NASA/TM—2020-220472

Characterization and Commissioning of a Ka-Band Ground Station for Cognitive Algorithm Development

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February 2020

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Acknowledgments

The authors would like to thank the Cognitive Communications Project and Propagation Team for their support in funding the design and construction of CADeT, as well as to the TSC Mission Operations Team for their efforts in coordinating TDRSS events directed to NASA Glenn Research Center enabling this type of testing to take place.

Level of Review: This material has been technically reviewed by technical management.

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***Abstract*—In 2018, the Cognitive Communications and Propagation projects completed installation and checkout testing of a new Ka-Band ground station at the NASA Glenn Research Center in Cleveland, Ohio. The Cognitive Algorithms Demonstration Testbed (CADeT) was developed to provide a fully characterized and controllable dynamic link environment to researchers looking to demonstrate hardware and software aligned with atmospheric sensing and cognitive algorithms. CADeT integrates a host of precision control and measurement systems in addition to repurposing a 5.5 meter beam-waveguide dish platform previously used with the Advanced Communications Technology Satellite (ACTS). This paper will discuss the laboratory testing of ground station components with a emphasis on elements vital to achieving link budget requirements including characterization of the new Gallium Nitride (GaN) Solid State Power Amplifier (SSPA) and far-field measurements of the new antenna feed. Finally, the paper discusses in-situ tests conducted with CADeT and the Tracking and Data Relay Satellite System (TDRSS) to validate laboratory results and make necessary link budget adjustments before reviewing the lessons learned.**

I. Introduction

Since 2016, the National Aeronautics and Space Administration (NASA) has focused efforts on the technology development of cognitive communications systems, which is envisioned to play a critical role in future satellite communications (SATCOM) architectures, impacting everything from data routing to ensuring high availability links can be maintained. To address the need to demonstrate various approaches toward cognitive communications, Glenn Research Center (GRC) developed and deployed the CADeT ground station. In summer of 2018, CADeT was completed as a joint venture between the Cognitive Communications and Propagation teams working at GRC to provide fade mitigation and cognitive algorithm testing platform for high data rate, wide-band, and increased availability demonstrations.

An end to end characterization of the system was conducted during the months leading up to the ground stations commissioning. Components utilized in the system were subjected to various tests before and after installation in order to build an accurate performance model prior to the start of operations. This paper describes the testing completed with extra attention given to the performance validation of a new SSPA used within the completed setup and the functional restoration of an existing beam-waveguide dish platform by replacement of the antenna feed. Next, the paper describes the characterization of CADeT using the geostationary satellite TDRS-12. Finally, there will be a comparison of the laboratory and post-installation testing results as well as a review of lessons learned using the selected methodology.

II. System Overview

CADeT is a Ka-Band (22.55 – 27.50 GHz) ground station with equipment dispersed among multiple labs of the Communications Laboratory building at GRC. An overview of the system topology highlighting the major Radio Frequency (RF) components is shown in Figure 1.

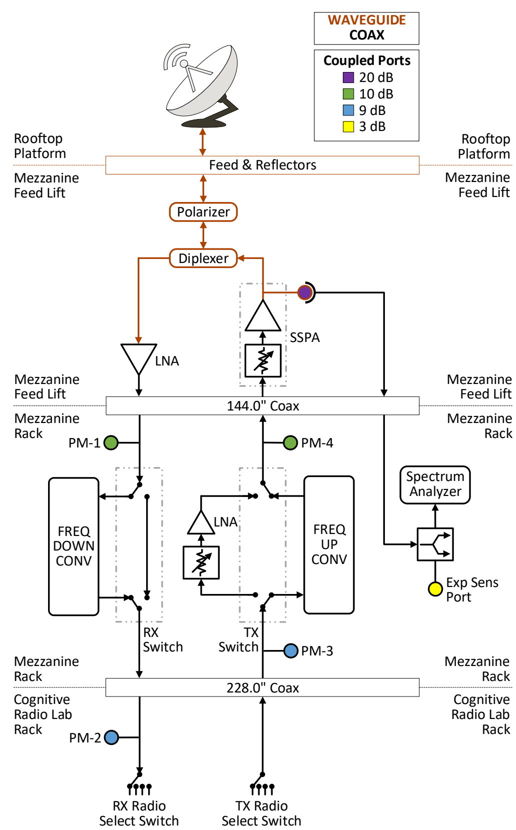

Fig. 1. CADeT RF Topology Diagram [1]

The mezzanine directly below the beam-waveguide platform houses the bulk of equipment used as part of CADeT. The mezzanine equipment rack and feed lift consists of devices to control and monitor the system such as the SSPA, Low Noise Amplifiers (LNA), Power Meters (PM), frequency up and down converters, attenuators, and the General Dynamics controller for the 5.5 meter dish. The equipment rack also houses a Single Pole Double Throw (SPDT) switch matrix which enables the Transmit (TX) and Receive (RX) chains in the system to be independently set to bypass the frequency converters. This feature gives researchers the option of using radio equipment which can TX or RX directly at Ka-Band frequencies or at a lower Intermediate Frequency (IF).

The Cognitive Radio Lab (CRL) located below the mezzanine is where researchers can connect their own equipment to CADeT's RF front-end or use available hardware for the purpose of their own experiments. The ground station is controlled from this same lab space which allows the operator to be near the other researchers and make adjustments quickly. Researchers can also utilize pairs of dedicated fiber lines within the lab to connect data and analog RF signals dispersed across GRC within the Telescience Support Center (TSC) and the Glenn Research Center S-Band Ground Station (GRC-GS) respectively [2]. The operators Graphical User Interface (GUI) software can be seen in Figure 2.

Fig. 2. CADeT Operators GUI [1]

CADeT is designed to operate exclusively within TDRSS Ka-Band frequencies with a forward (FWD) path from space to ground of 22.55 to 23.55 GHz and a return (RTN) path of 25.25 to 27.5 GHz. A waveguided diplexer placed directly below the antenna feed is used to filter signals outside of these bands. Power meters placed at points of interest throughout the TX and RX chains are used to validate characterized system data prior to each day's events and ensures operation within safe limits. A coupled port at the output of the SSPA is split among a spectrum analyzer running Vector Signal Analysis (VSA) software and an external port where researchers can attach their own monitoring equipment. A weather station placed near the ground station also collects wind speed/direction, temperature, barometric pressure, and rainfall throughout the course of a day's events. System settings and sensor data are recorded for the purpose of validation and review at the conclusion of testing.

Figure 3. shows CADeT's experimental data path from GRC to Whitesands Complex (WSC). In this scenario data is sent from GRC at Ka or S-Band to TDRS-12's Single Access (SA) or Multi Access (MA) antennas where it is returned to the WSC at Ku-Band. From WSC telemetry data is sent back to GRC using a Virtual Private Network (VPN) connection.

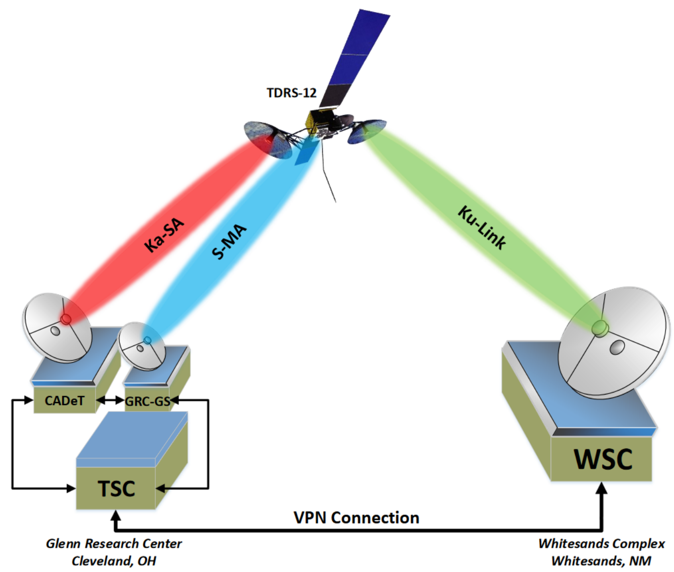

Fig. 3. Experimental Data Path between GRC and WSC

III. Element Characterization

Before beginning laboratory measurements, a power budget of each signal chain was modeled using readily available component data provided by vendors. The development of a custom SSPA was necessary in order to maximize the Equivalent Isotropic Radiated Power (EIRP) of our TX license. A testing regime was devised based on the classification of each component. Passive devices such as cables, waveguide, attenuators, and couplers were swept for their S-Parameters using a Vector Network Analyzer (VNA) over the band of operating frequencies. Active devices such as amplifiers were subjected to gain, noise figure, phase noise, and intermodulation distortion testing in addition to their S-Parameters. Components were characterized individually before being assembled into subsystems and tested again to ensure they remained within expected values.

The 5.5 meter beam-waveguide dish required a new antenna feed which closely matched the characteristics of the one it had been initially installed and characterized with. The new antenna feed was selected and swept for its gain, half power beamwidth, and roll off taper were measured using the GRC Far-Field Antenna Range before in-situ testing with the dish.

A. Passive Element Measurements

An example of S-Parameter measurements taken on passive elements of CADeT is the diplexer used to separate the TX and RX chains. Each component was characterized individually before being combined into subsystems and measured again. Figure 4. shows the S21 FWD and S31 RTN magnitude measurements of the diplexer subsystem. Table I. compares the results of initial component estimates to cascaded measurements and the total subsystem characterization taken along the FWD path signal chain.

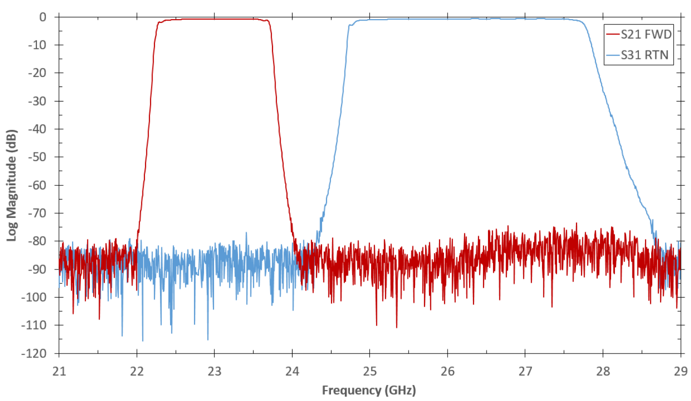

Fig. 4. Cascaded Diplexer Subsystem S-Parameters

TABLE I
FWD PATH DIPLEXER SUBSYSTEM MEASUREMENTS

Component Name	Attenuation (dB)		
	Datasheet Estimate	*Cascaded Measurements*	*Subsystem Measurement*
Circular WG	-0.255	-0.025	-
Polarizer	-0.308	-0.030	-
Circ to Rect WG	-0.240	-0.025	-
Diplexer	-0.600	-0.603	-
H-bend WG	-0.255	-0.025	-
H-bend WG	-0.255	-0.025	-
TOTAL	**-1.913**	**-0.733**	**-0.803**

B. Laboratory SSPA Characterization

CADeT uses an SSPA purchased from Millimeter Wave Systems LLC for the RTN signal to TDRSS. The amplifier features 0 to 20 dB gain control, 75 C thermal protection with 0.06 dB/C temperature compensation, and a 20 dB coupled output. Table II. outlines the vendor specs of the SSPA.

TABLE II
SSPA VENDOR SUPPLIED SPECIFICATIONS

Characteristic	Value
Frequency Range	25.25 – 27.5 GHz
Gain	39.0 dB Minimum
Gain Flatness	+/- 2.0 dB
Noise Figure	10.6 dB
P1dB	>35.1 dBm (25.25 – 26.0 GHz) >37.25 dBm (26.0 – 27.5 GHz)
OIP3	44.55 dBm @ 25.25 GHz 45.35 dBm @ 25.5 GHz 46.29 dBm @ 26.5 GHz
Power Efficiency	11.2% @ P1dB 12.6% @ Psat

Initial testing involved performing an S-parameter measurement of the SSPA. The VNA was calibrated using a known 20 dB coupler and high power load at the output of the Device Under Test (DUT) [3]. As an extra precaution, a 10 dB pad was added to each coupled output. The SSPA was swept beyond the range of operational frequencies to ensure performance matched the vendor data. Figure 5. shows the results of this testing and the vendor supplied versus actual coupling factor of the DUT coupled output.

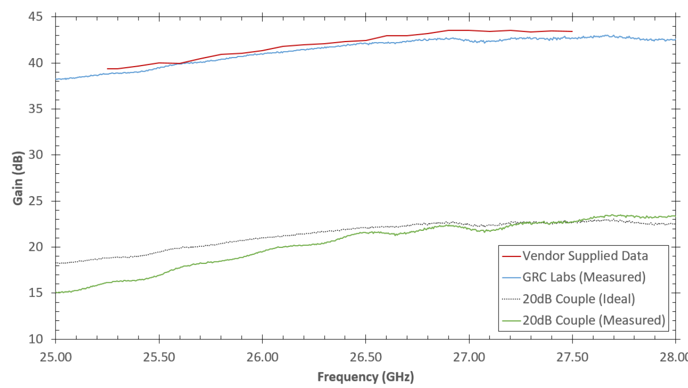

Fig. 5. SSPA Characterized Gain Levels

Next, using a similar setup as before a load was placed on the coupled port of the DUT and a gain compression application was run to calculate the 1 dB Compression Point (P1dB) of the SSPA. A calibrated power meter was used to calibrate the VNA measurement for absolute power supplied to the DUT. The amplifier was swept over a range of input power levels beyond the expected P1dB. Figure 6. shows the input versus output curve of the SSPA at the frequencies of interest. Table III. shows the P1dB calculated from the results.

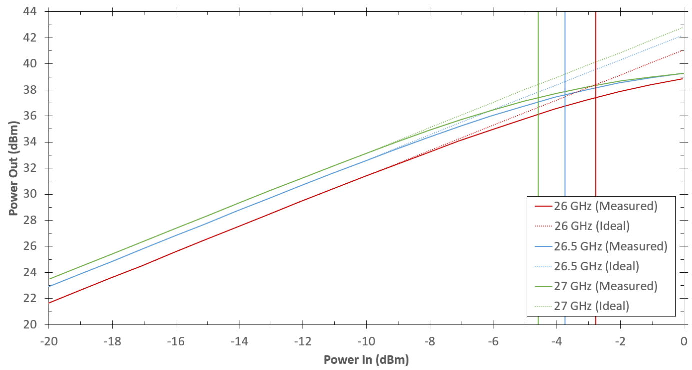

Fig. 6. SSPA Gain Compression Curve

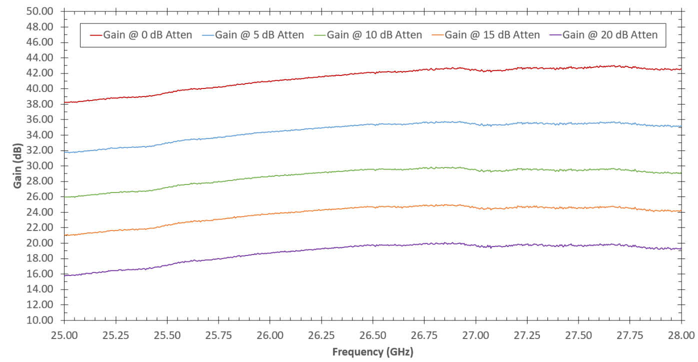

Fig. 8. SSPA Step Attenuator Testing

TABLE III
CALCULATED P1DB

Frequency (GHz)	P1dB Input (dBm)	P1dB Output (dBm)
26.0	-2.76	37.45
26.5	-3.73	37.62
27.0	-4.62	37.41

Then, the SSPA was characterized for its Third Order Intercept Point (OIP3) using the same setup in Intermodulation Distortion Measurement (IMD) mode. To use CADeT with the TDRSS 225 MHz bandwidth service, 27.35 GHz was selected from the list of recommendations specified in NASA's Space Network Users' Guide (SNUG) as a viable carrier given the gain flatness and highest output power achievable of the SSPA over that band [4]. Figure 7. shows the results from testing which determined an OIP3 of 47.58 dBm at 27.35 GHz.

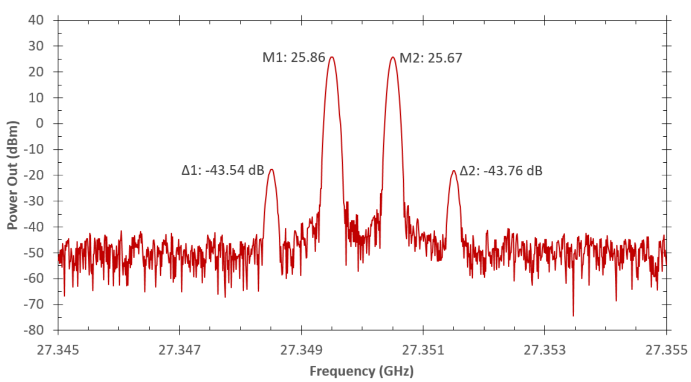

Fig. 7. IMD Testing at 27.35 GHz with 1 MHz Spacing

Finally, the SSPA was tested for accuracy when setting the gain. The SSPA was swept from 25 to 28 GHz in 5 dB increments of the variable attenuator to monitor the response. Data collected from this test was used to make modifications to the operators control GUI correcting for discrepancies between the commanded and actual attenuation in software. Figure 8. shows the results from this set of tests.

C. Antenna Feed Characterization

CADeT uses a custom designed antenna feed with the repurposed beam-waveguide platform that's located within the mezzanine beneath the dish [5]. The two points are connected via a series of reflectors placed at rotational axis to the Azimuth (AZ) and Elevation (EL) of the gimbaled structure as shown in Figure 9. To optimize performance, a feed with the proper gain and beam taper is placed at the focal point of the first reflector plate to fully illuminate the subreflector without spillover.

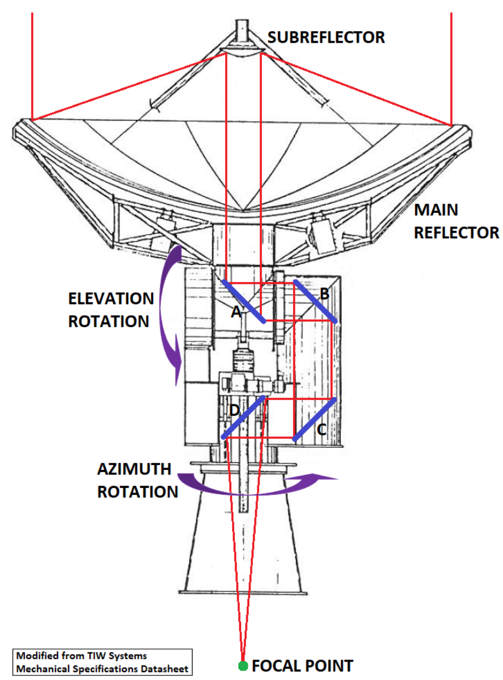

Fig. 9. Beam-Waveguide Platform Reflectors [1]

To meet gain and beam taper requirements specified by the vendor, potential feeds were characterized in the GRC Far-Field Antenna Range (GRC-FF) prior to installation [6][7]. A QuinStar Thechnology QRR series conical horn and QLA series lens antenna with an adjustable beam taper were tested to compare results for best design conformance. Table IV.

outlines vendor specifications of the beam-waveguide platform when it was installed July, 1990.

TABLE IV
BEAM-WAVEGUIDE PLATFORM SPECIFICATIONS

Characteristic	Value	
Frequency (GHz)	20.0	30.0
Diameter (Meters)	5.5	
Polarization	Dual Linear	
Half-Power Beamwidth (HPBW)	0.19°	0.13°
Gain (dB)	58.1	60.9

For testing, the Antenna Under Test (AUT) was secured within a temporary fixture aligning the phase center with the center of rotation. The AUT fixture was then mounted to a high precision AZ scanner stage 6.5 meters away from a known standard gain horn. The horn and AUT were aligned at their cross sections within the anechoic chamber using a 360 degree laser leveling system as seen in Figure 10.

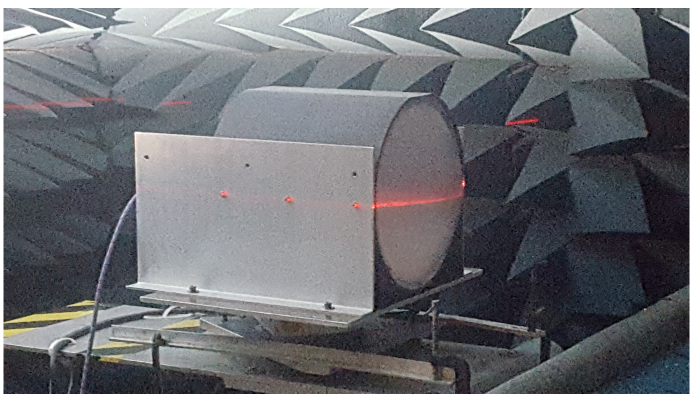

Fig. 10. Lens Antenna Setup in GRC-FF

The antennas were characterized at frequencies in the middle of the TX and RX bands for CADeT. The co-polar pattern and gain was measured in 0.25° increments over a 20° span corresponding to the spec requiring a 1.8 dB per degree taper up to +/- 7.12° from antenna broadside. Priority was given to matching the 23 and 26.5 GHz scan patterns to the 20 GHz pattern provided based on the beam-waveguide platforms performance when initially characterized. While the QRR horn had a fixed beam pattern, the QLA lens was tuned and measured multiple times until the patterns closely matched the vendor spec. The ability to tune the lens antenna made it the preferred candidate to proceed with installation. Figure 11. shows the resulting patterns from this testing at each frequency compared to the vendor spec.

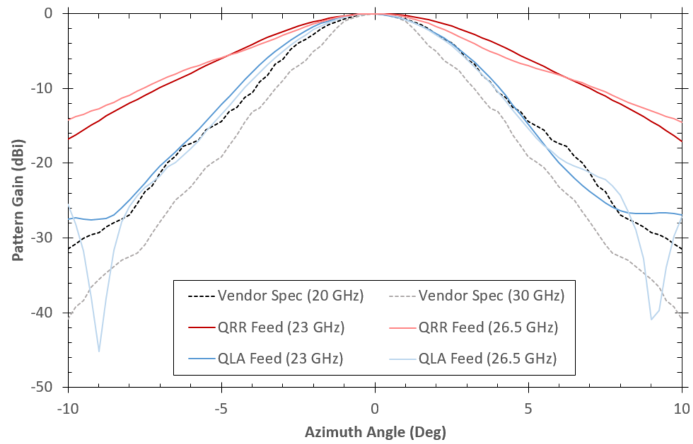

Fig. 11. GRC-FF Antenna Gain Patterns

IV. INSTALLATION AND IN-SITU VALIDATION

Upon completion of laboratory testing each subsystem was installed in preparation for in-situ validation as seen in Figure 12. Tests were spread out over several days and divided into parts measuring the performance of the beam-waveguide dish platform, Carrier Wave (CW) power measurements of the FWD and RTN signal chains, and VSA measurements of data sent from CADeT to TDRSS.

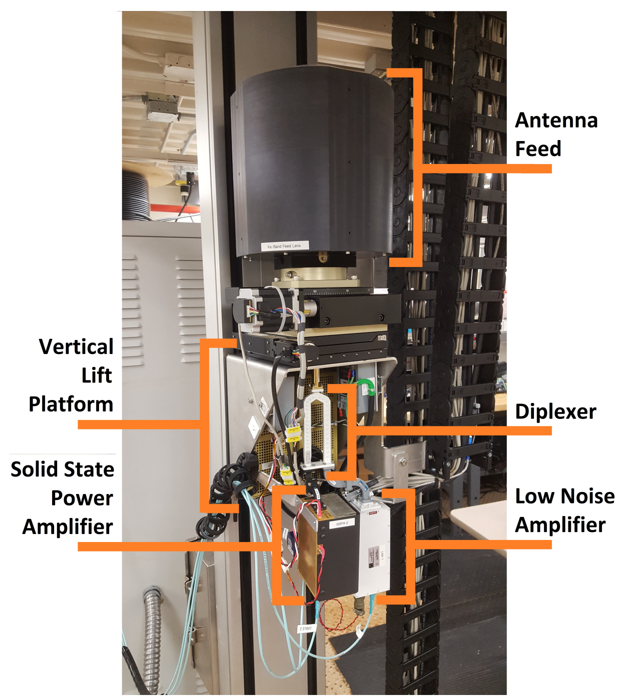

Fig. 12. Assembled CADeT Feed Subsystem [1]

A. *In-Situ Antenna Feed Characterization*

To accurately measure the performance of the new antenna feed within the beam-waveguide platform, a geostationary satellite with a known EIRP and detailed dynamic link budget was required. TDRS-12 was determined to be the ideal choice for ground station checkout and operations during the initial planning stages of CADeT due to the limited angular motion and tracking speed capabilities of the 5.5 meter dish.

For the purpose of these tests, TDRSS events were scheduled during clear weather days to eliminate rain fade at Ka-Band as a source of error. Atmospheric propagation data collected in the Cleveland area was used to refine the link budget taking into account a 22.6795 GHz carrier frequency and elevation angle of TDRS-12. Table V. compares the results from this testing to the calculated link budget with ideal values extracted from the SNUG and vendor supplied data.

TABLE V
IDEAL VS MEASURED FWD LINK BUDGET

Element	Ideal	Measured
TDRS-12 EIRP (dBW)	64.00	63.30
Free Space Path Loss	-211.35	
Atmospheric Loss	-0.50	
5.5m Dish Platform	58.10	55.55
Polarizer thru LNA Subsystem	53.29	
TOTAL (dBW)	-36.46	-39.71

Testing revealed approximately 2.45 dB degradation in dish performance from when it was first characterized which is not unexpected considering the platform's age. The dish gain still falls within an acceptable performance margin of the link budget for testing. Greater performance may be achieved if needed through further tuning of the platform such as re-polishing reflectors A thru D from Figure 9. The system link budget was updated accordingly to reflect these measurements.

B. *CADeT Power Checkout*

To complete the system power checkout a signal generator was placed at or near the beginning of the FWD and RTN signal chains with a spectrum analyzer placed at the end of the chain. Testing the system in bypass and frequency conversion modes, power levels were stepped through and measured at coupled ports and the final output before comparing results to laboratory measurements. This was then repeated with the entire system assembled using TDRS-12.

Using this data a series of power budgets were created to emulate event scenarios. With these tables a user can determine how to setup an experiment with CADeT before arriving on site by adjusting the desired EIRP and gain at fixed points within the system. The tables will then update to reflect the power expected at each radio and coupled port, and warn the user if a component nears or exceeds its maximum input power by highlighting cell colors in green, yellow, and red. Figures 13. thru 16. show the power budgets for the FWD and RTN paths.

Forward Link Passthrough (22.68 GHz)						
TDRS-12						
Element	Gain (dB)	Power (dBW)				
EIRP		64.000				
Free Space Path Loss	-211.350	64.000				
Atmospheric Loss	-0.500	-147.350				
CADeT						
Part	Gain (dB)	Power (dBm)	Max Input Power (dBm)	Coupled Gain (dB)	Coupled Power (dBm)	User Input
5.5m Dish / Lens Antenna	55.000	-117.850	50.000			
Circular Waveguide	-0.025	-62.850	50.000			
Polarizer	-0.030	-62.875	50.000			
Circular to Rectangular Waveguide	-0.025	-62.905	50.000			
Diplexer	-0.603	-62.930	50.000			
Rectangular Waveguide	-0.025	-63.533	50.000			
Low Noise Amplifier	60.600	-63.558	0.000			
144.0" Coax Cable Run	-6.930	-2.958	51.760			
Coupler	-0.931	-9.888	43.000	-9.580	-19.468	
Adapter	-1.784	-10.819	74.590			
RF Switch Matrix	-0.496	-12.603	45.440			
Adapter	-0.734	-13.099	74.590			
RF Switch Matrix	-0.496	-13.833	45.440			
Coax Cable	-1.970	-14.329	50.000			
Adapter	-0.067	-16.299	50.000			
228.0" Coax Cable Run	-9.260	-16.366	50.000			
Adapter	-0.092	-25.626	50.000			
Coax Cable	-1.230	-25.718	50.000			
Coupler	-1.536	-26.948	50.000	-9.120	-36.068	
Coax Cable	-2.100	-28.484	50.000			
RF Switch Matrix	-0.630	-30.584	45.440			
Coax Cable	-2.020	-31.214	50.000			
User Radio						
Device		Power (dBm)				
Final Input		-33.234				

Fig. 13. FWD Link Passthrough Spreadsheet

Forward Link Downconvert (22.68 - 1.2 GHz)						
TDRS-12						
Element	Gain (dB)	Power (dBW)				
EIRP		64.000				
Free Space Path Loss	-211.350	64.000				
Atmospheric Loss	-0.500	-147.350				
CADeT						
Part	Gain (dB)	Power (dBm)	Max Input Power (dBm)	Coupled Gain (dB)	Coupled Power (dBm)	User Input
5.5m Dish / Lens Antenna	55.000	-117.850	50.000			
Circular Waveguide	-0.025	-62.850	50.000			
Polarizer	-0.030	-62.875	50.000			
Circular to Rectangular Waveguide	-0.025	-62.905	50.000			
Diplexer	-0.603	-62.930	50.000			
Rectangular Waveguide	-0.025	-63.533	50.000			
Low Noise Amplifier	60.600	-63.558	0.000			
144.0" Coax Cable Run	-6.930	-2.958	51.760			
Coupler	-0.931	-9.888	43.000	-9.580	-19.468	
Adapter	-1.784	-10.819	74.590			
RF Switch Matrix	-0.496	-12.603	45.440			
Coax Cable	-2.010	-13.099	50.000			
Downconverter	28.950	-15.109	15.000			0
Coax Cable	-0.440	13.841	50.000			
RF Switch Matrix	-0.496	13.401	51.460			
Coax Cable	-0.420	12.905	50.000			
Adapter	-0.037	12.485	50.000			
228.0" Coax Cable Run	-2.720	12.448	50.000			
Adapter	-0.043	9.728	50.000			
Coax Cable	-0.256	9.685	50.000			
Coupler	-0.502	9.429	50.000	-9.120	0.309	
Coax Cable	-0.429	8.927	50.000			
RF Switch Matrix	-0.100	8.498	51.460			
Coax Cable	-0.424	8.398	50.000			
User Radio						
Device		Power (dBm)				
Final Input		7.974				

Fig. 14. FWD Link Downconvert Spreadsheet

Return Link Passthrough (27.35 GHz)						
TDRS-12						
Element	Gain (dB)	Power (dBW)				
Final Input		-145.850				
Free Space Path Loss	-211.350	65.500				
Atmospheric Loss	-0.500	66.000				
CADeT						
Element		Power (dBW)				
EIRP		66.000				
Part	Gain (dB)	Power (dBm)	Max Input Power (dBm)	Coupled Gain (dB)	Coupled Power (dBm)	User Input
5.5m Dish / Lens Antenna	58.000	38.000	50.000			
Circular Waveguide	-0.025	38.025	50.000			
Polarizer	-0.030	38.055	50.000			
Circular to Rectangular Waveguide	-0.025	38.080	50.000			
Diplexer	-0.583	38.663	50.000			
Rectangular Waveguide	-0.025	38.688	50.000	-33.560	5.128	
Power Amplifier	42.660	-3.972	2.000			0
144.0" Coax Cable Run	-7.460	3.488	51.760			
Coupler	-1.000	4.488	43.000	-9.650	-5.162	
Adapter	-1.876	6.364	74.590			
RF Switch Matrix	-0.496	6.860	44.770			
Adapter	-1.658	8.518	74.590			
Amplifier	40.000	-31.482	0.000			
Adapter	-0.650	-30.832	74.590			
Variable Attenuator	-3.200	-27.632	10.000			0
Adapter	-0.650	-26.982	74.590			
RF Switch Matrix	-0.496	-26.486	44.770			
Adapter	-1.185	-25.301	74.590			
Coupler	-1.421	-23.880	50.000	-9.120	-33.000	
Coax Cable	-1.350	-22.530	50.000			
Adapter	-0.107	-22.423	50.000			
228.0" Coax Cable Run	-10.100	-12.323	50.000			
Adapter	-0.080	-12.243	50.000			
Coax Cable	-1.330	-10.913	50.000			
RF Switch Matrix	-1.180	-9.733	44.770			
Coax Cable	-2.200	-7.533	50.000			
User Radio						
Device		Power (dBm)				
Expected Output		-7.533				

Fig. 15. RTN Link Passthrough Spreadsheet

Return Link Upconvert (1.2 - 27.35 GHz)						
TDRS-12						
Element	Gain (dB)	Power (dBW)				
Final Input		-145.850				
Free Space Path Loss	-211.350	65.500				
Atmospheric Loss	-0.500	66.000				
CADeT						
Element		Power (dBW)				
EIRP		66.000				
Part	Gain (dB)	Power (dBm)	Max Input Power (dBm)	Coupled Gain (dB)	Coupled Power (dBm)	User Input
5.5m Dish / Lens Antenna	58.000	38.000	50.000			
Circular Waveguide	-0.025	38.025	50.000			
Polarizer	-0.030	38.055	50.000			
Circular to Rectangular Waveguide	-0.025	38.080	50.000			
Diplexer	-0.583	38.663	50.000			
Rectangular Waveguide	-0.025	38.688	50.000	-33.560	5.128	
Power Amplifier	42.660	-3.972	2.000			0
144.0" Coax Cable Run	-7.460	3.488	51.760			
Coupler	-1.000	4.488	43.000	-9.650	-5.162	
Adapter	-1.876	6.364	74.590			
RF Switch Matrix	-0.496	6.860	44.770			
Coax Cable	-2.200	9.060	50.000			
Upconverter	14.184	-5.124	15.000			15
Coax Cable	-0.454	-4.670	50.000			
RF Switch Matrix	-0.496	-4.174	51.460			
Adapter	-0.125	-4.049	74.590			
Coupler	-0.486	-3.563	50.000	-9.120	-12.683	
Coax Cable	-0.259	-3.304	50.000			
Adapter	-0.035	-3.269	50.000			
228.0" Coax Cable Run	-2.700	-0.569	50.000			
Adapter	-0.040	-0.529	50.000			
Coax Cable	-0.256	-0.273	50.000			
RF Switch Matrix	-0.140	-0.133	51.460			
Coax Cable	-0.424	0.291	50.000			
User Radio						
Device		Power (dBm)				
Expected Output		0.291				

Fig. 16. RTN Link Upconvert Spreadsheet

C. VSA Measurement Testing

Ground station checkouts concluded with measurements of the RTN signal chain by sending modulated data over the channel. The channel was monitored at two points via the spectrum analyzer coupled to the output of CADeT's SSPA and at WSC where the data was retransmitted from TDRS-12. Tests involved stepping through modulation schemes at increasing bit rates and roll-off factors of the Root Raised Cosine (RRC) filter to ensure CADeT's operation within the allotted National Telecommunications and Information Administration (NTIA) Spectral Emission Mask (SEM). Figure 17. shows testing at 16 Amplitude Phase Shift Keying (APSK), 210 MBaud, and 0.2 RRC.

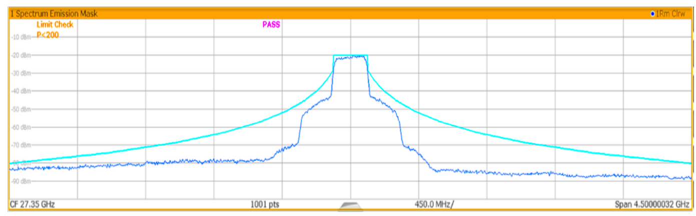

Fig. 17. CADeT SEM Testing

Testing focused on performance of the ground station's transmit capability using a channel bandwidth of 225 MHz over the 370 MHz IF service. The purpose of this testing was to operate various waveform modes to verify expected performance of the Return Link service. Measurements of the Carrier over Noise (C/No), Error Vector Magnitude (EVM), and Bit Error Rate (BER) were recorded for various waveforms and symbol rates.

A power sweep with a 27.35 GHz CW signal was used to determine the maximum C/No supported and to characterize the non-linear distortion of the channel. The results of the power sweep are shown in Figure 18. The noise density was measured with a spectrum analyzer in noise marker mode using a RMS power detector averaged over 500 samples. The resulting noise was averaged over the left and right side of the carrier, with noise marker bandwidth of 75 MHz band centered at 1.15 and 1.25 GHz. The green trace is the resulting C/No as measured at White Sands Complex. A linear system is shown in red for reference. Both curves are plotted against "PM-4" on the x-axis, a power sensor monitoring the input to the Ka-band Ground Station power amplifier. The difference between the yellow (GRC-GS) and green (WSC) curves show the additional compression through TDRSS.

The maximum C/No value of 110 dB-Hz was greater than expected, and is a result of the TDRSS G/T [8] and EIRP values [9] exceeding the minimum specifications in the link budget analysis. Note that this will vary between TDRS satellites, dedicated vs. composite service, weather, etc. Using the TDRS specifications (not actual values) the maximum C/No was estimated to be 107 dB-Hz assuming no atmospheric attenuation and no intermodulation distortion loss.

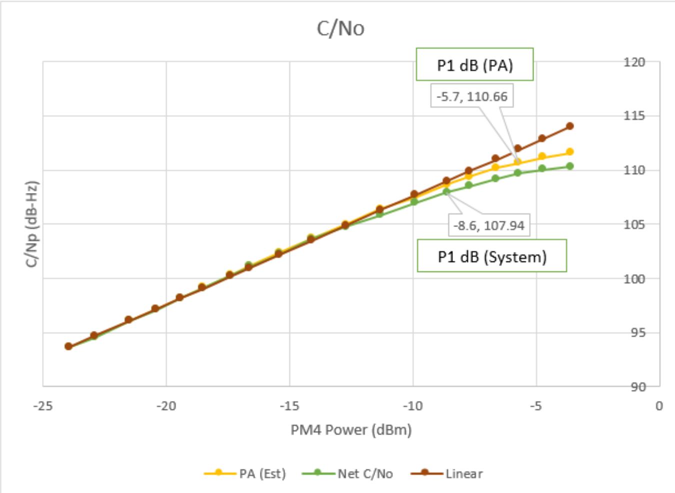

Fig. 18. CADeT C/No Testing

Much of the subsequent testing with modulated waveforms was operated at the P1dB compression point of the Ka-band ground station. It should be pointed out that while the user terminal was at the P1dB point, overall the system was operating at greater than 2 dB compression. Markers in Figure 2 highlight the P1dB operating points for each of the compression curves. Follow-on testing can use this characterization data to determine an appropriate operating point.

Next performance was evaluated with 8-PSK modulation and rate a 7/8 LDPC forward error correction code. The symbol rate was increased incrementally, starting at 150 Mbaud (393.75 Mbps). A RRC pulse shape was used, with an excess bandwidth parameter of 0.1 or 0.2. The peak data rate obtained was a symbol rate of 225 Mbaud, corresponding to a user data rate of 590.625 Mbps. Some instability was observed at the highest symbol rates, where uncorrectable frames would trickle in and cause a burst of uncorrected frames. This issue has been attributed to difficulties with the adaptive equalizer due to a combination of nonlinear distortions and bandlimited channel effects. Similar behavior has been observed in previous testing [9]. As shown in Table VI., a typical measurement was limited to 1-2 minutes of data reception before recording and changing configuration. A typical frame error rate was on the order of 1e-6.

TABLE VI
8-PSK PERFORMANCE

Symbol Rate (MBaud)	RRC	PM4 (dBm)	Post SSPA (dBm)	Eb/No (dB)	Rx Frames (Bad:Fixed Errs)
220	0.1	-5.8	3.3	–	13e6 (5:4)
220	0.1	-5.8	3.3	12.1	7e6 (12:3)
220	0.1	-5.8	3.3	–	12e6 (14:3)
225	0.2	–	–	10.9	5e6 (36:7)
225	0.2	–	–	12	5e6 (20:4)
225	0.2	–	–	–	4e6 (20:0)

Performance was also evaluated with 16-APSK modulation using the same LDPC 7/8 forward error correction code. The gamma parameter which is the amplitude ratio for the inner and outer rings of the APSK constellation was 3.14. The SRRC excess bandwidth parameter was varied throughout the testing, ranging from 0.1 to 0.35. As with previous testing, issues were encountered with the adaptive equalizer in the bandwidth-limited channel. Table VII. shows the performance as a function of symbol rate. When symbol rate rows were repeated, a burst of errors were observed which disrupted the link, as denoted by the (*). Despite the intermittent lock, the peak data rate obtained was 220 Mbaud, which corresponds to a user information rate of 770 Mbps.

TABLE VII
16-APSK PERFORMANCE

Symbol Rate (MBaud)	RRC	PM4 (dBm)	Post SSPA (dBm)	Eb/No (dB)	Rx Frames (Bad:Fixed Errs)
150	0.1	-5.8	3.0	13.6	15e6 (0:0)
175	0.35	-5.8	3.0	12.9	74.5e6 (0:0)
200	0.35	–	3.3	10.4	17e6 (16:40)
200*	0.35	-5.7	3.0	11.2	10e6 (3:14)
200*	0.35	-5.7	3.0	10.9	35e6 (14:)
210	0.2	-5.8	3.0	10.5	10e6 (3:10)
210*	0.2	-5.8	3.0	10.5	5e6 (8:10)
220	0.2	-5.9	2.99	9.8	7.5e6 (10:70)

There is a trade-off in determining the optimal operating point for a given modulation scheme. As the signal is operated towards compression there is higher output power, but more distortions. A back-off can be applied to operate more in the linear region, but the lower output power will degrade performance. A power sweep was performed with 16-QAM modulation to explore this trade-off and demonstrate how the optimal operating point can be determined experimentally. The chosen symbol rate was 100 MBaud, and results will vary for different symbol rates. For this test, the EVM was recorded for each drive level, as well as metrics from the LDPC decoder. The best drive level was determined to be -11 dBm, 5.3 dB from P1dB of the SSPA, which is 2.5 dB from P1dB of the System. This corresponds to the 0.5 dB compression point as shown in Figure 19.

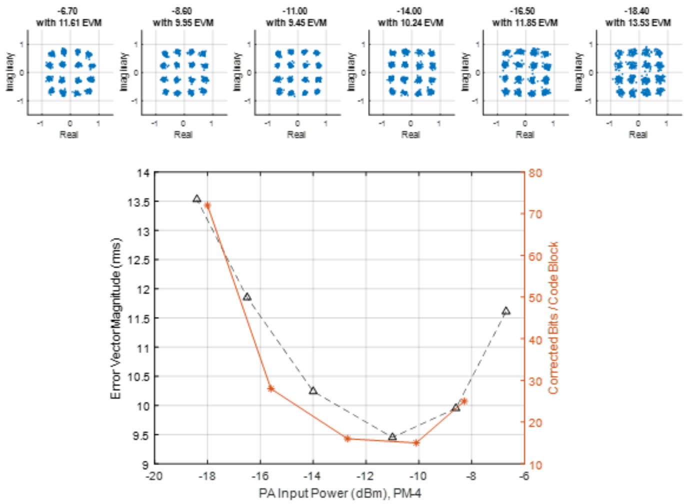

Fig. 19. 16-QAM Performance vs Drive Level

To show the feasibility of higher order modulations, 32-APSK modulation was evaluated. Due to receiver configuration issues, the modem had difficulties achieving lock with 32-APSK. Regardless, captured data in Figure 20 shows that the 32-APSK constellation was received with minimal nonlinear distortions from the channel. The amplifier was backed off 7 dB from the Ka-band Ground Station's P1dB compression point to minimize any nonlinear distortions.

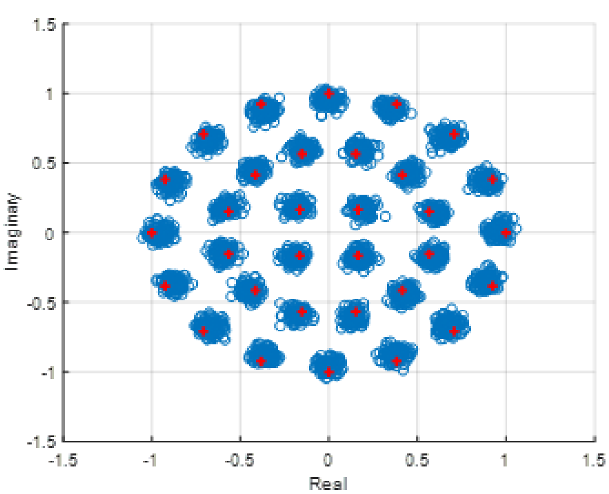

Fig. 20. Received Constellation for 32-APSK, 80 MBaud

V. Lessons Learned

Detailed laboratory characterization of each component and subsystem used with CADeT has been an invaluable asset during buildup and system checkouts. The availability of this data provides an excellent point of reference for diagnosing the system into its foreseeable future should any issues or changes arise. Combining this lab data with propagation measurements collected in Cleveland, archived vendor data from when the dish was first installed, and access to a well-defined geostationary satellite link has proven useful to characterizing the current performance of the beam-waveguide platform. With this current benchmark we may pursue options to further improve dish performance as required.

The inclusion of fixed measurement points dispersed throughout the FWD and RTN signal paths of CADeT has greatly reduced extrinsic uncertainties introduced when breaking and reassembling the RF chain to take measurements. Power meter values can be checked against characterized system tables to assess performance and isolate sources of error quickly. Providing researchers access to characterized system data prior to event testing allows them to plan experiments accordingly and arrive prepared. Live and recorded data from coupled RF ports and outdoor weather sensors has aided researchers in making changes to their experiments both in real-time or post processing.

VI. Conclusions

A series of tests was performed to measure the overall performance of CADeT, including measuring the signal-to-noise ratio, non-linear channel distortions, and bit-error-rate performance. High-order modulations, including 8-ary phase shift keying (8-PSK), 16-amplitude phase shift keying (APSK), and 32-APSK were tested over the 225 MHz channel, using Low Density Parity Check (LDPC) rate 7/8 encoding. Using the available test equipment, peak user data-rates of 770 Mbps were demonstrated. However, the link has sufficient margin to support multi-Gigabit communication with the appropriate equipment upgrades. Overall, the testing was successful, and demonstrates that the GRC Ka-band Ground Station is ready for future cognitive communications experiments.

References

[1] C. Seidl, "Operators Manual for use with the Cognitive Algorithm Development Testbed," NASA
[2] M. Piasecki, "SCaN Testbed Glenn Research Center Ground Station Description, Performance, and Interface Document," NASA GRC-CONN-DOC-1073.
[3] P. Dunsmore, *Handbook of Microwave Component Measurements: With Advanced VNA Techniques*, John Wiley & Sons, 2012.
[4] National Aeronautics and Space Administration, "Space Network Users' Guide. Revision 10," 2012.
[5] R. Reinhart et al., "ACTS Ka-Band Earth Stations: Technology, Performance, and Lessons Learned," NASA 20010019784.
[6] C. Balanis, *Antenna Theory, 3rd ed. Vol. 1.* John Wiley & Sons, 2005.
[7] F. Miranda, "Overview of the Advanced High Frequency Branch," NASA GRC-E-DAA-TN20663.
[8] J. Downay et al, "Bandwidth-Efficient Communication through 225 MHz Ka-band Relay Satellite Channel," NASA GRC-E-DAA-TN35188
[9] Y. Wong et al., "An Assessment of the Bit-Error-Rate Performance of QPSK, 8PSK, 8PSK/TCM and GMSK via the Tracking and Data Relay Satellite System 650 MHz-Wide Ka-Band Channal," AIAA, 2013.