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Space-Based Telemetry And Range Safety Flight Demonstration #1

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Introduction

This report describes the results from the first series of test flights of the Space-Based Telemetry And Range Safety (STARS) project flown on an F-15B at Dryden Flight Research Center (DFRC) during June and July 2003. STARS is a multicenter National Aeronautics and Space Administration (NASA) proof-of-concept project to determine if operational costs can be reduced and operational flexibility increased by using a space-based communications system to relay telemetry from reusable launch vehicles to the ground and flight termination signals from the ground to a vehicle while providing the necessary reliability and coverage. STARS can also be applied to expendable launch vehicles and unmanned aerial vehicles.

The Stars System

STARS is composed of two major systems: the Range Safety and Range User systems (Figure 1). The Range Safety system used for Flight Demonstration #1 (FD#1) included a new, versatile, low-power transceiver (LPT) with multichannel capabilities coupled with a custom-built command and data handler (C&DH) flight processor and a commercial Ashtech Z-12 C/A code Global Positioning System (GPS) receiver. The LPT received a four-channel 400-bps flight termination system (FTS) link and transmitted telemetry data at 10 kbps containing tracking data, and health and status indicators for the Range Safety system. The Range User system used broadband communications (125 kbps to 500 kbps) for voice, video, and vehicle/payload data. For the launch-head command link, radar data was used to dynamically attenuate the transmitted signal in an attempt to have constant power at the STARS receive antenna input. NASA's Tracking and Data Relay Satellite System (TDRSS) was the space communications link.

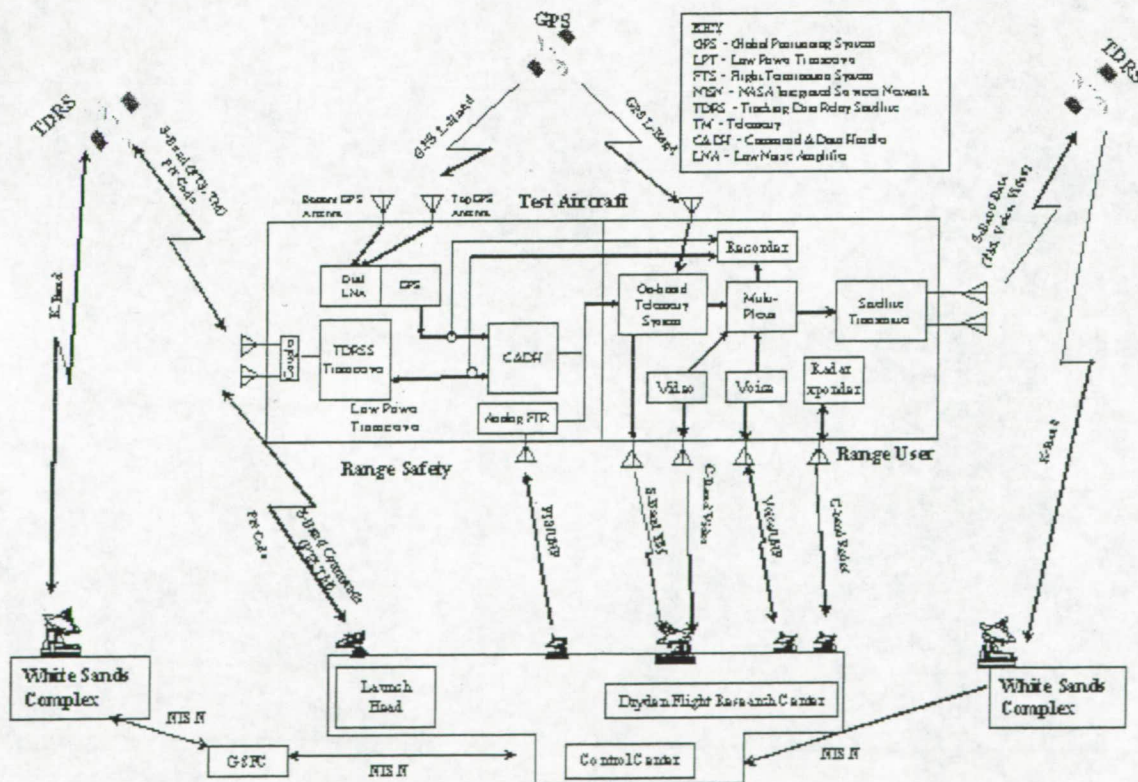


Figure 1. The STARS System for Flight Demonstration #1

The locations of the STARS antennas on the aircraft are shown in Figure 2. The Range Safety system used four S-band antennas (~ 4 inches square by 3/8 inches thick) from Physical Science Laboratories (PSL). There were two antennas on the top of the aircraft and two on the bottom of the aircraft. Each set contained one dual-element antenna for receiving TDRSS/launch-head and GPS signals and another single-element antenna for transmitting to TDRSS/launch-head. The centers of the Range Safety antennas were a few inches off the aircraft's centerline. The top Range Safety transmit antennas were about 27 inches forward of the bottom Range Safety antennas and canted from the horizontal due to the shape of the fuselage.

The Range User system used two transmit-only antennas identical to the Range Safety transmit antennas except for being tuned for different frequencies. One single-element antenna was on the top of the aircraft and another one was on the bottom of the aircraft. The center of the top Range User antenna was about 10 inches forward of the bottom antenna and 48 inches to the right of the aircraft's centerline. The bottom Range User antenna was 3.5 inches to the right of the aircraft's centerline.

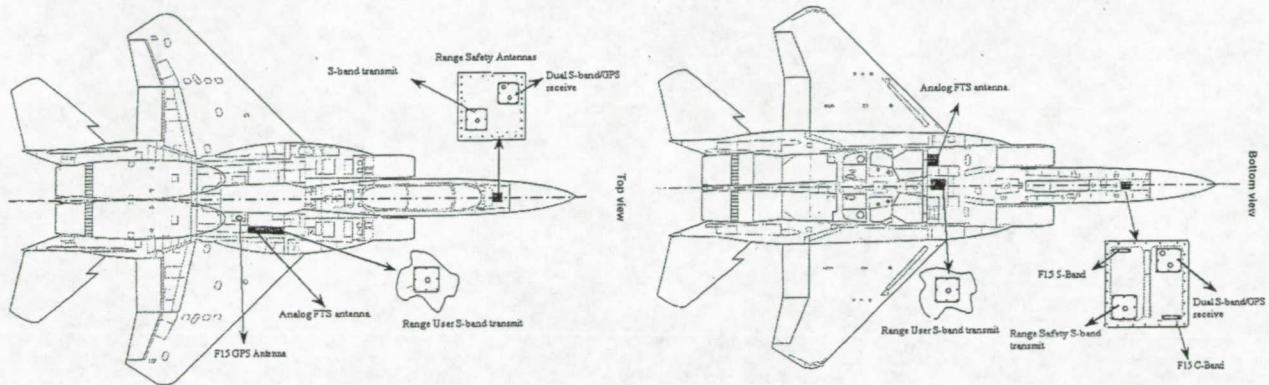


Figure 2. Antenna Locations on the F-15B

The Communications Link Analysis and Simulation System (CLASS) Antenna Radiation Pattern Analysis Tool (ARPAT) used a three-dimensional F-15 model and the patterns of the PSL antennas to estimate the total patterns for FD#1 considering the effects of the mounting on the F-15 and the interferometer effects. The combined Range Safety transmit pattern is shown in Figure 3. Theta is in the plane dividing the aircraft into right and left halves: 0° at the nose, 90° straight up from the aircraft, and 180° at the tail. Phi is in a plane perpendicular to the longitudinal axis of the aircraft: 0° straight up from the aircraft, 90° out the starboard wing, 180° straight down, and 270° out the port wing.

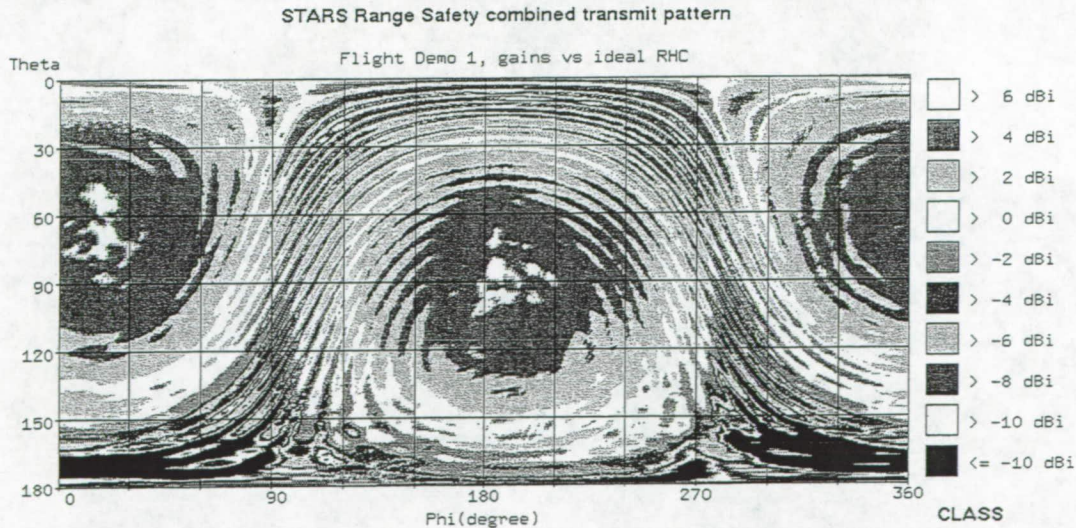


Figure 3. Range Safety Combined Transmit Pattern

Goals and Objectives

The primary goal of FD#1 was to demonstrate and baseline the basic ability of STARS to maintain a communications link* with TDRSS during dynamic aircraft flights. 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-based system. Data latency measurements will be made during Flight Demonstration #2 (FD#2).

The goal of achieving a 12-dB Range Safety command link margin was met. The goal of achieving a 6-dB Range Safety TDRSS telemetry link margin was not always met during the first five flights, although it was met during Flights 6 and 7 after additional power filtering was added as described below. The Range Safety system met additional objectives of simultaneously receiving command links from space and ground transmitters and providing near real-time telemetry to DFRC. This telemetry was also sent to Kennedy Space Center (KSC), Goddard Space Flight Center (GSFC), and Wallops Flight Facility (WFF) in near real time for monitoring.

The goal of achieving a 3-dB Range User telemetry link margin was met. The objective to transmit vehicle Range User data to the ground via TDRSS for relay to DRFC was satisfied.

Flight Summaries

There were seven flights between June 3 and July 15, 2003. A variety of maneuvers was performed and different configurations were tested as summarized in Table 1. Each flight lasted about an hour. All flights took off from and landed on the same runway. All flights except Flight 6 were accompanied by a chase plane.

Table 1. Flight Profiles

Flight	Date	TDRSS ¹	Maneuvers ²	Comments
1	June 3	RS TDRS-W,S RU TDRS-171 at 250 kbps	Straight & Level (Turns) Dynamic (Rolls, Loops, POPUs, Cloverleaves). Launch Vehicle Simulation (rapid ascent/descent)	
2	June 13	RS TDRS-W,S RU TDRS-171 at 500 kbps	Straight & Level (Turns) Supersonic Level Flight	
3	June 17	RS TDRS-171 RU TDRS-S,W at 125 kbps	Straight & Level (Turns) Launch Vehicle Simulation (rapid ascent descent)	Flight recorder problems. No post-flight analysis performed.
4	June 19	RS TDRS-S RU TDRS-W, 171 at 125 kbps	Dynamic (Rolls) Slow POPUs	No FTS commands transmitted.
5	June 24	RS TDRS-W RU TDRS-171 at 250 kbps	Dynamic (Rolls, Loops, POPUs) Launch Vehicle Simulation (rapid ascent descent) Supersonic Level Flight	No Range Safety telemetry link. Frequency clearance not authorized.
6	July 9	RS TDRS-W RU not used	Long Distance Level Flight Straight & Level (Turns)	Only top RS antenna used. Filtered power to HPA for top antenna for first time.
7	July 15	RS TDRS-W RU TDRS-171 at 125 kbps	Dynamic (Rolls, Loops, POPUs) Launch Vehicle Simulation (rapid ascent descent)	No STARS GPS. Filtered power to top/bottom RS transmit antennas.

¹RS=Range Safety, RU=Range User ²POPU=Push Over Pull Up

* "Telemetry link" refers to either a return link from the vehicle to the ground via a satellite or a downlink from the vehicle to a ground-based receiver. "Command link" refers to either a forward link from the ground to the vehicle via a satellite or an uplink from a ground-based transmitter to the vehicle.

Note that there was a pause between Flights 5 and 6 to investigate why the Range Safety telemetry link performance was less than predicted. It was discovered that the high-power amplifiers (HPAs) for the Range Safety transmit antennas used less than optimally filtered power. Additional filtering was added for Flights 6 and 7 and the results of these changes are discussed later.

FTS Command Performance

FTS commands consisting of Monitor, Arm, and Terminate were sent cyclically and manually during each flight except Flight 4 when the FTS frequency was not authorized. The command link data recorded on the ground was compared to the FTS commands received and processed by the Range Safety System that were recorded by the onboard flight recorder. There were approximately 350 sets of Monitor, Arm, and Terminate messages. All of these commands were successfully initiated and accepted during the flights. This does not imply that frames were not dropped, but rather that the commands were successfully received on at least one of the four TDRSS or launch-head channels. As expected, some FTS actions were not initiated due to out-of-sequence commands sent to verify that FTS actions would not be taken. This successfully demonstrated the logic implemented to prevent inadvertent terminations.

Telemetry and Command Data Quality

The data quality analysis was performed on the data transmitted just prior to takeoff until the F-15B returned for landing, except for Flight 6 when the time period was from takeoff to the time the pseudorandom noise generator was turned on. Data quality was characterized by determining the percentage of valid frames sent/received to the total number of frames sent/received for a particular link.

The validity of the Range Safety telemetry data was determined using fields containing predetermined values such as the frame sync pattern, the GPS checksum, and several other unused fields containing static values. This group of data represented nearly 50 percent of an entire telemetry frame. The validity of the Range Safety command data was a two-step process. First, since the onboard telemetry data was used, each frame of this data had to meet the criteria described in the preceding paragraph. Then, the frame sync lock bit for the command data had to be good for the data to be considered as valid. The validity of the Range User telemetry was determined by playing back real-time data tapes and using White Sands Complex (WSC) bit-error-rate (BER) data, predicted link margins, and frame sync statistics. The results are summarized in Table 2.

The Range Safety launch-head telemetry link had similar results for Flights 1, 3, and 4. Flight 2 was the best of the first four flights, probably due to a less dynamic flight profile. Flights 6 and 7 revealed a vast improvement over the first five flights. Recall that Flight 6 flew with only the top Range Safety antenna and that during Flight 7 both STARS HPAs were connected to a regulated power.

The Range Safety TDRSS telemetry link during Flights 1 through 4 had relatively similar results. Flight 6, with the single antenna configuration, showed improvements over the first four flights but flew a rather benign flight profile. Flight 7, which had high dynamics and regulated power for both Range Safety antennas, showed an improvement over the first four flights.

The performance of the command launch-head link remained very consistent except for Flight 6 when there were several large gaps when the command link was lost, most likely due to loss of signal while flying over the horizon from the launch-head with only the Range Safety antenna. The performance of the TDRSS command link remained fairly consistent for all flights. Flight 5 had the smallest percentage of successfully received frames, but the difference was only about 5 percent less than the other flights. The event log was not detailed enough to determine the cause.

The performance of the Range User telemetry links was in accordance with expectations.

Table 2. Data Quality Summary

Flight	RS ¹ Telemetry Link, % Valid Frames			RS Command Link, % Successfully Received Frames		RU Data Quality	
	Onboard	LH	TDRSS	LH	TDRSS	Data Rate (kbps)	Major Frame Match (%)
1	99.96	87.34	61.11	97.26	97.43	250	80.7
2	92.55	90.27	72.60	98.17	97.55	500	51.1
3	74.10	83.50	63.57	97.10	99.28	125	66.9
4	99.99	81.54	59.14	97.78	97.28	125	80.4
5	100.00	N/A	N/A	99.19	92.43	250	87.9
6	96.48	94.94	96.30	81.90	98.96	125	N/A
7	99.99	99.45	74.75	95.38	98.24	125	89.9

¹RS=Range Safety, RU=Range User, LH=Launch-Head

Trajectory and Attitude Determination

The C-band beacon radar tracking data from DFRC was used as truth for all flights except Flight 6, which was over the horizon for much of the flight and for which the STARS GPS data was used. The angular rates about the aircraft's body axes were recorded on the onboard flight recorder. The initial angular rate biases were provided for each flight. The yaw, pitch, and roll angles with respect to the initial orientation of the aircraft just prior to takeoff were obtained by integrating the system of differential equations that transforms from body axes to inertial axes. However, the angular rate data was very noisy and prone to large drifts over short periods of time (~30 s), especially during smooth flight. This required frequent restarts of the integration using the known or presumed orientation of the aircraft obtained from the timelines, videos, and/or radar heading and vertical velocity as initial conditions. Even so, this method was not always sufficient. There were many sections of flight where the pitch and roll were manually generated based on information provided by one of the pilots on the general flight characteristics of the F-15B during various maneuvers and visualization of the results with a 3-D software package (Satellite Tool Kit [STK]). The headings were always available from the tracking data.

GPS Tracking Analysis

A point-by-point comparison between the radar data and the STARS GPS data was done for Flights 1, 4, and 5. Flight 2 was not analyzed because it was not dynamic. Flight 3 was not analyzed because of the flight recorder problems. Flight 6 was not analyzed because much of it was over the horizon and no radar data was available for comparison. Flight 7 was not analyzed because the STARS GPS receiver was not used.

The root-sum-squared (RSS) position differences were ~20 m and the RSS velocity differences were typically a few meters per second, although there were some larger velocity differences due in part to the noisy velocities obtained by numerically differentiating the radar position data. Overall, the results were better than expected for the Ashtech Z-12. There were relatively few GPS dropouts and these usually correlated with times of extreme dynamic maneuvers (e.g., the tops and bottoms of loops and cloverleaves).

Link Margin Analysis

Post-flight dynamic link margin analyses was performed for all flights except for Flight 3. The onboard flight recorder malfunctioned during this flight and the reference data was unreliable. CLASS was used to predict the Range Safety and Range User link margins as functions of time based on the F-15's position, velocity, and attitude. Performance data obtained from the LPT and WSC, the manufacturer's antenna patterns and a 3-D model of the F-15 were also used. Link margins were defined so that a 0-dB margin corresponds to a BER of 10^{-5} .

It is very important to note that the WSC E_b/N_o 's[†] were recorded at 1 Hz, whereas the predicted E_b/N_o s were obtained at 10 Hz using the trajectory and attitude data described above. Moreover, it was discovered after most of the link margin analysis had been completed that the WSC E_b/N_o data was actually a 4-s moving average. It is difficult to assess the impact of this smoothing because the aircraft performed many dynamic maneuvers lasting just a few seconds or even less. This issue has already been resolved for FD#2.

Figure 4 and Figure 5 show the actual and predicted link margins versus time for the Range Safety TDRSS telemetry link during portions of Flights 6 and 7. These plots were chosen because they represent the performance of the Range Safety telemetry system after the additional power filtering was added for the HPAs. The STARS Final Report contains nearly 100 such plots for all the different link margins.

Note that the predicted values generally follow the actuals quite well, indicating that the attitude and trajectory data correlates well with the prediction models. The differences between the predicted and actuals are only 1 to 2 dB for Flight 6 and about 7 dB for Flight 7. The differences for Flights 1 to 5 were about 8 to 10 dB, with actuals being about 5 dB.

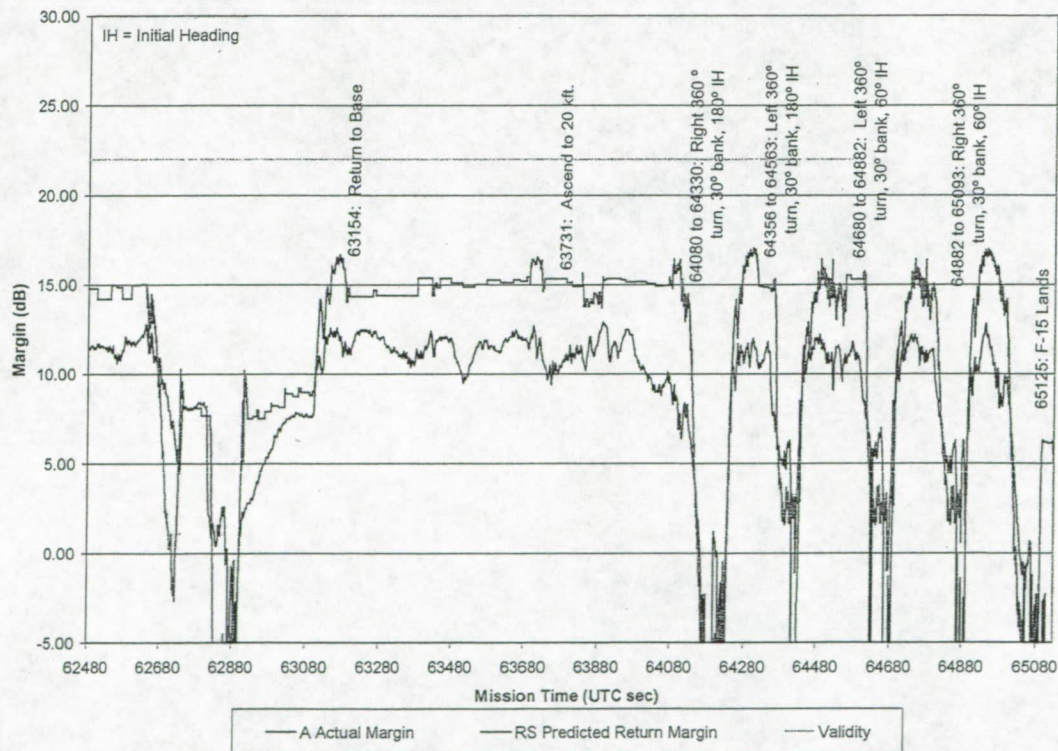


Figure 4. Flight 6 RS Telemetry Link Margins

[†] E_b/N_o is the bit energy E_b (in Watt-seconds) divided by the ambient radio frequency noise N_o (in Watts / Hertz) and is commonly thought of as a signal-to-noise parameter, which characterizes a particular received radio frequency (RF) link

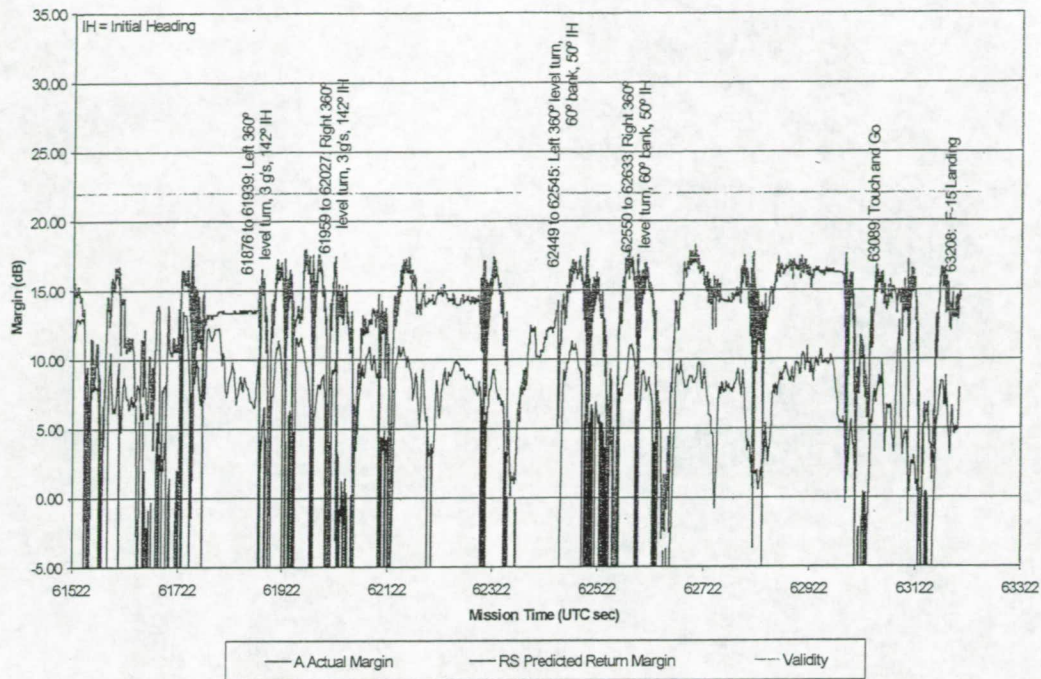


Figure 5. Flight 7 RS Telemetry Link Margins

The actual Range User link margins usually matched or surpassed the predicted. The command link margins were usually within a few dB of the predicted, although one of the TDRSS command channels was occasionally much less. Please see the STARS Final Report for additional details.

Post-flight Testing

Extensive post-flight analysis produced several main results. The positive findings are that the Range User link margins agreed well with predictions, the GPS tracking performed better than expected, and all the FTS commands were received and processed by the Range Safety system onboard the aircraft. The negative results are that the measured TDRSS Range Safety telemetry link margins were less than predicted and the link margins for one TDRSS command link LPT channel were occasionally much less than the other.

As mentioned above, there was a pause between Flights 5 and 6 to investigate why the Range Safety telemetry link performance was considerably less than predicted. It was discovered that the HPAs for the Range Safety transmit antennas used less than optimally filtered power. Additional filtering was added for Flights 6 and 7. The actual Range Safety telemetry link performance on Flight 7 was still less than predicted, although it was better than the first five flights. There is also the unanswered question of the one TDRSS command link LPT channel performing better than the other.

Consequently, additional testing was performed using the flight hardware to attempt to answer these questions. The Range Safety hardware was tested at GSFC and it performed as expected and matched the data taken during the pre-flight testing. The Range Safety antenna patterns were characterized on an F-15 at the Preflight Integration of Munitions and Electronic Systems (PRIMES) at Eglin Air Force Base. The STARS HPAs were not used because no problems had been found with them during the GSFC bench testing. A PRIMES-supplied RF source transmitted at 2287.5 MHz, the same as the Range Safety TDRSS telemetry link. Although resources were not available to measure the complete antenna patterns, enough data was taken to show that the manufacturer's supplied patterns matched the measured reasonably well. The only noteworthy result was that the cockpit seemed to produce more shading (blockage) in the PRIMES data than that predicted by ARPAT.

After the PRIMES testing was completed, additional STK simulations were performed to illustrate the blockage caused by the cockpit canopy. Figure 6 shows snapshots from Flight 7, which used TDRS-W for the Range User system and TDRS-171 for the Range Safety system. These pictures show vectors from the top antennas to the respective TDRSS satellites. Note that these are only vectors and not the full antenna pattern. Recall that the Range User antenna is located in the midsection of the aircraft and the Range Safety antenna is located on the nose of the aircraft.

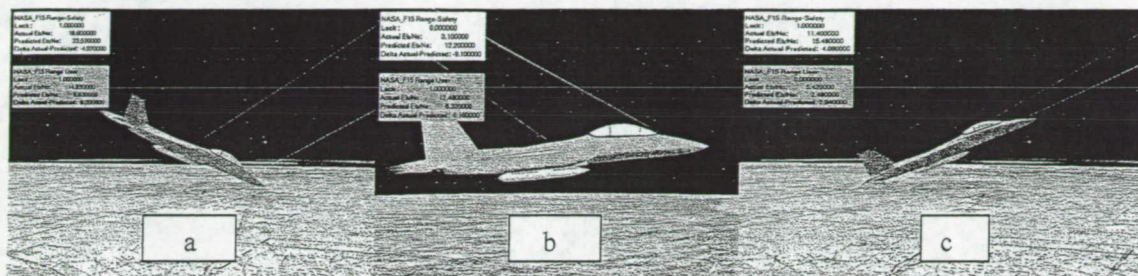


Figure 6. No Blockage of Range User or Range Safety Links

In Figure 6a, there is no blockage of either the Range User or Range Safety links. In Figure 6b, there is no blockage of the Range User link but the Range Safety link is blocked by the cockpit canopy. In Figure 6c there is no blockage of the Range Safety link but the Range User link is blocked by the cockpit canopy.

Conclusions and Lessons Learned for Flight Demonstration #2

The basic ability of STARS to maintain a satellite communications link with TDRSS satellites during dynamic aircraft flights was successfully demonstrated during FD#1. The Range Safety and Range User systems' link margins were measured. The ability to acquire/reacquire and maintain lock between a high-dynamic vehicle and a satellite-based system was demonstrated. The Range Safety system simultaneously received and processed command links from space and ground transmitters and provided near real-time Range Safety telemetry to DFRC, which then sent it in near real time to KSC, GSFC, and WFF for monitoring. The GPS receiver maintained track except during extremely dynamic maneuvers. The Range User system sent data at three different data rates. There were excellent cooperation and support from the different Centers, contractors, and Ranges.

A large amount of data was recorded and extensive post-flight analysis was performed. The Range User TDRSS link margin met or exceeded the predicted performance at three different data rates. The Range Safety launch-head link margins generally agreed with the predicted performance. The GPS positions and velocities agreed with those from tracking radar to within about 20 m and a few m/s.

The link margins for the Range Safety TDRSS telemetry link were less than expected. The link margin for one TDRSS command link LPT channel was occasionally much less than the other. Additional post-flight testing has yet to identify the root causes of these results.

There were many lessons learned from this first set of test flights. The most important one is that more time and testing are needed for each step to deal with the inevitable problems. It is vital that these lessons be among the primary areas of study that will carry over from FD#1 to FD#2, which is currently scheduled for early FY05 at DFRC and will use a specially designed Ku-band phased array antenna for the Range User system.

The next series of flight demonstrations scheduled for late 2004 at DFRC will incorporate many lessons learned from FD#1. A specially designed Ku-band phased array antenna will be used with the Range User system. A test flight on a hypersonic vehicle is planned by the end of 2006.

References

KSC-YA-6400 STARS Final Report, February 10, 2004, and other references contained therein on page 166.