Near Earth Network (NEN) CubeSat Communications

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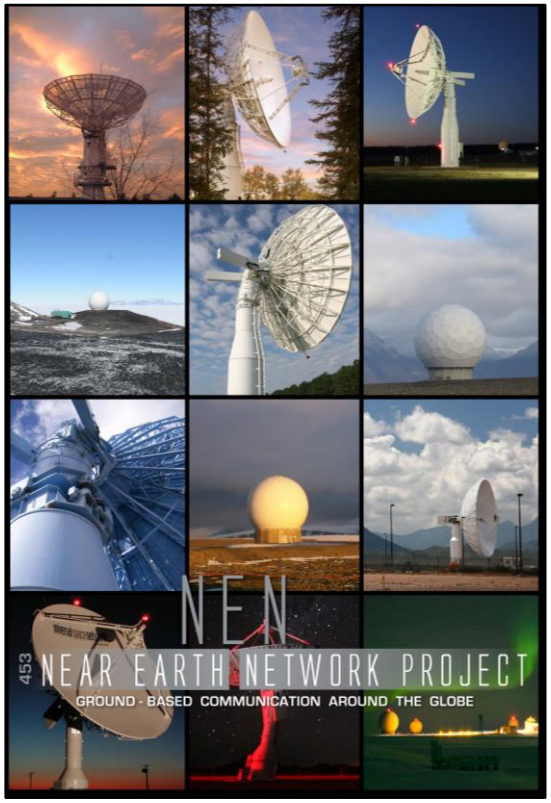
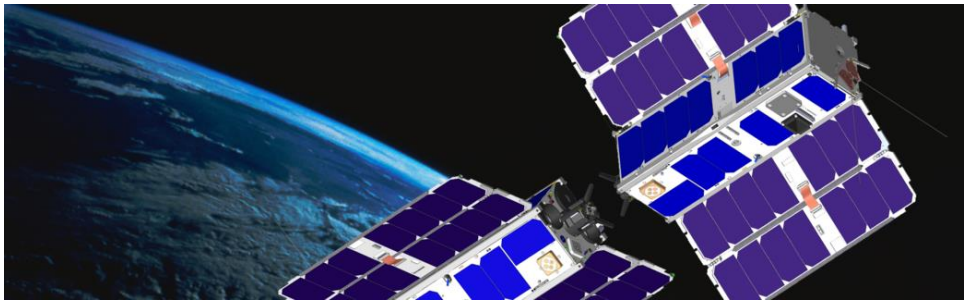
January 2017

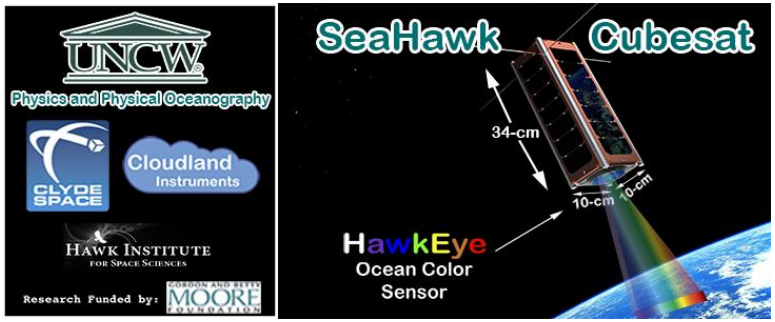




The CubeSat Proximity Operations Demonstration (CPOD) CubeSats will be the first CubeSats to make use of the Near Earth Network. They are scheduled to launch in 2017 and demonstrate rendezvous, proximity operations and docking (RPOD) using two 3-unit (3U) CubeSats.

Agenda

- Overview
- NEN CubeSat Analysis LEO
- Upcoming CubeSat Support
- CubeSat Flight Radio Capabilities
- CubeSat Flight Antenna Capabilities
- NEN Lunar/L1/L2 CubeSat Support
- NEN Evolution
- Conclusion



The SeaHawk CubeSat is scheduled to launch in 2017. It is a "proof of concept to demonstrate capability to construct low-cost autonomous nanosatellites to provide sustained, high spatial resolution and temporal resolution information about the surface ocean processes.“ The project is also known as SOCON: Sustained Ocean Color Observations using Nanosatellites. A second SOCON CubeSat may launch in 2018.

Near Earth Network Overview

- **As shown on the following slide, the NASA Near Earth Network (NEN) is composed of stations distributed throughout the world**
- **NEN services are provided through**
  - NASA-owned and operated ground stations
  - Partner agencies (e.g., National Oceanic and Atmospheric Administration (NOAA) Command and Data Acquisition (CDA))
  - Commercial ground station providers (e.g., Kongsberg Satellite Services (KSAT), Swedish Space Corporation (SSC) and its subsidiaries, Deutsches Zentrum für Luft- und Raumfahrt (DLR))
- **The NEN supports orbits in the Near Earth region from Earth to 2 million kilometers**
  - Communication services are provided for various low-Earth orbits (LEO), geosynchronous orbits (GEO), highly elliptical orbits (HEO), LaGrange orbits, lunar and suborbital, and launch trajectories

THE NEAR EARTH NETWORK PROJECT

NOAA: National Oceanic and Atmospheric Administration
FCDAS: Fairbanks Command & Data Acquisition Station
KSAT: Kongsberg Satellite Services
DLR: Deutschen Zentrums für Luft- und Raumfahrt (German Space Agency)
SANSA: South African National Space Agency
SSC: Swedish Space Corporation

White Sands Complex
White Sands, New Mexico
WS1 (18m), WSC VHF 1 (Quad Helix), WSC VHF 2 (Quad Helix)

Alaska Satellite Facility
Fairbanks, Alaska
AS1 (11m), AS3 (11m)

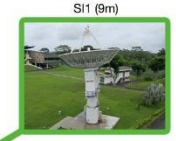
NOAA: FCDAS/Gilmore
Gilmore Creek, Alaska
GLA (13m), GLB (13m), GLC (13m)

SSC: North Pole Satellite Station
North Pole, Alaska
USAK01 (13m), USAK03 (5m), USAK04 (7m), USAK05 (11m)

KSAT: Svalbard Satellite Station
Svalbard, Norway
SG1 (11m), SG2 (11m), SG3 (13m)

SSC: Esrange Satellite Station
Kiruna, Sweden
KU1S (13m), KU2S (13m)

KSAT: Seletar Earth Station
Singapore
SI1 (9m)



South Point Hawaii Satellite Station
South Point, Hawaii
USHI01 (13m), USHI02 (13m)

DLR: Weilheim Ground Station Complex
Weilheim, Germany
WU1S (15m), WU2S (15m)

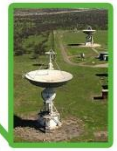
Launch Communications Stations
Florida and Bermuda
Tel-4 (6m) (Air Force), JDMTA (15m) (Air Force), BDA (7m) (Research Range Services)

SSC: Australia Satellite Station
Dongara, Australia
AUWA01 (13m), AUWA02 (7m)

Wallops Ground Station
Wallops, Virginia
WG1 (11m), WG2 (5m), WGS VHF 1 (Quad Helix), WGS VHF 2 (Quad Helix)

Launch Communications Stations
Florida
KUS (6m), PDL (6m)

SSC: Santiago Satellite Station
Santiago, Chile
SA1 (9m), SA2 (13m)



SANSA: Hartebeesthoek Station
Hartebeesthoek, Africa
HBK02 (12m), HBK05 (10m)

KSAT: Troll Satellite Station
Troll, Antarctica
TR2 (7m), TR3 (7m)

McMurdo Station
McMurdo, Antarctica
MG1 (10m)

NASA
Commercial
Partner

JUNE 2016

ABOUT:

Scheduling

The Near Earth Network (NEN) is comprised of tracking stations distributed throughout the world in locations as shown on this map.

The NEN provides Telemetry, Tracking, and Commanding (TT&C) and ranging services to an extensive and diverse customer base, which includes approximately 40 missions - from the high-rate Earth Observing System (EOS) missions such as Aqua, Aura, SMAP, AIM, EO-1, GPM, GRACE, DSCOVR, and OCO-2, to Small Explorer (SMEX) missions including IRIS and HESSI.

Pre-Mission Testing

It also provides TT&C services for an average of about 150 passes per day. Commercial stations such as Kongsberg Satellite (KSAT) Svalbard Ground Station (SGS) in Norway and SSC/USN Alaska Ground Station in North Pole, Alaska provide almost half of the 150 passes per day collectively.

QUICK FACTS:

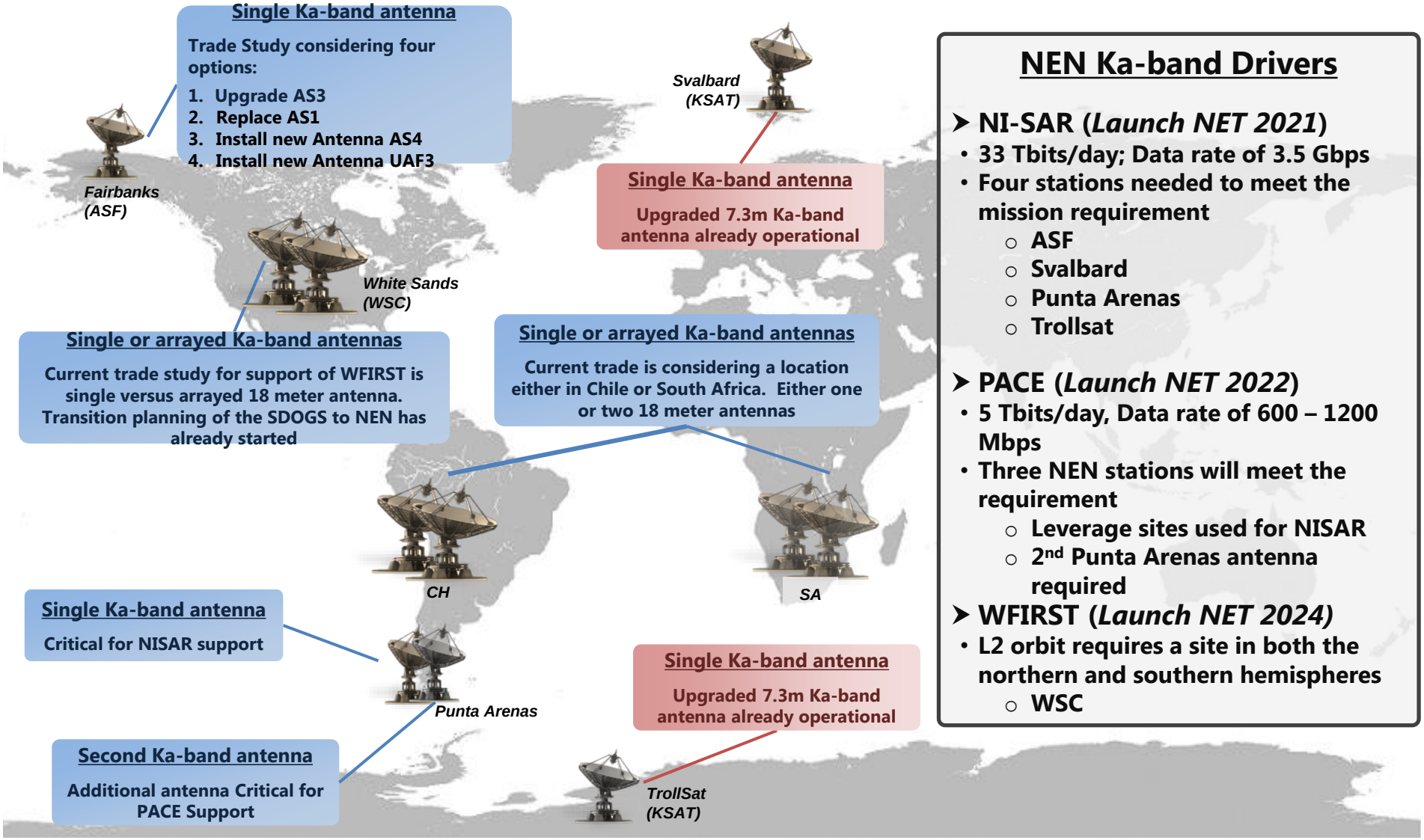
Pre-Mission Planning & Analysis

- Space communications at Goddard and Wallops goes back to the beginning days of NASA.
- GSFC software and hardware engineers in the 80's and 90's conceived and were responsible for what is today the NASA NEN 10 meter and 11 meter ground stations at Wallops, Alaska, and McMurdo.
- Today, GSFC is fortunate to continue its leadership role for the Near Earth Network.
- The Near Earth Network (NEN) supports about 40 NASA and other agency satellites.

Global Network Monitoring, Control & Coordination

- The NEN collects about 1,500,000,000,000 science bytes/day, which is the equivalent of 100 two-hour DVD quality movies/day.
- Today the NEN average data rate is 100 million bits/sec and the highest satellite downlink rate is 300 million bits/sec from the Lunar Reconnaissance Orbiter.
- Future satellite data rates are expected to be an order of magnitude greater, four thousand million bits/sec.
- The NEN constantly strives to reduce costs, improve the reliability of data transmission, and meet new and evolving mission requirements.

NEN Ka-Band Baseline Architecture Adds Stations for Increased CubeSat Capacity



NEN Ka-band Drivers

- **NI-SAR (*Launch NET 2021*)**
  - 33 Tbits/day; Data rate of 3.5 Gbps
  - Four stations needed to meet the mission requirement
    - ASF
    - Svalbard
    - Punta Arenas
    - Trollsat
- **PACE (*Launch NET 2022*)**
  - 5 Tbits/day, Data rate of 600 – 1200 Mbps
  - Three NEN stations will meet the requirement
    - Leverage sites used for NISAR
    - 2nd Punta Arenas antenna required
- **WFIRST (*Launch NET 2024*)**
  - L2 orbit requires a site in both the northern and southern hemispheres
    - WSC

NEN CubeSat Support Analysis – LEO

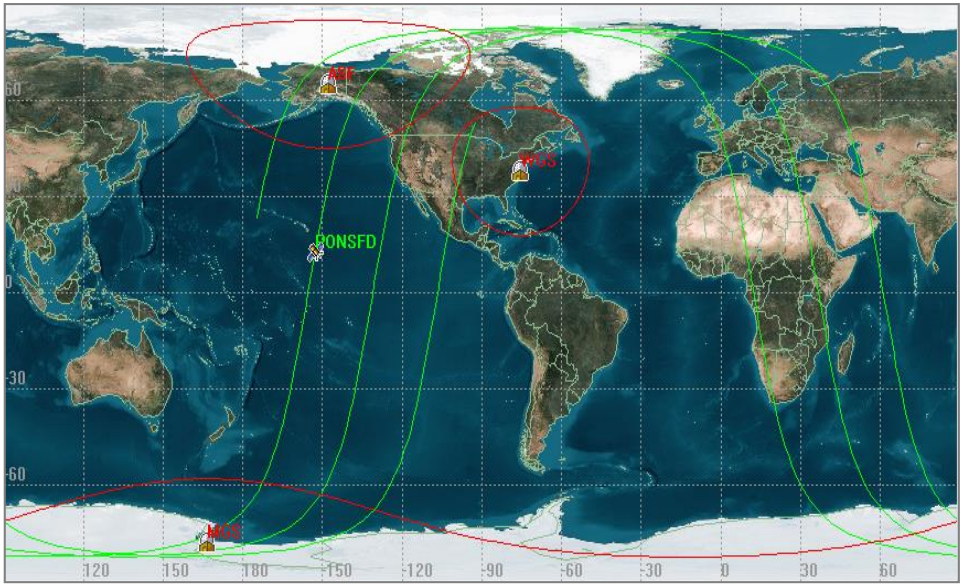
- CubeSat/SmallSat mission communication requirements including frequencies and data rates can be met by utilizing NEN S and X-band support based on 745 km low earth orbit
- Coverage analysis indicates adequate ground coverage and support time utilizing NEN ground stations for CubeSats at an altitude of 745 km

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	4 dBW	10.3 dB
X-band Downlink	130 Mbps	QPSK, ½ conv + RS	4 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)

Near Earth Network (NEN) Upcoming CubeSat Support

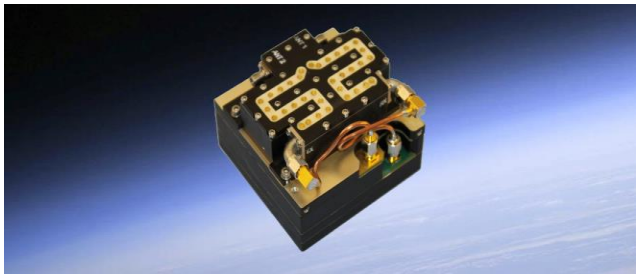
- **NEN will provide communications support to CubeSat Proximity Operations Demonstration (CPOD), when it launches in 2017**
  - Supporting Station: WGS 11m, ASF 11m, MGS 10m
  - Service Provided: S-Band Telemetry
  - Data Rates: 1 Mbps or 500 kbps
  - Service Duration: L+30 days to L+6 months (possible extension of up to L+12 months)



Mission	Launch Date (No Earlier Than)
CPOD/PONSFD (A and B)	2017
SOCON 1	2017
iSAT	2017
MicroMAS	2017
Jefferson High	2017
CryoCube	2018
Lunar IceCube	2018
BioSentinel	2018
CaNOP	2018
SOCON 2	2018
CuPiD	2019
Burst Cube	2019
RadSat	2019
TROPICS (12 CubeSats)	2020
Propulsion Pathfinder (RASCAL)	TBD
CSIM	TBD
Kit Cube	TBD
PIC/USIP	TBD

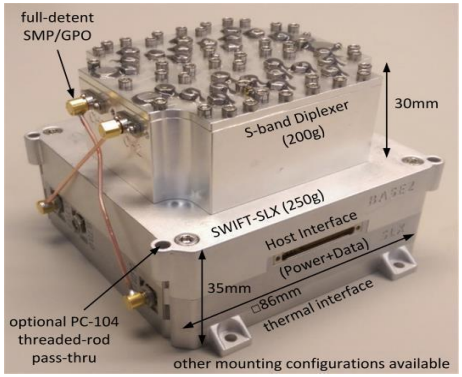
Current Selected CubeSat Flight Radio Capabilities

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
	Quasonix nano TX	3.3x3.3x3.3	?	CPOD	46 Mbps	PCM/FM, SOQPSK-TG, Multi-h CPM, BPSK, QPSK, OQPSK, UQPSK	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, Partially NEN
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

Quasonix S- Band Transmitter



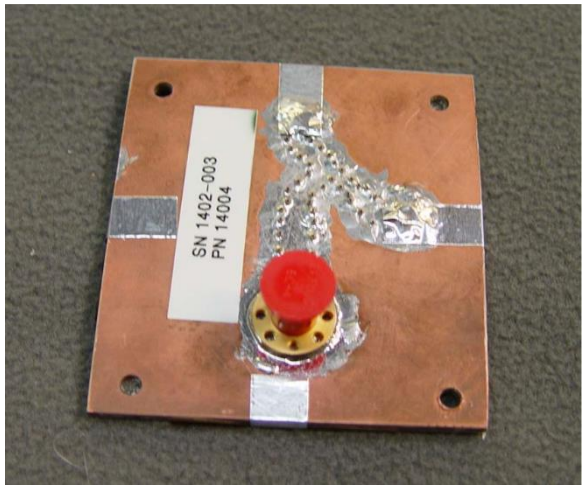
Tethers Unlimited SWIFT-SLX

*** Compatibility shown as advertised by vendor**

Current Selected CubeSat Flight Antenna Capabilities

Antenna Vendor Name	Band	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	TBD	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

NEN Potential Benefits for EM CubeSats

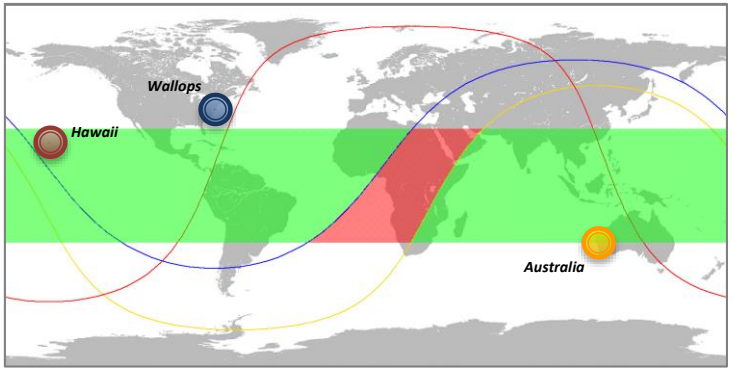
While the NEN is not anticipated to provide primary support to any of the thirteen EM-1 CubeSat missions, the NEN offers "as-is" and upgradable ground system solutions for lunar, L1/L2, and future exploration CubeSat missions, that could benefit the EM-1 CubeSat missions

- **The NEN may benefit EM-1 CubeSat missions utilizing the IRIS radio in the form of coverage and larger beamwidth**
  - NASA-owned NEN and NEN commercial ground systems are positioned around the globe and are able to provide significant to full coverage, depending on sites utilized, for CubeSats in Lunar orbit or beyond (e.g., L1/L2 missions)
  - NEN coverage could be utilized to provide higher data rate support to EM-1 CubeSat missions immediately following dispersal from Orion (~35,000 km through 100,000km)
  - Smaller NEN apertures (e.g., 11m), compared to other apertures, provide a larger beamwidth, which can benefit CubeSat missions in the event of navigation/ephemeris uncertainty
- **In order for the EM-1 CubeSats to realize the NEN coverage and beamwidth benefits, NEN ground stations would need varying levels of modifications, depending on services required; Options the NEN is currently investigating**
  - NEN modification (e.g., receiver Turbo decoding licenses, converters, switches) of either NASA-owned or commercial provider X-band downlink capable assets would allow support for the reception of EM-1 CubeSats using the IRIS radio (e.g. Turbo 1/6 decoding)
  - NEN could utilize the X-band uplink capability of certain commercial provider assets or could upgrade other NASA or commercial provider assets (NEN evaluating options) to support X-band uplink requirements, Doppler, and tone ranging for IRIS equipped EM-1 CubeSats

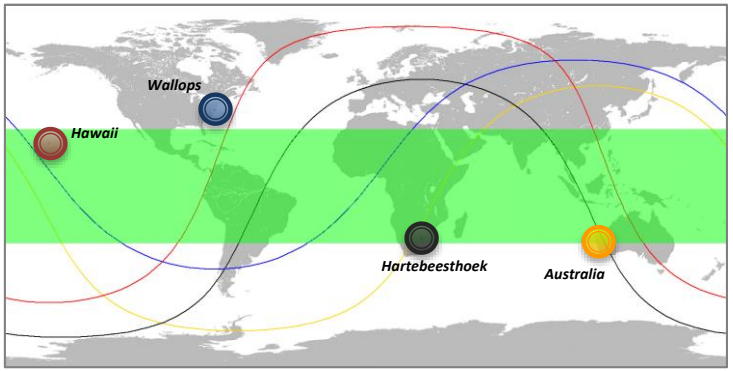
NEN Coverage to EM CubeSats at Lunar Distances

- **The NEN can provide ~89% coverage to a Lunar EM-1 CubeSat utilizing three NEN ground stations**
  - Coverage assumes the following stations/antennas:
  - NASA NEN Wallops (1 x 11m)
  - CSP SSC Hawaii (2 x 13m)
  - CSP SSC Australia (1 x 13m)
  - All sites currently support X-band downlink frequency range of 8.0 GHz to 8.5 GHz
- **Including the NEN CSP site in Hartebeesthoek would allow the NEN to provide 100% coverage**
  - NEN utilizes Hartebeesthoek through the SANSA Space Operations Services
  - The 10m Hartebeesthoek antenna, designated HBK-5, supports the full X-band receive frequency (8.0 – 8.5 GHz)

NEN Three Station Architecture Providing 89% Lunar Coverage



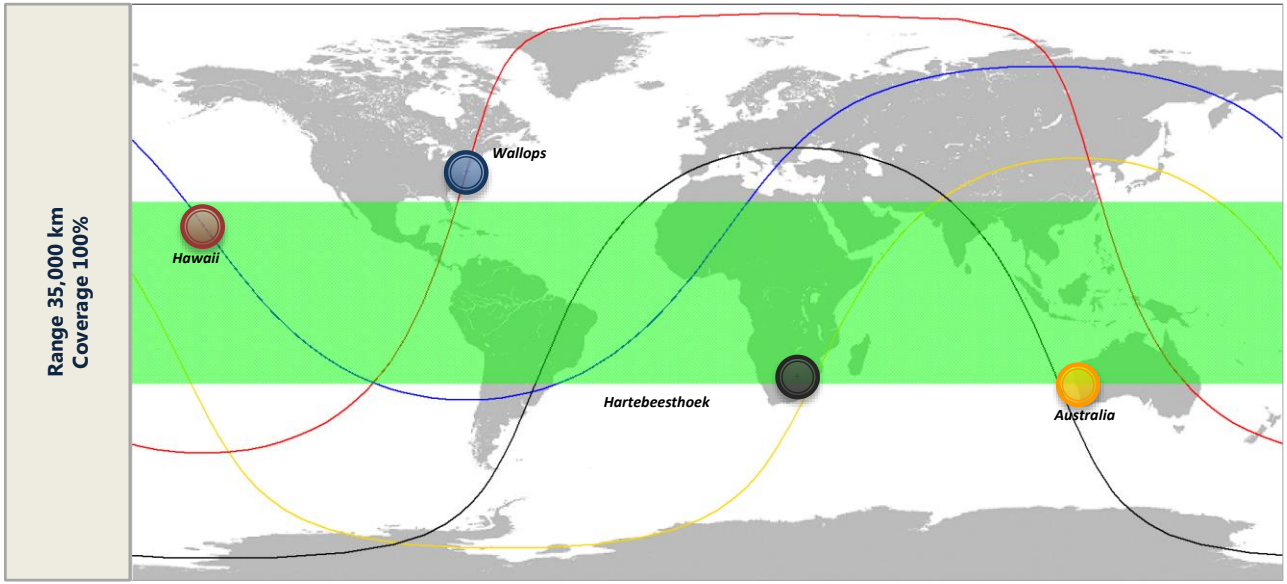
NEN Four Station Architecture Providing 100% Lunar Coverage



Note: Coverage percentages assumes mission is not behind moon (i.e., lunar occultation)

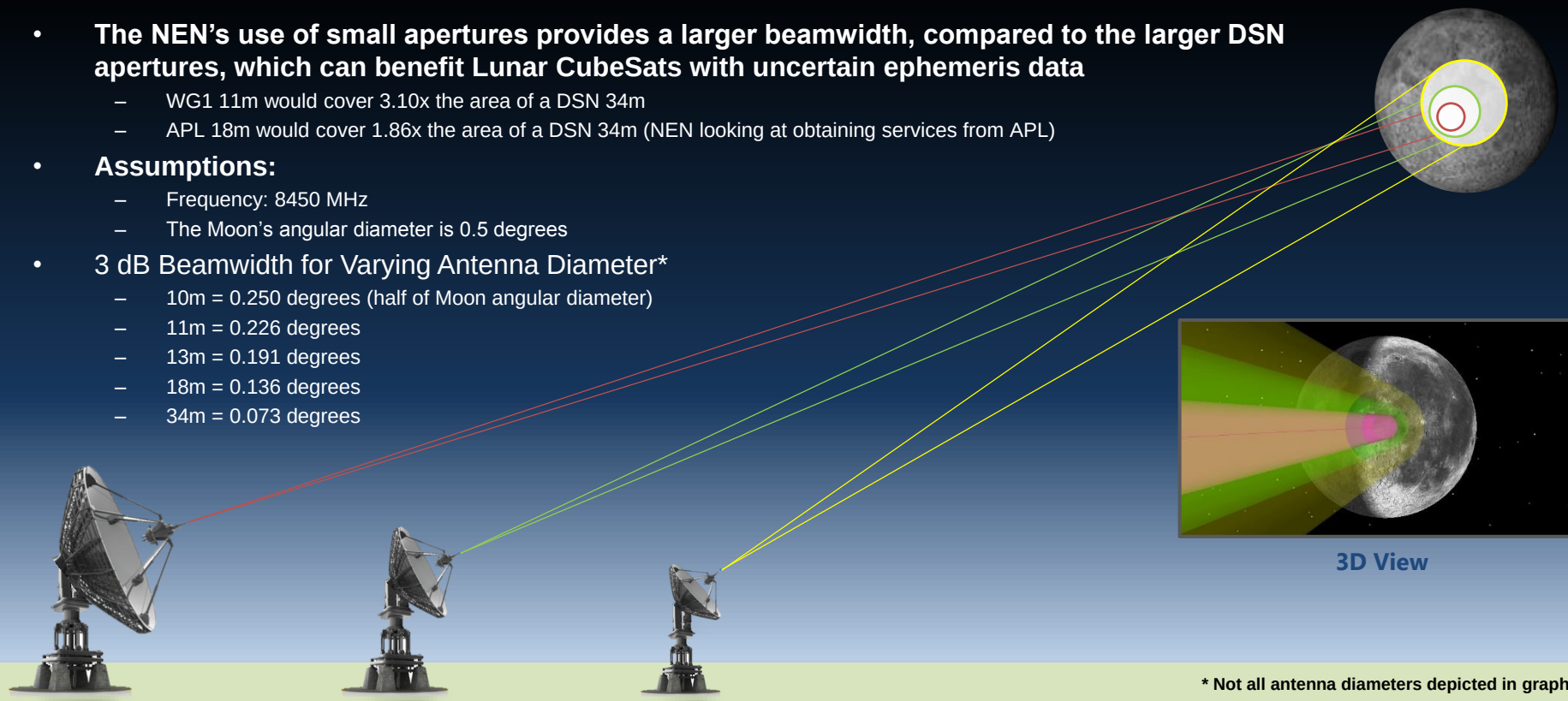
NEN Coverage to EM CubeSats During Trans-Lunar Orbit

- **The EM-1 CubeSats will be deployed from dispensers on Orion once at a safe distance (~35,000 km)**
  - Once released there is an anticipated range from 35,000 km to 100,000 km known as the “12 hours of terror”
  - The NEN could provide complementary coverage during this period utilizing the four NEN stations in Wallops, Hawaii, Australia, and Hartebeesthoek
  - The four ground stations together can provide 100% coverage at 35,000 km



NEN Beamwidth Advantage for Lunar EM-1 CubeSats

- **The NEN's use of small apertures provides a larger beamwidth, compared to the larger DSN apertures, which can benefit Lunar CubeSats with uncertain ephemeris data**
  - WG1 11m would cover 3.10x the area of a DSN 34m
  - APL 18m would cover 1.86x the area of a DSN 34m (NEN looking at obtaining services from APL)
- **Assumptions:**
  - Frequency: 8450 MHz
  - The Moon's angular diameter is 0.5 degrees
- 3 dB Beamwidth for Varying Antenna Diameter*
  - 10m = 0.250 degrees (half of Moon angular diameter)
  - 11m = 0.226 degrees
  - 13m = 0.191 degrees
  - 18m = 0.136 degrees
  - 34m = 0.073 degrees

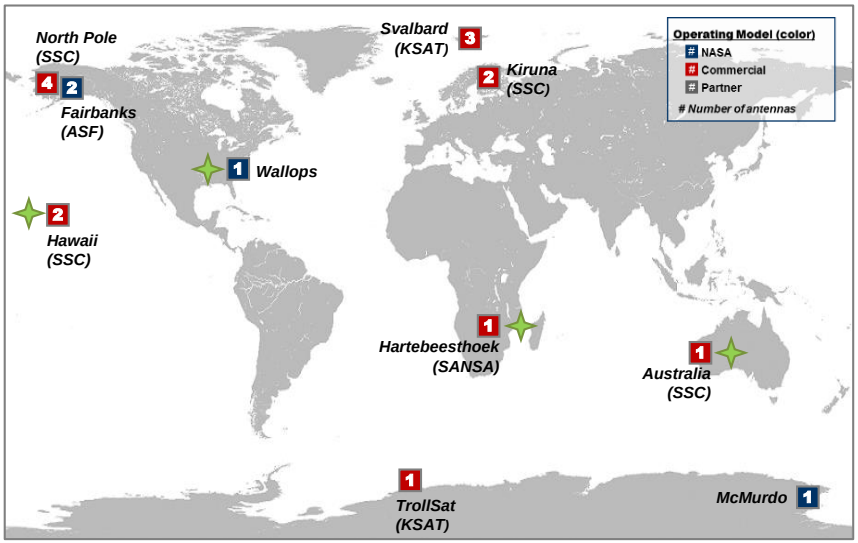


* Not all antenna diameters depicted in graphic

NEN Modification to Support IRIS X-band Downlink

- **The NEN currently includes multiple ground stations with X-band downlink capabilities that could be upgraded to support the IRIS radio**
  - Upgrades could be targeted to assets that currently use a Cortex modem, which has a clear upgrade path to support the necessary coding (i.e., Turbo 1/6)
  - Targeted sites include: Wallops, Hawaii, and Australia which utilize the Cortex as well as Hartebeesthoek (Receiver TBV)
- **Modification of NEN modems to add IRIS radio receive compatibility will vary by site, but would likely include:**
  - Addition of Cortex DS menu to existing Cortex to add Turbo Codes (this has added advantage of adding support for very low data rates)
  - Addition of switching system to switch Cortex input between S-band and X-band
- **If directed, the NEN would carry out the systems engineering process to upgrade a NASA site or oversee the modification of a commercial site to add IRIS X-band downlink compatibility**

NEN X-band Return Stations and Antennas



Targeted Station for Upgrade to Add IRIS Downlink Compatibility

NEN Achievable Data Rates with Representative EM CubeSat Missions (Based on Analysis)

- **NEN would be in a position to support a majority of the discrete IRIS radio downlink rates assuming the NEN implements the upgrade to ensure IRIS downlink compatibility**
  - The IRIS radio does not support a continuous range of data rates, but rather discrete rates (not all possible rates have been tested/verified)
- **Notes/Considerations:**
  - Morehead without cryogenic LNAs was not shown since Morehead is planning to upgrade the asset

- **CubeSat Radio/Antenna Assumptions:**
  - Frequency: 8.45 GHz
  - Modulation = BPSK
  - COTS CubeSat radio: PA output power of 4W
  - COTS antenna with 11 dBi gain @X-band [1]
  - Passive loss of 1 dB
- **General Assumptions:**
  - Acheivable rates assume a 2 dB margin
  - Slant range of 405,221 km (Max Lunar Distance)
  - 10 degrees elevation
  - Lunar Noise Temperature of 185 K (loss of 2.27 dB/K)
  - Link availability for propagation effects : 99%

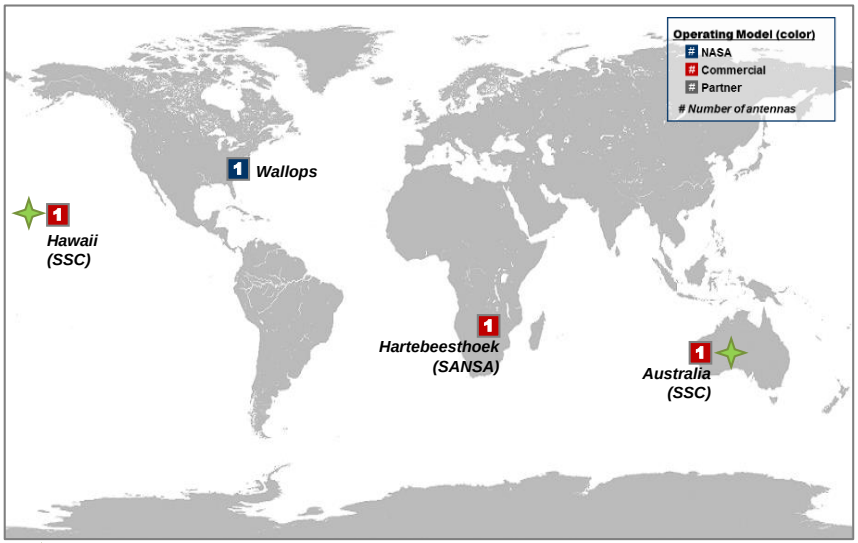
Asset Size	Reference Antenna	Cryogenic LNAs	G/T [2] (dB/K)	Conv. ½ [3] Rates kbps	Turbo 1/6 Rates kbps	NEN Asset Capable of Supporting IRIS Discrete Data Rates (kbps)							
						1	4	8	16	32	64	128 [3]	256
11m	WG1	No	32.23	19.68	52.60	✓	✓	✓	✓	✓	×	×	×
		Yes	33.13	24.21	64.71	✓	✓	✓	✓	✓	✓	×	×
13m	SSC Hawaii/ Australia	No	35.43	41.11	108.89	✓	✓	✓	✓	✓	✓	×	×
		Yes	36.33	50.38	133.97	✓	✓	✓	✓	✓	✓	✓	×
18m	APL	No	36.38	51.17	136.8	✓	✓	✓	✓	✓	✓	✓	×
		Yes	37.28	62.95	168.27	✓	✓	✓	✓	✓	✓	✓	×
21m	Morehead	*No*	*NA*	-	-	-	-	-	-	-	-		-
		Yes	40.34	37.41	99.08	✓	✓	✓	✓	✓	✓	×	×

[1] **The rates for the Morehead 21m assume an antenna gain of 6 dBi to reflect the known EM-1 CubeSat mission using that asset (i.e., Lunar IceCube).**
[2] **Includes a Lunar noise temperature losses.**
[3] **Capabilities are currently untested with the IRIS radio.**

NEN Modification to Support IRIS X-band Uplink

- **The NEN currently utilizes two commercial provider sites that are equipped with asset capable of supporting X-band uplink in the frequency range of 7025 – 7200 MHz**
  - SSC Hawaii has one 13m antenna capable of supporting X-band uplink with a published EIRP of 86 dBW
  - SSC Australia has one 7m antenna[1] with a published EIRP of 85 dBW
- **Modification to add X-band uplink would vary by site**
  - Upgrades required assuming existing X-band uplink support:
  - Addition of Tunable upconverter (convert from 70 MHz to X-band frequency)
  - Addition of IF distribution system to send IF from Cortex to upconverter
  - Updates to HWCTRL to control and monitor the new capabilities

Candidate NEN X-band Uplink Stations and Antennas



Targeted Station Currently Supporting X-band Uplink

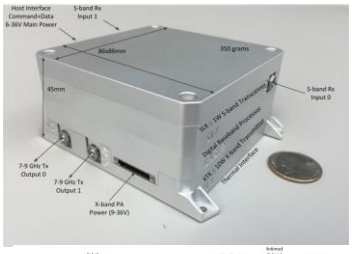
[1] **The Australia asset is uplink only, but can be slaved to a collocated 13m asset capable of X-band downlink**

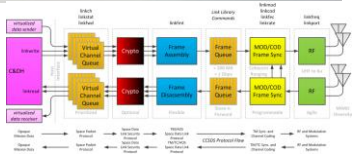
CubeSat Radio Support Requirements to Achieve NEN Compatibility Without Station Modifications

- RF Frequencies
  - Earth to Space
    - 2025 – 2120 MHz
  - Space to Earth
    - 2200 – 2300 MHz
    - 8025 – 8500 MHz
    - 25.5 – 27.0 GHz
- Modulation
  - Earth to Space
    - PCM/PSK/PM, PCM/PSK/PM, BPSK, SS-UQPSK
  - Space to Earth
    - PCM/PSK/PM, PCM/PSK/PM, OQPSK (SQPSK), QPSK, BPSK, Reed-Solomon, Convolutional, Viterbi
- Tracking
  - Coherent Doppler, Tone Ranging

IRIS Radio Alternatives

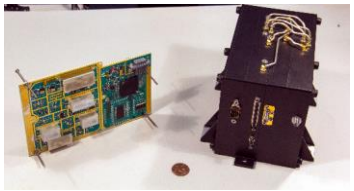
Innoflight® CubeSat S-Band Transceiver (SCR-100)

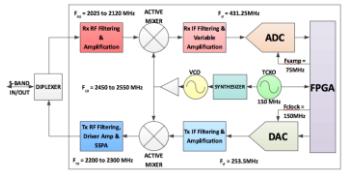




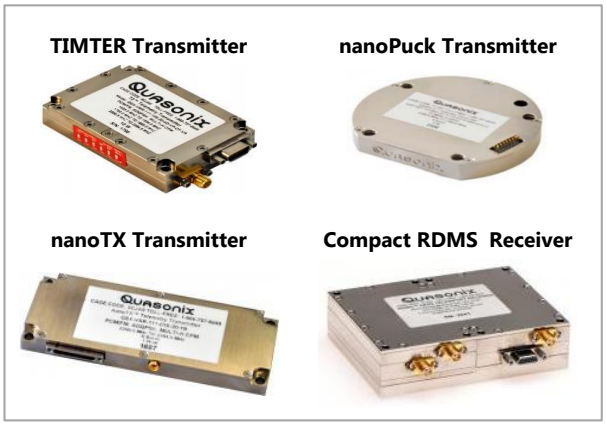
Tethers SWIFT® Software Defined Radios

Vulcan®





APL CORESAT® Frontier Radio Lite



Quasonix®

IRIS Radio to Alternatives High Level Comparison (1/2)

Radio	IRIS	Innoflight (SCR-100)	Tethers Swift Software Defined	Vulcan	APL Frontier	Quasonix
Cost	$700k	TBD	$200K	TBD	$200k-$500k+	Varies, <$50k
Network Compatibility	DSN, NEN*, SN*	DSN, NEN, SN	NEN, SN	DSN, NEN	DSN, NEN, SN	NEN, SN
Input Power**	0.5W – 38W	0.8W – 10 W	2.5W – 47.5W	12.8W – 21W	400mW – 4.2W	Varies
Output Power	X-band: 3.8W	S-band: 20mW – 2.0W X-band: N/A	S-band: 2.5W X-band: 1 – 7 W (adj.)	S-band: 4W	650mW – 1W (external PA optional)	Varies, 10mW – 25W
Size	568 cm^3 (0.5U)	238 cm^3	333cm^3	568 cm^3 (0.5U)	324 – 649 cm^3 (0.33-0.66U)	Varies up to 197 cm^3
Mass	1100 g	290 g (w/o Diplexer+Splitter	350 g	370 g	1700 g (S-band), 2100 g (X-/Ka band) 400g g (UHF-C band)	TBD
Frequency Bands (TX)	X-band: 7.145 – 7.190 GHz (7.190 – 7.235 GHz)*	S-band: 2.2k – 2.3k MHz	S-band: 1.7k – 2.7k MHz X-band: 7.0k – 9.0k MHz	S-band: 2200 - 2305 MHz	UHF, S, L, or C-band, X and Ka-band	Varies, Lower L-, Upper L- S-, C-, and P-
Frequency Bands (RX)	X-band: 8.4 – 8.45 GHz (8.45 – 8.50 GHz) *	S-band: 2025 - 2110 MHz	S-band: 1k – 3k MHz X-band: 6k – 12k MHz	S-band: 2025-2115 MHz	UHF, S, L, or C-band, X and Ka-band	Varies, Lower L-, Upper L- S-, C-, and P-

*** Capability being investigated or planned**
**** Input power dependent on services supported**
NEN/SN Compatibility is based on vendor claims

IRIS Radio to Alternatives High Level Comparison (2/2)

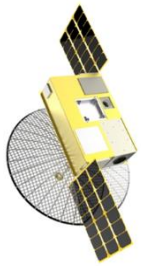
Radio	IRIS	Innoflight (SCR-100)	Tethers Swift Software Defined	Vulcan	APL Frontier	Quasonix
Modulations	RX: TBD TX: PM/PSK/NRZ	RX: GMSK, FSK, PCM/FM TX: BPSK, QPSK, OQPSK	RX: BPSK,QPSK,BPSK; TX: 8PSK, 16APSK, 32APSK, OQPSK, GMSK, PM, CPM, SGLS-Ternary, Spread Spectrum	BPSK, QPSK, FSK, STDN USB PM/PCM, SGLS AM/FSK, Commercial FM/PCM, TDRS-MA	Arbitrary waveforms (PM/PSK, M-PSK, M-QAM, GMSK)	PCM/FM, SOQPSK, Multi-h CPM, BPSK, QPSK, SQPSK, USQPSK
Coding	1/6 Turbo Code, Convolutional 7-1/2, Manchester, Bi-Phase, and bypass (NRZ), Reed Solomon (255,223)	Convolutional, Reed Solomon (TX)	Reed-Solomon, Convolutional, Viterbi, BCH, Turbo/LDPC, CRC	Rate ½ Viterbi K=7, RS(255,223). Turbo and others available	CCSDS ½ convolutional, LDPC, Turbo Coding	TBD
Ranging	Diff 1-way Ranging (coherent w/DL carrier) - X-Band 2F1: 19.2 MHz[1] programmable modulation index 17.5° typical	TBD	Coherent tone ranging, <1 Hz carrier tracking and Doppler estimation, Regenerative PN Ranging	Coherent Turn Around and Ranging	Two-way coherent architecture for Doppler navigation, PN, Tone-Ranging	Varies: 1-Way Doppler only, or None
Radiation	TBD	TID (3 mm Al): LEO - 10 krads; GEO - 100 krads;	≈1200 km polar orbit, 6.5 year lifetime: High energy (GCR) shielding being added under Langley SBIR contract	SEU Recovery, Al shield for TID	50 to 125k rad	TBD
Data Rates	62.5, 125, 250, 500, 1k, 2k, 4k, 8k, 16k, 32k, 64k, 128k, 256k, 512k*, 1.024M*, 2.048M*, 4.046M*, 8.192M*(bps)	TX: Up to 4.5 Mbps RX: 1 – 100 kbps	S-band, up to 15 Mbps, X-band, up to 300 Mbps.	TX: 100 bps to 3 Mbps RX: 100 bps - 64 kbps	0.2-2/2-50 (S-band) 0.2-2 / 2-150 (X/Ka-band) 2 / 10 (UHF to C-band)	Varies up to 46 Mbps
TRL	6 (Present) 9 (2018, MarCO launch)	9	7	6	9 (S-band), 6 + (S/Ka, X/Ka)	9

*** Capability under investigation or planned**

NEN Evolution

- **NEN is ready today to support CubeSats**
- **Planned NEN expansions provide increased CubeSat support**
- **Enhance CubeSat radios and NEN receivers to achieve high data rates for CubeSat missions**
- **Assist missions 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**
- **Continue to engage with the CubeSat community**

NEN Wallops 11 Meter class antenna



NASA GSFC/Wallops LunarCube with deployable X-band antenna based on University of Colorado/Goddard X/S band CubeSat Radio and NEN

Conclusion

- After selection, no charge for pass supports for NASA missions using NASA-owned stations
  - 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
- Questions – contact Scott Schaire, scott.h.schaire@nasa.gov, 757-824-1120, NASA Goddard Space Flight Center, Near Earth Network Wallops Manager