

NASA/TM—2008-215220



# High Power and Efficiency Space Traveling-Wave Tube Amplifiers With Reduced Size and Mass for NASA Missions

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Prepared for the  
2008 International Microwave Symposium  
sponsored by the IEEE Microwave Theory and Techniques Society (MTT-S) and the Institute  
of Electrical and Electronics Engineers (IEEE)  
Atlanta, Georgia, June 15–20, 2008

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## Acknowledgments

The authors greatly appreciate the excellent support we received from Neal R. Robbins, Daniel R. Dibb, Dr. W.L. Menninger, Dr. Xiaoling Zhai, Robert Benson, James Burdette, David E. Lewis, and Paul C. Spitsen at L-3 Communications, Electron Technologies, Inc.

This report contains preliminary findings,  
subject to revision as analysis proceeds.

*Level of Review:* This material has been technically reviewed by technical management.

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## Abstract

Recent advances in high power and efficiency space traveling-wave tube amplifiers (TWTAs) for NASA's space-to-Earth communications are presented in this paper. The RF power and efficiency of a new K-Band amplifier are 40 W and 50 percent and that of a new Ka-Band amplifier are 200 W and 60 percent. An important figure-of-merit, which is defined as the ratio of the RF power output to the mass (W/kg) of a TWT has improved by a factor of ten over the previous generation Ka-Band devices.

## Introduction

Signals transmitted from spacecrafts orbiting the outer planets or from the vicinity of the lunar surface need to travel enormous distances to ground antennas. In addition, as the distance from the sun increases, the amount of solar energy that is available for conversion to electrical power on board the spacecraft decreases. Hence, there is a need for developing reliable space amplifiers, which are capable of delivering high RF power as well as operating with very high efficiency (ref. 1). In addition, these amplifiers need to be lightweight and small in size. The two possible solutions to this problem are based on either solid-state or microwave vacuum electronics technology. Solid-state devices based on GaAs or GaN high electron mobility transistor (HEMT) technology, when characterized on-wafer using load-pull techniques, deliver only about 2 to 3 W of RF power at Ka-Band frequencies (ref. 2). Although these devices have efficiencies as high as 35 to 40 percent, the efficiency of the multi-stage monolithic microwave integrated circuit (MMIC) power amplifier (PA), built around these devices, is on the order of 25 to 30 percent due to additional circuit losses. In addition, when the output of several MMIC PAs are combined to realize a high power Ka-Band solid-state power amplifier (SSPA), the overall efficiency further drops to 15 to 20 percent due to combiner losses. Furthermore, the low efficiency results in thermal management issues, which impacts reliability. On the other hand, for space applications, microwave vacuum electronics based devices such as helix traveling wave tubes (TWTs) have demonstrated reliability at higher microwave frequencies with power output in the range of 10 to several hundred watts and corresponding efficiency in the range of 40 to 60 percent (refs. 3 and 4).

Communication from the vicinity of the Moon is considered to be near-Earth while that from the planets of our solar system is considered to be from deep space. The corresponding frequency band designated for near-Earth is 25.5 to 26.5 GHz (K-Band) and for deep space communications is 31.8 to 32.3 GHz (Ka-Band). In this paper, we present the microwave performance of a new K-Band helix TWT for near-Earth communications and also a new Ka-Band helix TWT for deep space communications. Both of these units are manufactured by L-3 Communications, Electron Technologies Inc. (ETI) under contracts from NASA Glenn Research Center (GRC).

## TWT Design and Modeling

In the early eighties, the design of TWTs was mainly done through trial and error, which was time consuming and expensive. The advances made in desktop computing and electromagnetic simulation/optimization tools have enabled the first pass design success of modern TWTs. These include the U.S. Naval Research Laboratory's CHRISTINE 3-D Code for high efficiency slow-wave interaction circuit and MITCHELLE 3-D Code for multi-stage depressed collector design (refs. 5 to (7). In addition, efficient thermal modeling/simulation tools are also available, which have enhanced the power handling capability of TWTs by integrating efficient conduction cooled packages. Furthermore, advances in materials technology have resulted in lightweight, temperature stable, high BH product samarium cobalt permanent magnets, which are used in focusing the electron beam. Moreover, advances in tungsten/osmium cathode technology have resulted in cathode lifetimes exceeding 20 years in space (ref. 8).

## K-Band and Ka-Band Space TWT Requirements

The K-Band TWT was developed for communications from the Lunar Reconnaissance Orbiter (LRO) spacecraft to Earth. The specifications for the model 9835H K-Band TWT are shown in table I.

The Ka-Band TWT was developed for communications from a spacecraft orbiting any of the outer planets, such as Jupiter or its icy moons. The specifications for the model 999HA Ka-Band TWT are shown in table II.

TABLE I.—TWT MODEL 9835H K-BAND TWT SPECIFICATIONS

Parameter	NASA specifications
Frequency band	25.5 to 25.8 GHz
Output power, CW	40 W min
Saturated gain	46 dB min
Saturated gain flatness	0.5 dB min
AM-to-PM	4.5 deg/dB max
VSWR	2.0:1 max
Overall efficiency	44 percent min
Overdrive	+6 dB
Mass	<1750 gm
Size	37 by 9 by 9 cm
Input/output ports	WR-34 waveguide
Operating life/mission life	14/26 months
Environment	Lunar orbit

TABLE II.—TWT MODEL 999HA KA-BAND TWT SPECIFICATIONS

Parameter	NASA specifications
Frequency band	31.8 to 32.3 GHz
Output power, CW	180 W min
Saturated gain	50 dB min
Saturated gain flatness	0.25 dB min
AM-to-PM	4 deg/dB max
VSWR	1.5:1 max
Overall efficiency	55 percent min
Overdrive	+5 dB
Mass	<1750 gm
Size	37 by 9 by 9 cm
Input/output ports	WR-28 waveguide
Operating life/mission life	7/20 yrs
Environment	Deep space

To transmit data from Jupiter at very high rates on the order of Mb/s, the spacecraft transmitter power has to be on the order of 1 kW. To achieve this kind of power level, the outputs from four of the above TWTs would be combined. Combining efficiency as high as 90 percent has been demonstrated at Ka-Band frequencies for a two-way combiner.

Both the K-Band and Ka-Band TWTs have four-stage depressed collector circuits for high efficiency. The collector circuits require high voltages, which are provided by a separate electronic power conditioner (EPC), which is attached by an umbilical power cord to the TWT.

## K-Band and Ka-Band TWT Measured Performance

### Model 9835H K-Band TWT

Three TWTs were manufactured and characterized and all three meet full specifications, resulting in first pass design success and 100 percent yield. The measured output power, overall efficiency, and saturated gain of the three TWTs are summarized in table III.

TABLE III.—LRO PROGRAM GOALS AND PERFORMANCE DATA OF MODEL 9835H K-BAND TWT AT  $f_0 = 25.65$  GHz

Performance parameters	LRO program goals
RF power output, (CW) (W)	40
Overall efficiency, (%) (min)	44
Saturated gain, (dB) (min)	46
Model 9835H TWT S/N 201	
RF power output, (CW) (W)	41.90
Overall efficiency, (%) (min)	50.84
Saturated gain, (dB) (min)	47.85
Model 9835H TWT S/N 202	
RF power output, (CW) (W)	41.79
Overall efficiency, (%) (min)	45.93
Saturated gain, (dB) (min)	47.10
Model 9835H TWT S/N 203	
RF power output, (CW) (W)	41.92
Overall efficiency, (%) (min)	51.15
Saturated gain, (dB) (min)	47.00

### Model 999HA Ka-Band TWT

A photograph of the fully packaged Model 999HA TWT is shown in figure 1. Three such TWTs were manufactured and characterized, and three units were able to demonstrate 180 W. The TWT S/N 202 was tested up to 250 W and set up at 200 W for additional flight qualification testing. The measured overall efficiency and saturated gain of this TWT exceeded 60 percent and 55 dB, respectively. The measured characteristics are presented in figure 2.

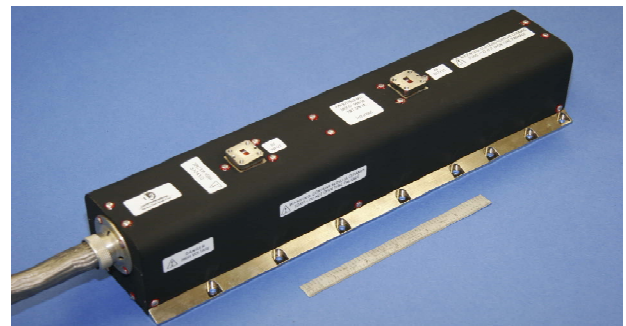


Figure 1.—The Model 999HA Ka-Band space TWT in a conduction cooled package.

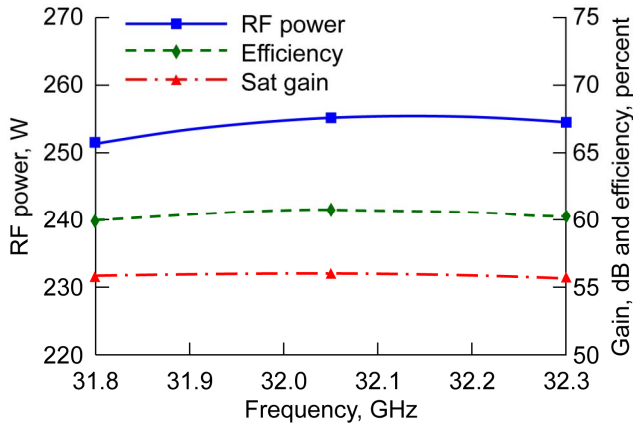


Figure 2.—Measured performance of Model 999HA space TWT over design bandwidth.

## Electronic Power Conditioners (EPC)

The model 2300HE 7-kV electronic power conditioner (EPC) is mated with the 40-W K-Band TWT and the model 1693HC 14-kV EPC is mated with the 180-W Ka-Band TWT to form two new TWT amplifiers. These EPCs are also manufactured by L-3 Communications ETI. These EPCs are highly reliable and efficient (90 percent). They can operate from either regulated or unregulated spacecraft bus voltages. The mass and dimensions of the TWT and the EPC are summarized in table IV.

TABLE IV.—MASS AND DIMENSIONS OF TWT AND EPC

Device type	Mass, (gm)	Dimensions, (cm) L×W×H
9835H K-Band TWT	1500	35.1×8.9×8
2300HE 7-kV EPC	1300	19.8×6.7×10.2
999HA Ka-Band TWT	1600	36.6×8.9×7.1
1693 HC 14-kV EPC	4300	33.8×12.2×13.7

## Conclusions and Discussions

The performance parameters of a K-Band TWT for NASA’s near-Earth and a Ka-Band TWT for deep space communications are presented. These results are state-of-the art and provide unprecedented performance. Prior to this development, the highest CW RF power produced by a space TWT at Ka-Band and flown in space was the Model 910H TWT manufactured by L-3 ETI for the Cassini-Huygens Mission with 10 W,

41 percent overall efficiency, and mass of 750 gm. The figure-of-merit (FOM) is defined as the ratio of the RF power output to the mass (W/kg), which for this TWT is about 13. In contrast, the Ka-Band Model 999HA traveling wave tube presented in this paper has a FOM of 133, which is an improvement by a factor of ten.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 01-06-2008		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE High Power and Efficiency Space Traveling-Wave Tube Amplifiers With Reduced Size and Mass for NASA Missions			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Simons, Rainee, N.; Wilson, Jeffrey, D.; Force, Dale, A.			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER WBS 342556.06.01.10.01.02		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-16507		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORS ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2008-215220		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 17 Available electronically at <a href="http://gltrs.grc.nasa.gov">http://gltrs.grc.nasa.gov</a> This publication is available from the NASA Center for AeroSpace Information, 301-621-0390					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Recent advances in high power and efficiency space traveling-wave tube amplifiers (TWTAs) for NASA's space-to-Earth communications are presented in this paper. The RF power and efficiency of a new K-Band amplifier are 40 W and 50 percent and that of a new Ka-Band amplifier are 200 W and 60 percent. An important figure-of-merit, which is defined as the ratio of the RF power output to the mass (W/kg) of a TWT has improved by a factor of ten over the previous generation Ka-Band devices.					
15. SUBJECT TERMS Telecommunications; Transmitters; Deep space network; Space communication; Satellite communications; Microwave transmission; Microwave amplifiers; Microwave tubes; Power amplifiers; Power conditioning; Power efficiency; Traveling wave tubes					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  UU	18. NUMBER OF PAGES  9	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: <a href="mailto:help@sti.nasa.gov">help@sti.nasa.gov</a> )
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 301-621-0390





