RESULTS FROM PRELIMINARY NASA/GSFC KA-BAND HIGH DATA RATE DEMONSTRATIONS FOR NEAR-EARTH COMMUNICATIONS

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1. Introduction

In early 2000, the National Aeronautics and Space Administration (NASA) commenced the Ka-Band Transition Project (KaTP) as another step towards satisfying wideband communication requirements of the space research and earth exploration-satellite services. The KaTP team upgraded the ground segment portion of NASA's Space Network (SN) in order to enable high data rate space science and earth science services communications. The SN ground segment is located at the White Sands Complex (WSC) in New Mexico. NASA conducted the SN ground segment upgrades in conjunction with space segment upgrades implemented via the Tracking and Data Relay Satellite (TDRS)-HIJ project. The three new geostationary data relay satellites developed under the TDRS-HIJ project support the use of the inter-satellite service (ISS) allocation in the 25.25-27.5 GHz band (the 26 GHz band) to receive high speed data from low earth-orbiting customer spacecraft. The TDRS H spacecraft (designated TDRS-8) is currently operational at a 171 degrees west longitude. TDRS I and J spacecraft on-orbit testing has been completed. These spacecraft support 650 MHz-wide Ka-band telemetry links that are referred to as return links. The 650 MHz-wide Ka-band telemetry links have the capability to support data rates up to at least 1.2 Gbps. Therefore, the TDRS-HIJ spacecraft will significantly enhance the existing data rate elements of the NASA Space Network that operate at S-band and Ku-band.

Prior to the Ka-band Transition Project, the existing SN ground segment infrastructure at WSC was capable of supporting Ka-band return services at data rates up to 300 Mbps via the 225 MHz-wide return link channels of the TDRS-HIJ spacecraft. The WSC ground segment upgrades implemented under the KaTP enabled a new SN Ka-band Single Access Return (KaSAR)-Wideband Intermediate Frequency (IF) service that uses the new TDRS-HIJ 650 MHz-wide channels. For this new IF service, the customer must provide their own receiver that will be connected at the 1.2 GHz IF output of the service equipment. Therefore, the end-to-end performance of the new Ka-band IF service will be a function of the customer receiver performance. In parallel to the SN Ka-band ground segment upgrades, KaTP implemented a Ka-Band demonstration ground terminal at NASA's Wallops Flight Facility (WFF) in Virginia. NASA developed this Ka-Band ground terminal in order to demonstrate that NASA's Ground Network (GN) can support wideband direct-to-ground communications with low-Earth orbiting science spacecraft in the allocated band of 25.5 to 27.0 GHz.

Detailed descriptions of the KaTP and TDRS-HIJ projects were provided in papers submitted to previous SpaceOps conferences and other international conferences. In those papers, the drivers for Ka-band operation were outlined, the implementation architectures and technical performance parameters were provided, and a summary of proposed high data rate Ka-band demonstrations was given.

The purpose of this paper is to describe the results of preliminary high data rate SN and GN demonstrations that were recently conducted as part of the KaTP. During the SN Demonstration, NASA personnel used the new SN KaSAR-Wideband IF service to simulate a 600 Mbps customer spacecraft Ka-band return data link through the TDRS-8 spacecraft. Within the ground segment terminal at the WSC, bit error rate (BER) and Eb/No measurements were performed to determine link performance. This paper will provide the results of the SN Ka-band return data link demonstration in addition to the results of the back-to-back tests that were performed to characterize the impact of the test modulator and test receiver on the overall return link performance. Similarly, this paper will also provide GN demonstration BER and antenna autotracking results. NASA personnel performed the GN antenna autotracking demonstration test by using a NASA helicopter that had a Ka-band transmitter. The helicopter was used during the antenna autotracking test in order to simulate a customer spacecraft in lieu of an orbiting Ka-band spacecraft.

2. SN Demonstration

2.1 SN Demonstration Objective

The objective of the SN demonstration was to demonstrate that the new SN KaSAR-Wideband IF service can use the new TDRS-HIJ 650 MHz–wide channels at data rates up to 600 Mbps.

2.2 SN Demonstration Description

The test team conducted the SN Demonstration at the NASA WSC by using a new TDRS-HIJ spacecraft and WSC Ka-band upgrades that are detailed in reference [1]. A SN Scheduling Order (SHO), coordinated with the SN Data Service Management Center (DSMC), was used to schedule the KaSAR-Wideband IF service with the TDRS-8 spacecraft. The test team used its own 600 Mbps test receiver which was connected to the 1.2 GHz IF output of the KaSAR-Wideband IF service equipment. Before conducting the end-to-end test with the TDRS-8 spacecraft, the test team conducted back-to-back tests on the bench with the test modulator and test receiver that both used a 1.2 GHz IF.

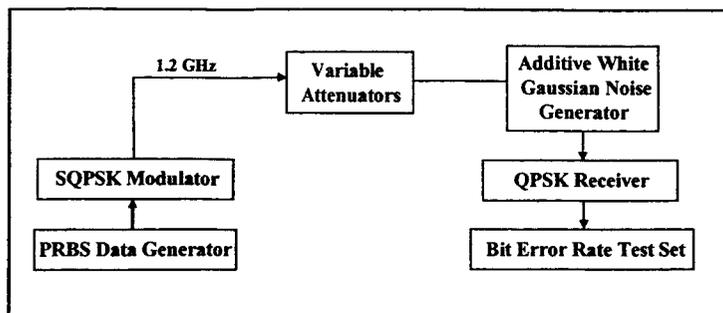Figure 1 and Figure 2 depict the back-to-back and end-to-end test configurations, respectively.

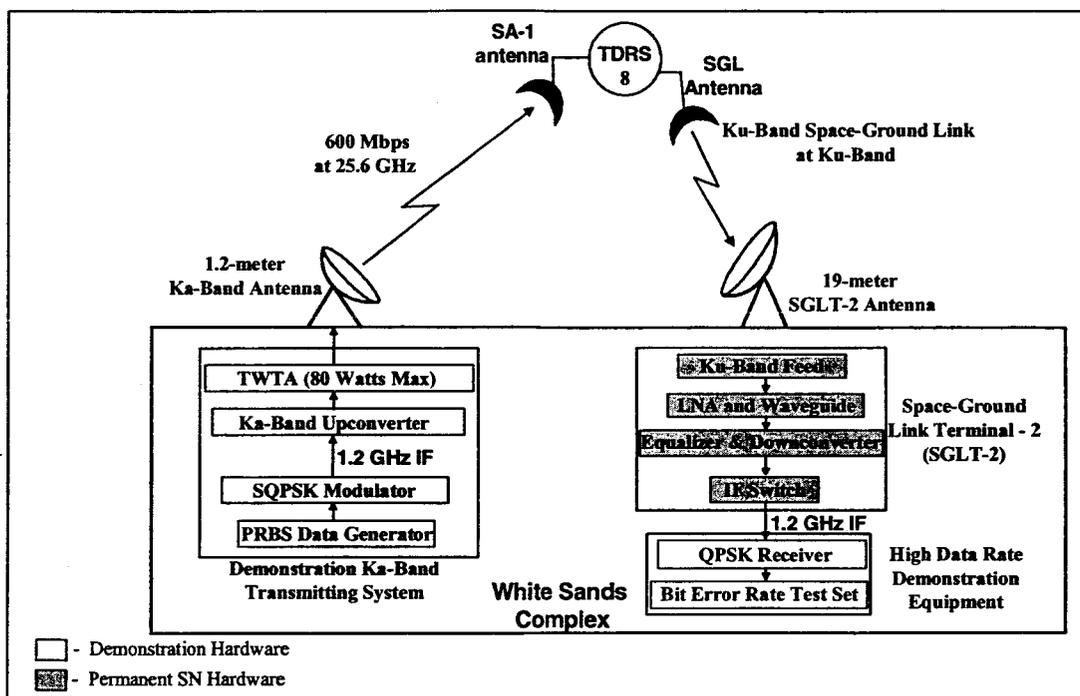**Figure 1. SN and GN Demonstration Back-To-Back Test Configuration**

Figure 2. SN Demonstration End-To-End Test Configuration

As depicted in Figure 2, the test team used the TDRS-8 spacecraft (operational designation of first TDRS-HIJ spacecraft also known as TDRS H), the Demonstration Ka-band Transmitting System located at WSC, and a WSC Space-Ground Link Terminal (SGLT). The Demonstration Ka-band Transmitting System antenna was pointed at the TDRS-8 spacecraft by using the current TDRS-8 state vector information. The TDRS-8 Single Access-1 (SA-1) antenna was pointed at the SGLT antenna by using the WSC state vector. The Demonstration Ka-band Transmitting System consisted of a 1.2 meter antenna mounted on the roof of a WSC building, an 80 Watt Ka-band Traveling Wave Tube Amplifier (TWTA), high rate test SQPSK modulator, and a Ka-band upconverter.

The TDRS-8 spacecraft received the 25.6 GHz signal by using its SA-1 antenna. The TDRS-8 spacecraft downconverted the Ka-band signal to Ku-band and relayed it to WSC via the TDRS Space-Ground Link (SGL) dedicated downlink. The dedicated downlink signal was received at Ku-band by a WSC SGLT 19-meter antenna. The SGLT used its new KaSAR-Wideband IF service downconverter to translate the

received signal from Ku-band to a 1.2 GHz IF. Then the 1.2 GHz IF was sent to the high data rate demonstration receiver via the KaSAR-Wideband IF Switch. The Equalizer (waveguide equalizer) and downconverter that are shown in Figure 2 were added to each WSC SGLT in order to implement the new SN KaSAR-Wideband IF service. A single IF switch was added at WSC to support the IF signals from the four Ka-band capable SGLTs.

To perform a back-to-back test as shown in Figure 1, the 1.2 GHz output of the test modulator was connected to the 1.2 GHz input of the test receiver. Also, the same back-to-back test configuration was used during the GN Demonstration tests that are discussed in Section 3 of this paper.

The test team performed BER measurements at 600 Mbps in order to characterize the new KaSAR-Wideband IF service performance at high data rates. The test modulator was configured for uncoded Staggered Quadrature Phase Shift Keying (SQPSK) modulation with a Psuedo Random Bit Stream (PRBS) 2^{23}-1 data sequence on each channel. The receiver was configured for Quadrature Phase Shift Keying (QPSK) and individual I and Q channel BER measurements were performed. The test team calculated the BER as a function of Eb/No by averaging the I channel and Q channel BERs.

During the end-to-end testing, the test team varied the output power of the Demonstration Ka-Band Transmitting System in order to obtain Eb/No values for BERs from 10^{-5} to 10^{-8}. The Eb/No was calculated from the measured C/No that was measured using a spectrum analyzer that was placed in parallel with the receiver input.

2.3 SN Demonstration Results

Figure 3 depicts the Eb/No versus BER results for the SN Demonstration that was conducted in December 2002. Figure 3 includes the 600 Mbps back-to-back and end-to-end test results. Table 1 lists the implementation loss results for the 10^{-5} and 10^{-7} BERs. As Figure 3 depicts, the 600 Mbps end-to-end implementation loss was 9.3 dB at 10^{-5} for uncoded SQPSK.

The primary reason for the high end-to-end implementation loss was that the test team had only a non-optimum 600 Mbps receiver available for this preliminary SN Demonstration as indicted by the high implementation loss during the back-to-back test (4.0 dB at 10^{-5} BER). Also, the test team had a Ka-Band test upconverter and test Ka-Band High Power Amplifier (HPA) that had non-optimum Frequency Response characteristics over the entire 650 MHz bandwidth. Another contributor to the high implementation loss was that this preliminary demonstration was conducted without an adaptive baseband equalizer (ABBE) and without coding. As stated in the introduction above, a SN customer must provide their own receiver in order to use the new SN KaSAR-Wideband IF service. Therefore, the end-to-end implementation loss performance of the new Ka-band IF service will be a function of the customer receiver performance.

NASA understands that a 9.3 dB end-to-end implementation loss is not acceptable for a practical SN data service. However, simulations have indicated that a 3.1 dB end-to-end implementation loss can be

achieved by using a receiver that has a low back-to-back implementation loss, an ABBE, and rate ½ convolutional coding. Therefore, the test team recommends that customers of the new SN KaSAR-Wideband IF Service use the following receiving equipment at the 1.2 GHz IF output of the service equipment for a 600 Mbps operation:

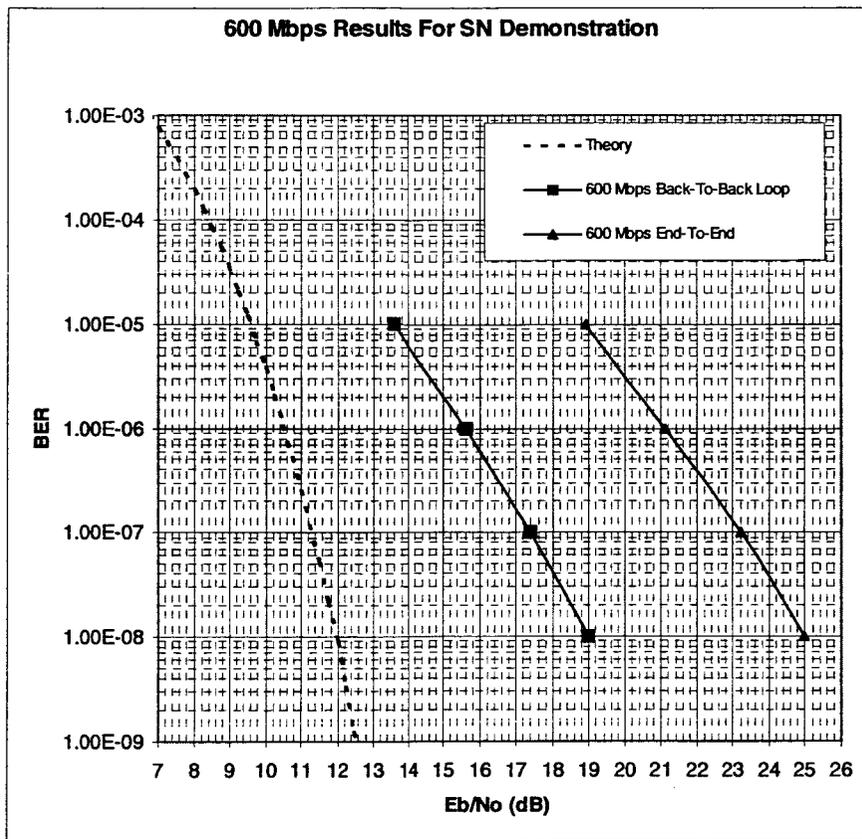a. Receiver with ≤2.0 dB Back-To-Back implementation loss

b. ABBE

c. Coding

Figure 3. SN Demonstration Eb/No Versus BER Results

Table 1. SN Demonstration Implementation Loss Results

Data Rate	BER	Back-To-Back Implementation Loss	End-To-End Implementation Loss
600 Mbps	10^{-5}	4.0 dB	9.3 dB
	10^{-7}	6.1 dB	11.9 dB

3. GN Demonstration

3.1 GN Demonstration Objectives

The objectives of the GN demonstration were the following:

    a. <u>BER Tests</u>: Demonstrate that the new Ka-Band Ground Terminal can support data rates up to 600 Mbps.

    b. <u>Antenna Autotracking Tests</u>: Demonstrate the dynamic autotrack performance of the Ka-Band Ground Terminal by autotracking a moving Ka-band target.

3.2 BER Portion Of GN Demonstration

3.2.1 Description Of GN BER Demonstration

The test team conducted the GN Demonstration at the NASA WFF by using the new Ka-Band Ground Terminal and a bore-site tower located approximately 2 km from the ground terminal. The Ka-band Ground Terminal can be used for direct Ka-band space-to-Earth downlinks, direct S-band space-to-Earth downlinks, and direct S-band Earth-to-space uplinks. Additional Ka-band Ground Terminal details are provided in reference [1].

Because a Ka-band orbiting spacecraft was not available for demonstrations, the test team used a bore-site tower as the Ka-band high data rate source during the end-to-end BER tests of the GN Demonstration. The test team used the same type of receiver that was used during the SN Demonstration except the back-to-back performance of the receiver at 600 Mbps was improved. Before conducting the end-to-end test with the bore-site tower, the test team conducted the back-to-back tests with the receiver that was modified after the SN Demonstration. Figure 1 and Figure 4 depict the back-to-back and end-to-end test configurations, respectively.

During the end-to-end tests, the receiver was connected to the 1.2 GHz IF output of the ground terminal. A broadbeam Ka-band antenna was pointed in the general direction of the ground terminal. A high power amplifier was not required for the testing. The bore-site tower equipment included a high rate test SQPSK modulator and a Ka-band test upconverter.

The bore-site tower transmitted a 25.7 GHz signal. The Ka-band signal was received by the 5.4-meter antenna of the Ka-band ground terminal. The ground terminal used its downconverter to translate the received signal from 25.7 GHz to a 1.2 GHz IF. Then the 1.2 GHz IF was sent to the high data rate demonstration QPSK receiver. The test team performed end-to-end BER measurements at 50 Mbps, 300 Mbps, 450 Mbps, and 600 Mbps. The modulator was configured for uncoded SQPSK modulation with a PRBS 2^{23}-1 data sequence on each channel. The receiver was configured for QPSK and individual I and Q channel BER measurements were performed. During the end-to-end testing, the test team varied the output power of the bore-site tower in order to obtain Eb/No values for BERs from 10^{-5} to 10^{-8}.
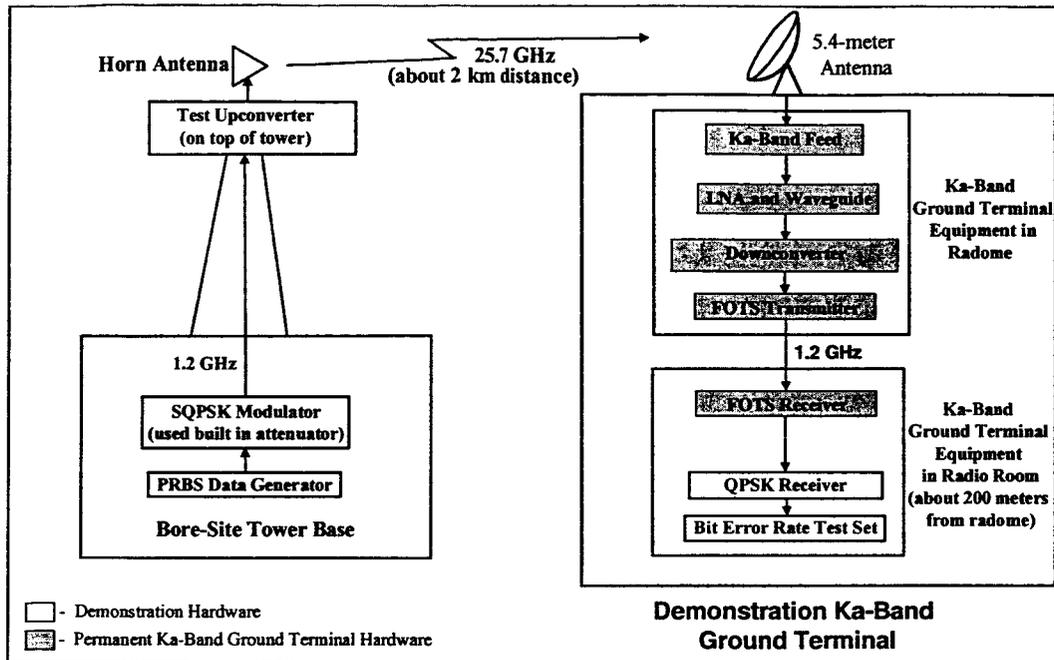
Figure 4. GN Demonstration End-To-End Test Configuration

The test team also conducted a 600 Mbps "medium loop" BER test within only the Ka-Band Ground Terminal. The "medium loop" test configuration included all of the permanent Ka-Band Ground Terminal equipment except for the 5.4 meter antenna.

3.2.2 Test Results For BER Portion Of GN Demonstration

Table 2 lists the implementation loss results for the back-to-back and end-to-end GN Demonstration tests.

The 600 Mbps back-to-back implementation loss results for the GN Demonstration and SN Demonstration were different because the test team used an external bit synchronizer with the receiver during the GN Demonstration. The external bit synchronizer improved the receiver performance at 600 Mbps. At 50 Mbps, the end-to-end implementation loss was not optimum. The majority of the implementation loss during the 50 Mbps end-to-end tests is attributed to the test receiver/modulator because the 50 Mbps back-to-back implementation loss was also not optimum. The external bit synchronizer did not improve the 50 Mbps performance.

NASA understands that the 5.5 dB end-to-end implementation loss value is higher than desired for an operational 600 Mbps GN link. However, approximately 1.4 dB of the loss can be attributed to the available test transmitter system (test upconverter and cabling) at the bore-site tower because the difference between the end-to-end implementation loss, 5.5 dB, and the medium loop implementation loss, 4.1 dB, was 1.4 dB. The test team has recommended the following upgrades in order to improve the 600 Mbps implementation loss performance of the GN Ka-Band Ground Terminal:

a. <u>Add Cable Equalizer and/or Adaptive Baseband Equalizer (ABBE)</u>: Computer simulations have indicated that a 3.4 dB implementation loss can be achieved by adding a cable equalizer that removes the gain versus frequency tilt characteristic and parabolic phase characteristic that exist in the Ka-Band Ground Terminal. Additionally, computer simulations have indicated that a 2.8 dB implementation loss can be achieved by adding an ABBE rather than a cable equalizer to the Ka-Band Ground Terminal.

b. <u>Add Coding</u>: Coding could be used to reduce the effects of signal distortions.

c. <u>Improve Receiver Performance</u>: Upgrade the test receiver by improving its back-to-back implementation loss performance.

Table 2. GN Demonstration Implementation Loss Results

Data Rate	BER	Back-To-Back Implementation Loss	End-To-End Implementation Loss
600 Mbps	10^{-5}	2.0 dB	5.5 dB
	10^{-7}	3.2 dB	8.7 dB
450 Mbps	10^{-5}	1.8 dB	4.7 dB
	10^{-7}	2.2 dB	5.8 dB
300 Mbps	10^{-5}	1.9 dB	3.7 dB
	10^{-7}	2.4 dB	4.3 dB
50 Mbps	10^{-5}	2.7 dB	3.7 dB
	10^{-7}	3.1 dB	5.1 dB

3.3 Antenna Autotracking Portion Of GN Demonstration

3.3.1 Description Of GN Antenna Autotracking Demonstration

During the antenna autotracking portion of the GN Demonstration, the dynamic autotrack performance of the Ka-band Ground Terminal was evaluated by autotracking a Ka-band signal that was transmitted by a NASA UH-1 helicopter. Because a Ka-band orbiting spacecraft was not available for demonstrations, the test team used the helicopter as the moving Ka-band target. The helicopter transmitted Ka-band signals that had different modulations, polarizations, and frequencies. The helicopter was flown in a manner that simulated the LEO range dynamics of a spacecraft as best as possible. Also, the helicopter transmitted an S-band signal that aided the ground terminal while it conducted the antenna acquisition process.

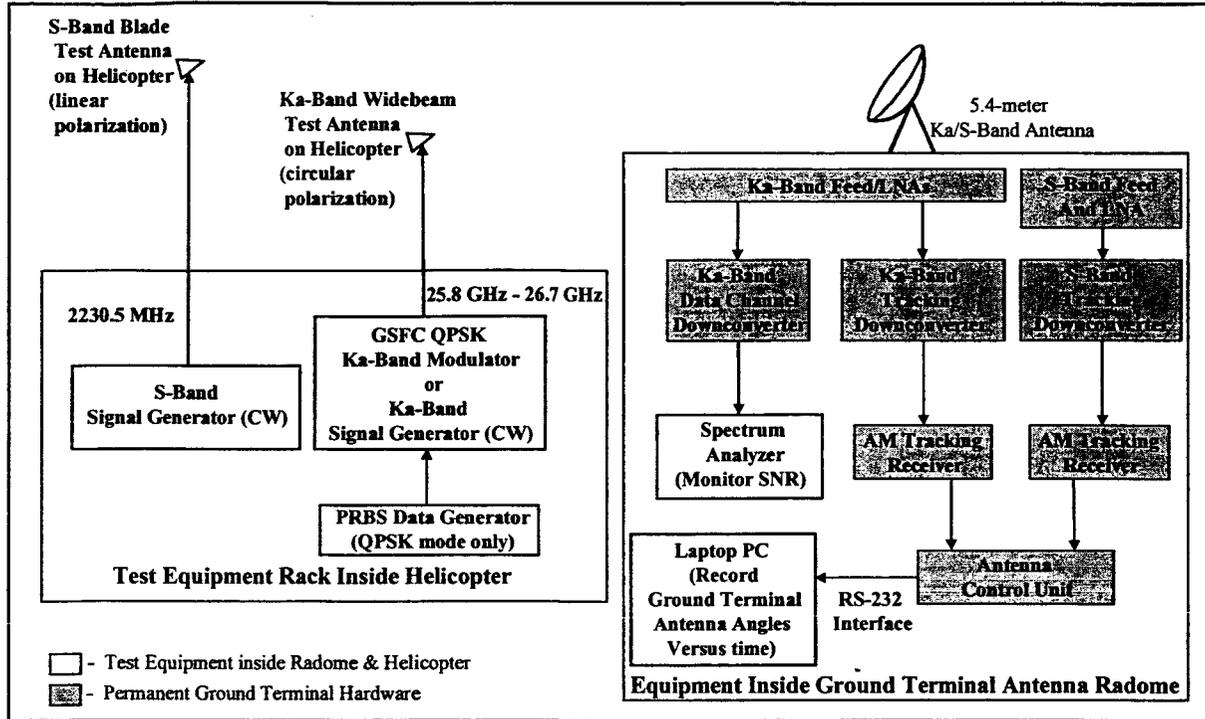Figure 5 depicts the ground terminal and helicopter test configuration.

Figure 5. GN Demonstration Antenna Autotracking Test Configuration

The test equipment on board the helicopter included continuous wave (CW) generators at Ka-band and S-band. For different test events, the KaTP test team switched the Ka-band circular polarized antenna between a Ka-band RF generator and the GSFC in-house Ka-band 150 Mbps QPSK modulator. The modulator output frequency was 26.5 GHz and a PRBS data generator was used as the data source.

The helicopter flew a four mile radius circular pattern. After using the manual handwheel controls of the antenna system to initially acquire the S-band signal, the S-band autotrack was manually selected. Then after several seconds of S-band autotracking, the test team manually selected Ka-band autotrack. The helicopter alternately transmitted QPSK signals and CW signals.

3.3.2 Test Results For Antenna Autotracking Portion Of GN Demonstration

Table 3 lists the four test events and results for the antenna autotracking test. Once a successful Ka-band lock occurred, the ground terminal did not drop the Ka-band autotrack until the test team manually de-selected it. Also, during one portion of the testing, the ground terminal successfully autotracked the helicopter at a 2.2 degrees per second rate when the helicopter made rapid maneuvers while it returned to WFF for a flight test break.

Table 3. GN Demonstration Antenna Autotrack Test Events and Results

Test Event	Frequency	Modulation	Polarization	Signal-To-Noise Ratio	Ground Terminal Antenna Elevation Angle
1	25.8 GHz	CW	RHCP	15 dB	13 degrees average
2	26.5 GHz	QPSK, 150 Mbps	RHCP	10 dB	13 degrees average
3	26.7 GHz	CW	RHCP	16 dB	5.5 degrees average
4	26.7 GHz	CW	LHCP	20 dB	5.5 degrees average

4. SN and GN Demonstration Conclusions

a. The new SN KaSAR-Wideband IF service that includes the TDRS-HIJ 650 MHz-wide channels can support data rates up to 600 Mbps. For this new IF service, the customer must provide their own receiver that will be connected at the 1.2 GHz IF output of the service equipment. Therefore, the end-to-end implementation loss performance of the new IF service will be a function of the customer receiver performance.

b. The GN BER demonstration results provide a baseline for the BER performance of the Ka-Band Ground Terminal and show that the new GN Ka-band Ground Terminal can support data rates up to 600 Mbps. Also, the GN Ka-band Ground Terminal can manually acquire and autotrack a moving Ka-band signal source. Therefore, the Ka-band Ground Terminal can begin activities as a test-bed to demonstrate Ka-band technologies like the NASA Ka-Band Phased Array Antenna that is described in reference [1].

5. Recommendations For SN KaSAR-Wideband IF Service Customers

Simulations have indicated that a 3.1 dB end-to-end implementation loss can be achieved by using a receiver that has a low back-to-back implementation loss, an ABBE, and rate ½ convolutional coding. Therefore, the test team recommends that customers use a receiver with a ≤2.0 dB back-to-back implementation loss, an ABBE, and coding when using the new SN KaSAR-Wideband IF Service for a 600 Mbps operation.

6. Recommendations For Additional GN Activities

The test team has recommended that NASA conduct additional GN BER and GN antenna autotracking demonstrations with a Ka-band orbiting spacecraft when one becomes available for GN testing. Also, if funding becomes available, NASA might implement some of the upgrades listed in paragraph 3.2.2 above in order to improve the 600 Mbps implementation loss performance of the Ka-Band Ground Terminal.

7. Reference

[1] Y. Wong, M. Burns, "NASA/GSFC Ground Segment Upgrades For Ka-Band Support To Near-Earth Spacecraft," SpaceOps 2002, Houston, Texas, USA, October 2002.