PAYLOAD PERFORMANCE OF THIRD GENERATION TDRS AND FUTURE SERVICES

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NASA has accepted two of the 3rd generation Tracking and Data Relay Satellites, TDRS K, L, and M, designed and built by Boeing Defense, Space & Security (DSS). TDRS K, L, and M provide S-band Multiple Access (MA) service and S-band, Ku-band and Ka-band Single Access (SA) services to near Earth orbiting satellites. The TDRS KLM satellites offer improved services relative to the 1st generation TDRS spacecraft, such as: an enhanced MA service featuring increased EIRPs and G/T; and Ka-band SA capability which provides a 225 and 650 MHz return service (customer-to-TDRS direction) bandwidth and a 50 MHz forward service (TDRS-to-customer direction) bandwidth. MA services are provided through a 15 element forward phased array that forms up to two beams with onboard active beamforming and a 32 element return phased array supported by ground-based beamforming. SA services are provided through two 4.6m tri-band reflector antennas which support program track pointing and autotrack pointing. Prior to NASA's acceptance of the satellites, payload on-orbit testing was performed on each satellite to determine on-orbit compliance with design requirements. Performance parameters evaluated include: EIRP, G/T, antenna gain patterns, SA antenna autotrack performance, and radiometric tracking performance. On-orbit antenna calibration and pointing optimization was also performed on the MA and SA antennas including 24 hour duration tests to characterize and calibrate out diurnal effects. Bit-Error-Rate (BER) tests were performed to evaluate the end-to-end link BER performance of service through a TDRS K and L spacecraft. The TDRS M is planned to be launched in August 2017. This paper summarizes the results of the TDRS KL communications payload on-orbit performance verification and end-to-end service characterization and compares the results with the performance of the 2nd generation TDRS J. The paper also provides a high-level overview of an optical communications application that will augment the data rates supported by the Space Network.

I. Introduction

NASA has accepted two of the 3rd generation Tracking and Data Relay Satellites (TDRS) with the acceptance of the TDRS K and L satellites. Known on-orbit as TDRS-11 and 12, the new satellites serve as replenishment to the existing fleet while filling the need for higher data rate communications and multiple access service with ground-based Demand Access System (DAS). Each satellite provides S-band Multiple Access (MA) forward and return service, and S-band, Ku-band and Ka-band Single Access (SA) forward and return service. A forward service is defined to be the path from the ground terminal through the TDRS spacecraft to a customer spacecraft. A return service is defined to be the path from a customer spacecraft through the TDRS to the ground terminal.

MA services are provided through a 47 element (15 transmit, 32 receive) phased-array antenna, and SA services are provided through two mechanically steered 4.6 m reflector antennas. Figure 1 shows the deployed spacecraft configuration. The S-band and Ka-band SA services are tunable, while S-band MA and Ku-band SA services operate on fixed frequencies. Table 1 gives the specified frequency channel coverage, tuning steps, and channel bandwidth for each service. The spacecraft forward channel bandwidths range from 6 MHz to 50 MHz and return channel bandwidths range from 6 MHz to 650 MHz. The satellites support two 225 MHz wide Ku-band or Ka-band SA return channels, and can be configured to make one a 650 MHz wide Ka-band return channel, capable of supporting data rates of 3.4 Gbps with 64 APSK modulation.

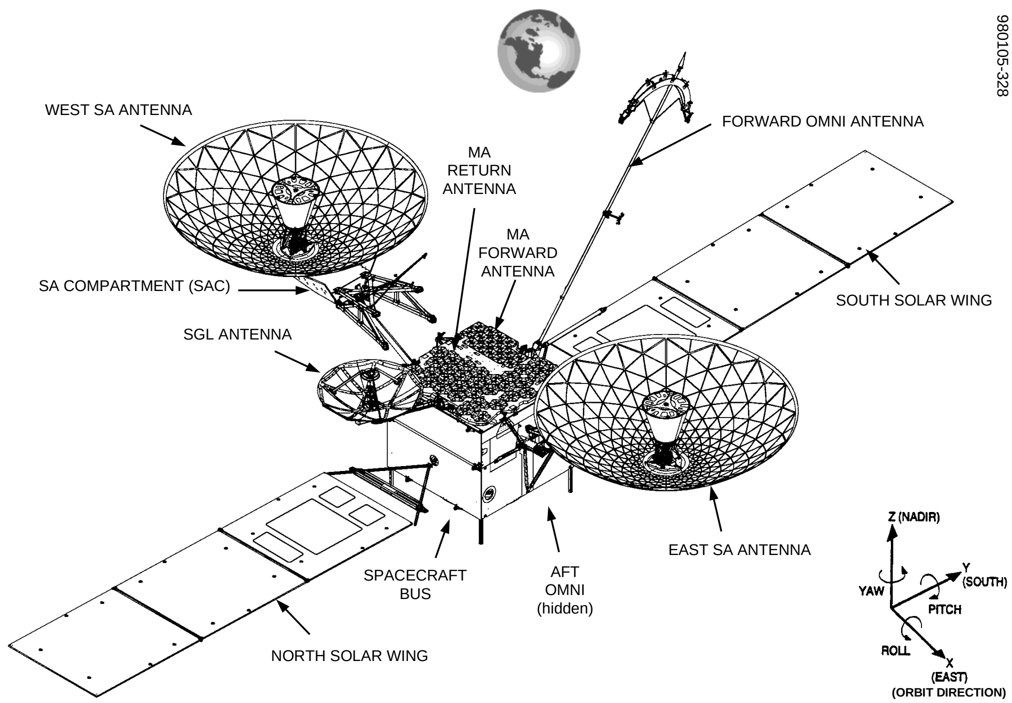


Figure 1. TDRS Spacecraft Deployed Configuration

Table 1. Frequency, Tuning Range and Bandwidth

Parameter	Forward				Return				
	S-band MA	S-band SA	Ku-band SA	Ka-band SA	S-band MA	S-band SA	Ku-band SA	Ka-band SA (Narrow)	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	5.0	Fixed	0.5	Fixed	25.0	25.0
Channel Bandwidth (MHz)	6	20	50	50	6	10	225	225	650

Prior to NASA's acceptance of the satellites, on-orbit payload testing was performed to determine each satellite's compliance with design requirements. This on-orbit testing measured forward service EIRP, return service G/T, MA and SA antenna gain patterns, SA antenna autotrack performance, channel magnitude response, and frequency accuracy for all service bands with primary and redundant electronics. On-orbit antenna calibration and pointing optimization was also performed on the MA and SA antennas including 24 hour duration tests to characterize and calibrate out diurnal effects. Bit-Error-Rate (BER) tests were performed to evaluate the end-to-end link BER performance of service through a TDRS K, L spacecraft. For SA services, on-orbit testing demonstrated that each TDRS K, L satellite met all of the performance requirements at each band with primary and redundant electronics. For MA services, the On-orbit testing demonstrated that the MA services on TDRS K and L met all of the performance requirements. The third satellite - TDRS M launch date is August 2017 and the on-orbit testing completion is expected by the end of the year.

The on-orbit payload testing is performed to calibrate the antennas and to confirm that the satellite operates with the same performance as measured in the factory. It uses TDRSS ground terminal operational test equipment located at WSC, New Mexico USA. Since the ground terminal test capability is intended to confirm operation, its performance and calibration is often not at the same level as factory test facilities.

II. Multiple Access On-Orbit Performance Verification

TDRS K,L,M MA services are provided through a 47-element phased array antenna. This 47-element array is comprised of 15 transmit-only elements, 12 of which are used nominally for forward service, and 32 receive-only elements, 30 of which are used nominally for return service. A total of two forward beams and six return beams can be formed by the ground-based beamformer. Additional users can be supported by the DAS system. The SN User Guide provides information regarding all the SN services including DAS. The Field of View (FOV) of the formed beam is ±13° from the center of the Earth (this FOV supports low Earth orbiting satellites from the TDRS geosynchronous orbit). Under normal operating conditions, the TDRS K,L,M satellites use only 12 of the 15 transmit-only elements. All results and discussion given in the remainder of this paper assumes this standard mode of operation.

Table 2 summarizes the measured on-orbit performance of the TDRS J, K and L spacecraft and the specified minimum performance. All the satellites exceed the multiple access performance requirements.

On-Orbit MA Beamformer Calibration

The MA phased array antenna is “pointed” by forming a beam in the desired direction. A beam is formed in a particular direction by shifting the phases of the element signals. During the calibration process of the beamformer, the procedure optimizes the phase and amplitude shift amounts. The calibration state settings are adjustable and are initially set based upon factory measurements. These settings were calibrated during the on-orbit tests for TDRS K and L.

Table 2. TDRS Multiple Access System On-Orbit Performance[1]

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.

III. Single Access System On-Orbit Performance

SA services are provided through two 4.6 meter diameter reflector antennas with S, Ku, and Ka-band feeds. Each feed can be switched between RHC and LHC polarization. For receiving return signals, the Ku and Ka-band antenna feeds include a provision for autotrack operation, as well as program track operation.

This is particularly important at Ka-band where the narrow antenna beamwidth makes accurate pointing critical to meet expected link performance.

A. Single Access On-Orbit Performance Verification

Table 3 summarizes the measured on-orbit performance of the TDRS J, K and L spacecraft and the specified minimum performance. All satellites exceed the performance requirements. Autotrack pull-in and tracking were verified and characterized for each antenna. The TDRS K and L test program also included on-orbit demonstration of Ku/Ka-Band autotrack acquisition with user dynamics and uncertainties.

B. Single Access Antenna On-Orbit Antenna Patterns

The SA antenna is a Cassegrain design with a tri-band feed assembly attached to the base hub. An electronics compartment behind each hub houses the Low Noise Amplifiers, High Power Amplifiers and related electronics for the three bands. The 4.6 meter diameter reflector is of graphite cloth on a springback frame, which allows folding to fit within the Atlas V 401 launch vehicle's 4 meter fairing. Once in orbit, the antenna reflectors are released and "spring back," and the antennas are folded out from the spacecraft to positions on the east and west sides, just in front of the spacecraft nadir face. A minimum of 45 days are needed for the reflectors to return to their expected shape.

On-orbit calibration of the SA antennas includes measuring boresight and adjusting gimbal pointing if necessary. Then antenna patterns are measured, and if necessary, the reflector shape is adjusted by a tuning mechanism near the hub. Reference [1] provides a discussion of the on-orbit hub tuning activities performed on TDRS HIJ. As an example, the TDRS-L West SA Ka-band antenna pattern is provided in Figure 2. It should be noted that the antenna patterns are measured by sweeping the antenna to make azimuth and elevation cuts while measuring the received power (Prec).

C. Single Access Antenna Pointing Optimization

Accurate program track antenna pointing is critical, particularly at Ka-band where the antenna beamwidth is about 0.17º. Table 4 shows the program track and autotrack fields of view and pointing requirements for all the SA antennas. These were derived from primary requirements to provide minimum service EIRP and G/T with specified ephemeris uncertainties. On-orbit testing indicated the TDRS K and L satellites performed better than these pointing requirements in each band.

Since the SA antenna boresight calibration described in the previous section is done in only one direction (from the satellite test location at 150º W to White Sands, New Mexico USA), it does not account for alignment errors over the entire antenna field of view, or for pointing variations from thermal distortion effects. A calibration method was developed to minimize antenna pointing errors over their entire fields of view. This method which uses autotrack pointing information to correct the pointing errors in program track pointing is described in Reference [1] with example results.

Figure 2. TDRS L Ka-band Single Access Forward Service Antenna Patterns

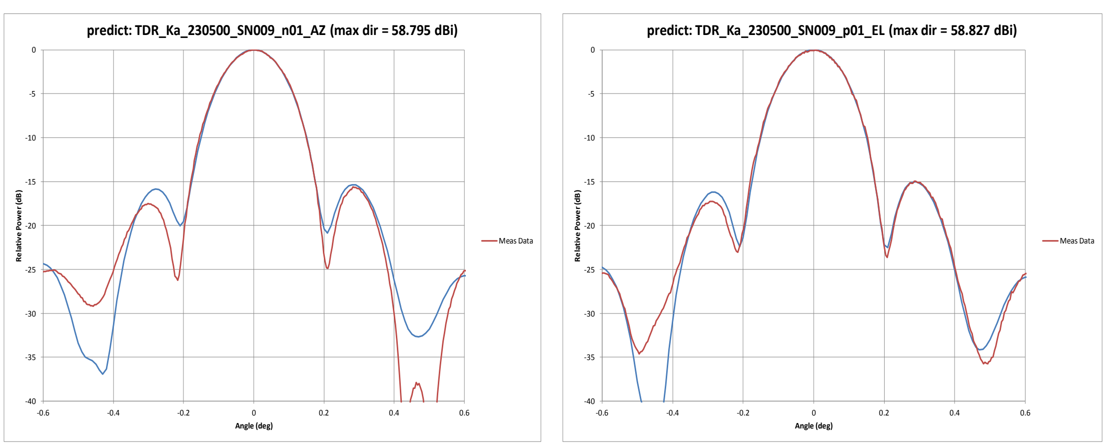


Table 3. TDRS Single Access Service On-Orbit Performance

Service			Parameter	TDRS-J (10)				TDRS-K (11)				TDRS-L (12)				Spec/
				SA West		SA East		SA West		SA East		SA West		SA East		Alloc
				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.

Table 4. 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	+/-10.5º Conical		-----	-----	-----	-----	0.105º	0.102º
PT PEFOV	+/-22.5º	+/-31.0º	0.360º	0.360º	0.155º	0.155º	0.114º	0.114º
AT PEFOV	+/-22.5º	+/-31.0º	-----	-----	0.087º	0.061º	0.073º	0.045º
Nominal Antenna Beamwidth			~2.1º	~2.0º	~0.31º	~0.28º	~0.18º	~0.17º
PEFOV	Primary Elliptical Field of View							

D. Frequency Tuning

The TDRS H,I,J & K,L,M satellites are frequency agile at S-band and Ka-band in both the forward and return directions, as detailed in Table 1. All translation frequencies are coherently derived from the 50 MHz spacecraft reference, which is in turn locked to the command uplink carrier from the ground station. When unlocked from the command uplink carrier, the frequency reference is accurate to within 10 ppm over the spacecraft lifetime.

IV. End-to-End BER Performance with Higher Order Modulation

The S, Ku and Ka-band return end-to-end BER performance were measured on the operational TDRS-K and L spacecraft. The ground-based equipment at the White Sands Complex in New Mexico emulated a Ka-band customer spacecraft, transmitting up to 300 Mbps SQPSK modulated signal to the spacecraft at 150º W longitude. The received signal was demodulated, and added noise varied to characterize BER versus Eb/No. 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.

In addition to on-orbit BER testing, TDRSS end-to-end link BER data based upon engineering units from the TDRS K Spacecraft were taken using the TDRS K Payload Test Bed. Reference [2] provides a discussion of the tests conducted at the Boeing facility in El Segundo, CA and the modems provided by L3. The Payload Test Bed consists of the TDRS K engineering model Low Noise Amplifiers, frequency converters, Solid State Power Amplifiers, Traveling Wave Tube Amplifiers, flight representative filters, and supporting equipment to assemble single string service channels for TDRS forward and return services. The Payload Test Bed was used for engineering evaluation of new communications waveforms and services.

The TDRS K Payload Test Bed provides flight-like performance for the Multiple Access and Single Access forward and return services at S, Ku and Ka-Band including KSAR wideband 650 MHz channel. The test bed will be used to augment the validation tools needed to demonstrate that SN users/TDRS can support bandwidth efficient modulations (BEM) and coding included in the SNUG and Digital Video Broadcasting standard DVB-S2. NASA should assess the implementation losses using these BEM for future users that require high performance and higher data rates support. Current tools include link budgets, communications simulations using SPW/ MatLab-Simulink and TDRS on-orbit demonstrations. On-orbit Ku and Ka-band demonstrations require scheduling time on TDRS and selected date could be affected by rain/atmospherics, antenna pointing, etc. making assessment difficult. Higher performance BEM requires higher fidelity characterization of user transmitter non-linearities, TDRS communication channels and WSC receivers than heritage BPSK/QPSK modulations. There are many variables that require further investigation in order to optimize these communication links such as pre/post equalization, pre-distortion like raised-cosine using FEC with non-linear amplifiers that require operating at a level that is backed-off from saturation.

A test plan was created and executed using the L3 CSW modem emulator to demonstrate performance of the TDRS-K satellite using a variety of different waveforms. Test cases executed included user waveforms defined in the Space Network User's Guide (SNUG) and different test cases utilizing Digital Video Broadcast – Satellite 2nd edition (DVB-S2) waveforms with extension to 64-APSK (Amplitude Phase Shift Keying). A new benchmark was established for TDRSS when the test team successfully demonstrated a 3.4 Gbps data rate through the TDRS K Payload Test Bed with a 64-APSK modulation. The maximum implementation loss observed end-to-end was only 3.2 dB, with most cases exhibiting around 2 dB or less. The Ka-Band BER data shown in Figure 3 with 64-APSK modulation and the constellation was still fairly well defined.

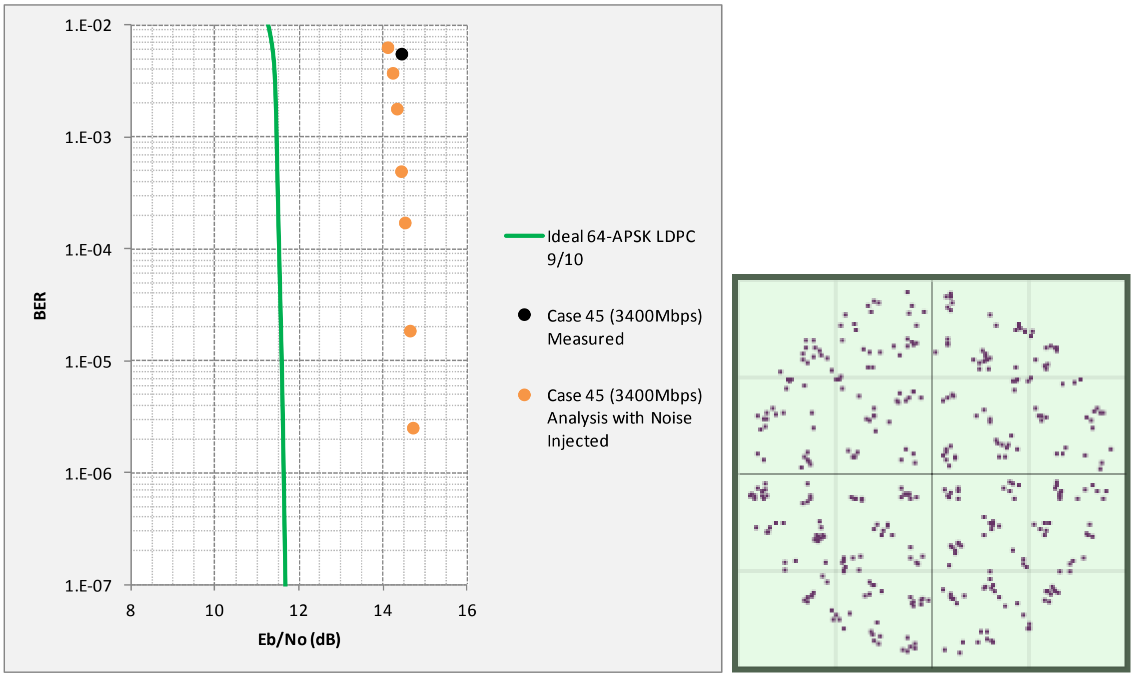


Figure 3. 3.4 Gbps Ka-band Return BER Performance

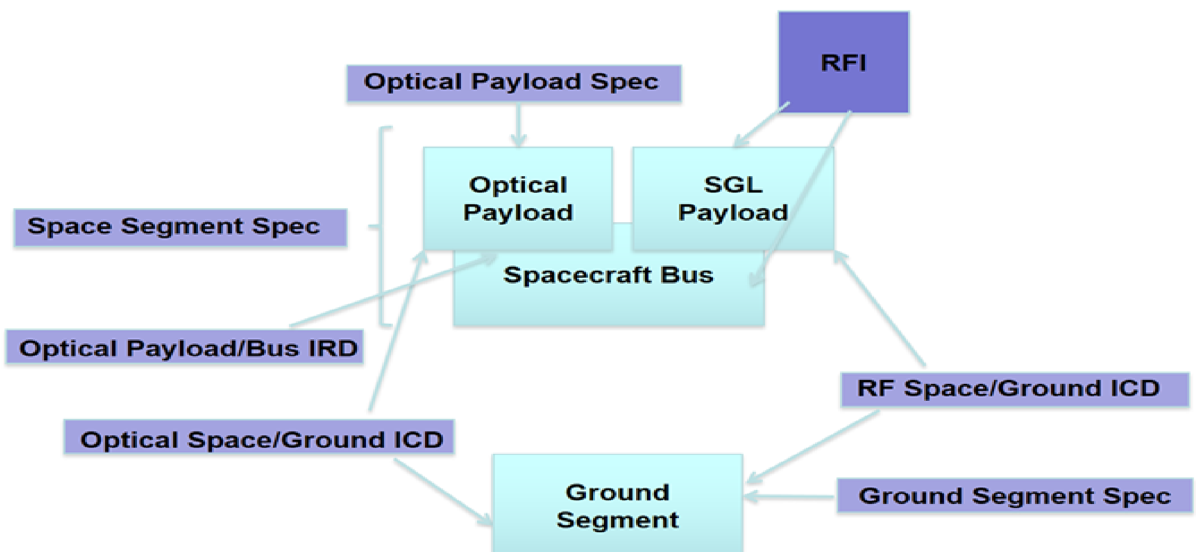
V. Future Services: Optical Communications

With the launch of TDRS M planned for this year, NASA will be positioned to continue to provide RF communications, Navigation, Ranging, Doppler Tracking, and Time Transfer services for space missions from LEO to beyond Geo well into the mid-2020s. During 2016, members of the NASA GSFC TDRS Project office supported NASA plans to include Laser Communications in the Next Generation Relay System. Armed with documentation from the Laser Communications Relay Demonstration (LCRD) Project, the GSFC Earth Regime Network Evolution Study (ERNESt) study, and material from a study of optical accommodations performed under the TDRS K/L/M Contract a draft optical/RF payload was conceived. The payload carried three 20 cm terminals, optical modems at 1550 nm wavelength band, a LCRD Space Switching Unit (SSU), a multichannel high rate RF modem, a Ku band (or Ka band) high rate transceiver and space ground link (SGL) steerable antenna. In addition, a low-rate S-band TT&C system was added as well to guarantee spacecraft control for periods when user services are not being provided. The maximum service data rates were expected to be in the 2-3 Gbps range, so the RF modem supported at least 2 data channels using 32 or 64 APSK modulation. The payload was in the 600 Kg/1600W range. This optical payload was considered applicable for a stand-alone spacecraft bus application. The selected payload architecture was flexible and allowed 2 SA services using only the optical terminals or 3 optical SA services using the RF payload for the space to ground link (SGL).

With this data, the NASA GSFC Rapid Spacecraft Development Office (RSDO) was contacted for assistance in locating a spacecraft bus capable of hosting the conceptual payload. The first order criteria was not limited to mass and power requirements, but also included stringent pointing knowledge, pointing capability, jitter requirements, and capability (be qualified) to fly at Geosynchronous altitude with a design life of at least 12 years. Fortunately, spacecraft busses meeting our selection criteria were added to the RSDO catalog in July of 2016. Based on this information, the design team was augmented with technical subject matter experts in reliability, laser electronics, laser ranging, optical modulation, spacecraft systems engineering, optical and RF link budgets, and senior technical advisors to prepare draft “procurement quality” documents.

The structure and relationship of the major technical documents generated is shown in Figure 4. In addition, a general Concept of Operations and a specialized Concept of Navigation were generated. Further, documents necessary for a procurement such as a Statement of Work for the Prime contractor, a Mission Assurance Requirements document, and a Contract Data Requirements Document were also developed.

Having the documentation structure shown in Figure 4 helped the team focus on the major technical questions and trades that needed to be addressed for any potential procurement. In general, the team decided that a Class B mission was needed to provide the service stability to attract users. This means all payload electronics are redundant. Second, the team decided that minimizing user burden was important. As a result we added: 1) an Acquisition Beacon to each terminal, 2) redundant GNSS receivers for on-board orbit determination, laser terminal pointing, and an absolute time reference for optimetrics, 3) introduced Coherently Detected burst Mode BPSK for increased receiver sensitivity, 4) provided modems that compensate for Doppler on forward and return signals, 5) added optimetric range and range-rate observations on the laser communication links[4], and 6) provided multi-channel wavelength division multiplexing for the optical SGL. The team elected to keep the SSU frame switching concept and adapted the optimetrics implementation to compensate for non-deterministic switch timing. The study results provided a solid basis for evolving the next generation of relay spacecraft. The concepts and acquisition strategies for an optical relay have been subjects of follow on studies and will be published by NASA when appropriate.



Notes: 1. The Optical Payload Specification addresses the Optical Space/Ground ICD.

2. The RF portion of the Ground Segment is addressed in Space Segment Document and in the Space/Ground RF ICD.

3. The Optical Payload/Bus Interface Requirements is a stand-alone document.

Figure 4. Optical Service Specification Documents

VI. Conclusions

The payload on-orbit performance verification of two of the 3rd generation TDRS spacecraft has demonstrated that they exceed the performance of the 1st generation TDRS fleet. The on-orbit performance of the MA and SA services on all vehicles meet or exceed the performance requirements. Satellite tests, including end-to-end BER performance tests, have shown their capability to provide S-band MA, S-band SA, Ku-band SA and Ka-band SA services to NASA customer spacecraft.

On-orbit antenna tuning of the SA antennas demonstrated the effectiveness of antenna reflector tuning to meet the required performance. MA and SA antenna pointing has been verified to be well within the pointing error allocated for guaranteed performance with user spacecraft.

VII. Acknowledgments

The authors would like to thank all involved Boeing, GSFC and WSC personnel for their efforts in the on-orbit testing and acceptance of the 3rd generation Tracking and Data Relay Satellites. We also would like to acknowledge the contributions of John Wesdock and Sanford Gardner, who passed away recently, to the success of the TDRS 2nd and 3rd generation programs.

VIII. References

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