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Variable Coding and Modulation Experiment Using NASA's Space Communication and Navigation Testbed

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Abstract

National Aeronautics and Space Administration (NASA)'s Space Communication and Navigation Testbed on the International Space Station provides a unique opportunity to evaluate advanced communication techniques in an operational system. The experimental nature of the Testbed allows for rapid demonstrations while using flight hardware in a deployed system within NASA's networks. One example is variable coding and modulation, which is a method to increase data-throughput in a communication link. This paper describes recent flight testing with variable coding and modulation over S-band using a direct-to-earth link between the SCaN Testbed and the Glenn Research Center. The testing leverages the established Digital Video Broadcasting Second Generation (DVB-S2) standard to provide various modulation and coding options. The experiment was conducted in a challenging environment due to the multipath and shadowing caused by the International Space Station structure. Performance of the variable coding and modulation system is evaluated and compared to the capacity of the link, as well as standard NASA waveforms.

I. Introduction

Variable Coding and Modulation (VCM) is a method to increase the overall throughput and efficiency of a communication system by dynamically changing the modulation and forward error correction. When link conditions are predicted to be favorable, high-order modulations and forward error correction schemes with minimal overhead are used to maximize the data transfer. Conversely in poor link conditions, robust modulation and coding are used to maximize the link margin, but at reduced throughput. VCM techniques are effective when the link dynamics can be predicted with accurate modeling, for example, varying free-space path loss. Otherwise, adaptive coding and modulation (ACM) can be more effective, aided by a feedback path to relay channel state information back to the source.

The second generation Digital Video Broadcasting for Satellites (DVB-S2) standard [1] includes a provision for VCM and ACM functionality. While the DVB-S2 standard is primarily used within the telecommunications industry for video broadcast and Internet access, it is also applicable to spacecraft telemetry. The original application of VCM in the DVB-S2 standard was to optimize bandwidth utilization based on data priority, while ACM was used to accommodate changes in the weather (rain fade). However, it can also be used to adapt to varying noise, interference, pointing errors, and dynamic link conditions (path loss) which are seen with spacecraft operations. Due to the availability of intellectual property (IP) cores and low-cost receiver hardware, it is becoming an attractive option for certain missions. See [2] for examples of missions using or considering DVB-S2 (CubeSats, etc). Recognizing the potential application for space missions, the Consultative Committee for Space Data Systems (CCSDS) has recommended a method of using the DVB-S2 standard [3] which accommodates the preferred Space Data Link Protocol for spacecraft telemetry [4]. Other relevant CCSDS standards which support VCM are the Serial Concatenated Convolutional Turbo Codes [5], and another currently in development [6] which uses modulations and codes already defined in existing CCSDS standards [7]. Due to the availability of receiver equipment, DVB-S2 was selected for this experiment.

NASA's communication systems traditionally use constant coding and modulation, and have been designed for the worst case link margin. VCM and 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 (e.g. interference) that would otherwise disrupt the link. With the advent and maturity of space-qualified software defined radios (SDRs), these techniques are becoming viable for future missions. These technologies are the building blocks of an intelligent radio system which has increased system-wide awareness, and could one day enable autonomous (or cognitive) operation. A distinguishing feature of a cognitive application is the ability to learn from operational experience and autonomously change the adaptations to the communications environment. Figure 1 highlights the building blocks of a cognitive communication system, and the role that variable and adaptive coding and modulation has in the overall picture (point-to-point link optimization).

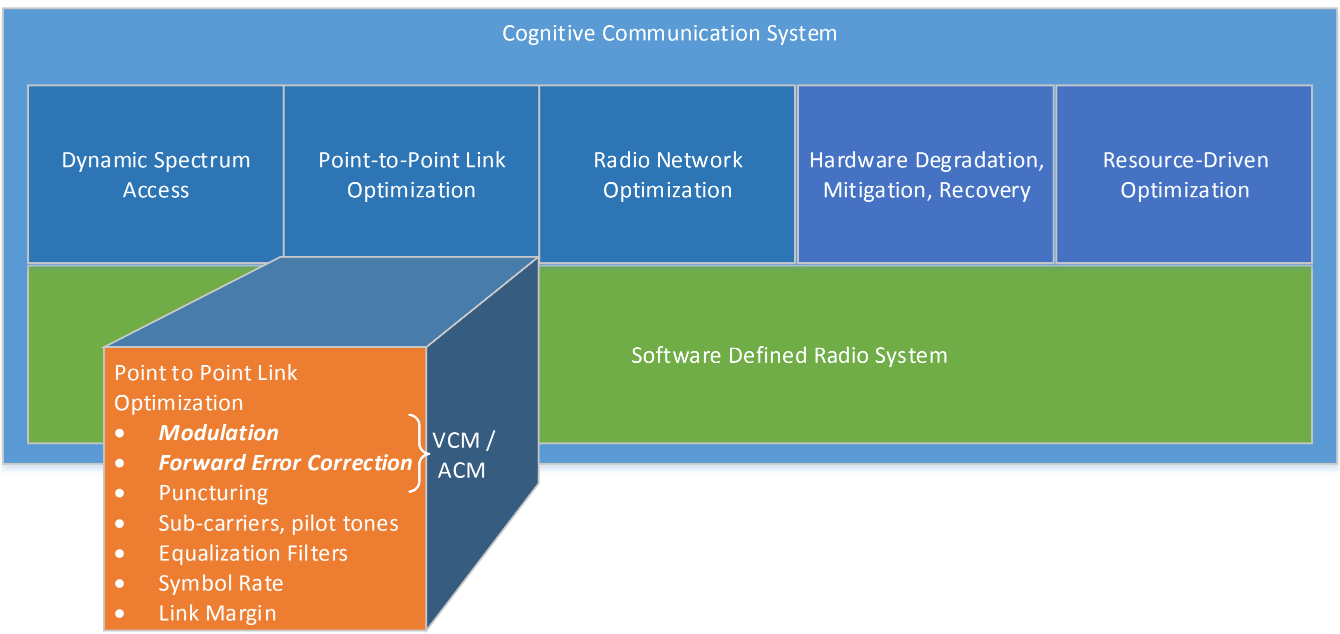

Fig. 1. Building Blocks Towards Cognitive Communication System

This report describes an experiment exploring the use of VCM techniques with a space-based SDR transceiver on-board the Space Communication and Navigation (SCaN) Testbed on the International Space Station (ISS). Link predictions are used to create a VCM profile for each event, which is translated into a script to operate the waveform. Running the experiment on ISS allows the investigation of real-world interference scenarios that arise in direct-to-ground and satellite relays. The ISS physical structure itself provides a dynamic interference environment due to the rotating photo-voltaic arrays and SCaN Testbed antenna location, especially for the direct-to-earth link. It should be emphasized that the VCM testing in this report is a precursor to closed-loop adaptive techniques (ACM) with the use of a feedback control uplink. This testing also provides an opportunity to evaluate the performance of the DVB-S2 standard and compare it to traditional NASA waveforms.

The report is organized as follows. After a brief background and summary of the objectives and test scenario, the key system components will be described. The link budget is explained, leading to prediction methods for the experiment test events. Results are presented, including a comparison with launch waveform capabilities. Finally there are conclusions and detailed event data appendices.

II. BACKGROUND

The NASA Space Communications and Navigation (SCaN) Program is responsible for providing communications and navigation services to space flight missions throughout the solar system. 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. The SDRs are reprogrammable and can run reconfigurable waveform applications. The Cognitive Communications Systems project at Glenn Research Center leverages the SCaN Testbed to advance intelligent system technologies through continued flight experiments and demonstrations. Figure 2 shows the payload enclosure and the various antenna locations. See [8] for more information on the SCaN Tested. This experiment utilizes the JPL / L3-Cincinnati Electronics SDR, and the S-band Near-Earth Network low gain antenna.

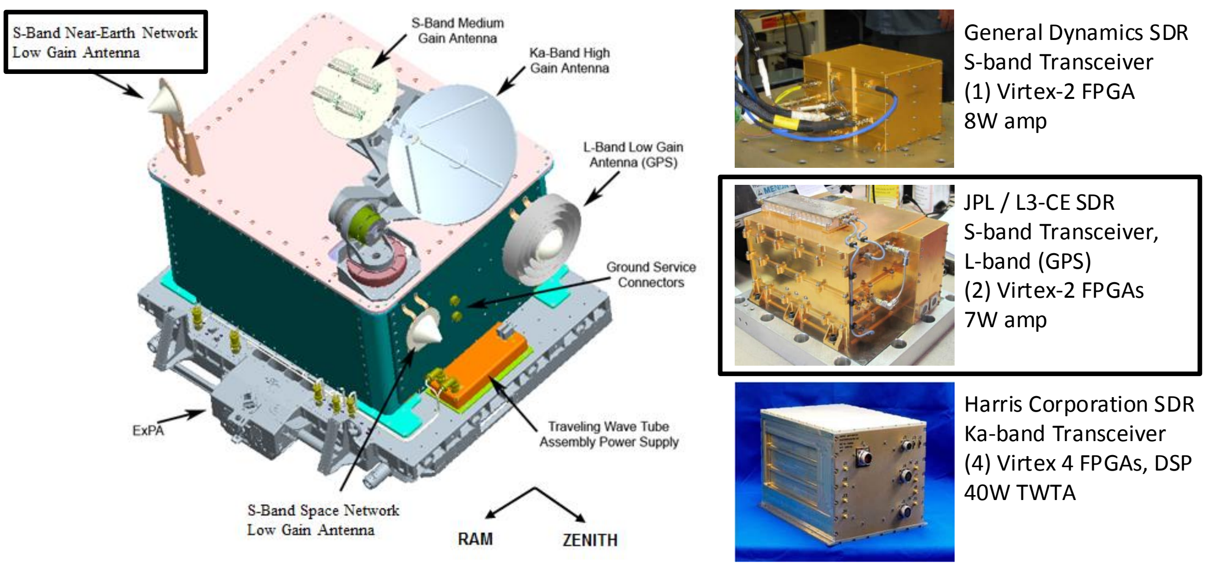

Fig. 2. SCaN Testbed

III. TEST OBJECTIVES

The testing described in this report has multiple objectives, all of which contribute to the overall Cognitive Communication Systems Project at NASA Glenn Research Center (GRC). More specifically, four objectives were primary, listed below in experiment progression order:

1) Integrate a commercial-off-the-shelf (COTS) DVB-S2 receiver with the GRC S-band Ground Station.

2) Verify that the high-order modulations used in the DVB-S2 standard function over this link. Test as many modulation and codings (MODCODs) as possible, over various symbol rates.

3) Evaluate performance of variable coding and modulation over varying link conditions. Assess ability of MODCOD changes to follow predicted link conditions and improve overall data throughput.

4) Gather data on the channel conditions for follow-on adaptive and cognitive experiments that will focus on mitigation of interference from multipath and other sources.

IV. Test Scenario

VCM techniques are typically applied to scenarios where the link dynamics can be predicted with accurate modeling, such as varying free-space loss. For this experiment, a direct-to-Earth communications link from the SCaN Testbed to the GRC Ground Station (GRC-GS) was used, as Figure 3 illustrates. The JPL SDR, loaded with a DVB-S2 waveform, transmits over S-band to the ground station and the signal is received with a commercial DVB-S2 receiver. Time triggered scripts on the JPL SDR were used to change the MODCOD as appropriate for the predicted link conditions. When the SCaN Testbed is on the horizon and the path loss is the greatest, a robust modulation is used, such as QPSK with a rate 1/4 code. As SCaN Testbed passes over the ground station, the signal-to-noise (SNR) ratio is maximized and permits high-order modulations to be used, such as 16- or 32-APSK with a rate 8/9 code. The SCaN Testbed flight computer controls and monitors the experiment via a separate ISS communications path through the Tracking and Data Relay Satellite System (TDRSS). The time triggered scripting ability permits testing to occur when the ISS communications path is not available for real-time commanding.

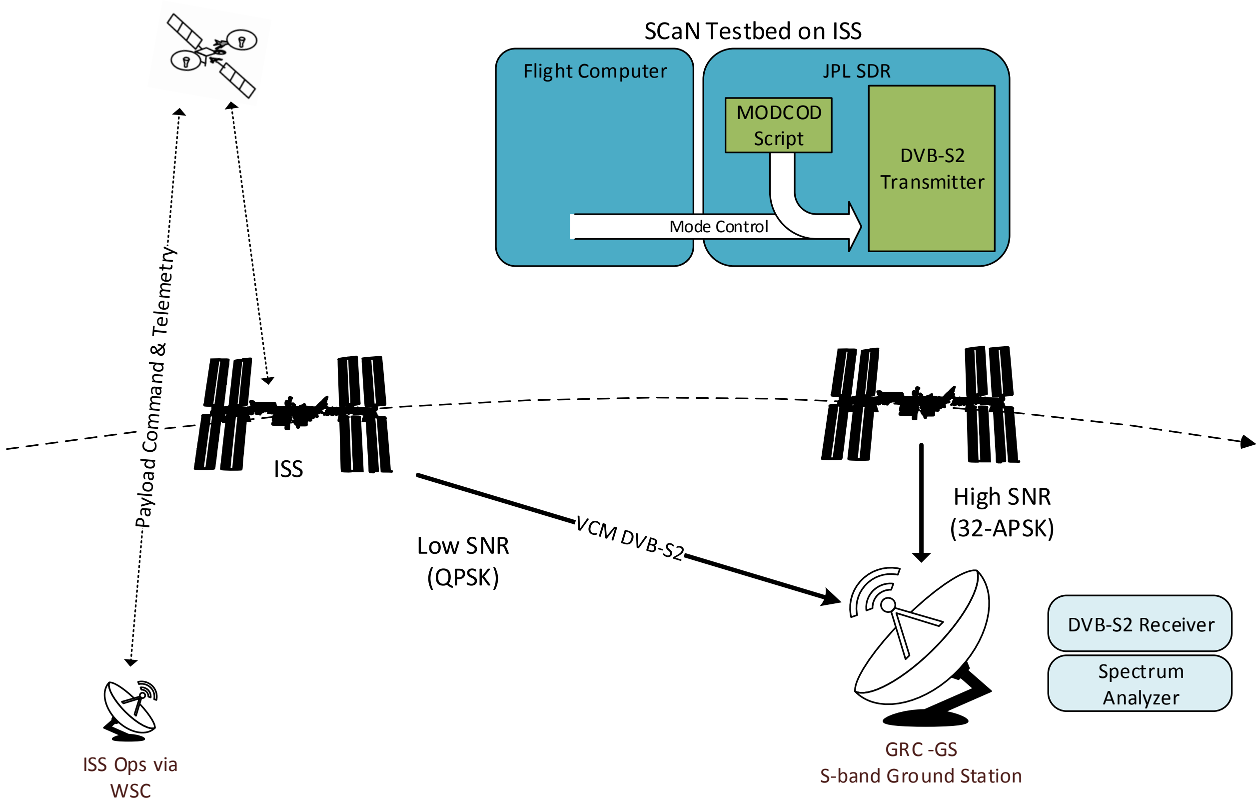

Fig. 3. Test scenario for experimental link between SCaN Testbed on ISS and the Glenn Research Center Ground Station

In addition to the varying path loss, this scenario also provides for a highly dynamic link due to shadowing/obstruction losses, and multipath effects from the complex ISS structure. See Figure 4 for a view of SCaN Testbed's location on ISS and the corresponding antenna boresight vector. Note the proximity to other payloads, and the ISS structure. Another consideration is the gain pattern of the fixed low-gain antenna, which varies as a function of angle.

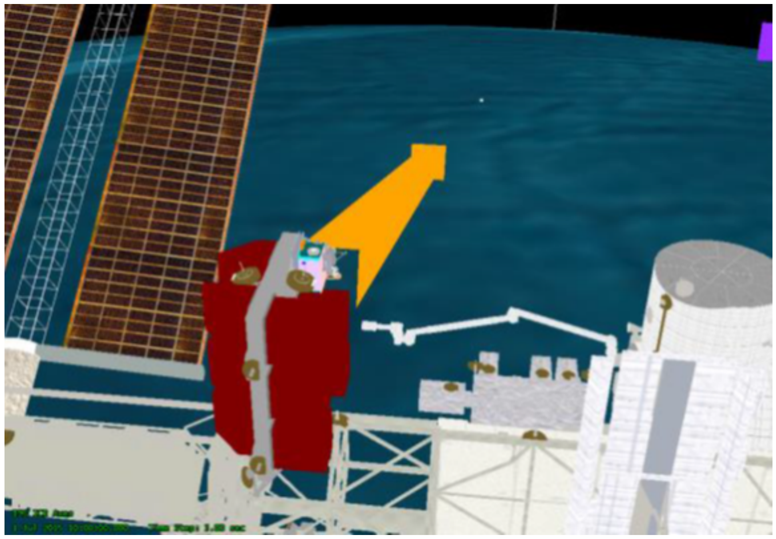

Fig. 4. SCaN Testbed onboard the ISS with boresight vector for the S-band Near Earth Network - Low Gain Antenna

A. SCaN Testbed Analysis Tool

The SCaN Testbed Analysis Tool (STAT) was used to provide detailed predictions for each event, which take into account antenna pattern variations, major line-of-sight obstructions, and averages the effects of potential multipath. Prior to this experiment, the direct-to-ground link was characterized over the course of several months, and an effective antenna pattern emerged. See [9] for details on the measurement approach. Figure 5 shows an example STAT model prediction compared to the actual received signal. Although the absolute magnitude differs by several dB, it accurately predicts when a nearby payload (the Japanese Experiment Module (JEM)) will disrupt the link, and when the signal will drop off as the antenna pattern transitions to the back lobe. This experiment attemps to account for these known obstructions by adjusting the modulation and coding (MODCOD) accordingly.

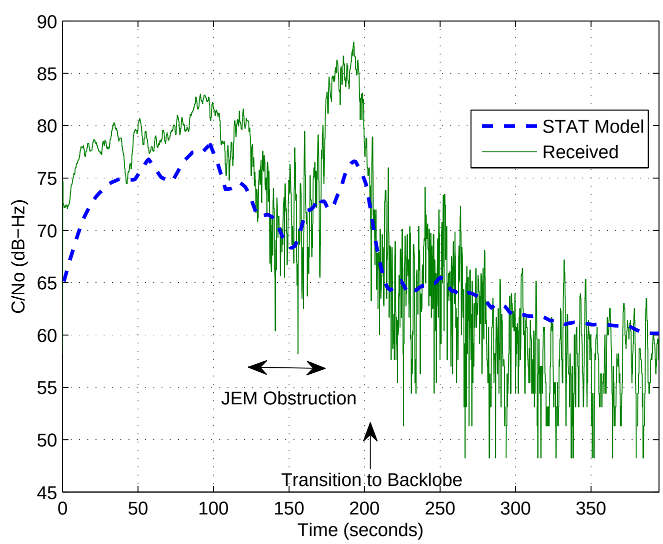

Fig. 5. STAT model prediction versus actual received signal including shadowing from JEM and multipath

B. GRC S-band Ground Station

The experimental S-band ground station (GS) used for these tests is located at GRC on the rooftop of building 110, a 3-story building. The ground station has a steerable antenna which tracks the SCaN Testbed using open-loop pointing. The GRC-GS is equipped with various power meters and a spectrum analyzer to monitor the link, as well as ports for easy integration of local ground modems and test equipment via an intra-building RF-over-fiber system. In this manner, the experimenter equipment can be adjacent to the SCaN Testbed operations center. Key ground station specifications are listed in Table I for the downlink. See [10] for more details on the GRC-GS.

TABLE I
GROUND STATION DOWNLINK PARAMETERS

Characteristic	Value
Frequency	S-band
Diameter	2.4 meter
Polarization	Left hand circular
Half-power beamwidth	3.9 degrees
Gain	31.5 dB
G/T	2 dB/K

Open-loop pointing error is an important consideration for this experiment, and is comprised of several factors: 1) Elevation angle restrictions - the GRC-GS antenna has a 10° restriction above the horizon. The beginning of each event will have additional pointing loss until SCaN Testbed is above 10° elevation. 2) Oblate versus spherical earth model - early versions of the antenna pointing software used a spherical earth model leading to pointing errors. 3) Key-hole effect - two-axis gimbaled antenna systems cannot rotate around fast enough near high elevation angles while tracking. For the GRC-GS, this occurs at elevation angles >80°.

Only the 10° elevation angle restriction was captured in the STAT model prediction at the time of testing. The spherical earth model error has been corrected in subsequent updates to the antenna pointing software, and the STAT model now accounts for the key-hole effect; however both were a source of error for this VCM experiment. Example pointing losses are shown in Figure 6 for a set of events. Note that the pointing loss for the spherical vs. oblate model error increases as a function of the elevation angle. The peak pointing error from the spherical model occurs when the signal-to-noise ratio is the highest, limiting data throughput.

C. Link Budget

The link budget for this scenario is described in Table II, using best case values for free space loss and the nominal boresight gain of the antenna. With these ideal conditions, there is sufficient link margin for the highest modulation and code rates (MODCODs) and the highest symbol rate of 4.55 MBaud. This basic link budget assumes no fade margin and the nominal boresight gain of the antenna; actual performance is dependent on the geometry, antenna pattern, and multipath environment. The spectrum license for the downlink between SCaN Testbed and the GRS-GS has 5 MHz of bandwidth, which limits the symbol rate to 4.55 MBaud.

In order to down-select potential ground station contacts, a minimum C/No of 63 dB-Hz was specified, which corresponds to an Es/No of at least 3 dB with the lowest symbol rate (1 MBaud). A higher level, 75 dB-Hz, was preferred for running higher symbol rates and high-order modulation modes. This criteria was used to down-select potential ground station contacts which were predicted to have poor signal strength, or limited duration above the specified thresholds. The thresholds are based on the performance of the commercial DVB-S2 receiver, as shown in Figure 10.

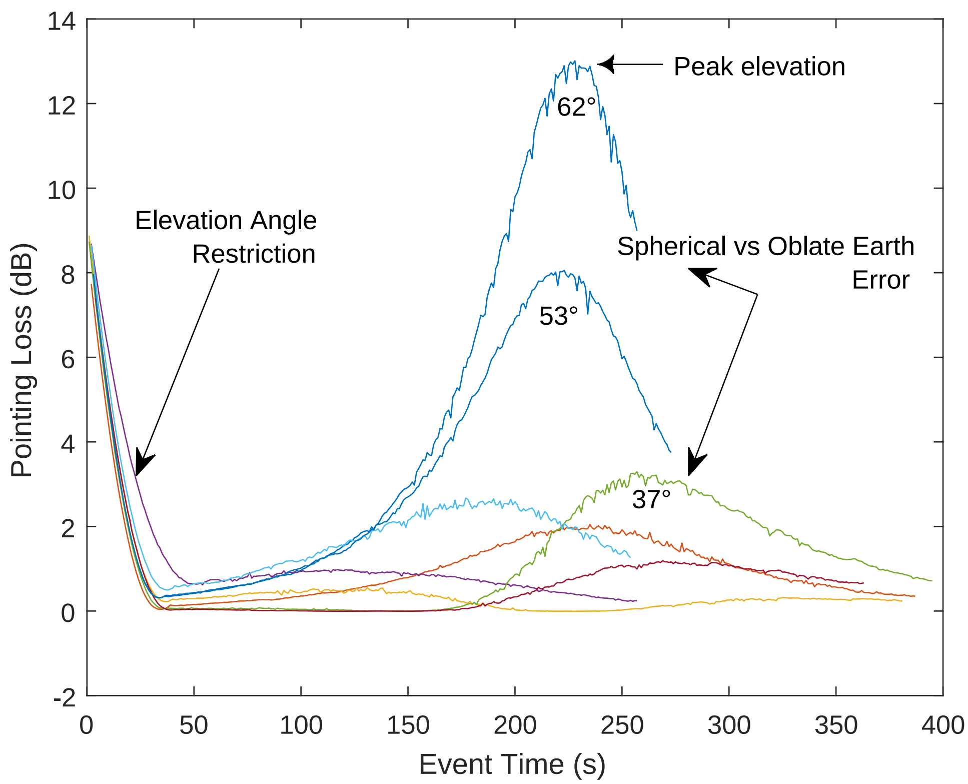

Fig. 6. Pointing Loss for Several Events

TABLE II
LINK BUDGET

Parameter	Value	Notes
Frequency (MHz)	2216.5	
Transmit Power (dBW)	7.5	
Transmit Circuit Loss (dB)	-1.7	
Boresight Antenna Gain (dBi)	1.81	Peak gain is 4.86 dBi
EIRP (dBW)	7.61	
Free Space Loss (dB)	152.62	Best case, 90 degrees elevation
Atmospheric Loss (dB)	0.37	5 degree elevation (worst case)
Rain Attenuation (dB)	0.14	99.9%
Fade Margin (dB)	0	
Ground Station Pointing Loss (dB)	2	2 dB assumed in STAT model predictions
Ground G/T (dB/K)	2	
Boltzmann's Constant	-228.6 dBW/K/Hz	
C/No at Ground (dB-Hz)	83.1	
1 MBaud		Lowest rate supported by receiver
Net Es/No (dB)	23.1	=C/No - 10log10(Symbol Rate)
Required Es/No (dB)	21.87	MODCOD 27: 32-APSK, Rate 8/9 Code
Link Margin (dB)	1.23	
4.55 MBaud		Highest rate supported in channel bandwidth
Net Es/No (dB)	16.52	=C/No - 10log10(Symbol Rate)
Required Es/No (dB)	14.45	MODCOD 22: 16-APSK, Rate 8/9 Code
Link Margin (dB)	2.07	

V. DVB-S2 Waveform Implementation

The DVB-S2 standard defines a set of modulation and coding options, designated MODCODs, which include QPSK, 8-PSK, 16-APSK, and 32-APSK. The forward error correction consists of a Bose-Chaudhuri-Hocquenghem (BCH) outer code and a LDPC inner code, with codes rates between 1/4 to 8/9 for the short frame length. A key feature of the DVB-S2 standard which is different than most communication systems used by NASA is the inclusion of a Physical Layer (PL) frame structure. 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. The various MODCODs used in the experiment are shown in Table III.

A DVB-S2 compatible transmit waveform was developed for this experiment, and implemented on the Jet Propulsion Laboratory (JPL) SDR on the SCaN Testbed. The waveform complies with the Space Telecommunications Radio Standard (STRS) for software defined radios, and as per that standard is available and intended for reuse by porting to other mission platforms. The waveform will be available via the STRS Application Repository [11].

Only the DVB-S2 short frames, which have n=16200 bits per frame, are implemented in this experiment. Short frames were selected for several reasons. Using the short frames minimizes Field Programmable Gate Array (FPGA) utilization, which is a concern for resource-constrained space-qualified platforms. Short frames have lower latency compared to DVB-S2 normal frames, which allow for faster mode changes. Finally, the short frames will permit lower symbol rates in the given low Earth orbit environment, without requiring Doppler compensation prior to the receiver.

TABLE III
DVB-S2 Short Frame MODCODs

MODCOD	Modulation	LDPC Code Identifier	Effective Code Rate
0	DUMMY PL		
1	QPSK	1/4	0.18
2	QPSK	1/3	0.32
3	QPSK	2/5	0.38
4	QPSK	1/2	0.43
5	QPSK	3/5	0.58
6	QPSK	2/3	0.65
7	QPSK	3/4	0.72
8	QPSK	4/5	0.76
9	QPSK	5/6	0.81
10	QPSK	8/9	0.87
11	N/A with Short Frames		
12	8PSK	3/5	0.58
13	8PSK	2/3	0.65
14	8PSK	3/4	0.72
15	8PSK	5/6	0.81
16	8PSK	8/9	0.87
17	N/A with Short Frames		
18	16-APSK	2/3	0.65
19	16-APSK	3/4	0.72
20	16-APSK	4/5	0.76
21	16-APSK	5/6	0.81
22	16-APSK	8/9	0.87
23	N/A with Short Frames		
24	32-APSK	3/4	0.72
25	32-APSK	4/5	0.76
26	32-APSK	5/6	0.81
27	32-APSK	8/9	0.87
28	N/A with Short Frames		

The following subsections describe the hardware, firmware, software, and scripting of the DVB-S2 waveform.

A. Hardware

The radio platform on which this waveform application was implemented consists of two main modules, as shown in Figure 7. First, the baseband processing module contains a SPARC general purpose processor (GPP) and two Xilinx Virtex II Field Programmable Gate Arrays (FPGAs). The waveform application can be a mix of software and firmware, but for the DVB-S2 application all the signal processing is done in one FPGA. The FPGA interfaces to two digital-to-analog converters (DACs), one for in-phase and the other for quadrature baseband samples. The analog signals are then sent to the Radio Frequency Module (RFM) where they are modulated onto the carrier and amplified with a solid state power amplifier (SSPA) and radiated by the antenna. The GPP interfaces to the Avionics (flight computer) and handles the waveform configuration and control, including the VCM scripts to change the MODCOD.

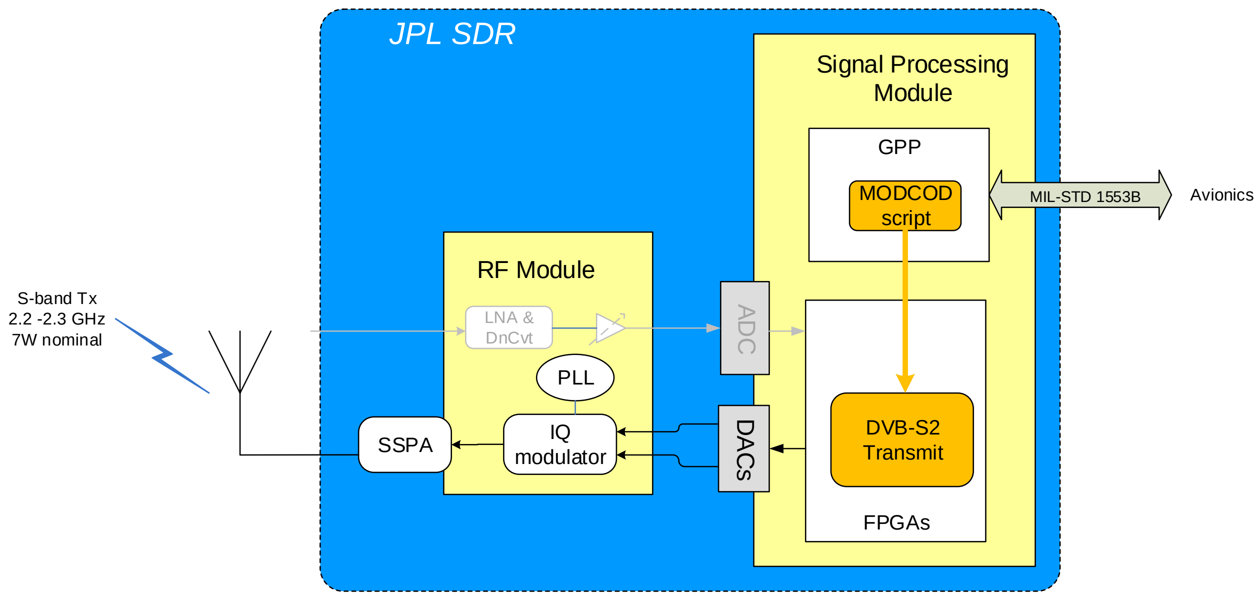

Fig. 7. JPL SDR Block Diagram

B. Firmware

The DVB-S2 transmit waveform signal processing is implemented in one of the two FPGA components available in the JPL SDR. The major functions of the waveform application are shown in Figure 8. Each module has a serial data interface and passes the current mode configuration between each module to support VCM. This information includes the MODCOD, pilots (on/off), and excess bandwidth information. The waveform implementation contains a fractional resampling filter for allowing arbitrary sample rates, and can operate up to 6.15 MBaud.

The DVB-S2 transmitter includes a PRBS-23 data generator to provide test data, but can alternatively use an external source via the SpaceWire data interface. With regards to DVB-S2 specific functionalities, this waveform only supports the following configurations: Generic Continuous (GS) and Single Input Stream (SIS). Additionally, the Physical Layer Scrambler uses the following Gold code sequence: n = 0. Lastly, the waveform allows for the option of pilot tone insertion. All other relevant waveform characteristics are considered mandatory, and are described in the DVB-S2 standard [1].

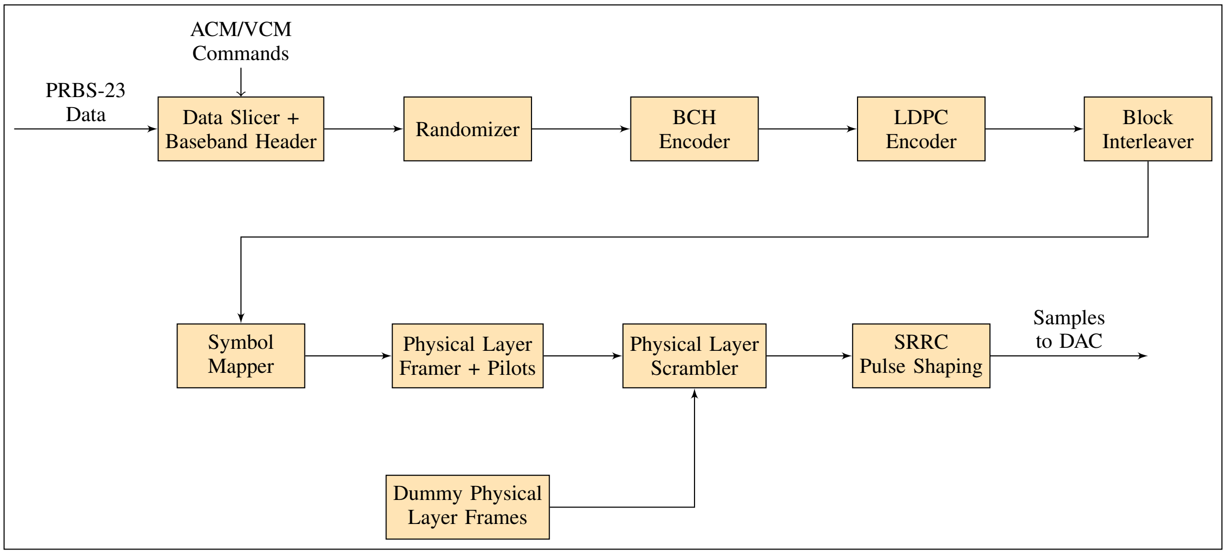

Fig. 8. DVB-S2 Waveform Processing Functions

C. Software

User control of the DVB-S2 waveform is provided through several layers. Since SCaN Testbed is an experimental payload on the International Space Station (ISS), it utilizes ground terminal applications developed for it using the Telescience Resource Kit (TReK) in order to provide a command and telemetry interface for experiment operators. An operator at the NASA GRC Telescience Center can therefore directly control the SCaN Testbed and JPL SDR in real-time through the NASA ground and space network. On orbit, the payload Avionics integrates control of all subsystems, interpreting commands and aggregating telemetry for each, including the JPL SDR.

The JPL SDR interfaces with Avionics via a MIL-STD-1553B connection and has two separate interface modes. The first mode acts as a bootloader where new software and FPGA configurations can be uploaded, stored and booted. The second mode provides full control of the waveform through the JPL Operating Environment (OE). The OE is a software framework for implementing an SDR waveform based on the NASA Space Telecommunications Radio System (STRS) architecture standard that runs on the Real-Time Executive for Multiprocessor Systems (RTEMS) operating system. This allows a consistent approach for developing and running different waveforms on the radio.

The DVB-S2 waveform consists of both an FPGA component and a software component to control and configure it. The software handles all aspects of getting the waveform up and running and manages its operation while running. To be STRS-compliant all waveforms must have a defined set of properties that can be configured or queried that are specific to the particular waveform. The DVB-S2 waveform is designed for VCM and ACM and has properties that can be configured dynamically while operating such as MODCOD, symbol rate, pulse-shape filter (PSF) roll-off, pilots, etc. These prominent properties exist within the waveform's FPGA components and the software gains access to them through an abstraction layer. The software also manages platform level components through existing drivers to control fixed resources such as Phase Locked Loops (PLL) and the transmitter SSPA.

D. Scripting

Initial testing relied upon the user manually commanding the MODCOD during an event, but proved cumbersome. In order to improve upon manually operating the VCM testing, time triggered scripting was added as a function in the waveform software to provide more precise MODCOD control to the tests. This allows a script to be executed automatically at the beginning of an experiment event and then sequence MODCOD changes to the waveform at appropriate times throughout the duration. Scripts were generated prior to each event based on the STAT predicted link characteristics.

The scripting requires that the JPL SDR be time synchronized with Avionics in order to begin executing the script at the proper time. On initial use of this feature, the script began 17 seconds prior to the time expected. It was found that Avionics is synchronized with ISS time which is global positioning system (GPS) time and that the scripting function expected Greenwich Mean Time (GMT) time. Because GPS time does not account for leap seconds, the time synchronization of the JPL SDR requires a small compensation for the delta. After identifying the discrepancy, all subsequent tests triggered properly and executed the scripts as expected.

VI. Experimenter Ground Equipment

The experimenter ground equipment is shown in Figure 9. The mobile rack supports laboratory tests with the SDR breadboard and engineering models, and can then be moved to the SCaN Testbed operations center to support flight testing. Key features of the rack include integrated additive white Gaussian noise (AWGN) testing, Doppler simulation, and internal loop-back testing. One lesson learned was that an automatic gain circuit (AGC) is needed between the GRC-GS and the experimenter test equipment. Predicted power levels are used to set an attenuator for each event, and if the actual signal level is significantly higher than predicted there is the potential to saturate the user test equipment. An AGC circuit is now integrated in the rack.

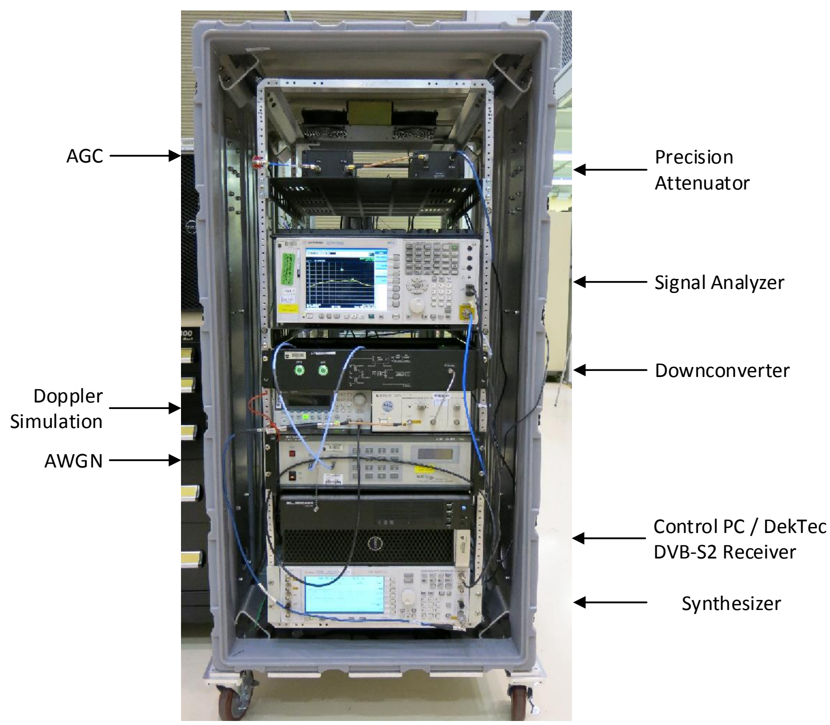

Fig. 9. Experimenter Equipment Rack

As a low-cost DVB-S2 receiver, DekTec's DTA-2137C PCI-Express-based card was used in a host computer for real-time bit collection and processing. The DekTek PCIe receiver can operate between 2 and 45 MBaud, and down to 1 MBaud with additional degradation. DekTec provided the APIs to transfer raw binary data from the card to the host PC, and a custom C++ application was written to align data frames and implement a bit-error rate tester. Additionally, the card provides metrics such as SNR, MER, decoder statistics, and current MODCOD value, which are all logged to file. The logging rate is configurable, but was set to 1 Hz for this testing.

An important factor when selecting DVB-S2 receivers was support for the 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). Support for raw DVB-S2 frames permits custom framing, as needed for the CCSDS recommended practice of sending Space Data Link Protocol frames over DVB-S2. The DekTec receive application saves the raw data within the L3 Baseband Frame format [12], which includes a time-stamp, and signal-to-noise estimate for each received DVB-S2 frame. The frame format is intended to be used in an adaptive coding and modulation system, and is also useful for analyzing link performance since it records the SNR for each frame.

Ground tests were performed to characterize the Dektec DVB-S2 receiver and to determine the threshold for quasi-error free performance. The JPL SDR development breadboard was used as the signal source, and a white Gaussian noise generator was added to the signal with a combiner. The signal amplitude of the DVB-S2 transmitter was varied with a precision step attenuator and swept over a range of SNR. Figure 10 shows the results of the characterization. Of note, there is significant degradation for the lowest MODCOD compared to the reference data provided in [13], and [14], as well as for 32-APSK modulations (highest MODCODs). The data provided is for a frame error rate (FER) of 1e-5.

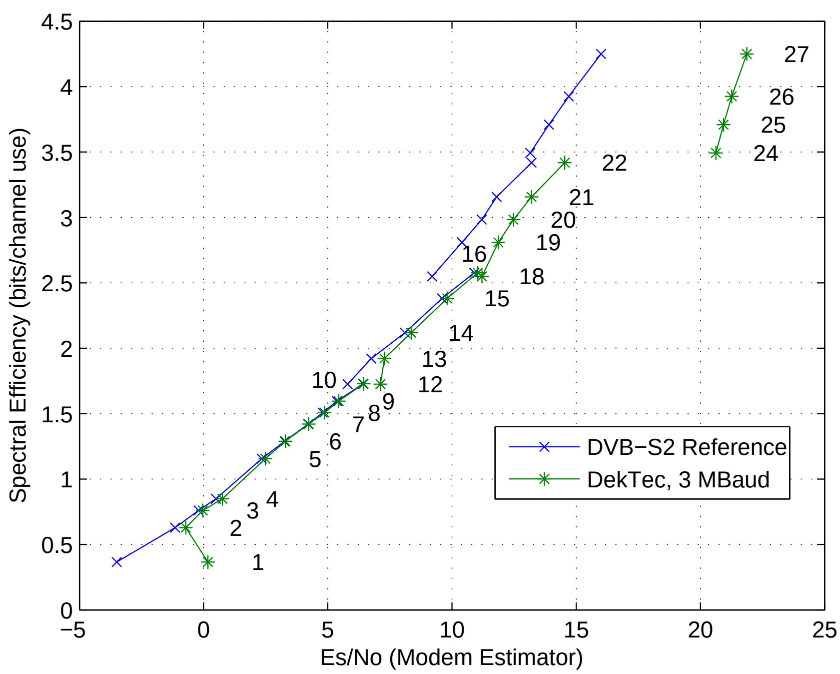

Fig. 10. Receiver Performance per MODCOD at 1e-5 FER, pilots off

During this characterization, several issues were observed with 32-APSK modulation modes, where the receiver would occasionally drop frames, especially during transitions between modulation types. This disrupted the real-time BER software implementation, and eliminated the ability to properly monitor the link during the brief duration of typical events. Consequently, 32-APSK modulation was used sparely, with the focus on 16-APSK. Since this testing, the real-time BER software has been improved to be resilient to dropped frames.

VII. VCM Predictions Becoming Operations

Preparing for an experiment event using VCM required a multi-step sequence leading up to operation of the link. Typical steps to select and prepare for a VCM test event are as follows:

1) Initial STAT assessment and ISS obstruction analysis of ground station passes for week(s) of testing.

2) Experimenter down-select of worthwhile events using predicted link performance, of which the carrier-to-noise ratio (C/No) variation over the event duration is of most interest.

3) Day of event, updated event timing and performance prediction is provided by GS operator based on updated ISS orbit and attitude information.

4) Using the predicted C/No, a recommended symbol rate and MODCOD profile is generated using a custom MATLAB script with a settable link margin, as shown in Figure 11. The script estimates the throughput for a set of user-defined symbol-rates.

5) A sequenced command script for the on-orbit SDR is generated from same MATLAB script as step 4. The script contains the start and stop times of the event, as well as all the timed MODCOD changes during the event. The appendices show plots of the actual VCM MODCOD over time for each event, which was controlled by this script.

6) SDR script is uploaded via the ISS primary communications path to the Avionics. The script file is then transferred to the SDR via the command and telemetry interface.

7) GMT-synchronized SDR waveform script is started.

8) Event occurs, SDR waveform script starts automatically and controls the MODCOD based on the predicted profile.

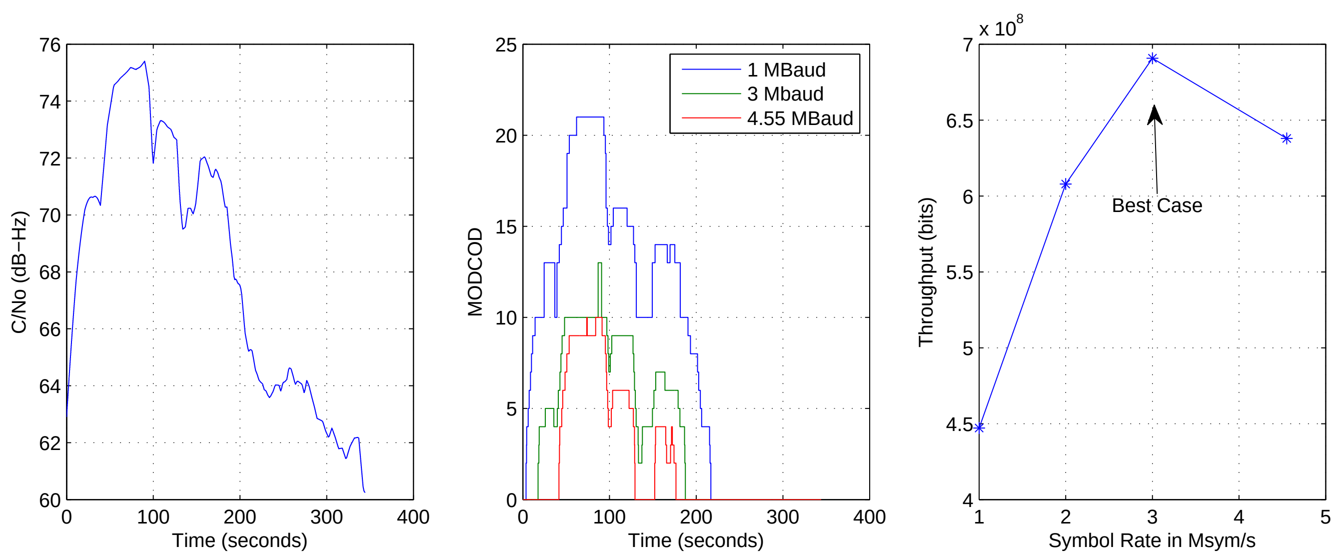

Fig. 11. Example pre-event MATLAB script output used to select symbol rate and generate MODCOD profile

VIII. Test Results

Variable coding and modulation tests were conducted October 20th to 23rd, and November 2nd to 4th. In total, 19 successful events were made between the JPL SDR and GRC-GS, during seven days. A subset consisting of 9 events were chosen for detailed analysis, after eliminating events used for system checkout and events with poor signal-to-noise ratio or excessive obstructions. In Appendix B there is detailed information and statistics for each event in the subset.

A. Throughput

One metric for comparing event performance is the total throughput (bits) of the link. In Table IV the total throughput is compared with the predicted throughput based on the STAT model, the theoretical capacity based on received signal Es/No, and the estimated performance of a standard NASA waveform. The standard NASA waveform is QPSK with an inner rate 1/2 convolutional code and an outer Reed Solomon (255,223) code. On average, the VCM protocol performed within 1.7 dB of the link capacity, and was 2.7 dB better than the standard NASA waveform.

TABLE IV
SUMMARY OF TEST RESULTS

Run Number	Actual vs Prediction (dB)	Actual vs Capacity (dB)	Actual vs NASA Standard (dB)
9	-2.14	-2.09	1.29
10	-1.22	-0.95	4.10
11	-0.37	-1.90	2.03
12	-0.30	-1.50	4.21
14	0.89	-2.82	1.19
16	0.09	-1.77	2.60
17	-0.03	-2.30	1.82
18	0.16	-1.76	1.60
19	-0.59	-0.80	3.71
Average		-1.73	2.66

B. Bit Error Rate Performance

There were two sources of bit errors observed in this experiment, expected errors when the link margin dropped near or below threshold, and large bursts of errors which occurred during modulation type transitions. The large bursts of errors were typically followed by a set of dropped / missing frames. This behaviour was not expected, and is possibly an issue with the DVB-S2 receiver performance or mode configuration. These error sources are independent, since the large bursts from modulation type transition are not dependent on SNR. Subsequent testing with a different DVB-S2 receiver did not have issues with modulation type transitions. The final BER of a typical event was 1e-5, and was dominated by the large bursts and errors near receiver threshold. Otherwise, the link operated error-free with no observable floor. Performance in this scenario could be improved by using a higher-level protocol with frame validation and a retransmission capability.

Figure 12 shows the BER and dropped frames observed from a typical event. The left plot shows the number of bit errors per DVB-S2 physical layer (PL) frame as the frames accumulate over the event. Overlaid on this is the actual measured link margin, so as a correlation between bit errors and low link margin can be observed. The link margin is calculated by comparing the recieved SNR to the receiver threshold. Note that the PL frames that cannot be recovered due to poor conditions are not included in this plot; these plots only include frames that were actually received. A look at the dropped frames over the event is shown on right, with an overlay of the MODCOD profile. Note the burst of errors and dropped frames which occur as the modulation transitions from QPSK to 8-PSK (MODCOD 10 to 13).

Plots are provided for each event in the Appendix.

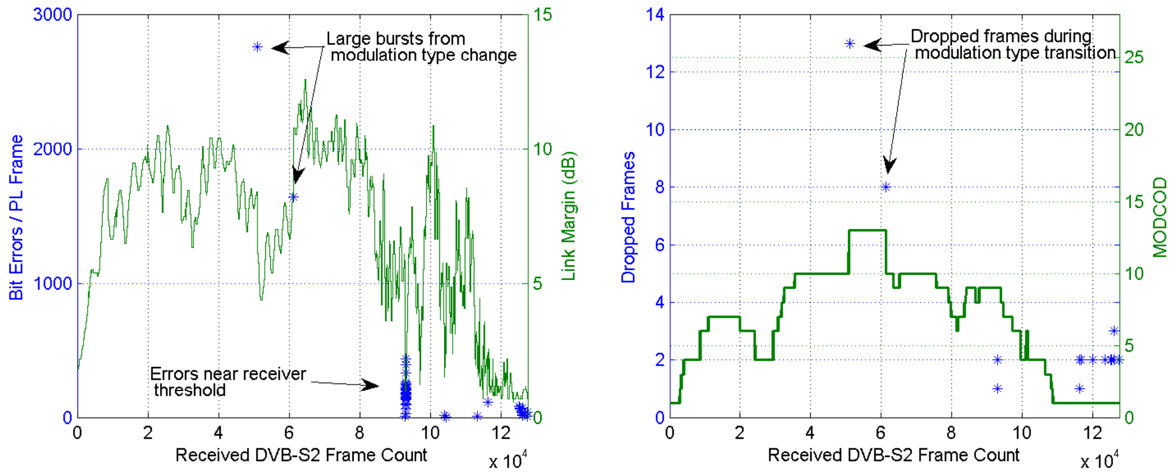

Fig. 12. BER and Dropped Frame Example (Run #11)

C. MODCOD Analysis

Figure 13 provides a histogram of MODCODs used across all 9 events. Note that the majority of the MODCODs were exercised. Some individual MODCODs were not used, due to imperfections in the receiver threshold characterization data which effectively eliminated several modes. This was discovered after testing, and is not believed to significantly impact the overall test results. A more thorough device characterization was performed and presented in Figure 10, which eliminated this issue for future testing.

D. Model Accuracy

By design, the STAT model generally provides a conservative estimate of the C/No, as shown in Figure 5 and the Appendix datasheets. These plots show that the predicted C/No is typically within 5 dB when there is line-of-sight. However, variation does occur often, making the prediction-based VCM profile sub-optimal for portions of the event. The model was able to accurately predict when an obstruction would occur, but did not capture the depth of the resulting signal fade or multipath, resulting in bit errors. This can be expected for a dynamic environment, and would be very difficult to model accurately. For example, if the solar panels are in a different position during characterization versus the actual event, the results will vary. Larger margins are needed, or a perhaps a different approach altogether. One way to improve the model for this application would be to identify areas of severe fades (such as the JEM obstruction), and provide a minimum value instead of the smoothed average.

The GRC-GS pointing error discussed earlier was a significant source of degradation for some of the events. The worst impact can be seen with Run #10, which has a peak pointing error of 13 dB, which effectively ends the event 20 seconds earlier than predicted.

E. Comparison to Launch Waveforms

SCaN Testbed launched with a relatively simple TDRSS-compatible BPSK waveform application on the JPL SDR. In terms of FEC it uses a rate 1/2 convolutional with no outer block code. No data link layer framing was utilized, and the data rate was also limited to 769 kbps. A typical event performance profile for the launch waveform is shown in Figure 14, with the estimated Eb/No and actual error count per second plots overlaid. With this waveform's single mode of operation there is no mitigation for the degrading signal as the event progresses.

A summary of downlink performance for the launch waveform with the GRC Ground Station is given in Table V. Notice that 1/3 of the 23-Feb-2015 event is underutilized and 1/3 is lost due to the fixed

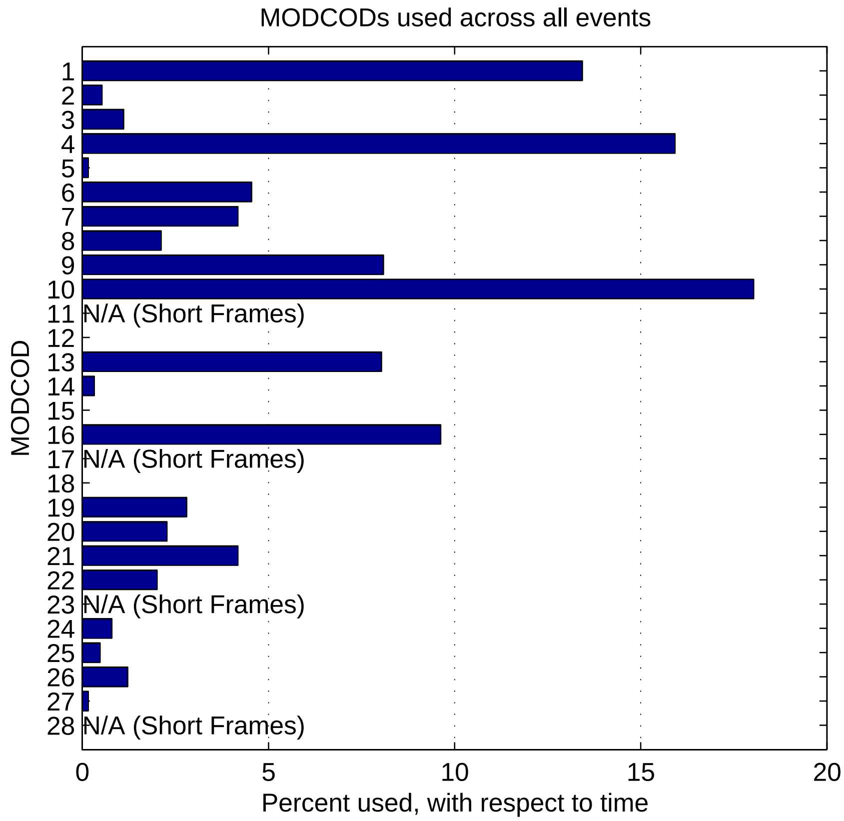

Fig. 13. Histogram of MODCODs

single mode of operations. The overall data throughput difference is significant when compared to the DVB-S2 waveform's VCM operations, 0.1-0.2 Gb versus 0.2-2.0 Gb with VCM. Also, note that the BER is significantly worse. With the new DVB-S2 waveform, the peak data-rate increased by a factor of 26x, capable of 20 Mbps in a 5 MHz channel. Due to SNR limitations, peaks rates up to 16 Mbps have been demonstrated on-orbit.

TABLE V
LAUNCH WAVEFORM PERFORMANCE SUMMARY

Event	Duration (s)	Received Bits	Average Throughput	Loss of Signal	Bit Error Rate
23-Feb-2015 (DOY054-2)	365	193,600,683	530.4 kbps	31.1 %	3.1e-3
19-Mar-2015 (DOY078-1)	319	142,446,628	446.5 kbps	42.0 %	6.5e-3
18-May-2015 (DOY138-1)	215	161,737,725	752.3 kbps	2.2 %	3.9e-4

IX. CONCLUSION

Variable Coding Modulation testing with the DVB-S2 compatible waveform was successful, accomplishing all of the test objectives. All available MODCODs were exercised over the link. The Dektec DVB-S2 receiver performed well, especially considering its relatively low-cost ($1000). Link characteristics were more challenging that predicted. There seems to be multipath effects as well as the predicted obscurations and antenna pattern fading, which may be explored further in future experiments. On average the VCM testing of the DVB-S2 waveform has shown an 2.7 dB improvement over the standard NASA waveform with constant coding and modulation. While this scenario was challenging due to the complex

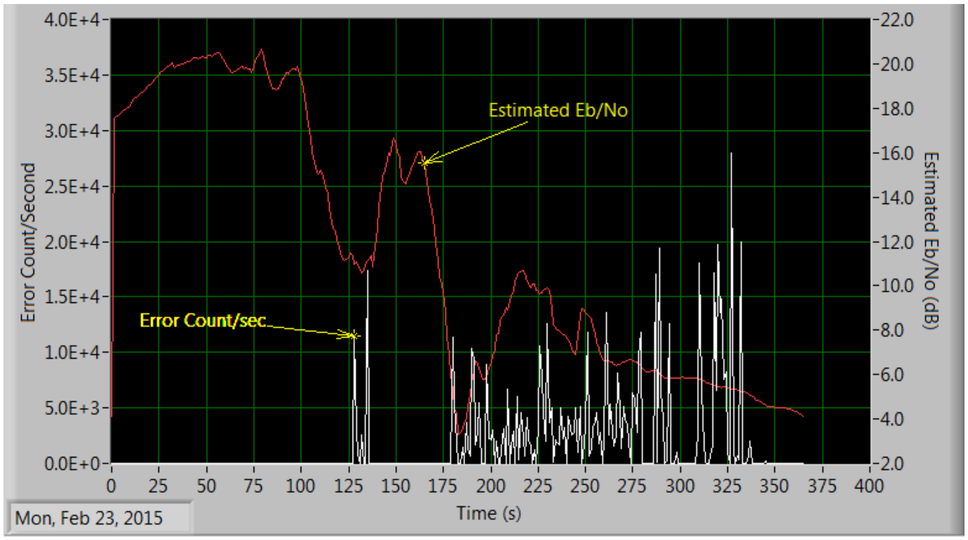

Fig. 14. Launch Waveform Performance

ISS structure, VCM did improve the total user data throughput and should be considered for missions with more deterministic link dynamics.

There are better methods to operate the VCM waveform in this scenario. The STAT model prediction accurately captures the overall link profile, but was not accurate enough for the aggressive link margins pursued. To avoid data loss a fade margin is needed, and could be determined from the data sets captured. A larger overall link margin is needed (>2 dB) to handle differences in actual versus predicted power. A robust retransmission protocol would be required to tolerate unforgiving link dynamics. Furthermore, the operational complexity of uploading custom MODCOD script files for every event would need automation to become practical.

ACM testing is expected to improve further on the VCM test results presented herein by an average of 1.8 dB, mainly due to unpredictable link variations in the ISS to ground link. This would yield a total improvement of 4.5 dB over the standard NASA waveforms. ACM is also expected to reduce the significant amount of preparations needed for VCM operations with this scenario.

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[2] JL. Issler, JP. Millerioux, "Use Cases of DVB-S2 for telemetry", CCSDS Meeting Presentation, April, 2014.

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[9] B. W. Welch and M. T. Piasecki, "Earth-Facing Antenna Characterization in Complex Ground Plane/Multipath Rich Environment", *Antenna Measurement Techniques Association*, Long Beach, CA, November, 2015.
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[13] *CCSDS Protocols over DVB-S2 - Summary of Definition, Implementation and Performance*, CCSDS 130.12-G-0. Draft Green Book. Washington, D.C: CCSDS, May, 2015.
[14] *Digital Video Broadcasting (DVB) User guidelines for the second generation system for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVB-S2)*, ETSI TR 102 376 V1.1.1 (2005-02).

APPENDIX A
SIGNAL-TO-NOISE CALCULATION

Link analysis is based on a conversion from the GRC ground station received power to signal-to-noise radio. The GRC ground station uses a HP 8566B Spectrum Analyzer to log the received power throughout the event. Power measurements are recorded at a 10 Hz rate, which provides a high resolution view of the link dynamics. The instrument span is set to 6 MHz, resolution bandwidth of 3 MHz, video bandwidth of 1kHz, no trace averaging, and a sweep time of 0.05 seconds. With the input signal disconnected the reading is -85 dBm, confirming that the measurements are above the instrument noise floor.

$$(S+N)/N = S/N + N/N = S/N + 1 \tag{1}$$

To estimate the noise N, the lowest power in the trace is assumed to contain noise only. Letting the spectrum analyzer power reading be $Pwr = S + N$, the estimated SNR is

$$SNR_{Est}(dB) = 10\log_{10}(10^{(Pwr-\min Pwr)/10} - 1) - X \tag{2}$$

where X is a symbol-rate dependent correction factor which was determined experimentally and provided in Table VI. The conversion from spectrum analyzer power reading to estimated SNR is shown in Figure 15.

TABLE VI
SYMBOL RATE DEPENDENT CORRECTION FACTOR "X"

Symbol Rate	**Correction (dB)**
1e6	1.5
2e6	-1
3e6	-1.5
4.55e6	-2

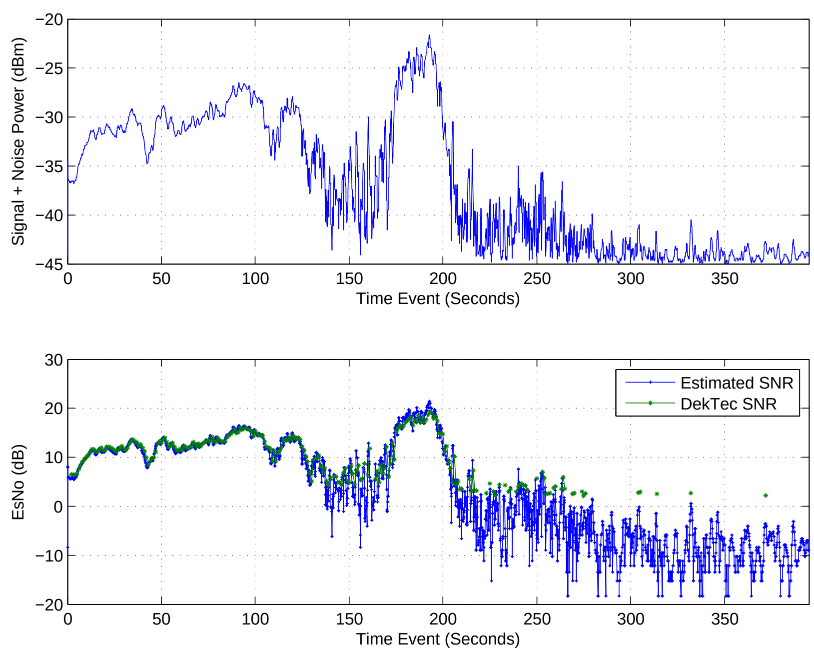


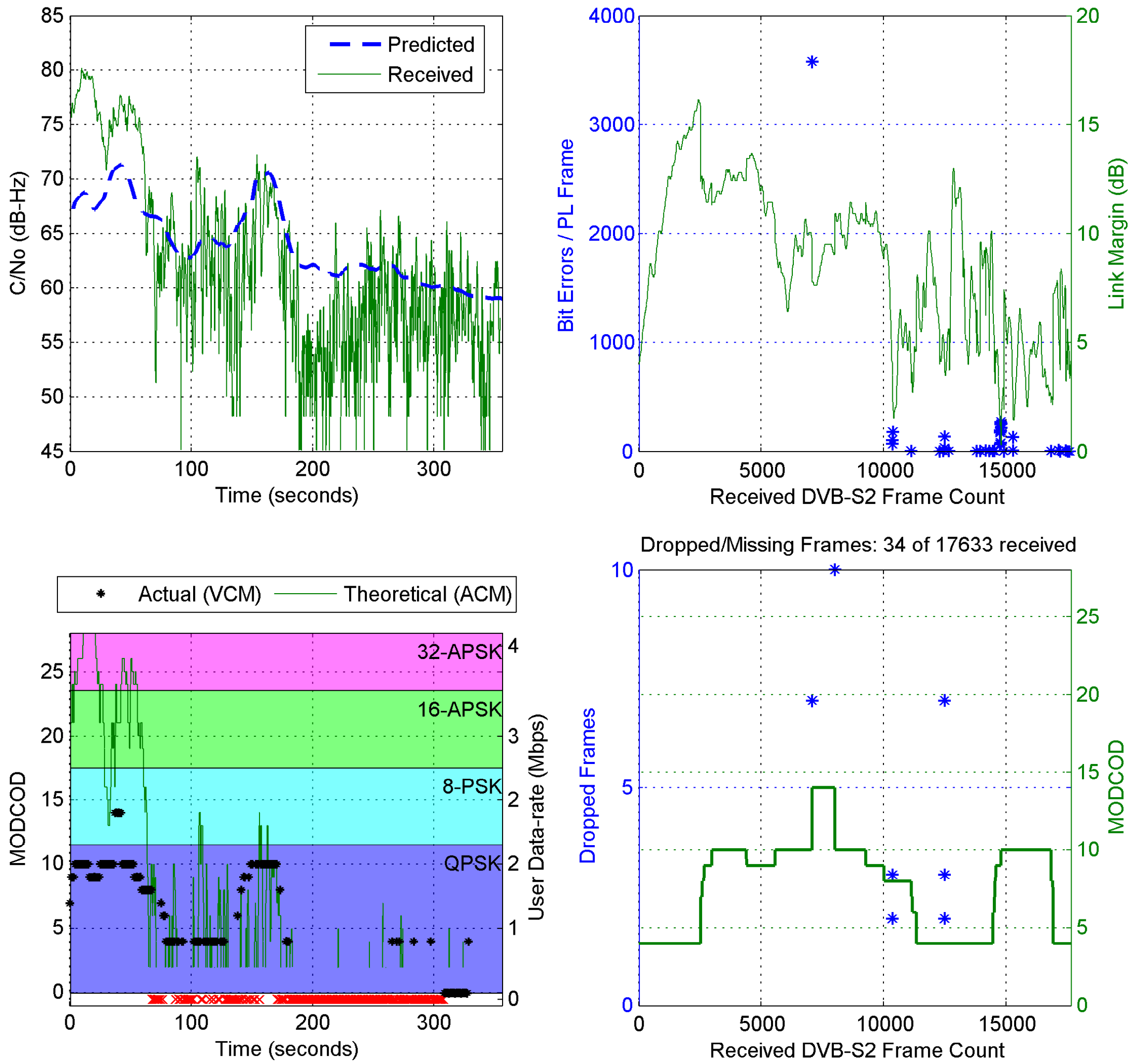
Fig. 15. Signal-to-Noise Ratio Estimation from Spectrum Analyzer Power Data

Appendix B
Event Datasheets

The event datasheets provide detailed information and statistics for each event. Each datasheet has a header containing date and time, symbol rate, link margin, and known obstructions. The datasheet contains four plots of event performance. The upper left plot compares the STAT model prediction versus the actual signal-to-noise ratio over the event time. The companion lower left plot compares the waveform MODCOD profile with the theoretical link capacity. Color bands indicate the four possible modulation schemes for the DVB-S2 waveform. Signal drop-outs are designated with a red "x" marker along the bottom axis. On the right side of the event datasheets there are two data link layer performance plots. The upper right plot shows the number of bit errors per DVB-S2 physical layer (PL) frame as the frames accumulate over the event. Overlaid on this is the actual measured link margin. A look at the dropped frames over the event is shown in the lower right plot, with an overlay of the MODCOD received.

Finally, there are two summary tables underneath the quad plots, summarizing event statistics and comparing overall VCM performance. The average throughput rate is simply the total received bits divided by the event time. The Gain/Loss table is computed from the ratios of these average data throughput rates. The bit error rate (BER) is only computed on valid received frames for the actual event data, while the Loss of Signal percentages are calculated from the corresponding prediction or measurement of received signal.

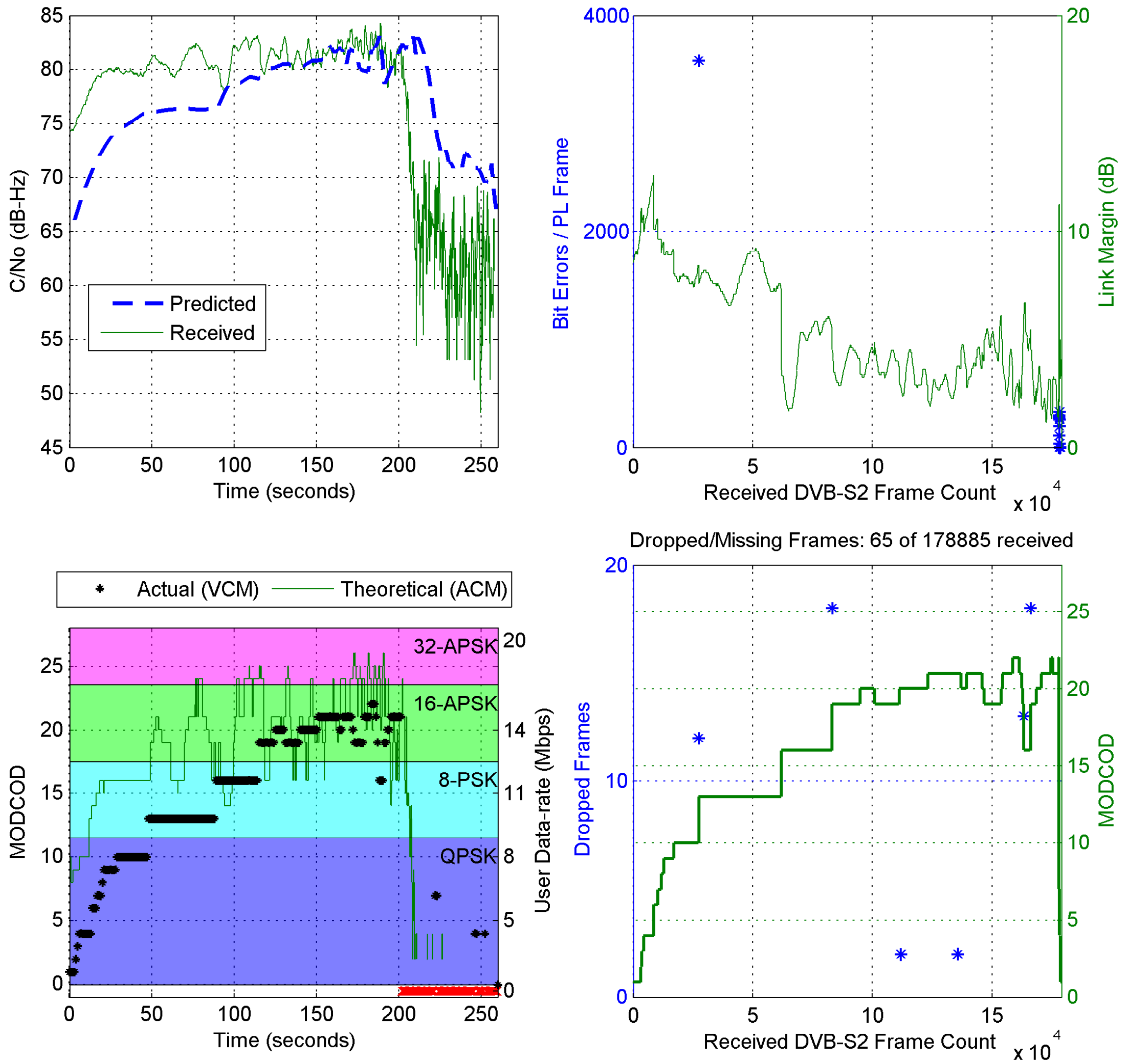
Run #:	9	Symbol Rate:	1.00 Msps
Event Start:	"22 Oct 2015 22:08:41.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"22 Oct 2015 22:14:37.00"	Link Margin:	2 dB
Obstruction:	JEM at t=55s		



	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	290070234	0.81 Mbps	48.0%	-
Capacity (Post-event)	286802694	0.81 Mbps	66.7%	-
Actual	177412824	0.50 Mbps	50.3%	3.22e-05
NASA Standard	131921448	0.37 Mbps	57.0%	-

	Gain/Loss
Actual vs Prediction	-2.14 dB
Actual vs Capacity	-2.09 dB
Actual vs NASA Standard	1.29 dB

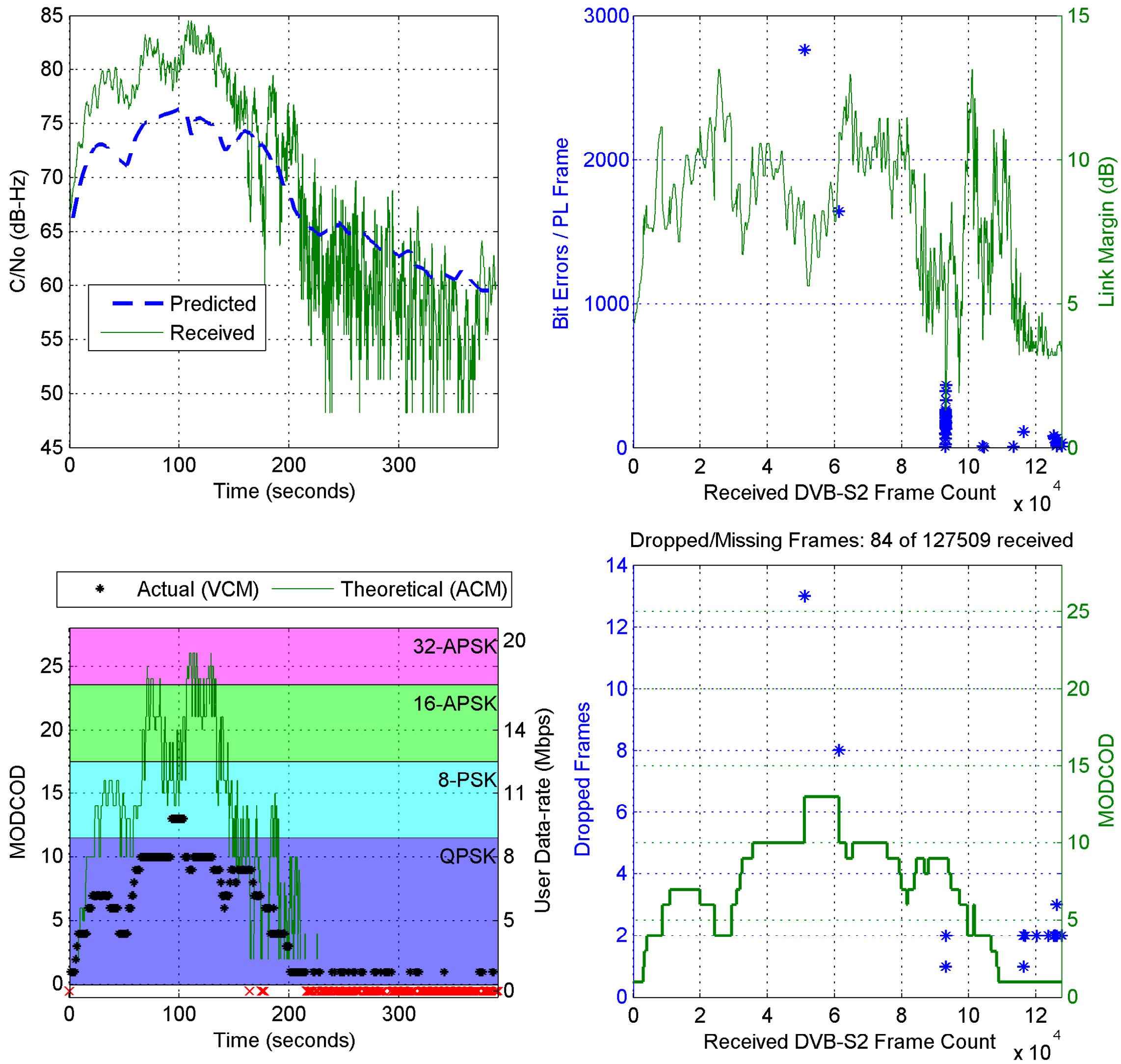
Run #:	10	Symbol Rate:	4.55 Msps
Event Start:	"22 Oct 2015 23:44:56.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"22 Oct 2015 23:49:16.00"	Link Margin:	2 dB
Obstruction:	Solar Panels at t=215s		



	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	2837350782	10.91 Mbps	5.0%	-
Capacity (Post-event)	2667672468	10.26 Mbps	19.2%	-
Actual	2142743808	8.24 Mbps	18.5%	2.52e-06
NASA Standard	834011080	3.21 Mbps	18.1%	-

	Gain/Loss
Actual vs Prediction	-1.22 dB
Actual vs Capacity	-0.95 dB
Actual vs NASA Standard	4.10 dB

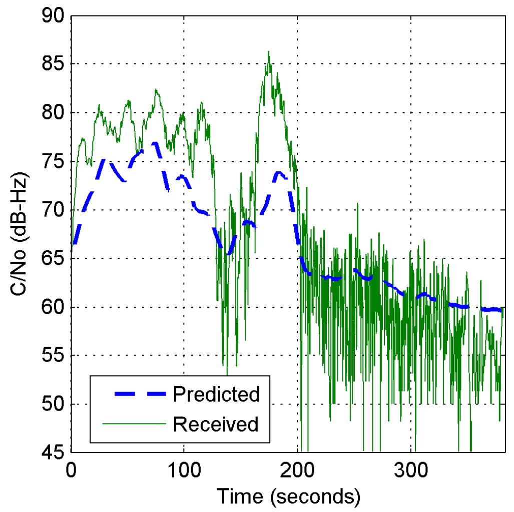
Run #:	11	Symbol Rate:	4.55 Msps
Event Start:	"23 Oct 2015 16:24:31.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"23 Oct 2015 16:31:01.00"	Link Margin:	2 dB
Obstruction:	Solar Panels at t=120s		

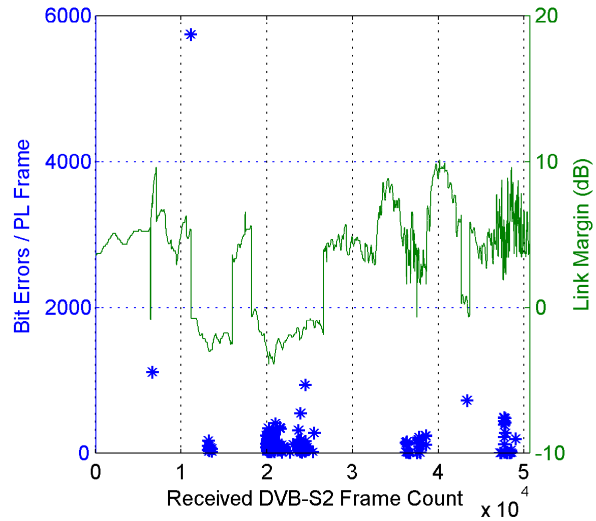


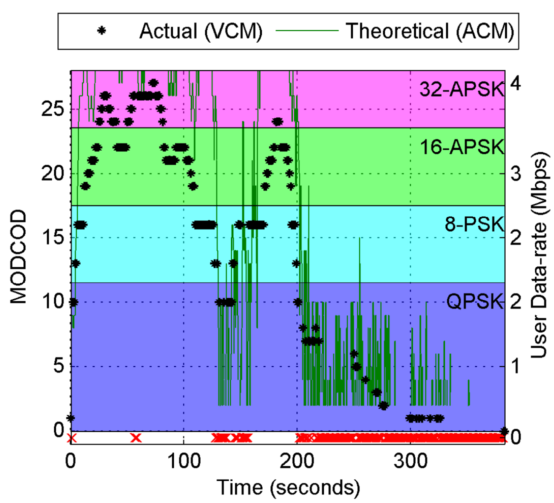
	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	1387038978	3.56 Mbps	52.1%	-
Capacity (Post-event)	1971323406	5.05 Mbps	51.5%	-
Actual	1272366448	3.26 Mbps	35.9%	9.27e-06
NASA Standard	797451568	2.04 Mbps	47.8%	-

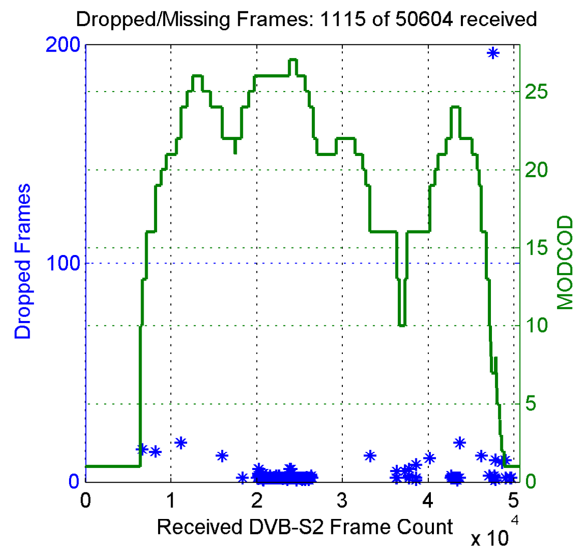
	Gain/Loss
Actual vs Prediction	-0.37 dB
Actual vs Capacity	-1.90 dB
Actual vs NASA Standard	2.03 dB

Run #:	12	Symbol Rate:	1.00 Msps
Event Start:	"23 Oct 2015 18:01:02.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"23 Oct 2015 18:07:25.00"	Link Margin:	-1 dB
Obstruction:	JEM at t=109s		





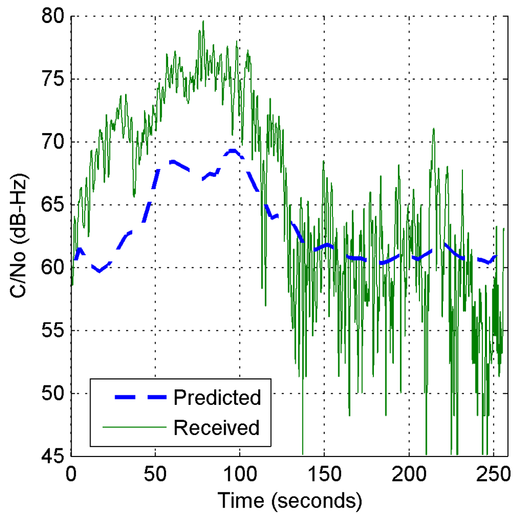


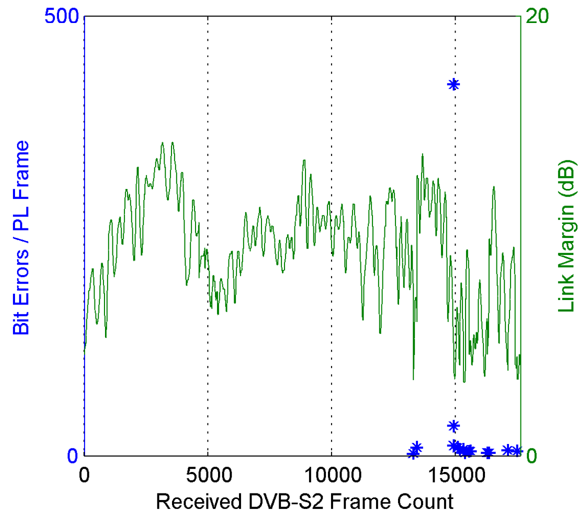


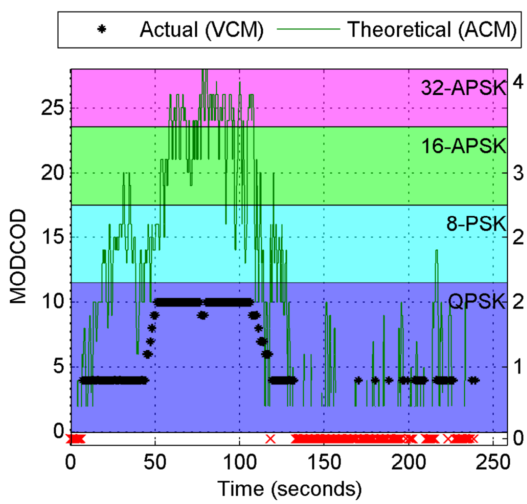
	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	596103300	1.56 Mbps	27.8%	-
Capacity (Post-event)	786039066	2.05 Mbps	36.7%	-
Actual	556051584	1.45 Mbps	39.4%	1.83e-04
NASA Standard	211057904	0.55 Mbps	36.0%	-

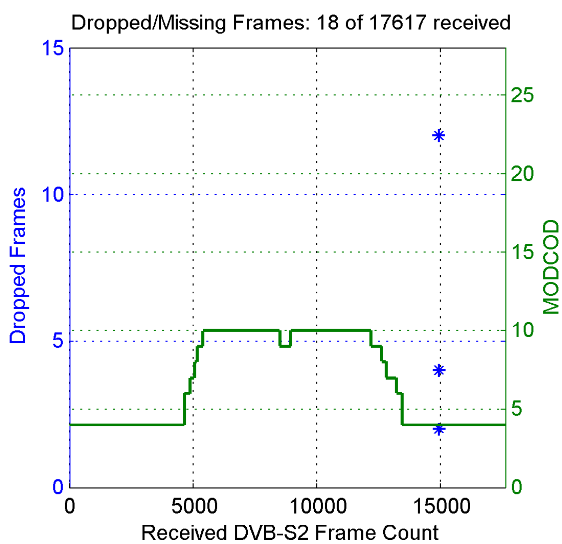
	Gain/Loss
Actual vs Prediction	-0.30 dB
Actual vs Capacity	-1.50 dB
Actual vs NASA Standard	4.21 dB

Run #:	14	Symbol Rate:	1.00 Msps
Event Start:	"2 Nov 2015 20:31:34.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"2 Nov 2015 20:35:52.00"	Link Margin:	1 dB
Obstruction:	Solar Panels at t=0s		





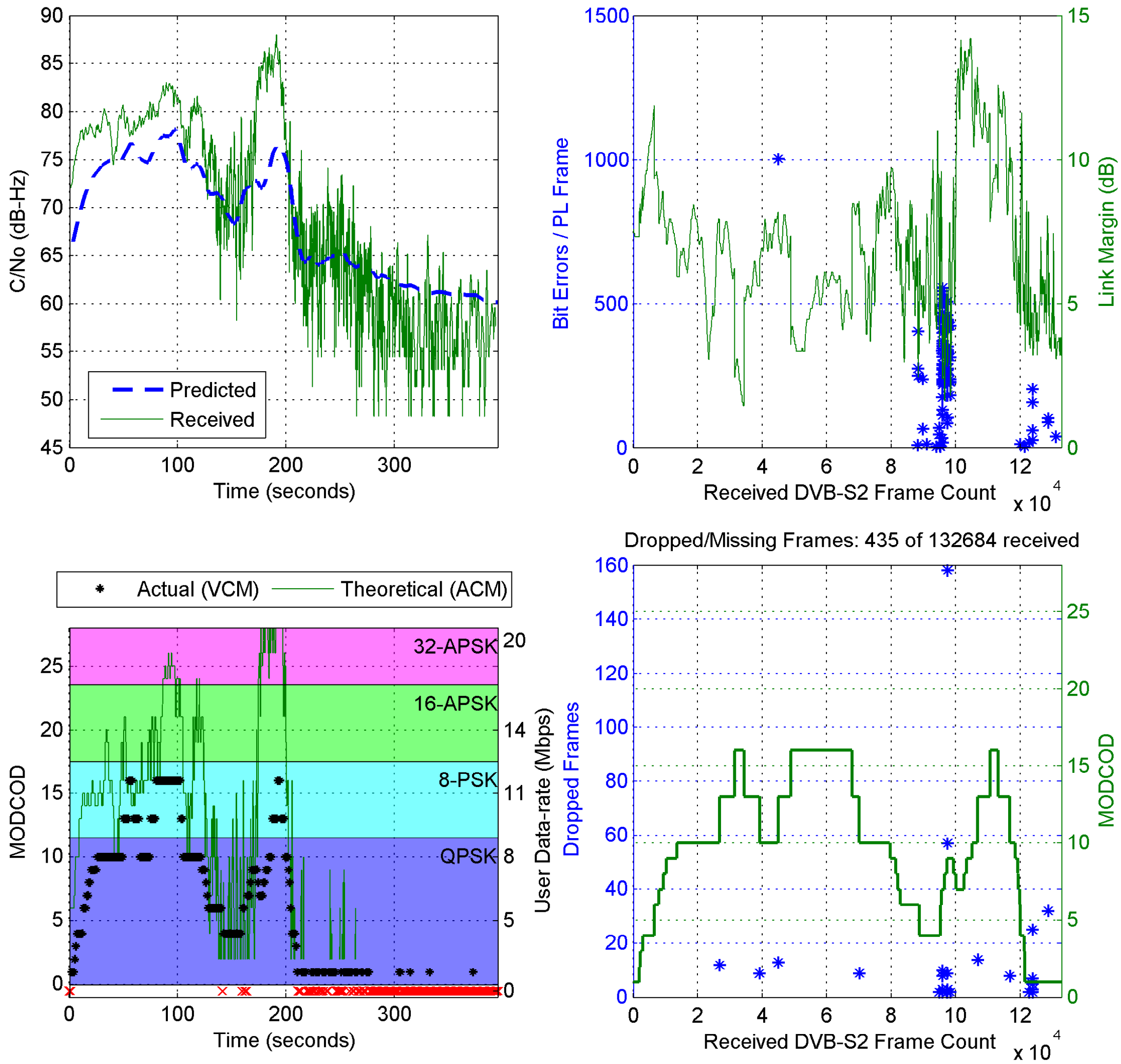




	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	147238884	0.57 Mbps	60.8%	-
Capacity (Post-event)	346394880	1.34 Mbps	43.8%	-
Actual	180866968	0.70 Mbps	41.9%	3.01e-06
NASA Standard	137596352	0.53 Mbps	38.1%	-

	Gain/Loss
Actual vs Prediction	0.89 dB
Actual vs Capacity	-2.82 dB
Actual vs NASA Standard	1.19 dB

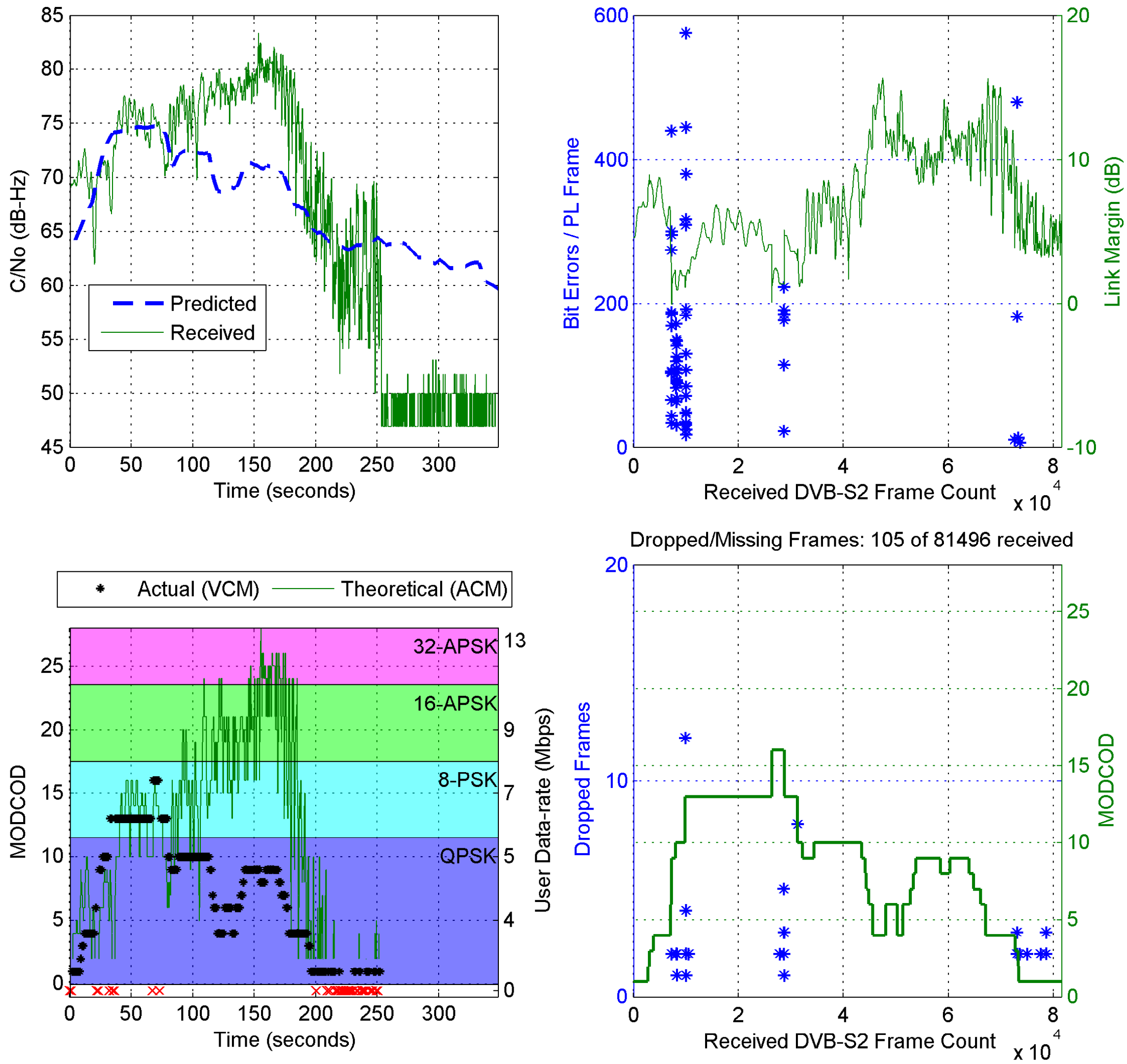
Run #:	16	Symbol Rate:	4.55 Msps
Event Start:	"3 Nov 2015 18:01:37.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"3 Nov 2015 18:08:12.00"	Link Margin:	1 dB
Obstruction:	JEM at t=138s		



	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	1462373028	3.70 Mbps	52.1%	-
Capacity (Post-event)	2242103490	5.68 Mbps	50.1%	-
Actual	1492585064	3.78 Mbps	37.5%	1.85e-05
NASA Standard	819355520	2.07 Mbps	47.1%	-

	Gain/Loss
Actual vs Prediction	0.09 dB
Actual vs Capacity	-1.77 dB
Actual vs NASA Standard	2.60 dB

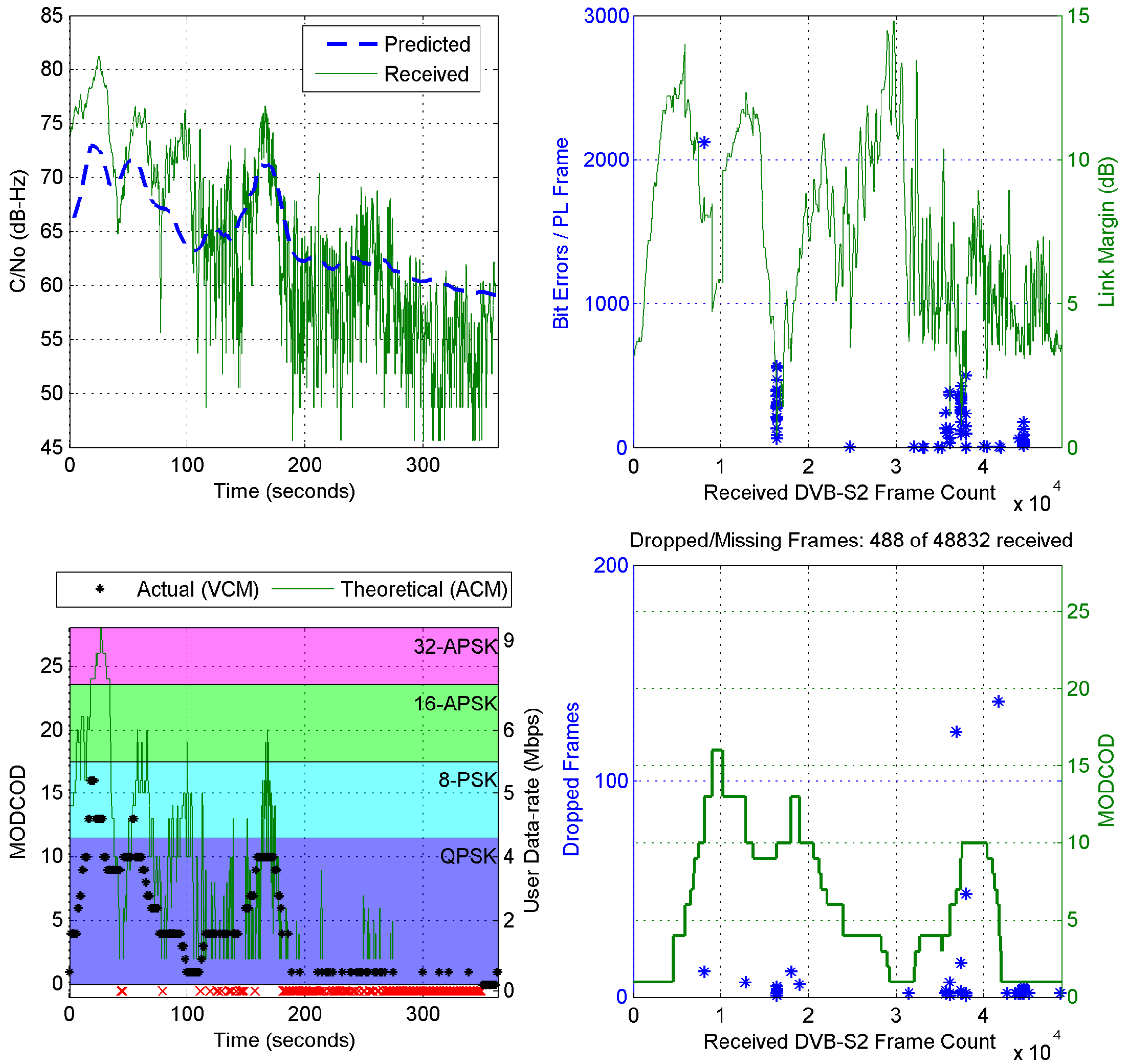
Run #:	17	Symbol Rate:	3.00 Msps
Event Start:	"3 Nov 2015 19:38:11.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"3 Nov 2015 19:43:59.00"	Link Margin:	1 dB
Obstruction:	Solar Panels at t=0s		



	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	819983250	2.36 Mbps	52.1%	-
Capacity (Post-event)	1383781158	3.98 Mbps	43.5%	-
Actual	814134360	2.34 Mbps	37.9%	1.07e-05
NASA Standard	534966296	1.54 Mbps	40.5%	-

	Gain/Loss
Actual vs Prediction	-0.03 dB
Actual vs Capacity	-2.30 dB
Actual vs NASA Standard	1.82 dB

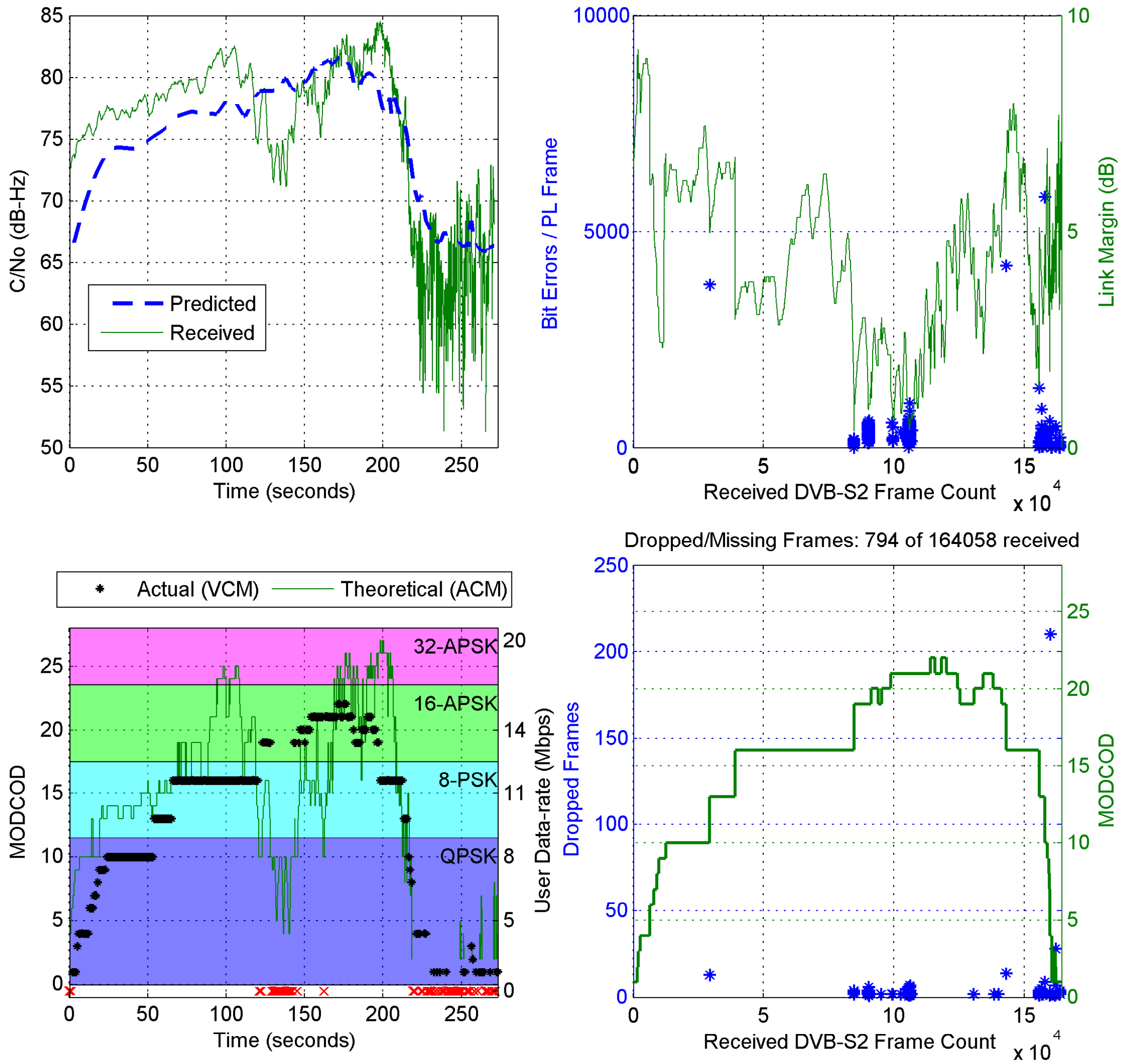
Run #:	18	Symbol Rate:	2.00 Msps
Event Start:	"4 Nov 2015 17:08:52.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"4 Nov 2015 17:14:55.00"	Link Margin:	1 dB
Obstruction:	JEM at t=70s		



	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	384636600	1.06 Mbps	64.5%	-
Capacity (Post-event)	599164614	1.65 Mbps	60.1%	-
Actual	399489320	1.10 Mbps	36.4%	3.96e-05
NASA Standard	276091840	0.76 Mbps	55.8%	-

	Gain/Loss
Actual vs Prediction	0.16 dB
Actual vs Capacity	-1.76 dB
Actual vs NASA Standard	1.60 dB

Run #:	19	Symbol Rate:	4.55 Msps
Event Start:	"4 Nov 2015 18:45:08.00"	VCM Method:	VCM Script (SDR)
Event Stop:	"4 Nov 2015 18:49:41.00"	Link Margin:	1 dB
Obstruction:	Solar Panels at t=126s		



	Received Bits	Avg Throughput	Loss of Signal	BER
Prediction (Pre-event)	2374957908	8.70 Mbps	20.3%	-
Capacity (Post-event)	2490589458	9.12 Mbps	19.0%	-
Actual	2072553160	7.59 Mbps	19.0%	4.59e-05
NASA Standard	882632216	3.23 Mbps	17.5%	-

	Gain/Loss
Actual vs Prediction	-0.59 dB
Actual vs Capacity	-0.80 dB
Actual vs NASA Standard	3.71 dB