NASA Technical Paper 2635

October 1986

Bit-Error-Rate Testing of High-Power 30-GHz Traveling Wave Tubes for Ground-Terminal Applications

Kurt A. Shalkhauser
and Gene Fujikawa

NASA

NASA
Technical
Paper
2635

1986

Bit-Error-Rate Testing of High-Power 30-GHz Traveling Wave Tubes for Ground-Terminal Applications

Kurt A. Shalkhauser
and Gene Fujikawa

Lewis Research Center
Cleveland, Ohio

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

Summary

Tests were conducted at NASA Lewis to measure the bit-error-rate performance of two 30-GHz, 200-W, coupled-cavity traveling wave tubes (TWT's). The transmission effects of each TWT on a band-limited, 220-Mb/sec SMSK signal were investigated. The tests relied on the use of a recently developed digital simulation and evaluation system constructed at Lewis as part of the 30/20-GHz technology development program. This paper describes the approach taken to test the 30-GHz tubes and discusses the test data. A description of the bit-error-rate measurement system and the adaptations needed to facilitate TWT testing are also presented.

Introduction

The continued increase in domestic and worldwide communications traffic has placed heavy demands on the satellite systems currently in use. Crowding of the geostationary orbit is prompting the communications industry to investigate the benefits of higher frequency allocations, increased data rates, and more efficient use of bandwidth. NASA, realizing the need to focus attention in this area, is conducting an extensive program for advanced communications technology development (ref. 1). This program, currently concentrating on 30/20-GHz technology risk mitigation, provides an extensive laboratory-based test and evaluation facility and a planned 2-year on-orbit experimental flight project.

The 30/20-GHz technology development program makes use of the 27.5- to 30.0-GHz up-link and 17.7- to 20.2-GHz down-link frequency ranges and a 220-megabit-per-second (Mb/sec) digital data rate.[1] The high frequencies and data rates involved in this program require the development of innovative components and their integration into advanced systems. NASA Lewis has accepted the challenge of this development task as a means of promoting the conservation of the rapidly diminishing satellite communications resources.

As part of NASA's overall objective in the space communications fields, the Advanced Communications Technology Satellite (ACTS) flight project is being conducted to demonstrate the feasibility of the new communications technologies. The ACTS experimental system, scheduled for launch in May 1990, will use the results of the in-house simulation, evaluation, and test programs to supplement the design of the spacecraft communications network. One device that is critical to the success of the ACTS system is the ground terminal transmitter. Preliminary calculations indicate that an amplifier providing approximately 200 W of radiofrequency (RF) output power is needed to support the proposed 220-Mb/sec data rates. In addition, a bandwidth of at least 330 MHz is required, within the up-link allocation of 27.5 to 30.0 GHz. Although traveling wave tube (TWT) amplifiers have been successfully developed at these frequencies and power levels and have been subjected to extensive continuous-wave RF testing, none have been tested at such high data rates using a spectrally efficient modulation scheme. Consequently, the bit-error-rate (BER) performances of such amplifiers have never been accurately determined.

Traveling wave tubes similar to the ones needed for the ACTS project were built by Hughes Electron Dynamics Division of Torrance, California, under contract to the U.S. Army (contract no. DAABO7-76-C-0015) in the mid-1970's. Although the tubes design is somewhat dated, their performance in the amplification of modulated digital data would be typical of the type of device needed for the ACTS program.

Two Hughes model 914H TWT's were loaned to NASA Lewis for testing in July 1985 (fig. 1). Each tube, using a coupled-cavity slow wave structure, is capable of delivering 200 W of continuous-wave RF output power over the frequency range of 30.0 to 31.0 GHz. The usable tube bandwidths were large enough that testing could be done at frequencies below the specified range and into the 27.5- to 30.0-GHz ACTS range of interest. The major point of concern in the testing of the tubes, however, was the RF gain ripple encountered at small signal drive levels. These variations, reaching as much as 7 dB at an RF drive level 20 dB below saturation (tube 1), were suspected of producing increased signal degradations that would preclude the operation of the tubes in a backed-off state. The gain variations were directly related to RF drive level, becoming more pronounced as the tubes were operated further below saturation. Quantifying the effect of the gain variations on a modulated signal was deemed necessary before the selection of a ground terminal amplifier for the ACTS program. Thus, the gain ripple, tube linearity, and the associated BER effects were the focus of critical experimental investigation.

The 220-Mb/sec BER measurement system, designed and fabricated at NASA Lewis, was completed just before the

---

[1] The actual data rate is 221.184 Mb/sec, referred to as 220 Mb/sec for convenience.

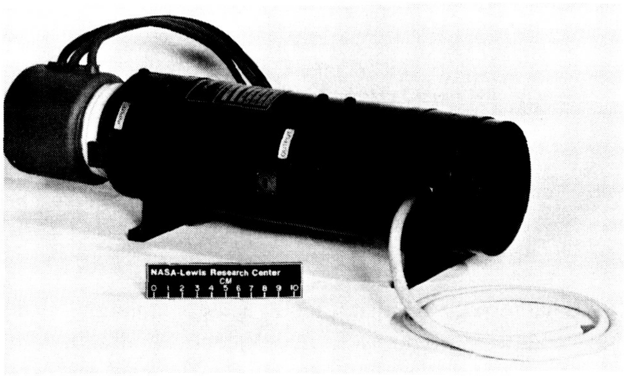


Figure 1.—Model 914H 30-GHz traveling wave tube.

Testing of the TWT's. This system is the first of its type to be constructed at this frequency and data rate and makes use of the latest modulation and digital processing technologies. Verification tests were conducted on the assembled system.

This paper describes the testing performed on the two Hughes 914H TWT's while fulfilling the two main objectives of the experimental effort: (1) to measure the BER performance of representative ground terminal TWT's and (2) to verify and illustrate the operation of the BER measurement system. The digital and RF test results will be presented to correlate the RF gain variation and the BER performance of each tube. Descriptions of the RF and digital test configurations, measurement strategies, and calibration procedures will also be included.

Radiofrequency Testing

Before BER measurement of each TWT, its continuous-wave RF performance was recorded and analyzed. Several operating characteristics, including output power versus frequency, power gain versus frequency, and gain linearity, were measured using conventional techniques. The tests were conducted to reaffirm each tube's forward transmission characteristics after an inactive period of several years and to document the magnitude of gain variations over the frequency band of interest at various RF input drive levels. The equipment used to perform the tests was configured as shown in figure 2. A single RF source was used to supply the test system with a continuous-wave, swept-frequency signal. A Hughes model 1077H TWT driver amplifier was used to amplify the test signal to obtain the input power levels required by the 914H. The driver was operated only in its linear gain region to avoid further distortion of the test signal. The power level at the input of the 914H tube was controlled using a precision rotary-vane attenuator. Output power was delivered directly into a high-power, water-cooled load that provided an accurate impedance match at each of the selected RF drive levels. The incident and transmitted power levels were measured through directional couplers at the 914H input and output ports. Calibration factors were recorded during system assembly to account for the frequency dependence of the couplers and waveguide test system. Power measurement data were collected and plotted using an automatic network analyzer.

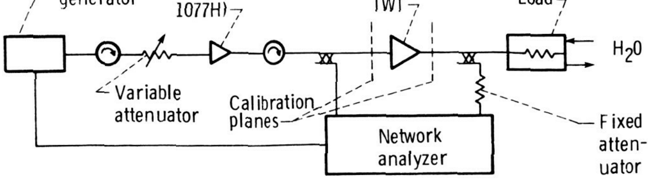


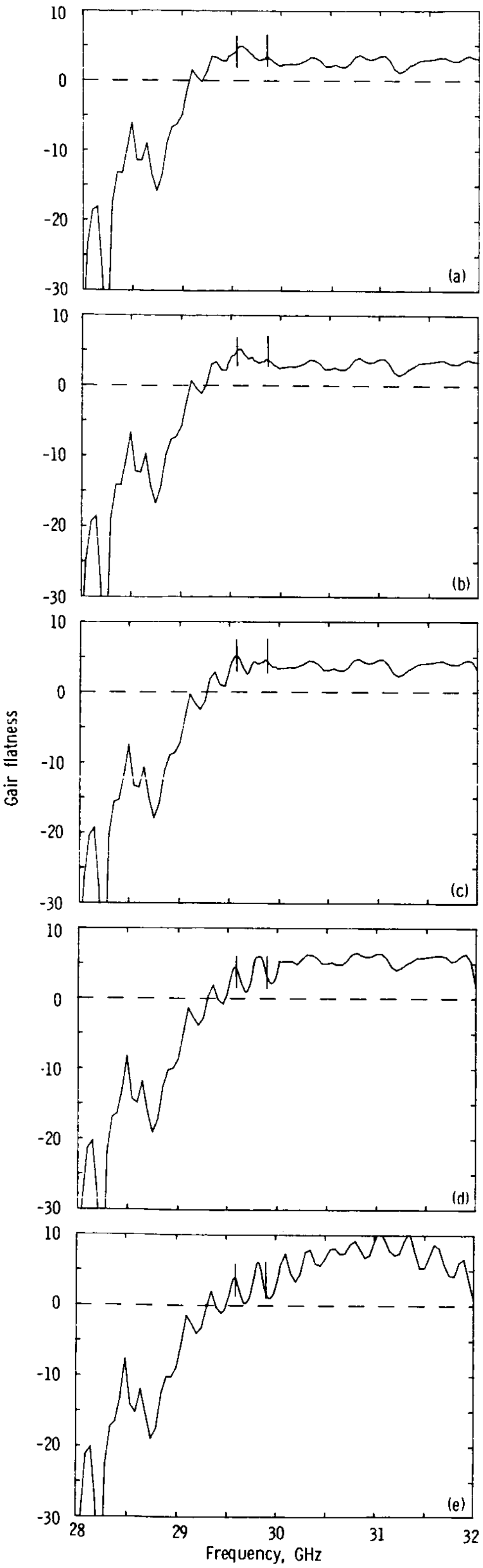
Figure 2.—Continuous-wave RF measurement configuration.

Each Hughes 914H tube was originally designed to operate over the 30.0- to 31.0-GHz frequency range. The ACTS system, however, uses the 27.5- to 30.0-GHz band. The lack of a common frequency coverage forced NASA to select 29.75 GHz as the center frequency for the testing. This point is outside of the specified tube passband, but within the usable range. It was also determined that the ACTS 220 Mb/sec data rate, using serial-minimum-shift-keying (SMSK) modulation, required a bandwidth of at least 1.5 times the data rate for an acceptable transmission path. Therefore, RF testing placed primary emphasis on the 330-MHz wide band surrounding the 29.75-GHz center frequency.

The output power plots for five RF drive levels are presented in figures 3 and 4. The highest input power level used, 100 mW, was 0.02 dB below saturation at 29.75 GHz for tube 1 and 1.02 dB for tube 2. The 100-mW RF drive condition, though not used in BER measurement, was tested to verify the leveling properties of each tube as it approached saturation. Power limitations in the frequency conversion system used in the BER tests permitted testing only at the 75-mW drive level and below. The reduced RF drive resulted in an increase in gain variation over the 330-MHz-wide passband, but still provided relatively flat gain responses to perform BER testing. The gain variations ranged from 2.5 dB at the 100-mW drive level to as much as 7.0 dB at 1-mW drive (tube 1). Amplitude variations over the 330-MHz frequency band are summarized in table I. The 330-MHz passband of interest is marked on each trace.

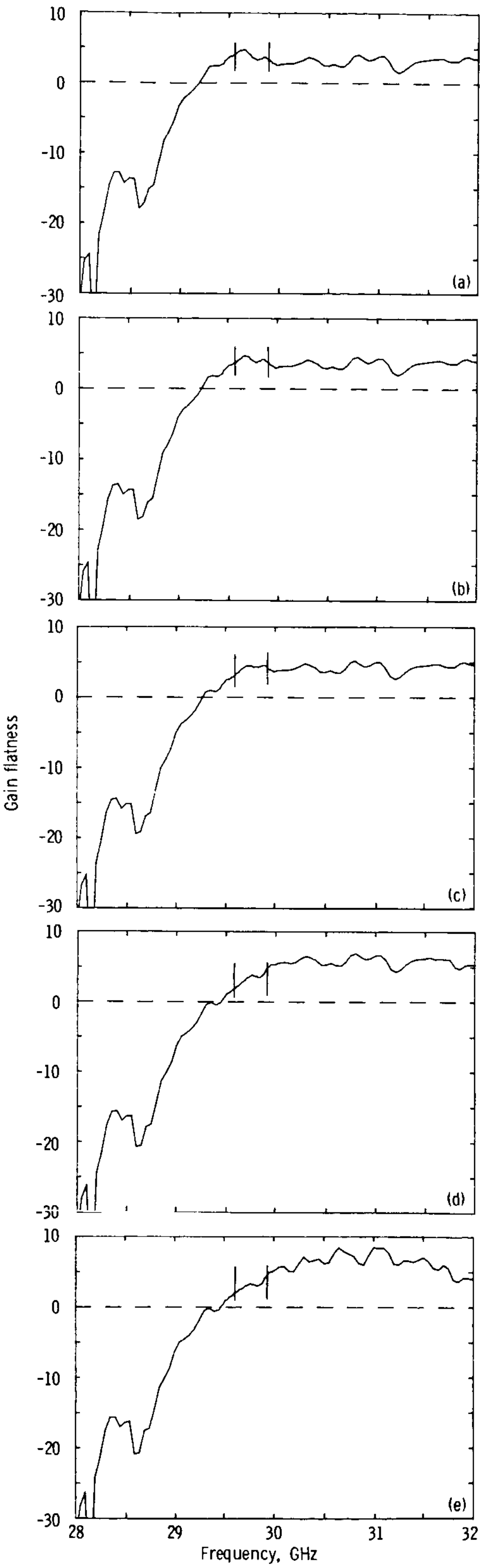
The ACTS operating scenarios involve operating the tubes in a backed-off state as part of a rain fade compensation strategy. The gain variations produced by such operation were therefore a source of major concern because of their potential effects on data transmission capabilities. For this reason RF testing was carried out at RF drive levels from near saturation down to 20 dB below saturation. This selection would yield test results for a drive range typical of the planned system requirements.

Both 914H TWT's were operated at a cathode voltage of −16.0 kV with a collector depressed 8.0 kV from the helix potential (body ground). The electron-beam current measured



(a) Total RF input drive level, 100 mW.
(b) Total RF input drive level, 75 mW.
(c) Total RF input drive level, 50 mW.
(d) Total RF input drive level, 25 mW.
(e) Total RF input drive level, 1 mW.

Figure 3.—Continuous wave performance of tube 1.



(a) Total RF input drive level, 100 mW.
(b) Total RF input drive level, 75 mW.
(c) Total RF input drive level, 50 mW.
(d) Total RF input drive level, 25 mW.
(e) Total RF input drive level, 1 mW.

Figure 4.—Continuous wave performance of tube 2.

TABLE I.—GAIN VARIATION

[Frequency range, 29.58 to 29.91 GHz.]

Total rf input power, mW	Gain variation, dB	
	Tube 1	Tube 2
100	2.5	2.5
75	3.0	2.0
50	3.0	2.5
25	5.0	4.0
1	7.0	5.0

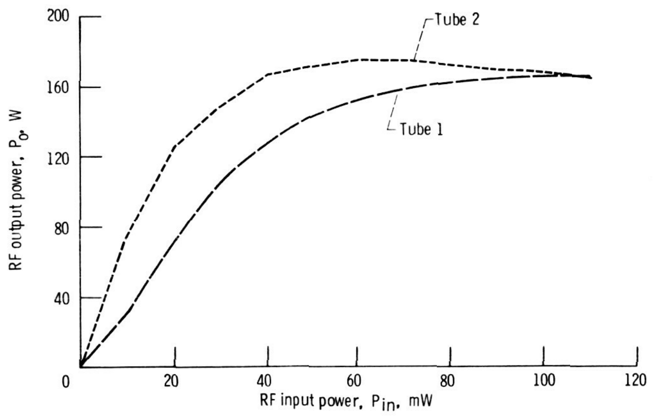


Figure 5.—Model 914H TWT power transfer characteristic. Frequency 29.75 GHz; cathode voltage, 16 kV.

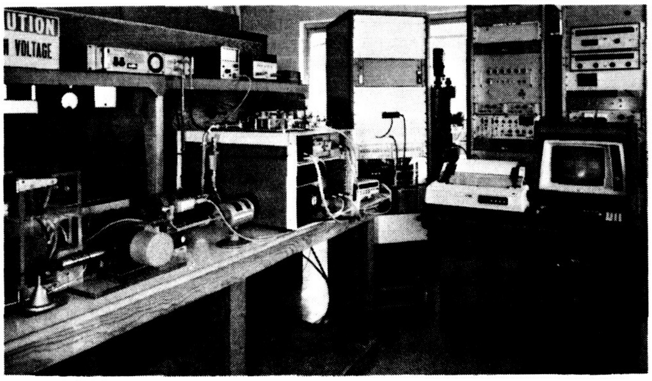


Figure 6.—NASA Lewis test facility.

at the cathode was approximately 68 mA (tube 1) and 63 mA (tube 2) for all drive conditions used. The overall efficiency of each tube was approximately 25 percent. The RF power output versus RF power input curves are shown in figure 5. The curves indicate that the 75-mW drive is slightly below saturation for tube 1 and near saturation for tube 2.

Bit-Error-Rate Testing

After the RF performance of each tube was measured, a test of its digital data transmission capabilities was conducted. This test allows the engineer to correlate the signal degradation imposed by the tube with its RF performance characteristics (nonlinearity, gain ripple, and phase deviations). The results of this test appear as a bit-error-rate measurement. The BER performance of each tube was dependent on the signal-to-noise ratio present at the device input. Testing, therefore, was conducted for a range of signal-to-noise ratios to display the BER characteristics over a wide range of possible operating conditions. A photograph of the test facility is shown in figure 6.

Digital Instrumentation

The digital transmission characteristics of each tube were determined through the use of an elaborate BER measurement system. This unique system, designed and built by NASA, is described in the block diagram of figure 7. Continuous, pseudorandom digital data are generated at a rate of 220 Mb/sec by a computer-controlled data generator. The transmitting ground terminal receives the data and attaches the necessary synchronization information (carrier and bit timing recovery signals, unique word, guard time, etc.) by inserting a preamble ahead of the data words. The data are converted from a parallel to serial format and are then modulated onto an intermediate frequency (IF) carrier by a serial-minimum-shift-keyed (SMSK) modulator. The modulated output signal, centered about the 3.373 GHz frequency, is then suitable for further processing, transmission, or immediate demodulation. For the planned testing the modulated output was combined with wide-band noise from a variable power solid-state noise source. This addition allows the engineer to measure the effects of the added noise on the ability to recover data from the communications channel. A typical modulated spectrum, without added noise, is shown in figure 8.

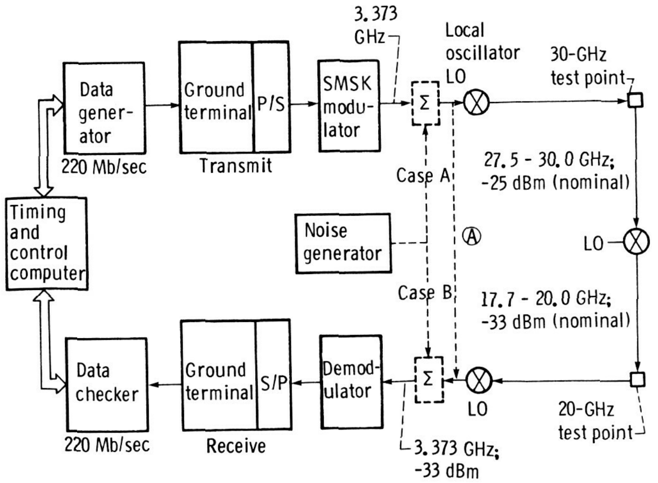


Figure 7.—BER measurement system.

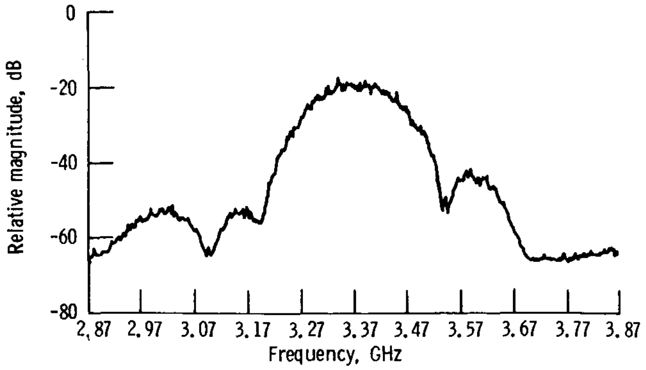


Figure 8.—SMSK modulator output spectrum.

To verify the accuracy of the BER measurement system, initial testing of the system used a modulator/demodulator pair in a back-to-back configuration. This circuit is shown as path A in figure 7. Using this method, the combined data and noise signals are received by the demodulator at a nominal power level of − 33 dBm. The demodulator synchronizes the appropriate carrier and bit timing recovery loops and sends the demodulated digital baseband information to the receiving ground terminal. The ground terminal then detects the unique word to signal the start of actual data transmission and sends the received data stream to a serial-to-parallel converter. A data checker then performs a bit-by-bit comparison of the received data and a reference data set. The bit error rate is calculated as

$$\mathrm{BER} = B_e/B_t$$

This calculation quantitatively indicates the number of digital data bits received in error (B_e) per number of bits transmitted (B_t) in a given period. The results of the comparison are calculated and recorded by a Sage model IV microcomputer.

The modulator and demodulator used in the BER measurement system were designed and built by Motorola's Government Systems Group of Scottsdale, Arizona, under contract to NASA Lewis (NAS3-22502). Both devices are prototypes of those to be used in the ACTS high-burst-rate ground terminals.

Frequency Conversion System

To conduct BER measurements above 3.373 GHz, a frequency conversion system (FCS) was used. The FCS selected for this effort, built by LNR Communications, Inc., of Hauppauge, New York (NASA contract NAS3-23966), supported frequency conversions from the 3.373-GHz intermediate frequency into either of the ACTS spacecraft link frequency ranges (27.5 to 30.0 GHz up link, 17.7 to 20.2 GHz down link). The FCS was designed and constructed so that testing could be carried out at the intermediate frequency or within either the up-link or down-link frequency ranges. Frequency conversion devices, such as receivers, could also be tested by appropriate selection of frequency translation components in the FCS. A block diagram of the FCS is shown in figure 9. Intermediate frequency input signals are first up converted into the 27.5- to 30.0-GHz range using two mixing stages, one of these supplied by a variable local oscillator. A fixed local oscillator operating at 9800 MHz translates the signal to the 17.7- to 20.2-GHz down-link band. Down conversion back to the intermediate frequency is accomplished using a single mixing stage, supplied by a variable local oscillator. The intermediate frequency output of the FCS is located at the 3.373-GHz frequency and thus allows direct input to the demodulator. For testing of the Hughes 914H TWT's, all three conversion segments of the FCS were to be used. The TWT, TWT driver amplifier, and associated waveguide hardware were connected at the 30-GHz test point indicated in the figure.

The FCS was subjected to BER testing to measure its effects on the transmission of the test signal. The data were then used as a reference with which to compare the results of later additions to the system. The data are presented and discussed in the Bit-Error-Rate Test Results section.

Noise Generation Unit

The ability of a device or system to transmit data without errors is dependent on the relative levels of the signal and noise powers. To control the signal-to-noise ratio *S/N*, a noise generation unit was built and added to the test system between the modulator and demodulator. White noise power was generated by a solid-state noise source and regulated by a solid-state step attenuator. The noise and test signals were then summed using a microstrip combiner and adjusted to a constant total power level with a second step attenuator. A block diagram of the noise generation unit is shown in figure 10. By selectively adjusting the attenuation settings in the noise generation unit, a wide range of *S/N* values could be obtained while maintaining a constant total IF power level. This variation of the *S/N* typically appears as a change in the number of erroneous data bits introduced by the device under test and thus a change in the BER performance. The results of back-to-back modulator-demodulator BER tests at several *S/N* values were then recorded, plotted, and analyzed. When possible, the resultant BER test data were compared with those obtained by the modulator-demodulator manufacturer, who used

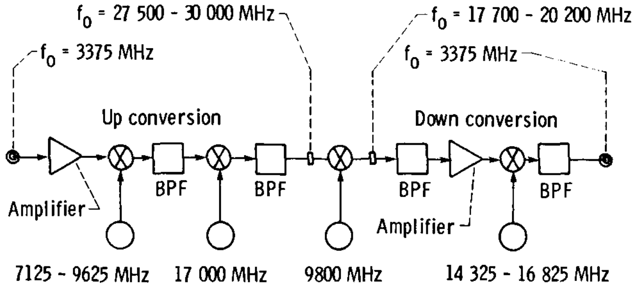


Figure 9.—Frequency conversion system. BPF denotes bandpass filter.

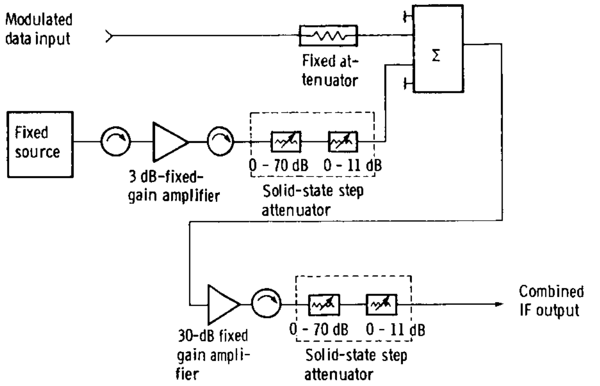


Figure 10.—Noise generation unit.

slightly different error-counting techniques. The noise generation unit operates over the 330-MHz band centered at the 3.373-GHz frequency.

It is obvious from figure 7 that the noise generation unit can be placed at either of two locations in the test circuit. When placed between the modulator and the FCS, the noise can be thought of as being added in the up-link portion of the communications channel. When placed between the FCS and the demodulator, the noise can be considered as being added in the down-link portion of the channel. Each location provides the ability to regulate the S/N value in the system, however, each location requires a very different calibration procedure and yields data on different component responses. Lewis testing measured the BER performance using both the up-link (case A) and down-link (case B) orientations. An elaboration of the calibration procedures for each case will be provided in later sections.

The modulated signal and noise powers recorded during calibration of the noise generation unit were used to determine two similar parameters, energy-per-bit (E_b) and noise-power-density (N_0). These values are based on the system data rate and are calculated using the expression

$$E_b/N_0(dB) = (P_s - P_n) + N_{bw} - R$$

where

P_s measured signal power, dB

P_n measured noise power, dB

N_{bw} noise bandwidth of calibration filter, = 379.69 MHz = 85.79 dB Hz

R data rate, = 221.184 Mb/sec = 83.45 dB Hz

The noise is assumed to be additive white Gaussian, which allows us to define the theoretical probability of error as

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\frac{E_b}{N_0}\right)^{1/2}$$

where the complementary error function is

$$\mathrm{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt$$

This quantity can then serve as a limit for the operation of a perfect demodulator.

The E_b/N_0 values, with direct ties to the S/N values, are used as the control variables throughout the BER testing. The attenuators in the noise generation unit used to proportion the E_b and N_0 powers are limited by a 1-dB resolution, but provide repeatability of better than 0.1 dB.

Computer Control

The Sage computer proved to be an effective and flexible method for the timing and control of the BER measurement system. Bit-error-rate measurements could be made over periods ranging from 3 sec to several hours. Each measurement could be made on the fly by maintaining a running total of bits and errors received, and then calculating the BER. This capability allows the BER performance of a dynamic device or system to be observed without requiring that the data flow be interrupted. For TWT testing the measurement period was selected so that several thousand bit errors were detected before a calculation was made. This method reduced the possibility of random errors affecting the accuracy of the measurements.

Depending on the performance of the system, the measurement times ranged from approximately 30 sec to 5 min. Each test was repeated at least five times to assure that the system or device under test was yielding consistent performance. An arithmetical average was then computed from the test results.

Test Results

Back-To-Back Modem Test

The back-to-back modulator-demodulator (modem) test configuration is indicated by path A in figure 7. This test compared the BER versus E_b/N_0 performance of the modem pair to the manufacturer's recorded results. This test was also used to confirm the accuracy of the calibration procedures used in these experiments and to verify the proper operation of the modulator and demodulator.

The results of the back-to-back modem test in terms of BER versus E_b/N_0 are shown in figure 11. The NASA back-to-back curve is plotted along with a similar curve reconstructed from the modem manufacturer's data. A maximum separation of 0.25 dB was measured between the two sets of results over the 5- to 13-dB range of E_b/N_0 settings tested. Both sets of data can be compared with the BER theoretical curve (broken line) based upon the mathematical calculations given in the Bit-Error-Rate Testing section of this paper. The theoretical curve is offered to the reader only as a reference point for comparison of test results.

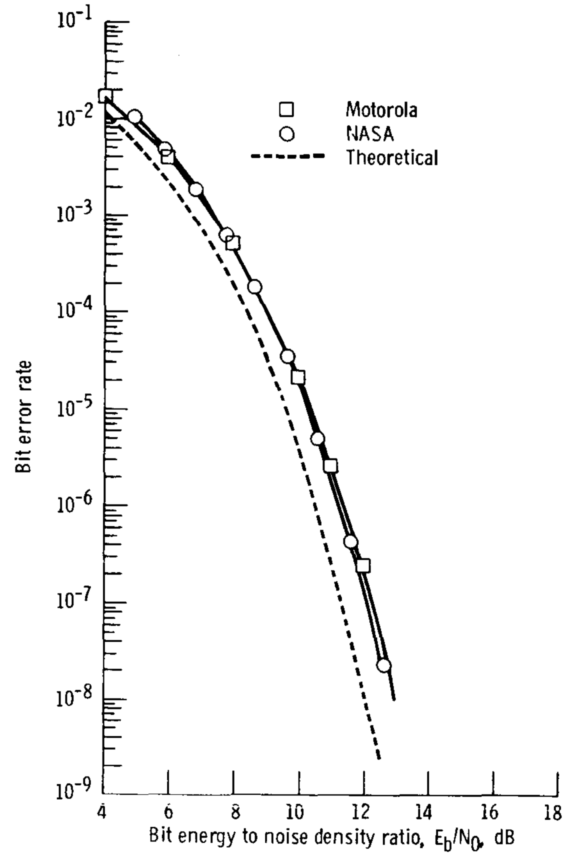


Figure 11.—Back-to-back modem BER performance comparison of contractor acceptance test with NASA test.

Once the proper operation of the modulator and demodulator had been confirmed, the subsequent BER testing was conducted in a building block fashion. This approach allowed data to be collected as each additional component was added to the system, thus allowing the effects of each component to be isolated. The power into the demodulator was maintained at a constant level within the nominal demodulator operating range during all testing.

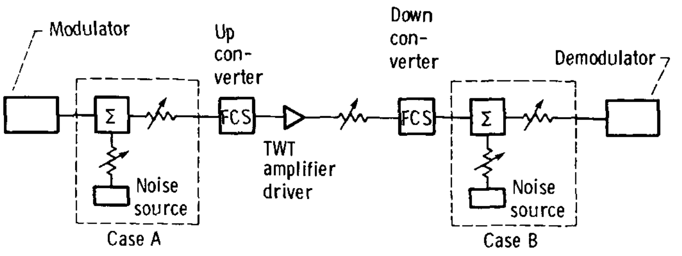


Figure 12.—Baseline system test configuration.

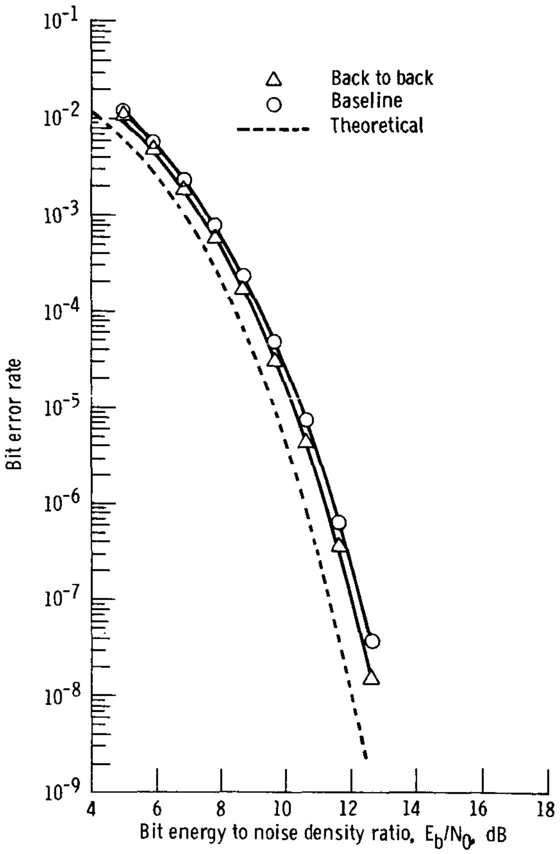


Figure 13.—Baseline BER performance.

Baseline Testing

The data obtained from FCS and driver amplifier testing was used to establish a baseline performance level to which the Hughes 914H BER results could be referenced. To make this measurement, the entire 30-GHz BER test system, with the exception of the 914H TWT, was assembled. The test configuration (fig. 12) includes the frequency conversion system, TWT driver stage, attenuators, directional couplers, and waveguide transmission lines. The noise generation unit is placed at the output of the modulator for the case A test and at the demodulator input for the case B test.

The results of the baseline system tests (fig. 13) indicate that the additional RF equipment imposes a slight degradation on the test signal. This effect is shown qualitatively by the BER curve moving to the right. Quantitatively, it is shown that the baseline test system produces a 0.2-dB degradation over the back-to-back modem test at a 5×10^{-7} bit-error-rate. No measurable difference was recorded between the case A and case B baseline BER results.

Careful attention was paid to ensure that power levels remained constant throughout the baseline test system. These power levels were kept the same as those needed for the 914H tube testing. Thus, the responses of any power-sensitive devices would not affect the accuracy of the final measurements. Power levels were continuously monitored through calibrated directional couplers located at the input of the frequency up converter, at the driver amplifier output port, and at the input of the frequency translator/down converter.

Traveling-Wave-Tube Test Results

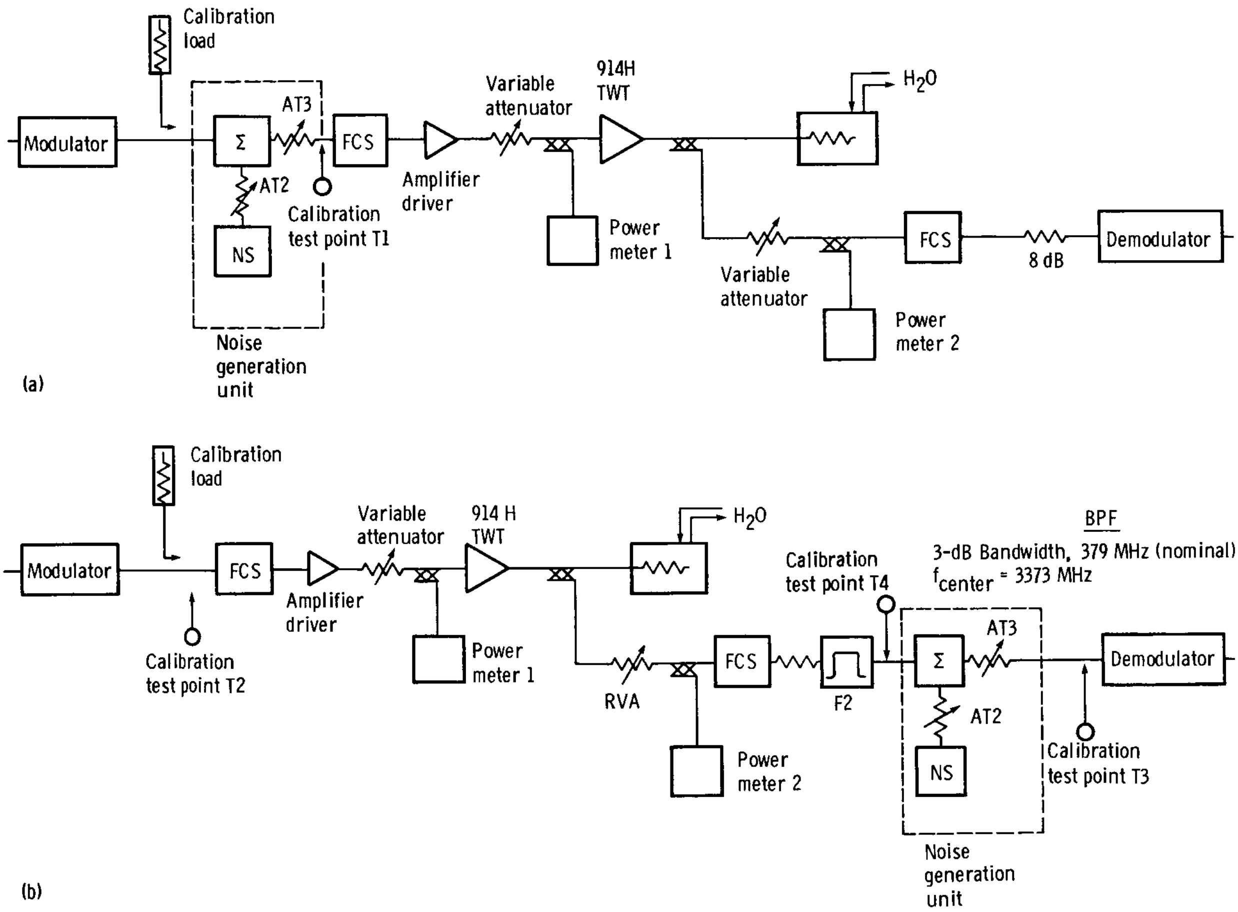
The BER performances of both 914H TWT's were obtained using the same measurement techniques and test equipment. Tube 1 was tested using two measurement approaches (cases A and B, fig. 14). Test engineers were thus able to carefully examine the BER performance of each tube while controlling E_b/N_0 values at two locations. Inspection of the tube 1 data, showed that the case B measurement approach was sufficient to accurately measure the imposed signal degradation. As a result, tube 2 was tested using only the case B measurement approach. Each method produces valuable data used to describe the tubes and their performance.

Case A Testing of Tube 1

The objectives of the case A full system test were to measure BER performance of tube 1 due to (1) changes in signal-to-noise ratio and or (2) changes in RF input power level. To correlate the BER results with the findings from RF testing, the total power levels present at the input of the TWT were maintained at 75, 50, 25, and 1 mW. Appropriate attenuation was supplied at the tube output to account for gain variations with drive level. This provided a constant power level at the input to the FCS which was monitored with a power meter through a directional coupler.

The results of the case A measurements at the four RF drive levels are shown in figure 15. It is obvious that, as the RF drive was decreased, the bit-error-rate performance of the TWT degraded significantly, even though the demodulator input power remained constant.

To achieve a bit-error-rate performance of 5×10^{-7}, the FCS/driver baseline system requires an E_b/N_0 at its input of approximately 11.7 dB. Introduction of the 914H TWT into the system produced an immediate degradation of 2.2 dB, with the tube operating at the 75 mW RF drive level. Reduction of the input drive from 75 to 25 mW (4.77 dB relative back-off) produced only an additional 0.36-dB degradation in E_b/N_0. Further reduction of the input signal to the 1-mW level yielded an E_b/N_0 requirement of 15.3 dB for a BER of 5×10^{-7}. Overall, it is observed that an 18.75-dB reduction in input RF drive level results in approximately 1.45 dB higher E_b/N_0 needed to obtain the same bit-error-rate.



(a) Case A. (b) Case B

Figure 14.—Measurement configuration.

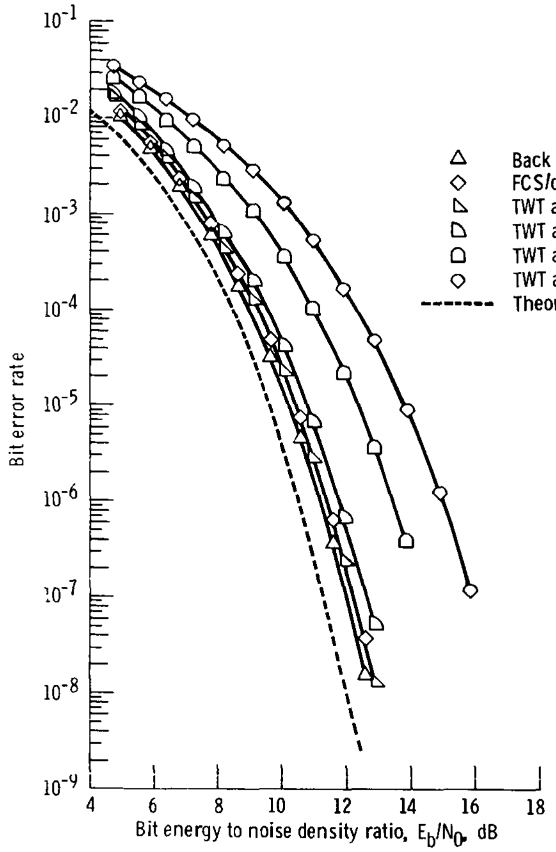


Figure 15.—Tube 1 case A BER performance, measured at FCS up converter input (T1).

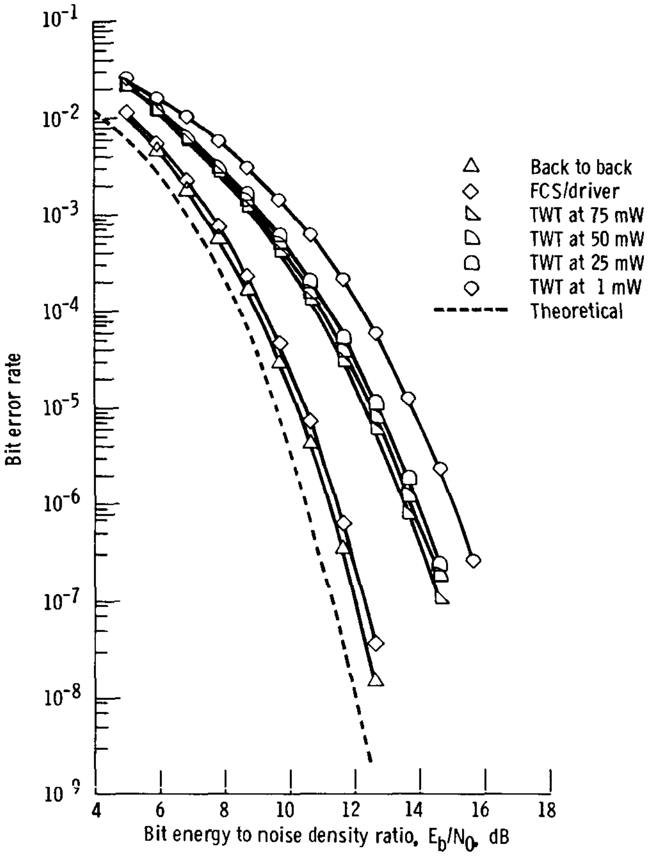


Figure 16.—Tube 1 case B BER performance, measured at FCS demodulator input (T2).

Case B Testing of Tube 1

The objectives of the case B full system test were to measure the BER performance of the TWTs due to changes in noise-free RF input power level. The block diagram of the case B measurement configuration is shown in figure 14(b). This method does not record the response of the tubes to various *S/N* values, but it does produce additional data on the BER performance of the TWT.

The BER curves obtained through the case B testing of tube 1 are shown in figure 16. The disruptive effects of the increasing gain ripple are still apparent as the BER curves move to the right with decreasing drive level. With the tube operating at the 75-mW RF drive level, no perceptible degradation was observed (Note that the 75-mW curve overlaps the baseline system curve). This indicates that the tube has successfully amplified the SMSK signal (without appreciable distortion) in the absence of added uplink noise. Reduction of the input drive from 75 to 25 mW produced a degradation of 2.1 dB in E_b/N_0 at a BER of 5×10^{-7}. Small-signal gain fluctuations in the amplifier pass band now become apparent. For a drive level of 1 mW, an E_b/N_0 requirement of 15.3 dB was needed to obtain a BER of 5×10^{-7}. In this case the 18.75-dB overall reduction in input RF drive level resulted in approximately 3.7 dB higher E_b/N_0 required to obtain the same bit-error-rate.

Comparison of Case A and Case B Results for Tube 1

A summary of the BER performance for both tube 1 test cases is shown in table II. As a whole, the case B performance was better than the case A results. Some improvement in BER performance may be attributed to the modified calibration techniques, in which the noise effects of the TWT were not considered. The largest contributing factor, however, results from the higher E_b/N_0 present at the input to the 914H tube. Due to the location of the noise insertion system, the case B TWT input signal is virtually noise-free. The tube's response to the clean modulated signal is apparent in the BER test results.

Direct comparison of the cases A and B BER performances is made difficult by the difference in modulated signal power and noise power contributions to the total (composite) test signal. For a given total power level into the 914H tube, the case A test signal has a significant noise component; case B, however, has no added noise component. Therefore, in addition to knowing the response of the tube to the various E_b/N_0 values, the response to noise input alone must be investigated.

TABLE II.—SUMMARY OF BIT-ERROR-RATE PERFORMANCE

Total RF input drive level, mW	Bit energy to noise power density ratio[a], E_b/N_0, dB		
	Tube 1, case A	Tube 1, case B	Tube 2
75	13.9	11.7	11.7
50	14.1	12.1	11.8
25	14.3	13.8	11.5
1	15.3	15.3	11.5

[a] BER = 5×10^{-7}

At low total RF drive levels, the TWT is less sensitive to the composition of the test signal. As a result, both tube 1 test cases yield similar BER performance when operated at the 1-mW RF drive level.

Case B Testing for Tube 2

A second TWT was tested to provide data for comparison of the two tubes. Tube 2, fabricated second in the 914H series, has a much flatter frequency response over the passband of interest. Gain variation data, given in figure 4 and table I, suggests that the BER performance of tube 2 would be significantly better that of tube 1. This suggestion was later confirmed by the data (fig. 17). For each of drive level tested the bit-error-rate curve falls essentially on top of the baseline system curve. With only a 0.25-dB E_b/N_0 variation, these test results approach the accuracy limits of the BER measurement system. Repeated samples of baseline BER data acquired during calibration yield a repeatability of ± 0.2 dB. As a result, the BER performance of the tube cannot be distinguished from that of the baseline system and therefore can be said to impose little or no signal degradation.

Comparison of Tubes 1 and 2

Although the two TWT's were built from the same design, obvious differences exist between their BER and RF performances. The most prominent difference lies in the relationship between the RF gain variation and the BER performance. These gain variations can be broken down into two main areas, where only one has a significant effect on BER performance.

One characteristic common to both tubes is a positive gain slope over the 330-MHz passband. This slope increased with the reduction in RF drive level. This effect, somewhat hidden in tube 1, is clearly exhibited by tube 2. In both tubes the gain slope has minimal effect on BER.

Large peak-to-peak gain ripple, most noticeable at small signal drive levels, is obvious in the frequency response of tube 1. These large, cyclic variations tend to degrade the tube's ability to maintain a BER of 5×10^{-7}. Tube 2, however, does not have this large gain ripple. In general, the test results indicate that a smoother passband frequency response provides a better BER.

Another point of concern in the testing of the two tubes was the phase distortions. Because SMSK demodulation relies on the phase angle of the received signal, it is critical that the TWT does not severely distort the signal waveform. If this occurs, the demodulator is unable to identify the signal states and a bit error is potentially recorded. To investigate these effects, phase angle data were recorded at each drive level and an analysis is underway.

Elaboration On Noise Calibration Procedures

Accurate measurement of the signal and noise powers was critical to the calibration of the system and to the validity of the resultant BER data. For this reason the calibration sequences of both cases were carefully planned to provide two separate approaches to the measurement.

The calibration of the noise generation unit for the case A testing was the same as that used during baseline testing. This method required that the signal and noise power levels be measured separately, then be regulated to obtain the desired E_b/N_0 at location T1 in figure 14(a). To begin the calibration, the noise source was removed from the test channel, allowing only the modulated signal power to pass through to the output of the noise generation unit. The output power level

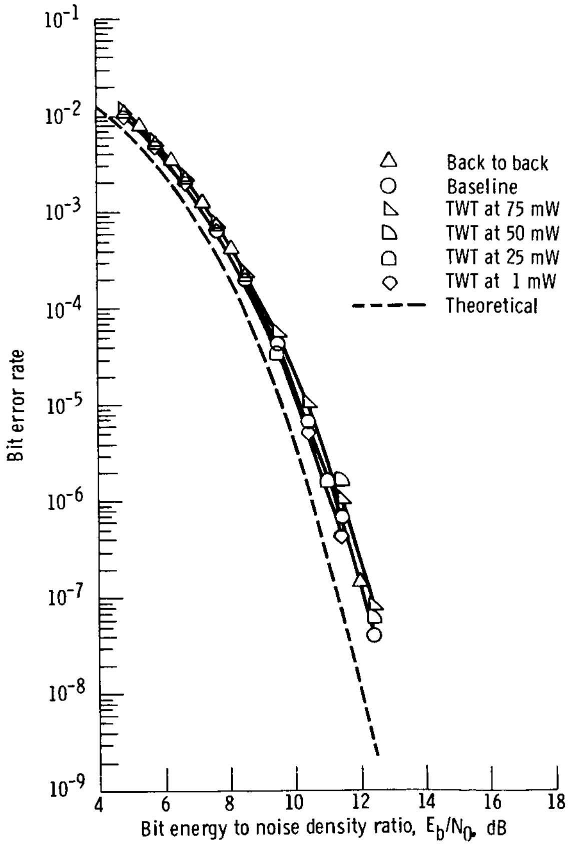


Figure 17.—Tube 2 BER performance.

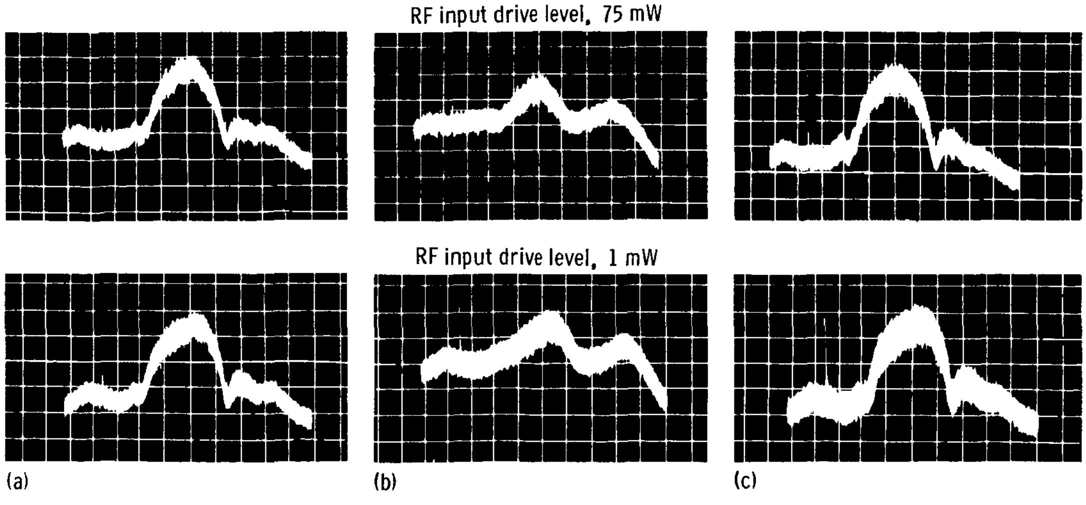
was then measured and recorded. In a similar fashion the modulated signal was removed from the test circuit and replaced with a matched load. The output of the noise generation unit now consisted of noise alone and was measured through a bandpass filter with a power meter. The filter used in the measurement had a measured passband of 379.69 MHz and was used to establish the noise bandwidth. The same filter was also used during measurement of the signal power so that any insertion loss and bandlimiting effects would be present in both measurements. With the calibration filter in place, the noise power was then adjusted using a step attenuator to obtain the desired set of E_b/N_0 values while keeping total power constant. The calibration sequence resulted in a table of attenuator settings that provided the desired E_b/N_0 values.

The case A approach was extremely useful in the progressive construction of the test system in that it provided data to the engineer describing the response of each component to various E_b/N_0's. As each new component was added to the circuit, its performance could then be evaluated and optimized, if desired. The disadvantage to this approach is that the components following the noise generator are subjected to lower E_b/N_0 values then may normally be encountered in an actual communications network. Comparison of the baseline system data for cases A and B points out that the low E_b/N_0 values had minimal effect on the elements of the baseline test system.

The case B calibration sequence was a modification to the case A approach. Modulated signal power was, again, measured at the output of the noise generation unit with the noise source effectively removed from the test circuit. Noise power, however, was measured with the measurement system terminated at point T2 (fig. 14(b)). This action allows the random noise generated by the TWT, driver, FCS, and test system components to be included in the total noise power figure. A 330-MHz bandpass filter (F2) similar to that used in the noise power bandwidth measurement was placed in the circuit to suppress an undesired mixing product generated in the FCS downconverter. The mixing product affects only noise measuring equipment, since it is outside of the passband of the demodulator input filter.

The case B testing simulates noise being added in the downlink radiation path, but eliminates the effects of the tube's own noise contributions. Using a matched termination at the input to the FCS upconverter (T2), this measurement scheme permits the collective noise contributions from all of the subsequent components, including the 914H TWT, to be included in the noise power measurement (test point T3, fig. 14(b)). In this way the effects of gain ripple, nonlinearity, and phase distortions in the tube can be observed, but the BER degradation imposed by the TWT noise is factored out of the measurements.

Of some concern in the system calibration sequence was the possibility of error due to the "capture" effect. This phenomenon is characterized by a change in noise power generated by the TWT based on input RF drive level. With the absence of RF drive, the tube will randomly generate noise. As RF drive is added to the TWT, much of the available power is now used to amplify the input signal, leaving less power to excite random noise signals. As a result, the level of internally generated noise is reduced. Data collected during calibration of the BER test configuration neither suggests nor eliminates the occurrence of the capture effect, but does show that the intrinsic noise variation over the drive range used in testing is less than 0.1 dB. To quantify the noise added by the tube, the matched termination was temporarily placed at



(a) Case A; no added noise.
(b) Case A; E_b/N_0 = 12.63 dB.
(c) Case B; E_b/N_0 = 30 dB.

Figure 18.—FCS intermediate frequency output spectra for tube 1.

the input to the noise generation unit (test point T4, fig. 14(b)) during the calibration sequence. Noise level measurements recorded in this configuration reveal that the total added TWT noise is less than 0.15 dB. Bit-error-rate testing in this orientation yielded results essentially identical to those obtained in case B.

Photographs describing tube 1's amplified signal spectra are presented in figure 18. At the 75-mW RF drive level, the amplified spectrum exhibits the general shape expected of an SMSK modulated signal, similar to the modulator output shown in figure 8. As the RF drive is reduced, the signal waveform becomes distorted, leaning slightly to the right, with a slight increase in the relative height of the secondary lobe to the right. The presence of noise at the input to the tube (case A) further increases the height of the secondary lobe. This effect cannot be measured with a power meter because the average power remains constant through the calibration filter. The demodulator, however, is able to detect distortions due to main lobe power loss and spectral content because of its narrowband input filter. The case B output spectra remained in the same general shape as case A with no added noise.

Concluding Remarks

The bit-error-rate performance of the Hughes 914H amplifiers indicate the potential use of a high-power coupled-cavity TWT's in a high data rate communications system. Although both tubes are quite aged, they nevertheless have provided system planners with valuable data to assess the potential use of such devices in a state-of-the-art communications network.

The RF gain variations recorded during initial RF testing obviously contributed to the changes in the tube's BER performance. The successful elimination of such variations would undoubtedly improve the tube's small signal BER performance and increase the potential uses of the amplifier. Amplitude equalizers, employed to reduce these gain variations, have proven successful, but characteristically impose sometimes intolerable insertion losses. Both tubes, even when operated at small signal RF drive levels, are capable of providing a usable amplification environment. The worst case E_b/N_0 value needed for 5×10^{-7} BER is 15.3 dB. This value is not unreasonably high or difficult to obtain in an actual communications system.

Both approaches (cases A and B) proved useful in measuring the BER performance of the TWT. In case B, however, the modulated signal is amplified by the tube without added noise. This method provided a more realistic simulation of a typical communications network. The case A system did, however, provide valuable data on the tube's response to various E_b/N_0 values.

The BER measurement system proved to be an accurate, flexible, and versatile tool. The addition of the frequency conversion system served to further extend the capabilities of the BER evaluation system. The entire digital evaluation system is currently being used to test a wide range of satellite communications system components and subsystems. Many high-risk components, systems, and technologies will be carefully analyzed and tested to help assess their suitability for satellite communications systems of the future.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 16, 1986

References

1. Bagwell, J.W.: A System for the Simulation and Evaluation of Satellite Communications Networks. NASA TM-83531, 1984.
2. Rasmussen, D.; and Stilwell, J.: 30/20 GHz Modem, Phase III, Data Package. Motorola, Inc., (NASA Contract NAS3-22502) 1986.

1. Report No.
NASA TP-2635

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Bit-Error-Rate Testing of High-Power 30-GHz Traveling Wave Tubes for Ground-Terminal Applications

5. Report Date
October 1986

6. Performing Organization Code

7. Author(s)
Kurt A. Shalkhauser and Gene Fujikawa

8. Performing Organization Report No.
E-2996

10. Work Unit No.

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Paper

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Tests were conducted at NASA Lewis to measure the bit-error-rate performance of two 30-GHz, 200-W, coupled-cavity traveling wave tubes. The transmission effects of each TWT on a band-limited, 220-Mb/sec SMSK signal were investigated. The tests relied on the use of a recently developed digital simulation and evaluation system constructed at Lewis as part of the 30/20-GHz technology development program. This paper describes the approach taken to test the 30-GHz tubes and discusses the resultant test data. A description of the bit-error-rate measurement system and the adaptations needed to facilitate TWT testing are also presented.

17. Key Words (Suggested by Author(s))
Traveling wave tube
Bit-error-rate
Ground terminals

18. Distribution Statement
Unclassified – unlimited
STAR Category 32

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No of pages
14

22. Price*
A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1986