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Using a Balloon Flight for End-To-End Testing of a Nanosatellite Mission

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Abstract

The results of testing the end-to-end system characteristics of a nanosatellite using a high-altitude balloon flight are described. This was the culmination of a senior design project and allowed the final design to be tested in near-LEO conditions. During the flight, the performance of sensors, hardware, and software were tested both in the space segment and the ground segment. From these tests, improvements in the design for actual orbital operations were developed.

1. Introduction

The students, faculty, and technical staff at New Mexico State University (NMSU) executed the design of a nanosatellite as participants in the Air Force University Nanosatellite Program. The New Mexico State University Satellite (NMSUSat) was part of this program managed by the Air Force Research Laboratory. As described in Horan et al., 2003, the planned science mission for the satellite was to perform near ultra violet emission intensity measurements of the earth's upper atmosphere over the night side of the earth. The engineering mission was to demonstrate techniques for distributed data relaying over the Internet and to conduct an energy storage experiment to assess the operational characteristics of double layer capacitors. The educational mission of the program was to assist in the further development of the aerospace engineering concentration area in the College of Engineering and to develop multi-disciplinary capstone design classes for students in engineering departments, computer science, and the engineering physics program. Based on in-lab experimenting, the original engineering mission plan of testing supercapacitors was dropped because they did not provide any real component-level power supply assistance as was initially thought they could due to the long recharge time given the available power in the overall design. The testing to be performed here was designed to validate the sensors chosen for the scientific measurements, most of the space segment subsystems, the operational software for the space and ground segments, and the ground segment hardware.

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The design and operational development of the NMSUSat project was based in the senior design classes provided in the College of Engineering at NMSU. Seniors could choose this class as one of their design experience options. Students in the design class took the class over a two-semester period and there were four cohorts in the design process with a total of 42 students participating. We also had four students work on varying aspects of their master's projects participate. As part of the pre-college outreach for the program, we had 12 students participate in highly-structured design support activities such as writing code segments. Most of the student participants came from the Electrical and Computer Engineering and the Aerospace and Mechanical Engineering departments. Additional students came from the Engineering Physics program and other departments in Engineering. In each class offering, students worked in small teams developing and testing the technology. Often, several iterations were possible over the four-year total design period. During the design classes, the students needed to make formal design review presentations that fed into the programmatic presentations required under Air Force sponsorship. The formal design review presentation process and templates were made a part of the overall Electrical Engineering senior design process for all projects.

The nanosatellite payload originally developed from the design class was not chosen by the Air Force to be launched into low-earth orbit. An alternative flight opportunity was obtained on a high-altitude research balloon that was expected to allow the final cohort to obtain some form of flight experience plus enable characterization of the mission elements. For this flight opportunity, the mission was renamed to BalloonSat to reflect the change in the operational envelope. The research balloons used in the flight operate at 36 km altitude for 24 hours. With this type of mission, the sensor design and the software design can be tested in a near-space environment. Also, the command and control operations of the payload can be fully tested. While the science and engineering environments do not exactly match the orbital case, they are considerably more challenging than a bench test and can be used to validate the orbital requirements. In particular, they are close enough to an orbital environment to test the operational performance of the main science sensor.

In this paper, we will discuss the flight configuration of the BalloonSat payload, the specific test goals of the flight, how the balloon flight operated, and the results of the tests during the flight.

2. BalloonSat Configuration

The BalloonSat had two major segments that needed to interoperate: the space segment and the ground segment. The space segment was designed to sustain the primary science goal of measuring the earth's background brightness level at 300 - 450 nm at least once per minute with associated position and timing information. To achieve this goal, the space segment was designed with the following elements:

- an aluminum structural bus to hold the components,
- photomultiplier tubes for making the science measurements,
- computer to control the payload elements and collect the data,
- communications system for command and telemetry data exchange with the ground station,
- power switching to control the on/off state of each subsystem except for the flight computer, and
- a data acquisition system and sensors for health and status monitoring.

The bus structure is a grid pattern based on the 3 Corner Sat mission design (see Horan et al., 2002). The bus can be seen in Figure 1. The health and status monitoring sensors are described in Horan, 2008. The health monitoring was battery voltage, temperatures of the flight computer and photomultiplier tubes, earth sensors, and subsystem on/off power switch settings. The communications and command & telemetry operations are described in Horan et al., 2008. Commands were sent as short text packets in the format of Synch Word + Subsystem ID + Action. The packets had error detection coding to prevent bad commands from being accepted by the flight computer. The original

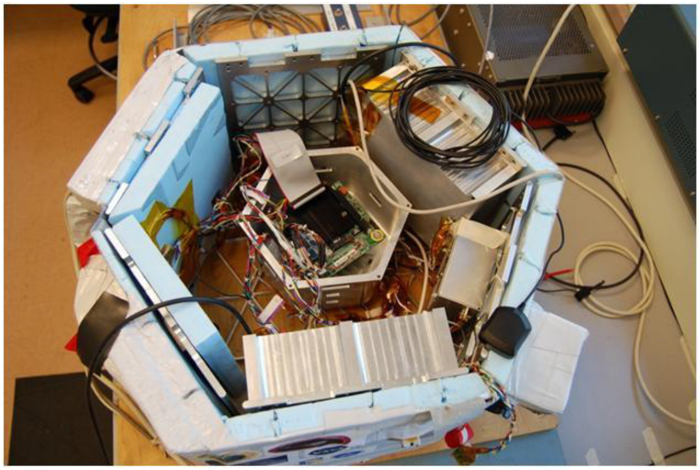

Figure 1. Payload electronics being prepared for launch. Blue foam insulation is placed around the structural walls for hermal control.

nanosatellite design had solar panels and an internal battery pack as part of the design. The balloon platform accommodation provided sufficient power to run the BalloonSat for over 24 hours so the solar power and internal battery system were not flown. The original nanosatellite design did not have an attitude control system, so six photomultiplier tubes were included. For the BalloonSat, only two tubes were used since orientation was properly maintained by the carrier. The electronic components were chosen to have extended temperature ranges whenever possible. Generally, this allows the electronics to operate below -20°C. The photomultiplier tubes were a major exception, having a lowest operating temperature of 10°C. The tubes were wrapped with an electrical heating tape that could be turned on and off by operator control. The balloon thermal environment is more difficult than the LEO environment due to the 8-hour hot and cold soaks rather than the 90-minute orbital variation. To accommodate this temperature profile, the satellite was wrapped in construction foam to provide insulation. This can be seen in Figure 1 where the open payload is shown with the structural elements, the flight computer, and insulating foam.

The BalloonSat was then attached to a carrier that was suspended beneath the balloon. The carrier also held the NASA infrastructure for running a balloon flight: NASA communications, tracking, control, and power. The BalloonSat did not use this equipment; rather, it had its own communications and GPS. Con-

Figure 2. The BalloonSat payload is mounted on the right side of the carrier at the flight line ready for launch. The carrier is suspended from the release vehicle.

Figure 3. The balloon inflated for launch. Note that this is not the fully inflated volume of the balloon at float altitude.

trol was provided by operator real-time commands over the radio link or via stored commands. The power supply was a battery pack mounted and controlled independently of the NASA equipment. The placement of the BalloonSat on the carrier is illustrated in Figure 2. This carrier is attached to a helium balloon that is illustrated in Figure 3.

The flight control software was developed using LabVIEW® and loaded onto the flight computer as a Windows® executable. The flight computer was a PC/104 single-board computer with 16-channel analog-to-digital converter, USB and RS-232 ports and 4 GB memory. The software design is described in Horan, 2008.

The mission utilized two ground stations during the flight: the primary station at the Fort Sumner, NM launch point and a down-range station at Holbrook, AZ. The ground station was based on the following elements:

- amateur radio VHF/UHF transceiver that operates at 1200 bps data rate for command and telemetry data;
- dual-band omni directional antenna;
- laptop computer with the operator interface and real- time data processing software; and
- Internet connection.

The command and telemetry data were transmitted using the NMSU amateur radio club call sign using the AX.25 protocol and amateur-standard call sign designators for the balloon and ground station. The operator interface on the laptop computer was developed in LabVIEW and is described in Horan, 2008. The operator interface is illustrated in Figure 4.

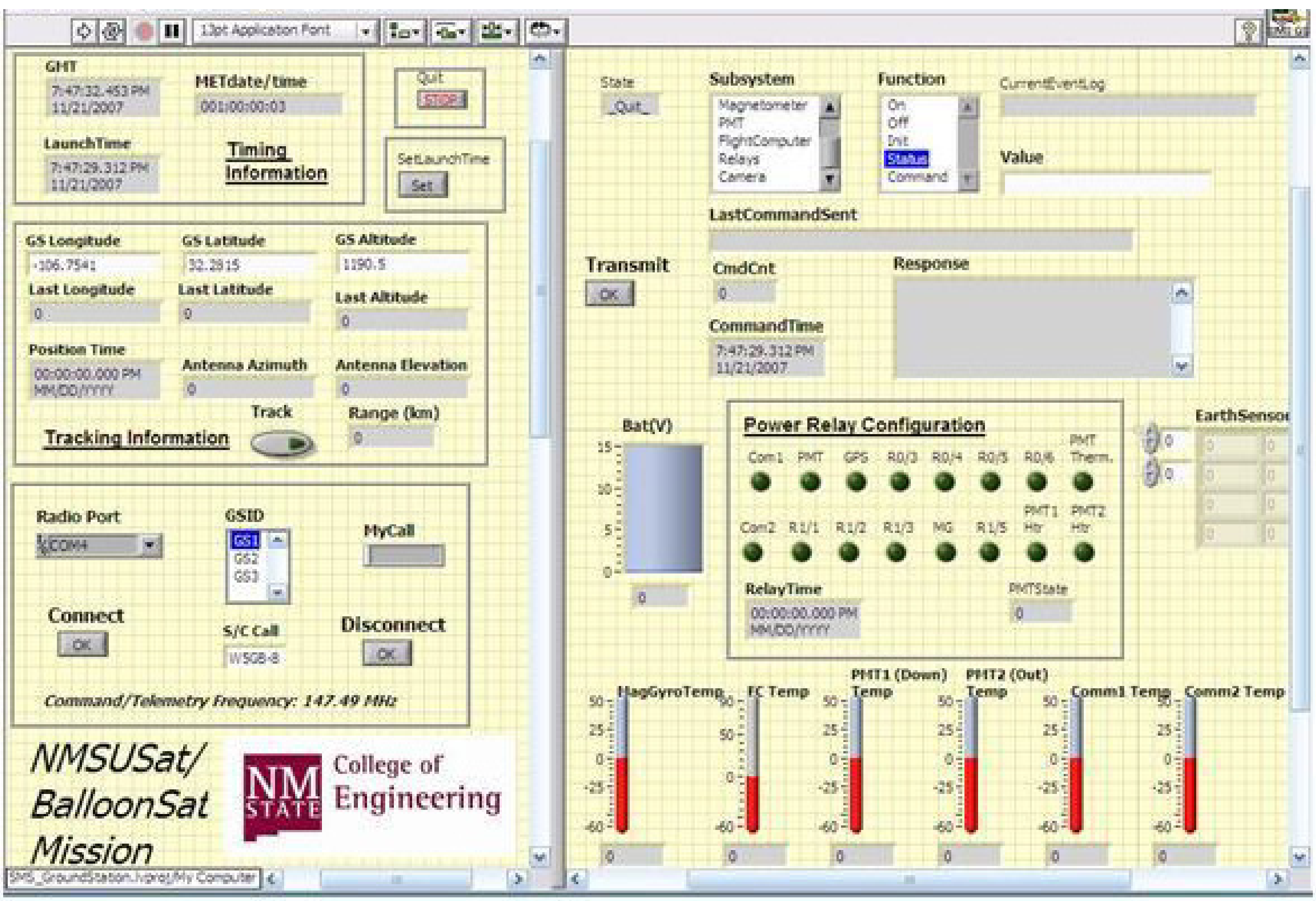

Figure 4. Ground station user interface running as a LabVIEW executable.

The Internet connection was required to permit remote control of the BalloonSat from either the Fort Sumner or NMSU campus locations when the payload was out of radio contact from the Fort Sumner location. (It was always out of radio contact from the NMSU campus.) This remote control was accomplished by having the operator perform a remote log-in to the ground station laptop computer and then control the ground station operations from the remote site. This process is described in Horan et al., 2008.

3. Test Goals

While the total nanosat payload and ground configurations were not tested in this BalloonSat flight, nor was it a "science mission," many critical system tests could still be accomplished. In particular, the specific test program for the BalloonSat mission is summarized in Table 1. In this table, the test is listed along with the mission-oriented goal for the test. The tests are divided into the mission areas of science sensor tests, engineer-

Table 1. BalloonSat Test Program Description

Test	Description	Purpose
	Science Tests	
1	Measure UV intensity on both photomultiplier tubes	Determine if photomultiplier tubes can make a measurement in a LEO-type environment
2	Obtain the measurements between the end of evening astronomical twilight and the beginning of morning astronomical twilight	Necessary for the science goals of the mission (moonlight will adversely affect measurements)
	Engineering Tests	
1	Obtain positioning and timing information from the GPS unit	Necessary for position-tagging the science measurements
2	Synchronize the flight computer's time to the GPS via operator command	Necessary to assure that the flight computer is reporting correct time for time-tagging the data.
3	Demonstrate the capability to set and reset power relays upon operator command	Because all instruments cannot be powered-up simultaneously, we need to verify that we can mange power and control subsystem on/off state
4	Demonstrate the capability to upload a command schedule file to the flight computer	On orbit, operations will need to be autonomous driven by a schedule
5	Demonstrate the capability to automatically collect photomultiplier data at least once every 10 seconds for 45 minutes	Demonstrate operations for a typical night side of the orbit
6	Demonstrate the capability to control the payload from at least two locations	To demonstrate operational flexibility and ground station networking capabilities.
7	Demonstrate the capability for the payload to operate without continuous operator involvement	Payload needs to operate autonomously on-orbit.
8	Test operations of candidate earth sensor design	Student-designed attitude control sensor test
9	Remotely operate ground stations over the Internet from a common operations point	To demonstrate operational flexibility and ground station networking capabilities
	Outreach Tests	
1	Transmit the position at least once every 5 minutes via Automatic Position Reporting System (APRS)	Provide a means to engage the public with spacecraft operations
2	Transmit the telemetry snapshot at least once every 5 minutes via APRS	Provide a means to engage the public with spacecraft operations
	Optional Test	
1	Demonstrate the capability to download a JPEG thumbnail image under operator control	Demonstrate photography from near-space environment

ing tests and outreach tests. While some of the tests, such as commanding, are not limited in time as they would be during an actual satellite pass, we can still determine the time necessary to complete a command transaction and then determine if it would have been possible during an orbital flight.

The primary science testing is to determine if the photomultiplier tubes can measure any signal above the noise threshold and below tube saturation. This testing cannot be performed in a laboratory setting because there is uncertainty about the exact signal level that is expected in nature. The engineering tests are to verify that each of the subsystems performs as expected and that the subsystem can be controlled through either a specific operator command or through executing a command file of pre-stored commands.

Each of these tests is based on operational procedures developed during in-laboratory testing and now executed in a mission environment. The outreach test was to see if the amateur radio Automatic Position Reporting System (APRS) sites on the Internet would capture and forward the real-time data from the operational altitude.

4. Flight Operations

The first step in the balloon flight process is to request the flight from NASA's Columbia Scientific Balloon Facility. Over several months, the exact flight was negotiated with NASA and we were able to secure a ride as an attached payload on a NASA engineering test flight scheduled for the Spring 2008 campaign. Because this flight was a scheduled engineering test, the flight opportunity was acquired at no cost provided that we did not place constraints on launch date, flight duration, or flight reliability. Additionally, NMSU could only ask for minimal accommodations on the balloon carrier, batteries, and ground station support.

Prior to the flight, the payload and the NASA infrastructure are required to pass an electromagnetic compatibility test. This test involved both the user payload and the NASA electronics being powered and operating, including data transmission, and then verifying that no apparent interference is present. This test is conducted with all of the electronics on the carrier in normal flight position with all antennas in the operation as illustrated in Figure 5.

Figure 5. The BalloonSat payload and NASA electronics during the EMI compatibility testings.

The actual balloon launch occurred approximately one hour after sunrise on May 31, 2008 from Fort Sumner, NM and cut down occurred late in the afternoon of June 1, 2008 near Winslow, AZ. The flight path is illustrated in Figure 6. Two NMSU personnel operated the ground stations: one near Fort Sumner and one on the NMSU campus who could switch between the primary and down-range ground stations by using the remote log-in capabilities over the Internet.

5. **Results**

The sensor and subsystem test results of the flight are given in Table 2. These test requirements were determined to be the minimum performance criteria necessary to give confidence that the payload would most likely operate as intended on orbit. An estimate is

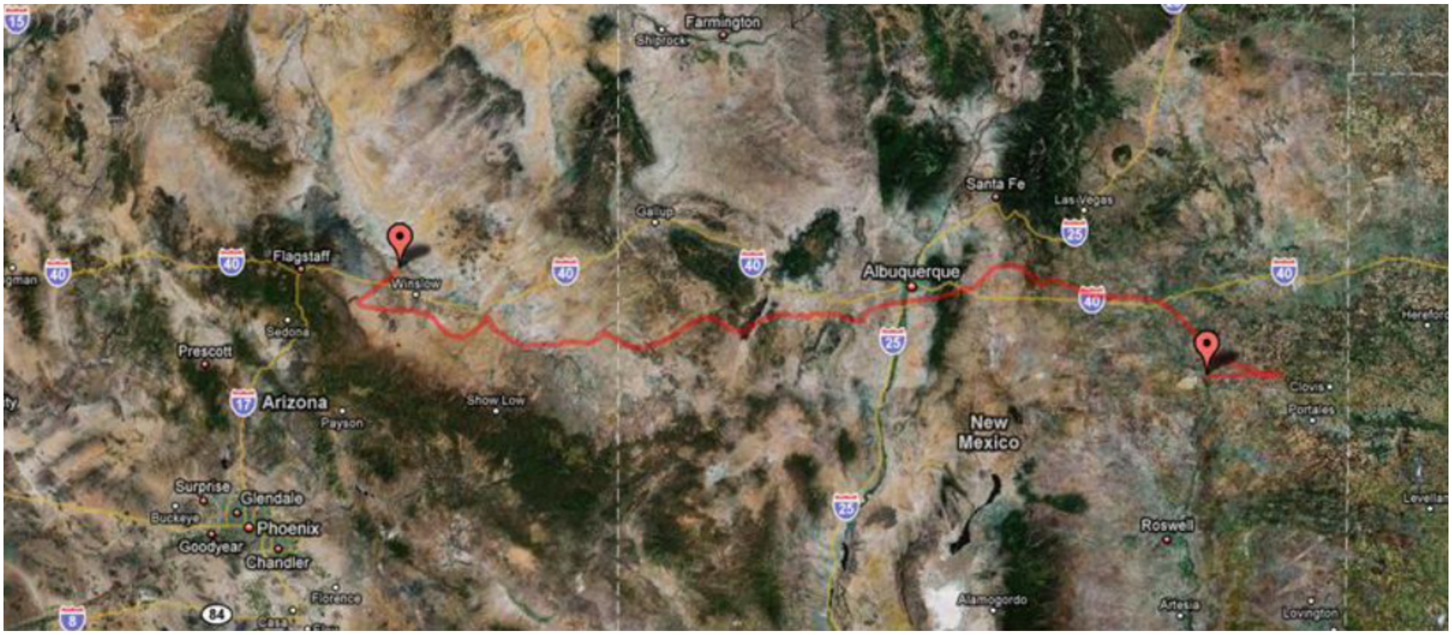

Figure 6. BalloonSat flight ground track over New Mexico and Arizona.

given of the level of success for each test.

As presented in Table 2, the science sensor did make measurements during the over-night hours of the flight. The counts were approximately 1000 times the tube dark current and well below saturation. Since the tubes were not calibrated, no attempt was made to characterize the meaning of the measurements.

While not required for the science mission of the payload, a camera was attached to the payload to give additional command and telemetry test points. An example photograph taken by operator command is given in Figure 7. Labeling features in the field of view were added as part of the post flight work. This image was saved to the flight computer flash drive during the flight and extracted after payload recovery.

As an operational experience, the team was satisfied with the overall result. Subsystems were exercised in a “hands-off” mode with the payload in a near-space environment. While not all subsystems worked perfectly, the level of operation was sufficient to point out where improvements were needed. The space segment and ground segment software received a rigorous test and demonstrated that the basic operational concept and procedures were working.

These results provided us with the following lessons learned on the operation of the payload electronics:

1. The command and telemetry communications link was very sensitive to multipath and link losses when the payload was close to the local horizon at a distance of approximately 100 miles away. The original design was to use a Yagi antenna with a gain

Figure 7. Example of a photograph taken by operator command during the flight. Altitude was approximately 36 km and shows the Laguna del Perro region between Estancia and Willard, NM, and the Rio Grande valley south from Albuquerque, NM towards Mexico.

Table 2. BalloonSat Success Criteria and Performance Achievements.

Goal	Minimum Success Criteria	Performance Achieved	% Achieved	Comments
		Science Tests		
1	Measure UV intensity on both photomultiplier tubes at least once every 10 seconds for at least 45 minutes	Measured intensity on both photomultiplier tubes every 10 seconds for 49 minutes	100%	Sensors did not last much longer than the minimum.
2	Obtain the measurements between the end of evening astronomical twilight and the beginning of morning astronomical twilight	Measurements began 2 hours after the end of astronomical twilight and extended until 3 hours before the beginning of morning astronomical twilight.	100%	
		Engineering Tests		
1	Obtain positioning and timing information from the GPS unit at least once every 5 minutes	GPS positioning measurements were obtained through 12362 m (40551 ft).	50%	GPS unit was still communicating with flight computer; positions were invalid above 40 kft where we suspect that the thermal limits on the active antenna were exceeded.
2	Synchronize the flight computer's time to the GPS via operator command	Synchronization was performed on the flight line prior to launch.	100%	
3	Demonstrate the capability to set and reset power relays upon operator command	PMT, GPS, magnetometer, Communications 1, and PMT heater relays all set and reset by operator command	100%	
4	Demonstrate the capability to upload a command schedule file to the flight computer	Command schedule file was uploaded prior to launch while payload was on the flight line. An attempt to upload a modified schedule during flight was unsuccessful.	75%	Command schedule upload failure was unsuccessful due to link quality problems. Link was designed for use with a ground station antenna with 10 dB more gain.
5	Demonstrate the capability to automatically collect photomultiplier data at least once every 10 seconds for 45 minutes	Data were collected automatically every 10 seconds for 49 minutes.	100%	
6	Demonstrate the capability to control the payload from at least 2 locations	Payload was controlled from Fort Sumner, NM and Holbrook, AZ.	100%	
7	Demonstrate the capability for the payload to operate without continuous operator involvement	Payload operated autonomously during the handover period between ground stations.	100%	
8	Test operations of candidate earth sensor design	Earth sensor measurement made every 3 minutes as part of payload status measurement.	100%	
9	Remotely operate ground stations over the Internet	Control of the payload through the two ground stations was accomplished over the Internet from NMSU.	100%	
		Outreach Tests		
1	Transmit position at least once every 5 minutes via APRS	APRS position beacons transmitted and received in the APRS network.	100%	
2	Transmit the telemetry snapshot at least once every 5 minutes via APRS	APRS telemetry beacons transmitted and received in the APRS network.	100%	

Table 2. (cont.). BalloonSat Success Criteria and Performance Achievements.

	Minimum Success Criteria	Performance Achieved	% Achieved	Comments
Optional Tests				
1	Take pictures from operator command	5 photos were taken by operator command.	100%	
2	Demonstrate the capability to download a JPEG thumbnail image under operator control.	Transmission was attempted but unsuccessful due to link errors.	25%	Link was designed for use with a ground station antenna with 10 dB more gain. Transm

in excess of 10 dB on the roof of a building. Because only omni-directional antennas were available at the ground station sites, the link had a lower signal-to-noise ratio than planned. Yagi antennas will be required for orbital operations to give a better signal-to-noise ratio and eliminate some of the multipath effects.

2. If the link quality cannot be improved by using better antennas, transfer of data files for command and telemetry support is problematic. This will inhibit operations because the periods of poor link quality made the radios undergo a great number of packet retransmissions to correct link errors. This degrades the link throughput to the point where only short bursts of data can be transferred in the equivalent of a 5-minute ground station pass time. Files longer than 128 bytes would have exceeded the pass time in many instances due to the high number of retransmits observed.

3. The mounting and thermal control for the photomultiplier tubes was inadequate. The tubes had insulation around them and they were exposed to the near-vacuum of the flight. Both tubes failed shortly after the end of the "minimum success" time period. Upon recovery, both tubes were inspected for damage and none was observed. We are led to believe that either the temperature or the vacuum caused an electronic fault in the devices. The tubes generate 1000V from the 5V supply, so arcing in the near-vacuum is a possible failure mode. The overnight control operator attempted to keep the tube temperatures above the 10°C lower limit by cycling the heating tape on and off. However, the heating efficiency was inadequate due, in part, to the near-vacuum conditions, only permitting a narrow heat conduction path between the thermal tape and the electronics where the sensor was located. After the flight, the participants decided that a pressurized repackaging to prevent arcing and give better thermal control would be needed for the tubes, and further testing is required before orbital use.

4. The active antenna for the GPS appears to be quite sensitive to the cold. The GPS system stopped providing position information above 40,000 feet altitude, although the unit was still in communication with the flight computer. The unit worked again after recovery and operated in a room temperature environment. The antenna was mounted on the exterior of the payload and the outside temperature at this altitude is below the temperature rating for the antenna. A tuned wire antenna should be used as a replacement. For orbital operations, a GPS without ITAR restrictions will be required in the design.

5. While no attempt was made to interpret the photomultiplier tube data, it was believed by the project scientist that a co-aligned camera to sample the field of view will be helpful in interpreting the data when a science mission is flown. That additional camera should be added to the design.

6. Additional thermal considerations are needed for the flight computer. The computer electronics were rated at operational through 80°C and by the time of local sunset, the temperature inside the flight

computer box was 75°C. No computer anomalies were observed, but a cooling method should be considered on similar test flights. Other than the photomultiplier tubes, no other components were observed to come near their temperature limits on either the day side or the night side of the flight.

The overall use of a balloon flight to test the payload resulted in the following lessons learned:

1. The use of the balloon gave a test environment that was more challenging than that available in the laboratory. For example, multiple link impairments on the command and telemetry link were naturally generated. The low atmospheric pressure is similar to a vacuum, so that orbital aspect is well simulated.
2. The use of a flight mission also forces the operators to work in a "hands-off" manner. If there is a problem, real-time problem solving skills are needed and a system reset is not always possible.
3. Operators experience realistic stress conditions, such as needing to operate the payload in the middle of the night.

6. Conclusions

In this paper, we have demonstrated the usefulness of a balloon flight in testing the components of a nanosatellite and demonstrating operations in a near-space environment. The BalloonSat project was used as a successful senior design project and technology testbed. The project sustained senior design projects for four academic years and gave students experience working in cross-disciplinary projects. Formal design reviews were part of the design process and the format for the presentations was a "technology transfer" into the reviews for the other Electrical Engineering senior design projects. From the flight lessons learned, subsequent design projects for follow-on cohorts were identified. Therefore, this project was successful in meeting its educational goals.

Using a non-pressurized design for the housing of the photomultiplier tubes was discovered to be a critical weakness that would have made for a one-orbit science mission if the nanosatellite had been launched to orbit. Generally, the operations were shown to work as intended. Communications were found to require a better antenna system but were not unworkable. The goal of demonstrating control over the Internet from a remote site was achieved. This demonstration gives confidence in having networked ground stations for operational support. The low-cost, low-risk flight opportunity discussed here enabled the team to discover weaknesses and verify operations before an on-orbit flight opportunity. Additionally, the recovery of the payload allowed for inspection of the components after exposure to near-space conditions.

Acknowledgments

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References

Horan, S., et al. (2002): The Three Corner Satellite Mission., in *Proc. International Symposium Formation Flying: Missions & Technologies*, Toulouse, France.

Horan, S. et al. (2003): The New Mexico State University Satellite (NMSUSat) Mission, in *Proc. 17th Annual AIAA/USU Conference on Small Satellites, SSC03-IX-5*, Logan, UT.

Horan, S. (2008): Using LabVIEW to Design a Payload Control System, in *Proc. International Telemetering Conf.*, 84-02-02, San Diego, CA.

Horan, S., et al. (2008): IP-based Networking as Part of the Design of a Payload Control System, in *Proc. International Telemetering Conf.,* 84-02-03, San Diego, CA.