National Aeronautics and Space Administration

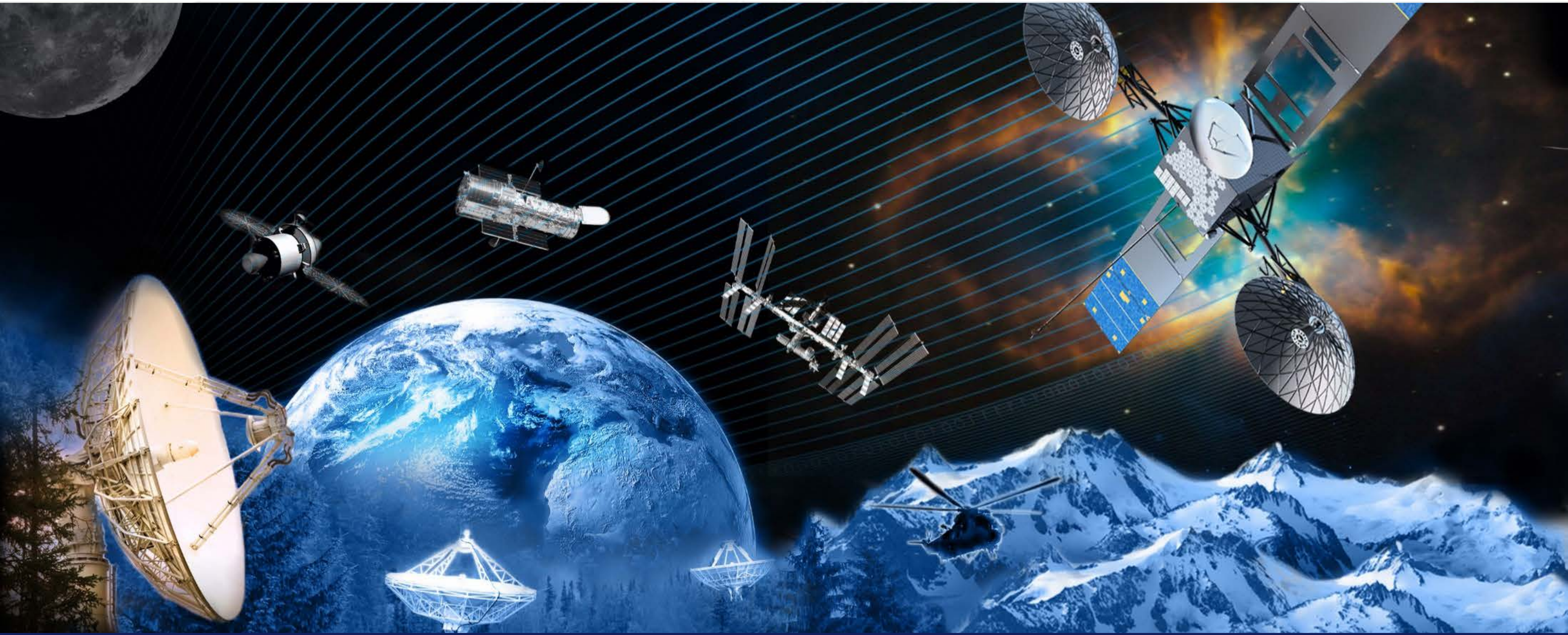
Exploration & SPACE Communications

More than you ever imagined...

NASA Space Network (SN) Support and Services for SmallSats

Dr. Haleh Safavi, Dr. Harry Shaw

SmallSat Conference, Logan Utah, August 6, 2018

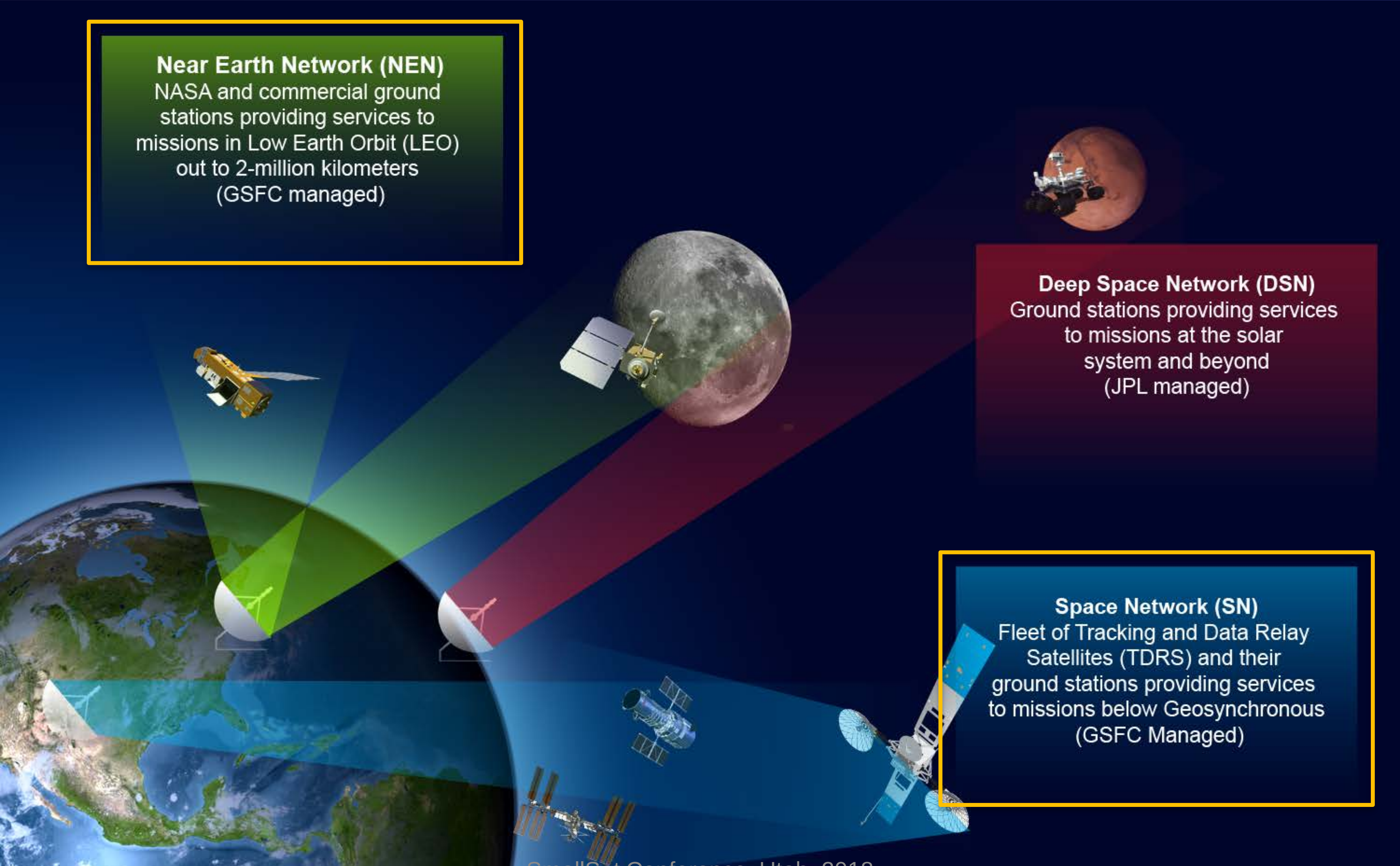


Outline

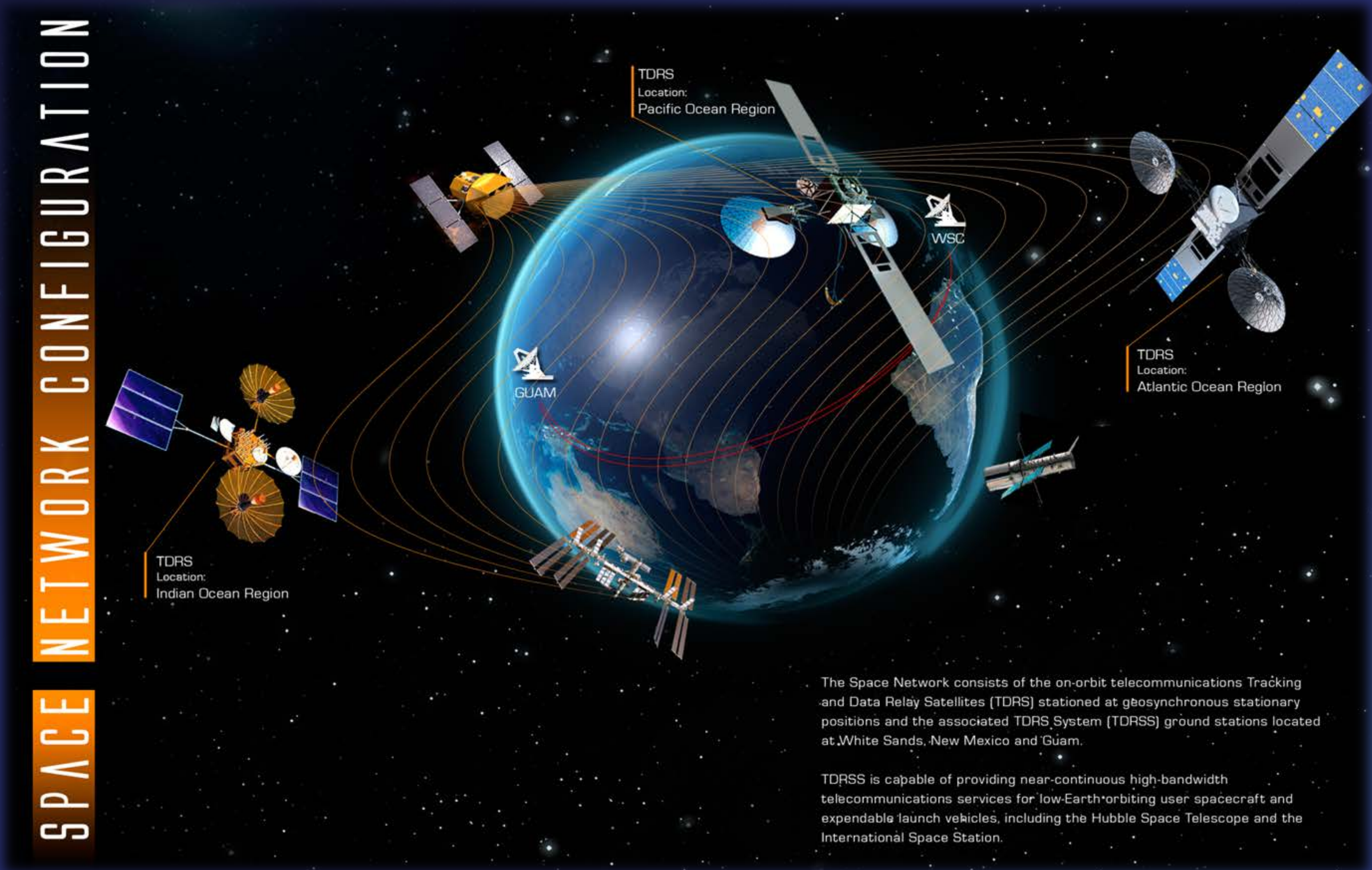
- Overview
- Space Network Services
- Current Space Network Customer Base
- Benefits and Challenges of Using Space Network
- CubeSat Technology Development
- Conclusion

NASA's Space Communications Networks:

Three networks: NEN, SN, DSN

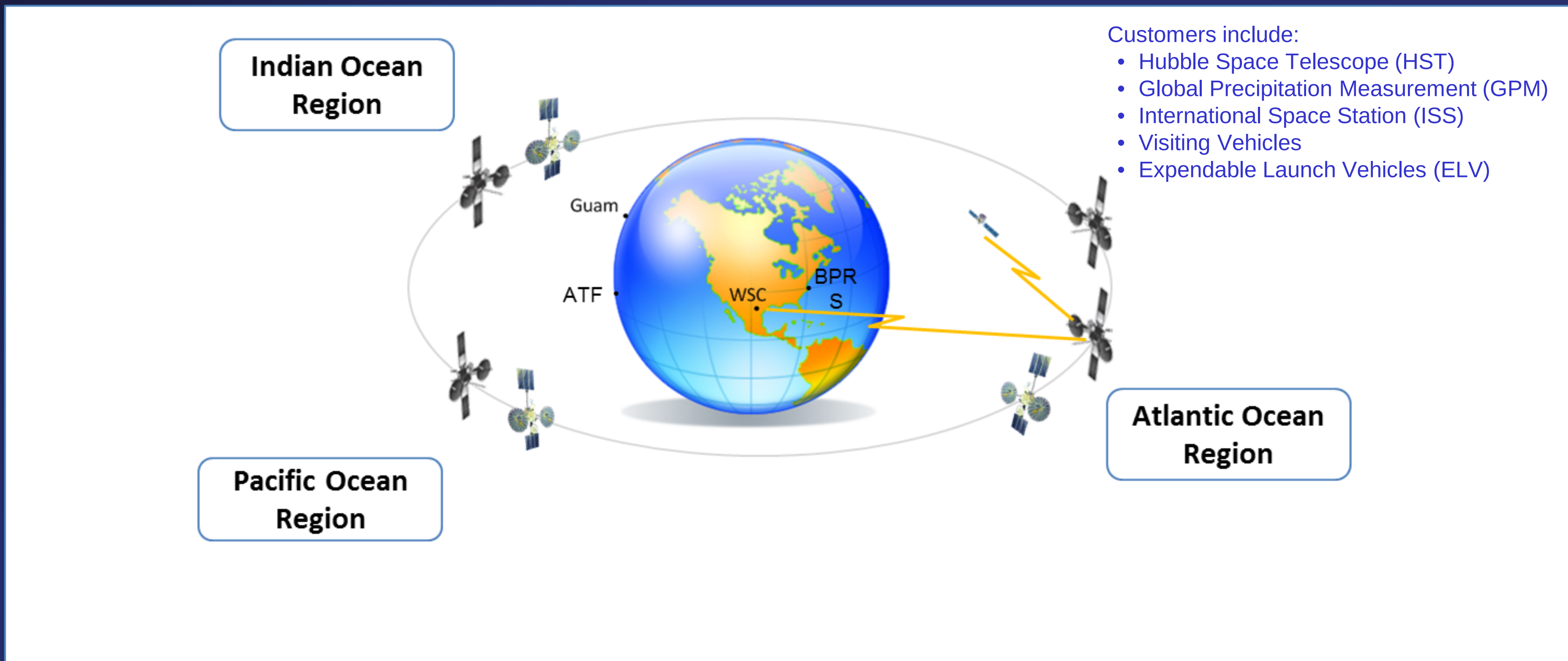


Space Network



Space Network

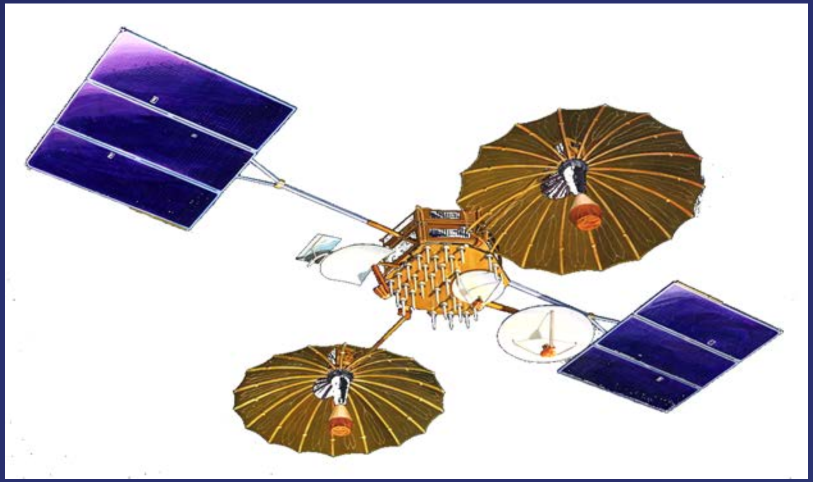
The Space Network (SN) is a bent pipe data communication system comprised of a constellation of geosynchronous Tracking and Data Relay Satellites (TDRS) and a network of geographically diverse ground terminals.

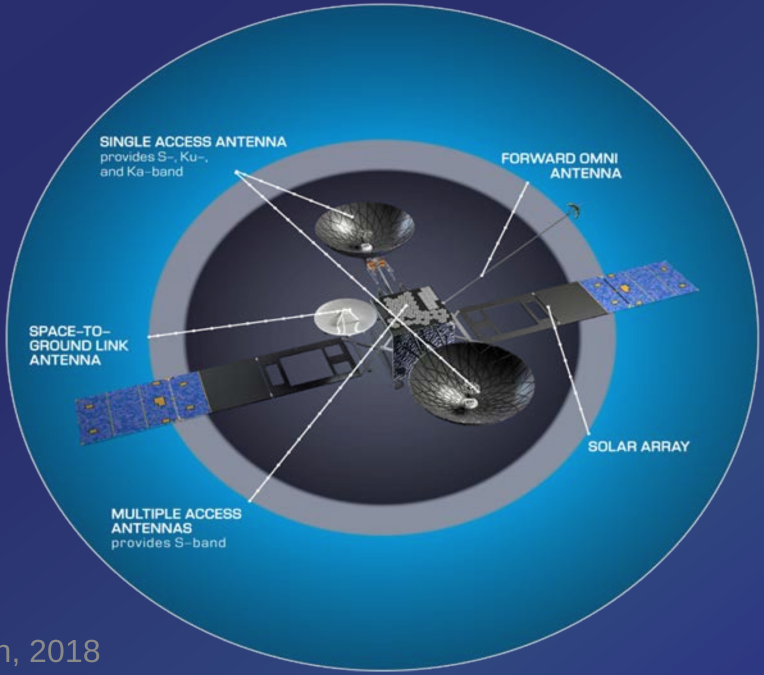


The SN provides nearly 8 million minutes of S/Ku/Ka-band communications services per year.

TDRS Antenna Systems

- Each TDRS has multiple antennas.
- Two 5-meter steerable dishes provide high-rate communications support.
  - However, these dishes are a limited resources that is carefully scheduled among users.
- There are also 30 small multiple access (MA) antennas that can support many simultaneous users at lower rates.





Description of TDRS services

The SN can provide any of the following services:

1. A forward service, which is the communication path that generally originates at the customer control center and is routed through WSC or GRGT to the TDRS to the customer platform

2. A return service, which is the communication path that generally originates at the customer platform and is routed through TDRS to WSC or GRGT back to the customer control center and/or data acquisition location

3. Both forward and return services simultaneously

Space Network Users Guide

TDRS Single Access (SA) Services

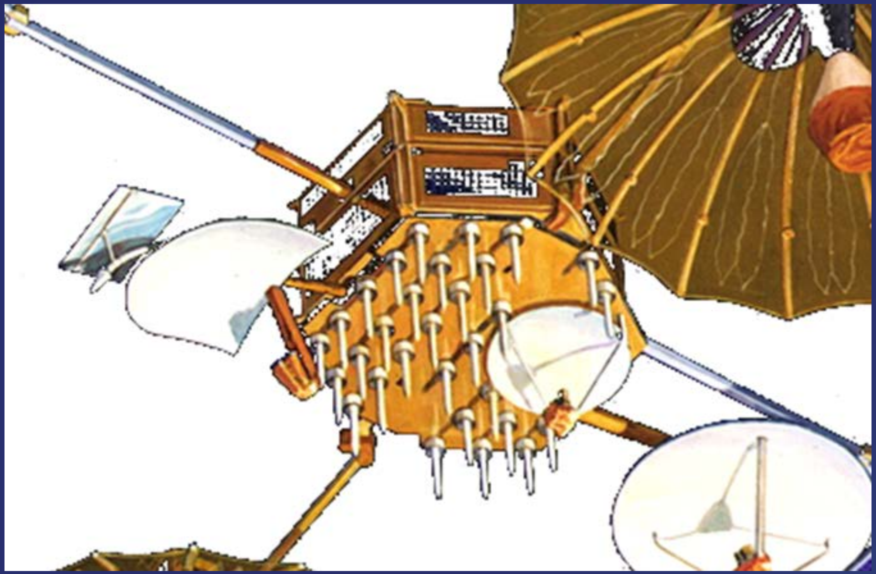
Forward and Return Services Via the Single Access Antennas

- S-band
- Ku-band (300 Mbps)
- Ka-band
  - Maximum data rate is 1.2 Gbps for users but has been demonstrated to support up to 3 Gbps.

TDRS Multiple Access Service

- On some TDRS, the 30 signals from the MA antennas are all sent to the ground for further processing.

- Ground equipment can then time shift and combine the signals to form multiple receive beams aimed in different directions.

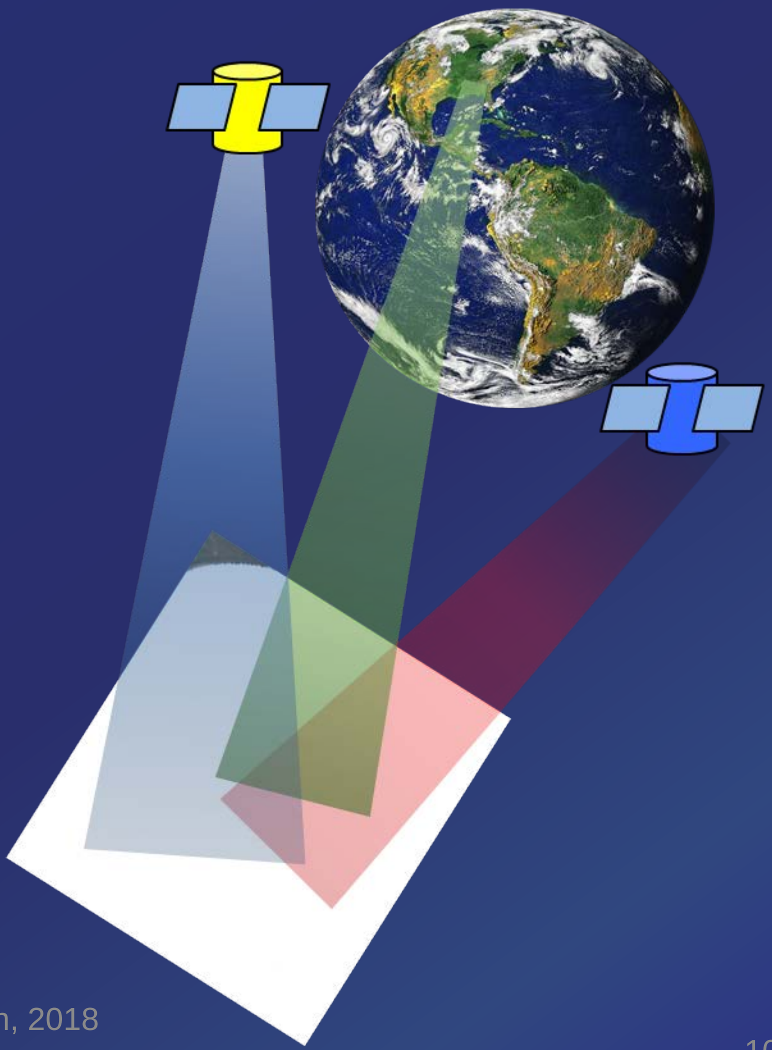


- MA service supports up to 30 users on one S-band frequency using spread spectrum technology.

- This allows support to many more users, but at lower data rates of up to 300 Kbps per user.

TDRS Beam-forming

- TDRS MA elements receive signals from everywhere at slightly different times.
- Each MA antenna sees a slightly different combination of signals.
- All 30 MA signals are sent to the ground, and by slightly shifting them, the separate spacecraft signals can be recovered.
- Ground-based beam formers can construct these beams and move them to track multiple spacecraft.
- New beam formers at White Sands can support up to 30 beams per TDRS.

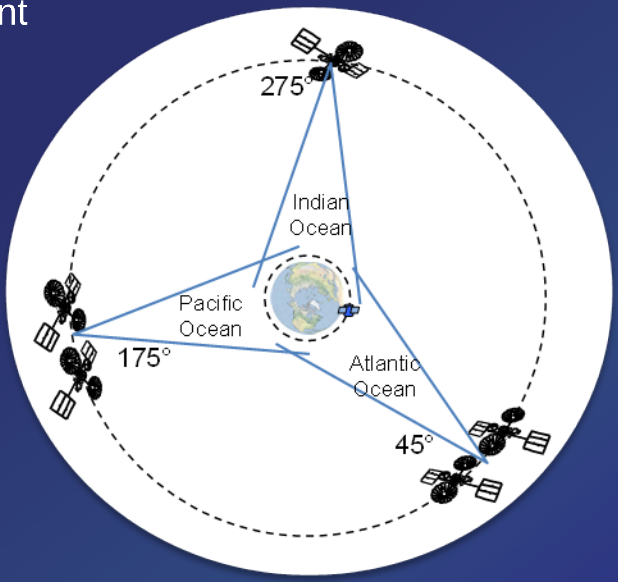


TDRS Demand Access Service

- The TDRS Demand Access Service (DAS) is intended to support multiple users for long durations with the MA/multiple-beam capability.
- Satellites looking for events like gamma-ray bursts use DAS for continuous, low-rate communications.
  - Many DAS users operate at 1 to 2 Kbps, but 24 hours a day.
- The SN can support many more MA users such as CubeSats.

TDRS Continuous Coverage Through DAS

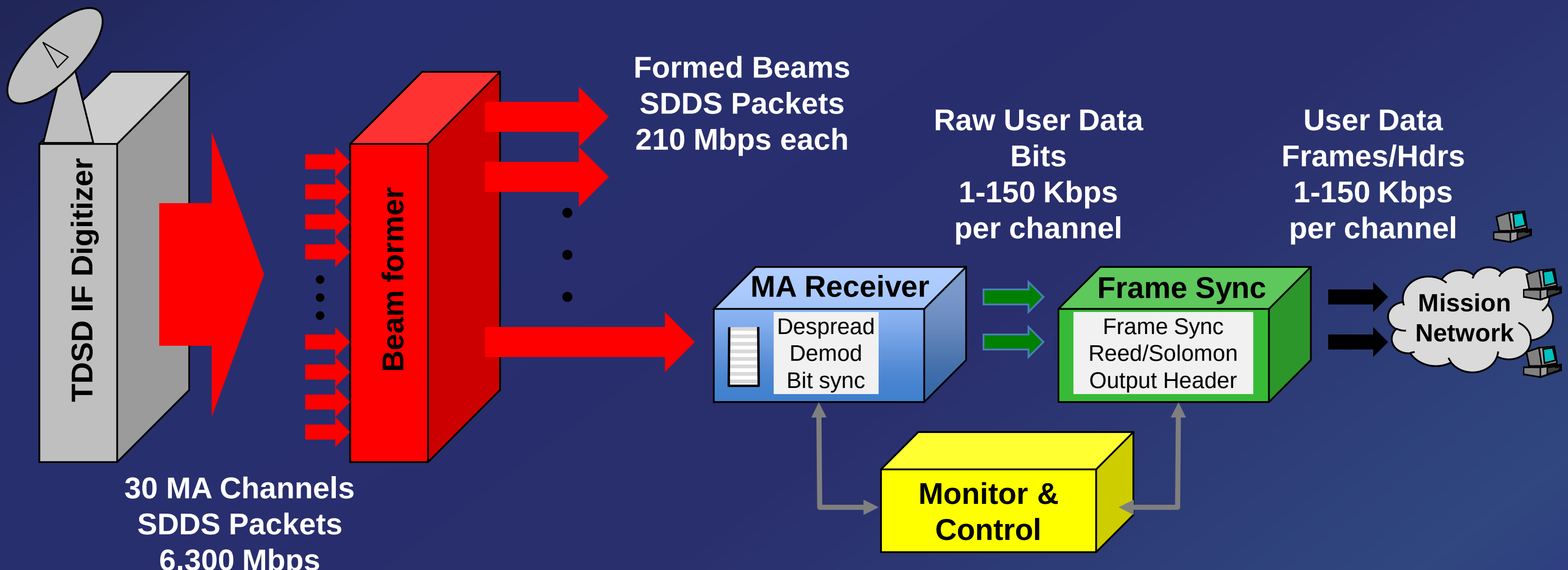
- TDRS multiple access service has the potential to provide continual coverage of CubeSats/SmallSats in low Earth orbit.
- The current DAS activities are demonstrating low-cost technology to enable each site to support 30 or more simultaneous CubeSats/SmallSats at each terminal.
- DAS system would constantly listen for CubeSat/SmallSat signals with at least 5 different TDRS to provide:
  - Continual, automated coverage without any operator involvement
  - Emergency support
  - Automatic data logging with user data file retrieval on demand
  - Location information by processing signal information from multiple TDRS viewing a satellite



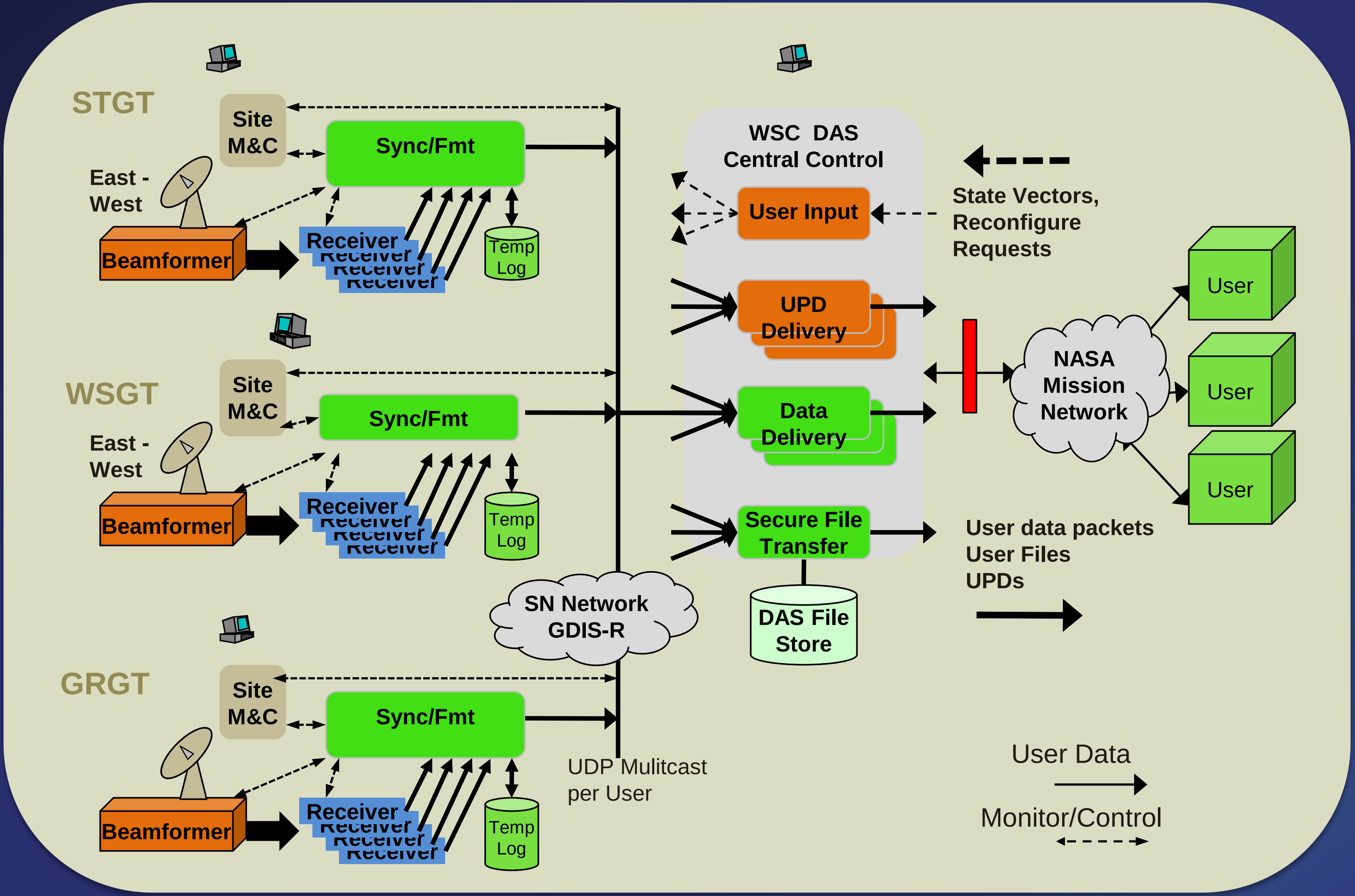
SmallSat Conference, Utah, 2018

DAS Key Components

- Data from TDRS antenna digitized at ground antenna.
- Beam former ingests MA streams, forms beams, outputs Signal Data Distribution Standard (SDDS) IF packets.
- MA receivers de-spread, de-modulate, remove coding, bit sync data and outputs bits in UDP/IP packets.
- Frame sync ingests bits, locates frames, Reed/Solomon processing and outputs with specified user headers.
- Monitor and control system observers and commands components.



Full System Architecture



SmallSat Conference, Utah, 2018

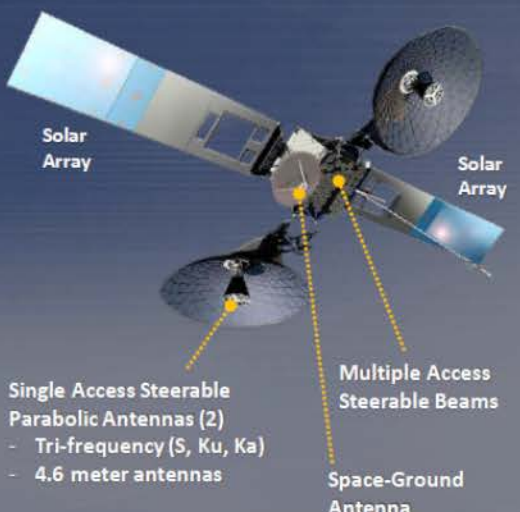
TDRS Navigation

- One-way and two-way Doppler measurement
- Time-transfer measurement
- Range measurement
- Return channel time delay
- Contact Space Network Project for details.

Why Customers Use TDRS

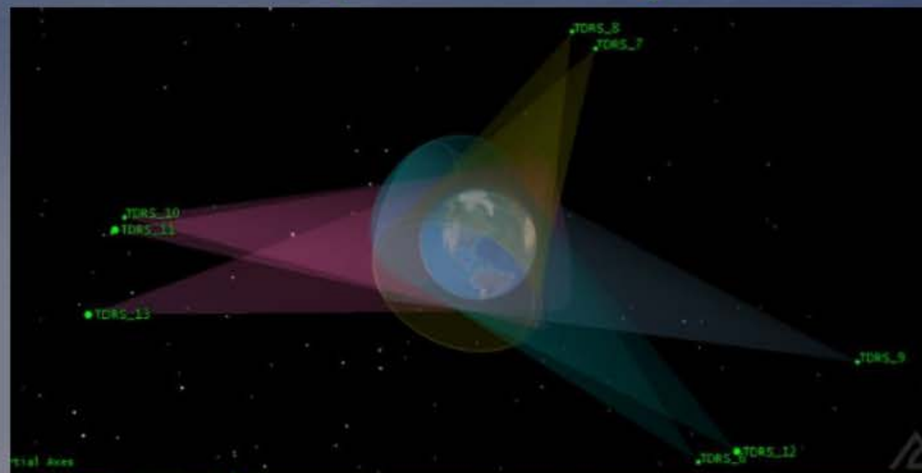
- Low latency/Fast response
- Global coverage
- Mission recovery/Launch and early operations support
- Orbital location determination
- Operating constellations
- High-reliability communications

Space Network Services & Users



Dry Spacecraft Mass = 1780.1 kg or 3924 lbs. (F10-13)

Space Network Earth Coverage



(Illustrated with 10.5 Field of View)

Key Service Attributes

- Global coverage from 3 geosynchronous regions
- 24 x 7 coverage of all missions below geosynchronous orbit
- High power beams that track users and minimize user communication payload size
- Doppler compensation and correction of signals
- Requires only ground stations in the US and its possessions

Space Network Users

Suborbital
- Altitude: < 40km
- Latency: Periodic

Human Space Flight
- Altitude: 300-600 km
- Inclination: 28-57°
- Latency: Real time
- Orbit Period: 90.5 min

Earth Science
- Altitude: 350-8,000 km
- Inclination: 35-99°
- Latency: Near Real Time
- Orbit Period: 91.5 min

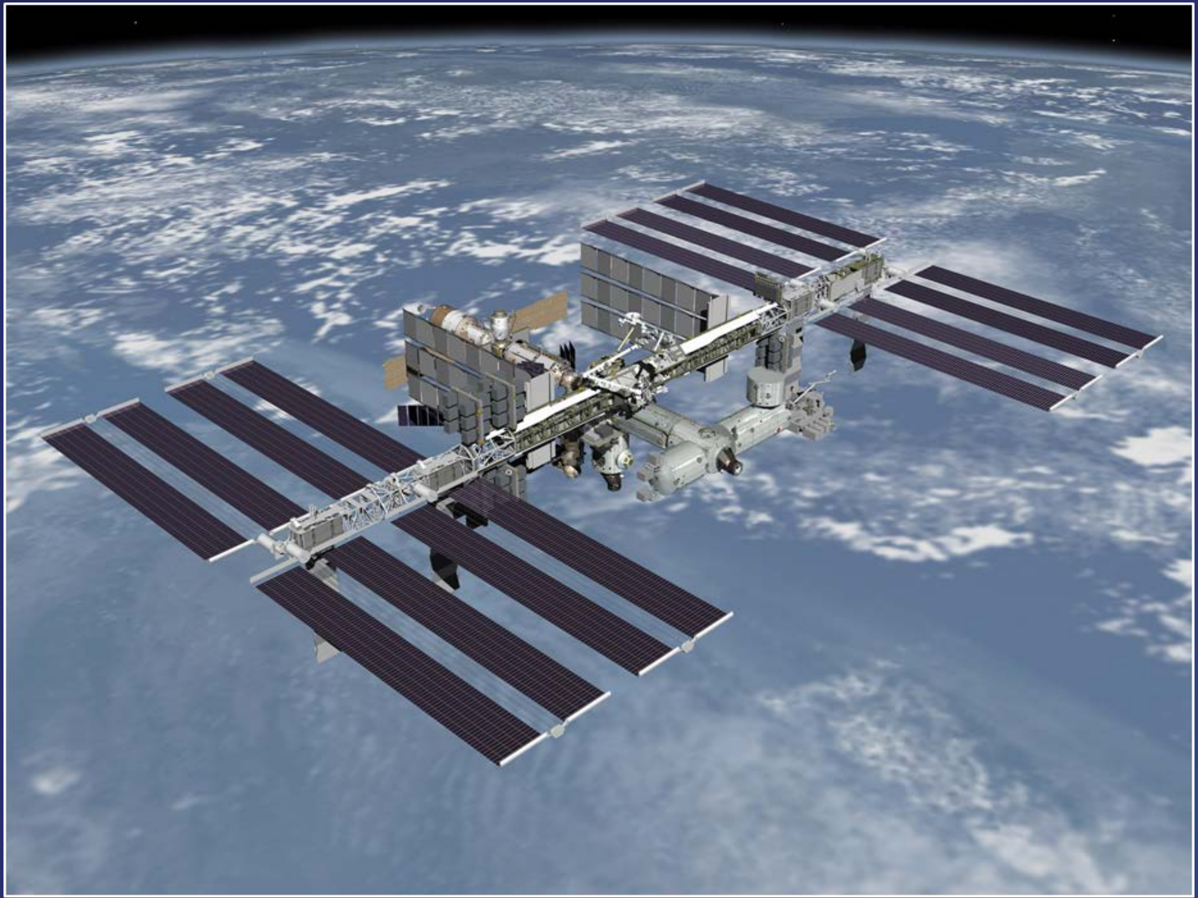
Heliophisics and Astrophysics Missions
- Altitude: 350-150,000 km
- Inclination: 20-35°
- Latency: Near Real Time
- Orbit Period: 91.5 min

Launch Vehicles
- Altitude: Varies
- Latency: Real time
- Speed: 7.9 km/sec

User receive support from all SCaN Networks with seamless handovers

Global Coverage and Low Latency

- Human spaceflight
  - International Space Station



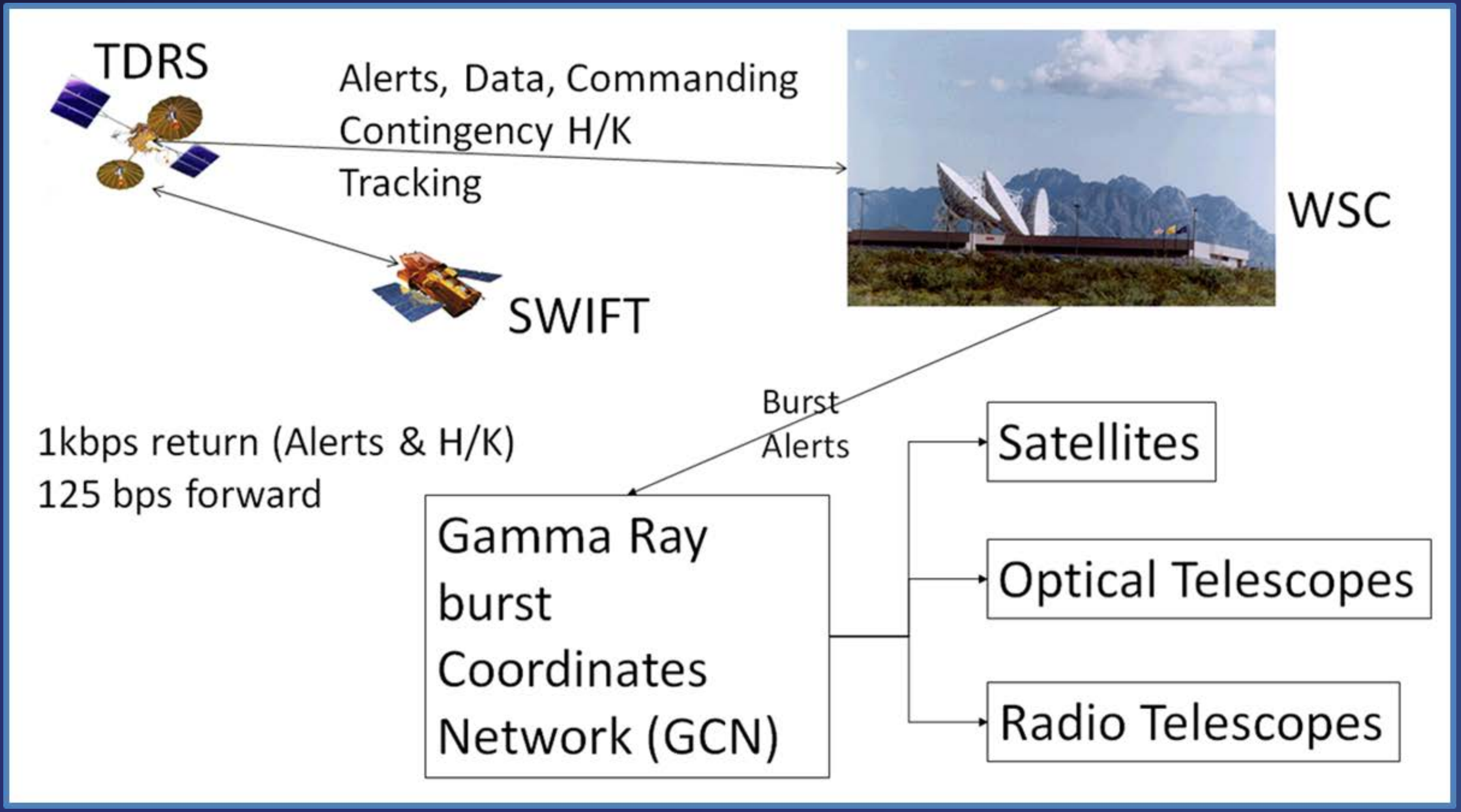
High-Reliability Communications

Hubble Space Telescope

SmallSat Conference, Utah, 2018

Low Latency/Fast Response

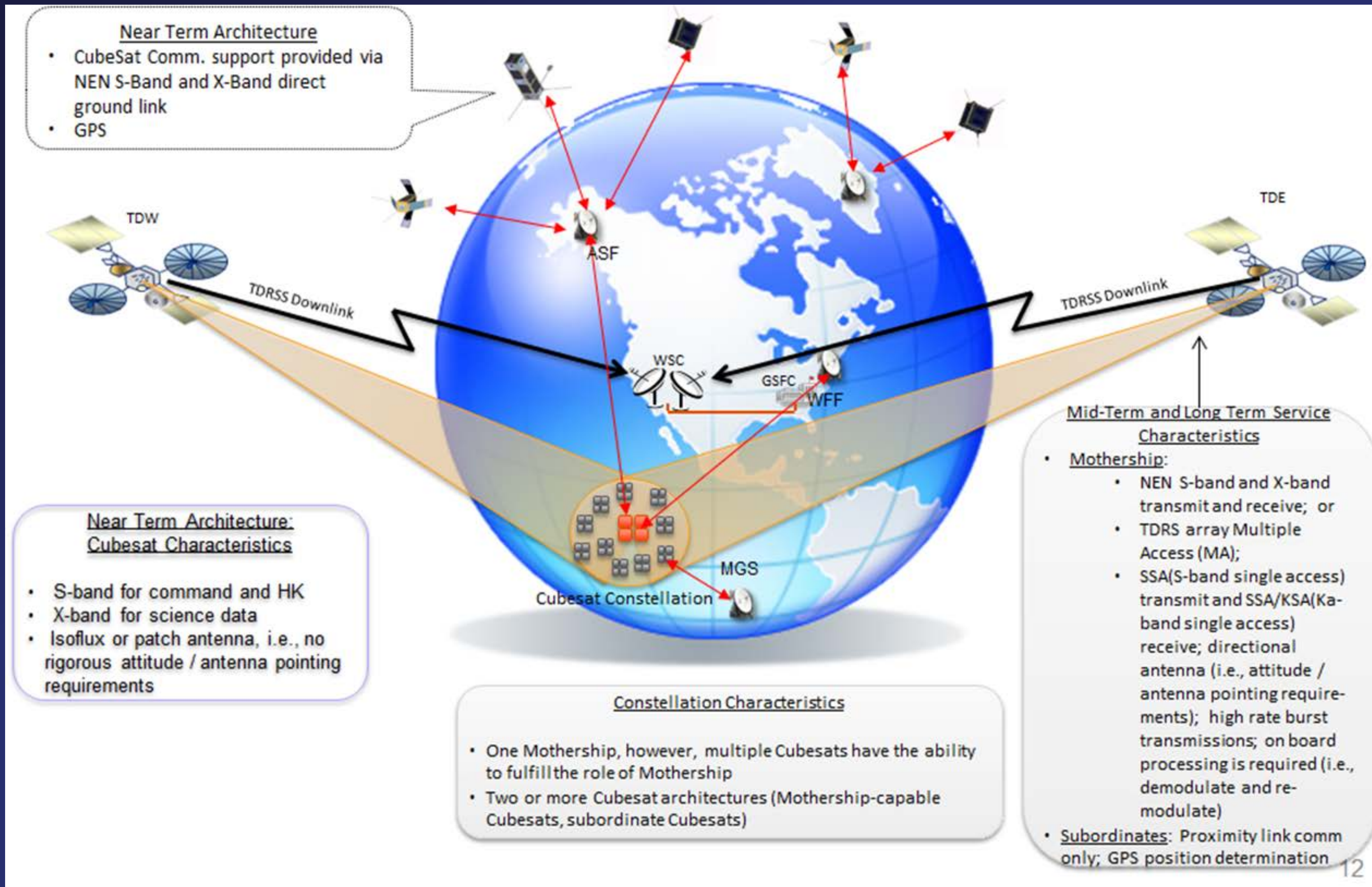
Swift



What Can TDRS Provide for CubeSat/SmallSat?

- TDRS 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.
- TDRS 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 viewing a CubeSat.
- TDRS DAS provide automatic data logging with user data file retrieval on demand.
  - User's control center would not need to be online 24 hours a day.

TDRS Management of CubeSat/SmallSat Constellations



SmallSat Conference, Utah, 2018

Link Scenario Challenges for CubeSat to TDRS Communications

Effective Isotropic Radiated Power (EIRP)

$$\boldsymbol{EIRP = P_{antenna} + P_{SSPA}}$$

For link distance (37,000 km, 1 kbps):

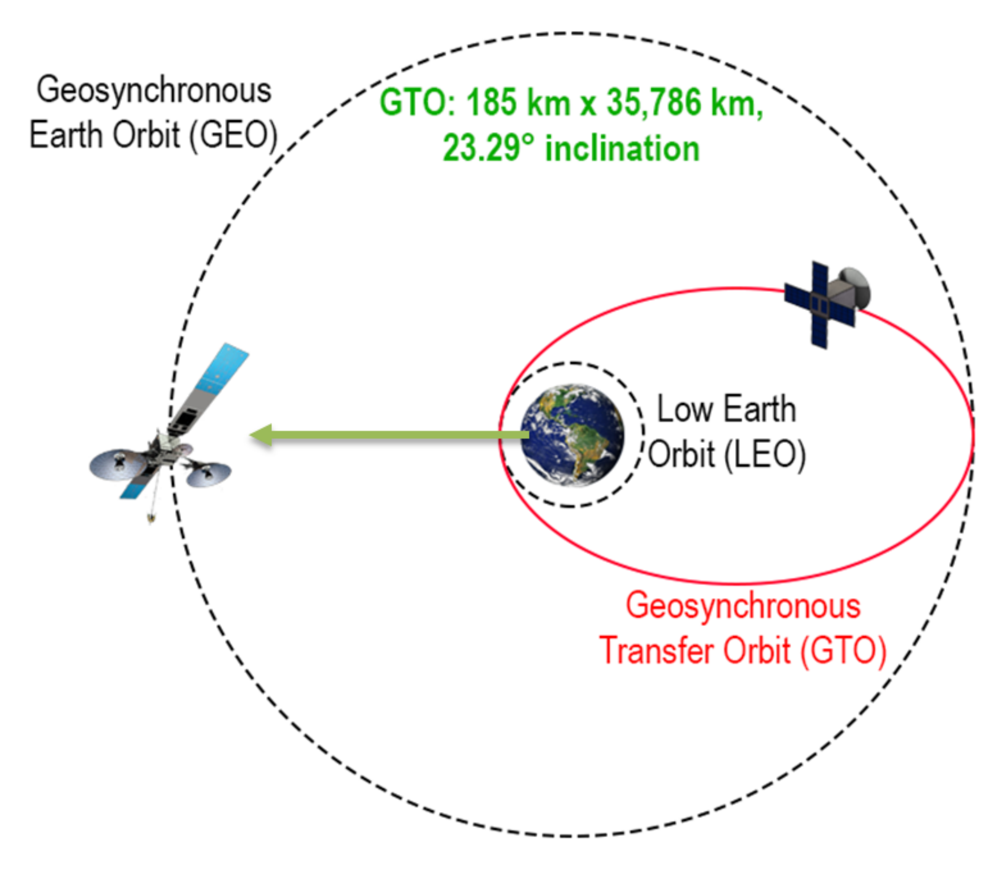
$$EIRP_{min} = P_{r_{min}} + loss = \mathbf{4.1\ dB}$$

Traditional CubeSat (patch antenna, η_{SSPA}=20%):

$$EIRP = 0\ dBi + 0\ dBW = \mathbf{0\ dB}$$

For higher data rate (150 kbps):

$$EIRP_{min} = \mathbf{25.8\ dB}$$



Sample Cubesat Link Budget to Connect with TDRS from LEO

Table 1. CubeSat-SN Link Summary Table

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	Rate ½ Convolutional Coding with Reed Solomon Coding	2.0 dBW	0.4dB
2nd/3rd generation TDRS MA Return	1.139 kbps	1.303 ksps	2.606 ksps			1.0dB
SSA Return	6.914 kbps	7.906 ksps	15.812 ksps			

Link Comparison

Links	Info Rate	Modu-lation	Coding	User EIRP	Link Margin
S-band Downlink via NASA 11.3-m WPS	1.3 kbps	BPSK	Rate 7/8 LDPC	-24.7 dBW	1.0 dB
X-band Downlink via NASA 11.3-m WPS At 10° Elevation Angle and 99% Rain Availability	250 kbps	BPSK	Rate 7/8 LDPC	0.35 dBW	1.0 dB
UHF Downlink via 18-3-m at Wallops	1.3 kbps	BPSK	Rate 7/8 LDPC	-27 dBW	1.0 dB

Notes:

1. The downlink margin is related to a BER of 10^{-5} at the output of the LDPC decoder.
2. The required S/C EIRP listed on this table includes pointing loss (if applicable).
3. Margin is relative to required BER for each scenario and does NOT include any required performance margin.
4. The minimum supporting data rate at 11.3-m WPS for BPSK modulation is 250 kbps.

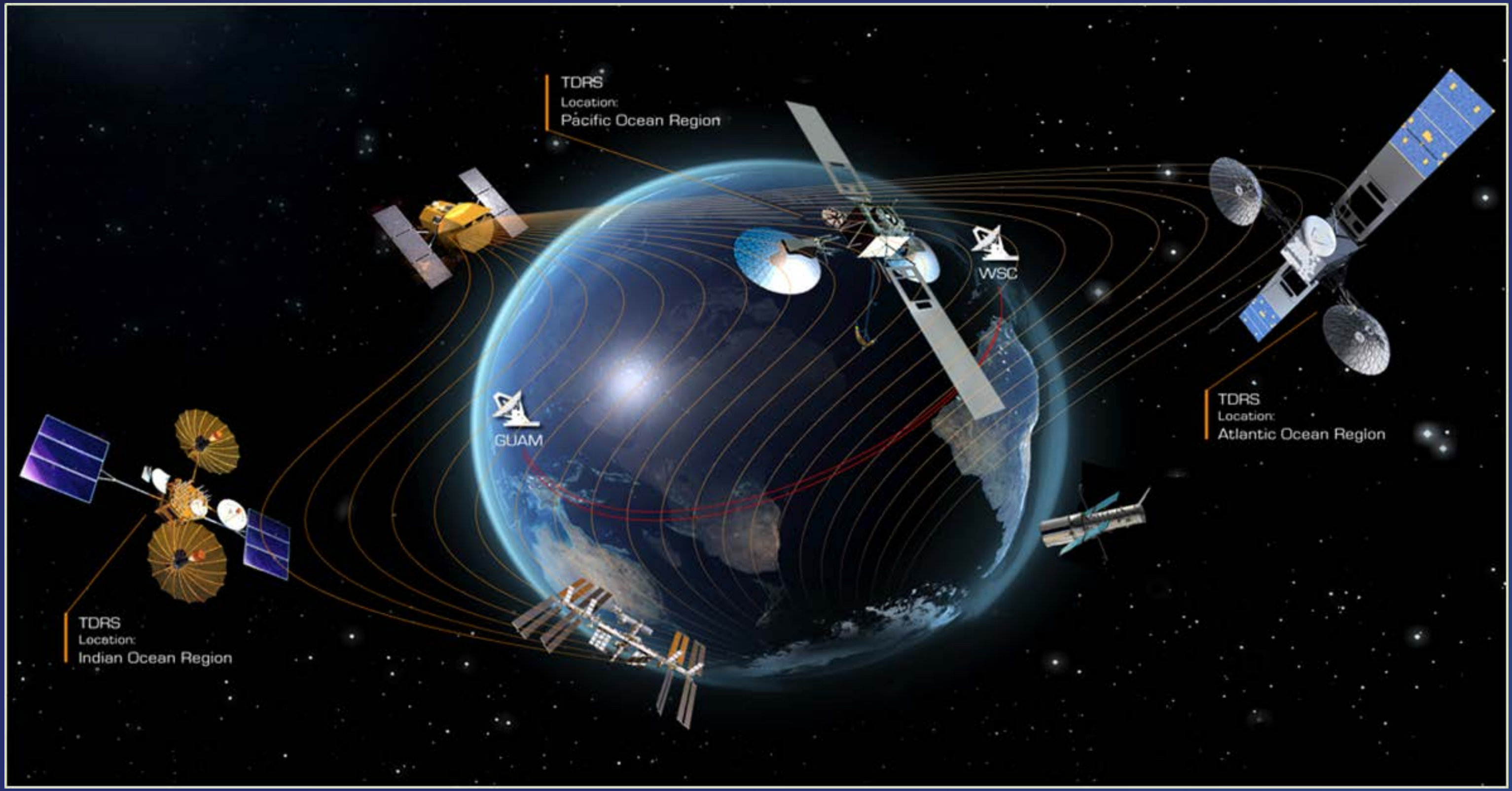
Link C	Info Rate	Symbol Rate (after RS)	Symbol Rate (after encoding)	Coding	Modu-lation	S/C EIRP	Link Margin
MA Return (PFOV; DG1 Mode 2)	1.3 kbps	1.5 ksps	3.0 ksps	Rate ½ Conv. & RS	SQPN	-1.6 dBW	1.0 dB
SMA Return (PFOV; DG1 Mode 2)						-3.0 dBW	1.0 dB

Notes:

1. For Rate ½ Conv and RS MA/SMA return, the link margin is related to BER of 10-5 @ Viterbi decoder. The SN Gateway can perform RS decoding; however, the SN requires 10-5 at Viterbi decoder, which will produce a BER much better than 10-5 at RS decoder.
2. The required S/C EIRP listed on this table includes pointing loss (if applicable).
3. Margin is relative to required BER for each scenario and does NOT include any required performance margin.

Technology Development

- A number of activities are ongoing all over GSFC.
- Planning an operational mission called RadSat to provide a roadmap for CubeSat missions to use TDRS.



SmallSat Conference, Utah, 2018

U of Florida/Goddard/KSC RadSat

Mission Concept combines three elements

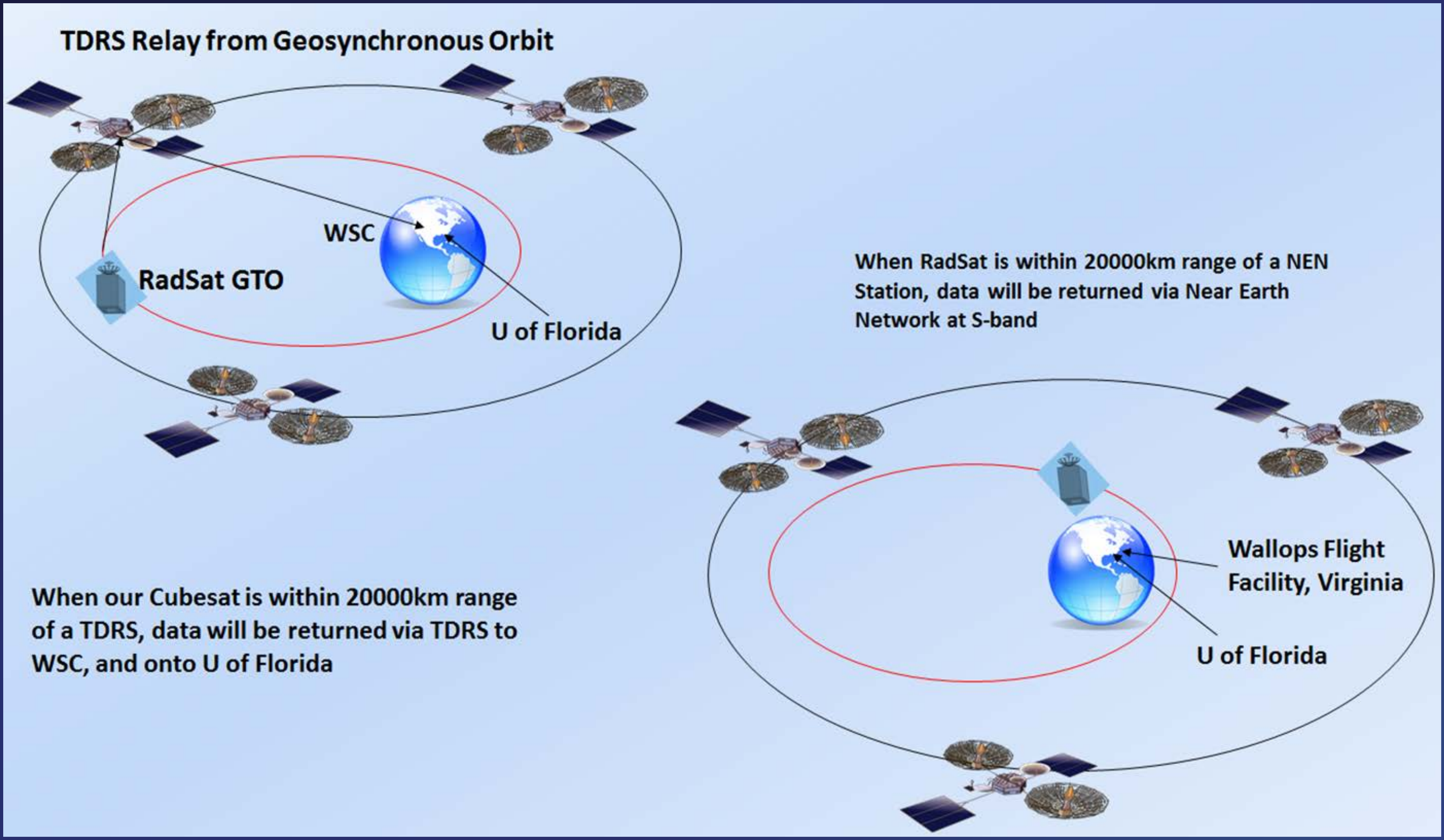
- University of Florida 12U Cubesat with two experiments
  - U of Florida (MgGd thermal neutron absorption)
    - Improving radiation shielding for astronauts and airline crews.
  - GSFC (SEGR lifetime reliability)
    - Improving data on power MOSFET reliability in actual space environment.
- Communications via S-band through TDRS and NEN.
- Fly in a high-radiation environment guaranteed to cause eventual failure of spacecraft and payload electronics.
  - Key is to retrieve as much accurately time-stamped data as possible before failure. De-orbit spacecraft after both payload experiments have failed.
  - Keep spacecraft electronics as simple as possible. Limit on-board storage of payload data that would be lost if not transmitted to the ground.

Key external partners

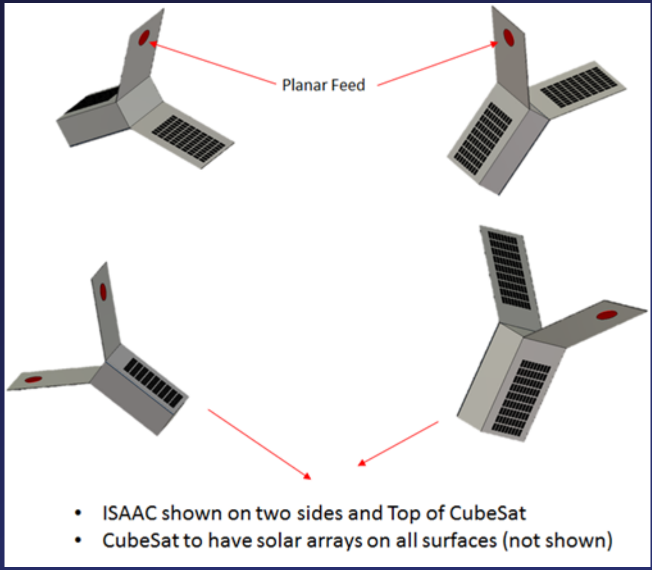
- University of Florida (PI, Deployable Antenna)*
- University of Colorado (Antenna Design, High Efficiency SSPA design*
- University of Maryland Baltimore County (Mechanical and Structures)*
- Morgan State University, Wichita State, MIT (Instrument development)*
- Utah State University (ISAAC)
- KSC (Integration and Test)

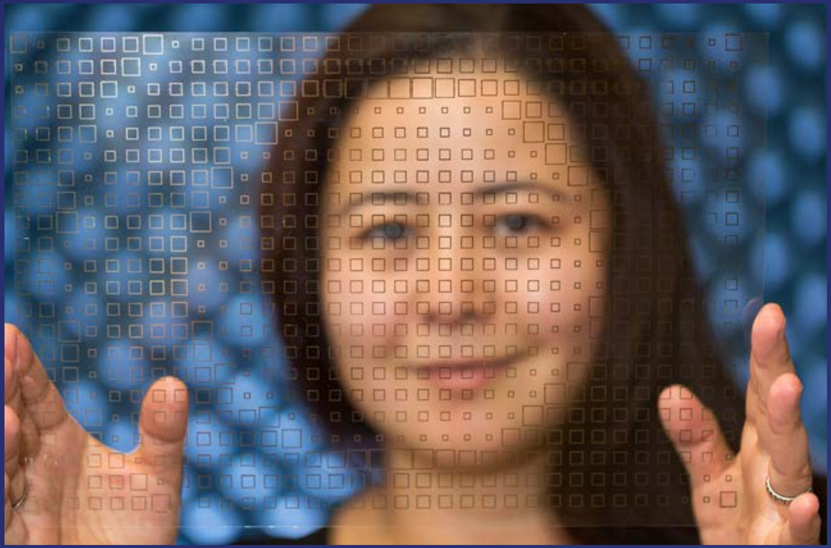
*Provided Interns

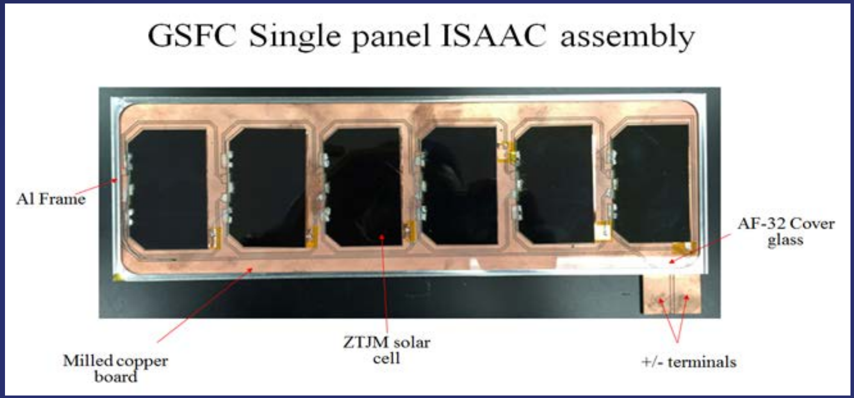
RadSat Communications Concept



Integrated Solar Array Antenna for CubeSats (ISAAC) – Utah State University/Goddard







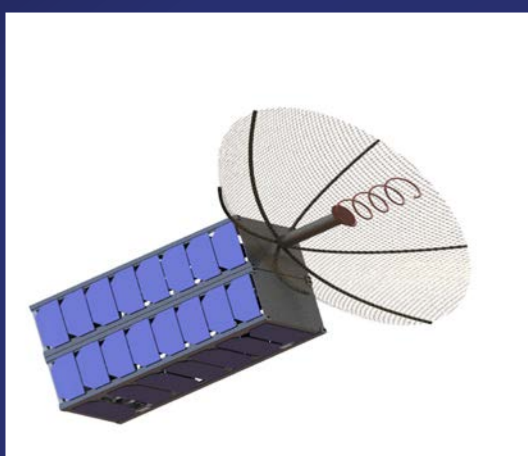
Demonstrated +22dBi gain at X-band. Goddard 9is already building prototypes with Utah State. Can be used in combination with other antennas to augment the TDRS return link; S-band version will have approximately +12dBi gain.

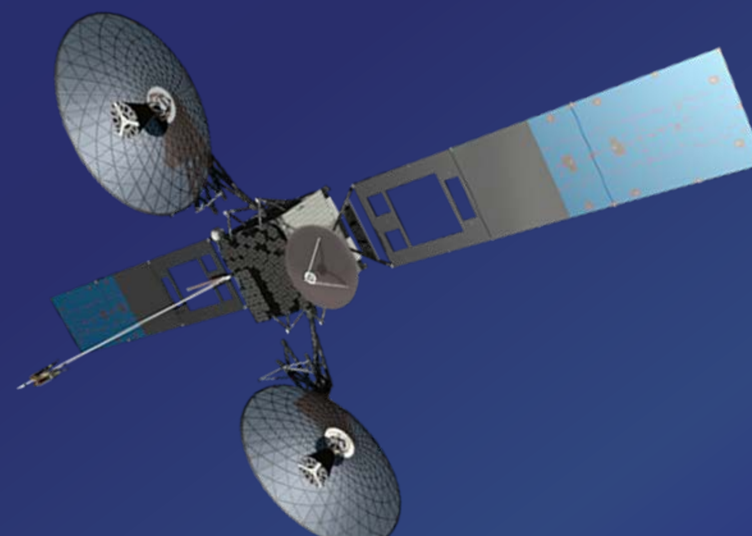
Goal to Enhance Existing CubeSat Comm Capabilities to Close Link with TDRS

	Existing Transmitter	Proposed Transmitter
Transmit Power	3 dBW	7 dBW
Antenna Gain	0 dBi	18 dBi
EIRP	**3 dBi**	**25 dBi**

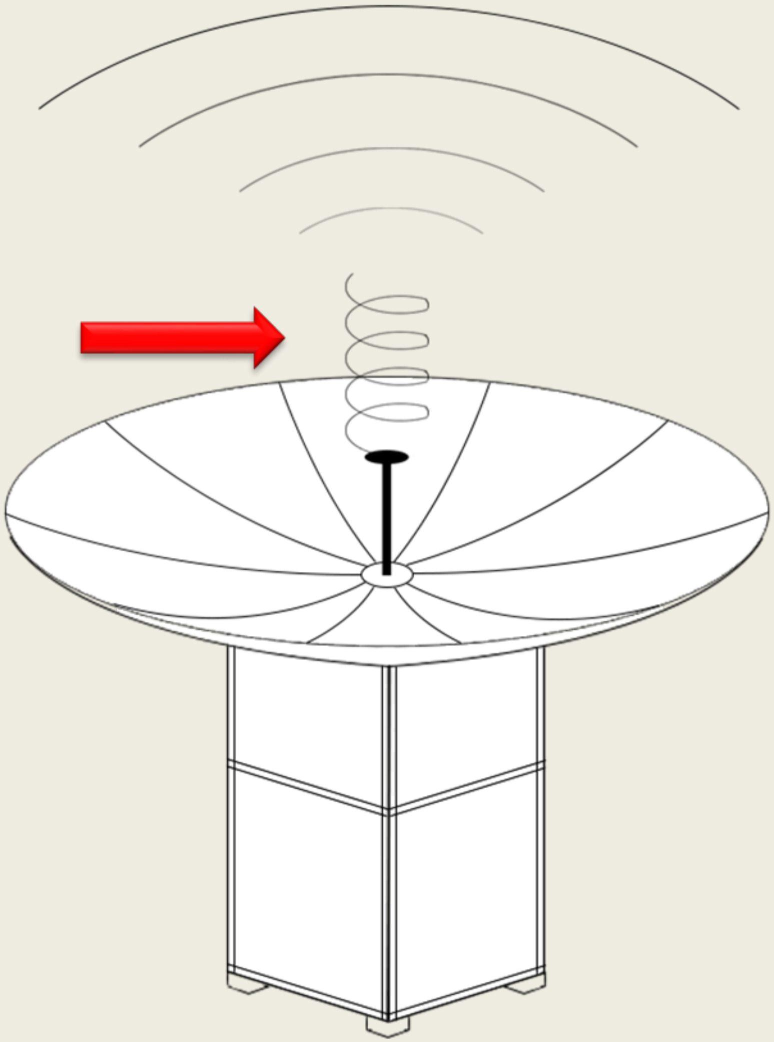
37,000 km

	Existing Transmitter	Proposed Transmitter
Prec @ TDRS	-190 dBW	**-168 dBW**
C/N	-43 dB	**-21 dB**
Eb/N0 @ demod	9.7 dB	**31.7 dB**
Data Rate	1.2 kbps	**191 kbps**





High-Gain Parabolic Antenna



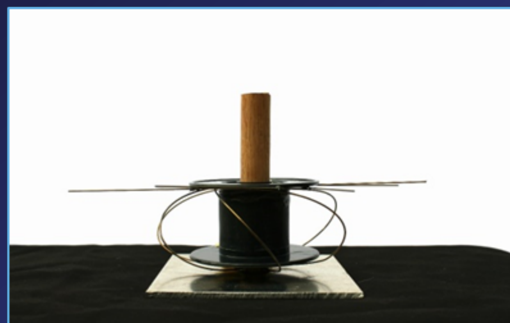
- Gain: >15 dBi
- Circular Polarization
  - Axial Ratio: < 1.5 dB over 3-dB bandwidth
- RF Bandwidth: 6 MHz
- Input impedance of 50Ω
- Parabolic reflector
  - Max Achievable Gain:

$$\left(\frac{\pi D}{\lambda}\right)^2 = 19.6\ dBi$$

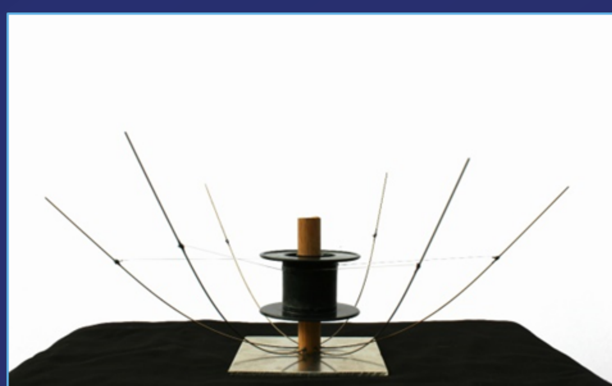
Reflector Structure Prototypes

Pseudoelastic NiTi Prototype

Stowed



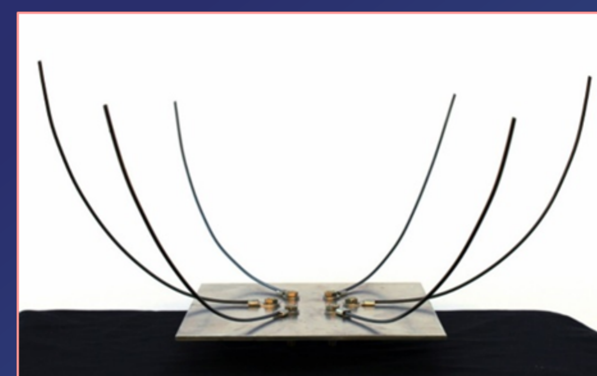
Deployed



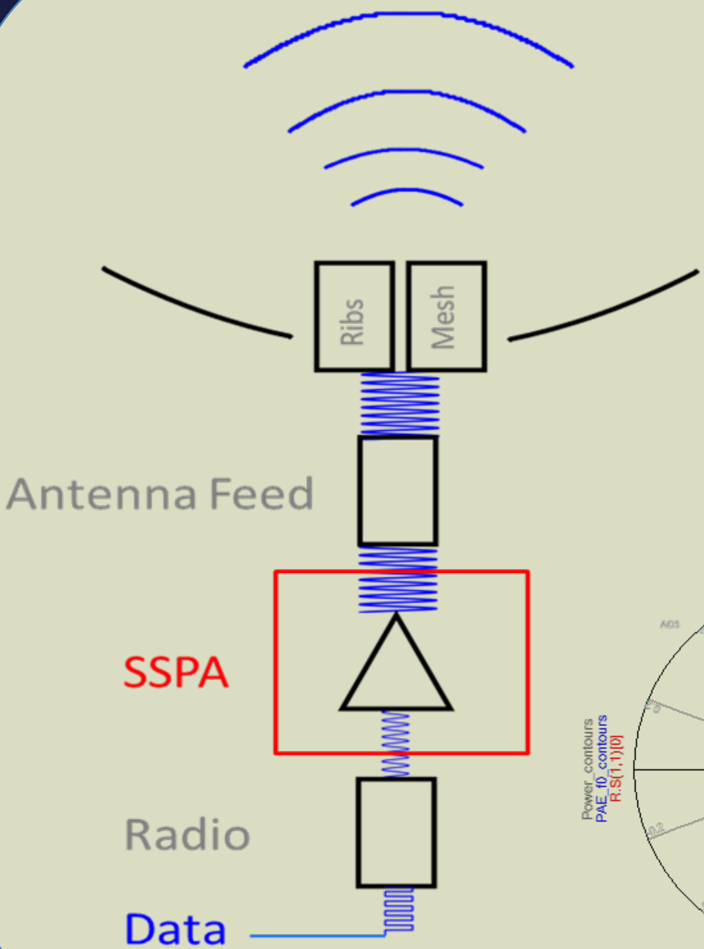
Shape Memory Effect NiTi Prototype

Stowed

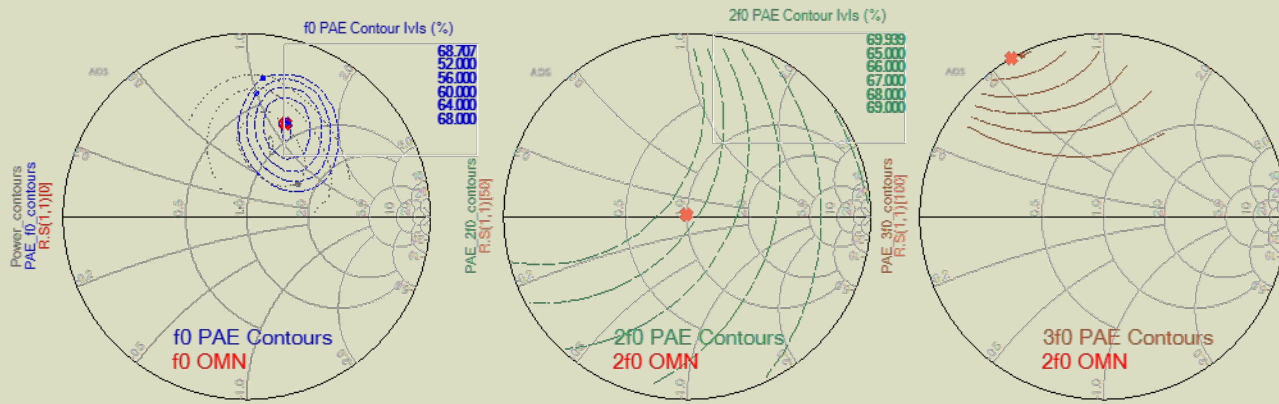
Deployed



High-Efficient Solid-State Power Amplifier (SSPA)

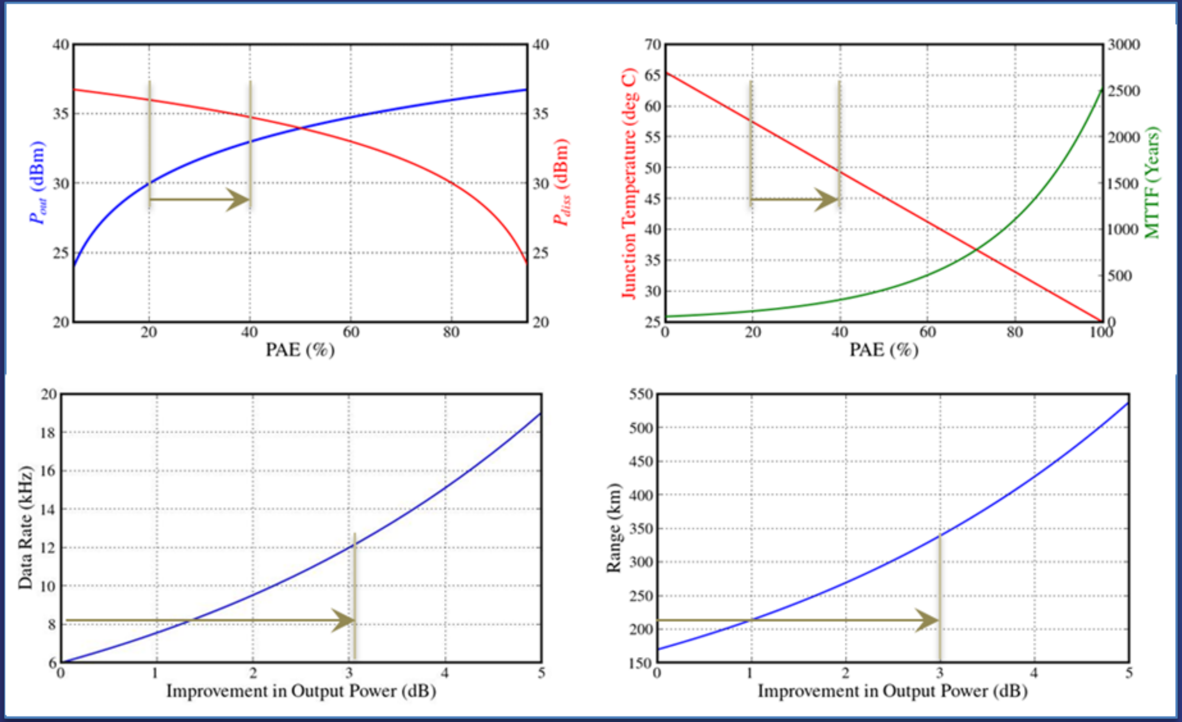


- Convert low-power S-band signal to high power.
- Limited DC power.
- Maximize RF output power.



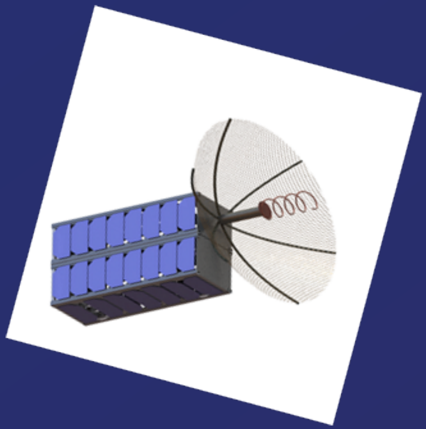
High-Efficiency SSPA

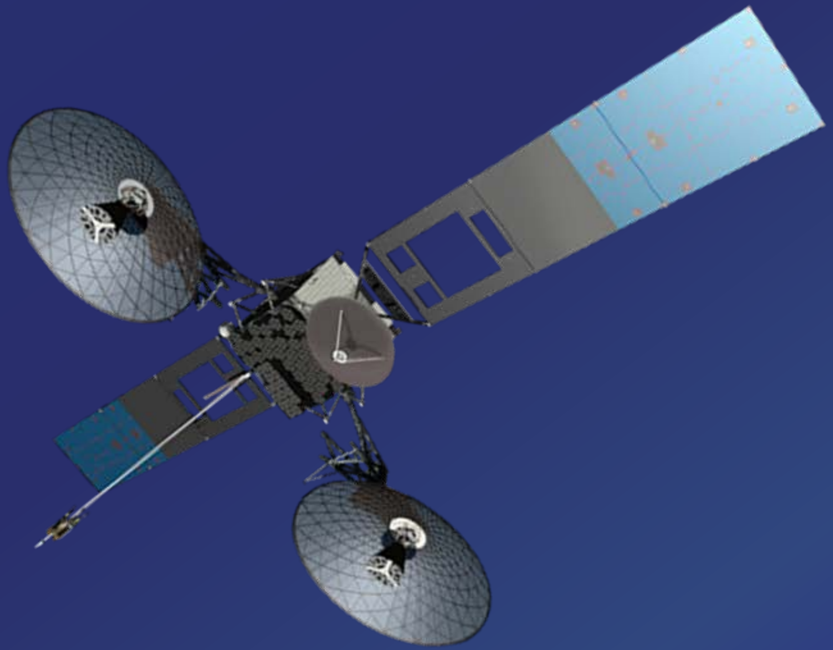
- 75-90% of satellite DC power is consumed by transmitter
- Standard SSPA Efficiency: 10-20%
- A **20% increase** in efficiency yields **twice the output power**
  - 50% less dissipated power in heat
  - 100% longer lifetime
  - 100% grater data rate
  - 100% increase in range



Future Work for RADSAT

- Planned launch date: 2021
- Finalize designs
- Further simulations
- Manufacture and prototype
- Environmental testing





RadSat Provides a Low-Cost Laser Ranging Opportunity

Satellite Laser Ranging on a CubeSat Platform for Geostationary Transfer Orbits

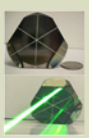
Marek Subernat
Massachusetts Institute of Technology *Mentor: Mihir Patel (GSFC-5660)*

Abstract

Satellite Laser Ranging (SLR) is the measurement of ultrashort laser pulses between a ground station and a retro-reflector equipped satellite in order to observe orbit ranges and velocities with millimeter precision. When applied to CubeSats, the limiting factor is often weight or size. At low earth orbit, one retro reflector is sufficient to receive a strong return signal. At higher altitude orbits, more mirrors are required to receive a sufficient signal .usually arranged in an array. Using the laser ranging link equation, the extent of these limits can be observed, which proves especially useful when applying this method to highly eccentric orbits.

SLR Hardware

SLR hardware consists of a laser sent from a ground station and retro-reflectors. The ground station sends a 532nm (green) laser at the satellite's retroreflectors in 1-100mJ pulses (<500ps). The ground station telescope receives the reflected beam and outputs the travel time. The strength of the signal is measured in photons returned per pulse. Accounting for refraction, atmospheric interference, and beam divergence, the travel time gives a precise measure of distance. The station can also track the satellite and get change in velocity over time. The retro-reflective mirrors are usually 3 orthogonally aligned or corner cube mirrors that reflect the x, y, and z components of a beam. When multiple cube corners are used in an array, the refelected beams will interfere sacrificing accuracy for signal strength and range. SLR ground stations are spread across the globe and are managed by the International Laser Ranging Service. SLR stations maintain air traffic avoidance systems and are also limited in pointing elevation angle from 90-20°.



Retro-reflective mirror

Goddard SLR ground station

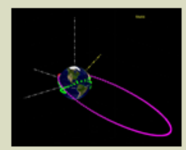
RadSat SLR Applications

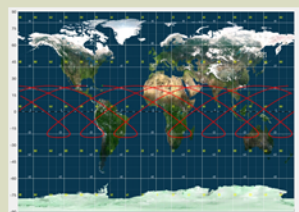
RadSat is a 12U CubeSat that will utilize SLR and maintain a Geostationary Transfer Orbit (GTO). Its main mission is to test a radiation resistant alloy in a high radiation environment while demonstrating communications with TDRS and NEN. The nadir pointing face will be covered in retroreflectors for SLR. Using SLR, the highly eccentric orbit, a first for a CubeSat, can be precisely studied. RadSat will be equipped with 16 or more retro reflectors allowing for SLR ranging at various altitudes through its orbit.

SLR Challenges for GTO

RadSat's orbit presents the challenges of long range SLR, fast short range SLR, and the lack of SLR stations in the southern hemisphere. At perigee, due to its low altitude, a ground station would have to be within a 500km of the satellite's ground path due to elevation angle restrictions. At apogee, multiple retro-reflectors would be required for a return signal. From analysis of the ground track (below), Riyadh has the only station usable at perigee. The South Africa and South American SLR stations can be used towards apogee. Due to the altitude extremes of the orbit, the altitudes between 400-22000km of altitude, standard altitudes for SLR, are best suited for ranging.

Semimajor Axis (km)	[illegible]
Eccentricity	[illegible]
Inclination (degrees)	[illegible]
RAAN (degrees)	[illegible]
Argument of Perigee (degrees)	[illegible]
True Anomaly (degrees)	[illegible]
Altitude at Perigee (km)	[illegible]
Altitude at Apogee (km)	[illegible]
Velocity at Perigee (km/s)	[illegible]
Velocity at Apogee (km/s)	[illegible]
Orbital Period (hr)	[illegible]





Satellite Ground Track

SLR Ground Station Locations

SLR Link Equation

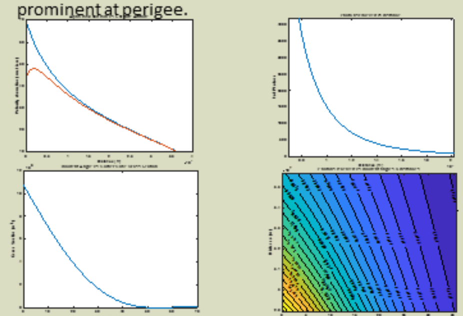
$$n_p = \frac{E_t \lambda}{hc} \eta_t \frac{G_T}{4\pi d^2} \frac{\sigma}{4\pi d^2} A_r \eta_r \eta_q T_a^2 T_c^2.$$

The SLR link equation measures the strength of the link in photons returned. To the right is a table of all the variables going into this equation. At 185km, the number of photons received is very large. The more interesting case occurs when considering apogee where the number of photons received is 9. The link also scales with incident angle - the angle at which the beam meets the RR-mirror. Past 30°, the loss increases immensely.

Variable	Definition	Example for SLR station in South Africa and 16 RR
σ	Optical Cross-Section	[illegible]
G_T	Transmitter Gain	[illegible]
E_t	Laser Energy (mJ)	[illegible]
λ	Wavelength (nm)	[illegible]
h	Planck's Constant	[illegible]
c	Speed of Light	[illegible]
η_t	Transmitter Efficiency	[illegible]
d	Range to Satellite (km)	[illegible]
A_r	Area of Transmitter (m^2)	[illegible]
η_r	Receiver Efficiency	[illegible]
η_q	Quantum Efficiency	[illegible]
T_a	Atmospheric transmission	[illegible]
T_c	Cloud Transmission	1
n_p	Number of Photons	[illegible]

Effects of Velocity Aberration

Due to the relative velocity, it cannot be assumed that a laser will reflect directly back at the ground station. The graph below displays the range of the deflection vs. altitude. The red is alpha min, corresponding to the effect at 20° elevation and the blue line is alpha max, corresponding to 90° elevation. The effect scales linearly with velocity and is therefore most prominent at perigee.



Future Work and Challenges

RadSat will have to take into account the trade off of signal strength and payload weight, attitude control during ranging, and coordination with ground stations in order to make SLR a possibility. RadSat will utilize SLR and gather data in hope of demonstrating the effectiveness of SLR for future CubeSat projects.

SmallSat Conference, Utah, 2018

SmallSat Conference, Utah, 2018

Optical Ground Station

The Lunar Laser Communications Demonstration Ground Terminal (LLGT) was built for supporting a short mission.

Two ground terminals:

- The LLGT at the White Sands Complex supported uplink and downlink: 622 Mbps downlink rates achieved from LADEE in orbit around the Moon. (~0.5W optical transmit power from the space terminal.)
  - LLGT had four 40-cm.-diameter receive telescopes and four 15-cm. transmit telescopes, each transmitting a 10-Watt uplink signal.
- The OCTL ground terminal supported downlink only: Transmit beacon only; no uplink communications.
  - OCTL used a single 1-meter telescope for receive and beacon transmission.

LCRD Ground Terminals

- The Laser Communications Relay Demonstration (LCRD) allows relay of data between ground terminals at 1 Gbps data rates via a relay terminal at geosynchronous orbit.
- Due to the DPSK format, the ground terminals require adaptive optics.
- Ground terminals will be located at Haleakala and at the OCTL.
- With the addition of the ILLUMA terminal, LCRD will also relay data from the ISS to ground.

The COTS Ground Terminal

- Cost for telescope, mount and satellite-tracking software: ~$40,000
- Goal was to demonstrate that a COTS telescope and mount could be used for GEO and LEO laser comm.
- Demonstrated that the mount was able to track GEO and LEO satellites.
- $230,000 set aside for construction of dome and shelter for future work.
- The telescope can reliably track LEO satellites provided we have up-to-date TLEs.
- For LEO satellites, there is a large, effective keyhole: the satellite must be located more than 30° from Polaris. Otherwise, the angular rates will be too high for the mount motors.
- Some slow drift occurs of LEO satellites on the camera sensor.
- Long setup time – eventually need to move to dome and permanent pier.
- The goal is to develop a low-cost transportable ground terminal that can quickly be co-located with the end user.

SmallSat Conference, Utah, 2018

Testing New Receiver Technologies

- Super-conducting nanowire detectors require that the light be guided by single, or few-mode, optical fibers, but coupling the received light from larger telescopes into these small-core fibers is difficult without adaptive optics. New technologies used in astronomy offer a potential solution for efficiently coupling the signal to the small nanowire detectors **without costly and complex adaptive optics**
- A photonic lantern is essentially a multimode fiber large in diameter that smoothly transitions to a collection of single-mode fibers.
- Different spatial modes of the multimode section are each coupled into a separate single-mode fiber with low loss.
- Among other things, photonic lanterns have found use in astronomy.
- The team is optimistic that the large blur spot of a telescope can be coupled into the multimode input of the lantern.
- This technology could directly benefit the ground terminal, allowing the use of a larger-aperture receiver WITHOUT resorting to adaptive optics.

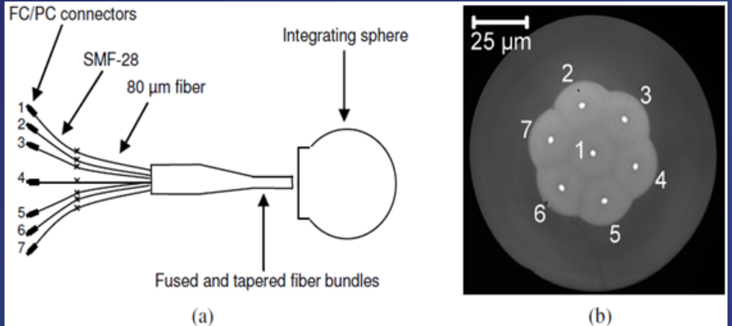


Fig. 3. (a) Illustration of setup used to measure SM to MM loss. (b) Microscope picture of the end-facet of the MM fiber. The original SM fibers are identified in the MM fiber and marked as seen in the image.

SmallSat Conference, Utah, 2018

Future Optical Work

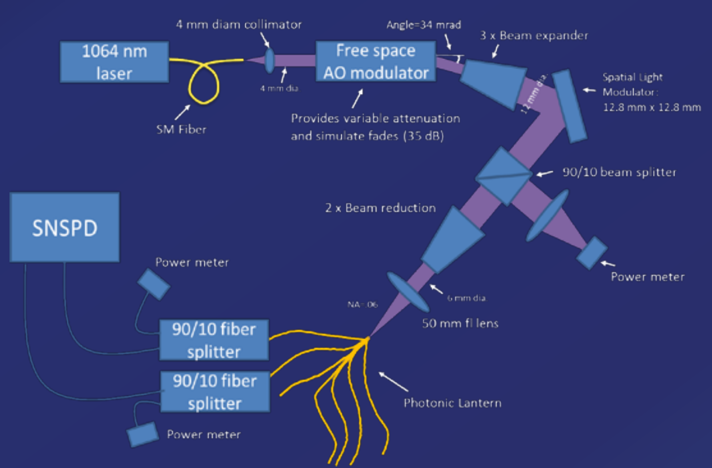
OCSD Update Photonic Lantern

Accomplishments:

- Designed 7:1 single-mode fiber lantern and purchased materials.
- Designed and purchased components for laboratory testing of lanterns with simulated atmospheric effects.
- Received spatial light modulator.

Plans:

- April: Build SMF photonic lantern.
- May: Build laboratory setup; receive 2 FMF coupled single-photon detectors.
- June and July: Test photonic lantern efficiency in lab.

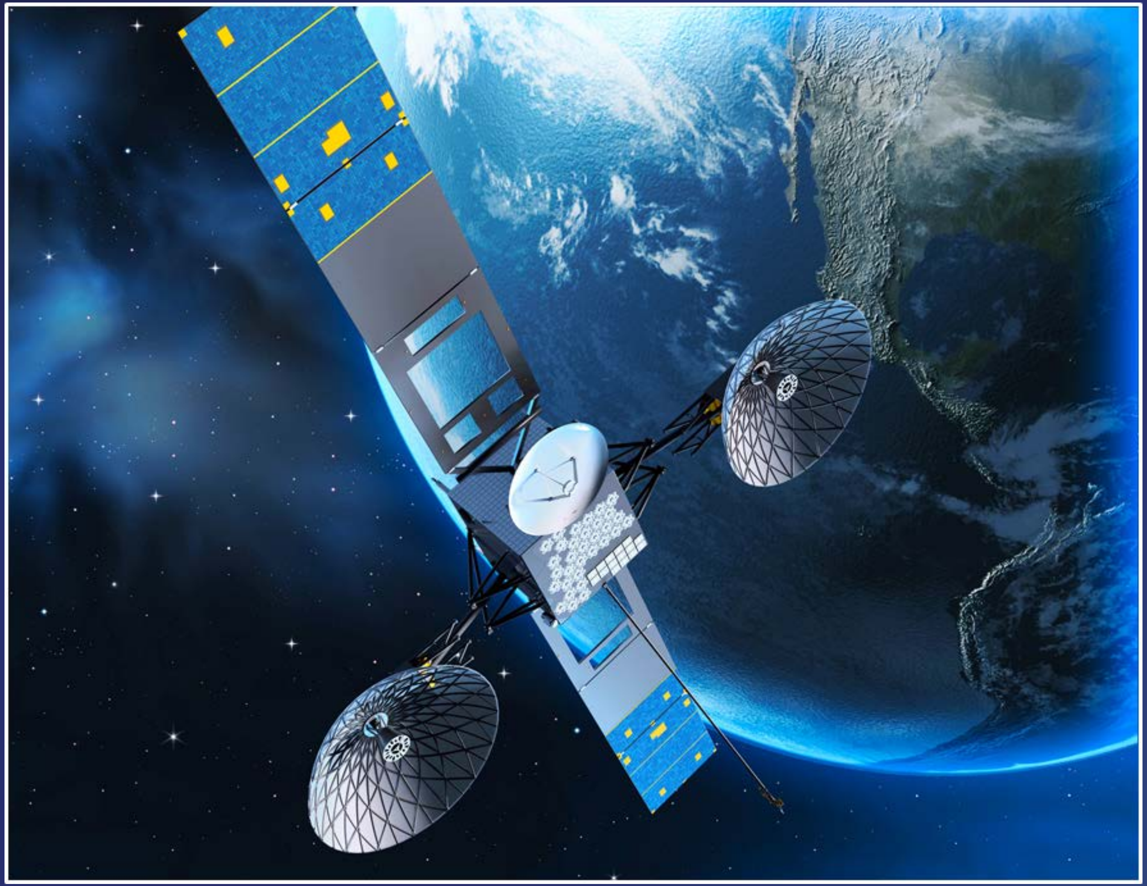


Sketch of lab test layout

GRC team members visited GGAO site

Conclusions

NASA/GSFC continues to work toward the goal of extending TDRS services to the CubeSat/SmallSat community.



Acronym List

- DAS: Demand Access System
- DSN: Deep Space Network
- EIRP: Effective Isotropic Radiated Power
- GEO: Geosynchronous Orbit
- GSFC: Goddard Space Flight Center
- GRGT: Guam Remote Ground Station
- ISAAC: Integrated Solar Array Antenna for CubeSats
- LCRD: Laser Communications Relay Demonstration
- LEO: Low Earth Orbit
- LLGT: Lunar Laser Communications Demonstration Ground Terminal
- NEN: Near Earth Network
- MA : Multiple Access
- SA: Single Access
- SN: Space Network
- SSPA: Solid-State Power Amplifier
- TDRS: Tracking and Data Relay Satellites
- WSC: White Sand Complex