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Anomalous TWTA Output Power Spikes and Their Effect on a Digital Satellite Communications System

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ON A DIGITAL SATELLITE COMMUNICATIONS SYSTEM

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SUMMARY

Several 30 GHz, 60 W traveling wave tube amplifiers (TWTA) were manufactured for the NASA Lewis Research Center's High Burst Rate Link Evaluation Terminal Project. An unusual operating problem characterized by anomalous nonperiodic output power spikes, common to all of the TWTAs proved during testing to significantly affect the performance of a digitally-modulated data transmission test system. Modifications made to the TWTAs significantly curtailed the problem and allowed acceptable system performance to be obtained. This paper presents a discussion of the TWTA output power spike problem, possible causes of the problem, and the solutions implemented by the manufacturer which improved the TWTA performance to an acceptable level. The results of the testing done at NASA Lewis on the TWTAs both before and after the improvement made by Hughes are presented, and the effects of the output power spikes on the performance of the test system are discussed.

I. INTRODUCTION

The High Burst Rate Link Evaluation Terminal (HBR-LET) project was begun in 1987 to address the need for an experimental ground terminal to exercise the microwave switch matrix operational mode of NASA's Advanced Communications Technology Satellite (ACTS) described in [1]. For the uplink transmission, the communication signal is upconverted to a center frequency of 29.634 GHz and amplified for transmission to the satellite.

The link calculation for the uplink transmission indicates that a power amplifier capable of providing 60 W is required. At the HBR-LET uplink operating frequency of 29.634 GHz, current technology allows that only a traveling wave tube amplifier (TWTA) can meet this requirement. A contract was awarded to Hughes Aircraft Corporation in February 1989 to provide three TWTAs. Before final delivery of the TWTAs, an unusual operating problem became apparent. The RF output of the TWTA randomly deviates from steady state with short spikes of power. The effect of TWTA output power spikes on the HBR-LET communications link was investigated to assess the acceptability of TWTA performance. Testing, including bit-error rate (BER) tests, were performed on several TWTAs at the NASA Lewis Research Center. Improvements in materials and processing of the TWTAs resulted in vastly improved performance.

II. TWTA PROBLEM

Communications Satellite Corporation (COMSAT) first discovered the anomalous TWTA behavior during testing of units which are nearly identical to that ordered by NASA Lewis. COMSAT is under contract to provide NASA Lewis an Earth terminal for the ACTS program which will use a Hughes 54 W, 30 GHz TWTA. During routine performance evaluation at COMSAT, TWTA protection circuitry spontaneously shut itself down with increasing frequency. High voltage breakdown was thought to cause the shut down and COMSAT instrumented the TWTA to verify this hypothesis. TWTA RF output monitored with a Spectrum Analyzer revealed random output power spikes when observing TWTA output power only at a specific frequency. Test results are reproduced in Fig. 1.

Figure 2 shows a Hughes engineering model (EM) TWTA Serial Number (S/N) 128901 with TWT S/N 012, similar to the COMSAT TWTA, loaned to NASA Lewis for performance evaluation. NASA Lewis confirmed the random output power spike phenomenon with a spectrum analyzer (Fig. 3).

A digital oscilloscope was used to record the output power spikes while observing the TWTA output power with a broadband diode detector. By triggering the oscilloscope on the spike leading edge, COMSAT recorded a display of the output power spike event reproduced in Fig. 4. The 14 kV power supply terminals were also instrumented and recorded transients throughout the integrated TWTA. It was not determined which event was a cause and what was the resulting effect. Output power spike events can be broadly characterized as 1 to 3 dB fluctuations in RF amplitude lasting 500 nsec.

The loss of data bits and frame preamble information due to an output power spike and associated phase transients were naturally found to be detrimental to the transmitter performance. NASA performed BER measurements at a continuous rate of 221.184 Mbps, using serial minimum shift keying modulation (SMSK), on TWTA S/N 128901 (Fig. 5). One can see that the BER curves flare away from ideal performance around $5 \cdot 10^{-9}$. The theoretical probability of error shown for SMSK with additive white Gaussian noise is:

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

where

E_b energy per bit

N_0 noise power density

and the complementary error function is

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

Investigations at Hughes focused at determining whether the output power spikes are generated within the vacuum envelope of the TWT or outside of the TWT. Figure 6 is a stylized drawing of the TWTA. The power supply on the left provides the high voltages required to achieve the 60 W RF output. The high voltages require that special insulation materials be used to prevent arcing external to the TWT vacuum envelope. Due to exposed external high voltage connections to the electron gun, the electron gun is completely encapsulated in a silicone insulator. Partial discharge (Biddle) testing was performed on TWTs with traceable heritage to the COMSAT TWTAs and the deliverable NASA Lewis

2

TWTAs. A COMSAT residual TWT S/N 009 in its original packaging was subjected to a partial discharge test, and test results indicate a relatively high number of discharges. A NASA Lewis TWT (S/N 102), not yet insulated, was outfitted with new high voltage wires. Very few discharges were counted when the gun was submersed in a Freon bath insulation. The liquid Freon substitutes for the gun insulation material. Liquid properties at room temperature and breakdown voltage of 46 kV (across a 2.54 mm gap) make Freon an excellent insulator. Results from this test indicate that normal internal discharges are aggravated by the external insulation material.

It is possible that the RF output power spike may be the result of one of several events originating within the TWT gun. A fraction of the electrons in the electron beam are likely to impact the anode and be reflected back into the gun. The NASA Lewis team investigating the RF spikes hypothesized that these reflected electrons cause positive charge to build-up at the ceramic insulator surface within the gun. An unknown corona or microdischarge mechanism from the focusing electrode are thought to relieve the charge build-up on the ceramic insulator. The effect of a transient in focusing electrode grid current is to modulate the electron beam. Common power transformer stack for the cathode, focusing electrode and collector voltages complicate the problem. Power conditioning circuits are also effected when the transients discharge filter circuits. Similar to capacitors, impurities, air bubbles or delamination of insulation material around the gun produce a voltage gradient which may discharge when power supply transients occur.

III. BER TEST PROCEDURE

NASA Lewis has developed a Ka-band (30/20 GHz) digital satellite communications systems simulator known as the SITE (Systems Integration, Test and Evaluation) Project described in [2]. A block diagram of the SITE test system is shown in Fig. 7. A data generator in the digital ground terminal creates pseudorandom continuous digital data at 221.184 Mbps. The data checker, which is also contained in the digital ground terminal, has the job of receiving the returning data bit stream and comparing it bit-by-bit with the originally transmitted data bit stream. The bit-error rate is calculated by dividing the number of bits in error (B_e) by the total number of data bits transmitted (B_t):

$$BER = \frac{B_e}{B_t}$$

In this particular test, the Hughes 30 GHz TWTA was inserted into the SITE system after the frequency conversion system (FCS), which upconverts the SMSK modulator's intermediate frequency (3.375 GHz) to the 30 GHz uplink signal. SMSK is theoretically equivalent to BPSK or QPSK in bit-error rate performance versus E_b/N_0, but is more spectrally efficient [4]. The placement of the TWTA puts it in the same location as it would be a real satellite network.

A solid state noise source with an excess noise ratio of 30 dB is combined with the downlink modulated data signal to produce a BER versus E_b/N_0 curve. The E_b/N_0 can be varied across any user defined range, usually from about 4 to 18 dB. Two computer controlled attenuators adjust the power levels of both the noise and the signal plus noise in 1 dB increments in order to maintain the proper E_b/N_0 and the proper demodulator input power levels within a 0.5 dB tolerance. E_b/N_0 of the test signal is calculated using the measurements of noise and signal power:

$$\frac{E_b}{N_0}(dB) = \left(P_s - P_n\right) + N_{bw} - R$$

3

where

P_s measured signal power, dB

P_n measured noise power, dB

N_{bw} noise equivalent bandwidth of the calibration filter = 393.14 MHz = 85.95 dB Hz

R   data rate = 221.184 Mbps = 83.45 dB Hz

The ground terminal receives the returning data bit stream, corrupted with added noise, and compares it bit-by-bit with the originally transmitted data bit stream to determine BER.

IV. TEST RESULTS FOR UNMODIFIED TWTA

BER measurements on the unmodified TWTA S/N 128901 in Fig. 5 show nearly normal operation at the higher BERs up to $1 \cdot 10^{-7}$, where the number of errors induced by the output power spikes is masked by the noise-induced errors. At the higher E_b/N_0s, however, the number of noise-induced errors decreases to the point where the dominant error mechanism is the TWTA output power spikes. The minimum BER available for HBR-LET operation becomes $1.5 \cdot 10^{-8}$. This minimum is not adequate for many types of experiments simulating system applications (data transfers, electronic funds transfers, computer networks, etc.) which the HBR-LET may be required to accommodate.

Most disturbing is the complete loss of demodulator carrier synchronization, apparently caused by large spikes. This complete loss of data would cause major disruptions of experiments and is thus unacceptable.

V. SOLUTIONS

Hughes proposed modifications to the NASA TWT which were found to minimize the output power spikes. Gun insulation material was upgraded from a silicone compound with a tear strength of 4.4 kN/m to Dow Corning's Sylgard 577 silicone adhesive with a tear strength of 12.3 kN/m. The Sylgard 577 material offers two important advantages: first, the material is less likely to separate from the TWT gun as indicated by the higher tear strength and second, the material does not require a uniform silicone primer on the surface to which it will be bonded. Perhaps more importantly, the process of encapsulating the gun was improved by pouring the insulation material in a partial vacuum thereby degassing the insulation material and eliminating bubbles when it sets.

High voltage wire leads to the TWT gun were upgraded from 22 kV rated wire to the AWG 20 Reynolds 25 kV rated fluorinated ethylene propylene insulated wire with a silicone casing. The silicone casing provides better bonding to the Sylgard 577 silicone material.

VI. TEST RESULTS FOR MODIFIED TWTAs

A TWT (S/N 207) of identical design from a new production run was subjected to the oscilloscope trace test. Freon was once again substituted for the insulation as the gun end of the TWT was submersed. New 25 kV wires provided the high voltages. A typical RF output oscilloscope trace from this test is reproduced in Fig. 8. Given that Freon is an excellent insulator, it can be concluded that the

phenomenon that results in power spikes, possibly corona, are generated internal to the TWT vacuum envelope. The magnitude of the spikes recorded during this test is comparable to that recorded on a TWTA with upgrades.

Investigations by Hinckeldey et al. [5] of a similar power spike phenomenon in 1978 resulted in the hypothesis that flashovers internal to the gun discharged power supply filter capacitors. The accumulated test data by COMSAT, Hughes and NASA Lewis is consistent with this hypothesis on the internal source of power spikes. The observed effect of different insulation materials remains open to interpretation.

A second TWTA, serial number 49001, with a modified TWT, was fully tested in the same manner as the unmodified TWTA (S/N 128901). The BER curves are shown in Fig. 9. These curves show a normal BER falloff with increasing E_b/N_0 with no minimum BER being reached, down to a BER of $1 \cdot 10^{-11}$.

The modified TWTAs were found to contribute no additional bit-errors or groups of errors caused by output power spikes and are acceptable for application to the HBR-LET ground terminal.

VII. CONCLUSION

The TWTA power spike anomaly described in this paper may impact only a very few users of the Hughes TWTA. Many TWTAs are reported to be operating in the field without incident. The application for these TWTAs may be insensitive to random power spikes. Transmitter requirements of megabit per second data rates and $1 \cdot 10^{-7}$ BER are at this time unique to the ACTS program. As the information age matures, services will evolve that match or exceed the ACTS technology. It is these high data rate, low BER satellite services that will be impacted by the power spikes described here.

Paralleling the trend for high data rate services, such as CRAY computer file transfers, and low BER services, such as electronic funds transfer, microwave equipment suppliers will continually find ways to improve their product. The testing performed on the 30 GHz TWTAs compelled Hughes to seek out better materials and processing that enabled their product to meet demanding performance requirements.

ACKNOWLEDGMENTS

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[2] R.V. Latham, High Voltage Vacuum Insulation: The Physical Basis, Academic Press, London, 1981.

[3] R.J. Kerczewski and G. Fujikawa, "Performance Measurements for a Laboratory-Simulated 30/20 GHz Communication Satellite Transponder," <u>AIAA 13th International Communications Satellite Systems Conference</u>, Part 1, AIAA, New York, 1990, pp. 277-284. (Also, NASA TM-102424.)

[4] R.J. Kerczewski, G. Fujikawa, J.S. Svoboda, and P.J. Lizanich, "Effects of Amplitude Distortions and IF Equalization on Satellite Communication System Bit-Error Rate Performance," <u>AIAA 13th International Communications System Satellite System Conference</u>, Part 2, AIAA, New York, 1990, pp. 807-817. (Also, NASA TM-102415.)

[5] A. Hinckeldey, D. Pfab, and M. Schnaedelback, "Improved TWTs for Reliable High Speed Data Transmissions," <u>Microwave J.</u>, vol. 21, pp. 65-67, 1978.
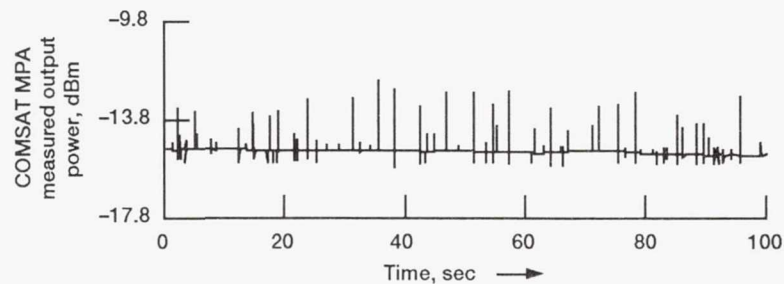
Figure 1.—COMSAT test data from spectrum analyzer monitoring a CW signal at 29.263 GHz. Spectrum analyzer span is 0.0 Hz, resolution bandwidth is 3 MHz, and video bandwidth is 3 MHz.
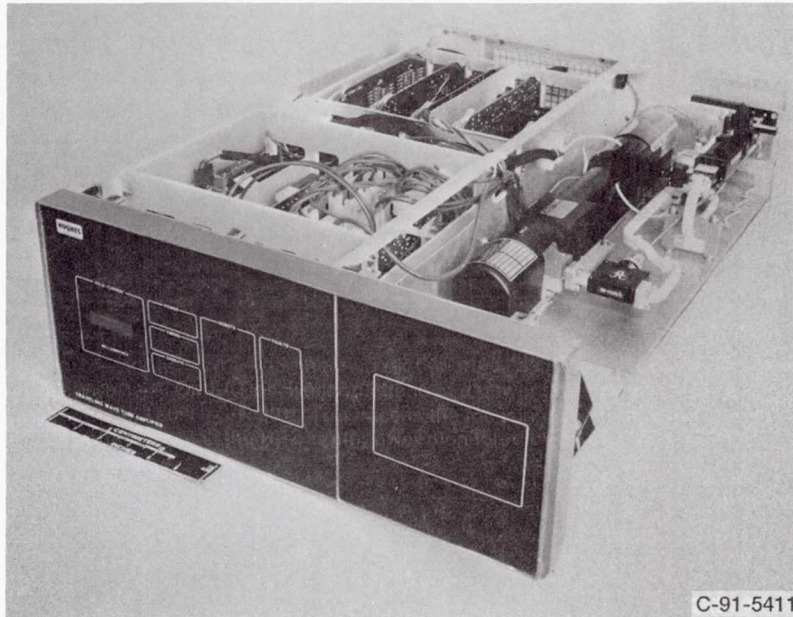
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Figure 2.—Hughes TWTA engineering model S/N 128901 without cover showing power supply and RF hardware details.
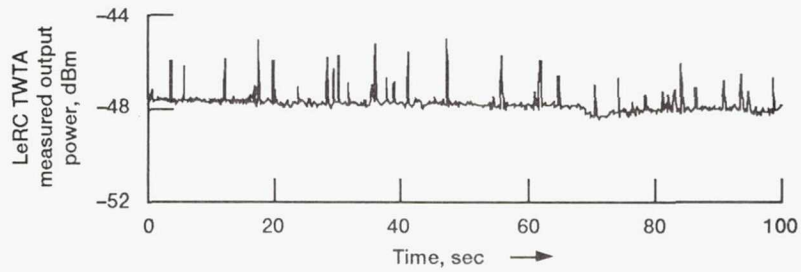

Figure 3.—NASA Lewis test data from spectrum analyzer monitoring a CW signal at 29.254 GHz. TWTA is operated at 10 dB below saturation. Spectrum analyzer span is 0.0 Hz, resolution bandwidth is 3.0 MHz, and video bandwidth is 3.0 MHz.
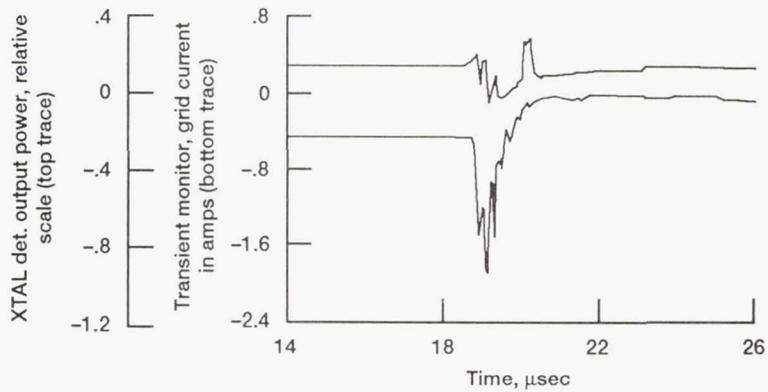

Figure 4.—COMSAT oscilloscope trace of a power spike event for MPA (model 1609H) S/N 001. Top trace is the focusing electrode (grid) current, bottom trace is the RF output power monitored by an inverting crystal detector.
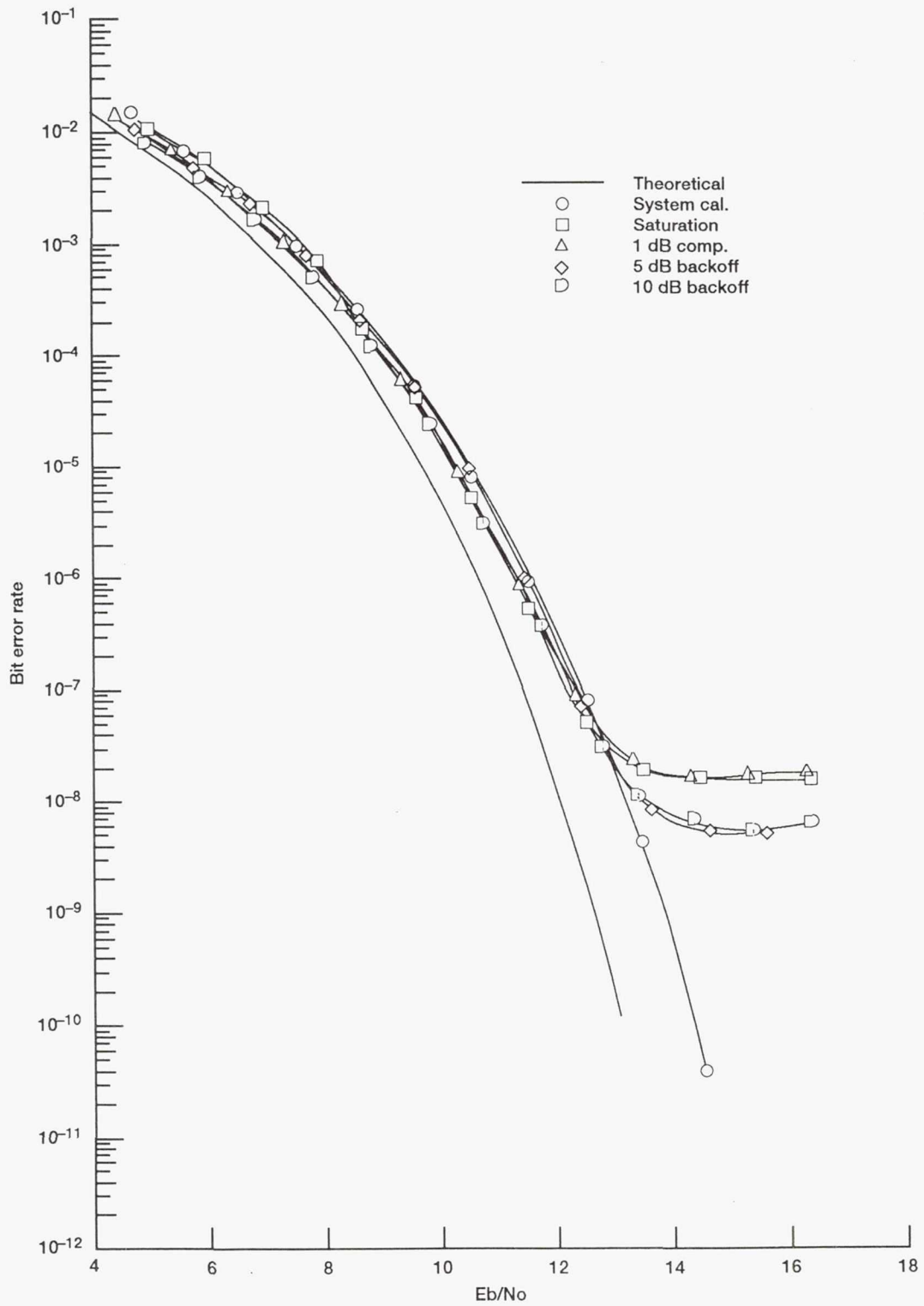
7

Figure 5.—NASA Lewis BER versus Eb/No measurements with TWTA 128901 at several operating points. This unit has original insulation materials.

Power supply

Ground

$E_f\,(-) = -6V$ Heater

$E_f\,(+) = +6V$ Heater

$E_k = 14KV$ Cathode

$E_g < -14KV$ Grid

$E_A = +400V$ Anode

$E_B = -9KV$ Collector

FEP 25KV wires

Dow Corning silicon adhesive

RF in

RF out

Electron gun

Ceramic insulator
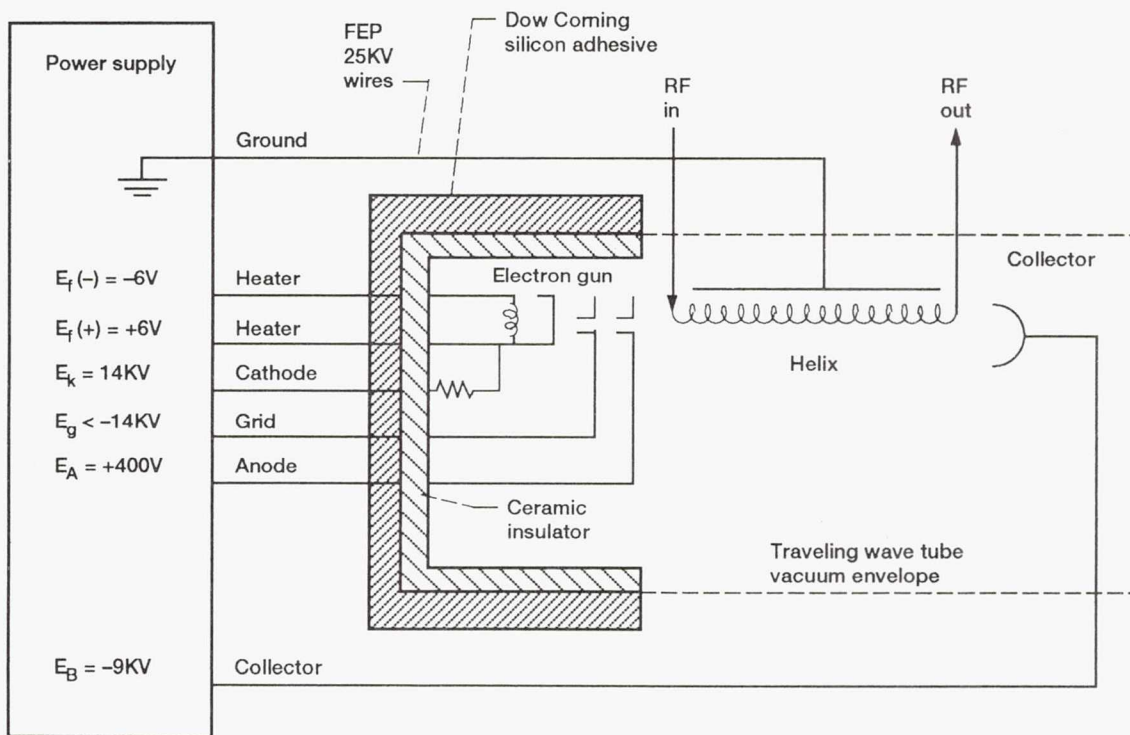
Helix

Collector

Traveling wave tube vacuum envelope

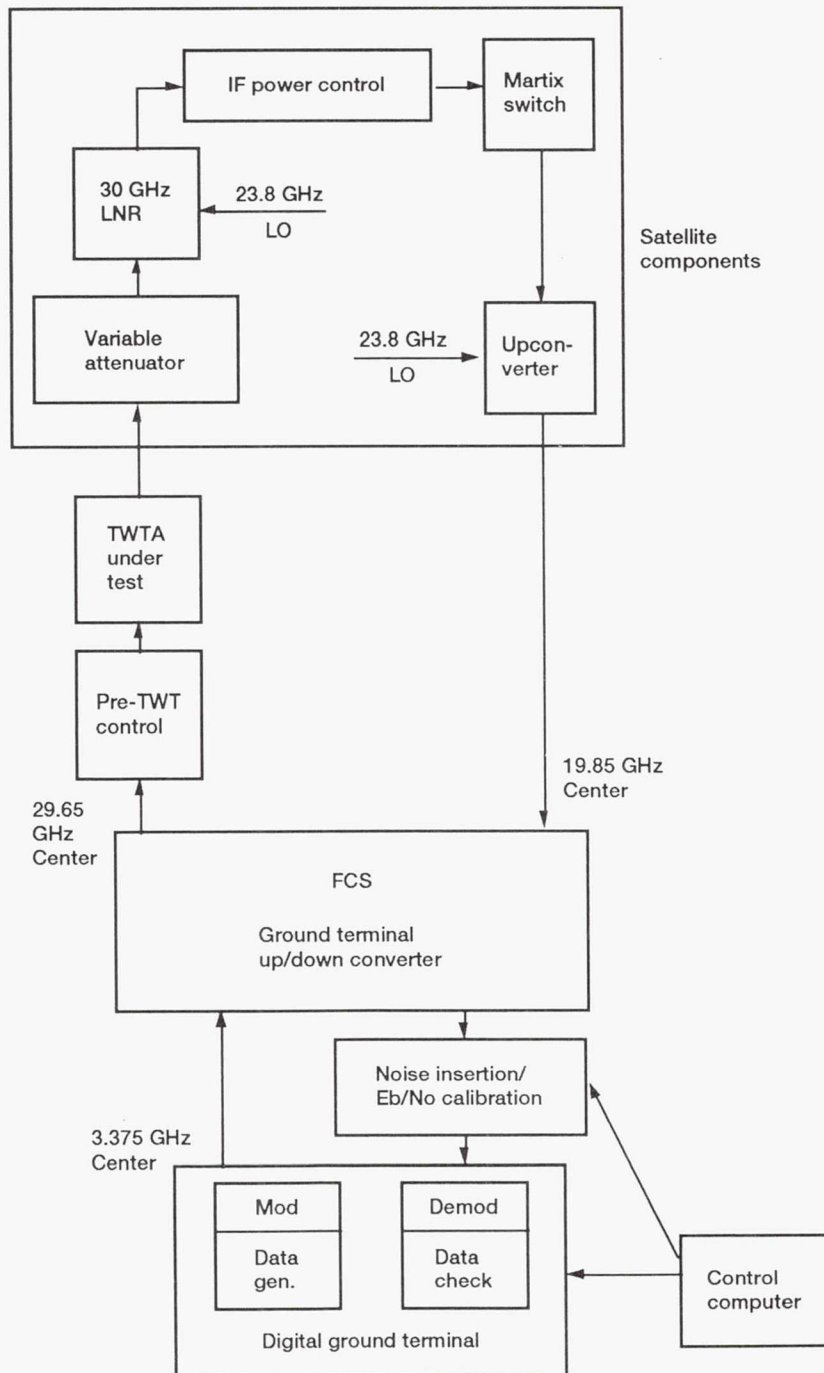Figure 6.—Simplified block diagram of the Hughes TWTA.

9

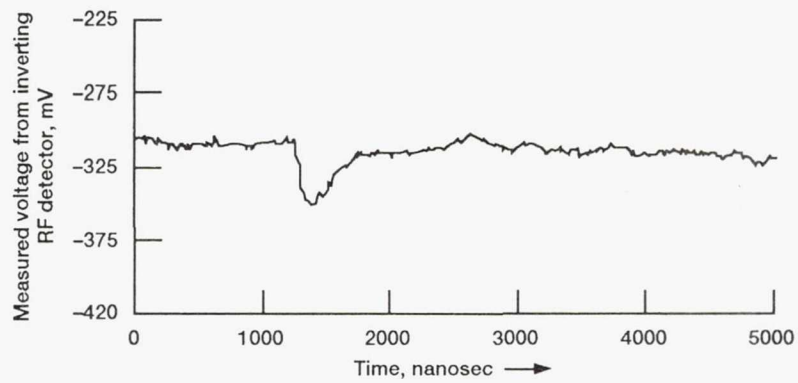Figure 7.—NASA Lewis SITE BER test setup for LET Hughes TWTA.

Figure 8.—Hughes oscilloscope trace of a power spike event. TWT 8904H, S/N 207 with new wires, immersed in FEP.
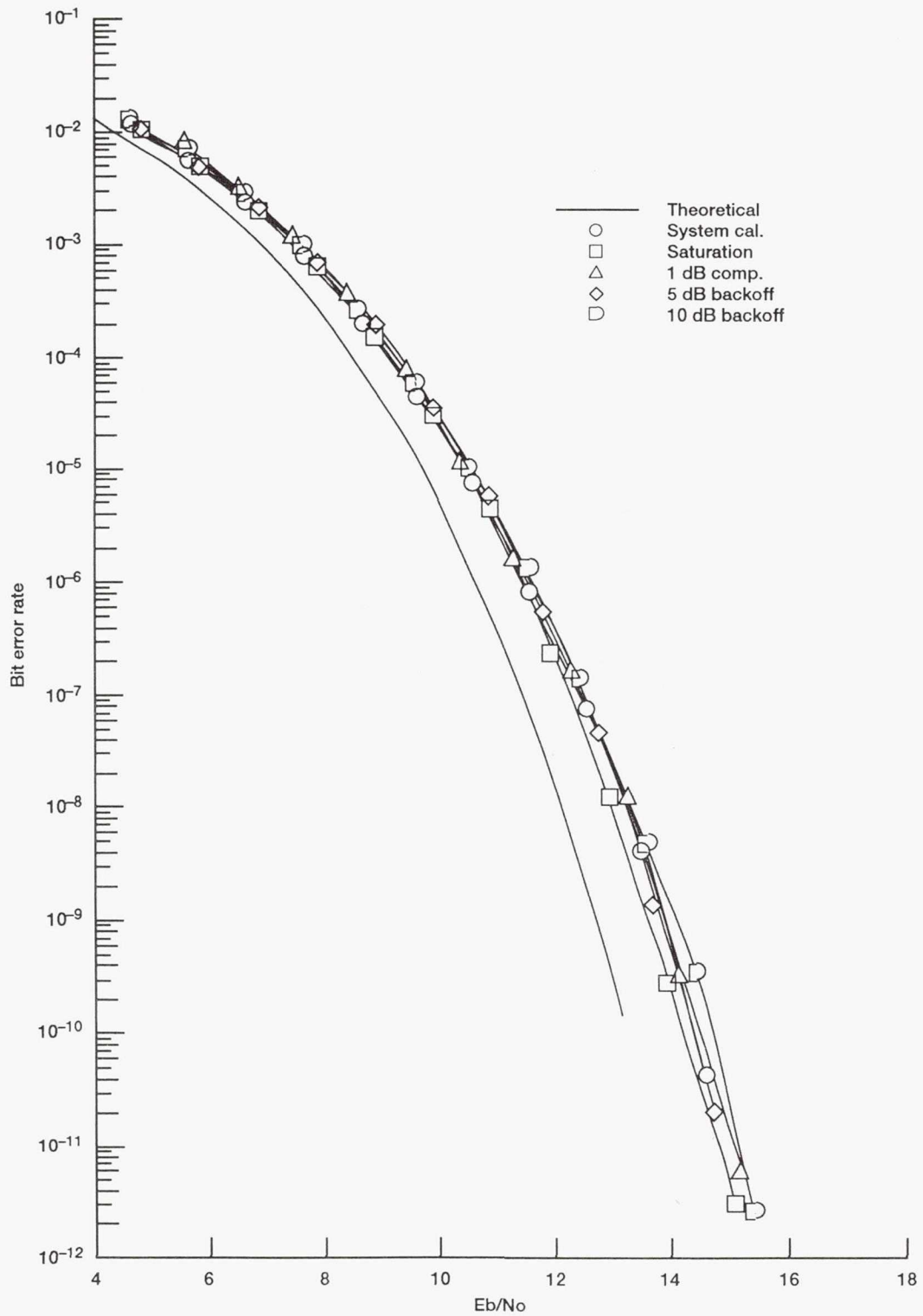
Figure 9.—NASA Lewis BER versus Eb/No measurements with TWTA 49001 at several operating points. This unit included insulation materials upgrade.

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13. ABSTRACT *(Maximum 200 words)*

Several 30 GHz, 60W traveling wave tube amplifiers (TWTA) were manufactured for the NASA Lewis Research Center's High Burst Rate Link Evaluation Terminal Project. An unusual operating problem characterized by anomalous nonperiodic output power spikes, common to all of the TWTAs proved during testing to significantly affect the performance of a digitally-modulated data transmission test system. Modifications made to the TWTAs significantly curtailed the problem and allowed acceptable system performance to be obtained. This paper presents a discussion of the TWTA output power spike problem, possible causes of the problem, and the solutions implemented by the manufacturer which improved the TWTA performance to an acceptable level. The results of the testing done at NASA Lewis on the TWTAs both before and after the improvement made by Hughes are presented, and the effects of the output power spikes on the performance of the test system are discussed.

14. SUBJECT TERMS

Traveling wave tube; Power spike; Bit-error-rate; Advanced communication technology satellite

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