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High Efficiency Traveling-Wave Tube Power Amplifier for Ka-Band Software Defined Radio on International Space Station—A Platform for Communications Technology Development

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Abstract

The design, fabrication and RF performance of the output traveling-wave tube amplifier (TWTA) for a space based Ka-band software defined radio (SDR) is presented. The TWTA, the SDR and the supporting avionics are integrated to forms a testbed, which is currently located on an exterior truss of the International Space Station (ISS). The SDR in the testbed communicates at Ka-band frequencies through a high-gain antenna directed to NASA's Tracking and Data Relay Satellite System (TDRSS), which communicates to the ground station located at White Sands Complex. The application of the testbed is for demonstrating new waveforms and software designed to enhance data delivery from scientific spacecraft and, the waveforms and software can be upgraded and reconfigured from the ground. The construction and the salient features of the Ka-band SDR are discussed. The testbed is currently undergoing on-orbit checkout and commissioning and is expected to operate for 3 to 5 years in space.

Introduction

The International Space Station (ISS) developed by NASA is one of the largest international under taking in history. It has brought together an international coalition of engineers and scientists with a common goal to pursue scientific endeavors in space and to leverage the ISS as a springboard for future exploration and scientific and industrial research. NASA's Space Communications and Navigation (SCaN) program is responsible for providing communications and navigation services to space flight missions throughout the solar system. In this context, NASA SCaN has recently installed a testbed on the exterior truss of the ISS (Ref. 1). The SCaN testbed is an advanced integrated communications system and laboratory facility. Using a new generation of Software Defined Radio (SDR) technologies, this ISS facility will allow researchers to develop, test, and demonstrate new communications, networking, and navigation capabilities in the actual environment of space (Ref. 2). The SCaN testbed will advance space communication technologies in support of future NASA missions.

The paper presents, the design, fabrication and RF performance of the output traveling-wave tube amplifier (TWTA) for a space based Ka-band SDR. The TWTA, SDR, and the supporting avionics are integrated to form the testbed, which is currently located on the exterior truss of the ISS. The SDR is NASA's first space qualified new generation of Ka-band software-reconfigurable transceiver in space. Re-configurability provides the capability to change the functionality of the on-orbit radio during a mission. This allows optimizing the data throughput. In addition, it reduces the development cost and risk through reuse of a common re-configurable space platform to meet specific mission requirements. Furthermore, re-configurability offers the flexibility to adapt to a new science mission after the primary mission is completed. Moreover, it allows recovery from anomalies within the science payload or communications system should they occur. The Ka-band SDR communicates through a high-gain antenna directed to NASA's Tracking and Data Relay Satellite System (TDRSS), which then communicates to NASA's ground station located at White Sands Complex (WSC), New Mexico. Another application of the testbed is for demonstrating new waveforms and software designed to enhance data delivery from scientific spacecraft and, the waveforms and software can be upgraded and reconfigured from the ground. Lastly, the paper presents the construction and the salient features of the Ka-band SDR. The testbed is currently undergoing on-orbit checkout and commissioning and is expected to operate for 3 to 5 years in space.

High Efficiency Space Traveling-Wave Tube Amplifier Design and Fabrication

The helical TWTAs have demonstrated high on-orbit reliability at microwave frequencies (Ref. 3). In addition, TWTAs can deliver much higher RF output power with higher efficiency at Ka-Band frequencies than monolithic microwave integrated circuit (MMIC) based solid-state power amplifiers (SSPAs) (Ref. 4). Furthermore, TWTAs are capable of handling spectrally efficient modulation techniques and very high data rates on the order of multi-Gbps at Ka-band frequencies (Ref. 5).

The baseline design for the SCaN testbed TWTA was the model 999HA Ka-band TWT (Ref. 6). Modern electromagnetic simulation/optimization software tools enabled the first pass design success. These software tools include the U.S. Naval Research Laboratory's CHRISTINE 3-D Code for high efficiency slow-wave interaction circuit and MICHELLE 3-D Code for multi-stage depressed collector design (Refs. 7 to 9). In addition, thermal modeling/simulation tools enabled the design of an efficient conduction cooled package (Ref. 6), which enhanced the power handling capability of TWT. Furthermore, advances in materials technology resulted in lightweight, temperature stable, high B-H energy product samarium cobalt permanent magnets, which enabled focusing the electron beam. Moreover, advances in tungsten/osmium cathode technology resulted in cathode lifetimes exceeding 20 years in space.

The TWT has a four-stage collector circuit for high efficiency. The collector circuit requires high voltages, which are provided by a standalone 7-kV EPC, which is attached by an umbilical power cord to the TWT. The EPC is designed to operate from an unregulated spacecraft bus voltage in the range of 21.25 to 35 V. The EPC has also a telemetry interface to the spacecraft bus, which provides the ON/OFF state of the TWTA as well as the anode voltage, helix current and the RF output power. The construction of the EPC is explained in Reference 6.

SCaN Testbed Traveling-Wave Tube Amplifier Performance Characteristics

The TWTA was characterized over the frequencies 25.5 to 25.8 GHz reserved for NASA’s near-Earth communications. The measured data reported here are at a nominal spacecraft bus voltage of 31 V and ambient temperature of 25 °C.

RF Output Power and Phase Shift

The measured relative RF output power and phase shift as a function of the input drive level is presented in Figure 1. These measurements were carried out at the center frequency of 25.65 GHz. The output power at saturation is 46.22 dB or 41.88 W, which exceeds the requirements of 40 W. The phase shift through the amplifier, as the input drive is increased from small signal to saturation drive, is about 30°. The saturated gain compression is 6.09 dB and the saturated AM-to-PM conversion is 3.5°/dB.

Saturated RF Gain, Saturated Output Power and Overall Efficiency

The measured saturated RF gain is about 49.25 dB across the operating frequency range and exceeds the requirements of 46 dB. The measured saturated RF output power is about 46.25 dB or 42.17 W across the frequency range and exceeds the end of life (EOL) requirements of 40 W. The efficiency of the TWT alone is 55.2 percent. However, when the efficiencies of the TWT and the EPC are combined, the overall efficiency of the TWTA is about 45 percent. The measured overall efficiency as a function of the operating frequency range is presented in Figure 2. The overall efficiency exceeds the requirements of 44 percent.

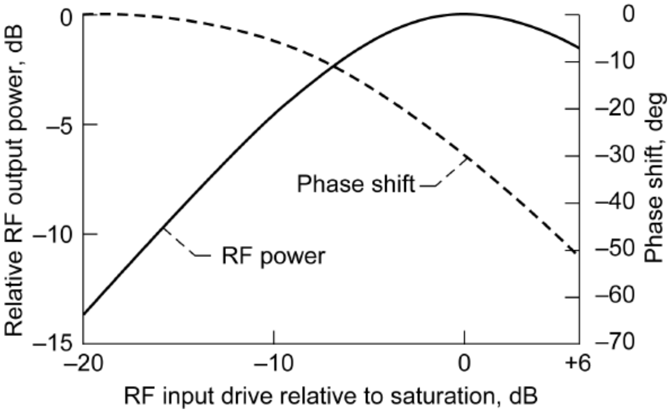

Figure 1.—Measured TWT relative RF output power and phase shift as a function of the RF input drive relative to saturation at the center frequency of 25.65 GHz.

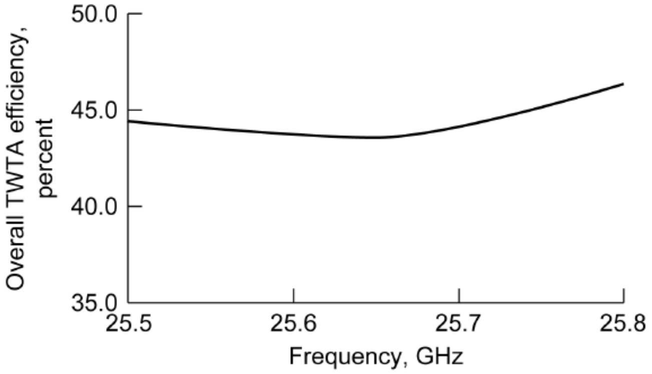

Figure 2.—Measured overall TWTA efficiency as a function of frequency.

Noise Figure, Second Harmonic Level, Small Signal Gain, Phase Shift and Input/Output VSWR

The measurements made at the center frequency of 25.65 GHz show that the noise figure is 29.97 dB and the second harmonic level is 23.52 dB below the fundamental. The measured small signal gain ripple is 0.46 dB peak-to-peak, which is within the requirements. The residual peak-to-peak small signal phase after subtracting the linear phase component corresponding to a group delay of 3.798 ns is 2.02°, which is also within the requirements. The measured input/output VSWR is in the range of 1.4 to 1.7, over the operating frequency range of 25.5 to 25.8 GHz, which is within the requirements.

Ka-Band Re-Configurable Software Defined Radio

Harris Corporation developed the Ka-band software defined radio (SDR). The SDR consists of a single board computer, modem boards, digital IO boards, sampler card, transmit/receive RF circuits, master oscillator and power supply. The SDR is illustrated in Figure 3. The SDR transmit center frequencies is 25.65 GHz and the receive center frequency is 22.6795 GHz. These frequencies are located in the band designated for TDRSS Ka-band operation. The transmit data rate is variable from 300 kbps to 100 Mbps, the modulation is offset-QPSK with rate one-half convolution coding. The receive data rate is variable from 300 kbps to 25 Mbps, the modulation is BPSK with rate one-half convolution coding.

Ka-Band Scan Testbed on ISS

The major microwave components of the testbed are the TWTA, the isolator, the diplexer, the gimbal assembly and the high gain antenna. The layout is shown in Figure 4. The high gain antenna is a 0.5 m diameter parabolic reflector with the feed horn placed at the focus. The antenna is designed to support TDRSS Ka-band communications. The Sierra Nevada Corporation provided the integrated antenna pointing system, which features an open-loop microstepping technology. The testbed avionics unit provides the DC power, handles the command and control signals and the telemetry. The SDR on the SCaN testbed payload, illustrated in Figure 5, communicates with the TDRSS over a full-duplex Ka-band link. This feature contrasts with prior NASA missions, such as the Lunar Reconnaissance Orbiter (LRO), Mars Reconnaissance Orbiter (MRO) and the Solar Dynamic Orbiter (SDO), which used Ka-band for communications; however, the Ka-band radios on these missions were transmit only.

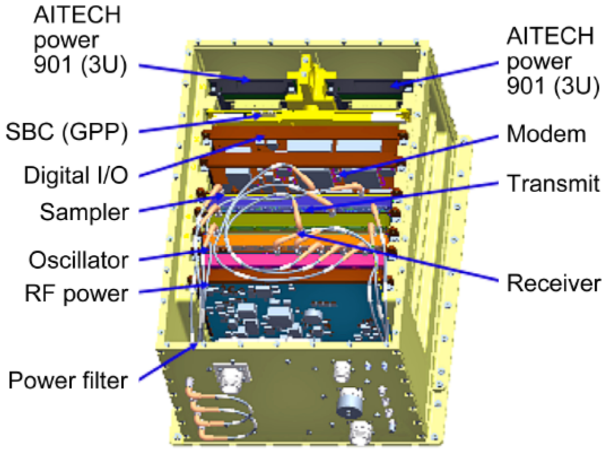

Figure 3.—Ka-band software defined radio hardware.

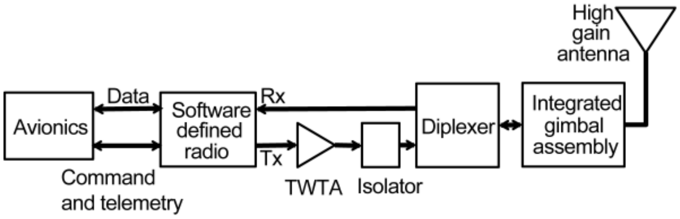

Figure 4.—Ka-band ScaN testbed flight system connections. The data, command and telemetry links are using SpaceWire standard.

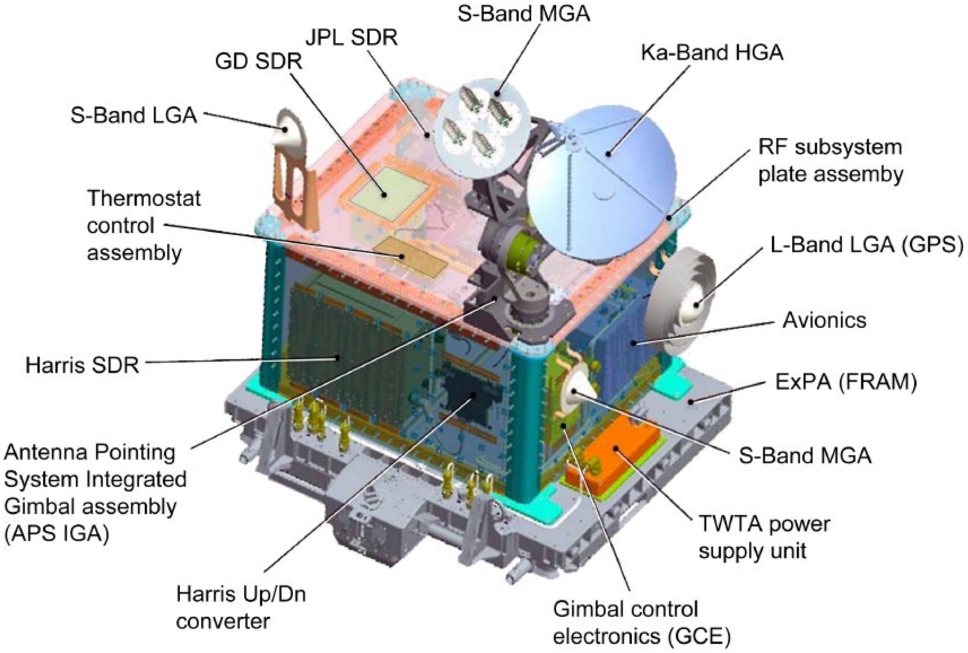

Figure 5.—SCaN testbed payload flight unit concept.

Conclusions and Discussions

The performance parameters of a state-of-the-art compact lightweight Ka-band TWTA for NASA's SCaN testbed is presented. The saturated RF output power exceeds 40 W and saturated RF gain exceeds 46 dB. The overall efficiency including that of the EPC is as high as 45 percent. The Harris SDR is NASA's first space qualified Ka-band SDR. The SDR and the TWTA have been integrated into the SCaN testbed and will support communications with NASA's TDRSS. The re-configurability of the SDR promotes experiments, which supports the next generation mission concepts and future science missions. Prior to launch the testbed successfully completed the system level random vibration, EMI/EMC, thermal vacuum, and TDRSS compatibility tests. The SCaN testbed was launched in July 2012 to the ISS on a Japanese H-II Transfer Vehicle (HTV-3) and is now located on the exterior truss of the ISS. The SCaN testbed is currently undergoing on-orbit checkout and commissioning, which will be followed by a multi-year experiment period starting mid-2013.

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