An Optimum Space-to-Ground Communication Concept for CubeSat Platform Utilizing NASA Space Network and Near Earth Network

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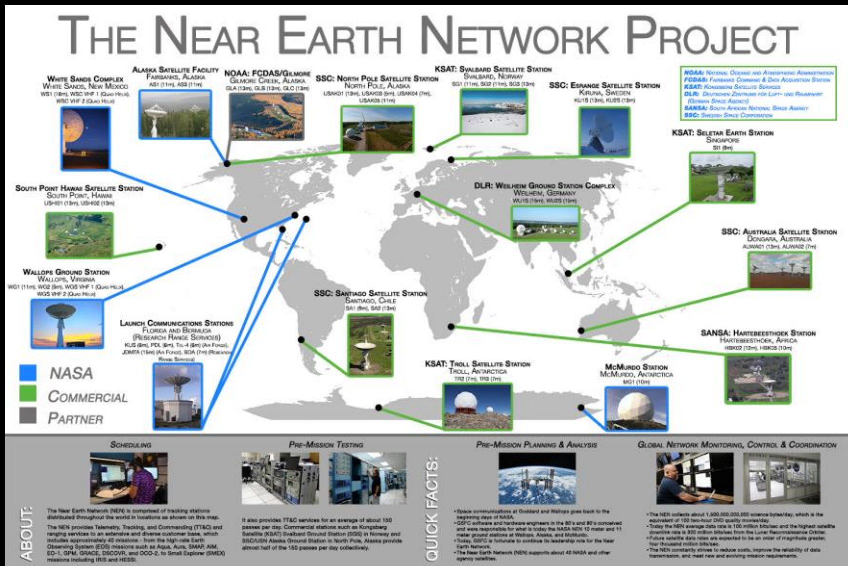
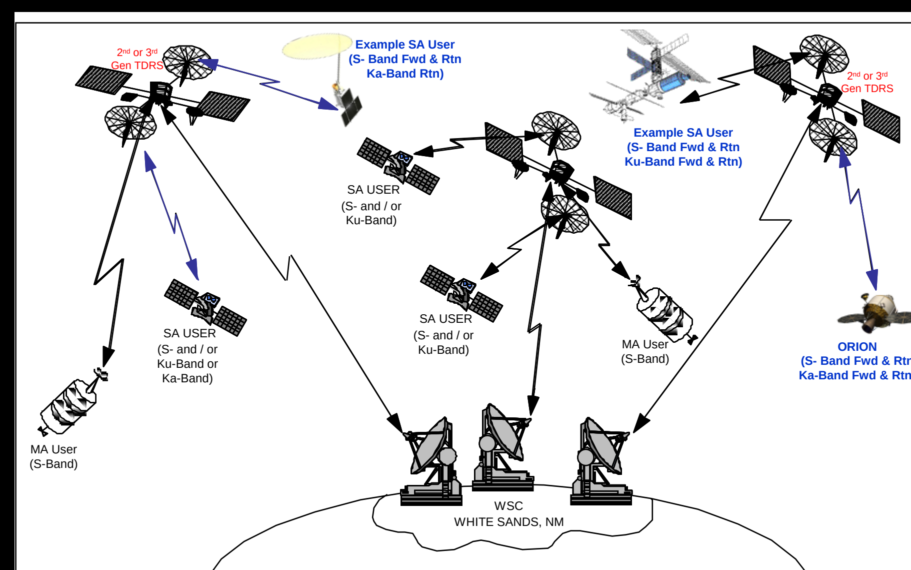
NASA Near Earth Network/Space Network Overview



- The Space Network (SN) Tracking and Data Relay Satellite System (TDRSS) fleet currently consists of nine satellites supported by three tracking stations, two at White Sands, New Mexico, and a third on the Pacific island of Guam
- TDRSS supports low earth orbiting satellites including the International Space Station, earth observing satellites, aircraft, scientific balloons, expendable launch vehicles, and terrestrial systems

- NASA Near Earth Network (NEN) is comprised of stations distributed throughout the world in locations including Svalbard, Norway; Fairbanks, Alaska; Santiago, Chile; McMurdo, Antarctica; Wallops Island, Virginia.
- The NEN supports orbits in the Near Earth region from Earth to 2 million kilometers.
- NEN and SN assets are assigned to missions based on priorities set by the NASA Science Mission Directorate



NASA Future CubeSat Communication Architecture Study

Study Objectives

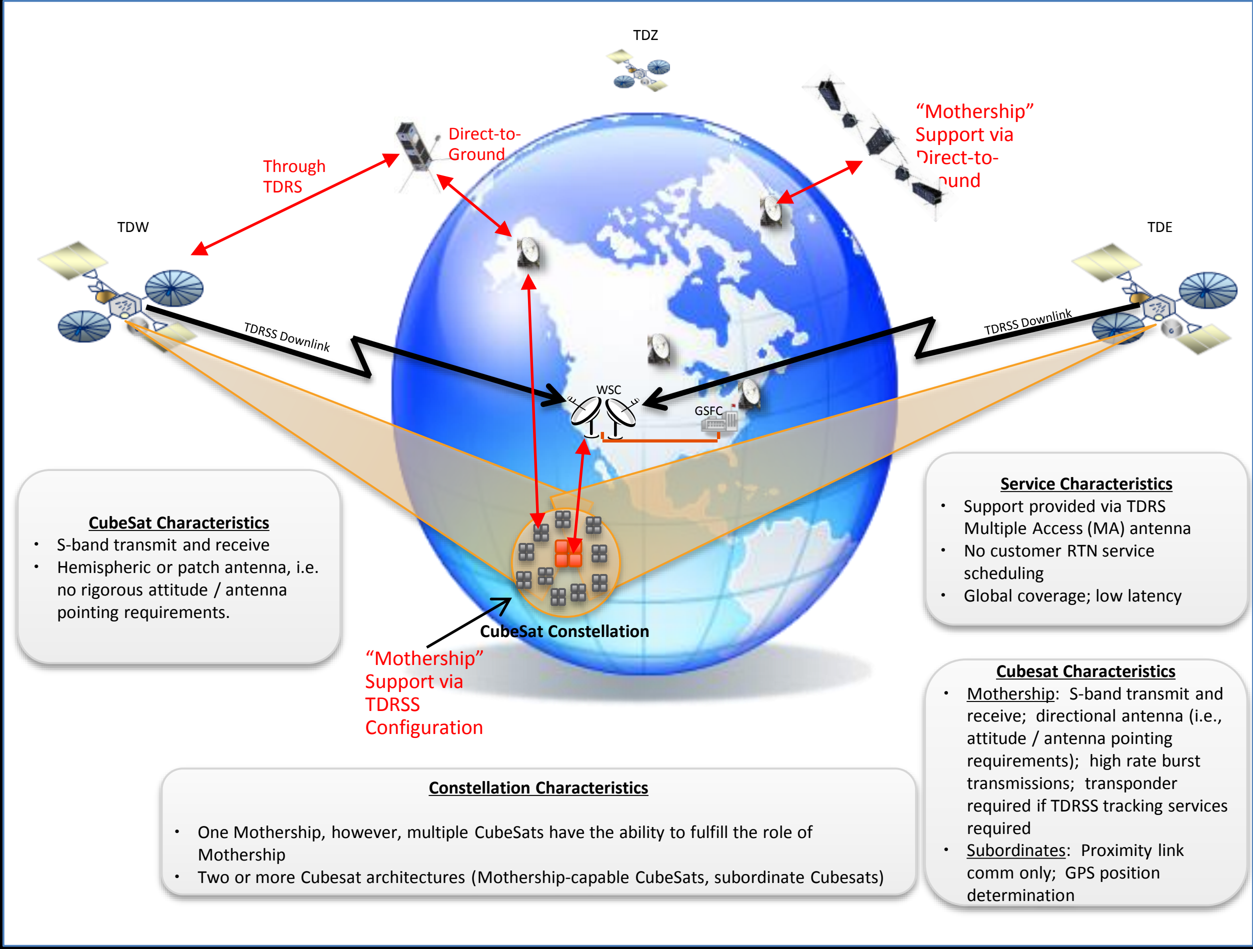
1. Develop optimum communication concepts for CubeSat platform utilizing NASA SN and NEN

2. Perform detailed analyses and simulations of the proposed communication architecture configurations. This includes CubeSat swarm, daughter ship/mother ship constellation, NEN S- and X-band direct-to-ground link, TDRSS MA array vs Single Access mode, notional transceiver/antenna configurations, ground asset configurations, signal trades, space science X-band downlink 10 MHz channel maximum achievable data rates

3. Explore CubeSat current technologies capabilities

4. Develop concepts of operations for NASA's future CubeSat/SmallSat end-to-end communication

5. Provide innovation concepts to meet future CubeSat/SmallSat communication needs

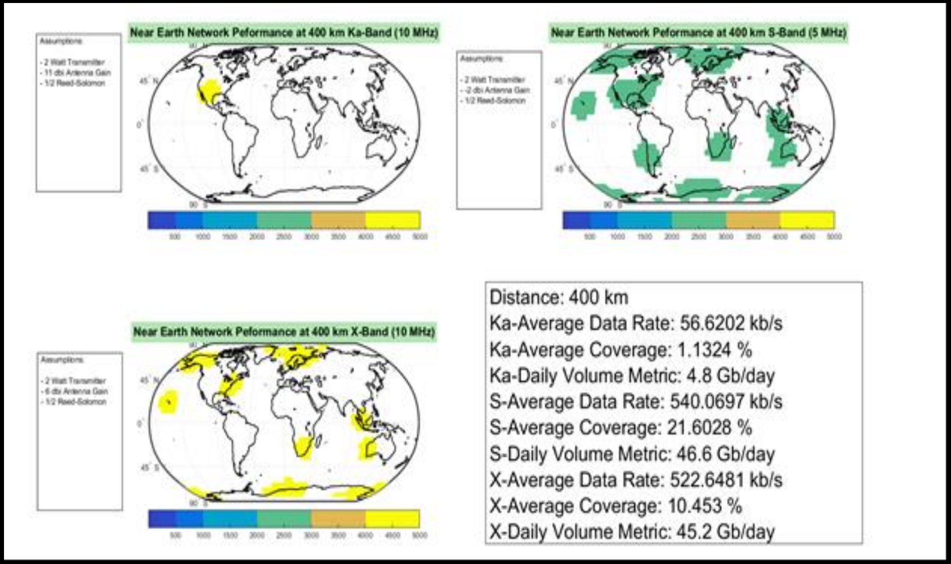


NEN CubeSat Support Analysis

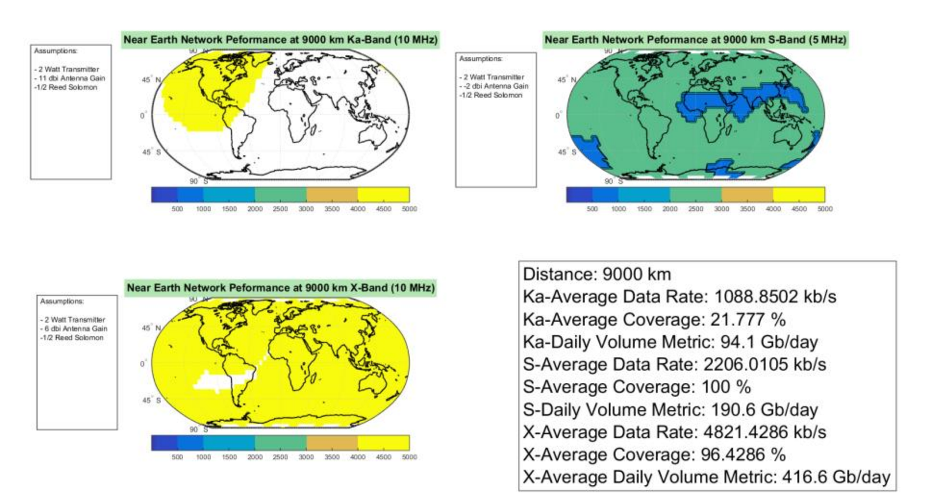
- NEN Support Link Analysis
  - CubeSat/SmallSat mission communication requirements including frequencies and data rates can be met by utilizing NEN S and X-band support

Links	Data Rate	Mod & Coding	CubeSat EIRP	Link Margin
S-band Downlink	2 kbps	BPSK, ½ conv + RS	-1 dBw	40.1 dB
S-band Downlink	4 kbps	BPSK, ½ conv	-1 dBW	36.5 dB
S-band Downlink	256 kbps	BPSK, ½ conv	-1 dBW	18.45 dB
S-band Downlink	513.7 kbps	BPSK, RS	-1 dBW	14.4 dB
X-band Downlink	13.1 Mbps	QPSK, 7/8 LDPC	5 dBW	10.3 dB
X-band Downlink	130 Mbps	QPSK, ½ conv + RS	5 dBW	3.2 dB

11.3 m at AS1, CubeSat PA = 1 W, 0 dBi Antenna Gain (S-band), Antenna Gain = 5 dBi (X-band)



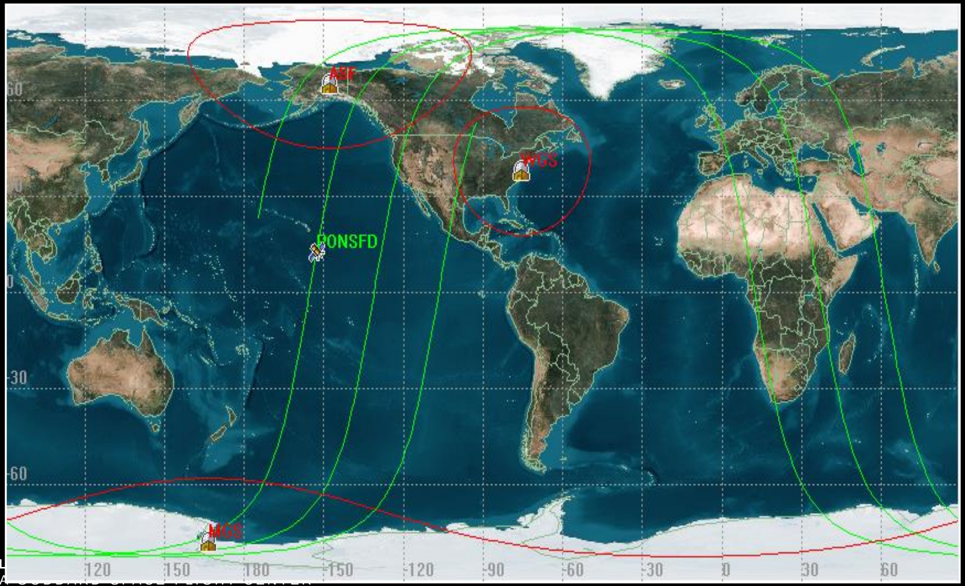
Performance Results at 400 km altitude.



Performance Results at 9000 km altitude.

Near Earth Network (NEN) Upcoming CubeSat Support

- **NEN will provide first time support to a CubeSat mission, CubeSat Proximity Operations Demonstration (CPOD), when it launches in 2016**
  - Supporting Station: WGS 11m, ASF 11m, MGS 10m
  - Service Provided: S-Band Telemetry
  - Data Rates: 1 Mbps or 500 kbps
  - Service Duration: L+30 days to L+6 months (possible extension of up to L+12 months)



Mission	Launch Date (No Earlier Than)
CPOD/PONSFD (A and B)	2016
SOCON	2017
iSAT	2017
CryoCube	2018
Lunar Ice Cube	2018
BioSentinel	2018
CUTIE	2018
Burst Cube	2019
RadSat	2019
Propulsion Pathfinder (RASCAL)	TBD
CSIM	TBD
KitCube	TBD
PIC/USIP	TBD
TRYAD/PULSAR	TBD

TDRSS CubeSat Support Analysis

- CubeSat TDRSS support will be limited by lower data rate due to power constraint on the spacecraft.
- TDRSS can provide global coverage to CubeSat with low latency. It is ideal for emergency support. A CubeSat could send status alerts instantly without waiting until a ground station is in view.
- TDRSS legacy Multiple Access (MA) is able to support CubeSat data rate at 1 kbps with practical S/C power amplifier 5 W and a zero dBi antenna gain.
- The new MA Direct Access System (DAS) can have over 100 in-beam MA users without too significant of a mutual interference at this data rate
- A CubeSat constellation demonstration mission using MA, consuming TDRS Unused Time, and scheduled through the Demand Access System at White Sands would be endorsed by the SN.
- CubeSat TDRSS S-band Single Access (SSA) and Ka-Band SA support need a high gain antenna on board the S/C to produce positive link
- TDRSS will provide 100% coverage for LEO CubeSat

CubeSat Constellation CDMA Trade Study

- Solve for the most appropriate CDMA signal characteristics/design and CubeSat orbit for daughter mother constellation inter-satellite link communications that will be able to downlink adequate daily data volume to the ground
- The mothership CubeSat (provided by the mission) will be a store-forward relay to downlink the science data to the ground either through NEN direct to ground link at X-band or through TDRSS K-band single access (KSA)

- Study results indicate :
- With the CDMA signal design, the constellation daughter/mother architecture is able to produce adequate daily data volume if the daughter and mother CubeSats are in a coordinated orbit (for instance, formation flying)
- If the daughter/mother CubeSats are in an un synchronization orbit, in order to downlink a meaningful/adequate daily volume of science data, the use of a mother ship CubeSat as a store-forward relay requires intelligent protocols capable of performing efficient management and operation control of signal flow for the inter-satellite links
- CubeSat inter-satellite link intelligent protocols are under development

Earth Science CubeSats High Data Rate

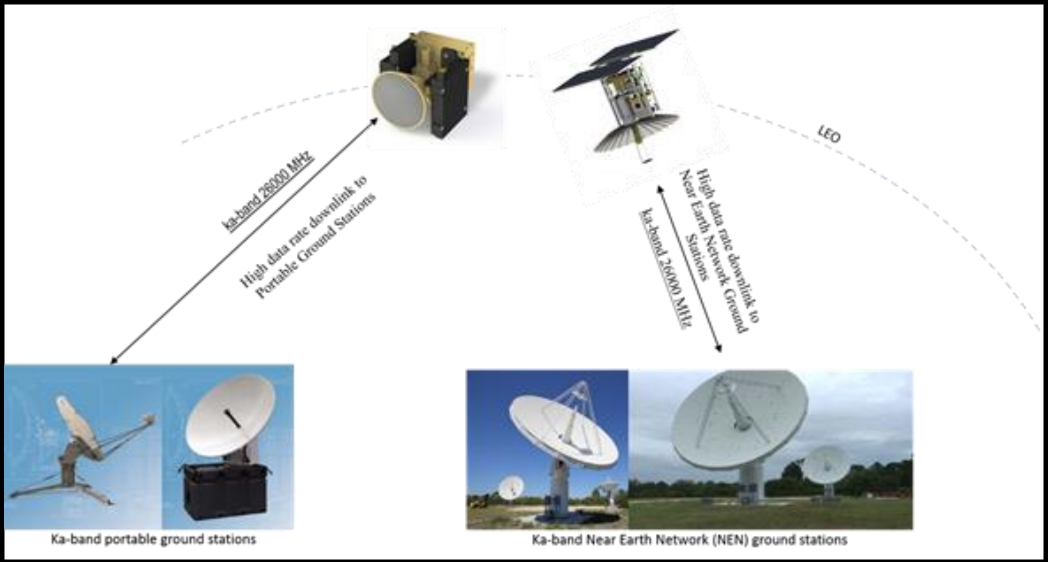
- Due to the limited power and mass for CubeSat spacecraft, power and bandwidth efficient signal techniques are recommended for use to achieve CubeSat high data rate requirements
- 7/8 LDPC code with low overhead to increase bandwidth efficiency is recommended for CubeSat NEN S-band 5 MHz channel communication links to achieve high data rate
- CCSDS and DVB-S2 signal schemes are recommended for CubeSat high rate missions

CubeSat Space Science NEN X-band 10 MHz Channel Downlink Maximum Achievable Data Rate with High Order Modulation and Bandwidth Efficient Coding Study

Summary of the study results

Modulation	Coding	Max Data Rate	Implementation loss at 10-5 BER	Comment
OQPSK	7/8 LDPC	16 Mbps	3.6 dB	There is significant positive link margin assuming a CubeSat equivalent isotropically radiated power (EIRP) with 8.0 dBW (2 Watt TX Power).
8PSK	7/8 LDPC	23.6 Mbps	4.1 dB	Same as in OQPSK
16 APSK	7/8 LDPC	28 Mbps	> 6 dB ~ 5 dB	For the 6 dB implementation loss case, it was assumed that the CubeSat transmitter distortions are the same as defined in the Space Network Users Guide (SNUG). S-band Single Access Return (SSAR) user distortions were used except with a lower Power Amplifier (PA) nonlinearity. For the 5 dB case, it was assumed the CubeSat transmitter had less distortions than the SNUG defined SSAR user distortions amount and lower PA nonlinearity
32 APSK	7/8 LDPC	30 Mbps	>> 6dB ~ 5 dB	32 APSK should not be considered because it has minimum benefits on data rate.
16 QAM	7/8 LDPC	28 Mbps	> 6 dB ~ 5 dB	Considering 16 APSK can achieve the same data rate with less stringent constraints, 16 QAM should not be considered.

CubeSat Ka-Band End-to-End Communication Analysis



- Evaluate the feasibility of Ka-band communication support for CubeSat/SmallSat science data downlink with ground antennas ranging from the small portable 1.2m/2.4m to apertures 5.4M, 7.3M, 11M, and 18M, for Low Earth Orbit (LEO) CubeSat missions

- COTS flight Ka-band flight hardware and NASA Ames Miniature Ka-band Transmitter CKAT-10 performance parameters are used for the analysis

Achievable Data Rate at Ka-Band

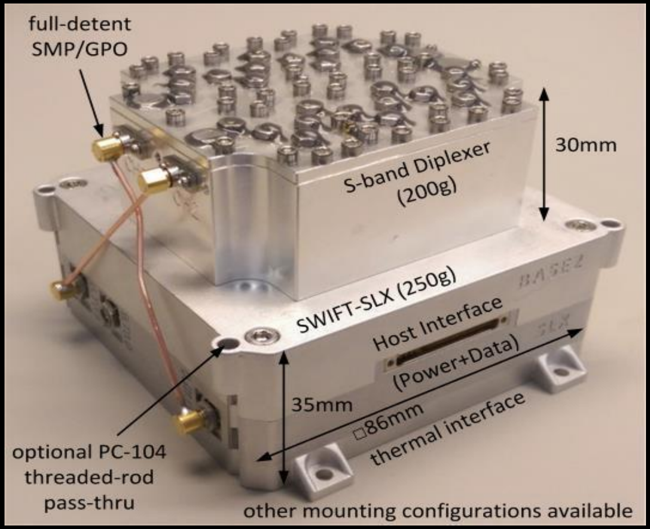
Ground Antenna	LEO Data Rate QPSK*	Data Rate LEO DVB-S2 **
ASF 1.2 m	477.5 kbps	16.943 Mbps
ASF 2.4 m	1.574 Mbps	55.847 Mbps
ASF 5.4 m	4.3 Mbps	153.4 Mbps
ASF 7.3 m	6.6 Mbps	233.2 Mbps
ASF 11 m	25.2 Mbps	892.9 Mbps
WSC 18 m	257.5 Mbps	1125 Mbps

* LEO (625 km) COTS QPSK Transceiver, 2W PA, earth coverage antenna of 4 dBi gain
** LEO (625 km) DVB-S2 Transceiver, 0.7 W PA, horn antenna of 23 dBi gain

Current Selected CubeSat Flight Radio Capabilities

Freq.	Transceiver Name/Vendor	Size (cm)	Mass (g)	Flight Heritage	Max. Data Rate	Modulation/FEC	NASA Network Compatibility
S-band	Innoflight SCR-100	8.2 x 8.2 x 3.2	300	Sense NanoSat	4.5 Mbps	BPSK,QPSK,OQPSK GMSK,FM/PCM FEC: Conv. and R/S	NEN, SN, DSN
	Tethers Unlimited SWIFT-SLX	10 x10 x 3.5	380	None	15 Mbps	BPSK	NEN,SN,DSN
	Clyde Space S-Band TX (STX)	9.6 x 9.0 x 1.6	< 80	UKube-1			
	MHX-2420	8.9X5.3X1.8	75	RAX	230 Kbps Downlink/115 Kbps Uplink	FSK	Partially NEN
X-band	LASP/GSFC X-band Radio	9.8 x 9 x 2	500	None	12.5 Mbps Downlink/50 Kbps Uplink	BPSK/OQPSK R/S and Conv.	NEN
	Syrlinks/X-band Transmitter	9 x 9.6 x 2.4	225	None	5 Mbps	BPSK/OQPSK R/S and Conv.	NEN
	Marshall X-band Tx	10.8 X 10.8 X 7.6	<1000	FASTSat2	150 Mbps Downlink/50 Kbps Uplink	BPSK/OQPSK LDPC 7/8	NEN
	Tethers Unlimited SWIFT-XTS	8.6 x 4.5 (0.375U)	500	None	300 Mbps	{8,16A,32A}PSK	NEN,SN,DSN
	JPL /Iris Transponder	0.4U	400	INSPIRE	62.5 Kbps Donwlink/1 Kbps Uplink	BPSK bit sync, CCSDS frame size	DSN
Ka-band	Canopus Systems/ Ames Ka-band Tx	18 x 10 x 8.5	820	None	125 Mbps	{Q,8,16A,32A}PSK, DVB-S2, CSSDS, LDPC Concatenated with BCH	NEN,SN,DSN
	Tethers Unlimited SWIFT-KTX	8.6 x 4.5 (0.375U)	500	None	300 Mbps	{Q,8,16A,32A}PSK, DVB-S2, CSSDS	NEN,SN,DSN

Innoflight SCR-100

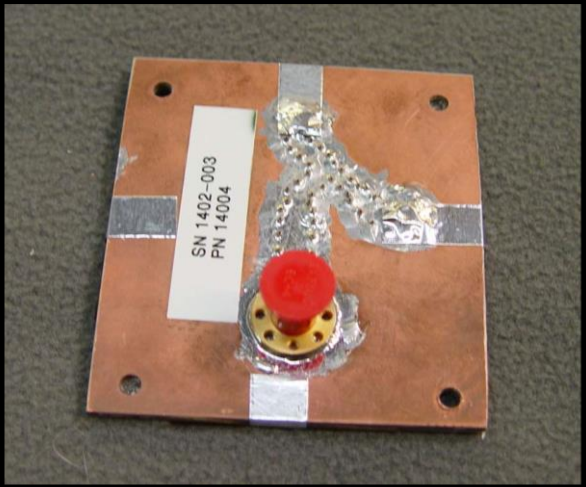


Tethers Unlimited SWIFT-SLX

Current Selected CubeSat Flight Antenna Capabilities

Antenna Vendor Name	Fr	Antenna Gain (dBi)	Dimensions	Mass (g)
Antenna Development Corporation S-Band Low-Gain Patch Antenna (LGA)	S	2	(4 x 4x0.25)"	115
Haigh Farr S-band Patch	S	2	(94x76x4) cm	62
University of Southern California's Information Sciences Institute Space Engineering Research Center (SERC)	S and X		50 cm	760
BDS Phantom Works Deployable High Gain S-band Antenna	S	18	50 cm	1000
Antenna Development Corporation X-Band Patch Array	X	9	(1.85x1.85x0.55)"	300
BDS Phantom Works Deployable High Gain X-band Antenna	X	25	50 cm	1000
Canopus System Horn	Ka	25	18 cm	820

University of Southern California's Information Sciences Institute Space Engineering Research Center (SERC)



Ant Dev Corp: Medium Gain X-band Patch Array Antenna

Operation Concepts for CubeSat End-to-End Communication Derived from the Study

- CubeSat end-to-end communication requirements are able to be met with NEN stations at S & X band with practical patch antenna/earth coverage antenna and 1-2W PA
- Higher data rate at X and Ka-band will reduce number of passes required
- The transition from S to X-band and Ka-band NEN support depends on the flight hardware evolution
- Software Defined Radio will provide flexibility for the standardization of CubeSat flight hardware that will reduce planning/testing costs and may reduce frequency authorization time
- TDRSS can provide global coverage to CubeSats with low latency, compared to limited contact time with just ground stations. Send status alerts instantly without waiting until a ground station is in view
- CubeSat-TDRSS support will be limited by lower data rate due to spacecraft power constraints
- Use of TDRSS high rate support at Ka-band depends on flight high gain antenna evolution
- The use of CDMA signal scheme for CubeSat daughter mother constellation inter-satellite cross link is good for those missions with coordinated orbit, for instance, formation flying
- Through appropriate CDMA signal and CubeSat orbit design, it will be able to downlink adequate daily volume to the ground
- The mother ship CubeSat will be a store-forward relay to downlink the science data to the ground either through NEN direct to ground link at X-band or through TDRSS K-band single access (KSA)
- For CubeSat unsynchronized flying, CDMA is not adequate to support the downlink of meaningful science data to the ground. Intelligent multiple access technique is needed to support those functions such as ad-hoc networking, cloud-based data routing, dynamic signal flow and protocol management
- Power and bandwidth efficient signal techniques will enable higher data rates for CubeSat missions
- High order modulation and bandwidth efficient coding 16APSK, 7/8 LDPC is feasible and will enable higher data rates for the space science CubeSat missions at X-band where the spectrum allocation is constrained to 10 MHz

NEN Lunar CubeSat Support

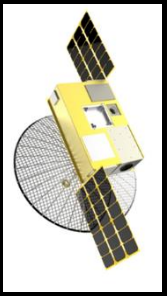
- NEN offers high gain ground system solutions for lunar missions especially EM-1, future exploration and L1/L2 CubeSat missions.
- High Gain NASA NEN and NEN commercial ground systems are around the globe to be able to provide full coverage for Lunar and L1/L2 missions.
- Although some of the NEN commercial providers have X-band uplink capability, NASA NEN is considering adding X-band uplink capability to it's current NASA NEN stations to be able to support exploration missions.
- NEN also considers adding Cooled LNAs to it's current Ground Station to enhance NEN Ground Systems G/T values around 3 dB.

	W/out Cryo. LNA	With Cryo. LNA
Asset	**Maximum Data Rate Lunar (1)**	**Maximum Data Rate Lunar (1)**
WG1 11m	10 kbps	20 kbps

Note (1) - 4 watt CubeSat output power and 12 dBi gain antenna at X-band,.

NEN/SN CubeSat Support Strategy

- NEN/SN is ready today to support CubeSats
- Flight hardware improvements for CubeSats will increase the utilization of NEN/SN
- Planned expansions provide increasing CubeSat support
- After selection, no charge for pass supports for NASA missions using NASA-owned assets
  - Use of Commercial Service Providers/Partners of NEN is subject to budget appropriations
- Mission Planning (e.g. RFICD, Coverage, Link Analysis, Loading Analysis), no charge prior to mission commitment
  - Mission Planning, Integration and Test (MPI&T) services after mission commitment are negotiable, function of risk versus cost
- Assist moving to X, S and Ka-band
- Capitalize on Commercial Service Providers (CSP)/Academic Partnerships including small apertures, large apertures and X-Band uplink
- Streamline mission planning and integration and test and scheduling activities
- What are your requirements?



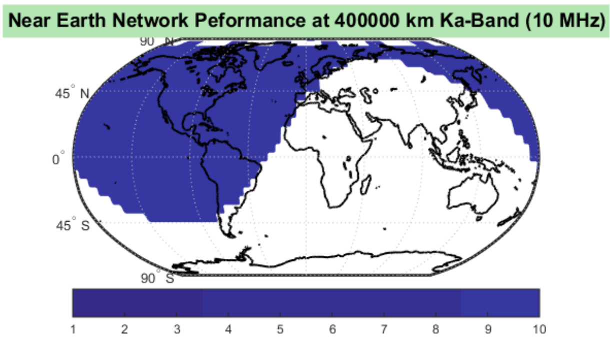
Questions – contact Scott Schaire, scott.h.schaire@nasa.gov, 757-824-1120, NASA Goddard Space Flight Center, Near Earth Network Wallops Manager
Contributions from George Bussey, Serhat Altunc, Yen Wong

Back-up Slides

NEN Performance at 400,000 km Ka-band 10 MHz

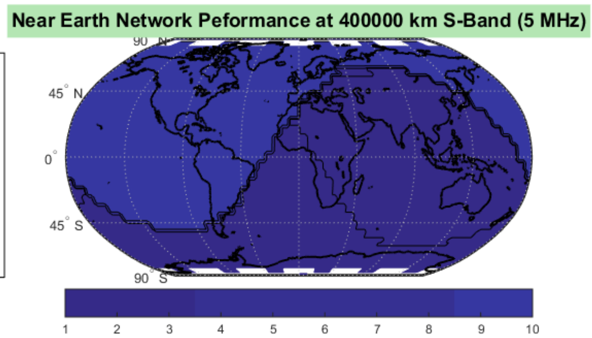
Assumptions:

- 2 Watt Transmitter
- -2 dbi Antenna Gain
- 1/2 Reed Solomon



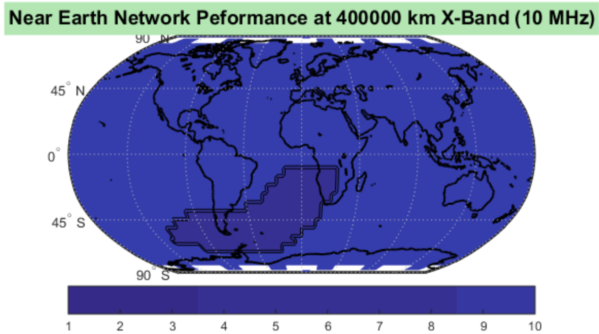
Assumptions:

- 2 Watt Transmitter
- -2 dbi Antenna Gain
- 1/2 Reed Solomon



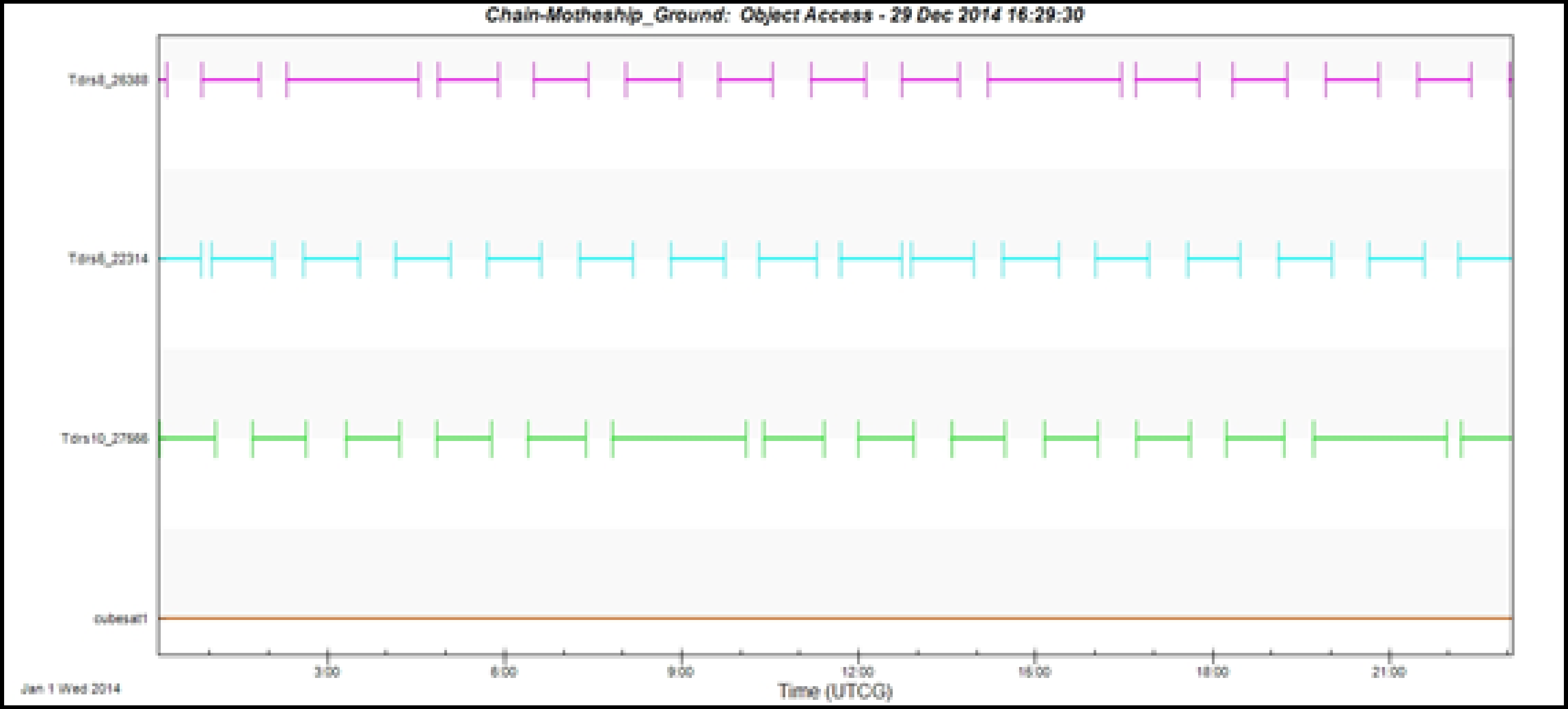
Assumptions:

- 2 Watt Transmitter
- 6 dbi Antenna Gain
- 1/2 Reed Solomon



Distance: 400000 km
Ka-Average Data Rate: 4.0592 kb/s
Ka-Average Coverage: 40.5923 %
Ka-Daily Volume Metric: 350.7 Mb/day
S-Average Data Rate: 3.0017 kb/s
S-Average Coverage: 100 %
S-Daily Volume Metric:259.3 Mb/day
X-Average Data Rate: 9.608 kb/s
X-Average Coverage: 100 %
X-Daily Volume Metric: 830.1 Mb/day

TDRSS Daily Coverage for CubeSat at 500 km Altitude

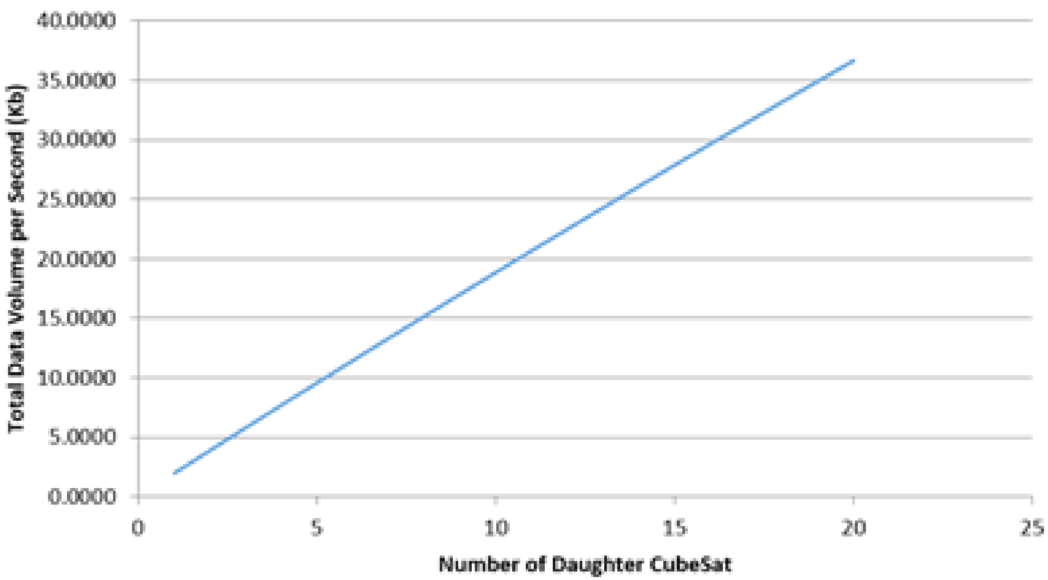


CubeSat Inter-Satellite Link CDMA Model Total Daily Volume Calculation Example

Modulation	QPSK
Carrier frequency (MHz)	2250
Chip rate (Mcps)	3
Eb/N0 for 10E-5 BER (dB)	3.85
Imp. Loss (dB)	2.4
margin (dB)	2
Eb/No required (dB)	8.25
Coding rate	0.875
Per channel Es/No required (dB)	7.67008053
Duty cycle	0.5

Daugher ship transmiting power (dBW)	3.010299957
Daughter ship cable loss (dB)	1
Daughter ship antenna gain (dBi)	0
Daughter ship transmitting EIRP (dBW)	2.010299957
Mother-daughter ship range (Km)	1000
Path loss (dB)	159.4936504
Power received (dBW)	-157.4833504
Boltzmann's constant (dBW/Hz-K)	-228.6
Mother ship G/T (dB/K)	-27
C/No(dB-Hz)	44.11664959
Per channel C/No(dB-Hz)	41.10634964

No. of daugher cubesat	MAI (No+Io)/No in dB	Max. achieveable data rate (Kbps)	Total data volumn per second (Kb)
1	0.0000	3.8607	1.9303
2	0.0124	3.8497	3.8497
3	0.0248	3.8387	5.7580
4	0.0372	3.8278	7.6555
5	0.0495	3.8169	9.5423
6	0.0618	3.8061	11.4184
7	0.0741	3.7954	13.2839
8	0.0863	3.7847	15.1389
9	0.0985	3.7741	16.9836
10	0.1106	3.7636	18.8179
11	0.1228	3.7531	20.6420
12	0.1348	3.7427	22.4560
13	0.1469	3.7323	24.2599
14	0.1589	3.7220	26.0538
15	0.1709	3.7117	27.8378
16	0.1829	3.7015	29.6121
17	0.1948	3.6914	31.3766
18	0.2067	3.6813	33.1314
19	0.2185	3.6712	34.8767
20	0.2304	3.6613	36.6125



CDMA Trade Studies for Formation Flying Scenarios

Parameter	Value			
Slant range (Km)	100			
Modulation	QPSK			
Chip rate (Mcps)	1		3	
Coding	1/2 LDPC	7/8 LDPC	1/2 LDPC	7/8 LDPC
Theoretical Eb/No for 10-5 BER (dB-Hz)	1.75	3.85	1.75	3.85
Imp. Loss (dB)	1.8	1.8	2.0	2.0
Margin (dB)	2.0	2.0	2.0	2.0
Max. achievable dara rate with 20 simultaneous daughter ships (Kbps)	39.7	24.5	95.0	58.6
Total data volume per second (Kb)	397.0	245.0	950.0	586.0
Total daily data volume (Gb)	34.3	21.1	82.1	50.6

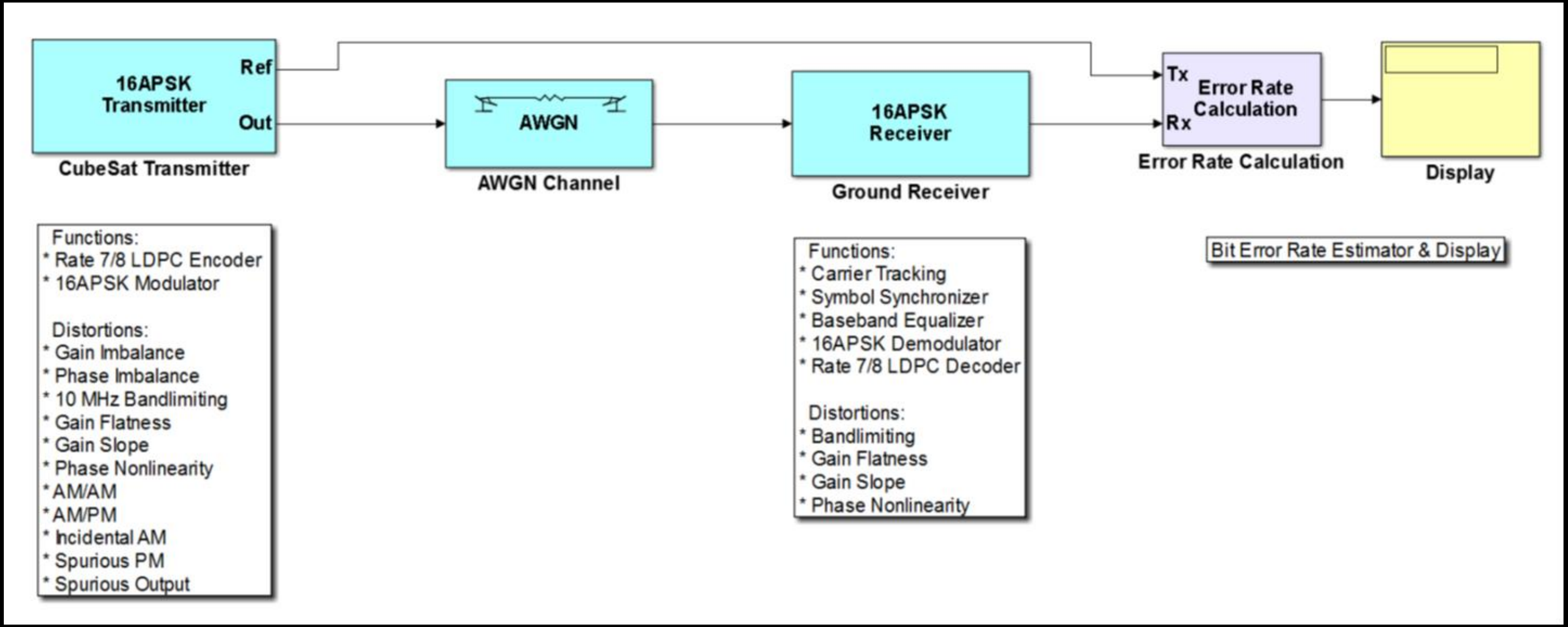
CDMA Trade Studies for Unsynchronized Flying Scenarios, Rate ½ LDPC

Max-Supported Mother-to-Daughter Slant Range (km)	Probability That Daughter Cubesat Is Within This Slant Range	Maximum Number of Daughters Within This Slant Range	Maximum Achievable Data Rate (per Daughter, Kbps)		Maximum Achievable Daily Data Volume (per Daughter, Mb)	
			1 Daughter	Max # of Daughters All effectively at Max-Supported Slant Range via Power Control	1 Daughter	Max # of Daughters All effectively at Max-Supported Slant Range via Power Control
250	0~0.13%	1	102.514	102.514	0~11.51	0~11.51
1000	0.26~3.98 %	3	6.407	6.371	1.44~22.03	1.43~21.91
3000	2.30~13.23%	6	0.712	0.711	1.41~8.14	1.41~8.13
5000	6.83~28.37%	10	0.256	0.256	1.51~6.27	1.51~6.27

CDMA Trade Studies for Unsynchronized Flying Scenarios, Rate 7/8 LDPC

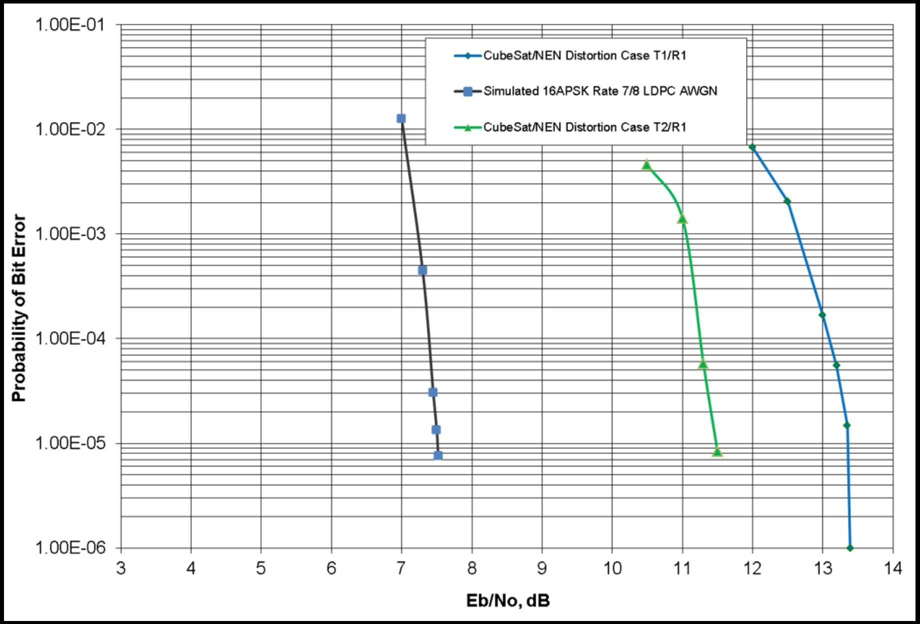
Max-Supported Mother-to-Daughter Slant Range (km)	Probability That Daughter Cubesat Is Within This Slant Range	Maximum Number of Daughters Within This Slant Range	Maximum Achievable Data Rate (per Daughter, Kbps)		Maximum Achievable Daily Data Volume (per Daughter, Mb)	
			1 Daughter	Max # of Daughters All effectively at Max-Supported Slant Range via Power Control	1 Daughter	Max # of Daughters All effectively at Max-Supported Slant Range via Power Control
250	0~0.13%	1	61.771	61.771	0~6.94	0~6.94
1000	0.26~3.98%	3	3.861	3.839	0.87~13.28	0.86~13.20
3000	2.30~13.23%	6	0.429	0.428	0.85~4.90	0.85~4.89
5000	6.83~28.37%	10	0.154	0.154	0.91~3.77	0.91~3.77

MATLAB®/SIMLINK NEN X-band 10 MHz NEN End-to-End Simulation Model

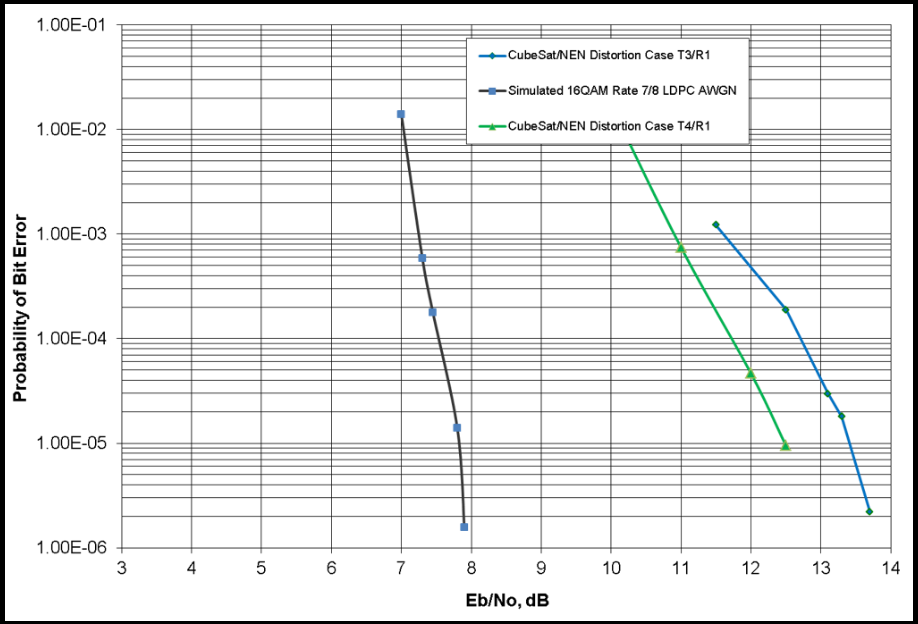


BER Simulation Results

- BER Results for 16 APSK



- BER Results for 16 QAM



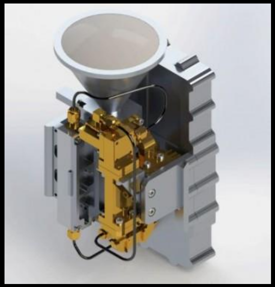
Ka-band Flight System Parameters

COTS Ka-Band Flight System Parameters

Ka-band Downlink Parameters
• S/C Altitude: 625 km and 600 km
• Atmospheric and Rain Attenuation: based on ITU Recommendation ITU-R P.618-10 (rain model) and ITU-R P.676-8 (gas model)
• Rain Availability: 95% and 99% (Ka-band)
• Frequency: 26000 MHz
• Transmit Power: 2 Watts
• Passive Loss: 1 dB
• Earth Coverage Antenna Gain: 4 dBi
• Polarization: RHCP
• Polarization Loss: 0.1 dB
• Modulation: OQPSK
• Data Format: NRZ-L
• Telemetry Coding: Rate 1/2 LDPC
• Required Eb/No: 2.29 dB (OQPSK at BER=10^{-9}@ Rate 1/2 LDPC Decoder)

Canopus System Parameters

Characteristics	Performance
Nominal operational frequency	26.8 GHz
Horn gain	23dB
Maximum transmit power	12.5 W
RF output power	0.7 W
High speed data input	Low voltage differential signaling
Modulation and coding	Full DVB-S2 specification
Volume envelope	(18 x 10 x 8.5) cm
Mass	820 g



Canopus System