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Space-Based Telemetry and Range Safety Project Ku-Band and Ka-Band Phased Array Antenna

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ABSTRACT

The National Aeronautics and Space Administration Space-Based Telemetry and Range Safety study is a multiphase project to increase data rates and flexibility and decrease costs by using space-based communications assets for telemetry during launches and landings. Phase 1 used standard S-band antennas with the Tracking and Data Relay Satellite System to obtain a baseline performance. The selection process and available resources for Phase 2 resulted in a Ku-band phased array antenna system. Several development efforts are under way for a Ka-band phased array antenna system for Phase 3. Each phase includes test flights to demonstrate performance and capabilities. Successful completion of this project will result in a set of communications requirements for the next generation of launch vehicles.

NOMENCLATURE

Ao	link unavailability
Az	azimuth
CFR	Code of Federal Regulations
C/N	carrier-to-noise ratio
C/No	carrier-to-noise power spectral density ratio
dB	decibels
dB-bps	dB - bits per second
dB-Hz	dB - Hertz
dBi	dB isotropic
dB/K	dB gain per noise temperature in degrees Kelvin
dBW	dB watts
Eb/No	bit energy to noise power spectral density ratio
EIRP	effective isotropic radiated power
El	elevation
G/T	antenna gain over noise temperature
GHz	gigahertz
I-Ch	in-phase channel
IM	intermodulation
IRIG	Interrange Instrumentation Group
IRU	inertial reference unit
kbps	kilobits per second
K	degrees Kelvin
look angle	angle from antenna boresight to satellite
LHCP	left-hand circular polarization

m	meters
Mbps	megabits per second
MMIC	monolithic microwave integrated circuit
NASA	National Aeronautics and Space Administration
Prec	received power
Region E	Crane Rain Model Subtropical Region
RF	radio frequency
RHCP	right-hand circular polarization
STARS	Space-Based Telemetry and Range Safety
Theta	angle in degrees from the axis of the main lobe
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
UAV	unmanned aerial vehicle
VDC	direct voltage current
VSAT	very small aperture terminal
VSWR	voltage standing wave ratio
W	watts

INTRODUCTION

Current telemetry systems for United States space lift operations have limited data rates and a rigid format (IRIG-106) (ref. 1), and require an extensive set of ground-based sites that are expensive to maintain and operate. These systems may not be able to meet the requirements of future missions.

The NASA Space-Based Telemetry and Range Safety (STARS) study was established to demonstrate the capability of space-based platforms to provide Range User (telemetry) and Range Safety (low-rate, ultra-high reliability metric tracking, and flight termination data) support. The goals are to reduce the need for down-range ground-based assets while significantly increasing the Range User data rates and operational flexibility.

The STARS is a multiphase project (ref. 2). Phase 1 tested an S-band telemetry system similar to those on current launch vehicles on an F-15B (McDonnell Douglas, St. Louis, Missouri) test aircraft in 2003 using the NASA Tracking and Data Relay Satellite System (TDRSS) as the space-based communications link. These flights characterized the performance during highly dynamic maneuvers and will serve as a baseline for Phases 2 and 3. Phase 2 will use a Ku-band phased array antenna to increase the Range User data rates by an order-of-magnitude. Phase 3 will use a much smaller, lighter weight phased array Ka-band antenna on a recoverable hypersonic vehicle. The TDRSS will be the space-based communications link for both Phases 2 and 3.

This report concentrates on the high-rate Range User telemetry for each of these phases and describes the selection process for the satellite system, antennas, and data format. The operational configurations are also discussed.

PHASE 1

Phase 1 used standard S-band omnidirectional right hand circularly polarized (RHCP) patch antennas on the top and bottom of an F-15B. Each antenna was fed by its own power amplifier. The telemetry modulation used was Binary Phase Shift Keying (BPSK) at rates of 125 kbps, 250 kbps, or 500 kbps for a given test flight. Compressed video was included only in the 500-kbps format.

The Range Safety and Range User systems met the specific objectives to measure the link margins, verify acquisition and reacquisition, and maintain lock between a high-dynamic vehicle and a satellite system. The goal of a 3-dB Range User telemetry link margin was met, and the objective to transmit telemetry to the ground via TDRSS was satisfied.

PHASE 2

The primary objective for Phase 2 is to increase the telemetry data rates. A major weakness in current satellite telemetry systems is the vehicle transmit antenna: most expendable and reusable launch vehicles (ELVs and RLVs) use multiple omnidirectional antennas. Although these systems may be supplemented by switching hardware to direct power to the antenna pointed at the relay satellite, they are inherently limited by transmitter power and low antenna gain. Unmanned aerial vehicles (UAVs) often make use of steerable dish antennas to achieve higher gain and therefore greater data rates. However, these systems need a radome that if placed above the vehicle’s surface can cause thermal problems for launch vehicles, or if recessed in the vehicle can limit the look angles.

The first decision was to select the satellite system. Several satellite systems were investigated for Phase 2, but only TDRSS and Intelsat Global Service Corporation (Washington, D.C.) could support the data rate requirements within the scheduled time frame. Although Intelsat offered lower cost commercial transceivers and antenna system hardware, TDRSS was chosen because it can support higher data rates at an equivalent Effective Isotropic Radiated Power (EIRP), thereby reducing transmitted power and/or antenna gain requirements. Figure 1 illustrates the performance of TDRSS as compared with Intelsat for a given data rate and EIRP (ref. 3).

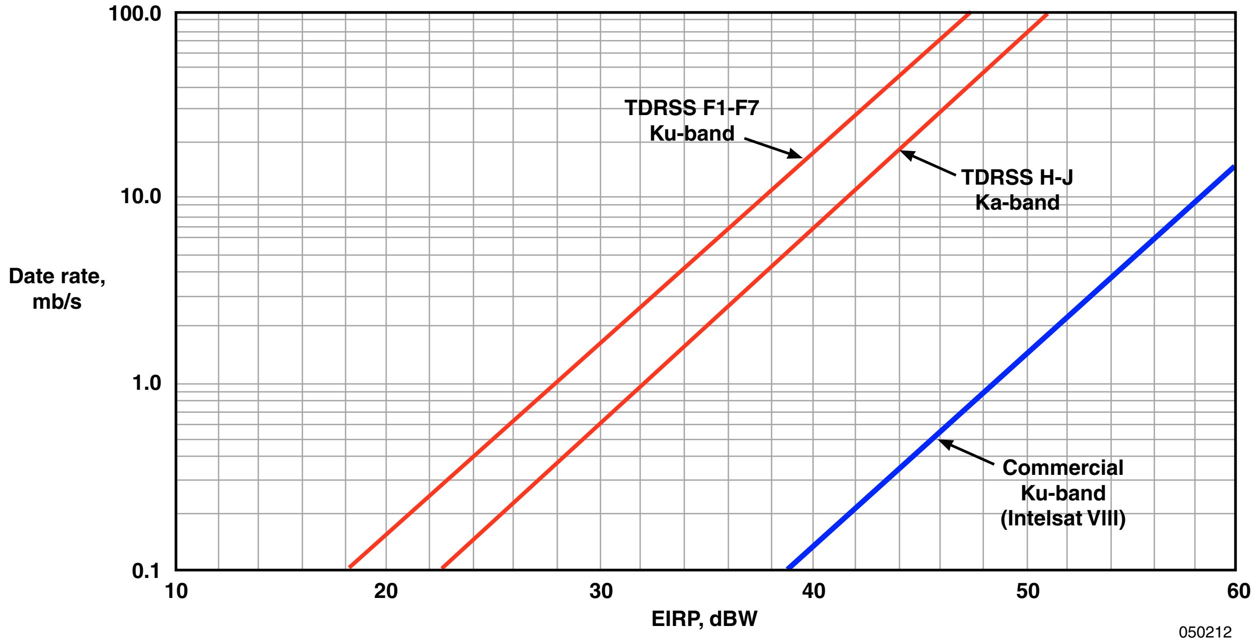

Figure 1. Tracking and Data Relay Satellite System and Intelsat VIII satellite capabilities.

The Ku and Ka TDRSS frequency bands were evaluated for Phase 2. Table 1 summarizes the advantages and disadvantages of each (refs. 4 and 5). Ku-band was selected because the hardware is less expensive and more readily available, and because the lower required antenna gain allows for a wider beam width and less pointing accuracy in an antenna controller system.

Table 1. Tracking and Data Relay Satellite System performance requirements: Ku versus Ka.

Parameter	Ku-band	Ka-band	Comment
TDRS gain advantage	–178.6 dB	–180.7 dB	2.1 dB advantage for Ka-band operation.
Path loss	209.44 dB	213.2 dB	4.8 dB advantage for Ku-band.
Rain loss	2.5 dB	7.8 dB	For Ao-5 percent, region E, 30° latitude, 10° look angle, UAV applications only.
Antenna pointing loss	0.5 dB	0.75 dB	Ka-band requires higher gain (narrower beam width) with 0.25 dB increased pointing error.
Required EIRP	35.82 dBW	38.75 dBW	Ka-band requires ~3 dB more EIRP.
Required antenna gain	23.82 dBi	26.75 dBi	Ka-band requires ~3 dB more gain.
Development complexity	High	Very high	Ku is lower complexity.
Development cost	High	Very high	Less complex, more available parts equals lower cost.
Component availability	Medium	Low	Estimate based on survey of VSAT components.
Asset availability	F series, H, I, J	H, I, J only	Ka-band is limited to H, I, J only.
Footprint	50 to 340 in^3	55 to 374 in^3	Passive Ka-band design slightly smaller.
Power consumption	Medium	High	Ka-band is higher, if MMIC approach is used (more elements, more circuitry).

The antenna selected for Phase 2 is a 184-element phased array from EMS Technologies (Norcross, Georgia) that was leveraged from another project. The antenna is shown in figure 2. It is electronically steerable in elevation and mechanically steerable in azimuth, and is 29.5 inches in diameter, 13 inches deep, and weighs 119 pounds. It will be mounted on the top of the F-15 behind the cockpit. A sample Ku-band TDRSS communications link margin budget is given in table 2 (refs. 4 and 5).

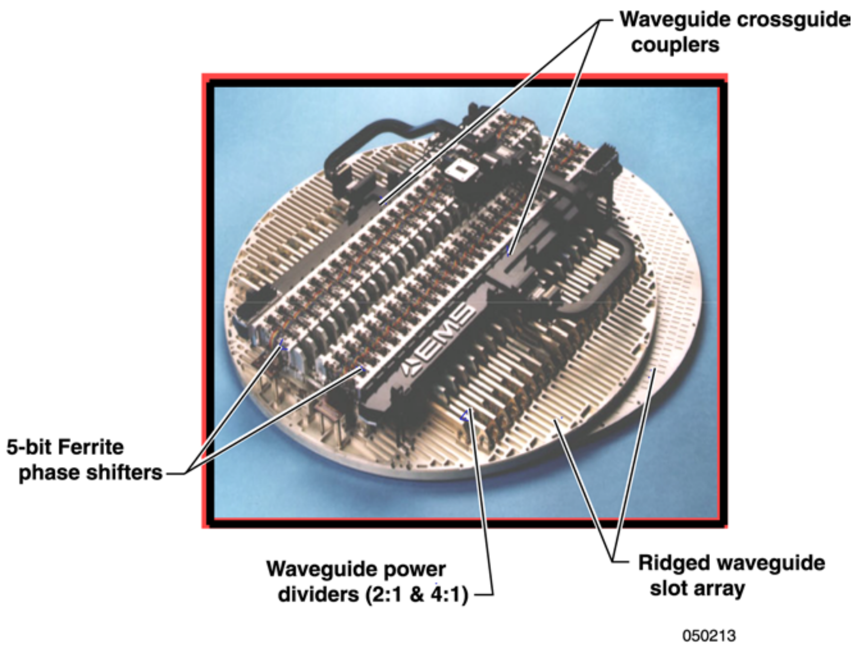

Figure 2. Two-dimensional scanned phased array antenna system from EMS Technologies.

Table 2. Sample Tracking and Data Relay Satellite System Ku-band link margin budget.

Vehicle to satellite link	Value	Satellite to ground link	Value	Ground terminal	Value
User transmit power, dBW	12.00	TDRS EIRP, dBW	51.50	C/N at ground, dB	–4.97
Passive loss, dB	3.00	Path loss, dB	207.29	Bandwidth, dB-Hz	83.52
User antenna gain, dBi	28.00	Rain attenuation, dB	6.00	C/No at ground, dB-Hz	78.55
User EIRP, dBW	37.00	Prec at ground, dBW	–161.99		I-Ch
Space loss, dB	212.65	Ground G/T, dB/K	40.30	Bit rate, dB-bps	70.00
Miscellaneous	0.86	TDRS downlink thermal C/No, dB-Hz	106.91	Eb/No into demodulator, dB	8.55
Prec at input to TDRS, dBW	–176.50	IM degradation, dB	2.28	Implementation loss, dB	2.60
TDRS G/T, dB/K	26.50	Miscellaneous	0.21	Miscellaneous	0.00
C/No at TDRS, dB-Hz	78.60	Total TDRS downlink C/No, dB-Hz	104.63	Net Eb/No, dB	5.95
Bandwidth, dB-Hz	83.52	Bandwidth, dB-Hz	83.52	Theoretical required Eb/No, dB	4.20
C/N at TDRS, dB	–4.93	Total TDRS downlink C/N, dB	21.11	Margin, dB	1.75

Additional technical specifications for this antenna include:

- slew rates: El (elevation): < 7 ms (electronic), Az (azimuth): 40 deg/s (mechanical)
- 28 ± 4 VDC input voltage
- power consumption: 70 W average, 110 W peak
- airborne 2D steered array: Az, mechanical 360 deg; El, electronic ± 60 deg
- 14.85 to 15.15 GHz frequency band
- slotted waveguide array
- right-hand circular polarization (RHCP)

Because fixed data formats require specific and often expensive hardware, and inhibit data distribution to multiple locations, Phase 2 will use a fixed rate IP (Internet protocol) -based data format. This choice will enable seamless routing of data and services. It will also simplify the hardware needed at the ground station. The ultimate goal is to be able to purchase receivers with decoders included and build simple interfaces between the receivers and commercial routers.

All of the required hardware for the Phase 2 test flights has been procured. Integration on the test aircraft will begin late in 2005, followed by compatibility testing of the TDRSS transmitter hardware, testing of the phased array antenna systems, and an interface test with the Global Positioning System (GPS) and inertial navigation system. Eight test flights on an F-15B at the NASA Dryden Flight Research Center (DFRC) are planned for early 2006 using a 5-Mbps Ku-band telemetry link with TDRSS. The overall test configuration is shown in figure 3. The Range Safety configuration will continue to use an S-band TDRSS link.

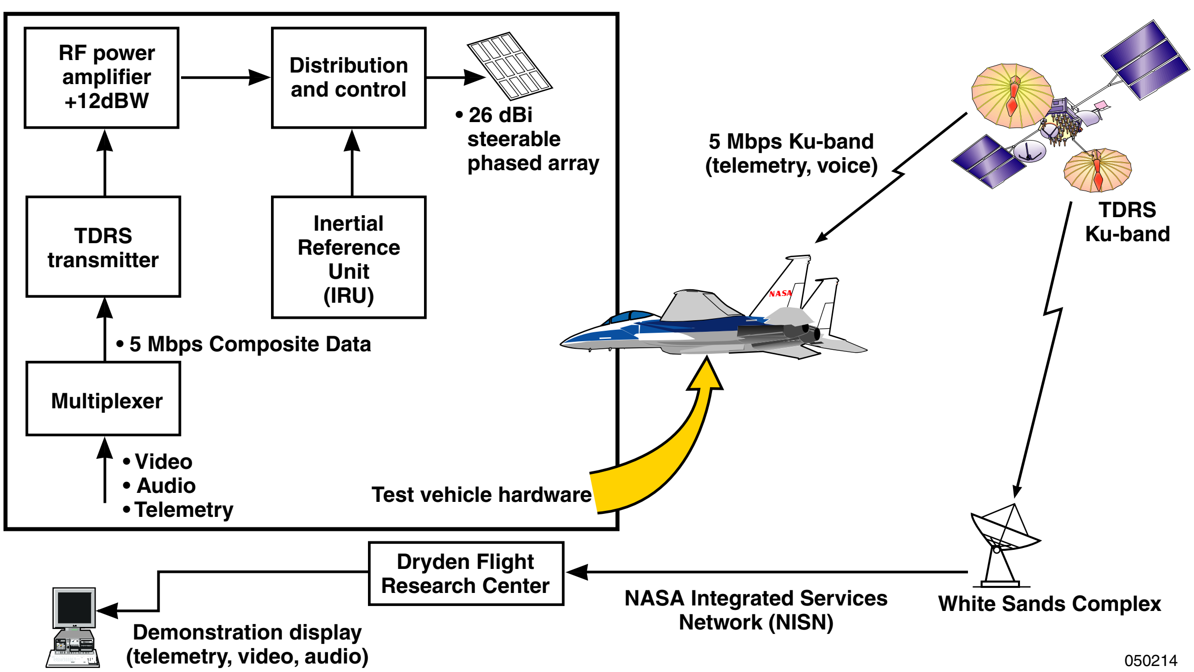

Figure 3. Space-Based Telemetry and Range Safety Phase 2 test configuration.

PHASE 3

This phase will test a prototype of an operational system on a recoverable hypersonic vehicle. The hardware must, of course, be as small and lightweight as possible, so the Phase 2 antenna will be replaced. The requirements for this antenna are:

- airborne 2D steered array: Az, electronic 360 deg; El, electronic ± 60 deg
- 25.25 to 25.7 GHz frequency band (Ka)
- slotted waveguide array
- LHCP

A sample link margin budget for a TDRSS Ka-band link is given in table 3 below (refs. 4 and 5).

Table 3. Sample Tracking and Data Relay Satellite System Ka-band link margin budget.

Vehicle to satellite link	Value	Satellite to ground link	Value	Ground terminal	Value
User transmit power, dBW	12.00	TDRS EIRP, dBW	47.40	C/N at ground, dB	–6.43
Passive loss, dB	3.00	Path loss, dB	207.30	Bandwidth, dB-Hz	83.36
User antenna gain, dBi	23.82	Rain attenuation, dB	6.00	C/No at ground, dB-Hz	76.93
User EIRP, dBW	32.82	Prec at ground, dBW	–166.12		I-Ch
Space loss, dB	208.43	Ground G/T, dB/K	40.30	Bit rate, dB-bps	66.99
Miscellaneous	1.00	TDRS downlink thermal C/No, dB-Hz	102.78	Eb/No into demodulator, dB	9.94
Prec at input to TDRS, dBW	–176.61	IM degradation, dB	1.48	Implementation loss, dB	2.60
TDRS G/T, dB/K	25.03	Miscellaneous	0.22	Miscellaneous	1.00
C/No at TDRS, dB-Hz	77.01	Total TDRS downlink C/No, dB-Hz	101.30	Net Eb/No, dB	6.34
Bandwidth, dB-Hz	83.36	Bandwidth, dB-Hz	83.36	Theoretical required Eb/No, dB	4.20
C/N at TDRS, dB	–6.35	Total TDRS downlink C/N, dB	17.94	Margin, dB	2.14

In conjunction with the NASA Goddard Space Flight Center (GSFC), Harris Corporation (Melbourne, Florida) has developed a Ka-band antenna, shown in figure 4, that meets the following requirements:

- 33 dBW EIRP met for 97 percent scan volume
- approximately 80 W power consumption
- LHCP, 8 to 11 dB cross-polarization isolation
- 71 W dissipated to spacecraft
- 1773 fiber optic command–control interface
- 155 Mbps data rate
- single beam scans ± 60 deg

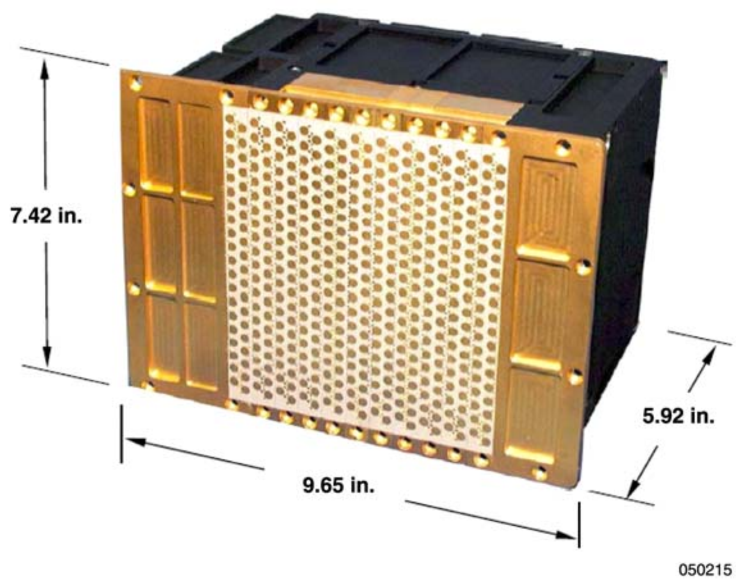

Figure 4. Harris–NASA-developed Ka-band phased array antenna.

The NASA Kennedy Space Center (KSC) holds a Small Business Innovation Research (SBIR) contract with Paratek Microwave, Inc. (Columbia, Maryland) to develop a passive Ka-band phased antenna that uses a new, proprietary method to introduce the phase shifting. The Phase II SBIR will develop a 100-element array, and if successful, a Phase III effort will develop a 1700-element antenna. The conceptual design is shown in figure 5 and additional specifications are given in table 4.

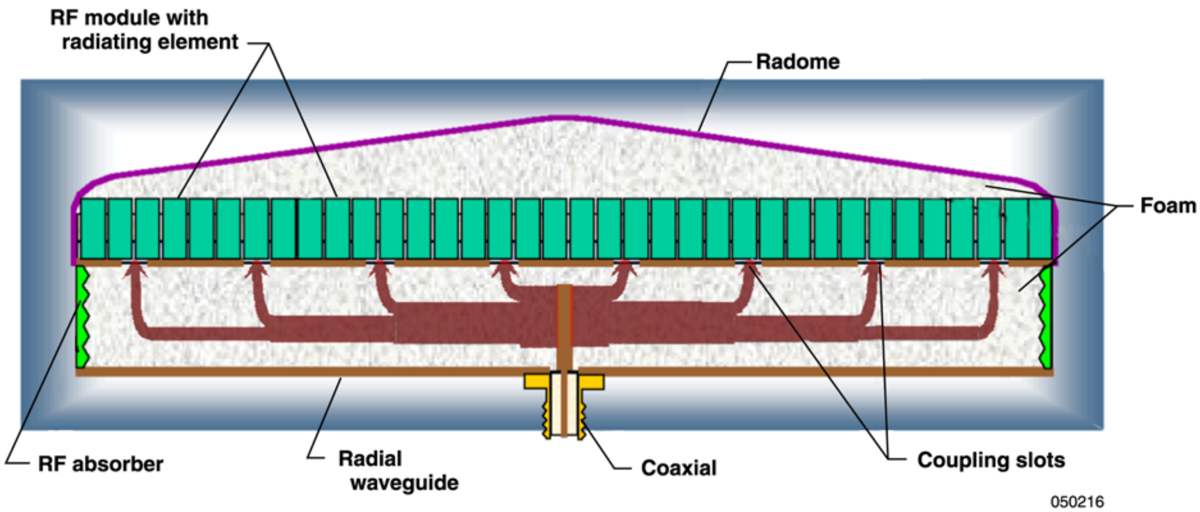

Figure 5. Paratek Ka-band antenna design concept.

Table 4. Phase 3 electrical–radio frequency specifications, 100-element array; 1700-element array.

Electrical–radio frequency specs	100-element array	1700-element array
Frequency of operation	25.25 to 27.5 GHz	25.25 to 27.5 GHz
Instantaneous bandwidth	0.225 GHz	0.225 GHz
Beam scan angle from boresight	60 deg	60 deg
Aperture shape and size	Circular: 0.064 m diameter	Circular: 0.28 m diameter
Half power of beam width		
@ 0 deg scan	9.9 by 9.9 deg	2.3 by 2.3 deg
@ 60 deg scan	9.9 by 19.8 deg	4.6 by 2.3 deg
Net gain		
@ 0 deg scan	> 18.2 dBi	> 30.8 dBi
@ 60 deg scan	> 14.3 dBi	> 26.8 dBi
G/T (90 K effective sky temp)		
@ 0 deg scan	> –5.6 dB/K	> 7.0 dB/K
@ 60 deg scan	> –9.5 dB/K	> 3.0 dB/K
RF input power	15 W maximum	15 W maximum
EIRP		
@ 0 deg scan	30.0 dBW	42.6 dBW
@ 60 deg scan	26.1 dBW	38.6 dBW
Sidelobe level	47 CFR 25.209; < 29-25log(Theta) dB	47 CFR 25.209; < 29-25log(Theta) dB
Front-to-back ratio	> 30 dB	> 35 dB
Polarization	LHCP	LHCP
RF port VSWR	< 1.5:1	< 1.5:1

The test flights for STARS Phase 3 are planned for late fiscal year 2007. The objectives are to demonstrate the ability to maintain a Ka-band TDRSS communications link during a hypersonic flight using small, lightweight hardware compatible with a fully operational system. After these flights are completed and the performance analyzed, a specification will be generated containing requirements to develop and implement an operational system.

SUMMARY

The National Aeronautics and Space Administration Space-Based Telemetry and Range Safety project is developing and testing new high-rate communications systems for a space-based range. The first set of test flights used S-band systems typical of those currently used operationally to obtain a baseline for subsequent development. Phase 2 will use a Ku-band phased array antenna for the telemetry link with the Tracking and Data Relay Satellite System, and Phase 3 will use a Ka-band phased array antenna.

Successful demonstration of the Space-Based Telemetry and Range Safety system will help provide the technology to increase the data rate systems on future expendable launch vehicles, reusable launch vehicles, and unmanned aerial vehicles by at least an order-of-magnitude while eliminating the need for expensive ground support infrastructure.

Dryden Flight Research Center
National Aeronautics and Space Administration
Edwards, California, May 26, 2005

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14. ABSTRACT

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15. SUBJECT TERMS

Ka-band, Ku-band, Phased array antenna, Space-Based Telemetry and Range Safety, TDRSS

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