Communication satellite power amplifiers: current and future SSPA and TWTA technologies

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SUMMARY

This study captures the state of current satellite transponder technology, specifically, solid-state power amplifiers (SSPAs) and traveling wave tube amplifiers (TWTAs), and describes expected future advances, including GaN SSPAs. The findings of five previous SSPA and TWTA studies, including the 1991 European Space and Technology Center study, the 1993 National Aeronautics and Space Administration study, and three Boeing studies conducted in 2005, 2008, and 2013, are tabulated and summarized. The results of these studies are then compared with new analyses of two validated sources of amplifier data: a commercially licensed database, Seradata's Spacetrak, and a publicly available database, Gunter's Space Page. The new analyses consider a total of 18,902 amplifiers (6428 TWTAs, 2158 SSPAs, and 10,316 unspecified amplifiers) onboard 565 communications satellites launched from 1982 to 2016. This new study contains the largest number of satellites and amplifiers to date and compares output power, redundancy, and bandwidth capabilities. We find an increase in output power from the 1993 study of >200% for Ku-band TWTAs and C-band SSPAs, and >1000% increase for C-band TWTAs. The ratio of operational to redundant amplifiers is 10 times higher for TWTAs than SSPAs, and the majority of amplifiers over the past 30 years operate with bandwidth less than 100 MHz. A second analysis is conducted using failure records and telemetry of 16 geostationary satellites equipped with 659 amplifiers: 535 SSPAs and 124 TWTAs. We find that <2% of TWTAs and 5% of SSPAs experience anomalies. Overall, this research was performed to update and clarify how the power and bandwidth needs and redundancy trends of the SatCom community have evolved over the past 30 years. Copyright © 2015 John Wiley & Sons, Ltd.

1. INTRODUCTION

Having weathered market uncertainty and even the bankruptcy of several commercial satellite companies in the 1980s and 1990s, commercial satellite telecommunications represent one of the most profitable space-based industries today. Communications satellite technologies are evolving to meet growing demands for high-rate data, video, and multimedia content distribution [1]. To enable satellites to provide higher bandwidth and data rates, higher power and more efficient components that are reduced in size and mass are needed [2–4].

Radio-frequency (RF) power amplifiers are one of the key components onboard communications satellites. RF power amplifiers are used to increase the power of an uplinked signal prior to retransmission (downlink). The uplinked signals experience substantial losses (free-space path loss, transmission line loss, polarization loss, etc.) and must be amplified to survive similar losses during downlink for sufficient receiver detection [2, 5, 6].

Radio-frequency power amplifiers consume 80–90% of the spacecraft bus power [7, 8]. Therefore, amplifier Direct Current (DC) to RF power conversion efficiency is of utmost importance. Increased

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efficiency decreases wasted power, which forms heat and directly affects thermal management, payload capability, and ultimately the spacecraft sizing and mass [5, 8, 9].

Traveling wave tube amplifiers (TWTAs) and solid-state power amplifiers (SSPAs) are the two main amplifier choices for space-based RF communication [10]. Historically, demand for higher power at higher frequencies has resulted in TWTAs as the logical amplifier of choice; this is due to the fact that traditional SSPA technology was unavailable at similar performance levels [2, 11]. However, technological advancements such as linearization, miniaturization, and the use of different materials such as GaN, have leveled the playing field for SSPAs. These developments motivated the analyses in the current work and the summary of previous comparisons of amplifier characteristics [5, 12].

In this study, we review current TWTA and SSPA technologies available for space-based applications and discuss future planned technologies. We begin by summarizing and comparing five previous studies of amplifier technologies. Then, we analyze trends in TWTA and SSPA technologies using payload data from a commercially licensed database and a publicly available database.

This data set consists of amplifier technologies onboard 565 communications satellites launched between 1982 and 2016. To the author's knowledge, this is the largest number of satellites and amplifiers included in a power amplifier comparison study to date. Finally, we analyze proprietary amplifier telemetry and failure records onboard 16 satellites, which were equipped with a combined total of 579 amplifiers: 470 SSPAs and 109 TWTAs.

2. TRAVELING WAVE TUBE AMPLIFIERS

Traveling Wave Tube Amplifiers were the first successful RF power amplifier technology for communication systems [8]. TWTAs were extensively used in satellite payloads at the birth of the space age in the 1960s and exclusively used on 69% of all geostationary communications satellites between 1992 and 2006 [13]. This section describes the physical amplification process behind TWTA technology and the advantages and disadvantages of these devices.

Traveling wave tube amplifiers consist of an electronic power conditioner (EPC) and a traveling wave tube (TWT). The EPC consists of several components including DC-DC and DC-Alternating Current (AC) converters, protection circuits, and telecommand-telemetry circuits [4]. The EPC directly interfaces with the satellite bus primary power and converts the satellite bus voltage to the necessary electrode voltage (kV DC) for the TWT [9]. The EPC can supply thousands of volts of regulated power for stable TWT output power (minimizing the impact of effects such as intermittent power generation and thermal variation experienced during periods of sunlight and eclipse) [4, 14].

The TWT is a vacuum electron device that consists of an electron gun, a slow wave structure (SWS), a magnetic focusing system, RF input and output couplers, and a collector. As noted, the TWT requires a conditioned power source for supplying voltage to the electron gun. When voltage is supplied, the electron gun emits an electron beam from a cathode heated to $1000\,^\circ$C. The electron beam is injected into the SWS, which includes a magnetic focusing system that confines the beam as it travels down the center of the SWS. For space applications, a simple helix SWS and a coated tungsten matrix (M-type) cathode have historically been used. The helix SWS provides the greatest dispersion control and greatest operating bandwidth; the coated tungsten matrix cathode provides high mean currents and is capable of surviving and functioning under severe vibration and shock levels [15]. New methods for cathode fabrication can replace the metal composites of the cathode with a microfabricated silicon substrate with enhanced electric field features [16].

The RF signal, at the desired power and frequency, is injected through the input coupler onto the SWS. The SWS extends from the RF input coupler to the RF output coupler. An energy exchange occurs between electron beam particles and the RF wave as both travel down the SWS at similar speeds; this energy exchange generates the amplification of the RF signal. Attenuators prevent the wave from traveling back to the cathode, and a collector is located at the end of the helix coil, where the spent electron beam is deposited. Approximately 70% of the total consumed power is converted into RF energy, and the remaining 30% is converted to waste heat. The largest fraction of waste heat is in the collector; therefore, one of the primary focuses for improving amplifier efficiency is to reduce

Figure 1. L-3 Communications Electron Technologies, Inc. traveling wave tube amplifier (TWTA) devices: (a) Ku-band TWT [18] and (b) V-band TWTA [19].

this fraction [9]. Passive thermal control including heat pipes and surfaces of high emissivity is used to dissipate the concentrated heat in the payload [3].

Traveling wave tube amplifiers are uniquely rated in terms of saturated power level, which is the ultimate threshold for output power regardless of increased input level. Thus, devices often operate at an RF output 'back off' from saturation. When TWTAs are not operated backed off from saturation, consumed power converted into useful RF energy decreases and power converted into waste heat in the collector increases. When operating in saturation, interference can occur because of intermodulation distortion (IMD) that can generate unwanted frequencies outside of the designed channel. The saturation power level and the amplifier operating point, in terms of output back off, must both be carefully engineered to minimize power consumption and IMD [17]. IMD is not only an issue for TWTAs, but also for solid-state devices (SSPAs) [9, 16]. Figure 1 shows a schematic of two L-3 Communications Electron Technologies, Inc., TWTA devices.

2.1. Traveling wave tube amplifiers failure mechanisms

The majority of power amplifiers tend to live beyond their expected lifetime of 15–20 years. Amplifier failures do occur; however, it is generally assumed that these failures are related to the cathode design. A study of 90 Boeing satellites concluded that TWTA failures were more likely to occur in early years of life [20]. TWT failures that occur are often due to interface problems, poor workmanship, or material defects [7]. Failures have significant impact on the satellite systems, and a single failure can range from gradual power degradation to sudden, unexpected switch off. In the gradual degradation scenario, TWTAs can sometimes operate for long periods (on the order of months to years) before failure, as well as experience other anomalies, such as spurious switch offs (SSOs) due to voltage breakdowns.

2.2. Advantages and disadvantages of traveling wave tube amplifiers

Traveling wave tube amplifiers yield higher data rates and greater bandwidth than their alternatives because these devices are generally capable of providing high power at high frequencies with better efficiency [2, 4, 15]. TWTAs are also able to operate at higher temperatures, which is an advantage given the challenges of communications satellite thermal management [5, 21].

One of the main concerns cited with TWTA performance is guaranteeing operation for 15–20 years on orbit [4, 8], even though they do tend to meet these lifetime requirements on average. Cathodes have finite sources of available electrons, which ultimately limit the life of the TWT. Well-designed TWTs, however, have been known to continuously operate more than 100,000 h and generally reach the 20-year mission lifetime [15, 21]. As previously mentioned, another disadvantage of the TWTA is the need for kilovolt-level power supplies, which are often heavy and expensive. In comparison, SSPAs use between 1 and a power of 2, (1, 2, 4, 8, etc.) power transistors; this results in useful quantized power combinations for these devices, however, these configurations can also lead to significant losses for SSPAs [6].

2.3. Current traveling wave tube amplifiers technology

This section provides information on current TWTA technology. Specifically, the section includes a description of TWTA reconfigurability and linearization as well as information on modern-day TWTA manufacturing and capabilities.

2.3.1. Flex-traveling wave tube amplifiers and reconfigurability. Currently, increasing payload bandwidth and power is addressed through reconfiguration and linearization of the RF power across different beams and channels. Reconfigurability utilizes flexible payloads, such as flexible TWTAs (flex-TWTAs or bias adjustable TWTAs). These types of TWTAs are capable of redistributing available power in the event of traffic imbalances between multiple beams over time. Flex-TWTAs utilize a telecommand to modify an amplifier's anode voltage, or bias conditions, which dictates the range of TWT output powers [22]. Specifically, varying the anode voltage yields a different cathode current, which produces a different TWT gain and output power. Flex-TWTAs enable power conservation, which is beneficial for reducing overall mission size and supporting additional satellite capabilities [5]. Reconfigurable payloads attempt to address uncertainties such as non-uniform traffic, multi-mission satellites that support both interactive and broadcast data services, and evolving user demands. Reconfigurable designs require payloads to efficiently combine coverage, power and bandwidth flexibility, and reduce power consumption and cost [23].

2.3.2. Traveling wave tube amplifier linearization. Traveling wave tube amplifiers are not inherently linear devices, yet significant progress has been made over the past decade toward the linearization of TWTAs. Linearizers are incorporated in an amplifier system to reduce the distortion of the signal. As saturation is approached, TWTA nonlinearity increases and gains compression (the result of an increased input that is not proportional to the increase in output) occurs. TWTA nonlinearity can hinder power efficiency and compliance with out of band unwanted spurious emission requirements [10].

For single carriers, linear performance is defined in terms of spectral regrowth, also referred to as spectral broadening. For multiple carriers, linear performance can be defined in terms of two-tone IMD, a more complex definition of linear performance. Specific TWTA operating levels are characterized by measured peak power and extrapolated intermodulation intercept points to better quantify distortion. Common terms for describing distortion are amplitude modulation-to-phase modulation (AM/PM) conversion and AM-to-AM (AM/AM) conversion. AM/PM conversion describes change in phase angle of the output RF voltage for various input signal levels; an AM/PM conversion of 0°/dB is desired. AM/AM conversion describes the change in output RF voltage for various input signal levels; an AM/AM conversion of 1 dB/dB is desired.

For TWTAs, predistortion linearizers are commonly used. These linearizers correct nonlinearities in the phase and gain of the input/output transfer response [14]. Digital or hardware predistorters can improve linearity with limited bandwidth and enable higher efficiencies [16]. L-3 Communications Electron Technologies, Inc. provides linearized TWTAs, which consist of integrated EPCs, TWTs, and linearizers. Linearizer-channel amplifiers (LCAMPs) have also been implemented in systems to manage the input power. These amplifiers provide either controlled constant gain to the input signal, known as fixed gain mode, or constant output level over the dynamic range of input power [14].

2.3.3. Modern-day traveling wave tube amplifiers manufacturer/supplier capabilities. Determining the current state of TWTA technology is difficult because of program restrictions on the publication of data and increased commercial confidentiality. Since the launch of Syncom II in 1963, TWTA technology has experienced substantial advancements with design changes focusing on increasing RF power output, efficiency, and packaging compactness [2, 4]. Today, the space TWTA suppliers are L-3 Communications Electron Technologies, Inc. (formerly Hughes Aircraft EDD, Boeing EDD), which provides TWTs and EPCs; L-3 Narda West, which provides LCAMPs; Thales Electron Devices, which provides TWTs; and Tesat Spacecom, which provides EPCs and LCAMPs.

L-3 Communications Electron Technologies, Inc. provides a list of publically available data for their EPCs and TWTs [24]. The space-qualified EPCs are available with conduction or radiation

cooling, and for both regulated and unregulated bus voltages. The EPCs are capable of up to 94% efficiency, with mass ranging from less than 1.2 to 1.75 kg, and DC processed power up to 600 W. L-3 Communications Electron Technologies, Inc., also provides space-qualified TWTs in all frequency bands between L-band and Ka-band. These TWTs have efficiencies of up to 72% and power ranges from as low as 20 W (in C-band, X-band, and Ka-band) to as high as 300 W for S-band. TWTA efficiencies are currently in the mid to upper 60%, which is the combined efficiency of the EPC and TWT – up to 94% and 72%, respectively, for L-3 Communications Electron Technologies [24]. In terms of mass and size, the TWT mass ranges from 0.76 to 3.2 kg, and the size ranges from 11.3 × 3.0 × 2.5 inches for K-band to 28.0 × 6.5 × 6.5 inches for L-band.

Similar to L-3 Communications Electron Technologies, Inc., Thales Electron Devices provides TWTs for space for all frequency bands between L-band and Ka-band. S-band TWTs from Thales can produce up to 275 W of power, the highest of all its produced TWTs.

2.4. Future traveling wave tube amplifiers technology

As previously mentioned, TWTA technologies have had significant improvements over the past decades. But there is not as clear of a future game-changing advancement for the TWTA compared with the GaN advancement for the SSPA discussed in Section 3.4. Meanwhile, TWT manufacturers continuously work to refine TWT and power supply integration, increase frequency coverage, improve efficiency and reliability, and reduce size, weight, and cost.

One potential advancement or future change for the TWTA is the increased use of Mini-TWTs. Mini-TWTs are a shorter (approximately 7 inches long), lighter, and lower-power version of the traditional TWT but are not able to reach as high of RF output power. Mini-TWTs are considered advantageous as they can provide a 5:1 reduction in size and weight as well as a 50% improvement in efficiency. Mini-TWTs also serve as the basis of microwave power modules, which are compact units that consist of a solid-state RF power amplifier and a mini-TWT integrated with power and control circuits [22].

3. SOLID-STATE POWER AMPLIFIERS

Solid-state power amplifiers were first used in space in the late 1970s in the form of bipolar junction transistors and GaAs metal-semiconductor field effect transistors (MESFETs) [6]. SSPAs became more prevalent in the 1980s, when the ability of an SSPA to output RF power of 5–10 W became a successful alternative to the TWTA. Historically, SSPAs have been used at lower frequencies such as L-band and S-band with output powers of approximately 10 W, due to lower mass compared with TWTAs of the same capability [5]. While SSPAs are still generally preferred for lower frequency bands and for lower transmitter power applications [6], SSPAs have also been used for higher power levels (e.g. 20–40 W) despite having lower efficiencies than TWTAs at these power levels [8].

Like TWTAs, SSPAs generally are configured to have an electronic power conditioner (EPC), as described in Section 2. Unlike TWTAs, SSPAs use a field effect transistor (FET) as their primary mean of RF power amplification. To achieve high-power amplification, many power transistors, which include cell transistors with resistors, are placed in parallel, and the device outputs are combined. Dissipation of the heat generated from this process is a design challenge, and failure to adequately limit heat from the devices can ultimately destroy the RF system [6].

For space applications, the two primary types of SSPA technology in space applications use FETs: GaAs MESFETs and GaAs high-electron mobility transistor (HEMT) devices. HEMT devices are more commonly used in space today [6].

Metal-semiconductor FETs consist of an $n+$ source region that is grounded and an $n+$ drain region that is positively biased, with an n-channel between the two terminals [25]. The channel is connected to the gate by a Schottky junction, which limits trap formation in the gate insulator and enables higher frequency operation [26]. When a negative gate source voltage is applied, the metal semiconductor junction is reverse biased. A depletion layer in the channel is formed and enables the control of current flow between the drain and source [6]. The performance of the device is dictated by the length, width, and depth of the channel and by depletion layer width [26]. For example, the length of the channel

Figure 2. Airbus Defence and Space (formerly Astrium) L/S Band solid-state power amplifier for mobile communications satellites [28].

defines the time required for electrons to travel through the channel and determines the cutoff and maximum frequency of the device. MESFETs are generally fabricated with GaAs, an III–V semiconductor, and are capable of operating at frequencies approaching W-band [6].

High-electron mobility transistor devices are variations of MESFET devices and consist of a junction between two materials of different band gaps, known as a heterojunction. The two materials are a highly doped wide-bandgap *n*-type donor-supply layer (generally AlGaAs) and an undoped narrow bandgap channel layer (generally GaAs). The heterojunction forms a potential well in the undoped GaAs, where highly mobile electrons are free from colliding with impurities and from which the electrons cannot escape. The heterojunction also leads to the formation of the two-dimensional electron gas in the undoped GaAs layer enabling a 2× higher frequency response, which is why HEMTs are used over MESFETs for microwave applications [27].

The SSPA shown in Figure 2 was flown onboard Alphasat, with a nominal RF output power of 15 W with an efficiency of 31% [28].

3.1. Solid-state power amplifiers failure mechanisms

Solid-state power amplifiers failures can occur both as the result of extended use and unexpectedly [8]. Within an SSPA, the EPC and the RF output stage generate substantial heat; stresses and degradation due to thermal forcing is one of the most likely causes of amplifier anomalies. Operators may classify SSPA anomalies as either 'soft' or 'hard' failures. Soft failures occur in one of the output stages when low-current conditions are observed. These failures are considered manageable, and no redundant SSPA is required. Hard failures occur when a drive stage fails or when anomalies in the EPC occur. These failures are not recoverable, and a redundant SSPA must be turned on to continue providing the required output power [29]. The 'soft' and 'hard' failure terminologies are not commonly used with TWTA failures, which are generally assumed to be hard.

3.2. Advantages and disadvantages of solid-state power amplifiers

There are several advantages that encourage the use of SSPA technology over other amplifier types. The basic SSPA RF module is comparatively smaller in mass, more compact, lower in cost, and has superior intermodulation performance to provide higher linearity [30, 31]. SSPAs are also considered safer for personnel in comparison with the TWT. Additionally, SSPAs require lower voltage (5–10 V DC for GaAs FET types, compared with kilovolts for the TWTA cathode and collector) [32].

The primary disadvantages of SSPAs include high-current draws, lower efficiencies at high frequencies, and lower power generation than TWTAs. Further, the power of FETs in the SSPAs generates large amounts of heat; this is one of the most challenging problems with SSPA design. While the basic RF module is smaller in comparison with those of TWTAs, the required heat sinks typically cause the overall SSPA package to be larger than the TWTA [6].

3.3. Current solid-state power amplifier technology

This section provides information on current SSPA manufacturers and capabilities. Several of the leading manufacturers/suppliers of SSPAs for space-based applications are Airbus Defence and Space (formerly EADS Astrium), Thales Alenia Space, L-3 Communications Narda Satellite Networks, Mitsubishi Electric (Melco), NEC Toshiba Space Systems Ltd., and Tesat Spacecom. Similar to TWTAs, publicly available data sheets and component specifications are often limited, and available information generally does not describe the supplier's highest capabilities [33].

Airbus Defence and Space currently develops SSPAs in L-band, S-band, and C-band. The L-band and S-band devices produce output powers of 15 W with 31% efficiency and have a nominal gain of 67 dB. The mass of these devices is approximately 0.75 kg with an operating temperature range of −20 to +75 °C [28]. The Airbus Defence and Space C-band SSPA has an output power capability of 20 W with an efficiency of 37% and a nominal gain of 70 dB. The mass of this device is 1.285 kg, and it has an operating temperature range of −30 to +75 °C [34]. NEC Toshiba Space Systems also provides L-band, S-band, and C-band SSPAs. The output power and nominal gain of the L-band SSPA is 55 W and 61 dB, whereas the output power and nominal gain of the S-band SSPA is 24 W and 70 dB [35, 36]. The NEC Toshiba Space Systems C-band SSPA is specified to have an output power of 20 W and 86 dB nominal gain [37].

Thales Alenia Space provides efficiency and mass specifications of their C-band, X-band, Ku-band, and Ka-band SSPAs. These four devices have efficiencies of 36%, 25%, 15%, and 10%, respectively. The masses of these four devices range from 1 to 1.5 kg, with the Ka-band SSPA at 1 kg, and the X-band SSPA at 1.5 kg. [37]. Melco provides a C-band SSPA, which is capable of 60 W output power, has 48% efficiency, has a nominal gain of 84 dB, and a mass of 1.9 kg [38].

3.4. Future solid-state power amplifier technology

Because of limitations from SSPA device output power combining techniques, high-power and high-frequency applications historically have required the use of TWTAs [6]. However, recent development of Gallium nitride (GaN) HEMT SSPAs is expected to change the playing field with improved efficiency, linearity, power density, and reliability [5, 15]. SiC is also considered promising for MESFET designs, yet the current material cost has been cited as the limiting factor in the development of SiC devices for space-based applications [32].

In GaN HEMTs, the heterostructure consists of AlGaN and undoped GaN. Like GaAs, GaN is a III–V semiconductor. GaN has a bandgap of 3.2 eV, whereas GaAs has a bandgap of 1.42 eV; the difference in bandgap is indicative of the high power density of the GaN device. The high power density of GaN means smaller devices, and reduces the size, cost, and need for thermal management. [6]. GaN is also capable of withstanding high-temperature environments before performance degradation occurs, whereas GaAs degrades at temperatures greater than 175 °C. However, the EEE-INST-002 quality standard currently prohibits junction temperatures greater than 125 °C and microwave monolithic integrated circuit temperatures greater than 110 °C for space applications [39]. GaN also has higher power added efficiency and higher breakdown voltage (~100 VDC), which in turn should increase device reliability.

The robustness of these devices in space cannot yet be assessed, as they have yet to be flown. However, significant efforts from European Space Agency and the Department of Defense have been put forth for the advancement of GaN SSPAs. Airbus Defence and Space, formerly EADS Astrium, has a 1.05 kg GaN S-band SSPA capable of achieving 85 W nominal RF output power with 40% DC to RF conversion efficiency [40]. Airbus Defence and Space also has a 1.35 kg GaN C-band SSPA capable of a nominal output power of 80 W [41]. Other vendors, such as NEC, Melco TriQuint, Northrop Grumman, RFHIC, and Sumitomo, also have developed GaN devices.

4. PREVIOUS SOLID-STATE POWER AMPLIFIER VERSUS TRAVELING WAVE TUBE AMPLIFIER TECHNOLOGY AND RELIABILITY COMPARISON STUDIES

Since the introduction of the SSPA in the 1970s, there have been debates as to which amplifier technology, TWTA or SSPA, is best suited for communication satellite applications. Comparisons of these two satellite components generally focus on the metrics of amplifier reliability, performance,

cost, and mass [5, 8]. Conducting an accurate comparison of the two technologies can be difficult, as there are numerous frequency bands and power requirements to consider [5].

Prior to 1990, there had been very few published studies comparing SSPAs and TWTAs. Since then, only a few major studies have compared the capabilities of the two technologies. These studies took place in 1991, 1993, and 2005. The 1991 study was funded by the European Space and Technology Center (ESTEC) and focused on satellites launched between 1984 and 1992. In 1993, National Aeronautics and Space Administration (NASA) sponsored a study expanding on the 1991 ESTEC study [8, 11], and in 2005, Boeing supported a study comparing SSPAs and TWTAs onboard satellites launched from the mid-1980s to 2004 [11]. Updates to the Boeing 2005 study were made in 2008 and 2013 [20, 42].

Table I provides a summary of the findings of these three comparison studies (ESTEC, NASA, and Boeing 2005) along with the 2008 and 2013 updates to the 2005 Boeing study. The table includes information on how many satellites and amplifiers were considered, the methods of measuring reliability of the amplifiers, the comparisons of failures in time (FIT) experienced per billion amplifier operating hours, and additional findings from each of the studies.

Weekley and Mangus [11] noted in the Boeing 2005 study that SSPA technology with low enough mass and high enough efficiency was simply not available for high-power and high-frequency demands. Strauss [8] stated that for output powers of 15–50 W, either technology can be implemented, but at higher frequencies (Ku-band and Ka-band); TWTAs are historically more common. The five studies all saw an improvement, or decrease of FITs over time, indicating an overall improvement in either amplifier design or integration and test. In terms of FITs, the 1991, 1993, and 2005 studies found TWTA FITs to be lower than that of SSPAs. The 1991 study was the only study to analyze reliability in terms of redundancy, and in that respect found that SSPAs, which had an average redundancy configuration of 6:5, were more reliable than TWTAs with an average redundancy configuration of 3:2. Based on the 1993 NASA study, Strauss [8] predicted a future redundancy of 7:5 for C-band TWTAs and SSPAs.

These five studies motivate our investigation of the current and future status of SSPA and TWTA technologies for communications satellites. Section 5 contains analysis of 565 communications satellites via payload data from a commercially licensed database and a publicly available database. In this analysis, the frequency, output power, redundancy, and bandwidth of more than 18,000 amplifiers are investigated. Section 6 focuses on failure analysis using satellite telemetry from amplifiers onboard 16 geostationary communication satellites, for a combined total of 579 amplifiers: 470 SSPAs and 109 TWTAs.

5. PREVIOUS SOLID-STATE POWER AMPLIFIER VERSUS TRAVELING WAVE TUBE AMPLIFIER TECHNOLOGY AND RELIABILITY COMPARISON STUDIES

For this study, communications satellite payload data were obtained for 565 communication satellites with launch years from 1982 to 2016. We have used two validated sources of amplifier data from a commercially licensed database, Seradata's Spacetrak (http://www.seradata.com), and a publicly available database, Gunter's Space Page (http://space.skyrocket.de/). The data contained the following information on the satellite and payload: satellite name, launch date, orbit (low earth orbit or geostationary orbit (GEO)), manufacturer, bus type, frequency band (ultra high frequency to Ka-band), amplifier type (SSPA vs. TWTA), redundancy, bandwidth, and output power. Table II provides an initial summary of the collected data.

Of the 565 satellites, the 16 low earth orbit satellites are part of the O3b satellite constellation, some of which have a future launch date. The remaining 549 satellites are in GEO. In total, 18,902 amplifiers were considered: 6428 TWTAs, 2158 SSPAs, and 10,316 amplifiers of unspecified type.

Of the 565 satellites, the amplifier type (TWTA/SSPA) was not specified for 260 payloads. Of the remaining 305 satellites, 226, or 74%, of the total satellites had payloads that consisted of entirely TWTAs, whereas only 19, or 6%, of the satellites had entirely SSPA payloads, and 20% of the 565 satellites had a combination of both amplifier types onboard. Mallon [13] found that of the GEO communications satellites launched from 1992 to 2007, 69% used TWTAs exclusively, 24% used a hybrid of SSPAs and TWTAs, and 6% used SSPAs exclusively. Mallon [13] also found that 1% of the satellites consisted of a phased array, but this payload type is not considered in our study. Unfortunately, we cannot include

Table I. Summary of TWTA versus SSPA technology and reliability comparison studies.

	1991 ESTEC	1993 NASA	2005 Boeing	2008 Boeing	2013 Boeing
Band	C and Ku	C and Ku	L, S, C, Ku, and Ka	L, S, C, Ku, and Ka	UHF, L, S, C, Ku, and Ka
Satellites	75	72	104	~90	101
Operational years	463	497	~1500	~1600	Not specified
TWTAs	1603 – 64% C-band and 36% Ku-band	1860 – 66% C-band and 34% Ku-band	1783 – 3% S-band, 20% C-band, 77% Ku-band, and 1% Ka-band	1997 – 7% S-band, 20% C-band, 71% Ku-band, and 3% Ka-band	2345 – 6% S-band, 18% C-band, 62% Ku-band, and 14% Ka-band
TWTA hours	56.4 million (63.5% C-band)	69 million (51.5 C-band and 17.5 Ku-band)	80.5 million	129 million	211 million
SSPAs	309 C-band	437 C-band	944 – 30% L-band, 14% S-band, 55% C-band, and 1% Ku-band	957 – 33% L-band, 14% S-band, 52% C-band, and 1% Ku-band	1076 – 1% UHF, 38% L-band, 14% S-band, 46% C-band, and 1% Ku-band
SSPA hours	11.4 million	59.9 million	30.5 million	64 million	92 million
Method for measuring reliability	FITs and redundancy	FITs and output power versus FITs	FITs and watts/FITs	FITs and failure age	FITs and failure age
FITS comparisons	TWTAs more reliable: TWTA 680 FITs versus SSPA 790 FITs	TWTAs more reliable: TWTA 660 FITs versus SSPA 880 FITs	TWTA FITs lower than SSPA FITs	Overall FITs improvement for both TWTAs and SSPAs between 1998 and 2005	FITs decrease between 2001 and 2013, SSPA greater improvement; SSPA FITs constant over entire life, TWTA FITs even over first 10 years then vanish
Failure analysis	Mentioned possible failure mechanisms	Mentioned possible failure mechanisms; failure rates at Ku-band increased by 8%	'Graceful degradation' attributed to SSPA not supported; 80% SSPA failures SSO	Most TWTA failures occurred in first 5 years. Most SSPA failures occurred after 5 years of operation	Failure analysis not conducted
Additional findings	SSPAs more reliable in terms of redundancy, SSPA 6:5, TWTA 3:2. RF output powers and gains similar for SSPAs and TWTAs	Highest output power is 65 W at Ku-band for TWTAs and 17 W at C-band for both SSPAs and TWTAs. C-band tends to adopt SSPAs for 20–40 W output power requirements and TWTAs for 50–70 W	SSPAs provided on average 66 W less at C-band than equivalent Ku-band TWTAs. TWTA 0.456 W/FITs versus 0.078 W/FITS (TWTAs 6x improvement in performance)	SSPA and TWTA FITs appear identical after 2004 because of improved quality of SSPA design	TWTAs advantageous for linear power over all frequencies above C-band

ESTEC, European Space and Technology Center; NASA, National Aeronautics and Space Administration; TWTA, traveling wave tube amplifier; SSPA, solid-state power amplifier; FIT, failures in time; SSO, spurious switch off; RF, radio frequency; UHF, ultra high frequency.

Table II. Communications satellite and payload data summary.

Parameter	Value
Total satellites	565
LEO satellites	16
GEO satellites	549
Entirely TWTA payloads	226
Entirely SSPA payloads	19
TWTA/SSPA hybrid payloads	60

LEO, low earth orbit; GEO, geostationary orbit; TWTA, traveling wave tube amplifier; SSPA, solid-state power amplifier.

the 260 satellites with an unspecified payload type in our SSPA versus TWTA analysis. However, from the specified amplifiers on the remaining 305 satellites, we can infer a 5% increase in exclusively TWTA payloads of GEO communications satellites launched between 1982 and 2016, which consisted of 74% exclusively TWTA payloads compared with the study of GEO communications satellites launched between 1992 and 2007, which consisted of 69% exclusively TWTA payloads [13].

Section 5.1 provides analysis of the frequency distribution of the amplifiers and satellites considered in this study. Section 5.2 describes the level of output power achieved for each type of amplifier, and Section 5.3 presents the level of redundancy designed for the payloads. Finally, Section 5.4 details the distribution of amplifier bandwidth for the different payload types.

5.1. Frequency breakdown of amplifiers and satellites

While amplifier payload type was not specified for every satellite, the operating frequency band was provided for every satellite and amplifier. Figure 3 shows the operating frequency breakdown of the 18,902 amplifiers. The highest percentage of TWTAs, 68%, and unknown amplifier types, 55%, falls in Ku-band. For SSPAs, the highest percentage of SSPAs, 60%, operates in C-band. Only five ultra high frequency amplifiers were recorded among the 565 satellites, and these were not designated as SSPA or TWTA.

As previously mentioned, the Boeing 2005 study, which included 944 SSPAs, found that SSPA technology with low enough mass and high efficiency was not available for high-frequency demands [11].
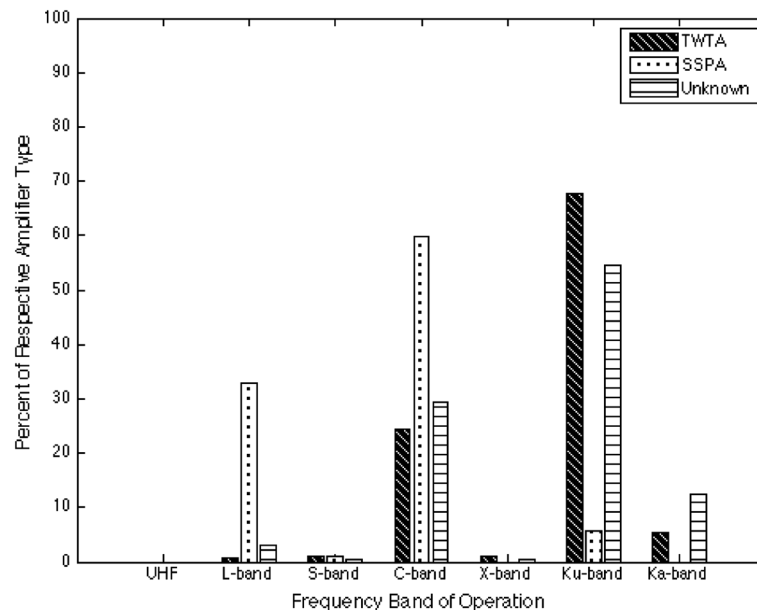

Figure 3. Frequency breakdown of traveling wave tube amplifiers (TWTAs), solid-state power amplifiers (SSPAs), and amplifiers of unknown type. TWTAs appear to dominate higher frequencies and SSPAs in lower frequencies (C-band and below). However, we note that there are still SSPAs being used for some high-frequency (Ku-band) applications.

Figure 3 shows that of the 2158 SSPAs considered here, that SSPAs were in fact used for frequencies as high as Ku-band, and the percentage of SSPAs in Ku-band increased from approximately 1% in Boeing 2005, 2008, and 2013 studies to 6% in this work.

Figure 4 shows the frequency breakdown of the satellites that have (1) exclusively SSPA payloads; and (2) exclusively TWTA payloads. The significant difference in the number of exclusively SSPA payloads compared with the number of exclusively TWTA payloads, 19 versus 226, respectively, also is a reflection of the variety of payload power and frequency band combinations. We note that there were no exclusive SSPA Ka-band payloads. This finding is consistent with the Boeing 2005 study, which claimed SSPAs were not available for high frequencies but would be a metric to reexamine in future studies. On the other hand, there were also no exclusive TWTA L-band payloads.

The percentage of exclusively TWTA payloads that consist of a single L-band transponder make up only 4% of all the exclusively TWTA payloads. The largest percentage of exclusively SSPA payloads operates at C-band, and the largest percentage of exclusively TWTA payloads operates at Ku-band. Note that Figure 3 depicts the operating frequency breakdown of all SSPAs, whereas Figure 4 depicts the frequency breakdown of exclusively SSPA payloads.

5.2. Amplifier output power

The output power of an amplifier is one of the key performance characteristics. Figure 5 shows the maximum output power of each of the three amplifier types for a particular frequency band. There was no available data for SSPAs that operate at X-band or Ka-band.

The variability in the maximum output power capability of the SSPAs and TWTAs does not support the 1991 ESTEC study, which claimed that RF power output levels were similar for both amplifier technologies. As expected, the TWTAs provide higher output power capabilities at higher frequency bands, and SSPAs generate higher output powers at lower frequency bands. This is evident in L-band, where the SSPA with highest output power produced 150 W, compared with the L-band TWTA with a highest output power of 45 W. The 150 W SSPA was onboard Optus B1, launched in 1992; the second highest output power for SSPAs was 38 W and was onboard both the AMSC 1 and MSat 1 satellites. It is important to note that the Optus B1 output power is likely an anomalously high data point. It is also

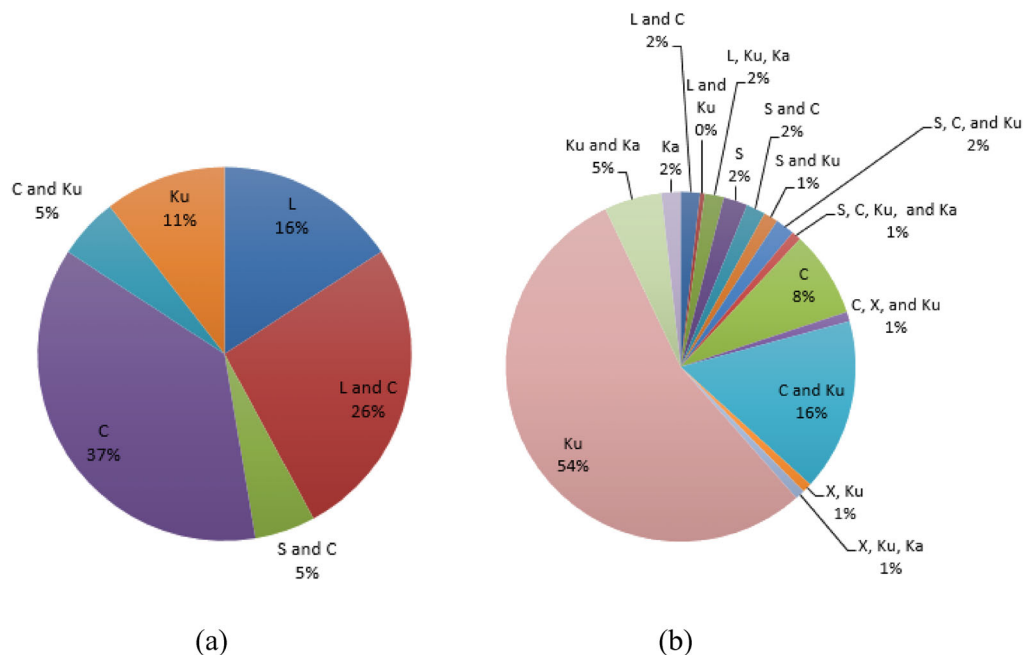(a)   (b)

Figure 4. Frequency distribution of (a) payloads that are exclusively solid-state power amplifiers (19 out of 305 payloads) and (b) payloads that are exclusively traveling wave tube amplifiers (226 out of 305 payloads).
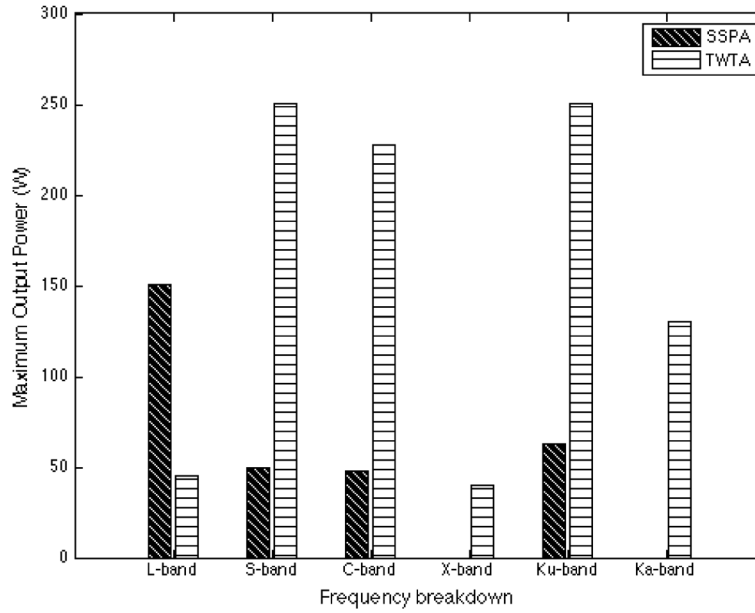
Figure 5. Frequency breakdown of maximum output power (W) for solid-state power amplifier (SSPA) and traveling wave tube amplifier (TWTA) payloads.

evident in the Ku-band, where the SSPA with the highest output power produced 63 W, compared with the maximum output power for the TWTA of 250 W.

The 1993 NASA study found that 66 W was the highest output power for Ku-band TWTAs and that 17 W was the highest output power for both C-band SSPAs and TWTAs. Figure 5 depicts an increase in the maximum output power capability for Ku-band TWTAs to higher than 180 W, more than a 250% increase. We also note an increase in the maximum C-band output power capabilities of both SSPAs and TWTAs. Specifically, there is a 282% increase for C-band SSPAs, which reached a maximum output power of 48 W, and more than a 1000% increase for C-band TWTAs, which reached a maximum output power of 228 W.

Figure 6 shows the output powers for all TWTAs, SSPAs, and amplifiers of unspecified type with available output power data. The general claim that SSPAs are used for lower output powers compared with TWTAs is supported. We find a general increase in the TWTA output power capability with time
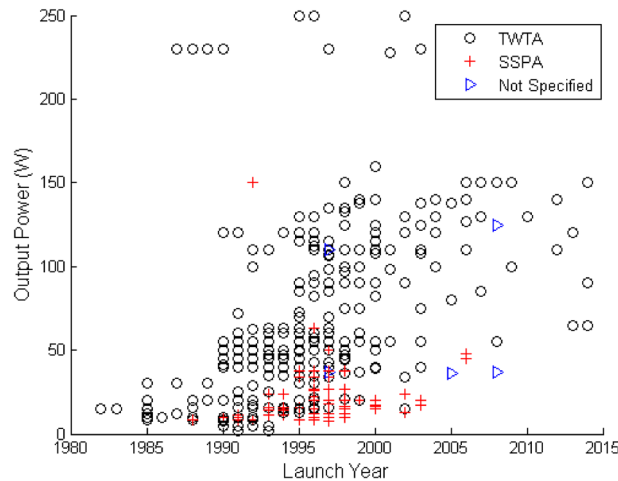

Figure 6. Output power (W) of amplifiers onboard satellites with traveling wave tube amplifiers (TWTAs) (marked with a black o), solid-state power amplifiers (SSPAs) (marked with a red +), and unspecified payloads (marked with a blue triangle).

for moderately high-power TWTAs; the TWTAs with output powers specified above 200 W did not increase. Output power data for SSPAs were not available after 2006.

Strauss noted that both SSPAs and TWTAs could be used for an RF output power of 15–50 W [8]. Figure 9 supports this claim from 1987 to 2006, yet after 2003, the lowest output power cited for a TWTA was 55 W.

The 1993 NASA study suggested that SSPAs were more commonly used in C-band for RF output powers of 20–40 W and that TWTAs were more common for RF output powers between 50–70 W. From Figure 8, the highest output power of a C-band SSPA is observed to be 34 W. In Figure 9, it is clear that the number of TWTAs with an RF output power between 50–70 W is greater than the number of SSPAs with the same range of output powers.

5.3. Amplifier redundancy

As shown in Table I of Section 4 with the 1991 ESTEC study, the level of amplifier redundancy designed in a system can serve as an indicator for the expected reliability of the component. However, redundancy was not analyzed in any of the other studies included in Table I. Figure 7 shows the number of redundant TWTAs, SSPAs, and amplifiers of unspecified type onboard satellites with launch dates from 1982 to 2016. The specific redundancy schemes, such as the one given in the 1991 ESTEC study (SSPA 6:5 and TWTA 3:2), are not identified in our analysis. Redundancy data for SSPAs were not available after year 2000.

The number of SSPA amplifiers shown in Figure 7 is greater than 19, the total number of exclusively SSPA payloads. This is because data from hybrid payloads, consisting of both SSPAs and TWTAs, were also included in this analysis. It is interesting to note that the highest number of redundant amplifiers reached a total of 20 for TWTAs, 12 for SSPAs, and 22 for unspecified amplifier type. The payload equipped with 20 redundant TWTAs consisted of eight TWTAs that operated in C-band and 12 TWTAs that operated in Ku-band. The payload equipped with 12 redundant SSPAs and the payload equipped with 22 redundant amplifiers of unspecified type both operated in C-band.

Figure 8 expands upon Figure 5 to show the ratio of the number of operational amplifiers to the number of redundant amplifiers for the three amplifier types (SSPA, TWTA, and unspecified). Figure 8 does not include two outlier satellites, Thuraya 1 and Thuraya 2 satellites launched in 2000 and 2003, each with 125 C-band TWTAs and two spares, and thus a ratio of operational TWTA to redundant TWTA equal to 62.5.

The ratio of operational to redundant SSPAs never exceeded a ratio of 6, whereas the ratio of operational to redundant TWTAs reached as high as 27 (shown in Figure 8), with two outlier points of 62.5 that are not shown in Figure 8. Two unspecified payloads were designed with an operational to
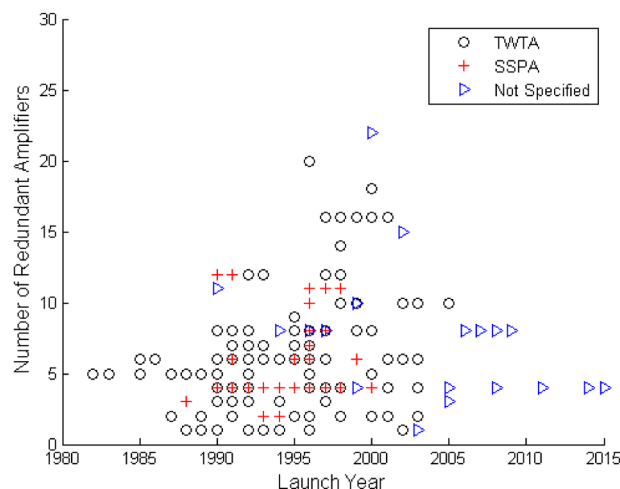

Figure 7. Number of redundant amplifiers onboard satellites with traveling wave tube amplifiers (TWTAs) (marked with a black o), solid-state power amplifiers (SSPAs) (marked with a red +), and unspecified payloads (marked with a blue triangle).
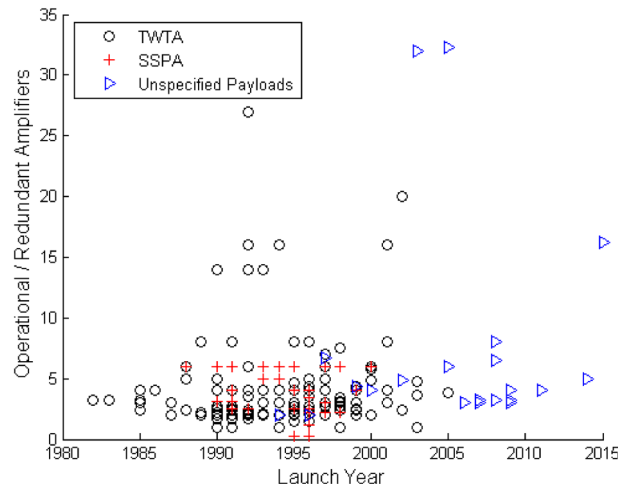
Figure 8. Ratio of operational to redundant amplifiers onboard satellites with traveling wave tube amplifiers (TWTAs) (marked with a black o), solid-state power amplifiers (SSPAs) (marked with a red +), and unspecified payloads (marked with a blue triangle).

redundant amplifier ratio of 32. On average, the ratio of operational to redundant TWTAs is 5.13, and the ratio of operational to redundant SSPAs is 0.47. Unfortunately, the data gathered for this study do not contain information on redundancy for payloads designated as either SSPA or TWTA after 2005. However, for both the worst-case and average scenarios, the ratio or operational to redundant amplifiers is 10 times higher for TWTAs than SSPAs. This suggests that TWTAs are more considered and more reliable, as they are equipped with fewer redundant amplifiers.

5.4. Amplifier bandwidth

The bandwidth of the amplifier is another important performance characteristic for communication satellites because it indicates the range of frequencies over which data are transmitted. Wider bandwidth transponders, currently capable of hundreds of MHz, provide more power and higher data rates, at the expense of increased size and weight.

None of the studies presented in Table I include a comparison of the bandwidth capabilities for the amplifiers. Figure 9 shows the bandwidth, measured in MHz, for the three amplifier types.
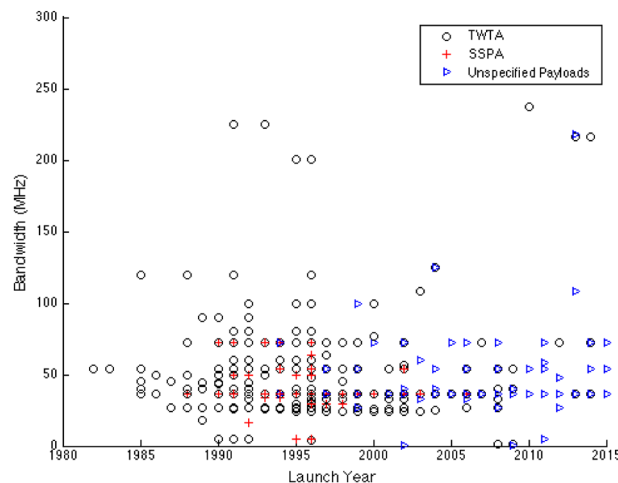

Figure 9. Bandwidth (MHz) of amplifiers onboard satellites with traveling wave tube amplifiers (TWTAs) (marked with a black o), solid-state power amplifiers (SSPAs) (marked with a red +), and unspecified payloads (marked with a blue triangle). The majority of all payloads operate with bandwidths of less than 100 MHz, which is likely due to licensing regulations.

One outlier is not included in this figure; the outlier was onboard the advanced communications test satellite launched in 1993 with four Ka-band TWTAs that operated with a bandwidth of 800 MHz.

Bandwidth data exist for only one out of the 19 exclusively SSPA payloads and for only 15 out of the 226 exclusively TWTA payloads after 2005. Therefore, it is difficult to make conclusions on the trends in bandwidth over time. However, the majority of all three amplifier types operate with bandwidths below 100 MHz, which is likely the result of technology limitations. Seven SSPAs operated at a bandwidth of 72 MHz, which was the highest bandwidth for an SSPA. As previously mentioned, the highest bandwidth for a TWTA was 800 MHz, but this point was not included in Figure 9. The highest bandwidth for a TWTA that is included in Figure 9 is 237 MHz, which was onboard KA-SAT launched in 2010.

The recent launch of satellites like Europe's KA-SAT, equipped with wide bandwidth transponders, and other programs like the US' Viasat1, which intends to provide high-speed Internet services, are evidence of a growing trend toward wider band devices. Previously, bandwidth was limited by the available frequency-dependent transponder technologies. Today, transponders with bandwidths of 500 MHz are desired in order to decrease communication burst sizes to microsecond counts. This in turn reduces the amount of time receiving antennas need to be powered up. Wider band transponders are also beneficial for single carrier operation, because they provide high-data rates without the intermodulation penalties that arise with multi-carrier mode operation. The disadvantage with wider band transponders operating in single carrier mode is that the terminal demodulators have to use sophisticated waveforms to not overwhelm the demodulation/decoding chain.

6. ANALYSIS OF COMMUNICATIONS SATELLITE POWER AMPLIFIER FAILURE RATES

In this study, we also analyze spacecraft telemetry from power amplifiers onboard 16 geostationary communications satellites from the Inmarsat and Telenor satellite fleets. Amplifier reliability is determined through analysis of anomaly logs and analysis of satellite telemetry (specifically amplifier current), prior to the anomaly. Anomaly logs are consulted for the age of the device at the time of the anomaly, and the amplifier current levels prior to amplifier anomalies are used to distinguish between hard and soft failures.

The 16 satellites have a combined total of 659 amplifiers: 124 TWTAs and 535 SSPAs. The 124 TWTAs consisted of 92 Ku-band TWTAs, 24 L-band TWTAs, and eight C-band TWTAs. Of these, three Ku-band TWTAs, eight L-band TWTAs, and four C-band TWTAs were spares. The 535 SSPAs consisted of 525 L-band SSPAs and 10 C-band SSPAs, of which, 33 L-band SSPAs were spares. Of the 124 TWTAs, two TWTA failures occurred, each on separate satellites. The two TWTA anomalies both occurred within the first 2 years of operation. Of the 535 SSPAs, 26 SSPA anomalies occurred, taking place anywhere from within the first 3 months of operation to 15 years after launch [29].

In this group, the SSPAs operate at L-band or C-band, and the TWTAs operate at L-band, C-band, or Ku-band. One of the TWTA failures occurred for a Ku-band amplifier and the other occurred on an L-band amplifier. The Boeing 2005 study found that 100% of their TWTA anomalies were in Ku-band and that the SSPA anomalies were primarily in C-band. Of the 535 SSPAs in our study, 26 SSPA failures occurred, with 100% occurring at L-band. This is expected as more than 98% of the SSPAs in this analysis operated at L-band.

The Boeing 2005 study also found that 83% of the satellites experienced zero TWTA anomalies, and 80% of the satellites recorded zero SSPA anomalies. Of the 20% of satellites that did experience SSPA anomalies, only 9% experienced more than two SSPA anomalies per satellite. Of the 16 satellites in our study, half of the satellites are exclusively TWTA payloads, and the other half of the satellites are exclusively SSPA payloads. Six out of the eight (75%) exclusively TWTA payloads experienced zero TWTA anomalies, and only one of the eight (13%) exclusively SSPA payloads experienced zero SSPA anomalies. Seven of the eight SSPA payload satellites experienced at least one anomaly, and six of the eight (75%) SSPA payload satellites experienced anywhere from two to eight SSPA anomalies.

Section 3.1 gives insight into the different failure types for SSPAs: hard and soft failures. TWTAs failures are typically 'hard failures', and thus, the distinction between hard and soft failures is not common. Hard failures occur when an excessively low-current or high-current measurement breaches a specified current threshold, and the device loses ability to operate. The anomaly thresholds are often amplifier and operator specific. For the 26 SSPA anomalies, 22 of the anomalies or 86% experienced hard failures. Only one of the four SSPAs that experienced a soft failure was recoverable. Therefore, 25 out of 26 of the SSPA anomalies required a redundant amplifier to be switched on [29]. The two TWTA anomalies were hard failures. The Boeing 2005 study stated that a single satellite component failure has essentially zero impact on the communications function. While the ability to turn on redundant amplifiers often alleviates the impact of amplifier failures, issues do arise when a satellite utilizes all available redundant amplifiers. This has not yet been experienced on any of the 16 satellites. However, there were three amplifier anomalies for which a redundant amplifier was already in use, and thus not available, due to a previous amplifier failure.

More detailed satellite payload data are necessary for conclusions to be drawn; however, there is a clear difference between the number of amplifier anomalies described in the 2005 Boeing study of 104 satellites (1783 TWTAs and 944 SSPAs) and the 16 satellites (124 TWTAs and 535 SSPAs) of this analysis. One potential explanation for this difference could be related to the fact that as technological capabilities evolve (e.g. smaller feature sizes), the susceptibility of newer technologies to radiation also increases [43, 44].

7. CONCLUSION

For communications satellites, RF power amplifiers consume 80–90% of the spacecraft bus power as the key component in the communications payload [7, 8]. The two primary amplifier technologies are TWTAs and SSPAs. TWTAs are electron devices that consist of an EPC and a TWT, and are generally more advantageous for higher power and higher frequencies. These devices tend to survive beyond their 15–20 year life expectancy, with failures typically within the first 5 years of operation [2, 4, 13, 15, 20, 21]. SSPAs are generally used at lower operating frequencies [5]. SSPAs contain an EPC and numerous parallel FETs for RF power amplification [6]. SSPA failures tend to occur because of extended use and high heat loads. Overall, SSPAs are considered advantageous in terms of mass and cost but are not as efficient as TWTAs at high frequencies [30, 31]. In the near future, GaN SSPAs are expected to deliver high efficiencies at a reduced size, cost, and with improved thermal performance compared with GaAs SSPAs [6].

Prior to this work, there have been five major studies comparing SSPA and TWTA technologies; these studies were conducted by the ESTEC (1991), NASA (1993), and Boeing (2005, 2008, and 2013). They suggested that SSPAs were not contenders for the high-power and high-frequency applications where TWTAs were typically used [11, 8]. All studies saw an improvement in reliability of both devices, or decrease in FITs over time, and three of the studies reported TWTA FITs to be lower than SSPA FITs. We compared the results of the five previous studies on SSPA and TWTA technologies with similar analyses using updated data gathered from Seradata's Spacetrak and Gunter's Space Page. In addition, we also evaluate payload capability. Specifically, we include analyses of amplifier frequency, output power, number of redundant amplifiers, and bandwidth from 565 communications satellites launched between 1982 and 2016. Of the 565 satellites considered, 260 satellites had unspecified amplifiers, and 305 satellites had payloads that were exclusively TWTA, exclusively SSPA, or a combination of both technologies. Of the 305 satellites with clearly identified payloads, 226 satellites (74%) were exclusively TWTA payloads, 19 satellites (6%) were exclusively SSPA payloads, and 60 satellites (20%) were hybrid payloads. A total of 18,902 amplifiers including 6428 TWTAs, 2158 SSPAs, and 10,316 amplifiers of unspecified type were included in this analysis. Of the 18,902 amplifiers, 68% of the TWTAs and 55% of the unspecified amplifier types operated at Ku-band. Only 4% of the TWTA payloads operated at L-band. The largest percent of SSPAs, 60%, operated in C-band, and none of the SSPAs operated in Ka-band. These findings support the Boeing 2005 study, which suggested that SSPAs were not commonly used for high-frequency and high-power applications where TWTAs were typically utilized.

The maximum output power capability for TWTAs exceeded 200 W in C-band, S-band, and Ku-band, and peaked at 250 W for C-band and Ku-band. For SSPAs, the maximum output power peaked at 150 W for L-band. This finding does not support the 1991 ESTEC conclusion that power output levels were similar for both amplifier types. Since the 1991 ESTEC study, there has been an increase in maximum output power capability of 250% for Ku-band TWTAs, more than 280% for C-band SSPAs, and more than 1000% for C-band TWTAs.

In this work, we considered amplifier redundancy design as an indicator of the expected reliability of a satellite component, an approach that was not taken in the five previous studies. It should be noted that in our study, redundancy data were not available in either Gunter's Space page or Seradata's Spacetrak for payloads specified as SSPA or TWTA launched after 2005. The ratio of operational amplifiers to redundant amplifiers for TWTA payloads reached more than 10 times the ratio of the SSPA payloads (62.5 for TWTAs vs. six for SSPAs). Therefore, higher redundancy for SSPA payloads compared with TWTA payloads could suggest higher expected reliability for TWTAs.

We also considered bandwidth in this study, a parameter that was also not directly addressed in the previous five studies. Because of limited bandwidth data from our sources, (only available for one exclusively SSPA payload and for 15 TWTA payloads), we did not draw conclusions on bandwidth capability over time. However, trends toward wider bandwidth devices are expected with the current drive to provide high-speed data via satellites like KA-SAT and Viasat1.

To understand more about component failure and reliability, we assessed the anomaly logs for age at time of failure from 16 geostationary communications satellites. The 16 satellites consisted of a combined total of 659 amplifiers, of which 124 were TWTAs and 535 were SSPAs. Only two of the 124 TWTAs failed, one Ku-band and one L-band; both failures occurred in the first 2 years of operation. Of the 535 SSPAs, 26 experienced anomalies, which occurred between 3 months and 15 years of operation; 100% of the SSPA anomalies occurred at L-band, which is expected as 98% of the SSPAs included in this analysis operated at L-band. More than 85% of the SSPA anomalies were hard failures, and only one of the four SSPA soft failures was recoverable. Thus, a total of 25/26 SSPA anomalies required a redundant amplifier. The Boeing 2005 study claimed that a single component failure has essentially zero impact on the satellite's communication capability. There were three instances in which the intended redundant SSPA was already in use because of a previous amplifier anomaly. These findings and the fact that network engineering is required to sustain communications service and performance levels indicate that failures may have some impact on the satellite's capability. While safeguards and systems exist to reduce the impact of failures on performance to levels that approach zero, this is not entirely without impact or effort.

Based on the 16 payloads that had bandwidth data, we observed that SSPAs had a higher total percentage of failures onboard satellites and that these payloads required more redundant amplifiers in comparison with TWTA payloads. Overall, however, more data are required to make a clear conclusion based on operational failures as a greater population size than 16 is needed to improve statistics.

Advances in communication amplifier technology are required as user demands for higher data rates and increased bandwidth continue to grow. SSPAs and TWTAs must not only continue to develop with innovative adjustments to previous designs but must also improve beyond their current capability limits in reliability, efficiency, and operating frequency as well as size, weight, and power. Based only on amplifier redundancy data and failure percentages, this study suggests TWTAs are currently a more reliable choice.

While enough data were available to enable our initial analyses, these analyses cannot be considered conclusive because additional data would improve statistics. Future studies must be conducted with larger, more complete, and detailed data sets that cover all of the parameters of interest in order to generate a comprehensive conclusion regarding SSPA versus TWTA selection, as well as updated periodically as technology evolves.

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