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SSC15 – VI - 8

Ka-Band for CubeSats

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Conference on Small Satellites
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Introduction

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It is Highly Evident that Small Satellite Missions are Becoming Throughput Bound

Contemporary Modest Requirement

- Small Satellite Sensor/ Data Generator:
  - 4-5 watts (100% duty factor)
  - 100 Million *Pixel* Data Array
  - (10,000 X 10,000 Array)
  - 10 Bit per Pixel
  - Store 100 Events (Images) / Orbit
  - Factor of 2 Lossless Compression

  - 10E+11 bits per orbit
  - 5 X 10E+10 compressed bits/orbit
  - 14 Orbits/ Day
  - **7 X 10E +11 compressed bits/day**

…And, Resultant Data Rate Expectation

Downlink Consequences:

- Downlink 4 Passes/Day
- 11 Minutes/Pass (Average)

- 2640 sec/day downlink time
- Required data rate to downlink 7 X 10 E +11 bits:
  - **265.2 Mbps**

Our Background

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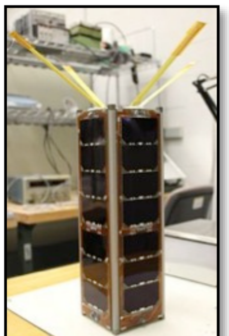
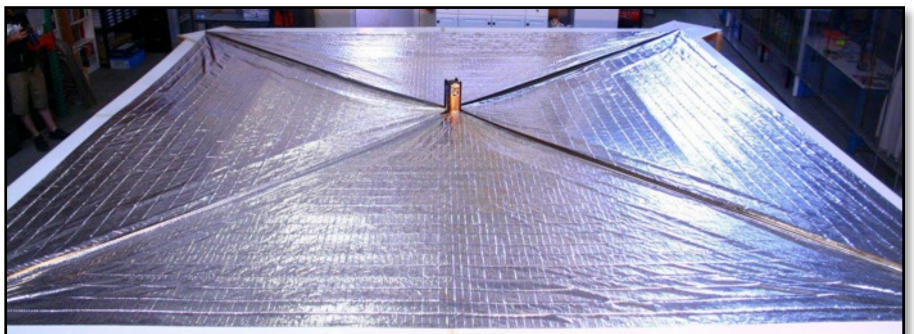
- 17-person team in Silicon Valley
- Core engineering team worked at Canopus Systems
- 100% of current team completed Perseus-M mission
- Broad range of experience in the space industry
- Now focused on generating 22m and 2.5m multi-spectral Earth imagery

SRI –RAX 1

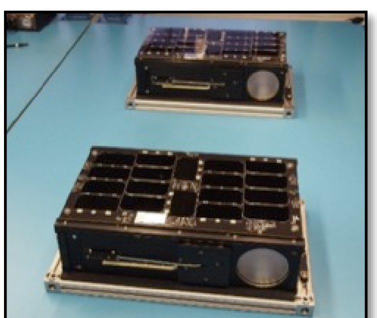


LightSail

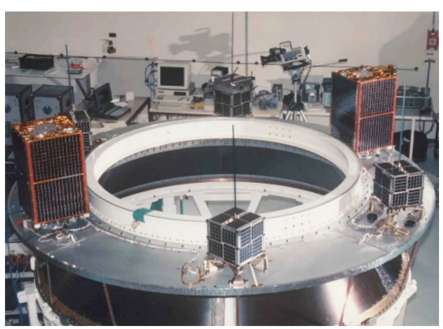


SSL-ABS2

Perseus-M

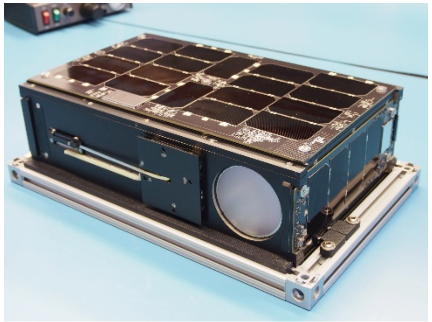


AMSAT – OSCAR Series

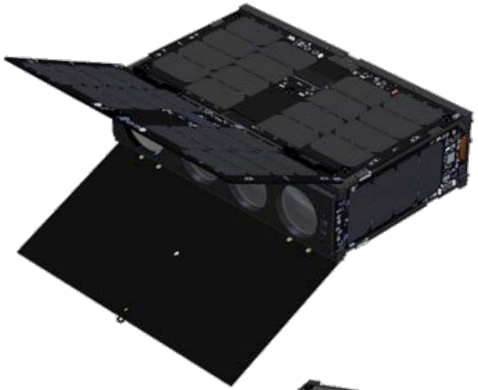


Current Projects

- **Perseus-M**
  - Launched in June 2014
  - 2x 6U Automatic Identification System (AIS) CubeSat
  - Characterizing AIS payload performance
  - On-orbit test bed for future missions



- **Corvus-BC**
  - Launch Q1 2016
  - 4 x 6U remote sensing CubeSat
  - Multispectral: Red, Green, NIR
  - 22 m GSD



- **Corvus-HD**
  - Launch Q3 2016
  - 4 x 16U remote sensing CubeSat
  - Multispectral: Red, Green, Blue, NIR, Red Edge
  - 2.5 m GSD

Ka-Band ITA (1st Gen)
(Integrated Transmit Assembly)

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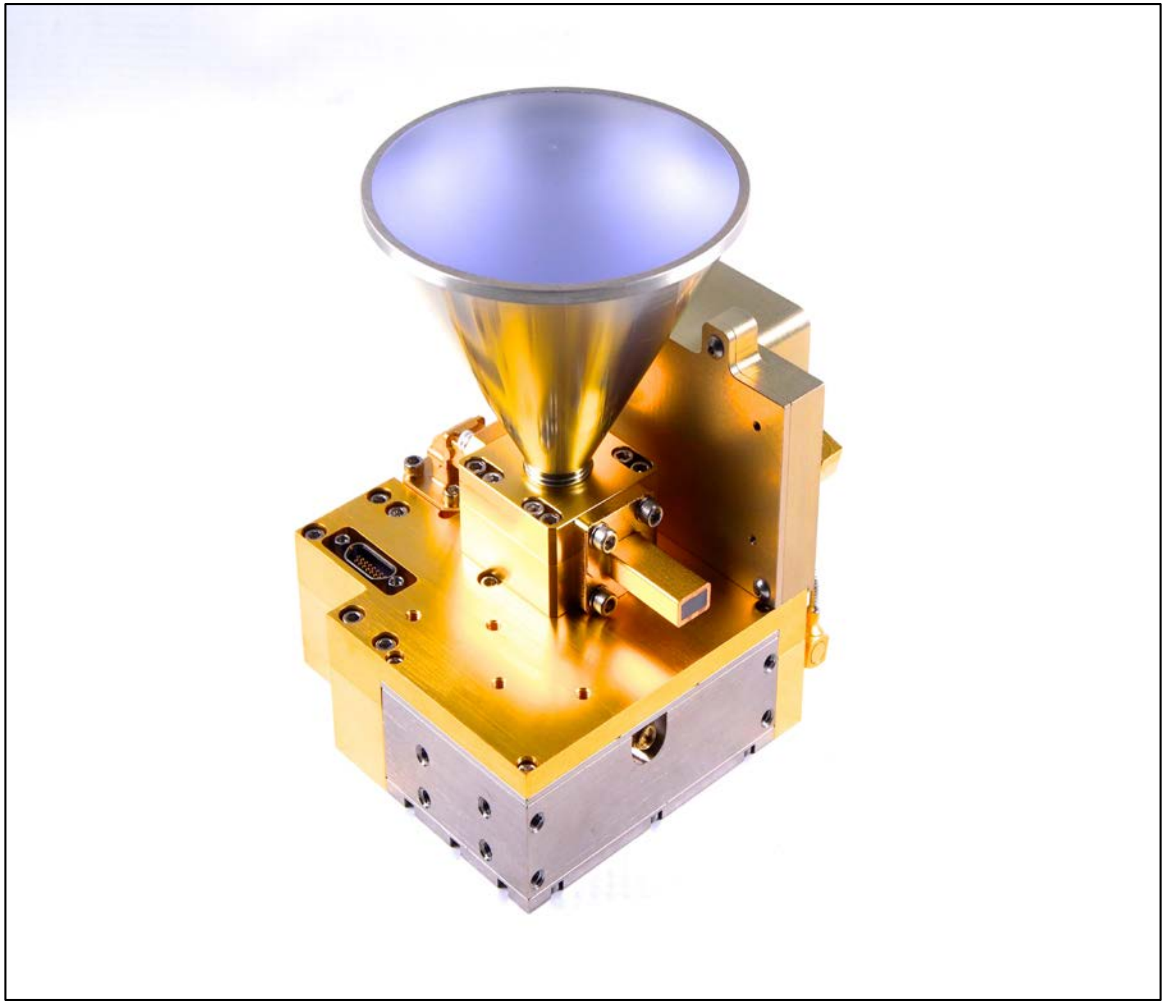

ITA With Modulator & Coder (2nd Generation)

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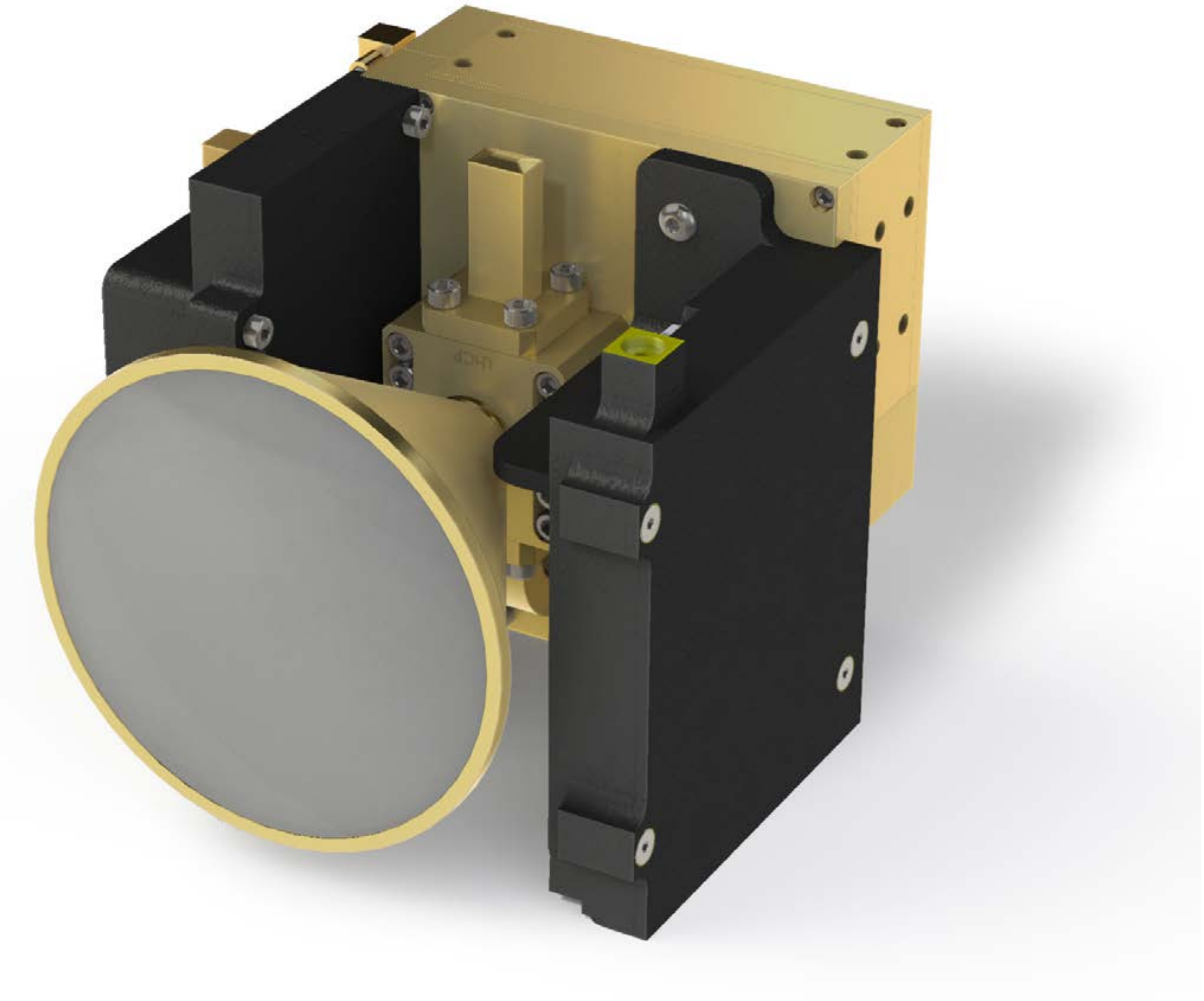

Corvus-BC Overview

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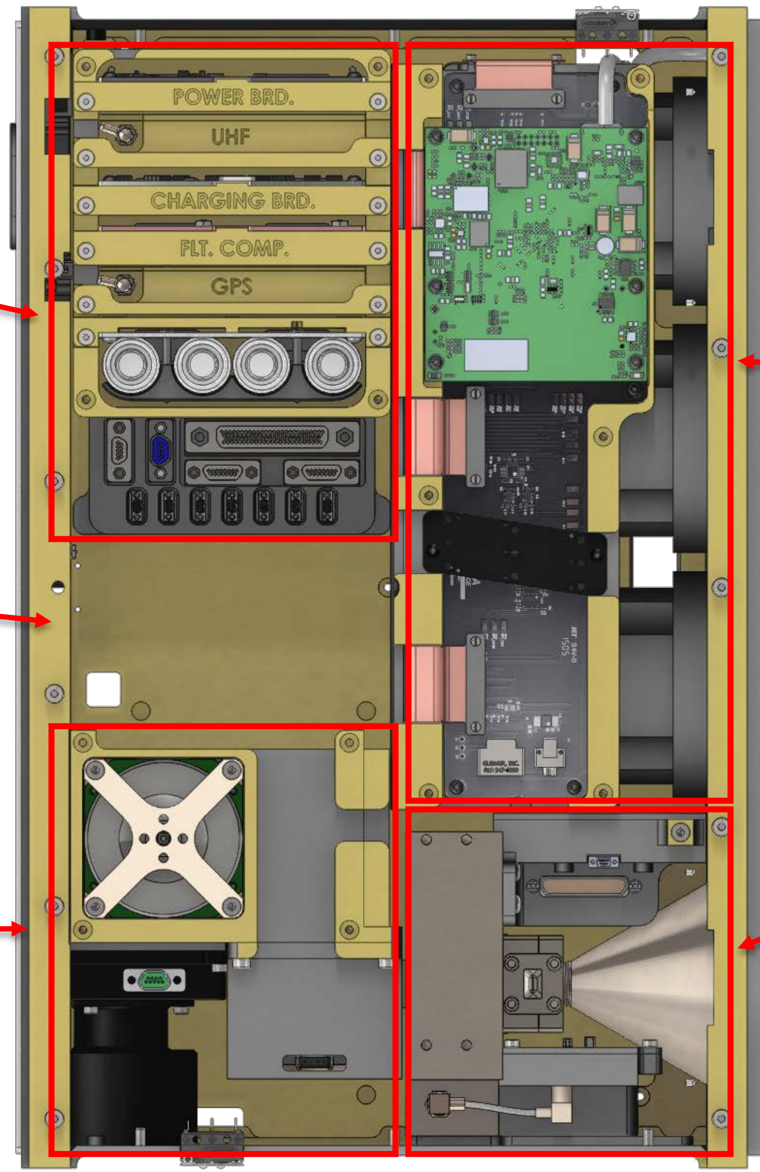
Flight Control System ("the rack")

- UHF Radio
- GPS Radio
- EPS boards
- Batteries

Open volume for future use (Propulsion!)

Star-tracker & Reaction Wheels



Imaging Payload

Ka-Band Transmitter

Corvus-HD Overview

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- Upgraded bus to be used for Corvus-HD, launching Q3 2016
- Improved ACS accuracy and availability
- >200 Mbps data transfer with adaptive ModCod
- Miniaturized Ka Transmitter assembly
- S-Band, UHF, and Globalstar radios included
  - Results in high command & telemetry availability (>20%)
- Doubled battery capacity

26.8 GHz Spectrum @ 0.6 W RF
(27.8 dBm SSPA Power Output)

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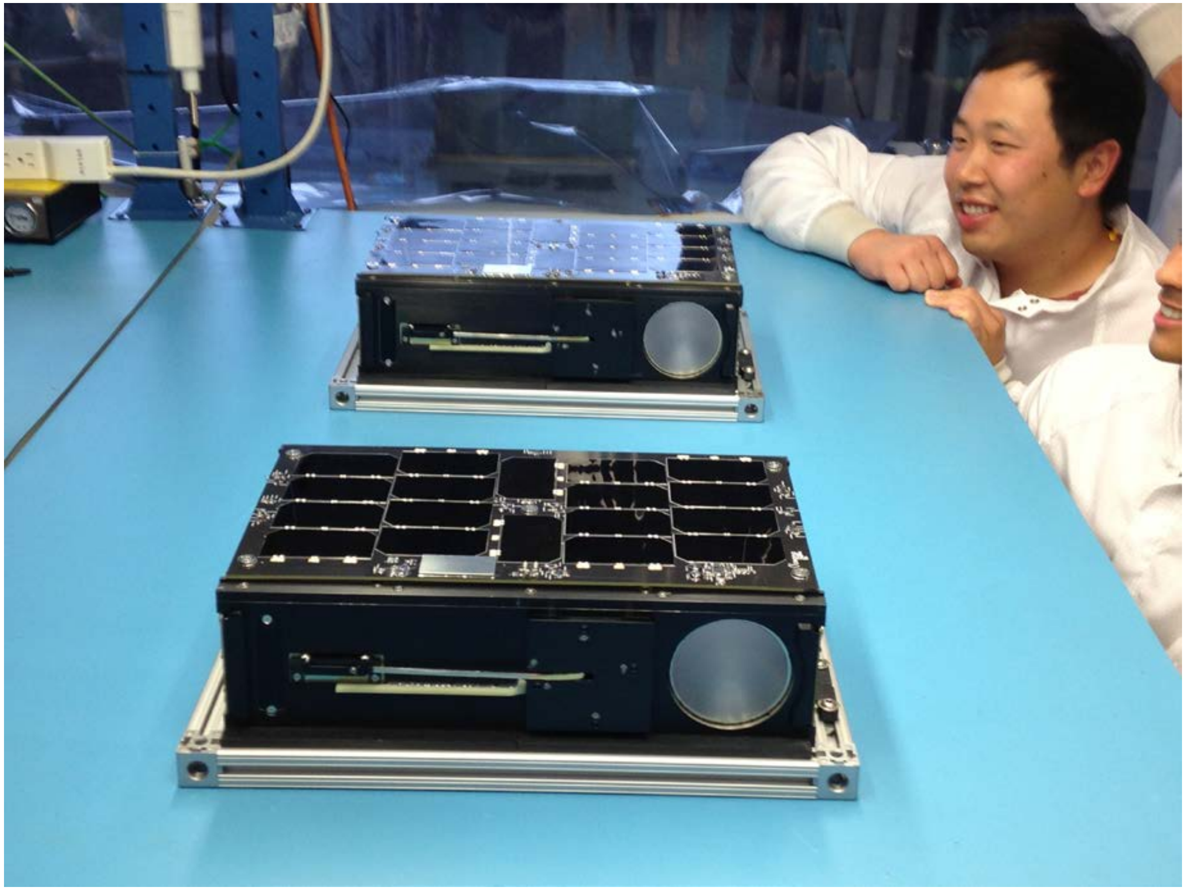
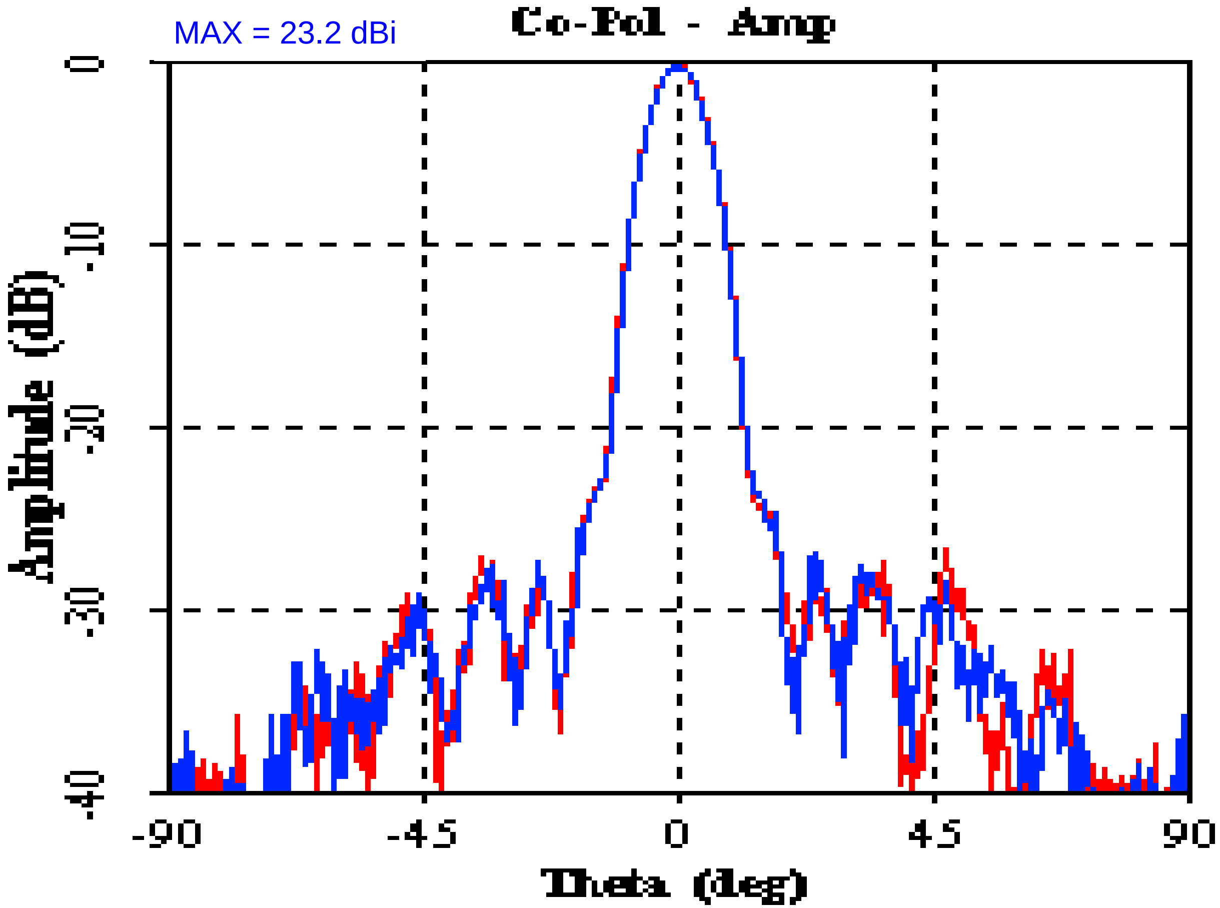
@ Approximately -1 dB Compression Point

In-Orbit Performance to Date (Perseus-M1 and –M2)

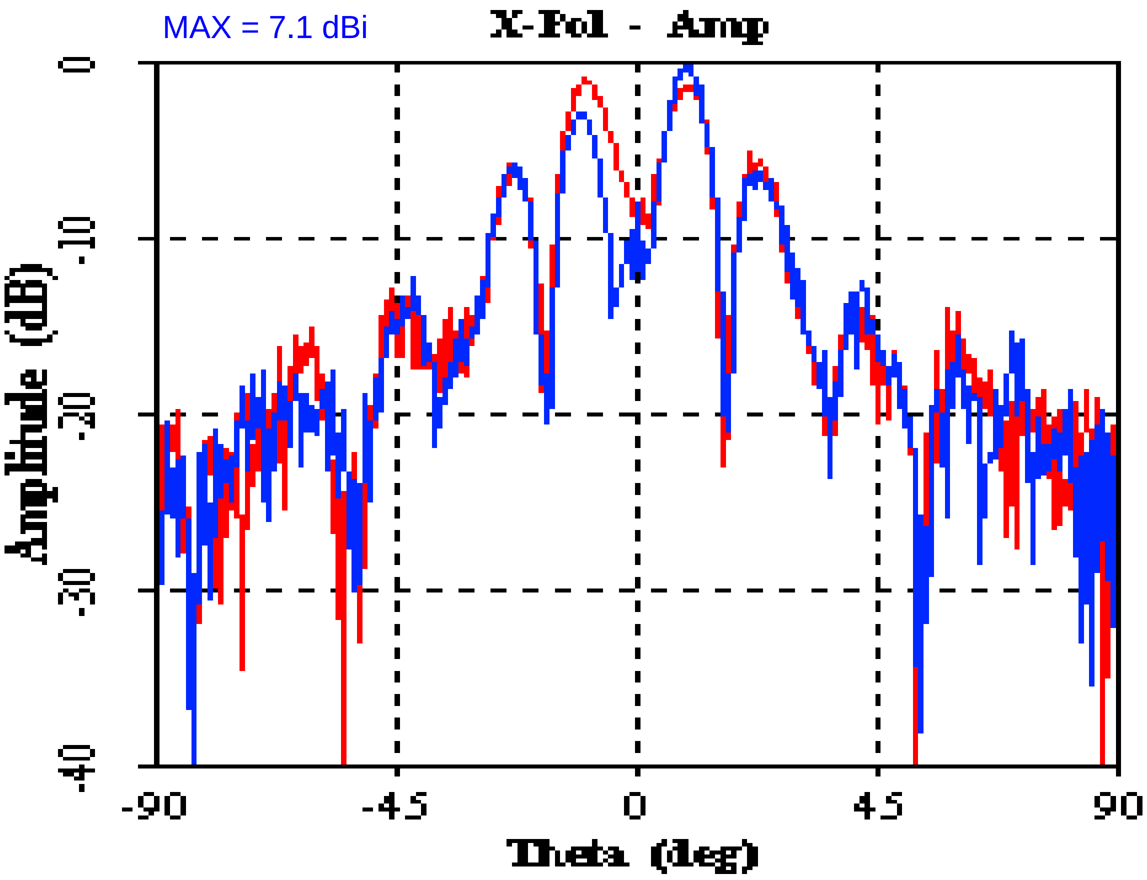


Horn Measured Pattern
(Co-Polarized = RHCP)



----- Blue Plot: φ = 0°; θ Cut from -90° to +90°
----- Red Plot: φ = 90°; θ cut from -90° to +90°

Horn Measured Pattern
(Cross-Polarized = LHCP)



----- Blue Plot:	φ = 0°; θ Cut from -90° to +90°
----- Red Plot:	φ = 90°; θ cut from -90° to +90°

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Link Budget For CW Case (10 kHz BW)

Ka-Band Telemetry Transmitter (ACS Unstabilized CW Performance)
Downlink TLM Transmitter Budget:

CW Mode Only	Downlink Freq.:	26.7998 GHz
Parameter:	*Value:*	*Units:*
Spacecraft:		
Spacecraft Total HPA Power Allocated per User Channel:	0.6	watts
In dBW:	-2.2	dBW
In dBm:	27.8	dBm
Spacecraft Transmitted IM or Spectrum Regrowth Power:	0	watts
Spacecraft Total HPA Power Allocated per User Channel:	0.6	watts
Spacecraft Transmission Line Losses:	-0.1	dB
S/C Connector, Filter and In-Line Switch Losses:	0	dB
Spacecraft Transmit Antenna Gain (X-POLE Peak Gain):	7.1	dBiC
Spacecraft EIRP per User:	4.8	dBW
Spacecraft Transmit Antenna Pointing Loss:	0.0	dB
Downlink Path:		
Antenna Polarization Loss (at 90° Off-Axis from S/C Boresight):	-20.0	dB
Path Loss:	-186.8	dB
Atm. Gaseous Attenuation (1, 2)	-5.39	dB
Rain Attenuation	-2.82	dB
Cloud Attenuation	-2.82	dB
Scintillation	-2.16	dB
Total Meteorological Losses (With or Without Rain)	-9.67	dB
Rain and Cloud Losses Included in Meteorological Losses?	Yes	Use?
Isotropic Signal Level at Ground Station:	-202.0	dBW
Isotropic Signal Level at Ground Station with Met. Losses:	-211.7	dBW
Ground Station:	Svalbard Existing 7.3 m Ant.	
Ground Station Antenna Pointing Loss:	-1.5	dB
Ground Station Antenna Gain:	59.9	dBiC
Ground Station Radome Losses:	-1.0	dB
Ground Station Transmission Line, Filter and/or Switch Losses:	-1.0	dB
Ground Station LNA Noise Temperature:	120	K
Ground Station Transmission Line Temp.:	290	K
Ground Station Sky Temperature:	25	K
Ground Station Sky Temperature faded:	233	K
G.S. Transmission Line Coefficient:	0.631	
Ground Station Effective Noise Temperature:	243	K
Ground Station Effective Noise Temperature faded:	374	K
Ground Station Figure of Merrit (G/T):	34.0	dB/K
Ground Station Figure of Merrit (G/T) faded:	32.1	dBi/K
G.S. Signal-to-Noise Power Density (clear sky)	60.6	dBHz
G.S. Signal-to-Noise Power Density faded	49.0	dBHz
Tracking Loop Bandwidth:	10.00	kHz
Tracking Loop Bandwidth (in dBHz):	40.0	dBHz
Downlink C/(N) in Tracking Loop Bandwidth (Unfaded/Clear Sky):	20.6	dB
Downlink C/N inTracking Loopl Bandwidth (Faded/99.5% Link Avail.:	9.0	dB
Required C/N to Lock Traking PLL:	5.0	dB
Link Margin to Lock Tracking Loop (Unfaded/Clear Sky):	**15.6**	**dB**
Link Margin to Lock Tracking Loop (Faded/99.5% Link Availability):	**4.0**	**dB**

First 26.8 GHz Tests at Svalbard, Norway

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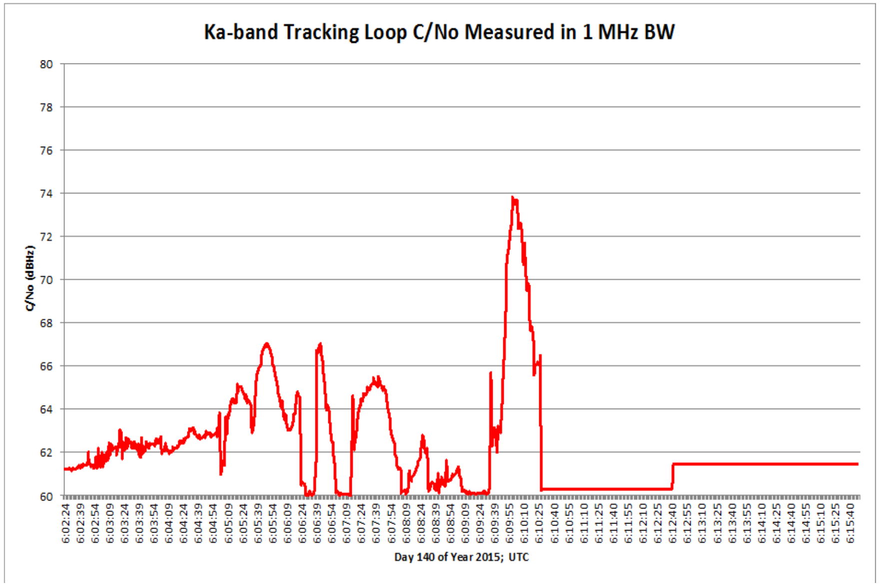
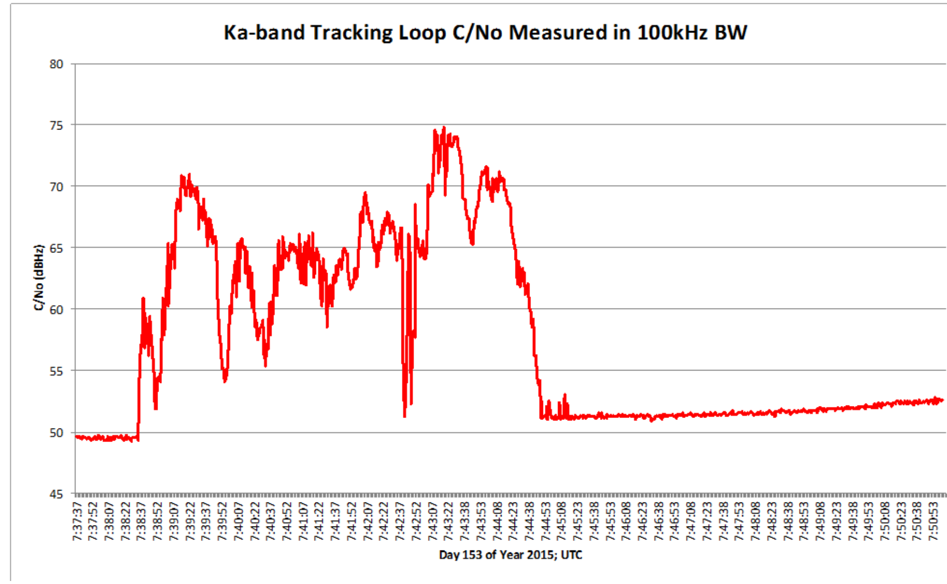
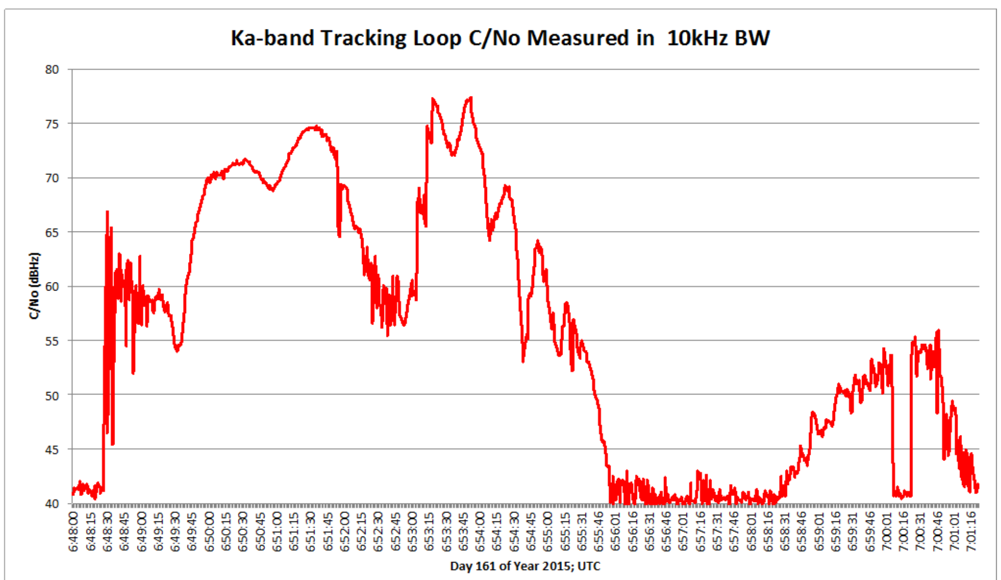


May 20, 2015



June 2, 2015



June 10, 2015

Current Best Result from Svalbard, Norway

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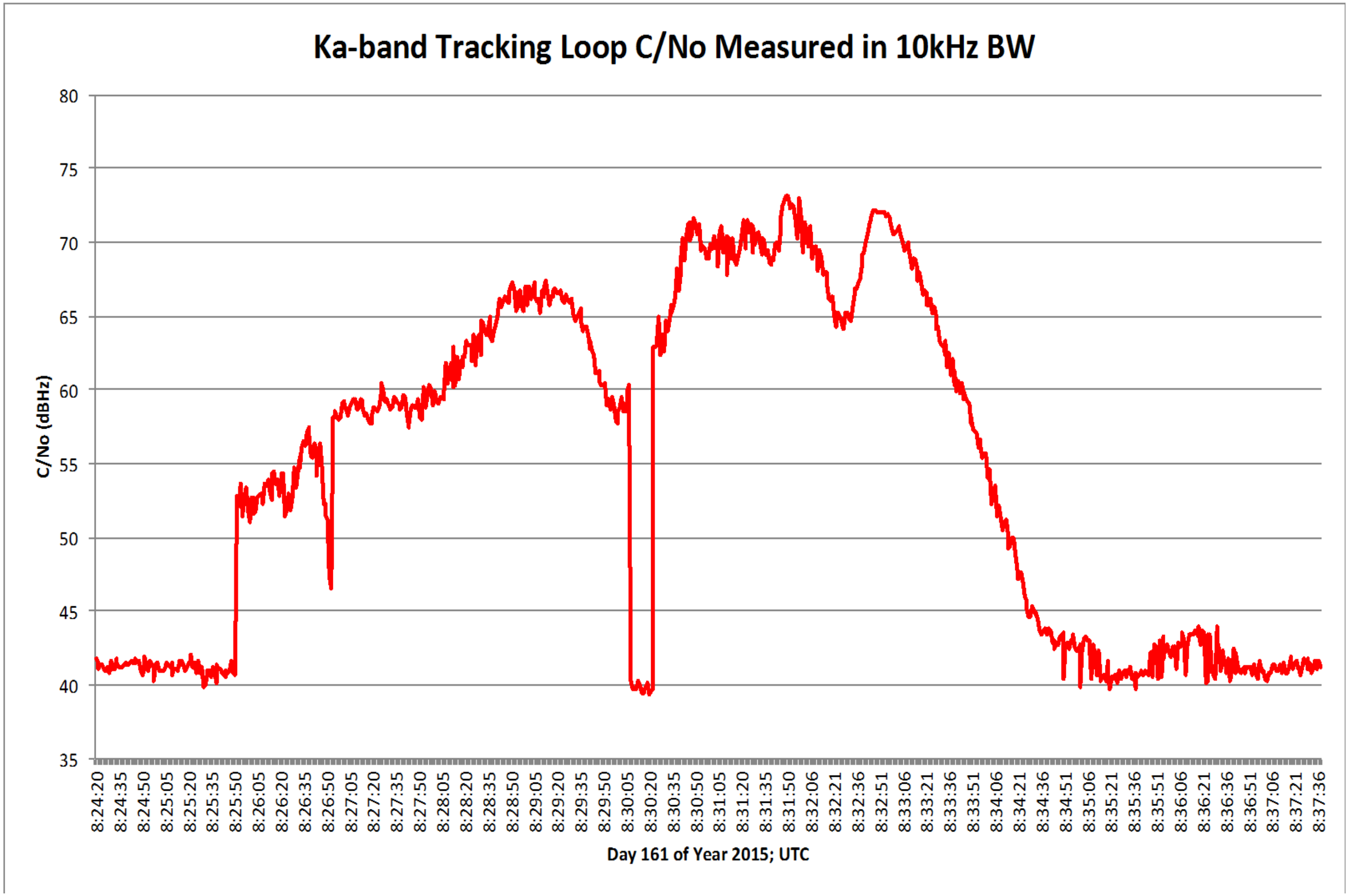

June 10, 2015

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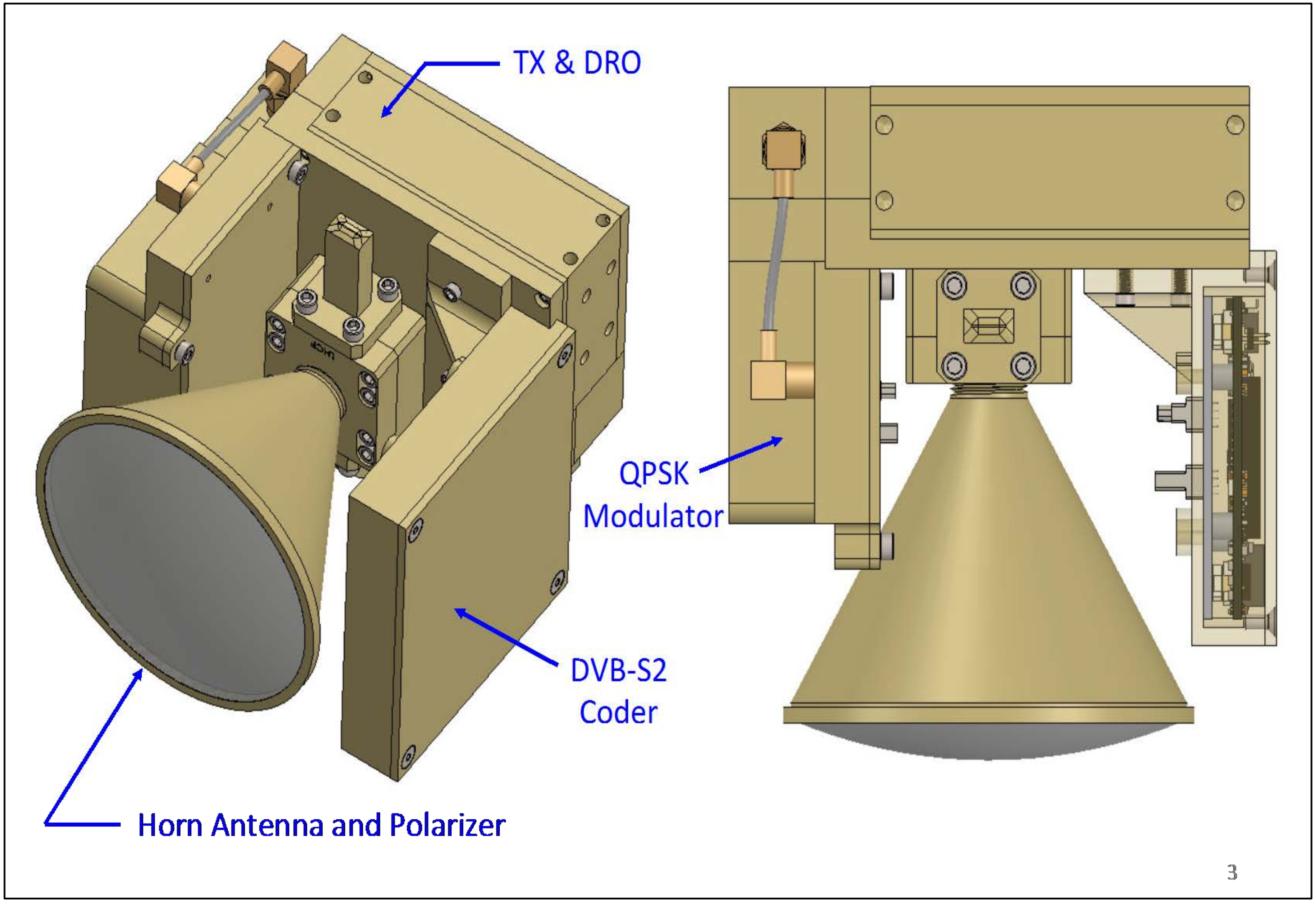
Second Generation Ka-Band Transmitter

- ITA → Leave As Is
- Horn Antenna → Leave As Is
- Modulator → Leave As Is
- Add New DVB-S2 Encoder
  - QPSK Steps Only
  - Steps 1 Thru 12; Except Skip Step 10
  - Leave Nyquist Filter at 25 MHz; R = 0.2

2nd Generation Ka-Band Configuration



2nd Generation DVB-S2 MODCOD Settings

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DVB-S2 STEPS Not Requiring Significant Amplifier Linearity — Bandwidth and Nyquist Filtering Adjusted for Perseus Case

Specified Bandwidth in MHz (Per Channel)	25.00	Specify Nyquist rolloff	0.2

ETSI EN 302307 DVB S2 Theoretical Performance for Target ModCOD

Step Available:	MODulation	CODing Rate	Es/No	Sym rate	BW (nyq)	C/No	C/N	Spectral Efficiency	Bits/ symbol	Data Rate	Ebi/No	Eb/No	Gross Bit Rate	Info bits	code bits	"overhead"	
			dB	Msym/sec	MHz	dBHz	dB	info bit/symbol		Mbps	dB	dB	MbIt/sec	MbIt/sec	MbIt/Sec		
1	QPSK	1/4	-2.35	20.83	25.00	70.84	-3.14	0.490243	2	10.2134	0.746	-5.360	41.67	10.42	31.25	1.951%	R=1/4
2	QPSK	1/3	-1.24	20.83	25.00	71.95	-2.03	0.656448	2	13.6760	0.588	-4.250	41.67	13.89	27.78	1.533%	
3	QPSK	2/5	-0.3	20.83	25.00	72.89	-1.09	0.789412	2	16.4461	0.727	-3.310	41.67	16.67	25.00	1.324%	
4	QPSK	1/2	1.00	20.83	25.00	74.19	0.21	0.988858	2	20.6012	1.049	-2.010	41.67	20.83	20.83	1.114%	
5	QPSK	3/5	2.23	20.83	25.00	75.42	1.44	1.188304	2	24.7563	1.481	-0.780	41.67	25.00	16.67	0.975%	
6	QPSK	2/3	3.10	20.83	25.00	76.29	2.31	1.322253	2	27.5469	1.887	0.090	41.67	27.78	13.89	0.831%	
7	QPSK	3/4	4.03	20.83	25.00	77.22	3.24	1.487473	2	30.9890	2.306	1.020	41.67	31.25	10.42	0.835%	
8	QPSK	4/5	4.68	20.83	25.00	77.87	3.89	1.587196	2	33.0666	2.674	1.670	41.67	33.33	8.33	0.800%	
9	QPSK	5/6	5.18	20.83	25.00	78.37	4.39	1.654663	2	34.4721	2.993	2.170	41.67	34.72	6.94	0.720%	
10	8PSK	3/5	5.50	20.83	25.00	78.69	4.71	1.779910	3	37.0815	2.996	0.729	62.50	37.50	25.00	1.116%	N/A
11	QPSK	8/9	6.20	20.83	25.00	79.39	5.41	1.766451	2	36.8011	3.729	3.190	41.67	37.04	4.63	0.637%	
12	QPSK	9/10	6.42	20.83	25.00	79.61	5.63	1.788612	2	37.2628	3.895	3.410	41.67	37.50	4.17	0.633%	R=9/10

DVB-S2 Downlink Set-Up
(DVB-S2 Demod & Signal Analyzer)

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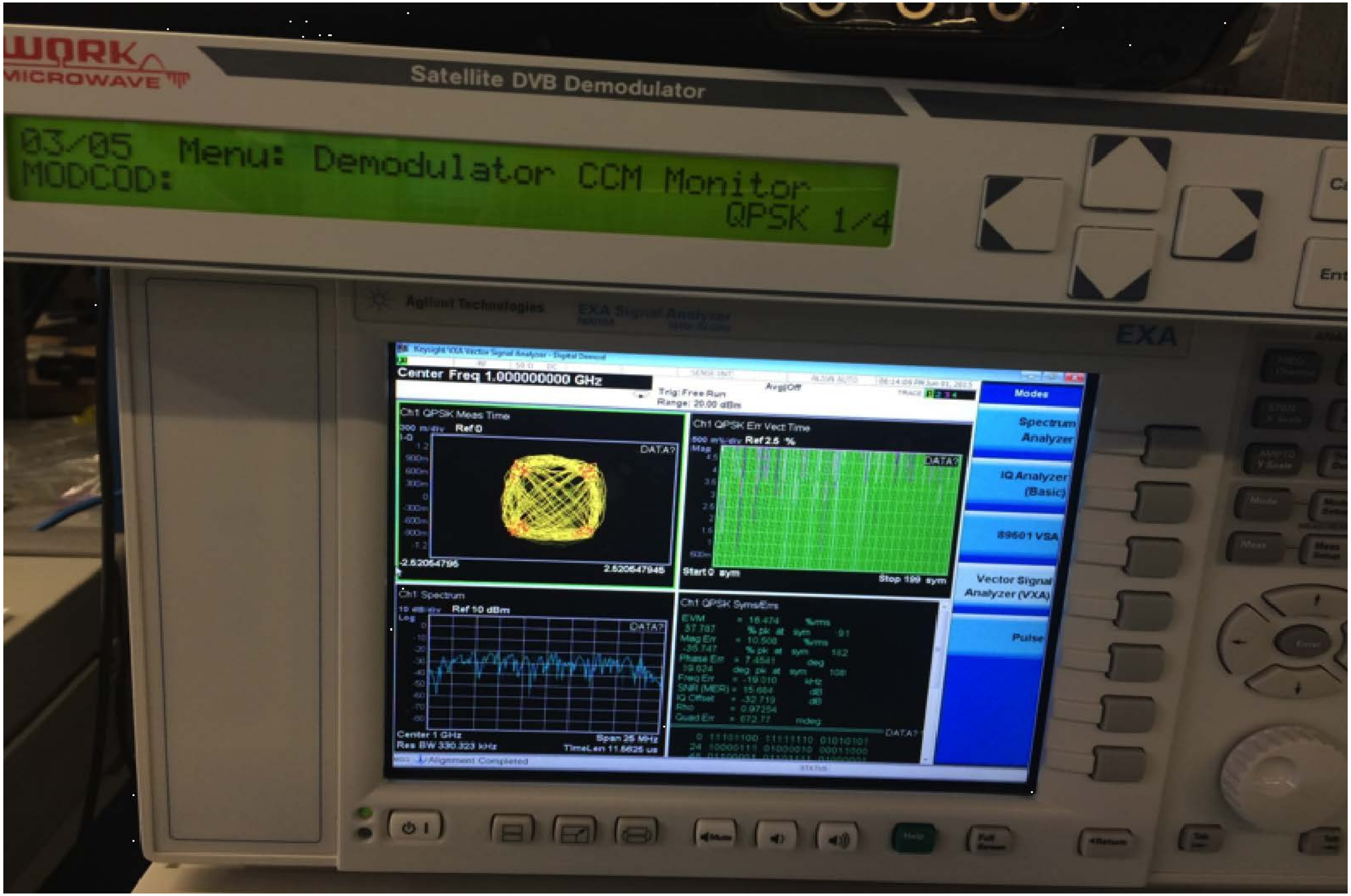

Under Test: MODCOD Step 1: QPSK @ R=1/4

Test Results of All 11 MODCOD Steps

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	ModCod	Datarate (bps)	BB fr loss	Cor LDPC Err *	RF input(dBm)	Es/No(dB)	EVM(%)	SNR(dB)
1	1/4	9968759	0	0	-34	16	16	15.5
2	1/3	13348424	0	0	-34	16	16	15.5
3	2/5	16052155	0	0	-34	15.9	16	15.5
4	1/2	20107754	0	0	-34	16	16	15.5
5	3/5	24163350	0	0	-34	15.3	16	15.5
6	2/3	26887110	0	0	-34	16	16	15.5
7	3/4	30246746	0	0	-34	16	16	15.5
8	4/5	32274546	0	0	-34	16	16	15.5
9	5/6	33646440	0	0	-34	16	16	15.5
11	8/9	35919576	0	0	-34	16	16	16
12	9/10	36370200	0	0	-34	16	16	15.5

No Step 10

* NOTE: Test Run for 10s of Minutes per MODCOD Setting

The Effects of Intermodulation

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In fact, the SNR is really a combination of three factors:

1) The system white noise (thermal noise)
2) The system intermodulation created by (mostly) the TX SSPA
3) The system interference received from other sources

$$SNR_{dB} = S_{dB} - (kTB_{dB} + IMR_{dB} + I_{dB})$$

Third Generation Ka-Band Transmitter

- ITA → Leave As Is
- Horn Antenna → Leave As Is
- Modulator → Remove
- Add Expanded DVB-S2 Encoder
  - Implement All 28 DVB-S2 MODCOD Steps
  - Incorporate New Modulator into Coder
  - Increase Nyquist Filter Bandwidth to at 87 MHz; R = 0.2
  - Utilize System in ACM
- Watch This Space: 3 months to Readiness

3rd Generation Expected Performance in ACM

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Orbit Predictions

utc	elev deg	azim deg	range km	lat deg	lon deg	height km
Sun 10May15 00:25:00	5.4	41	2385	76.8	119.9	639
Sun 10May15 00:26:00	10.7	41.4	1975	79.5	107.4	640
Sun 10May15 00:27:00	17.7	41.8	1573	81.5	88.2	640
Sun 10May15 00:28:00	28.2	42.5	1191	82.1	62.4	641
Sun 10May15 00:29:00	45.9	43.8	857	81.1	37.7	641
Sun 10May15 00:30:00	77.4	51.7	655	78.9	20.2	641
Sun 10May15 00:31:00	63.4	217.4	708	76.1	8.9	641
Sun 10May15 00:32:00	37.8	220.3	976	73	1.4	641
Sun 10May15 00:33:00	23.6	221.2	1333	69.6	-3.8	640
Sun 10May15 00:34:00	14.7	221.8	1725	66.2	-7.7	640
Sun 10May15 00:35:00	8.5	222.2	2131	62.7	-10.6	639

Ground Station at Svalbard, Norway

Avg. Data Rate: 205 Mbps

Link Results

achieved C/No:	achieved spectral rate:	achieved MODCOD:	achieved data rate:	throughput:
80.68 dBHz	0.989 bits/sym	QPSK; R=1/2	71.28 Mbps	534.60 MB
85.03 dBHz	1.789 bits/sym	QPSK; R=9/10	128.93 Mbps	966.98 MB
87.97 dBHz	2.479 bits/sym	8PSK; R=5/6	178.66 Mbps	1339.95 MB
90.78 dBHz	3.300 bits/sym	16APSK; R=5/6	237.89 Mbps	1784.18 MB
93.59 dBHz	4.120 bits/sym	32APSK; R=5/6	296.95 Mbps	2227.13 MB
95.56 dBHz	4.453 bits/sym	32APSK; R=9/10	320.99 Mbps	2407.43 MB
95.02 dBHz	4.453 bits/sym	32APSK; R=9/10	320.99 Mbps	2407.43 MB
92.53 dBHz	3.952 bits/sym	32APSK; R=4/5	284.84 Mbps	2136.30 MB
89.71 dBHz	3.166 bits/sym	16APSK; R=4/5	228.19 Mbps	1711.43 MB
86.91 dBHz	2.280 bits/sym	8PSK; R=3/4	160.61 Mbps	1204.58 MB
83.69 dBHz	1.587 bits/sym	QPSK; R=4/5	114.41 Mbps	858.08 MB
				17.578 GBytes

DARPA Sat-to-Sat Relay BAA (What IF?)

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Parameter:	Value:	Unit:
Spacecraft #1 Transmitter Power Output:	30.0	dBm
Transmitter Losses:	-1.0	dB
S/C #1 Antenna Gain (Current Horn Antenna):	23.5	dBiC
S/C EIRP:	52.5	dBm
Path Loss (24.55 GHz, 2000 km):	-186.3	dB
Polarization Loss:	-0.5	dB
Pointing Loss (Pointing Accuracy = 3°; Ant. BW=10.2°):	-1.0	dB
Other Misc. Losses (Atmosphere, Ionosphere):	-0.1	dB
Isotropic Signal Level at Spacecraft #2:	-135.4	dBm
S/C #2 Antenna Gain (Current Horn Antenna):	23.5	dBiC
S/C #2 Antenna Pointing Loss (Same as S/C#1):	-1.0	dB
S/C #2 Receiver Losses (Line Loss, Filter Loss, Etc.):	-0.25	dB
S/C #2 Receiver Effective Noise Temperature:	250	K
S/C #2 G/T:	-1.7	dB/K
S/C #2 C/No:	61.47	dBHz
Nyquist Channel Bandwidth (0.2 Roll-Off):	2.0	MHz
DVB-S2 MODCOD Level Supported:	QPSK	R = 1/3
Required C/No to Support MODCOD:	60.98	dBHz
Margin at this MODCOD Step:	0.49	dB
Margin Above DVB-S2 Threshold:	4.61	dB
Symbol Rate Supported by Nyquist Filter:	1,670,000	sps
Spectral Efficiency:	0.6565	bits/sps
Data Rate Supported:	1,096,355	bps

Spectrum Management for Ka-Band EESS (Remote Sensing) Missions

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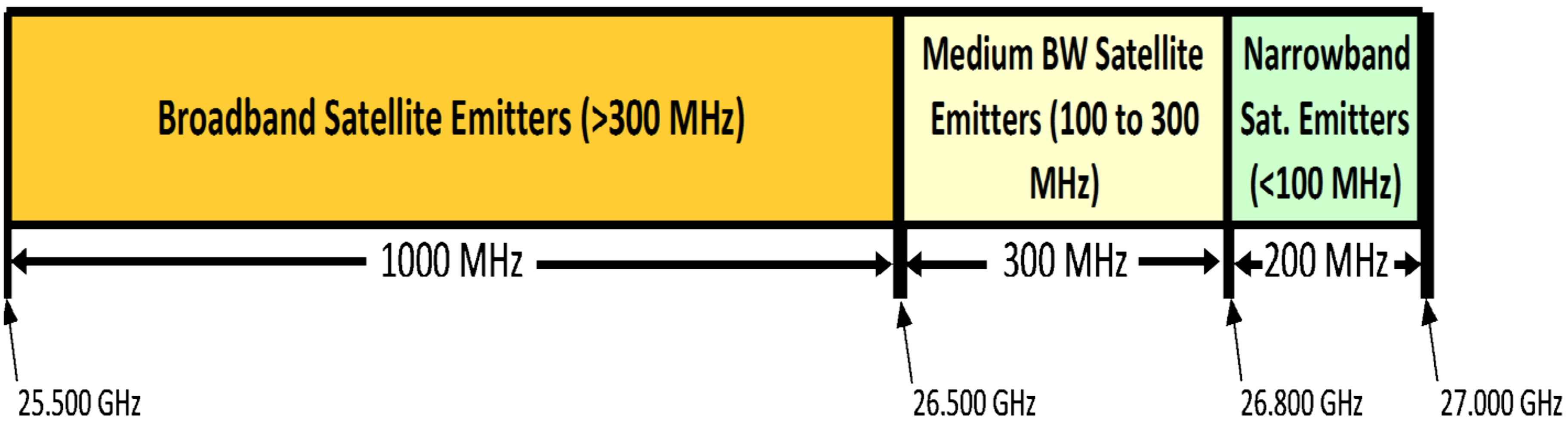

Questions?