ON-ORBIT PERFORMANCE VERIFICATION AND END-TO-END CHARACTERIZATION OF THE TDRS-H KA-BAND COMMUNICATIONS PAYLOAD

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Abstract

In June 2000, NASA launched the first of three next generation Tracking and Data Relay Satellites (TDRS-H) equipped with a Ka-band forward and return service capability. This Ka-band service supports forward data rates up to 25 Mb/sec using the 22.55 – 23.55 GHz space-to-space allocation. Return services are supported via channel bandwidths of 225 and 650 MHz for data rates up to 800 Mb/sec (QPSK) using the 25.25 – 27.5 GHz space-to-space allocation. As part of NASA's acceptance of the TDRS-H spacecraft, an extensive on-orbit calibration, verification and characterization effort was performed to ensure that on-orbit spacecraft performance is within specified limits. This process verified the compliance of the Ka-band communications payload with all performance specifications and demonstrated an end-to-end Ka-band service capability. This paper summarizes the results of the TDRS-H Ka-band communications payload on-orbit performance verification and end-to-end service characterization. Performance parameters addressed include Effective Isotropically Radiated Power (EIRP), antenna Gain-to-System Noise Temperature (G/T), antenna gain pattern, frequency tunability and accuracy, channel magnitude response, and Ka-band service Bit-Error-Rate (BER) performance.

1.0 Introduction

NASA added the Ka-band capability to the newest generation of TDRSs in response to the need for higher data rate communications and increasing congestion in the Ku-band. Since NASA has only a secondary allocation for space-to-space links at Ku-band, operations have been on a non-interfering basis. NASA holds a primary allocation at Ka-band for space-to-space links.

TDRS-H Ka-band services are provided through two 15-foot diameter Single Access (SA) reflector antennas. TDRS-H has two 50 MHz channels capable of supporting two simultaneous Ka-band forward services at data rates up to 25 Mb/sec. A forward service is defined as data transmitted from the TDRSS to the Space Network (SN) User spacecraft. A summary of TDRS-H Ka-band forward service specifications is given in Table 1.

TDRS-H has two 225 MHz return service channels capable of supporting two simultaneous Ka-band return services at data rates up to 300 Mb/sec (QPSK). In lieu of one of the 225 MHz channel, TDRS-H can provide a 650 MHz return service channel capable of supporting a Ka-band return service at data rates up to 800 Mb/sec (utilizing QPSK; higher data rates are achievable with a more bandwidth efficient modulation scheme). A return service is defined as data transmitted from the SN User spacecraft to TDRSS. A summary of TDRS-H Ka-band return service specifications is given in Table 1.

Table 1. Summary of TDRS-H Ka-Band Service Specifications

Parameter	Forward	Return
Field of View (autotrack mode)[(1)]	± 22.5° East-West ±31.0° North-South, Elliptical	± 22.5° East-West ±31.0° North-South, Elliptical
Carrier Frequency	22.55 – 23.55 GHz, tunable in 5.0 MHz steps	25.25 – 27.50 GHz, tunable in 25.0 MHz steps
Polarization	RHC and LHC, selectable	RHC and LHC, selectable
RF Channel Bandwidth	50 MHz	225 MHz and 650 MHz
Data Rate, max	25 Mbps	300 Mbps (225 MHz) [(2)] 800 Mb/sec (650 MHz)[(2, 3)]
Required Received User Power (300 Mbps, uncoded, autotrack mode)	NA	-156.3 dBW
EIRP (autotrack mode), max	63 dBW	NA
G/T (autotrack mode), min	NA	26.5 dB/K

1. TDRS-H has the capability to gimbal each SA antenna up to 77° outboard, in spacecraft body azimuth, providing Extended Elliptical FOV (EEFOV) coverage. EEFOV performance data is not included in this paper.
2. Maximum data rate assumes QPSK; higher data rates are achievable with a more bandwidth efficient modulation scheme.
3. The current TDRSS ground terminal can only support the 225 MHz channel. On-going ground terminal modifications will enable support of the 650 MHz channel up to an IF interface.

All of the on-orbit payload and end-to-end test data presented in this paper was collected using test equipment at the TDRSS ground terminal emulating a Ka-band SN User. Since this Ka-band test equipment was provided by the contractor for testing purposes and is not part of the operational ground terminal, its performance has not been well characterized. This performance uncertainty of the Ka-band test equipment introduces some slight uncertainties in the test results presented here. Other factors introducing uncertainty in the data include atmospheric conditions during tests, test antenna pointing limitations, and system noise temperature variations.

It should also be noted that the majority of the results in this paper were collected with the TDRS-H return service in autotrack mode. Autotrack mode is a closed-loop antenna pointing mode that enables the TDRS-H spacecraft to point the Single Access (SA) antennas with a high degree of accuracy, thereby, producing the maximum levels of EIRP and G/T in the direction of interest. The TDRS-H spacecraft also supports an open-loop SA antenna pointing mode called program track. This on-orbit test program successfully demonstrated very accurate and repeatable antenna pointing of the SA high-gain,narrow beamwidth antennas at Ka-Band frequencies.

2.0 Payload Performance Data

2.1 Forward Service EIRP

The TDRS-H on-orbit Ka-band forward service EIRP was determined by transmitting a Continuous Wave (CW) signal, measuring the power of the resultant signal on the TDRS-H Ka-band space-to-space link at the Ka-band test equipment, and using link budget calculations to estimate the EIRP. This test was performed for both SA antennas configured for Left-Hand Circular Polarization (LHCP) and Right Hand Circular Polarization (RHCP). Table 2 summarizes these on-orbit EIRP measurement values.

Table 2. On-Orbit TDRS-H Ka-Band Forward Service EIRP Measurement Data(1)

Service Configuration		Performance (dBW)	Requirement (dBW)	Margin (dB)
SA Antenna	Polarization			
1	LHCP	70.2	63.0	7.2
	RHCP	66.1		3.1
2	LHCP	71.6		8.6
	RHCP	69.9		6.9

Notes:
1. EIRP values collected using a 23050.0 MHz forward service carrier frequency.

Observations:
- Both SA antennas are fully compliant with the EIRP requirement.
- EIRP compliance strongly indicates antenna pointing performance design goals have been met. Section 2.3 presents the antenna pointing design goals.

2.2 Return Service G/T

The TDRS-H on-orbit SA antenna autotrack G/T at Ka-band was determined by transmitting a CW signal from the Ka-band test equipment to the TDRS-H spacecraft, measuring the ratio of the carrier power to the average measured noise in the specified bandwidth of the TDRSS Ku-band space-to-ground downlink channel, and using link budget calculations to estimate the G/T. This test was performed for both SA antennas configured for LHCP and RHCP. Table 3 summarizes these on-orbit G/T measurement values.

Table 3. On-Orbit TDRS-H SA Antenna Autotrack G/T at Ka-Band

Service Description				Performance (dB/K)	Requirement (dB/K)	Margin (dB)
Channel	SA Antenna	Polarization	Carrier Frequency (MHz)			
225 MHz	1	LHCP	25253.4	26.8	26.5	0.3
		RHCP	25253.4	27.0		0.5
	2	LHCP	25253.4	28.6		2.1
		RHCP	25253.4	26.6		0.1
650 MHz	1	LHCP	26370.0	27.8		1.3
		LHCP	25595.0	28.3		1.8
	2	LHCP	25595.0	30.0		3.5

Observations:
- Both SA antennas are fully compliant with the G/T requirement.
- G/T compliance strongly indicates antenna pointing performance design goals met have been met. Section 2.3 presents the antenna pointing design goals.

2.3 Antenna Gain Pattern

The TDRS-H SA antenna is a 15 ft. diameter reflector antenna with a shaped Cassegrain arrangement to illuminate the main reflector. During launch, the reflector is furled into a taco shape. After launch, the reflector is released to spring back to its original shape. A mechanical tuner has been integrated into the antenna to compensate for systematic distortion due to stowage [1] if excessive distortions are observed during the on-orbit test phase.

The TDRS-H SA antenna uses a tri-band feed (S, Ku and Ka-band) with the Ka-band feed located near the focal point of the reflector system since it is most sensitive to scan loss. The Ka-band feed horn is a square aperture, corrugated horn that employs hybrid waveguide modes to produce a nearly cosine-cosine amplitude distribution in the horn aperture [2]. The Ka-band feed uses a multi-mode coupler to produce the azimuth and elevation error signals. The magnitude and phase of the azimuth and elevation error signals are used in the antenna autotrack algorithm; the sum and error signals are processed at the ground terminal [1] in order to generate corrections to the program track antenna pointing estimates.

Table 4 provides the Ka-band gain design objectives of the TDRS-H SA antenna. While TDRS-H on-orbit testing did not directly measure SA antenna gain, estimates of the Ka-band gain can be determined from the EIRP measurement data. Table 5 provides a summary of the estimated on-orbit Ka-band gain performance of both TDRS-H SA antennas.

Table 4. TDRS-H SA Antenna Ka-Band Design Objectives

Parameter	Forward	Return
Program Track		
Coverage angle	± 0.114 °	± 0.114 °
Gain	47.9 dBi	48 dBi
Program Track, LEO		
Coverage angle	± 0.105 °	± 0.102 °
Gain	51.2 dBi	51.9 dBi
Autotrack		
Coverage angle	± 0.073 °	± 0.045 °
Gain	54.2 dBi	56.4 dBi

Table 5. On-Orbit TDRS-H SA Antenna Ka-Band Gain Estimates

Service Configuration			Performance(1) (dBi)	Design Objective(2) (dBi)	Margin (dBi)
SA Antenna	Polarization	Carrier Frequency (MHz)			
1	LHCP	23050.0	60.6	54.2	6.4
	RHCP	23050.0	56.5		2.3
2	LHCP	23050.0	62.0		7.8
	RHCP	23050.0	60.3		6.1

1. Gain estimates were derived from the EIRP measurement data. Due to the uncertainty associated with this derivation process, the results in this table should only be considered estimates.
2. A design objective, not a specification. Specifications were levied on the TDRS-H spacecraft EIRP and G/T. The TDRS-H spacecraft met all EIRP and G/T requirements.

As part of the on-orbit TDRS-H calibration, azimuth and elevation axis searches for the antenna boresight were performed at Ka-band for each SA antenna. This boresight search yielded coarse azimuth and elevation antenna gain patterns for the two SA antennas. Further refinement of the boresight location was obtained during the autotrack calibration test phase. Figure 1 provides a plot of the SA#2 on-orbit antenna gain azimuth sweep pattern. Figure 2 provides a plot of the SA#2 on-orbit antenna gain elevation sweep pattern. It should be noted that this azimuth and elevation data was collected before the SA antennas had fully relaxed. As the antennas relax, higher gain and more sidelobe definition should result.

For comparison purposes, Figures 3 and 4 show azimuth and elevation slice gain patterns for TDRS-H SA antenna #2 prior to furling for launch.

Figure 1. On-Orbit TDRS-H SA#2 Antenna Azimuth Sweep Measurement Data

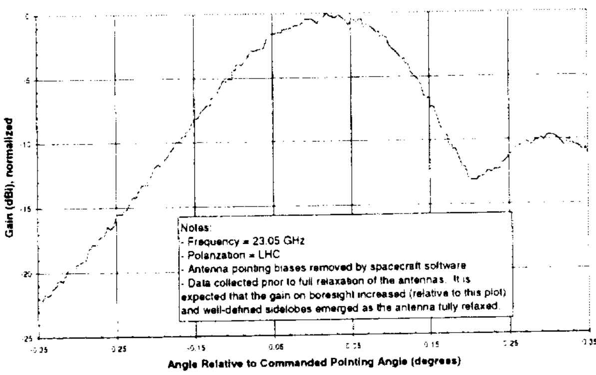


Figure 2. On-Orbit TDRS-H SA#2 Antenna Elevation Sweep Measurement Data

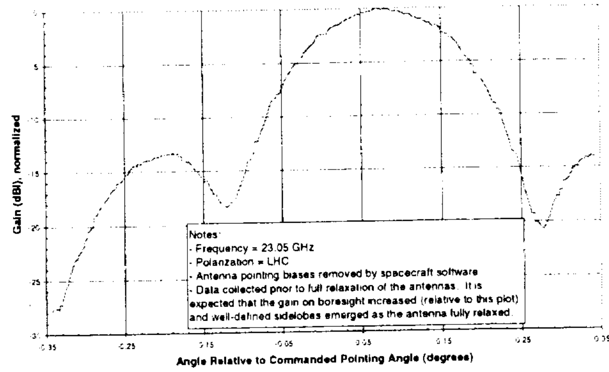


Figure 3. TDRS-H SA Antenna #2 Azimuth Sweep Measured Prior to Launch

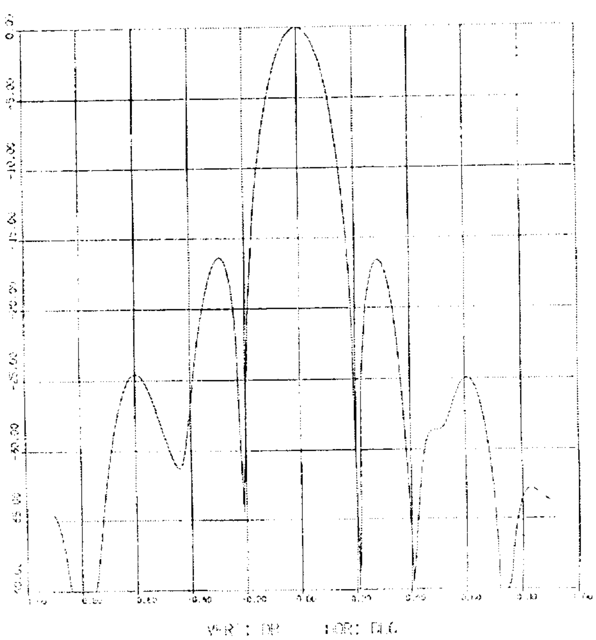
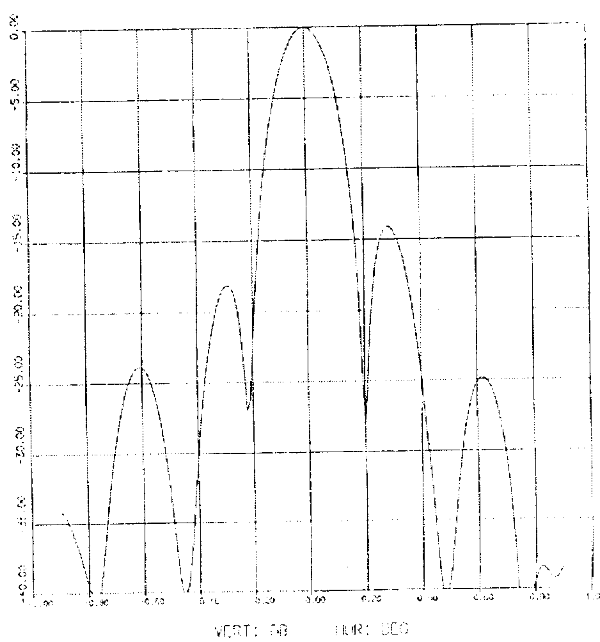


Figure 4. TDRS-H SA Antenna #2 Elevation Sweep Measured Prior to Launch



2.4 Frequency Tunability and Accuracy

To provide service at Ka-band, accurate and stable Local Oscillator (LO) frequencies must be maintained on the spacecraft. For TDRS-H, a combination of frequency converters and LOs are required to translate the Ku-band uplink frequency to the Ka-band space-to-space forward service frequency. Similarly, TDRS-H equipment translates the customer spacecraft space-to-space link Ka-band signal to Ku-band for the downlink to NASA's ground stations at the White Sands Complex (WSC).

To demonstrate the frequency tunability of the TDRS-H spacecraft on-orbit, the spacecraft was configured to provide forward service at 22555.0 MHz, 22565.0 MHz, 23050.0 MHz and 23545.0 MHz and configured to provide return service at 25253.4 MHz, 25595.0 MHz, 26370.0 MHz, 26378.4 MHz, 27195.0 MHz and 27478.4 MHz. The frequency accuracy was measured and a selection of forward and return service worst-case frequency accuracy results are provided in Tables 6 and 7.

Table 6. On-Orbit TDRS-H Ka-Band Forward Service Frequency Accuracy Measurement Data

Service Configuration		Performance(1) (ppm)	Requirement (ppm)	Margin (ppm)
SA Antenna	Polarization			
1	LHCP	0.1	3.9	3.8
	RHCP	2.07		1.83
2	LHP	1.27		2.63
	RHCP	1.99		3.91

Notes:
1. Due to required test approach, measurement data includes frequency accuracy errors due to TDRS-H, the Ka-band test equipment and TDRSS ground terminal equipment.

Observation:
- TDRS-H frequency accuracy is within the required limit.

Table 7. On-Orbit TDRS-H Ka-Band Return Service Frequency Accuracy Measurement Data

Service Configuration			Performance(1) (ppm)	Requirement (ppm)	Margin (ppm)
Channel	SA Antenna	Polarization			
225 MHz	1	LHCP	0.12	3.9	3.78
		RHCP	1.68		2.22
	2	LHCP	0.13		3.77
		RHCP	1.58		2.32
650 MHz	1	LHCP	0.13		3.77
		LHCP	1.77		2.13
	2	LHCP	0.02		3.88

Notes:
1. Due to required test approach, measurement data includes frequency accuracy errors due to TDRS-H, the Ka-band test equipment and TDRSS ground terminal equipment..

Observation:
- TDRS-H frequency accuracy is within the required limit.

2.5 Channel Magnitude Response

TDRS-H forward and return service magnitude response measurement data was collected during on-orbit testing. Figures 5 and 6 provide the magnitude response of the SA #1 225 MHz channel and the SA #2 225 MHz channel, respectively. Figure 7 provides the magnitude response of the 650 MHz channel. The measured end-to-end TDRS-H magnitude response plots include the effects of the Ka-band test equipment and the TDRSS ground terminal equipment.

Figure 5. On-Orbit TDRS-H Magnitude Response for the SA #1 225 MHz Channel

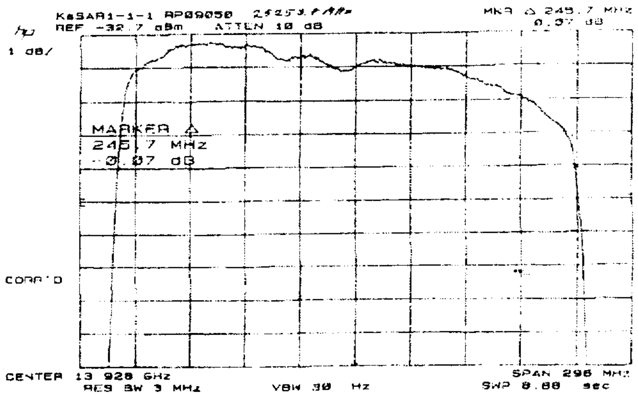


Figure 6. On-Orbit TDRS-H Magnitude Response for the SA #2 225 MHz Channel

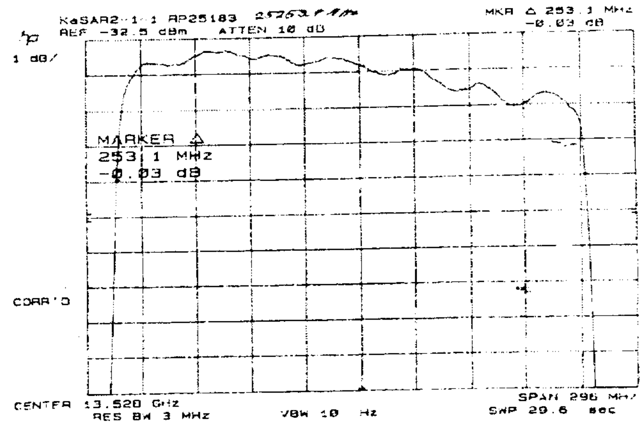
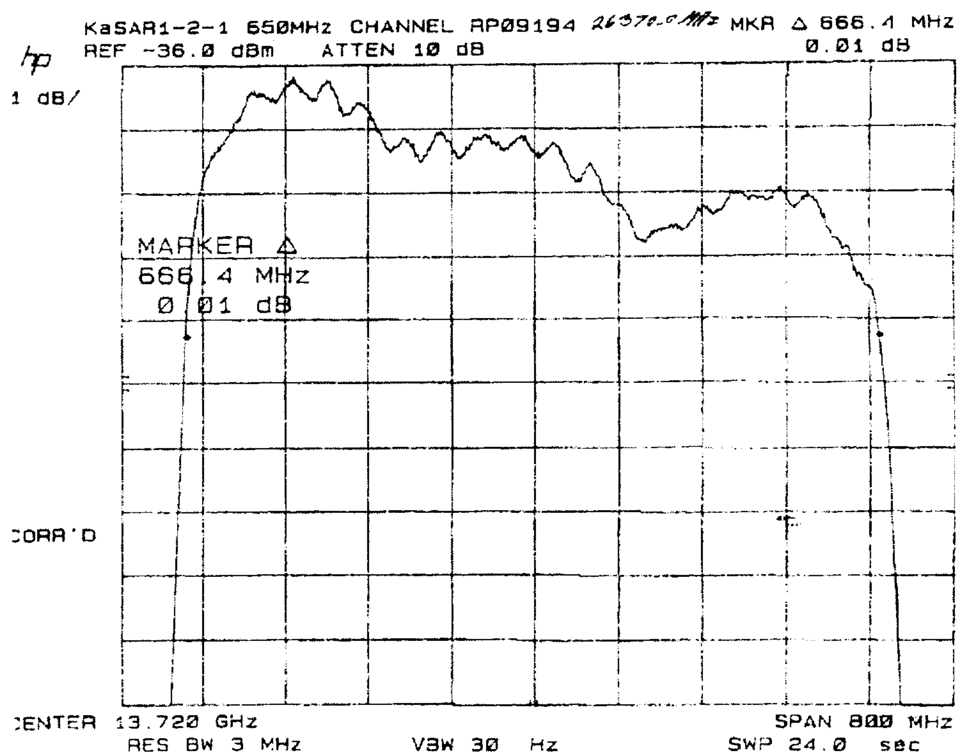


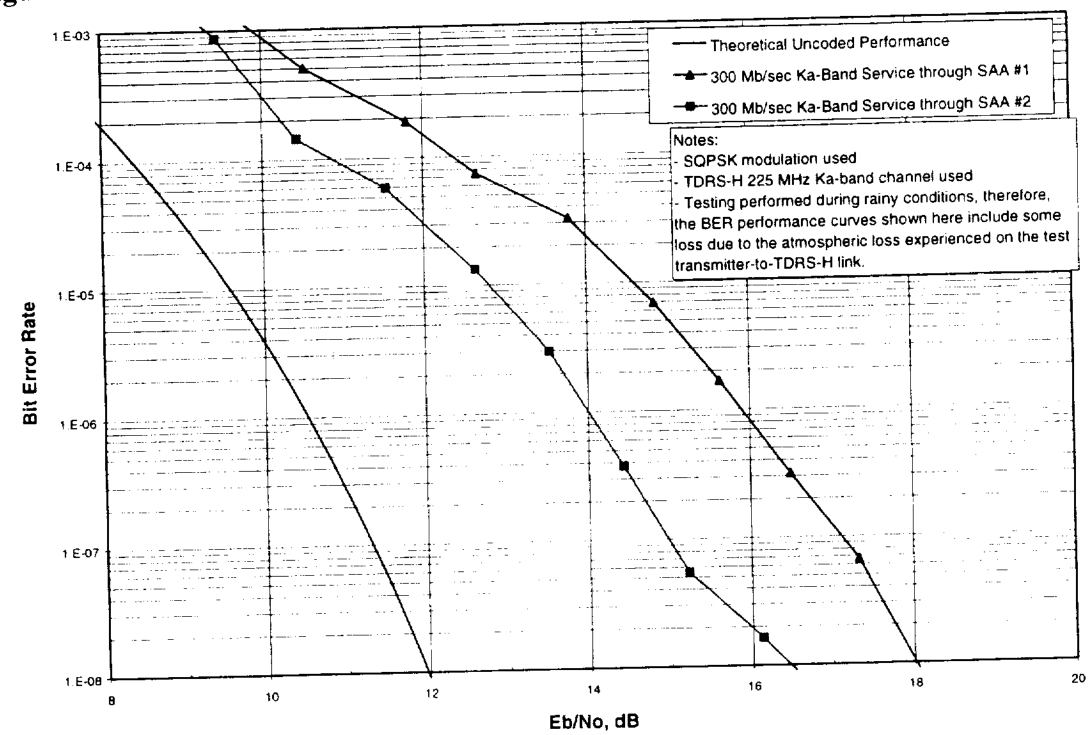
Figure 7. On-Orbit TDRS-H Magnitude Response for the 650 MHz Channel



3.0 End-to-End Service Bit-Error-Rate Data

As a final phase of the TDRS-H on-orbit testing, end-to-end Ka-band service testing was performed using ground-based test equipment to emulate the Ka-band customer. Figure 8 provides the measured BER versus E_b/N_o curve at a data rate of 300 Mbps using the 225 MHz channel. It should be noted that BER test data was collected under rainy conditions, therefore, the BER performance curves shown in Figure 8 include some additional atmospheric losses experienced on the test transmitter-to-TDRS-H link that on-orbit users will not experience.

Figure 8. TDRS-H 300 Mb/sec BER Performance Using the Ka-Band 225 MHz Channel



4.0 Conclusion

This paper summarizes the results of the TDRS-H Ka-band communications payload on-orbit performance verification and end-to-end service characterization. The pointing calibration and performance verification of the 15-foot Single Access high gain antennas operating at Ka-band were successfully accomplished with the Ka-band test terminal. Furthermore, the TDRS-H measured EIRP and G/T at the 150° West longitude orbital test location fully comply with NASA specifications. The measured BER performance is also acceptable taking in consideration the WSC equipment implementation loss, uncertainties associated with the Ka-Band atmospheric loss, and antenna pointing limitations of the test terminal. Through a combination of test and analysis, it has been determined that TDRS-H fully meets and exceeds its specified Ka-band performance and is ready to provide service to Ka-band customers.

5.0 References

[1] *NASA Ka-Band Service and Technology*, B. Younes, et al, Proceedings of the Fifth Ka-Band Utilization Conference, pp. 277, 18-20 October 1999.

[2] *Antenna Performance Analysis/Verification Report*, PS-DA-02, Hughes Space & Communications, 17 December 1999.