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ANALYSIS OF RETURN AND FORWARD LINKS FROM STARS' FLIGHT DEMONSTRATION 1

James A. Gering
Instructor and Director of Laboratories
Department of Physics and Space Sciences
Florida Institute of Technology

KSC Colleague: Dr. James C. Simpson
Range Systems Design & Development Branch
Spaceport Engineering & Technology Directorate

ABSTRACT

Space-based Telemetry And Range Safety (STARS) is a Kennedy Space Center (KSC) led proof-of-concept demonstration, which utilizes NASA's space network of Tracking and Data Relay Satellites (TDRS) as a pathway for launch and mission related information streams. Flight Demonstration 1 concluded on July 15, 2003 with the seventh flight of a Low Power Transmitter (LPT) a Command and Data Handler (C&DH), a twelve channel GPS receiver and associated power supplies and amplifiers. The equipment flew on NASA's F-15 aircraft at the Dryden Flight Research Center located at Edwards Air Force Base in California. During this NASA-ASEE Faculty Fellowship, the author participated in the collection and analysis of data from the seven flights comprising Flight Demonstration 1. Specifically, the author examined the forward and return links' bit energy E_B (in Watt-seconds) divided by the ambient radio frequency noise N_0 (in Watts / Hertz). E_b/N_0 is commonly thought of as a signal-to-noise parameter, which characterizes a particular received radio frequency (RF) link. Outputs from the data analysis include the construction of time lines for all flights, production of graphs of range safety E_b/N_0 values for all seven flights, histograms of range safety E_b/N_0 values in five dB increments, calculation of associated averages and standard deviations, production of graphs of range user E_b/N_0 values for the all flights, production of graphs of AGC's and E_b/N_0 estimates for flight 1, recorded onboard, transmitted directly to the launch head and transmitted through TDRS. The data and graphs are being used to draw conclusions related to a lower than expected signal strength seen in the range safety return link.

ANALYSIS OF RETURN AND FORWARD LINKS FROM STARS' FLIGHT DEMONSTRATION 1

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1. INTRODUCTION

Space-based Telemetry And Range Safety (STARS) is a Kennedy Space Center (KSC) led proof-of-concept demonstration, which utilizes NASA's space network of orbiting communication satellites as a pathway for launch and mission related information streams. NASA's space network (SN) consists of seven Tracking and Data Relay Satellites (TDRS) in geosynchronous Earth orbit. The project also makes use of another group of orbiting satellites, the Global Positioning System, (GPS) to determine the position and velocity of the flight vehicle. The long-term expectation is for STARS to demonstrate and develop the technology needed to replace much of the extensive, down-range, land-based infrastructure currently used to launch spacecraft and support space missions.

Originally, STARS began as a combination of two Space Launch Initiative proposals: the Space Network Range Safety project proposed by KSC and Goddard Space Flight Center (GSFC) and the Range Safety and Telemetry proposal made by Dryden Flight Research Center (DRFC). Today, STARS receives its continuing funding via the Next Generation Launch Technology (NGLT) program. Today, STARS includes personnel from seven NASA centers. The STARS project management is also in communication with elements of the U.S. Air Force and that organization's effort to modernize its telemetry path through the use of assets in space.

Before each launch of an American rocket (civilian or military) or the space shuttle, the U.S. Air Force and the Federal Aviation Administration opens and clears a volume of air space over either the Atlantic or Pacific oceans. These volumes of air space constitute the Eastern and Western Test Ranges (ER and WR). Each range utilizes a unique assembly of tracking radar antennas, optical tracking telescopes, two-way communication antennas and one-way Flight Termination Signal (FTS) antennas. These facilities must maintain a radar and optical lock on the ascending space vehicle for the first 8.5 minutes of flight. The facilities of the ER are distributed down the length of the Florida coast, on islands in the Atlantic and on U.S. Navy ships in the eastern Atlantic. This extensive infrastructure is complicated, aging and increasingly expensive to maintain. It is estimated each launch in the ER periodically occupies the efforts of 700 people in several civilian and military government agencies. It is further estimated that a space-based replacement of much of this infrastructure would cost on the order of $6 million per year as compared to today's $15 million. [1].

Furthermore, STARS represents a paradigm shift from reliance on personnel, ground-based facilities and analog communications to reliance on significantly fewer personnel, space-based assets and digital communications technologies. At some point in the future, it is expected that numerous spaceports will be distributed across the United States and many countries around the world. Given the large geographic coverage provided by constellations of satellites, STARS can be viewed as one step toward enabling the eventual development of a network of spaceports for more routine and frequent access to space.

2. FLIGHT DEMONSTRATION 1

The STARS project is divided into three chronological phases: Flight Demonstrations 1, 2 and 3. Each phase of the project involves several flights of a set of GPS and TDRS transceivers. Flight Demonstration 1 concluded on July 15, 2003 with the seventh flight of a Low Power Transmitter (LPT) a Command and Data Handler (C&DH), a twelve channel GPS receiver and associated power supplies and amplifiers. The equipment flew on NASA's F-15 aircraft at the Dryden Flight Research Center located at Edwards Air Force Base in California. Flight Demonstration 2 is anticipated to again fly on NASA's F-15 while Flight Demonstration 3 will utilize an expendable launch vehicle to test the system through orbital insertion.

The purpose of this NASA-ASEE Faculty Fellowship was to assist in analyzing a portion of the data gathered through Flight Demonstration 1 and to gain increased knowledge and experience in digital satellite communications and other space launch and range technologies. Due to the size and complexity of the project, the remainder of this report will focus on

- A qualitative description of the data streams
- Examination of a parameter to characterize one data stream for all seven flights
- Examination the same parameter for the Flight Termination System (FTS) signals.
- A summary of notable events which marked the seven flights

3. THE DATA STREAMS

The data streams acquired during Flight Demonstration 1 are typically characterized by the terms 'forward' and 'return' link with the LPT and C&DH on the aircraft as the reference point for these two terms. The LPT terminates in two patch antennas, which are 4-inch by 4-inch plates mounted on the top and bottom of the F-15 fuselage, forward of the pilot's canopy. Each patch antenna receives flight termination commands (sent via TDRS) on two S-band frequency channels. Thus, in the forward link, four data streams are received by the LPT. The forward link to the aircraft consists of the monitor, arm and terminate commands of the FTS. This information is transmitted in 64 bit words. The same two antennas transmit a return link consisting of

- range safety information: x, y, z position and velocity components derived from signals received by the GPS antenna
- vehicle orientation information derived from the F-15's inertial measurement unit
- timing information
- a variety of digital frame synch information
- calculated values which correspond to the signal-to-noise ratio of the forward link information.

The return link consists of frames of 62 words, each word contains 16 bits and it is transmitted at 10,000 bits per second (bps). This contrasts with the FTS rate of 400 bps. The difference in data rate owes to an inherent trade-off, which occurs in any digital spread spectrum radio frequency transmission. Essentially, there is an inverse relationship between data rate and signal strength-to-noise. Since flight termination commands occupy the highest priority signal within the range safety community, they are transmitted at the lowest bit rate to maximize the probability of reception.

This project examined the forward and return links' bit energy E_B (in Watt-seconds) divided by the ambient radio frequency noise N_0 (in Watts / Hertz). For the return link, personnel at the White Sands Complex (WSC) in New Mexico calculate this ratio, E_b/N_0. For the forward link, values for E_b/N_0 are estimated from the automatic gain control on the LPT. Eb/N_0 is commonly thought of as a signal-to-noise parameter, which characterizes a particular received RF link. [2] Eb/N_0 is indicative of the received strength of the signal carrying the information. It is not the information itself. Hence the forward link Eb/N_0 characterizes the FTS data stream (i.e. the forward link). These values are recorded on a magnetic tape cartridge onboard the aircraft, they are also transmitted directly to the launch head at Dryden and also transmitted through TDRS as part of the 10 Kbps return link. The significance of a high value of E_b/N_0 can be seen in Figure 1 where a precipitous drop in the bit error rate occurs when E_b/N_0 decreases by a relatively small amount. [3]

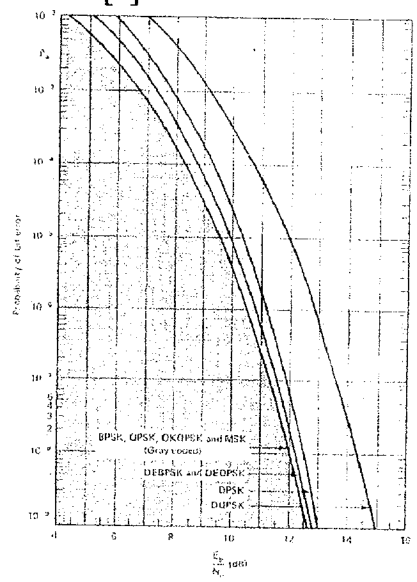

Figure 1. Theoretical probability of bit error vs. E_b/N_0 for several types of phase modulation.

4. OUTPUTS FROM THE DATA ANALYSIS

- Construct timelines for all flights from summaries and flight cards provided by DRFC
- Return Link Analysis:
    - 37 graphs of range safety E_b/N_0 for all seven flights
    - Histograms of range safety E_b/N_0 in five dB increments
    - Calculated averages and associated averages and standard deviations

    - 30 graphs of range user E_b/N_0 for all seven flights
    - Correlate all graphs with timelines
- Forward Link Analysis:
    - 50 graphs of AGC's and E_b/N_0 estimates for flight 1, recorded onboard, transmitted directly to the launch head and transmitted through TDRS

The STARS range safety experiment hypothesis is the anticipation that both forward and return links will exhibit sufficient signal strength, information quality and incidence of confirmed signal reception. An important secondary test is to characterize yet another group of data streams termed the 'range user' information. These signals consist of only a TDRS return link and are generated onboard the aircraft. The data rate for the range user signals is significantly higher, 125 Kbps, and (in the future) would contain information generated by the launch vehicle's payload and/or video cameras.

The return link E_b/N_0 values are calculated once every second by NASA-JSC personnel at WSC. [4] This value accounts for various energy losses that occur while the digital RF signal is travels from the aircraft through TDRS and then to the ground station in White Sands, New Mexico. Examples of ways in which power can be lost include atmospheric moisture, thermal background RF noise, and interference from reflected microwave frequency signals, antenna inefficiencies. Figures 2 displays the approximately 10,000 E_b/N_0s calculated for the first flight as a function of universal coordinated time (UTC) and Figures 3-4 display expanded segments of the flight with vertical markers indicated when the aircraft executed a particular maneuver. The F-15 flew several compass headings, 360° loops, push-over / pull-ups (i.e. dives) and 360° rolls. The rolls were executed at three differing angular rates of change and are labeled quarter, half and full stick, which is a reference to how far the pilot moves the flight control stick to rotate the aircraft about it's long body axis. One maneuver was designed to mimic (in reverse) the climb and rotation the space shuttle executes immediately after launch.

The forward link E_b/N_0 values are calculated ten times every second in the C&DH and then transmitted through TDRS to WSC. This higher data rate made generation and manipulation of the plots more time consuming and cumbersome, as did certain limitations in Microsoft Excel. [5] Four Visual BASIC scripts where developed to automate portions of the task. Nevertheless, since each flight had its own unique timeline of maneuvers, it was necessary to repeatedly handle the data and the graphs manually. Also it was of interest to compare the forward link values from the onboard data recorder and the same values transmitted to the launch head and through TDRS. Since the forward link is received on two channels for each of two antennas and is recorded at three locations, the multiplicity of the task for the forward link grew. For the first flight 60 plots were generated for the forward link and over 60 for the return link for all flights.

Figures 3 and 4 depict the drops in received power suffered after takeoff, push-over / pull-ups (POPUs) and rolls. The stepped 5 dB decline seen late in Fig. 4 is a typical example of the performance obtained in other flights when the aircraft flew level at a particular compass heading. Ostensibly, these portions of the flight should provide the most constant value of E_b/N_0. However, in many instances this was not the case.

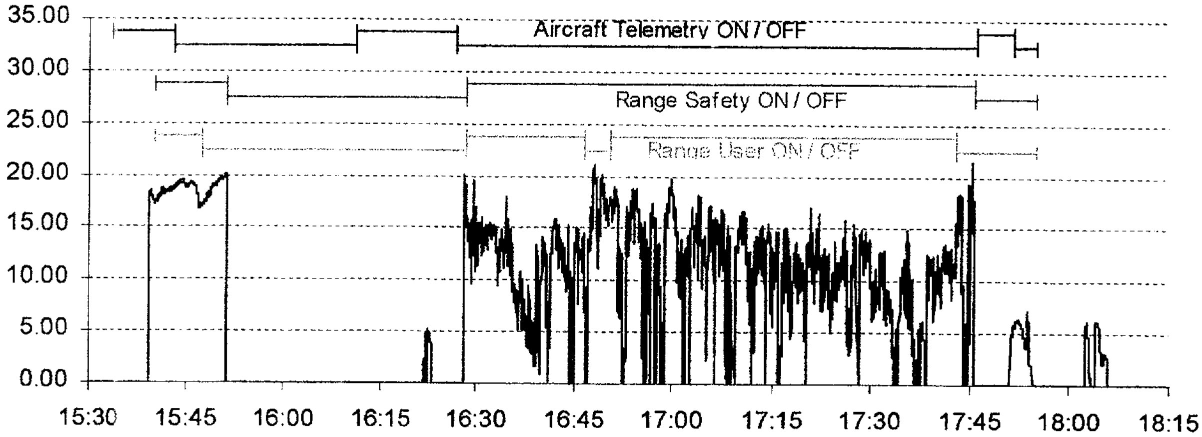

Figure 2. E_b/N_0 for flight 1's return link

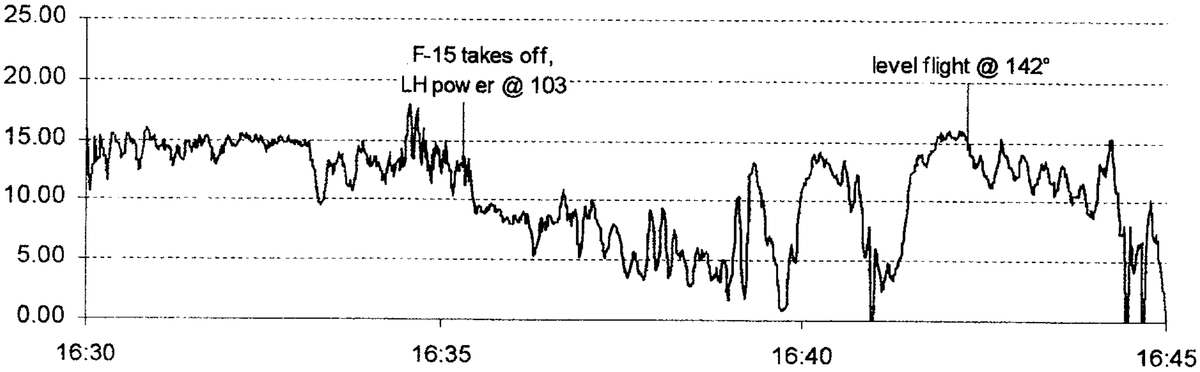

Figure 3. Expanded and labeled E_b/N_0 for flight 1

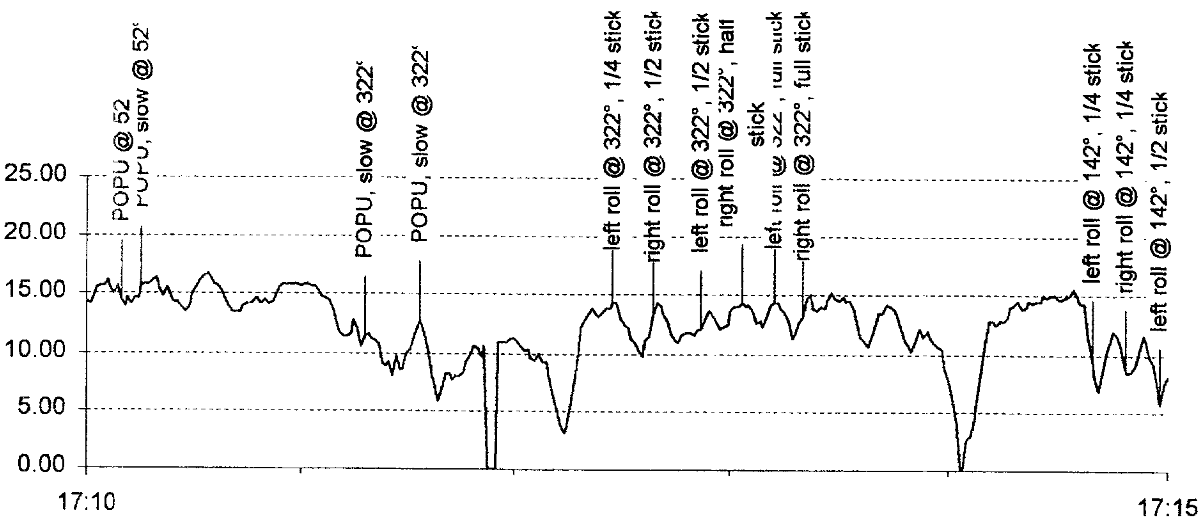

Figure 4. Expanded and labeled E_b/N_0 for flight 1

5. EVENTS DURING THE FLIGHTS

As the flights and data analysis progressed, the low average values of E_b/N_0 for the return link caused concerns among the STARS team. Competing hypotheses developed to explain the low values. One was possible interference between the range safety and range user transmissions. Another was that the voltage generated onboard the aircraft contained sufficient ripple to compromise the performance of the LPT's high power amplifiers. After the fourth flight, the decision was made to temporarily suspend further flights. A plan developed to install a power filter on the F-15 to address the second hypothesis. Also there was insufficient time between flights 4 and 5 to implement this change so flight 5 was conducted on schedule. Perhaps as an omen, an electronic problem onboard the aircraft made it impossible to transmit range safety information during flight 5. Additionally, the range user transmission was turned off during all of flight six to address the first hypothesis.

As the reader may note, two changes to the system were implemented for flight 6 rather than making one change at a time and addressing its impact. To further complicate matters, flight 6 had a very different character than all other flights. During flight 6 the aircraft flew aa level box pattern around the perimeter of the Dryden Flight Research Center to test the system beyond the reach of the launch head radars. Thus flight 6 contained none of the high dynamic maneuvers of flights 1 through 5. The values of the return link E_b/N_0 for flight 6 did show an average increase of 2 dB over earlier flights. Flight 7 contained a smorgasbord of maneuvers from all previous flights and the range user transmitter was on for the entire flight. The E_b/N_0 values again dropped to previous levels. A histogram of the values of E_b/N_0 in 5 dB increments is seen in Figure 5. Table 1 gives the average and sample standard deviations of this parameter for the return link's range safety transmissions.

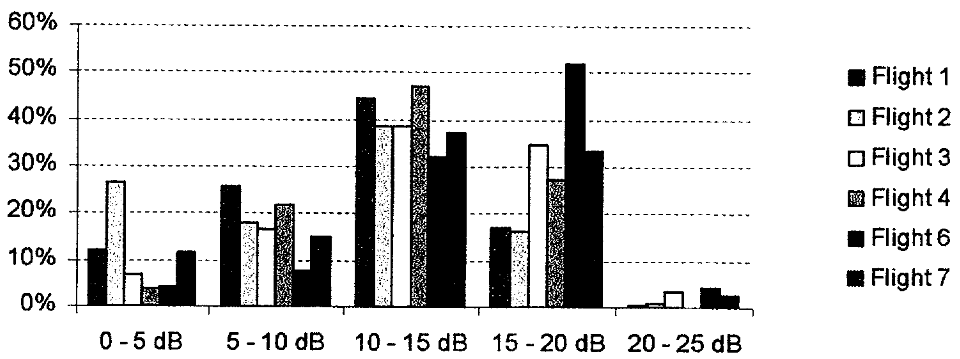

Figure 5. Histogram of range safety, return link E_b/N_0 values for all flights

Flight No.	1	2	3	4	6	7
Average	10.9	9.9	12.9	12.2	14.5	12.1
Stnd. Dev.	4.5	5.1	4.9	3.3	4.3	5.3

Table 1. Return link, range safety averages and standard deviations of E_b/N_0 values

In order to terminate the flight of an errant launch vehicle, the vehicle must receive a sequence of Monitor, Arm and Terminate commands. Again, this relies upon a low bit error rate and sufficient signal strength to noise. Flight 1's forward link E_b/N_0 values indeed demonstrate some fluctuations due to the high dynamic flight maneuvers. However, overall signal strength appears to be sufficient. Figures 6 and 7 compare one channel from the forward link as recorded onboard the aircraft and relayed through the TDRS to WSC. The numerous drops to zero are indicative of the signal's path through the ionosphere (twice) and inherent losses in passing through the TDRS.

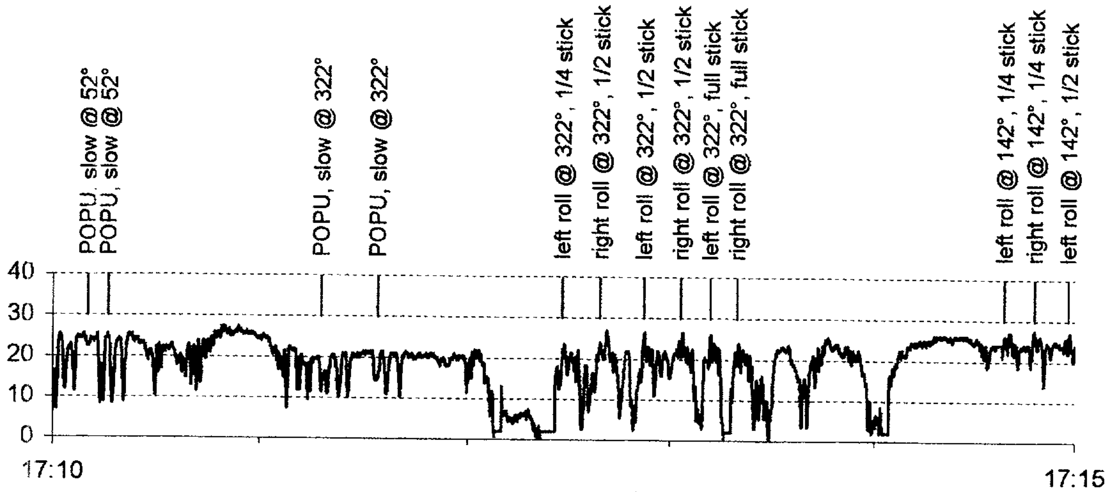

Figure 6. Forward link values of E_b/N_0 recorded onboard the aircraft

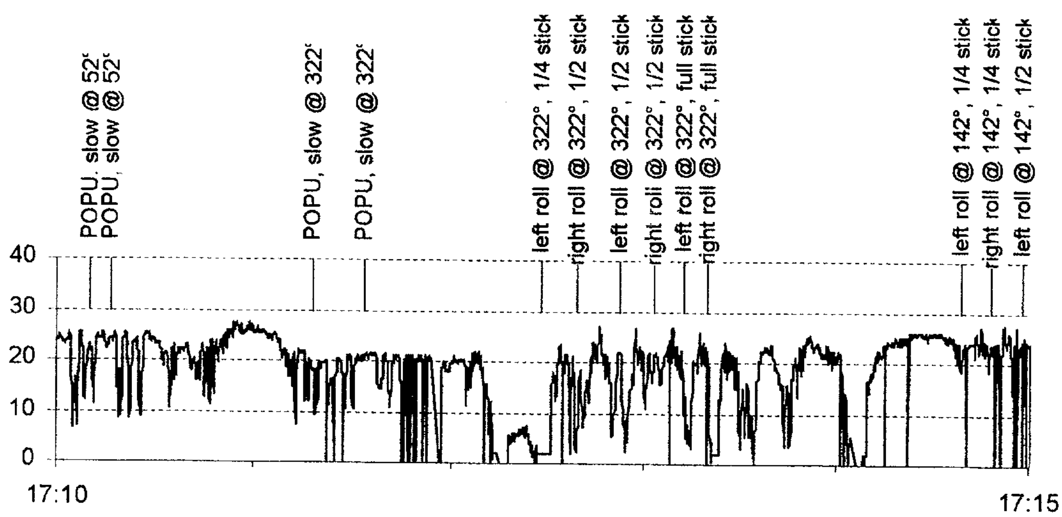

Figure 7. Forward link values of E_b/N_0 transmitted through the TDRS

6. CONCLUSIONS

During flight 7, transmitted power from the launch head was decreased by 7dB to challenge the system to receive the signals. Nevertheless, the range safety forward link through the launch head and through TDRSS appeared to be strong as determined by real-time indicators on the control consoles during the flight. The range user system also appeared to perform well based upon this first assessment and post-flight graphs of E_b/N_0 as prepared by the author. At this point in the post-flight analysis, the increase in the return link's signal strength seen in flight 6 was likely due to the level flight pattern. The patch antennas nominally radiate power in a hemisphere. However, they do have null regions and these likely give rise to the dips seen in Figs. 3 and 4. An open question remains as to the impact of interference caused by signals reflecting off of the aircraft's fuselage, wings and tail fins during high dynamic maneuvers. This issue must await a more detailed RF interference analysis of the F-15. Overall, the seven test flights comprising Flight Demonstration 1 were extremely successful. A tremendous amount of data was collected and is being analyzed. This NASA-ASEE fellowship evolved into a project in data management and visualization, which is necessary for further analysis by the STARS team.

The author would like to acknowledge and sincerely thank all the members of the STARS team and the NASA-KSC Faculty Fellowship team. In particular, Dr. Jim Simpson devoted significant time and energy in support of this work. I greatly enjoyed and benefited from the opportunity to attend the ASTWG/ARTWG conference in May and travel to Dryden for the first flight. I look forward to a continued relationship with the Range Systems Design & Development Branch of Kennedy Space Center.

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