TDRSS K-Band Ultra High Data Rate Demonstration

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I. Introduction

THE National Aeronautics and Space Administration (NASA's) Space Network (SN) consists of a constellation of nine Tracking and Data Relay Satellites (TDRS) with supporting ground terminals at White Sands, New Mexico and Guam, Mariana Islands. The ground terminals were designed and implemented in the early 1990s, and some of the systems are reaching obsolescence. Additionally, NASA exploration systems and earth and space science missions are expected to evolve to higher data rates at Ka-Band and will desire to improve performance and minimize spacecraft burden by taking advantage of modern bandwidth efficient coding techniques. Existing Ku-Band customers of the SN are also expected to benefit from the availability of coded data rates up to 600Mbps.

In early 2006, the TDRSS K-Band Single Access Return (KSAR) Upgrade (TKUP) Augmentation (TKUP-A) Project was established to address Space Network high rate equipment obsolescence and potential enhancements to the SN TDRSS KSAR services for improved SN support to next generation missions. The TKUP-A Project, now as part of the SN Modernization User Services Subsystem Replacement Project (USSR), will be completed in two phases, a demonstration phase to mitigate technical risk, validate expected performance improvements and prove technology readiness; and a production phase to replace the obsolete KSAR and high rate switch equipment and increase the KSAR equipment performance to a level validated by demonstrations.

During the demonstration phase, prototype receiver systems were developed to enhance the TDRSS KSA (both Ku and Ka) return data service by adding the capability to process bandwidth efficient signal designs, including OQPSK and 8PSK modulation types and Rate 7/8 Turbo Product Code (TPC) and Low Density Parity Check (LDPC) forward error correction codes. The Rate 1/2 AR4JA LDPC code expected to be used by the NASA Constellation Program (CxP) was also demonstrated.

In early 2008, the TKUP-A project demonstrated data rate capabilities far in excess of the current 150Mbps, coded and 300Mbps uncoded maximum of the TDRSS KSAR service. The Project's goal was to demonstrate coded data rates at Ku-Band and Ka-Band in excess of 600Mbps using the TDRS 225MHz channel and 1.2 Gbps at Ka-Band using the TDRS 650MHz channel. TKUP-A has successfully demonstrated a 1 Gbps data rate using OQPSK Rate 7/8 LDPC code through the 2nd generation TDRS satellites Ka-Band 650 MHz channel. Other modulation and coding schemes including 8PSK and Rate 7/8 TPC along with the Rate 7/8 LDPC code have also been demonstrated with maximum achieved data rates up to 1.2 Gbps.

This paper describes the demonstration objectives, requirements, test configurations and approach as well as a summary of the TDRSS K-Band modulation & coding study. Results of the demonstrations conducted in January/February 2008 are presented as well as the status of the current technical risk assessment and the mitigation of risk achieved by the demonstration. In light of the results of the TKUP-A demonstrations, the potential enhancements to future SN Ku-Band and Ka-Band high rate data services are discussed. Finally, the plans for

addressing the technical issues uncovered during the demonstration regarding the performance of 8PSK and TPC are presented.

II. Summary of Modulation and Coding Study

AT the outset of the TKUP project and the Ka-Band Data Service (KaDS) project (a precursor to the TKUP project), a modulation and coding study was performed to:

1. assess the performance of a wide variety of candidate modulation and coding techniques via the TDRSS Ku/KaSAR 225 MHz and KaSAR 650 MHz channels
2. identify the maximum achievable data rate via the TDRSS Ku/KaSAR 225 MHz and KaSAR 650 MHz channels
3. identify and recommend the most appropriate signal structures for future NASA SN Ku/Ka-band communications links and
4. derive service performance specifications, including BER performance, for the recommended signal structures.

The KaDS and TKUP modulation and coding studies were completed in Fall 2003 and Spring 2004, respectively, and the results are documented in References [1] and [2]. Both studies recommended that the legacy SN signal structures continue to be supported (e.g., uncoded OQPSK, rate 1/2 convolutionally coded OQPSK, etc) and recommended that 8PSK and rate 7/8 Turbo Product Code (TPC) and rate 7/8 Low Density Parity Check Code (LDPCC) techniques be investigated as possible new SN modulation and coding options..

The KaDS and TKUP modulation and coding studies were performed by first formulating the modulation and coding trade space and then applying an increasingly more rigorous downselection to the trade-space. As the initial trade space was very large, a first pass downselection was performed by identifying and eliminating all signal structures which failed to have sufficient technology readiness or hardware availability at the data rates required by the TKUP-A project. The evaluation space was further reduced by identifying and eliminating all signal structures which would obviously perform poorly in the customer plus TDRSS distortion environment. With the remaining signal structures, detailed analysis and simulation were performed to 1.) characterize the BER performance in the TDRSS plus customer distortion environment and 2.) to identify the maximum achievable data rate in the TDRSS channel. Based upon this analysis and simulation and a collection of other performance metrics (e.g., spectrum efficiency, hardware availability, customer burden, infrastructure burden, proprietary restrictions), the signal structures most appropriate for future NASA SN Ku/KaSAR links were identified.

The analysis and simulation techniques used to evaluate the candidate signal structures considered all customer and TDRSS hardware distortions. It should be noted that the study considered maximum allowed customer distortion levels, worst-case TDRS measurement data across the fleet, and expected ground terminal distortion performance. Worst-case TDRS measurement data across the fleet indicates a worst-case 3 dB channel bandwidth of 240 MHz for the “225 MHz channel” and 670 MHz for the “650 MHz channel.” Figure 1 provides an overview of the hardware distortions considered.

Considered in the evaluation of the maximum achievable data rate via the TDRSS channel was customer transmitter PA and antenna size. TDRSS link budget analysis based upon the BER performance results found via simulation was used to determine the customer EIRP required to close the link with acceptable mission link margin. From the resultant EIRP values, the customer transmitter PA size was computed for various customer antenna sizes at the upper data rates identified via simulation.

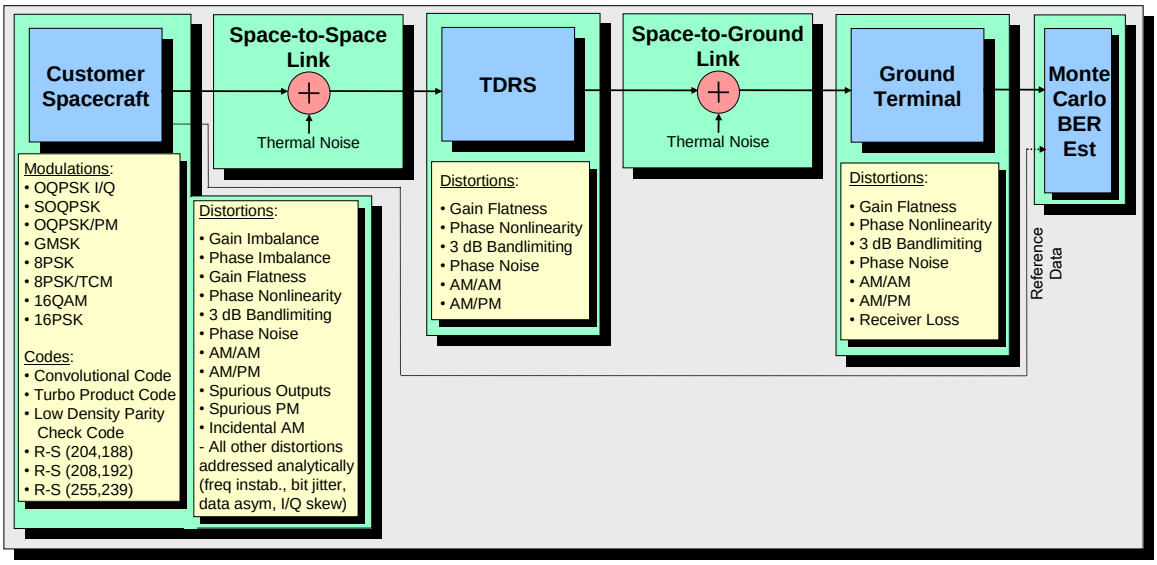


Figure 1. Overview of Simulation Model With Hardware Distortions

Figure 2 provides a selection of BER performance results as found via analysis and simulation for various signal structures at various data rates. Figure 3 provides example required customer transmitter PA sizes for various signal structures at various service data rates assuming a 1.2 m customer antenna size (deemed the largest realistic antenna size that a customer could support).

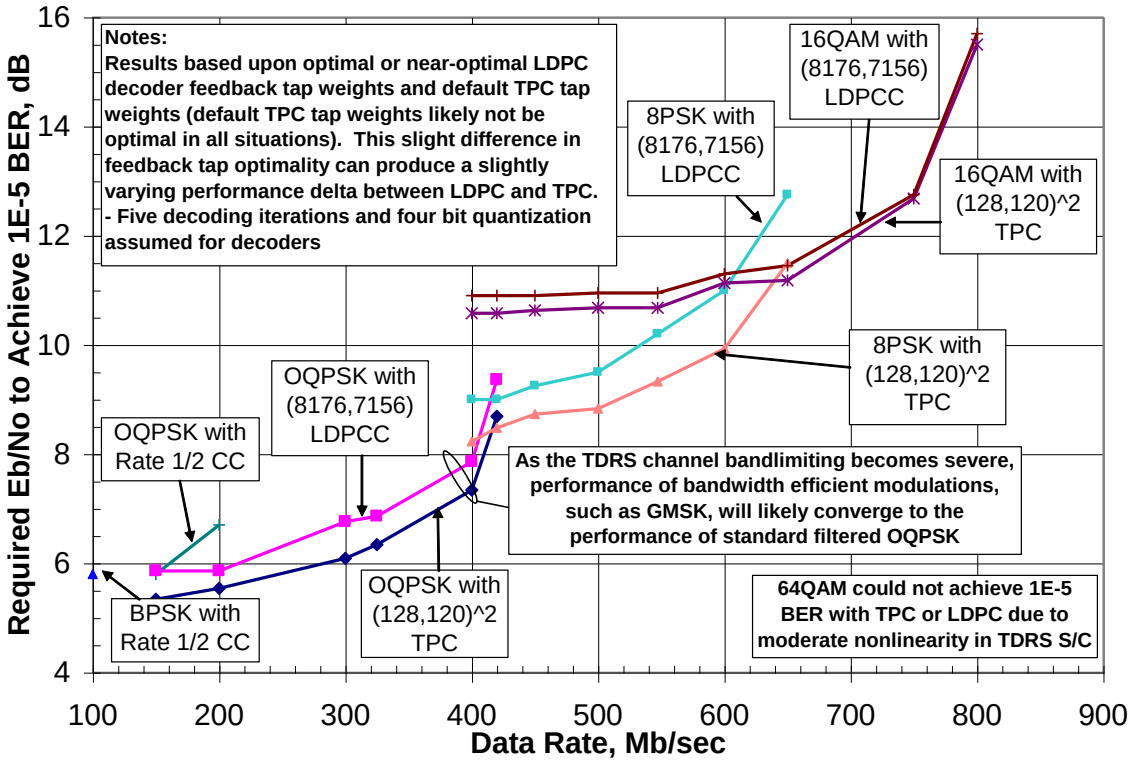


Figure 2. Example Ku/KaSAR "225 MHz Channel" BER Performance Results As Found Via Simulation

It can be seen from Figure 2 that data rates as great as those described in Table 1 below are possible via the TDRSS Ku/KaSAR 225 MHz (actual 3 dB bandwidth is 240 MHz) and KaSAR 650 MHz (actual 3 dB bandwidth is 670 MHz) channels using the recommended modulation and coding techniques and assuming reasonable customer EIRP burden – possible at least in simulation and assuming sufficient customer EIRP capability.

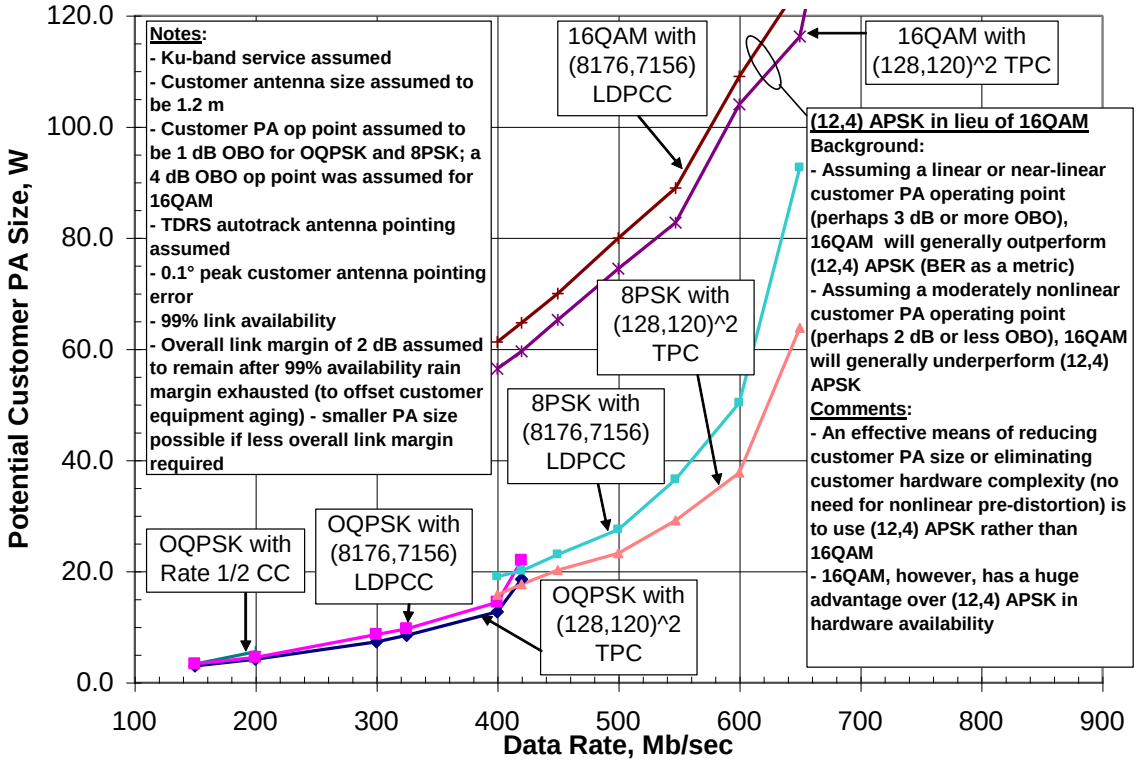


Figure 3. Example Required Customer PA Size As Found Via Link Budget Analysis Using the Simulation BER Performance Results – For KuSAR "225 MHz Channel"

The Modulation and Coding Study eliminated 16QAM modulation from further consideration for use with TDRSS for the following reasons:

- Under performs OQPSK and 8PSK for the data rates considered in the simulation and coding study
- Customer transmitter must either be backed-off or use nonlinear pre-distortion
- 16QAM is more sensitive to hardware noncompliances, interference and cross polarization

Modulation	Coding	Realistic Maximum Achievable Data Rate (As Found Via Simulation)	
		Via Ku/KaSAR 225 MHz Channel	Via KaSAR 650 MHz Channel
OQPSK	Rate 7/8 TPC or LDPCC	410 Mb/sec	1.0 Gb/sec
8PSK	Rate 7/8 TPC or LDPCC	625 Mb/sec	1.5 Gb/sec

Table 1. Realistic Maximum Achievable Data Rate Using Recommended Signal Structures – As Found Via Simulation

In addition to identifying modulation and coding techniques which maximize data rate through the TDRSS Ku/KaSAR channels, the TKUP-A modulation and coding study evaluated the performance of the NASA

Constellation Program (CxP) signal structures OQPSK Rate ½ LDPC code via the TDRSS KaSAR 225 MHz channel.

III. Demonstration and Testing Results through TDRSS Channel

THIS section will provide a brief description of the TKUP-A demonstration objectives and the methodology used to develop them and a brief description of the requirements derived from those objectives. A description of the TKUP-A demonstration configurations will then be provided, followed by a summary and discussion of the demonstration results.

A. Demonstration Objectives

The primary objective of the TKUP-A demonstration phase was to assess the risk of achieving the higher throughput transmission via the TDRS channel recommended by the Modulation and Coding Study at performance levels suggested possible by that study. In addition, requirements that are standard for TDRSS K-band data services that were considered to be high-risk with the TKUP-A signal structures were included. The original demonstration objectives, as presented at the *TDRSS KSAR Upgrade Augmentation Project Demonstration Requirements Review*, were as follows:

1. Verify adequate demod and symbol synchronizer performance to meet BER requirements in conjunction with coding designs (TPC, LDPCC, and Rate-1/2 convolutional code), where applicable.
2. Verify ability to detect signal presence for C/N0 ≤ "10-5 BER minus 6 dB" with acceptable rate of false detect.
3. Verify acquisition time requirements are achievable. Include ABBE stabilization time, the effects of frequency uncertainty, and code frame synchronization markers.
4. Verify reacquisition time requirements are achievable.
5. Verify mean-time-to-cycle-slip requirements are achievable.
6. Verify mean-time-to-symbol-slip requirements are achievable.
7. Verify LDPC (8160,7136) decoding will support BER performance requirements at data rate.
8. Verify TPC $(128,120)^2$ decoding will support BER performance requirements at data rate.
9. Verify TPC $(256,239)^2$ decoding will support BER performance requirements at data rate.
10. The modem shall have self-test capability.
11. Verify Doppler frequency counter meets performance requirements.
12. Verify capability to perform real-time decoding (at data rate) that, in conjunction with symbol recovery, meets all performance requirements.
13. Verify receiver meets acquisition requirements for all TPC and LDPCC modes with a frame synchronization marker of 42 bits or less.
14. Verify receiver meets performance requirements under worst case conditions of allowable frequency dynamics.
15. Demonstrate that the receiver protects against false lock to modulation side lobes

From these objectives, requirements for the TKUP-A demonstration were developed. Not all objectives were covered by the final demonstration requirements; some objectives were dropped, some modified, and others added, as enumerated below.

a. Objectives (10) and (11) (self-test and Doppler frequency counter) were not included as requirements to be demonstrated due to cost consideration.

b. The LDPC Rate-1/2 AR4JA code to be used by the Constellation program was added to the requirements.

c. Objective (9) (TPC (TPC $(256,239)^2$) was dropped to reduce the amount of development necessary for the demonstration and because it was determined to be comparable to the LDPC Rate-7/8 code in objective (7).

d. Objective (13) (acquisition with a 42 bit frame marker) was modified to be consistent with CCSDS recommendations that were published after the initial demonstrations requirements were developed. The

final requirements called for use of CCSDS recommended frame markers, a 32-bit frame marker for the Rate-7/8 codes (LDPCC and TPC) and a 64-bit frame marker for the LDPC Rate-1/2 code.

B. Requirements

The demonstrations requirements with brief descriptions are provided in this section.

1. **BER/Implementation Loss**

For all operational configurations, the demonstration requirements provided benchmark C/N0 values at which specific bit error rates (BER) should be achieved.

2. **Autotrack Signal Present**

For selected operational configurations, the demonstration requirements provided benchmark C/N0 values at which the demodulator should be able to detect a customer signal presence in the received spectrum.

3. **Acquisition Time**

For selected operational configurations, the demonstration requirements provided benchmark C/N0 values at which the demodulator should be able to successfully acquire data recovery within one (1) or three (3) seconds with a carrier frequency within a normal range (27,183 Hz) or an expanded range (61,183 Hz), respectively.

4. **Reacquisition Time**

For selected operational configurations, the demonstration requirements provided benchmark C/N0 values at which the demodulator should be able to reacquire data recovery in less than one-half second for a signal dropout of less than or equal to one second.

5. **Mean-Time-to-Cycle-Slip (Carrier)**

For selected operational configurations, the demonstration requirements provided benchmark C/N0 values for which the demodulator should exhibit a mean-time-to-cycle-slip of greater than 90 minutes.

6. **Mean-Time-to-Symbol-Slip**

For selected operational configurations, the demonstration requirements provided benchmark C/N0 values for which the demodulator should exhibit a mean-time-to-symbol-slip of greater than 90 minutes.

7. **Self-Test Capabilities**

This requirement was not included in the formal demonstrations. The suppliers were required to address in their proposals how they would meet this requirement in production TKUP-A equipment.

8. **Frame Synchronizer**

For selected operational configurations, the demonstration requirements provided benchmark C/N0 values at which the demodulator should be able to meet acquisition and tracking requirements with the prescribed frame synchronizer markers. The demonstration did not include specific tests of this requirement; rather, suppliers were required to verify their use of the prescribed markers. This test was considered "passed" for modes for which suppliers successfully achieved acquisition and tracking.

9. **Frequency Dynamics**

For selected operational configurations, the demonstration requirements provided benchmark C/N0 values at which the demodulator should be able to meet acquisition and tracking requirements with frequency dynamics based on the following orbital dynamics at 27.48 GHz:

a. $dR/dt \leq 12$ km/s
b. $d2R/dt2 \leq 15$ m/s2
c. $d3R/dt3 \leq 0.02$ m/s3

10. **False Carrier Lock Protection**

This requirement was not included in the formal demonstrations. The suppliers were required to address by analysis in their proposals how they would meet this requirement in production TKUP-A equipment.

For each signal structure included in the demonstration, various tests were performed at several data rates. Tables 2 and Table 3 illustrate the signal configurations and data rates tested for the Ku-band and Ka-band tests, respectively, and illustrates which requirements were tested at each configuration-data rate combination.

Ku-band (225 MHz Channel)		Testing							
Modulation	**Coding**	**Data Rate**	**BER**	**SP**	**AT**	**RAT**	**MTT**	**FD**	**FCA**
SQPSK	Uncoded	12, 150	X						
		300	X						
SQPSK	R1/2 CC	6	X	X	X	X	X	X	X
		12	X						
		150	X	X					
SQPSK	R7/8 TPC	150	X	X	X	X	X	X	X
		300, 400	X						
		410	X	X			X		
SQPSK	R1/2 LDPC	25	X	X	X	X	X	X	X
		150	X	X			X		
SQPSK	R7/8 LDPC	25	X						
		150	X	X	X	X	X	X	X
		300, 400	X						
		410	X	X			X		
8PSK	R7/8 TPC	150	X	X	X	X	X	X	X
		500, 600	X						
		625	X	X			X		
	R7/8 LDPC	150	X	X	X	X	X	X	X
		500, 600	X						
		25	X						
		625	X	X			X		
CW	N/A	N/A		X					

BER = Bit Error Rate
SP = Signal Presence
AT = Acquisition Time
RAT = Re-acquisition Time
MTT = Mean Time to Cycle Slip and Mean Time to Symbol Slip
FCA = False Carrier Acquisition

Table 2 Test Cases at Ku-Band in the 225 MHz Channel

Ka-band (650 MHz Channel)		Testing							
Modulation	**Coding**	**Data Rate**	**BER**	**SP**	**AT**	**RAT**	**MTT**	**FD**	**FCA**
SQPSK	Uncoded	500, 600	X						
		300	X						
SQPSK	R7/8 TPC	300	X	X	X	X	X	X	X
		600, 800	X						
		1000	X	X			X		
SQPSK 225 MHz Channel	R1/2 LDPC	25	X	X	X	X	X	X	X
		150	X						
SQPSK	R7/8 LDPC	25, 150	X						
		300	X	X	X	X	X	X	X
		600, 800	X						
		1000	X	X			X		
8PSK	R7/8 TPC	400	X	X	X	X	X	X	X
		800, 1000	X						
		1200, 1500	X	X			X		
	R7/8 LDPC	400	X	X	X	X	X	X	X
		800, 1000	X						
		1200, 1500	X	X			X		
CW	N/A	N/A		X					

BER = Bit Error Rate
SP = Signal Presence
AT = Acquisition Time
RAT = Re-acquisition Time
MTT = Mean Time to Cycle Slip and Mean Time to Symbol Slip
FCA = False Carrier Acquisition

Table 3 Test Cases at Ka-Band in the 650 MHz Channel

C. Test Configurations

Modulated signals were transmitted from Space Network ground stations to a TDRS satellite and relayed back to a ground station where the signal was recovered and demodulated. In particular, two separate physical propagation paths were utilized. One path was utilized for Ku Services testing and an alternate path was utilized for Ka Services testing. For the Ku services path, transmissions originated at the NASA White Sands Complex (New Mexico, USA) and were appropriately relayed through a TDRS and received back at the White Sands Complex. The other path (corresponding to the Ka Band services) transmitted from NASA's Goddard Space Flight Center (Maryland, USA) and was relayed through a TDRS and received at the White Sands Complex.

The Ku services were tested with both the KSA1 and KSA2 service configurations which have a minimum specified 3dB bandwidth of 239 MHz. Signals were modulated with the demonstration modems onto the station IF, up converted and transmitted to TDRS. Coarse adjustments to the required C/N_0 and corresponding Eb/N_0 were accomplished by changing the value of the stations EIRP attenuator. Fine C/N_0 adjustments were made with a continuously variable attenuator inserted in the transmit path. Received signals were either down converted utilizing the pre-existing station equipment or down converted as part of the demonstration equipment. Down converted

signals were demodulated with the TKUP-A demonstration modems. Signal monitor points were accessible at both the incoming RF and down converted IF frequencies. An overview of the Ku Services test setup is shown in Figure 4

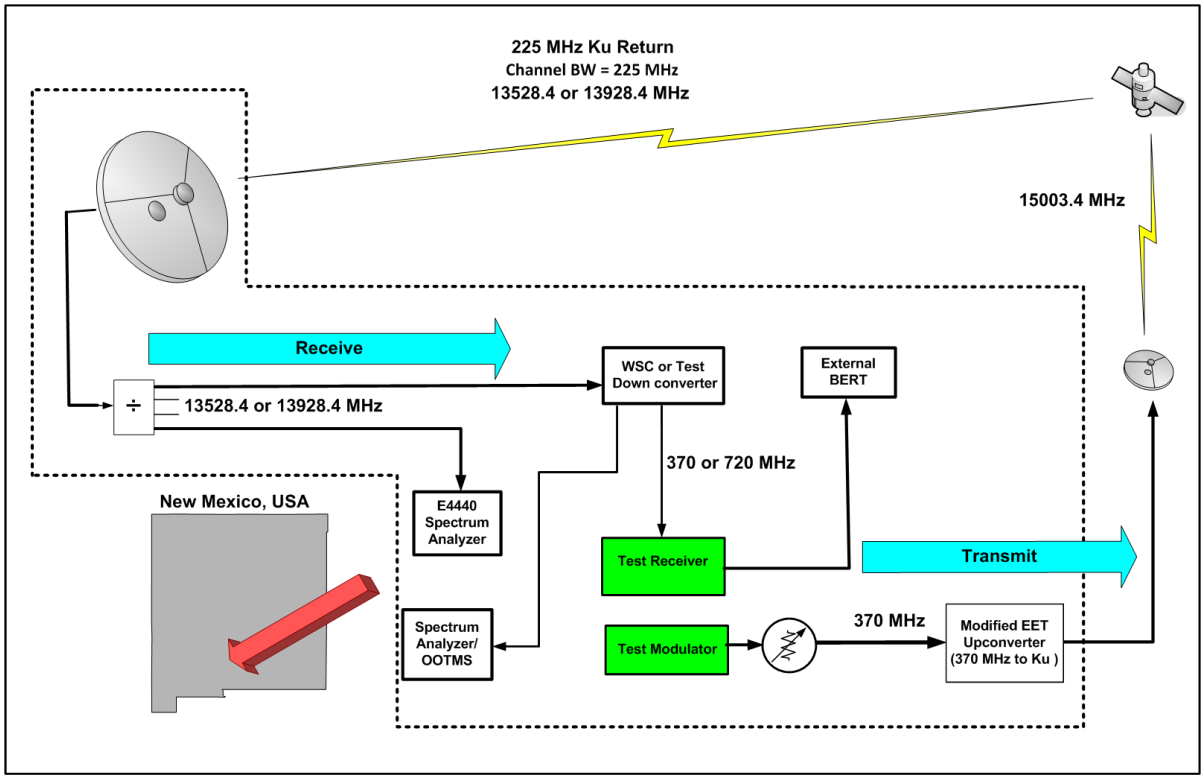


Figure 4 Ku Services Demonstration Setup

The Ka services were tested with both the narrow-band (KaNB) and wide-band (KaWB) operational modes each having a minimum specified 3 dB bandwidth of 239 MHz and 660 MHz respectively. Signals were modulated with the demonstration modems onto the GSFC test facilities IF, upconverted and transmitted to TDRS. Received signals were received at the NASA White Sands Complex, downconverted utilizing the pre-existing Ka services station equipment and demodulated with the demonstration modems. An overview of the Ka Services setup is shown in Figure 5.

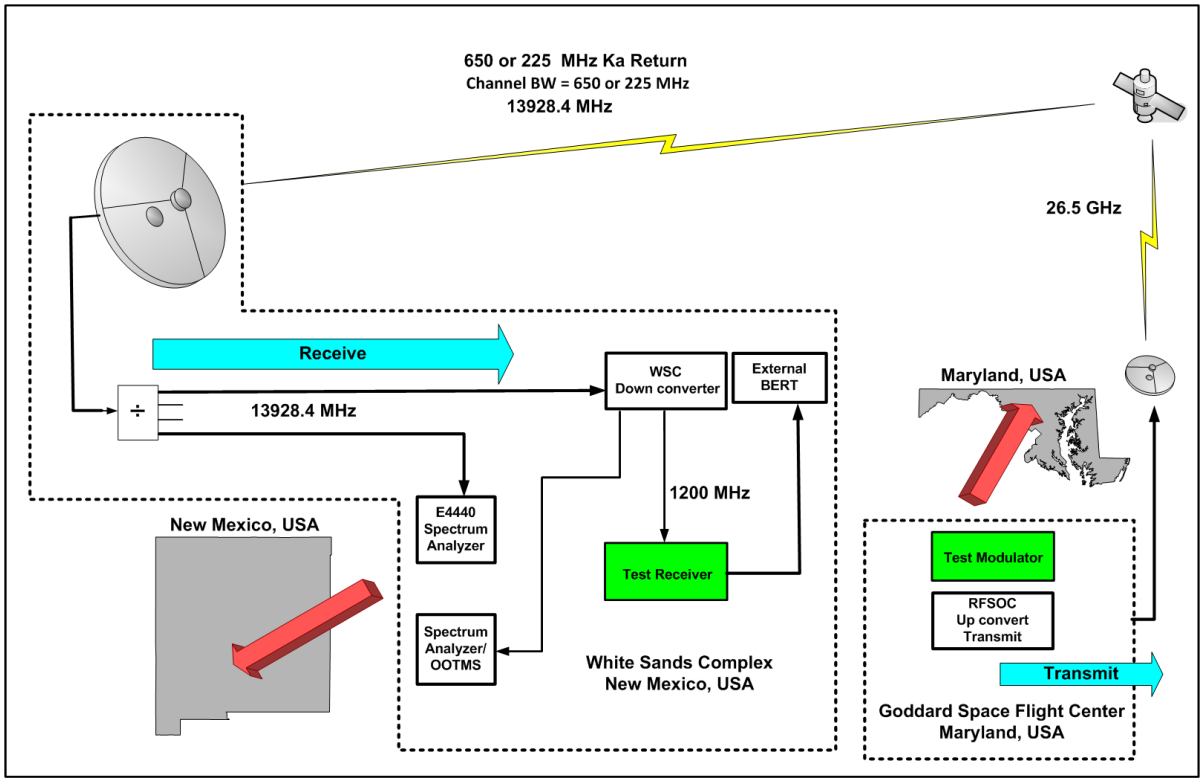


Figure 5 Ka Services Demonstration Overview

D. Demonstration Test Narrative

1. General

Demonstration tests were performed with two Modulator-Demodulator pairs, supplied by different suppliers. The two suppliers were selected from a larger field in a competitive procurement to develop and demonstrate TKUP-A prototype equipment. Vendor modulators were interfaced with both the WSC and GFSC Radio Frequency Simulation and Operation Center (RFSOC) equipment and provided Ku- and Ka-band transmissions respectively. Each vendor used two of their modulators – one for use at the WSC and another for use at the RFSOC. Note that each vendor supplied their own modulator for all of their respective tests. In no case was there cross connection of different vendor modulator-demodulators. Further, the WSC TDRSS system did not supply a third-party modulator for any tests.

The tests were treated as laboratory tests in that the two vendors were allowed to optimize their equipment as the demonstrations progressed. The vendors could choose to optimize the demodulators by adjustments of the various tracking loop bandwidths as well as adjustments of the internal numerical scaling of magnitudes and processing thresholds. The individual vendor teams documented these adjustments in their test records.

The modulators were, in general, operated in a stable configuration. There were periods, however, where the vendors performed certain experiments with adjustments of the modulators. Such adjustments included changes in the digital filtering of the modulator output (changes to the root raised cosine filter coefficients, for example) and adjustment of the modulator output gain tilt equalizer (used to compensate for gain slope at the RF SOC transmitter location.

Tests were performed on an ad hoc “target of opportunity” basis. Engineering judgment was used to select the sequence of tests to best utilize the stability of the channel and the test time available in the individual contact periods. Such selections were guided by the preference of using the KSA1 channel whenever possible. The weather

at RFSOC was also a driver. There were periods of rain and clouds during both vendors' test periods – the link margin was observed to decrease as rain intensity increased. The weather at White Sands was dominated by periods of high winds. The winds caused variability in the link margins due to vibration and deflection of the EET antenna. Finally the orbit of the TDRS has a twenty four hour period and has times with relatively high orbital dynamics. These high dynamic periods caused relatively high angle change rates and therefore rapid changes in the link margin. It should be noted that the test modulator-to-TDRS link weather variations experienced in the demonstration won't be present in operational space links.

2. Test Limitations

The White Sands Complex End to End Test equipment is mature and under relatively strict configuration management. There is, however, a problem that manifests itself when the TDRS is in a high dynamic portion of its orbit. During those periods the EET antenna, slaved to the SGLT 18 meter Ku-band antenna at the STGT, is subjected to relatively rapid angle corrections. The EET positioning system is relatively coarse and therefore subjects the antenna to abrupt jumps that discontinuously change the pointing of the antenna. This causes abrupt changes in the gain of the EET antenna in the direction of the TDRS and therefore changes the C/No measured during the BER determination. This characteristic of the EET system was compensated for by disabling the slaving of the EET to the SGLT 18 meter antenna during certain of the BER-C/No measurements. Low bit error rate tests required long contact periods to acquire statistically significant numbers of bits. Long BER tests conducted during high dynamic periods were problematic in that there was significant drift in the SNR. Note that the slope of the BER curves for LDPC and TPC codes is very steep and a small shift in SNR can significantly change the BER.

The RFSOC is a more dynamic system than the EET. That is, RFSOC is subject to significant reconfigurations that are required to support other tests in addition to the configuration for the TKUP-A tests. The dynamic nature of the RFSOC evidenced itself in an observed variability of the Ka-channel characteristics.

The first vendor detected a characteristic of the transmitter channel manifested in a region of the pass-band with a reduced gain (the effect of this region on the phase characteristics of the channel were not determined). The effect of this reduced gain was a perceived inability of the channel/modem system to pass high rate data. The channel did, however, successfully pass low data rate communications with the reduced gain present. Modifications were made to the RFSOC channel that ameliorated this problem and permitted successful high rate communications – unfortunately, these modifications degraded the ability of the channel to pass lower rate signals.

These modifications seemed to be somewhat unstable in that the second vendor observed similar problems in the channel characteristics even though the modifications had been made and were presumed to be present in the second test period. Therefore the second vendor's tests were more problematic and subject to more day-to-day variability in the Ka band channel performance. Compounding this problem, the RFSOC weather was poor during their testing.

The transmitter/antenna system at RFSOC also had a limited EIRP capability. This limited capability degraded certain tests at the highest data rates because of probable compression of the transmitted signal and the lower power levels. Both vendors' tests were limited by the available EIRP from the RFSOC.

E. Demonstration Results

The demonstration tests included performance verification tests for the following requirements: BER, Signal Presence, Acquisition Time, tracking under frequency dynamics. Other demonstration requirements were evaluated based on analysis or supplier Factory Tests. The BER tests are by far the most critical in considering future signal structures to achieve higher data rates for the TDRS System. This is particularly true in light of the fact that, in general, the TKUP-A receivers were compliant with the other requirements included in the demonstrations. Consequently, this paper will concentrate on the BER test results.

Figures 6 through 10 present the results of the BER tests for select configurations and data rates of interest. As discussed above, much variability was observed during many of the BER tests. Due to this variability, specific BER operating points should be assumed to have a significant variance in the measured E_b/N_0. In addition, the authors wish to be sensitive to providing specific performance values achieved with the suppliers prototype equipment. For

these reasons, the following figures illustrate the region in which the BER results of, in most cases, both vendors fell rather than illustrating each specific BER point for all individual error counts.

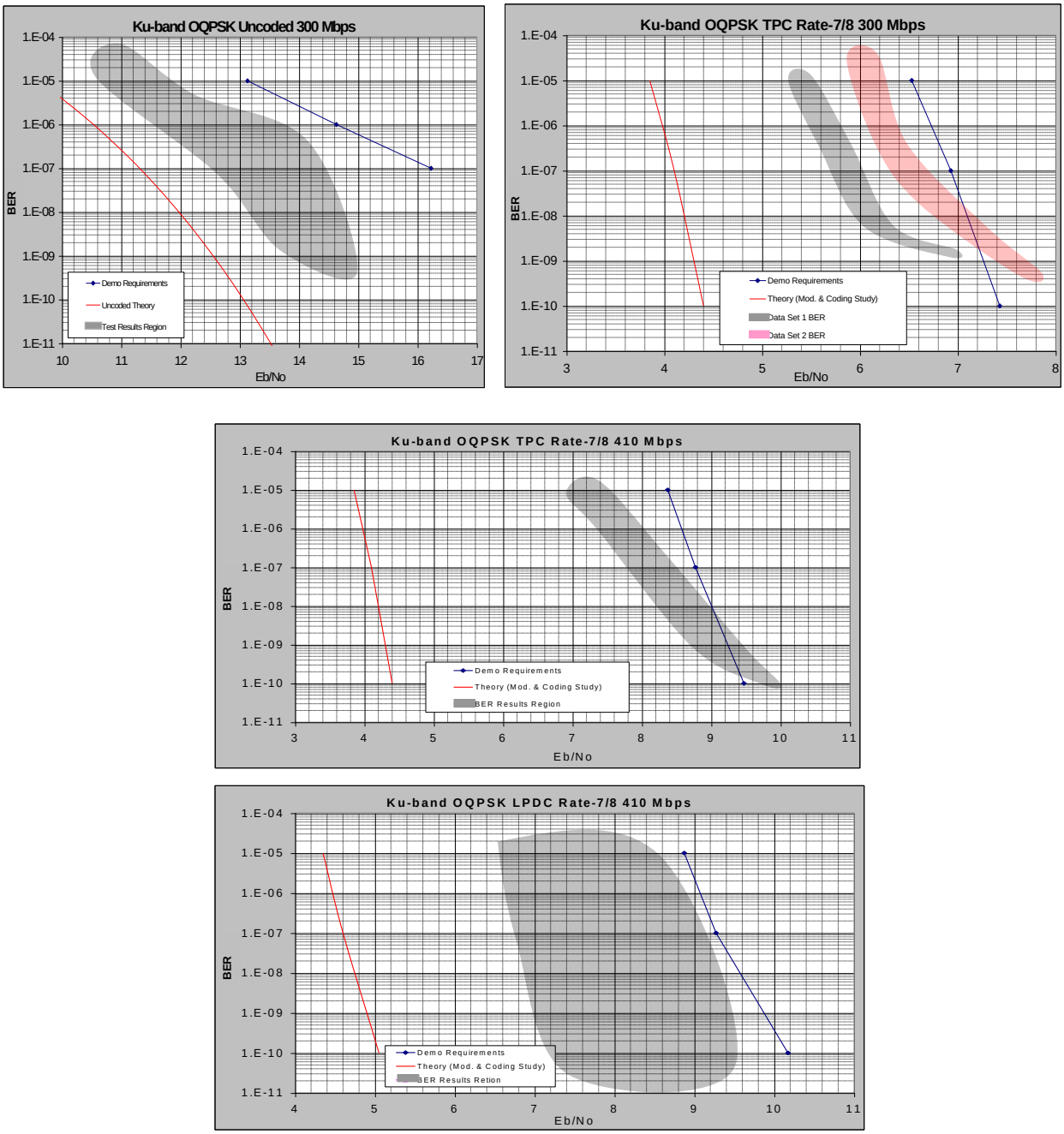
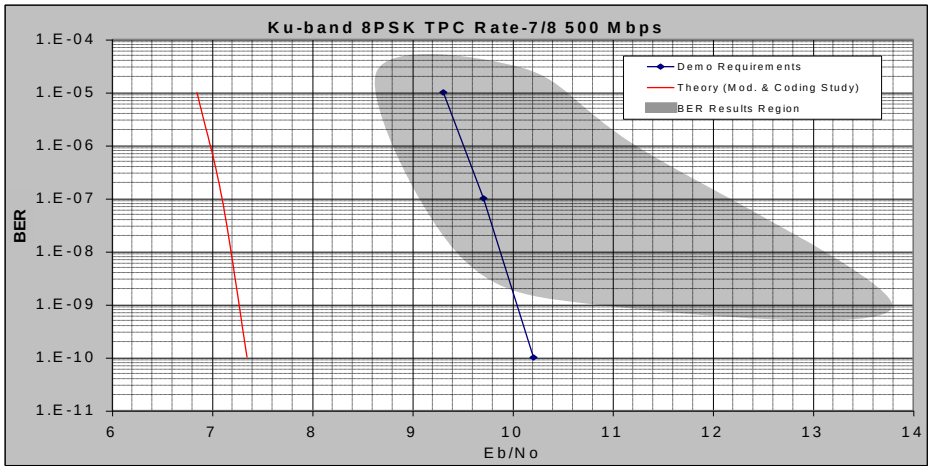
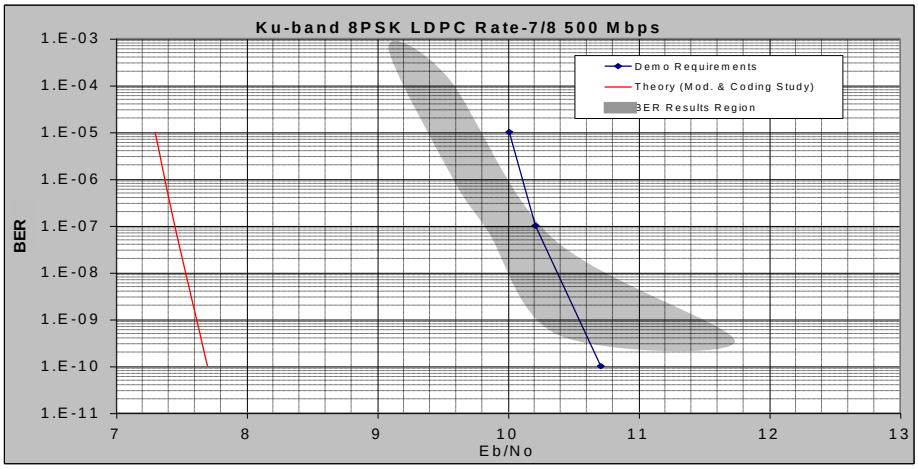


Figure 6 BER Results using OQPSK at Ku-Band in the 225MHz Channel





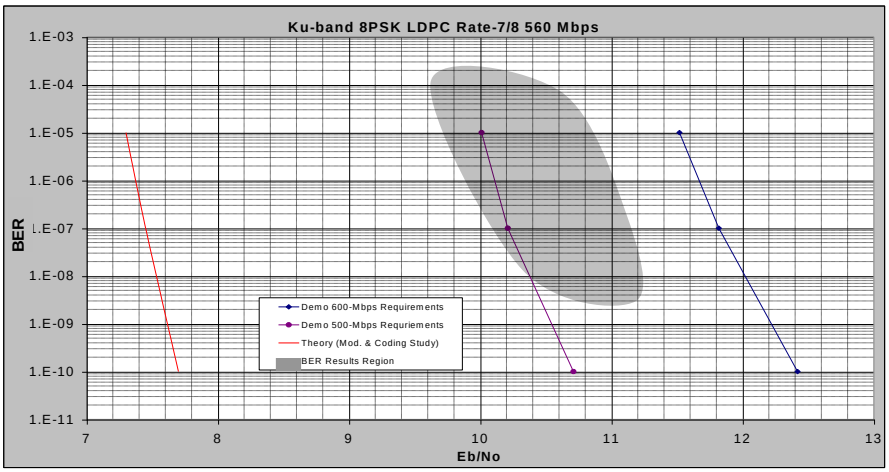
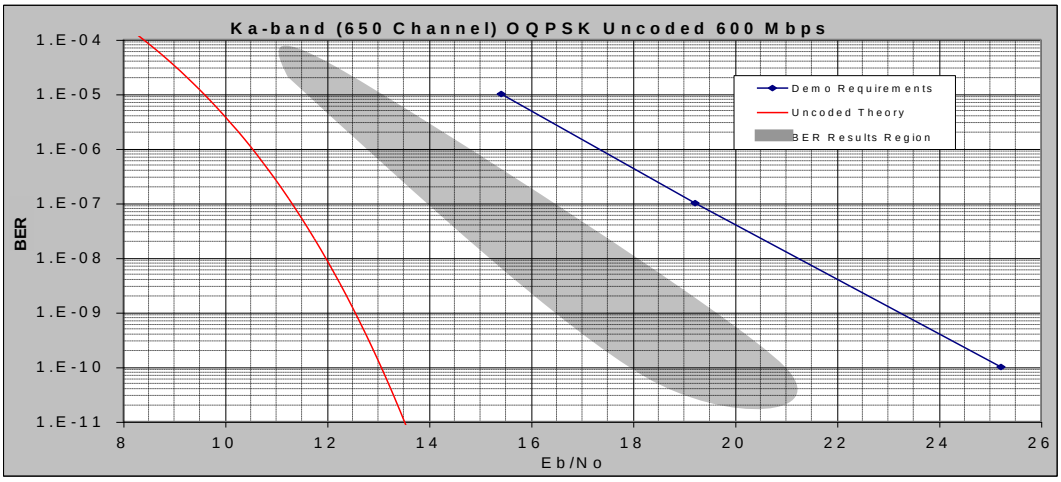
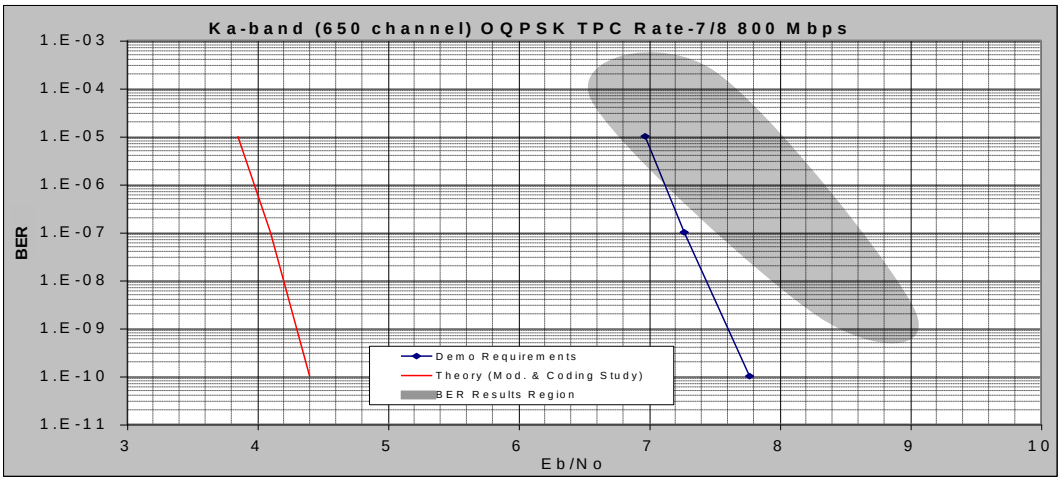


Figure 7 BER Results using 8PSK at Ku-Band in the 225MHz Channel





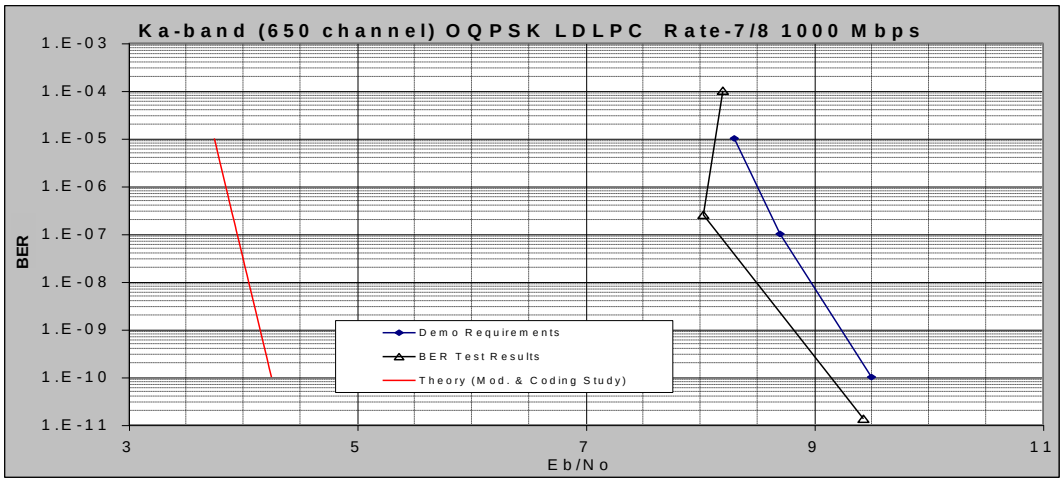
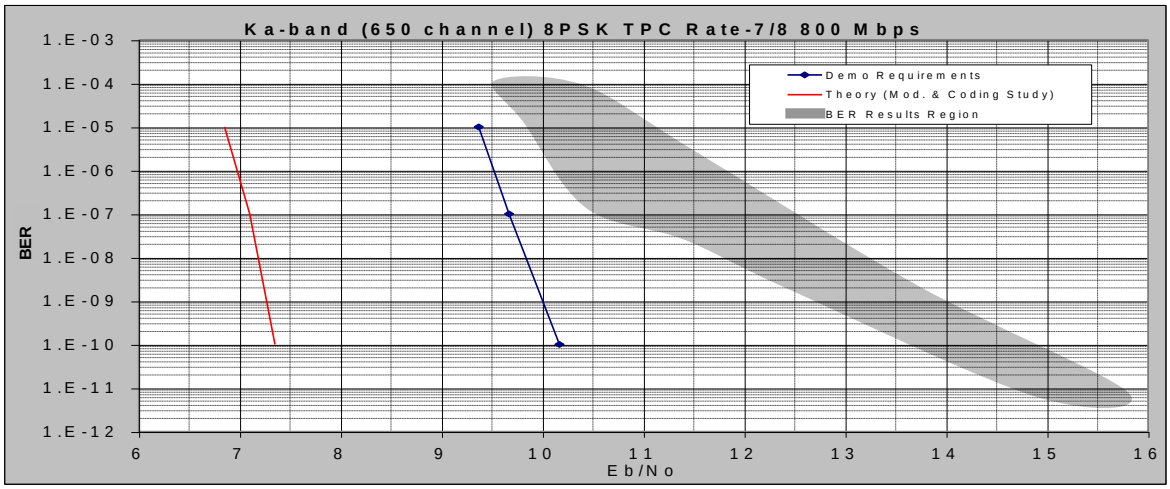
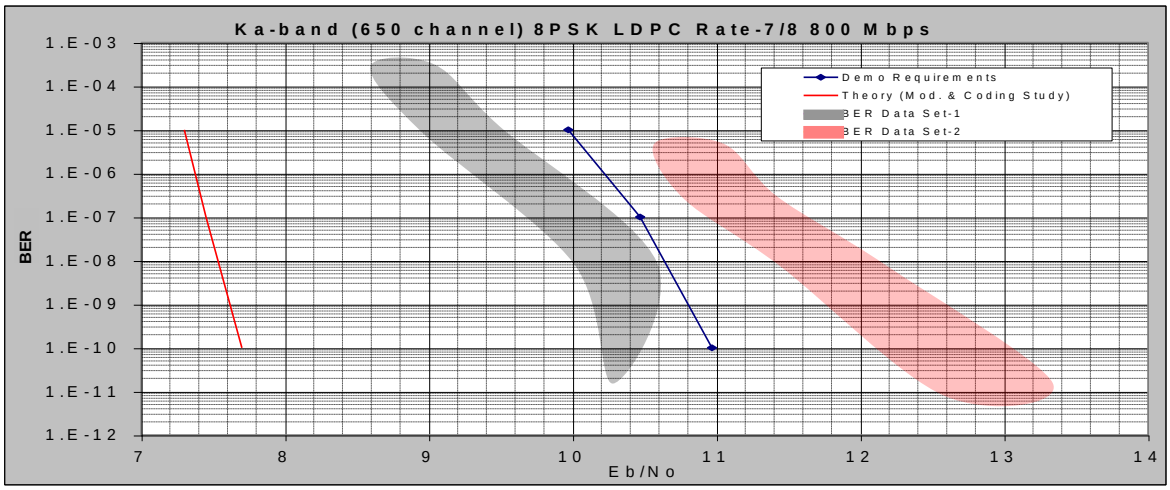


Figure 8 BER Results using OQPSK at Ka-Band in the 650 MHz Channel





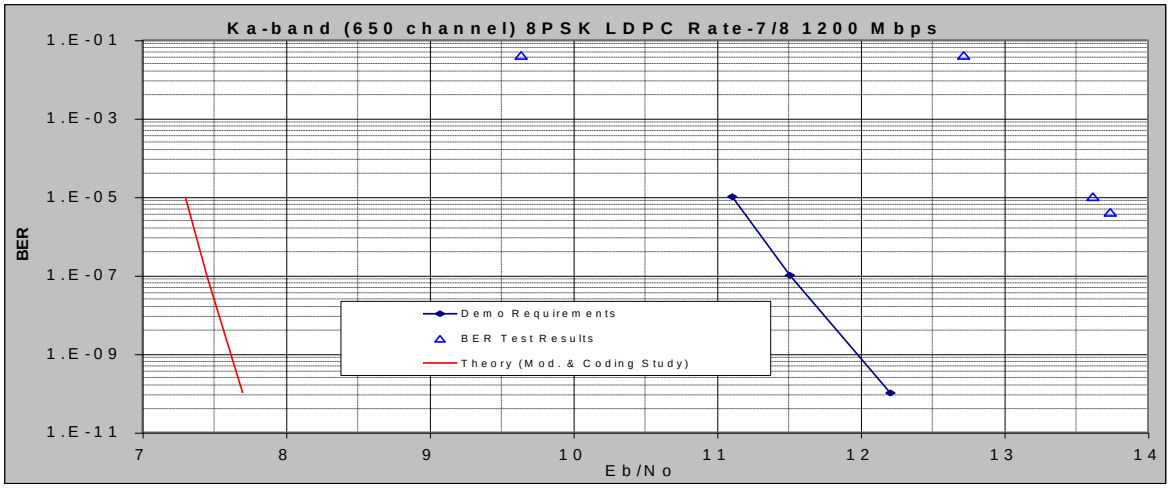
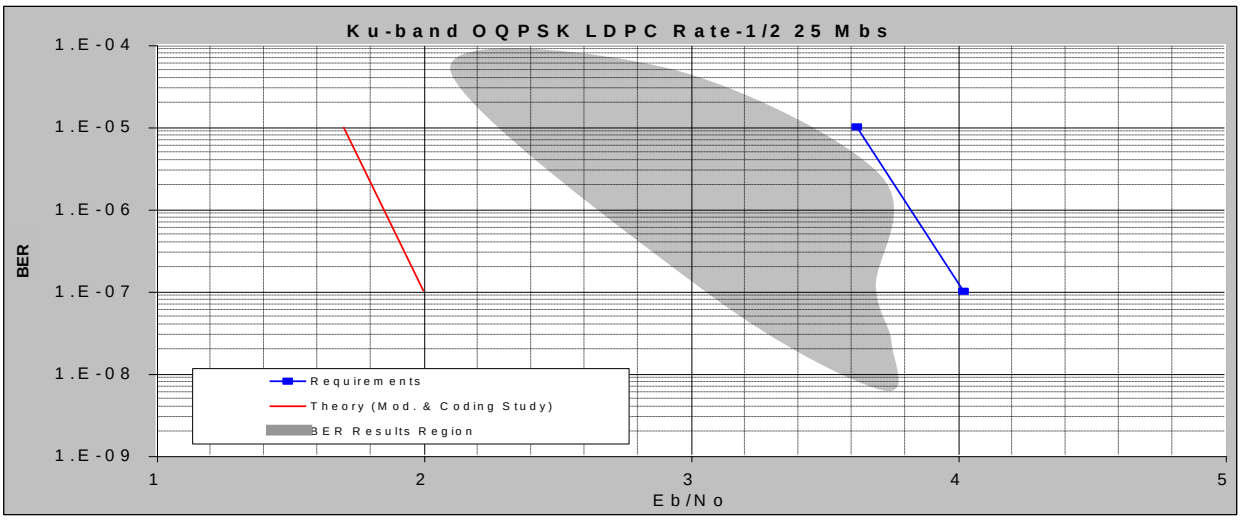


Figure 9 BER Results using 8PSK at Ka-Band in the 650 MHz Channel



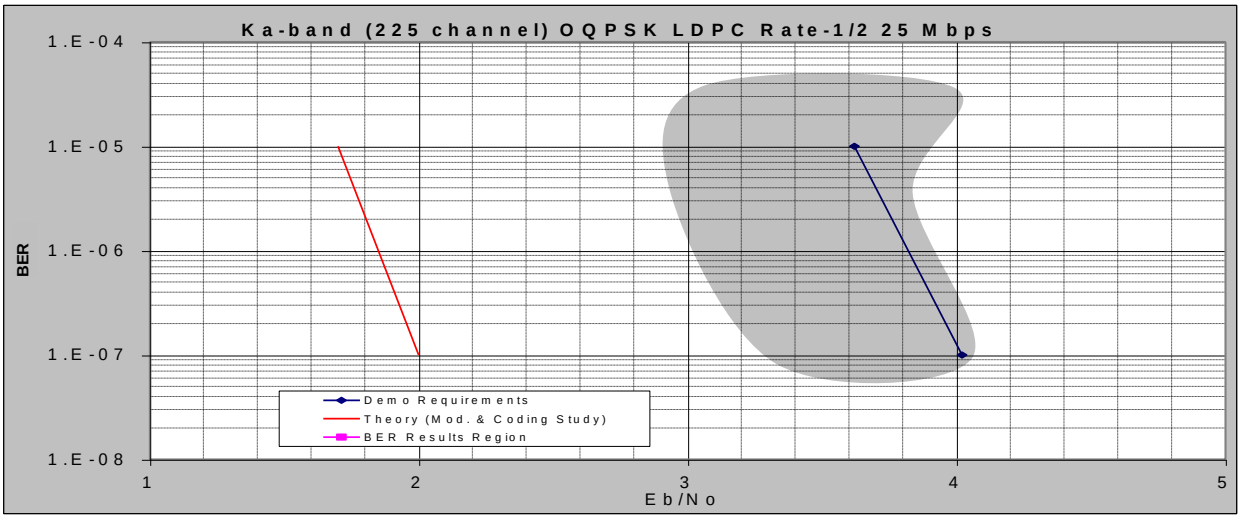


Figure 10 BER Results at 25 Mbps using OQPSK at Ku- & Ka-Band in the 225MHz Channel

F. Test Results Discussion

1. General Observations

Both suppliers achieved good results for Ku-band uncoded and rate-1/2 convoutional coded BER tests, as well as for the Ka-band uncoded test cases. Both suppliers achieved excellent results for the LDPC (8160,7136) code, observing that LDPCC was a relatively easy code (and core) to work with. Both suppliers had less success with the TPC (128,120)[2] code. This is discussed more below. Acquisition tests with both suppliers were supportive of the SN traditional one-second acquisition time being achievable with the TKUP-A modulation and coding formats.

2. Technical Risk Assessment and Mitigation

The original primary objective of the TKUP-A demonstrations was to mitigate the perceived areas of risk in the TKUP requirements and to advance the level of technology readiness in these perceived risk areas. Table 4 provides generalized segmentation of risk areas of primary interest at this time with a three-level assessment score indicating the success in risk mitigation for each area; a larger number indicates more successful risk mitigation. Each area is discussed in the following sections.

General Area of Perceived Risk Mitigation	**Assessment**
Use of high rate, 8PSK modulation through TDRS K-band channels	2
Efficacy of LDPC (8160,7136) in TDRS K-band channels	3
Efficacy of TPC $(128,120)^2$ in TDRS K-band channels	1
Efficacy of AR4JA LDPC (Rate-1/2) in TDRS K-band channels	3
Acquisition performance of required signal configurations	3
Ability to detect signal presence for autotrack system of new, BEM signal configurations at Space Network User Guide (SNUG)-comparable levels	2
Assessment Key: 1 – Risk mitigated only slightly or not at all 2 – Risk mitigated somewhat but not completely 3 – Risk mitigated completely or nearly completely	

Table 4 Summary Risk Assessment

Both suppliers had more implementation loss than anticipated for 8PSK modulation, particularly at data rates where the channel band-limiting effect was significant. The unexpected implementation loss was not due strictly to the band limiting, as suppliers achieved better results in laboratory tests conducted with appropriate band-limiting filters.

Both suppliers had very good success with the LDPC (8160,7136) code. When not associated with other risk areas, performance in most cases was excellent, in some cases slightly better than listed as "theoretical" in the BER performance charts. This better-than-theory performance was probably attributable to the fact that the suppliers used more iterations in the decoder than were used in the modulation and coding study, upon which the "theoretical" values were based.

Both suppliers experienced "flaring" of the BER performance curves at or below 10^{-7} when operating with the TPC $(128,120)^2$ code. Both suppliers predicted this phenomena based on laboratory testing and/or simulations. This result was unexpected to the TKUP-A team based on the TKUP-A modulation and coding study simulations and analysis as well as relevant published results [3, 4]. It should be noted that each supplier used algorithms different from the one used for the TKUP-A modulation and coding study; this may explain some difference in performance. Both suppliers reported the TPC code they used as being more sensitive to symbol scaling and other parameters than the LDPC; it is possible that had the schedule allowed more experimentation that the performance could have been improved. It is recommended that the demonstration results should not be considered the final word on the efficacy of this TPC code in the TDRS channel, but the results here can certainly not be considered to adequately mitigate the risk associated with using this code.

One supplier achieved very good results in all modes tested with the AR4JA LDPC (Rate-1/2) code. The other supplier had impressive results at Ku-band but was outside the requirements benchmark at Ka-band.

Autotrack signal presence was successfully tested in all Ku-Band configurations. Both suppliers demonstrated good acquisition performance with all configurations tested. For the 3-second expanded acquisition range, (+/- 61KHz uncertainty) the results ranged from 1.4 to 3.1 seconds across all configurations. If the one-second acquisition for the normal uncertainty range is an important requirement, this risk should not be considered to be

completely retired by the demonstration results, primarily because the test environment and the time allowed did not allow for a rigorous verification of this requirement.

Frequency dynamics tests were successfully completed by both suppliers for all the Ku-Band configurations identified.

3. Addressing Channel Capacity

The TKUP-A team believes that, in all likelihood, the modulation and coding study has found a reasonable upper bound for channel capacity for both the Ku/Ka-225-MHz band and Ka-650-Mhz band channels utilizing the TKUP-A modulation and coding formats. It was the hope of the TKUP-A team that these demonstrations would verify, or at least support the supposition, that these upper bounds are achievable. This has been the case for OQPSK, however this has not been the case for 8PSK.

An obvious corollary question arises: can the reasonably achievable capacities for these channels be inferred from the results of these demonstrations? The risk to achieving the 625 Mbps data rate in the 225-MHz channel (actual channel 3 dB bandwidth is 240 MHz) is probably greater than that of achieving the 1,500 Mbps data rate in the 650-MHz channel (actual channel 3 dB bandwidth is 670 MHz). Two points are made in support of this supposition. (1) The highest data rate achieved in the 650-MHz channel is proportionally closer to the maximum attempted than in the 225-MHz channel. (2) The team believes that a greater portion of the distortions experienced in the 650-MHz channel were due to the transmission source rather than the channel than is the case for the 225-MHz channel. In other words, there is far more potential for improving the 650-MHz channel performance by improving the performance of the transmission source. The WSC End-to-End system is a mature and stable system that has been sustained since the early 1990's. On the other hand, the RFSOC Ka-band system is less mature, relies on much newer Ka-band technology and, due to the nature of the variable testing requirements of the RFSOC, is not as stable.

It was the intent of the TKUP-A team to execute a fairly rigorous characterization of the two supporting test transmission systems. Were this data available today, it might provide much additional insight into the demonstration test results, and might provide further insight into the implications these results have on the reasonable channel capacities. Unfortunately, the project schedule did not allow for this characterization. It is important for future requirements development to further assess the channel capacity, and perform an RFSOC characterization to supplement the test results of this demonstration.

IV. Future SN K -Band (Ka and Ku) Services

A. Potential Enhancements to future SN Ku-Band and Ka-Band Data Services

In light of the results of TKUP-A demonstration and the technical risk level, the TKUP-A project will incorporate the signal designs meeting the demonstration requirements into the future SN Ku-Band and Ka-Band Data Services

1. SQPSK Rate 7/8 LDPC code

SQPSK with rate 7/8 LDPC code performed very well in nearly all test configurations. The results are in compliance with TKUP-A performance specification. TDRSS channel maximum data rate using SQPSK will be significantly increased to 1 Gbps.

2. SQPSK Rate ½ LDPC code

SQPSK with rate ½ LDPC code performed well with respect to TKUP-A performance requirements. As a signal design selected by the Constellation program, the rate ½ LDPC exhibits excellent performance at low BER at data rates up to the 150Mbps currently of interest to the CxP.

B. Further Investigation for 8PSK and TPC

1. 8PSK Modulation

Results of the demonstration indicate more implementation loss than anticipated for 8PSK modulation, particularly at data rates where the channel band-limiting effect was significant. The unexpected implementation loss was not due strictly to the band-limiting effect as suppliers achieved better results in laboratory tests conducted with band-limiting filters. Since 8PSK is well known for sensitivity to link distortion, TDRSS channel group delay, gain flatness and other distortions probably contribute to the additional implementation loss. Further investigation on using a channel equalizer for carrier and symbol synchronization lock improvement is planned. Introduction of complex taps for the adaptive baseband equalizer to improve implementation loss is also being considered. Using a pre-compensation filter at the transmitter to mitigate the channel distortions may also be of benefit.

Excess distortions were encountered at the RFSOC during the demonstration. In order to get more insight into the distortions and their impact to the BER performance results, a full characterization of the RFSOC system is planned. Replacement of some of the system components may also be required.

2. TPC

TPC BER flaring occurred at BER's < 1E-7 during the demonstration. Based on simulation and analysis performed during the modulation and coding study, this result was unexpected. The fact that the TPC algorithms used for the FPGA core in the demonstration were different from the ones used in the study may explain some difference in performance. Further investigation of parameters related to the core such as selection of soft-decision values, symbol scaling, feedback coefficient settings, etc is planned.

Since it has been reported in some conference papers that there is no error floor for TPC down to <1E10, further consultation with the TPC community is planned. If the results indicate that rate 7/8 TPC is difficult to work with or isn't likely to achieve the anticipated performance in the TDRS channel, NASA will consider removing the option for TPC from the requirements since rate 7/8 LDPC performed so well. If, however, the results, of the investigation indicate that performance could be improved if more experimentation is allowed, NASA may consider this code as an option in the requirements specification, perhaps testing a refined TPC implementation in the K-Band production equipment engineering model.

V. Conclusions

TKUP-A has successfully demonstrated a 1 Gbps data rate using OQPSK and rate 7/8 LDPC code through the 2nd generation TDRS satellite's Ka-Band 650 MHz channel. The maximum data rate demonstrated was 1.2 Gbps using 8PSK and either rate 7/8 LDPC code or rate 7/8 TPC but only achieving partial compliance with the demonstration requirements. It is expected that the issues with 8PSK during the demonstration will be resolved allowing maximum data rates of at least 1.2 Gbps using the Ka-Band 650 MHz channel and 600 Mbps for the Ku and Ka-Band services using the 225 MHz channel.

The TKUP-A project plans to consider the results and lessons learned from the TKUP-A demonstrations in developing the K-Band high rate modem requirements specification which will ultimately lead us to the upgrade of the core of the satellite communications infrastructure of NASA's Space Network. Visit the web site at http://scp.gsfc.nasa.gov/ussr/ for more information.

References

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[2] Ka-Band Data Services Modulation and Coding Study, Revision 3, CSOC-SODA55-872, John Wesdock / ITT, Chitra Patel / ITT, Leonardi Tran / ITT, Abby Kassa / ITT, 17 November 2003.

[3] Multi-Modulation Programmable Transceiver System with Turbo Coding, Eugene Grayver, Phillip Dafesh, The Aerospace Corporation, 2005 IEEE Aerospace Conference.

[4] High Speed Turbo Decoder for WINDS Burst Modem, Mike Dollard, et.al, Efficient Channel Coding (ECC) Inc.