Three Generations of Tracking and Data Relay Satellite (TDRS) Spacecraft

Boeing Customer Conference 2016

Ron Zaleski
TDRS Sustaining Engineering
NASA/Goddard Space Flight Center

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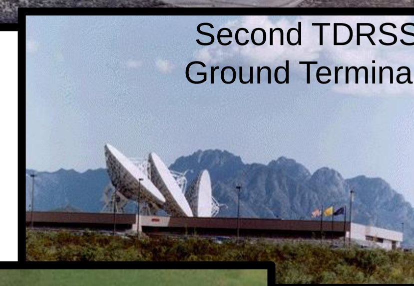
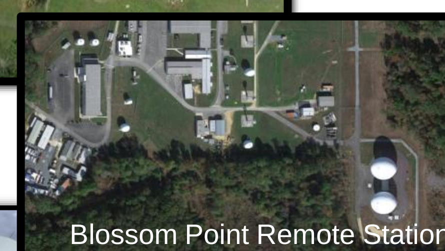
Space Network

The Space Network (SN) was established in the early 1980s to replace NASA's worldwide network of ground tracking stations.

- The Space Network is comprised of:
  - A constellation of geosynchronous (Earth orbiting) Tracking Data Relay Satellite (TDRS) satellites.
  - WSC with two co-located ground terminals located in New Mexico (WSGT and STGT).
  - There are remote extensions in Guam (GRS) and Blossom Point, MD (BPRS)
  - There is a contingency TT&C facility in Australia





Australian TDRSS Facility

Space Network Services Provided

- Telecommunications
  - Forward, Return or simultaneous Fwd/Rtn TDRS service
    - Multiple Access & Single Access services available.
- Tracking and Clock Calibration Services
  - Range
  - Doppler
  - Customer Time Transfer.
- Testing and analysis
  - TDRS End-to-End Test (EET) Services
  - SN Simulation Testing

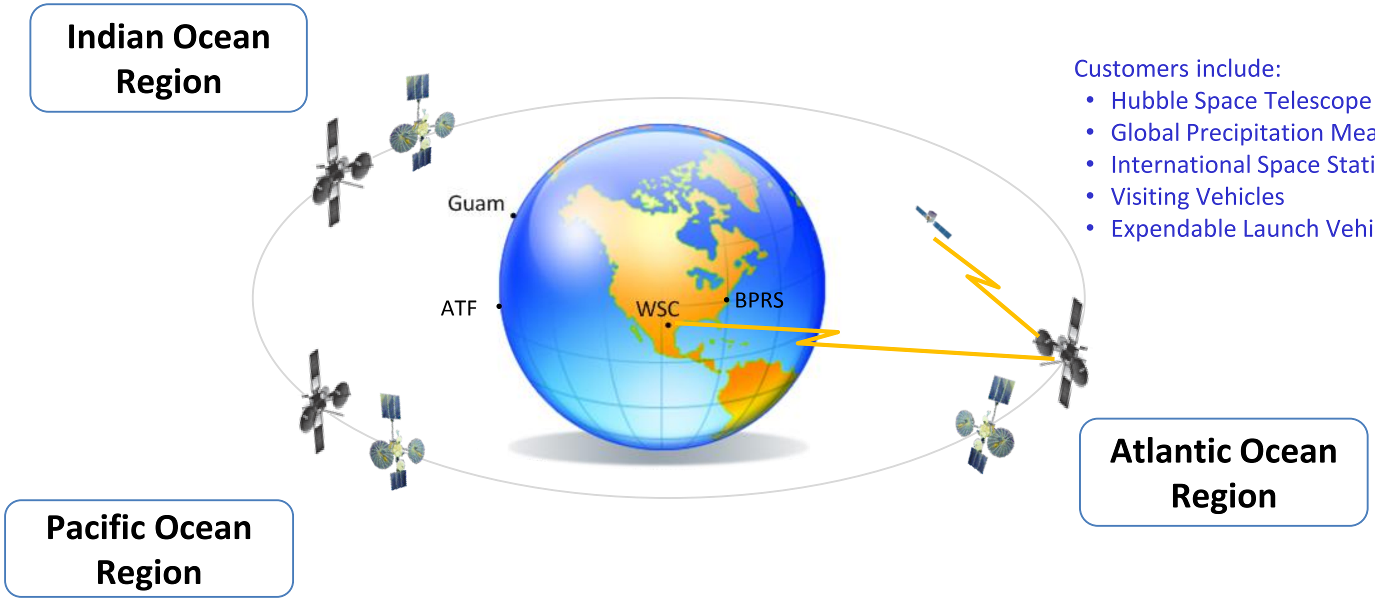
The Space Network Users' Guide (SNUG)

- Publically available guide to customer community for obtaining TDRS communication services.
  - Link is:

    http://esc.gsfc.nasa.gov/assets/files/450-SNUG.pdf

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.

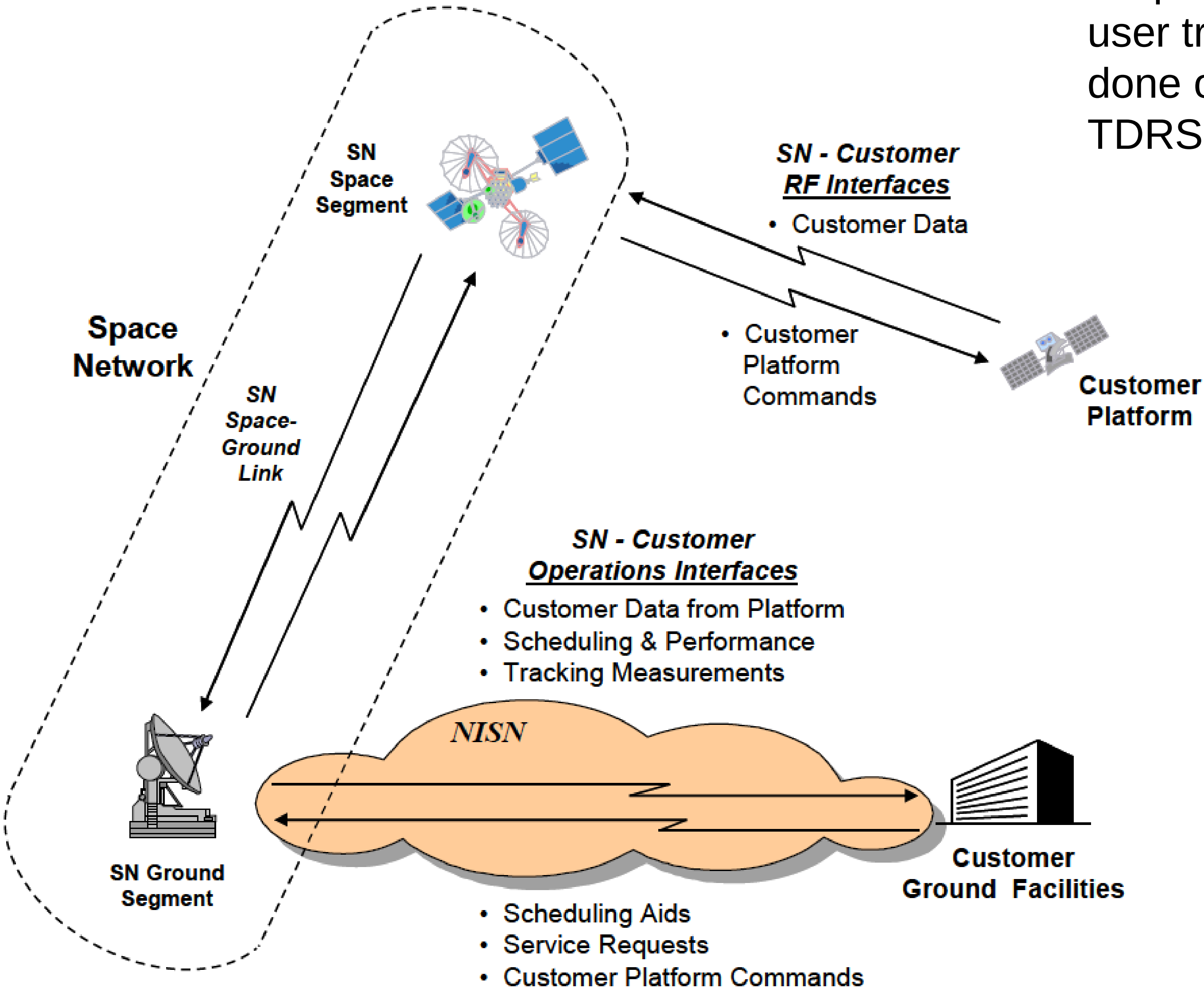


Customers include:

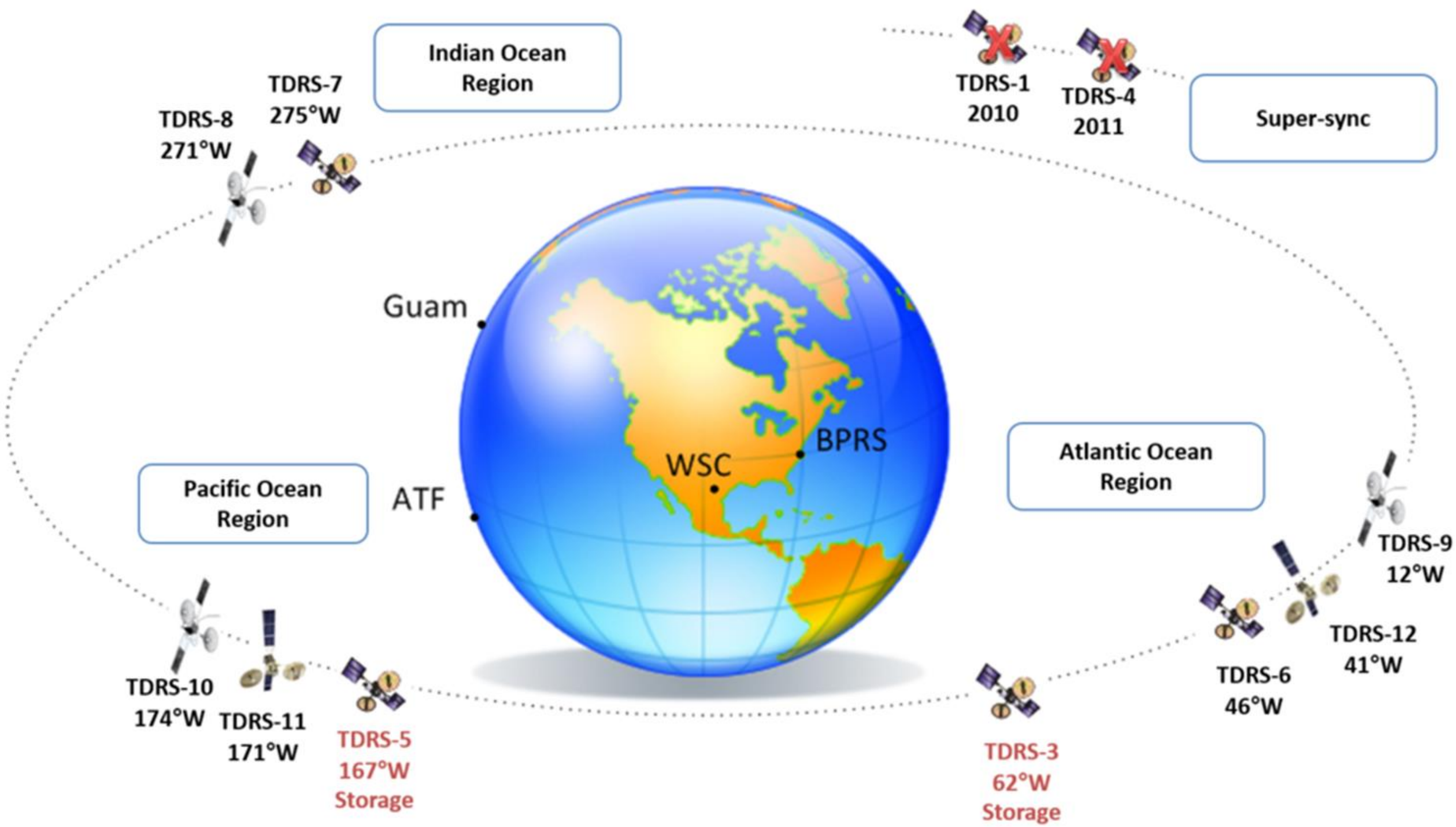
- Hubble Space Telescope (HST)
- Global Precipitation Measurement (GPM)
- International Space Station (ISS)
- Visiting Vehicles
- Expendable Launch Vehicles (ELV)

TDRS relay communications traffic between customer S/C and the ground terminal.

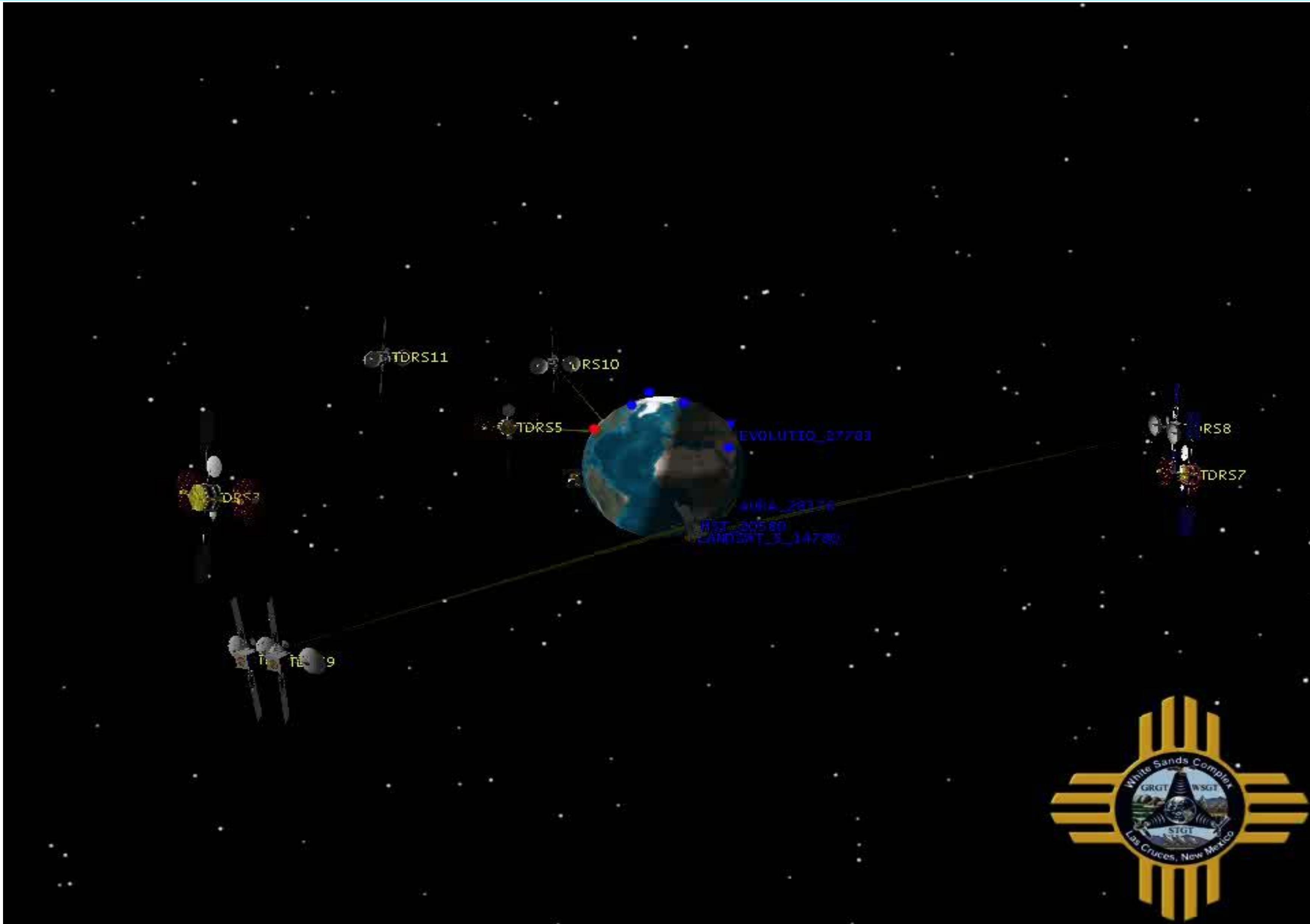
No processing of user traffic is done on-board TDRS



TDRS Constellation



Video of TDRS Support to Some Customers



TDRS Single Access (SA) Services

- For TDRS-3 through TDRS-7 (1^{st} Gen)
  - S-band, Ku-Band SA service is provided by two 15-foot-diameter graphite mesh antenna reflectors.
    - S-band data rates are up to 23.6 Mbps (Rate 7/8 LDPC; 8PSK) for return and 14 Mbps for forward data.
    - Ku-band data rates are up to 600 Mbps for return and 50 Mbps for forward data.
- For TDRS-8, 9 & 10 (2^{nd}Gen) & TDRS-11, 12 (3^{rd}Gen).
  - S-, Ku-, and Ka-Band SA service is provided by two pointable 15-foot-diameter graphite mesh antenna reflectors
    - S-band data rates are up to 23.6 Mbps (Rate 7/8 LDPC; 8PSK) for return and 14 Mbps for forward data.
    - Ku-band data rates are up to 600 Mbps (Rate 7/8 LDPC; 8PSK) for return and 50 Mbps for forward data.
    - Ka-band data rates are up to 600 Mbps (225 MHz Channel; Rate 7/8 LDPC; 8PSK) & 1200 Mbps (650 MHz Channel; Rate 7/8 LDPC; 8PSK) for return and 50 Mbps for forward data.

TDRS Multiple Access (MA) Services

- MA services through all generations of TDRS provide global coverage for S-Band Demand Access (access any time) Users and Scheduled Users.
  - return services are at same frequency (2287.5 MHz) and use code division multiple access to avoid interfering with each other.
- For TDRS-3 through TDRS-7 (1^{st} Gen).
  - MA return service is provided by an on-board 30 element phased array antenna.
  - Beam-forming equipment located in the ground station.
  - data rates are up to 525 Kbps (Rate 7/8 LDPC; SQPN) for return and 300 Kbps for forward data.
- For TDRS-8, 9 & 10 (2^{nd} Gen) & TDRS-11, 12 (3^{rd} Gen).
  - MA return service is provided by an array of 32 elements.
  - Beam-forming is done on-board the spacecraft.
  - data rates are up to 7 Mbps (Rate 7/8 LDPC; SQPSK) for return and 3 Mbps for forward data.

Support for Customer altitudes out to Geosynchronous orbit and above

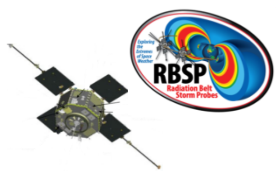
- Users can schedule communication for:
  - Launch services (vehicle and/or payload in-flight).
  - Low earth orbit spacecraft including highly elliptical.
  - High-altitude balloons.
- Some Missions Supported:
  - International Space Station (ISS)
  - Commercial Resupply Spacecraft to ISS
  - Hubble Space Telescope
  - Earth Observing & Space Science Spacecraft
  - Science to Antarctica.

Space Network Users

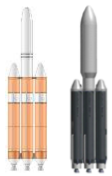
The SN is the provider of choice for many customers, including critical communications support to commercial missions from ULA, SeaLaunch, SpaceX, and OSC, and provides prime support to NOAA (JPSS), HST, ISS, ATV, HTV, provides science relay for remote Antarctica, key support to the Earth Science missions, and a large set of Special Projects and Missions (SP&M).   A subset is below:


HST


ISS




JPSS


Delta Atlas

ULA United Launch Alliance

Orbital Innovation You Can Count On®

SPACEX


Aqua

Science from remote Antarctica:


McMurdo Relay


South Pole

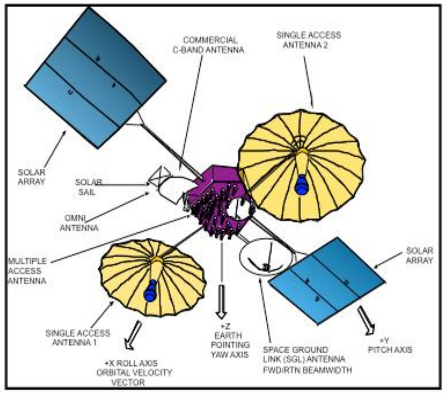
Customer Support Metrics

During year 2015, the Space Network performed more than 183,132 hours of service for over 25 missions.

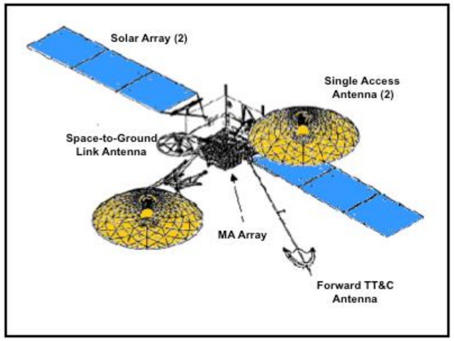
- This includes multiple simultaneous services at each TDRS.

Overall SN Service Proficiency was nearly 99.97%.

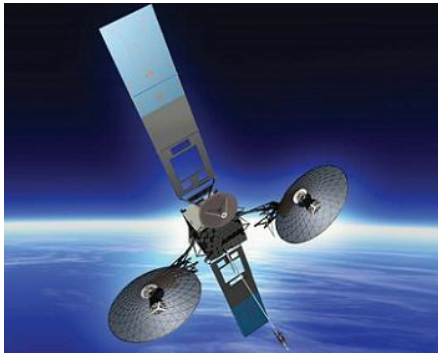
Tracking and Data Relay Spacecraft (TDRS)



1st Generation: F1, F3-F7
Built by TRW, launched by STS (Space Shuttle)
Ku & S Band Single Access Services
S Band Multiple Access Services

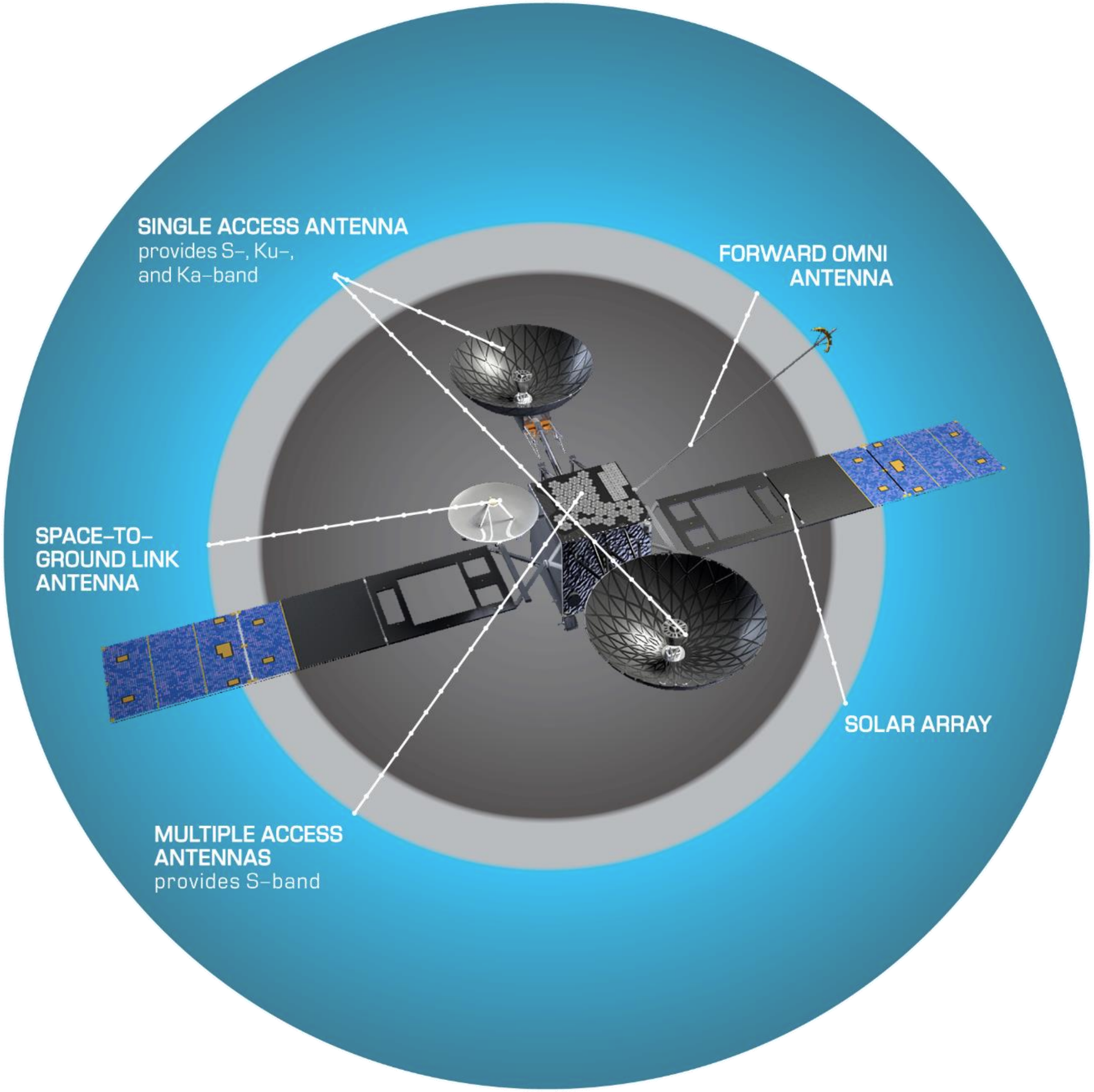


2nd Generation: F8-10
Built by Boeing, launched by Atlas
Ka/Ku & S Band Single Access Services
S Band Enhanced Multiple Access Services
Expanded Antenna Field-of-View



3nd Generation: F11 - 13
Built by Boeing, launched by Atlas
Ka/Ku & S Band Single Access Services
S Band Enhanced Multiple Access Services
Expanded Antenna Field-of-View

Space Network



TRW* Designed & Built 1st Generation TDRS

First Generation Tracking Data Relay Satellite (TDRS)

- TDRS-1 – Launched April 04, 1983
  - Retired Fall 2009; Disposal June 2010
- TDRS-B – Destroyed January 28, 1986 in Challenger explosion
- TDRS-3 – Launched September 29, 1988
- TDRS-4 – Launched March 13, 1989
  - Retired December 2011; Disposal April 2012
- TDRS-5 – Launched August 02, 1991
- TDRS-6 – Launched January 13, 1993
- TDRS-7 – Launched July 13, 1995

* Northrop Grumman Corporation acquired TRW in 2002

Boeing Designed & Built 2nd & 3rd Generation TDRS

Second Generation Tracking Data Relay Satellite (TDRS)

- TDRS-8 – Launched June 30, 2000
- TDRS-9 – Launched March 8, 2002
- TDRS-10 – Launched December 4, 2002

Third Generation Tracking Data Relay Satellite (TDRS)

- TDRS-11 – Launched January 30, 2013
- TDRS-12 – Launched January 23, 2014
- TDRS-M – Available for Launch in 2016
  - TDRS-M launch is for August 2017

TDRS are Geosynchronous Satellites

TDRSs have the same orbit period as a geostationary satellite, but are not North/South Station-kept and therefore their orbits may be highly inclined.

- They move in a figure-8 pattern as viewed from earth.
- Inclination evolves between 0 to 15 degrees.
- High inclination provides visibility to South Pole.

Stationkeeping without Inclination Control

Inclination is not managed as part of stationkeeping.

- Very little fuel is needed for station-keeping when not managing inclination.
  - 1st generation TDRS.
    - Use ~2.5 kg/year of monopropellant.
  - 2nd & 3rd generation TDRS.
    - Use ~2 kg/year of bipropellant.

FUEL DOES NOT LIMIT LIFE OF TDRS FOR ANY GENERATION.

- Wear-out items and failures will limit life.

Reliability Analysis supports Constellation Projection

Reliability analysis plays a key role in constellation management.

- Since TDRS longevity is largely a function of wear-out & failures,

Aerospace Corp develops failure models and reliability analysis in support of TDRS.

- Spacecraft <u>build data</u> combined with <u>on-orbit failure data</u> is used to produce bus & payload reliability analysis.

Life-limiting Elements Trended, Analyzed and Extrapolated

On-orbit Experience combined with reliability analysis indicates ALL Boeing delivered TDRS should exceed the 15 year design life.

- Anticipate at least 25+ years life expectancy for TDRS-8, 9 & 10.
  - Have good baseline on-orbit failure experience for the three 2nd generation Boeing built TDRS spacecraft.
    - Launched 2000 through 2002.

Failures on 2nd Generation Boeing TDRS (Slide 1 of 7)

Stuck-on FETS in the Bus Voltage Limiter

- FETs in BVL regulate solar array voltage output.
  - Performed by modulating solar array output to either ground or passing to power bus.
- Spacecraft operations can only detect anomalous FET shunting during eclipse season.
  - Detect only during transition into or out-of eclipse.
  - stuck-on FETs could come & go during solstice season without any capability to detect.

Failures on 2nd Generation Boeing TDRS (Slide 2 of 7)

<u>Bus Voltage Limiter (BVL) shunting anomalies</u>

Chronic problem with 2nd Generation TDRS (appears to be resolved for 3rd generation TDRS).

- On TDRS-8, anomalous shunting anomaly has appeared and disappeared repeatedly.
  - Anomalous shunt current just reappeared this 2016 eclipse season representing <u>~2 solar array circuits</u>.
  - After initial occurrence, went 4 years with no anomalous shunting before signature reappeared followed by 2 years before anomalous shunting appeared.
  - Initial 2008 shunting anomaly was in conjunction with a elevated BVL temperature.
    - Elevated signature resolved when stuck-on shunting anomaly resolved.
  - Unknown how many FET are fully functioning.
    - Fortunately, significant redundancy by nature of BVL module design and natural degradation of solar array output.
- On TDRS-9 & TDRS-10, shunting anomaly started early in life and appears unchanged (~13 years later).
  - TDRS-9 shunt current represents ~<u>1 solar array circuit</u>.
  - TDRS-10 shunt current represents ~<u>2 solar array circuits</u>.

- Capability exists to command the suspect shunt module open thereby removing the parasitic continuous shunt.
  - Will only do when power margin is at risk.

- Bus voltage is properly being regulated.
  - <u>Not a serious problem needing mitigation at this time</u>.

Failures on 2nd Generation Boeing TDRS (Slide 3 of 7)

Battery Cell Failures

TDRS-8 has experienced three different, suspect battery cell pressure leaks that have resulted in:

- One cell is bypassed.
- One expected to bypass in the next few eclipse seasons.
- One cell with degraded performance but still retaining ~ 60% nameplate capacity.

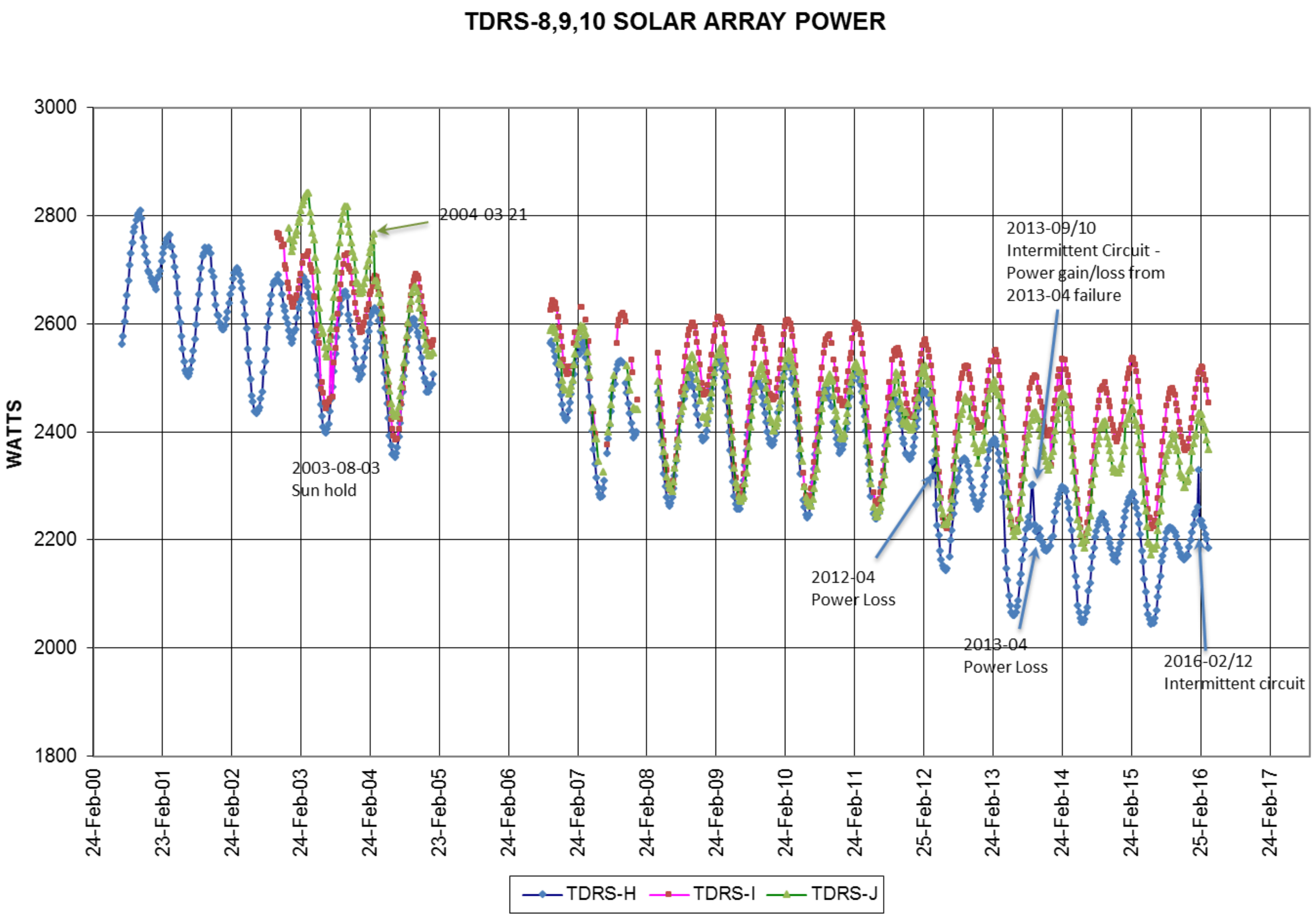
Failures on 2nd Generation Boeing TDRS (Slide 4 of 7)

Solar Array Circuits

- ~154 series solar cells make up a solar array circuit.
- 32 solar array circuits make up the total solar array (16 on each wing).

- TDRS-8 has experienced two failed solar array circuits.
  - One of the two failed solar array circuits continue to have short, sporadic recovery events.
- TDRS-9 has no solar array circuit failures.
- TDRS-10 has experienced one failed solar array circuit.
  - No sporadic recovery events observed.

TDRS Solar Array Trended ~1% per year degradation



Failures on 2nd Generation Boeing TDRS (Slide 5 of 7)

Thruster Failures

TDRS-9 thruster issues:

1. A3 22-newton thruster burn-through.
   - Due to off-nominal operation resulting in two phase flow (Helium & fuel) thruster operation during orbit raising.
   - Occurred year 2002.
2. W2 10-newton thruster suspected stuck fuel valve.
   - Failed to provide any appreciable thrust when commanded to fire.
   - Using combination of ACS thrusters to substitute for failed thruster.
   - Occurred year 2003.
3. N1 22-newton thruster suspected orifice blockage.
   - ~14% performance degradation.
   - Occurred year 2002.

TDRS-10 thruster issues:

1. Thermal runaway problems with initial “LTT – BSC” design resulted in operational constraint limiting E/W burns to 60 seconds steady-state max.
2. E2 10-newton thruster thermal runaway/burn-through.
   - Thermal runaway followed by burn-through occurred 30 sec into 60 sec operation.
   - Failure resulted in further limitation from 60 seconds to 10 second burn duration.
   - Using combination of ACS thrusters to substitute for failed thruster.
   - Occurred year 2011.

Failures on 2nd Generation Boeing TDRS (Slide 6 of 7)

TDRS-8 Battery Cell Scanner Failure

- Intermittent anomalous cell voltage signature on Cells 12, 14, & 16.
  - Occurred in 2008.
  - Diurnal intermittent characteristic continues on and off over the years.
  - Anomalous signature not observed for past few years but is beginning to reappear April 2016.

Failures on 2nd Generation Boeing TDRS (Slide 7 of 7)

Temperature Sensor Failures:

TDRS-9 Sensor Failures:

1. TDRS-9 E1A and W2A Injector Temperature Sensor Failures.
   - Sensors only monitored on RTCU-2 channels.
     - Observed year 2004 spacecraft only after switching to the RTCU-2.

TDRS-10 Sensor Failures:

1. TDRS-10 E1A Injector Temperature Sensor Failure.
   - Following initial observation, the telemetry became more erratic and eventually remained at a value of around 585° C.
   - Occurred year 2004.
2. TDRS-10 Gimbal Temperature Sensor Failure.
   - Intermittent - correlated with diurnal thermal variations.
   - Occurred year 2009.

No significant impacts to spacecraft operation resulted from the temperature sensor failures.

Failures on 3rd Generation Boeing TDRS (Slide 1 of 1)

Battery Cell Scanner Partial Failure

TDRS-11 loss of battery scanner visibility into four cells.

- Cell voltages are information only and not used by operations.
- Visibility nominal into the other 28 cells.
- Suspect foreign object or debris shorting associated pins in a connector.

Even When Considering the various Failures and Wear-out Rates

- 25+ years life expectancy are anticipated for TDRS-8, 9 & 10.
- An equivalent or greater life expectancy is anticipated for TDRS-11 & 12.
  - Only one minor (infant mortality) failure between TDRS-11 & 12.
    - Even better track record than with TDRS-8, 9 & 10

EOL Deorbit Objectives

Geosynchronous Orbit is one of the most important and essential orbits.

NPR 8715.6A, "*NASA Procedural Requirements for Limiting Orbital Debris*" is followed in managing TDRS spacecraft.

- At end-of-life TDRS are maneuvered into an disposal orbit approximately 350 km above synchronous altitude.
  - remains out of active geosynchronous belt for a minimum of 100+ years.
- Have performed on TDRS-1 & TDRS-4 to date.

Past Boeing Customer Satellite Conferences have been valuable in learning of Boeing series 376, and 601 spacecraft deorbit experiences.

- Open-loop burns when near fuel depletion.
- Cold gas propulsion experiences.

Thank You!!