this requires a higher bit energy-to-noise ratio to maintain the same bit error rate. A computer program to simulate channel interference is used to calculate the loss from ideal in an assumed system model. The program basically takes the Fourier transform of a sampled time domain signal, converts it to the frequency domain, multiplies by the spectral response functions of the assumed configuration, and finally determines the degradation of the signal by finding the inverse transform.

The configuration shown in figure 2 was used to calculate the degradation of signal in channel A due to the presence of channels B and C. A Gaussian white noise source is included in the computation. The effect of the TWT and the spacecraft circuitry is not included except as an otherwise distortionless but band limited component. Finally, the signal is recovered by a simulated integrate and dump (I & D) detector.

The result of the computation is plotted in figure 3 and gives the loss from ideal, in dB, as a function of channel spacing. The table in the figure indicates that a single channel without the interfering presence of other channels would experience a loss of 2.36 dB due only to the band pass filters and to the I & D detector. For practical purposes this loss would occur at a channel spacing of $4R_s$. However, for this case only four channels could be assigned to the available bandwidth (2.5 GHz). In order to fit all nine channels a spacing of $2R_s$ (274 MHz) must be used and this results in a loss of 3.73 dB per channel.

An estimate of the output circuit losses in the spacecraft is given in figure 4. The amplifier is considered distortionless as in the previous analysis. Although the figure indicates a TWT, at this point in the analysis the type of amplifier should be regarded as unspecified. The total output circuit loss is estimated at 3.85 dB.

The results of a link calculation using the estimated output circuit loss (3.85 dB) and the degradation loss (3.73 dB) due to filtering and adjacent channel interference are given in figure 5. The computation yields the downlink power required per channel (8.2 W). Some of the significant details in the power budget include rain margin (10 dB), spacecraft antenna diameter (14 ft), and ground station antenna diameter (40 ft). For a bit energy-to-noise (E_b/N_o) ratio of 10.53dB, which is required to maintain the BER at 10^{-6}, the amplifier output power must be 8.2 watts per channel. It is emphasized that this power requirement is for 10 dB of rain margin and for two ground stations (separated between 10 and 20 km) to insure an assumed system reliability of 0.999.

The predicted power level is independent of the type of device to be used as the downlink amplifier. However, it may indicate that it is beyond the capability of solid state devices. Even without the 10 dB rain allowance the required linear power of 0.82 watts per channel seems to be a marginally attainable level for solid state amplifiers at these frequencies.

III. SATURATED POWER OUTPUT REQUIRED OF A TWT FOR MULTICHANNEL USE

The channel arrangement within the available bandwidth of 2.5 GHz with a spacing of $2R_s$ (274 MHz) is shown in figure 6. Also given in this figure is the expression relating the output rf power of a TWT at saturation to the channel power (8.2 W) in multichannel operation. The denominator accounts for the amount of power lost to intermodulation products (third order products are dominant). The power back-off ratio (PBR) is the ratio of saturated to operating point power. This ratio is chosen both to reduce the intermodulation products and to allow operation in the linear region of the tube. Reducing the fraction of power $\left(F_{IM_3}\right)$ dissipated in the third order intermodulation products decreases the total power required of the TWT. There is obviously a tradeoff between PBR and F_{IM_3}.

Operating points are between 4 and 5 dB below saturation (output). For three channels/TWT, and backing-off 4 dB, the rated output power of the tube at saturation is 63 watts. Backing down 5 dB requires 80 watts at saturation.

Typical values of third-order intermodulation products (IM_3) are given in figure 7. At -4 dB and -5 dB from saturation IM_3 are -18 dB and -21 dB below the signal level in the channel.

Assuming three channels/TWT, the channel assignments shown in this figure cause the IM_3 products to fall outside the filter bandwidths and hence to be dissipated before multiplexing takes place.

IV. ESTIMATED TWT EFFICIENCY

Overall TWT efficiency is a strong function of MDC efficiency. Below saturation the spent electron beam of a TWT is less turbulent, has less of an energy spread, and can be collected more efficiently than at saturation if the collector is properly optimized.

Figure 8 shows the collector efficiency as a function of TWT output power for a three stage collector in which the efficiency at each measured point was optimized by changing plate voltages. In the particular tube (8.4 GHz) in which these measurements were made the perveance is about seven times higher than the design point for the downlink TWT amplifier in the 30/20 GHz system under consideration. Collector efficiency improves for low perveances because the energy spread within the beam is less. For the 20 GHz communication tube the perveance will be about 0.05 micropervs and the collector will be designed with five stages.

Figure 9 gives the formula for the overall efficiency of a TWT (η_{total}) in terms of circuit efficiency (η_{ckt}), interaction efficiency (η_{int}), transmission efficiency (η_{tr}) and collector efficiency (η_c). The circuit efficiency is a measure of the circuit losses and is expected to be about 85 percent for the 20 GHz tube.

The interaction efficiency (or electronic efficiency) measures the beam/wave coupling and is taken to be a linear function of the output rf power. It decreases as the tube is backed-off from saturation. At saturation and at 20 GHz an interaction efficiency of 15 percent is estimated. Hence,

$$\eta_{int} = 0.15\left(\frac{P_o}{P_{o,\,sat}}\right)$$

The fraction of beam which passes through the tube and is not lost by interception is given by the transmission efficiency. Beam transmission should be nearly perfect (0.995) for dc ($P_o = 0$) conditions and perhaps vary linearly to 0.95 at saturation ($P_o = P_{o,\,sat}$). The transmission efficiency is taken as

$$\eta_{tr} = 0.995 - 0.045\left(\frac{P_o}{P_{o,\,sat}}\right)$$

Finally, the collector efficiency is assumed to vary linearly from 85 percent at saturation to 98 percent for dc conditions.

$$\eta_c = 0.98 - 0.13\left(\frac{P_o}{P_{o,\,sat}}\right)$$

Shown on figure 9 is a plot of overall TWT efficiency as a function of output power normalized to saturation power and expressed in dB. The dotted curve on this figure shows a hypothetical case in which the collector efficiency is a constant. The difference between the two curves illustrates the role of an MDC in recovering overall efficiency as the TWT is backed down from saturation.

It is anticipated that the TWT would be designed for multichannel use. In order to minimize the amount of power lost to intermodulation products the operating point will be about 4 or 5 dB down from output saturation. Referring to figure 9 the estimated overall efficiency is about 33 percent.

Implicit in this prediction of overall efficiency is the assumption that high rf power is required to overcome 10 dB of rain attenuation. For those periods without rainfall it is proposed that the tube be operated in a low power mode. Designing for dual mode operation, however, presents the problem that the electronic efficiency will fall off badly because of improper focusing. A periodic permanent magnet (PPM) focusing structure will be used and the magnetic fields must be chosen for the high mode of operation.

A possible method of maintaining proper focusing for both modes is to control the amount of magnetic field which threads the cathode. Such a field causes the beam to be launched with a fixed amount of angular momentum. This technique, called immersed or confined flow, can theoretically maintain the same beam radius for both modes. Analytical work is being performed to develop a practical design for this type of gun. A small solenoid near the cathode will probably be used to supply the magnetic flux.

A constant beam radius helps to improve the interaction efficiency of the low mode but because the current (and hence the beam admittance) is necessarily smaller the low mode basic efficiency will always be less than in the high mode. The efficiency of the low mode is extrapolated to be 28 percent at saturation and 22 percent at 4 dB below saturation.

V. SUMMARY OF TWT REQUIREMENTS

Figure 12 summarizes the fundamental requirements of a traveling wave tube which may be used as the downlink, 20 GHz, amplifier in a proposed 30/20 GHz digital communications' satellite.

The available bandwidth of 2.5 GHz (between 17.7 and 20.2 GHz) limits the choice of a slow wave structure to a helix or some derivative of a helix such as the ring and bar construction rather than a narrow bandwidth coupled-cavity structure.

The assumed rain attenuation of 10 dB emphasizes the power requirements of the amplifier. The distribution of signal traffic and the probability of rain loss in any particular beam is assumed to be uniform. It is therefore not feasible to determine the extent that high power will be required. Complete statistics of rainfall and traffic patterns may indicate that high power operation of the amplifier will be more in demand than the low power option. In any case, the tube will be designed for dual mode operation and the development of a confined flow gun will help maintain a high efficiency in both modes.

The TWT will be designed for multichannel use. This will require operation below saturation. Minimizing the circuit losses through the use of a polished copper or copper-plated slow wave structure and the use of a multistaged depressed collector designed for operation below saturation will result in a highly efficient tube that will overcome the disadvantages of operating below saturation.

Operating in the linear portion of the power gain curve in order to minimize intermodulation products and/or to maintain a given bit error rate again requires backing-off from saturation. The loss in efficiency in this kind of operation can be minimized in the same way as designing for multichannel use, that is, through careful designing of a high efficiency TWT equipped with a multistage depressed collector.

ACKNOWLEDGMENT

The authors wish to thank Mr. Peter Ramins of Lewis Research Center for supplying the collector efficiency measurements shown in figure 8.

DOWNLINK ASSUMPTIONS (20 GHz):

NO. OF BEAMS	12
CHANNELS/BEAM	9
AVAILABLE BANDWIDTH	2500 MHz
MODULATION	QPSK
BIT RATE/CHANNEL	274 Mb/s
BIT ERROR RATE	10^{-6}
SYSTEM RELIABILITY	0.999 (10 dB RAIN MARGIN)

Figure 1. - Downlink (20 GHz) assumptions. CS-79-174

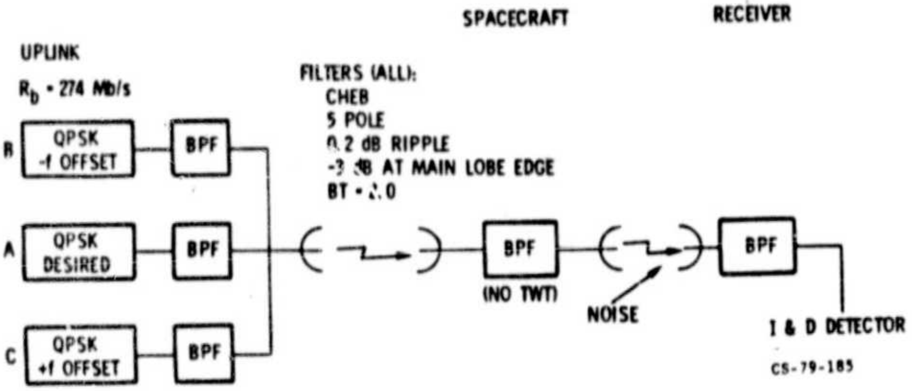
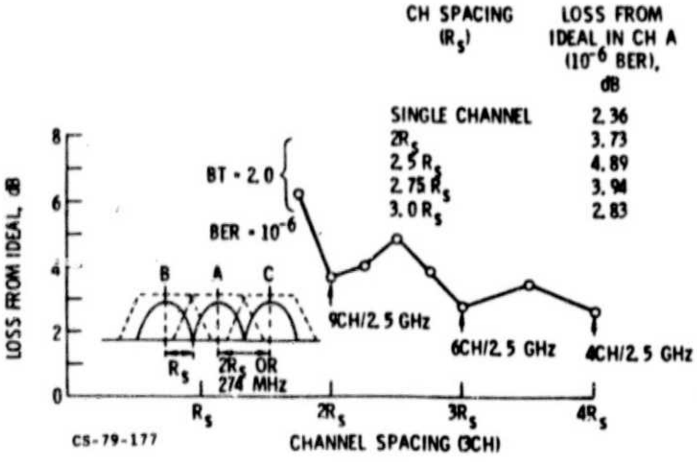
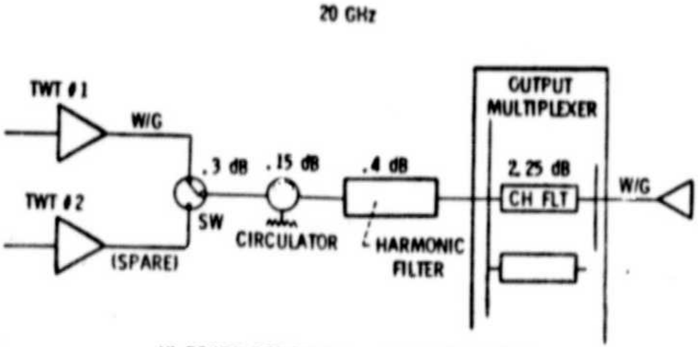


Figure 2. - Signal degradation model.



CH SPACING (R_s)	LOSS FROM IDEAL IN CH A (10^{-6} BER), dB
SINGLE CHANNEL	2.36
$2R_s$	3.73
$2.5R_s$	4.89
$2.75R_s$	3.94
$3.0R_s$	2.83

Figure 3. - Signal degradation as a function of channel spacing.



HI-POWER COMPONENT	ESTIMATED LOSS, dB
WAVEGUIDE	0.75
CIRCULATOR	.15
HARMONIC FILTER	.4
CHANNEL FILTER (MUX)	2.25
SWITCH (SS)	.3
	3.85

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Figure 4. - Estimate of circuit losses per channel in the spacecraft.

SPACECRAFT OUTPUT POWER, dBW (8.2 W)	9.14
ANTENNA GAIN (14 ft DIAM)	56.34
FEED LOSS	-3.85
EFFECTIVE ISOTROPIC RADIATED POWER	61.63
LOSS:	
SC ANTENNA POINTING ERROR	-0.39
MARGIN (RAIN + MISC)	-11.00
SYSTEM AGING	-1.00
RANDOM VARIATION OF ELEMENTS	-1.50
POLARIZATION LOSS	-0.25
ATMOSPHERIC LOSS	-0.70
PROPAGATION LOSS	-210.21
TERMINAL ANTENNA POINTING ERROR	-1.00
TERMINAL ANTENNA FEED LOSS	-1.50
TERMINAL ANTENNA GAIN (40 ft DIAM)	+65.46
TERMINAL RECEIVED CARRIER POWER, dBW	-100.46
NOISE:	
RECEIVED NOISE POWER DENSITY, dBW/Hz	-200.44
BANDWIDTH (274 MHz)	84.38
UPLINK NOISE CONTRIBUTION	1.35
TERMINAL RECEIVED NOISE POWER, dBW	-114.71
LINK CARRIER/NOISE POWER	14.26
HARDWARE SC LOSS	-3.73
ENERGY/BIT/NOISE DENSITY (BER = 10^{-6})	10.53

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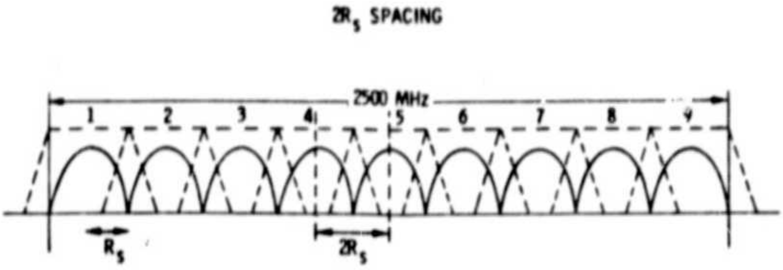
Figure 5. - Downlink power budget per channel.



$P_{CH} = 8.2$ W AT BER $= 10^{-6}$ (3.73 dB LOSS FROM IDEAL)

$$P_{SAT,TWT} = \frac{P_{CH} \times (\text{NO. CH})}{\left(1 - F_{IM_3}\right)} \times (\text{PBR})$$

FOR 3CH/TWT: $P_{SAT,TWT} = 63$ W (AT 4 dB → PBR)

$= 78$ W (AT 5 dB → PBR)

Figure 6. - Arrangement of nine channels in 2.5 GHz; TWT saturated power required.

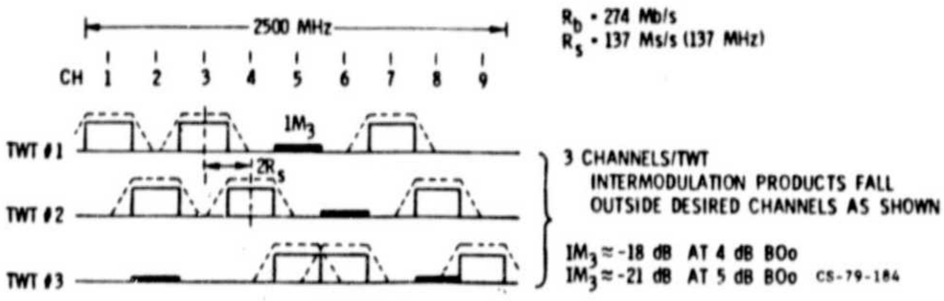


Figure 7. - Channel assignment per TWT.

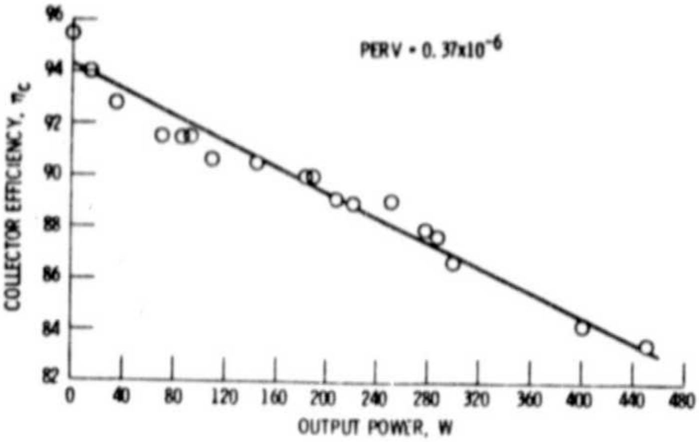


Figure 8. - Measured collector efficiencies in a 8.4 GHz TWT.

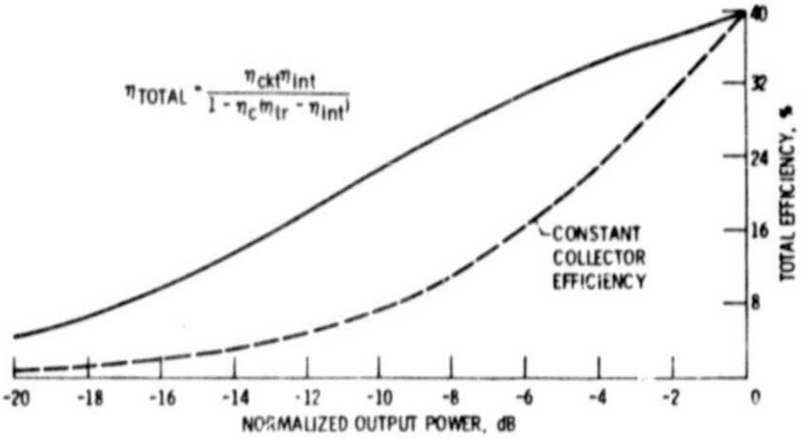


Figure 9. - Estimated total efficiency of 20 GHz TWT.

BANDWIDTH
HELIX OR HELIX DERIVATIVE SLOW WAVE STRUCTURE

RAIN ATTENUATION
DUAL MODE OPERATION WITH CONFINED FLOW GUN

CHANNELIZATION
HIGH EFFICIENCY MULTI-STAGE DEPRESSED COLLECTOR; MIN. LOSS SLOW WAVE STRUCTURE (COPPER))

LINEARITY
HIGH EFFICIENCY TWT

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Figure 10. - Summary of TWT requirements.