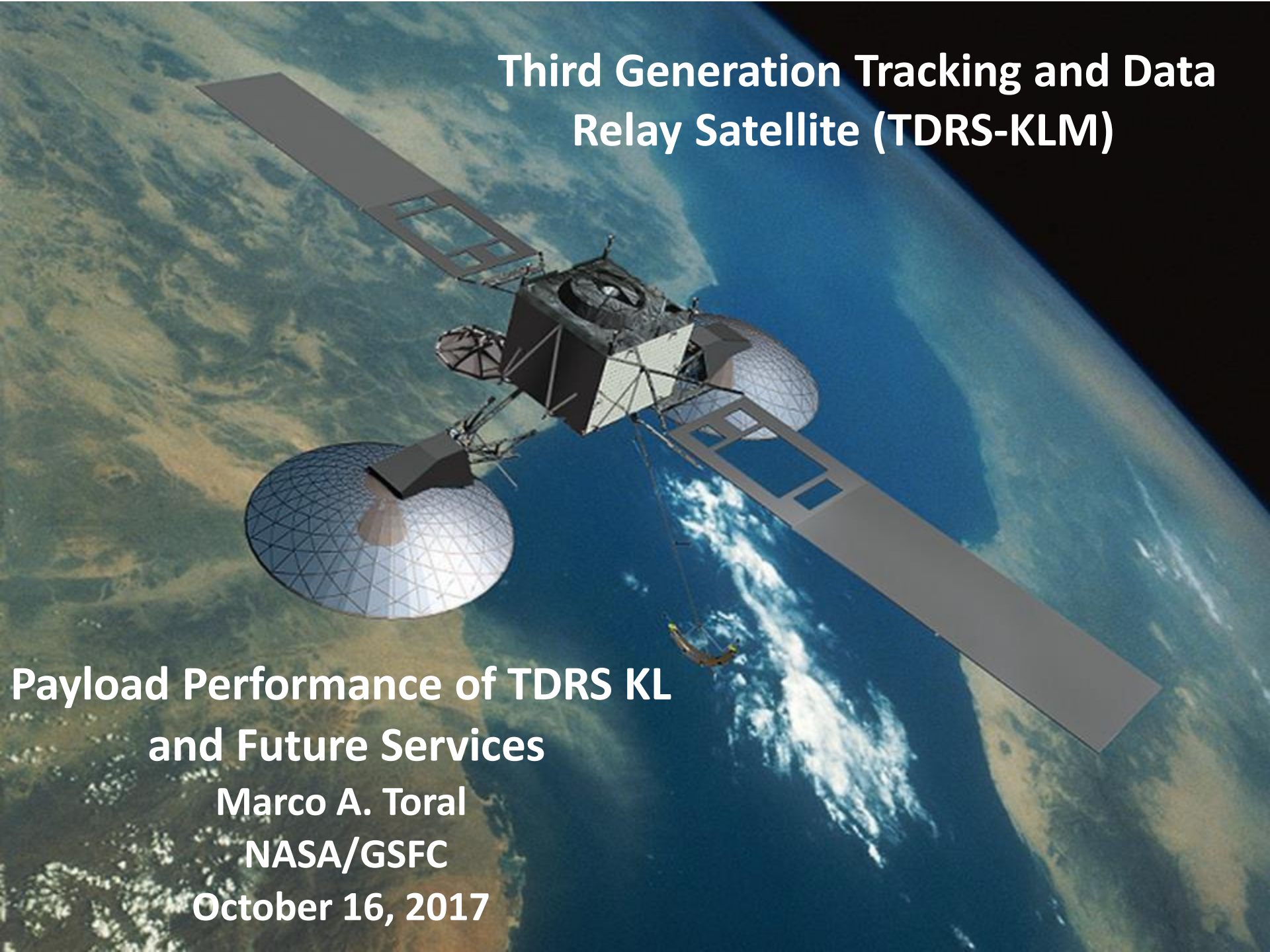


Third Generation Tracking and Data Relay Satellite (TDRS-KLM)

Payload Performance of TDRS KL and Future Services

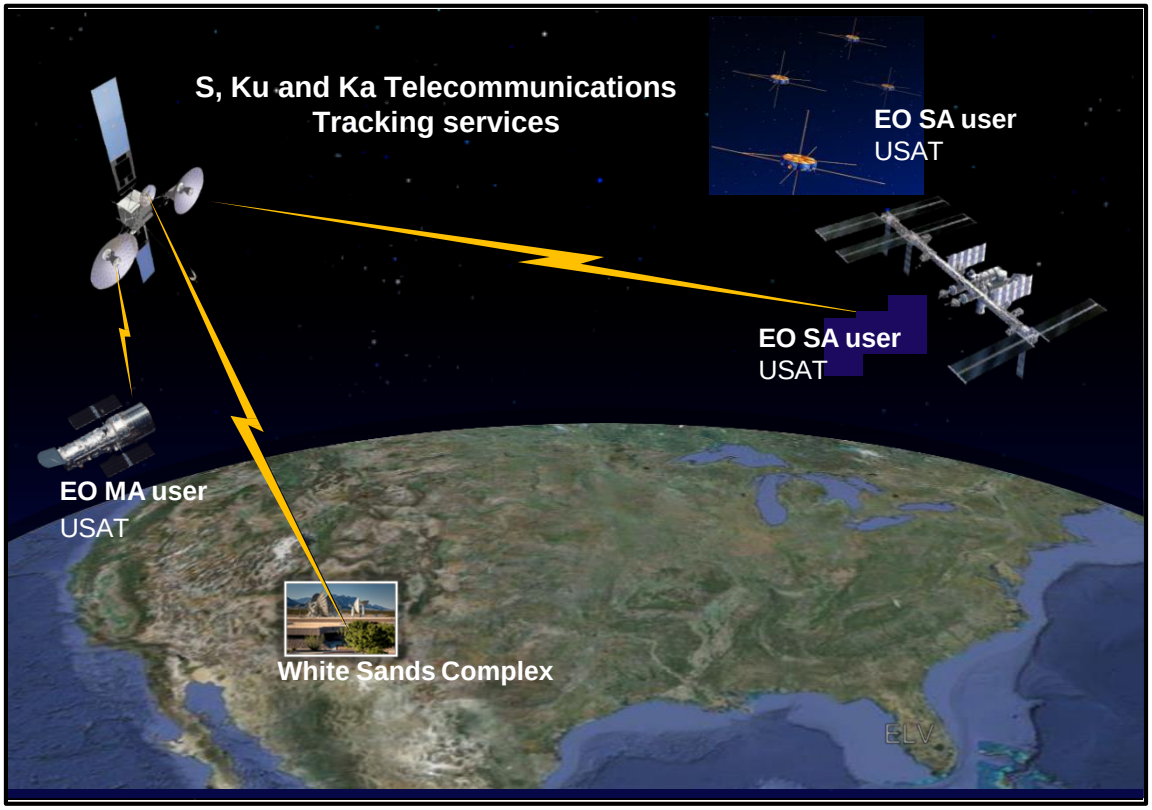
Marco A. Toral
NASA/GSFC

October 16, 2017

TDRS System Capabilities

TDRS Project Office

Provide communications, data relay, and tracking services for Near Earth Orbiting (EO) satellites, Human Space Flight including ISS, Expendable Launch Vehicles (ELV), and Scientific Customers. Enable missions with near real-time observations such as Gamma Ray detections via Fermi Gama-ray Space Telescope

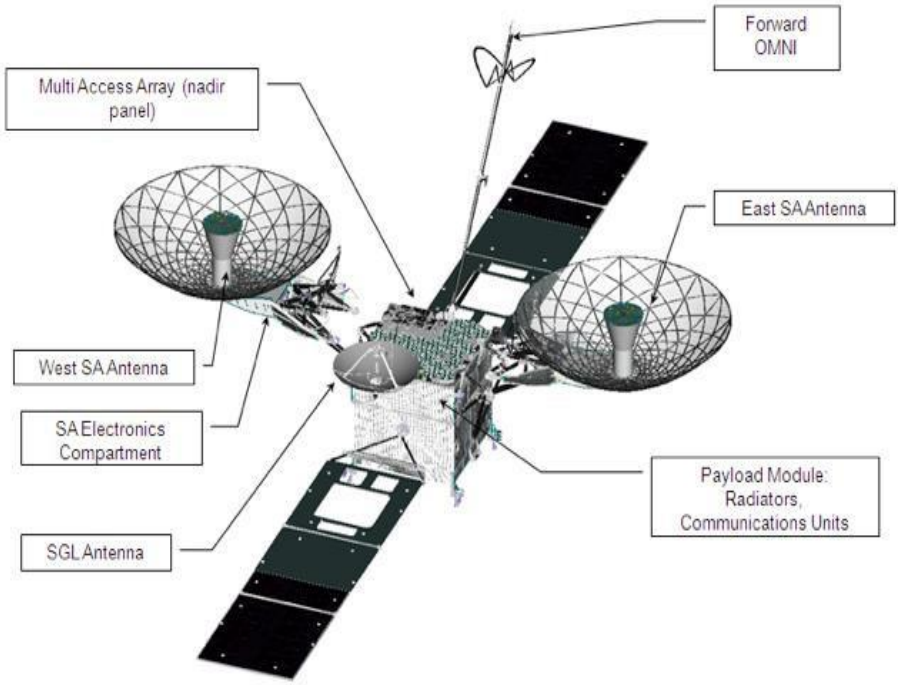


- SN/TDRS provides ~ 100% coverage of satellites in Low Earth orbit
- Single access user services
  - Scheduled services at S-band, Ku-band and Ka-band
- Multiple access user services
  - Ground based beam forming on TDRS 3 - 7, TDRS 11- 13 (KLM)
  - 24/7 support at S-band
  - On board beam forming for TDRS 8 - 10

TDRS K,L,M Satellite

TDRS Project Office

- Payload module contains communication electronics
- Two gimbaled 15 foot Single Access antennas
  - SA field of view +/- 31° N/S and 22.5° inboard and 77° outboard E/W
- One Multiple Access phased array antenna with 15 transmit and 32 receive elements
  - MA field of view +/- 13°
- One gimbaled Ku- band Space Ground Link antenna
- Two S-Band Omni antennas



Frequency, Tuning Range and Bandwidth

Parameter	Forward - (Transmit)				Return - (Receive)				
	S-band MA	S-band SA	Ku-band SA	Ka-band SA	S-band MA	S-band SA	Ku-band SA	Ka-band SA (Nar)	Ka-Band SA (Wide)
Channel Frequency Range (GHz)	2.1064	2.030-2.1135	13.775	22.555-23.545	2.2875	2.200-2.300	15.0034	25.2534-27.4784	25.545-27.195
Frequency Step (MHz)	Fixed	0.5	Fixed	5	Fixed	0.5	Fixed	25	25
Channel Bandwidth (MHz)	6	20	50	50	6	10	225	225	650

Multiple Access Phase Array

TDRS Project Office

S-Band phased array: 47-element array is comprised of 15 transmit-only elements, and 32 receive-only elements

- Receive array has 32 elements 30 of which are used nominally
- Six return beams can be supported by the ground-based beamformer
- Additional users can be supported by the Demand Access System (DAS) beamformer; Space Network User Guide (SNUG) provides information regarding all the SN services including DAS.
- Up to two forward beams can transmit data to users (6 elements/beam)
  - Transmit array has 15 elements 12 of which are used for one single forward service

On-orbit calibration testing includes:

- Onboard forward beamformer calibration includes amplitude and phase verification of the factory values
- Antenna pattern raster scans are used to verify electrical boresight biases
- EIRP, C/N and BER testing are used to verify MA performance

TDRS Multiple Access System On-Orbit Performance[1]

TDRS Project Office

Service Description	Parameter	TDRS-J (10)	TDRS-K (11)	TDRS-L (12)	Specification/ Allocation[2]
S-Band MA Forward	EIRP (dBW)	45.2	45.2	45.0	≥ 42.0
	Bandwidth (MHz)	8.2	9.6	10.9	≥ 6.0
S-Band MA Return	G/T (dB/K)	7.2	6.4	7.6	≥ 4.0[3]
	Bandwidth (MHz)	7	7.1	7.3	≥ 6.0

Notes:

1. Performance using spacecraft primary electronics. Similar performance measured using redundant spacecraft electronics.

2. TDRS KLM specification

3. For a field-of-view ≤ ±10.5° conical. For a field-of-view > ±10.5° conical and ≤ ±13° conical, G/T spec is -1.5 dB/K.

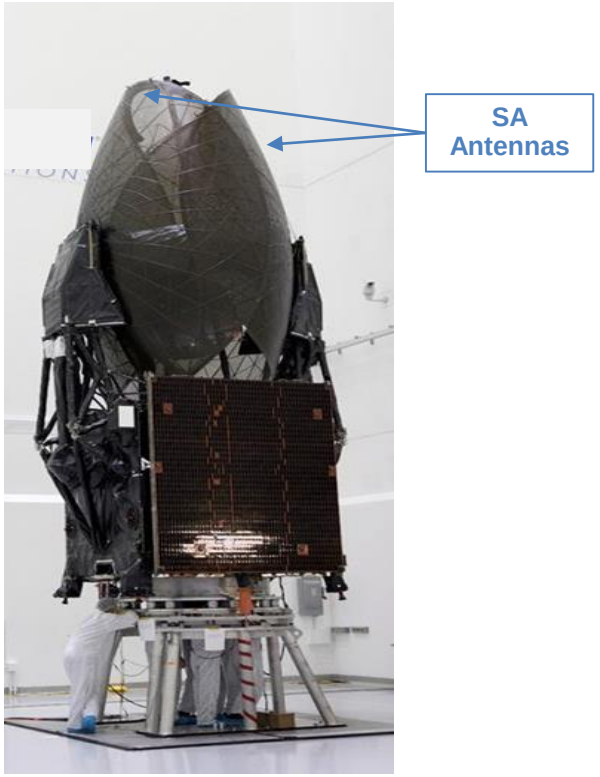
Observation: TDRS J uses on-board beamformer vs ground-based for TDRS K&L for third generation

TDRS-KL performance similar to TDRS-J

Single Access Antenna

4.6 meter Diameter Main Reflector with Carbon Fiber “Springback” Reflectors that are folded during launch to fit in the Atlas V 4 meter fairing

- Tri-band Feed: Ka, Ku and S-band with polarization/selectable – RHCP or LHCP
- Antenna Pointing:
  - Program track Ka, Ku and S-Band
  - Autotrack provided for Ka-band and Ku-band to minimize pointing loss due small antenna 3 dB beamwidth
- Pointing Requirements driven by EIRP & G/T Over Specified Field of View

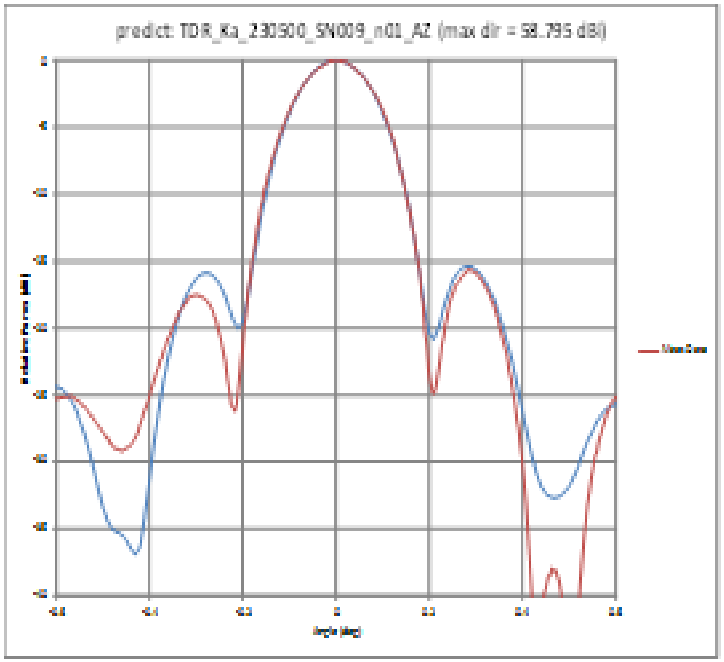


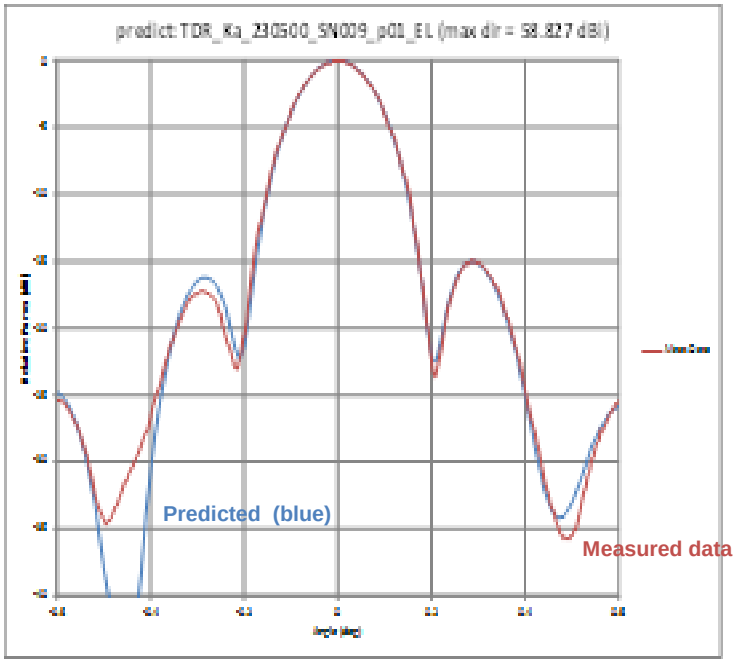
TDRS in launch configuration

SA Antenna Pointing Requirements

	Field of View (degrees)		Maximum Antenna Pointing Error (degrees)					
	E-W (AZ)	N-S (EL)	SSAF	SSAR	KuSAF	KuSAR	KaSAF	KaSAR
PT, LEO	+/-10.5° Conical		-----	-----	-----	-----	0.105°	0.102°
PT PEFOV	+/-22.5°	+/-31.0°	0.360°	0.360°	0.155°	0.155°	0.114°	0.114°
AT PEFOV	+/-22.5°	+/-31.0°	-----	-----	0.087°	0.061°	0.073°	0.045°
Nominal Antenna Beamwidth			~2.1°	~2.0°	~0.31°	~0.28°	~0.18°	~0.17°
PEFOV	Primary Elliptical Field of View							

SA Antenna Ka-band Performance After Tuning





- SA antenna reflectors return to original shape after release in approximately 45 days
- Effectiveness of on-orbit reflector tuning demonstrated; Ka Band antenna pattern data shows good agreement with predicted results
- Tuning increased Ka-band gain as much as 2.1 dB of the measured forward EIRP for the TDRS L spacecraft

TDRS L Ka-band Single Access Forward Service Antenna Patterns

SA Performance Summary

TDRS Project Office

Service			Parameter	TDRS-J (10)				TDRS-K (11)				TDRS-L (12)				Spec/ Alloc
				SA West		SA East		SA West		SA East		SA West		SA East		
				LHCP	RHCP	LHCP	RHCP	LHCP	RHCP	LHCP	RHCP	LHCP	RHCP	LHCP	RHCP	
Ka-Band SA	Forward		EIRP [1], dBW	70.2	69.9	69.8	69.7	69.2	66.9	67.5	68.0	70.3	70.3	70.1	70.1	**>63.0**
			Antenna Gain [2], dBi	58.2	57.8	57.6	57.9	58.6	58.6	58.2	58.3	59.0	59.1	58.7	58.8	54.7
			Bandwidth, MHz	64.7	62.3	65.8	65.7	66.5	54.4	64.8	62.8	63.0	53.5	63.3	56.0	**>50**
	Return	Narrow	G/T, dB/K	30.2	30.3	30.3	32.1	31.5	30.8	29.5	30.7	31.6	31.6	30.3	30.8	**>26.5**
			Antenna Gain [2], dBi	58.3	58.3	58.1	58.3	59.4	59.4	58.7	58.8	59.5	59.5	59.1	59.1	56.4
			Bandwidth, MHz	241	247	251	251	252	252.5	252	251	252	253	254	253	**>225**
		Wideband	G/T, dB/K	30.3	-----	29.7	-----	-----	-----	31.3	-----	-----	-----	30.8	-----	**>26.5**
			Antenna Gain [2], dBi	58.6	-----	58.2	-----	58.7	-----	58.7	-----	59.1	-----	60.2	-----	56.4
			Bandwidth, MHz	686	-----	696	-----	739	-----	731	-----	727	-----	733	-----	**>650**
Ku-Band SA	Forward		EIRP, dBW	53.6	53.8	54.2	54.2	57.1	56.7	57.6	57.9	58.0	58.7	58.4	58.3	**>49.0**
			Antenna Gain [2], dBi	54.1	53.8	53.9	53.8	54.0	54.1	53.8	53.6	53.7	53.8	53.7	53.8	51.7
			Bandwidth, MHz	62.2	63.2	65.2	65.6	65.7	65.3	64.0	54.5	62.8	61.8	62.8	61.7	**>50**
	Return		G/T, dB/K	26.2	25.5	27.0	27.9	27.0	25.0	27.4	27.3	26.6	27.7	26.5	26.8	**>24.4**
			Antenna Gain [2], dBi	54.4	54	54.4	54.3	54.5	54.5	54.4	54.3	54.3	54.3	54.3	53.4	52.6
			Bandwidth, MHz	247	248	253	250	253	252	252	253	254	253	254	254	**>225**
S-Band	Forward		EIRP, dBW	51.8	51.1	51.5	51.0	52.3	53.0	52.6	52.5	52.1	51.8	51.9	51.6	**>48.5**
			Antenna Gain [2], dBi	36.2	36.2	36.3	36.2	36.4	36.4	36.5	36.5	36.2	36.2	36.1	36.0	35
			Bandwidth, MHz	26.8	26.4	27.8	27.5	41.8	29.8	38.2	30.9	30.4	30.3	30.9	31.7	**>20**
	Return		G/T, dB/K	11.7	10.4	11.3	10.2	10.7	11.9	11.1	12.7	11.8	12.3	11.6	11.6	**>8.5**
			Antenna Gain [2], dBi	37.3	37.3	37.2	37.1	37.2	37.2	37.0	37.0	37.5	37.5	37.4	37.3	35.8
			Bandwidth, MHz	17.2	17.2	17.6	17.6	17.7	18.0	18.5	18.5	17.8	17.9	18.7	18.5	**>10**

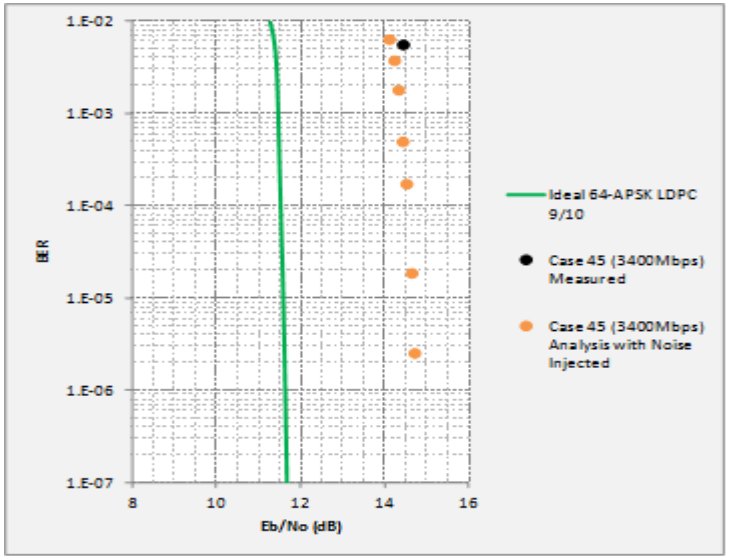
Notes:

1. Ka-band calibration uncertainty can overstate EIRP.
2. Antenna gain determined based upon nominal expected spacecraft power amplifier performance.

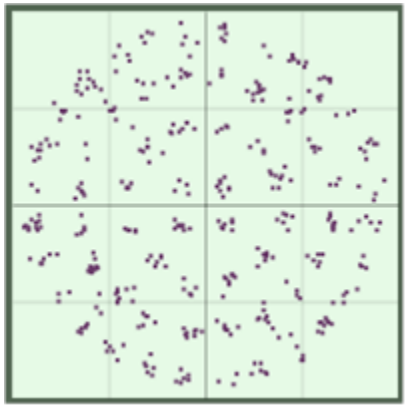
TDRS K&L Spacecraft Exceed Required SA Performance

Ka-band Return BER Performance

TDRS Project Office



Ka-Band BER Performance



64 APSK Constellation

- TDRS K Payload Test bed measured performance with different test cases utilizing SNUG and Digital Video Broadcast – Satellite 2nd edition (DVB-S2 and DVB-S2X) waveforms
  - Tested up to 3.4 Gbps with 64-APSK (Amplitude Phase Shift Keying) and Low Density Parity Check Code) with the 650 MHz Bandwidth wideband channel, measured performance shows 3.2 dB Implementation Loss

- TDRS KL on-orbit measured KaSAR performance at 25.25 GHz is about 1.6 dB from theoretical at 10^{-5} BER, and about 2.0 dB from theory at 10^{-7} BER for 300 Mbps (225 MHz channel) with QPSK. WSC is in the process of updating receivers to support higher modulation to support 8PSK including planned support for ISS (600 Mbps).

Demonstrated up to 3.4 Gbps Ka-band Wideband Return BER Performance with test bed

Future Services: Optical Communications

TDRS Project Office

NASA/GSFC TDRS project supported NASA plans to include Laser Communications in the Next Generation Relay System

Optical Primary Payload: (Study results – 2016)

- Three 20 cm optical terminals, optical modems at 1550 nm wavelength (additional terminals are in plan)
- Two optical channels (2.5 Gbps) to the ground, and up to 3 return channels via RF (one 2.5 Gbps and two 1 to1.5 Gbps)
- Field of Regard: +/- 80°conical supports Near Earth, Geostationary orbital arc, cis-Lunar space
- User Enhancements:
  - Acquisition Beacon to each terminal
  - Redundant GNSS receivers for on-board orbit determination, laser terminal pointing, and an absolute time reference for optimetrics
  - Introduced Coherently Detected burst Mode BPSK for increased receiver sensitivity
  - Provided modems that compensate for Doppler on forward and return signals
  - Includes optimetric range and range-rate observations on the laser communication links
  - Provided multi-channel wavelength division multiplexing for the optical SGL

RF SGL payload

- Ku/Ka requires two 2.5 to 2.8 Gbps channels for the RF Space to Ground link
- Ka provides wider uplink/downlink channels

Note: The concepts and acquisition strategies for an optical relay have been subjects of follow on studies and will be published by NASA when appropriate.

Future Services: Optical Communications

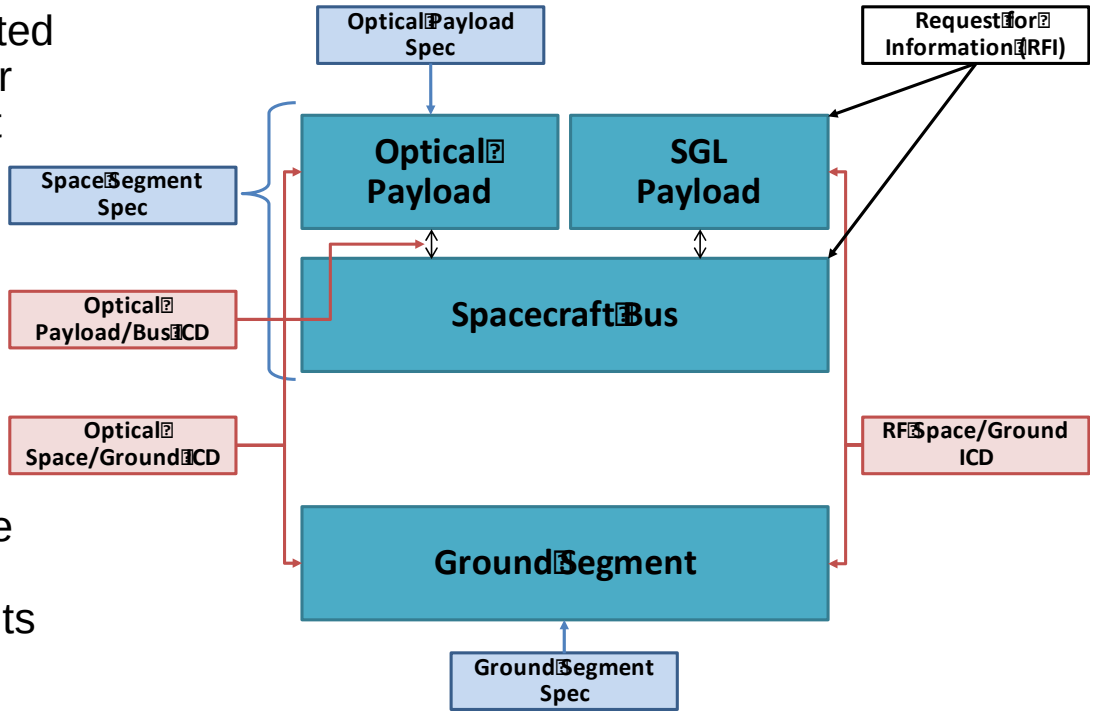
TDRS Project Office

TDRS Project Optical Payload Documentation

The structure and relationship of the major technical documents generated helped the team focus on the major technical questions and trades that needed to be addressed for any potential procurement.

Additional documents
- Concept of Operations
- Concept of Navigation

Procurement
- Statement of Work for the Prime contractor
- Mission Assurance Requirements document
- Contract Data Requirements



Study results provided a solid basis for evolving the next generation of relay spacecraft

Conclusions

TDRS Project Office

- On-orbit testing confirms TDRS-K and L spacecraft exceed required MA & SA performance
  - TDRS K&L satellites provide 650 MHz Wideband Channel for support of higher data rates and MAR ground based beamforming
  - Effectiveness of on-orbit SA antenna reflector tuning demonstrated
  - On-orbit antenna pointing accuracy is better than specified
  - 3rd generation TDRS MAR ground based beamformer was validated and provided performance equivalent to 2nd generation TDRS
- Measured on-orbit performance of return BER better than requirement for all services; demonstrated on-orbit 300 Mbps at Ku and Ka-Band (225 MHz)
- Future SN higher data rates supporting DVB-S2/S2X : demonstrated up to 3.4 Gbps using 64-APSK with TDRS K Payload test bed error correction Low Density Parity Check Code with the 650 MHz channel
- Future laser/optical communications provides ultra-wide bandwidths with potential higher data rates support. The study results provided a solid basis for evolving the next generation of relay spacecraft with optical communications.

3rd Generation TDRS will provide NASA communications services well into the mid-2020s

Contact Information

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TDRS M was launched on August 18, 2017 and is in the process of the on-orbit testing/acceptance activities

TDRS: tdrs.gsfc.nasa.gov