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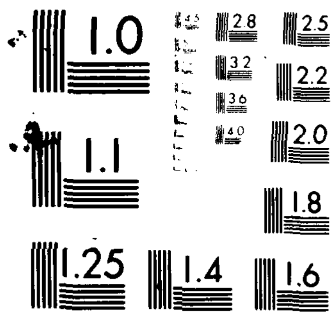

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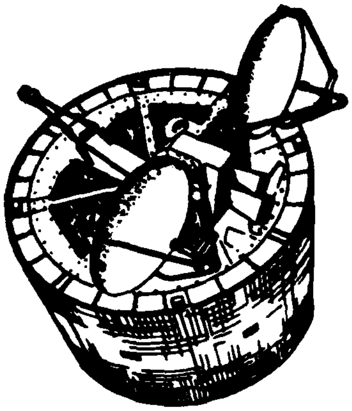

SATELLITE 9443
DSCS II ANOMALY REPORT
NARROW COVERAGE DOWNLINK NOISE

14 AUGUST 1981

Report No. 36060-AR-024-01
CDRL No. 009A3
F04701-80-C-0022

Prepared for

Space Division
Air Force Systems Command
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
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TRW

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This report was submitted by the TRW Defense and Space Systems Group, Redondo Beach, CA 90278, under Contract F04701-80-C-0022 with the Space Division, Deputy for Space Communications Systems, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for TRW Defense and Space Systems Group by R. H. Alborn, Manager, DSCS II Orbital Operations. Capt John A. Fredricks, SD/YKD was the project engineer.

This report has been reviewed by the Office of Public Affairs (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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Presents the results of an investigation of the cause of noise pulses in the RF downlink, considering orbital data and laboratory simulation. Ascribes the cause to an arc in the cathode circuitry of the TWT, which is a function of the vacuum level.

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SATELLITE 9443

DSCS II ANOMALY REPORT

NARROW COVERAGE DOWNLINK NOISE

CDRL No. 009A3
F04701-80-C-0022
14 August 1981

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TRW
DEFENSE AND SPACE SYSTEMS GROUP

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

1. INTRODUCTION

On February 19, 1981, a narrow coverage high level traveling wave tube amplifier (NCHLTWTA-2, S/N 24-6) on Satellite 9443 shut off without warning or receiving ground commands. A redundant HLTWTA (SN 24-1) was commanded on and communication service was restored. This occurrence represented the first on-orbit failure of a 40 watt HLTWTA. Within a few hours after turn-on, several ground stations reported occasional loss of data on their narrow coverage high data links which was attributed to noise on the RF link. Monitoring of the narrow coverage down link showed that noise spikes were occurring at a repetition rate varying from thirty to sixty spikes per minute. Also observed were quiescent periods lasting several minutes where no spikes occurred.

An anomaly team was formed to investigate the RF noise spikes. This report summarizes the investigations and findings of the team made up of TRW, Hughes, Aerospace, Space Division, and Harris engineers.

1.1 Summary of Investigation

Figure 1.1-1 shows a block diagram of the communication transponder and Figure 1.1-2 shows an expanded version of the transmitter section. Study of these block diagrams shows that a number of possible sources exist to cause an RF spike on the narrow coverage output. By performing a series of on-orbit tests, described in Section 3.1, the primary cause was narrowed down to the HLTWTA, with a very remote possibility of the LLTWTA or TDSA. Ground testing at Hughes Electron Dynamics Division (HEDD), as described in Section 3.2, was able to reproduce the on-orbit anomaly signature by causing arcs to occur in the cathode circuitry. Analysis of all test data, as described in Section 4.0, led to the conclusion that the RF spikes were caused by an arc occurring in a relatively high vacuum (10^{-5} Torr) from a wire in the cathode circuit of the tube to the end of the TWTA housing. The arc did not occur in any potting material.

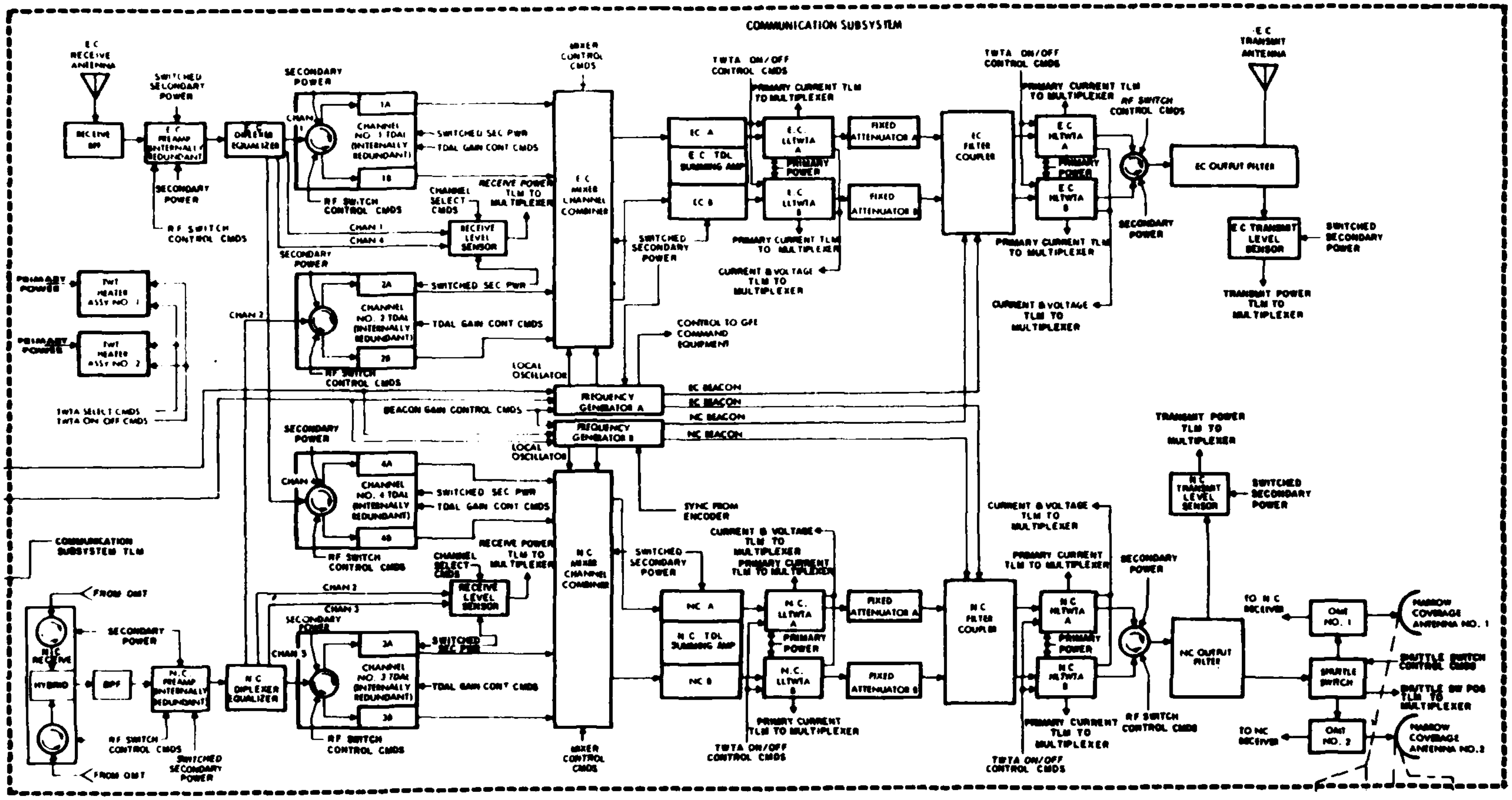
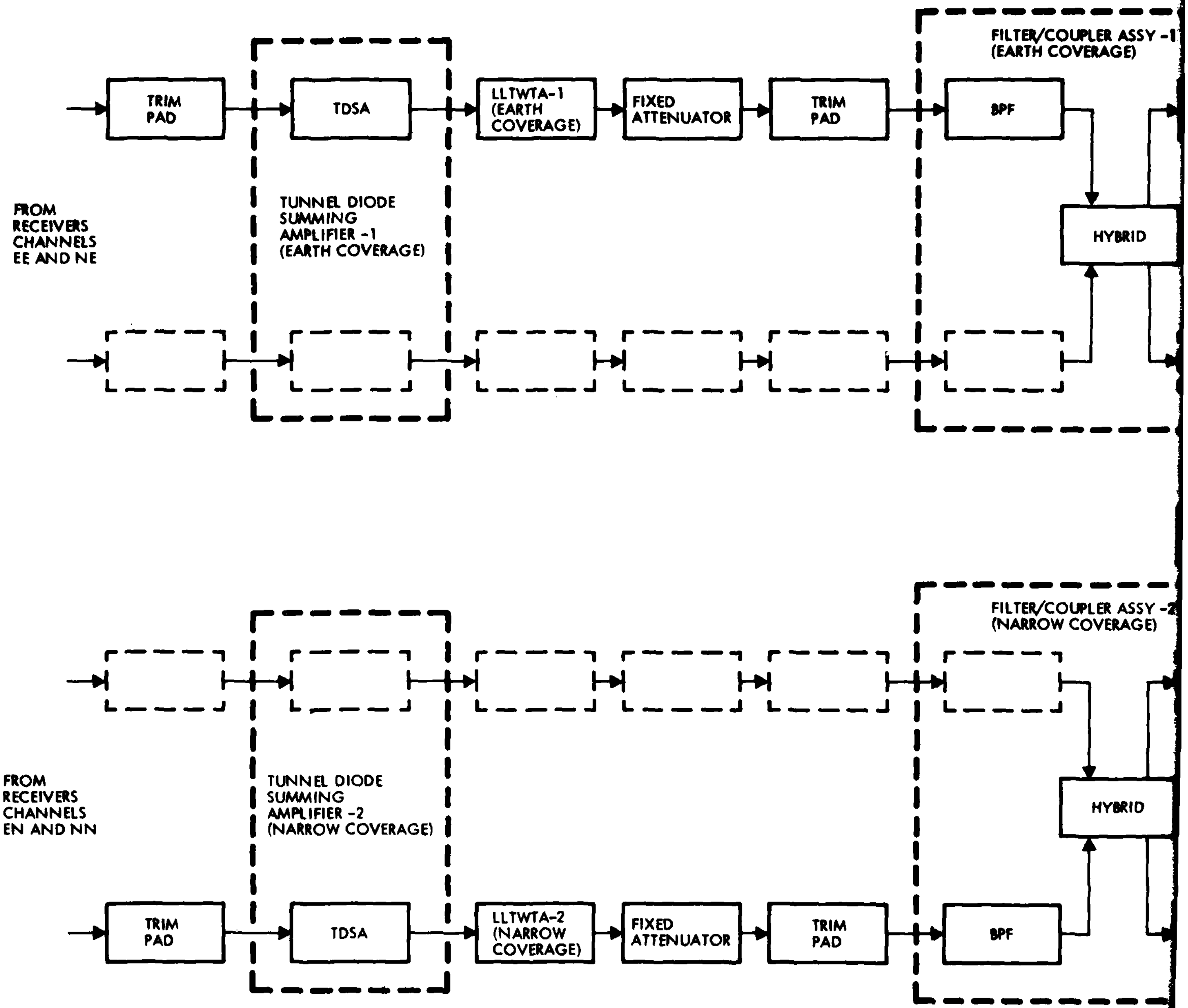
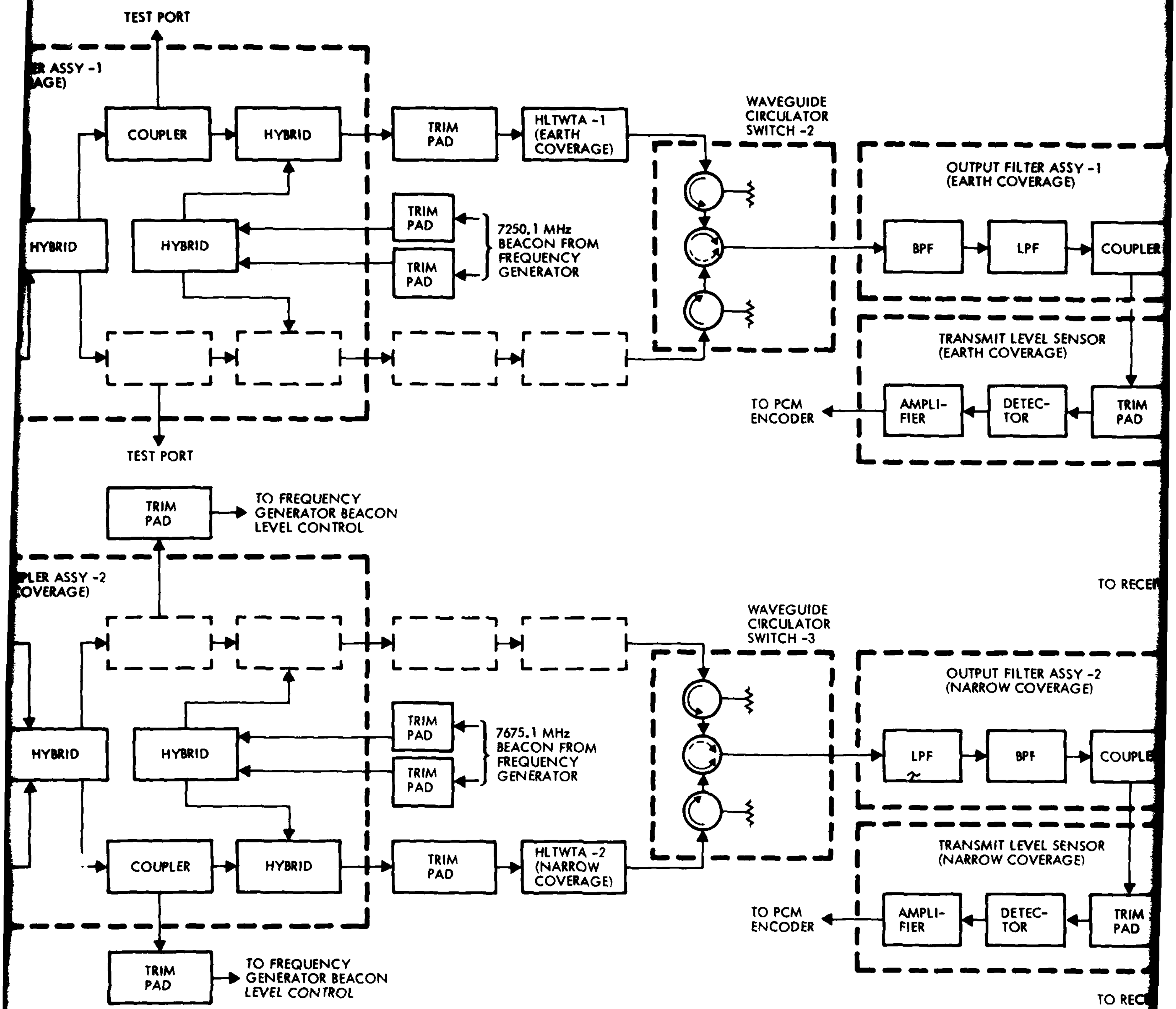


Figure 1.1-1. DSCS II Communications Subsystem Block Diagram



NOTE: CIRCULATOR SWITCHES ARE CONTROLLED BY COMMANDS USED TO TURN HLTWTA'S ON AND OFF.

Figure 1.1-2.



1.1-2. Communications Transmitter Section

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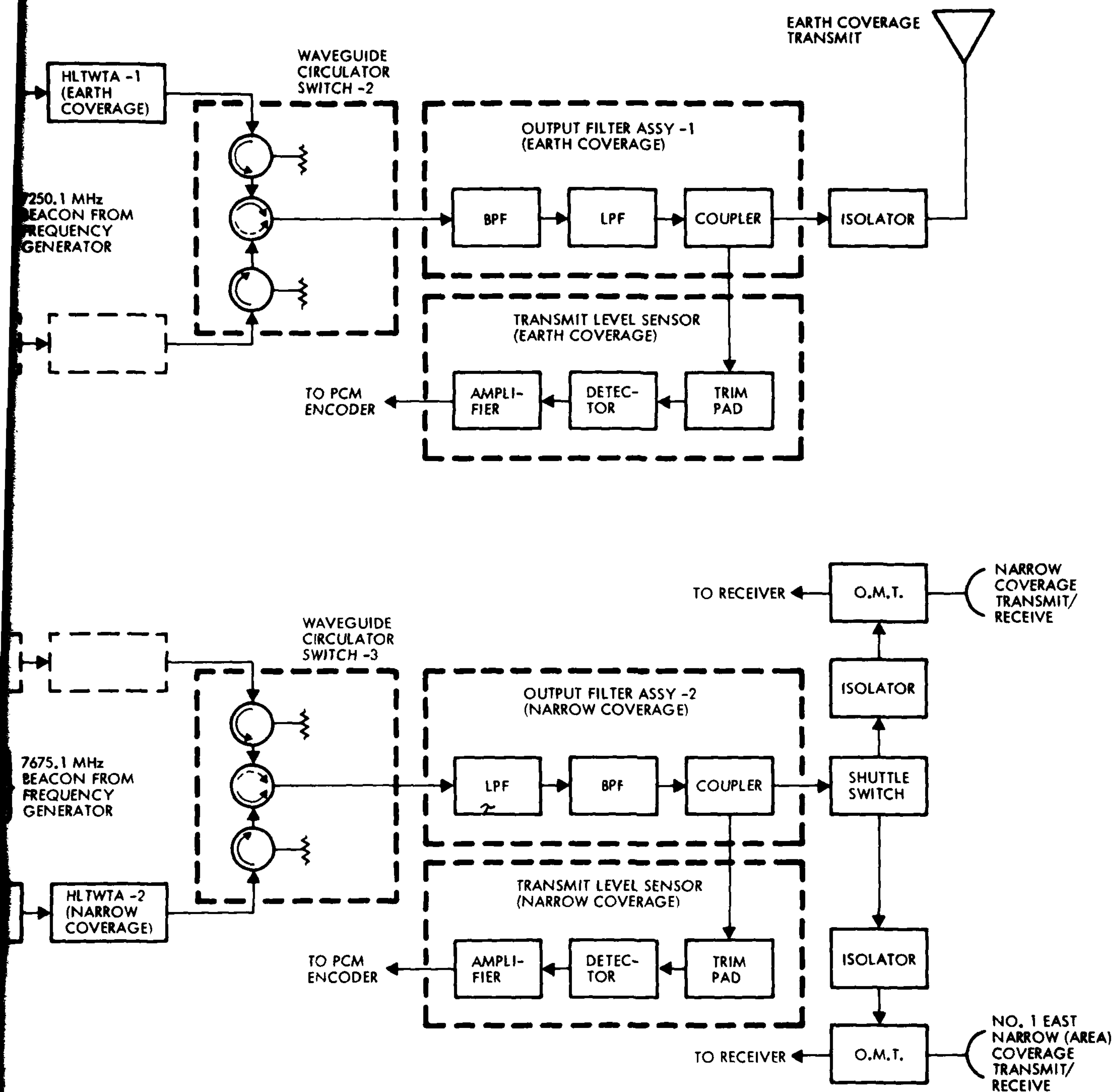

EARTH COVERAGE TRANSMIT
HLTWTA -1 (EARTH COVERAGE)
WAVEGUIDE CIRCULATOR SWITCH -2
OUTPUT FILTER ASSY -1 (EARTH COVERAGE)
BPF
LPF
COUPLER
ISOLATOR
250.1 MHz BEACON FROM FREQUENCY GENERATOR
TRANSMIT LEVEL SENSOR (EARTH COVERAGE)
TO PCM ENCODER
AMPLI-FIER
DETEC-TOR
TRIM PAD
TO RECEIVER
O.M.T.
NARROW COVERAGE TRANSMIT/ RECEIVE
WAVEGUIDE CIRCULATOR SWITCH -3
ISOLATOR
OUTPUT FILTER ASSY -2 (NARROW COVERAGE)
7675.1 MHz BEACON FROM FREQUENCY GENERATOR
LPF
BPF
COUPLER
SHUTTLE SWITCH
TRANSMIT LEVEL SENSOR (NARROW COVERAGE)
HLTWTA -2 (NARROW COVERAGE)
TO PCM ENCODER
AMPLI-FIER
DETEC-TOR
TRIM PAD
ISOLATOR
TO RECEIVER
O.M.T.
NO. 1 EAST NARROW (AREA) COVERAGE TRANSMIT/ RECEIVE

3

In order to preclude this type of problem in the future, it is necessary to vent the TWTA housing to space to maintain a high vacuum (< 10^{-5} TORR) which will not sustain an arc. As part of the HLTWTA collector depotting program for F15 and F16, the TWTA case has had a venting hole added. This fortuitous change will preclude any arcing of the type seen on 9443.

2. ORBITAL CHRONOLOGY

2.1 Orbital History

Satellite 9443 was launched on November 21, 1979. The number 1 traveling wave tube amplifiers (TWTA's) were commanded ON on 10 December, after allowing time (minimum of 14 days) for outgassing. Communications testing performed by the Satellite Control Facility (SCF) at Camp Parks demonstrated normal operation. On 12 December, the number 2 TWTA's were commanded ON (number 1 OFF), and again, tests showed normal operation.

On 26 and 27 January, 1980, the Defense Communications Agency (DCA) performed additional tests, which again confirmed normal operation. The satellite was then placed in operational service.

2.2 Anomaly Chronology

On 19 February, 1981, the Satellite Test Center (STC) was notified by DCA that the 9443 NC downlink turned off at 0022Z. An emergency support was scheduled. When telemetry became available, the narrow coverage high level TWTA number 2 (NCHLTWTA-2) parameters were all zero. Commanding the unit on yielded the same data. The -1 amplifier was commanded on at 0055Z, with normal data resulting.

On 24 February, DCA reported noise problems with the NC downlink (it was later learned that noise problems were logged shortly after the NCHL-1 was turned on). Only stations using QPSK were affected; these stations switched to BPSK. Ft. Dietrick performed tests on the satellite on 24 February, comparing a signal through the earth-to-earth (EE) channel with one through the narrow-to-narrow coverage (NN) channel. EE was normal; NN had high bit error rates using QPSK. Noise pulses were observed approximately every 45 seconds.

On 7 March, Ft. Dietrick again checked the NC downlink, and observed the pulses at two to three minute intervals. On 11 March, DCA reported that the noise was much worse, and BPSK was now unusable also. Most NC links were rerouted by DCA.

On 17 March, a test was run to attempt to ascertain the cause of the noise. Ft. Monmouth monitored the NC downlink. The test consisted of the following steps:

NC beacon off
Switch frequency generators (-2→ -1)
EN and NN receivers -2 off
Transfer shuttle switch to NCA -2, then back to 1/2
EN and NN receivers -1 on
Switch communications bus (-2→-1)
Saturate channel NN

None of these steps affected the noise spikes, except that at saturation the spikes were downward only, without the initial upward change that was normally seen (see Section 3).

On 26 March, the NN channel was saturated during an eclipse, providing maximum temperature reduction. This test was similar to the one performed on 17 March.

On 3 April, the satellite spin rate was changed, initially from 55.5 rpm to 60.6 rpm. After about an hour at that spin rate, the spin rate was reduced to 49.1 rpm. This test was performed to determine possible correlation of the noise pulse repetition rate with the spin rate.

On 30 April, a delta velocity maneuver was performed on the satellite to drift it westward so that Camp Parks could monitor its performance. This monitoring started on 8 June for five days, 24 hours per day. No pulses were observed. On 15 June, another five days of continuous monitoring was started. On 16 June, a NC antenna was slewed. Again, no pulses were observed during that period.

A discussion of these tests and the conclusions are contained in Section 3.

3. ANALYSIS OF ORBITAL AND GROUND TEST DATA

3.1 On-Orbit Test Analysis

In an effort to define the source of the noise spikes, a series of on-orbit tests were performed on the satellite. These tests included switching redundant units, changing RF levels, changing satellite spin rate, and lowering the TWTA temperature by changing its operating characteristics. A summary of these tests is contained in the following sections.

The first series of tests were concerned with establishing the source of the noise as internal or external to the satellite and identifying those units within the satellite which could possibly cause a spike on the RF output. Certain redundant units were switched and the output observed for any change. The specific tests performed and the results were as follows:

(a) The transponder TDAL's and mixers were turned-off. The spikes continued to appear on the beacon signal thereby proving that the problem was internal to the satellite and not an external signal being picked up by the receiver. Also, the cause was isolated to a point beyond the TDALS's (see Figure 1.1-1).

(b) The beacon was switched off. The spikes continued on the RF carrier. The redundant frequency generator was then selected. The spikes continued. Then the SLA converter was switched to the redundant unit. Again, the spikes continued. These tests demonstrated that the spikes were not being caused by the frequency generator or the transponder DC power supply.

(c) The narrow coverage antenna power split was changed using the shuttle switch. No change was observed in the spikes. This test isolates the problem to somewhere before the shuttle switch.

(d) The RF signal was increased, driving the TWTA into saturation. The spikes reversed direction on the carrier and on the beacon, with an increase in relative amplitude on the beacon. No conclusion could be drawn from this test.

(e) In order to check if the spikes were sensitive to temperature variations, the TWTA temperature was reduced by driving the TWTA into saturation just before the onset of an eclipse. The collector temperature dropped from 142°F to 122°F in the middle of the eclipse and then rose back to about 135° after the eclipse. The change in repetition rate was within the normal random variation previously observed.

(f) The spin rate of the satellite was varied ±5 RPM to determine if the spike repetition rate would change. No change of the rate could be discerned. It was therefore concluded that the spiking was not related to a vibration effect caused by spacecraft rotation.

The only test not performed was turning off the low level TWTA chain which also includes the TDSA. If the spiking disappeared from the beacon signal, then it could be concluded that the source was in the LLTWTA chain. This test was not performed for two reasons. First, no hypothesis could be developed which explained how the spikes could be produced in the LLTWTA chain which would appear on the RF output even with no RF signal into the receiver. Second, there was concern that if the LLTWTA was turned off, it may not be possible to turn it back on or it may come on in a degraded mode due to cathode coating separation which has been seen on another TWTA. If the satellite becomes unusable due to the spiking, then this is a test which should be considered.

Another activity for on-orbit analysis was a correlation analysis of the continuously recorded RF output signal. This analysis covered about 30 days of data taken over a period of two months. The data was plotted in a format shown in Figure 3.1-1, which is a typical day.

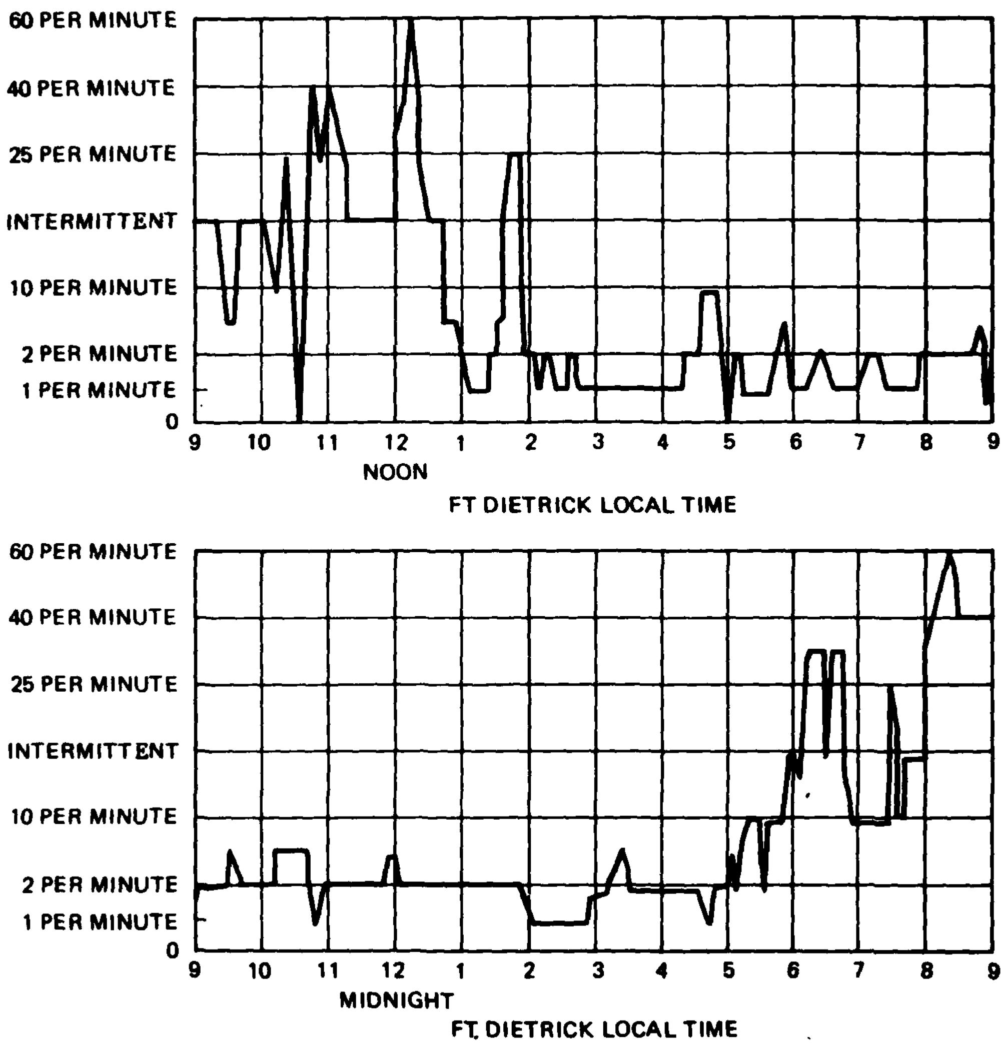


Figure 3.1-1. Typical Noise Pulses During One Day (19 & 20 March 81)

An attempt was made to correlate spiking activity with time-of-day but no pattern could be discerned. However, it was clear that the number of spikes occurring each day was slowly decreasing as a function of time. At the end of two months, the spiking rate was significantly lower than at the beginning. This phenomenon will be discussed in more detail in Section 4.

Telemetry data from the satellite during this period showed some low or zero readings for the helix current for NCHLTWTA-1. Helix current is sampled at 8-second intervals, with a sampling gate of only a few microseconds. Therefore, not many samples could be expected to be coincident with the noise spikes. However, a camparison of the times that low readings were observed on telemetry with the times of occurrence of the noise spikes showed a good correlation. Generally, the low readings occurred during periods of high noise spike activity; no low readings occurred when there were no noise spikes.

3.2 Ground Test Analysis

A number of laboratory tests were performed by Hughes Electron Dynamics Division in an attempt to simulate the on-orbit anomaly. In addition to the laboratory tests, Hughes performed a documentation review on TWTA S/N 24-1 and a general review of other tube failures to determine if there has been any similarity in the various anomalies and their causes. This section will address these specific issues.

3.2.1 S/N 24-1 Test and Documentation Review

Documentation packages for S/N 24-1 (TWTA Type 1241H) were reviewed to determine if problems occurred during the manufacture or test of the TWTA that could be related to the orbital anomaly of the amplifier on 9443. A detailed analysis showed no evidence of aberration or precursor that would indicate a possible future condition that would lead to the symptoms observed in orbit.

3.2.2 General TWTA Anomaly History Review

The histories of other TWTA's, including DSCS II and designs related to DSCS II, were also reviewed for similar occurrences in hardware other than the DSCS II/DSCS III amplifiers. While some failures have occurred, no comparable anomalies were found.

3.2.3 TWTA Laboratory Tests

A systematic series of tests were performed on a laboratory power supply and TWT in an attempt to correlate ground performance with the on-orbit signature. Before the various tests were defined, preliminary measurements were performed on a DSCS II TWT (Type 293H) to determine the amplitude and phase characteristics as a function of cathode and anode voltages. The results of these measurements showed that only a significant cathode voltage variation had the possibility of matching the on-orbit behavior. Using this result as a basis, the following tests were performed.

(a) Arcing of the TWT collector circuit to ground and TWT cathode to ground.

(b) Interrupt of the ON command signal.

(c) Shorting of the input filter capacitors.

(d) Momentary interrupt of the helix regulator.

(e) RF phase and amplitude sensitivity to cathode and anode voltage variations.

(f) Partial vacuum spark tests.

These tests were performed using the 1241H breadboard and 293HA/D TWT S/N 381. The results of these tests are as follows.

3.2.3.1 Arcing Tests Results

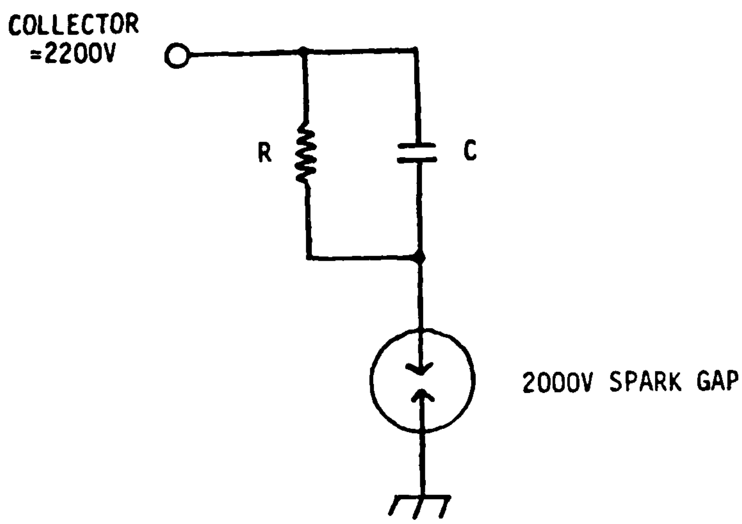
Periodic sparking from either the cathode or collector circuits would cause abrupt changes in TWT cathode voltage followed by a transient recovery period. The effect on the RF output would likely be a momentary drop in power followed by an increase. In addition to the power output changes, a corresponding phase modulation would result.

Experiments were performed to simulate periodic sparking from either the cathode or collector circuits to ground. To obtain a good representation of the type and magnitude of discharge likely to occur, a controlled amount of charge was dumped from the circuit by charging a known capacitance through a spark gap. The configuration of this spark circuit is shown in Figure 3.2.3.1-1. Initially, the capacitor is in a discharged state. The voltage applied to the spark gap through the resistor causes ignition to occur. The capacitor then charges, through the fired gap, to the TWT element voltage. Once charged, the capacitor ceases to sustain current and the spark is extinguished. The capacitor then discharges through the resistor until the critical voltage again is placed across the spark gap. The circuit behaves as a relaxation oscillator whose period is determined by the RC time constant. The size of the capacitor determines the amount of charge extracted from the circuit during the spark discharge. The mechanism of limited spark discharge is different from that expected in space but the effect should be similar.

(a) Cathode Circuit Experiment. With the spark gap circuit of Figure 3.2.3.1-1B in place on the TWT cathode lead, the unit was operated while observing the telemetries and RF output on the strip chart recorder. Various values of capacitance from 0.001 to 0.01 μf were used to simulate different amounts of transferred charge. The effects on helix current (Iw) telemetry and RF output amplitude were particularly noted. The closest match to orbital symptoms was obtained with 0.01 μf.

RF amplitude spikes were observed for both saturated drive and for saturation minus 10 dB drive. Both an increase and a decrease in amplitude could be observed. The apparent

-1A. Collector Circuit



-1B. Cathode Circuit

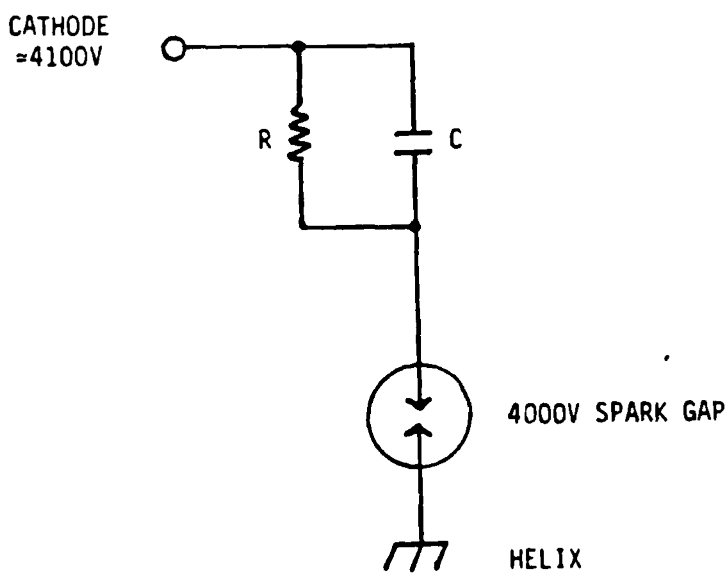


Figure 3.2.3.1-1 Spark Test Configuration

amplitude shift varied from plus 1 dB to -0.8 dB during saturation and up to plus 3 dB with saturation minus 10 dB drive. The helix current showed negative transients similar to the on-orbit data. A typical section of the strip chart recording is shown in Figure 3.2.3.1-2. The true amplitude of the spikes was likely somewhat less than that indicated from the strip chart. Some ground loop coupling from the spark current source through the crystal detector output may have occurred.

Two other tests were made to corroborate the data from the strip chart. A spectrum analyzer was used as an amplitude detector with the horizontal axis acting in time scan. A typical waveform photograph is shown in Figure 3.2.3.1-3. From the analyzer photo, we see that the negative excursion occurs first and is very narrow. The positive excursion has a much greater time duration though lower in peak amplitude. The phase variation of the RF during the spark was also measured and is shown in Figure 3.2.3.1-4B. Phase waveforms for both the cathode circuit spark and the collector circuit are shown together for comparison. Note that for the cathode spark, the initial phase peak was of short duration followed by a long recovery period.

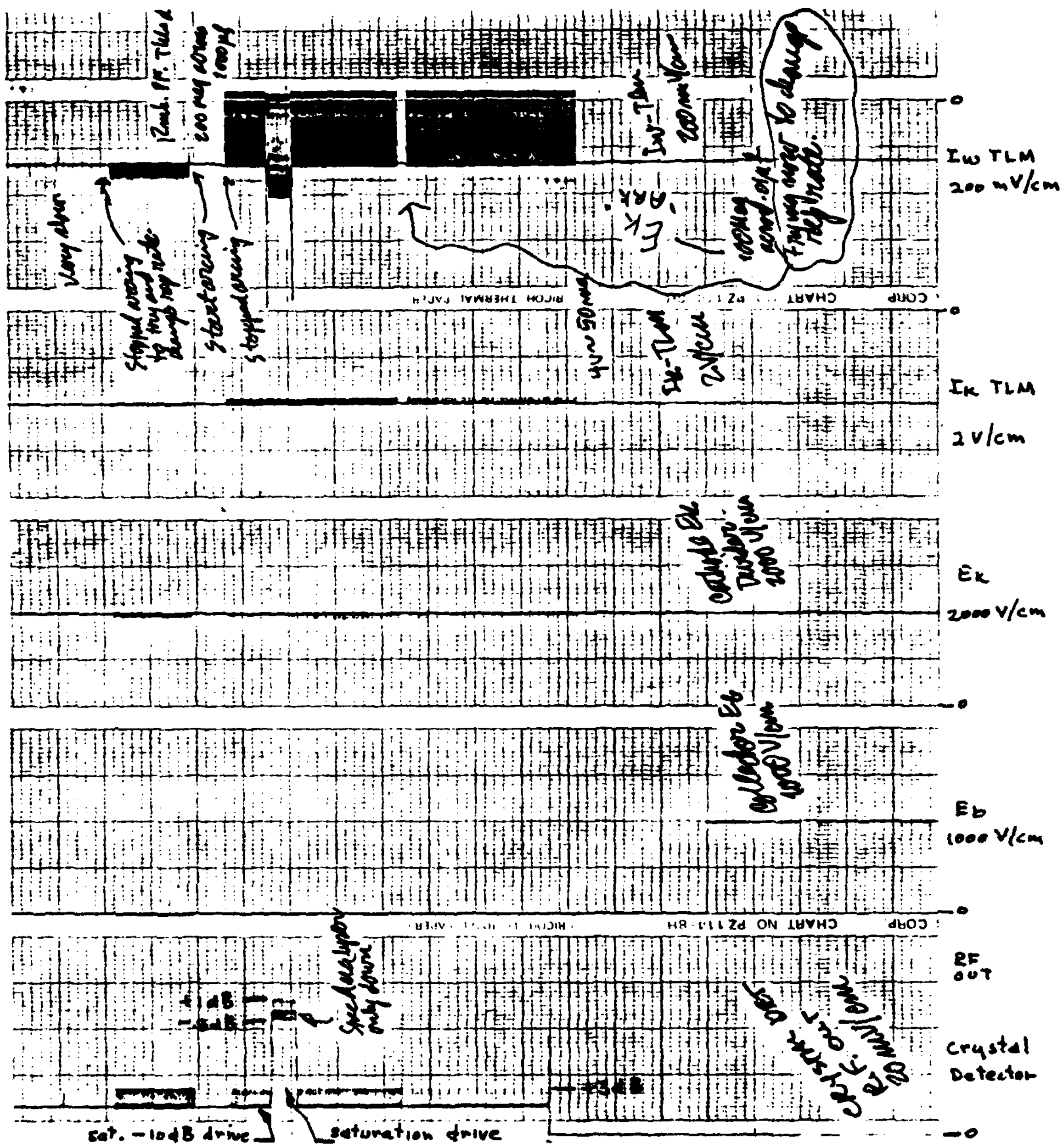


Figure 3.2.3.1-2. Cathode Spark Strip Chart

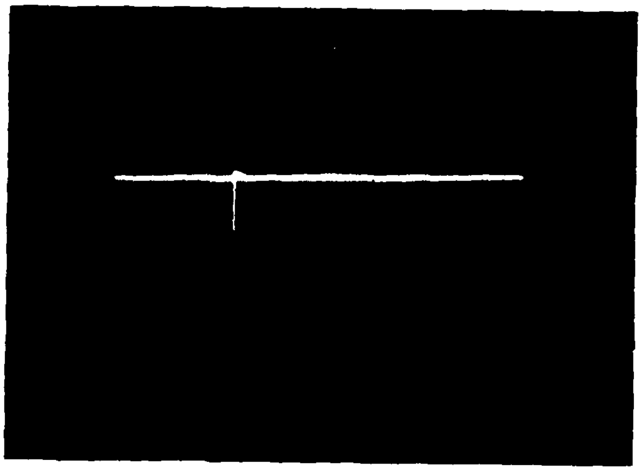


Figure 3.2.3.1-3. RF Amplitude Waveform from Spectrum Analyzer

The data from this test was a close match to that observed on orbit.

It is a peculiarity of this power supply that abrupt changes in tube voltages tend to produce reversed polarity or drops to zero in the helix current telemetry. The strip chart readings show this effect markedly at this capacitor value, with zero or low helix current indication at each spike. This effect can be seen in the results of arcing at cathode and collector, and is not diagnostic of any specific condition.

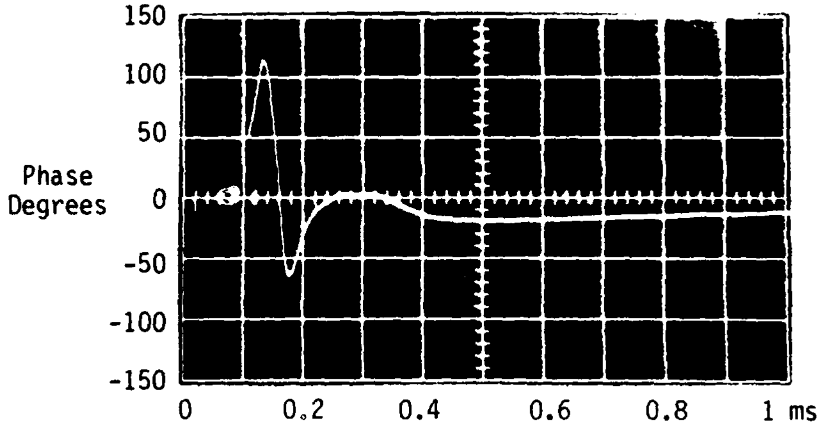


Figure 3.2.3.1-4A. Collector Spark RF Phase Transient

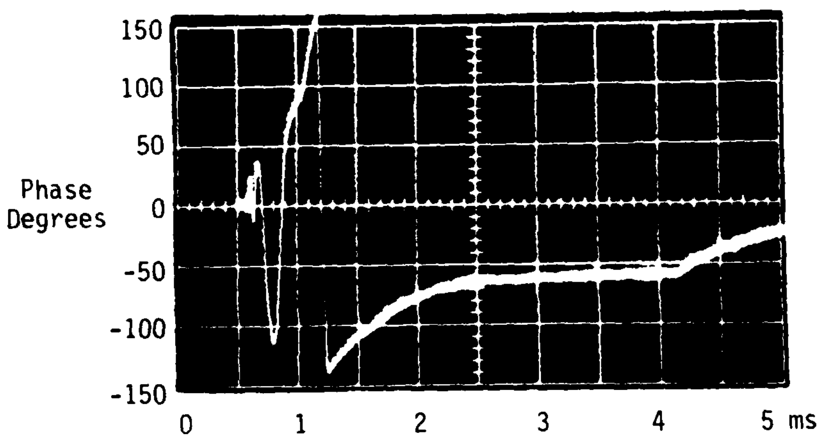


Figure 3.2.3.1-4B. Cathode Spark RF Phase Transient

(b) Collector Circuit Experiment. The collector spark test was conducted similarly to the cathode test with only the change in spark gap voltage rating as shown in Figure 3.2.3.1-1A. The capacitors used in the collector test varied from 0.01 to 0.1 μf. Again the preferred value was 0.01 μf.

The data for this experiment follows closely that for the cathode circuit test as can be seen by comparing the collector data of Figure 3.2.3.1-5 with the cathode chart in Figure 3.2.3.1-2. The principal differences were that when the RF output spikes were similar to the orbital data, the Iw transients were positive compared with the negative transients for the cathode. The Iw transients alone cannot distinguish the validity of the cathode versus collector spark mechanisms because the polarity of the transients can vary with the degree of discharge level. This is reported in a HAC report of July 1979. The phase pulse also was of different character as can be seen in the photographs of Figures 3.2.3.1-4A and -4B. The recovery tail of the collector pulse is very much shorter.

3.2.3.2 Command and Power Interrupt Tests Results

Momentary interruption in either the ON command or the 28 volt power input could result in downward fluctuations in TWT cathode or anode voltage. Recovery from these transients might also be accompanied by some overshoot. Reflected to the TWT RF output, the voltage transients should be detectable as amplitude and phase variations.

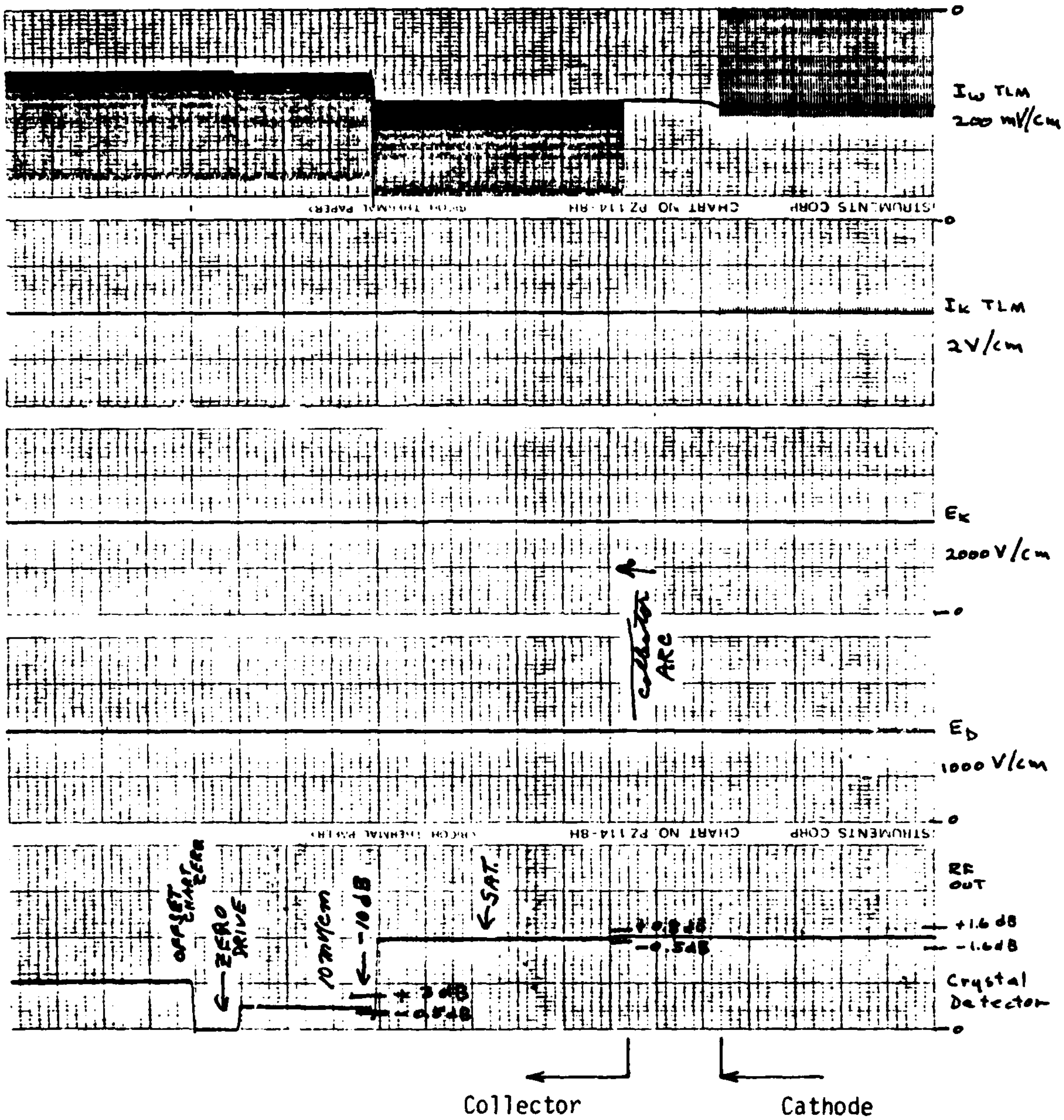
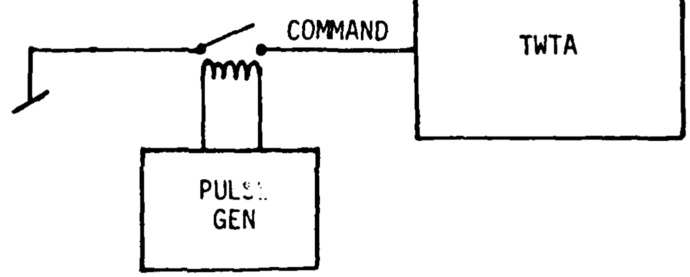


Figure 3.2.3.1-5. Collector Spark Strip Chart with Cathode Spark Data Comparison

To test this hypothesis, the 1241H breadboard with 293H TWT S/N 381 was subjected to periodic interruptions of both command and 28 volt power inputs. An interruption frequency of 8 Hz was chosen for convenience because that was the lowest frequency available from the pulse generator used. While the actual frequency observed from the spacecraft was somewhat under 1 Hz, the difference should not be significant because the EPC recovery time constant is much less than 0.1 second.

(a) Command Interrup Test. With the breadboard EPC connected to the TWT and RF power applied, the command circuit was opened periodically using a fast operating relay as shown in Figure 3.2.3.2-1A.

-1A. Command Interrupt



-1B. 28V Interrupt

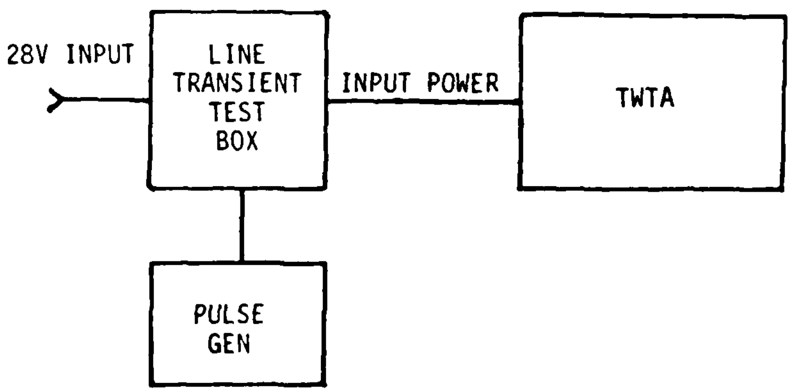


Figure 3.2.3.2-1. Interrupt Test Configuration

Input current, TWT cathode voltage and current, helix current, and RF output power were monitored on a strip chart recorder. Typical results are shown in Figures 3.2.3.2-2.

The most significant parameters were helix current and RF output power. The helix current is shown dropping to zero which conforms to the orbital data. RF power output, however, shows almost no activity when the TWT is saturated. When the RF drive level is reduced 10 dB, downward transients of the order of 0.8 dB can be seen (Figure 3.2.3.2-2). Because the output power conforms so poorly to orbital data, no further tests were warranted.

(b) Power Line Interrupt Test. The test setup for the 28 volt line interrupt experiment is shown in Figure 3.2.3.2-1B. Measurements were made similar to those described for the command interrupt test.

The 28 volts was switched off for about 4 ms at an 8 Hz rate. Off time was varied up to 10 ms. When the off time approached 10 ms, the EPC output shut down and the RF output went to zero. No significant modulation was evident on the RF output until the shutdown condition was reached. Neither the saturated nor the -10 dB test yielded RF output transients as were seen on S/N 24-1. A sample of the strip chart data for the saturated RF output case is shown in Figure 3.2.3.2-3. The reduced drive results are similar.

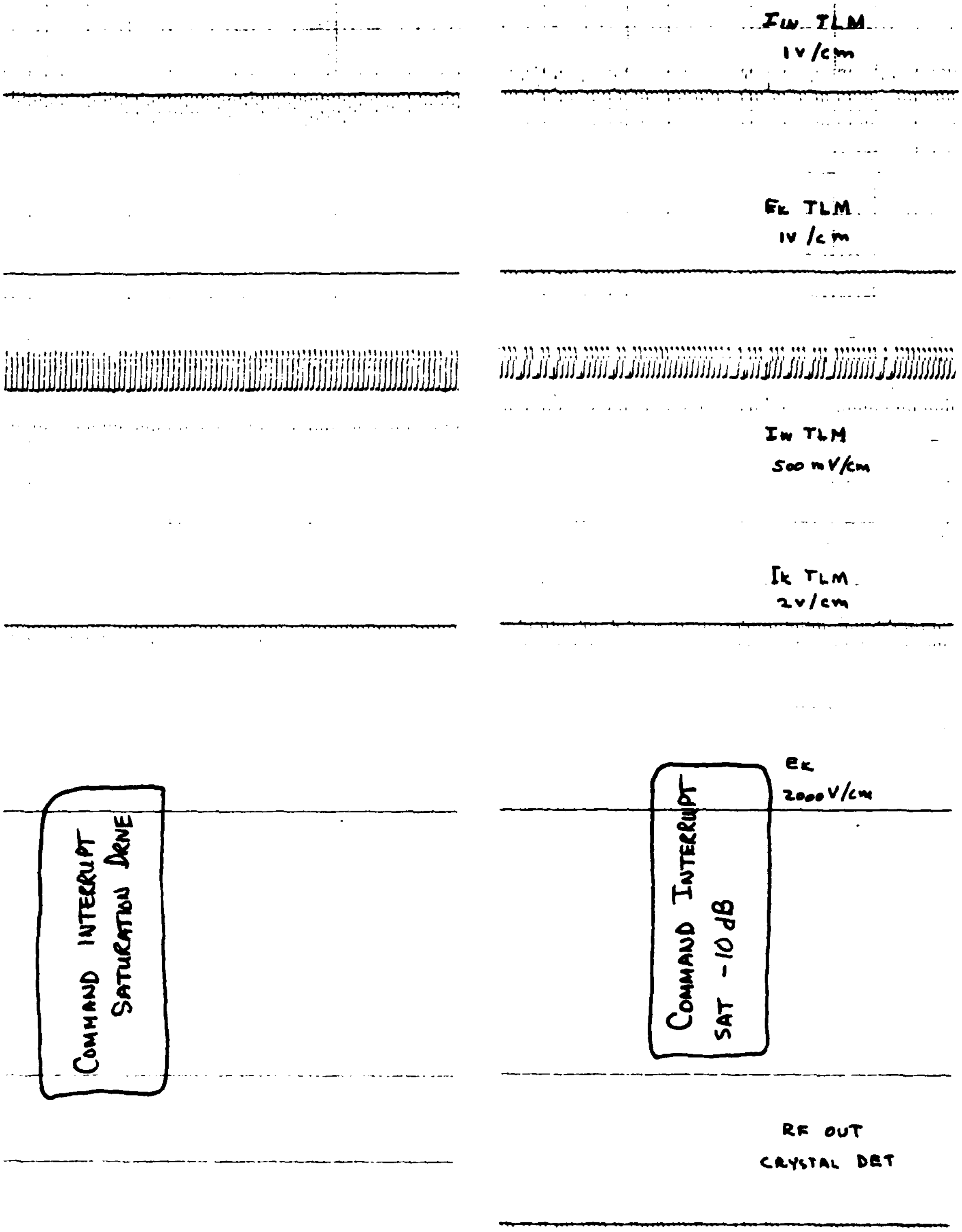


Figure 3.2.3.2-2.

Command Interrupt Test with RF Saturated

Command Interrupt Test with RF Output 10 dB Below Saturation

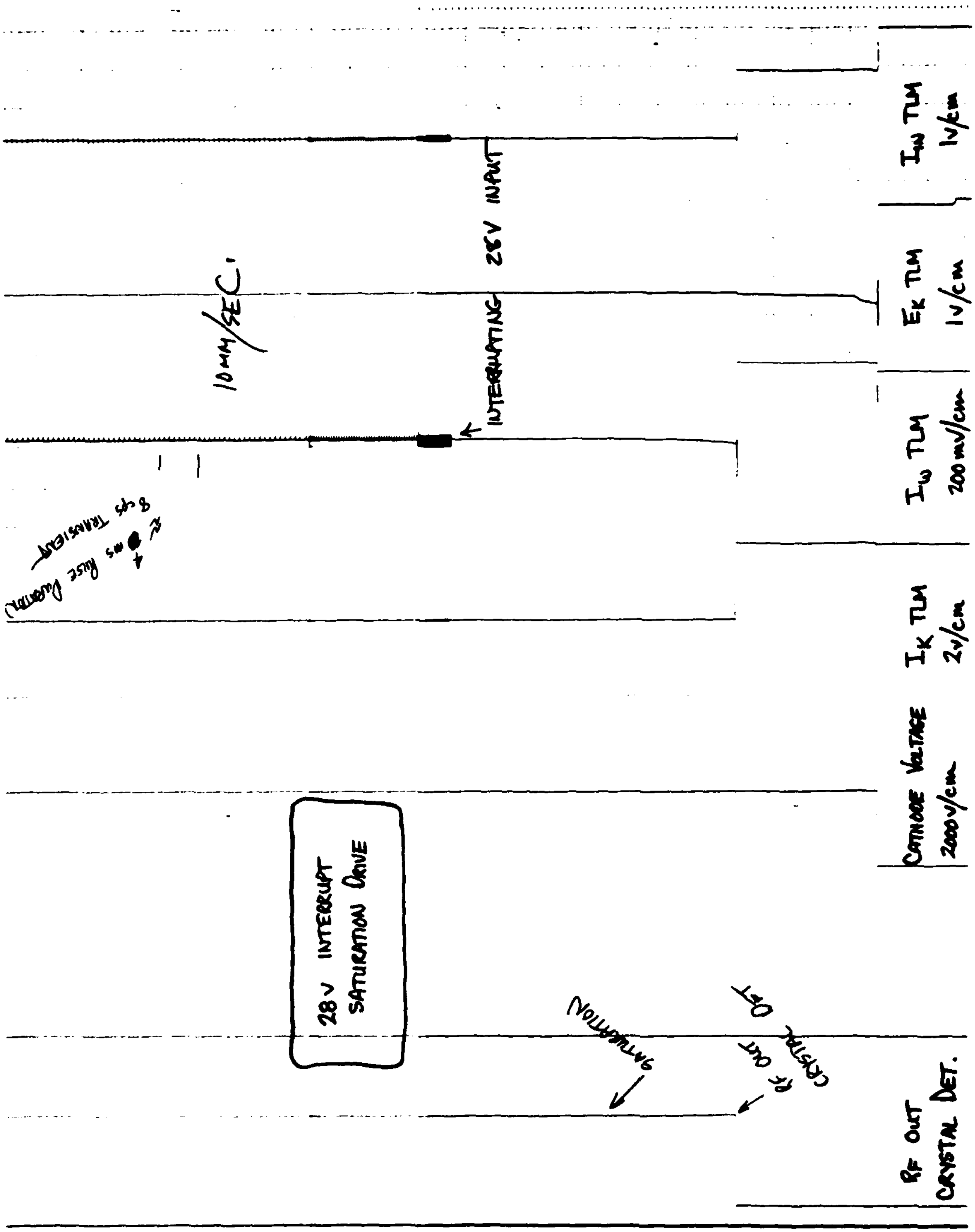


Figure 3.2.3.2-3. Power Line Interrupt Test Data, Saturated RF Output

Neither the command nor the 28 volt line interrupt resulted in an RF envelope characteristic resembling the orbital data. The line voltage transients were relatively well filtered from the TWT voltages and did not cause significant RF power fluctuations. The command transients, however, were shown as downward spikes in RF output of about 0.8 dB at drive levels 10 dB below saturation although with the TWT saturated, the perturbations were minimal.

3.2.3.3 Shorted Input Filter Capacitor Tests Results

An intermittent short circuit of one of the power line filter capacitors would cause a momentary decrease in input voltage to the main power converter of about 20%. This would be followed by a similar increase when the short was removed. These fluctuations, modified by the circuit response, would be reflected as changes in the TWT element voltages. An experiment was performed to determine if the modulation thus produced could cause symptoms similar to the orbital signature of TWTA S/N 24-1. The test configuration is shown in Figure 3.2.3.3-1 and the observed data are shown in Figure 3.2.3.3-2. The time axis is from right to left.

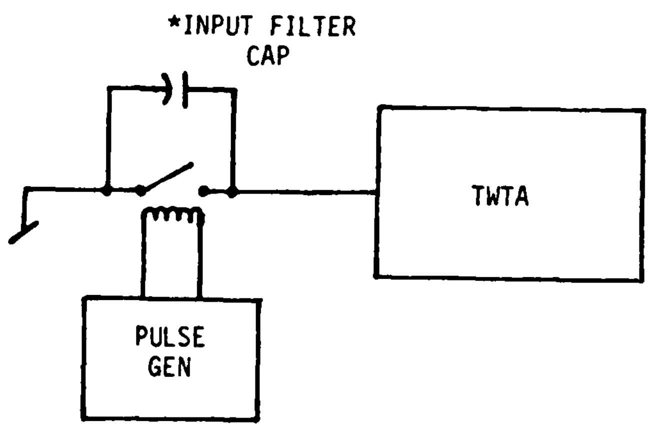


Figure 3.2.3.3-1. Shorted Filter Capacitor Test Configuration

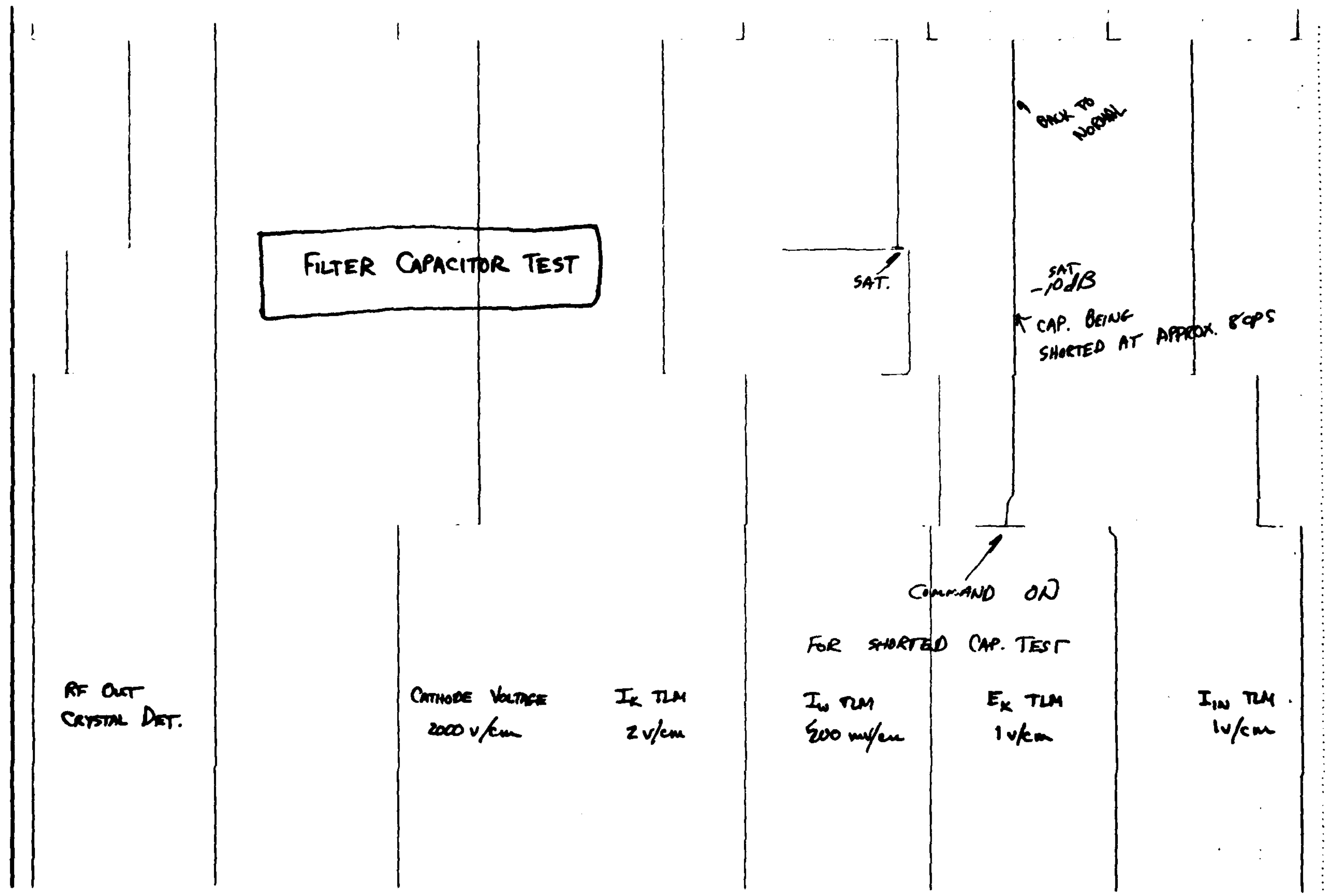


Figure 3.2.3.3-2. Filter Capacitor Test Data

Two conditions of RF output are shown; 10 dB below saturation and saturated. The RF output is seen to be effectively unperturbed by the intermittent short for either level of drive. It is concluded that this could not be the mechanism of failure for 9443.

The perturbations in effective input voltage are modified by the regulation response of the switching regulator, the filtering of the high voltage dc output of the power supply, and the helix regulator. The combination of these three circuits reduces the changes in TWT voltages sufficiently to maintain nearly constant RF output.

3.2.3.4 Helix Regulator Interrupt Test Results

A possiblity exists that the helix regulator could cause the RF anomalies since it has a dynamic range of the right order of magnitude and is closely coupled to the cathode voltage output of the EPC. While no actual failure mode has been suggested, it was decided to test the dynamics of the regulator by injecting noise pulses into the error input and observing the TWTA RF as well as the regulator output to see if a match of symptoms could be produced.

The experiment test setup is shown in Figure 3.2.3.4-1. Figure 3.2.3.4-2 shows the helix regulator schematic diagram illustrating the test signal input and the regulator output monitoring point.

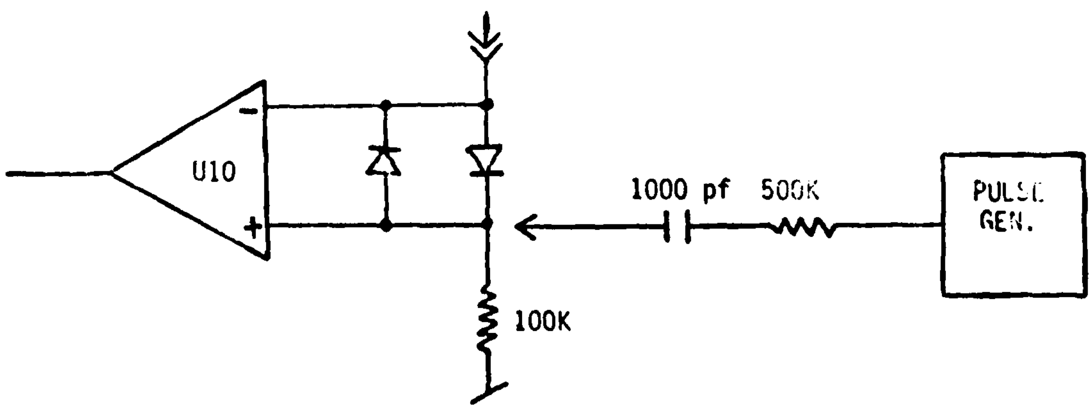


Figure 3.2.3.4-1. Helix Regulator Test Setup

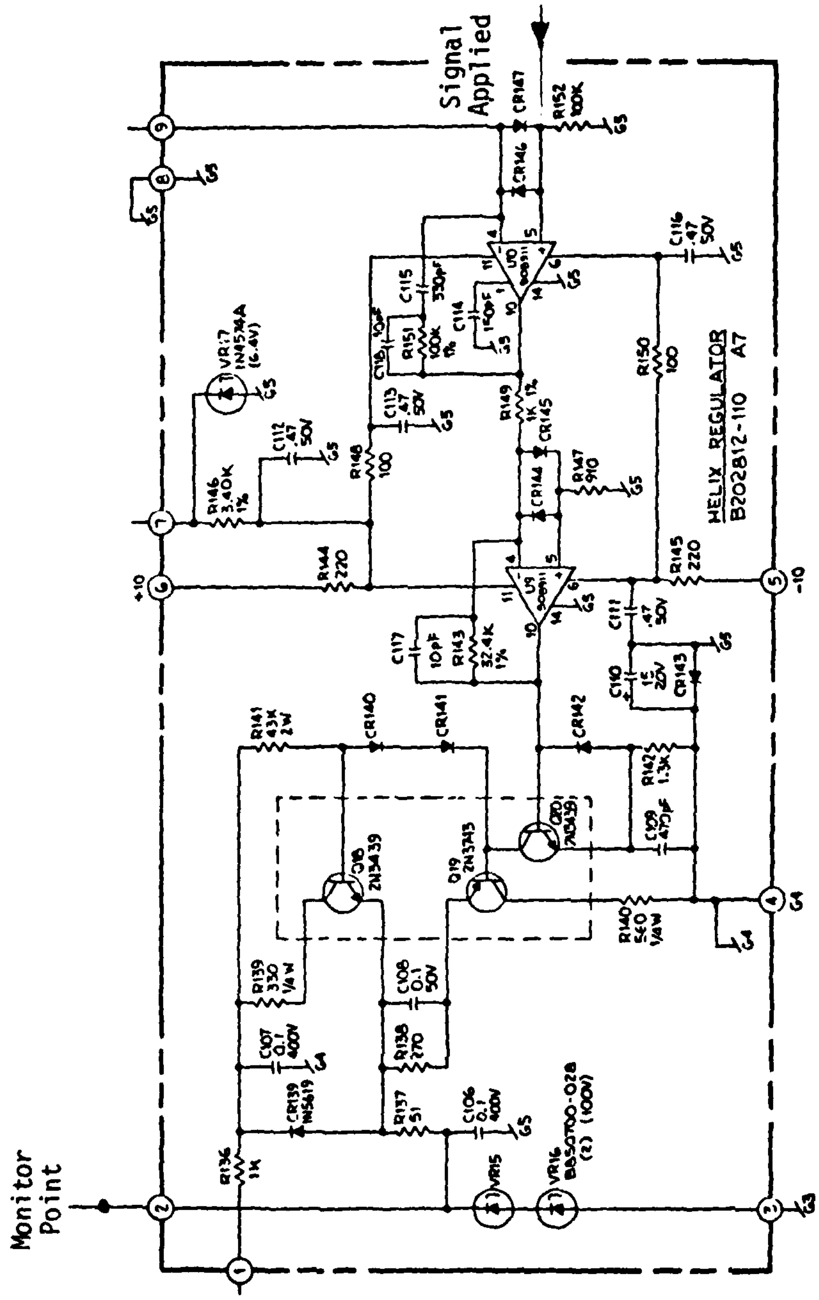


Figure 3.2.3.4-2. Helix Regulator Schematic

Various pulse widths from 1 ms to 40 ms at amplitudes of 0.5 to 4 volts were injected and the results observed. The closest approximation to the anomaly signature was for a 10 ms pulse. The recovery time constant of the helix regulator is about 5 ms. The 10 ms pulse then allows a maximum amplitude transient with full recovery for each transition of the differentiated noise pulse.

The output of the regulator, observed at the "monitor point" of Figure 3.2.3.4-2, may be seen in Figure 3.2.3.4-3. A negative swing of 80 volts is followed by a positive recovery swing of 50 volts. The corresponding RF output pulse, for drive 10 dB below saturated value, may be seen in the waveform photograph of Figure 3.2.3.4-4. The RF envelope was obtained through a spectrum analyzer set for 300 kHz bandwidth with a 20 ms/cm scan rate. The waveform is seen to be of about one dB peak amplitude and to have a wave shape similar to the voltage output of the regulator. A strip chart recording corresponding to the photographs of Figures 3.2.3.4-3 and 3.2.3.4-4 is shown in Figure 3.2.3.4-5 which compares the results during RF saturation with those for RF drive reduced 10 dB.

It is noted that perturbations of the order of 1 to 2 dB may be seen in the RF output. The match to the orbital signature, however, is not satisfactory because the downward swings are more prominent than the upward swings. While it is probable that the spacecraft output pulses did include negative swings, they were of such short durations that they were not recorded by the chart recorders at Ft. Monmouth. The similarity of positive and negative recovery characteristics of the regulator preclude a very fast negative transient followed by a long positive recovery.

3.2.3.5 TWT Sensitivity to Cathode and Anode Voltage Variations

In support of the anomaly investigations, several tests were run to determine the RF phase and amplitude sensitivity to the cathode and anode voltage variations. The results of these

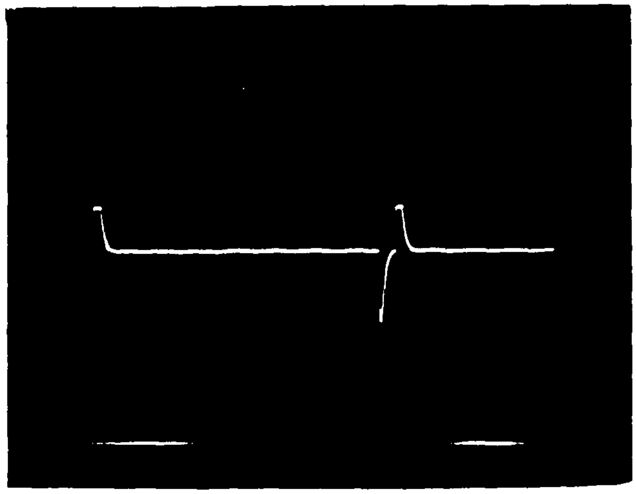


Figure 3.2.3.4-3. Helix Regulator Output (50V/cm, 20 ms/cm)

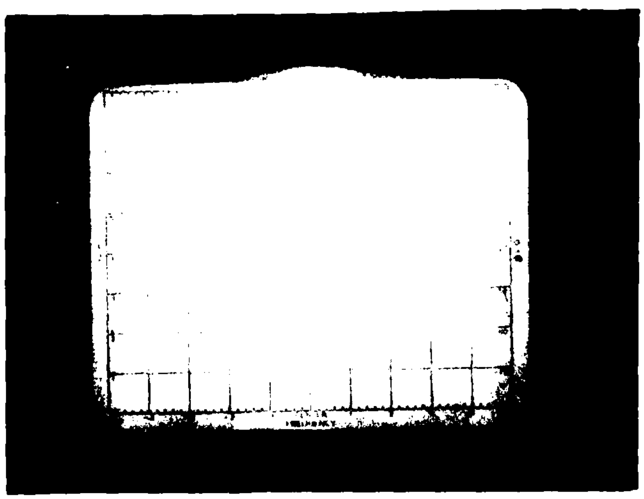
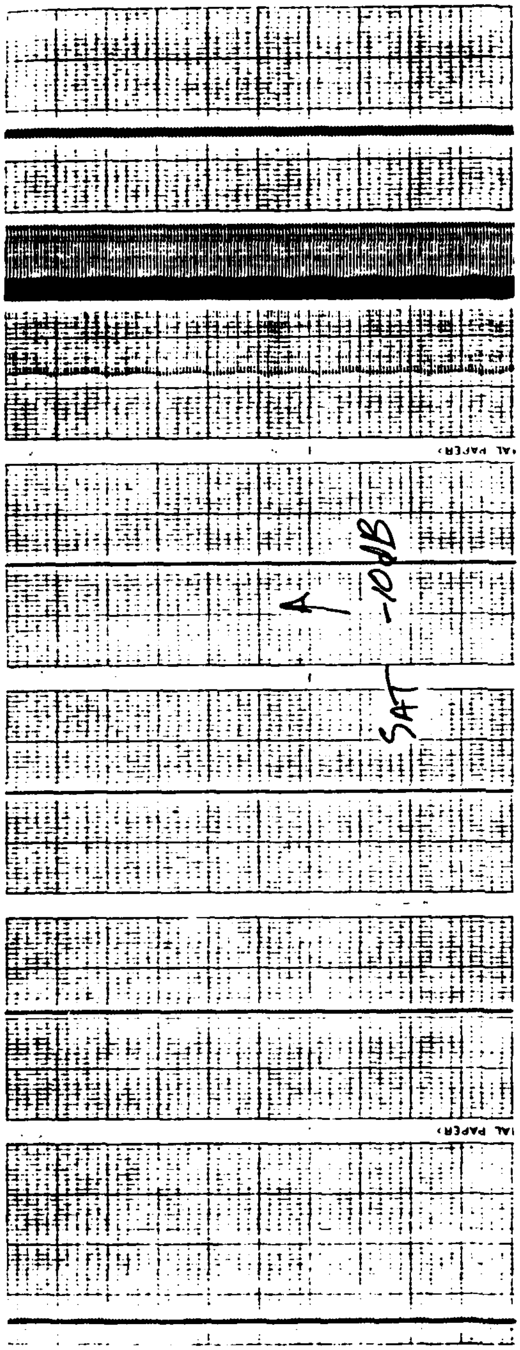


Figure 3.2.3.4-4. Spectrum Analyzer Waveform of RF Output at 10 dB Down from Saturation (300 kHz BW, scan mode)



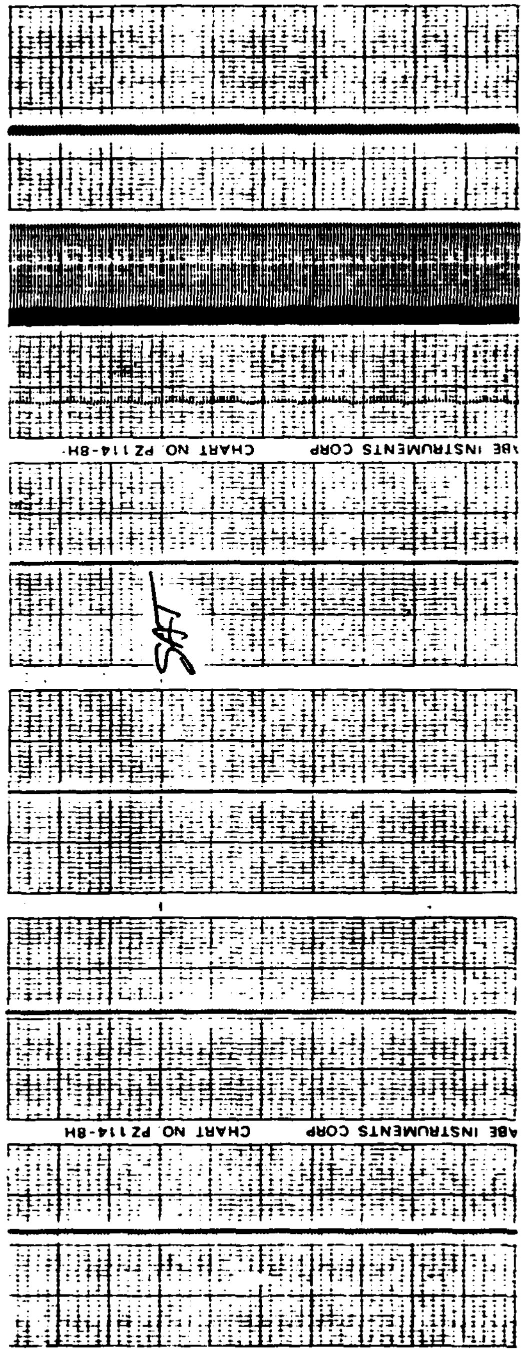


Figure 3.2.3.4-5

Helix Regulator Test Strip Chart, 10 dB Below RF Saturation

Helix Regulator Test Strip Chart at RF Saturation tests are as follows.

(a) Amplitude Sensitivity. RF power output for the TWT was measured as a function of variations in cathode voltage and anode voltage for constant input power. The input power reference was that required to saturate the tube at nominal Ek and Ea. For the saturation curves, the input power was held constant while the element voltages were varied. For the small signal curves, the input power was reduced 10 dB and 20 dB, respectively, from the saturation value determined above and held constant for the duration of the tests. Curves for the output power variation with cathode voltage are shown in Figure 3.2.3.5-1. Similar curves for the anode voltage change is shown in Figure 3.2.3.5-2. The curves for the three drive levels are superimposed. The change in output is expressed in dB and the absolute output in dBm has been subtracted out to yield 0 dB for the nominal value in each case. In this way, the relative characteristics can be easily compared.

Two phenomena are observable in the curves. Small signal gain dependence is seen in the curves at 10 and 20 dB down from saturation. Variation in saturated power output, with constant input drive power, is also in evidence. The results show that for the 293HA TWT, there is a total variation of +0.3 dB for increases in cathode voltage of 125 volts to -0.7 dB for a similar decrease in voltage. For small signal condition, the gain is seen to vary from -2.5 dB for the increase in cathode voltage to +1.0 dB for the corresponding decrease. Anode voltage variation

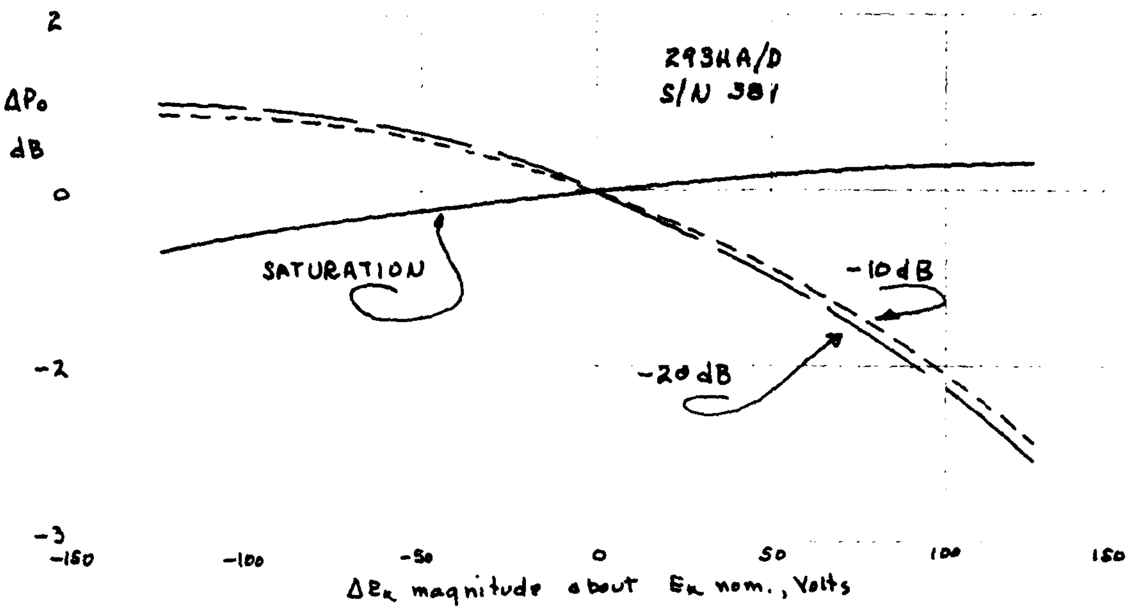


Figure 3.2.3.5-1. RF Power Output Variations About the Nominal Value For Three Levels of Power Output Vs Changes in Ek Magnitude

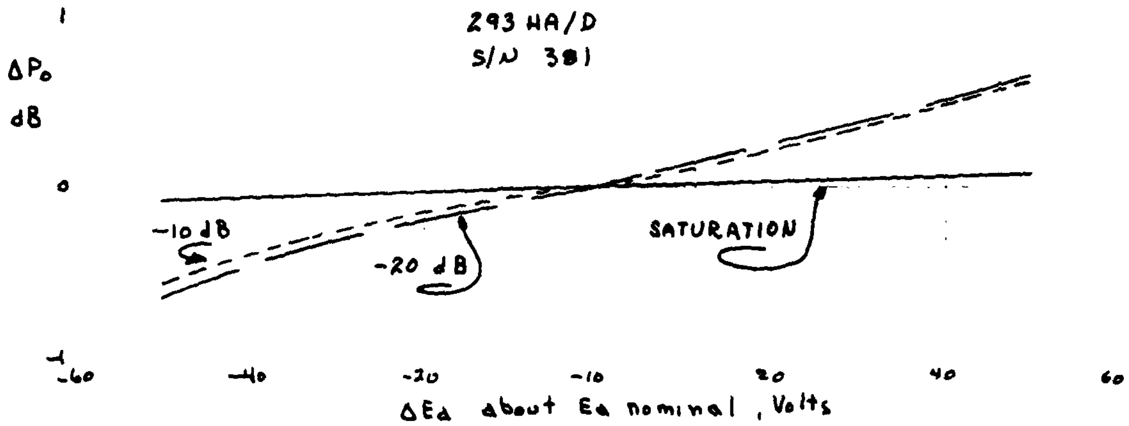


Figure 3.2.3.5-2. RF Power Output Variations About the Nominal Value For Three Levels of Power Output Vs Changes in Ea

curves show a similar pattern except for the magnitudes and a reversed sense for small signal gain dependence.

(b) Phase Sensitivity. The sensitivity of RF phase to changes in cathode voltage is shown in Figure 3.2.3.5-3. Three sets of data were taken, including the conditions of RF saturation, 10 dB down from saturation, and 20 dB down from saturation. The three curves were identical within measurement tolerance and are shown as a single curve. The change in cathode voltage magnitude is plotted on the abscissa with the nominal value at zero. Increase in magnitude is to the right of zero. The slope of the curve is approximately 1.0 degree per volt for any excitation.

Figure 3.2.3.5-4 shows the relationship of RF phase to changes in anode voltage. Again, the voltage magnitude increases toward the right and the nominal value is shown as zero. The phase sensitivity is about 0.12 degrees per volt at saturation declining to 0.1 degree per volt at -20 dB drive.

3.2.3.6 Partial Vacuum Spark Test Results

An experiment was designed to verify that relatively long sparks can occur at reduced pressure. A diagram of the apparatus used is shown in Figure 3.2.3.6-1. To simulate the condition within the 1241H EPC, a box was assembled consisting of a baseplate, end plate, center gusset, and cover from a 1241H EPC. A high voltage wire was placed within the box at a location approximately where the wire would enter the TWT in an actual TWTA. This assembly was mounted in a vacuum chamber with the wire routed out of the chamber to a 4100 volt

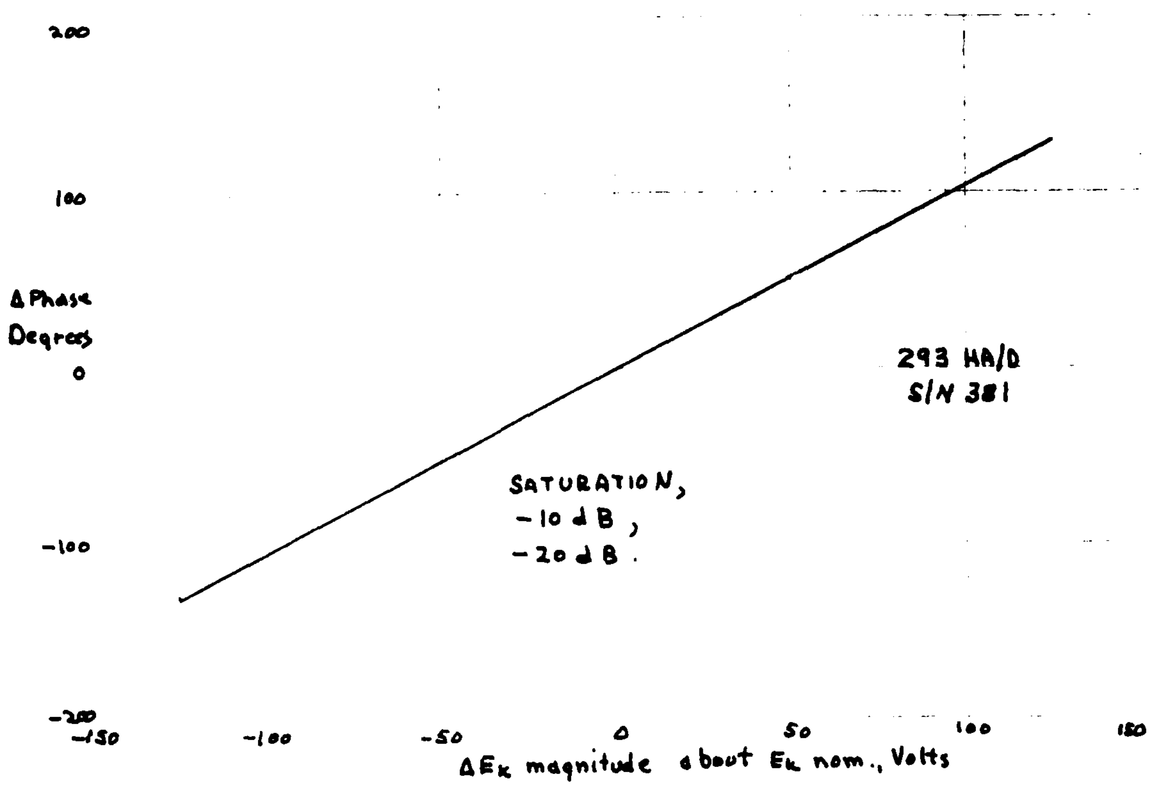


Figure 3.2.3.5-3. Variations in RF Output Phase For Two Drive Levels Vs Changes in Ek Magnitude

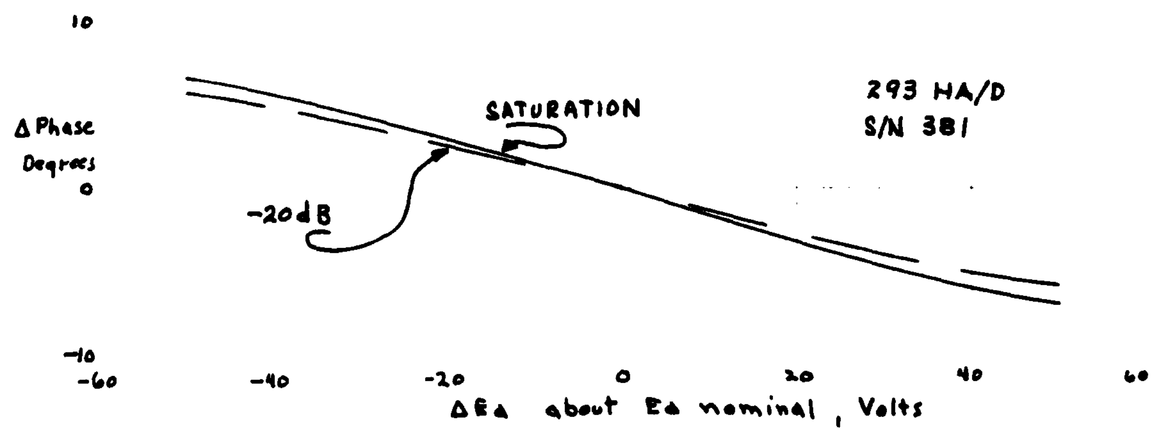


Figure 3.2.3.5-4. Variations in RF Output Phase For Two Drive Levels Vs Changes in Ea

NOTES: A. 40 Watt Baseplate, End Plate, Center Gusset and Cover

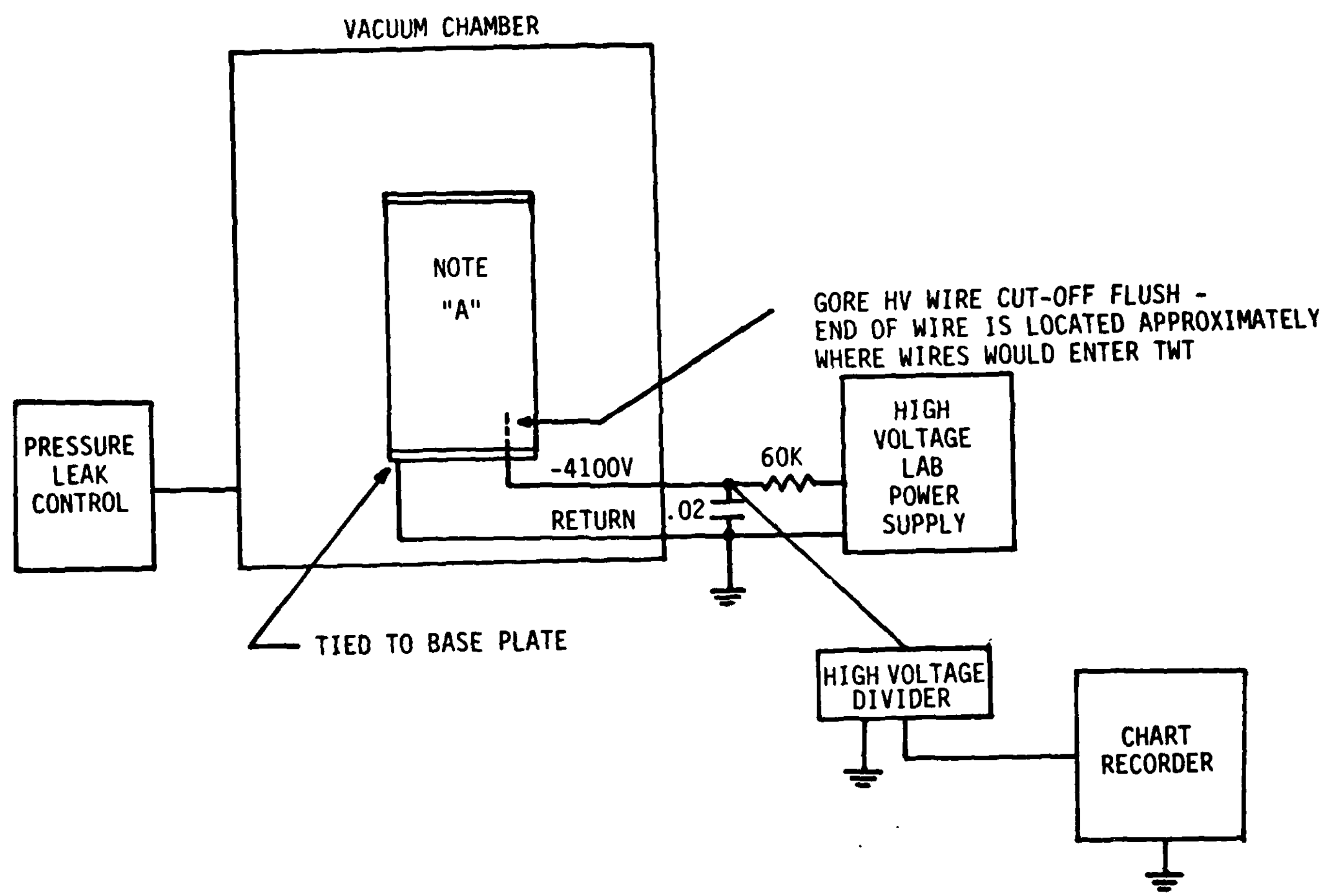


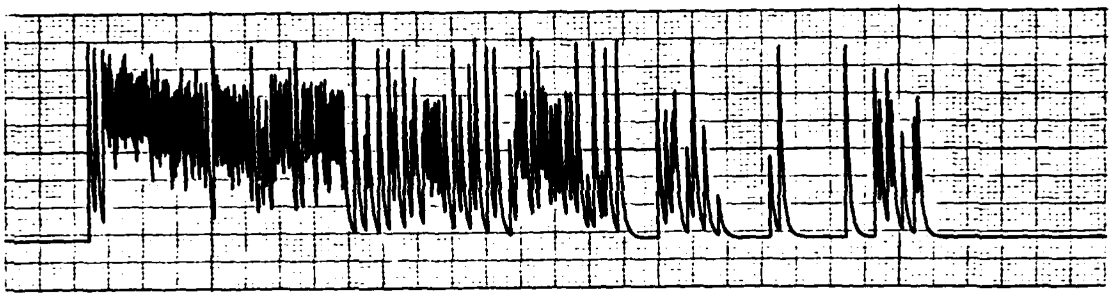
Figure 3.2.3.6-1. Configuration for Low Pressure Spark Tests

dc power supply as shown in the figure. The lead wire was monitored with a high voltage divider connected to a strip chart recorder.

The chamber was pumped to a high vacuum and the dc voltage was raised to -4100 volts. With the voltage applied to the wire, the chamber pressure was permitted to rise by using a controlled gas leak until a spark discharge occurred. The spark was observed visually and the character of the spark was recorded on the chart recorder. This experiment was repeated several times and the results shown in Figure 3.2.3.6-2. The pressure at which the spark occurred varied but was within the range of 0.01 to 0.5 mTorr. Spark lengths of the order of 200 mm were observed.

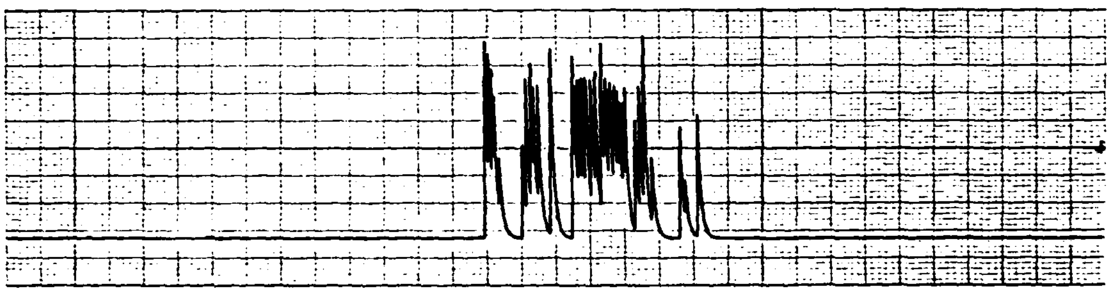
Occurrence of discharges over long paths at high voltage can be predicted by the Townsend or streamer (Kanal) mechanisms. A curve, for uniform field conditions, relating breakdown voltage to the product of pressure and distance (pd) shows that, as the pd product diminishes, the breakdown voltage decreases until we reach a minimum at a pd of about 4 Torr mm. The breakdown voltage at this minimum is approximately 300V rms. As pd is reduced further, the breakdown voltage again rises. This curve is usually called Paschen's curve. This curve has been verified for 60 Hz ac for several decades of pd product. The implication of this function is that for a given voltage between electrodes, that the spacing alone cannot ensure that no breakdown can occur. Indeed, since the curve abscissa is the product pd, an increase in distance is offset by a decrease in pressure.

For a voltage of 4000 volts and a spacing of 200 mm, a pressure of 3.5 mTorr or higher can precipitate a discharge. The pressure indicated at the time of the sparks recorded in Figure 3.2.3.6-2 varied from 0.01 to 0.5 mTorr. This is less than the critical value indicated from the Paschen curve. The curve, however, was derived for Townsend discharge under uniform field conditions. The field in this experiment was strongly nonuniform. This would favor sparking at pressures



A. Pressure = 0.01 mTorr

B. Pressure = 0.5 mTorr



C. Pressure = 0.5 mTorr

D. Pressure = 0.07 mTorr

Figure 3.2.3.6-2. Spark Discharges at Reduced Pressure much less than 3.5 mTorr. We were probably observing a streamer discharge enhanced by field emission at the point electrode (wire end).

The character of the spark discharges was of interest. The discharge was not continuous but consisted rather of a series of discrete sparks in repetition. The mechanism appears to be an initiation at some voltage, the rapid reduction in voltage to where the spark extinguishes, voltage increase, then reignition. These spark trains were not continuous but did serve to show that under the right conditions of voltage and pressure, that a series of minor discharges can occur causing perturbation of the power supply voltage without initiating shutdown of the TWTA.

No effort was made to do an analytical study of the phenomena but only to demonstrate ad hoc that such discharges can be produced and that this mechanism must be considered a viable anomaly candidate in the analysis of the TWTA S/N 24-1 anomaly.

3.3 RF Signal Evaluation

The appearance of the spikes when first recorded at Fort Monmouth on a strip chart recorder showed a sharp + 2 → 3 dB pulse. When examined on an oscilloscope, however, the shape of the spike was actually a sharp negative pulse of about 6 dB followed by an overshoot of 2 dB extending over a relatively longer time period. On a slow recording strip chart, only the overshoot pulse could be seen.

In order to characterize the pulse more completely, the assistance of the Harris Corporation was requested since they built the ground demodulators and had available a test ground station equipped to communicate with the DSCS II spacecraft. The purpose of the tests at Harris was twofold: first, to determine the exact signature of the pulse including the carrier phase shift and second, to determine if the demodulator could be modified to operate satisfactorily with a high data rate QPSK signal in the presence of the noise pulses.

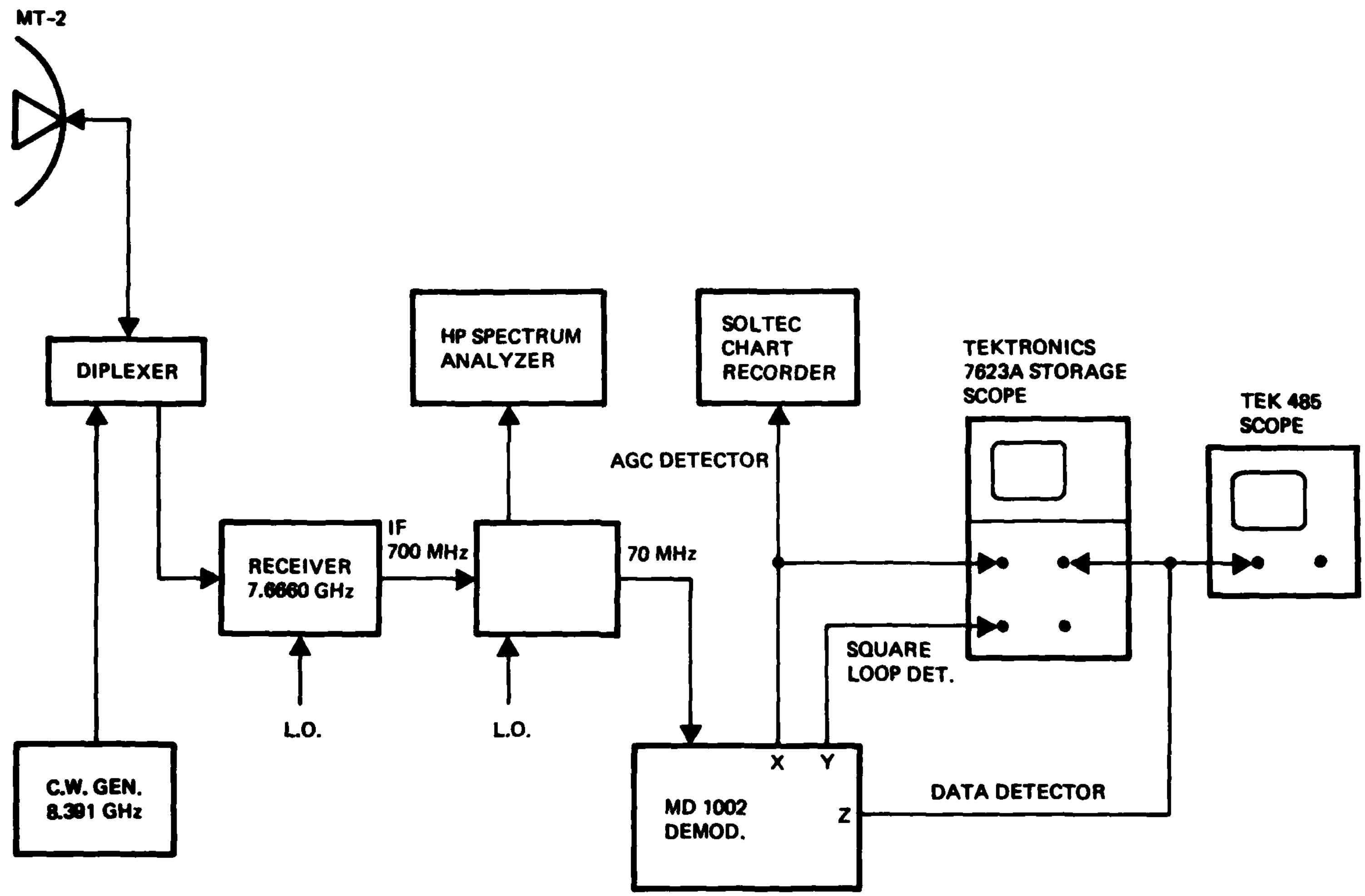


Figure 3.3-1. Harris Test Set-up

The test set-up to perform these tests is shown in Figure 3.3-1. On April 7, Harris began a series of tests by transmitting a CW signal and locking the MD1002 demodulator to the downlink carrier. Amplitude and phase variations were observed at the AGC power detector output and at the phase detector for the carrier phase-lock-loop (after the squaring process). These tests were continued a few hours per day over several days. Unfortunately, the number of spikes occurring at this time dropped off rapidly and good data was obtained only on the first day. On the latter days, few or no spikes were seen and no useful data was obtained.

The amplitude and phase characteristics obtained from these tests are shown in Figure 3.3-2, plots (a) and (b). Since the carrier recovery phase-lock-loop phase detector was used, the data in (b) does not represent the phase shift directly.

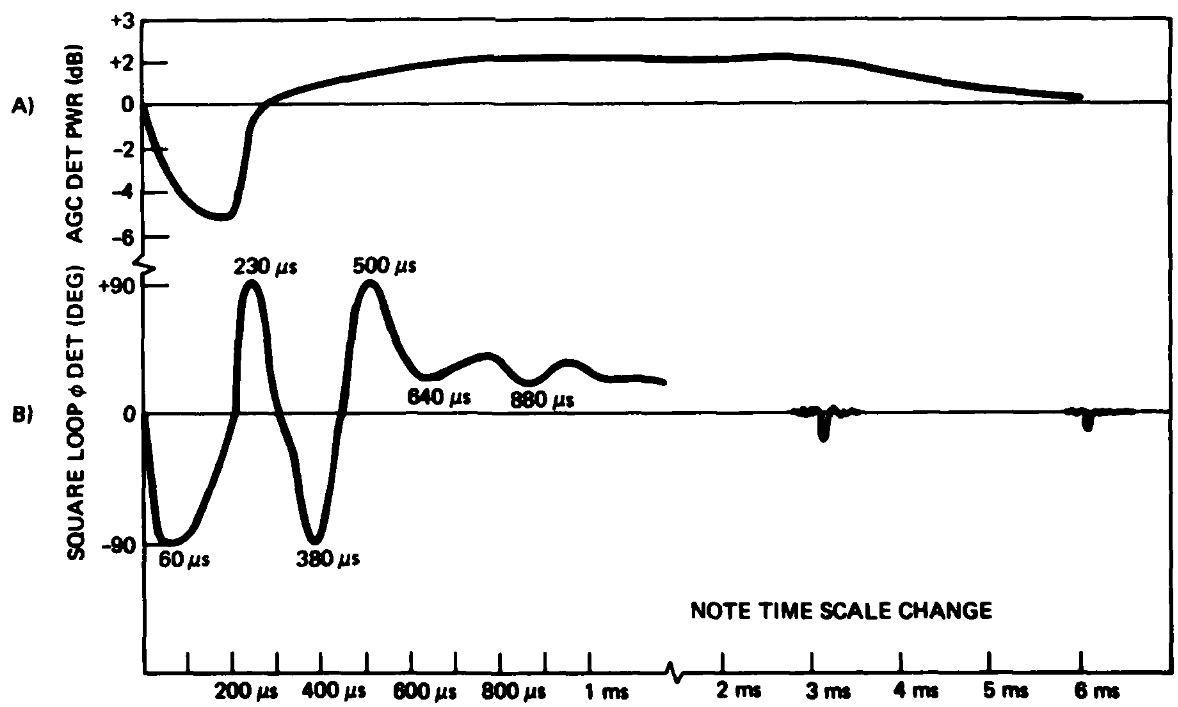


Figure 3.3-2. Harris Test Measurements

However, since the phase detector output has the typical "S" curve characteristics, phase shift can be measured from (b), since one complete cycle at the phase detector output (with excursions through $\pm$ 90°) represents 360° of phase shift. From Figure (b), approximately 720° of phase shift has occurred during the initial 640 μsec. The actual phase shift would be half this value, since the recording includes the effects of the squaring process of the carrier recovery loop.

The 360° phase shift in the carrier is of particular significance since this is the cause of loss of signal lock and thereby, data. It was planned to modify a breadboard model of the demodulator to extend the tracking loop and determine if the system could operate satisfactorily in the presence of noise spikes. Unfortunately, before this test could be run, the noise spikes ceased (at least during the period of testing). Therefore, no conclusions could be reached on the usefulness of modifying the demodulator.

4. CAUSES OF ANOMALOUS PERFORMANCE

4.1 Analysis of Signature

The appearance of the orbital signature and the results of the various breadboard tests clearly point to a cathode to ground arc as the direct cause of the anomaly. The arc causes a drop of about 200 volts in the cathode potential, and on extinction, the power supply overshoots about 100 volts. The RF output follows the cathode voltage variation. On the pen recorder at Ft. Monmouth, only this overshoot is visible. The helix current telemetry tends to drop towards zero during transient disturbances of several types, so the occasional zeros indicated on NCHLTWTA-1 are consistent with the arc phenomena but not diagnostic.

Three peculiarities of the arc need explanation:

1. Hundreds of thousands of arcs occurred without apparent degradation of the power supply or change in waveform.

2. The arc extinguishes after pulling the supply down only 200 volts.

3. The unit passed at least two weeks thermal vacuum and initial orbital test without showing the symptoms.

4.2 Possible Arc Locations

The cathode circuitry at -4.2 kv consists of:

a. The cathode structure internal to the tube.

b. The external tube connection and segment of lead enclosed by the gun potting and cosmetic cover.

c. The exposed cathode lead, in two sections joined by the splice block.

d. The wiring within the high voltage module

e. The parts in the module, especially the filter capacitors.

A 200 volt drop at 4.2 kv dissipates in the vicinity of .2 joules at the arc site (depending on exactly how the supply responds)*. If the arc were taking place inside an insulator (locations b, d, or e), there is therefore some 4 kilowatt hours of power dissipated at the site per 100,000 occurrences.

Arcs inside any potted part are inherently short, typically less than 2 cm. The pressure for an arc of this length is above 10^{-3} Torr. Unless otherwise limited, a discharge at pressures around critical will typically draw substantial current and persist down to low voltage. Precursor discharges in collector potting have been recorded which do not behave like this at first. These are probably occurring in narrow cracks, and rapidly degenerate to a permanent short (because the surfaces are rapidly burnt). The large numbers of light discharges in

*A .2 μf capacitor dropping from 4.2 to 4 kv gives up .16 joules.

S/N 24-1 are thus inconsistent with their occurring inside a solid insulator. All diagnosed internal potting failures have either gone to a permanent short at once or in, at most, a few dozen strikes. Actual cases of cathode arcs in the 1241H amplifier also tend to damage the EPC, supporting the observation that the orbital occurrence is drawing relatively low current.

The possibility that the arc is not from cathode to ground but is to some intermediate point must be considered. If this is modeled by imagining a capacitor abruptly connected to the cathode, note that by calculation and breadboard simulation the value of this capacitor is in the 0.01 to 0.001 μf range. With any reasonable dielectric, such a capacitor has a plate area in the 100 square cm range. Inspection of the power supply and tube does not reveal any ungrounded object of sufficient area. It therefore appears the arc must be terminating at ground. Thus, we are forced to hypothesize locations (a) or (c) as the only feasible possibilities so far proposed.

In the case of (a), (an arc internal to the tube) two arguments can be cited against the possibility. First, while occasional tube internal arcs are known, occurrence of many thousands in a working tube is unprecedented. Second, the chemical environment created (e.g., liberated metal ions) would surely have at least degraded the cathode activity by now. Since the amplifier currents and performance are (as far as we can tell) unchanged, it appears the cathode is in good working order. Thus, it seems very unlikely that the problem could be internal to the tube.

We are led to the conclusion that the ony reasonable possibility is an arc from the cathode wiring to ground. Requirements for the occurrence of such an arc are discussed below.

4.3 Arcing at Low Pressures

The 1241H case venting characteristics were measured during the 1241HD (depot) development. The box has no positive venting system, and was found to remain in the 10^{-3} to 10^{-4} Torr range internally for long periods after pump down to hard vacuum. However, the normal expectation from measurements between polished large diameter electrodes is that breakdown of air at this pressure and 4 kv will not occur in the dimensions of the case (maximum path < 25 cm).

Experiment with a bare high voltage wire and a spare case showed however that arc discharges do occur at pressures in the 10^{-4} to 10^{-5} Torr region. These low pressure arcs are difficult to initiate, and the phenomena comes and goes apparently at random. It was found that arcs would only appear with a capacitive output impedance of the power supply, and that a pulse of gas pressure appeared in the vacuum chamber at each discharge. There were indications that a very low current glow discharge was present when visible arcs were not happening. There are hints in the literature that this type of behavior has been seen before, (for example, Figure 3 of reference 1).

Experiments by H. Shelton (TRW Advanced Technology Division) indicate that the initiating mechanism for current flow in moderate to high vacuum is field emission. He reports that substantial emission can occur from nonmetallic whiskers, (e.g., from the tip of a glass fiber). He has found that thread-like character marks in insulators are also fruitful sources of field emission. It should be noted that published average work-function estimates on large surfaces do not seem to tell the whole story - on a microscopic scale materials may contain points of low work function at which emission is relatively easy to obtain.

The orbital behavior of S/N 24-1 may also correlate with fast electron (> 2 MeV) events. Detailed environmental data

Ref. 1 - "Gas Discharges in Insulating Systems at Pressure Between Atmospheric and High Vacuum," Dakin and Works, "Dielectrics in Space" Symposium, June 1963.

are not available, but the apparent diurnal variations in spike frequency and some of the dates of maximum frequency of occurrence seem to correspond with fast electron occurrences.

From all available information, (including problems experienced with a similar but unpotted high voltage supply), it appears that long path, low current, easily extinguished arcs can occur at -4 kv in pressures of the 10^{-4} to 10^{-5} Torr range. As mentioned earlier, such arcs were found occasionally when a cut piece of the high voltage wire used in this amplifier was exposed in an empty 1241H case. Without attempting to explain an evidently very complicated phenomena, a reasonable description of the behavior of S/N 24-1 can be proposed.

It must be supposed that the cathode lead has a minor defect. This defect need not be as severe as a cut, but could be a crack or an inclusion in the insulation. During acceptance thermal vacuum and initial orbital testing, the pressure in the case does not drop low enough to permit the type of arcing in question, so no recognizable symptoms occur, which would not affect amplifier operation but might cause cumulative damage to the hypothesized weak spot in the insulation.

During the 15 months the unit was off in orbit, presumably the pressure within the case dropped to a high vacuum. When it was turned on after the -2 unit failure, some outgassing of the tube potting and power supply occurred, as some areas reach temperatures approaching 100°C. While there is no way to estimate the pressure reached, whatever it was must decay through the critical 10^{-4} to 10^{-5} interval. Arcing between the insulation fault and some remote ground point started, possibly facilitated by externally caused ionization. Since the cathode wire is bundled with the other tube leads, the discharge may be partly confined, further limiting the current and raising the extinction voltage. At each arc, a pulse of gas is liberated (presumably from the paint or conformal coat at the end of the arc), so the effect is to some extent self-supporting. The exact mechanism by which field emission provides an environment for the arc, and how it might be triggered by electron irradiation, are matters beyond the scope of an anomaly investigation.

The three peculiarities cited in 4.1 are thus explained as follows:

Item	Explanation
1. Large number of arcs without degradation.	Arc is in the open and current limited by low pressure and a long path.
2. Arc extinguishes after small voltage drop.	Low gas pressure and tortuous path, plus local gas cloud may be dissipated by shock of discharge.
3. Problem did not show up in test.	Case pressure was too high before extended time in orbit.

If the above hypothesis is correct, it is probable that the arcing will slow down and cease after a period of time for two reasons. First, the local pressure will eventually drop to the point where an arc is impossible and second, the hypothesized field emission may end due to burning of the site. Further confirmation for this theory is the fact that the arcing has essentially stopped after three months - probably caused by the case again reaching a high vacuum.

5. RECOMMENDATIONS

As discussed in Section 4, the cause of the anomalous performance was an arc in the cathode circuitry which occurred in a rather high vacuum (10^{-5} Torr). If the vacuum can be increased to 10^{-6} Torr or greater, the arc cannot be triggered. This can be accomplished by venting the TWTA case, as already demonstrated in the HLTWTA collector depot program. Since all the HLTWTA's on F15 and F16 have already been reworked to depot the collector and add venting holes, no further action is recommended.

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