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High-Rate Wireless Airborne Network Demonstration (HiWAND) Flight Test Results

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March 2008

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ABSTRACT

An increasing number of flight research and airborne science experiments now contain network-ready systems that could benefit from a high-rate bidirectional air-to-ground network link. A prototype system, the High-Rate Wireless Airborne Network Demonstration, was developed from commercial off-the-shelf components while leveraging the existing telemetry infrastructure on the Western Aeronautical Test Range. This approach resulted in a cost-effective, long-range, line-of-sight network link over the S and the L frequency bands using both frequency modulation and shaped-offset quadrature phase-shift keying modulation. This report discusses system configuration and the flight test results.

NOMENCLATURE

ATF	Aeronautical Tracking Facility
BER	bit error rate
demod	demodulator
DFRC	Dryden Flight Research Center
FM	frequency modulation
FPGA	field-programmable gate array
FTP	file transfer protocol
HDLC	high-level data-link control
HiWAND	High-Rate Wireless Airborne Network Demonstration
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet protocol
IRIG	Inter-Range Instrumentation Group
Mbps	megabits per second
msec	millisecond
MSL	mean sea level
NASA	National Aeronautics and Space Administration
PCM	pulse code modulation
pre-mod	premodulation
SOQPSK	shaped-offset quadrature phase-shift keying
TCP	transmission control protocol
TM	telemetry
TR	TinyRouter™
UDP	user datagram protocol
WAN	wide area network
WATR	Western Aeronautical Test Range

INTRODUCTION

Flight research and testing has traditionally featured instrumenting a flight vehicle with a wide variety of sensors and telemetering the measured data to a single mission control center. Typically, a highly-specialized system designed for the sole task of multiplexing data from sensors or other slave systems and generating a pulse code modulation (PCM) output is utilized on the aircraft for providing this data downlink. Today, research and airborne science aircraft are becoming more heavily integrated with network-ready systems and sensors that are inherently capable of high-speed bidirectional communications. The goal of the High-Rate Wireless Airborne Network Demonstration (HiWAND) testing was to utilize existing commercial off-the-shelf (COTS) equipment to provide a high-speed bidirectional network communication link between the aircraft and ground assets identical to that of a wide area network (WAN).

OBJECTIVES

1. Demonstrate that existing IRIG-106 (ref. 1) telemetry (TM) hardware can support high-rate Internet protocol (IP) based bidirectional communications over existing TM bands.
2. Use Advanced Range Telemetry (ARTM) Tier I shaped-offset quadrature phase-shift keying (SOQPSK) (ref. 2) modulation for double the bandwidth efficiency of pulse code modulation / frequency modulation (PCM/FM).
3. Quantify overall system performance:
   - data throughput: conduct file transfer protocol (FTP) file transfers and transmission control protocol (TCP) and user datagram protocol (UDP) throughput tests
   - packet loss: conduct ping tests and transmit UDP packets at various bit rates up to the TM link rate to measure the packets lost
   - packet round-trip time: conduct ping tests to measure the round-trip time of packets of various sizes to within 1 msec
   - repeatability: evaluate system performance at the same flight conditions multiple times.
4. Evaluate system performance at 5 Mbps and 10 Mbps TM link rates.

SUCCESS CRITERIA

For the purpose of distinguishing between merely transmitting and receiving network data and demonstrating that the system is a viable option to support future flight test programs, the following success criteria were defined:

1. Distance: demonstrate an operational bidirectional link to a range of at least 150 miles
2. Throughput: achieve at least 4.5 Mbps data throughput at or beyond the distance criteria.

EXPERIMENT IMPLEMENTATION

The HiWAND utilized a TinyRouter™ (TR) (RAD Data Communications, Inc., Mahwah, New Jersey) to provide the interface between ground and aircraft IP-based systems, and the TM systems as shown in figure 1. The TR is a miniature IP router with a local area network (LAN) interface compatible with the IEEE 802.3 (wired Ethernet) standards on a standard RJ-45 connector. The HiWAND configured the WAN interface for high-level data-link control (HDLC) protocol over a half-duplex link. The main reason the HDLC protocol was chosen for the WAN interface was that HDLC allows the generation of a constant bit stream from packetized data by inserting fill bytes (0x7E) during data null periods. It should be noted that this is inherently different from generating a PCM bit stream according to a fixed frame format. For proper SOQPSK modulation and bit synchronization, the HDLC data was randomized prior to TM transmission. The HiWAND used a small field-programmable gate array (FPGA) board to randomize and de-randomize the HDLC data.

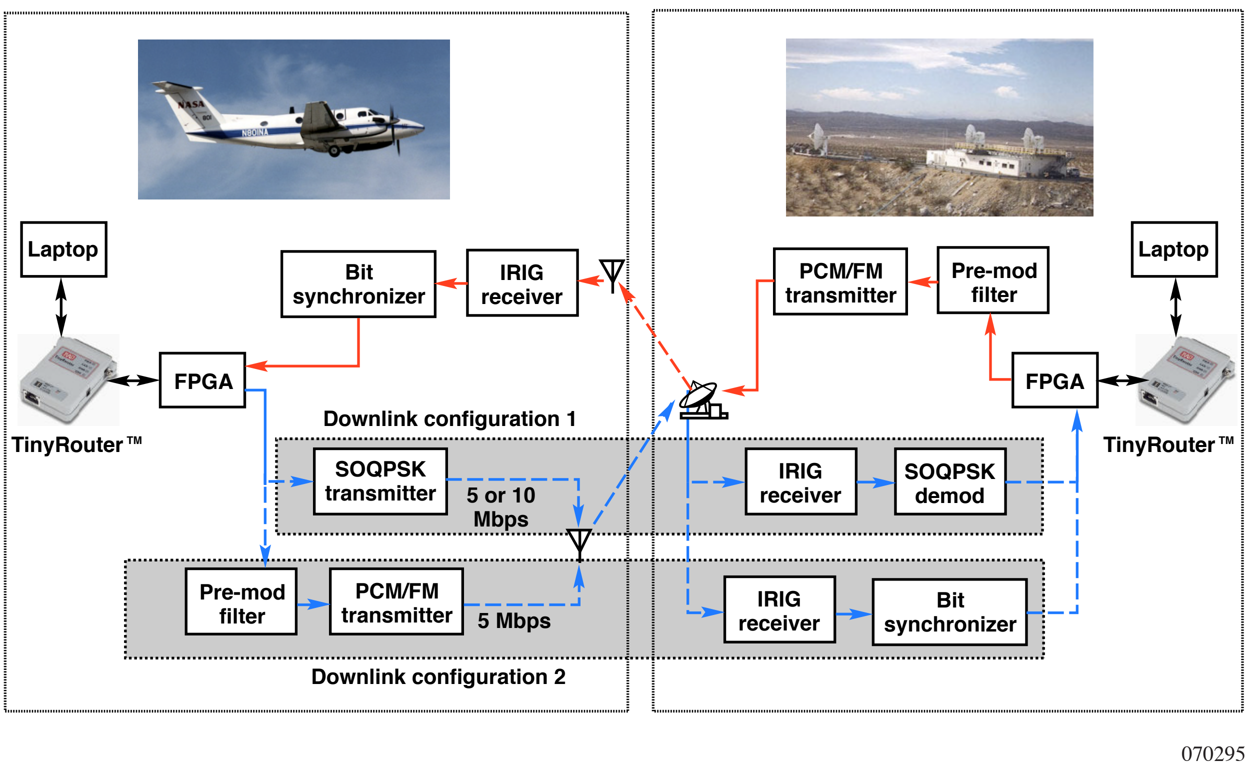

Figure 1. The High-Rate Wireless Airborne Network Demonstration flight-test configurations.

The ground TM uplink/downlink system was located at the Aeronautical Tracking Facility (ATF) within the Western Aeronautical Test Range (WATR) (ref. 3) and used a 7-meter reflector. A standard PCM/FM transmitter was used to transmit, or uplink, on upper L-band frequencies for all flights. A PCM/FM receiver with either a separate SOQPSK demodulator or a bit synchronizer was used to receive data on S-band or lower L-band frequencies, depending upon the aircraft configuration for a particular flight.

The TM uplink/downlink system on the airplane (a Beechcraft 200 Super KingAir) (Hawker Beechcraft Corporation, Wichita, Kansas) used two separate omnidirectional blade antennae on the lower surface of the wings near the fuselage. All flights used a 19-inch rack-mounted PCM/FM receiver and bit synchronizer to receive data on upper L-band frequencies. Different transmitters were tested while troubleshooting a downlink problem encountered during the initial five flights. The downlink transmitter types tested were: 5-watt S-band SOQPSK, 5-watt L-band PCM/FM, and 10-watt S-band PCM/FM. The first six of a total of seven flights were configured for both an uplink and downlink rate of 5 Mbps. The last flight was configured for an uplink rate of 5 Mbps and a downlink rate of 10 Mbps. The overall system configurations are presented in figure 1, including both SOQPSK and PCM/FM downlink configurations 1 and 2, respectively.

FLIGHT CONDITIONS AND MANEUVERS

All flights were conducted under the following conditions within the normal Super KingAir flight regime:

Altitude:	25,000–35,000 ft MSL
True airspeed:	250 kn
Maneuvering:	straight and level
Flight duration:	2–3 hr

FLIGHT SUMMARIES

Seven flights were conducted over 18.7 hr of flight time. A description of each flight configuration and the results are presented below.

Flight 1, September 21, 2005: The SOQPSK transmitter was used for downlink. Ground preflight tests measured the system operating at full performance (approaching 5-Mbps throughput). Data dropouts and inversions were noted while the airplane was taxiing and were not eliminated when the airplane became airborne. Data inversions were corrected manually through the demodulator at the ATF. The data inversions led to low throughput measurements, aborted tests, and high packet losses.

Flight 2, September 22, 2005: The SOQPSK demodulator at the ATF was suspected of having contributed to the data dropouts and inversions experienced during Flight 1. The demodulator was replaced before Flight 2; however, there was no measured improvement.

Flight 3, September 28, 2005: Because the data dropouts and inversions appeared predominantly in the downlink, the SOQPSK transmitter was replaced with an L-band PCM/FM transmitter and premodulation filter. This reconfiguration eliminated the data inversions, but the throughput still suffered substantially. During Flight 3, it was noted that the throughput increased with decreasing range, as shown in figure 2. It was also noted that within a range of 35 mi, throughput approached the 5-Mbps limit.

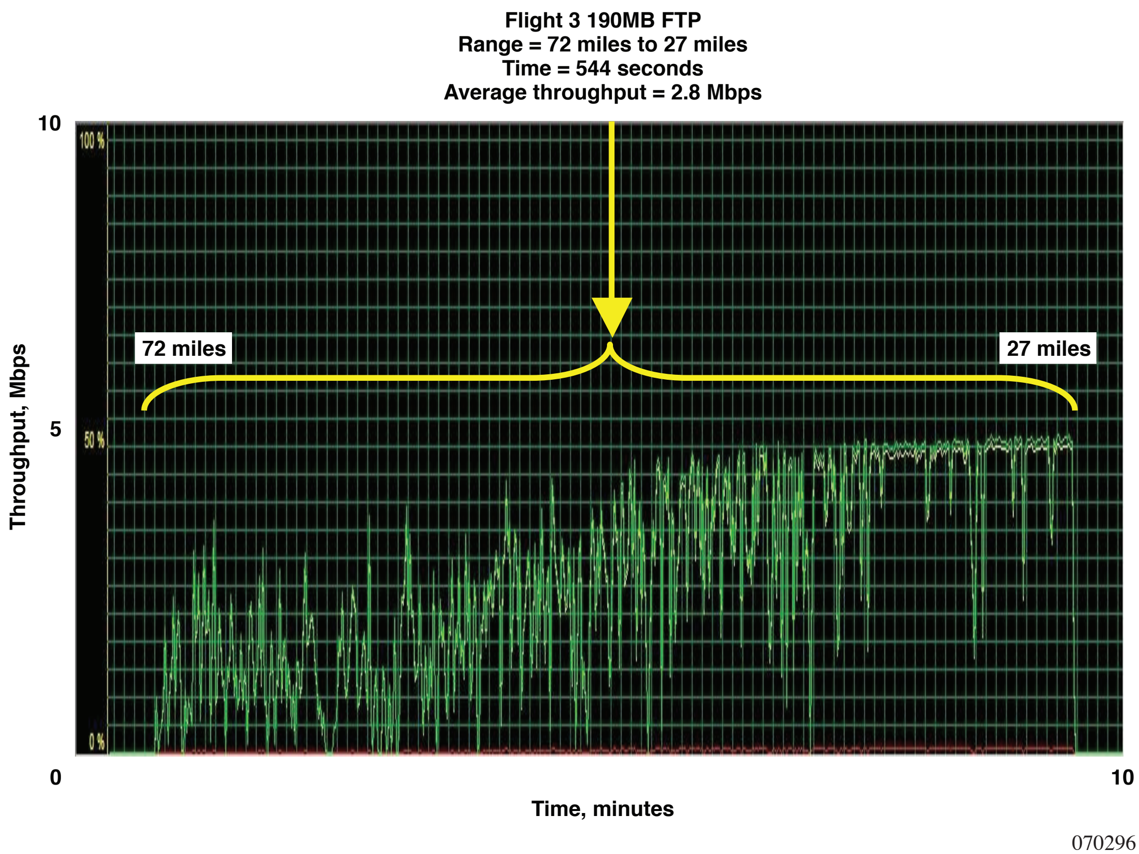

Figure 2. Flight 3 FTP transfer with decreasing range.

Flight 4, September 29, 2005: In order to characterize the system, the testing range for Flight 4 was restricted to 35 mi from the ATF. By testing within this limited range, the system throughput was greater than 4.5 Mbps and had few lost packets. It was also noted during Flight 4 that the deviation of the radio frequency (RF) spectrum was insufficient. The incorrect deviation was attributed to using an airborne transmitter that was configured for a much lower data rate.

Flight 5, October 11, 2005: The 5-watt transmitter having incorrect deviation was replaced with a 10-watt S-band transmitter having proper deviation. The higher power and correct deviation did not improve the testing range noticeably. Flight 5 attempted to extend the 35-mile testing range, but was unsuccessful. Throughput remained low and packet losses were high; however, relatively large fluctuations in the downlink data rate on the bit synchronizers were noted at the ATF. The system was reviewed and it was determined that there could be a problem with using the clock from the bit synchronizer to drive both the transmit and the receive input clocks on the TR. A new firmware version was loaded to the FPGA board to use an onboard crystal oscillator for the transmit clock and the bit synchronizer clock for the receive clock. This also allowed the transmit rate and receive rate to be independent of each other.

Flight 6, October 19, 2005: Flight 6 successfully demonstrated a minimum of 4.5 Mbps throughput to a range of 150 miles with minimal packet loss.

Flight 7, October 28, 2005: The original SOQPSK downlink transmitter was reinstalled. The uplink data rate was set to the usual 5 Mbps and the downlink was increased to 10 Mbps. Packet round-trip time as well as the downlink throughput was improved, and packet loss remained minimal. The range was extended to 160 miles, only losing connection when the aircraft was beyond line of sight with respect to the ATF. Whereas figure 2 depicts a single downlink FTP transfer, figure 3 depicts the end of an uplink test, a nontest period and, a downlink FTP transfer. Comparing these figures shows that a significant performance improvement was achieved from Flight 3 to Flight 7. After correcting the data-clocking problem and reverting to SOQPSK for downlink, the same 190-MB FTP transfer resulted in more than twice the throughput.

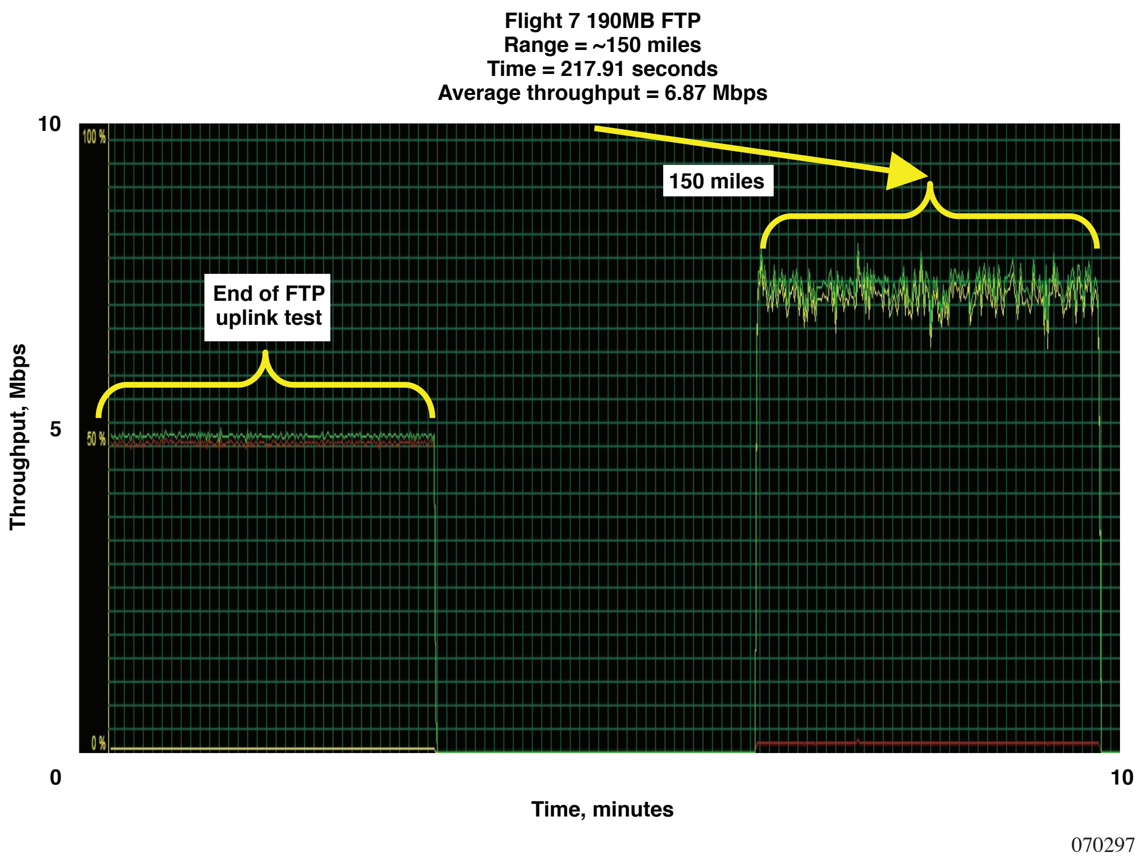

Figure 3. Flight 7 FTP transfer at 150-mile range.

Table 1 provides a summary of each flight configuration.

Table 1. Flight configurations summary.

Flight number	Uplink transmitter	Uplink bit rate	Downlink transmitter	Downlink bit rate	FPGA clock sources for TinyRouter™
1	PCM/FM (L-band)	5 Mbps	5-watt SOQPSK (S-band)	5 Mbps	Receive = bit synchronizer Transmit = bit synchronizer
2	PCM/FM (L-band)	5 Mbps	5-watt SOQPSK (S-band)	5 Mbps	Receive = bit synchronizer Transmit = bit synchronizer
3	PCM/FM (L-band)	5 Mbps	5-watt PCM/FM (L-band)	5 Mbps	Receive = bit synchronizer Transmit = bit synchronizer
4	PCM/FM (L-band)	5 Mbps	5-watt PCM/FM (L-band)	5 Mbps	Receive = bit synchronizer Transmit = bit synchronizer
5	PCM/FM (L-band)	5 Mbps	10-watt PCM/FM (S-band)	5 Mbps	Receive = bit synchronizer Transmit = bit synchronizer
6	PCM/FM (L-band)	5 Mbps	10-watt PCM/FM (S-band)	5 Mbps	Receive = bit synchronizer Transmit = internal oscillator
7	PCM/FM (L-band)	5 Mbps	5-watt SOQPSK (S-band)	10 Mbps	Receive = bit synchronizer Transmit = internal oscillator

SYSTEM PERFORMANCE

The overall performance of the system for each flight configuration was categorized by data throughput, packet loss, and packet round-trip time. The specific tests performed included FTP file transfers, ping requests, and Iperf (ref. 4) measurements. Iperf is software package designed as a network performance testing tool and enables the evaluation of both TCP and UDP transmissions.

Data Throughput

The FTP throughput for each flight is shown in figure 4. The downlink problem is clearly visible on Flights 1 through 3, and because FTP uses the TCP protocol and requires some bidirectional communication, the downlink problem also resulted in poor FTP uplink performance. The throughput measurements above 4.5 Mbps in Flight 3 occurred within the 35-mile range as did all of the Flight 4 measurements. Although the downlink problem remained during Flight 5, some throughput measurements were high and corresponded to small file transfers of between 1 Megabyte (MB) and 37.5 MB for diagnostic purposes. Larger file transfers of between 37.5 MB and 375 MB were used on all other flights. Flights 6 and 7 were the first flights to fully meet the success criteria. Downlink throughput was much increased during Flight 7 by utilizing SOQPSK modulation at 10 Mbps.

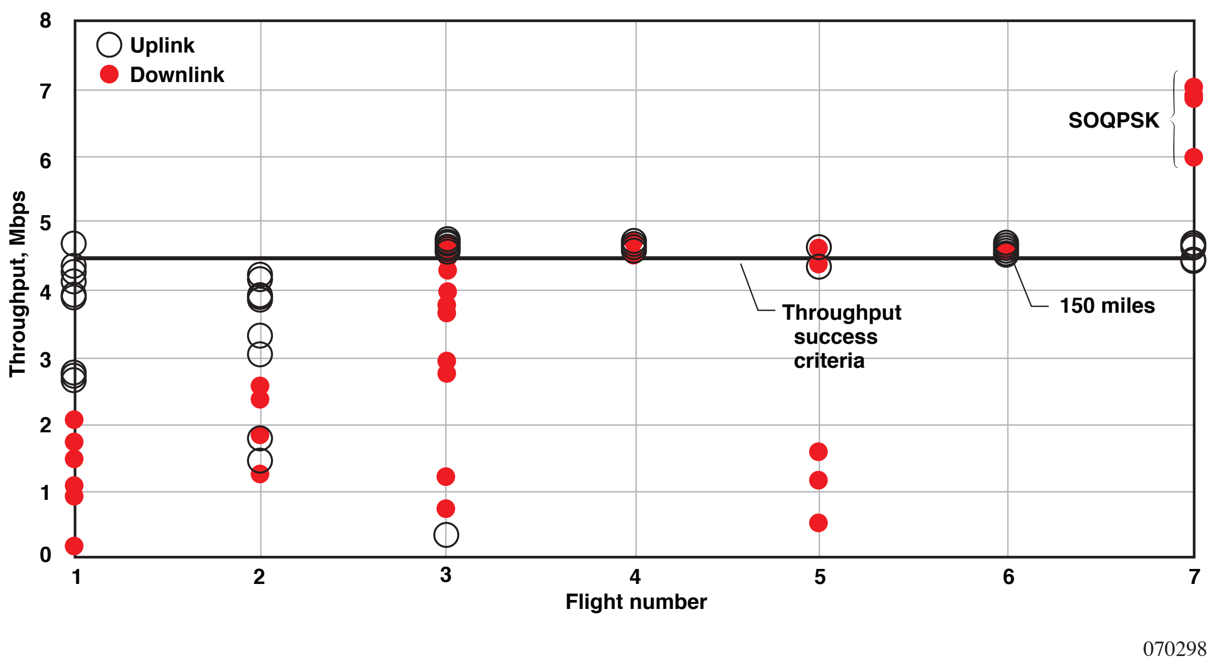

Figure 4. FTP throughput versus flight number.

Figure 5 shows the throughput for each flight as measured by Iperf. Both TCP and UDP downlink throughput suffered on Flights 1 and 2. The high throughput on Flights 3 and 4 is attributed to all Iperf tests having been conducted within the 35-mile range. One Iperf test was conducted on Flight 5; the majority of that flight used FTP transfers for troubleshooting. The UDP downlink throughput approached the bandwidth of 10 Mbps and was measured at a maximum of 9.4 Mbps during Flight 7.

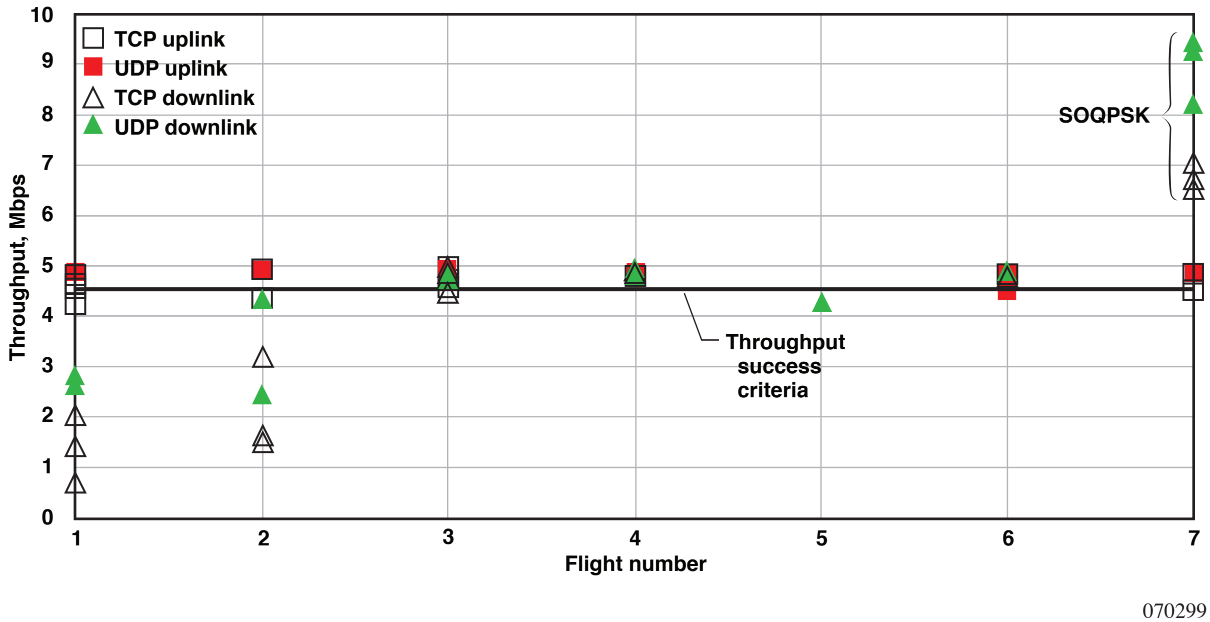

Figure 5. Iperf-measured UDP and TCP throughput versus flight number.

Packet Loss

Two methods were used to measure packet loss: ping tests which required the round trip of packets, and Iperf UDP tests which required only a one-way trip of packets. Ping tests occurred at a 1 Hz rate and utilized packets from 32 bytes to 10240 bytes. Iperf tests occurred at the TM link rate and utilized packets from 8000 bytes to 32000 bytes. Because the larger packets were more susceptible to loss from a single bit error, Iperf packet loss results are generally higher.

The percentage of pings lost is shown for each flight, as well as the baseline ground test, in figure 6. No pings were lost during the baseline. Ping tests were conducted only within the 35-mile range for Flights 3 and 4. It was not until Flights 6 and 7 that the system matched the baseline ground performance at a range of up to 160 miles.

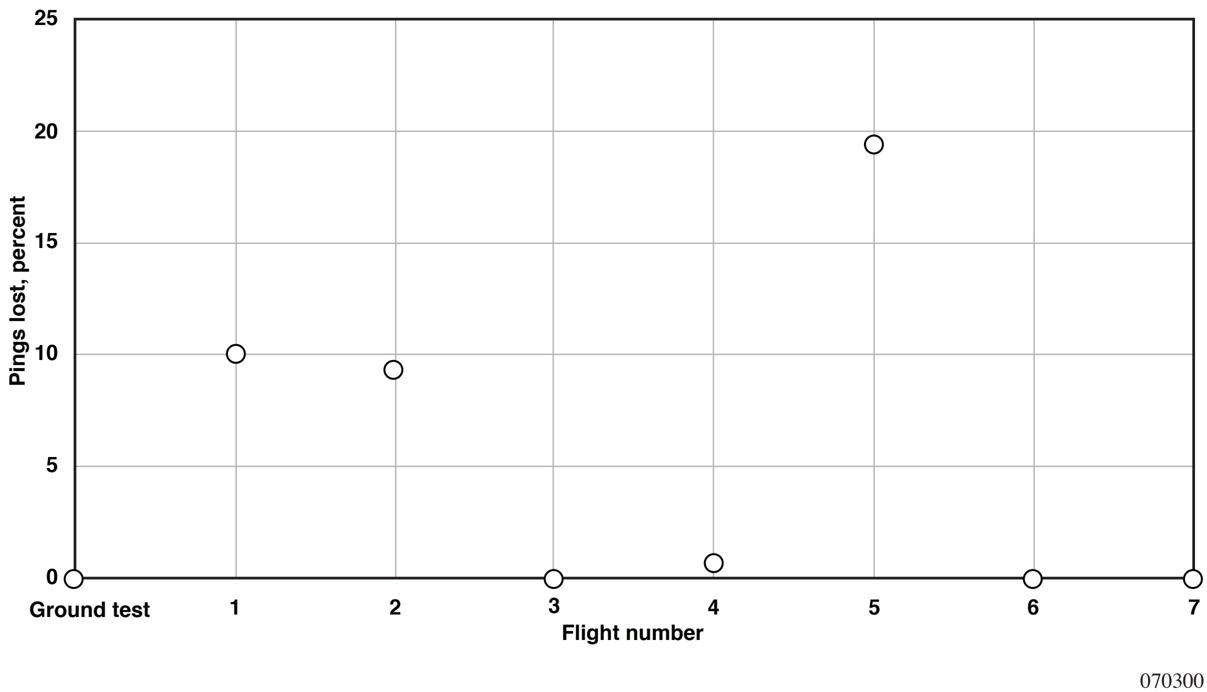

Figure 6. Pings lost versus flight number.

Figure 7 shows Iperf-measured UDP packet losses for each flight. It is important to note that a single bit error will cause an entire packet to be discarded. If packet size is large and bit errors are randomly located in the data, a low bit error rate (BER) can cause a high packet loss. For example, in Flight 7 three packets were lost out of a total of 157, which is a 2 percent packet loss. This relatively high packet loss, however, could be caused by a bit error rate (BER) as low as 7.3E-8, still assuming that a single bit error caused a packet loss. Implementing forward error correction (FEC) algorithms could be beneficial for use in applications in which data retransmission is impossible and data loss is unacceptable.

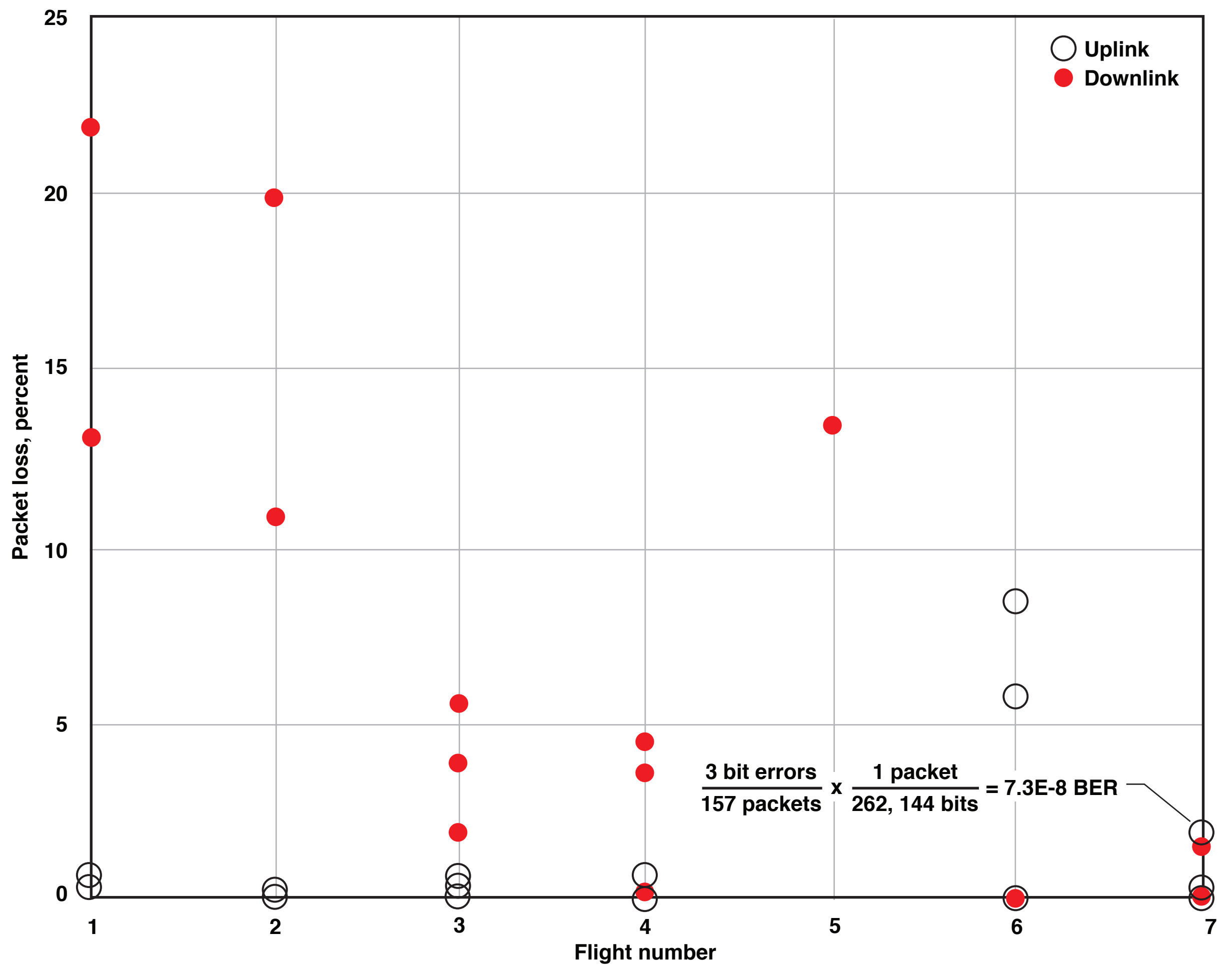

Figure 7. Iperf-measured UDP packet loss versus flight number.

Packet Round-trip Time

Ping tests were conducted for all flights to determine packet round-trip time, and the ground checkout was used as a baseline. The ground checkout was conducted between the ATF and the aircraft, which was parked 1.7 miles away and in line of sight. One important result to note in figure 8 is that for large packets of data (10240 bytes), the round-trip time was reduced by more than 5 milliseconds when using the 10 Mbps SOQPSK downlink transmitter during Flight 7.

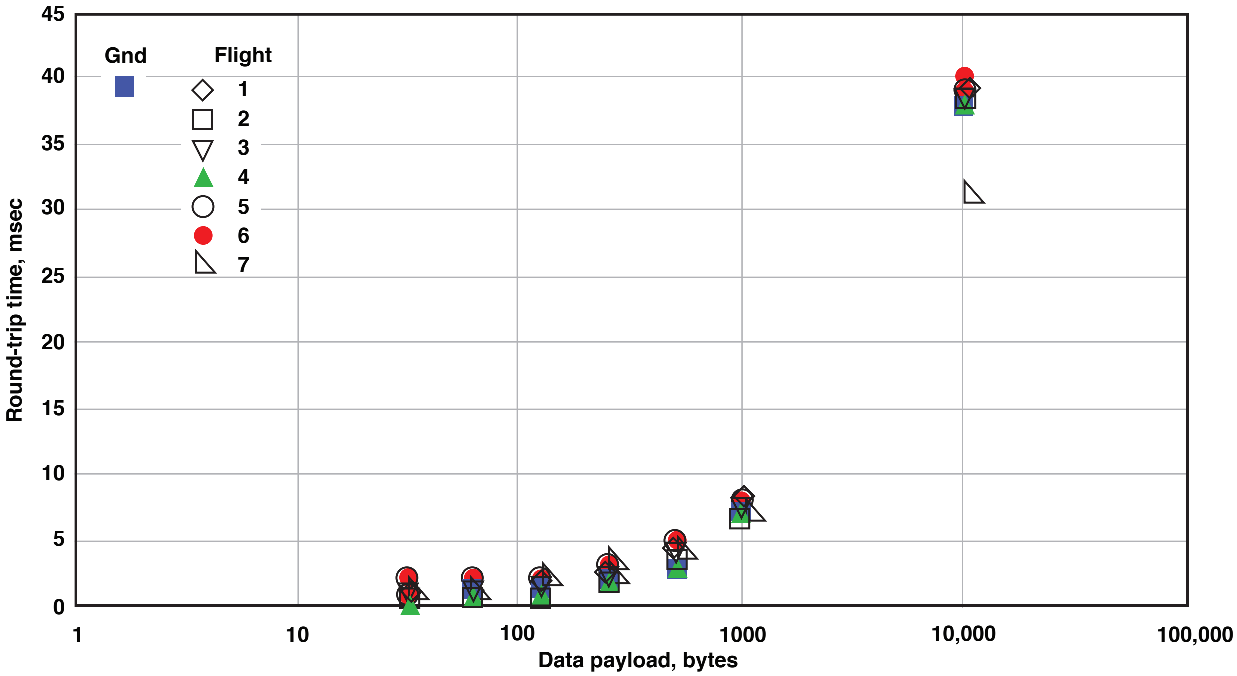

Figure 8. Ping round-trip time versus data payload.

Flight 7 successfully demonstrated the HiWAND link out to a range of 160 miles at an altitude of 35,000 feet. The link was lost only when the aircraft went beyond line of sight from the ATF. Tall mountains of the Sierra Nevada mountain range, particularly Olancha Peak, prevented testing of the link to the point at which the aircraft was over the horizon. The demonstrated 160-mile range was used to generate the HiWAND area of coverage shown in figure 9. The actual area of coverage depends on terrain and obstructions to line-of-sight positioning.

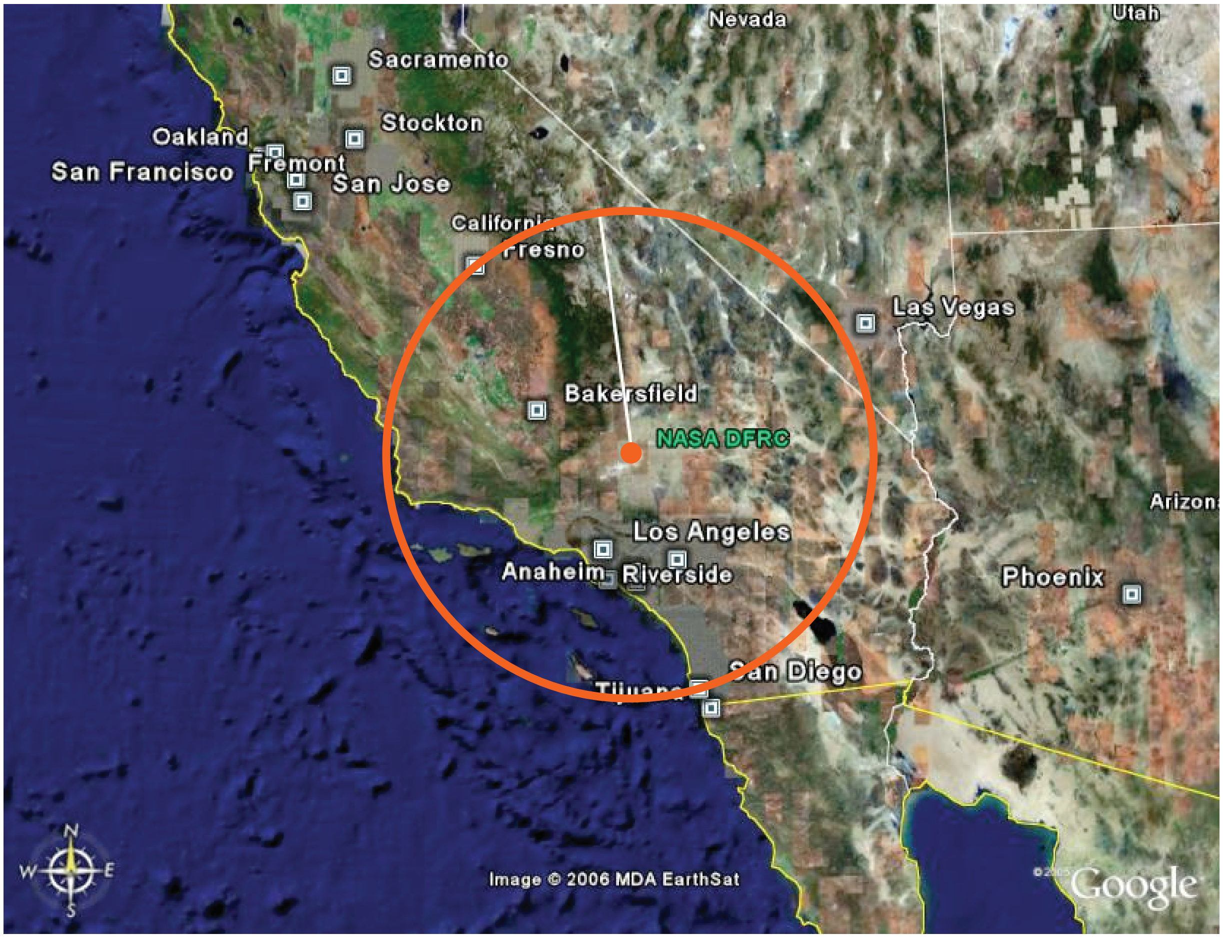

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Figure 9. The High-Rate Wireless Airborne Network Demonstration area of coverage.

ADDITIONAL ACCOMPLISHMENTS

1. Degraded aircraft UHF communications were augmented by text messaging capabilities provided by the HiWAND link and software.
2. Data transfer included both the downlink and uplink of live video.
3. Test points were remotely initiated from both the ground and aircraft.
4. Remote Desktop Sharing with encryption was enabled on the dual-homed ground computer and allowed for the following:
    - Remote control of the ground computer from the aircraft
    - Web surfing, which was used to download weather information and satellite imagery
    - Sending and receiving e-mail on the aircraft.

CONCLUSIONS

As demonstrated by the High-Rate Wireless Airborne Network Demonstration flight tests, commercial off-the-shelf network equipment can be integrated with existing aircraft and test range assets to provide a high-data-rate bidirectional network connection for flight research and airborne science purposes. For a range exceeding 150 miles, transmission control protocol throughput of 4.8 Mbps and user diagram protocol throughput of 4.9 Mbps were achieved using pulse code modulation / frequency modulation over a 5 Mbps telemetry link. In another configuration, shaped-offset quadrature phase-shift keying modulation was implemented for the downlink. Because of the improved bandwidth efficiency of shaped-offset quadrature phase-shift keying compared with pulse code modulation / frequency modulation, the downlink rate was increased to 10 Mbps. In this configuration, transmission control protocol throughput of 7.2 Mbps and user diagram protocol throughput of 9.4 Mbps were achieved.

FUTURE WORK

Such a system could also be used in simplex mode if solely a unidirectional uplink or downlink capability was required. It should also be noted that it would be a fairly simple task to configure the system so that the aircraft is one of many nodes on the Internet; to stream multicast data to multiple destinations around the world; and to allow for remote control, reconfiguration, and reprogramming of airborne systems. The system could also be easily integrated with a satellite communications system to enable high-speed over-the-horizon network communications. Future work will involve miniaturization of the receiver and packaging with the transmitter to create a small form factor airborne Advanced Range Telemetry Tier I transceiver that can be used in conjunction with the TinyRouter™. The new system will enable networking of uninhabited aerial vehicles and high-performance jet aircraft with ground and space assets.

ACKNOWLEDGMENTS

Imagery from Google Earth Pro 4.0.2416 was used to generate figure 9.

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14. ABSTRACT
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