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DVB-S2 Experiment Over NASA's Space Network

Joseph A. Downey and Michael A. Evans
Glenn Research Center, Cleveland, Ohio

Nicholas S. Tollis
Vantage Partners, LLC, Brook Park, Ohio

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Joseph A. Downey and Michael A. Evans
National Aerospace and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Nicholas S. Tollis
Vantage Partners, LLC
Brook Park, Ohio 44142

Abstract

The commercial DVB-S2 standard was successfully demonstrated over NASA's Space Network (SN) and the Tracking Data and Relay Satellite System (TDRSS) during testing conducted September 20-22nd, 2016. This test was a joint effort between NASA Glenn Research Center (GRC) and Goddard Space Flight Center (GSFC) to evaluate the performance of DVB-S2 as an alternative to traditional NASA SN waveforms. Two distinct sets of tests were conducted: one was sourced from the Space Communication and Navigation (SCaN) Testbed, an external payload on the International Space Station, and the other was sourced from GRC's S-band ground station to emulate a Space Network user through TDRSS. In both cases, a commercial off-the-shelf (COTS) receiver made by Newtec was used to receive the signal at White Sands Complex. Using SCaN Testbed, peak data rates of 5.7 Mbps were demonstrated. Peak data rates of 33 Mbps were demonstrated over the GRC S-band ground station through a 10 MHz channel over TDRSS, using 32-amplitude phase shift keying (APSK) and a rate 8/9 low density parity check (LDPC) code. Advanced features of the DVB-S2 standard were evaluated, including variable and adaptive coding and modulation (VCM/ACM), as well as an adaptive digital pre-distortion (DPD) algorithm. These features provided additional data throughput and increased link performance reliability. This testing has shown that commercial standards are a viable, low-cost alternative for future Space Network users.

I. INTRODUCTION

DIGITAL Video Broadcasting Satellite - Second Generation (DVB-S2) is a commercial standard used within the telecommunication industry for video broadcast, Internet services, and data distribution. The standard offers a wide range of modulation and forward error correction capabilities, which allow flexible operation and efficient use of the spectrum. While DVB-S2 is widely used for video broadcasting, it also has potential applications to spacecraft telemetry. The performance of DVB-S2 is comparable to modern NASA waveforms, and there is a wide variety of receivers and test equipment available in the commercial market. The Consultative Committee for Space Data Systems (CCSDS) has recommended a method of using the DVB-S2 standard that accommodates the preferred Space Data Link Protocol for spacecraft telemetry [1]. This allows a mission to use DVB-S2 without necessarily committing to the transport layers and protocols typically used by the telecommunications industry.

NASA's communication systems traditionally use constant coding and modulation, and are designed for the worst case link margin. Variable and adaptive coding and modulation (VCM / ACM) allow for any excess link margin to be minimized, increasing the overall data throughput. With ACM, the adaptive nature also allows the system to mitigate unexpected link conditions that would otherwise disrupt the link. The DVB-S2 standard includes a provision for VCM and ACM, which enables a spacecraft to automatically adapt to dynamic link conditions, such as varying path loss, noise, interference, pointing errors, and obstructions. Furthermore, the modulation schemes in DVB-S2 can accommodate a non-linear channel, by using various digital pre-distortion (DPD) techniques to improve the performance of high-order modulations.

This paper describes a DVB-S2 experiment using a space-based software-defined radio (SDR) transceiver on-board the Space Communication and Navigation (SCaN) Testbed on the International Space Station (ISS). The test provides an opportunity to evaluate the performance of DVB-S2 over the Space Network, using space-based SDR technology for the user terminal, and commercial off the shelf (COTS) equipment at the ground terminal. Secondly, this test provides an opportunity to demonstrate how advanced features (e.g. ACM, DPD) could be integrated and operated by a mission within the Space Network.

II. TEST OBJECTIVES

1) Demonstrate the DVB-S2 standard over the Space Network, using the SCaN Testbed, and evaluate performance of the system using commercially available receivers.

2) Evaluate the Variable / Adaptive Coding and Modulation (VCM / ACM) features of the DVB-S2 standard, and quantify performance gains over constant coding and modulation (CCM).

3) Compare performance to standard waveforms (as defined in the SNUG) currently used within the Space Network.

III. BACKGROUND

A. SCaN Testbed

The SCaN Testbed is an advanced integrated communications system and laboratory installed on the ISS, and has been operating experiments with multiple software defined radios (SDRs) since 2012 [2], [3], [4]. The SDRs are reprogrammable and can run reconfigurable waveform applications [5]. Figure 1 shows the payload enclosure and the various antenna locations and each of the three software defined radios. There are five antennas around the system: three S-band, one Ka-band, and one L-band (Global Positioning System (GPS)). This experiment uses the Jet Propulsion Laboratory (JPL) / L3-Cincinnati Electronics SDR, the S-band Space Network low gain antenna (SN-LGA) and the S-band medium gain antenna (MGA). The MGA antenna is mounted on a gimbal and controlled with open-loop pointing, while the SN-LGA antenna is zenith-facing with fixed pointing.

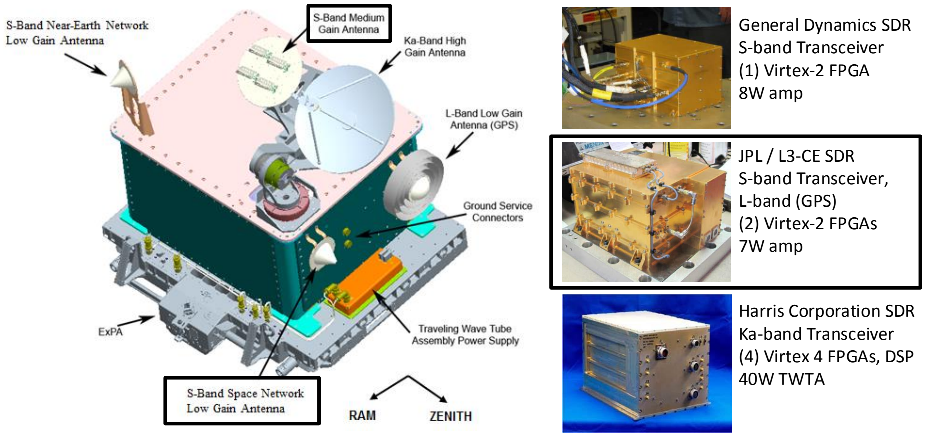

Fig. 1. SCaN Testbed

For this experiment, the primary antenna will be the MGA to take advantage of the higher gain. The SN-LGA will be used for a subset of the events to emulate a spacecraft with a lower EIRP. Typical commercial DVB-S2 receivers are not designed for symbol rates below 300 kBaud, which limits the potential testing with the SN-LGA path.

B. *DVB-S2 Standard*

The DVB-S2 standard [6] was developed by the European Telecommunications Standards Institute (ETSI) and published in 2005. The standard defines a set of modulation and coding options, designated MODCODs, which include QPSK, 8-PSK, 16-amplitude phase-shift keying (APSK), and 32-APSK. The forward error correction consists of a Bose-Chaudhuri-Hocquenghem (BCH) outer code and a Low Density Parity Check (LDPC) inner code, with code rates between 1/4 to 9/10. Two code block lengths are defined, n=16200 for short frames and n=64000 for normal frames. The code performance of the normal frames are approximately 0.5 dB better than the short frames. Table I provides a table of the 28 MODCODs defined by the standard, and the effective code rate and spectral efficiency of the short frames. The effective code rate accounts for the BCH code and the physical layer overhead of the DVB-S2 standard. Spectral efficiency is presented as bits per channel use (bpcu), and is calculated by multiplying the effective code rate by the number of bits per symbol.

TABLE I
DVB-S2 SHORT FRAME MODCODS WITH PILOTS

MODCOD	**Modulation**	**LDPC Code Identifier**	**Effective Code Rate**	**Spectral Efficiency**
0	DUMMY PL			
1	QPSK	1/4	0.18	0.36
2	QPSK	1/3	0.31	0.62
3	QPSK	2/5	0.37	0.74
4	QPSK	1/2	0.42	0.83
5	QPSK	3/5	0.57	1.13
6	QPSK	2/3	0.63	1.26
7	QPSK	3/4	0.69	1.39
8	QPSK	4/5	0.74	1.48
9	QPSK	5/6	0.78	1.56
10	QPSK	8/9	0.85	1.69
11	N/A with Short Frames			
12	8-PSK	3/5	0.56	1.69
13	8-PSK	2/3	0.63	1.89
14	8-PSK	3/4	0.69	2.08
15	8-PSK	5/6	0.78	2.34
16	8-PSK	8/9	0.84	2.53
17	N/A with Short Frames			
18	16-APSK	2/3	0.63	2.51
19	16-APSK	3/4	0.69	2.76
20	16-APSK	4/5	0.73	2.93
21	16-APSK	5/6	0.78	3.10
22	16-APSK	8/9	0.84	3.36
23	N/A with Short Frames			
24	32-APSK	3/4	0.68	3.42
25	32-APSK	4/5	0.73	3.63
26	32-APSK	5/6	0.77	3.84
27	32-APSK	8/9	0.83	4.16
28	N/A with Short Frames			

A key feature of the DVB-S2 standard is the inclusion of a Physical Layer (PL) frame structure, and pilots to aid in receiver acquisition and tracking. The PL header is $\pi/2$-BPSK modulated and is used to identify the MODCOD of the frame, which can vary between each subsequent frame. The receiver reads the PL header and configures the demodulator and decoder appropriately. Changes between different MODCODs are done on a frame by frame basis with no loss of data. Pilot symbols, when enabled, are known data sequences which are regularly inserted into the modulated signal and aid the receiver in carrier tracking and channel estimation.

C. *Space Link Data Protocol*

Beyond the functionality provided by the physical layer (e.g., forward error correction, modulation), protocols that operate at the data link layer and above are needed to provide an abstraction for the system user. The Consultative Committee for Space Data Systems (CCSDS) Advanced Orbiting Systems (AOS) Space Data Link Protocol, described in [7], is a data link layer protocol designed for various types of space missions, targeting efficient transfer of data over space communication links. This standard provides a mechanism for transferring data using a fixed-length protocol data unit called a Transfer Frame, where the length of the frame is mission-dependent. By design, the AOS Space Data Link Protocol provides inclusion into the Open Systems Interconnection (OSI) reference model, allowing for the potential use of TCP/IP-based networking over space communication links.

D. Waveform Comparison

The Space Network User's Guide (SNUG) [8] defines the waveforms supported by the receivers at White Sands Complex. After the Space Network Ground Segment Sustainment (SGSS) effort is deployed, both QPSK and 8-PSK modulations will be available for high-rate telemetry, as well as LDPC decoding. Several code rates are supported, including rate 1/2 and 7/8. A comparison of the Eb/No thresholds for a Code Word Error Rate (CWER) of $1e-5$ is provided in Table II for the SNUG and DVB-S2 waveforms. The modem Eb/No threshold includes the implementation loss of a representative receiver.

TABLE II
COMPARISON OF DVB-S2 AND CURRENT NASA WAVEFORMS FOR CWER = $1E-5$

Waveform	**Modulation**	**Code Rate**	**Modem Eb/No Threshold**	**Notes**
DVB-S2	QPSK	0.42	1.48	MODCOD 4
NASA LDPC 1/2	QPSK	0.48	3	As reported in [9]. Between 2.1-2.5 dB reported in [10]
DVB-S2	QPSK	0.57	2.01	MODCOD 5
DVB-S2	QPSK	0.85	4.28	MODCOD 10
NASA LDPC 7/8	QPSK	0.87	4.5	As reported in [9]
NASA LDPC 1/2	8PSK	0.48	≈5.3	As reported in [9]
DVB-S2	8PSK	0.56	6	MODCOD 12
DVB-S2	8PSK	0.84	7.15	MODCOD 16
NASA LDPC 7/8	8PSK	0.87	7.5	As reported in [9]

In comparison, the short frame DVB-S2 modes generally out-perform the comparable NASA waveforms by several tenths of a dB. Some performance improvement is expected, since DVB-S2 has a longer code block length of 16200, versus 2048 or 8160 for the NASA LDPC codes. The gap is closer, if the small difference in code rate is accounted for. The combination of 8-PSK with the rate 1/2 NASA LDPC code does outperform the closest DVB-S2 counterpart (rate 3/5 code) by 0.7 dB; however 8-PSK with a rate 1/2 code is not anticipated to be used often with the Space Network, since QPSK with a high-rate code can achieve the same spectral efficiency at a lower Eb/No threshold. Additional performance improvement of ~0.5 dB would be expected with the DVB-S2 normal frames.

E. Bandwidth Considerations

Although the TDRS minimum 3 dB bandwidth for the S-band single access service (SSA) is specified as 10 MHz, NASA spectrum managers will not license more than 6 MHz of bandwidth without a waiver due to spectrum congestion and interference concerns [8]. Spectrum is regulated by the National Telecommunications and Information Administration (NTIA) which defines an emission mask for transmitters [8]. For a fixed ground terminal such as the GRC S-band ground station, use of the full 10 MHz is permitted. This bandwidth limitation provides some motivation to use bandwidth-efficient modulation and encoding, such as DVB-S2.

IV. TEST CONFIGURATION

The test configuration for this experiment is shown in Figure 2. Two signal paths are shown, one using the SCaN Testbed on the ISS, and another using an S-band ground station at GRC. In both cases a JPL SDR (breadboard, engineering, or flight model), loaded with a DVB-S2 transmit waveform, transmits over TDRS to the ground station at White Sands Complex. The 370 MHz intermediate frequency (IF) service is used to route the received signal to a DVB-S2 modem (Newtec MDM6000). The Newtec modem demodulates and decodes the signal, and the user data and link statistics are sent back to GRC via a network connection. The modem is controlled and monitored remotely through the same network.

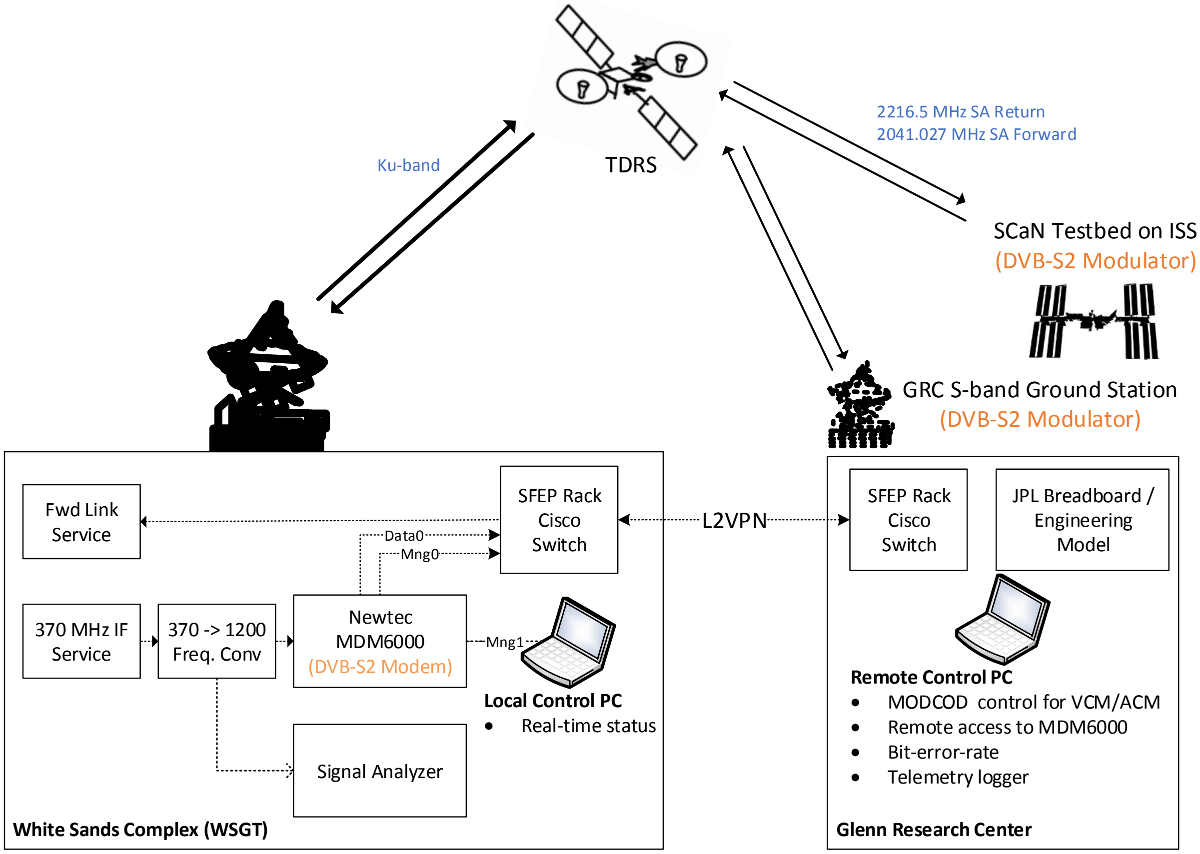

Fig. 2. Test Configuration

Detailed descriptions are provided in Section V for the DVB-S2 transmit waveform implementation, ground software, and the Newtec modem performance.

V. SYSTEM DESCRIPTION

A. *DVB-S2 Transmit Waveform Implementation*

The major functions of the SDR waveform application are shown in Figure 3. The waveform allows arbitrary modulation symbol rates, and can operate up to 6.15 MBaud on the JPL SDR. The data source is a single input stream consisting of CCSDS-framed PRBS-23 test data. With regards to DVB-S2 modes of operation, this waveform only supports the continous Generic Stream (GS) format. Pilot tone insertion is configurable, but was enabled for this testing. Only the DVB-S2 short frames, which have 16200 bits per frame, are implemented in this waveform. All other relevant waveform functions are shown in Figure 3 and are described in the DVB-S2 standard [6].

The feedback path and protocol for relaying channel state information required for ACM is not standardized by DVB-S2 or by the CCSDS standards, and is left to the mission to decide. For this

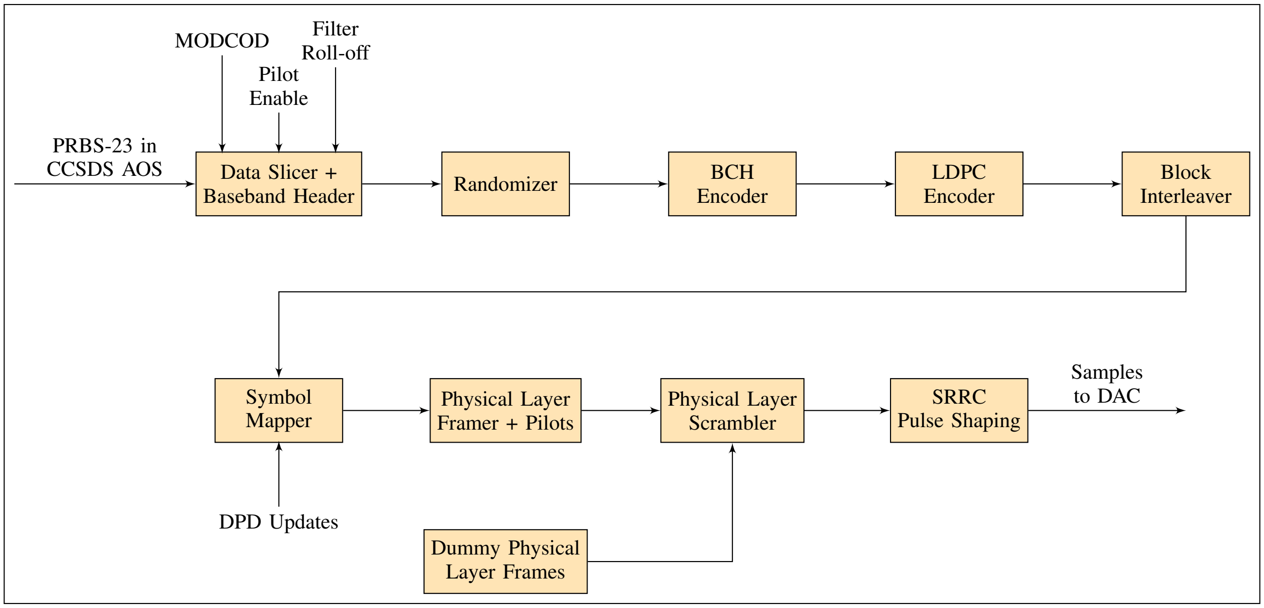

Fig. 3. DVB-S2 Waveform Processing Functions

experiment, feedback is provided via a forward link BPSK waveform operating at 155.346 kbps with a rate 1/2 convolutional code. ACM feedback commands are implemented using the frame structure defined in the AOS Space Data Link Protocol [7]. The Operational Control Field (OCF) of the Transfer Frame (TF) trailer is used to send the MODCOD, pilot enable, and pulse shape filtering settings from the ground system to the JPL SDR.

In both link directions, a 32-bit Attached Sync Marker is added to 2048-bit AOS Transfer Frames. However, the high-rate DVB-S2 return link waveform does not use either of the following optional trailer fields that comprise the last 48 bits of the Transfer Frame: Operational Control Field or Frame Error Control Field. This is shown in Figure 4. In the case of the forward (feedback) link waveform, both the Operational Control Field and Frame Error Control Field are used to reliably send DVB-S2 configuration information to the space-side transmitter, as shown in Figure 5. For more specific information regarding how the feedback data is formatted, see [11].

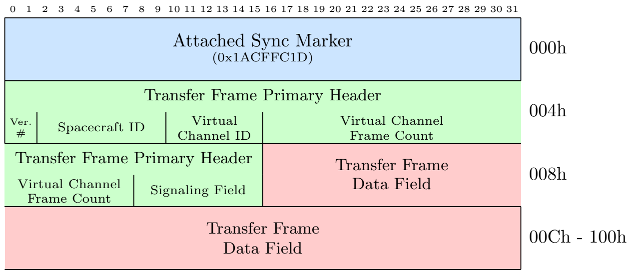

Fig. 4. AOS Structure for Return Link

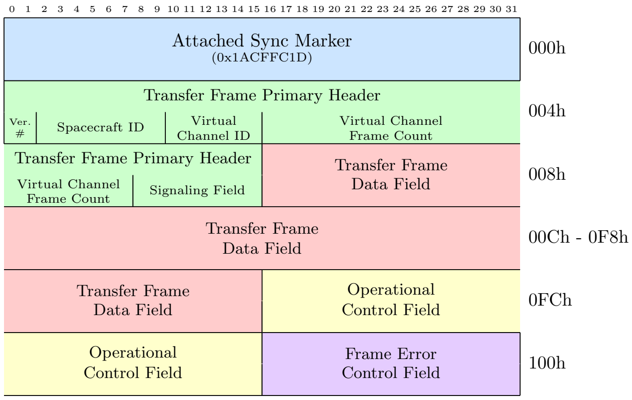

Fig. 5. AOS Structure for Forward Link

On-orbit, the received commands are sent to the DVB-S2 transmitter, provided that the Frame Error Control Field's error detection syndrome is zero. Once new operational parameters are received, they are applied to the next available PL frame. Based on the bit rate and the AOS frame length, the effective update rate of the feedback channel is approximately 75 Hz.

Additional details on the waveform implementation can be found in [11] and [12]. The waveform complies with the Space Telecommunications Radio System (STRS) architecture standard for software defined radios, and per that standard is available and intended for reuse on other radio platforms. The waveform is available for request via the STRS Application Repository [13].

B. Ground Software

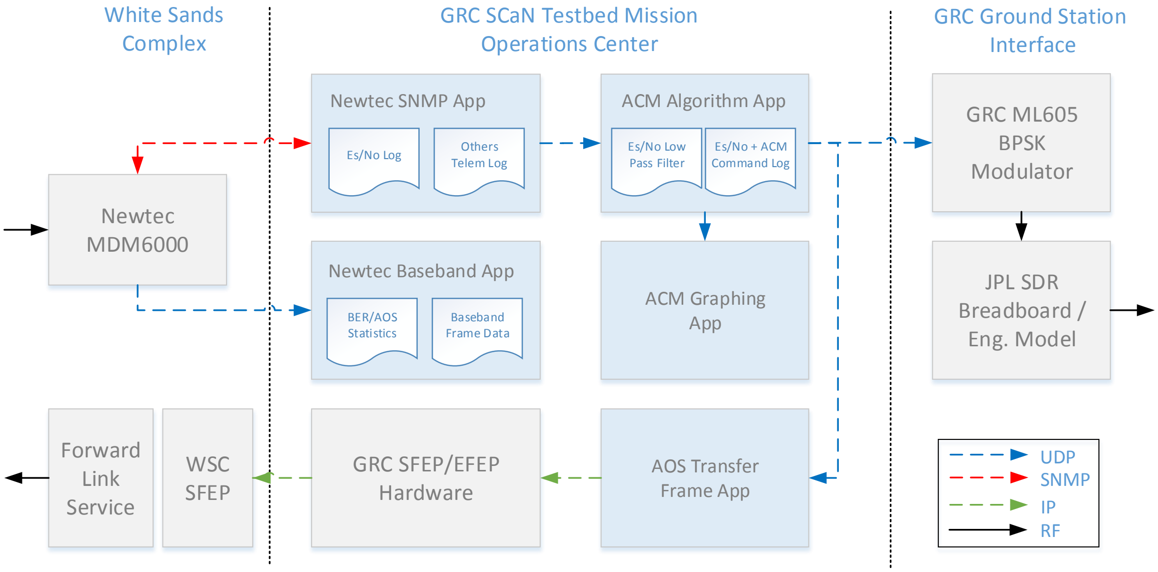

Fig. 6. Ground System

The ground software used to support this experiment is shown in Figure 6. Various software applications (highlighted as blue) were written to support the test, as described below.

Newtec Baseband - this application receives and logs User Datagram Protocol (UDP) packets from the Newtec MDM6000 at WSC. Additionally, it computes real-time BER, frame error rate (FER) and CCSDS AOS framing performance metrics of the baseband data, logging those statistics as well.

Newtec SNMP - this application receives and logs Simplified Network Management Protocol (SNMP) packets from the WSC Newtec modem that contain telemetry information about the receiver's operation and performance while it receives data from the SCaN JPL radio. It also forwards the Es/No metric from the Newtec modem through UDP packets to the ACM Algorithm application.

ACM Algorithm - this application receives the Es/No metric from the Newtec SNMP application to drive the ACM algorithm. The Es/No values are low-pass filtered to remove estimation noise with a moving average filter. The resulting MODCOD decision is then logged and forwarded as UDP packets to the AOS Transfer Frame application when performing on-orbit events, or the ML605 modulator when performing GRC ground station events.

AOS Transfer Frame - this application is used during on-orbit events to package the OCF data from the ACM Algorithm application into AOS frames and then forwards those frames as IP packets to the GRC EFEP/SFEP hardware, which is the data source for the Forward Link service.

ACM Graphing - this application plots in real-time the Es/No, MODCOD and margin sent as UDP packets by the ACM Algorithm application.

C. DVB-S2 Receiver Characterization

After a survey of commercially available DVB-S2 receivers, the Newtec MDM6000 High Speed Satellite Modem was selected. An important factor was support for raw DVB-S2 baseband frames, bypassing any transport layer protocols which are normally used with DVB-S2 such as Multi-protocol Encapsulation (MPE) or Generic Stream Encapsulation (GSE). This allows custom framing, as needed for the CCSDS recommended practice of sending Space Data Link Protocol frames over DVB-S2. Other notable features of the modem include high data-rates (up to 425 Mbps) and support for DVB-S2 extensions (DVB-S2x). None of the commercial receivers were directly compatible with the 370 MHz IF that is used at the White Sands Complex. Typical coverage ranged from 50-180 MHz, and 950-2150 MHz (L-band). An external frequency converter was built to translate the 370 MHz IF to 1.2 GHz.

Before testing with the SN, the compatibility and performance of the Newtec modem was evaluated. The test setup used to characterize the Newtec modem is shown in Figure 7. This test setup was used to characterize the modem performance in the presence of additive white Gaussian noise (AWGN), frequency offsets, and Doppler. The JPL SDR breadboard generates DVB-S2 modulated data at the SSA return link frequency of 2216.5 MHz. Then, the RF signal is downconverted to 1200 MHz and is combined with additive white Gaussian noise (AWGN). For a given MODCOD, the fixed noise attenuator is set such that the variable signal attenuator can produce the required Es/No range near the desired total receive signal power specification for the modem.

Results are presented in the following subsections.

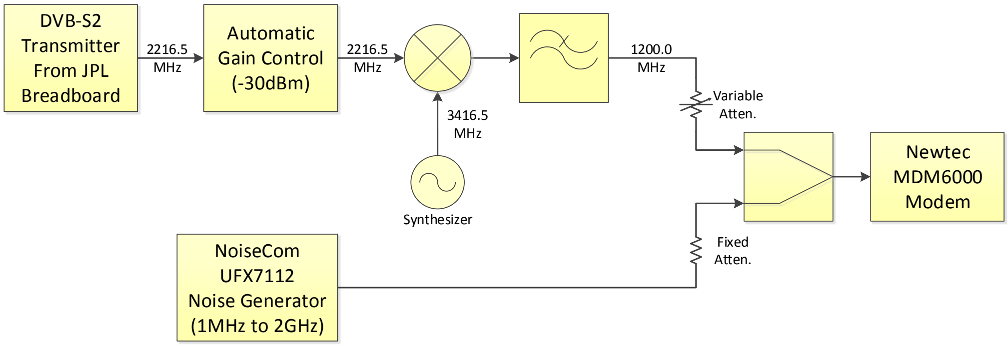

Fig. 7. CWER Test Setup

1) Quasi-Error Free Performance Threshold: In order to run VCM and ACM modes, it was essential to identify the Es/No thresholds that guarantee a certain Quasi-Error Free (QEF) performance level. A Codeword Error Rate (CWER) of $1e-5$ is targeted, and data is taken at the following modulation symbol rates in MBaud: 0.3, 1, 3, 5, and 8.

Characterization data is shown in Table III. Data from each entry assumes that pilot tones are being inserted at the physical layer. Each table entry corresponds to running a full CWER curve, averaging among several symbol rates (if applicable), and determining the QEF point via interpolation (see Figures 8 and 9). The data is split into two distinct columns: when running above 300 kBaud and when running at 300 kBaud. Not all rows in the right-most column are populated because of the large time duration associated with running CWER curves at lower symbol rates. Therefore, only a subset of MODCODs from each modulation type were run. In general, the implementation loss from running at 300 kBaud was slightly higher. As a safe rule of thumb, adding 0.5 dB to the >300 kBaud column will provide sufficient characterization data for missing data points at 300 kBaud. However, this margin can likely be reduced in the case of the lower-order modulation schemes.

TABLE III
Es/No Threshold for CWER of 1e-5

MODCOD	**Es/No (dB) (> 300kSym/s)**	**Es/No (dB) (= 300kSym/s)**
1	-1.845	-2.756
2	-1.028	-
3	-0.065	-
4	0.677	-
5	2.550	2.690
6	3.401	-
7	4.225	-
8	4.895	-
9	5.460	-
10	6.556	6.714
12	6.020	6.107
13	6.910	-
14	8.206	-
15	9.767	-
16	11.174	11.206
18	9.469	9.912
19	10.711	-
20	11.476	-
21	12.106	-
22	13.441	13.835
24	13.655	14.206
25	14.371	-
26	15.124	-
27	16.799	17.350

Additionally, the FER curves for MODCOD 1 exhibited a broadened waterfall curve not seen with the other MODCODs (see Figure 8 vs Figure 9). The cause of this is unknown; error floors are not expected with these codes. This behavior explains the 1 dB difference in thresholds for MODCOD 1 in Table III, since the 300 kBaud FER curve was extrapolated several orders of magnitude. The 300 kBaud case may have the same performance issue; however, the increased measurement time required made the test impractical.

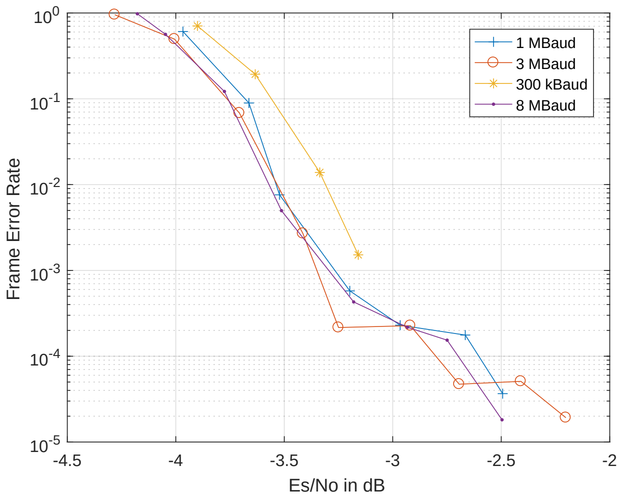

Fig. 8. FER Results for MODCOD 1

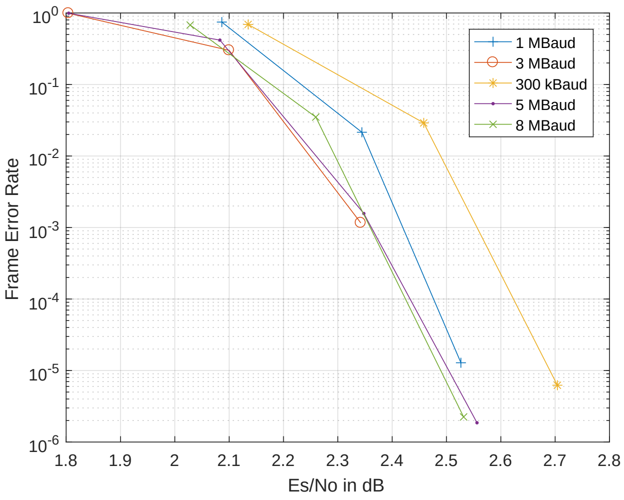

Fig. 9. FER Results for MODCOD 5

2) Receiver Acquisition Performance: An important aspect of receiver operation is the ability to acquire in the presence of carrier offsets and noise. Table IV shows the effect of changing the following categories on the receiver's average acquisition time: carrier frequency offset, Es/No, symbol rate, and pilot tone insertion status. The observed acquisition time is the result of polling the receiver status using the SNMP protocol.

TABLE IV
RECEIVER ACQUISITION TIME IN SECONDS AT HIGH SNR AND NEAR THE QEF ES/NO THRESHOLD

		300 kBaud				**3 MBaud**				**Symbol Rate**
		40 kHz		*80 kHz*		*40 kHz*		*80 kHz*		*Carrier Offset*
MODCOD	**Pilot**	**Near QEF**	**High SNR**	**Near QEF**	**High SNR**	**Near QEF**	**High SNR**	**Near QEF**	**High SNR**	
1	ON	2.26	1.82	3.77	2.57	0.72	0.56	0.21	0.70	
1	OFF	3.10	2.29	9.75	2.89	0.93	0.40	0.42	0.61	
12	ON	2.15	1.42	2.79	2.30	0.43	0.54	0.52	0.59	
12	OFF	1.39	1.36	5.90	2.63	0.53	0.78	0.57	0.42	
18	ON	1.54	1.21	3.13	5.09	0.68	0.75	0.43	0.56	
18	OFF	3.47	5.62	19.23	6.78	0.74	0.73	0.59	0.92	
24	ON	1.02	2.37	3.92	2.07	0.87	0.58	0.71	0.42	
24	OFF	2.76	4.04	4.03	2.71	0.57	0.69	0.38	0.68	

The following observations are made from data contained in Table IV. In general: 1) Applying a larger frequency offset increases the acquisition time. 2) Disabling pilot tones increases the acquisition time. 3) Reducing the SNR increases the acquisition time. 4) For 3 MBaud, receiver acquisition is near instantaneous, however there is latency in polling the lock indicator. For 300 kBaud, most cases take approximately 2-3 seconds to acquire. There was one unexpected outlier for 300 kBaud, MODCOD 18 at 80 kHz offset with pilots off, which took 19 seconds to acquire.

3) Doppler Performance Characterization: A Doppler shift is emulated by frequency modulating the synthesizer shown in Figure 7 with a waveform generator. By modifying the period and peak-to-peak voltage of the triangle wave, Doppler rate and offset are respectively changed. For all data shown in Table V, no bit errors were observed. The Doppler offset was swept between ±80 kHz, and pilots were enabled at the DVB-S2 physical layer. The targeted Es/No was within 1 dB of the QEF threshold (or less).

TABLE V
DOPPLER RATE/OFFSET PERFORMANCE FOR ±80 KHZ

	300 kBaud		3 MBaud	
MODCOD	**Es/No (dB)**	**Doppler Rate (Hz/sec)**	**Es/No (dB)**	**Doppler Rate (Hz/sec)**
1	-1.27	160	-1.99	3200
12	5.98	160	6.21	3200
18	10.43	160	10.61	3200
24	15.63	160	14.41	3200

For 3 Mbaud, the receiver will handle Doppler rates of greater than 3.2 kHz/sec. For 300 kBaud, additional testing proved that 175.2 Hz/sec is the worst-case allowable Doppler rate. The expected worst case Doppler rate for SCaN Testbed over the relay satellite link is ~50 Hz/sec, therefore no Doppler compensation from the Space Network is required.

VI. LINK BUDGET

The link budget for this scenario is described in Tables VI and VII. For the SCaN Testbed link, the results generally follow the GSFC Communications Link Analysis and Simulation System (CLASS) analysis, with some updated numbers based on actual performance. The predicted performance of the MGA path with 300 kBaud is 623 kbps of user information, with no margin, using 8-PSK modulation and a 3/4 LDPC code. At 4 MBaud, the predicted performance is 1.43 Mbps, using QPSK and a rate 1/4 LDPC code. For the LGA path (not described in Table) the predicted performance is 107 kbps, using QPSK modulation and a rate 1/4 LDPC code. Note that the transmit power of the JPL transmitter was conservatively backed off from the 1 dB compression point by 3.7 dB for all MODCODs to accommodate the high-order modulations.

TABLE VI
SCAN TESTBED LINK BUDGET

Parameter	**Value**	**Notes**
Frequency (MHz)	2216.5	6 MHz bandwidth
Transmit Power (dBW)	5.8	3.7 dB backoff from P_{1dB}
Transmit Circuit Loss (dB)	-2.4	-2.4 for MGA path, -1.6 for LGA path
Antenna Gain (dBi)	14	MGA 13.1 dBi specification, LGA 3 dBi
EIRP (dBW)	17.4	
Free Space Loss (dB)	192.14	460 km altitude, 5° TDRS elevation
Polarization Mismatch Loss (dB)	0.29	
Rx Isotropic Power (dBW)	-175.03	
TDRS G/T (dB/K)	10.7	SNUG 9.5 dB/K, CLASS: 10.7 dB/K
Boltzmann's Constant	-228.6 dBW/K/Hz	
C/No at TDRS (dB-Hz)	64.27	
TDRS Downlink C/No (dB-Hz)	94.1	
C/No at Ground (dB-Hz)	64.24	Parallel channel calculation
300 kBaud		
Net Es/No (dB)	9.47	= C/No - $10\log_{10}$(Symbol Rate)
Required Es/No (dB)	8.21	MODCOD 14: 8-PSK, Rate 3/4 Code, **623 kbps**
Link Margin (dB)	1.26	
4 MBaud		
Net Es/No (dB)	-1.78	= C/No - $10\log_{10}$(Symbol Rate)
Required Es/No (dB)	-1.845	MODCOD 1: QPSK, Rate 1/4 Code, **1.43 Mbps**
Link Margin (dB)	0.06	

The GRC ground station link budget predicts a maximum data-rate of 30.74 Mbps, using 32-APSK and a rate 5/6 LDPC code.

TABLE VII
GRC S-BAND GROUND STATION LINK BUDGET

Parameter	**Value**	**Notes**
Frequency (MHz)	2216.5	10 MHz bandwidth, Left hand circular
Transmit Power (dBW)	5	
Antenna Gain (dBi)	32	2.4m, 31.5 dB specification
EIRP (dBW)	37	
Free Space Loss (dB)	191.2	GRC to TDRS-E
Rx Isotropic Power (dBW)	-154.2	
TDRS G/T (dB/K)	10.7	SNUG 9.5 dB/K, CLASS: 10.7 dB/K
Boltzmann's Constant	-228.6 dBW/K/Hz	
C/No at TDRS (dB-Hz)	85.1	
TDRS Downlink C/No (dB-Hz)	94.1	
C/No at Ground (dB-Hz)	84.55	Parallel channel calculation
8 MBaud		
Net Es/No (dB)	15.52	= C/No - $10\log_{10}$(Symbol Rate)
Required Es/No (dB)	15.12	MODCOD 26: 32-APSK, Rate 5/6 Code, **30.74 Mbps**
Link Margin (dB)	0.4	

VII. TEST PLAN

The test event matrix is provided in Table VIII. Testing progressed from manual coding and modulation, to variable coding and modulation, and finally adaptive coding and modulation. As time permitted, additional tests were conducted with adaptive digital predistortion. Minor updates to the plan were made, as noted in the table. A general description of each test is provided below:

Manual Coding and Modulation (MCM) - Manually step through MODCODs, based on reported real-time metrics of the modem's link margin. Walk through as many MODCODs as possible to verify functionality.

Variable Coding and Modulation (VCM) - Vary the MODCOD based on predicted SNR profile, due to path loss variations throughput the pass (SCaN Testbed events only).

Adaptive Coding and Modulation (ACM) - Adapt to changing SNR from path loss variations or multi-path fading (SCaN Testbed events only). For ground station events, adapt to simulated variations with antenna mispointing or digital step attenuator.

Digital Pre-distortion (DPD) - Perform digital pre-distortion on the transmitted signal, accounting for the combined effects of the user power amplifier, and any nonlinearities from the TDRS power amplifier. The NTIA transmit license for STB is restricted to PSK modulations, therefore DPD was only planned for GRC ground station events using 16/32-APSK modulations.

TABLE VIII
TEST PLAN

Date	Event #	Mbaud	TDRS	Tx Source	MCM	VCM	ACM	DPD	Notes
DOY[1] 264	Event 1	0.3	TDE, SA2	GRC-GS[2]	√				
DOY 264	Event 2	0.3	171, SA1	STB[3]	√				
DOY 264	Event 3	3	TDE, SA1	GRC-GS	√				
DOY 264	Event 4	3	171, SA1	STB	√				Changed from 1 MBaud
DOY 264	Event 5	5	TDE, SA2	GRC-GS	√				
DOY 264	Event 6	8	TDE, SA2	GRC-GS	√				
DOY 264	Event 7	3/4.55	TDW, SA2	STB	√				
DOY 264	Event 8	1	TDE, SA2	GRC-GS	✗				Network debug
DOY 265	Event 1	0.3	TDE, SA2	GRC-GS	✗				Network debug
DOY 265	Event 2	4.55	171, SA1	STB		√			Changed from 0.3 MBaud
DOY 265	Event 3	0.3	TDW, SA2	STB	√				LGA Event
DOY 265	Event 4	1	TDE, SA1	STB		√			
DOY 265	Event 5	0.3	TDE, SA2	GRC-GS	√				Changed from 1 MBaud
DOY 265	Event 6	4.55	TDE, SA2	STB		√			Changed from 3 MBaud
DOY 265	Event 7	3	TDE, SA2	GRC-GS	✗				Network debug
DOY 265	Event 8	1	TDE, SA1	STB		√			Changed from 3 MBaud
DOY 266	Event 1	8	TDE, SA2	GRC-GS			√		
DOY 266	Event 2	0.3	171, SA1	STB			√		LGA Event
DOY 266	Event 3	8	TDE, SA2	GRC-GS			√		
DOY 266	Event 4	0.3	171, SA1	STB			√		
DOY 266	Event 5	8	TDE, SA2	GRC-GS			√		
DOY 266	Event 6	3	TDW, SA2	STB			√		
DOY 266	Event 7	0.3	TDE, SA2	GRC-GS				√	
DOY 266	Event 8	4.55	TDE, SA1	STB			√		
DOY 266	Event 9	1	TDE, SA1	GRC-GS				√	
DOY 266	Event 9b	1	TDE,	GRC-GS				√	Additional event (TUT)[4]
DOY 266	Event 10	1	TDE, SA1	STB			√		

---

[1] Day of year (DOY)

[2] GRC-Ground Station (GRC-GS)

[3] SCaN Testbed (STB)

[4] TDRS Unused Time (TUT)

VIII. TEST RESULTS

A. *Testing with Ground Station at GRC*

1) Manual Coding and Modulation: In order to determine the operational bounds, the MODCOD was manually increased from mode 1 to 27, dwelling on each mode for at least 1 minute. The test was repeated for a set of symbol rates, including 300 kBaud, 3, 5 and 8 MBaud. Results for the 8 MBaud event are shown in Figures 10 through 13. The peak data rate observed was 33.28 Mbps (MODCOD 27 at 8 MBaud). The results for all the symbol rates are summarized in Table IX. All MODCODs had positive margin for the symbol rates tested. The estimated C/No is provided, based on the modem's Es/No estimation. Compared to the link budget predictions, the link performed ~2 dB better than expected, with the exception of the 300 kBaud case. The 300 kBaud case reported an Es/No several dB lower than expected. This could possibly be attributed to the increased impact of phase noise for low symbol rates, or degraded accuracy of the modem Es/No estimator which appears to be approaching its upper limit.

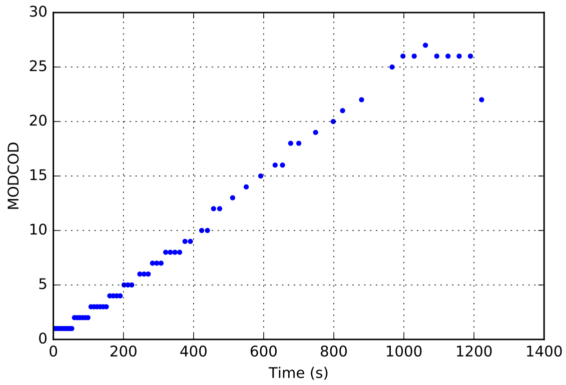

Fig. 10. MODCOD vs Time

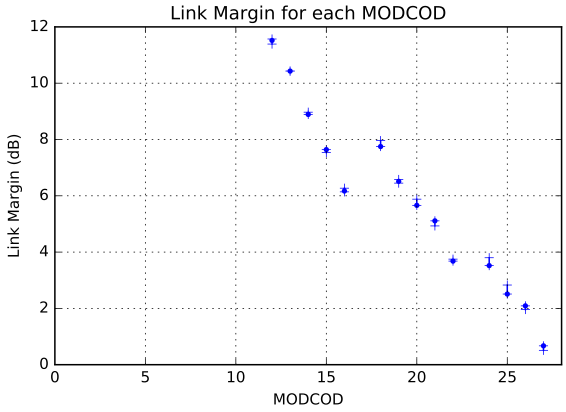

Fig. 11. Link Margin

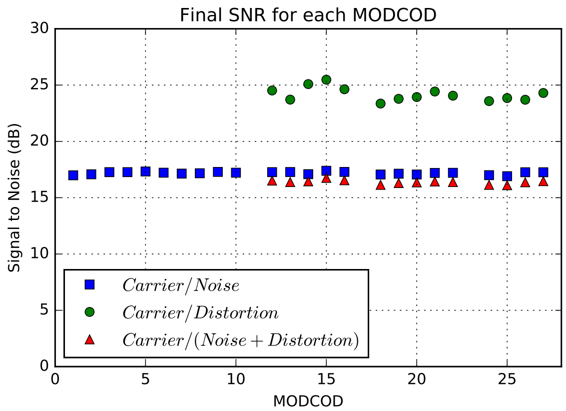

Fig. 12. SNR Metrics

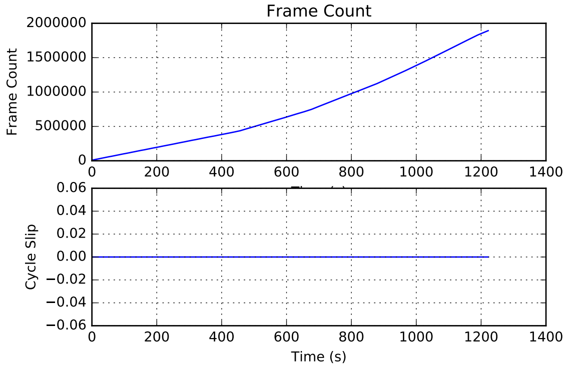

Fig. 13. Frame Count

TABLE IX
GRC-GS - MANUAL CODING AND MODULATION

Event	Symbol Rate (MBaud)	MODCODs	Peak Data Rate (Mbps)	Reported C/No (dB-Hz)	Final Margin (dB)
DOY 264, Event 1	0.3	1-27	1.25	83.4	9.12
DOY 264, Event 3	3	1-27	12.48	87	5.18
DOY 264, Event 5	5	1-27	20.80	86.66	2.78
DOY 264, Event 6	8	1-27	33.28	86.42	0.51

2) Adaptive Coding and Modulation (Simulated Dynamics): To simulate path loss variations or other link dynamics which result in time-varying signal power, two methods were employed: 1) intentionally off-pointing the GRC ground station antenna, or 2) digitally varying the transmit power. Both these methods were used to verify that the ACM controller was operating properly and could automatically compensate for the varying signal power. Antenna off-pointing is performed manually by setting a desired attenuation value, after which the antenna moves to the corresponding angle off of boresight. Due to current limitations in controlling the slew rate of the GRC ground station antenna, off-pointing could not be performed without the receiver momentarily losing lock. While the ACM controller properly adjusted for the change in signal level, a large burst of frame errors could not be avoided. Therefore, more time was spent on digitally varying the signal level using a fraction of a dB step size, which resulted in no dropped frames.

Figures 14 through 17 show results for DOY 266 Event 5, operating at 8 MBaud. The desired link margin for the ACM controller was set to 1 dB. An anomaly was observed at the beginning of this event, where uncorrectable DVB-S2 frames periodically appeared (Figure 17). The same behavior was seen in DOY 266, Event 1, where an in-band interferer was observed on the spectrum analyzer and degraded the link performance. It is believed that the same interferer also degraded this event during the first 5 minutes, since the same MODCODs operated error-free at the end of the event. Figure 14 shows the calculated link margin versus time. The system was able to maintain the specified 1 dB link margin, until the Es/No dropped below -0.8 dB (which corresponds to the lowest MODCOD). Although the calculated link margin goes negative, no frames are lost since the time spent below margin is minimal.

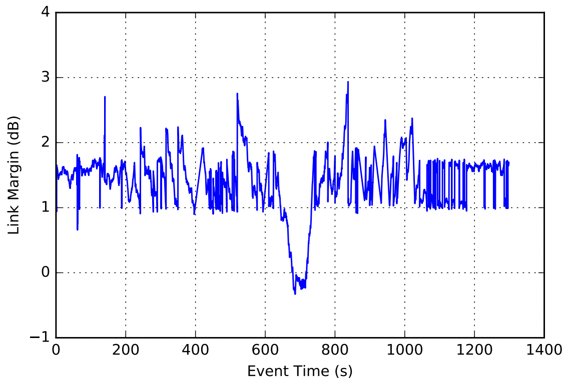

Fig. 14. Link Margin vs Time

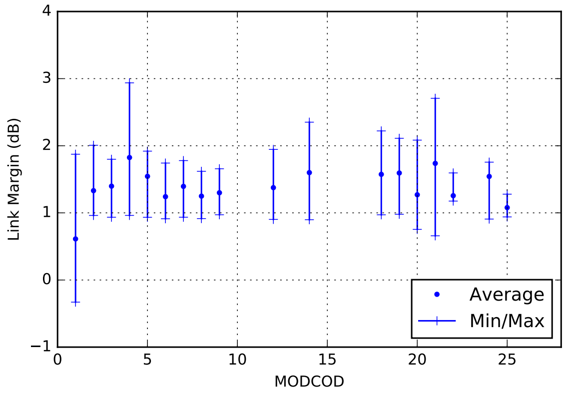

Fig. 15. Link Margin vs MODCOD

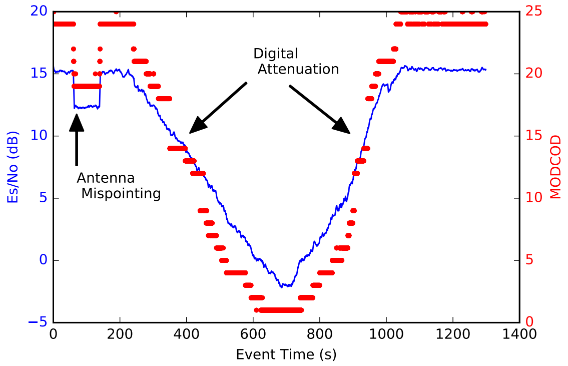

Fig. 16. ACM Controller Log

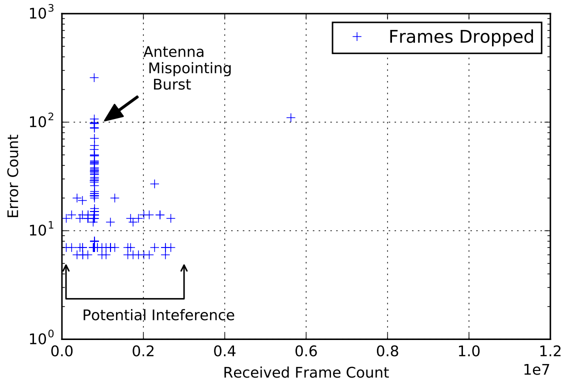

Fig. 17. Frame Count

3) Adaptive Digital Pre-distortion: Digital pre-distortion (DPD) is a mechanism for applying the inverse distortion of a signal to compensate for varying amounts of amplifier non-linearities (i.e., AM/AM, AM/PM) that result from being driven with too much input power. Primarily, it is intended for use with multi-level modulation schemes (e.g., 16-APSK, 32-APSK) that are susceptible to amplitude-dependent effects and increased sensitivity to noise. The overall goal is to achieve better link performance with decreased amplifier input back-off.

Additionally, there is a desire to adaptively generate DPD updates. Fundamentally, power amplifiers have frequency- and temperature-dependent performance, which can change over time. Therefore, the ability to apply iterative corrections and converge on an optimal output would enable in-situ characterization. As a result, a slight modification was made to the waveform application, adding the ability to reprogram its I/Q constellation points on a per-MODCOD basis (see Figure 3). This information is sent to the transmit waveform on the spacecraft using a specific Virtual Channel ID in the forward link AOS frame structure and is protected by the Frame Error Control Field.

To measure the non-linear distortions of the received signal, a Rohde and Schwarz signal analyzer (FSW-43) was used in Vector Signal Analyzer mode. Computing new DPD coefficients begins with measuring the centroid of the received symbols based on their nearest constellation point. Next, an amplitude adjustment factor is computed for each centroid. Following that, constellation centroids are grouped per amplitude-level, and a phase adjustment factor is computed for each centroid in the group. Lastly, new I/Q constellation points are sent to the spacecraft and are applied to the current transmitter MODCOD configuration.

Adaptive DPD was successfully demonstrated during several of the GRC ground station events, as the closed-loop adaptive system was able to iteratively resolve AM/AM and AM/PM distortions. The primary source of the distortions was the user power amplifier; TDRS did not significantly distort the signal. Figure 18 shows the inherent non-linear effects before applying adaptive DPD, and Figure 19 shows the result after algorithm convergence. In both figures, cyan markers represent noisy received symbols, red markers represent the true symbol location defined by the DVB-S2 standard, and black markers represent the centroided symbols after nearest neighbor grouping.

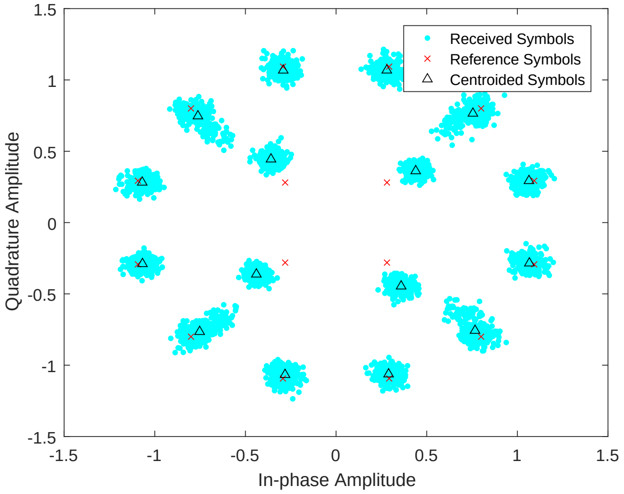

Fig. 18. Received Constellation Before Adaptive DPD

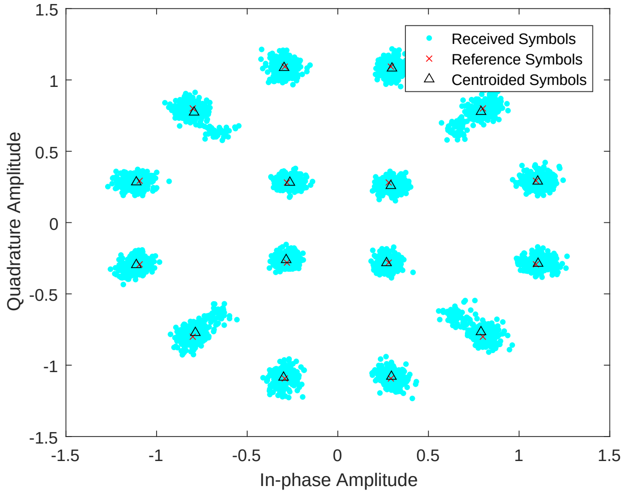

Fig. 19. Received Constellation After Adaptive DPD

B. Testing with SCaN Testbed

1) Manual Coding and Modulation: Similar to the GRC ground station testing, the MODCOD was manually increased in order to determine the operational bounds. The reported Es/No and link margin from the Newtec modem were monitored throughout the event. A set of symbol rates were tested, including 300 kBaud, 3 MBaud, and 4.55 MBaud. Results for the 3 MBaud event are shown in Figures 20 through 23. The large bursts of errors in Figure 22 are the result from an unsuccessful attempt to use MODCOD 8, as well as a signal fade which produced a negative link margin. The results for all the symbol rates are summarized in Table X. The peak data rate observed was 5.7 Mbps (MODCOD 27 at 4.55 MBaud). The estimated C/No is provided, based on the Newtec modem's Es/No estimation. Compared to the link budget predictions in section VI, the link performed ~6 dB better than expected.

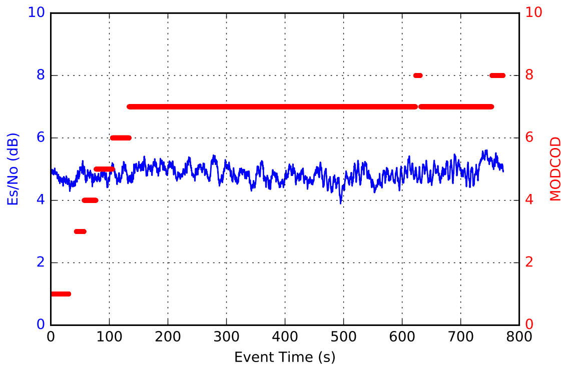

Fig. 20. Es/No and MODCOD vs Time

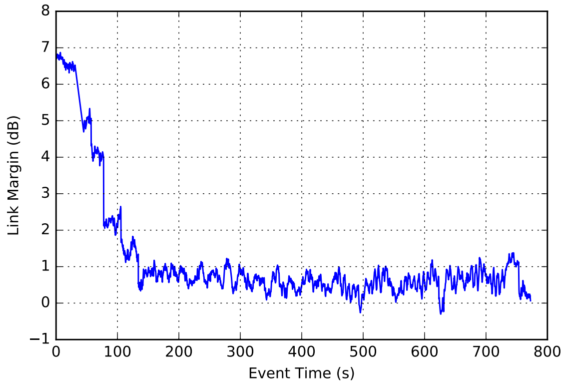

Fig. 21. Link Margin vs Time

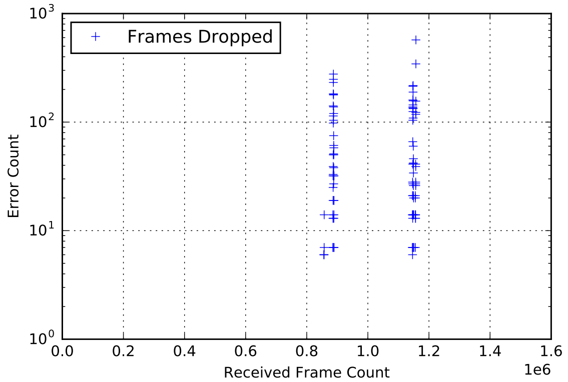

Fig. 22. Frame Count

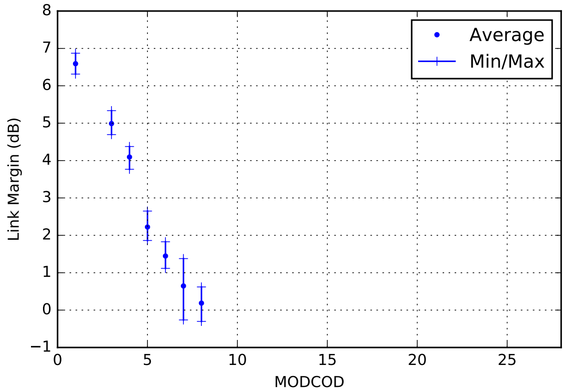

Fig. 23. Link Margin vs MODCOD

TABLE X
SCAN TESTBED - MANUAL CODING AND MODULATION

Event	**Symbol Rate (MBaud)**	**Max MODCOD**	**Peak Data Rate (Mbps)**	**Reported C/No (dB-Hz)**	**Max MODCOD Avg. Margin (dB)**
DOY 264, Event 2	0.3	16	0.76	70.4	3.69
DOY 264, Event 4	3	7	4.17	70.0	0.65
DOY 264, Event 7	4.55	6	5.74	70.8	0.22

2) Variable Coding and Modulation: The path loss variation of a typical relay satellite link varies by 1-2 dB. While VCM is better suited for direct-to-Earth links, it can provide minimal gains over a relay link if the MODCOD is adjusted accordingly throughput the pass. For this experiment, link predictions were calculated using orbital analysis tools. An example pre-event analysis is shown in Figure 24. The optimal symbol rate which maximizes the total data throughput is 4.55 MBaud. At this optimal data rate, VCM provides a 0.4 dB improvement in throughput versus staying at the same MODCOD throughput the event (constant coding and modulation (CCM)). The CCM mode is determined by the highest MODCOD with at least 1 dB margin at the lowest expected SNR during the event.

In a relay satellite scenario, VCM could also be used to handle different quality of service (QoS) data streams. For example, critical telemetry could always be transmitted with the most robust mode (MODCOD 1), while science data could be simultaneously transmitted at a higher MODCOD.

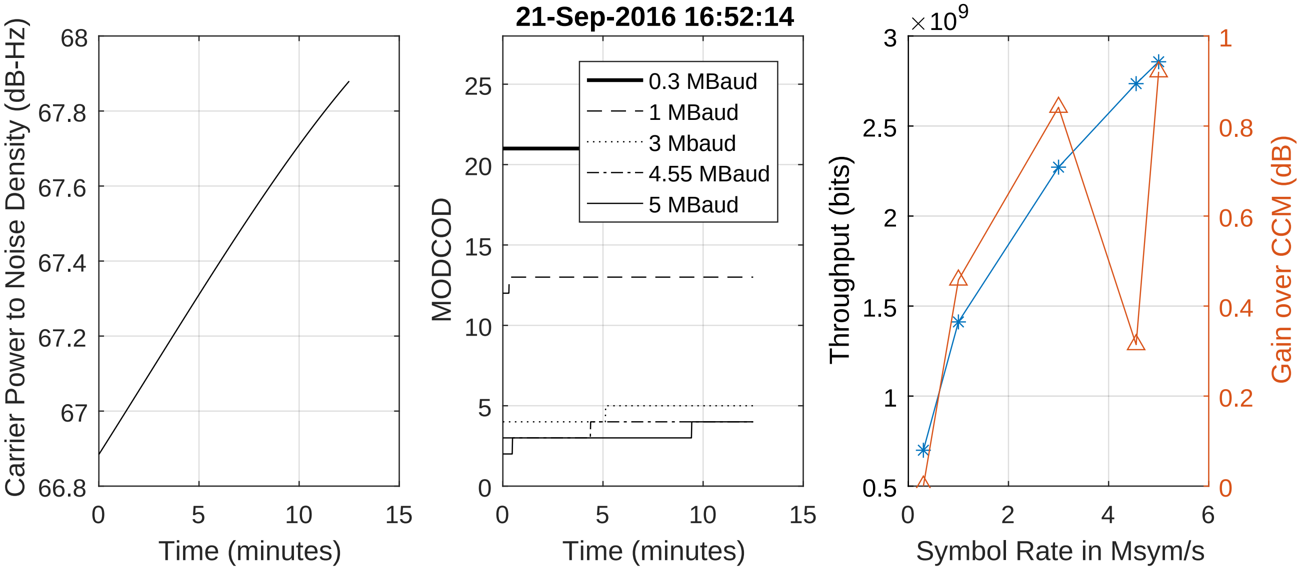

Fig. 24. VCM Pre-event Analysis

A summary of the VCM results is provided in Table XI. Since the link analysis in Section VI was conservative, the actual link margin is around 3 to 4 dB throughout the event, instead of the targeted 1 dB margin. Performance could also vary between different TDRS's, etc. Dropped frames are only observed at the higher baud rate (4.55 MBaud), the 1 MBaud test cases operated without error. The frames were received properly at the Newtec receiver, but were dropped in the network between WSC and GRC. More information on the network layer issue is provided in Section IX.

TABLE XI
VARIABLE CODING AND MODULATION RESULTS

Event	Symbol Rate	Gain over CCM	Link Margin	AOS Dropped Frames	Bit Errors
DOY 265, Event 2	4.55	0.3	3±1	8 / 1.2e6	0
DOY 265, Event 4	1	0.35	4.5±1	0 / 4e5	0
DOY 265, Event 6	4.55	0.76	3±1	17 / 1.7e6	0
DOY 265, Event 8	1	0.33	4.3±1	0 / 4e5	0

3) Adaptive Coding and Modulation: A total of five ACM events were run over various symbol rates, including 0.3, 1, 3 and 4.55 MBaud. The target link margin for the ACM controller was set to 1 dB for all events. The raw Es/No values were low-pass filtered with a 1-2 second integration window to remove noise. Table XII provides a summary of all events, including the number of dropped frames and bit-errors. Results for the 4.55 MBaud event are shown in Figures 25 and 26. The ACM controller was generally able to maintain at least 1 dB link margin throughout the event.

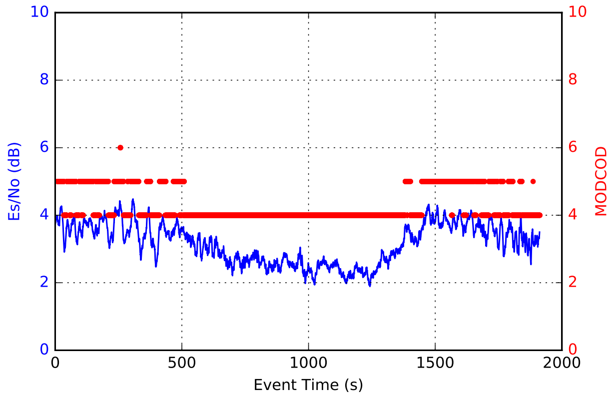

Fig. 25. Event 6: 4.55 MBaud, Es/No and MODCOD vs Time

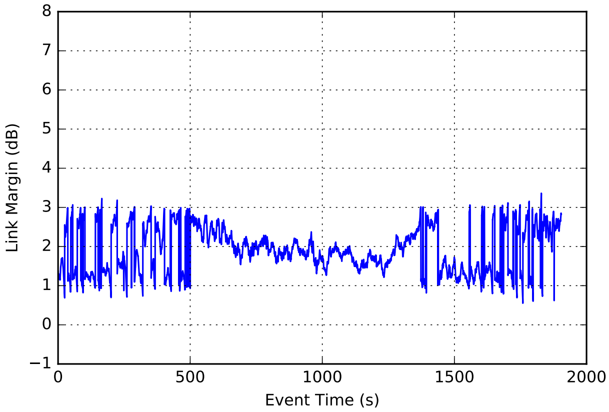

Fig. 26. Event 6: 4.55 MBaud, Link Margin vs Time

One event was run over the Space Network using the LGA path. Results are shown in Figures 27 and 28. Note the ACM controller was unable to maintain 1 dB margin, and that the MODCOD values fluctuate throughout the event. The most probable cause is the high variance of the Newtec MDM6000's signal-to-noise ratio estimation algorithm, especially for low symbol rates. See Figure 29 for a comparison of modem Es/No before and after low-pass filtering. Note that the filtered Es/No trace is improved but still has considerable variance, which results in unnecessary MODCOD transitions. Multi-path fading, which is more severe using the LGA path, is another possible cause of the link margin dropping below the desired threshold.

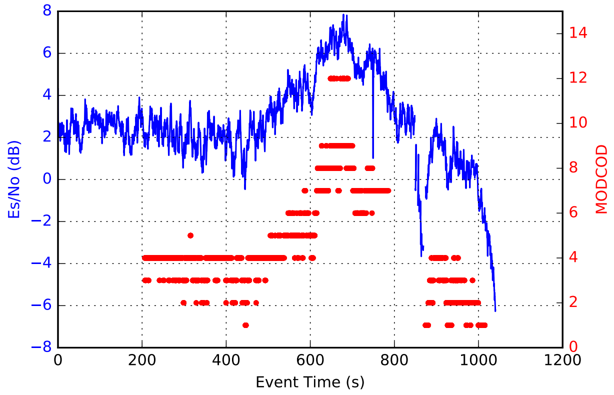

Fig. 27. Event 4: 300 kBaud, Es/No and MODCOD vs Time

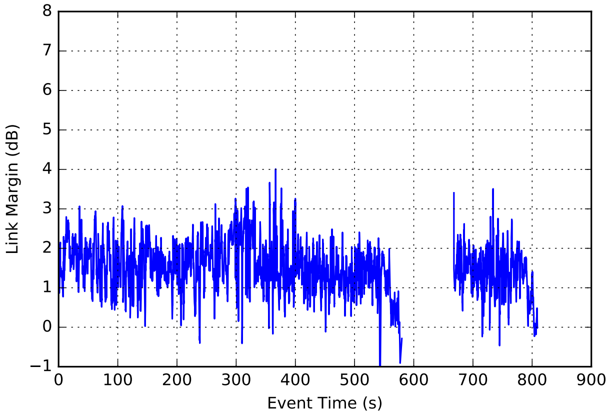

Fig. 28. Event 4: 300 kBaud, Link Margin vs Time

Toward the end of the event, the TDRS uplink was momentarily lost due to hardware malfunction. This caused the Newtec receiver to momentarily go out of lock, during which time the modem reported nonsensical Es/No values. This explains the missing data in Figures 27 and 28. The ACM controller inadvertently used these invalid Es/No estimates, which is an issue that will be corrected in future software updates.

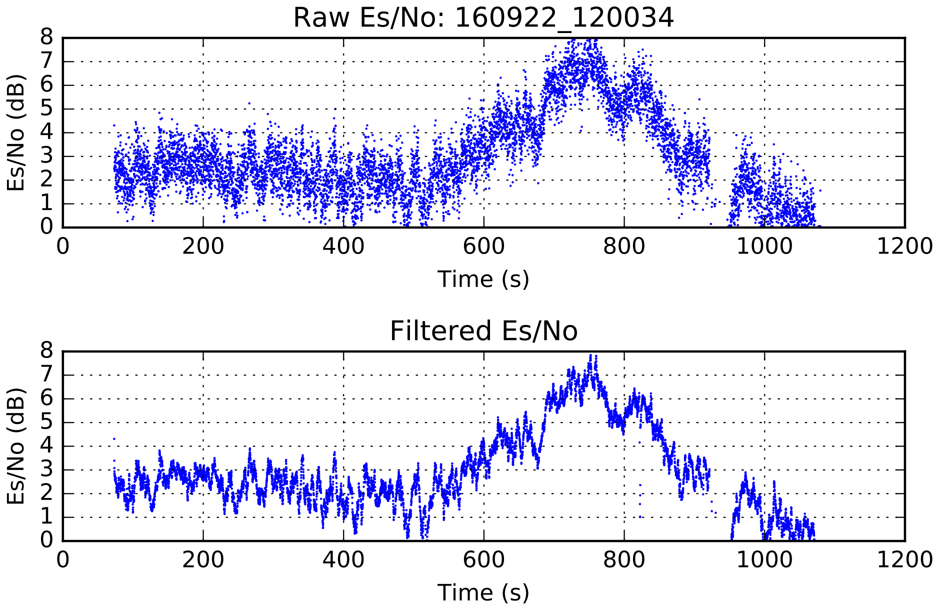

Fig. 29. Event 4: Raw and Filtered Es/No versus Time

TABLE XII
ADAPTIVE CODING AND MODULATION RESULTS

Event	**Symbol Rate**	**AOS Dropped Frames**	**Bit Errors**
DOY 266, Event 2	0.3	1838 / 98700	0
DOY 266, Event 4	0.3	102 / 0.8e6	0
DOY 266, Event 6	3	0 / 2.5e6	0
DOY 266, Event 8	4.55	71 / 3.9e6	0
DOY 266, Event 10	1	0 / 0.7e6	0

IX. LESSONS LEARNED

A. Ground IP Network Performance

During early testing, it was determined that the Newtec modem's reported baseband frame counts did not match the number of frames received by the baseband application software, indicating that frames were being dropped across the network connecting GRC and WSC. In some cases, the AOS frame drop rate was 1e−3 for the highest symbol rates. The first attempt to address the problem was to increase the default Windows socket buffer size from 8 kB to 2 MB, which solved the issue for some events, but other events still had a frame drop rate of 1e−5. The second attempt to address the problem was to port the application from Windows to Linux so that the application could be run remotely on a Linux computer that was physically located at WSC, eliminating as much network as possible. Results for 4.55 MBaud indicate that the networks drops were eliminated (previously a frame drop rate of 1e−5). Further testing is required at the highest symbol rates (8 MBaud) to verify that this configuration solves the networking issue.

If drops of this nature are to be completely eliminated in the future, the baseband application software would be best served by connecting the host PC directly to the modem, removing all network hops. It is also recommended that the data be converted to a two-way protocol, such as Transmission Control Protocol (TCP), for increased reliability. User Datagram Protocol (UDP) is susceptible to both packet loss and packets arriving out of order. When in transport bypass mode (needed for CCSDS frames), UDP is the only protocol that the Newtec modem currently supports, so additional hardware is needed to implement reliability through TCP.

B. Feedback on CCSDS over DVB-S2 Standard

The DVB-S2 transmit waveform uses the CCSDS recommendation [1] to provide the interface between the CCSDS AOS Space Data Link Protocol [7] and the DVB-S2 standard [6]. Specifically, fixed length Transfer Frames are inserted into the data field portion of the DVB-S2 baseband frame, and the DVB-S2 baseband header is configured for a single input, continuous generic stream. As a result, the software that processes received baseband frames from the modem must synchronize to the ASM inserted between Transfer Frames without prior knowledge of the ASM's location. Due to the potential frame asynchronicity that exists from differences between Transfer Frame length and the data field length of the DVB-S2 baseband frame, this is especially problematic when received frames are dropped by the physical layer. Additionally, it is customary of other framing protocols to automatically provide a trailing checksum when a user frame is fragmented between multiple baseband (physical layer) frames. When using the continuous generic stream mode, there is no checksum for fragmented data verification.

However, if using the packetized generic stream mode defined in the DVB-S2 standard, the location of the ASM is embedded within the baseband header. Therefore, ASM synchronization is not needed and dropped baseband frames are handled much more easily. However, to use the packetized generic stream mode defined in the DVB-S2 standard, minor waveform changes are required to properly utilize the previously unused baseband header fields. While the continuous generic stream mode was sufficient for our testing, it is recommended that the packetized generic stream mode be evaluated for inclusion into the CCSDS standard.

In the case of variable length user data frames, such as Internet Protocol (IP) data, different encapsulation methodologies should be investigated to determine the optimal method for the use case. One common practice is to embed IP traffic into an MPEG transport stream, which has a common packet size of 188 bytes. Both Multiprotocol Encapsulation (MPE) and Unidirectional Lightweight Encapsulation (ULE) employ this approach. In contrast, Generic Stream Encapsulation (GSE) allows for use of variable length packets, allowing for a reduction in framing overhead compared to MPE/ULE and improved performance in VCM/ACM systems. It should be noted that the commercial modems, including the Newtec MDM6000, already include support for MPE, GSE, and ULE. In conclusion, when variable length user data frames are used, a different strategy may be required than the one taken with this implementation, and the optimal framing method is dependent on the type of user data to be transferred over the link.

C. Variance of Received Signal Strength Indicator

The Received Signal Strength Indicator (RSSI) plays an important role in an ACM system, as it is used to choose the optimal MODCOD setting based on the current signal-to-noise ratio estimate. Deviation between the true Es/No and the Newtec-reported Es/No causes operation above or below the desired system margin, which can negatively impact the link performance. The discrete probability density function (PDF) observed for a fixed signal-to-noise ratio during modem characterization is shown in Figure 30. The spread of the RSSI metric follows that of a Gaussian random variable.

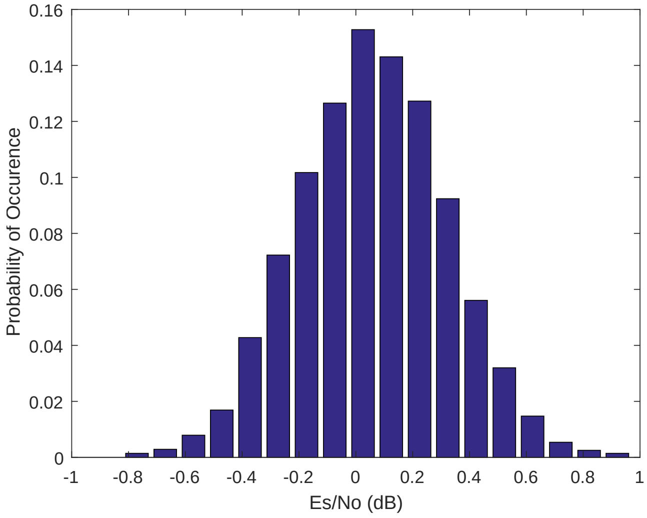

Fig. 30. Discrete PDF of RSSI Metric for MODCOD 3 at 3MSym/s. Note that the Es/No QEF threshold for MODCOD 3 is -0.065 dB.

TABLE XIII
STANDARD DEVIATION OF RSSI DATA FOR FIXED SNR

	Symbol Rate (MBaud)				
MODCOD	**0.3**	**1**	**3**	**5**	**8**
1	0.727	0.466	0.281	-	0.173
2	-	-	0.267	0.204	0.171
3	-	-	0.263	-	0.159
4	-	-	0.250	-	0.168
5	0.656	0.406	0.255	0.199	0.149
6	-	-	0.254	-	0.152
7	-	-	0.251	-	0.150
8	-	-	0.242	-	0.157
9	-	-	0.243	-	0.148
10	0.612	0.391	0.238	0.178	0.142
12	0.534	0.338	0.198	0.160	0.122
13	-	-	0.190	-	0.117
14	-	-	0.190	-	0.120
15	-	-	0.201	-	0.122
16	0.552	0.318	0.185	0.152	0.122
18	0.493	0.286	0.163	0.135	0.105
19	-	-	0.175	-	0.103
20	-	-	0.169	-	0.109
21	-	-	0.167	-	0.103
22	0.483	0.293	0.171	0.132	0.104
24	0.445	0.261	0.155	0.122	0.092
25	-	-	0.159	-	0.096
26	-	-	0.150	-	0.094
27	0.451	0.251	0.155	0.118	0.093

Table XIII displays the standard deviation $\left(\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}\right)$ of the measured RSSI metrics with respect to MODCOD and symbol rate. Data was collected during modem characterization, and therefore, some entries are not populated. However, enough data exists to make the following conclusions regarding the performance of the Es/No estimator. 1) Increasing symbol rate decreases estimator variance, as shown by moving left to right column-wise through the table. 2) Increasing MODCOD decreases estimator variance, as shown by moving top to bottom row-wise through the table. This is most noticeable for MODCODs 1-10 (QPSK). 3) Large discontinuities exist at modulation type boundaries (e.g. MODCOD 10 to 12), despite many of these cases having very comparable SNRs. Therefore, this suggests that the estimator algorithm has strong dependence on modulation type.

Since DVB-S2 physical layer frames have decreasing total number of symbols for increasing modulation order, this allows for more received frames in a given period of time. Also, increasing the symbol rate increases the amount of physical layer frames received in a given period of time. Therefore, it is a reasonable assumption that having more received frames produces a RSSI metric with less variance, as this offers an explanation for Table XIII's results.

Future ACM testing should account for the variance of the RSSI (Es/No) estimator. An optimal estimator should be developed to reduce the mean square error of the Newtec's RSSI estimator, especially for low symbol rates. This will reduce unnecessary MODCOD transitions in an ACM system. Alternatively, a different receiver with a better Es/No estimator could be pursued.

D. *TDRS Nonlinearity*

Simulations of the worst-case TDRS non-linearity were run using the amplifier characteristics (AM/AM and AM/PM) provided in [14] for the 225 MHz service. Since the SNUG performance specifications are similar with respect to AM/AM and AM/PM, it's assumed that the S-band single access return service also has the same amplifier response. These distortions are conservative based on 1st and 2nd generation measurement data. The simulation results for 32-APSK modulation are shown in Figure 31, assuming the worst case drive level to the TWTA on TDRS. Note the amplifier compression and phase shift between the constellation points.

For this experiment, the GRC ground station only had events with TDRS East, a 3rd generation satellite, which revealed little to no distortion (see Figure 32). One possible explanation is that the 3rd generation satellites may use linearized TWTAs (L-TWTAs), or the actual drive level to the TWTA is further backed-off from saturation from the simulation. The conclusion is that in this test configuration, the TDRS nonlinearity was not a limiting factor for high-order modulations.

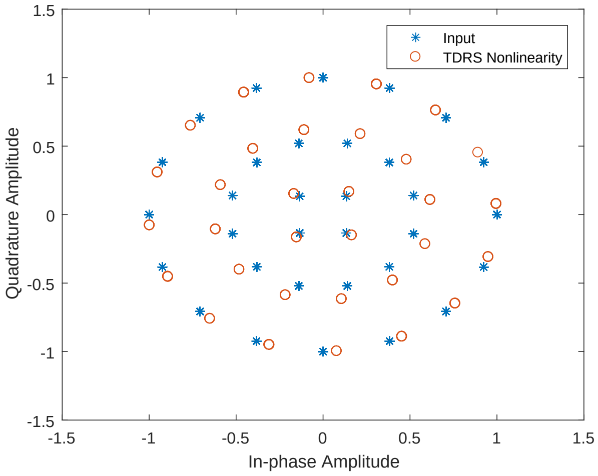

Fig. 31. Simulated Worst Case TDRS Nonlinearity

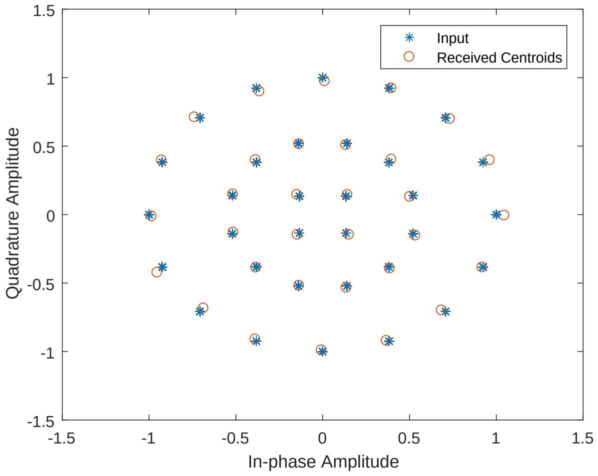

Fig. 32. Observed TDRS Nonlinearity

E. *QEF Thresholds for ACM System*

The modem was characterized for QEF performance in an AWGN channel. In live-sky testing, the presence of interferers appeared to degrade the performance, requiring additional margin. The lesson learned is to apply more link margin (more than the 1 dB used in this testing) to account for potential interference or signal fades. Furthermore, by monitoring link performance (including erroneous or dropped frames, or other telemetry available from the modem), the QEF thresholds for ACM could be updated in real-time, avoiding performance degradation. This can be considered a form of active interference mitigation.

X. APPLICATION EXAMPLE: HUBBLE SPACE TELESCOPE

Although the GRC ground station has a higher EIRP than a typical S-band user of the Space Network, it is interesting to note that other NASA missions also have do higher EIRPs. For example, the Hubble Telecommunication System has a high gain 52-inch parabolic dish antenna with a 13.5 W power amplifier. Although the Hubble RFICD does not provide sufficient information for a detailed analysis, it is apparent from Table XIV that the Hubble telecommunication system could support high rates on the order of 10 Mbps with an advanced waveform such as DVB-S2. Due to the improved performance of modern LDPC codes and bandwidth-efficient modulation, this would be a substantial improvement over the 1 Mbps currently used, under the same 6 MHz bandwidth limitation. The Command and Data Handler on Hubble has a 12 Gbit data recorder that is used to store science data (images). Either test case (25 or 35 dBW) with a DVB-S2 waveform would be able to empty the 12 GBit buffer within a single 30 minute event, versus 6-7 events at 1 Mbps.

TABLE XIV
LINK BUDGET FOR HUBBLE EXAMPLE

Parameter	**Value**	**Notes**
Frequency (MHz)	2216.5	
Transmit Power (dBW)	11.3	13.5-Watt
Transmit Circuit Loss (dB)	5*	Unknown losses
Antenna Gain (dBi)	27.5*	52-inch dish, 60% efficient
EIRP (dBW)	33.8*	Minimum of ~ 25 dBW based on required dBW at TDRS
Net C/No at Ground (dB-Hz)	~72-80	
4.55 MBaud, 25 dBW		
Net Es/No (dB)	5.42	= C/No - $10\log_{10}$(Symbol Rate)
Required Es/No (dB)	4.9	MODCOD 8: QPSK, Rate 4/5 Code, **6.71 Mbps**
Link Margin (dB)	0.52	
4.55 MBaud, 33 dBW*		
Net Es/No (dB)	13.42	= C/No - $10\log_{10}$(Symbol Rate)
Required Es/No (dB)	11.2	MODCOD 16: 8-PSK, Rate 8/9 Code, **11.51 Mbps**
Link Margin (dB)	2.22	

* Actual values unknown by author. Reasonable estimations are used instead.

XI. CONCLUSIONS

The commercial DVB-S2 standard was successfully demonstrated over NASA's Space Network. A DVB-S2 transmit waveform was developed and implemented on software-defined radios on the SCaN Testbed as well as an S-band ground station at GRC. The commercially available Newtec MDM6000 modem performed well, off-the-shelf, with no modifications. Peak data rates of 33 Mbps were demonstrated over the GRC S-band ground station using 32-amplitude phase shift keying (APSK) and a rate 8/9 low density parity check (LDPC) code. Advanced features of the DVB-S2 standard were evaluated, including variable and adaptive coding and modulation (VCM/ACM), as well as an adaptive digital pre-distortion (DPD) algorithm. Some refinement is needed for ACM, to compensate for the variance of the Newtec modem's SNR estimator at low symbol rates. Several lessons learned were provided, including the need to improve the network reliability between the modem at White Sands and the mission control center. Feedback on the CCSDS over DVB-S2 standard was presented with suggested improvements. Overall, this testing has shown that commercial standards are a viable alternative for future Space Network users, and provide a very flexible framework for spacecraft telemetry.

XII. FUTURE TESTING

Potential follow-on testing is provided below:

1) DVB-S2 over Ka-band
   - Add normal frames and higher data-rates. Start off with saturating the 425 Mbps capability of the Newtec MDM6000. Potential for even high rates with receivers such as the Cortex High Data-Rate Receiver (HDR) or other suitable modem.
2) CCSDS Framing Protocol Improvements
   - Investigate the packetized generic stream profile of DVB-S2, using fixed length CCSDS packets. Improves ability to track received data boundaries, especially when dealing with dropped packets (RF or network).
   - Add conversion from UDP to TCP at ground terminal for improved network reliability between DVB-S2 receiver and customer MOC.
3) Internet Protocol Support
   - Investigate IP packet encapsulation protocols supported by DVB-S2, such as MPEG Encapsulation (MPE), Generic Stream Encapsulation (GSE) and Unidirectional Lightweight Encapsulation (ULE)
   - Update waveform application and test over relevant environment to compare protocol performance.
4) Improve ACM Controller
   - Develop intelligent ACM controller which can monitor link performance and adjust link margin and/or QEF thresholds in real-time.
5) DVB-S2 Extensions (DVB-S2x)
   - Implement subset of the DVB-S2x standard, focusing on improved performance in the Very Low SNR (VL-SNR) region.
   - Potential improved resilience to interference and signal fades from VL-SNR support.
   - Test updated waveform over Space Network and compare performance with DVB-S2.

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