NASA Near Earth Network (NEN), Deep Space Network (DSN) and Space Network (SN) Support of CubeSat Communications

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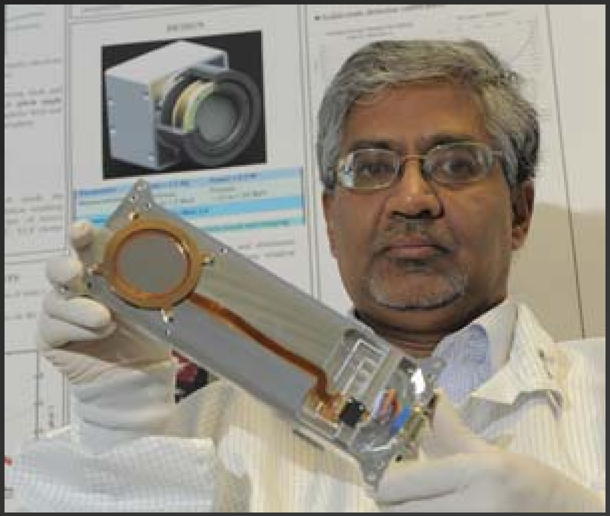
Contributions from **Serhat Altunc**, **George Bussey**, **Harry Shaw**, **Bill Horne**, **Jim Schier**



GSFC Compact Radiation belt Explorer (CeREs) Principal Investigator Shri Kanekal holds an early version of one of the mission's solid-state detectors – demonstrates a shift in the paradigm for satellite development. CeREs is a 3U CubeSat ~10 cm by 10 cm by 30 cm, mass ~3 kg. For the purposes of this presentation a CubeSat is defined as up to 6U, ~10cm by 20cm by 30cm, mass ~6 kg.

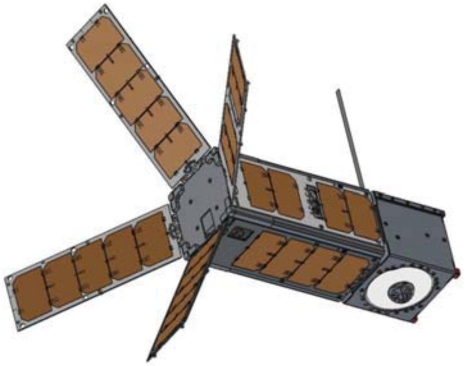
June 2015

Agenda

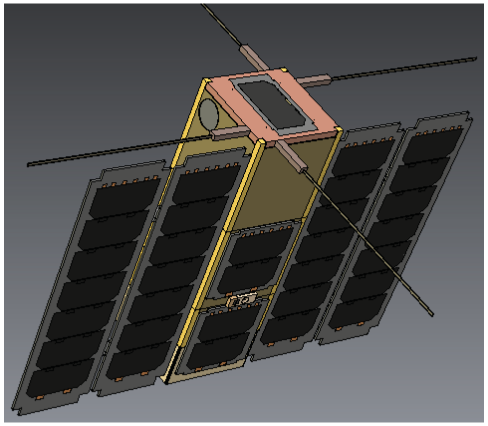
- Age of Small Satellites is Here or on the Horizon
- NASA is Developing Exciting CubeSat Concepts
- Small Satellite Mission Characteristics
- NASA Support for CubeSats
- Flight Radios and Antenna Development
- CubeSat Data Rates Achievable
- SCaN Evolution for Small Satellites
- Summary
- Workshop Discussion

Age of Small Satellites is Here or on the Horizon

- **Numerous organizations including NASA developing concepts for exploiting small spacecraft**
- **Per the NASA Spectrum program's list of small satellites (<100 kg), more than 370 small satellites, many of which were CubeSats, have launched between 2002 and February 2015**
- **Many more have been identified but not launched (>500 not counting concepts for large constellations with numbers in the 1000's)**
- **The number of small satellites may be constrained by launch opportunities in the near term remaining at about 100-120/year**

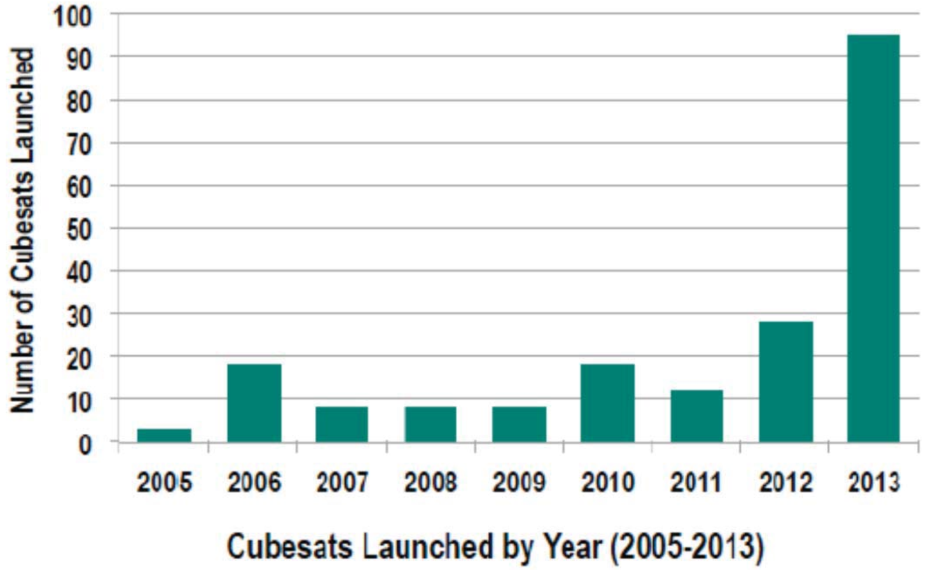


MIT's Micro-sized Microwave Atmospheric Satellite (MicroMAS) demonstrates an increase in science sophistication of CubeSats



GSFC's IceCube 3U CubeSat team will develop and validate a commercially available flight-qualified 874-GHz receiver for future use in ice cloud radiometer missions

CubeSat launches (SIA State of the Satellite Industry Report 2014)

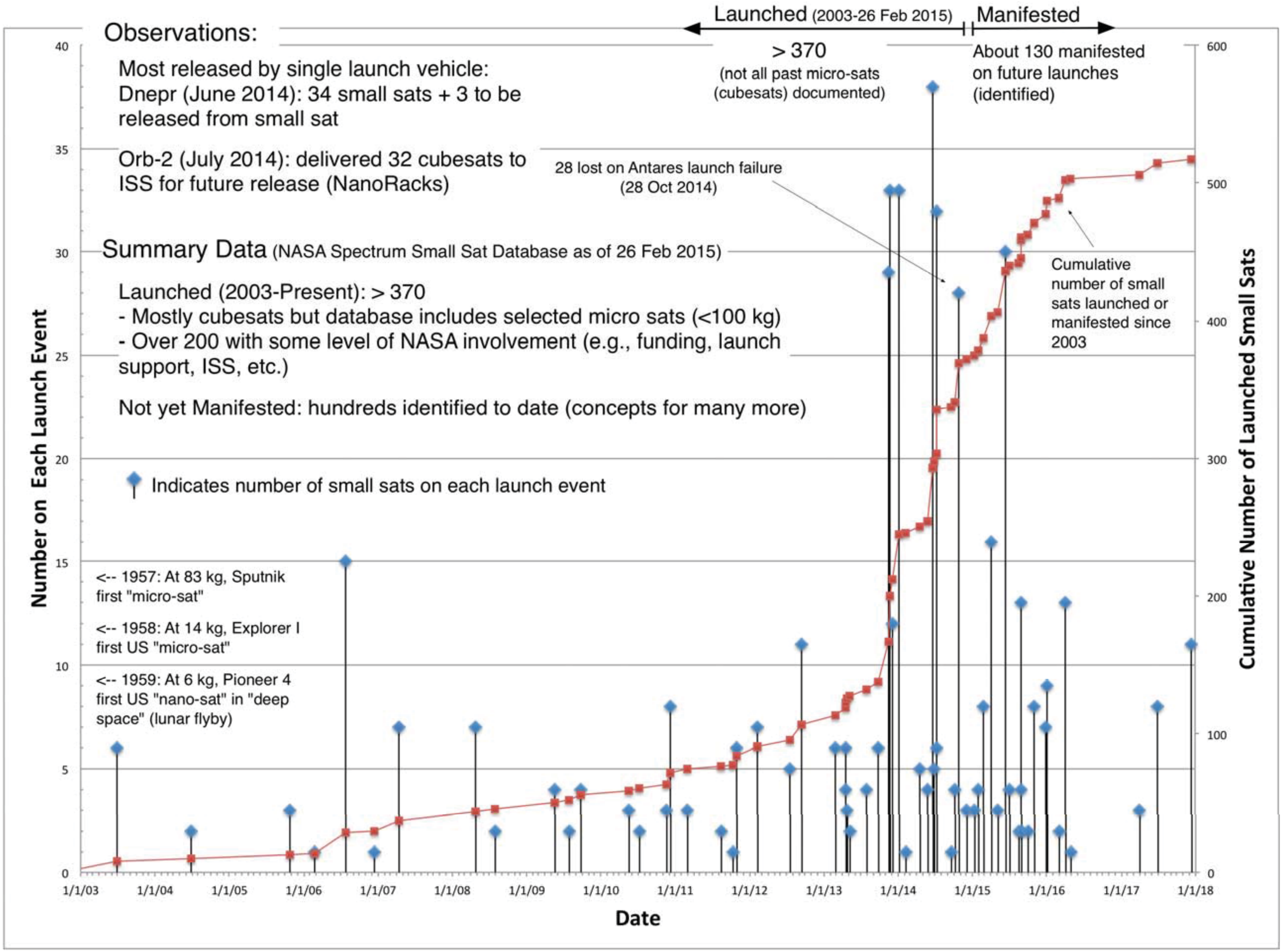


Satellite Industry Association Study (2014) shows recent growth in CubeSats
Other reports (e.g., Space Works) also shows the growth with projections of over 300 launched per year by 2017

Nano satellites released from the International Space Station (ISS)

Smallsat/CubeSat Launches: Past & Future

(as captured in NASA/Spectrum data set - data does not include all Smallsats)



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CubeSat Launch Initiative (CSLI) CubeSat Selections, Launches and Manifests (as of Feb 2015)

- **NASA, across its mission directorates and Centers, is actively involved in all aspects of small satellite missions**
  - Launch & deployment support: CubeSat Launch Initiative, deployment from ISS
  - Technology development (e.g., Small Spacecraft Technology Program)
  - Applying small satellites to NASA's science and exploration missions is still limited with studies underway on how best to utilize Smallsats
    - Example Mission: NASA Earth Science Cyclone Global Navigation Satellite System (CYGNSS) mission using eight (8) 18 kg micro satellites to study tropical ocean winds
  - One notable NASA function with only limited activity related to small satellites is space communications and navigation support

Year	Selected	Launched	Manifested-Future
2009	4		
2010	12		
2011	20	8	
2012	33	4	
2013	24	17	
2014	16	6	
2015	14	3	7
2016			2
Total	123	38	9

NASA CubeSat Launch Initiative (CSLI) began in 2009
Left: CSLI Activity; Right: Antares lifts off from Goddard/Wallops Flight Facility (WFF), with 3 CubeSats onboard in April 2013

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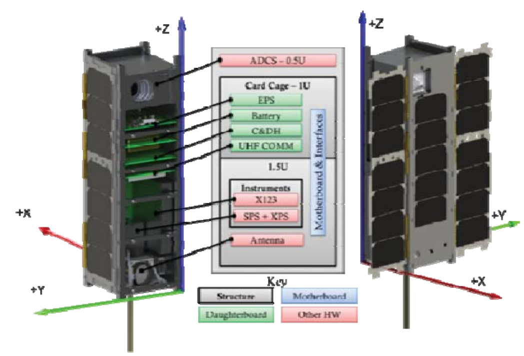
Small Satellite Mission Observations

- **To date, almost all small satellites have operated in low-Earth orbit**
  - Deployments at orbits (<450 km) where decay occurs rapidly, so most do not operate more than a few weeks or months (< 6 months), but . . .
  - Some small spacecraft have operated for years
  - Future: Small satellites will operate from LEO to highly elliptical, lunar, and deep space regions
- **Communication and navigation support**
  - Available power (e.g. 2W), modest gain antennas (e.g. patch antennas) and processing capabilities are becoming similar to traditional, larger spacecraft
  - Many different spaceflight communication and navigation (e.g., GPS for LEO/MEO) hardware sub-systems are becoming increasingly available

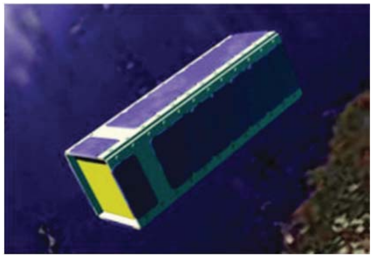
Goddard's Firefly CubeSat determining linkage between lightning & Terrestrial Gamma-Ray Flashes



University of Colorado Boulder and the Laboratory for Atmospheric and Space Physics (LASP) Miniature X-ray Solar Spectrometer (MinXSS) 3U CubeSat funded by NASA

Small Satellite Communication Support

- **Many different support approaches have been used**
  - Many small satellite projects have procured their own ground stations (e.g. Ultra-High Frequency (UHF) Yagi antenna, or a small 2m dish)
  - Commercial ground networks (e.g., KSAT) are increasingly deploying systems to support small satellites
  - A few small satellite systems, solicit support from amateur operators around the world ("crowd sourcing") to collect and send data packets back to a mission control center
  - Example: University of Michigan
  - Both Iridium and Globalstar mobile satellite systems have supported Smallsats
  - No one or set of standards has emerged as the obvious choice for small satellites



Ames Research Center (ARC) GeneSat CubeSat – 1st CubeSat launched in the US – Dec, 2006, from GSFC/Wallops Flight Facility

- **NASA support has been limited to date**
  - NASA Wallops range (not SCaN) has supported and plans to support several CubeSats
  - To date, the NASA Space Communication and Navigation (SCaN) Network (Space Network, Near Earth Network (NEN), and Deep Space Network (DSN)) have not directly supported any CubeSat mission but plans to support future missions

Beyond Earth Orbit Smallsat & CubeSat Support

- **To date, no identified CubeSat has operated in cis-Lunar space or in deep space (> 2M km); however, Smallsats (e.g. micro-sats < 100 kg) have . . .**
  - Lunar fly-by: Pioneer 4 (1959, 6 kg) first U.S. probe to escape from the Earth's gravity
  - Lunar orbit-first micro-sat?: Apollo 15 subsatellite (PFS-1) (36 kg) (1971)
  - Current Operational Example: ARTEMIS P1 & P2 (THEMIS B & C) (77 kg + 49 kg fuel at launch) currently operating in cis-Lunar and supported by DSN and NEN
  - Deep Space Example: Three (3) microsatellites were released with Hayabusa 2 (launch Dec 2014) in trajectories toward deep space including PROCYON (65 kg) which plans an asteroid flyby in 2016

- **Deep Space (> 2M km) Planned Missions**
  - Mars Cube One (MarCO): Two (2) 6U CubeSats launching with Insight mission to Mars (March 2016)
    - Relay from InSight to MarCO at 401 MHz (8 kbps, Proximity 1 protocol standard)
    - Space-Earth support from DSN in 7/8 GHz deep space bands (8 kbps)
  - Other systems have been proposed and are even in development, but no deep space CubeSats are known to be manifested (except on EM-1 mission, next chart)

Concept Art of MarCO

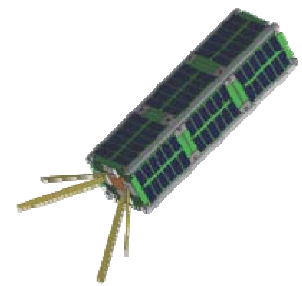
Beyond Earth Orbit Smallsat & CubeSat Support: EM1[1]

- **NASA's Space Launch System (SLS) has a requirement to support up to eleven (11) 6U CubeSats per launch**
- **The first SLS launch (with unmanned Orion spacecraft) in 2018 plans to carry 11 CubeSats**
  - CubeSats may enter cis-Lunar space or may continue to deep space
  - Due to the large number of Smallsats being released in trajectories departing Earth orbit, special considerations for communication and navigation services will be needed and will likely include multiple ground sites
  - Candidate EM1 CubeSat Manifest Allocation (NOT Final)
    - Human Exploration and Operations (HEO) Mission Directorate sponsored
      - BioSentinel
      - Lunar Flashlight
      - Near Earth Asteroid Scout
      - NextSTEP effort recently announced 2 candidate CubeSats
    - Science Mission Directorate (SMD) sponsored
      - Both Heliophysics and Planetary Divisions are reviewing proposals
      - Other SMD-sponsored CubeSats may be proposed
    - NASA's Cube Quest Centennial Challenge may book a few slots
      - Cube Quest is offering prizes to successful demos of CubeSats in lunar orbit & innovative deep space communications; Bidders (non-NASA) may choose DSN or alternative ground stations

[1] See the "Next-Generation Ground Network Architecture for Communications and Tracking of Interplanetary Smallsats" for information on how ground networks can support the EM1 scenario. Paper was presented at the CubeSat Developer's Workshop, April 22-24, 2015, San Luis Obispo. To be published in the Interplanetary Network Directorate Progress Report.

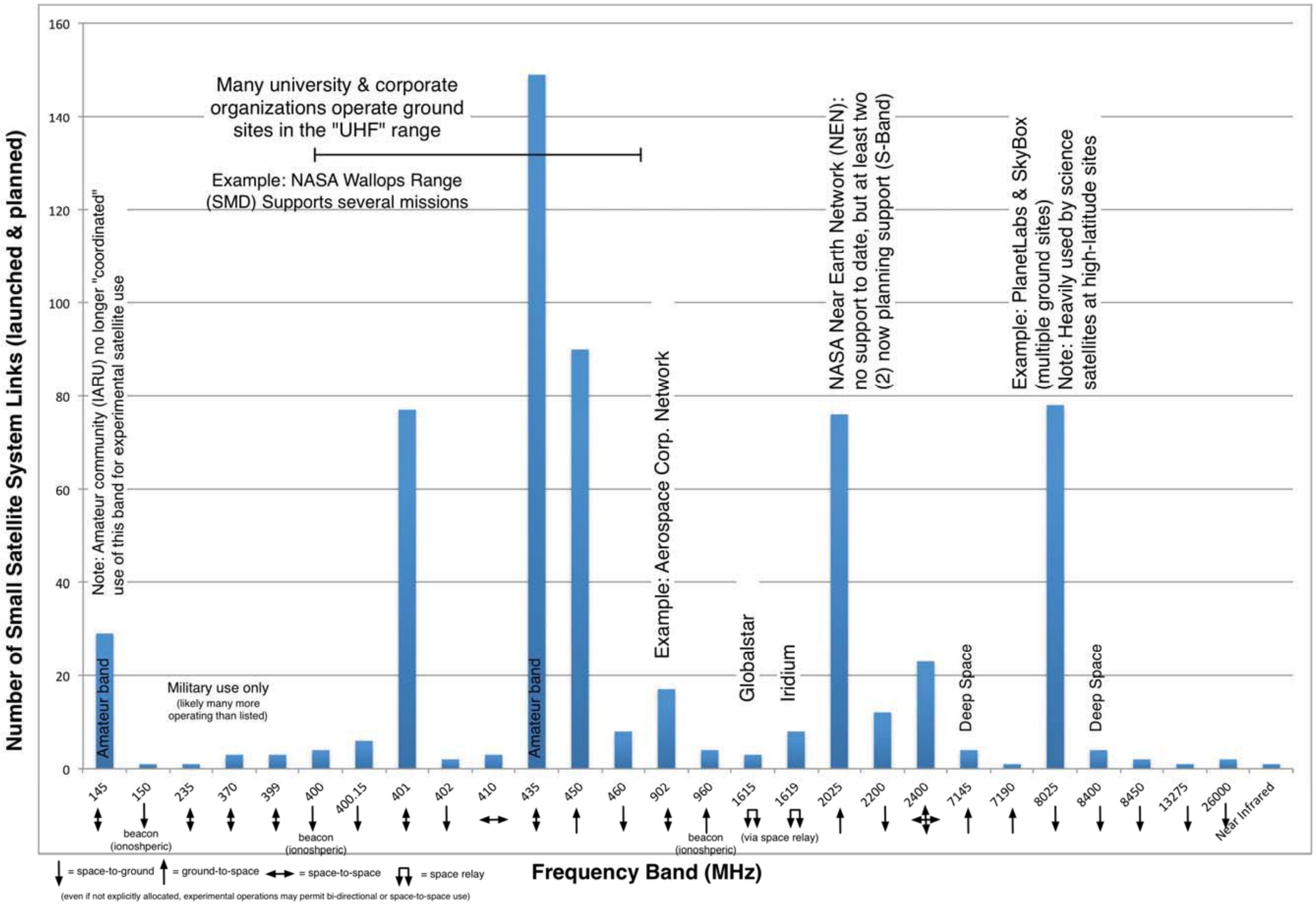
Spectrum for Smallsats

- **From a spectrum requirements and frequency coordination perspective, small satellites (e.g., nanosatellites, etc.) can not be defined as a distinct satellite class . . . An emitter is an emitter no matter what size the platform (spacecraft) (per ITU)**
- **Existing spectrum regulations apply to ALL spacecraft no matter what size . . .**
  - Authorization/licensing required
  - Must follow regulations including technical parameters (e.g., power flux density limits)
  - Must follow satellite notification and coordination processes
  - The typical two year spectrum coordination process can be a challenge for Smallsats that typically have a fast development life-cycle
- **Based on partial insight into mission designs, at least 25 different frequency bands have been or are planned to be used by small satellites for communications . . . Not all are appropriate for sustained operations**



Radio Aurora Explorer (RAX-2) – U. of Michigan, SRI International

Spectrum Used for Smallsat Communications (Continued)



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NASA Supports National Telecommunications and Information Administration (NTIA) Satellite Communication Bands

- **Bands with significant global network support and NTIA licenses for near-Earth and deep space Smallsats include, but are not limited to:**
  - 400 – 470 MHz
  - 2025-2120 MHz & 2200-2300 MHz
  - 7145-7235 MHz & 8025-8500 MHz
  - 22.55-23.55 GHz & 25.5-27.0 GHz
  - 31.8-32.3 GHz & 34.2-34.7 GHz
- **NASA Space Communication and Navigation (SCaN)**
  - NASA funded infrastructure for NASA missions
  - Near Earth Network: S, X, Ka
  - Space Network: S, Ku, Ka
  - Deep Space Network: S, X, Ka

Near Earth Network McMurdo Ground Station

NASA Responded to Popularity of UHF for CubeSats Wallops UHF CubeSat Ground Station (not SCaN)

- **Specifications**
  - Beamwidth: 2.9 degrees
  - Frequency Range: 380 to 480 MHz
  - Secondary Frequency Band: X-Band available for future high data rate CubeSat communication
  - Antenna Main Beam Gain: 35 dBi
  - Diameter: 18.3 meters (60')
- **UHF Radar as a CubeSat Ground station**
  - 1st used with Utah State University Dynamic Ionosphere CubeSat Experiment (DICE)
    - Interference
    - Morehead added as a back-up
  - Cutting-Edge CubeSat communication over a government-licensed UHF frequency allocation that enables high data rates (3.0 Mbit/Sec)
  - Currently communicating with the Firefly and MicroMAS spacecraft
  - Slated for use for MiRaTA, Delingr, CeREs, HARP, IceCube, and many proposed CubeSats

Wallops UHF on left, S-Band on right

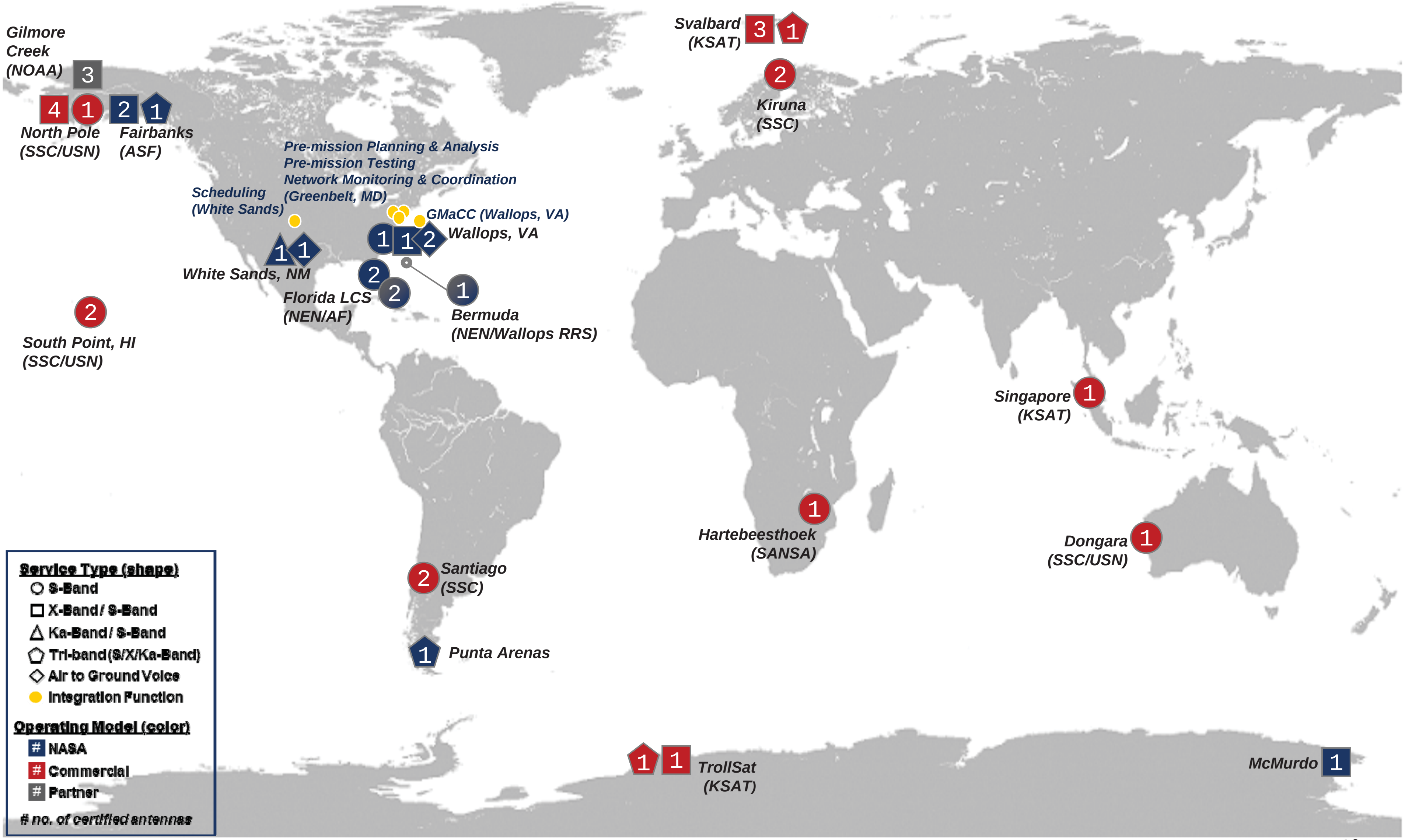
Morehead State University 21 Meter antenna

Near Earth Network (NEN) Description

- **Best value communications & tracking services**
- **Missions in near-earth region**
- **Supports multiple robotic missions in low Earth, geosynchronous, highly elliptical, and lunar orbits using a mix of NASA-owned stations and cooperative agreements with commercial and international space communications providers**
- **Lights out automation on each ground station**
- **Small staff at Wallops Global Monitor and Control Center (GMaCC) for 24*7 365 day monitoring of passes**
- **Streamlined planning process to maximizes reuse of ground station configurations**

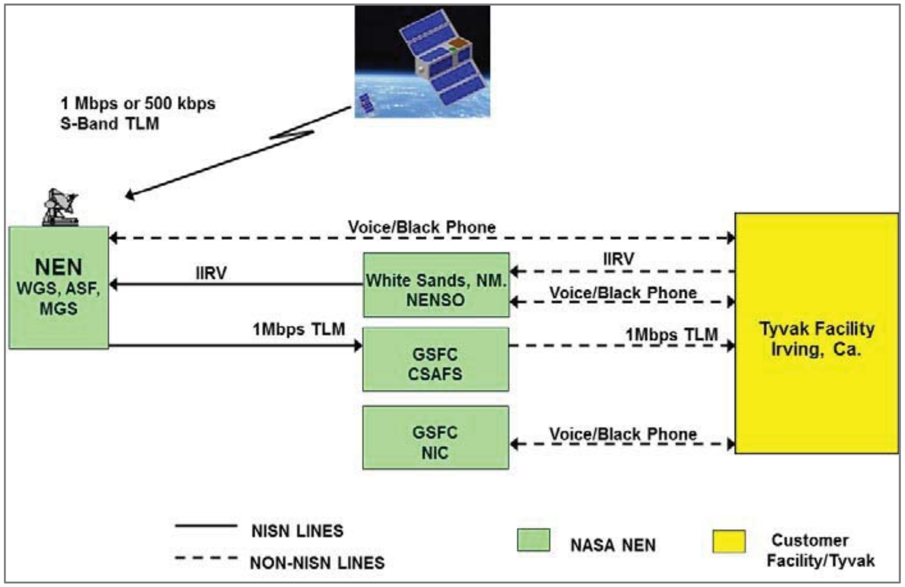
Near Earth Network Alaska Satellite Facility 11 Meter class antennas

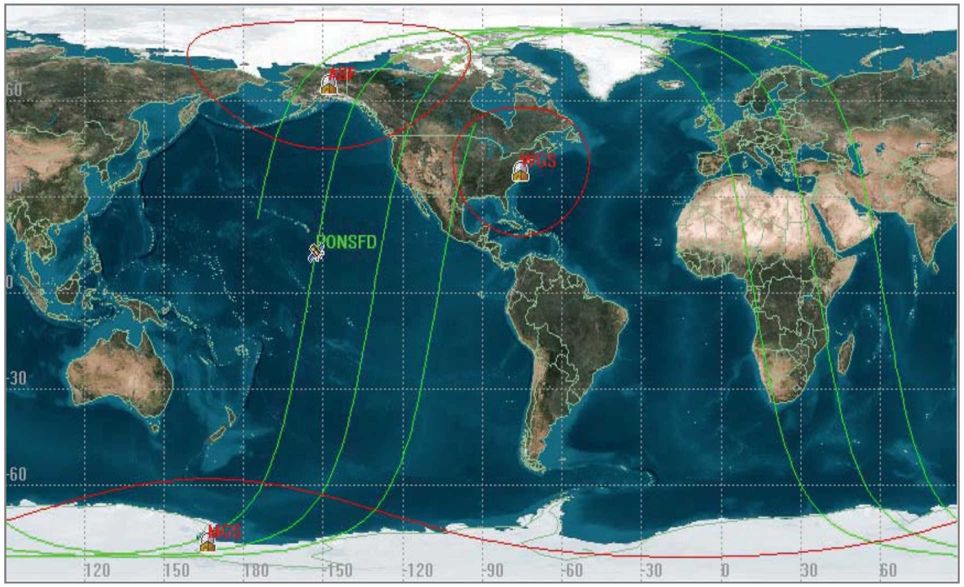
NEN Baseline after Projected Expansions (FY20)



NEN Upcoming CubeSat Support

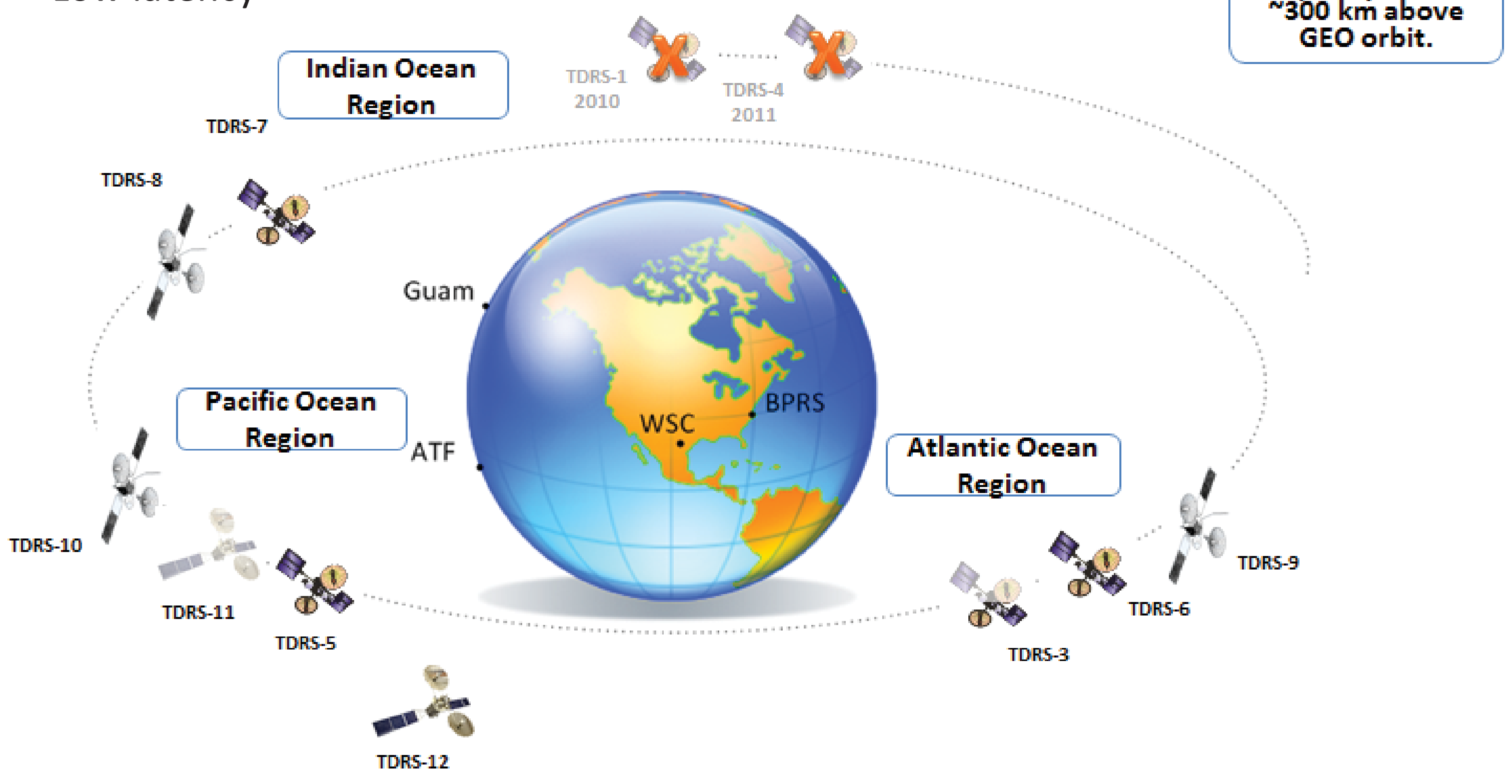
- **The NEN will provide first time support to a CubeSat mission, CubeSat Proximity Operations Demonstration (CPOD), when it launches in 2015**
  - Supporting Station: WGS 11m, ASF 11m, MGS 10m
  - Level of Support: 2 contacts per day with a minimum duration of 5 minutes
  - Service Provided: S-Band 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)





Space Network (SN) Description

- **A constellation of geosynchronous (Earth orbiting) satellites named the Tracking Data Relay Satellite (TDRS)**
  - Ground systems that operate as a relay system between satellites
  - Satellites in low Earth orbit (LEO) above 73 km
  - Supports 24 by 7 coverage
  - Low latency



TDRS Spacecraft Constellation – The Space Segment

Space Network White Sands Complex – The Ground Segment

- **The WSGT is composed of the following subsystems:**
  - Two Space-Ground Link Terminals
  - Three 18.3-meter Ka-Band antennas
  - One 10-meter S-Band Telemetry, Tracking and Command (STTC)
  - Two dual S/Ku-Band 4.5-meter antennas for end-to-end tests
  - Data Interface System
  - One TDRS Operations Control Center (TOCC)

- **The STGT includes the following subsystems:**
  - Three Space-Ground Link Terminals (SGLTs)
  - Three 19-meter Ka-band antennas
  - One 10-meter S-Band (STTC)
  - Two dual S/Ku-band 4.5-meter antennas for end-to-end tests
  - Data Interface System
  - One TDRS Operations Control Center (TOCC)

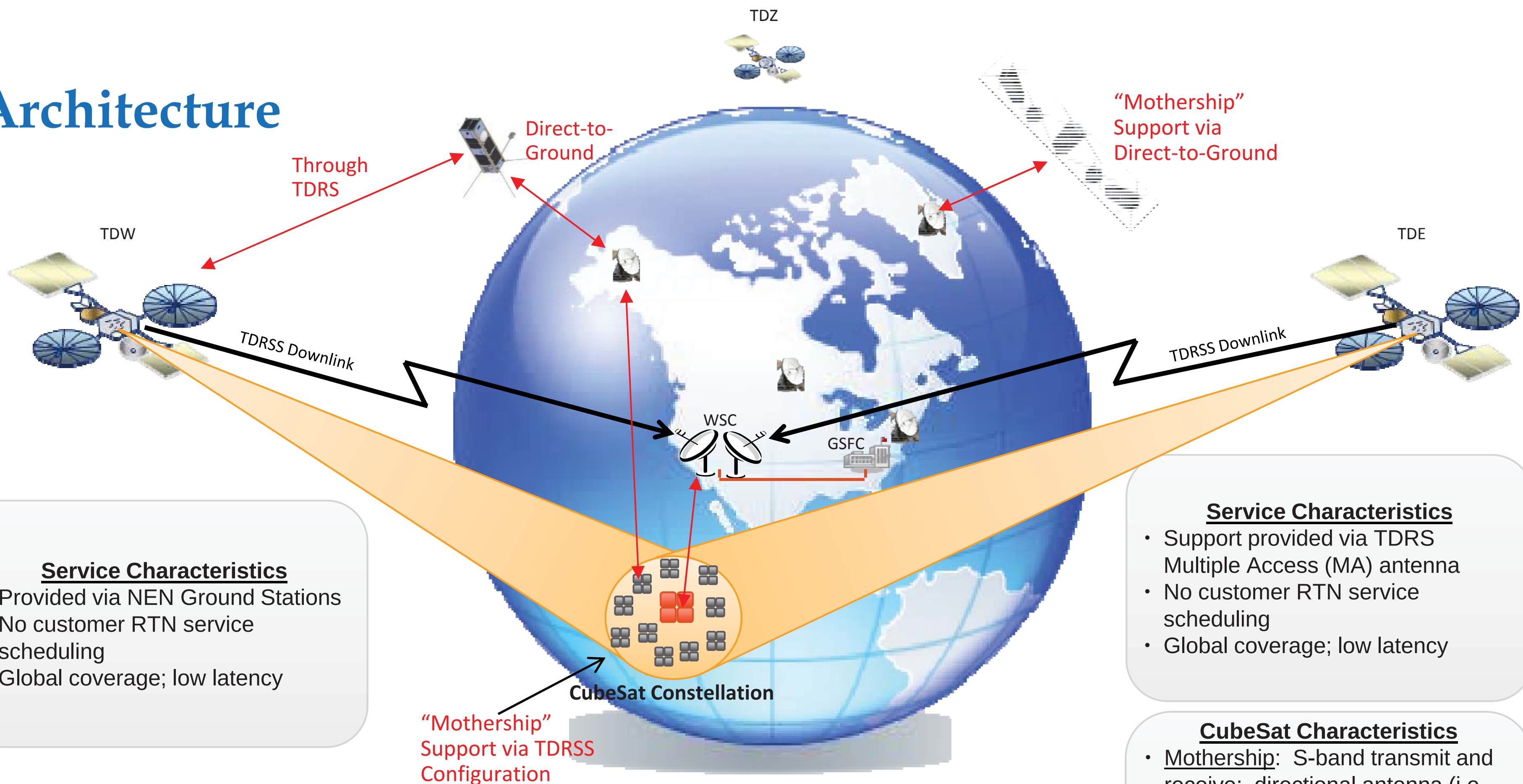
White Sands Ground Terminal (WSGT)

Second TDRSS Ground Terminal (STGT)

SN: Various CubeSat Communication Configurations

Goddard Space Flight Center

Architecture



Service Characteristics
- Provided via NEN Ground Stations
- No customer RTN service scheduling
- Global coverage; low latency

Service Characteristics
- Support provided via TDRS Multiple Access (MA) antenna
- No customer RTN service scheduling
- Global coverage; low latency

CubeSat Characteristics
- Mothership: S-band transmit and receive; directional antenna (i.e., attitude / antenna pointing); high rate burst transmissions; transponder required if TDRSS tracking services required
- Subordinates: Proximity link comm. only; GPS position determination

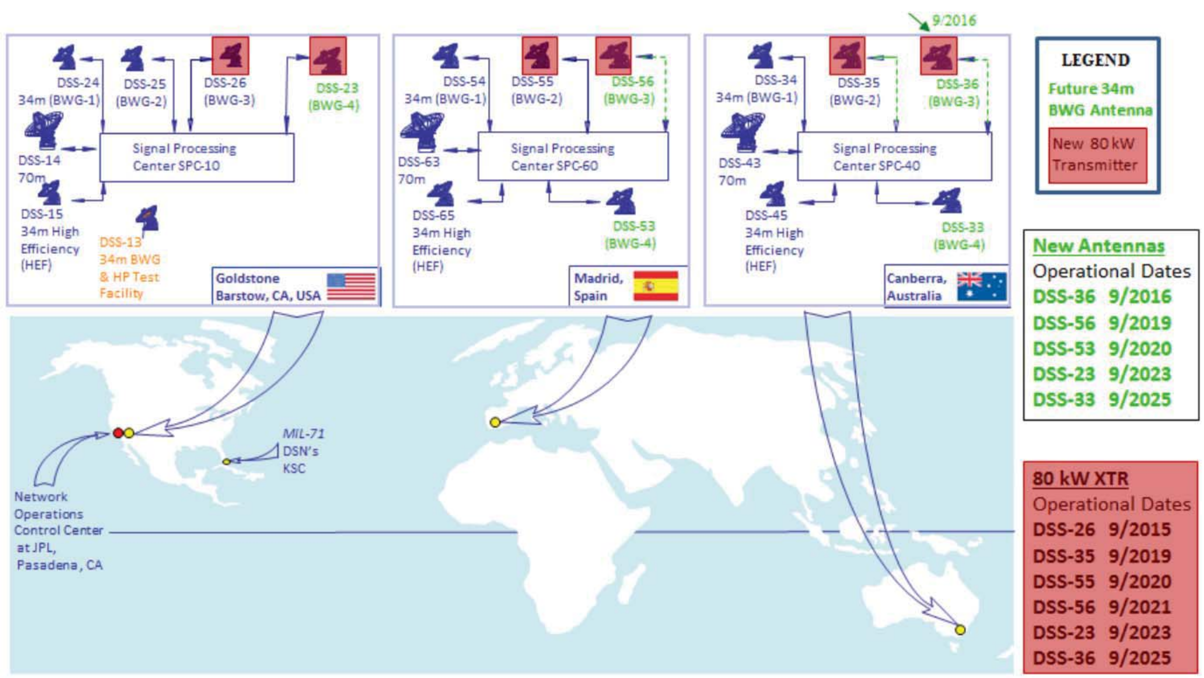
Constellation Characteristics
- One Mothership, however, multiple CubeSats have the ability to fulfill the role of Mothership
- Two or more CubeSat architectures (Mothership-capable CubeSats, subordinate CubeSats)

SN CubeSat Services

- **LEO CubeSats typically have low RF power output, low EIRP, and long slant ranges to TDRS**
- **Typical concepts of operations would include:**
  - CubeSat location finding and emergency recovery
  - High percentage global coverage with low latency (up to 24 x 7)
- **Low data rate users (e.g., CubeSat constellations) will utilize the Multiple Access Service, which will require Spread Spectrum communications systems onboard the user CubeSat**
  - Non-spread systems will cause spectrum management and interference issues. (Exceptions can be made on a case-by-case basis)
  - We are working on identifying spread spectrum radio options for CubeSat users

Deep Space Network (DSN) Description

- **NASA's international array of giant radio antennas that supports interplanetary spacecraft missions**
- **Operated by NASA's Jet Propulsion Laboratory (JPL), which also operates many of the agency's interplanetary robotic space missions**
- **Consists of three facilities spaced equidistant from each other – approximately 120 degrees apart in longitude – around the world, Goldstone, near Barstow, California; near Madrid, Spain; and near Canberra, Australia**



DSN Deep Space Station (DSS) Resources as of December 11, 2014

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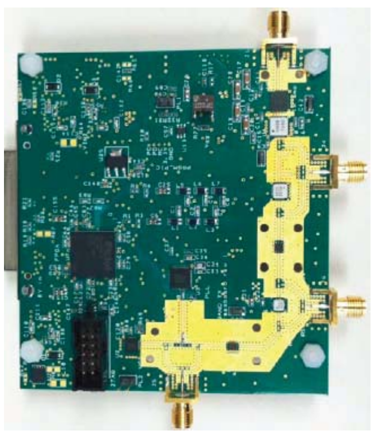
Selected Common CubeSat Radios and Antennas

Board	TRL	Flight Heritage	Frequency Bands	Data Rate	Mass (g)	Output Power(watt)	Input Power (watt)	Volume (cm^3)	Modulation; FEC	Network Compatibility
Tethers Unlimited	TRL4	No	S-band downlink/ S-band uplink	15 Mbps downlink	380	1	5	10X10X3.5	BPSK; FEC can be added	NEN,TDRS,DSN
MHX-2420	TRL9	RAX	S-band downlink/ S-Band uplink	230 kbps downlink/ 115 kbps uplink	75	1	5	8.9X5.3X1.8	FSK, CDMA	Partially NEN
AstroDev Lithium Radio	TRL9	RAX, Firefly, CSSWE, CXBN	UHF downlink/ UHF uplink	76.8 kbps downlink	52	250 mW – 4 W	1.25-20	10X6.5X3.3	FSK, GMSK	None
L3 Cadet	TRL9	DICE	UHF downlink/ UHF uplink	24 Mbps downlink/ 250 kbps uplink	215	2	10	6.9X6.9X1.3	OPSK,FSK,GMSK; Turbo FEC, Conv.	None
	TRL4	No	S-band downlink/ UHF uplink	24 Mbps downlink/ 250 kbps uplink	215	2	10	6.9X6.9X1.3	OPSK, FSK,GMSK; Turbo FEC, Conv.	None
Nimitz Radio	TRL3	No	S-band downlink/ UHF uplink	1 Mbps downlink/ 50 kbps uplink	500	1	5	9X9.6X1.4	BPSK, FSK, GFSK	None
MSFC	TRL 7	FASTSat2	S/X-band downlink/ S-band uplink	150 Mbps X-Band downlink/ 50 kbps uplink	<1kg	2	8	10.8X10.8X7.6	BPSK, OQPSK; LDPC 7/8	NEN
Innoflight	TRL 9	Sense NanoSat	S-band downlink/ S-band uplink	4.5 Mbps downlink	300	2	10	8.2X8.2X3.2	BPSK,QPSK,OQPSK, GMSK, FM/PCM; Conv. and RS	NEN,TDRS,DSN
IRIS (JPL)	TRL 6	No	X-band downlink/ X-band uplink	256 kbps downlink/ 1 kbps uplink	400	4	20	0.4 U	BPSK; RS	DSN
LASP/GSFC	TRL 5/ TRL 8 (7/15)	No	S/X-band downlink/ S-band uplink	12.5 Mbps X-Band downlink/ 200 kbps uplink	<600	1.5	10	0.5 U	BPSK/OQPSK Conv. and RS	NEN
Syrlinks	TBD	No	S-band downlink/ S-Band uplink	3 Mbps downlink/ 256 kbps uplink	325	3	15	9x9.6x5.1	QPSK/OQPSK, Conv. (7;½) Differential Coding	NEN
Syrlinks	TBD	No	X-band downlink	100 Mbps downlink	225	2	10	9x9.6x2.4	OQPSK/ Conv. (7;½)	NEN
Quasonix nanoTX	TRL 9	CPOD	L/S-Band downlink	46 Mbps downlink	*TBD*	10	50	3.2x8.6x0.8	PCM/FM, SOQPSK-TG, Multi-h CPM, BPSK, QPSK, OQPSK, UQPSK	NEN

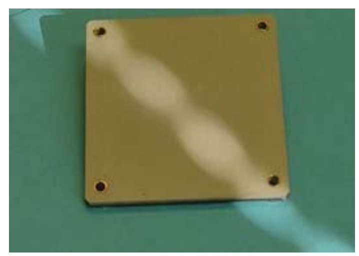
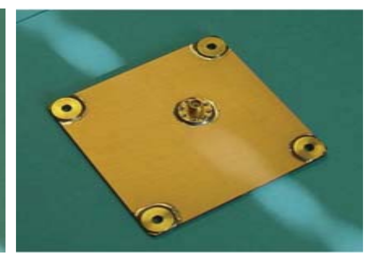
LASP/GSFC X-Band Radio Development Effort

LASP and GSFC are currently undertaking a X-Band Cube Satellite Communication System development project with the following objectives:

1. Investigate different X-band communication system architectures that can be used as a baseline
2. Design, simulate and test a NEN compatible CubeSat S- and X-band communication system
3. End-to-end demo of X-band CubeSat communication system with a Balloon to a NEN station
4. An end-to-end innovative, compact, efficient and low cost S-band uplink and X-band downlink CubeSat Communication System Demonstration between a balloon and a NEN ground




HRCCS X-Band transmitter prototype module top and bottom view

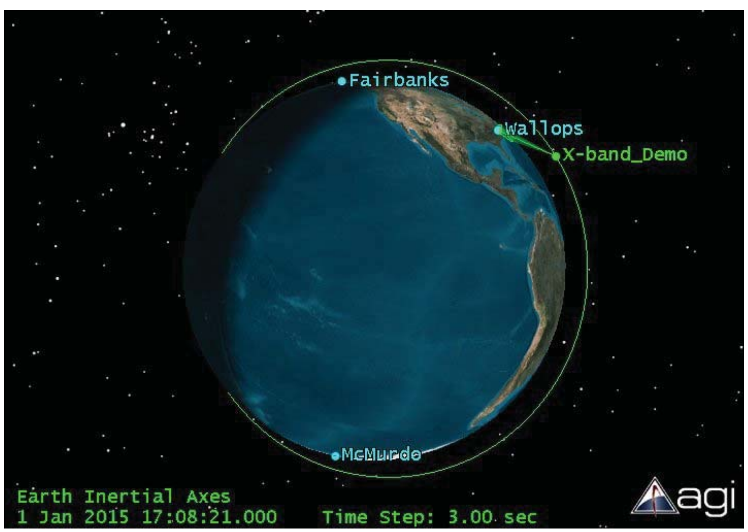
Ant Dev Corp Low Gain S-band Patch
- 0 dBi +/- 40 deg
- 2210 MHz
- 4X4X0.25 inches

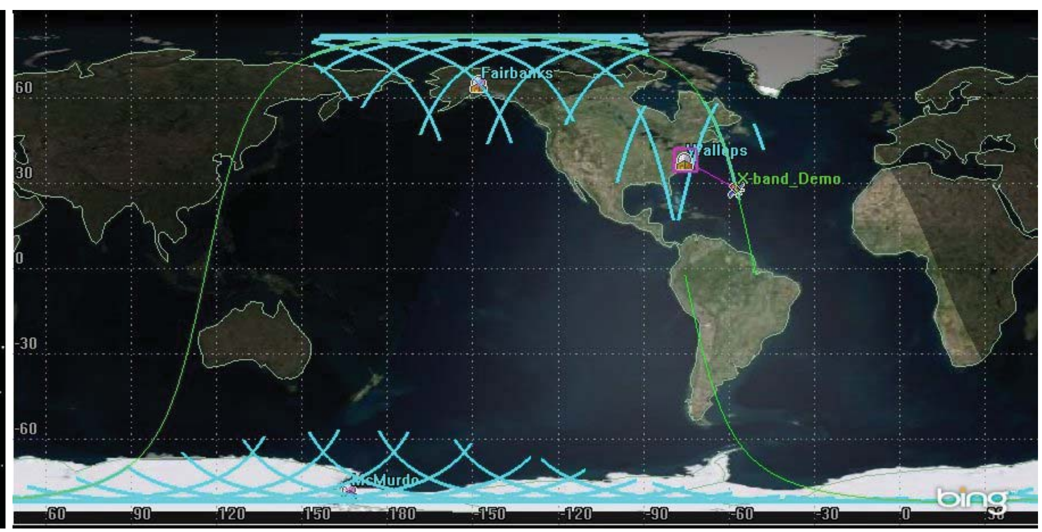

Ant Dev Corp Medium Gain X-band Patch Array Antennas
- 8250 MHz
- 4 elements/16 elements
- 2.5X2.75X0.13 inches

STK Simulations of LASP/GSFC Radio

- **An STK simulations was conducted with the LASP/GSFC radio and a LEO satellite with distances up to 705 km, which concluded the link could be closed with at least + 3 dB margin**

		Wallops		Fairbanks				McMurdo		Grouped	
Ground Station		WGS 11.3M		ASF 10M		ASF 11M		MGS (10m)		(inclusive)	
Frequency		S-band	X-band	S-band	X-band	S-band	X-band	S-band	X-band	S-band	X-band
Elevation Angle (deg)		5	10	5	10	5	10	5	10	5	10
Min Data Rate (Mbps) OCO-2 Model (from 705km Alt.)		5.00	7.71	5.00	10.90	5.00	13.11	5.00	10.00	5.00	7.71
Contact Time Per Day (hrs)	Average	0.71	0.494	1.674	1.136	1.674	1.136	2.253	1.546	4.64	3.18
	Minimum	0.71	0.494	1.674	1.136	1.674	1.136	2.253	1.546	4.64	3.18
Latency (hrs)	Average	4.556	2.032	1.983	4.599	1.983	4.599	1.416	1.829	0.65	0.84
	Maximum	11.843	10.032	8.374	11.879	8.374	11.879	1.6	6.094	1.45	1.52



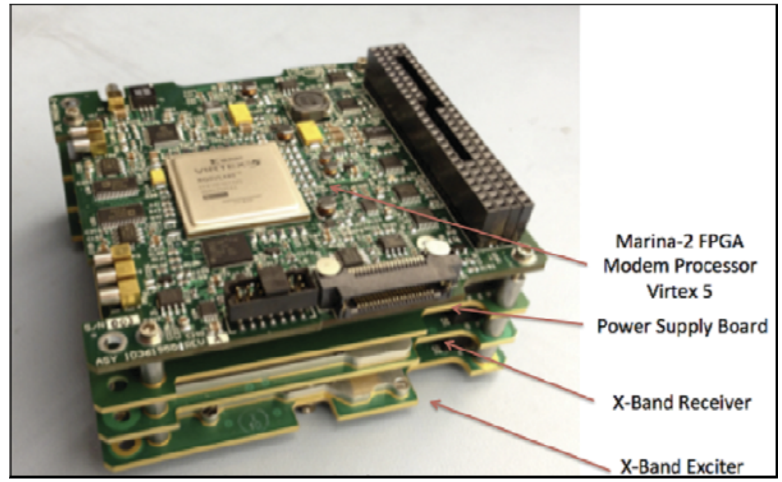


LASP/GSFC Radio Schedule

- **Test will be performed during Summer 2015**
  - Anechoic Chamber Antenna test
  - Lab tests with Transceiver and Cortex XXL
  - Closed Loop test with WGS 11m, inject the signal from receiver to the WGS 11m
  - Far Field test - call tower testing with WGS 11m (No frequency license required)
  - Full Balloon Demo
- **Transceiver development schedule**
  - X-band transmitter will be completed in June 15
  - S-band portion will be completed late Summer/Early Fall 2015

JPL IRIS Radio and Antenna Development

- **Iris Radio Development**
  - Development began in 2013
  - DSN-compatible X-band transponder
  - Volume of 0.4 U and mass of 0.4 kg
  - CCSDS standards (e.g., AOS, Turbo, Conv., BPSK)
  - Return rates from 62.5 to 256,000 bps
  - Forward rates from 62.5 to 8000 bps
  - 32 Mbits of storage
  - Doppler, ranging, and delta-DOR tones supported



Iris Version 1 Prototype Stack

- **Developing multiple CubeSat-Compatible High-Gain Antennas to increase EIRP**
  - Deployable reflector: Designed for Ka-Band but potentially applicable to X-Band, can provide the necessary surface accuracy due to deployment and folding rib mechanism
  - Reflectarrays: Combine the advantages of arrays and reflectors
  - Inflatable reflectors: Provides the highest stowing efficiency allowing for larger sized antennas and bigger gain

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NEN: CubeSat Capabilities/Data Rates (LEO 400 km Orbit)

- **The following table provides anticipated achievable data rates between a LEO CubeSat equipped with different compatible radios and typical NEN antennas**

						Achievable Data Rate (# dB Margin)				
Radio	**Antenna**	**Gain**	**Power**	**Band**	**Req. CubeSat Pointing**	**Yagi**	**Low Gain**	**5m**	**11m**	**18m**
L3 Cadet	Omni	0 dBi	2 W	UHF	*NA*	50 kbps	200 kbps	750 kbps	3 Mbps	3 Mbps (+7 dB)
Innoflight	2xPatch	0 dBi	2 W	S-Band	*NA*	60 kbps	250 kbps	4.5 Mbps	4.5 Mbps (+2 dB)	4.5 Mbps (+9 dB)
Innoflight	High Gain	10 dBi	2 W	S-Band	10 deg	500 kbps	8 Mbps	10 Mbps (+13 dB)	10 Mbps (+19 dB)	10 Mbps (+26 dB)
LASP/GSFC	2xPatch	0 dBi	2 W	X-Band	*NA*	125 kbps	500 kbps	6 Mbps	12.5 Mbps (+3 dB)	12.5 Mbps (+10 dB)
LASP/GSFC	High Gain Dep. or Patch Array	15 dBi	2 W	X-Band	10 deg	6.25 Mbps	12.5 Mbps (+6 dB)	12.5 Mbps (+12 dB)	12.5 Mbps (+18 dB)	12.5 Mbps (+25 dB)
MSFC	High Gain Dep. or Patch Array	15 dBi	2 W	X-Band	10 deg	6.25 Mbps	12.5 Mbps (+6 dB)	12.5 Mbps (+12 dB)	150 Mbps (+8 dB)	150 Mbps (+15 dB)

NEN: CubeSat Capabilities/Data Rates (Lunar Orbit)

- **The following table provides anticipated achievable data rates between a Lunar CubeSat equipped with different compatible radios and typical NEN antennas**

Radio	Antenna	Gain	Power	Band	Req. CubeSat Pointing	Achievable Data Rate (# dB Margin) 11m	Achievable Data Rate (# dB Margin) 18m
L3 Cadet	Omni	0 dBi	2 W	UHF	*NA*	*NA*	*NA*
Innoflight	2xPatch	0 dBi	2 W	S-Band	*NA*	0.04 kbps	0.2 kbps
Innoflight	High Gain	10 dBi	2 W	S-Band	10 deg	3 kbps	16 kbps
LASP/GSFC	2xPatch	0 dBi	2 W	X-Band	*NA*	0.2 kbps	1 kbps
LASP/GSFC	High Gain Dep. or Patch Array	15 dBi	2 W	X-Band	10 deg	1 kbps	32 kbps
MSFC	High Gain Dep. or Patch Array	15 dBi	2 W	X-Band	10 deg	1 kbps	32 kbps

SN: CubeSat Capabilities/Data Rates

- **The limiting case for CubeSats utilizing TDRSS is the Return Service (signals originating at the CubeSat up to TDRSS down to WSC).**
- **CubeSat-TDRSS support will be limited by lower data rate due to S/C power constraints; however SN can provide full global coverage and low data latency**

Link Description	Information Rate (prior to all coding)	Symbol Rate (after RS encoding)	Symbol rate (after all coding applied)	Coding	CubeSat EIRP	Margin
1st generation TDRS MA Return	874 bps	1 ksps	2 ksps			0.4dB
2nd/3rd generation TDRS MA Return	1.139 kbps	1.303 ksps	2.606 ksps	Rate ½ CC with Reed Solomon Coding	2.0 dBW	1.0dB
SSA Return	6.914 kbps	7.906 ksps	15.812 ksps			

Link characteristics are for a CubeSat with 2W RF out, 0dBi patch antenna in a ISS-like orbit. Communication mode is S-band SQPN, via either 1st gen Multiple Access, 2nd/3rd gen Multiple Access or Single Access Service.

DSN: CubeSat Capabilities/Data Rates

- **The following table provides anticipated achievable data rates between a Lunar CubeSat equipped with different compatible radios and a 34m DSN class antenna**

						Achievable Data Rate (# dB Margin)
Radio	**Antenna**	**Gain**	**Power**	**Band**	**Req. CubeSat Pointing**	**34m**
L3 Cadet	Omni	0 dBi	2 W	UHF	*NA*	1 kbps
Innoflight	2xPatch	0 dBi	2 W	S-Band	*NA*	10 kbps
Innoflight	High Gain	10 dBi	2 W	S-Band	10 deg	160 kbps
LASP/GSFC or IRIS (JPL)	2xPatch	0 dBi	2 W	X-Band	*NA*	20 kbps
LASP/GSFC	High Gain Dep. or Patch Array	15 dBi	2 W	X-Band	10 deg	1 Mbps
IRIS (JPL)	High Gain Dep. or Patch Array	15 dBi	2 W	X-Band	10 deg	256 kbps
MSFC	High Gain Dep. or Patch Array	15 dBi	2 W	X-Band	10 deg	1 Mbps

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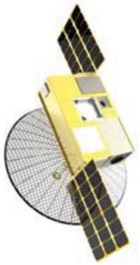
Near Earth Network Evolution

- **Transition from S-band to X-Band to Ka-Band depends on flight hardware evolution**
- **NEN S, X and Ka-Band ground system is already standardized**
- **Higher data rate will reduce number of passes required**
- **Standardization on radios and configurations will reduce planning/testing costs and may reduce frequency authorization time**
- **11 Meter class dishes yields high gain for X-band**
  - Link budget shows 12.5 Mbps can be achieved in low Earth orbit with a 1 Watt output satellite transmitter over X-band
  - LASP and Goddard/Wallops Flight Facility have partnered to design a CubeSat X-Band transmitter, S-Band receiver (NEN compatible)
  - Project funded by NASA Space Technology and Mission Directorate (STMD) and GSFC IR&D
- **Developers can focus on end use and maximize science "bang-for-the-buck"**
- **Possibility of adding UHF capability**

Near Earth Network 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 Near Earth Network

SN Evolution for CubeSats

- **TDRSS can provide continual coverage of CubeSats compared to very limited contact time with just ground stations**
  - Continual coverage can be used by CubeSats to send status alerts instantly without waiting until a ground station is in view
  - Supports continual, real-time data flows without interruption
  - More coverage time allows using lower data rates (i.e. less power) to deliver more data than brief, intermittent ground station contacts
- **TDRSS can provide emergency support for CubeSats**
  - TDRSS 360° coverage can constantly listen for signals from CubeSats around the world and locate them when they are not visible to ground stations
  - TDRSS may be able to provide CubeSat location information by processing signal information from multiple TDRS's viewing a CubeSat

DSN Evolution

- **The DSN is pursing multiple efforts in response to the challenges associated with communication and navigation of Smallsats outside LEO, in lunar and deep space[1]**
  - Radio and antenna development (*see "Flight Radios and Antenna Development" section*)
  - Streamlining access and utilization processes for DSN and related services
  - Developing methodologies for tracking & operating multiple spacecraft simultaneously
  - Coordination and collaboration with non-DSN facilities
- **Streamlining and Upgrading Existing DSN Capabilities and Processes**
  - DSN Resource Allocation Process: Plans are underway to integrate DSN resource allocation tools into a single tool for end-to-end scheduling needs, increasing efficiencies
  - DSN Costs: DSN is considering CubeSat tracking packages to assist mission with high DSN costs as well as reduced pre-launch testing when a CubeSat mission consists of several spacecraft
- **New Techniques for Simultaneous Tracking of Multiple Spacecraft in an Antenna Beam**
  - DSN is working to develop low-cost techniques to enable its antennas to support more spacecraft simultaneously such as Multiple Spacecraft per Antenna (MSPA)
- **DSN Operation and its Interfaces with Non-DSN Antenna Facilities and Missions**
  - DSN is investigating aspects of Smallsat operations concepts and interfaces including the following topics: (1) Spectrum coordination, (2) DSN compatibility and interfaces, (3) Cross-Support with University stations, and (4) Potential ESA antennas

[1] See the "Next-Generation Ground Network Architecture for Communications and Tracking of Interplanetary Smallsats" paper from corresponding author Kar-Ming Cheung for in depth details for each topic discussed regarding DSN Evolution. Paper was presented at the CubeSat Developer's Workshop, April 22-24, 2015, San Luis Obispo. To be published in the Interplanetary Network Directorate Progress Report.

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Summary

- **NASA SCaN is in the process of studying further the user needs for CubeSats within the NASA user community**
  - What level of service is appropriate to provide to CubeSats?
  - TDRS location
  - UHF support
  - Spacecraft emergency
- **NASA SCaN intends to provide standard services and capabilities to CubeSats and to evolve and enhance network capabilities as budget permits**
- **Increased knowledge of key lessons learned and improved efficiencies (more coordinated operations and communications support) will likely be necessary to fully mature the small satellite domain**
- **Evolution depends on both flight hardware and ground station development**
- **UHF use will likely continue until other band solutions become more mature and affordable**
- **X-band is recommended solution in the near-term for maximizing the use of the NASA Near Earth Network resources and high data rates**
- **NASA Space Network could today provide low-latency, low data rate service**
- **NASA Deep Space Network is preparing to support multiple planetary CubeSats in parallel**
- **NASA is investigating streamlining planning and testing**

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Workshop Discussion & Candidate Action: SpaceOps 2016

- **Previous: SpaceOps 2016**
  - Plenary Panel: Smallsat Operations
  - Small Satellite Operations Technical Track (Chair: James Cutler (U of Michigan))
    - Topics: CubeSat and Nanosat Operations, TT&C Systems, Flight Operations, Constellation Operations, Frequency Allocation Challenges, Regulations and their Challenges, Challenges with Small Satellite Operations, End of Life Operations, CubeSat Networks/Swarms; Constellation Operations, Nano-Technologies, Lessons Learned
    - SSO Tech Session: Trimmed Communication Architectures
      - Adapting a Large-Scale Multi-Mission Ground System for Low-Cost CubeSats
      - NASA Wallops Flight Facility-Morehead State Ground Network for Small Satellite Mission Operations
      - Development and Operation Results of CubeSat RAIKO Using Ground Network System
    - SSO Tech Session: Advanced Operations Concepts
      - Operational Considerations for a Swarm of CubeSat-Class Spacecraft
      - Operations of a Radioisotope-based Propulsion System Enabling CubeSat Exploration of the Outer Planets
      - Operations Cost Reduction for a Jovian Science Mission using CubeSats
- **Candidate Action: Define sessions & panels for SpaceOps 2016 (Korea)**
  - Considerations:
    - Are Smallsat operations sufficiently distinct from “standard” missions such that different approaches and technologies are needed? (i.e., is there a need for a separate SpaceOps tech track?)
    - What about ops for large satellite constellations (regardless of spacecraft size)?
    - Should standard services be defined for Smallsat operations such that support can be provided by multiple, distinct networks (e.g., Gov., commercial, university, etc.)? If so, what would those standard services and interfaces be?
  - Workshop Outcome
    - Define candidate SpaceOps 2016 Panels and Tracks

Workshop Discussion & Candidate Action: Cross Support for Small Satellites

- **Candidate Action: Establish Small Satellite Cross Support Framework for Space Agencies**
  - Considerations:
    - What are space agency plans for using small Satellites?
      - Note: To date, NASA has primarily supported small satellite technology development and launch support with only minimal use to meet exploration and science objectives. Essentially, what is the "real" market of space agency small satellites requiring C&N services?
    - Are Smallsat operations sufficiently distinct from "standard" missions such that different approaches and services are needed?
    - What about ops for large satellite constellations (regardless of spacecraft size?
    - Should standard services be defined for Smallsat operations such that support can be provided by multiple, distinct networks (e.g., Gov., commercial, university, etc.)? If so, what would those standard services and interfaces be?
    - Are existing IOAG recommendations (e.g., Service Catalog) and CCSDS Standards sufficient or appropriate for small satellites?
    - What about spectrum . . . Are current frequency allocations sufficient? Are current spectrum processes (e.g., licensing, coordination) adequate? If not, what is needed?
  - Candidate Workshop Outcomes
    - Recommendation on need for and potential content for Smallsat Cross Support Framework for Space Agencies

Backup

Acronyms

AF	Air Force
AGO	Santiago Ground Station
AGS	Alaska Ground Station
ARC	Ames Research Center
ASF	Alaska Satellite Facility
BPSK	Binary Phase Shift Keying
CeREs	Compact Radiation belt Explorer
CPOD	CubeSat Proximity Operations Demonstration
CSLI	CubeSat Launch Initiative
CYGNSS	Cyclone Global Navigation Satellite System
DICE	Dynamic Ionosphere CubeSat Experiment
DSN	Deep Space Network
DSS	Deep Space Station
FEC	Forward Error Correction
FSK	Frequency Shift Keying
G	Grams
GHz	Gigahertz
GMaCC	Global Monitor and Control Center
GN	Ground Network
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HARP	Hyper Angular Rainbow Polarimeter
ISS	International Space Station
ITU	International Telecommunication Union
JPL	Jet Propulsion Laboratory
Kbps	Kilobits per second
Kg	Kilogram
Km	Kilometer
KSAT	Kongsberg Satellite Services AS
LASP	Laboratory for Atmospheric and Space Physics

LEO	Low Earth Orbit
M	Meter
Mbps	Megabits per second
MGS	McMurdo Ground Station
MHz	Megahertz
MicroMAS	Micro-sized Microwave Atmospheric Satellite
MinXSS	Miniature X-ray Solar Spectrometer (MinXSS)
MiRaTA	Microwave Radiometer Technology Acceleration
NASA	National Aeronautics and Space Administration.
NEN	Near Earth Network
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
RRS	Research Range Services
SANSA	South African National Space Agency
SCaN	Space Communications and Navigation
SMD	Science Mission Directorate
SNIP	SCaN Network Integration Project
SIA	Satellite Industry Association
SN	Space Network
SSC	Swedish Space Corporation
STGT	Second TDRS Ground Terminal
TDRS	Tracking and Data Relay Satellite
USN	Universal Space Network
W	Watt
WFF	Wallops Flight Facility
WGS	Wallops Ground Station
WSC	White Sands Complex
WS1	White Sands NEN 18m Antenna #1