IN-ORBIT TESTING OF SATELLITE TWTAs WITHOUT COMMERCIAL TRAFFIC INTERFERENCE

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(ABSTRACT)

TWTAs (Traveling Wave Tube Amplifiers) are presently the primary life-limiting element of a communications satellite transponder. Satellite operators rely on spare TWTAs to ensure that most of the transponders will be operating at the spacecraft end-of-life. We wish to track the 'health' of the operating TWTAs in order to accurately predict the remaining useful lifetime of the satellite transponder. This information is very useful for system planning and risk assessment.

The primary failure mechanism of a TWTA is cathode deactivation, symptoms of which are measurable from an earth station. Present testing methods require the interruption of the communications traffic signal, which leads to a loss in revenue generated by the satellite. We present new methods to test TWTAs without significant interference to the communications signal. These methods include the use of test-tone signals and spread spectrum techniques. The test-tone method is readily implemented using commercially available hardware. The spread-spectrum technique requires customized hardware, and so is more expensive.

Finally, the data from these tests can be inserted into a transponder reliability model. The model is then used to predict the availability

of the satellite transponder, up to and including the end-of-life of the satellite.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

A typical communications satellite is presently designed to have a useful lifetime of 7 to 10 years in orbit. The satellite lifetime is limited by several parameters, including: fuel (for stationkeeping), battery degradation, solar cell degradation and TWTA degradation. Satellite operators need to be able to monitor these parameters in order to predict accurately the remaining useful lifetime of the satellite [Owens].

Fuel levels, battery degradation and solar cell degradation are easily measured via the spacecraft telemetry. TWTA degradation, however, cannot be accurately determined by telemetry information alone. Active measurements must be taken, using signals uplinked through the communications channel. TWTAs at present are considered to be the primary life-limiting component of a communications satellite, and thus tracking TWTA degradation is important in assessing the longevity of a satellite.

The majority of satellite operators presently test their in-orbit TWTAs by re-routing or halting their traffic load for a short period of time. Testing is then performed during this "free" period. Re-routing or halting of the communications traffic leads to a direct reduction in the revenues generated by that traffic. Thus most satellite operators prefer to perform little or no testing which interferes with the normal communication traffic. Without testing, there is no accurate way to predict the remaining lifetimes of the TWTAs. The availability and reliability estimates of the satellite channels can only be crudely calculated. The satellite operators basically rely on the built-in redundancy (spare TWTAs) to ensure that spacecraft end-of-life capability meets specifications.

In order to obtain accurate, long-range predictions of the channel availability and reliability, we must be able to test the TWTAs without disrupting or interfering with normal traffic flow through the transponder. Presently only one method for such testing has been developed, and it is only used on TDMA systems. This thesis reviews in-orbit TWTA testing methods in use by the space industry, and also develops and discusses original testing methods to be used in all three forms of multiple access: TDMA, FDMA, CDMA. The new methods use test-tones and spread spectrum signals to test the TWTA actively. The test-tone methods are capable of determining the total input power to a transponder, even when the test equipment is not co-located with the earth station which is transmitting the commercial traffic. This is especially useful, since a typical satellite serves many geographically dispersed uplink stations. The spread spectrum method uses noise-like signals which are practically undetectable by the user.

It is shown that with data collected via these new tests, one will be able to directly measure the degradation of each operating TWTA. Knowing the degradation, one can accurately determine the remaining useful lifetime of each TWTA and thus estimate both the short-term and long-term reliability of the satellite channels. Using a reliability model for the communications subsystem of the satellite, the availability of the satellite channels could then be predicted.

2.0 TRANSPONDER FAILURE MECHANISMS

Revenues generated by in-orbit satellites come directly from fees paid for use of the transponders. Typically a transponder generates anywhere from one to three million dollars of revenue for the satellite operator, depending on how the transponder is utilized. A temporary or permanent loss of a transponder leads to a direct reduction in revenues. Thus the main concern of the satellite operator is to provide a reliable, long-life set of transponders. In this section we shall examine how this is achieved, why TWTA degradation plays such an important role in transponder reliability, and how TWTA degradation can be detected.

2.1 SATELLITE CHANNEL ARCHITECTURE

A typical satellite communications subsystem is shown in Fig. 2.1.1. The subsystem contains all hardware which directly controls the flow of the communications signals through the satellite. The subsystem is divided into 'channels', or transponders. The satellite channels are cross-connected by switches at several points to provide for switching signals around failed hardware elements. Low-reliability elements, such as receivers and TWTAs, typically have a number of spares to provide a level of redundancy in the system.

The reliability of a satellite transponder can be broken down into two parts. A given configuration of hardware elements, arranged in a specific way to form a channel, has a short-term reliability associated with it. This short-term reliability is simply the multiplication of the reliabilities of the individual channel elements. The long-term reliability of a transponder is a function of the short-term reliability and the reliability of all other subsystem elements.

Fig. 2.1.2 details a typical satellite transponder. The majority of the elements are passive devices which exhibit a high reliability. There are three active devices which basically determine the reliability of the channel; switches, receivers, and TWTAs.

Microwave switches are usually either electro-mechanical (coaxial or waveguide) devices, or ferrite magnetic devices [Matthews]. These devices exhibit a relatively low failure rate. Switch failure usually results in the switch being 'frozen' in one of the switch positions. When this happens, the redundancy of the entire subsystem is considerably reduced. Unfortunately, the literature does not indicate that any symptoms of impending switch failure exist [Winch]. It is no surprise, then, that satellite operators typically perform switching of elements only when loss of a transponder is imminent (or when one has already actually been lost). Once a satellite has been launched, one can only estimate switch reliability from life-test data of similar switches.

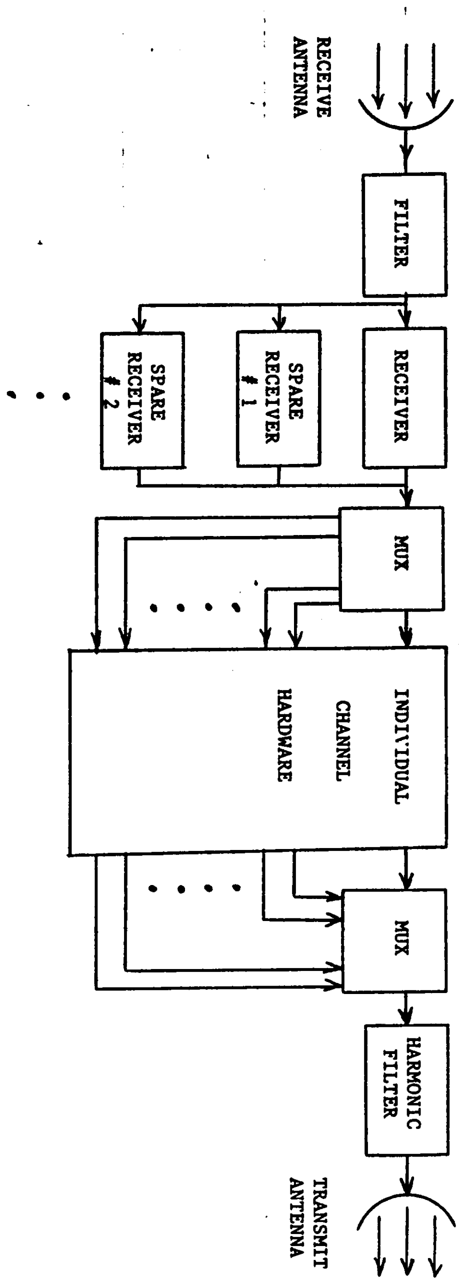


Figure 2.1.1 Satellite RF Subsystem

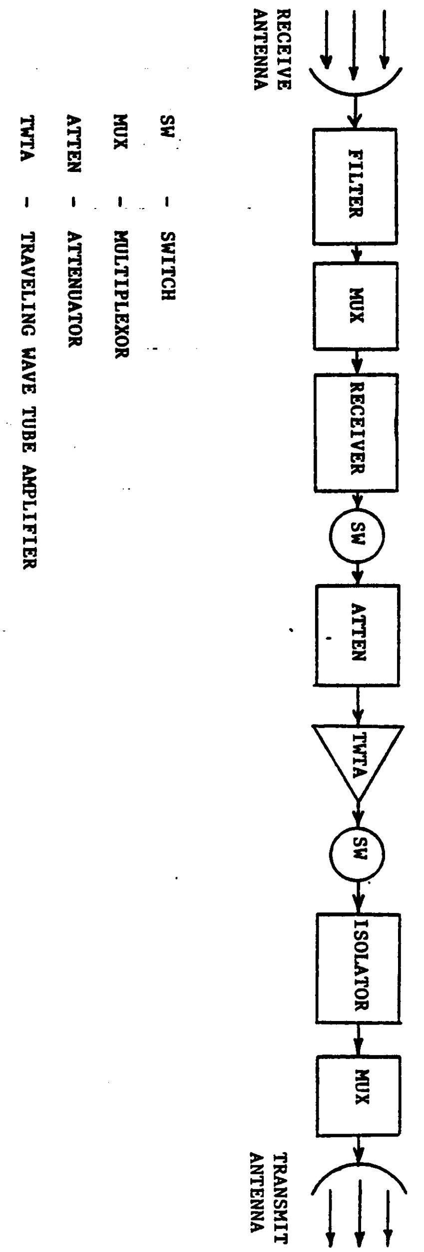


Figure 2.1.2 Satellite Transponder

A receiver basically consists of a low-noise amplifier (LNA, typically GaAs FET technology) and a down converter for translating the receive frequency to the transmit frequency. Some of the older satellites presently in-orbit use TWTs for the low-noise amplifiers, but most satellites being launched now employ solid-state technology. These devices exhibit high reliability. The most common cause of receiver failure is the failure of the down converter to correctly frequency - translate the signals. Local oscillator technology usually employs a reference crystal, and failures are sudden with no symptoms of degradation. Only one receiver is needed at a time, so they are typically operated until they fail, whereupon a spare receiver is switched in. As failure of a receiver is catastrophic to all transponders, a high level of redundancy is employed with typically four receivers on board the satellite.

TWTAs are nonlinear microwave amplifiers which operate at a few tens of watts output power. These devices exhibit the highest failure rate of any element of the communications subsystem, and thus are the main factors deciding subsystem reliability. Luckily, the majority of TWTA failures are not sudden in nature, but exhibit gradual degradation, usually over a period of years. Symptoms of TWTA degradation have been found and verified [Strauss1]. These symptoms are detectable by the satellite operator while the satellite is in-orbit.

By measuring the degradation of a TWTA, one can determine its remaining useful lifetime. With other information supplied by the spacecraft telemetry, one can accurately determine both the short-term and long-term reliability of the satellite transponders. This information helps the operator to decide on switching options within the spacecraft, and to decide when a new satellite should be launched to replace the existing one. With the possibility of refueling and servicing the future communications satellites via the Space Station, the need to know TWTA degradation is even more important. Insurance companies which underwrite satellite transponders also need accurate transponder reliability information to assess risk to users and to adjust their premiums accordingly [Christel].

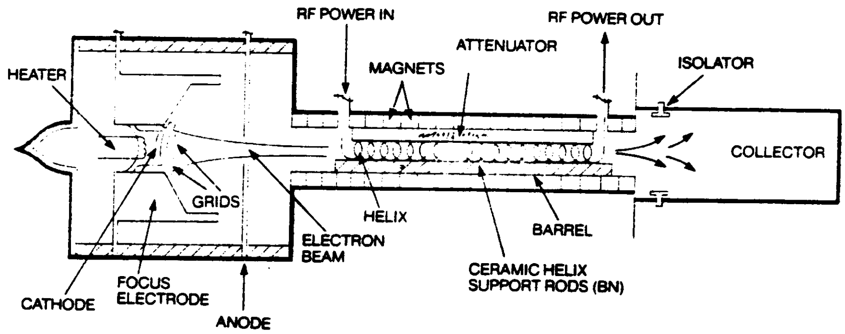
2.2 TWTA FAILURE MECHANISMS AND SYMPTOMS

Fig. 2.2.1 details the internal components of a typical TWT [Hughes]. A filament is used to hear the cathode to ideally maintain the cathode temperature at a nominal operating point. The electron beam passes through the controlling anode and then through the helix. The beam is held in shape, or focused, by the powerful magnets (typically ceramic) surrounding the axis of the helix. The energy from the electron beam is transferred to the RF signal in the tube. The amplified RF signal emerges from the helix with a phase delay (typically 20° to 50 °) compared to the input RF signal. After passing through the helix, the remaining energy of the electron beam is absorbed by the collector in the form of heat. The entire TWT is maintained in a vacuum.

Associated with the TWT is the electronic power conditioner (EPC) which is an elaborate power supply for converting the spacecraft DC voltage into the high voltage for the electron beam. The EPC also delivers the anode voltage, which directly controls the electron beam and thus the cathode current. Together the TWT and the EPC make up the TWTA. Almost all of the in-orbit TWTAs have failed due to a failure in either the TWT or EPC electronics. Other failure modes do exist, such as vacuum leaks, mechanical and thermal failures, etc. However, these problems are usually detected and corrected during the extensive burn-in tests performed on all spacecraft electronics before launch.

2.2.1 EPC FAILURES

EPC failures are typically catastrophic in that the TWTA fails very quickly and with no symptoms of degradation. These failures are not as common as TWT failures, and so are not documented thoroughly in the literature. Most EPC failures appear to occur because of some failure in the high-voltage electronics. These circuits operate in the kilovolt range and so are very susceptible to arcing and pitting of contacts, insulation failure, etc. Switching on and off the TWTA (and thus the high-voltage circuitry and cathode heater) seems to be particularly



*VACUUM INSIDE TWT IS ABOUT 10^{-8} TORR NORMALLY

Figure 2.2.1 Simplified TWTA Diagram [Hughes] unhealthy for TWTAs [Strauss1]. As a result, most satellite operators employ a minimum-switching strategy with their TWTAs. Essentially, the primary TWTAs are turned on and left on until they fail, whereupon a spare TWTA is switched on and allowed to run until it too fails. This is compared to the equal-aging strategy, whereby the TWTAs are cycled on and off in order to keep the degradation of all the TWTAs approximately uniform. The switching strategy used depends on the level of TWTA redundancy, the expected lifetime of the satellite channels, and other factors.

2.2.2 TWT FAILURES

TWT failures in space are usually due to cathode deactivation or failure of the cathode heater filament. The filament is by far the hottest part of the TWT, operating anywhere from 650°C tp 1100° C [Forman1]. Typically the filament fails upon switching on and off the TWTA, probably due to the electrical and thermal transients inherent in such a process. Filament failures are catastrophic with no symptoms of degradation reported in the literature.

Cathode deactivation is the most prevalent form of TWTA failure. It is essentially the only failure mode which exhibits well-defined symptoms before failure. The deactivation takes the form of decreasing electron-emission capability due to physical and chemical processes that proceed at a prescribed rate [Strauss1]. This means that, given a constant operating temperature, the cathode current will decrease with time. Since the electron beam energy of the TWT is directly related to the cathode emission current, the gain of the TWT decreases with time. TWTA 'failure' is a relative term, but typically it is defined to be that point where the small signal gain has dropped 3 or 4 dB compared to the start of life (SOL) value. The decrease in the small signal gain (or linear gain) of a TWT is related to the decrease in cathode current by the following equation [Strauss1]:

$$\Delta G_{ss} \text{ (dB)} = K (G_{ss} + A) \Delta I_K / I_K \qquad (1)$$

where

ΔG_{ss} - change in small signal gain
ΔI_K - change in cathode current
I_K - start of life value of cathode current
G_{ss} - start of life value of small signal gain
A, K - constants which depend on TWT type

The effect of cathode deactivation on the cathode current is shown clearly in Fig. 2.2.2.1, which plots cathode current as a function of cathode temperature. At the SOL, the operating point on the curve is well into the space-charge limited region. The cathode current is limited only by the physiochemical process. As cathode deactivation occurs, the curve shifts to the right. Since our operating temperature is held constant, the operating point falls off the 'knee' of the curve into the temperature limited region, where the electron-emission rate is greatly reduced due to insufficient activation energy in the cathode. Once this temperature limited region is reached, the gain of the TWTA decreases rather quickly. In order to produce long-life TWTs, they are designed to have an operating temperature well above the SOL knee temperature. A higher operating temperature, however, increases the speed of cathode deactivation and thus shifts the curve to the right faster. A balance must be struck to maximize the longevity of the TWT.

The effect of cathode deactivation on the TWT RF characteristics has been studied and verified [Strauss1]. Cathode deactivation can be simulated by reducing the voltage to the cathode heater filament, thus reducing the operating temperature. The cathode current decreases

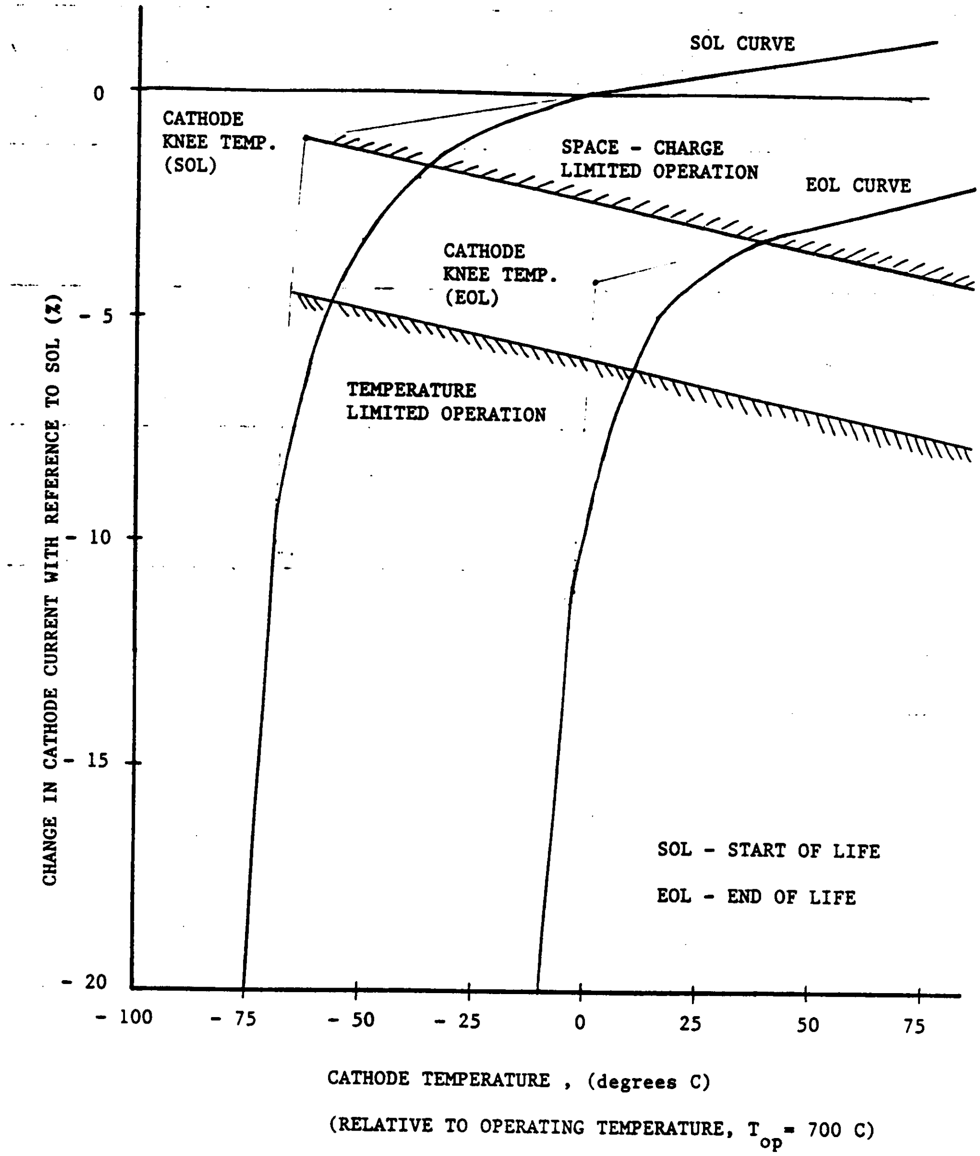


Figure 2.2.2.1 Cathode Current versus Operating Temperature - Oxide Cathode [Strauss1]

accordingly. Fig. 2.2.2.2 shows the results of just such 'underheating' tests on the Hughes 261H TWT. Output power, helix current and relative phase shift of the TWT are plotted versus input power. These underheating curves can be obtained for any TWT model via ground tests. The families of curves are the key to measuring TWT degradation. If we can measure the RF characteristics and the shift of the curves, then we can directly calculate the corresponding decrease in cathode current. Specifically, if we can obtain a database of 'signatures' of cathode deactivation for each TWT, then we can determine the remaining useful lifetime of the TWTA before it reaches 'failure' or end-of-life conditions.

Degradation of the above RF parameters as a result of cathode deactivation is strongly dependent on the type of cathode used, its operating temperature, and the current loading. There are two types of cathodes that are used in space applications. Oxide cathodes are used for C-band (4 GHz), and represent the majority of in-orbit TWTAs. They operate at low current densities (120 to 300 mA/cm^2), and low cathode temperatures (650 to 750°C) [Strauss1]. This limits oxide cathodes to low-power applications, with typical output powers of tens of watts. Fig. 2.2.2.1 is the cathode current characteristic for an oxide cathode, which has a fairly sharp 'knee'. This means that these cathodes exhibit little decay in cathode current until end of life, when the knee is reached and the current decreases quickly.

For the K-band satellites which require higher output power, matrix dispenser cathodes are employed. They operate at current densities of

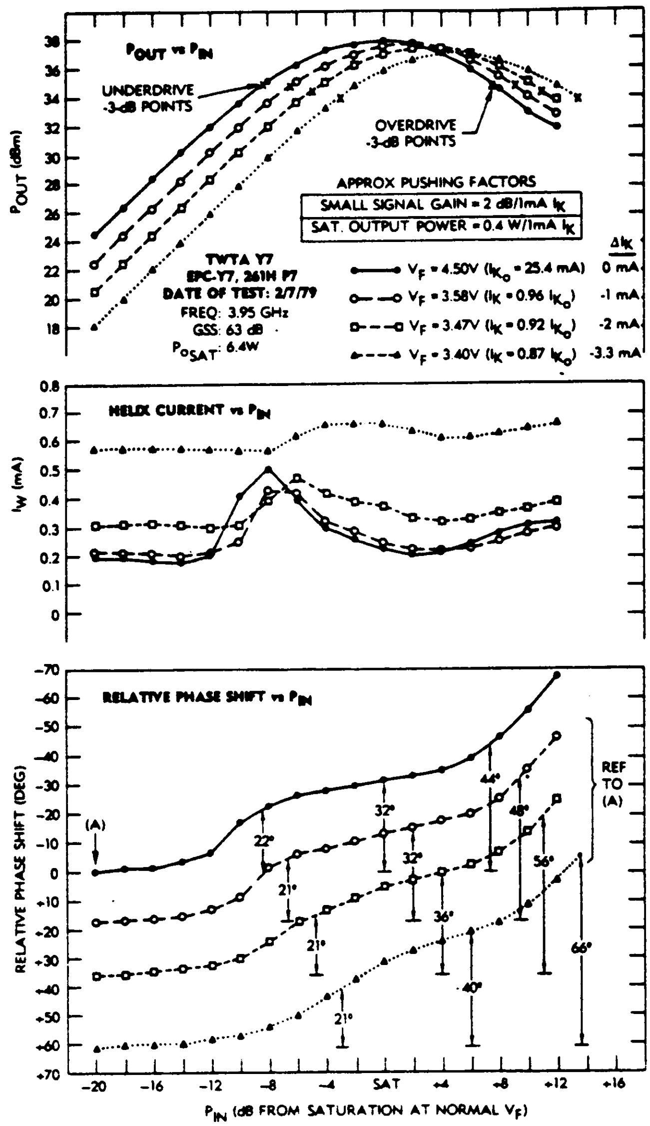


Figure 2.2.2.2 Effects of Cathode Deactiviation on the RF Characteristics of a TWTA [Strauss1]

650 to 700 mA/cm^2, with cathode temperatures in excess of 1000°C. The high-power capability of these cathodes makes them ideal for use in the direct broadcast satellites, which operate in the area of hundreds of watts of output power. The cathode current characteristic for a matrix cathode is shown in Fig. 2.2.2.3. Note that the knee of the curve is very smooth. This means that as the cathode deactivates, the cathode current exhibits a decay from SOL. As this effect is somewhat undesirable, a number of TWTA manufacturers have included a second anode on the TWT, which allows them to control the cathode current to a small extent. The electronics are designed as a feedback circuit to maintain a constant cathode current. Once the limit of the correction circuit has been reached, the cathode current will quickly drop to the failure point, perhaps within only a few months. Sometimes the second anode voltage is included in the telemetry, so that the slow increase in the voltage can be monitored [Hulley].

2.2.3 HISTORY OF FAILURES

Since the mid-1960's, over 1000 TWTAs have been launched into synchronous orbit aboard a multitude of communications satellites. There are four major manufacturers of space-qualified TWTAs: AEG Telefunken, Hughes, Watkins Johnson, and Siemens. Each of the companies conducts extensive ground life tests of its TWTAs, as well as keeping track of the

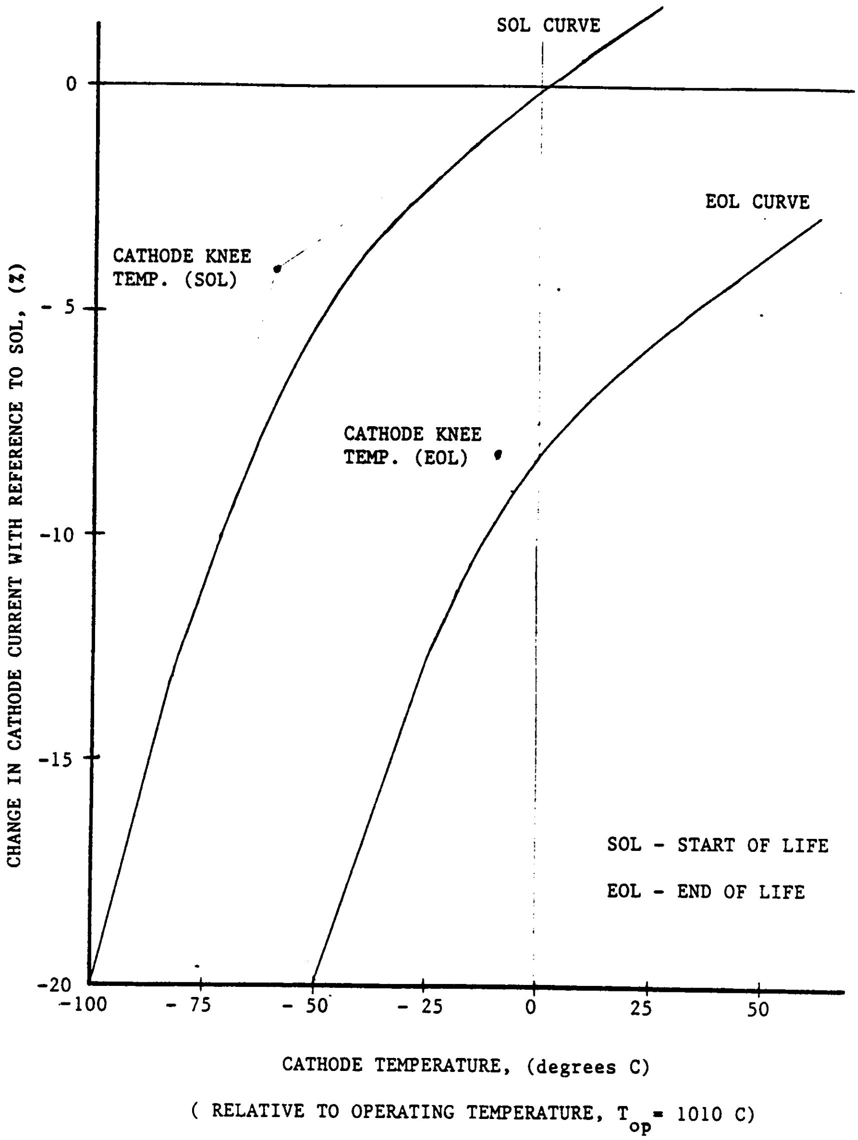


Figure 2.2.2.3 Cathode Current versus Operating Temperature - Matrix Cathode [Straussl]

lifetime of its in-orbit TWTAs. A literature search found several valuable papers revealing life test data on the Hughes and AEG TWTAs. Watkins Johnson is presently conducting a large-scale lifetime test of matrix cathodes, especially M-type cathodes. Their results show that the M-type matrix cathode outperforms the oxide cathode, with an average lifetime of over eight years without significant degradation [Forman2].

Table 2.2.3.1 lists the C-band TWTAs and some of their electrical characteristics. All of the transmitter TWTAs use oxide cathodes with an average current loading of 170 mA/cm^2. This limits their average saturated output power to about eight watts with less than 50 dB gain. Efficiency of these TWTAs is approximately 35%. The receiver TWTAs are low-noise devices typically operated well in the linear region of the AM-AM power transfer curve. Average values for these devices are: Saturated power - 0.6W; gain - 70 dB; efficiency - 10%; current loading - 150 mA/cm^2. GaAsFET technology has replaced the TWTAs in the receiver for most satellites to be launched in the future.

Table 2.2.3.2 details the C-band transmitter TWTA lifetime data. Both ground and in-orbit test data are included, where possible. Some of the AEG TWTA ground test data include the longest/shortest time to failure for the group of TWTAs tested. The total hours indicates the accumulated time of all TWTAs in the group up until the date listed in the left-hand column. Most of these tests are on going, in that the TWTAs will be run until they all fail (or until the satellite is decommissioned and sent out of orbit). Individual TWTA data were not found in the literature except for the INTELSAT IV satellites. Thus from these tables we can get only a rough idea of the lifetimes of the individual TWTA models. This is especially true of in-orbit test data, since the satellites are usually decommissioned before most of the TWTAs reach the failure point.

Fig. 2.2.3.1 details the history of the failed transmitter TWTAs (261H) aboard the INTELSAT IV series of seven satellites. Of the 168 TWTAs, 84 are primary units and 84 are spare units (two-for-one redundancy). Twenty-three of the primary units have failed, and one spare unit has failed. The failures are classified as either due to cathode deactivation or to EPC failure. Note that 80% of the failures were due to cathode deactivation, and of these, 85% occurred immediately after eclipse cycling was started. Eclipse cycling is when the TWTAs are switched off for a few months at a time to conserve the aging spacecraft batteries. All 84 of the primary TWTAs have been through short on-off periods for testing the spare TWTAs, but only 46 of the primary units have been through eclipse cycling. A third of these cycled TWTAs have failed soon afterward. It is not clear whether these failures are due to the TWTA model, method of operation, or a general failure mechanism [Koskos]. If these cycling failures are common to other TWTAs, it is clear that the reliability of the transponder would be directly dependent on the quality of the spacecraft batteries (and thus the need to cycle the TWTAs).

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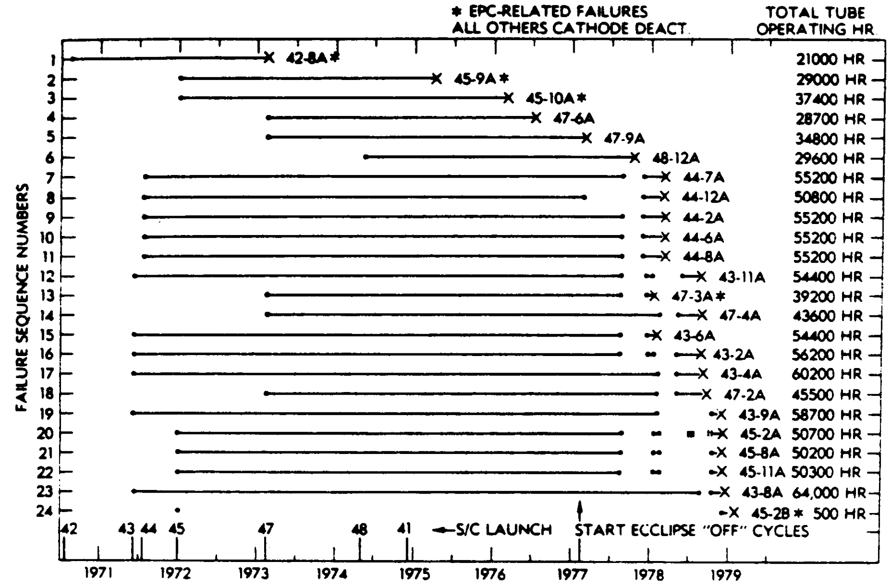
Table 2.2.3.2 C-band Transmitter TWTA Life Test Data

[Kornfeld, Kosmahl, Strauss2]

			GROUND TESTS			SPACE TESTS	
THROUGH	TUBE TYPE	PROGRAM	NO.	TOTAL HRS	SHORT/LONG SAMPLE RUN	NO.	TOTAL HRS.
3/31/75	215H	EARLY BIRD	8	162,098	----	2	56,000
12/31/81	215H	INTELSAT II	12	65,754	----	16	200,160
1/05/79	235H	INTELSAT III	--	---	----	10	711,772
3/76	235H	ATS-6	--	---	----	2	15,000
1/30/80	261H	INTELSAT IV	--	---	----	168	4,723,040
6/30/80	271H	INTELSAT IVA	4	191,056	----	50	743,580
3/31/80	275H	TELESAT	--	---	----	36	1,753,228
6/30/80	275HA	INTELSAT IVA	1	4,340	----	110	1,766,390
6/30/80	275HA	WESTAR	--	136,784	----	36	1,243,782
3/76	296H	SATCOM	--	---	----	48	60,000
7/78	TL4003	SYMPHONY	50	1,145,000	11,000/ 40,000	4	280,000
8/83	TL4010	ANIK B	4	172,000	43,000	12	440,000



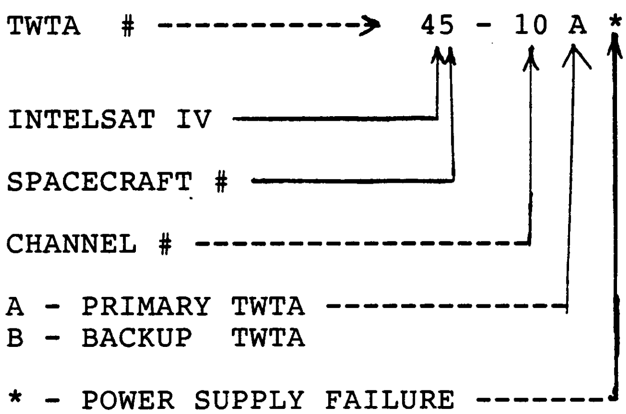


Figure 2.2.3.1 INTELSAT IV Hughes 261H TWTA Failures [Strauss1]

Table 2.2.3.3 details the C-band receiver TWTA lifetime data. Due to lower power requirements slightly lower current loading is achieved, resulting in longer average lifetimes than the transmitter TWTAs. The 262H is an exception to this rule, with a faulty design causing cathode deactivation failure in just two years. The short lifetime provides dramatic evidence of cathode deactivation effects, shown in Fig. 2.2.3.2. No EPC failures were reported for the receiver TWTAs in general.

K-band TWTAs are listed in Table 2.2.3.4. All of them employ matrix cathodes and operate at substantially higher power than the C-band TWTAs. Average electrical characteristics are: saturated power - 20W; gain - 60 dB; efficiency - 40%, current loading - 500 mA/cm^2. There was no reference in the literature to receiver TWTAs for Ku-band. This is probably due to their replacement by GaAsFET technology. Most of the listed TWTAs have only recently been launched. Thus lifetime data, shown in Table 2.2.3.5, are based mainly on data collected from ground tests.

It is clear from the literature that accurate prediction of TWTA lifetime is not possible given only lifetime data from previous ground and in-orbit tests. The variance of useful lifetime of TWTAs (of the same model) is high, as shown by the INTELSAT IV data for the 261H. Also, the effect of switching the TWTA on and off for whatever reason is presently impossible to predict. Thus we must resort to measurements of the TWTA while in-orbit to predict its remaining useful lifetime.

Table 2.2.3.3 C-band Receiver TWTA Life Test Data

[Kornfeld, Kosmahl, Strauss2]

THROUGH	TUBE TYPE	PROGRAM	GROUND TESTS NO.	TOTAL HRS.	SHORT/LONG SAMPLE RUN	SPACE TESTS NO.	TOTAL HRS.
3/76	226H	INTELSAT II	--	----	----	8	200,000
3/76	233H	INTELSAT III	--	----	----	10	416,000
3/76	233HC	ATS-6	--	----	----	2	15,000
3/31/80	262H	INTELSAT IV	6	117,844	----	26	286,879
3/76	272H	INTELSAT IV	--	----	----	2	8,000
3/76	276H	INTELSAT IVA	--	----	----	12	7,000

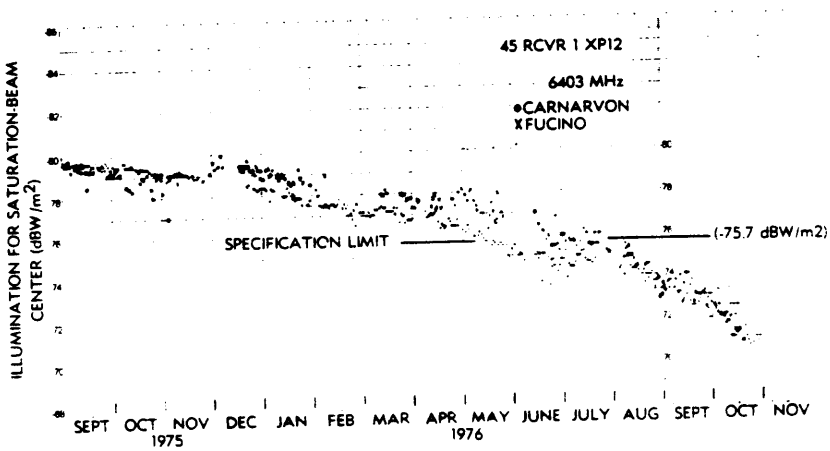


Figure 2.2.3.2 INTELSAT IV Hughes 262H TWTA Failure [Strauss 1]

Table 2.2.3.4 K-Band TWTAs

TRANSMITTER TWTAs

[Korn, Kosmahl]

TUBE TYPE	SATURATED OUTPUT POWER(W)	GAIN(dB)	CENTER FREQUENCY (GHz)	NOMINAL TOTAL EFFICIENCY(%)	CATHODE LOADING A/cm^2
286HP(1)	20.0	60	15.0	40	0.500
286HP(2)	20.0	60	11.9	40	0.500
TL12006	20.0	--	12.0	--	---
TL12016	15.0	--	11.95	42.5	---
TL12022	20.0	--	11.35	40.0	---
TL12025	20.0	--	12.1	40.0	---
TL12026	20.0	--	11.95	42.5	---

H suffix - Hughes Aircraft Corp., Torrence, California
TL prefix - AEG/Telefunken, Ulm, West Germany
A dash indicates unknown information

Table 2.2.3.5 K-band TWTA Life Test Data

[Kornfeld, Kosmahl, Strauss2]

THROUGH	TUBE TYPE	PROGRAM	NO.	TOTAL HRS.	SHORT/LONG SAMPLE RUN	SPACE TESTS NO.	SPACE TESTS TOTAL HRS.
---	286 HP(1)	---	3	58,914	(1) and (2)	--	---
---	286 HP(1)	---	2	35,570	have diff. cathode design	--	---
---	286 HP(2)	---	2	9,915		--	---
8/83	TL12006	---	6	450,000	68,000/ 78,000	--	---
			(2 tubes removed at 68,000 hrs.)				
8/83	TL12016	Anik C	--	---	---	20	50,000
8/83	TL12022 /25/26	STP-PROGRAM	25	913,000	31,000/ 56,000	--	---
			(14 tubes still running)				
8/83	TL12025	Anik B	--	---	26,000/ 36,800	4	136,000
8/83	TL12026	SBS	--	---	---	48	200,000

3.0 PRESENT IN-ORBIT TWTA TESTING

In this section, we wish to examine how in-orbit TWTAs are being tested today by satellite operators. There are two types of tests performed on a satellite. When a satellite is first launched and placed into orbit, an initial performance test is made of all spacecraft functions. This is to determine if the spacecraft survived the launch without damage, and to determine if all specifications have been met. After a satellite has been transferred to the operating company's control, it is monitored by the operator until the end of its useful life, typically seven to ten years. The purpose of the monitoring is to verify correct spacecraft operation and to correct any deviations from a nominal operating condition.

It is important to note that telemetry information is vital to any testing of the satellite, especially in testing the communications channels. Information on the switching state of the RF subsection is critical for such tests. There are also a few critical TWTA voltages and currents which are usually included in the telemetry that can directly indicate TWTA degradation. We shall assume in our test methods that full access to real-time telemetry data is available to us.

3.1 SATELLITE CHANNEL TEST CONFIGURATION

Before discussing the test procedures in detail, let us first examine the measurement problems peculiar to satellite testing. The basic test configuration is shown in Fig. 3.1.1. Test signals to be transmitted are typically generated at IF frequencies. They are then translated by a local oscillator to RF (6/12 GHz) frequencies. In order to reduce intermodulation products, multiple test signals are each passed through their own high power amplifier (HPA). After mixing and bandpass filtering of the signals, a power meter or spectrum analyzer is directionally coupled to the waveguide in order to measure the uplink power. Note that one of the test signals could be a communications signal, if the test method takes this into account.

The uplink signal is then transmitted to the satellite. The satellite receiver amplifies and translates the signal to the downlink RF (4/11 GHz) frequency. The signal may pass through a switchable attenuator before being amplified by the TWTA. The setting of the attenuator is known from the telemetry. After bandpass filtering the signal is transmitted by the spacecraft antenna down to the earth station antenna. The signal is then filtered and run directly into a spectrum analyzer.

It is clear that the communications path between the original uplink signal and the final downlink signal contains many elements which affect the power and quality of the signal. In order to measure precisely the

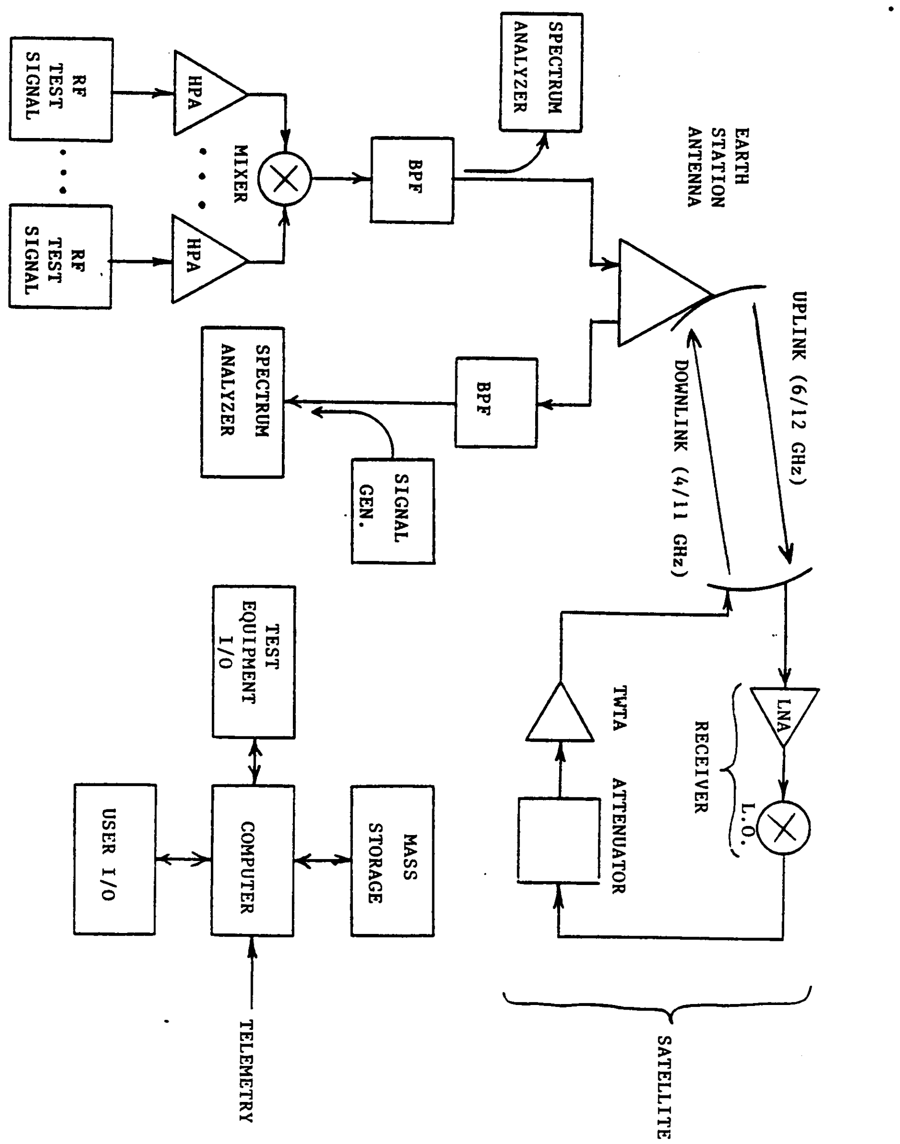


Figure 3.1.1 Satellite Test Equipment Diagram

effect of the TWTA on the signal, we must eliminate or nullify the effect of the other elements. Each of these elements and its effect on the signal are summarized below.

1. Transmit Electronics - includes all electronic equipment which directs the uplink signal to the antenna port. In order to nullify parameter variations in the generators, local oscillators and HPAs, the signals are typically sampled just before being fed to the antenna port. Usually we wish to know the uplink power of each test signal as well as the total uplink power. A power meter or spectrum analyzer can be coupled in as shown in Fig. 3.1.1. The signal generators can then be adjusted until the desired signal power is obtained. It is then only necessary to calibrate accurately the power sensing device in order to know the uplink signal power entering the antenna port.

2. Earth Station Antenna - The uplink and downlink antenna gains must be known precisely. Typically, the same antenna is used for both sending and receiving the signals. The antenna gain and pattern should be measured at approximately yearly intervals to account for variations due to structural deformation. The beamwidth of the antenna should be chosen to be as broad as possible, to minimize variations due to pointing errors. The beamwidth must be less than 2°, or intersatellite interference will certainly result. A tracking

system should be employed on the antenna, provided it is not allowed to move during a measurement.

3. Atmospheric and Propagation Effects - Attenuation due to weather can be significant, especially at the Ku-band frequencies. The attenuation can be measured by using a radiometer, or by measuring the strength of the satellite beacon. The latter method is preferred since this measures the same physical path that the test signals traverse. Variations in path loss must be accounted for also, especially in the older satellites which do not keep their positions as well as newer satellites. Path loss can be determined accurately by sending a ranging signal to and from the spacecraft using a separate RF system.

4. Spacecraft Antenna - The comments on the earth station antenna apply to the satellite antenna as well. The satellite antenna patterns are accurately measured after the spacecraft is placed in orbit, so we can determine the gain at our earth station location. Although there is some variation due to satellite antenna pointing errors, they are fairly small, especially for global beam antennas.

5. Satellite Receiver - Satellite receivers are highly reliable, long-life devices with extremely stable oscillators and amplifiers. The GaAsFET technology now used in these receivers results in

practically no variation in gain. However, there is a way to detect significant receiver gain variations. Changes in receiver gain affect all of the satellite channels, whereas a change in TWTA gain affects only one channel. Thus we can distinguish between receiver and TWTA gain variations.

6. TWTA - Variations in RF parameters due to the TWTA are what we are trying to measure.

7. Receive Electronics - In order to nullify variations in the gain of the downlink receive electronics, a signal of known power is injected in the downlink channel just after the bandpass filter. This signal can be adjusted until the spectrum analyzer shows the injected signal at the same power as the signal to be measured. We thus can determine not only the downlink power of any signal in the band, but also the total downlink power.

Three general points on our testing methodology arise from the above comments. First, we are only interested in measuring and recording changes in RF parameters due to changes in the TWTA characteristics. In other words, our measurements are mostly relative in nature, not absolute. Second, it is important to perform our measurements as close as possible to the earth station antenna port, in order to minimize variations due to earth station components. Third, the testing should be automated whenever and wherever possible to eliminate variations caused by human error. This is especially true when one considers the complexity of the measurement processes described in Section 4, and the necessity of combining the telemetry information with the test data. Only a computer can adequately handle the resulting database.

3.2 TESTING TWTAS WITHOUT COMMERCIAL TRAFFIC LOADING

We shall now examine those tests which are performed on TWTAs when they are not carrying any commercial traffic. This includes all the TWTA tests performed during the initial performance test. Any signal may be applied to the transponder (power levels up to saturation) and the TWTA may be switched on and off at will. A literature search has revealed that most of the work done in this area was performed by COMSAT labs for the INTELSAT series of satellites [Dostis, Gray]. I found test information on the RCA satellites and experimental satellites built by NASA [Smetana], ESA [Gough], and Japan's NASDA [Tsukamoto]. However, most of the tests were developed by COMSAT. Table 3.2.1 lists the various tests and those satellite operators who have performed them. We discuss each test below.

1. AM-AM Curve Characteristic - This test involves uplinking a single CW carrier at the center frequency of the transponder. As the carrier power is varied, the input and output power of the TWTA are measured.

Table 3.2.1 - TWTA Tests

Parameter Tested	INTELSAT	RCA	ESA	NASDA	NASA
<u>AM-AM</u>					
AM-AM Curve Characteristic	*	*	*	*	*
Gain Stability		*			
<u>AM-PM</u>					
Group Delay		*	*		
TWT Linearity		*			
<u>MISC</u>					
TWTA Turn-on Transients	*				
Amplitude Frequency Response	*				*

Plotting the results yields the AM-AM curve. The carrier power is only varied up to and including saturation, but not beyond, as this could damage the TWTA. This is probably the most fundamental test of the TWTA.

2. Gain Stability - A single CW carrier is uplinked at a constant TWTA input power at center frequency. The TWTA output power is measured and the gain is computed. This measurement is then performed over a period of time to check for gain variations due to solar eclipse of the satellite and diurnal variations. For the OTS satellite, these variations were less than 0.5 dB [Gough]. In order to avoid these variations in our tests, we should perform the test measurements when the spacecraft electrical system is in a nominal state.

3. Group Delay - This is essentially a measurement of the amount of AM-PM which the TWTA exhibits for a given input power. The measurement (see Section 4.3.1.2) is 'swept' across the entire bandwidth of the transponder in order to provide a frequency response graph of the AM-PM. Two carriers, one sent on each polarization, (and thus through separate TWTAs) are used in the measurement. One carrier is a reference and remains at the center frequency of its TWTA. The other carrier is swept across the frequency band of the other TWTA. Both signals are amplitude modulated by the same signal before being

uplinked. The AM-PM characteristic of the TWTA causes the envelope of the swept carrier to be delayed with respect to the envelope of the reference carrier. The reference signal is used so that variations in phase due to satellite motion will be cancelled out, since both signals traverse the same path. Thus the frequency response of the AM-PM can be calculated.

4. TWT Linearity - This is the classic method to measure the AM-PM of the TWTA. Two closely spaced, unmodulated CW carriers of equal power are uplinked. The resulting C/I of the third order intermodulation products in the downlink is measured. The C/I is directly proportional to the AM-PM. Usually this measurement is performed by varying the total input power to the TWTA, so that a graph similar to Fig. 4.3.1.2.2 can be obtained.

5. TWTA Turn-on Transients - This is a measurement of the cathode deactivation of the TWTA. The effects of cathode deactivation can be clearly seen by measuring the RF output power of the TWTA as it is turned on. The explanation of this effect will not be given here, since we are concerned with testing TWTAs that are running continuously, and cannot be turned off. For a more complete analysis, see the paper by Strauss [Strauss1].

6. Amplitude Frequency Response - This test essentially measures the frequency response of the spacecraft filters, since the TWTA is a fairly wideband device. A single, constant-power CW carrier is uplinked, and the resulting downlink power is measured. This measurement is swept across the entire frequency band to obtain the frequency response.

3.3 TESTING TWTAS WITH COMMERCIAL TRAFFIC LOADING

Let us now consider the possibility of testing a TWTA while it is carrying commercial communications traffic. All of the satellite operators monitor the downlink signals of their transponders. The level and capability of this monitoring varies among the operators, but they all wish to verify that the satellite channels are being used optimally. A literature search has revealed three monitoring systems that are currently in operation. Two of them were developed by COMSAT over the past 15 years for monitoring the INTELSAT and SBS (Satellite Business Systems) satellites [Gray, Gupta]. The third was developed by Miller Communications of Canada (about 1980) for monitoring the WESTAR satellites [Idasiak]. All but one of the measurements are passive in that they require no signals to be uplinked. It will be shown in Section 4 that passive measurements do not reveal much information about TWTA degradation unless you have control over the total uplink power of the transponder. All of the measurements are listed in Table 3.3.1 and are discussed below. The first four measurements are passive and are performed using a spectrum analyzer. See the paper by Idasiak for a discussion on what analyzer settings to use. The last measurement is an active one and is only used on TDMA systems.

1. Individual Carrier Power - The spectrum analyzer is set to measure the power within a small section of bandwidth. The analyzer then sweeps across the entire bandwidth of the carrier of interest. Summing the powers gives us the total carrier power.

2. Carrier Spectral Shape - Several points in the carrier bandwidth are measured by the spectrum analyzer in order to obtain a general outline of the spectrum. This measurement is useful for determining the type of modulation being impressed on the carrier.

3. Total Output Power - In this measurement, the spectrum analyzer is allowed to sweep the entire bandwidth of the transponder. The power measured in the sweep is the output power plus thermal noise of the system. A system noise measurement is made with the antenna pointing away from the spacecraft. This system noise (in dB) is subtracted from the transponder measurement (dB) to determine total output power. Note that this removes any variations due to receive system hardware degradation or replacement.

4. C/N - A measurement of the total noise power is obtained by sampling a noise segment within the transponder bandwidth. The noise power (dB) is then subtracted from the total output power (dB) to obtain the carrier to noise ratio.

5. TWT Linear Gain - This measurement is used in TDMA systems only. A low power CW carrier is uplinked during a guard space (when no traffic is present in the transponder for a few microseconds). The downlink carrier power is measured, and the small signal (or linear) gain is computed. This will be discussed further in Section 4.3.2.

Table 3.3.1 - TWTA Tests (with commercial traffic)

Measurement	COMSAT(FDMA)	COMSAT(TDMA)	WESTAR(FDMA)
PASSIVE			
Individual Carrier Power	*		*
Carrier Spectral Shape			*
Total Output Power	*		*
C/N			*
ACTIVE			
TWT Linear Gain		*	

4.0 NEW TESTING TECHNIQUES

In Section 2.2.2, we introduced underheating curves which detailed changes in the RF characteristics of a TWTA as its cathode degrades. In Section 3, we discovered that only one method for measuring TWTA degradation is in use today, and it requires a period where no commercial traffic passes through the channel. We shall now re-examine the underheating curves, and determine how the changes in the TWTA RF characteristics can be measured from a ground station without interfering with the commercial traffic.

4.1 INTRODUCTION

The underheating curves show us three RF characteristics that change with TWTA degradation (Refer to Fig.2.2.2.2). We wish to measure these changes over a period of many years from an earth station. Thus the measurements must be easily repeatable. There are three general methods for ensuring a repeatable measurement of a TWTA:

1. Perform the measurement with a constant input power at the TWTA. As the underheating curves shift, the change in the RF characteristics

can be measured. In order to obtain a specific value of input power, we must know the following: uplink transmitted power, antenna pointing losses, path loss, attenuation due to weather, and any attenuation switched into the satellite channel.

2. Adjust and measure the input power needed to obtain a constant value of an output RF characteristic. For example, one can adjust and measure the total input power required to obtain a specified value of total output power. As the power transfer (AM-AM) curve shifts, the input power will increase. However, it is not always possible to obtain a certain output value. For example, the helix current increases as the TWTA degrades, regardless of input power. Thus it will be impossible to obtain a certain value of helix current after much degradation.

3. Perform each measurement with the same 'operating point' of the TWTA. Notice that the shape of the power transfer curve does not significantly change when it shifts. Thus we can define a specific operating point on the curve at which we will perform our measurements. As the power transfer curve shifts, we can see that, for the same operating point, the input power will increase, while the output power will decrease. The main drawback to this method is determining exactly where the operating point is on the curve.

Note that all three of the above methods require knowledge and control of the total uplink power. The uplink power determines the operating point of the TWTA. Transponder users typically set the operating point to maximize the effectiveness of the satellite channel to transmit the user traffic. The operating point on the power transfer curve varies depending on the modulation and type of multiple access employed. Once an uplink power is set, it is usually not changed unless the change will somehow improve performance of the satellite channel. For example, a heavy rainstorm may cause fading of the channel, and so the uplink power may be temporarily boosted to compensate. In our measurements, we shall permit changes in the uplink power only if it does <u>not</u> degrade channel performance. This automatically excludes any and all reductions in uplink power from the desired operating point, as this is guaranteed to reduce the channel performance.

Let us now perform a closer inspection of each of the underheating curves shown in fig.2.2.2.2. We wish to find ways of measuring the 'shift' of each of the curves as the TWTA degrades. The accuracy and capability of these measurements are strictly dependent on the type of measurement performed and the form of multiple access used. Thus we shall organize the discussion under these categories.

4.2 TELEMETRY ANALYSIS

The most direct way of measuring TWTA degradation is by actually measuring the TWTA input voltages and currents on board the spacecraft. Specifically, if one could accurately measure the cathode current directly via telemetry, it would be the best indicator of the cathode degradation. However, almost all satellites built today do not include cathode current sensors on their TWTAs. There are evidently three reasons for this [Hulley].

1. The electronics of the cathode circuitry operate at a very high voltage, typically in the 1000 VDC range. Any circuitry associated with the cathode must be carefully designed and insulated.

2. Satellite designers are hesitant to measure anything but helix current and anode voltage (for matrix cathodes only). TWTA designers have traditionally elected to monitor helix current, as this is typically what is monitored in terrestrial-use TWTs. Because of the added weight and increased complexity, satellite designers have opted not to include any other TWTA voltages and currents in the telemetry.

3. The cathode current only drops about 10% before the TWTA is considered to have failed. Due to the limited accuracy of the digitized telemetry, a minimum change of one to two percent is required to

produce a change in the telemetry readings. Thus sensing of cathode current, or any other parameters, is only crudely represented in the telemetry.

As seen in Fig. 2.2.2.2, the helix current increases as the TWTA degrades. In the Hughes 261H, the helix current increased by a factor of three before reaching end-of-life specifications. Thus the change in helix current would be relatively easy to measure. One of the most widely used spacecraft, the Hughes 376, includes the TWTA helix currents in the telemetry downlink [SBS]. Knowing the uplink power and the resulting helix current, we can calculate TWTA degradation.

In those satellites that employ matrix-type cathodes with anode voltage compensating circuitry, the anode voltage is usually included in the telemetry. We know that as the cathode degrades, the anode voltage rises to keep the current constant. Thus simply measuring the change in anode voltage over time provides a direct way of measuring TWTA degradation.

4.3 TEST-TONE METHODS

A test-tone is an unmodulated continuous wave (CW) carrier, which we can inject into the uplink just before the antenna (using separate HPAs). These test-tones are easy to generate, and the resulting downlink test-tones are easy to measure using a spectrum analyzer with a narrow bandwidth. From the downlink measurements, one can determine the shift of both the AM-AM curve and/or the AM-PM curve (see Fig.4.3.1.2.1). Exactly how this is done will be discussed later.

Any test-tones injected into the uplink signal must be carefully monitored. We do not wish to significantly interfere with the communications traffic. In order to assure the transponder user of this, we must place two restrictions on the use of test-tones:

1. The test tones must be located (in frequency) outside of the downlink demodulator bandwidth, but inside the satellite bandpass filters. For example, on a typical 36 MHz C-band transponder, the demodulator bandwidth covers approximately the center 30 MHz. This requirement generally leaves adequate space for our test-tones.

2. The test-tones must be kept at least 20 dB down (in power) from the uplink value required for saturation. This is to prevent the carrier to intermodulation ratio (C/I) from dropping significantly.

The test-tone measurements must be repeated at exactly the same frequencies. This is to eliminate any changes caused by edge effects of the spacecraft filters. Since the filters are passive devices, they generally do not degrade with time, and the filter characteristics will remain unchanged.

We will examine the use of test tone measurements for all three types of multiple access: FDMA, TDMA and CDMA.

4.3.1 TESTING FDMA SYSTEMS

There are essentially two types of FDMA systems. The simplest type is a single FM carrier occupying the entire transponder. The FM can be either digital or analog. The majority of satellite transponders use this method to deliver high-quality television signals with analog FM. The other type of FDMA uses multiple carriers. The carriers, which originate from different earth stations, occupy different sections of the transponder bandwidth. The most complex of these systems is the single channel per carrier (SCPC) system. The transponder is divided into many 'slots' of narrow bandwidth. Each slot may or may not have a particular earth station assigned to it. The slot may or may not be in active use (carrier present). Thus the main problem with testing multiple carrier systems is that we have no control over the uplink power and the operating point of the transponder. The main advantage of SCPC systems is that one could temporarily procure one or more slots for testing purposes without disrupting traffic flow, providing that the traffic load is light.

4.3.1.1 MEASUREMENT OF POWER TRANSFER CURVE SHIFT

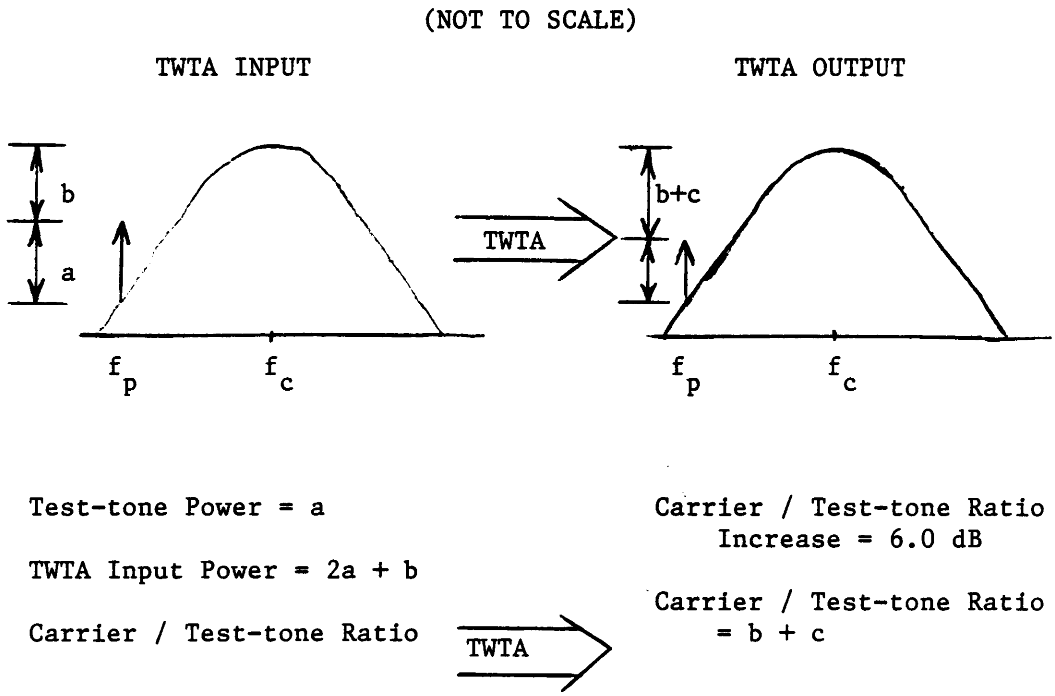
Examining the power transfer, or AM-AM (Amplitude modulation to Amplitude modulation) curves given in Fig. 2.2.2.2 we see that as the TWTA degrades, the curves shift to higher input powers and lower output powers. Note that the curve shape essentially remains unchanged.

When only a single carrier is used in the transponder, the TWTA is typically operated close to saturation with anywhere from 0.5 to 2.0 dB input back-off (IBO). This operating range is very nonlinear. If the uplink power is known, then we can simply measure the output power of the downlinked communications signal to calculate the gain of the TWTA for that value of input power. As the TWTA degrades, the gain for any value of input power will decrease as shown by the curves. Thus the curve shift can be computed. Note that it is not necessary to use the same value of input power every time the measurement is performed.

A typical domestic satellite has many different users, uplinking from many different earth stations. Thus if the testing is to be performed from the satellite control center, we can at best only have a crude estimate of any one of the uplink's transmitted power. However, we can use a single test-tone to determine the uplink signal power as long as the TWTA is a hard-limiting device. A hard-limiting amplifier exhibits carrier suppression. When two signals of unequal power are passed through a saturated TWTA, then at the output the larger signal grows stronger and the smaller signal weakens. Specifically, the ratio of the larger carrier to the smaller carrier is greater at the output than at the input. For very large values of the input carrier ratio, the increase in the output carrier ratio over the input carrier ratio is a constant of approximately 6.0 dB [Gagliardi].

Let us now apply the above information to the problem of determining the input power to the TWTA. Fig. 4.3.1.1.1 details the measurement. A test-tone of known power (a) is injected into the uplink. In the downlink, we measure the ratio of the carrier signal power to the test-tone power (b + c). We then subtract the known value of carrier suppression (c = 6.0 dB) and this yields the input carrier-to-test-tone ratio (b). The total uplink power is simply twice the test-tone power plus the input carrier ratio (2a + b). Since we know both the total input power and the total output power, we can calculate the gain and determine the shift of the power transfer curve. Note that the test-tone or communications carrier does <u>not</u> have to be at exactly the same level each time the measurement is performed, as long as the communications carrier power remains near saturation. This measurement is specifically useful for testing transponders carrying television signals from geographically spread uplink stations.

For the case of multiple carriers in an FDMA format, the measurement of the power transfer curve shift becomes even more complex. Automatically we have the problem of not knowing what the total input power to the TWTA is, since the uplink transmitters are typically scattered geographically. However, for any large number of carriers, the



We determine b from the downlink measurement.

We know the value of a.

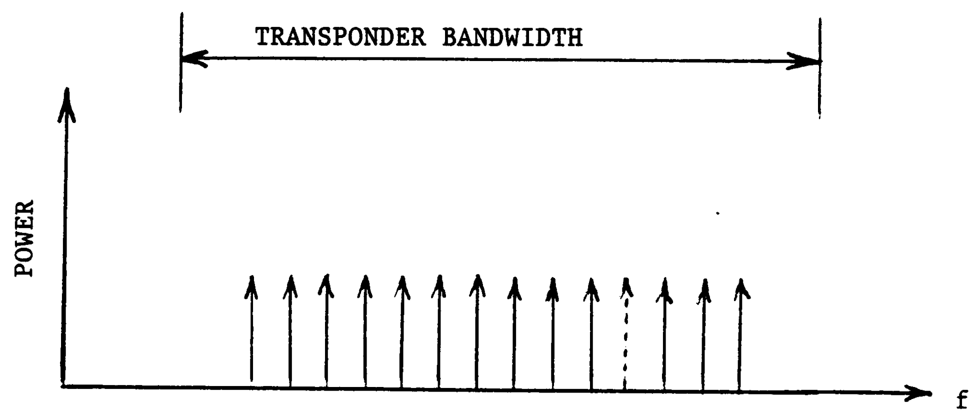
Thus a + b = Input power to TWTA.

Figure 4.3.1.1.1 Single Test-tone Measurement to Determine Input Power to TWTA (FDMA-single carrier)

TWTA must be operated within its linear region, usually with 8 to 5 dB IBO, depending on the number, power, and frequency spacing of the carriers. To analyze all the different FDMA systems and how to test each one is beyond the scope of this thesis. However, a simple single test-tone measurement can be performed to determine the total input power where a large number of carriers are present.

Let's examine the case where we have a transponder loaded with k equi-power communications carriers, as in Fig. 4.3.1.1.2. The test-tone is uplinked at an empty (no carrier) slot in the transponder bandwidth. The uplink power is adjusted until the test-tone is equi-power with all the other carriers. The total input power to the TWTA is then simply k + 1 times the test-tone input power. The total downlink power is k + 1 times the test-tone downlink power. The power transfer curve shift can then be calculated. Note that the value of k can vary from measurement to measurement. The main disadvantage to this method is that the number k should be held constant during a single measurement. In actuality, of course, the downlink carriers will not be exactly equi-power, due to transmitter and weather variations among the uplink carriers. Thus an average of several carriers in the downlink should be taken as the value for comparison with the test-tone downlink power.

Even though the TWTA is operated in its linear region, intermodulation products will exist. The amount of output power diverted to intermodulation products varies with the TWTA operating point, the number of carriers k, the individual carrier powers, and the carrier



FDMA DOWNLINK SPECTRA - MULTIPLE (K) EQUI-POWER
COMMUNICATIONS CARRIERS, WITH SINGLE TEST-TONE.

Figure 4.3.1.1.2 Single Test-tone Measurement to Determine Input Power to TWTA (FDMA-Multiple carriers) spacing in frequency. Many computer programs have been written to calculate the intermodulation products for various combinations of carriers applied to the input. Further study is required to determine if the intermodulation products are significant, and if so, how they may be accounted for in the above measurement scenario.

For TWTAs that operate in the quasi-linear range of approximately 2 to 8 dB IBO, measurement schemes must overcome difficulties caused by intermodulation products and carrier suppression, both of which vary greatly in this region. Note that a measurement scheme which includes both effects would work effectively in any IBO region of TWTA operation.

4.3.1.2 MEASUREMENT OF AM-PM CURVE SHIFT

Examining Fig. 2.2.2.2, we see that the phase shift curve shifts down and to the right, with some change in the curve shape. In general, the phase shift of a TWTA increases as the device degrades. Unfortunately, there does not appear to be a way of measuring the relative phase shift of the device due to variations in the slant path distance and other factors. However, the derivative of the phase shift curve (with respect to frequency) yields the familiar AM-PM curve, shown in Fig. 4.3.1.2.1. AM-PM can be measured from our earth station. Fig. 4.3.1.2.2 shows the change in the AM-PM curve as the TWTA degrades (as seen from the curves in Fig. 2.2.2.2).

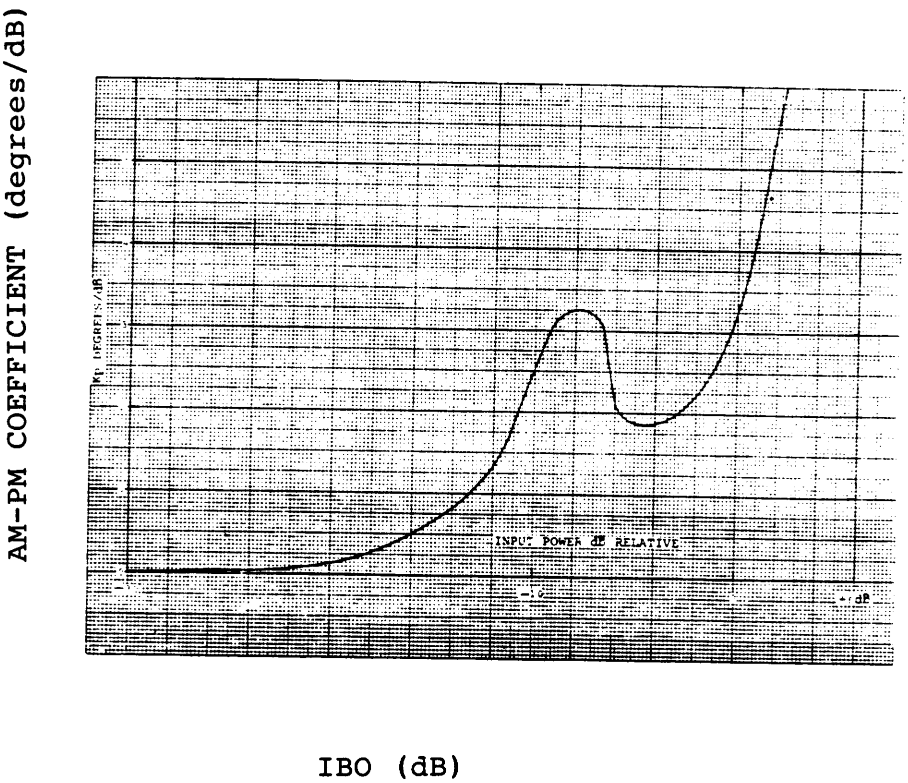


Figure 4.3.1.2.1 AM-PM versus IBO [Berman]

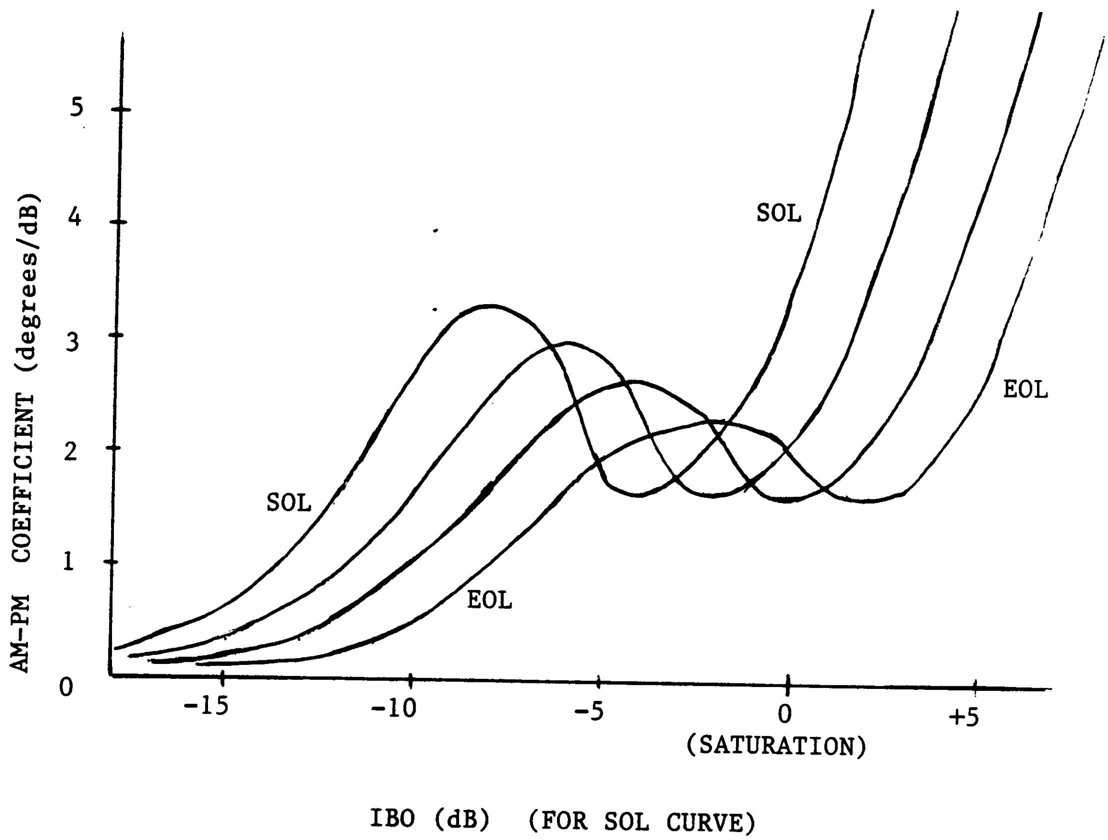


Figure 4.3.1.2.2 Effect of Cathode Deactivation on the AM-PM curve.

The AM-PM curve is a direct indicaton of the intermodulation distortion that will result when multiple carriers are passed through the TWTA. The intermodulation power level is due to two different nonlinear effects. The nonlinearity of the AM-AM (power transfer curves) casues multiple carriers to generate intermodulation components at the following frequencies

$$f_{\ell mn} = \ell f_1 + mf_2 + nf_3 + \ldots$$

where

f_1, f_2, f_3 are frequencies of input signals
ℓ, m, n are the harmonic number

This intermodulation effect dominates the AM-PM curve for values of IBO at or near saturation. The nonlinearity of the relative phase transfer curve (Fig. 4.3.1.2.1) also causes multiple carriers to generate intermodulation components at the same frequencies mentioned above. The AM-PM generated by the nonlinear phase shift dominates the AM-PM curve at higher values of IBO (typically IBO > 4 dB). The intermodulation products due to the amplitude and phase nonlinearities add in quadrature [Berman]. We wish to measure the intermodulation products due to our test signals, determine the value of the AM-PM coefficient and thus determine the TWTA degradation. It is clear that if we are going to measure just the amplitude of the intermodulation products, we must be sure that we perform the measurements with the TWTA operating near saturation, or with IBO > 4 dB. This assures us that the amplitude of the intermodulation products is always due to one of the two nonlinearities, but <u>not</u> both.

The value of AM-PM due to either nonlinearity has been shown to be a function of TWTA degradation, and AM-PM curves due to either nonlinearity can be generated for any TWTA. We can thus measure TWTA degradation by measuring the amplitude of the third-order intermodulation products which result when two closely-spaced test-tones are transmitted through the TWTA. We describe just such a measurement below.

1. Determine the uplink power level following one of the methods outlined in the previous section.

2. Uplink two closely-spaced, equi-power test-tones near the band edge of the transponder (see Fig. 4.3.1.2.3).

3. Measure the resulting carrier to interference ratio (C/I) using the third-order intermodulation products. Calculate the value of AM-PM.

Once we know the input power and the AM-PM, we can consult our family of AM-PM curves to determine the amount of TWTA degradation. For the single carrier case when we are operating near saturation, we see that the AM-PM rises as the TWTA degrades (for a constant input power). The main drawback to this technique is that the AM-PM does not change by a large amount as the TWTA degrades. If a specific operating point is maintained by the user, there will be only a small change in AM-PM over time. Performing this measurement with the same total uplink power level

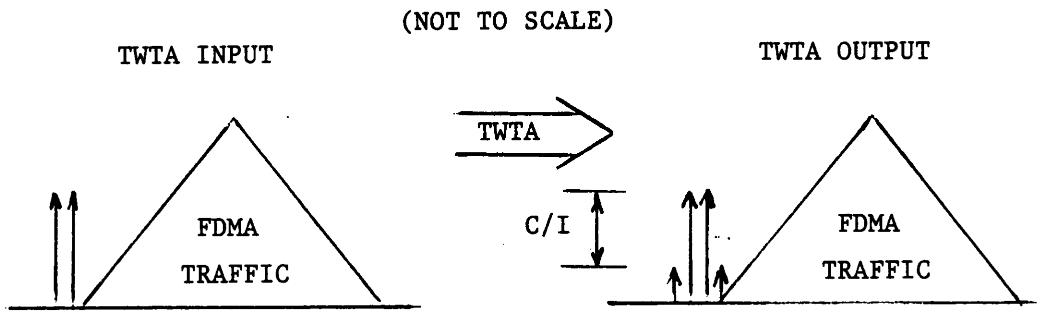


Figure 4.3.1.2.3 Dual Test-tone Measurement of C/I (FDMA Traffic)

each time will probably provide better measurements. Also, the measurement of intermodulation products is a more indirect way of measuring TWTA degradation than the power transfer curve tests, and so probably will prove to be not as accurate as the latter.

4.3.2 TESTING TDMA SYSTEMS

Time Division Multiple Access (TDMA) systems allow each user in the system unlimited access to a transponder for a short time period. All the uplink stations are synchronized to the same time reference, and each transmits frames of data for other stations to receive. Each station has a periodic slot of time in the transponder to transmit its data. TDMA systems differ by when and how long a slot of time is devoted to a particular station, and what exactly is transmitted during that slot of time.

A typical TDMA frame using QPSK is shown in Fig. 4.3.2.1. The frame basically consists of four time periods. During the carrier recovery time, the carrier is unmodulated, allowing receivers to lock onto the new carrier. During the clock recovery period, the carrier is modulated with alternating ones and zeros, producing two equi-power spectral components in the downlink, as well as their intermodulation products. The information period is when the traffic data are transmitted, and has a

QPSK signal spectrum. Finally, there is always a guard time between successive frames, where no carrier is transmitted.

A unique opportunity for testing exists in the TDMA format, since there are three periods of time when the transponder spectrum is very clear and consists of only CW signals. We can break our test analysis down into two cases; when we have access to the data or guard time, and when we don't. In either case, the TDMA measurements are complicated by two factors. First of all, equipment to synchronize to the TDMA format is complex; thus a TDMA test set would be expensive. Secondly, measurements performed on our test-tones are hampered because the test-tones only exist periodically for very short periods of time, typically in the range of a few microseconds. Sophisticated measurement equipment and techniques must therefore be employed, adding to the system cost. It is worthy to note, though, that the SBS TDMA satellite system is monitored by just such a complex system of test equipment [Potukchil]

Most TDMA systems have variable slot assignment, whereby slots of time are assigned to stations according to their traffic demands. Thus it is feasible that our test station could ask for and obtain a slot for sending a test frame to the satellite. If so, we would have a period of time when the transponder was completely free of signals. This is also the case if we have access to the guard space. Our testing problem then becomes as straightforward as the initial test measurements discussed in Section 3. To measure AM-AM curve shift, we simply uplink a test-tone, measure the power of the downlink test-tone, and compute the small-signal

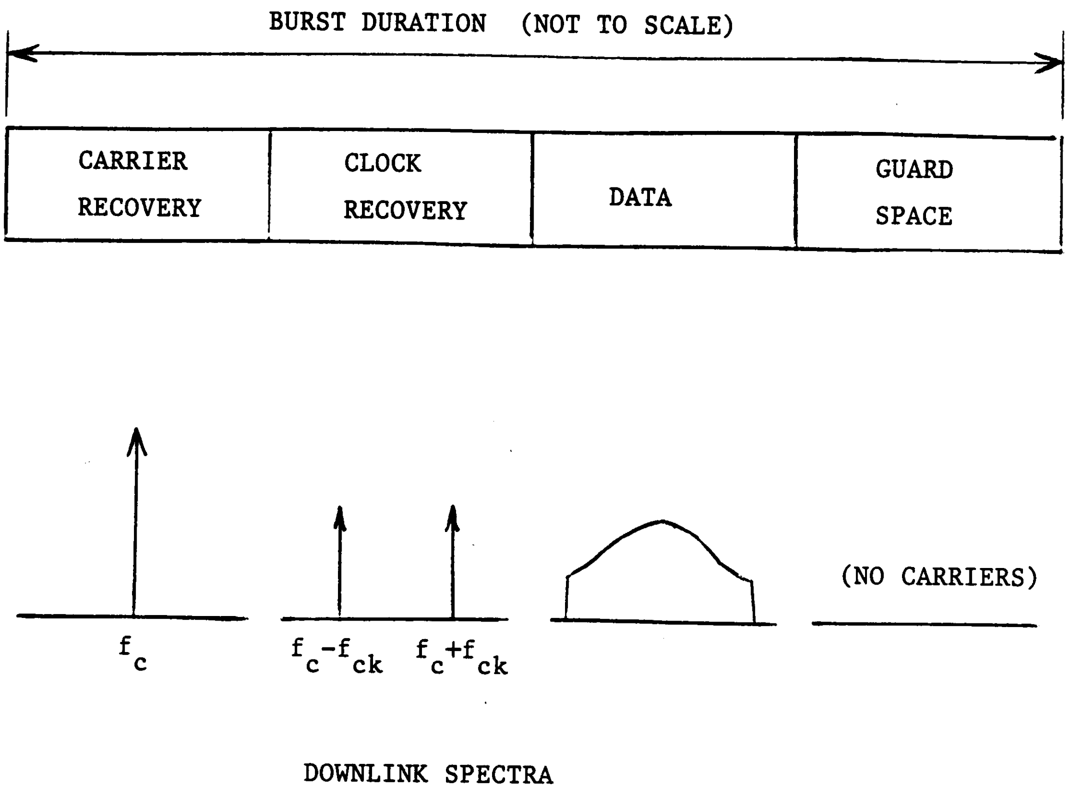


Figure 4.3.2.1 TDMA Burst Format and Spectrum

gain. The gain will decrease (for a constant input power test-tone) as the TWTA degrades. The SBS monitoring system uses the guard space for exactly this same measurement [Potukchi2]. We may also measure the shift of the AM-PM curve by uplinking two equi-power test-tones and measuring the resulting intermodulation products in the downlink. Depending on the total input power of the two test-tones, the intermodulation products will either increase or decrease, as discussed in Section 4.3.1.2. The intermodulation products are actually due to not only the AM-PM caused by the TWTA, but also due to the initial modulation of the single carrier with a square wave of alternating ones and zeros. These two components exist at the same frequencies, and in general do not add in-phase. This makes it impossible for us to distinquish between contributions due to the TWTA and contributions due to the initial modulation. However, if the TWTA is operating close to saturation, the intermodulation products due to the TWTA would probably dominate.

For practical reasons it may not be possible to obtain a free frame for testing. System specifications might also specify that the guard space remain empty of any signals, large or small. In this case, we are restricted to accessing only the carrier recovery and clock recovery portions of a frame. As it turns out, we can perform the same measurements employed in the FDMA case (see Fig. 4.3.2.2). During the carrier recovery time, an uplink station sends an unmodulated carrier through the transponder. Since TDMA systems operate the TWTA close to saturation, we can use the carrier suppression measurement described in

Section 4.3.1.1 to measure the TWTA input power and the AM-AM curve shift. During the clock recovery period, two equi-power carriers are passed through the transponder. We simply measure the resulting carrier-to-intermodulation ratio to determine the value of the AM-PM. Knowing the TWTA input power, we can determine the AM-PM curve shift. However, it is clear that these measurements would not be as precise as the above measurements made during 'signal-free' time slots.

4.3.3 TESTING CDMA SYSTEMS

Code Division Multiple Access (CDMA) systems use spread spectrum techniques to distribute a fairly low data rate signal over the entire transponder bandwidth. Each station has its own addressable code, and the codes have a very low cross-correlation. Each uplinked signal appears as a random noise signal in the spectrum. These uplinked signals overlap each other within the transponder. Spread spectrum techniques have been used mostly in military satellites, but CDMA systems have found increased use in the Ku-Band very small aperature terminal (VSAT) market.

CDMA systems are characterized by a large number (typically 100-1000) of geographically dispersed users, each one uplinking a low-power signal to the satellite. It is impossible to determine the individual signal power, or the total input power to the TWTA. However, it is possible to determine the output power of the TWTA from measurements

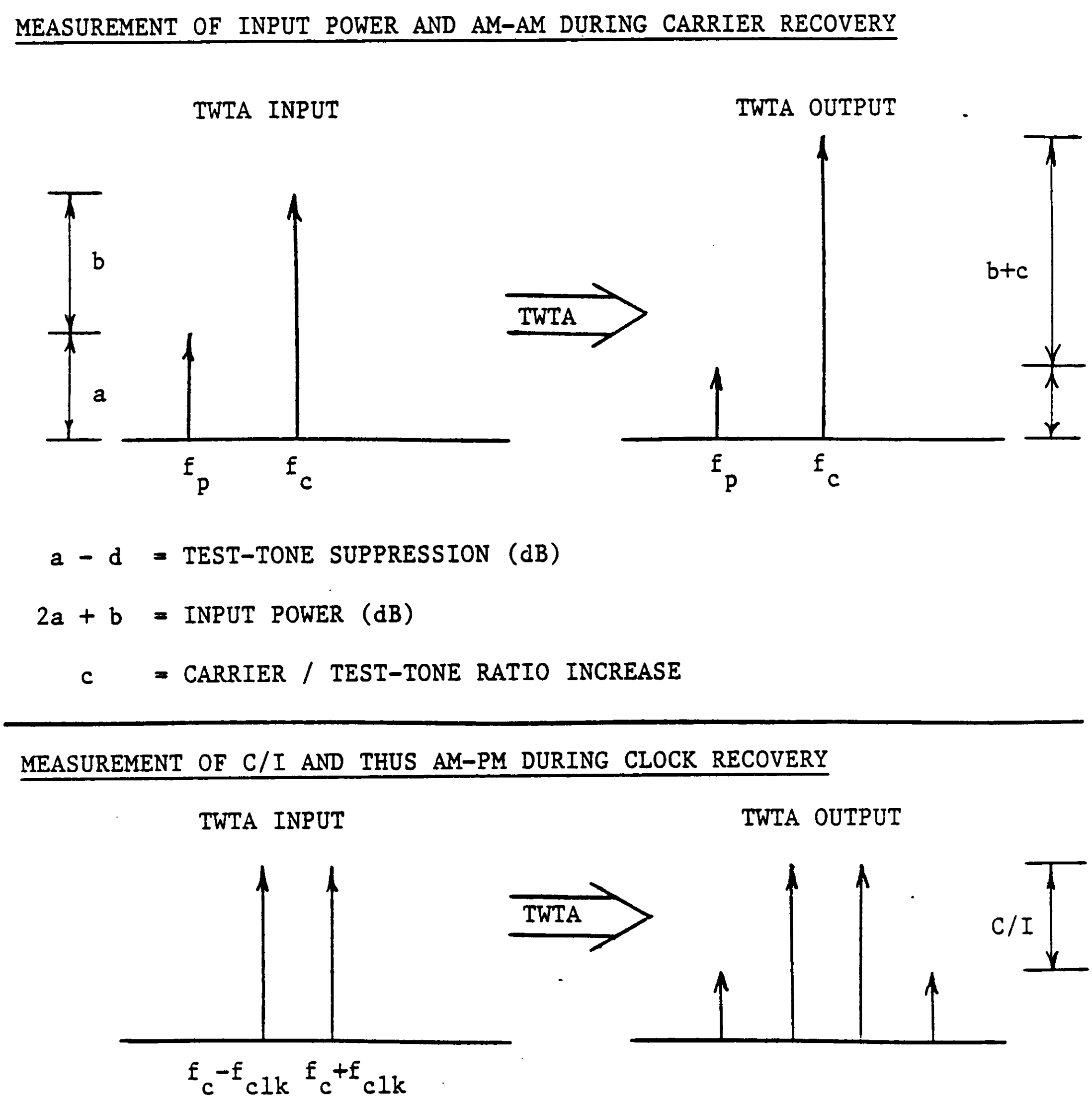


Figure 4.3.2.2 TDMA System Measurements Performed During Carrier and Clock Recovery Times.

of the downlink. In order to repeat a measurement, we must be able to set the output power to some constant value. This can be accomplished by uplinking a 'flat' noise signal and adjusting its strength until a certain value of output power is measured in the downlink. This noise signal is uncorrelated with the information signals, so no degradation in performance will be noticed as long as the transponder is not driven beyond saturation.

Once the downlink power has been established, we can then uplink our test-tones to test the TWTA. Note that the test-tones may be placed anywhere within the bandwidth of the transponder channel, since they produce equal levels of interference regardless of where they are in frequency. As long as the test-tones are kept fairly low in power, they will not adversely affect the performance of the spread spectrum signals. This is because the communication signal power is spread across the transponder bandwidth, and thus the test-tone power only interferes with a tiny portion of the communications signal power.

If the transponder is operated close to saturation, test-tone suppression by the large combined 'noise' signal will take place. For a constant output power, the TWTA operating point must move farther up the curve, as the TWTA degrades. This brings the operating point closer to saturation, increasing the test-tone suppression. Thus we can measure the test-tone power in the uplink and downlink to determine the amount of suppression and thus the location of the operating point see (Fig.

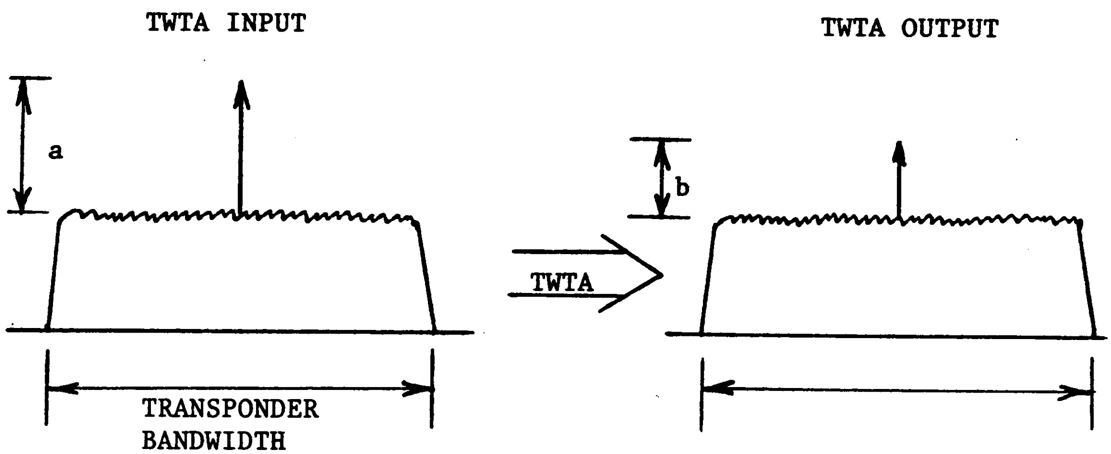
4.3.3.1). Since we know the downlink power, we can then determine the shift of the AM-AM curve.

Similarly, we can measure the shift of the AM-PM curve. We first obtain our constant value of output power. Secondly, we uplink two closely-spaced, equi-power test-tones and measure the resulting C/I in the downlink (See Fig. 4.3.3.2). This is a direct measure of AM-PM. Again, with constant output power, the operating point on the AM-PM curve moves closer to saturation, increasing the level of AM-PM, and as the TWTA degrades. This decreases the resulting C/I. Therefore the value of the C/I directly indicates the shift of the AM-PM curve.

If the transponder is operated well into the linear region of the AM-AM curve, test-tone suppression is negligible, and there does not appear to be any way to measure the shift in the AM-AM curve. Also, the change in AM-PM is very low for a constant output power, so it is questionable whether the C/I measurement would be useful.

4.4 SPREAD SPECTRUM METHOD

In this section, we introduce a new method for measuring TWTA degradation using spread spectrum signals versus test-tones as our test signals. Since a spread spectrum signal is spread out over the transponder bandwidth, it adds negligible interference to the communications traffic, regardless of access type or modulation form.



$$a \text{ (dB)} - b \text{ (dB)} = \text{Test-tone Suppression (dB)}$$

Figure 4.3.3.1 Test-tone Suppresion by CDMA Traffic

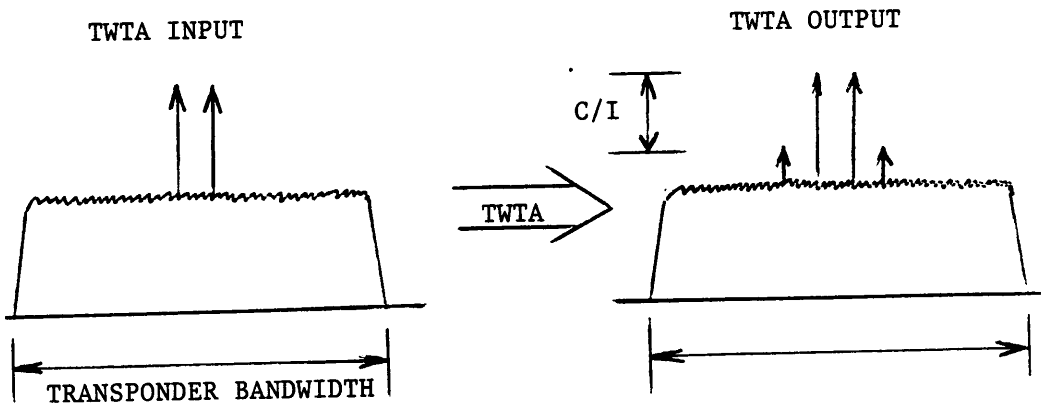


Figure 4.3.3.2 Measurement of C/I in TWTA Carrying CDMA Traffic

The result of uplinking a single spread spectrum signal through a transponder is to raise the 'noise floor' by an almost undetectable amount.

The test method is straightforward. A large block of known bits ($> 10^9$) is transmitted through the satellite via the spread spectrum signal (without error-correction coding). The bit error rate (BER) of the received block of bits is then calculated. The BER is a direct indicator of the overall quality of the satellite link. As the TWTA degrades, the link quality degrades and the BER increases. Unfortunately, a large number of other parameters also affect the quality of the link and thus the BER. In order to make this an effective test of the TWTA, all variations in these parameters must somehow be held constant, nullified, or otherwise accounted for in the measurement. Only in this way can we effectively isolate the change in BER to be solely due to TWTA degradation. The parameters which affect the BER include:

1. Uplink transmitter power-This is a precisely known and controlled quantity, which can be adjusted (based on the following two parameters) to provide a constant level of input power to the transmitter.

2. Weather attenuation - calculated from spacecraft beacon measurements.

3. Slant path variations - calculated form spacecraft ranging signals.

4. Antenna pointing losses - The spread spectrum signal will not significantly interfere with any traffic at its uplink frequency (on other satellites), so we can use a small (typically 2 meters in diameter) antenna with a large beamwidth. This will provide a constant antenna gain despite uplink antenna pointing errors.

5. TWTA degradation - Decreased gain (due to AM-AM curve shift) or increased signal distortion (due to AM-PM curve shift) will result in a lower carrier-to-noise ratio in the downlink, thus increasing the BER. It is this effect which we wish to measure.

6. Downlink receive chain variations - Includes receiver gain. These variations can be nullified by performing a local loop test, whereby a BER measurement is performed while bypassing the satellite portion of the link. We then subtract the loop-test value of BER from the value of BER obtained during the satellite test.

7. Traffic Loading - The BER will be affected by the location of the operating point on the AM-AM curve. For FDMA and TDMA systems, then, we must limit ourselves to the situation where we have control over the uplink power. Thus this method is not so attractive for these systems. For CDMA systems, however, we may employ the method used in Section 4.3.3 to obtain a constant value of total output power for

the TWTA. The only shift of the operating point will then be due to the shift in the AM-PM curve.

Note that the above list includes no mention of the type of traffic or modulation employed. Due to the large processing gain of spread spectrum signals, the communications signal can only have a small effect on the quality of the spread spectrum signal. This effect can be made negligible as long as the carrier-to-interference ratio (C/I) of the spread spectrum signal is designed sufficiently high enough. The level of C/I required depends on the test equipment used, the bit rate, and the satellite EIRP.

A major problem exists with the spread spectrum test. A single spread spectrum signal is typically of very low power and has a correspondingly low bit rate. In order to measure the BER accurately, we require on the order of 10^9 bits to be sent. Assuming a bit rate of 56 kbps (a typical number), a single BER measurement would take about five hours to complete. During this time, many of the above parameters which affect BER may change significantly. We must increase the bit rate significantly, either by sending a higher power signal or perhaps sending the bit stream through several low-power spread spectrum signals. Either way, by increasing the bit rate of the test, we have also increased the interference to the communications signal. Thus there is a tradeoff between communications signal interference and BER variations due to a lengthy test time. Further study must be conducted to determine if a good balance can be struck between the tradeoffs.

5.0 IMPLEMENTATION

The actual implementation of the test methods described in Section 4 will now be discussed. The physical location of the earth station used to perform the tests is constrained only by the spacecraft antenna footprints on the face of the earth. For example, if we wish to test a TWTA which is transmitting with a spot beam antenna, then the station must be located well within the coverage area of that antenna. This may not always be practical. TWTAs connected to global beam antennas would be easily measurable. It would be useful to perform the tests at a permanent location, in order to minimize variations in the spacecraft antenna gain seen by our ground station antenna. However, a transportable set of test equipment may be needed to test the spot beam TWTAs mentioned above.

The test station equipment should be totally separate from any equipment carrying the communications signal. This is to minimize variations in either the test or communication signal parameters due to changes or modification of the equipment. The test measurements must be accurate and repeatable in order to build up a quality data base. A high degree of automation should be employed to ensure repeatability and to minimize parameter variations due to human error. The test equipment should be of the highest quality to ensure the best accuracy possible. This is especially true of the RF signal generators and spectrum analyzers, which must have good spectral purity and resolution, respectively.

Although there is essentially no difference in the test methods for C versus Ku-band transponders, there are several significant differences in the test equipment. In general different antennas will be required, as well as other RF electronics, including HPAs and LNAs. It is feasible that the same IF test equipment could be used for testing both C and Ku-band transponders. This would result in substantial cost savings over two completely separate systems.

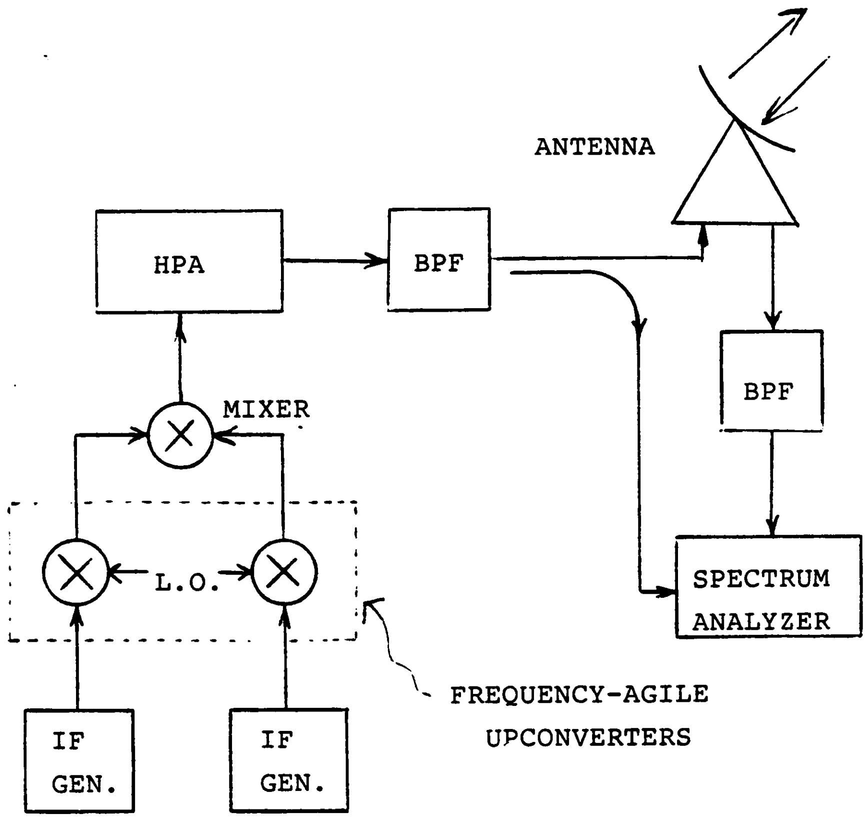
As noted in Section 2.1, we must have full access to real-time telemetry information when performing our measurements. If the test equipment is located at the satellite control center, then the telemetry is directly available. If the test equipment is not located at the control center, provisions must be made for accessing the telemetry either by terrestrial line from the control center, or via the satellite directly.

In the following subsections we will present test equipment configurations for the two methods presented in section 4. We will not include the equipment needed to determine the range to the spacecraft, or to measure the beacon level. This equipment varies depending on the spacecraft being tested. Typically the beacon is included at one end of the frequency band, and can be measured directly by the spectrum analyzer.

5.1 TEST-TONE EQUIPMENT

The equipment configuration for the test-tone methods is shown in Fig. 5.1.1. Two test-tone generators produce CW carriers which are frequency-translated through separate frequency-agile upconverters to the RF frequencies required for the measurement. The signal must then be amplified. A single HPA may be used as long as its operating point is maintained well into the linear range. This can be achieved with a standard HPA, since our test-tones are always low power. After bandpass filtering for the specific frequency band, the signal is directionally coupled into the spectrum analyzer input for measurement of uplink signal power. The computer forms a feedback loop between the spectrum analyzer and the HPA so that the uplink signal power can be controlled at all times. The downlink signal is bandpass filtered and fed directly into the spectrum analyzer. The same spectrum analyzer can be used for measuring both the uplink and downlink power.

The test equipment in Fig. 5.1.1 is suitable for testing TWTAs carrying either FDMA or CDMA traffic. For a TDMA system, equipment is needed to synchronize the burst transmission and reception of the test signals. An analysis of the equipment necessary is beyond the scope of this thesis, but it is clear that a TDMA test system would be much more complex and expensive than the FDMA/CDMA system. In order to get an idea of the equipment costs for a test system based on Fig 5.1.1, a cost



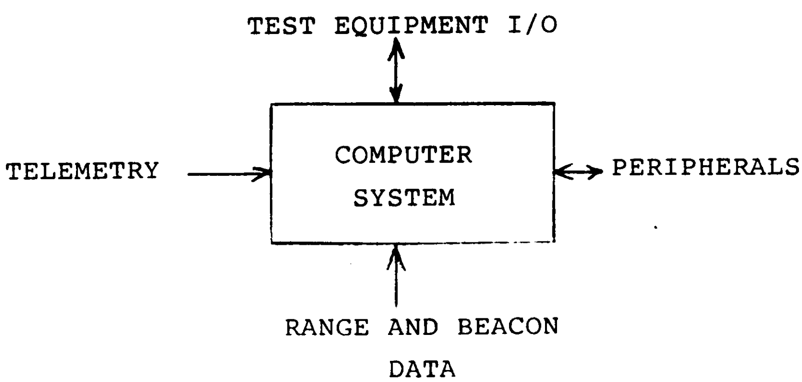


Figure 5.1.1 Test-tone Equipment Configuration

analysis was performed for a Ku-band system. The results are shown in Table 5.1.1.

Table 5.1.1 Ku-band Test-tone Equipment Cost Analysis

	Equipment Description	Approximate Cost( )
(2)	IF Signal Generators	10,000
(2)	Frequency-agile upconverters (computer-controlled)	20,000
(1)	HPA	25,000
(1)	Spectrum Analyzer (computer-controlled)	18,000
(1)	Ku-Band 10 foot diameter antenna (with LNA and BDF filters)	9,000
(1)	Personal Computer (with peripherals)	5,000
Subtotal		87,000
	additional 10% for cabling etc.	9,000
Total Equipment Cost		96,000

5.2 SPREAD SPECTRUM EQUIPMENT

Fig. 5.2.1 shows the test equipment configuration for the spread spectrum test method. The BER detector is a standard telecommunications device for testing transmission channels. It generates the stream of bits to be transmitted and stores them for comparison with the stream of bits that is received through the return channel. The spread spectrum modulator/demodulator is the device which converts the bit stream into a spread spectrum signal at IF, and vice versa. The noise generator is a wideband, flat power-frequency response device capable of producing a spread spectrum noise-like signal. The up/down converters perform the IF-RF frequency translation. The antenna would probably be 2-4 meters in diameter, depending on the transmit speed and output power of the modulator. Finally, the spectrum analyzer forms a feedback loop to the noise generator to keep a constant downlink power during the test.

Spread spectrum modulators/demodulators capable of transmitting bit rates greater than 56 kbps are only now emerging into the commercial marketplace. Unfortunately, they are packaged as proprietary 'black boxes' which perform FEC coding on the bit stream. Since we do not want the FEC, it appears a customized device must be built for this test set. The cost of this device will clearly dominate the otherwise inexpensive costs of the other hardware involved in Fig. 5.2.1. Thus one could expect the total cost for the spread spectrum system to be greater than the cost for the test-tone equipment.

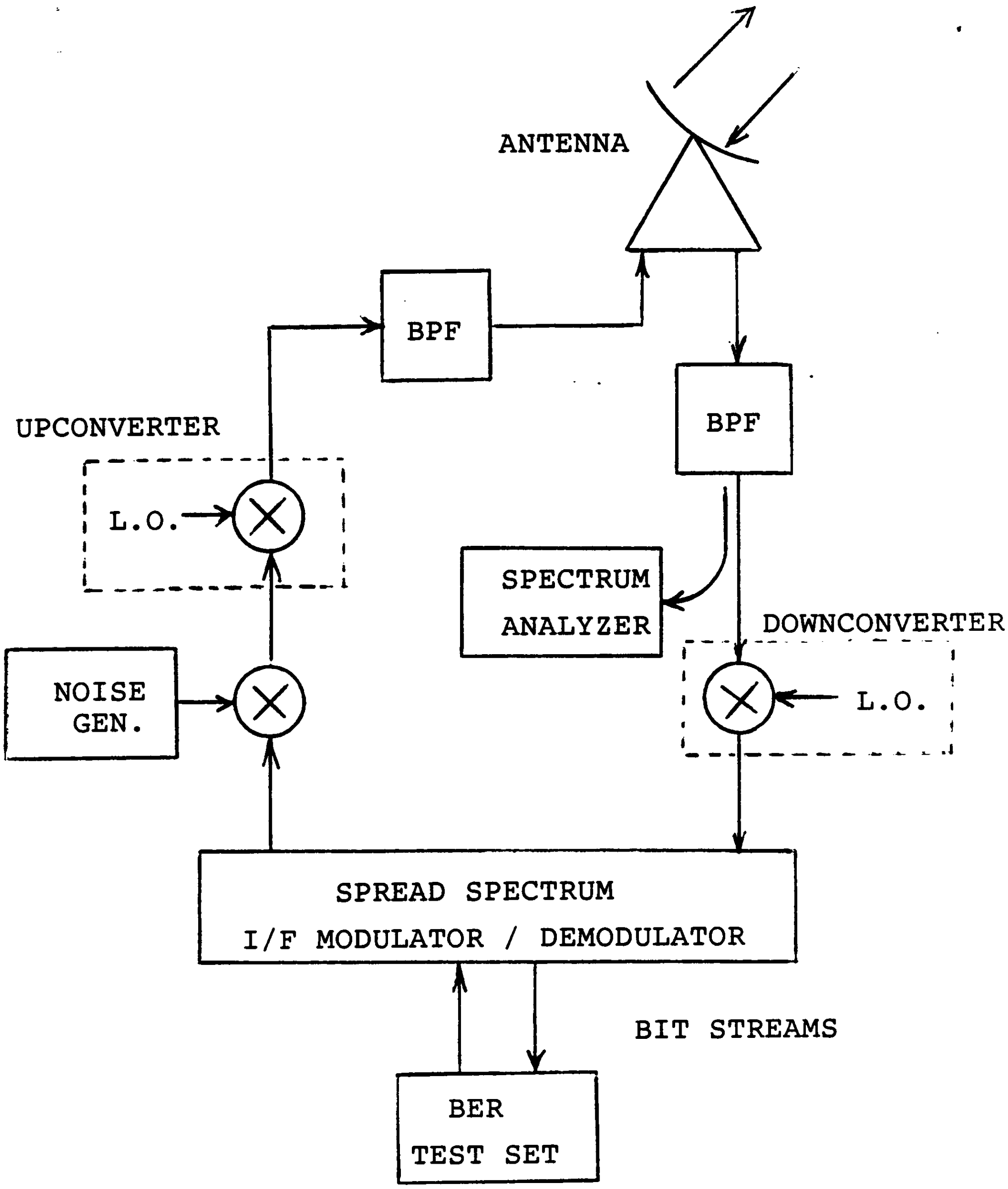


Figure 5.2.1 Spread Spectrum Equipment Configuration

5.3 OPERATIONAL CONCERNS

5.3.1 DATA MANAGEMENT

The computer system for our test configuration will clearly have to be a versatile machine. It must control a half-dozen devices, probably all with different interfaces. It must be able to store and have access to a large data base. The initiation and execution of all the measurements, as well as processing the subsequent data must all be handled by the computer. As this is a custom-built system, the majority of the software must be developed from scratch. Thus the software development costs could easily be comparable to the equipment costs.

The system software must perform the following functions:

- position and track the antenna
- control all test equipment (HPA, Spectrum Analyzer, etc.)
- decode and store telemetry information
- perform calculations on measured data.
- store underheating curve information for comparison with measurement data.
- Input/Output (printers, monitors, disk drives)

A personal computer (such as an IBM PC) with plenty of memory, expansion slots and hard disk storage should be sufficient to handle all testing needs.

Before each measurement is performed, the following should be recorded:

- date and time
- satellite under test identification
- satellite transponder under test
- TWTA under test
- changes in switching configuration (TWTAs, receivers attenuators, etc.)
- For the TWTA under test, record:
    - Helix current, Anode voltage

We shall assume that no switching of the spacecraft RF components will occur between the telemetry sample time and the actual measurement. Note we only record changes in the RF subsystem switching state. This is to minimize the amount of storage space required for the resulting data base of measurements.

5.3.2 TEST PROCEDURE

In Section 4 we discussed how to perform a set of tests to measure TWTA degradation. The question of when to perform the tests naturally arises. The answer to the question depends on the type of TWTA to be tested, and more specifically, the type of cathode in the TWTA. Oxide cathodes do not exhibit much degradation until about five years into their lifetime, whereupon the degradation increases fairly rapidly, with the failure point typically reached in seven to eight years of life. For example, on the 261H TWTA discussed earlier, a 4% drop in cathode current can be expected at about 5 years of operation. This results in about a

2 dB drop in linear gain and about a 50% increase in helix current [Strauss1]. This suggests the following test strategy:

1. For the first year of operation, perform tests on the TWTA once a week. This ensures that we will catch any early failures due to 'infant mortality'.

2. For the second through fifth year, perform the test once a month.

3. For the sixth year and on, perform the tests once a week again in order to carefully track the TWTA as it quickly degrades.

The matrix cathode TWTAs have different longevities depending on their construction and whether they are compensated or not. If they are compensated, a simple check of the anode voltage once a month through telemetry is sufficient to track degradation. For all matrix cathodes, though, one point is clear. Once the TWTA reaches end of life, its RF performance will tend to degrade quickly, and so must be monitored closely, just as for the oxide cathodes.

The telemetry of each satellite should be recorded (as described in the previous section) once a week in order to have an accurate history of the RF subsystem switching state. This is in addition to the telemetry samples taken just before each measurement.

Finally, we confront the issue of what to do with the TWTA degradation data as we compile it for each TWTA. Each model of TWTA should have a set of underheating curves taken from ground test data. The measurement data is compared to the underheating information to determine how far the TWTA has degraded, and how much longer it has got until it reaches failure point. Once a number of TWTAs of a particular model have failed, they provide 'signatures' of failure data which allows us to estimate more precisely the remaining lifetime of other degraded TWTAs of the same model.

6.0 CONCLUSIONS

We have identified TWTAs to be one of the main life-limiting devices of a communication satellite. Satellite operators presently rely on spare TWTAs to ensure that most of the satellite transponders will be operating at the end of life of the satellite. Accurate prediction of remaining TWTA lifetime allows us to predict the availability and reliability of the satellite transponders up to and including the end of life of the satellite. This prediction capability is useful to the satellite operators for long-range planning, and it is useful to insurance agencies which insure users against transponder loss.

The primary failure mechanism of a TWTA is cathode deactivation. Symptoms of cathode deactivation are readily measurable using test signals generated by an earth station. These symptoms include a drop in gain, an increase in helix current, changes in the intermodulation distortion, and an increase in anode voltage. Present methods for measuring these parameters require the transponder to be carrying no commercial traffic at the time of the test. This generally entails loss of revenue to the satellite operator due to traffic re-routing or pre-emption. In this thesis we have presented new methods of testing TWTA degradation without any significant interference to commercial traffic. The two methods involve the use of test-tones and spread spectrum techniques. Implementation of the test-tone method is straight-forward, using commercially available test equipment. The spread spectrum method requires further study to determine if it is as accurate as the test-tone method. Implementation of the spread spectrum method requires custom-built hardware and thus will be more expensive than the test-tone method.

Once data on the degradation of a TWTA has been collected, it can be compared to previous ground-test data as well as other in-orbit TWTA data. The results of this comparison will allow us to accurately predict the remaining useful lifetime of the TWTA. The lifetime etimates of all the TWTAs in a satellite can then be inserted into a transponder reliability model, from which we can predict the availability of the transponders as a function of time.

REFERENCES

1. Berman, A. L., Mahle; Christoph E., "Nonlinear Phase Shift in Traveling-Wave Tubes as Applied to Multiple Access Communications Satellites," IEEE Trans. Comm Tech., vol. COM-18, No. 1, Feb. 1970.

2. Christel, Kevin J., "Risk Management: A Necessary Tool for Satellite Owners and Users," Space Comm. and Broadcasting, Vol. 2, 1984, pp. 47-57.

3. Dostis, I.; Mahle, C., "In-Orbit Testing of Communications Satellites," COMSAT Technical Review, Vol. 7, No. 1, 1977, pp. 1567-1572.

4. Emmert, C., "In-Orbit Measurement of the SBS Satellite," AIAA 9th Comm. Satellite Systems Conf., 1982, pp. 167-173.

5. Forman, Ralph; Smith, David H., "Thermionic Cathode Life-Test Studies," IEEE Trans. on Electron Devices, Vol. ED-26, No. 10, Oct 1979, pp. 1567-1572.

6. Forman, Ralph; Elmer, Paul, "Life Test Studies on Tungsten Impregnated Cathodes," IEEE Trans. on Electron Devices, Vol. ED-27, No. 7, July 1979, pp. 1309-1310.

7. Gagliardi, Robert M., Satellite Communications, (Belmont, CA: Lifetime Learning Publications, 1984.)

8. Gough, R. A.; Hughes, C. D., "In-Orbit Measurements of OTS Payload Performance," ESA Journal, Vol. 4, pp. 73-87.

9. Gray, L. F.; Steinbrecher, E. E., "A Computer Controlled Satellite Signal Monitoring System," COMSAT Technical Review, Vol. 1, No. 1, 1971, pp. 79-116.

10. Gupta, R. Forcina, G., "Ground-Based Techniques for Monitoring Performance of SS-TDMA Communications Satellites," IEEE 1983 National Telesystems Conf., San Francisco, California, Nov. 14-16, 1983, pp. 336-342.

11. Hughes Aircraft Company, "Hughes TWT and TWTA Handbook," Electron Dynamics Division, Torrence, California.

12. Hulley, Mike, From personal communication with Mike Hulley, member of technical staff, COMSAT Labs, Clarksburg, Maryland, April 30, 1986.

13. Idasiak, B., "Automated Monitoring of Satellite Carriers," AIAA paper 84-0686, 1984.

14. Kornfeld, Gunter, "Reliability Considerations for Satellite TWTs," Microwave Journal, Aug. 1984, pp. 113-125.

15. Koskos, P. "INTELSAT IV C-band Transmitter Wearout Statistics," NASA Workshop on Spacecraft Transmitter Reliability, Sept., 1979, NASA Conf. Publ. 2159, pp. 4-6.

16. Kosmahl, Henry, "Space Tubes - A Major Challenge," NASA Technical Memo 82971.

17. Matthews, P. A. Microwave Components, (London: Chapman and Hall Ltd., 1968) pp. 130-132.

18. Owens, J. R.; Strauss, R., "Design Factors Affecting Communications Satellite Lifetime," Proc. 28th International Astronautical Congress, Vol. 2, 1977, pp. 119-137.

19. Potukchi, J. R.; Assal, F. T.; Mott R. C. "A Computer Controlled Satellite Communications Monitoring System for Time Division Multiple Access," COMSAT Technical Review, Vol. 14, No. 2, Fall 1984, pp. 391-430.

20. Potukchi, J. R.; Assal F. T., "TDMA Performance Monitoring of Communications Satellite Transmitters," IEEE National Telesystems Conf., San Francisco, California, Nov. 14-16, 1983, pp. 410-414.

21. SBS. From an internal Hughes document on the telemetry of HS 376 series satellite.

22. Smetana, Jerry; Curren, A. N., "Life Characteristics Assessment of the Communications Technology Satellite Transmitter Experiment Package," NASA Technical Memo 79181, July 1979.

23. Strauss, R.; Owens, J. R., "Past and Present INTELSAT TWTA Life Performance," AIAA 8th Comm. Satellite Systems Conf., Orlando, Florida, April 20-24, 1980, pp. 491-498.

24. Strauss, R., "Traveling Wave Tubes for Communications Satellites," Proc. IEEE, Vol. 65, No. 3, pp. 387-400.

25. Tsukamoto, Ken-Ichi; Otsu, Yuichi, "Experimental Program and Performance of Japan's Communication Satellite (CS) and Its First Results," IEEE Trans. on Comm, Vol. COM-27, No. 10, Oct. 1979, pp. 1392-1404.

26. Winch, R. G., "High-Power Coaxial RF Switches for Space Applications," Microwave Journal, Vol. 18, No. 11, 1975, pp. 56-58.

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